Constraining Sommerfeld-Enhancement via Inflationary Perturbations: Dark Matter and Neutrino Interactions

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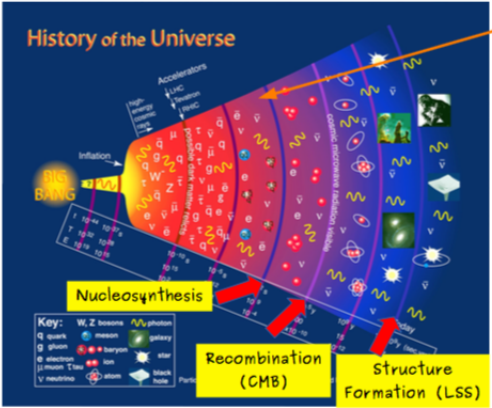
Outline of talk:

- Inflationary Perturbations of DM and Neutrinos Species.
- Effect on CMB.
- Effect of DM-neutrino interactions.
- Effect of DM annihilation to neutrinos.
- Constraining such interactions from PLANCK-2018 data.
- Viable DM Model and constraints on the parameter space.
- Conclusions.

History of the Universe



~ 1 MeV:
neutrino decoupling

→ **cosmic neutrino background:**

Temperature:

$$T_\nu^0 = \left(\frac{4}{11}\right)^{1/3} T_\gamma^0$$
$$= 1.95\,\mathrm{K}$$

Number density:

$$n_\nu^0 \approx 112\,\mathrm{cm}^{-3}$$

Energy density:

$$\rho^{rad} \equiv \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

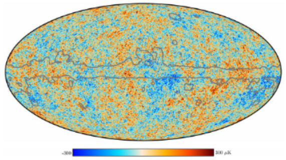
Standard: $\mathbf{N_{eff} = 3.045}$ *(de Salas & Pastor 2016)* 1

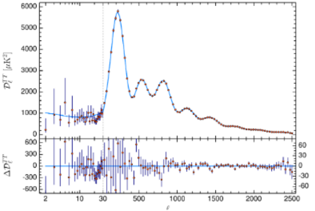
CMB

Cosmic Microwave Background $\mathcal{O}(0.3\,\mathrm{eV})$

Recombination → Universe gets transparent to photons

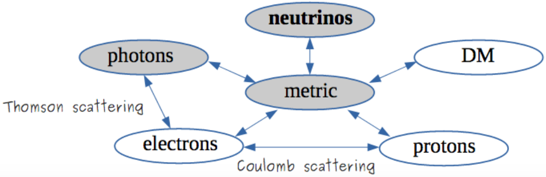
(Redshifted) photo of the early Universe





(Planck 2018)

→ Fluctuations in the photon temperature/density:



CMB: LCDM fit

For we can fit the CMB data with just 6 parameters quite well:

Minimal ΛCDM: $\{\omega_b,\ \omega_{cdm},\ h,\ A_s,\ n_s,\ z_{reio}\}$

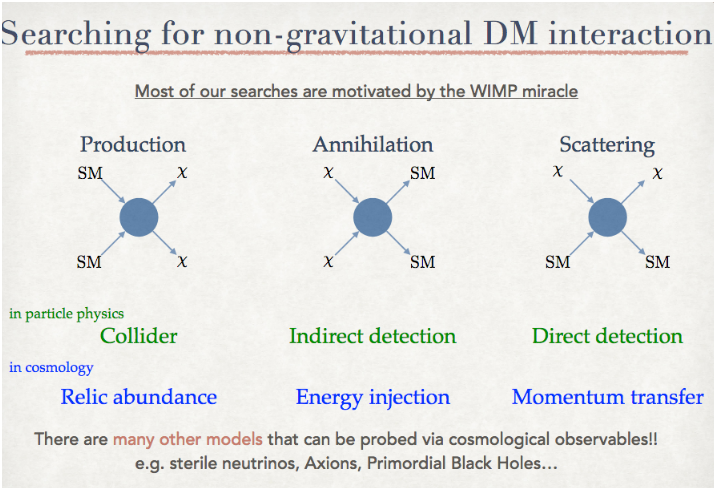
Matter content Inflation Stars

Assumptions in Neutrino Cosmology

Assumptions about neutrinos made in ΛCDM

- Neutrinos are free-streaming after 1 MeV (i.e. they are stable and have no interactions)
- Neutrinos follow a relativistic Fermi-Dirac spectrum
- They have a temperature of $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$
- There are as many neutrinos as anti-neutrinos (negligible lepton asymmetry)

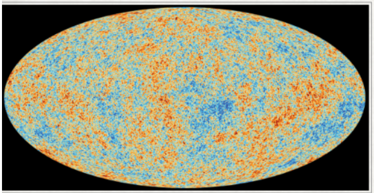
Dark Matter Primer

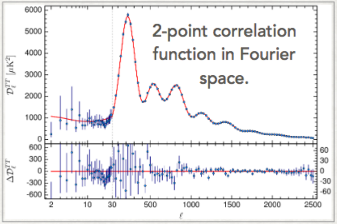


Slides (Poulin)

Dark Matter in CMB

DM and the CMB in a nutshell





- Snapshot of inhomogeneities at photons last scattering around z ~ 1000, when free electrons and proton (re)combine.
- Most precise probe of the DM density — a **matter** component sensitive to gravity, , i.e. its energy density dilutes like $(1+z)^3$, but insensitive to the radiation pressure.
- The CMB is highly sensitive to the free electron density through Thomson scattering, which dictates the visibility function and the optical depth.
- Energy injection from DM affect the free electron density around/below recombination. This can change the thickness/time of last scattering and residual scattering.

Slides (Poulin)

Inflationary Perturbations: DM interactions

ΛCDM model of cosmology assumes DM has no interactions. With DM-neutrino scattering interactions present, the perturbation Euler equations, in Newtonian gauge,

$$\begin{aligned}
\dot{\delta}_{\rm DM} &= -\theta_{\rm DM} + 3\dot{\phi}, \\
\dot{\theta}_{\rm DM} &= k^2\psi - \mathcal{H}\theta_{\rm DM} - S^{-1}\dot{\mu}(\theta_{\rm DM} - \theta_\nu) \ , \\
\dot{\delta}_\nu &= -\frac{4}{3}\theta_{\rm DM} + 4\dot{\phi}, \\
\dot{\theta}_\nu &= k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}(\theta_\nu - \theta_{\rm DM})
\end{aligned}$$

Parametrizing $\mu = a\sigma_{\Psi-\nu} c n_{DM}$, $S = \frac{3}{4}\frac{\rho_{DM}}{\rho_\nu}$ and

$$u \equiv \left[\frac{\sigma_{\Psi-\nu}}{\sigma_{\rm Th}}\right]\left[\frac{M_\Psi}{100\ {\rm GeV}}\right]^{-1} \ ,$$

In principle $\sigma_{\Psi-\nu}$ can be velocity-dependent.

Inflationary Perturbations: DM annihilation

Including DM annihilating to neutrino species, the perturbation equations, in Newtonian gauge,

$$\dot{\delta}_{\rm DM} = -\theta_{\rm DM} + 3\dot{\phi} - \frac{\delta\langle\sigma v\rangle}{M_\Psi}\rho_{\rm DM}a - \frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm DM}\delta_{\rm DM}a - \frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm DM}a\psi \ ,$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} - S^{-1}\dot{\mu}(\theta_{\rm DM} - \theta_\nu) + 2\frac{\langle\sigma v\rangle}{M_\Psi}\rho_{\rm DM}\theta_{\rm DM}a \ ,$$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_{\rm DM} + 4\dot{\phi} + \frac{\delta\langle\sigma v\rangle}{M_\Psi}\frac{\rho_{\rm DM}^2}{\rho_\nu}a + \frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho_{\rm DM}^2}{\rho_\nu}(2\delta_{\rm DM} - \delta_\nu)\,a + \frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho_{\rm DM}^2}{\rho_\nu}a\psi,$$

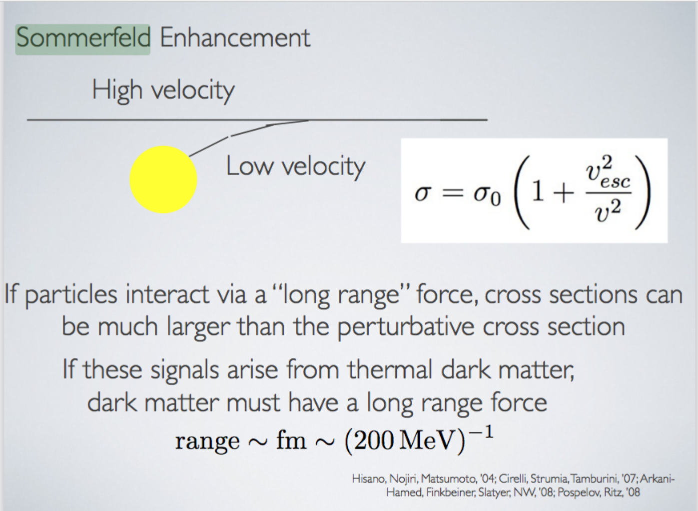
$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}(\theta_\nu - \theta_{\rm DM}) - a\frac{\langle\sigma v\rangle}{M_\Psi}\frac{\rho_{\rm DM}^2}{\rho_\nu}\left(\frac{3}{4}\theta_{\rm DM} + \theta_\nu\right)$$

$\mu = a\sigma_{\Psi-\nu}cn_D M$ Parametrizing

$$\frac{\langle\sigma v\rangle}{M_\Psi} = \Gamma a$$

Scope for Sommerfeld enhancement of DM annihilation.
We will constrain the quantities u and Γ from PLANCK-2018 data. Analysis done with Boltzmann solver CLASS.

Sommerfeld Enhancement of DM Annihilation Rates



Sommerfeld Enhancement of DM Annihilation Rates Cont.

QFT picture with dressed propagator:

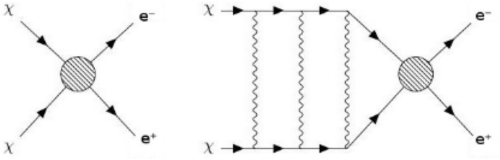


FIG. 1: Left: bare annihilation cross section. Right: dressed annihilation cross section; corrections by light mediator particle with Yukawa potential.

The annihilation rate is increased with the velocity of the particle due to the loop corrections arising due to non-perturbative physics. Very similar to the classical case.

Effects of DM-nu Scattering in CMB

- DM-ν scattering leads to clustering (in contrast to free-streaming) of the neutrinos during radiation domination. This means we have deeper gravitational potential fluctuations, affecting the photon-baryon fluid oscillations. Gravitational boosts to all the peaks barring the first one.
- Due to the DM-ν scattering, the combined fluid attains a sound speed, which is smaller than that of the baryon-photon fluid as non-relativistic matter fraction is higher in the first fluid. This in turn drags back the sound waves of the photon-baryon fluid, letting them move to a smaller distance than for the standard scenario. So, the peaks get shifted to larger l values.
- The contrast between even and odd peaks of CMB Power Spectrum will occur due to shift of temperature fluctuation oscillations by metric perturbation. Having DM-ν scattering during recombination suppresses the metric perturbation, hence decreasing the contrast between even and odd peaks.

Effects of DM-nu Scattering in CMB

- Metric fluctuations evolve with time as long as DM stays coupled to neutrinos efficiently. As stated before, CMB PS gets contribution from variation of metric fluctuations along the photon path known as integrated Sachs-Wolfe effect. Variation of this kind just after recombination (after the mode corresponding to the first peak has entered the horizon) thus results in further enhancement of the first peak.
- The features of the tail of CMB PS is highly suppressed due to diffusion damping, so no visible difference due to non-standard scatterings is present at those modes. On the other hand, small l modes are mainly dependent on the initial PS and late time evolution of the Universe (as these modes enter the horizon at late time and also the late integrated Sachs-Wolfe effect due to metric fluctuation variation during Matter-Dark Energy equality contributes to these modes). As these are not much affected by the DM-ν scattering, changing the scattering strength does not affect low l modes.

DM-nu Plots

Numerical Results:

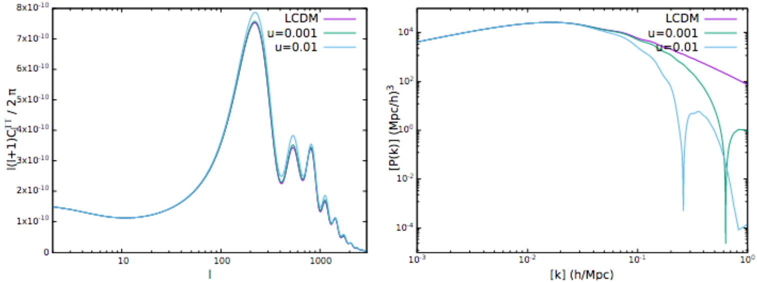


Figure 1. *The effect of DM-ν scattering on the TT power spectrum and on matter power spectrum. We keep* $\Gamma = 0$ *for these plots.*

Effects of DM-annihilation

Due to the presence of DM annihilation to neutrinos (invisibles):

- The height of the peaks of CMB power spectra is lowered when the annihilation channels of the DM particles are open (left panel), resulting in less power in TT correlations. This is primarily because of the fact that annihilation of DM into relativistic species decreases the DM density fluctuations, resulting in shallower gravitational potential fluctuations.
- This also decreases the contrast between even and odd peaks, similar to the scenario in DM-ν scattering

Effect of DM-annihilation Plots

Numerical Results:

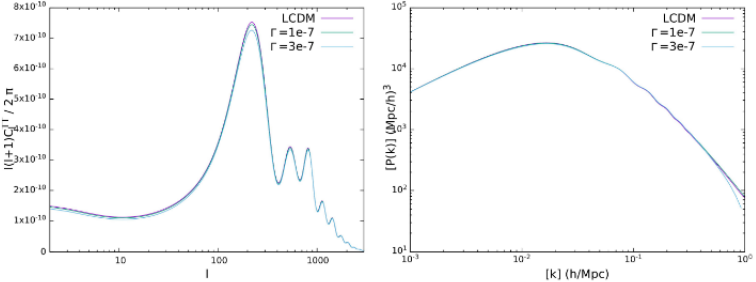


Figure 2. *The effect of DM annihilation on the TT power spectrum and on matter power spectrum. We keep $u = 0$ for these plots.*

Results

We have (ΛCDM + u +) parameter model:

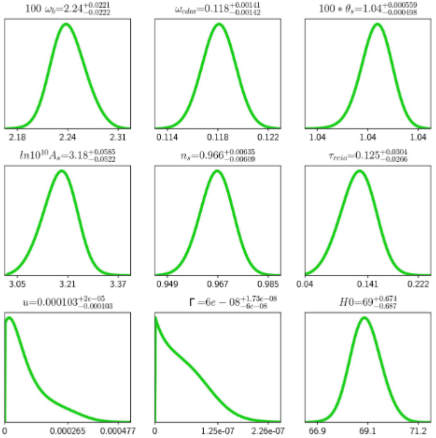


Figure 3. *1-d posterior distribution of 6+2 parameter model with parameters* $\{\omega_{\rm b},\ \omega_{\rm cdm},\ \theta_{\rm s},\ A_{\rm s},\ n_{\rm s},\ \tau_{\rm reio},\ u,\ \Gamma\}$ *using* ***Planck 2018 high-l TT, BOSS-BAO 2014*** *data-sets.*

Results: Best-fit Values

MCMC analysis:

Parameter	best-fit	mean$\pm\sigma$	95% lower	95% upper
$100\ \omega_b$	2.249	$2.244^{+0.022}_{-0.022}$	2.2	2.287
ω_{cdm}	0.1183	$0.1184^{+0.0014}_{-0.0014}$	0.1156	0.1212
$100 * \theta_s$	1.042	$1.042^{+0.00056}_{-0.0005}$	1.041	1.043
$\ln(10^{10} A_s)$	3.193	$3.183^{+0.059}_{-0.052}$	3.07	3.29
n_s	0.97	$0.9661^{+0.0063}_{-0.0061}$	0.9539	0.9782
τ_{reio}	0.13	$0.1251^{+0.03}_{-0.027}$	0.06748	0.18
u	–	1.225×10^{-4} $(1-\sigma$ upper)	–	2.948×10^{-4}
Γ	–	7.698×10^{-8} $(1-\sigma$ upper)	–	1.501×10^{-7}
H_0	68.81	$68.97^{+0.67}_{-0.69}$	67.6	70.33

Table 1. *Statistical results of 6+2 parameter model with parameters $\{\omega_b, \omega_{cdm}, \theta_s, A_s, n_s, \tau_{reio}, u, \Gamma\}$ using Planck 2018 high-l TT, BOSS-BAO 2014 data-sets.*

3d poteriors

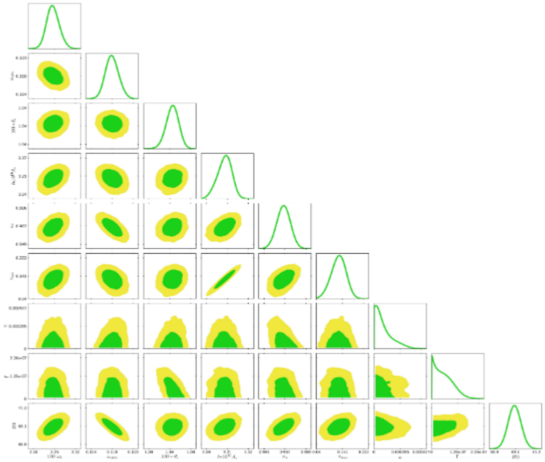


Figure 4. *2-d posterior distributions of 6+2 parameter model with parameters* $\{\omega_{\rm b},\ \omega_{\rm cdm},\ \theta_{\rm s},\ A_{\rm s},\ n_{\rm s},\ \tau_{\rm reio},\ u,\ \Gamma\}$ *using* ***Planck 2018 high-l TT, BOSS-BAO 2014*** *data-sets.*

Neff open

We have ΛCDM + u + Γ + N_{eff} parameter model:

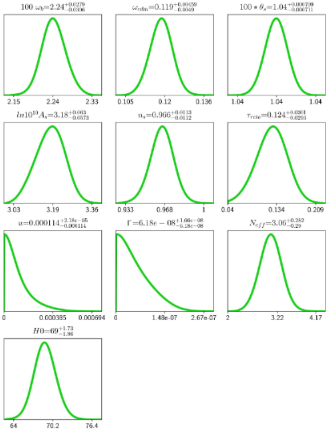


Figure 5. *1-d posterior distribution of 6+3 parameter model with parameters* $\{\omega_b, \omega_{cdm}, \theta_s, A_s, n_s, \tau_{reio}, u, \Gamma, N_{eff}\}$ *using* ***Planck 2018 high-l TT, BOSS-BAO 2014*** *data-sets.*

Neff open: best-fit values

MCMC Analysis:

Parameter	best-fit	mean$\pm\sigma$	95% lower	95% upper
$100\ \omega_b$	2.254	$2.243^{+0.028}_{-0.031}$	2.185	2.303
ω_{cdm}	0.1171	$0.1187^{+0.0046}_{-0.0049}$	0.1094	0.1283
$100 * \theta_s$	1.042	$1.042^{+0.00071}_{-0.00071}$	1.04	1.043
$\ln(10^{10}A_s)$	3.213	$3.181^{+0.063}_{-0.057}$	3.058	3.302
n_s	0.9693	$0.9657^{+0.011}_{-0.011}$	0.9435	0.9882
τ_{reio}	0.1428	$0.1243^{+0.03}_{-0.029}$	0.06379	0.1837
u	–	1.355×10^{-4} $(1-\sigma$ upper)	–	3.351×10^{-4}
Γ	–	7.881×10^{-8} $(1-\sigma$ upper)	–	1.592×10^{-7}
N_{eff}	3.041	$3.058^{+0.28}_{-0.29}$	2.493	3.62
H_0	69.3	$69^{+1.7}_{-1.9}$	65.5	72.65

Table 2. *Statistical results of 6+3 parameter model with parameters* $\{\omega_b, \omega_{cdm}, \theta_s, A_s, n_s, \tau_{reio}, u, \Gamma, N_{eff}\}$ *using* `Planck 2018 high-l TT, BOSS-BAO 2014` *data-sets.*

Neff open: 3d poteriors

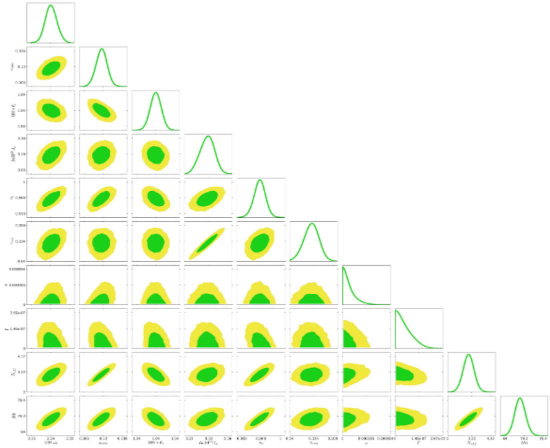


Figure 6. *2-d posterior distributions of 6+3 parameter model with parameters* $\{\omega_b, \omega_{cdm}, \theta_s, A_s, n_s, \tau_{reio}, u, \Gamma, N_{eff}\}$ *using* ***Planck 2018 high-l TT, BOSS-BAO 2014*** *data-sets.*

Viable Dark Matter Model

Let us discuss a viable particle DM model now:

$$-\mathcal{L} \supset g_s \bar{\nu}_s \gamma_5 \nu_s \phi + g_\Psi \bar{\Psi} \gamma_5 \Psi \phi$$

Processes that we wish to have in he dark sector:

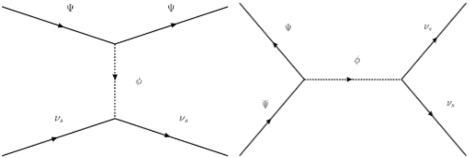


Figure 7. *Feynman diagrams representing DM–ν_s scattering and DM annihilation into ν_s.*

DM needs to light (sub-MeV) and such candidates usually have some involded phenomenology of forming the thermal relic. See Berlin (2017), D'Agnolo (2018), Evans (2019).

Viable Dark Matter Model

Translates in the DM independent parameter space:

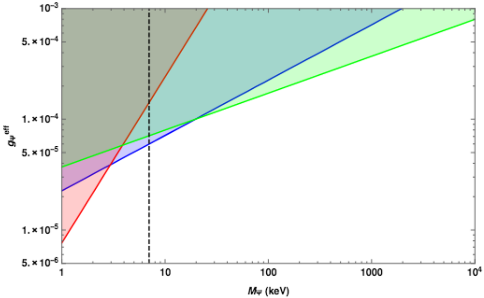


Figure 8. *Constraints on g_Ψ^{eff} vs M_Ψ plane from DM-ν scattering and DM annihilation. We have used $g_\Psi^{\mathrm{eff}} = g_\Psi \sin^2(\theta_{\mathrm{m}})$ for the scattering process and $g_\Psi^{\mathrm{eff}} = g_\Psi$ for the annihilation processes to keep them on the same footing, as during scattering the DM particles scatter to the active neutrinos through mixing with ν_s, whereas during annihilation, the more stringent bound comes from annihilation of DM into ν_s. The red, blue and green lines correspond to bounds from scattering and annihilation of DM into sterile neutrinos and pseudoscalars respectively. We have used $g_s = 10^{-4}$ and $\theta_{\mathrm{m}} = 0.1$ for these plots. The vertical dashed line at $M_\Psi \sim 7$ keV corresponds to the lower mass bound of fermionic DM from Lyman-α observations [70].*

Conclusions

- Light dark sector if it exists can be constrained via CMB.
- Such dark sector composing of DM is naturally expected to involve DM-nu scattering and DM annihilation to neutrinos.
- DM-nu interactions are highly constrained from PLACK data.
- DM-annihilation is highly constrained.
- Usually such DM annihilations do not lead to better constraints on DM parameter space. However if we have Sommerfeld-enhancement in the DM annihilation cross-section, it can leave its impact on CMB.
- Viable DM candidate involving light psuedoscalar (or pseudo-vector) mediators for Sommerfeld can be tested and be investigated from CMB.
- Invitation to imagine and construct such light dark sector models and complement the cosmic footprints with laboratory observable predictions.

Thank You