Strong electroweak phase transition in t-channel simplified dark matter models

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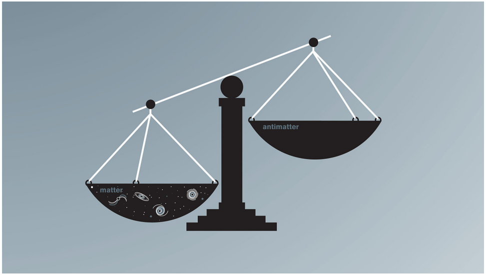
in collaboration with Philipp Schicho and Tuomas Tenkanen
arXiv 2207.12207

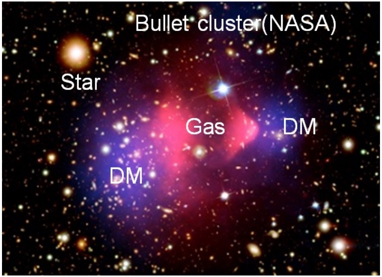
BSM for cosmological evidences

- Beyond the Standard Model Physics is required for
  Baryon Asymmetry in the Universe (BAU) and Dark Matter (DM)

$$\eta = \frac{n_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}\,, \quad \Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$$

Planck Collaboration 1807.06205





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- Can a given BSM model account for *both* BAU and DM in some regions of the paramater space?

Examples: real/complex scalar extensions of the SM, Inert Doublet Model ...

V. Barger et al [0811.0393]; J. R. Espinosa, T. Konstandin and F. Riva [1107.5441]; J. M. Cline and K. Kainulainen [1210.4196] ...

$$\mathcal{L}_{\rm int}^{\rm BSM} = -\lambda_{\phi\, s} \phi^\dagger \phi S^2 \, , \quad \boxed{\text{S acts as DM and affect the EWPT}}$$

- New fields and interactions are included: how do they affect the thermal history of the Universe?

Baryon asymmetry and EWPT

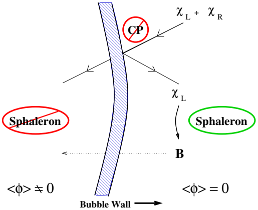
Sakharov conditions

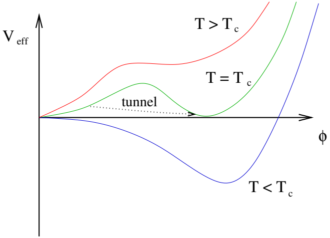
- B-number violation, C and CP violation, out-of-equilibrium dynamics

- a viable option for BAU is via Electro-Weak Baryogenesis (EWBG)

  V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **155** (1985)

- successful EWBG requires a first-order electroweak phase transition





figures from E. Morrissey and M. J. Ramsey-Musolf 1206.2942

discontinuity of $V_{\rm eff}(v_\phi, T)$ at $T = T_c$

Thermal potential and scale dependence

- $V_{\text{eff}}^{T=0}(\mu)$ is scale independent at one-loop
- $V_{\text{eff}}^{T}(\mu)$ is scale dependent at one-loop!

  $\rightarrow$ Misalignment of coupling versus loop expansion (due to $m_{\text{soft}} \sim gT$)

- impact on $V_{\text{eff}}(v_\phi, T)$: one-loop $\mathcal{O}(g^4)$ leaves a strong-μ dependence

O. Gould and T.V.I. Tenkanen [2104.04399]; D. Croon et *al* [2009.10080]

Required 2-loop calculation

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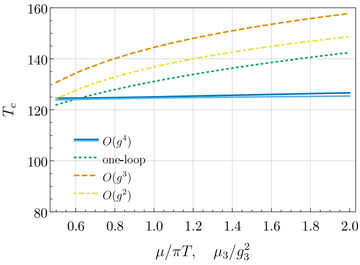

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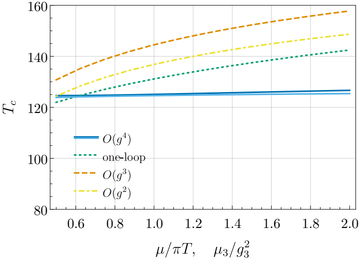
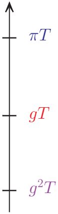


3D - EFTs

(i) πT: fermions and non-zero bosonic modes

(ii) gT: temporal gauge bosons

(iii) work in the 3d theory for zero-mode of bosonic fields



Simplified DM model

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - \mu_\chi)\chi \; , \quad \mathcal{L}_\eta = (D_\mu \eta)^\dagger (D_\mu \eta) - \mu_\eta^2 \eta^\dagger \eta - \lambda_2 (\eta^\dagger \eta)^2 \; ,$$

$$\mathcal{L}^{\rm portal}_{\rm scalar} = -\lambda_3 (\eta^\dagger \eta)(\phi^\dagger \phi) \; , \quad \mathcal{L}^{\rm portal}_{\rm Yukawa} = -y\, \bar{\chi} P_{\rm R}\, \ell \eta + \text{h.c.}$$

- $\mathcal{Z}_2$ symmetry for χ and η: stability of the DM particle
- RH-SM lepton $\Rightarrow$ covariant derivative for η is $D_\mu \eta = (\partial_\mu - i g_1 \frac{Y_\eta}{2} B_\mu)\eta$
- model has ties with supersymmetry, however $\lambda_3 \approx \mathcal{O}(1)$ [necessary to affect the EWPT]
- DM energy density both freeze-out and freeze-in (connection with EWPT see J. Liu et *al* 2104.06421)

J. Bollig and S. Vogl 2112.01491; ; M. Garny, A. Ibarra and S. Vogl 1503.01500; S. Junius, et *al* 1904.07513

- assess the thermodynamics of the EWPT: strong FOPT

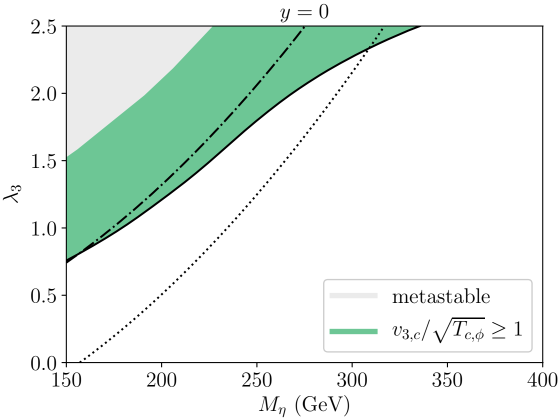
$$\frac{v_\phi}{T}(M_\chi, M_\eta, y, \lambda_3) \gtrsim 1$$

- extract the DM energy density via the freeze-out mechanism

$$\Omega_{\rm DM} h^2 (M_\chi, M_\eta, y, \lambda_3) = 0.1200 \pm 0.0012$$

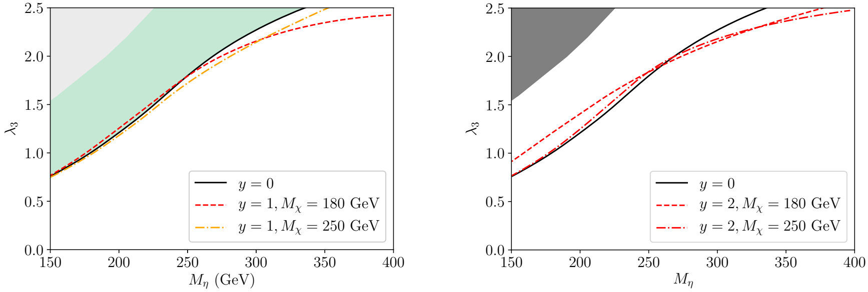
$$\underbrace{\chi \longleftrightarrow}_{\rm DM} \eta \underbrace{\longleftrightarrow \phi}_{\rm EWPT}$$

Result for $y = 0$



- perturbative estimate via discontinuous background fields at the critical temperature $T_{c,\phi}$
- dot-dashed line that corresponds to $\mu_\eta^2 = 0$ (strongest transition between gray area and this line)

Inclusion of the Majorana fermion



- regions above the contour lines $\frac{v_{c,\phi}}{T_{c,\phi}} > 1$ corresponds to a strong first order phase transition (FOPT)
- $y \neq 0$ has a mild effect on the regions for a strong FOPT
  $\rightarrow$ expected NLO effect, χ does not interact directly with the Higgs boson
- non trivial dependence on y and M_χ (more on next slides)

DM ENERGY DENSITY VIA FREEZE-OUT

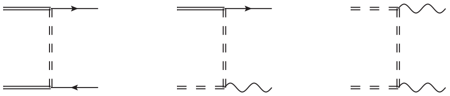
- effect of coannihilating states can be captured by a single Boltzmann equation K. Griest and D. Seckel (1991)

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2) \,, \quad \langle \sigma_{\rm eff} v \rangle = \sum_{i,j} \frac{n_i^{\rm eq} \, n_j^{\rm eq}}{(\sum_k n_k^{\rm eq})^2} \langle \sigma_{ij} v \rangle$$

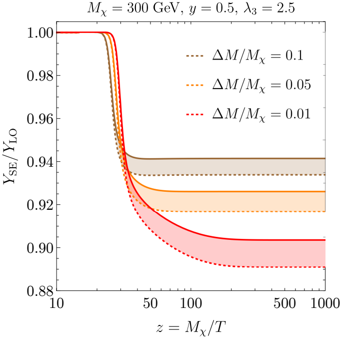
- χ and η: $n_{\rm eq} = \int_{\boldsymbol{p}} e^{-E_p/T} \left[2 + 2\, e^{-\Delta M/T} \right]$;

  co-annihilations for $\Delta M / M_\chi \lesssim 0.2$, where $\Delta M = M_\eta - M_\chi$

$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle \approx \langle \sigma_{\chi\chi} v_{\rm rel} \rangle + \langle \sigma_{\chi\eta} v_{\rm rel} \rangle e^{-\Delta M/T} + \langle \sigma_{\eta\eta^\dagger} v_{\rm rel} \rangle e^{-2\Delta M/T}$$



$\chi\chi \to \ell\ell^\dagger$ $\quad$ $\chi\eta \to \gamma\ell^\dagger$ $\quad$ $\eta\eta^\dagger \to \gamma\gamma$



DM energy density via freeze-out

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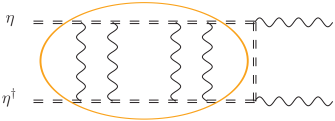
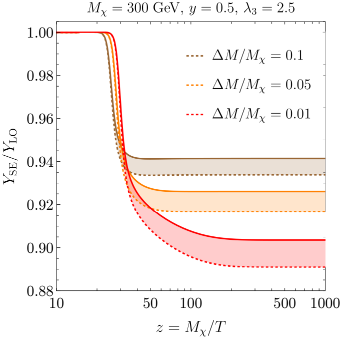


Sommerfeld effect and BSF



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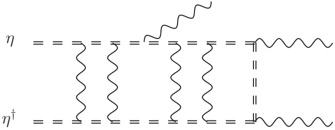

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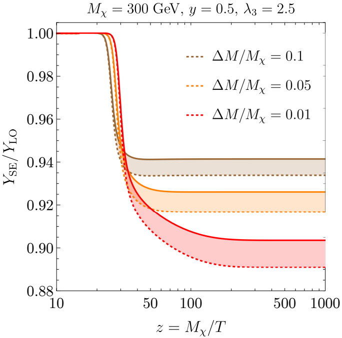
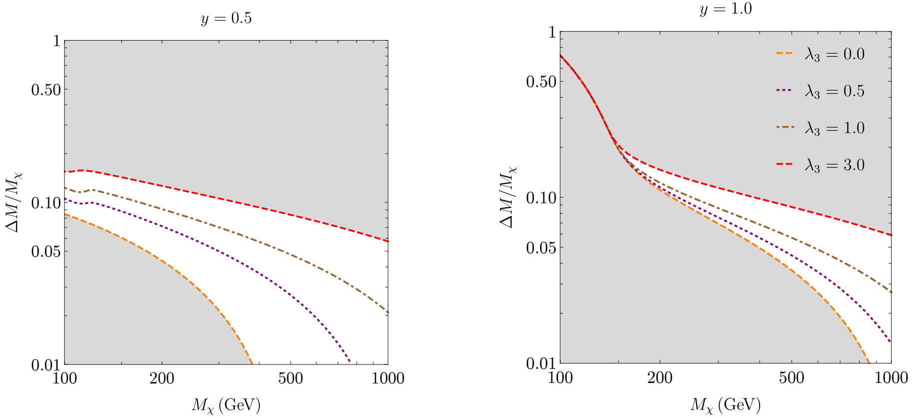


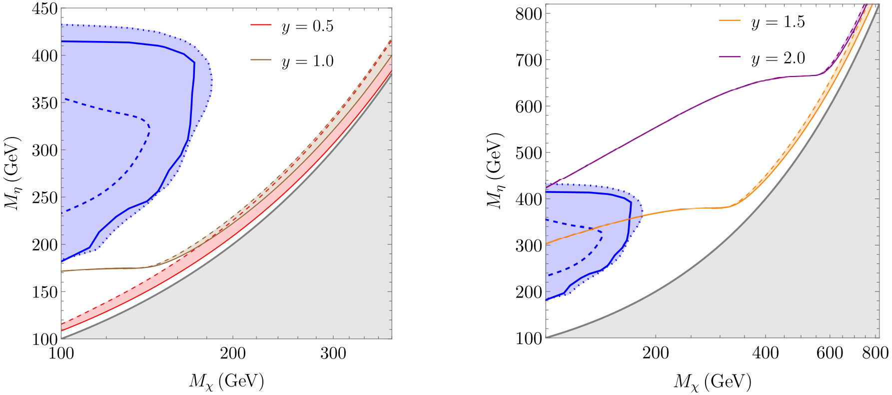
Parameter space for DM



- $\chi\eta$ and $\eta\eta^\dagger$ annihilation processes are more relevant for smaller y
- λ_3 enters $\eta\eta^\dagger$ annihilations (additonal channles mediated by the Higgs boson)

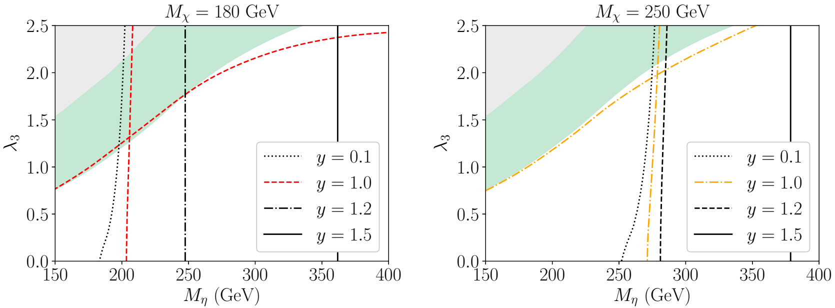
$\rightarrow$ up to one-order of magnitude on the mass splitting $\Delta M/M_\chi$

Parameter space for DM



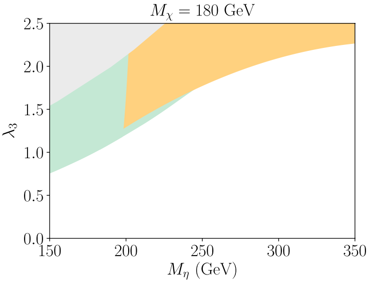
- ATLAS Collaboration search $2\ell + \not{E}_T$ 1908.08215, 1911.06660
- Drell-Yan production of $\eta\eta^\dagger$ and subsequent decays $\eta \to \chi + \ell$
- most (less) stringent limits from muons (taus)

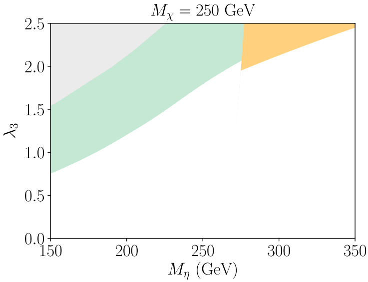
Combining DM and EWPT: (M_η, λ_3) plane



- mild dependence on λ_3 of the curves for $\Omega_{\rm DM} h^2 = 0.1200$ [only at small y's]
- for $M_\chi \gtrsim 180$ GeV the line $y = 0.1$ is an accumulation limit for the DM energy density
- larger M_χ imply larger M_η $\Rightarrow$ shrink the parameter space of FOPT and DM

(M_η, λ_3) and (M_χ, y)





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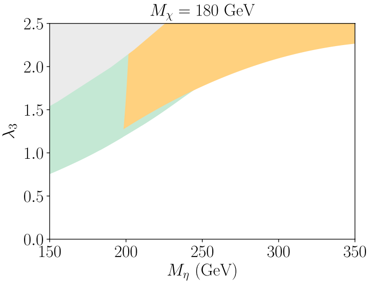
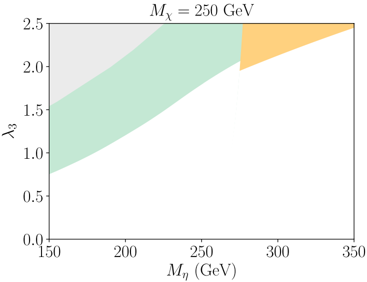
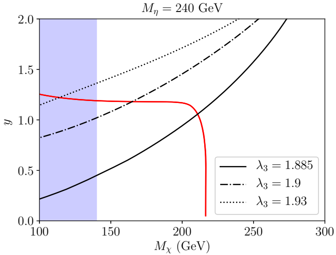




- non-trivial dependence of FOPT(M_χ, y, λ_3)
- very small changes on λ_3 are
  1) important for thermodynamics of EWPT
  2) irrelevant for DM



Conclusions

- BSM physics may induce a strong first order EWPT and provide the correct DM energy density

$$\eta = \frac{n_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10} \,, \quad \Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$$

- start the exploration of next-to-minimal models and make contact with DM simplified models

$$\underbrace{\chi \longleftrightarrow \eta}_{\rm DM} \underbrace{\longleftrightarrow \phi}_{\rm EWPT}$$

- used dimensionally reduced EFTs: perturbative matching at the hard and soft scale

$$\pi T \gg gT \gg g^2 T : \quad \text{taken care of } \mu\text{-dependence and isolated IR-sensitivity}$$

- for DM inclusion of Sommerfeld and bound-state effects (moderate for this model $\sim \mathcal{O}(10\%)$)
- including limits from collider searches: **DM and FOPT** for $180 \text{ GeV} < M_\chi \lesssim 300 \text{ GeV}$

- **Future directions**: (i) extend the investigation to larger M_η and M_χ: integrate out $M_\eta \sim \pi T$
  (ii) contact with GWs production; (iii) look at other DM simplified models

Non-perturbative aspect...

- Why should one be cautious about $V_{\rm eff}(v_\phi, T)$ as derived in perturbation theory?

$$\epsilon_b \sim \frac{1}{\pi} g^2 n_{\rm B}(p) = \frac{1}{\pi} \frac{g^2}{e^{p/T}-1} \approx \frac{g^2 T}{\pi p}$$

- for $p \lesssim g^2 T/\pi \;\to\; \epsilon_b \gtrsim 1$ even if $g^2/\pi \ll 1$

- relatively light d.o.f. interacting with the Higgs(es) should be studied non-perturbatively [$m \sim g^2 T$]

K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov [hep-ph/9508379]; [hep-lat/9510020]; [hep-lat/9612006]