A probe into leptophilic scalar dark matter

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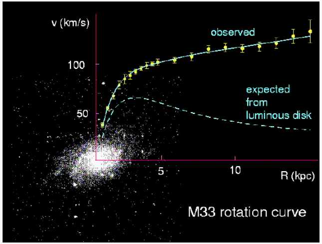
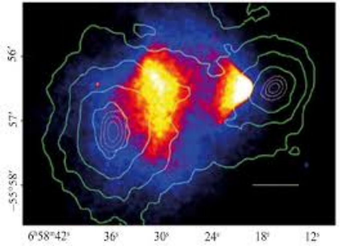
based on

I. *SC and R. Islam*, Phys. Rev. D 101 (2020) 115034, arXiv : 1909.12298

II. *SC and R. Islam*, JHEP 03 (2021) 032, arXiv : 2007.13719

Dark matter : what we know

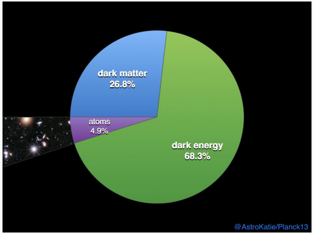




Astrophysical validation

- Flatness of rotation curves in spiral galaxies
- Bullet clusters

hint at some invisible mass distribution



Quantitative estimate

- Measurements of anisotropy in CMB power spectrum
- Relic density of dark matter

$$\uparrow$$

$$\Omega h^2 = 0.1199 \pm 0.0027$$

Dark matter : what we don't know

- No concrete idea about possible candidates
- Proposed mass range for candidates : 10^{-22} eV (fuzzy DM) - a few solar mass (primordial black holes) !!

But candidates must be

- Charge neutral
- Weakly interacting
- Stable
- Massive

Can particle physics help ?

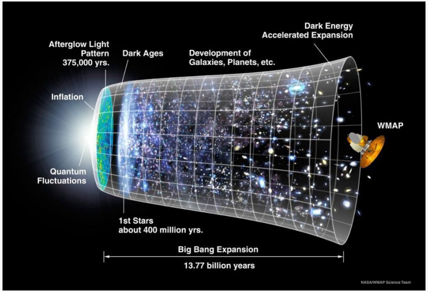
No suitable candidate in the Standard Model.

Maybe a BSM particle then ? But...

- relativistic or non-relativistic ? (*both contradict cosmological data*)
- single particle or multi-particle ?
- how about spin ? mass ?
- detectability ?

Origin

cosmic timescale

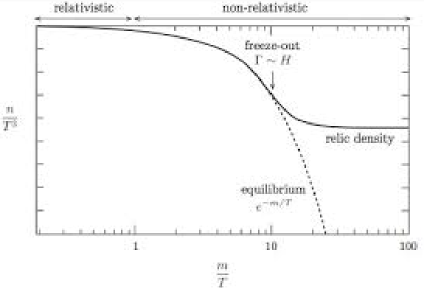


- DM evolved in the early Universe (dark ages)
- what we see today is the saturated *relic* abundance
- so what happened in the meantime ? ⟶ theorist's job

Theory ?

Thermal evolution of DM

- In the early Universe, DM and the visible particles were in equilibrium in the hot thermal plasma
- Simultaneously, the Universe began to expand with cooling
- When the interaction rate between the particles could not compete with the expansion rate, the DM particles decoupled from thermal soup
- DM abundance becomes Boltzmann suppressed $\longrightarrow$ saturates $\longrightarrow$ *freeze-out*



Weakly **I**nteracting **M**assive **P**articles are candidates for thermal freezeout $\longrightarrow$ how massive ?

WIMP of mass around the electroweak scale gives the correct order of weak scale cross-section

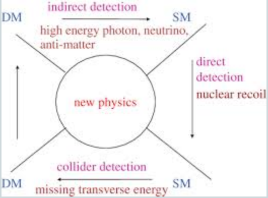
Correct relic abundance $\quad \Omega h^2 \approx 3 \times 10^{-27} / \langle \sigma v \rangle$

Let's talk about WIMPs then

candidates

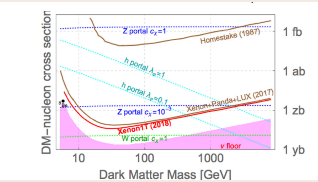
- *SUSY : neutralino, sneutrino, gravitino. . .*
- *Non-SUSY : scalar singlet, inert doublet CP even scalar, fermionic singlet, vector boson DM. . .*

detection



problems

- *direct search experiments measure recoil rate when WIMP scatters off detector nuclei*
- *very difficult to satisfy relic while keeping DM-SM interaction below the current DD limits*
- *"safe" DM-SM coupling almost kills collider search prospects*



◇ limited prospect. need alternatives

Alternatives ?

Broadly, two possibilities

- *Modifying WIMP freezeout :* multi-component WIMP, coannihilation, annihilation near a pole, SIMP etc.
- *Characteristically different thermal history:* FIMP, superWIMP, co-decay etc.

Coannihilation : a promising alternative ?

Features

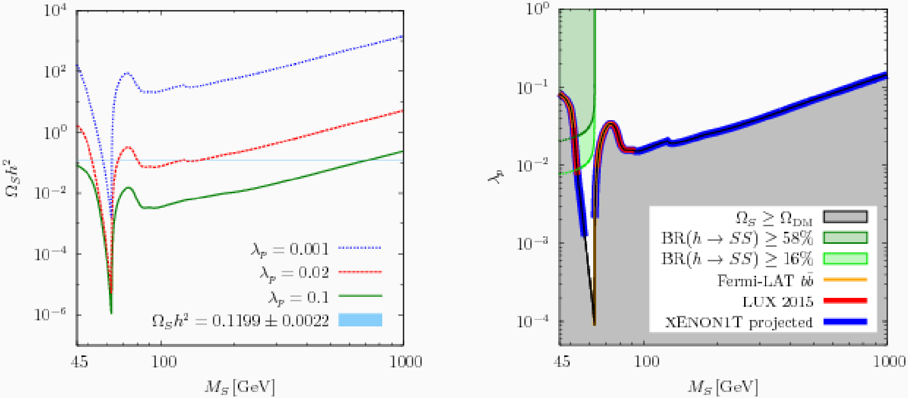
- Contains more particles in the dark sector other than DM
- Interaction within the dark sector is fairly large, so thermal equilibrium is maintained. Even after the dark sector decouples from SM, there can be energy exchange within the dark sector. Ultimately, DM number density is depleted when all the heavier dark particles decay into DM

Pros and cons

- Interaction within dark sector is independent of DM-SM interaction, so safe from DD 🙂
- Extended dark sector introduces more annihilation diagrams, enriching the DM phenomenology 🙂
- Works only for small mass split between DM and heavier dark sector particles, because $\langle \sigma_{eff} v \rangle \propto e^{-\delta m / m_{DM}} \longrightarrow$ compressed parameter region. Also difficult to find characteristic signal in conventional collider searches 🙁

Let's take the minimal dark extension of SM : scalar singlet

- Scalar singlet DM is excluded by DD bounds except around $m_{DM} \sim m_h/2$.
- The Higgs portal coupling being very restricted, the search strategy of scalar DM in the colliders are very limited.



JHEP06(2016)152

Extensions of scalar singlet dark matter

extra singlet lepton

- Internal bremsstrahlung
  - Giacchino, Lopez-Honorez and Tytgat, JCAP **10** (2013), 025
  - Toma, Phys. Rev. Lett. **111** (2013), 091301
- Long-lived fermions
  - Khoze, Plascencia and Sakurai, JHEP **06** (2017), 041

extra vectorlike quarks

- Giacchino, Ibarra, Lopez Honorez, Tytgat and Wild, JCAP **02** (2016), 002
- Baek, Ko and Wu, JHEP **10** (2016), 117
- Biondini and Vogl, JHEP **11** (2019), 147

extra scalar

- Wang, Han and Zhu, Phys. Rev. D **98** (2018) no.3, 035024
- Bandyopadhyay, Chun and Mandal, Phys. Lett. B **779** (2018), 201

Leptophilic extension of scalar singlet DM

	ℓ_L	e_R	H	Δ	Ψ	ϕ
$SU(2)_L$	**2**	**1**	**2**	**3**	**2**	**1**
$U(1)_Y$	$-1/2$	-1	$1/2$	1	$-1/2$	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$-$	$-$

$$\Psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}$$

- Interaction Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{\lambda_{h\phi}}{2}(H^\dagger H)\phi^2 - \frac{1}{\sqrt{2}}\left[y_\Delta \bar{\Psi}^c\ i\tau_2 \Delta \Psi + \mathrm{h.c}\right] - \left[y_j(\bar{\ell}_{jL}\Psi)\phi + \mathrm{h.c}\right]$$

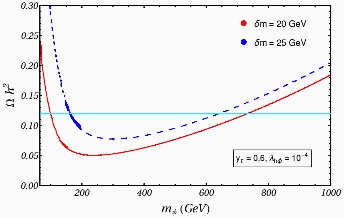
The mass splitting between the dark lepton fields in the doublet

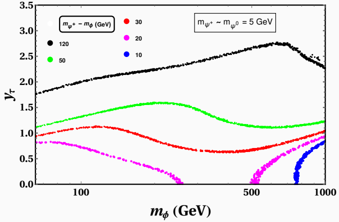
$$\delta = |m_{\psi^0} - m_{\psi^+}| = y_\Delta v_\Delta,\ \ , v_\Delta \rightarrow \textit{triplet vev}.$$

- Dark leptonic doublet is introduced to improve the search prospect in colliders. Multilepton final state is not constrained by $(g-2)_{\mu/e}$ measurements here unlike singlet leptonic addition.

SC and R. Islam, Phys. Rev. D 101 (2020) 115034

Transition between different regime in dark sector

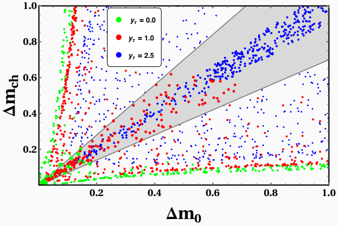


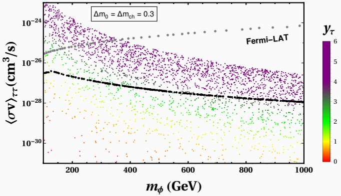


New annihilation channels

- **Pair annihilation** : $\phi\phi \rightarrow$ SM SM with dark leptons in t-channel
- **Coannihilation** : $\phi X \rightarrow$ SM SM, $\langle \sigma v \rangle_{\text{eff}} \propto e^{-\Delta m}$
- **Mediator annihilation** : $XX \rightarrow$ SM SM, $\langle \sigma v \rangle_{\text{eff}} \propto e^{-2\Delta m}$ where $X = \psi^{0\pm}$ and $\Delta m = (m_X - m_\phi)/m_\phi$.
- The strength of pair annihilation and coannihilation is controlled by $y_\tau \bar{\ell}_L \Psi \phi$. The mediator annihilation channels are Gauge mediated.
- Depending on y_τ and Δm's, the most efficient number changing process can change from one to another.

Pros and cons of possible search strategies



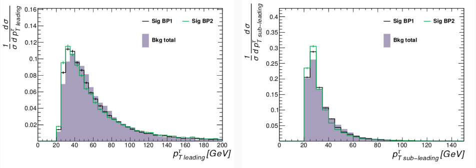


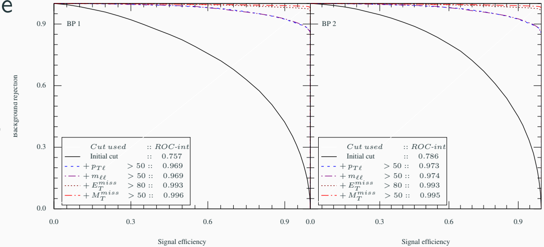
- ρ parameter restricts the triplet vev. So, mass splitting between the components of the lepton doublet becomes too restricted. Off-shell W reduces cross-section for multi-lepton signals in colliders 😕
- From DM dynamics, one cannot possibly distinguish between the neutral and charged component of the doublet 😕
- The pair annihilation channel pair produces τ pairs, the flux of which can be detected in indirect search experiments 🙂

Collider searches

Selection parameter	$p_T^{\ell\ (j)}$	$\lvert\eta_{\ell\ (j)}\rvert$	ΔR_{ik}
Cut value	10 (20) GeV	5	0.4

- Extra dark leptons introduce new multi-leptonic final states + MET in the colliders. These channels have negligible cross-section for simple scalar singlet DM case, due to feeble Higgs coupling with the light SM leptons.
- Mass splitting between the charged and neutral dark leptons was constrained ($\lesssim$ 10 GeV), whcih makes W boson was highly off-shell $(\psi^+ \to \psi^0 W^{+*})$: small multilepton cross-section and signal profile overshadowed the background





Motivation for another study

	ℓ_L	e_R	H	ξ	Ψ	ϕ
$SU(2)_L$	**2**	**1**	**2**	**1**	**2**	**1**
$U(1)_Y$	$-1/2$	-1	$1/2$	1	$-1/2$	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$	$-$

$$\Psi = \begin{pmatrix} \psi^0 \\ \psi_1^- \end{pmatrix}$$

$$\psi = c_\alpha \, \psi_1 + s_\alpha \, \xi$$
$$\chi = -s_\alpha \, \psi_1 + c_\alpha \, \xi$$

- Interaction Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{\lambda_{h\phi}}{2}(H^\dagger H)\phi^2 - \left[y_j^D \, (\bar{\ell}_{jL} \, \Psi) \, \phi + y_j^S \, (\bar{e}_{jR} \, \xi) \, \phi + y \, (\bar{\Psi} \, H) \, \xi + \text{h.c}\right]$$

- y and m_{ψ^0} are dependent on other parameters

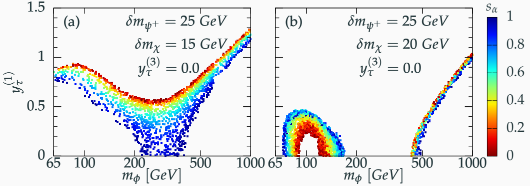
$$y = \frac{(m_\psi - m_\chi) \, s_{2\alpha}}{\sqrt{2} \, v} \qquad m_{\psi^0} = m_\psi \, c_\alpha^2 + m_\chi \, s_\alpha^2$$

SC and R. Islam, JHEP 03 (2021) 032

Improvements over previous study : naive guess

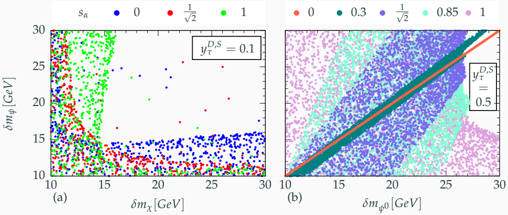
- The mass splitting between the dark lepton fields in the doublet is now arbitrary, so multi-lepton cross-sections are improved 🙂
- Mixing between the same charged dark leptons adds interesting handle in the collider phenomenology and dictates the DM number changing processes 🙂
- Interaction of charged dark leptons with W boson now plays an important role in the distinction between the neutral and charged leptons 🙂

Enriched DM dynamics

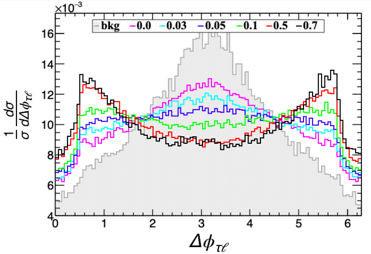


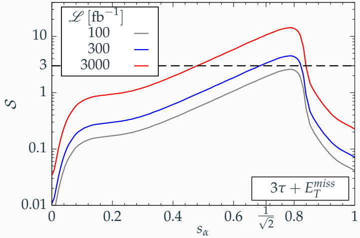
- The mixing angle and the mass splitting between DM and the charged dark leptons (δm's) dictate the dominant annihilation channels.

- Coannihilation is the suitable choice to demonstrate mixing effects : mixed states appear in the initial as well the propagator in the calculation of $\langle \sigma v \rangle$.
- Mixing relaxes the parameter space.



Improved search strategies





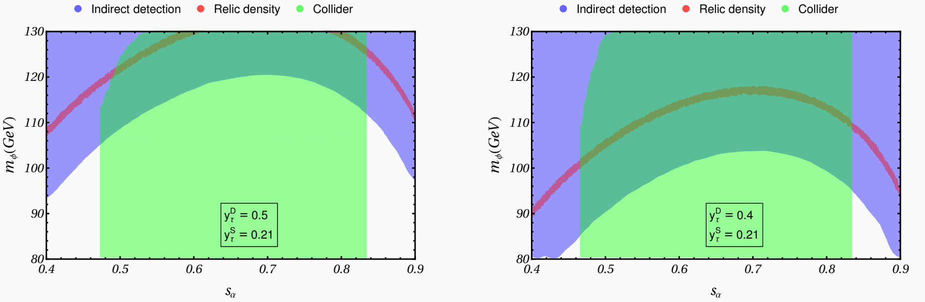
- We studied the mixing effects $3\tau + E_T^{miss}$ and $\ell\,\tau + E_T^{miss}$ channels for LHC at $\sqrt{s} = 13$ TeV.

Selection parameter	$p_T^{\ell\,(\,j\,)}$	$\lvert\eta_{\ell\,(\,j\,)}\rvert$	ΔR_{ik}
Cut value	10 (20) GeV	5	0.4

- The variation with mixing is a contant feature in distributions, independent of other free parameters.
- Mixing dictates the dominant production channel(s).
- Statistical significance is best around the value $s_\alpha = \frac{1}{\sqrt{2}}$.
- $3\tau + E_T^{miss}$ shows better prospect for a collider probe.
- It allows large region of mixing to come under scrutiny.

Combined parameter region for best detectability

- A combined scan shows that for fixed values of the dark sector masses, it is indeed possible to exclude a portion of parameter space, but this can be tuned with the proper choice of DM-SM couplings.



Projection at HL-LHC with $\mathcal{L} = 3000\ fb^{-1}$

Summary

- We studied a leptophilic extension of scalar dark matter.
- Direct search bound is at bay due to small Higgs-portal couplings.
- Interaction with the dark leptons relax the parameter space and make way for interesting search strategies.
- Mixing between the dark charged leptons adds an additional feature in the phenomenology. It significantly dictates the dominant channels controlling the relic density, as well as search prospects in indirect detection and colliders.
- Various multi-lepton signatures have a good prospect of detection for future luminosities at LHC.
- Compressed dark sector in coannihilation can be tested with metastable signatures such as *disappearing tracks* or *displaced leptons*
- Mixing affects ID as a mixed charged lepton is in the propagator of the pair annihilation.
- For low DM mass, a finite mixing relaxes bound on the upper limit of Yukawa coupling.

Thank you!

Backup slides : Possible DM annihilation

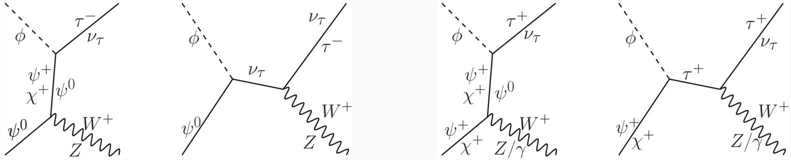


Figure 1: Coannihilation possibilites

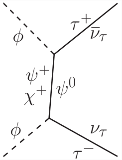


Figure 2: Pair annihilation possibilities

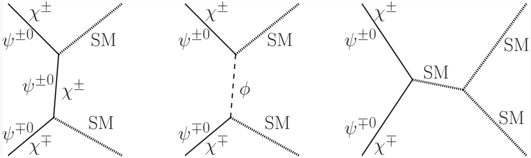
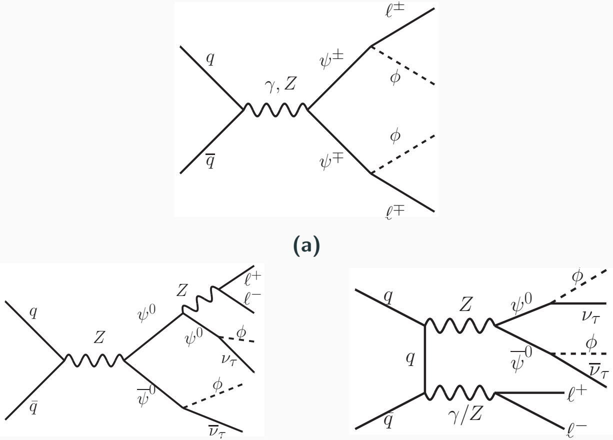


Figure 3: Mediator annihilation possibilities

Backup slides : Case I : Collider probe



(a)

(b) **(c)**

Figure 4: Feynman diagrams contributing to the dilepton channels.

Backup slides : Case II : Collider probe

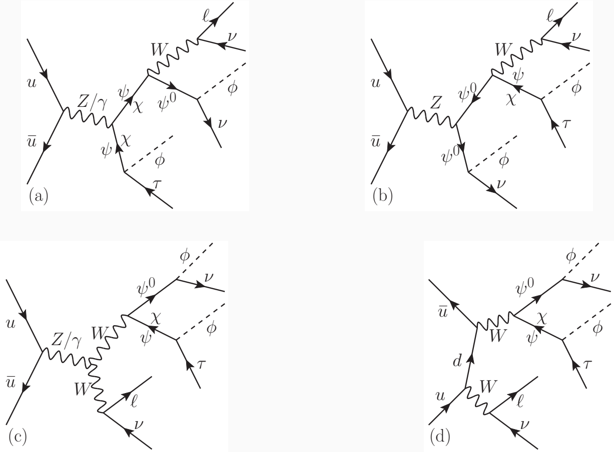


Figure 5: Feynman diagrams contributing to the $\ell\,\tau\,2\nu\,2\phi$ channel at the LHC.

Backup slides : Case II : Mixing affects indirect search prospects

	m_ϕ	$m_{\psi^\pm}$ [GeV]	m_χ	y_τ^D	y_τ^S	s_α	$\langle \sigma v \rangle_{\tau\tau}$ [cm^3/s]
BP1	100	600	110	2.5	0.0	0.03	8.64×10^{-28}
BP2	105	600	130	2.0	0.0	0.45	6.23×10^{-27}
BP3	125	300	140	1.75	0.03	0.25	1.39×10^{-27}
BP4	150	400	175	2.5	0.0	0.27	5.98×10^{-27}