DarkCosmoGrav 2023
Università degli studi di Pisa

Ultra−relativistic Electroweak bubbles from simplest Higgs portal

SISSA & INFN Trieste
Giulio Barni
gbarni@sissa.it

Supervisor: Aleksandr Azatov

Collaborators: M. Vanvlasselaer
W. Yin
S. Chackraborty

Outline

1. FOPT: What & bubbles dynamic
2. FOPT: Why?
3. Simplest BSM extension of the SM: What & Why?
4. Ultrarelativistic EWPT
5. Production of Heavy DM

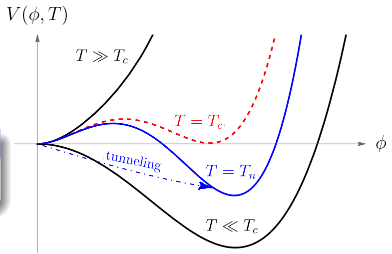
FOPT: What?

FOPT: What?

A FOPT can occur when $\exists\, T_c$ s.t.
two degenerate minima develop

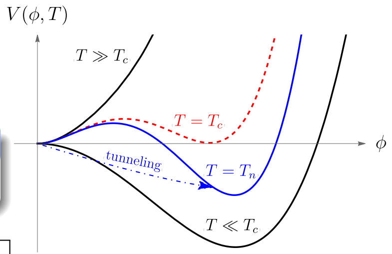
Tunneling decay rate of the false vacuum

$$\Gamma \sim T^4 e^{-S_3/T}, \qquad \text{Euclidean action}$$



FOPT: What?

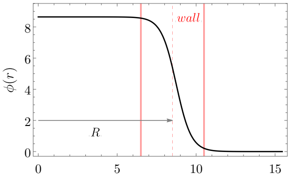
A FOPT can occur when $\exists\ T_c$ s.t. two degenerate minima develop

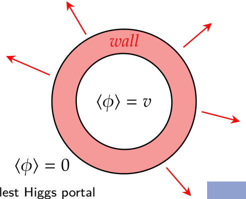


Tunneling decay rate of the false vacuum

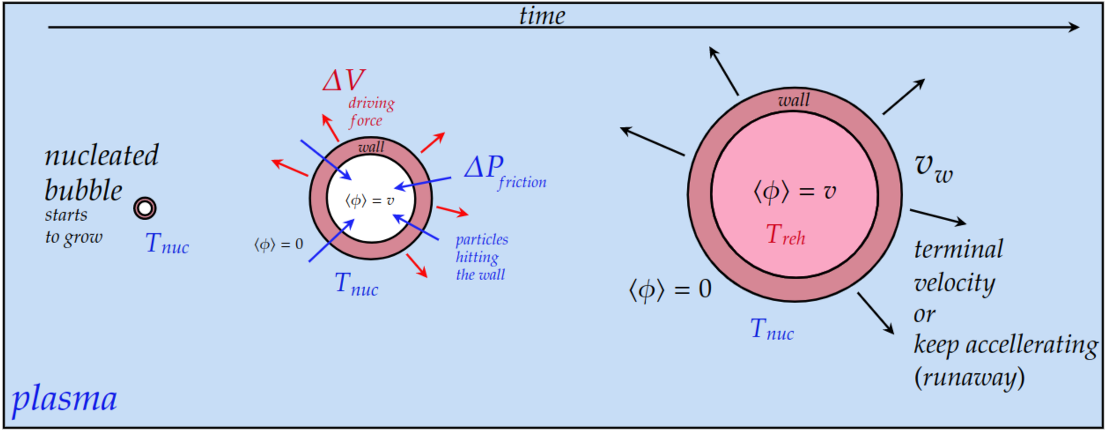
$$\Gamma \sim T^4 e^{-S_3/T},$$ Euclidean action

Solution w/ minimal action [Callan, Coleman (1977)] $\Rightarrow$ $O(d)$ spherical symm. $\phi \equiv \phi(r), \quad r = \sqrt{\tau^2 + x^2}$ $\Rightarrow$ **Bubbles!**





FOPT: Bubble dynamic



FOPT: Bubble dynamic ($\gamma_w \gg 1$)

[JCAP05(2009)009] & [JCAP05(2017)025]: Boodeker, Moore

During the expansion the bubble experiences some pressure:

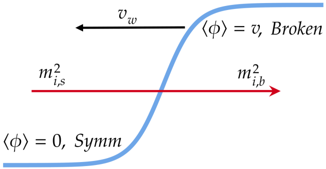
FOPT: Bubble dynamic ($\gamma_w \gg 1$)

[JCAP05(2009)009] & [JCAP05(2017)025]: Boodeker, Moore

During the expansion the bubble experiences some pressure:

1. recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\rm nuc}^2, \quad \Delta m_i^2 = m_{i,bro}^2 - m_{i,symm}^2$$



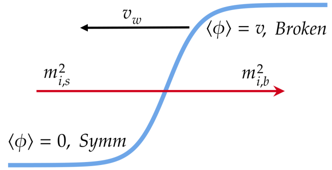
FOPT: Bubble dynamic ($\gamma_w \gg 1$)

[JCAP05(2009)009] & [JCAP05(2017)025]: Boodeker, Moore

During the expansion the bubble experiences some pressure:

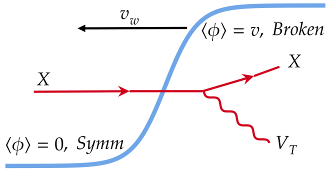
1. recoil of particles getting mass passing through the wall

$$\Delta\mathcal{P}_{LO} \sim \sum_i c_i \frac{\Delta m_i^2}{24} T_{\rm nuc}^2, \quad \Delta m_i^2 = m_{i,bro}^2 - m_{i,symm}^2$$



2. emission of soft vector bosons

$$\Delta\mathcal{P}_{NLO} \sim \sum_i \frac{g_i}{16\pi^2} g^2 m_{V,i} \gamma_w T_{\rm nuc}^3$$

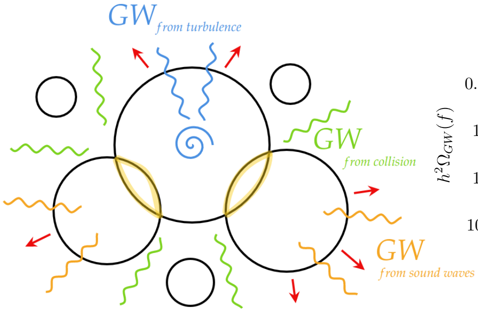


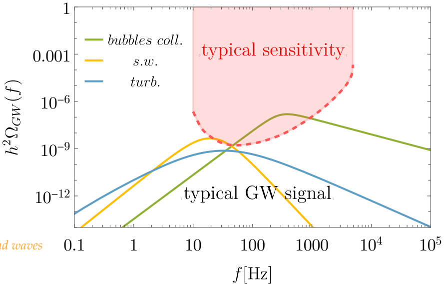
The less $T_{\rm nuc}$ the more γ_w.

FOPT: Why?

FOPT: Why?

1. Bubbles can produce a stochastic GW background from
   - bubble collision
   - sound waves
   - turbulence





Primordial GWs could be observed soon!

FOPT: Why?

[JCAP01(2021)058]: Azatov, Vanvlasselaer

2. Heavy states can be produced if the walls are ultra-relativistic ($\gamma \gg 1$)

FOPT: Why?

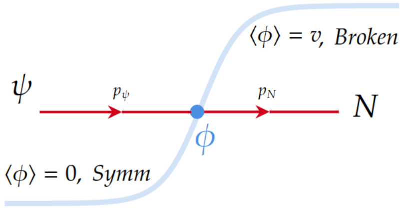
[JCAP01(2021)058]: Azatov, Vanvlasselaer

2. Heavy states can be produced if the walls are ultra-relativistic ($\gamma \gg 1$)

Plasma particle hitting the DW ($\equiv$ **Higgs at rest**)

Wall frame: $p_\psi = (\gamma T, 0, 0, \gamma T) \quad p_\phi = (m_\phi, 0, 0, 0)$

$$\sqrt{s} \sim M_N \sim \sqrt{\gamma T m_\phi} \quad \gg m_\phi, T$$



FOPT: Why?

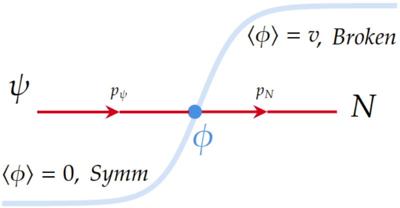
[JCAP01(2021)058]: Azatov, Vanvlasselaer

❷ Heavy states can be produced if the walls are ultra-relativistic ($\gamma \gg 1$)

Plasma particle hitting the DW ($\equiv$ **Higgs at rest**)

Wall frame: $p_\psi = (\gamma T, 0, 0, \gamma T) \quad p_\phi = (m_\phi, 0, 0, 0)$

$$\sqrt{s} \sim M_N \sim \sqrt{\gamma T m_\phi} \quad \gg m_\phi, T$$



Applications:

- **Heavy DM** production
- FOPTs + $C/CP-$**violating** & $B-$**violating** interactions w/ heavy states ⇒ Baryogenesis

Ultrarelativistic FOPTs

Relativistic FOPT: Aim

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

Aim: find general features for relativistic FOPT & explicit relativistic EWPT

Relativistic FOPT: Aim

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

Aim: find general features for relativistic FOPT & explicit relativistic EWPT

- Well-known that **in** SM **all the PT are** 2^{nd} **order**
- **simplest extension of the** SM **with FOPT**: $SM+$ real Z_2 singlet.

$$V_0(\mathcal{H}, s) = \underbrace{-\frac{m_h^2}{2}(\mathcal{H}^\dagger\mathcal{H}) + \lambda(\mathcal{H}^\dagger\mathcal{H})^2}_{\text{Higgs potential}} \underbrace{-\frac{m_s^2}{4}s^2 + \frac{\lambda_s}{4}s^4}_{\text{real singlet}} + \underbrace{\frac{\lambda_{hs}}{2}s^2(\mathcal{H}^\dagger\mathcal{H})^2}_{\text{mixing}}$$

- Already studied in detail but **previous studies not focused on relativistic bubbles**. (usual EW Baryogenesis required slow bubbles)

EWPT: Effective potential

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$V_{\text{eff}}(h,s,T) = \underbrace{V_0(h,s)}_{\text{tree-level}} + \sum_{i\in SM} \underbrace{V_{CW}\Big(\overbrace{m_i^2(h,s)}^{\text{field-dependent masses}} + \Pi_i(T)\Big)}_{1-\text{loop quantum corr.}} + \underbrace{V_T\Big(m_i^2(h,s) + \Pi_i(T),\ T\Big)}_{\text{thermal corr.}}$$

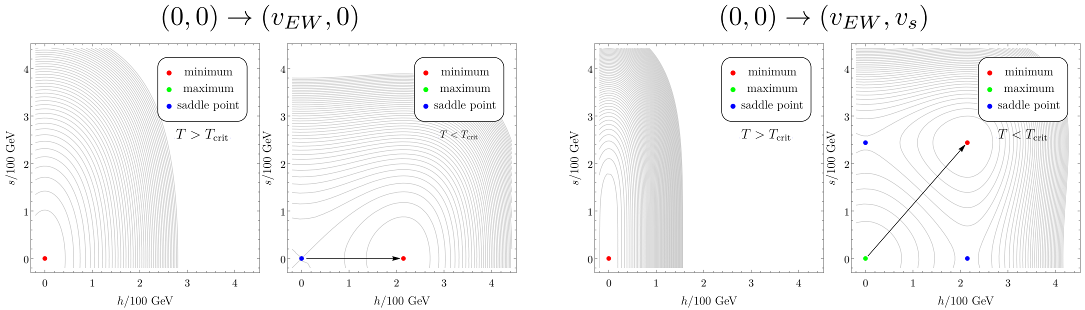
- $V_{CW}(m_i^2(\phi)) = (-1)^{F_i} g_i \left[\frac{m_i^4(\phi)}{64\pi^2}\left(\log\left(\frac{m_i^2(\phi)}{m_i^2(v_\phi)}\right) - \frac{3}{2}\right) + 2m_i^2(\phi)m_i^2(v_\phi)\right]$ (on-shell ren. scheme)
- $V_T(m_i^2(\phi)) = (-1)^{F_i}\frac{g_i}{2\pi^2}T^4 J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right)$ $\quad J_{B/F}(y^2) = \int_0^\infty dx\ x^2 \log\left[1 \mp \exp\left\{-\sqrt{x^2+y^2}\right\}\right]$
- Thermal masses from Daisy Resummation (TFD): $\Pi_i(T) = c_i T^2$

Scalar: $\Pi_h(T) = T^2\left(\frac{3g^2}{16} + \frac{g'^2}{16} + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{\lambda_{hs}}{24}\right)$, $\quad \Pi_s(T) = T^2\left(\frac{\lambda_{hs}}{6} + \frac{\lambda_s}{4}\right)$,

Gauge: $\Pi_g^L(T) = T^2 \text{diag}\left(\frac{11}{6}g^2, \frac{11}{6}(g^2+g'^2)\right)$, $\quad \Pi_g^T(T) = 0$,

Relativistic EWPT: 1−step PT

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

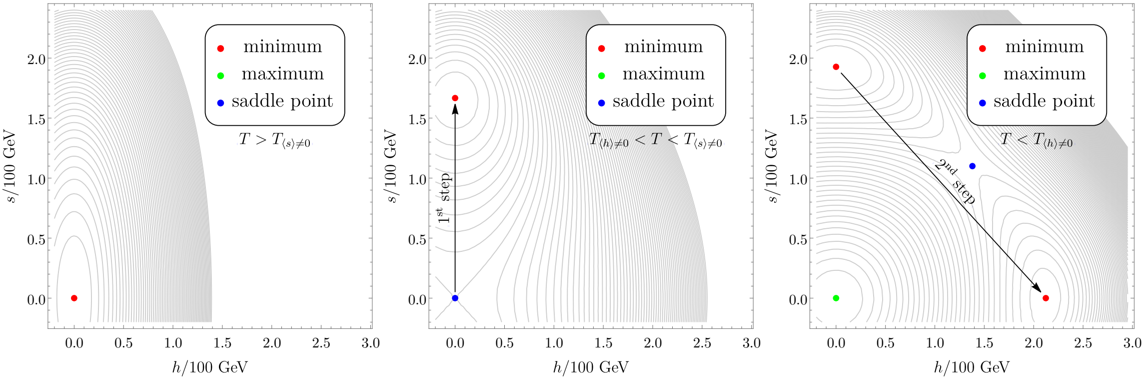


$T^{\rm nuc}_{min} \gtrsim O(100)$ GeV $\quad\to\quad \gamma_w \lesssim O(10)$

$+$ Collider constraints on Higgs-scalar mixing

Relativistic EWPT: $2-$step PT

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin



$$(0,0) \xrightarrow{\quad SOPT \quad} (0, v_s) \xrightarrow{\quad FOPT \quad} (v_{EW}, 0)$$

EWPT: Bounce action

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

Euclidean action S_3/T **contains all the info** about the PT

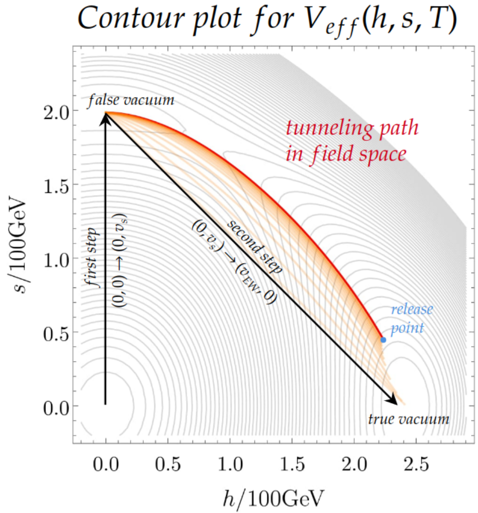
EWPT: Bounce action

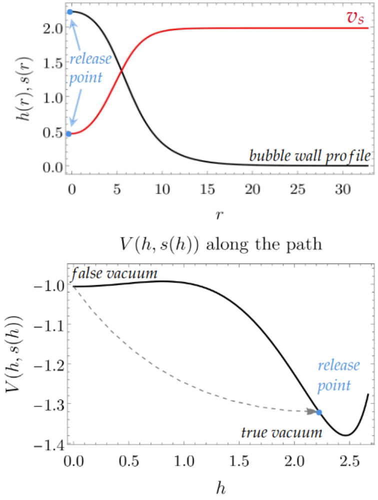
[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

Euclidean action S_3/T **contains all the info** about the PT

$\Downarrow$

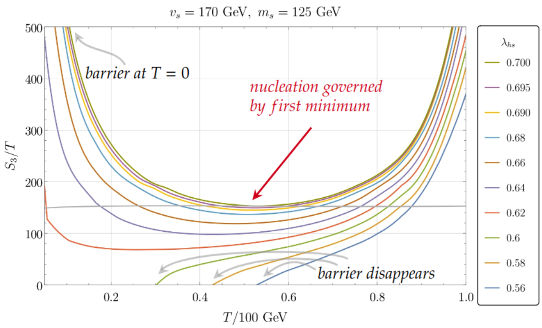
We built our own code for the computation of S_3/T

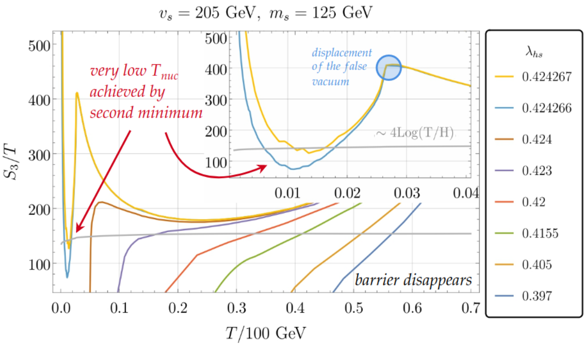




EWPT: Bounce action (II)

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin





Lowest nucleation temperature $T_{nuc} \sim 1$ GeV!

Relativistic EWPT: Parameter scan

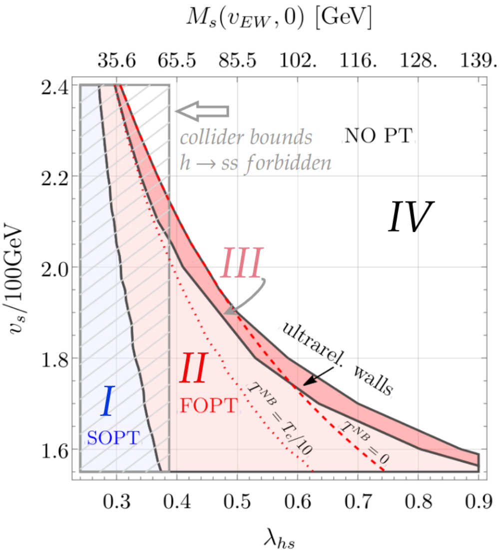
[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

I. SOPT: there is **never a barrier** separating the two minima

II. FOPT

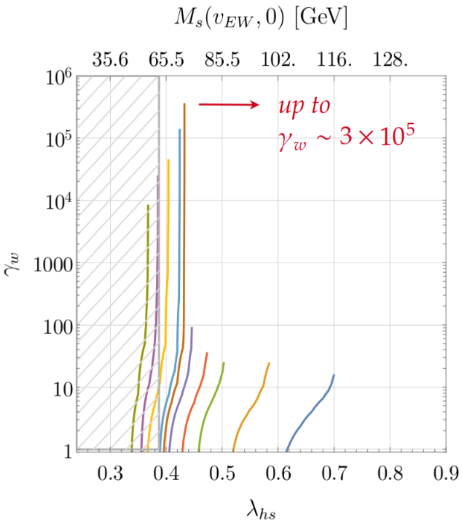
III. Ultrarelativistic FOPT

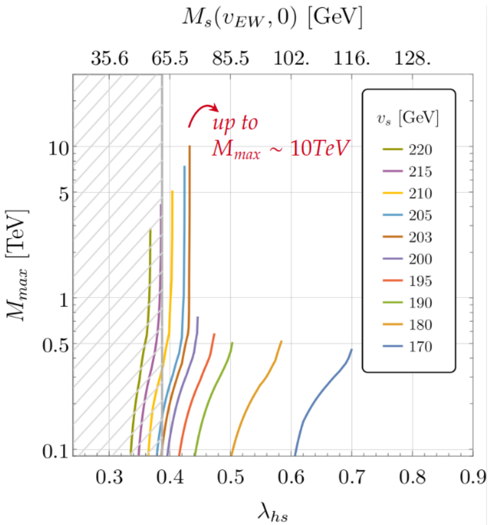
IV. No PT: the **system remains stuck** in the FV and never nucleates



Results for $m_s = 125$ GeV

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin





Heavy particles production through the wall

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

If $\gamma_w \gg 1$ non zero probability of **production of heavy particles**, $P(\text{light} \to \text{heavy}) \neq 0$:

Heavy particles production through the wall

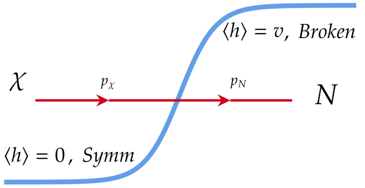
[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

If $\gamma_w \gg 1$ non zero probability of **production of heavy particles**, $P(\text{light} \to \text{heavy}) \neq 0$:

1. **Fermionic transition**: $\mathcal{L} \supset -yh\bar{N}\chi - M_N\bar{N}N$

   χ: light, N: heavy, $h = \tilde{h} + v$

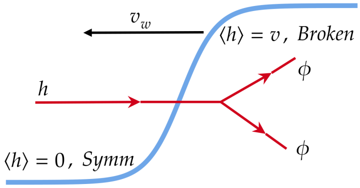
$$P(\chi \to N) \approx \frac{y^2 v^2}{M_N^2}\,\theta(p_z - M_N^2 L_w) \qquad [p_z \sim \gamma_w T_{\text{nuc}}]$$



2. **Scalars emission**: $\mathcal{L} \supset -\frac{\lambda_{h\phi}}{2}\phi^2 h^2 - \frac{1}{2}M_\phi^2\phi^2$

   ϕ: heavy, $h = \tilde{h} + v$

$$P(h \to \phi\phi) \approx \frac{1}{24\pi^2}\frac{\lambda_{h\phi}^2 v^2}{M_\phi^2}\,\theta(p_z - M_\phi^2 L_w)$$



Heavy DM production via Bubble Expansion (BE)

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

After h transition the abundance of massive ϕ, $n^{\phi}_{\rm BE}$ is

$$n^{\phi}_{\rm BE} \approx \frac{2}{\gamma_w v_w} \int \frac{d^3p}{(2\pi)^3} \frac{p_z}{p_0} f_h(p, T_{\rm nuc}) \cdot P(h \to \phi\phi)$$

$$\approx \frac{2}{24\pi^2} \frac{\lambda^2_{h\phi} v^2}{M^2_\phi} \cdot T^3_{\rm nuc} \cdot \exp\left[-\frac{M^2_\phi}{2\gamma_w v T_{\rm nuc}}\right] + \mathcal{O}(1/\gamma_w)$$

2 ϕ emission, wall frame, incident flux, transition probability

After redshifting to today

$$\Omega^{\rm today}_{{\rm BE},\phi} h^2 \approx 5.4 \cdot 10^5 \left(\frac{\lambda^2_{h\phi} v}{M_\phi g_{\star,s}(T_{\rm reh})}\right) \left(\frac{v}{1{\rm GeV}}\right) \left(\frac{T_{\rm nuc}}{T_{\rm reh}}\right)^3 \exp\left[-\frac{M^2_\phi}{2\gamma_w v T_{\rm nuc}}\right]$$

DM production vs observations

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

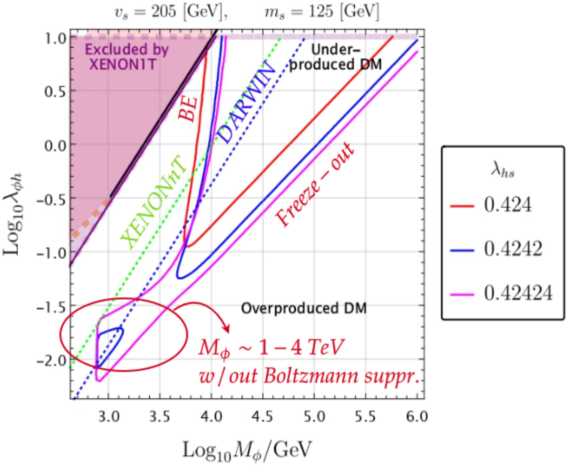
$$\Omega_{\phi,\mathrm{tot}}^{\mathrm{today}} h^2 = \Omega_{\phi,\mathrm{BE}}^{\mathrm{today}} h^2 + \Omega_{\phi,\mathrm{FO}}^{\mathrm{today}} h^2 \approx 0.1$$

DM production vs observations

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

$$\Omega^{\text{today}}_{\phi,\text{tot}} h^2 = \Omega^{\text{today}}_{\phi,\text{BE}} h^2 + \Omega^{\text{today}}_{\phi,\text{FO}} h^2 \approx 0.1$$

1. Inside the isocontours DM is under-produced, outside is over-produced.
2. **Upper curve**: DM production dominated by BE.
3. **Lower curve**: DM production dominated by FO.
4. **Vertical line**: thermal production after reheating.

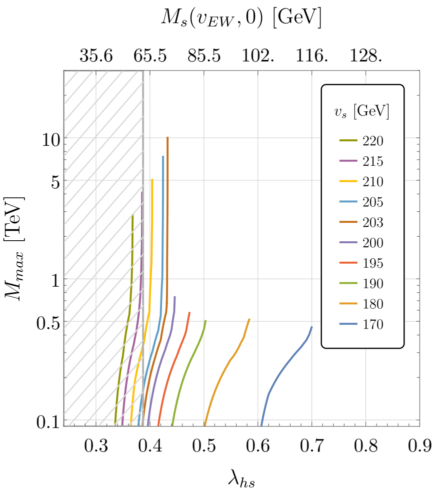


[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

- It has been studied **in detail** an explicit relativistic realisation of the EWPT focusing on **ultra−relativistic parameter space**.

- walls Lorentz factor $\gamma_w^{max} \sim 10^5$
  maximal mass of heavy states $M_{max} \in [2, 10]$ TeV

- This model can account for **heavy DM production** [JHEP10(2021)043]



Thanks for your attention!

Backup slides

Conditions for $2-$step phase transition

Relativistic EWPT: $2-$step PT

$$2-\textbf{step PT}: V_{\rm eff}(h,s,T) \overset{\text{high}-T}{\approx} \overbrace{\underbrace{\left(-\frac{m_h^2}{4}+c_h T^2\right)}_{m^2_{\rm eff}(T)} h^2 + \frac{m_h^2}{8v_{EW}^2}h^4}^{\text{mexican-hat potential}} + \left(-\frac{m_s^2}{4}+c_s T^2\right)s^2 + \frac{m_s^2}{8v_s^2}s^4 + \underbrace{\frac{\lambda_{hs}}{4}s^2h^2}_{\text{mixing}}$$

1. **Correct vacuum at** $T=0$: $m_s^2 v_s^2 < m_h^2 v_{EW}^2$
2. **first step** $(0,0) \overset{SOPT}{\longrightarrow} (0, v_s\neq 0)$: we need $T_{\langle s\rangle\neq 0} > T_{\langle h\rangle \neq 0}$ $[c_s < c_h]$
3. **second step** $(0,v_s\neq 0) \overset{FOPT}{\longrightarrow} (v_{EW},0)$: first order if there is a potential **barrier in** $h-$**direction**, i.e.

$$\left.\frac{\partial^2 V}{\partial h^2}\right|_{v_s, h\to 0} > 0 \quad \to \quad T^{\text{no barr.}} = \sqrt{\frac{m_h^2-\lambda_{hs}v_s^2}{4c_h}}$$

λ_{hs} **controls the size of the barrier** $\to (0,v_s)$ local minimum even at $T=0$

2D Tunneling

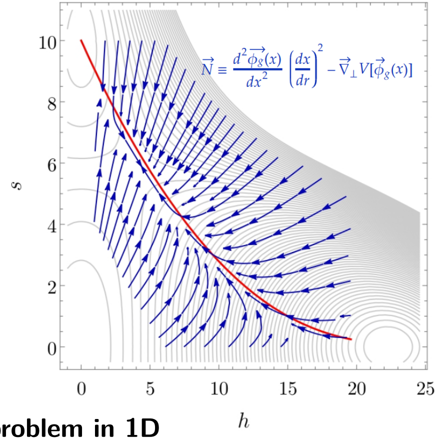
2D Tunneling

[JHEP 10 (2022) 017]: Azatov, GB, Chackraborty, Vanvlasselaer, Yin

EOM : $\dfrac{d^2\vec{\phi}}{dr^2} + \dfrac{d-1}{r}\dfrac{d\vec{\phi}}{dr} = \vec{\nabla}V[\vec{\phi}]$

$$\lim_{r\to\infty}\vec{\phi}(r) = \text{FV}, \quad \left.\frac{d\vec{\phi}}{dr}\right|_{r=0} = 0$$

Difficult to solve, so we can disentagle parallel/perpendicular directions parametrising the path as $(h, s) \equiv (h, s(h))$



Curvilinear abscissa (2D): $x(h) = \int_{h_{\text{fv}}}^{h}\sqrt{1+\left(\frac{ds(h')}{dh'}\right)^2}\,dh'$

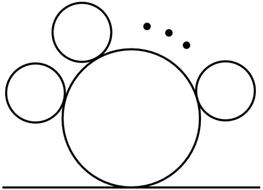
$$\begin{cases} \dfrac{d^2x}{dr^2} + \dfrac{d-1}{r}\dfrac{dx}{dr} = \partial_x V[\vec{\phi}_g(x)] & \textbf{undershoot/overshoot problem in 1D} \\ \dfrac{d^2\vec{\phi}_g(x)}{dx^2}\left(\dfrac{dx}{dr}\right)^2 = \vec{\nabla}_\perp V[\vec{\phi}_g(x)] & \text{can be thought as a force field deforming the path} \end{cases}$$

Daisy resummation

Daisy resummation

$$D = \text{ superficial degree of divergence of a Feynman diagram } (\mathcal{G}) \to \mathcal{G} \sim \begin{cases} T^D & D > 0 \\ T & D \leq 0 \end{cases}$$

- **CW+thermal correction** $=$ $1-$loop resummation
- In FTQFT w/ massive scalar there are two scales: m & T $\Rightarrow$ **large ratio** T/m **must be resummed**
- Daisy resummation takes into account $n-$**loops contribution to the mass**

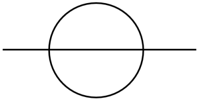


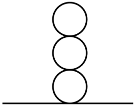
$$\delta m_n^2 \sim \frac{m^3}{T^2}\left(\lambda \frac{T^2}{m^2}\right)^n \sim \frac{m^3}{T^2}\alpha^n \Rightarrow$$

$$m^2_{\text{eff}}(T) \to m^2_{\text{eff}}(T) + \Pi(T)$$

$$\begin{cases} \Pi(T) = \lambda T^2 + \dots & \text{FD procedure} \\ \Pi(T) = \lambda T^2 & \text{TFD procedure} \end{cases}$$

- Still missing (but **negligible if** $\alpha \ll 1$)



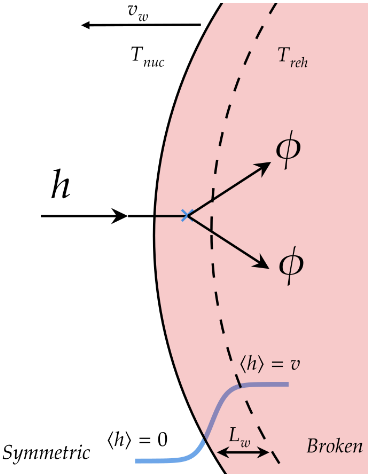


Heavy Scalars emission

Heavy Scalars emission (I)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/ $M_\phi \lesssim T_{nuc} \sim v_\phi$? $\Rightarrow$ $\boxed{n_{heavy} \sim e^{-M_\phi/T_{nuc}}}$



- Toy model w/ ϕ heavy:

$$-\mathcal{L}_{int} = \frac{\lambda_{h\phi}}{2} h^2 \phi^2 + \frac{1}{2} m_\phi^2 \phi^2 \quad M_\phi \gg T_{nuc}$$

- Kinematics in the wall-frame

$$p_a^h = \left(E, 0, 0, \sqrt{E^2 - m_h^2}\right)$$

$$p_b^\phi = \left((1-x)E, 0, 0, \sqrt{(1-x)^2 E^2 - k_\perp^2 - M_\phi^2}\right)$$

$$p_c^\phi = \left(xE, 0, 0, \sqrt{x^2 E^2 - k_\perp^2 - M_\phi^2}\right)$$

when **no wall** $h \to \phi\phi$ forbidden.

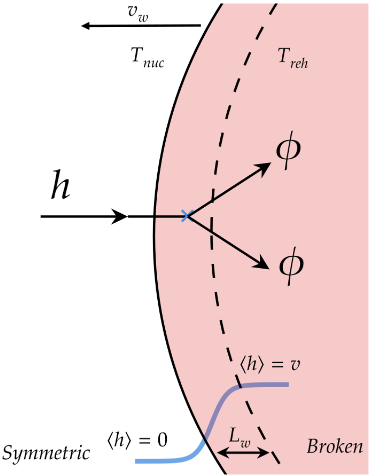
- In **presence of the wall** $\sum_i p_{z,i}$ is no longer conserved:

$h \to \phi\phi$ allowed.

- $\Delta p_z = p_a^z - p_b^z + p_c^z \sim \dfrac{M_\phi^2 + k_\perp^2}{2E_\phi}$

Heavy Scalars emission (II)

[JCAP01(2021)058]: Azatov, Vanvlasselaer



- Matrix element $\mathcal{M}$:

$$\mathcal{M} = \int dz\ \chi_a(z)\chi_b^*(z)\chi_c^*(z)V(z), \qquad V(z) : \text{vertex}$$

- WKB approximation

$$\chi(z) \simeq \sqrt{\frac{p_{z,s}}{p_z(z)}} \exp\left(i \int_0^z dz'\ p_z(z')\right)$$

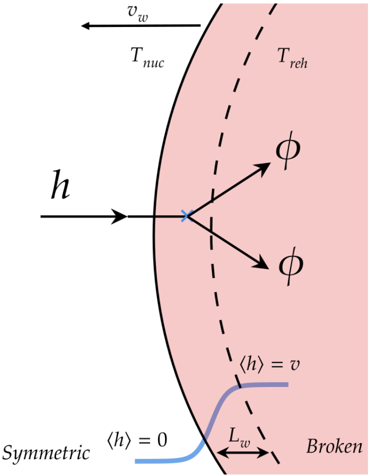
- Assuming a linear wall:

$$h(z) = v\frac{z}{L_w}\Big(\theta(z) + \theta(L_w - z) - 1\Big) + v\theta(z - L_w)$$

$$|\mathcal{M}|^2 \simeq \frac{\lambda_{h\phi}^2 v^2}{\Delta p_z^2}\left(\frac{\sin\alpha}{\alpha}\right)^2, \qquad \alpha = \frac{l_w \Delta p_z}{2}$$

Heavy Scalars emission (III)

[JCAP01(2021)058]: Azatov, Vanvlasselaer



- In the wall frame: $E_h \sim p_h^z \sim \gamma_w T_{nuc} \gg v$
- Transition probability

$$P(h \to \phi\phi) \approx \frac{\lambda_{h\phi}^2 v_\phi^2}{24\pi^2 M_\phi^2} \underbrace{\left(\frac{\sin(\Delta p_z L_w)}{\Delta p_z L_w}\right)^2}_{\text{wall shape effect*}} \underbrace{\Theta(\gamma_w T_{nuc} - M_\phi^2 L_w)}_{\text{need ultrarelativistic wall}}$$

$*$ = assuming a linear wall profile

States w/ $M_\phi \gg T_{nuc}$ can become dynamical during the PT

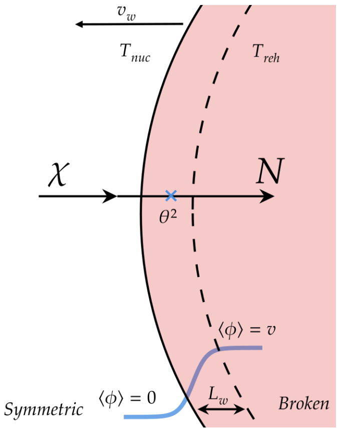
Efficient production: $M_\phi < M_{max} \sim \sqrt{\frac{\gamma_w T_{nuc}}{L_w}} \sim \sqrt{\gamma_w T_{nuc} \langle h \rangle}$

Heavy Fermion transition

Heavy Fermion transition (I)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/ $M \lesssim T_{nuc} \sim v_\phi$? $\Rightarrow$ $\boxed{n_{heavy} \sim e^{-M/T_{nuc}}}$



- Toy model w/ χ light, N heavy:

$$-\mathcal{L}_{int} = Y\phi\bar{\chi}N + M\bar{N}N, \quad M \gg T_{nuc}$$

- In the χ frame

$$p_\chi = (E, 0, 0, E) \quad p_N = (E, 0, 0, \sqrt{E^2 - M^2})$$

when **no wall** $\chi \to N$ forbidden.

- In **presence of the wall** $\sum_i p_{z,i}$ is no longer conserved:

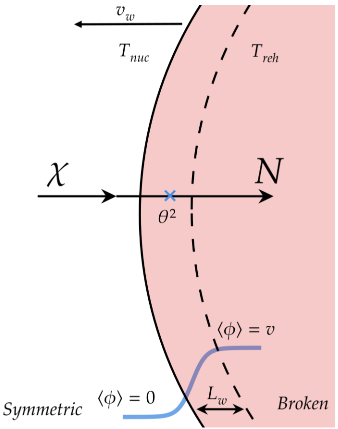
$\chi \to N$ allowed.

- $\Delta p_z = p_\chi^z - p_N^z \sim \dfrac{M^2}{2E_\chi}$

Heavy Fermion transition (II)

[JCAP01(2021)058]: Azatov, Vanvlasselaer

Q: Transition dictated by fields w/ $M \lesssim T_{nuc} \sim v_\phi$? $\Rightarrow$ $\boxed{n_{heavy} \sim e^{-M/T_{nuc}}}$



- In the wall frame: $E_\chi \sim p^z_\chi \sim \gamma_w T_{nuc} \gg v_\phi$
- Transition probability

$$P(\chi \to N) \approx \underbrace{\frac{Y^2 v_\phi^2}{M^2}}_{=\theta^2} \underbrace{\left(\frac{\sin(\Delta p_z L_w)}{\Delta p_z L_w}\right)^2}_{\text{wall shape effect*}} \underbrace{\Theta(\gamma_w T_{nuc} - M^2 L_w)}_{\text{need ultrarelativistic wall}}$$

$*$ = assuming a linear wall profile, θ = mixing angle

States w/ $M \gg T_{nuc}$ can become dynamical during the PT

Efficient production: $M < M_{max} \sim \sqrt{\frac{\gamma_w T_{nuc}}{L_w}} \sim \sqrt{\gamma_w T_{nuc} \langle\phi\rangle}$

Baryogenesis

Baryogenesis: Sakharov Conditions

- $B-$violating interactions or sphaleron
- $C/CP-$violating interactions due to physical phases in Yukawa matrices
- Out-of-equilibrium states: possibly produced during the expansion of the Universe or FOPTs

Electroweak Baryogenesis

Leptogenesis

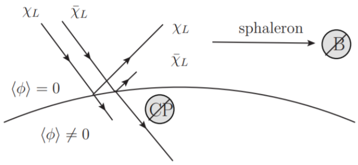


Figure: from [1302.6713]

VS

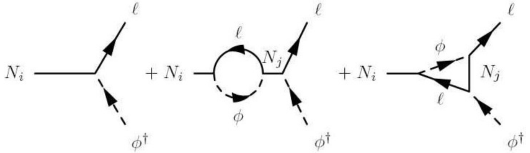


Figure: from [1302.6713]

- Scattering of quarks with $CP-$violating Yukawas off the (*slow*) bubble wall.
- $B-$violation via *sphalerons*

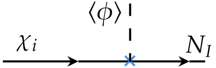
- *Out-of-equilibrium* decay of heavy $L-$violating RH neutrinos.
- $B-$violation via sphalerons.
- $CP-$violation via *loops*

$CP-$violation inside the bubble wall

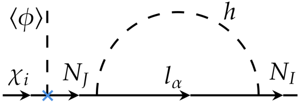
[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content: Higgs field H & $SU(2)_L-$leptons l_α + scalar ϕ + 2 heavy N_I + light χ_i fermions

$$\mathcal{L} \supset i\bar{\chi}_i P_R \partial\!\!\!/ \chi_i + i\bar{N}_I \partial\!\!\!/ N_I - M_I \bar{N}_I N_I - Y_{iI}\phi\bar{N}_I P_R \chi_i - y_{I\alpha}(H\bar{l}_\alpha)P_R N_I + h.c.$$



$$\Rightarrow \quad \mathcal{M}_{\text{tree}} \sim Y_{iI}$$



$$\Rightarrow \quad \mathcal{M}_{1-\text{loop}} \sim \sum_{\alpha,J} Y_{iJ} y^*_{\alpha J} y_{\alpha I} \cdot f^{(hl)}_{IJ}$$

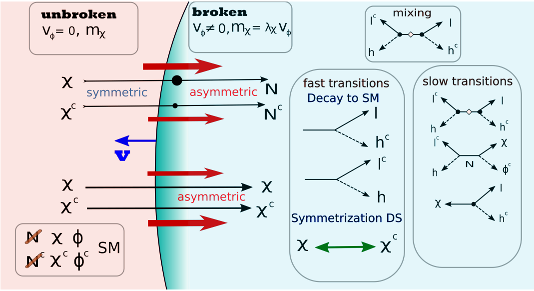
$|\mathcal{M}|^2 = |\mathcal{M}_{\text{tree}} + \mathcal{M}_1|^2$ develops an imaginary part due to interference

Asymmetry in N_I: $$\epsilon_I = \frac{\Gamma(\chi \to N_I) - \Gamma(\bar{\chi} \to \bar{N}_I)}{\Gamma(\chi \to N_I) + \Gamma(\bar{\chi} \to \bar{N}_I)} \simeq \frac{2\sum_{\alpha,J,i} \text{Im}(Y_{iI} Y^*_{iJ} y_{\alpha J} y^*_{\alpha I})\text{Im} f^{(hl)}_{IJ}}{\sum_i |Y_{iI}|^2}$$

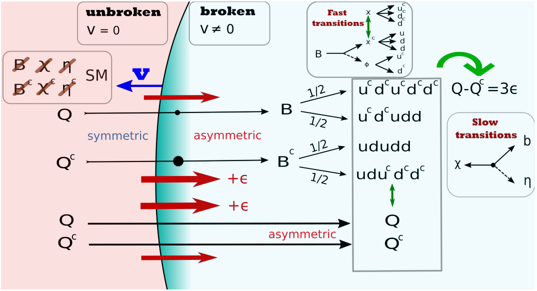
Baryogenesis via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

PT induced Leptogenesis



Low energy EW Baryogenesis



Low Energy Baryogenesis via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

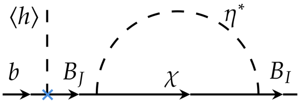
Field content: SM + 2 B_I (vectorlike $b-$like quarks) + Majorana χ + colored scalar η w/ $Q(\eta)=\dfrac{1}{3}$

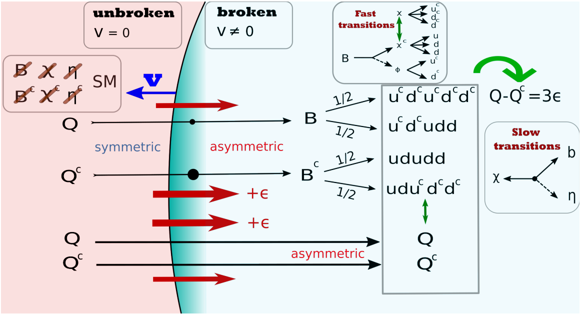
$$-\mathcal{L} = -\mathcal{L}_{SM} + M_I \bar{B}_I B_I + \underbrace{Y_I(\bar{B}_I H)P_L Q}_{B_I \text{ production}} + \underbrace{y_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c d u}_{\text{decay dark sector}} + \underbrace{\frac{1}{2} m_\chi \chi^c \chi}_{B-\text{violating}} + m_\eta^2 |\eta|^2$$

- $B(\eta)=2/3$, $B(\chi)=1$
- $P(Q\to B_I)\neq P(Q^c \to B_I^c)$ then collision of $b-$quarks with bubbles produce $B_I, \bar{B}_I$

$$n_b - n_{b^c} = -\sum_I (n_{B_I} - n_{B_I^c}) = \sum_I \theta_I^2 \epsilon_I n_b^0$$

- $CP-$violation via loop





Low Energy Baryogenesis via relativistic walls

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

Field content: SM + 2 B_I (vectorlike $b-$like quarks) + Majorana χ + colored scalar η w/ $Q(\eta) = \frac{1}{3}$

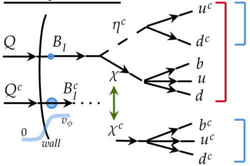
$$-\mathcal{L} = -\mathcal{L}_{SM} + M_I \bar{B}_I B_I + \underbrace{Y_I(\bar{B}_I H) P_L Q}_{B_I \text{ production}} + \underbrace{y_I \eta^* \bar{B}_I P_R \chi + \kappa \eta^c du}_{\text{decay dark sector}} + \underbrace{\frac{1}{2} m_\chi \chi^c \chi}_{B-\text{violating}} + m_\eta^2 |\eta|^2$$

Baryon asymmetry: (θ_I = mixing angle, ϵ_I = asymm. due to $CP-$violation)

$$\Delta n_B \equiv n_q - n_{\bar{q}} \approx \sum_I \underbrace{3 n_b^0 \theta_I^2 \epsilon_I}_{n_{B_I} - n_{B_I^c}} \times \underbrace{\frac{|y_I|^2}{|y_I|^2 + |Y_I|^2}}_{\substack{\text{decay back of} \\ B_I \to \chi \eta^c}} \times \underbrace{\frac{2|\kappa|^2}{2|\kappa|^2 + |\sum y_I \theta_I|^2}}_{\substack{\text{decay back of} \\ \eta \to ud}}$$

wash-out from slow transitions ($b\eta \to \chi$ & $\eta b \to \eta^c b^c$): $\frac{m_{B,\chi,\eta}}{T_{reh}} \gtrsim 30$

Decay chains



wash – out : $B_I \to b u d u^c d^c$
$B_I^c \to b^c u^c d^c u d$
$B_I \to bh$

asymmetry : $B_I \to b^c u^c d^c u^c d^c$
$B_I^c \to budud$

Constraints

[JHEP10(2021)043]: Azatov, Vanvlasselaer, Yin

1. **Neutron oscillations**: $\frac{1}{\Lambda^5_{n\bar{n}}} u^c \bar{d}^c d^c u d d \rightarrow \delta m_{n\bar{n}} \overset{exp.}{\lesssim} 10^{-33}$ GeV $\rightarrow m_{\eta,\chi} \gtrsim 10^5$ GeV
   Weaker bound if new particles couples only to the 3^{rd} generation.
2. **FCNC**: absent at tree level for η, but loop effects strongly constraint $\eta d u$ coupling.
3. **EDMs**:
   - $d_q \sim \mathrm{Im}[y_I^2] \frac{\theta_I^2 m_b}{16\pi^2} \frac{1}{\Lambda^2_{EDM}} \sim ?$ $\quad |d_q^{exp}| \lesssim 1.2 \times 10^{-22}\mathrm{cm}$
   - $\frac{d_e}{e} \sim \frac{m_e (yYe)^2}{(4\pi)^6} \sim 3 \times 10^{-33}\mathrm{cm}$ $\quad |d_e^{exp}| \lesssim 1.1 \times 10^{-29}\mathrm{cm} \cdot e$
4. **Gravitational Waves**: SGWB peaked at $f_{peak} \sim 10^{-3} \frac{T_{reh}}{\mathrm{GeV}} \mathrm{mHz}$
5. **Direct production @ collider**: $m_{LCP} \gtrsim 2$ TeV $\quad$ LPC = lightest colored particle

Upshot: Model favored for $M_B \sim m_\chi \sim m_\eta \in [2, 20]$ TeV