Light Dark Matter: Interplay of Colliders and Cosmology

based on 1806.06864 (JHEP), 1912.08215 (JHEP), 2012.09181

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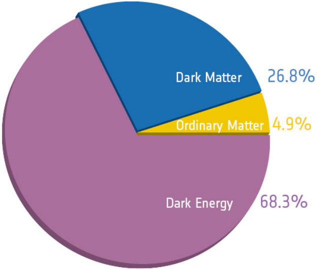
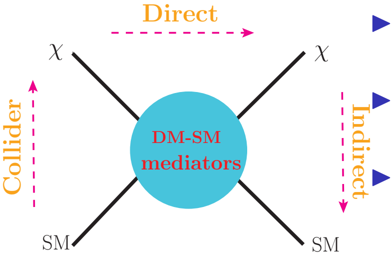
Dark Matter - The Mystery of This Century



- not charged under $U(1)_{EM}$ and $SU(3)_C$
- stable or long lived
- not in SM particle list



- Direct detection
  - nuclear recoils from DM scattering
- Collider searches
  - typical signal:missing energy + mono object
- Indirect detection
  - classified by annihilation product: γ, ν, e^+...

Neutrino Mass and Baryon Asymmetry of the Universe

- a large number of models for explaining neutrino mass
- the most popular realization is type-I seesaw in which heavy right-handed neutrinos are introduced

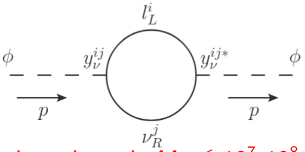
$$\mathcal{L} \supset -\frac{1}{2}\,\overline{n_L^c}\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} n_L \qquad n_L = \begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix}$$

$$m_\nu = -M_D M_R^{-1} M_D^T$$

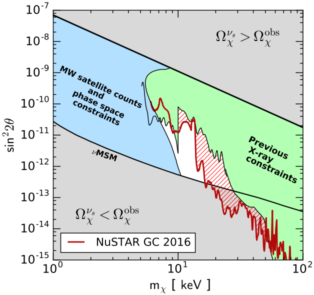
- Sakharov conditions: Violation of baryon number, C and CP violation and departure from equilibrium
- baryon asymmetry produced from lepton asymmetry through sphaleron processes
- high-scale thermal leptogenesis and low-scale ARS mechanism work within type-I seesaw

The νMSM Model

- proposed by Asaka, Blanchet and Shaposhnikov (hep-ph/0503065,0505013)
- 3 RH neutrinos in type-I seesaw framework:
  one is DM candidate at the keV-scale, produced through mixing with active neutrinos, including resonant effects from the lepton number asymmetry induced by heavier two $\mathcal{O}$(GeV) RH neutrinos
- the latter are responsible for baryon asymmetry through ARS mechanism
- solves "all problems" and in addition there is no hierarchy problem



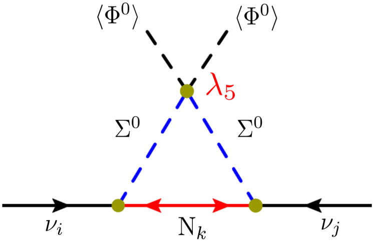
- naturalness bound: $M_R \lesssim 10^7$-10^8 GeV
- Ghiglieri, Laine (1905.08814) insufficient abundance of keV-scale DM in νMSM?



Scotogenic Model

- proposed by Ma (hep-ph/0601225)
- our idea: explain neutrino masses and generate observed baryon asymmetry and dark matter abundance within the *scotogenic* model (1806.06864)
- one of the main motivations: Z_2 symmetry forbids $N \to \nu\gamma$ implying no X-ray limits

	$SU(2)_L$	$U(1)_Y$	Z_2
Σ	2	1/2	-
N_i	1	0	-
Φ	2	1/2	+
L	2	-1/2	+



lepton sector Lagrangian: $\mathcal{L} \supset y_{ki}\bar{N}_k\tilde{\Sigma}^\dagger L_i - \frac{1}{2}\bar{N}_k^c M_k N_k + \text{h.c.}$

neutrino mass: $(\mathrm{m}_\nu)_{ij} \approx \frac{\lambda_5 v^2}{8\pi^2}\frac{y_{ki}y_{kj}}{m_0^2}M_k$ for scalar masses $m_0 \gg M_k$

Neutrino parameters

- Casas-Ibarra Parametrization (hep-ph/0103065)

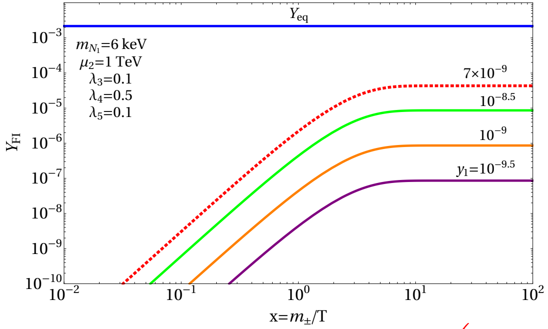
$$y = \mathrm{i}\sqrt{\Lambda^{-1}}\, R\, \sqrt{m_\nu}\, U^\dagger_{\mathrm{PMNS}}$$

- global fits indicate a certain preference for normal mass ordering
- lightest *N* field is at keV-scale and has tiny Yukawa couplings; effectively two *N* states contribute to neutrino mass generation leaving lightest active neutrino approximately massless
- $m_\nu = \mathrm{diag}\left(0,\ \sqrt{\Delta m^2_{\mathrm{solar}}},\ \sqrt{\Delta m^2_{\mathrm{atm}} + \Delta m^2_{\mathrm{sol}}}\right)$
- $R = \begin{pmatrix} 0 & \cos(\omega - i\,\xi) & -\sin(\omega - i\,\xi) \\ 0 & \sin(\omega - i\,\xi) & \cos(\omega - i\,\xi) \end{pmatrix}$

Dark Matter

- production via freeze in from the decays of Z$_2$-odd scalars
- $A, S \to N_1\,\nu_\alpha, \qquad \sigma^\pm \to N_1\, l_\alpha^\pm$

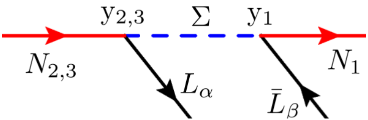
$$\frac{dn_{N_1}}{dt} + 3Hn_{N_1} = \frac{1}{2\pi^2}\,\Gamma_{\Sigma\to N_1 L}\, m_\Sigma^2\, T\, K_1\left(\frac{m_\Sigma}{T}\right)$$

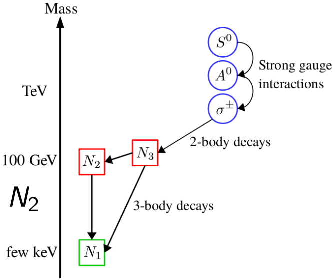


$$Y_{\rm FI} \approx 7.82\times10^{11}\,|y_1|^2\left(\frac{1\,\text{TeV}}{m_\pm}\right) \longrightarrow \Omega h^2_{\rm FI} \approx 0.12\left(\frac{|y_1|}{2.36\cdot10^{-8}}\right)^2\left(\frac{m_{N_1}}{1\,\text{keV}}\right)\left(\frac{1\,\text{TeV}}{m_\pm}\right)$$

Dark Matter

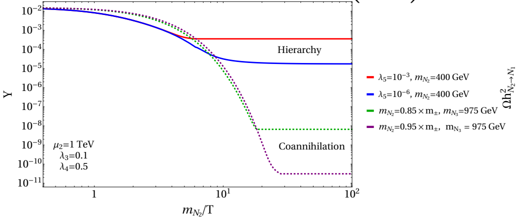
- production via decays of frozen out next-to-lightest Z_2-odd fermion N_2

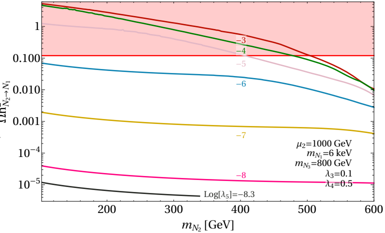




- using `micrOMEGAs` for getting abundance of N_2

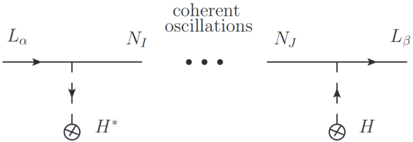
$$\Omega_{N_2\to N_1}h^2 = \Omega_{N_2}h^2\left(\frac{M_1}{M_2}\right)$$



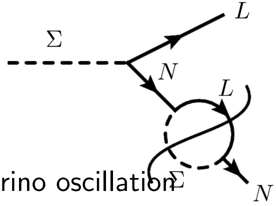


Leptogenesis

ARS



Decays $\Sigma \to NL$



- ARS leptogenesis proceeds via right-handed neutrino oscillation (hep-ph/9803255)
- lepton asymmetry generated in each flavor
- decays of the Σ doublet at finite temperatures serve as an additional source of CP violation
- the process was often neglected in literature being proportional to $(M_{N_2}/T)^2$
- however, this production mechanism can dominate ARS in some regions of parameter space (hep-ph/1606.00017)

Leptogenesis

Hambye, Teresi 1705.00016
Hernandez et al. 1508.03676,1606.06719
Drewes et al. 1606.06690; Abada et al. 1810.12463

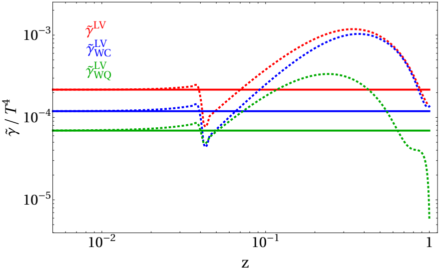
- to account for both mechanisms, we employ density matrix approach from 1705.00016 without taking relativistic approximation for RH neutrinos

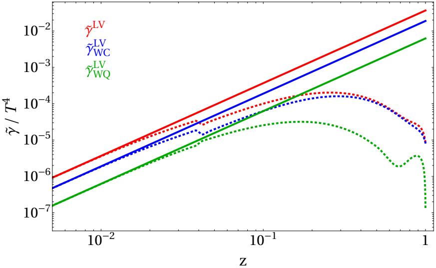
$$
\begin{aligned}
\frac{dn^N_{\alpha\beta}}{dt} &= -i[E_N, n^N(\mathbf{k})]_{\alpha\beta} - \frac{1}{2}\left\{\gamma^{LC}+\gamma^{LV}, \frac{n^N}{n^N_{\rm eq}} - I\right\}_{\alpha\beta} \\
&\quad + \frac{\delta n^L_l}{2n^L_{\rm eq}}\left(\left(\gamma^{LC}_{WQ,l}-\gamma^{LV}_{WQ,l}\right) + \frac{1}{2}\left\{\gamma^{LC}_{WC,l}-\gamma^{LV}_{WC,l}, \frac{n^N}{n^N_{\rm eq}}\right\}\right)_{\alpha\beta} \\
\frac{d\bar{n}^N_{\alpha\beta}}{dt} &= \frac{dn^N_{\alpha\beta}}{dt}(n \to \bar{n},\, \gamma \to \gamma^*, \delta n^L_l \to -\delta n^L_l) \\
\frac{d\delta n^L_l}{dt} &= \frac{1}{n^N_{\rm eq}}\mathrm{tr}\left\{\left(\gamma^{LC}_l - \gamma^{LV}_l\right) n^N\right\} - (\gamma \to \gamma^*, n \to \bar{n}) \\
&\quad - \frac{\delta n^L_l}{n^L_{\rm eq}}\mathrm{tr}\left\{\gamma^{LC}_{WQ,l}+\gamma^{LV}_{WQ,l}\right\} \\
&\quad - \frac{\delta n^L_l}{2n^L_{\rm eq}}\frac{1}{n^N_{\rm eq}}\mathrm{tr}\left\{n^N(\gamma^{LC}_{WC,l}+\gamma^{LV}_{WC,l})\right\} - (\gamma \to \gamma^*, n \to \bar{n})
\end{aligned}
$$

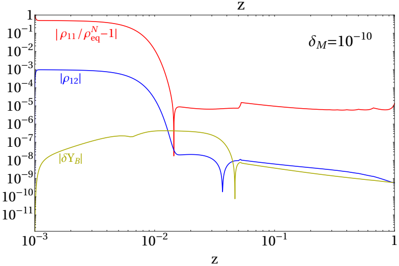
$$\delta Y_B = -\frac{2}{3}\sum_i \delta Y^L_i$$

Leptogenesis

- reaction densities and washout terms

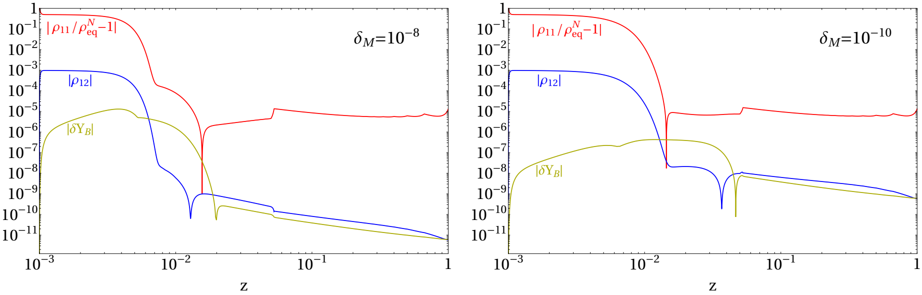






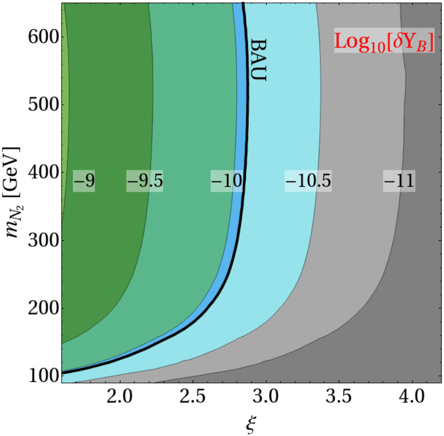
- we find successful scenarios only for $M_{2,3} > T_c$
- $z_{\rm osc} = T_s \left(2\sqrt{45/(4\pi^3 g_*)}\, m_{N_2}\,\delta_M\, M_{\rm Pl}\right)^{-1/3}$
- production for smaller δ_M occurs later and washout effects are effective during a shorter time

Leptogenesis

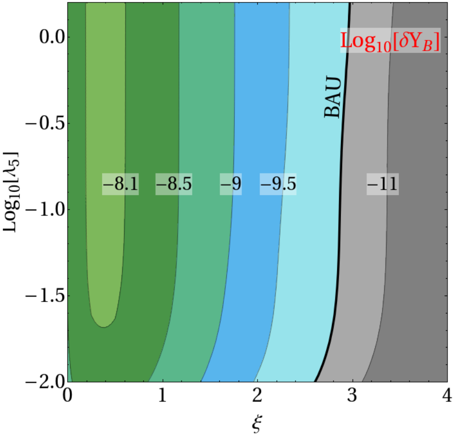


- $y_{2\alpha}, y_{3\alpha}$ can not be made smaller than $\mathcal{O}(10^{-6})$
- strong washout regime

Leptogenesis



$\lambda_5 = 0.01$

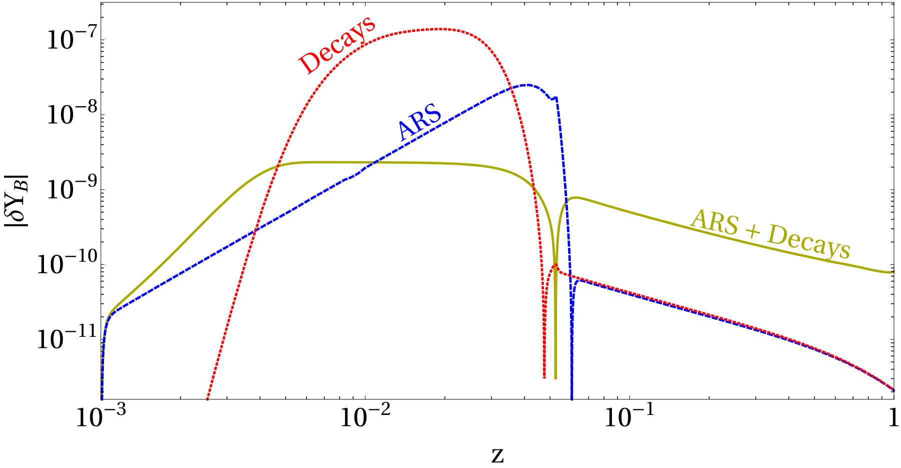


$M_{N_2} = 200$ GeV

- $\delta_M = 10^{-10}$ in both panels

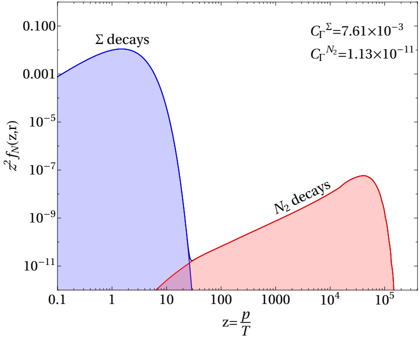
Leptogenesis

- both ARS and $\Sigma \to NL$ decays matter



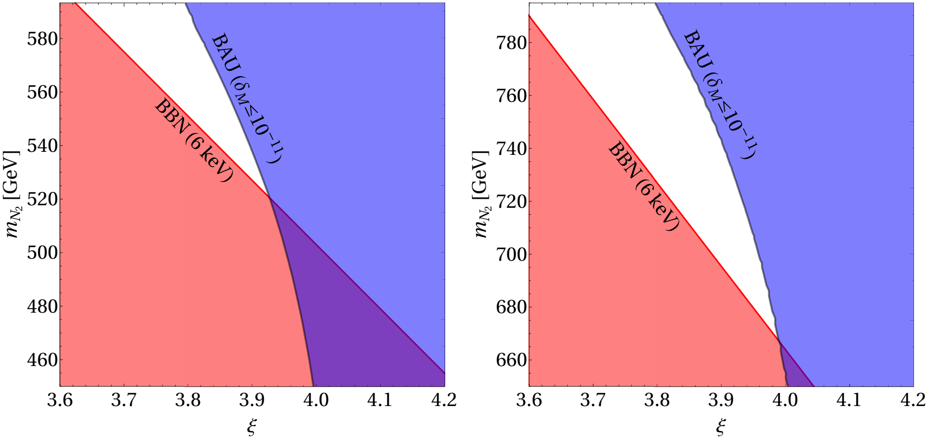
DM and Baryon Asymmetry

- avoid overproduction of DM $\longrightarrow$ large Yukawa couplings
- successful baryogenesis $\longrightarrow$ small Yukawa couplings
- reconcile these requirements by taking small couplings and employing small mass splitting between Z_2-odd scalars and fermions → coannihilations set DM abundance
- BBN constraints: $|y_{2\alpha}|^2 \gtrsim 6.3 \cdot 10^{-7} \left(\frac{m_\pm}{1\,\mathrm{TeV}}\right)^4 \left(\frac{1\,\mathrm{TeV}}{m_{N_2}}\right)^5 \left(\frac{10^{-8}}{|y_1|}\right)^2$



- $\Omega_{N_2\to N_1}$ DM contribution is negligible being in accord with N_{eff} and structure formation limits (Heeck, Teresi 1706.09909)

DM and Baryon Asymmetry



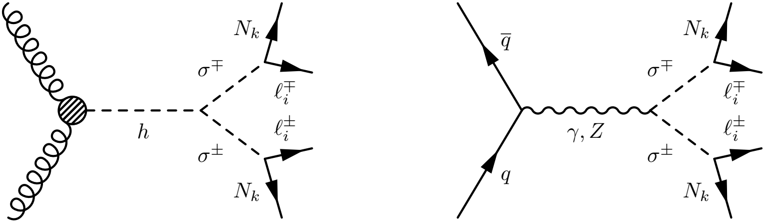
$\mu_2 = 600$ GeV

$\mu_2 = 800$ GeV

- we identified the parameter space in which the produced DM abundance and BAU are in accord with the observed values

Collider prospects?

- If coannihilations of N_2 with new scalars are significant, N_2 can stay longer in the thermal equilibrium and freeze-out with much smaller abundance → coannihilations are only effective if the mass splitting between N_2 and scalar is tiny



- in our consideration are dilepton signatures; small splittings would lead to very soft final state leptons that are hard to reconstruct at LHC
- production from N_2 decays is not suppressed

Structure formation and N_{eff}

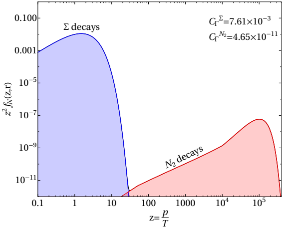
- Σ decays

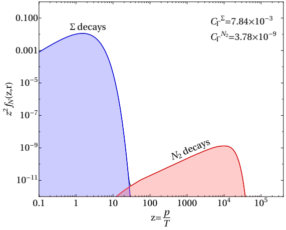
$$f_{N_1}^{\Sigma}(z,r) = 4\, C_\Gamma^{\Sigma} \left(\frac{e^{-z}\sqrt{\pi}\,\text{Erf}\left[\frac{r}{\sqrt{4z}}\right]}{2\sqrt{z}} - e^{-z\left(\frac{r^2}{4z^2}+1\right)}\frac{r}{2z} \right) \xrightarrow[r\to\infty]{} 4\, C_\Gamma^{\Sigma}\sqrt{\frac{\pi}{z}}e^{-z}$$

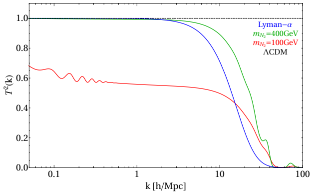
$$x = m_{parent}/T \qquad C_\Gamma^{\Sigma} = \frac{M_0}{m_\pm^2}\left(\frac{6|y_1|^2 m_\pm}{16\pi} + \frac{3|y_1|^2 m_S}{16\pi} + \frac{3|y_1|^2 m_A}{16\pi}\right)$$

- average DM momentum $z_{FI}^{prod} = p/T \approx 2.5$

- N_2 decays
- DM distribution from N_2 decays adopted from 1502.01011
- $T_\Gamma = (g_*)^{-1/4}\left(\frac{\Gamma}{2.72\times10^{-25}\text{GeV}}\right)^{1/2}$ MeV $\qquad \Gamma \propto y_1^2 \qquad z \gg 1$



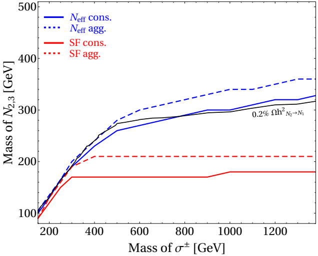




Structure formation and N_{eff}

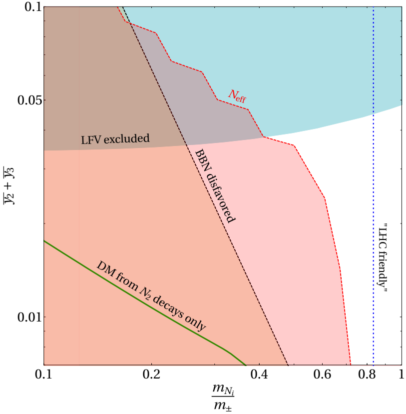
- The effective number of relativistic species after electron-positron annihilation $\rho_{\text{rad}} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma$
- The contribution to ΔN_{eff} from N_1 can be estimated by comparing its energy density against the one corresponding to a fully relativistic neutrino with temperature T_ν (Merle, 2015)
- $\Delta N_{\text{eff}}(T_\nu) =$

$$\frac{60}{7\pi^4}\frac{m_{N_1}}{T_\nu}\int_0^\infty \left[\sqrt{1+\left(\frac{z\,T_\nu}{m_{N_1}}\right)^2} - 1\right] z^2 f_{N_1}(z, T_\nu)\,\mathrm{d}z \times \begin{cases} 1, & \text{if } T_\nu > 1\,\mathrm{MeV} \\ \left(\frac{11}{4}\right)^{4/3}, & \text{if } T_\nu < 1\,\mathrm{MeV} \end{cases}$$

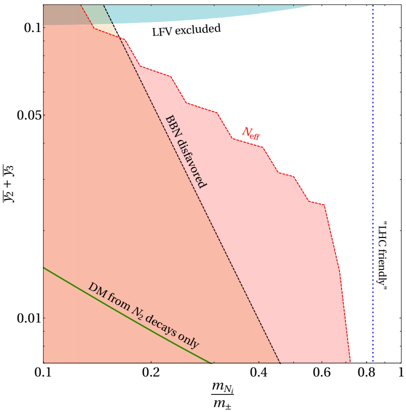


Collider prospects

dominant decay to $e^{\pm}$ and $\mu^{\pm}$



dominant decay to $\tau^{\pm}$

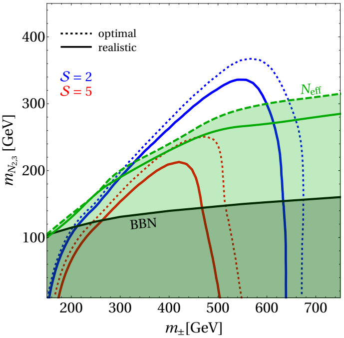


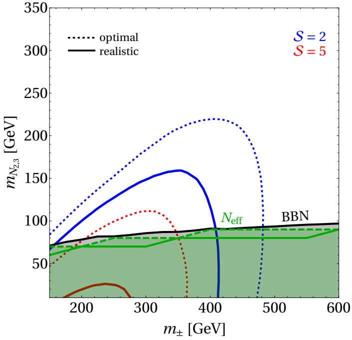
HL-LHC

- compared the simulation with the recent ATLAS results and found that current sensitivities are not strong enough to place limits
- HL-LHC → integrated luminosity of up to 4000 fb^{-1} at $\sqrt{s} = 14$ TeV

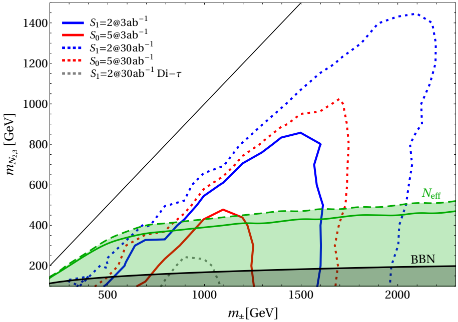
	ω_0	η_0	α_2^0	δ_0	$\mathrm{BR}(\sigma \to \ell_i N_k)$
NO	2.37	< -2	π	2π	86.42 %
IO	3.07	< -2	$-\pi$	π	99.75 %

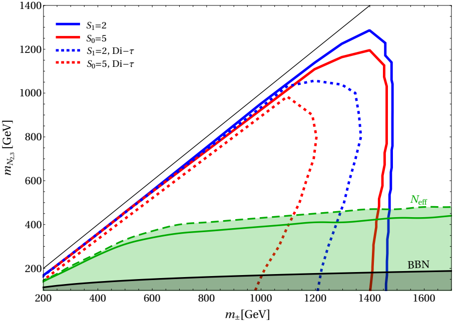
	ω_0	η_0	α_2^0	δ_0	$\mathrm{BR}(\sigma^\pm \to \tau^\pm N_k)$
NO	1.61	> 2	π	2π	38.26 %
IO	1.31	> 2	$-\pi$	π	27.30 %





FCChh and CLIC: dilepton signature



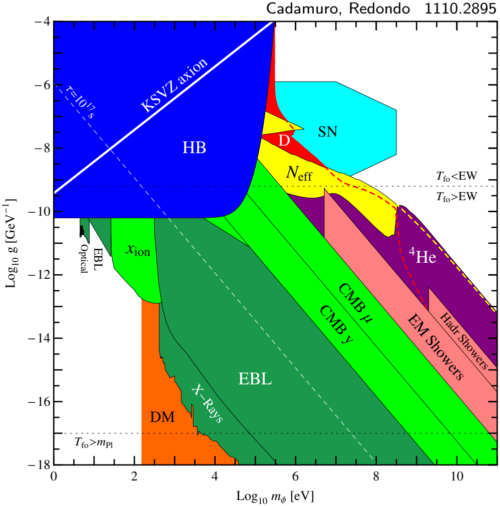


- FCC-hh and CLIC will provide the possibility of scanning a large portion of parameter space that is not restricted by BBN and N_{eff}
- FCC-hh will test higher $\sigma^\pm$ masses while CLIC can test the region with small mass splittings between N_2 and scalar states

Discussion:

- How do we systematize neutrino mass models? Are those with minimal BSM particle content the most appealing ones or should we be driven by phenomenology (models that could simultaneously explan baryon asymmetry of the Universe and dark matter)
- Cosmology and collider searches (terrestrial experiments) are typically discussed separately. Is there any work toward assessing the full picture in a straightforward way? GAMBIT?

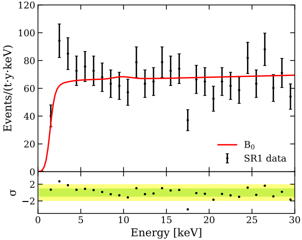
Axion-Like Particles (ALPs) Across the Scales

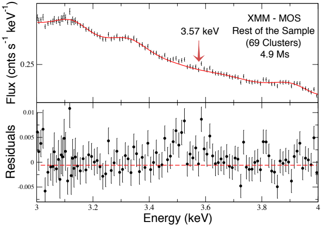


Model

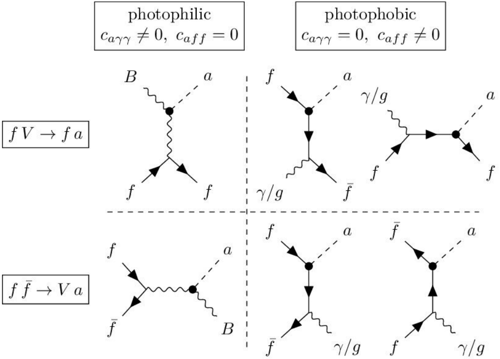
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a + \frac{1}{2}m_a^2 a^2 + \bar{f}(i\not{\partial} - m_f)f - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$- q\,e\,\bar{f}\not{A}f + \frac{c_{a\gamma\gamma}}{4f_a}aF_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{c_{aff}}{f_a}\partial_\mu a\,\bar{f}\gamma^\mu\gamma_5 f$$

- photophilic keV-scale ALP DM $\Longrightarrow$ hints in X-ray data (3.55 keV line, see Jaeckel et al., 1402.7335)
- photophobic keV-scale ALP DM $\Longrightarrow$ excess electronic recoil events in XENON1T (2006.09721)





Model



- freeze-out leads to overproduction → FREEZE-IN
- using equations of motion, coupling to fermions can be reexpressed as $(2m_f/f_a)\, a\bar{f}\gamma_5 f$
- in the photophobic case, the DM production rate is suppressed with respect to photophilic one by m_f/T_{RH}

ALP DM

- ALP DM distribution function, f, is a crucial ingredient to compute DM relic abundance as well as address structure formation

$$\left[\frac{\partial}{\partial t} - H p_a \frac{\partial}{\partial p_a}\right] f(p_a, t) = \mathcal{C}(p_a)$$

- collision term $\mathcal{C}$ contains squared amplitude for ALP production and distribution function for SM particles in the bath
- assuming Maxwell-Boltzmann statistics and with abbreviations $r = m_H / T$ and $x = p/T$ the distribution reads (Heeck, Teresi, 1706.09909)

$$f(x, r) = \frac{M_0}{16\pi^2\, m_H\, x^2} \int_{r_i}^{r_f} dr \int_{y^*}^{\infty} dy\, \hat{\sigma}\left(\frac{m_H^2\, y}{r^2}\right) \mathrm{Exp}\left[-x - \frac{y}{4x}\right]$$

- ALP distribution function for both philic and phobic case can be expressed analytically

ALP DM

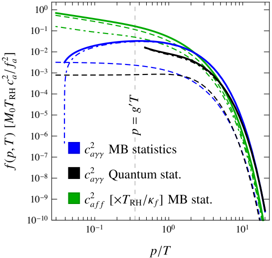
- DM freeze-in abundance in photophilic scenario

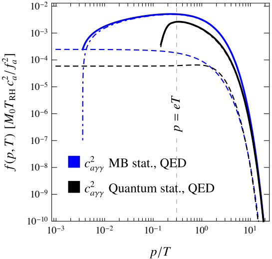
$$\Omega_{\rm DM} h^2 \approx 0.12 \left(\frac{106.75}{g_*}\right)^{3/2} \left(\frac{c_{a\gamma\gamma}/f_a}{10^{-17}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_{\rm DM}}{10\,\mathrm{keV}}\right) \left(\frac{T_{\rm RH}}{2.6{\cdot}10^{15}\,\mathrm{GeV}}\right)$$

- $\Omega_{\rm DM}^{\bar f f\to Ba}/\Omega_{\rm DM}^{fB\to fa} \approx 1/20$ due to logarithmic divergence in t-channel regulated by thermal mass of a photon
- DM freeze-in abundance in photophobic scenario

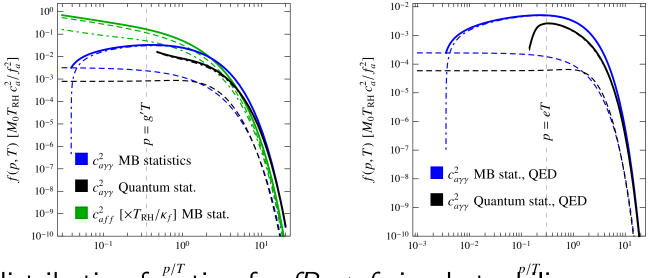
$$\Omega_{\rm DM} h^2 \approx 0.12 \left(\frac{80}{g_*}\right)^{3/2} \left(\frac{m_{\rm DM}}{10\,\mathrm{keV}}\right) \left(\frac{\sum_f m_f n_c q^2 e^2}{38.9\,\mathrm{GeV}}\right) \left(\frac{c_{aff}/f_a}{7.6{\cdot}10^{-11}\,\mathrm{GeV}^{-1}}\right)^2$$

- $\Omega_{\rm DM}^{\bar f f\to Va}/\Omega_{\rm DM}^{fV\to fa} \approx 2$





ALP DM



photophilic
$\langle p\rangle/T \approx 3.24$

photophobic
$\langle p\rangle/T \approx 2.36$

- distribution function for $fB \to fa$ in photophilic scenario turns negative at $p/T = \mathrm{Exp}\left[-1/4 + \gamma_E\right] \frac{m_\gamma^2}{4T^2}$
- the cutoff occurs at a value of p/T that is at least two orders of magnitude smaller than the expected mean
- black lines represent calculation following approach from Bolz et al. arXiv:0012052 (quantum statistics, term from ALP self energy removing the divergence; however, the calculation holds only for $p_a > gT$)

Structure formation probes: Lyman-α and satellite counts

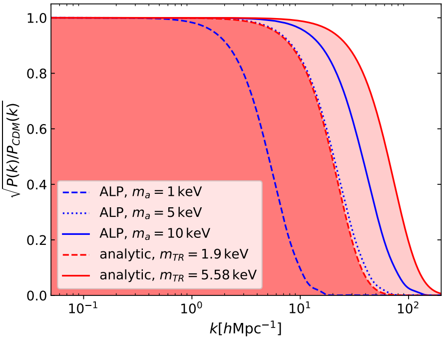
- warm DM can wash out structures at small scales and this can be quantified by the suppression of the matter power spectrum P(k)
- two complementary probes: *Ly-α forest* and the *number of MW subhalos*
- Ly-α stands for a number of absorption lines occurring in the spectra of quasars and galaxies at higher redshift stemming from the hydrogen in the intergalactic medium
- define a transfer function T(k) computed using CLASS

$$T(k) \equiv \sqrt{\frac{P(k)}{P(k)_{\Lambda\mathrm{CDM}}}}$$

and compare to the analytic fit of the transfer function of a warm thermal relic (that is a function of m_{TR})

$$T(k) = (1 + (\alpha k)^{2\nu})^{-5/\nu}$$

Structure formation probes: Lyman-α and satellite counts



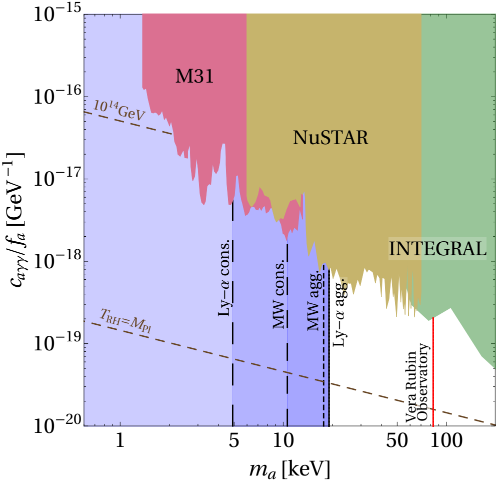
- half mode analysis: define a scale $k_{1/2}$ at which $T^2(k_{1/2}) = 0.5$ and check whether $T(k)^2 \geq T_{\lim}(k)^2$, $\forall\, k \leq k_{1/2} \Rightarrow$ if not, tested point is disfavored
- lower bounds on m_{TR} appearing in the literature span the range $[1.9, 5.58]$ keV

- $N_{sub} = 64$ to be compared to the number of MW satellites

$$\frac{\mathrm{d}N_{sub}}{\mathrm{d}M_{sub}} = \frac{1}{C}\frac{1}{6\pi^2}\frac{M_{MW}}{M_{sub}^2}\frac{P(1/R_{sub})}{R_{sub}^3\sqrt{2\pi(S_{sub}-S_{MW})}}$$

- $1 \times 10^{12}\,M_\odot < M_{MW} < 1.5 \times 10^{12}\,M_\odot$

Photophilic ALP

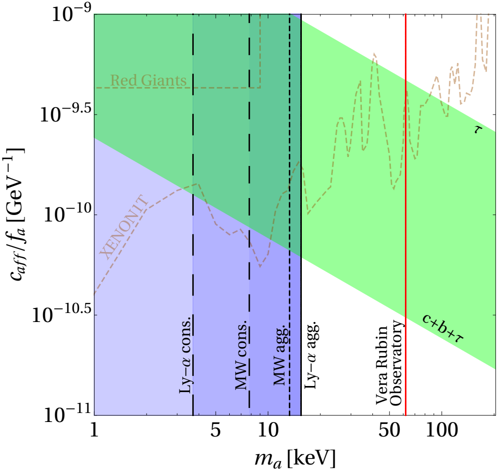


- between $T_{\rm RH} = M_{\rm Pl}$ and 10^{14}GeV production from misalignment is significant → can be avoided by assuming P-Q symmetry breaking after inflation

	cons.	*agg.*
Lyman-α	4.9 keV	19.1 keV
MW subhalo	10.3 keV	17.4 keV

- aggressive structure formation limits are clearly disfavoring decaying DM interpretation of the excess in X-ray data, while conservative ones are marginally consistent with it

Photophobic ALP



- milder structure formation limits due to colder DM with respect to the photophilic scenario

	cons.	*agg.*
Lyman-α	3.7 keV	15.5 keV
MW subhalo	7.8 keV	13.3 keV

- flavor universal scenario disfavored
- with data from forthcoming Vera Rubin Observatory existing limits can be improved significantly to $m_a \gtrsim 50$ keV

Summary

- ALPs are currently one of the most popular BSM extensions, being studied and tested across several mass scales
- we studied keV-scale ALP DM produced via freeze-in through feeble interactions with photons and SM fermions
- ALP momentum distribution has been calculated with two distinct approaches utilizing Maxwell-Boltzmann and quantum statistics
- using Lyman-α forest data and the observed number of MW companions we derived structure formation limits
- for the photophilic ALP DM, the most aggressive limits exclude ALP DM masses below $\sim 19\,\mathrm{keV}$, complementing constraints from X-ray data, while constraints for photophobic ALP are slightly weaker
- future experiments will improve the limits to $m_a \gtrsim 60\,\mathrm{keV}$ for both scenarios