DIRAC NEUTRINO PORTAL DARK MATTER

In collaboration with Anirban Biswas (Sogang Univ.), Dibyendu Nanda (KIAS), Nayan Das (IITG)

Based on arXiv:2103.05648 (JCAP), arXiv:2205.01144

Debasish Borah
Indian Institute of Technology Guwahati

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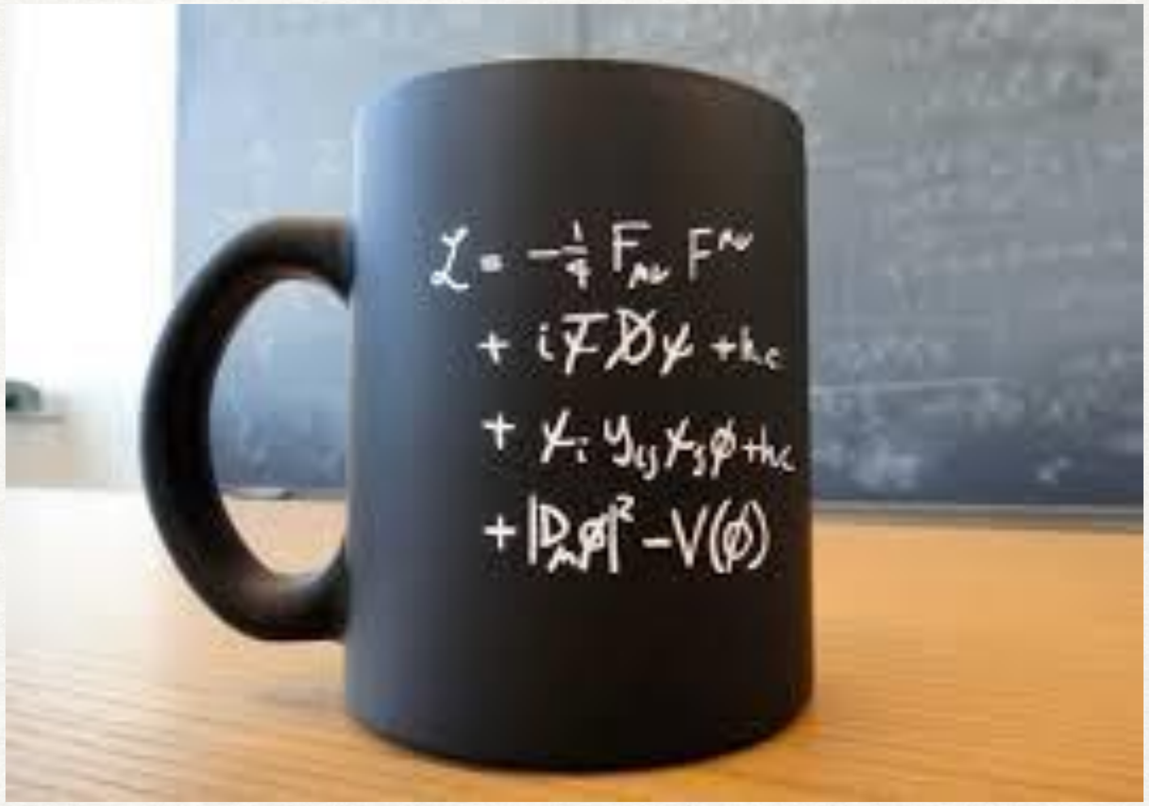
THE MOTIVATION

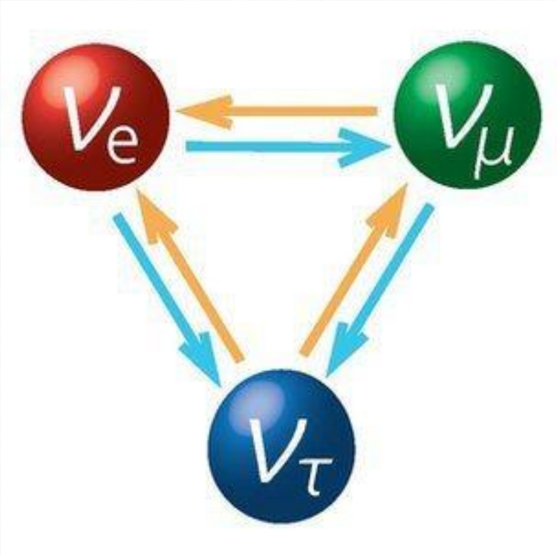
The Standard Model (SM) has been very successful, but it has several limitations. For example,

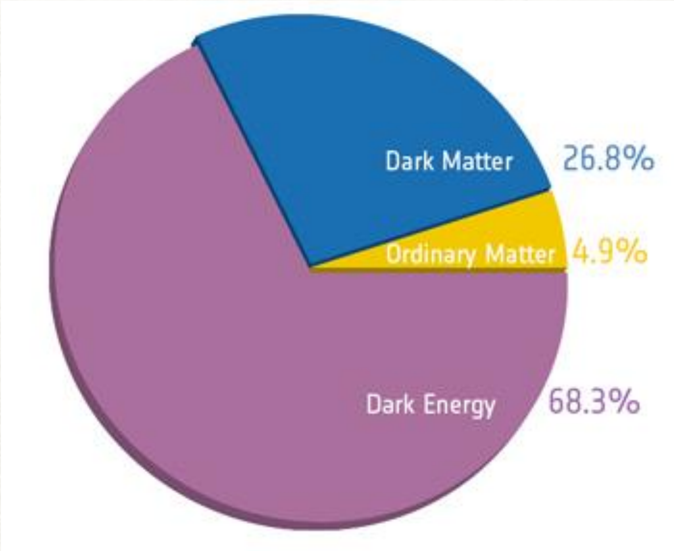
- The SM can not explain the origin of light neutrino masses.
- The SM does not have a particle dark matter (DM) candidate.



Origin of DM & ν mass can be linked in several ways; e.g.,

- ❑ Scotogenic scenarios (E Ma 2006++), νMSM (Shaposhnikov et al++) etc.
- ❑ Heavy neutrino portal DM (Falkowski et al 2009, Batell et al 2017, Blennow et al 2019 ++).





Talk by Shreyashi Chakdar

LIGHT DIRAC NEUTRINO PORTAL: AN ALTERNATIVE

SM ← ν_R ← Dark Sector $\Psi, \ \varphi$

$y_H \, \bar{\ell} \, \tilde{H} \, \nu_R$ $\qquad$ $y_\phi \, \bar{\psi} \, \nu_R \, \phi$

	Z_4
ℓ, e_R	i
ν_R	i
Ψ	-1
φ	i

- Neutrinos have sub-eV Dirac mass.
- Dark matter is a fermion Ψ having renormalisable interactions only via right handed neutrinos ν_R.
- Production of DM will also produce ν_R and increase the effective relativistic degrees of freedom

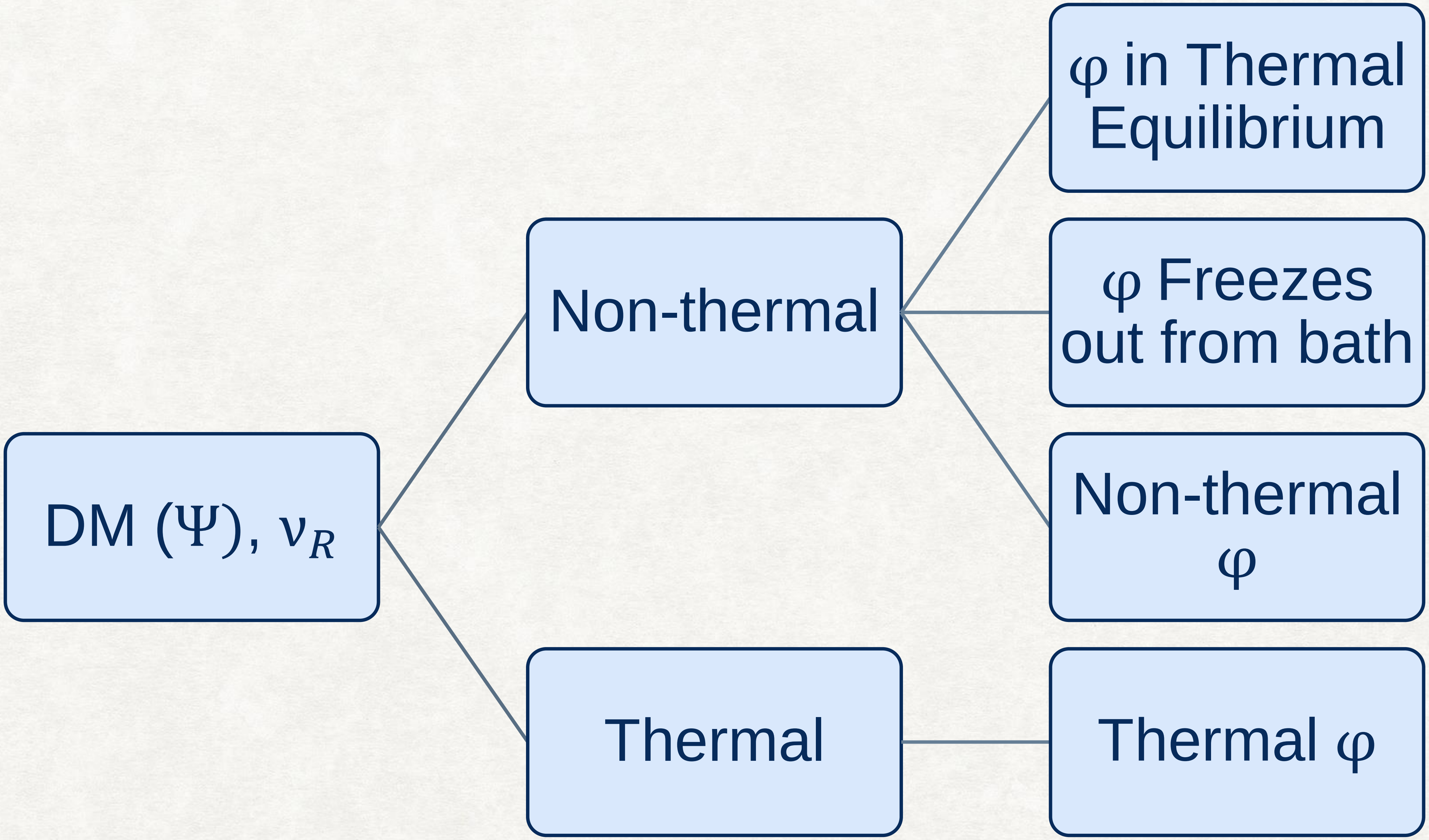
$$\mathrm{N_{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma}\right)$$

$$\mathrm{N_{eff}} = 2.99^{+0.34}_{-0.33}$$ (Planck 2018, 1807.06209)

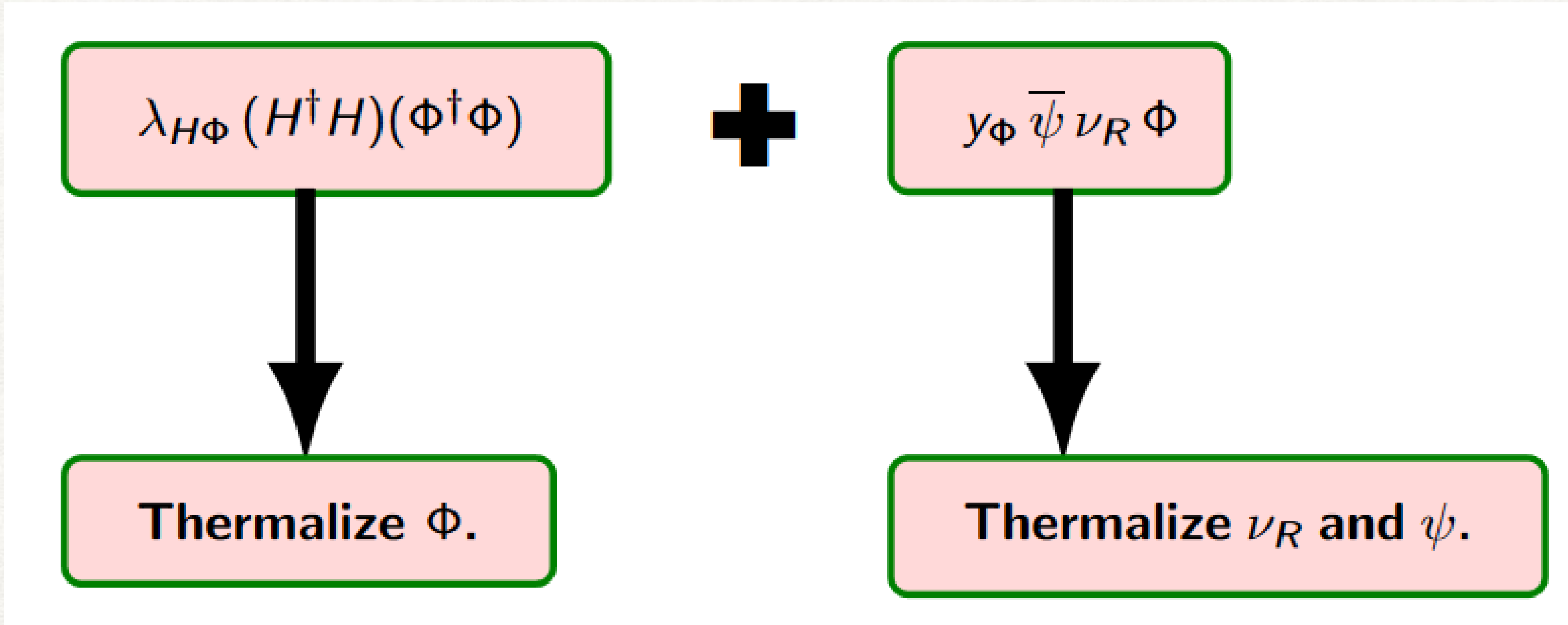
- While $N_{\rm eff}^{\rm SM} = 3.045$ CMB-S4 can probe up to $\Delta \mathrm{N_{eff}} = \mathrm{N_{eff}} - \mathrm{N_{eff}^{SM}} = 0.06$

Mangano et al 2005 $\qquad$ Abazajian et al 2019

POSSIBILITIES



THERMAL DARK MATTER



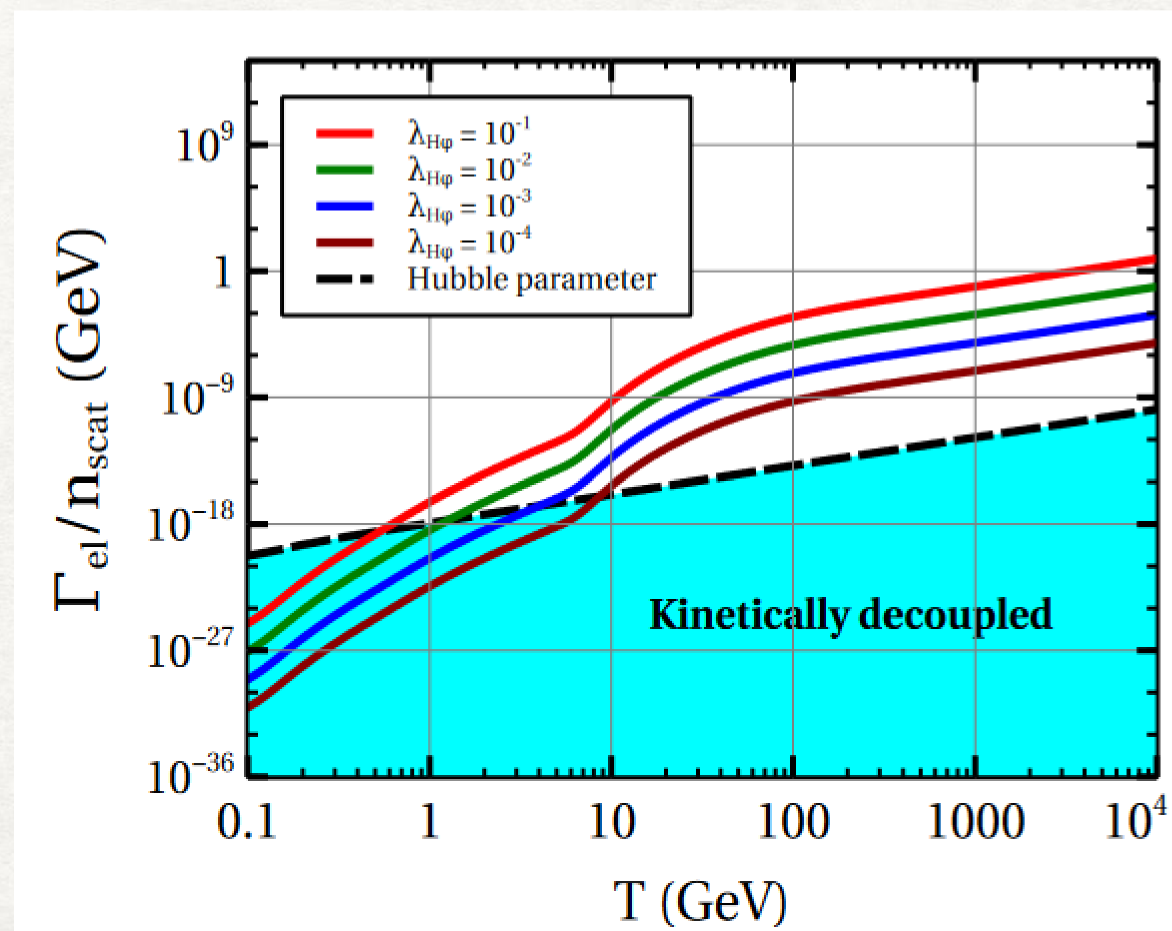
- Depending on $\lambda_{H\varphi}, M_\varphi$, φ will decouple from the bath at T_{dec}.

When $T < T_{\rm dec}$, $T_{\rm dark} \neq T_{SM}$

- Simple estimate based on entropy conservation

$$\Delta N_{\rm eff} \simeq 0.027 \left(\frac{106.75}{g_\star(T_{\rm dec})}\right)^{4/3} g_s$$

Abazajian & Heeck 2019



arXiv:2103.05648

RELIC ABUNDANCE

DM (Ψ)

When $T > T_{\rm dec}$

$$\frac{dY}{dx} = -\frac{1}{2}\frac{\beta\, s}{\mathcal{H}\, x}\langle\sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right]$$

$$\left(\beta(T) = \frac{g_\star^{1/2}(T)\sqrt{g_\rho(T)}}{g_s(T)}\right)$$

When $T < T_{\rm dec}$

$$\frac{dY}{dx} = -\frac{1}{2}\frac{\beta\, s}{\mathcal{H}\, x}\langle\sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right],$$

$$x\frac{d\xi}{dx} + (\beta - 1)\xi = \frac{1}{2}\frac{\beta\, x^4\, s^2}{4\,\alpha\,\xi^3\,\mathcal{H}\, M_0^4}\langle E\sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right]$$

$$\left(\xi = \frac{T_{\nu_R}}{T}\right)$$

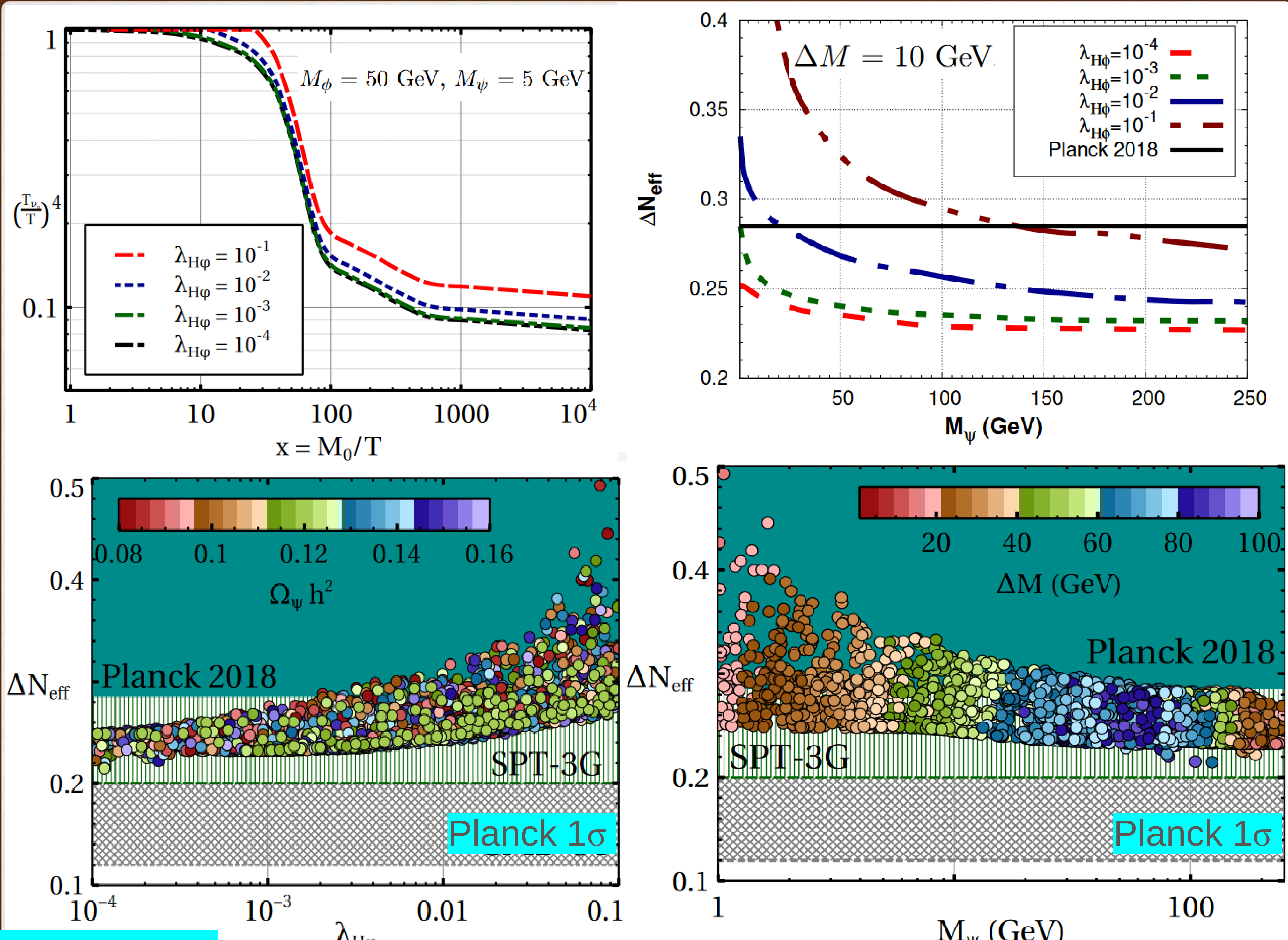
$$\Delta N_{\rm eff} = \frac{\sum_\alpha \varrho_{\nu_R^\alpha}}{\varrho_{\nu_L}}, = 3\times\frac{\varrho_{\nu_R}}{\varrho_{\nu_L}}, = 3\times\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4\Bigg|_{T_{\rm CMB}},$$

Neglecting spectral distortions →

$$\Delta N_{\rm eff} = 3\times\left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4\Bigg|_{T>T_{\nu_L}^{\rm dec}}, = 3\times\left(\frac{T_{\nu_R}}{T}\right)^4\Bigg|_{T>T_{\nu_L}^{\rm dec}}, = 3\times\xi^4\Big|_{T>T_{\nu_L}^{\rm dec}},$$

Talk by Xuheng Luo

arXiv:2103.05648



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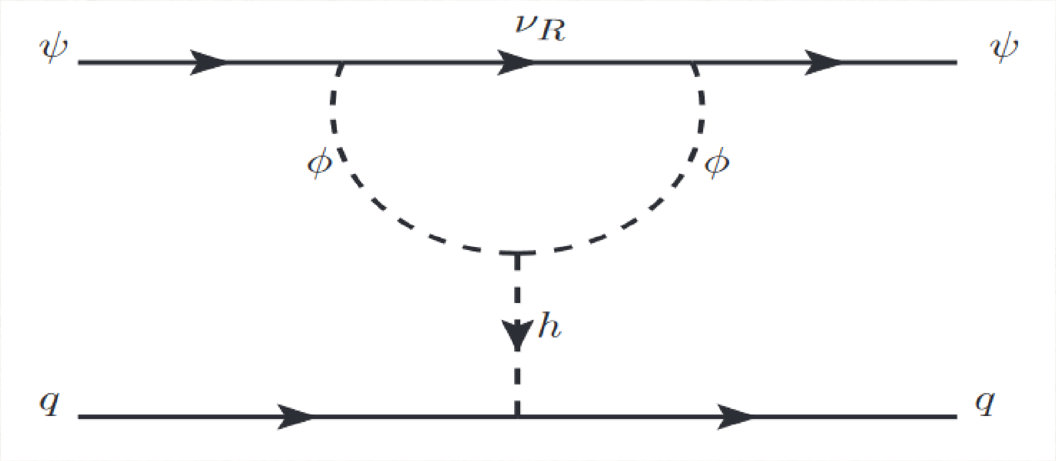
Direct detection of DM

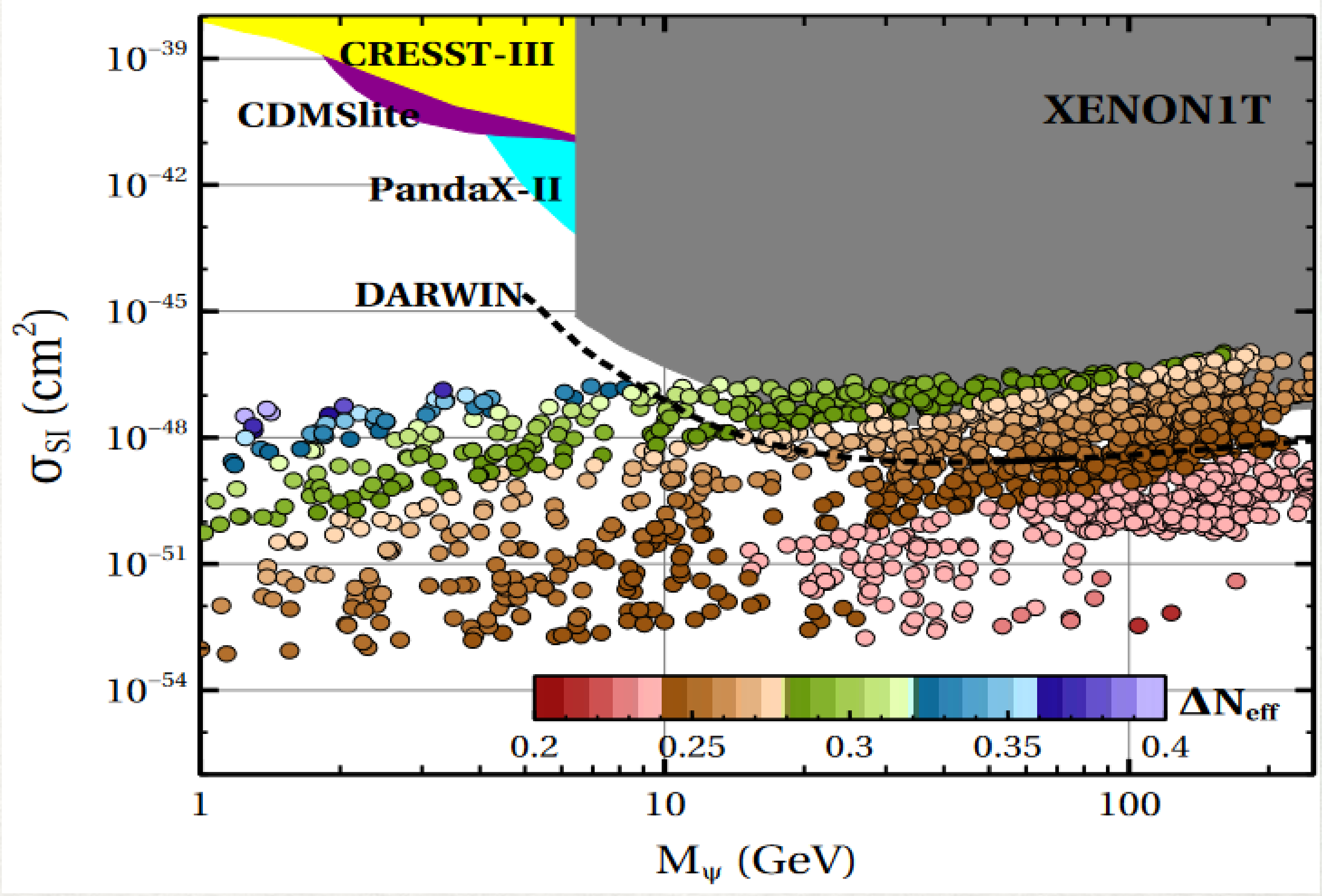
- Light Dirac neutrino portal DM can be probed via direct detection experiments as well as future CMB probes.

- Keeping N_{eff} within CMB-S4 reach naturally leads dark sector particles around or below a 100 GeV. Heavier particles leads to early decoupling: $\Delta N_{\rm eff} \simeq 0.027$

- Singlet scalar can lead to invisible Higgs decay, if kinematically allowed.

- Possible UV completions of tiny Dirac neutrino mass (see K S Babu's talk) can have other interesting phenomenology while keeping the generic conclusions related to DM, N_{eff} arrived in this work unchanged.





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NON-THERMAL OR FREEZE-IN DARK MATTER

Non-thermal DM (Ψ), ν_R

φ in Thermal Equilibrium (Case I)

$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi^{\rm eq},$$
$$\frac{dY_{\nu_R}}{dx} = \frac{\beta}{\mathcal{H} s^{1/3} x}\langle E\Gamma\rangle Y_\phi^{\rm eq},$$

φ Freezes out from bath (Case II)

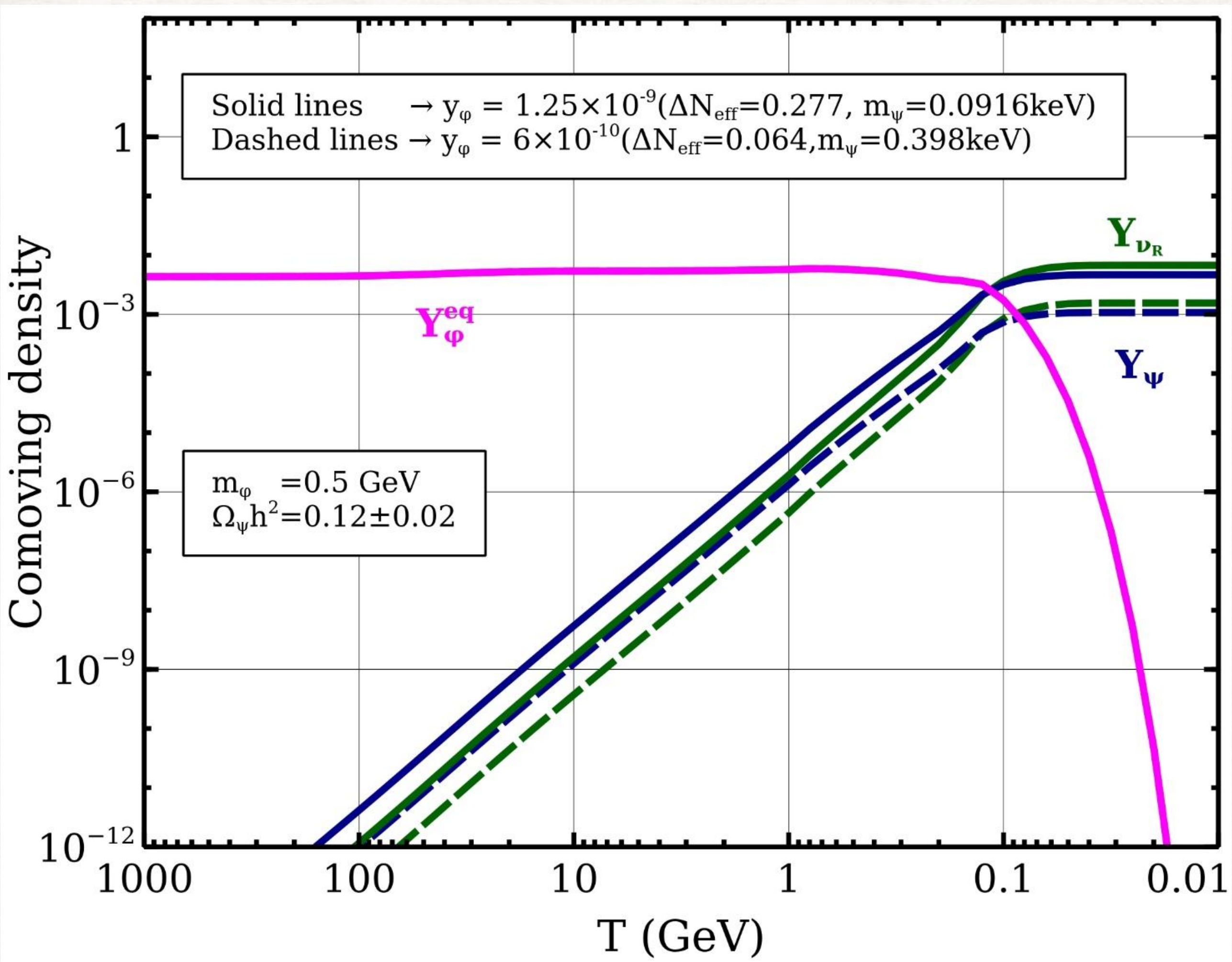
$$\frac{dY_\phi}{dx} = \frac{\beta s}{\mathcal{H}x}\left(-\langle\sigma v\rangle\left((Y_\phi)^2 - (Y_\phi^{\rm eq})^2\right) - \frac{\Gamma_\phi}{s}\frac{K_1(m_\phi/T)}{K_2(m_\phi/T)} Y_\phi\right),$$
$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi,$$
$$\frac{dY_{\nu R}}{dx} = \frac{\beta}{\mathcal{H} s^{1/3} x}\langle E\Gamma\rangle Y_\phi.$$

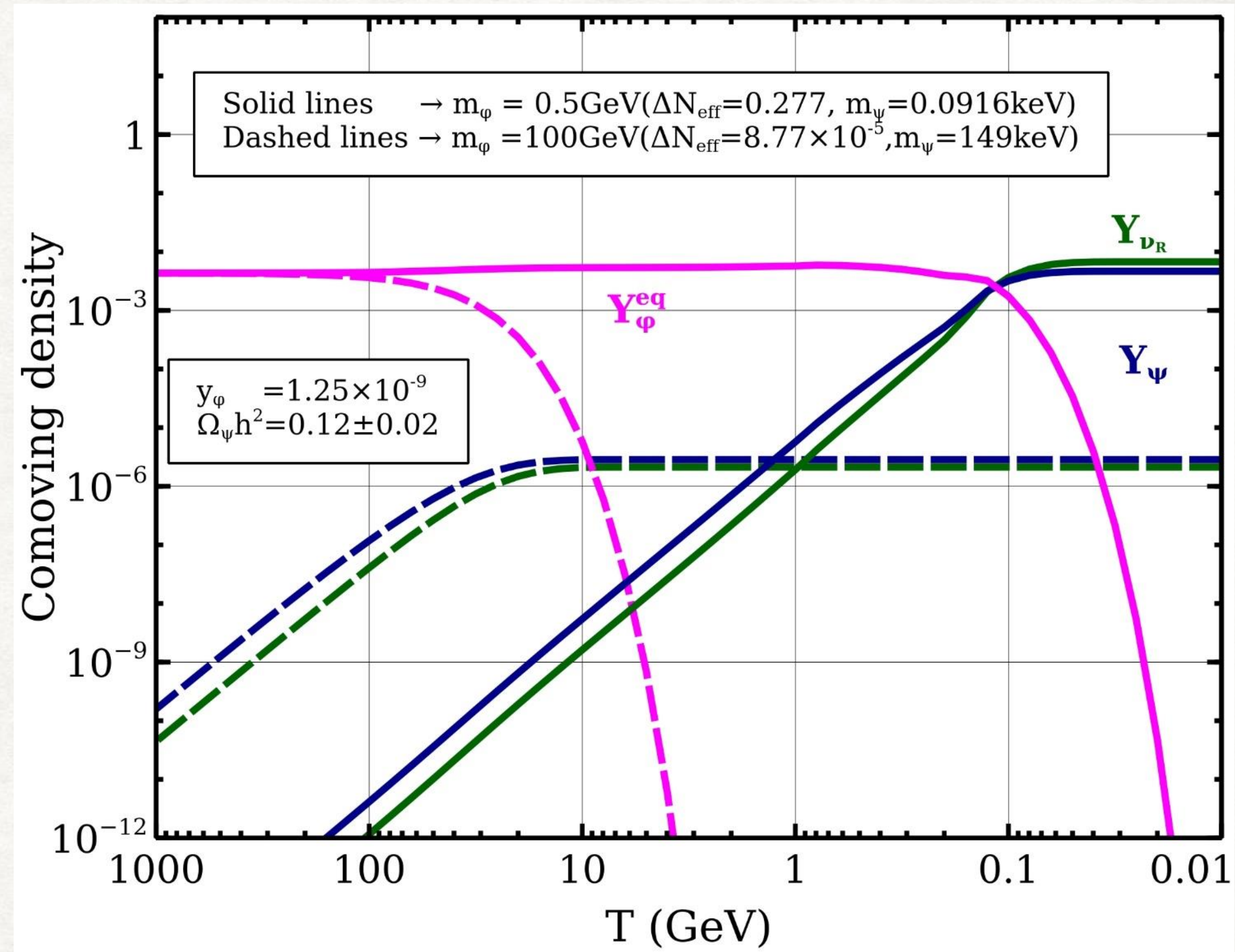
Non-thermal φ (Case III)

$$\frac{\partial f_\phi}{\partial t} - \mathcal{H} p_1 \frac{\partial f_\phi}{\partial p_1} = C^{h\to\phi\phi^\dagger} + C^{hh\to\phi\phi^\dagger} + C^{\phi\to\bar\nu_R\psi},$$
$$\frac{dY_\psi}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s}\frac{\Gamma_\phi m_\phi}{2\pi^2}\int \frac{\left(\mathcal{A}\frac{m_0}{r}\right)^3 \xi^2 f_\phi(\xi, r)}{\sqrt{\left(\xi\mathcal{A}\frac{m_0}{r}\right)^2 + m_\phi^2}} d\xi\,,$$
$$\frac{dY_{\nu_R}}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s^{4/3}}\langle E\Gamma\rangle \frac{1}{2\pi^2}\int_0^\infty \left(\mathcal{A}\frac{m_0}{r}\right)^3 \xi^2 f_\phi(\xi, r) d\xi\,,$$

Freeze-in DM by Hall et al 2010

Non-Thermal dark matter: Case I





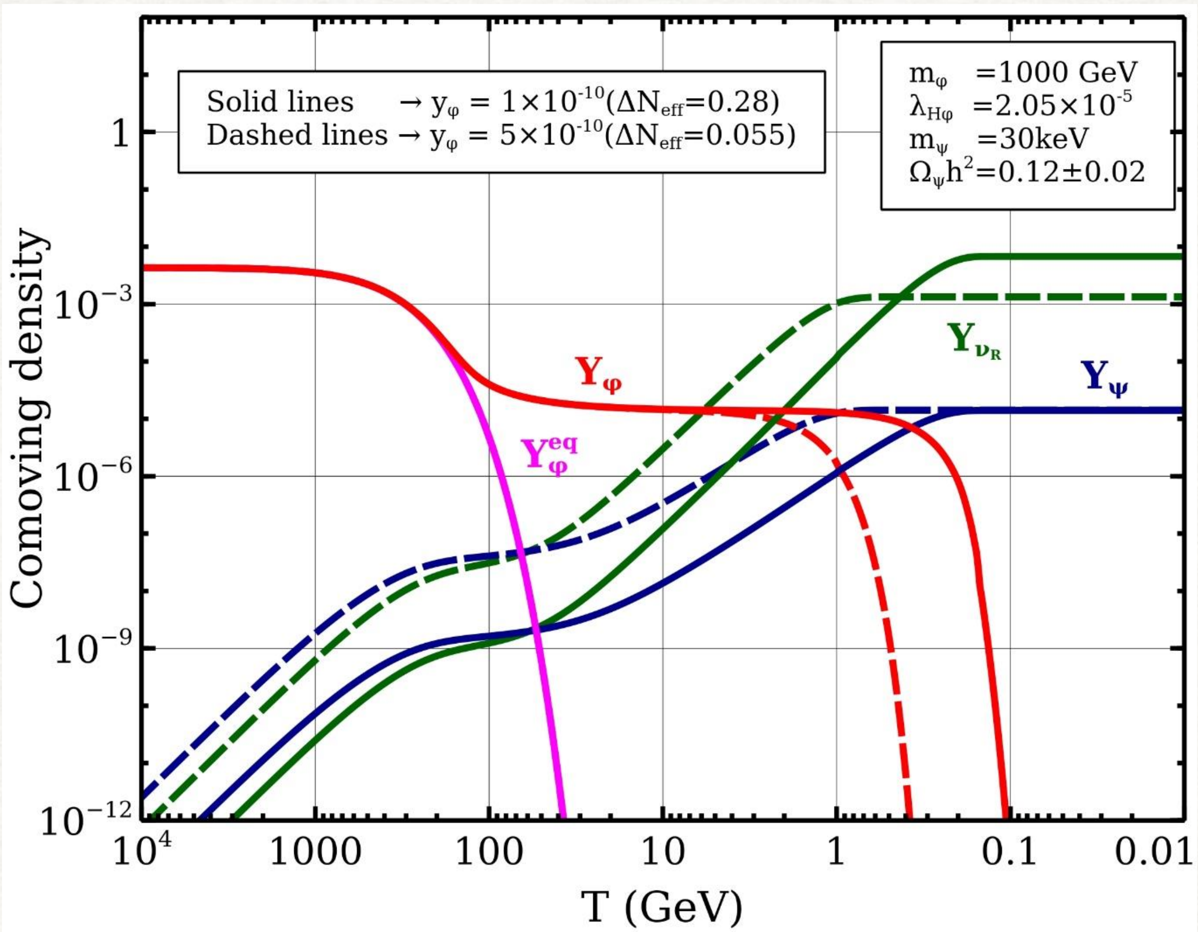
$$\mathbf{Y_{DM} \propto y_{\varphi}^{2}}$$

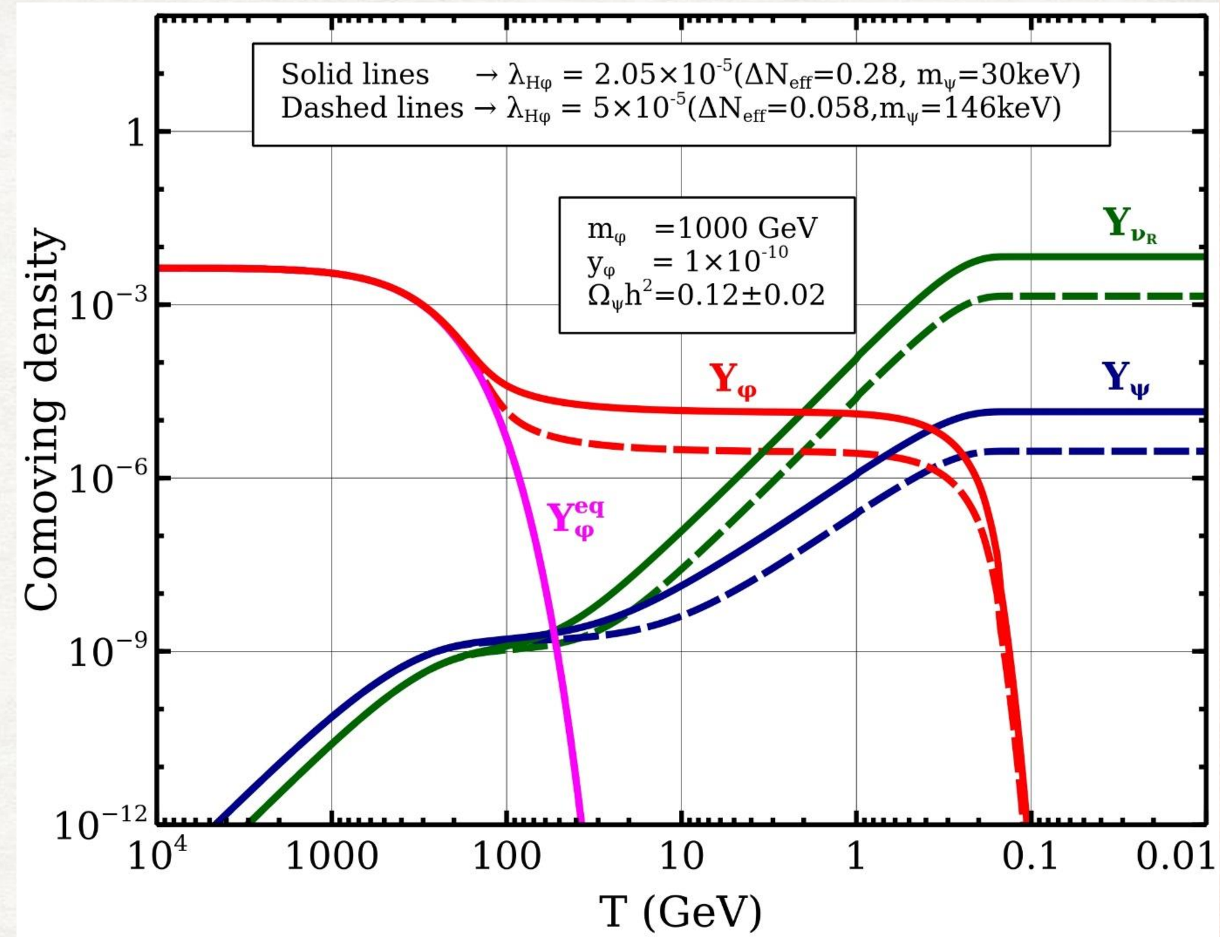
$$\mathbf{Y_{DM} \propto 1/m_{\varphi}}$$

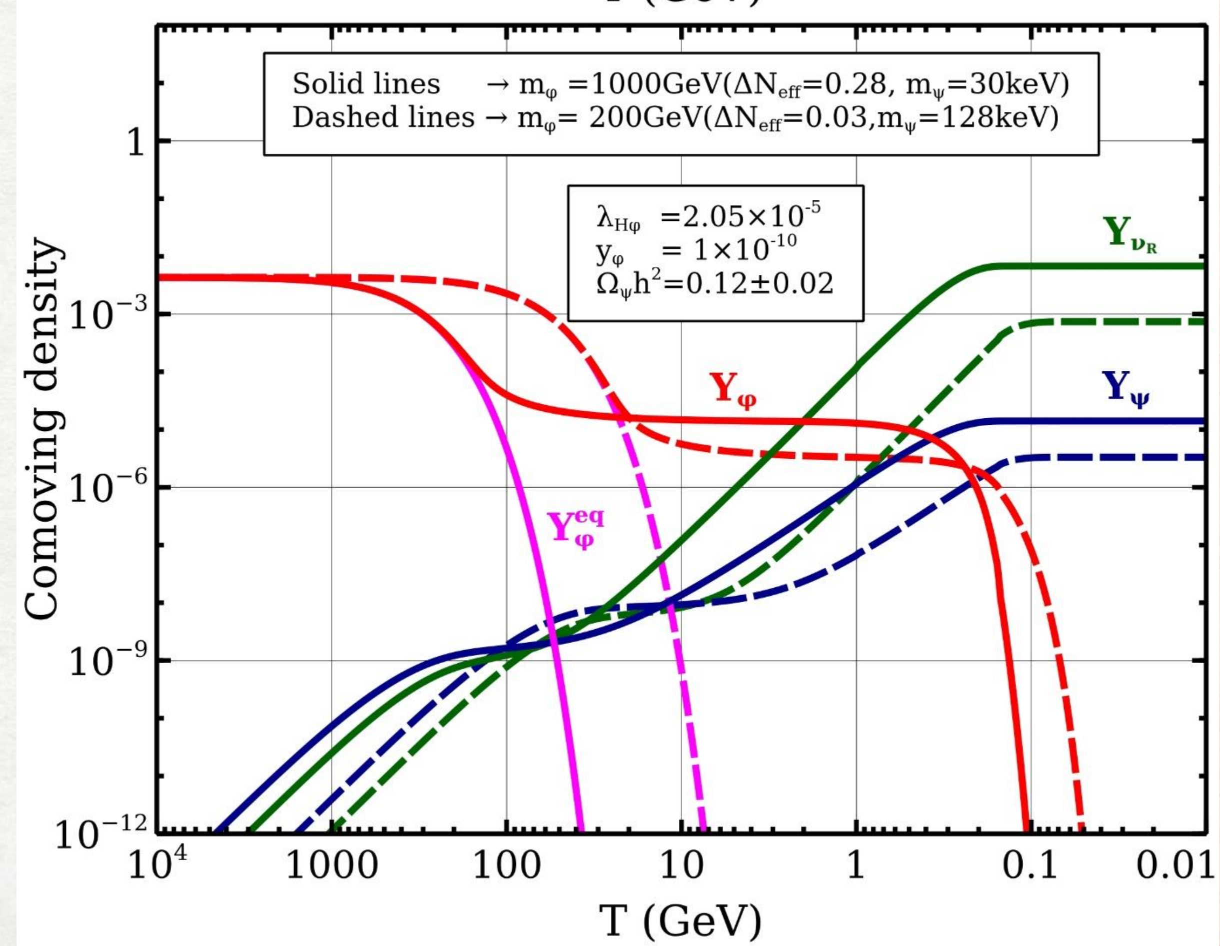
arXiv:2205.01144

Freeze-in DM by Hall et al 2010

Non-Thermal dark matter: Case II







For $T < T_{fo}^{\varphi}$

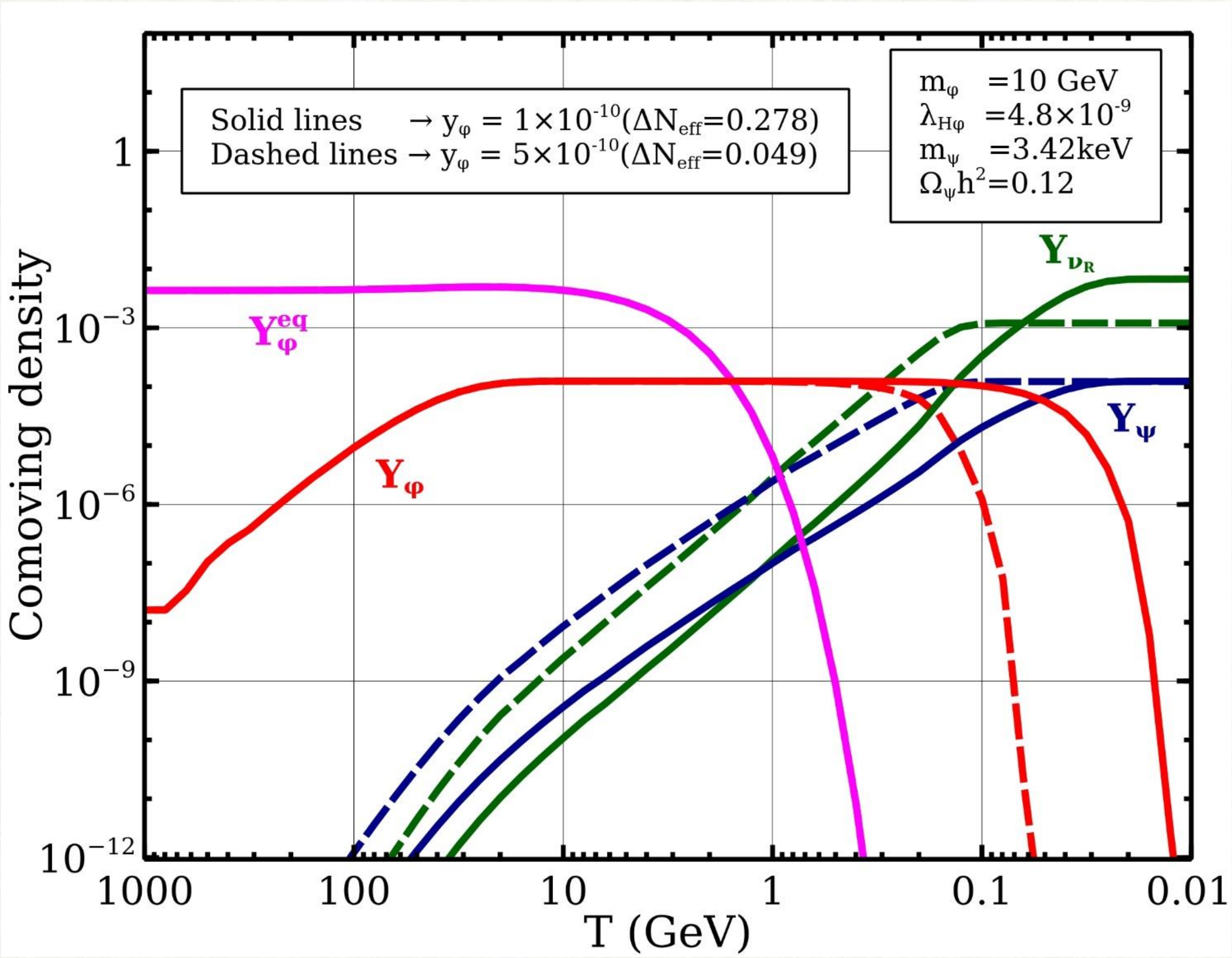
$$\frac{dY_{\upsilon R}}{dx} \propto \Gamma_\varphi\, x^3 e^{-\frac{r(x^2-x_F^2)}{2}}, r \propto \Gamma_\varphi \propto y_\varphi^2$$

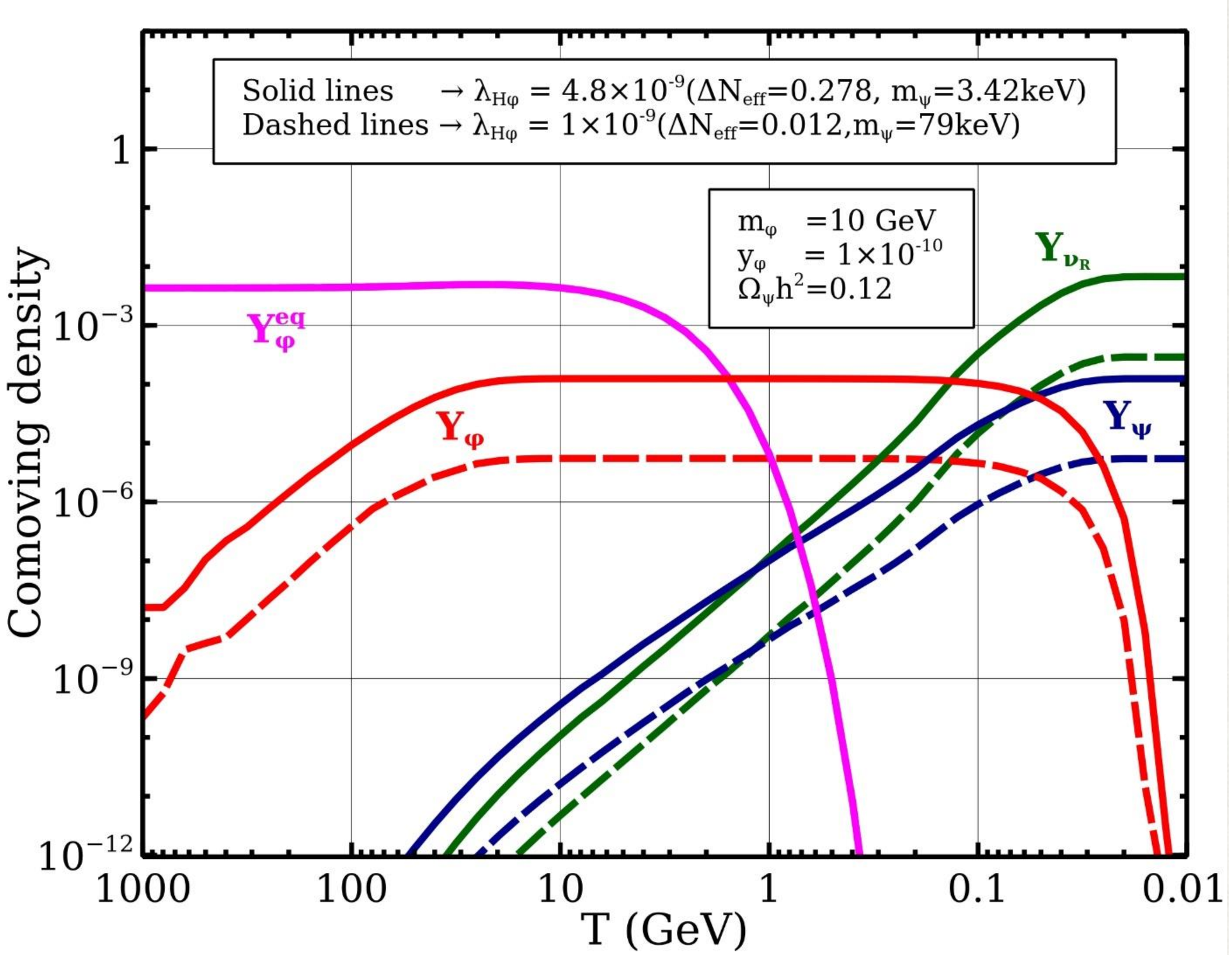
$$Y_{DM} = Y_{fo}^{\varphi}$$

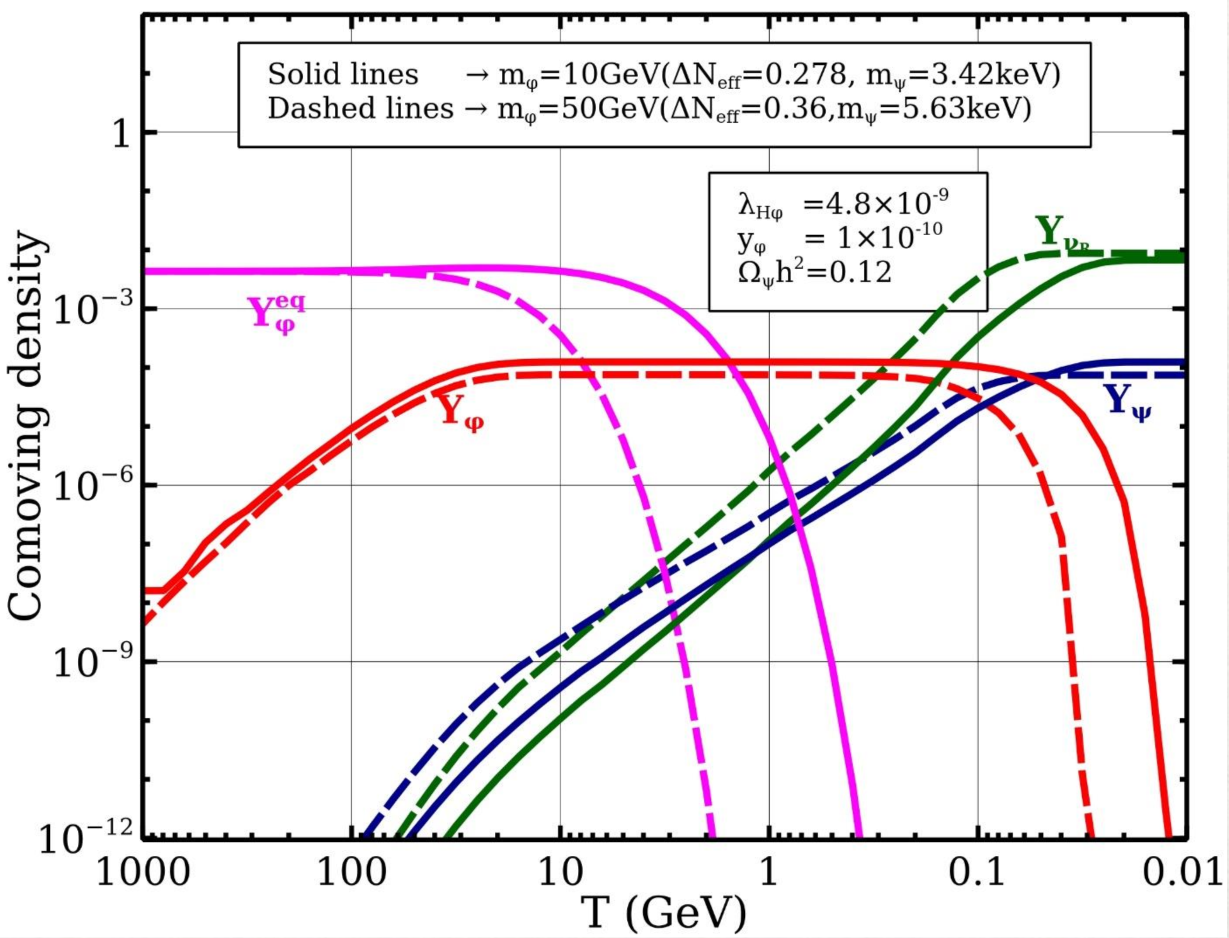
DB, A Gupta 2017 (PRD)

arXiv:2205.01144

Non-Thermal dark matter: Case III







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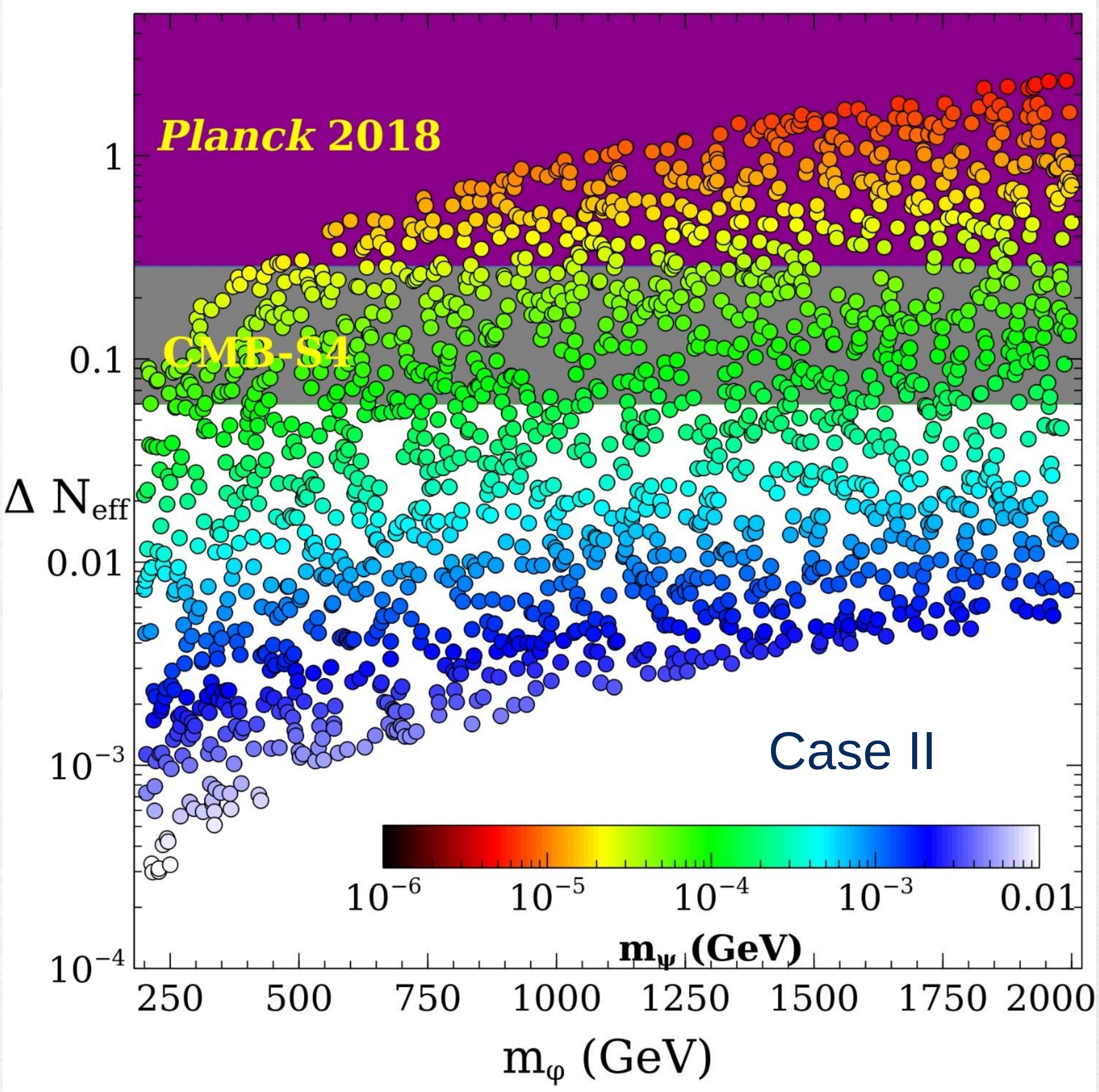
- Non-thermal Dirac neutrino portal DM can saturate Planck 2018 limits on N_{eff}, for light DM masses upto a few tens of keV.
- DM mass up to a few hundred keV can be probed at CMB-S4.
- Constraints from Lyman-alpha observations will disfavor some more region of parameter space in this scenario (upto a few tens of keV)
- In addition, such Dirac neutrino portal DM is falsifiable by future observations of neutrinoless double beta decay.



THANK YOU FOR YOUR ATTENTION