Electroweak phase transition with scalar portal to Majorana fermion dark matter

Simone Biondini

Department of Physics - University of Basel

ICHEP 2022 - Bologna

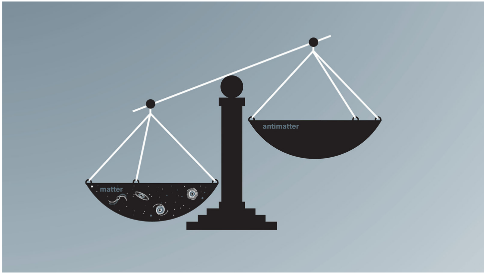
July 8th, 2022

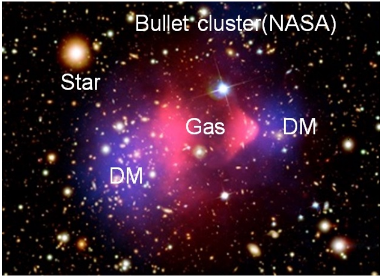
in collaboration with Philipp Schicho and Tuomas Tenkanen
arXiv 2207....

BSM for cosmological evidences

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

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





BSM for cosmological evidences

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

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

- 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]

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

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

Baryon asymmetry and EWPT

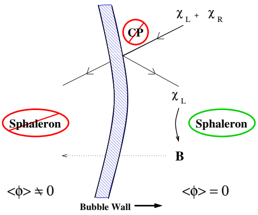
Sakharov conditions

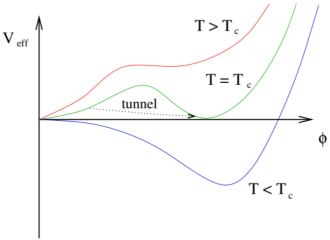
- B-number violation, C and CP violation, out-of-equilibrium dynamics

- 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 the $V(v_\phi, T)$ at $T = T_c$

EWPT and 3-d reduced theories

- Why not simply trust $V(v, T)$ as derived in perturbation theory?

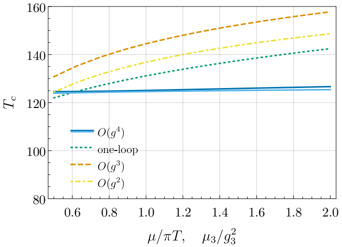
$$g^2 n_{\rm B}(m) = \frac{g^2}{e^{m/T} - 1} \approx \frac{g^2 T}{m}\,, \quad \text{actual expansion paramater} \quad \epsilon \equiv \frac{g^2 T}{\pi m}$$

- 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]

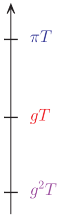
- appearance of odd powers in the couplings (due to $m_{\rm eff} \sim gT$)
- impact on $V(v_\phi, T)$: one-loop $\mathcal{O}(g^4)$ leaves a strong-μ dependence

Required 2-loop calculation



- πT and gT scales integrated out perturbatively
- work in the 3d theory for zero-mode of bosonic fields

figure from O. Gould and T. V. I. Tenkanen [2104.04399]



Simplified DM model

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

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

- RH-SM lepton $\Rightarrow$ covariant derivative for η is $D_\mu\eta = (\partial_\mu - ig_1\frac{Y_\eta}{2}B_\mu)\eta$
- 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

J. Bollig and S. Vogl 2112.01491; M. Garny, A. Ibarra and S. Vogl 1503.01500; S. Junius, L. Lopez-Honorez and A. Mariotti 1904.07513

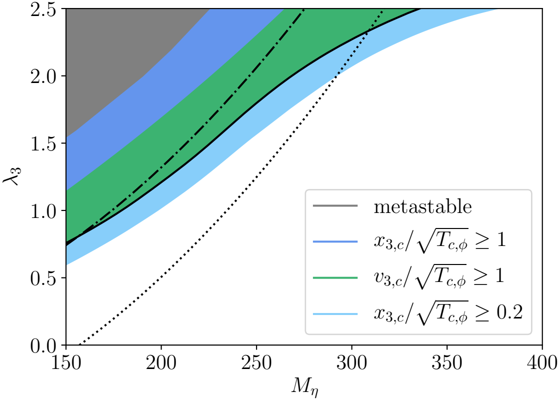
Thermodynamics of the model

- we study the behaviour of the vev of the scalars (Higgs and η)
- treat the scalar η as a light degree of freedom
- **one loop** matching for the hard scale and **two loop** of the soft scale [thermal masses];

for recent analyses and impact on phase transitions D. Croon, O. Gould, P. Schicho, T. V. I. Tenkanen and G. White [2009.10080]

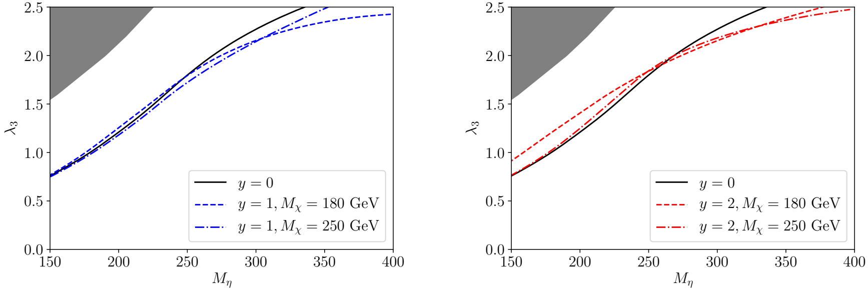
$$\underbrace{\chi \;\longleftrightarrow}_{\rm DM}\; \boldsymbol{\eta} \;\underbrace{\longleftrightarrow\; \phi}_{\rm EWPT}$$

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 phase transition**
- $y \neq 0$ has a mild effect on the region of a strong transition [expected NLO effect]
- non trivial dependence on y and M_χ (more on next slides)

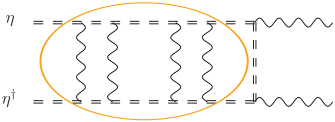
DM energy density via freeze-out

- effect of coannihilating states can be captured by a single Boltzmann equation

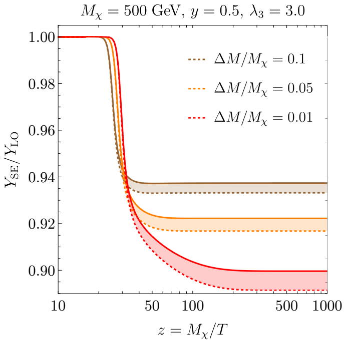
$$\frac{dn}{dt} + 3Hn = -\langle\sigma_{\rm eff} v\rangle(n^2 - n_{\rm eq}^2)\,, \quad \langle\sigma_{\rm eff} v\rangle = \sum_{i,j} \frac{n_i^{\rm eq}\, n_j^{\rm eq}}{(\sum_k n_k^{\rm eq})^2}\langle\sigma_{ij} v\rangle$$

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

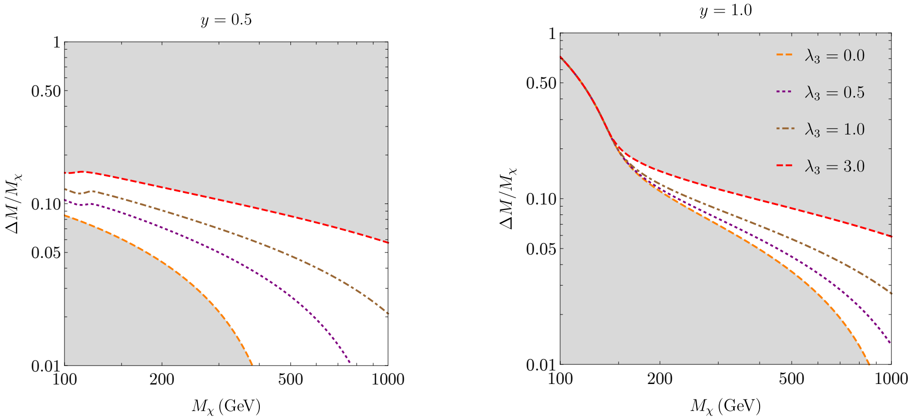
$$\langle\sigma_{\rm eff} v_{\rm rel}\rangle \approx \langle\sigma_{\chi\chi} v_{\rm rel}\rangle + \langle\sigma_{\chi\eta} v_{\rm rel}\rangle e^{-\Delta M/T} + \langle\sigma_{\eta\eta^\dagger} v_{\rm rel}\rangle e^{-2\Delta M/T}$$



Sommerfeld effect and BSF



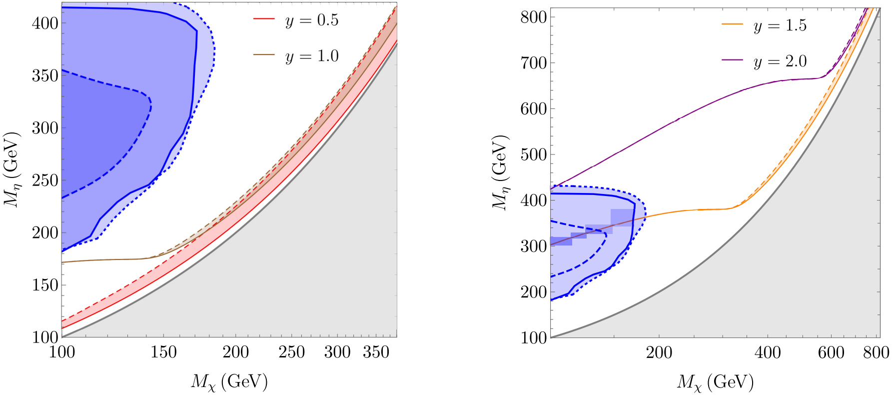
Paramater space for DM



- $\chi\eta$ and $\eta\eta^\dagger$ processes are more relevant for smaller y
- λ_3 enters $\eta\eta^\dagger$ annihilations

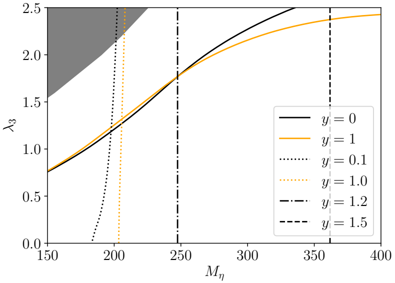
  up to one-order of magnitude on the mass splitting $\Delta M/M_\chi$

Paramater space for DM



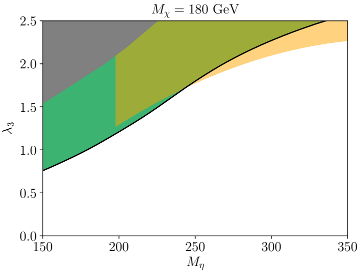
- ATLAS Collaboration search $2\ell + \not{E}_T$ 1908.08215, 1911.06660
- Drell-Yan production of $\eta\eta^\dagger$ and subsequent decays $\eta \to \chi + \ell$
- most (less) stringent limits from muons (taus)

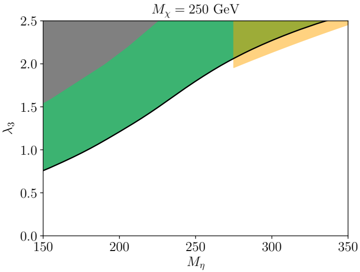
(M_η, λ_3) plane



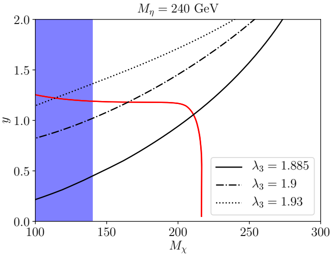
- solid lines for EWPT: $v_c/T_{c,\phi}$; dashed, dotted and dot-dashed for DM
- for $M_\chi \gtrsim 180$ GeV the line $y = 0.1$ is an accumulation limit for the DM energy density
- larger M_χ imply larger M_η $\Rightarrow$ shrink the parameter space of FOPT and DM

(M_η, λ_3) and (M_χ, y)





- 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 models 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

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

- for DM inclusion of Sommerfeld and bound-state effects (moderate for this model $\sim \mathcal{O}(15\%)$)
- 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