Constraining keV sterile neutrino dark matter through lab and cosmo surveys

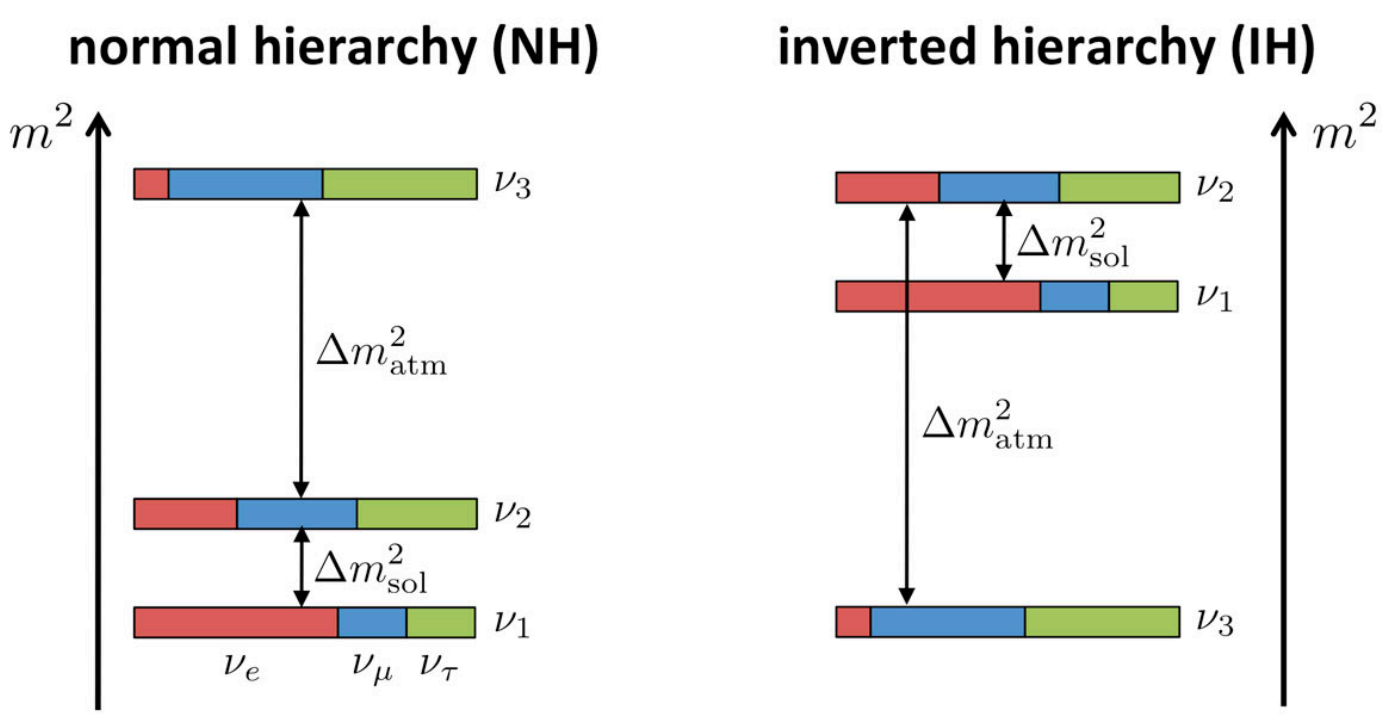
Manibrata Sen
Max-Planck-Institut für Kernphysik, Heidelberg

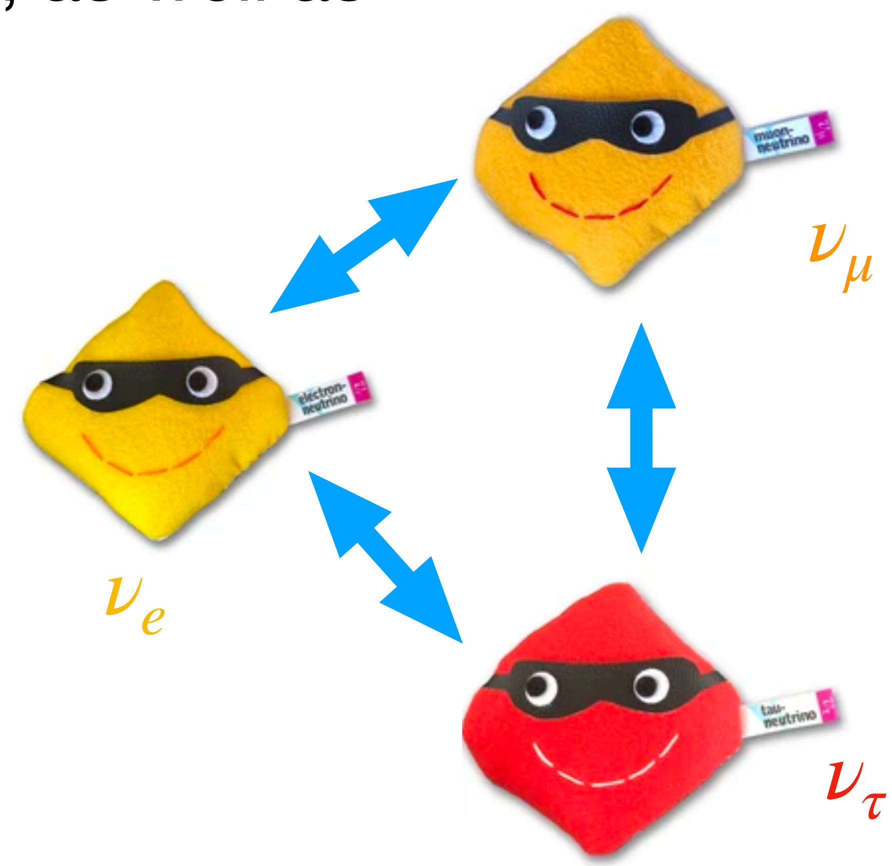
Particle and Astroparticle Theory Seminar
MPIK + ITP, Heidelberg
28/10/2021

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Standard paradigm…

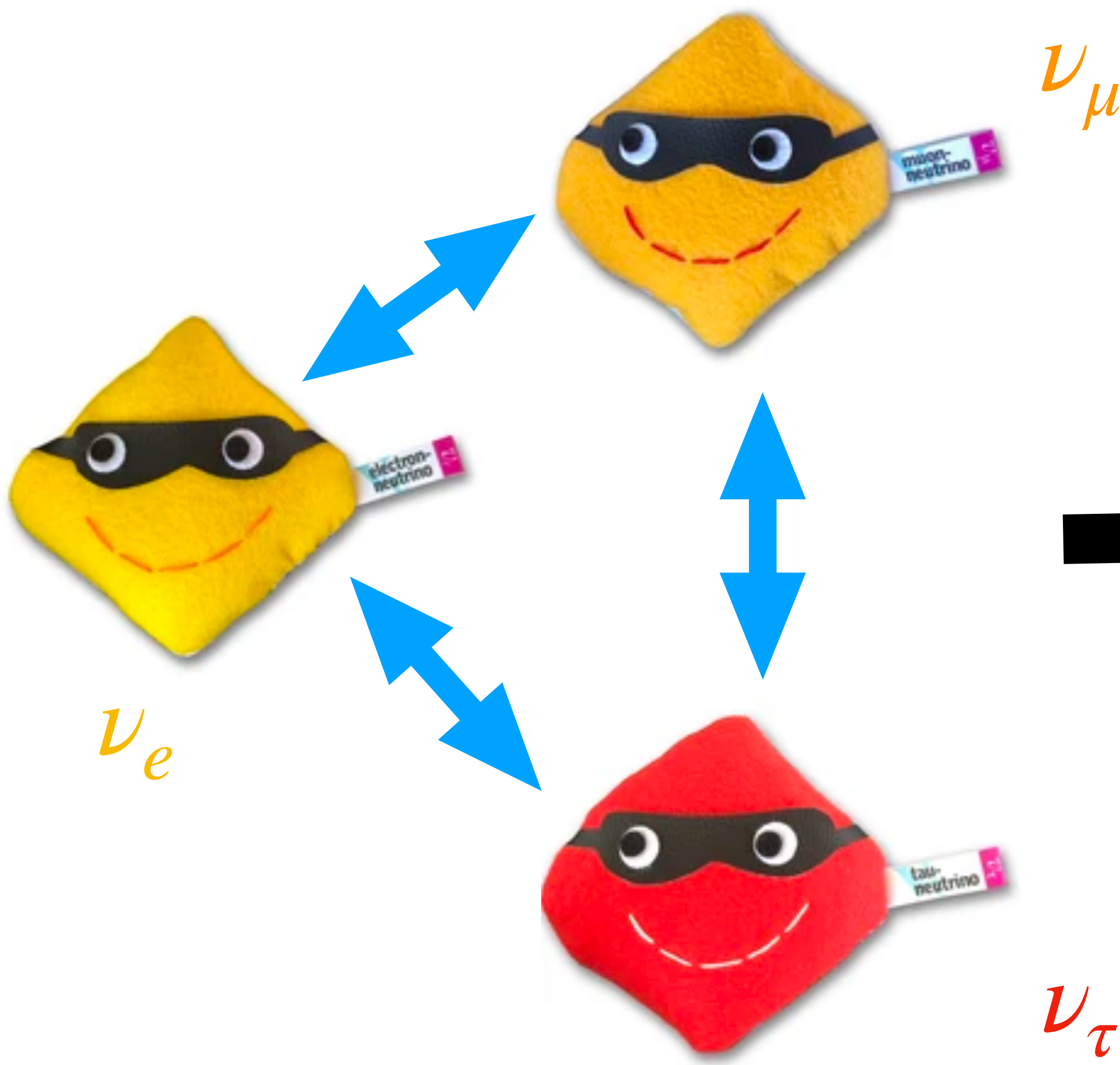
- Neutrinos are massive, and can change flavor.
- Neutrinos interact “weakly” with the rest, as well as with themselves.
- There are 3 active light neutrinos.





Credit: The Particle Zoo

The sterile neutrino: the Riddler



+

ν_s

Are there more of these ?

Four riddles:

1. Theoretical bias.
2. Short baseline anomalies.
3. Reactor anomalies.
4. Cosmology.

Why do we like sterile neutrinos?

- Provides the SM neutrinos with the ‘right’ partner.

- Can give masses to neutrinos.

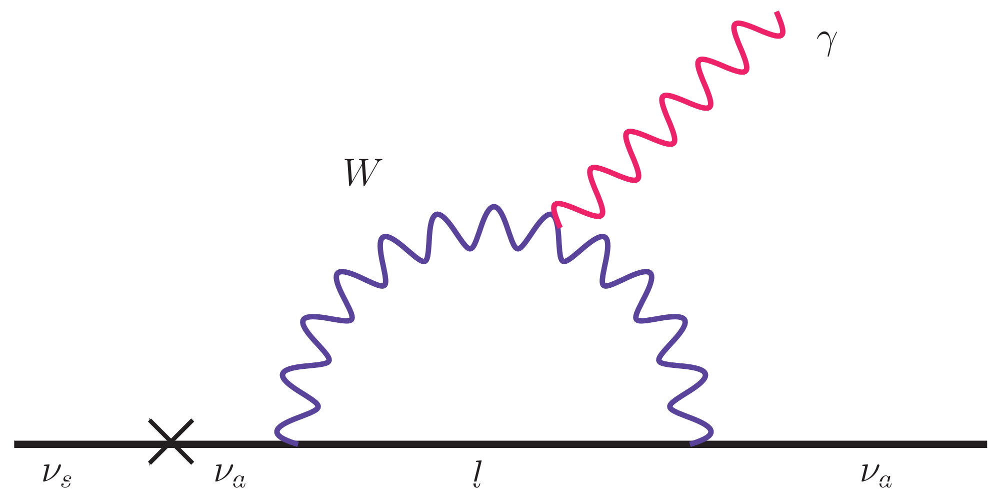
- Can be used to answer the baryon-asymmetry of the universe through leptogenesis.

- Possible dark matter candidate. Can also be used to solve small-scale structure problems.

- Hints in terrestrial experiments?

See Abazajian (2017) for a detailed review

Sterile neutrinos as Dark Matter

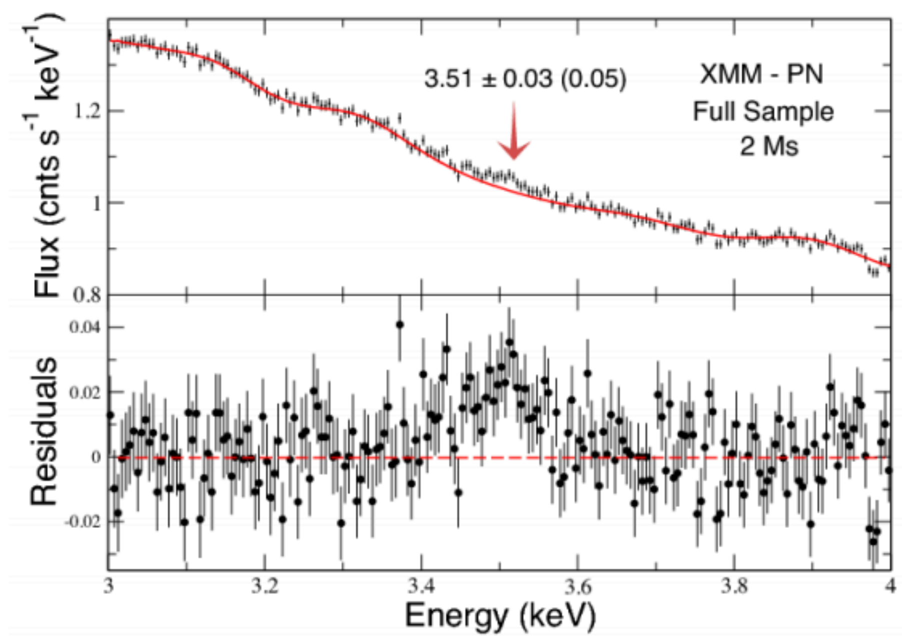


- 4th mass eigenstate $\nu_4 = cos\theta\,\nu_s + sin\theta\,\nu_a$

- Can be detected through 1-loop decay into photons: $\nu_s \rightarrow \nu_a\gamma$.

- Decay rate $\Gamma \propto m_4^5 \sin^2 2\,\theta$. Radiative decay detectable.

  Pal and Wolfenstein, PRD1982
  Abazajian, Fuller and Patel, PRD2001 + many more…



- Non-observation puts bound on $m_4 - sin\,2\,\theta$ plane.

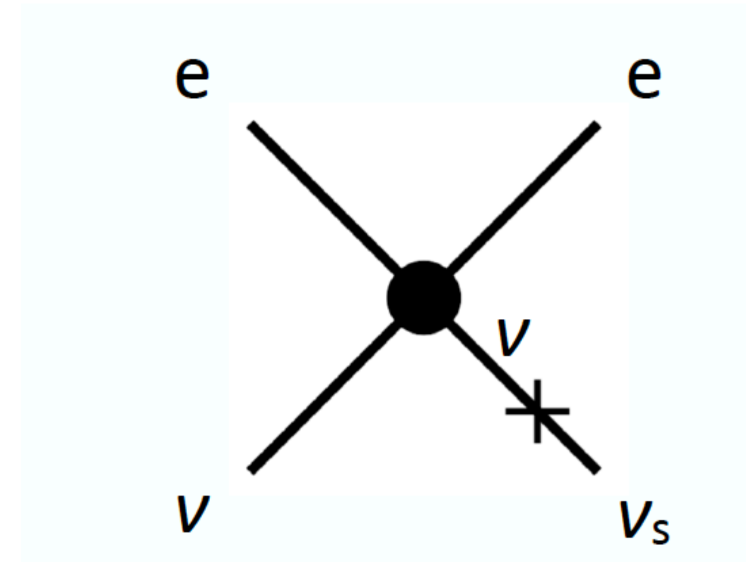
- Radiative decay leads to line at $E_\gamma = m_4/2$.

  Hints of a line at $E = 3.55\,\mathrm{keV}$? Sterile neutrino at 7.1 keV?— Bulbul et al. Astro. 2014, Boyarski et al., PRL 2014.
  See a contrary report by Dessert et. al. (Science, 2020). Comments on that followed at Boyarski et. al.2004.06601, and Abazajian, 2004.06170.

- But how do we produce these neutrinos?

Production: the Dodelson-Widrow mechanism

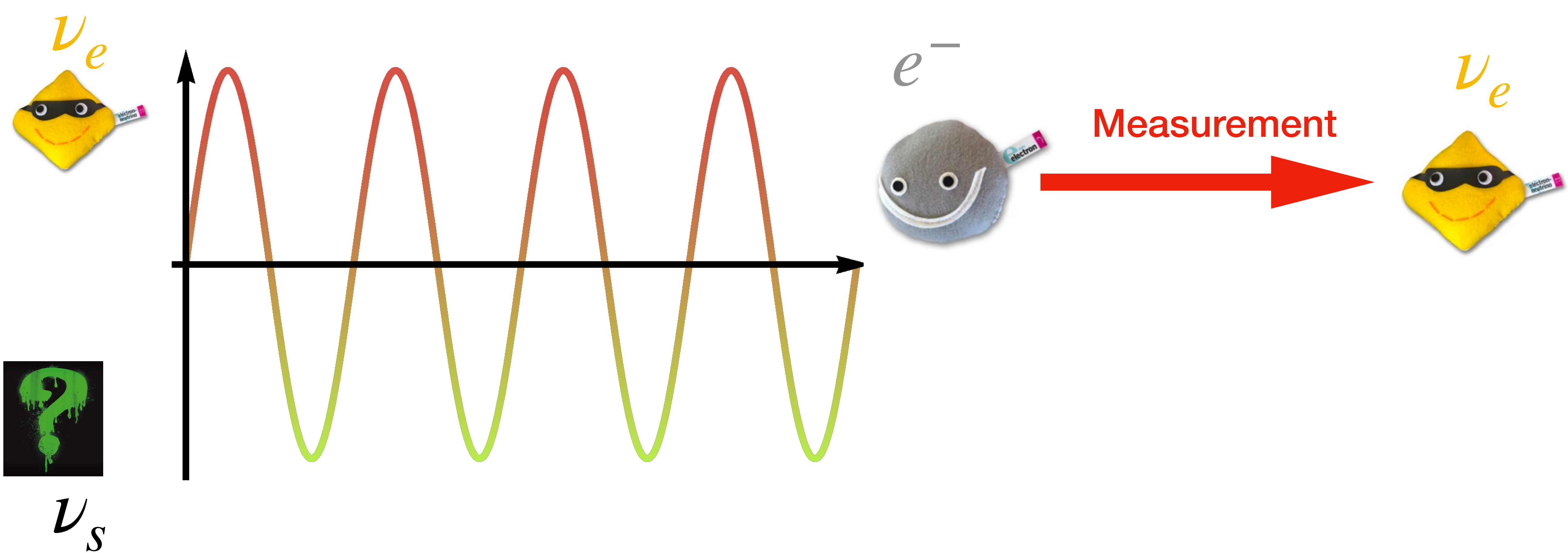
- The ν_s cannot be in thermal equilibrium with SM particles before BBN.



- Must be produced non-thermally with $\theta \ll 1$.

- ν_a oscillates into ν_s before decoupling. Creates a non-thermal population of ν_s.

Dodelson and Widrow, PRL1994.



Production: the Dodelson-Widrow mechanism

ν_a oscillates into ν_s before decoupling. Creates a non-thermal population of ν_s. Dodelson and Widrow, PRL1994

$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H}\ \langle P(\nu_a \to \nu_s)\rangle\ f_{\nu_a}\ ,$$

$$\langle P(\nu_a \to \nu_s)\rangle = \frac{1}{2}\frac{\Delta^2 sin^2 2\theta}{\Delta^2 sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta cos 2\theta - V)^2}$$

Averaged over one mean free path

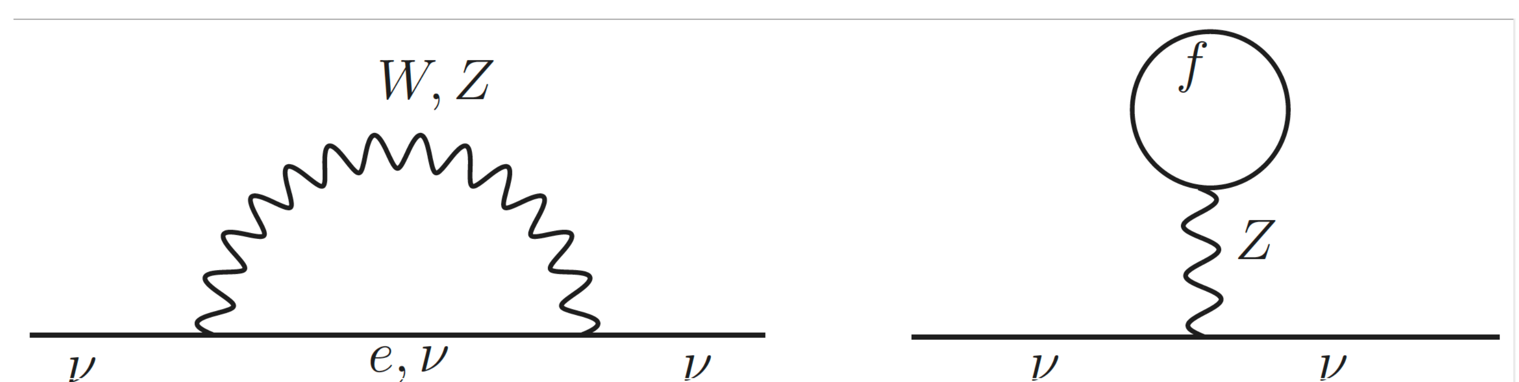
$\Delta = m_s^2/2E$

Quantum Zeno damping

Matter potential $V = V_T + V_D$

Finite temperature: $V_T \propto T$

Finite density: $V_D \propto n_f$



Analyzing the Dodelson-Widrow mechanism

$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H} \ \langle P(\nu_a \to \nu_s)\rangle \ f_{\nu_a} \ ,$$

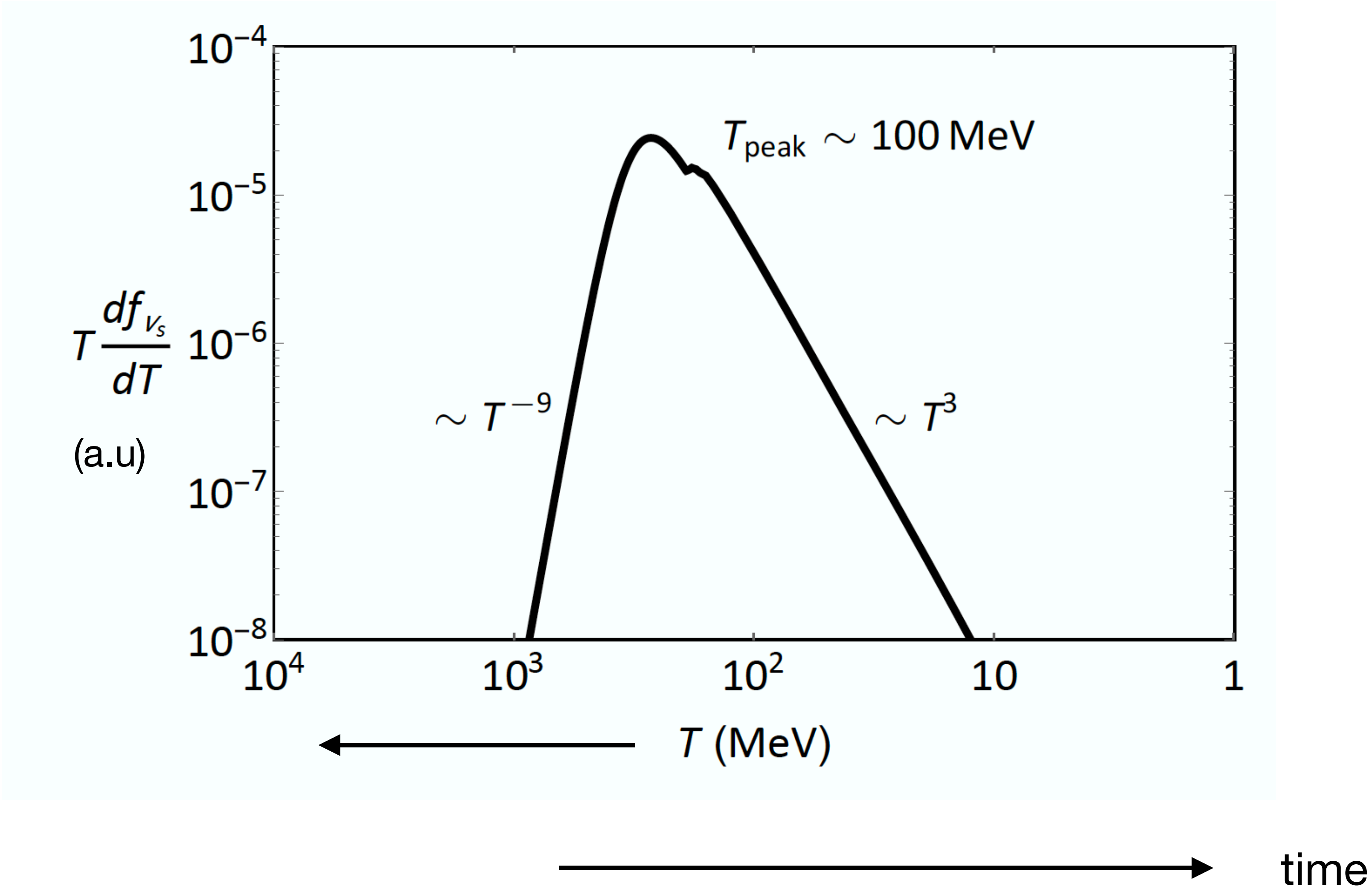
$$\langle P(\nu_a \to \nu_s)\rangle = \frac{1}{2}\frac{\Delta^2 sin^2 2\theta}{\Delta^2 sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta cos 2\theta - V)^2}$$

SM

$V^{W,Z} \sim T^5$
$\Gamma_a \sim T^5$
$\Delta \sim T^{-1}$

- Case 1: When $\Gamma \gg \Delta$, $T\frac{df}{dT} \sim \frac{\Gamma}{H}\frac{\Delta^2}{\Gamma^2} \propto T^{-9}$
- Case 2: When $\Gamma \ll \Delta$, $T\frac{df}{dT} \sim \frac{\Gamma}{H} \propto T^3$

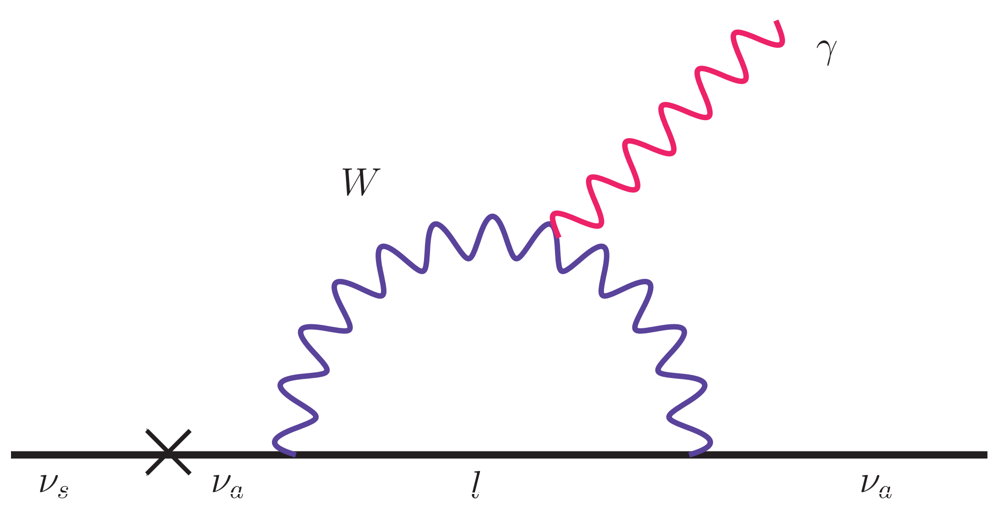
The Dodelson-Widrow mechanism… contd

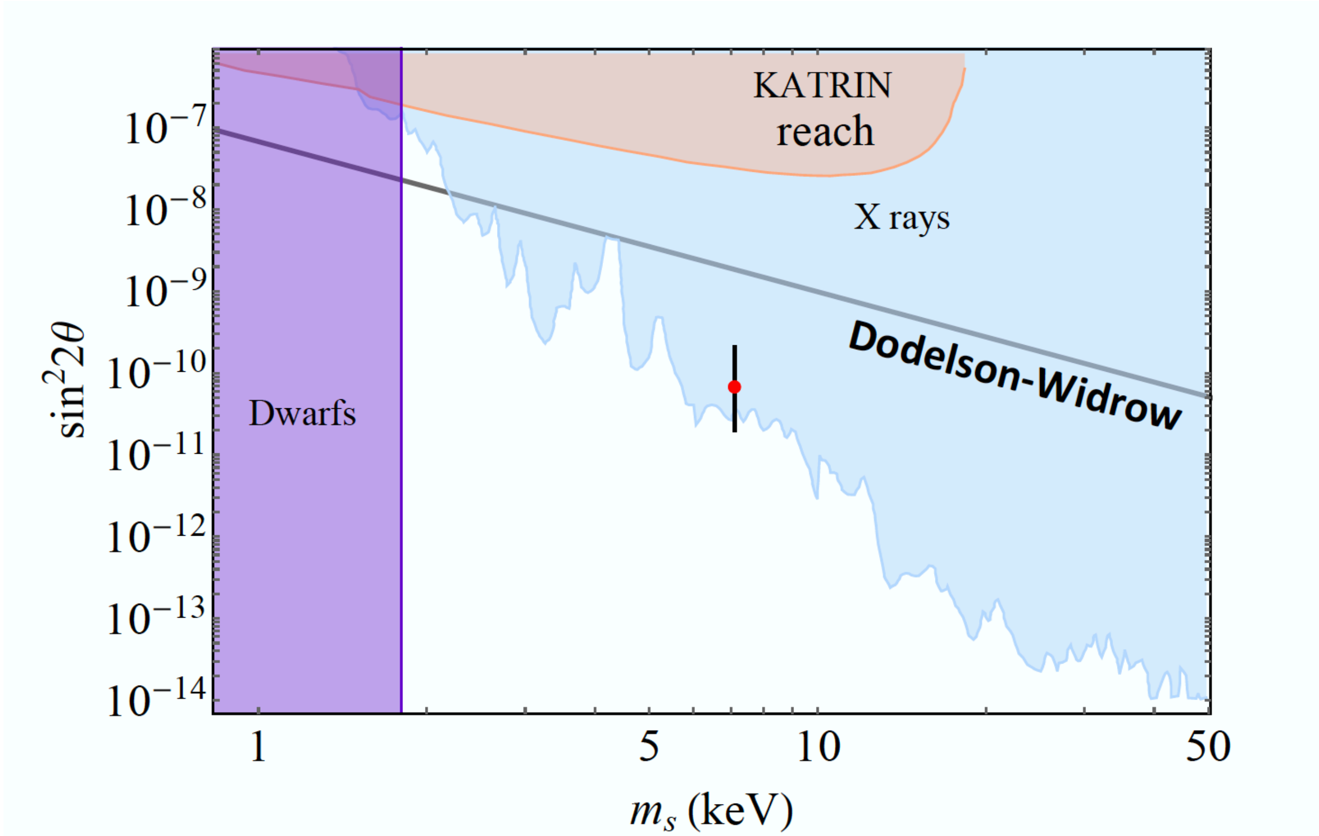


- ν_s freeze in. Production is maximized at T~100 MeV.

- Can satisfy relic density of DM. But as with all theories, this is too good to be allowed…

The Dodelson-Widrow mechanism…constrained





- Ruled out by X-ray bounds and phase-space considerations (Tremaine-Gunn, Lyman alpha, etc.).

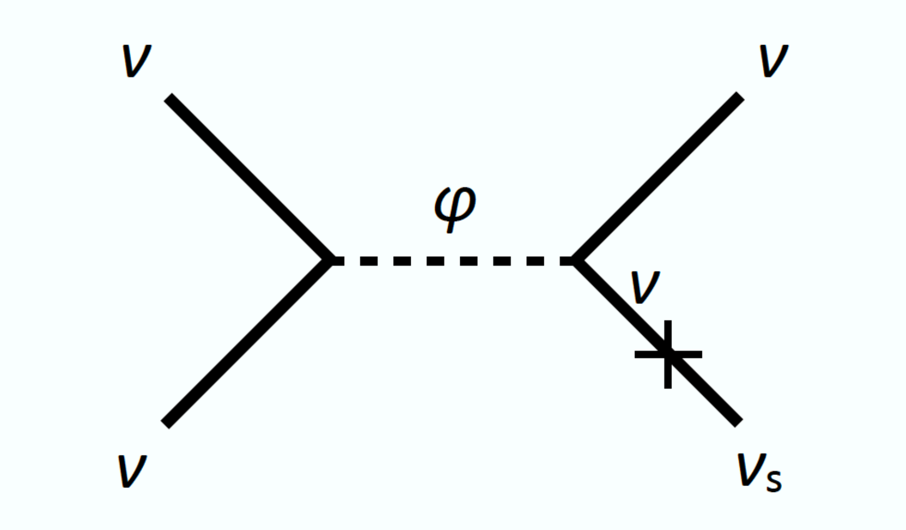
- A finite lepton asymmetry (Shi-Fuller Mechanism) can help. Required lepton asymmetry difficult to constrain. Shi and Fuller, PRL 1999, Fuller, Abazajian and Patel PRD 2001

- Can we open up parameter space without introducing a lepton asymmetry?

Secret neutrino self-interactions

Opening up the chamber of secret : NSSI

- Active neutrino self-interactions. Can be much stronger than ordinary weak interactions.



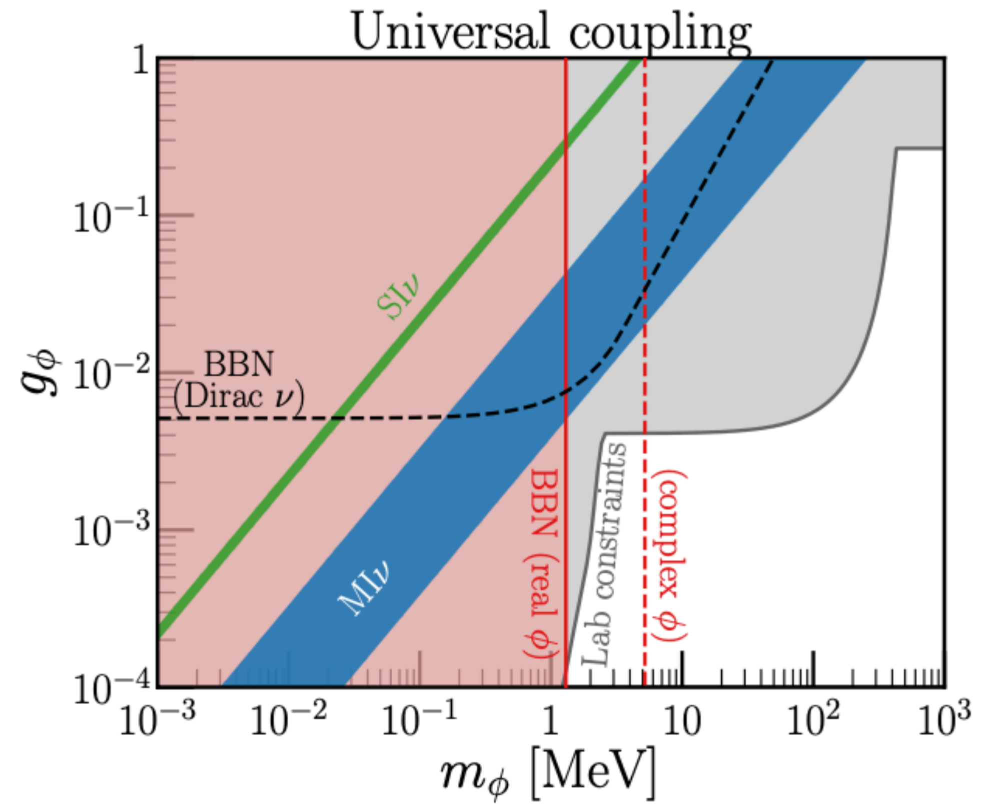
de Gouvêa, **MS**, Tangarife and Zhang PRL 2020

- Model building aspect?
  Consider
  $$\mathscr{L}_\nu = \frac{y}{\Lambda^2}(LH)^2\varphi \quad \xrightarrow{\text{EWSB}} \quad \lambda_\varphi \nu_a \nu_a \varphi$$

  φ has lepton number.

- Relic ~ (rate) X (mixing angle).

  Increasing rate can satisfy same results for small
  This allows us to shift DW line
  below X-ray bounds.

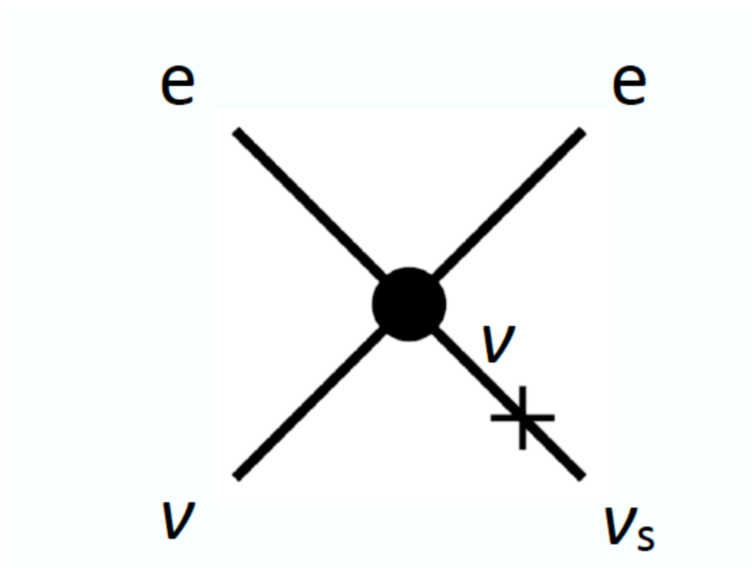


Blinov, Kelly, Krnjaic and McDermott, PRL 2019

- This opens up new production channels for sterile neutrino DM.

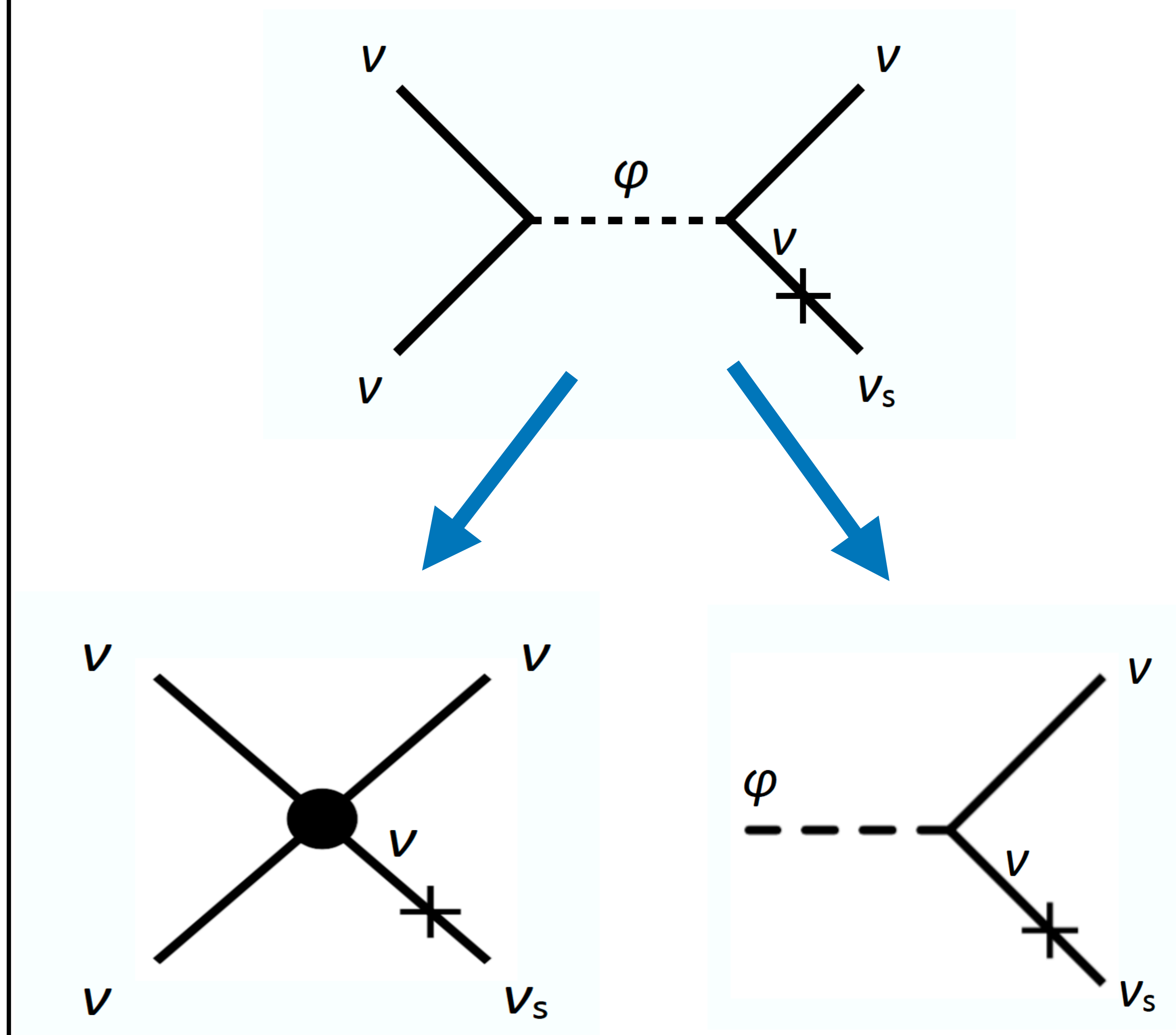
What changes in the DW mechanism?

S.M



$M_{W,Z} \geq T_{peak}$

S.M + Self-Interactions



$M_{\varphi} > T_{peak}$

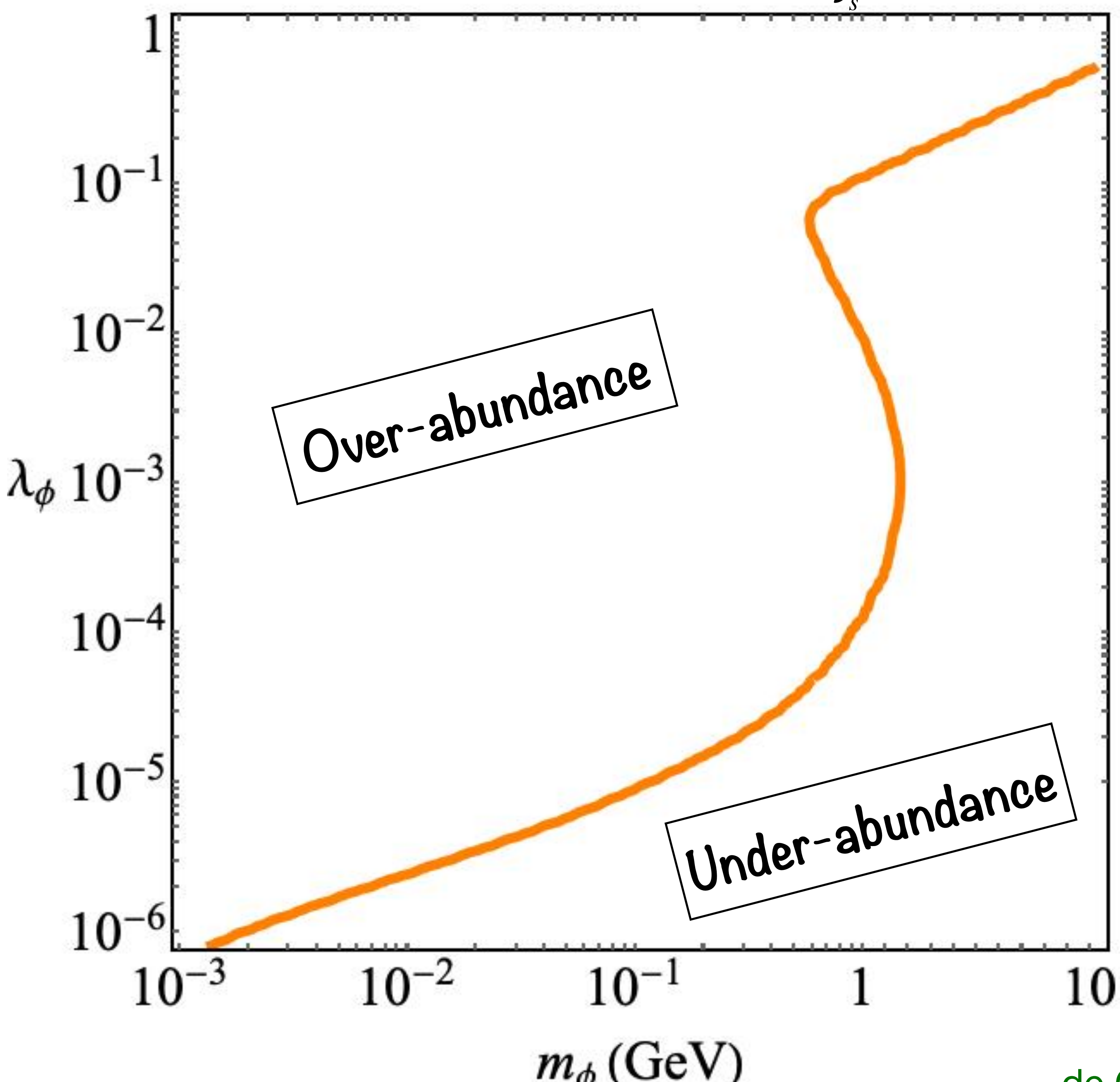
$M_{\varphi} \lesssim T_{peak}$

$$m_\phi > \mathrm{MeV}$$

Numerical estimates

$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{4H}\ \frac{\Delta^2 sin^2 2\theta}{\Delta^2 sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta cos 2\theta - V)^2}\ f_{\nu_a}$$

$\Omega h^2 = 0.12$, $m_{\nu_s} = 7.1\,\mathrm{keV}$, $sin^2 2\theta = 7\times 10^{-11}$



Not a monotonic dependence! Why?

de Gouvêa, **MS**, Tangarife and Zhang PRL 2020

Numerical and analytical estimates

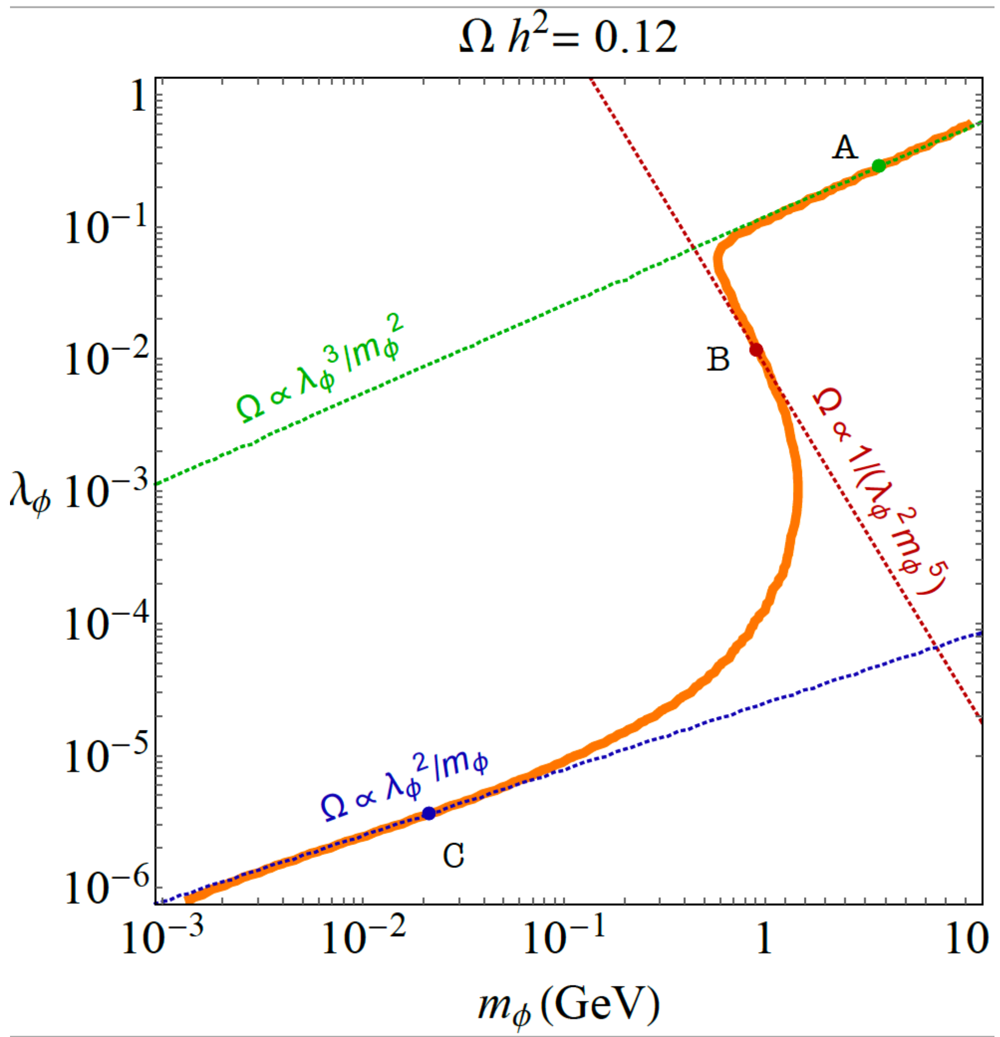
$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H}\,\frac{1}{2}\,\frac{\Delta^2 sin^2 2\,\theta}{\Delta^2 sin^2 2\,\theta + \frac{\Gamma_a^2}{4} + (\Delta cos\,2\,\theta - V)^2}f_{\nu_a}$$

- Two scales in problem:

1. $t_{\Gamma=H}$: When $\Gamma/H = 1$, to determine when interactions are in equilibrium.
2. $t_{\Delta=V}$: When $|\Delta| \sim |V|$, mixing angle is unsuppressed.
3. t_{φ}: When $T = m_{\varphi}$, mediator cannot be produced on-shell for lower temperature

de Gouvêa, **MS**, Tangarife and Zhang PRL 2020
Cherry, Friedland, Shoemaker 1605.06506

Explanation of Results

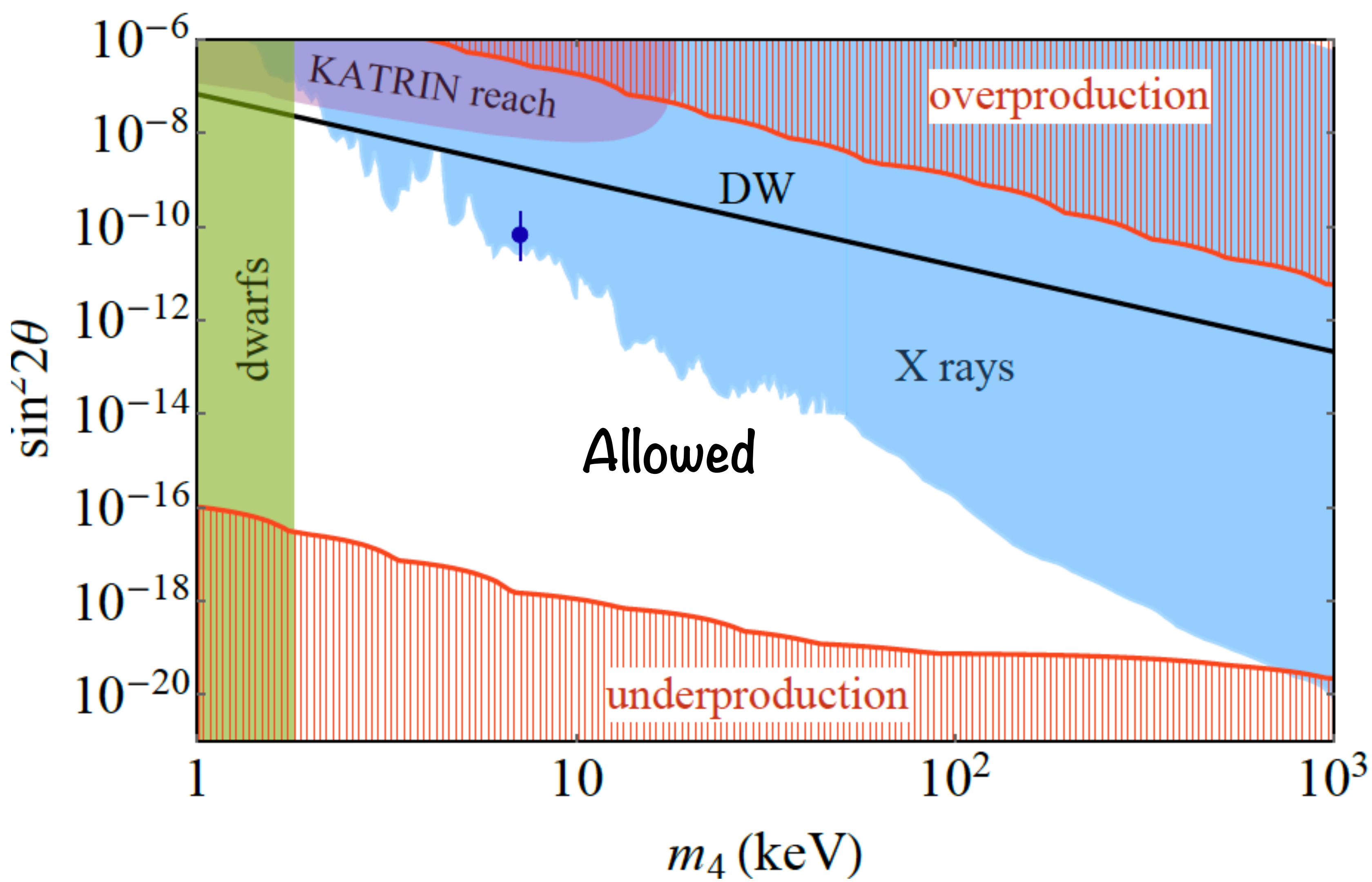


1. A: $t_\varphi < t_{\Delta=V} < t_{\Gamma=H}$. Production around $t_{\Delta=V}$ from scattering via an off-shell φ. Similar to the usual DW mech.

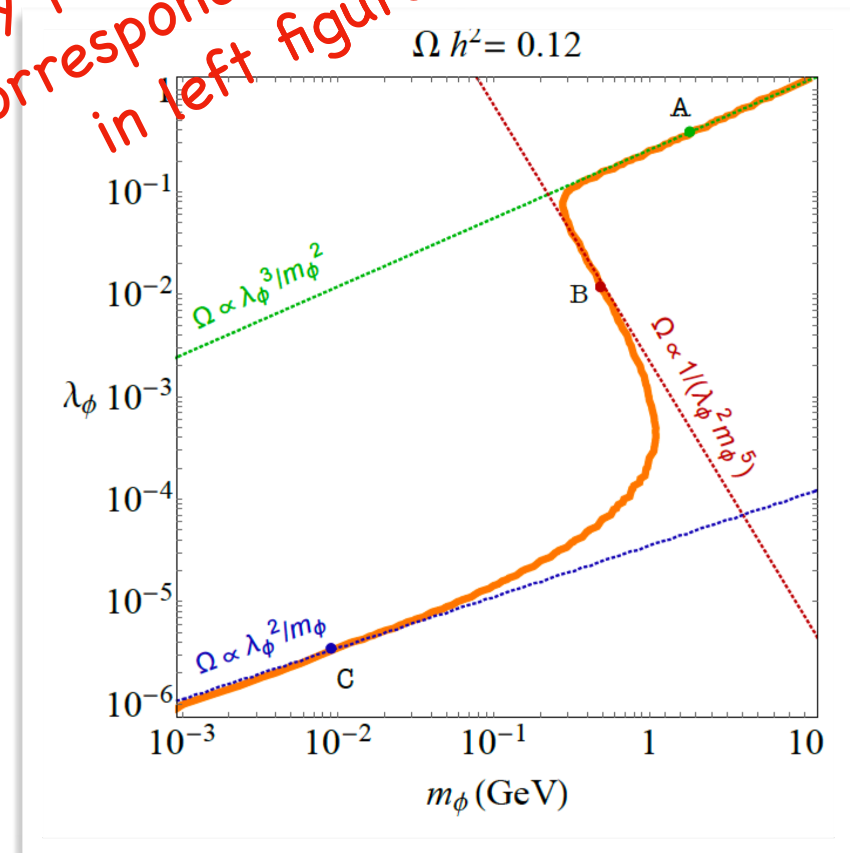
2. B: Intermediate mass, coupling: $t_\varphi < t_{\Gamma=H} < t_{\Delta=V}$ .Peak production happens in $(t_\varphi < t < t_{\Gamma=H})$ when θ_{eff} is suppressed. Production through scattering via on-shell φ.

3. C: $t_{\Delta=V} < t_\varphi < t_{\Gamma=H}$. DM produced most efficiently through on-shell φ exchange between $(t_{\Delta=V} < t < t_\varphi)$

Allowed Relic Density window

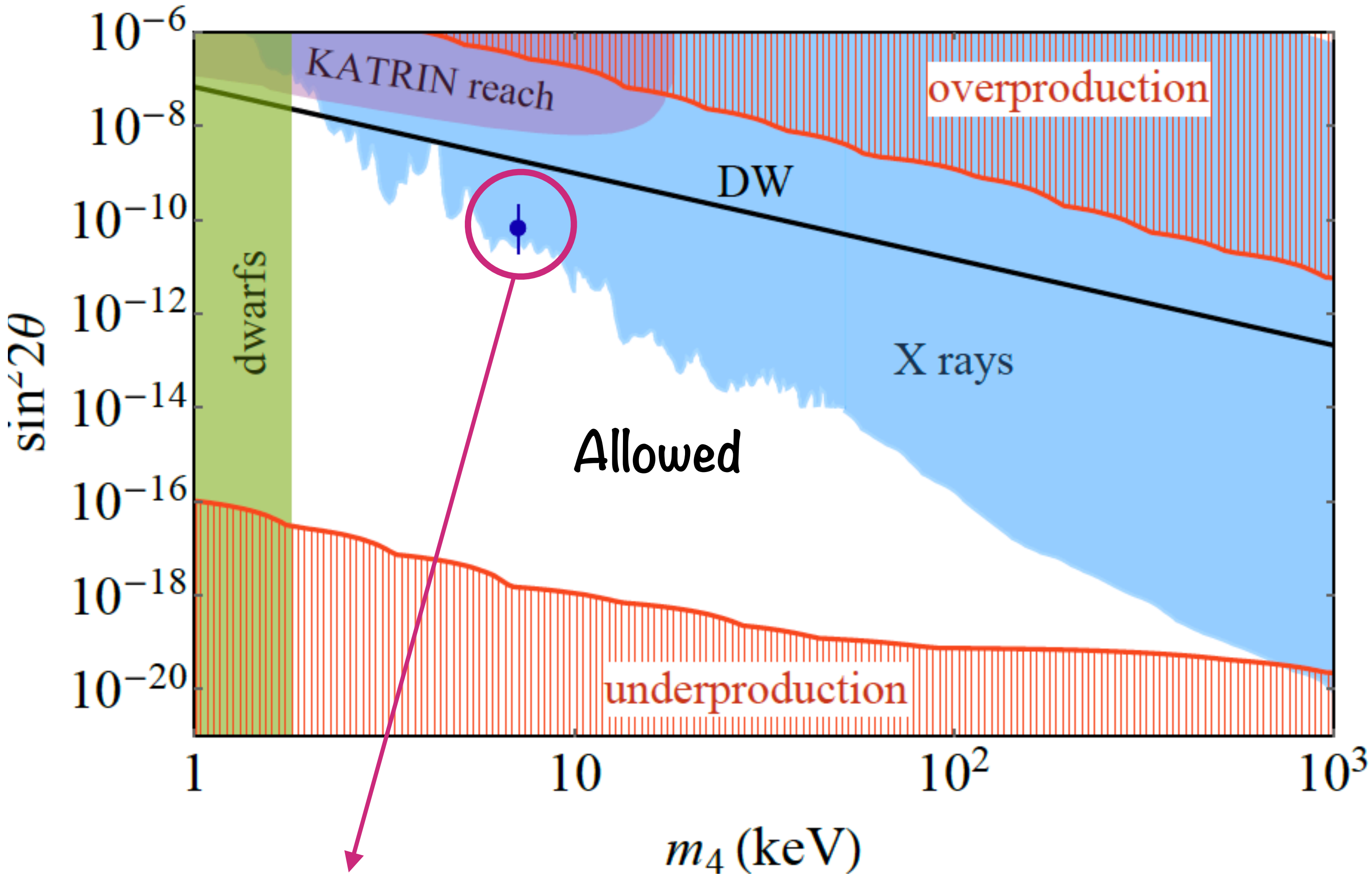


Every point in this plane corresponds to a line in left figure

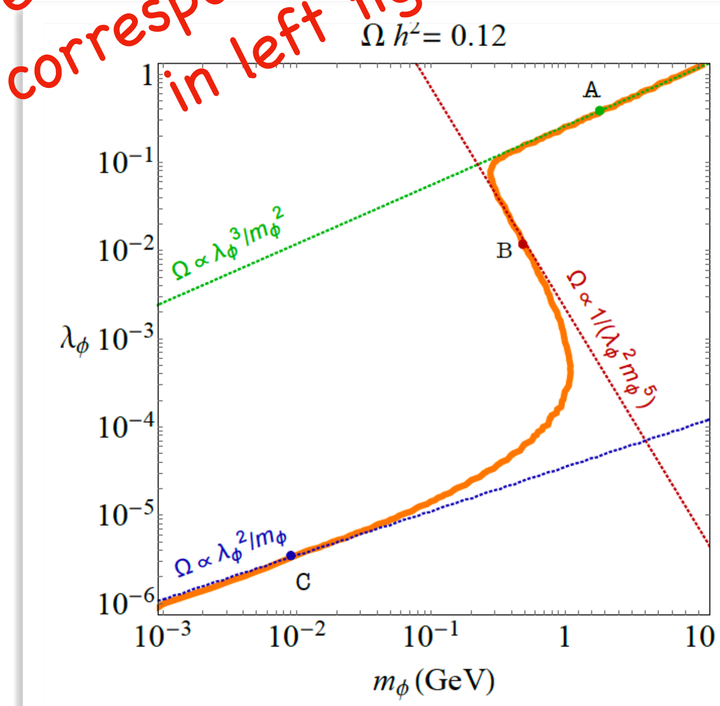


de Gouvêa, **MS**, Tangarife and Zhang PRL 2020

Allowed Relic Density window



Every point in this plane corresponds to a point in left figure

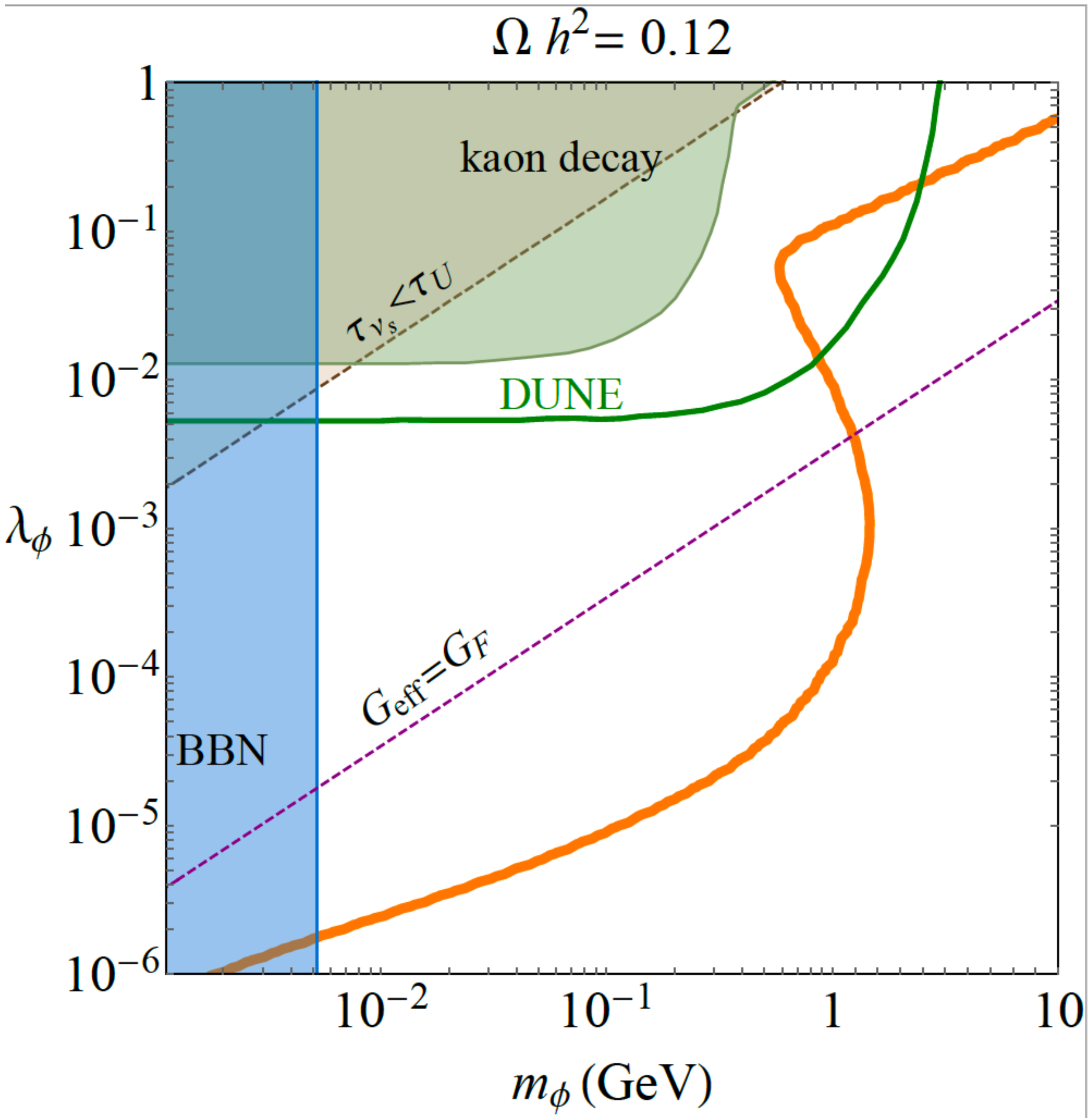


Can be used to satisfy the 3.5 keV X-ray line also ~

$m_{\nu_s} = 7.1\,\text{keV},\ sin^2 2\theta = 7\times10^{-11}$ Bulbul et al. Astro. 2014+many more

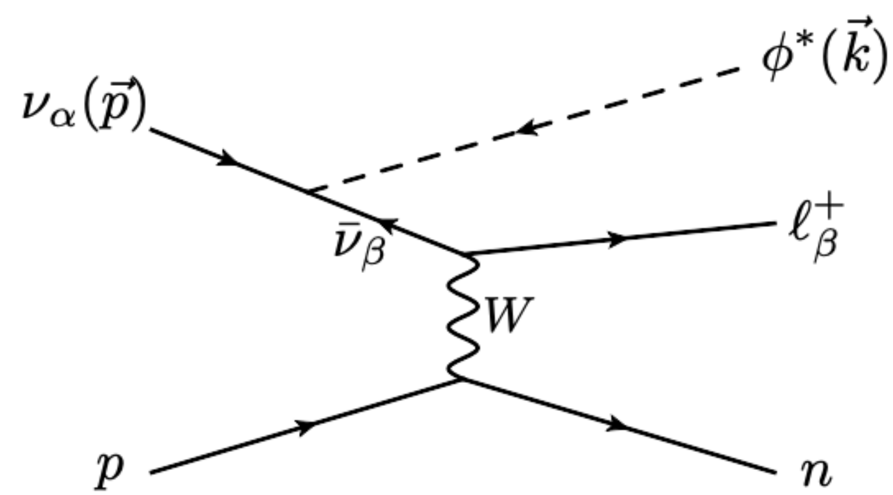
Experimental tests

The vertex: $\mathscr{L} = \nu_a \nu_a \varphi$



de Gouvêa, **MS**, Tangarife and Zhang PRL 2020

- Interested in range
  $1\,\text{MeV} \leq m_\varphi \leq 10\,\text{GeV}$
- $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu\,.$
  Bounds from $\text{Br}(K^- \to \mu^- 3\nu) < 10^{-6}\,.$
- BBN bounds on m_φ.
- DUNE can look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$. Parameter space can be probed.

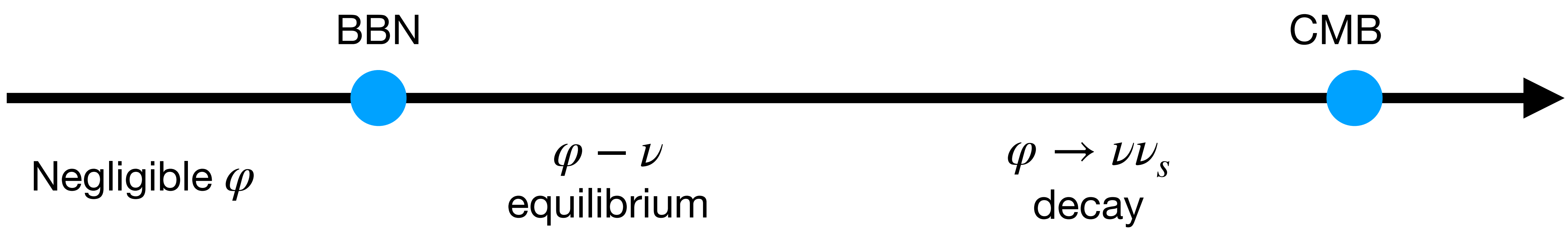


Berryman, de Gouvêa, Kelly and Zhang PRD2018
Blinov, Kelly, Krnjaic and McDermott, PRL2018

$$m_\phi < \mathrm{MeV}$$

Low mass, low coupling limit

How do we evade BBN bounds? — —
Partial thermalization of φ before BBN, require feeble coupling to neutrinos.



$$\frac{dY_\phi}{dz} = -\frac{\gamma_{\phi\leftrightarrow\nu\nu}}{sHz}\left(\frac{Y_\phi}{Y_\phi^{\rm eq}} - 1\right)$$

Energy density, lepton number conservation.

Entropy, lepton number conservation

A chemical potential develops for neutrinos

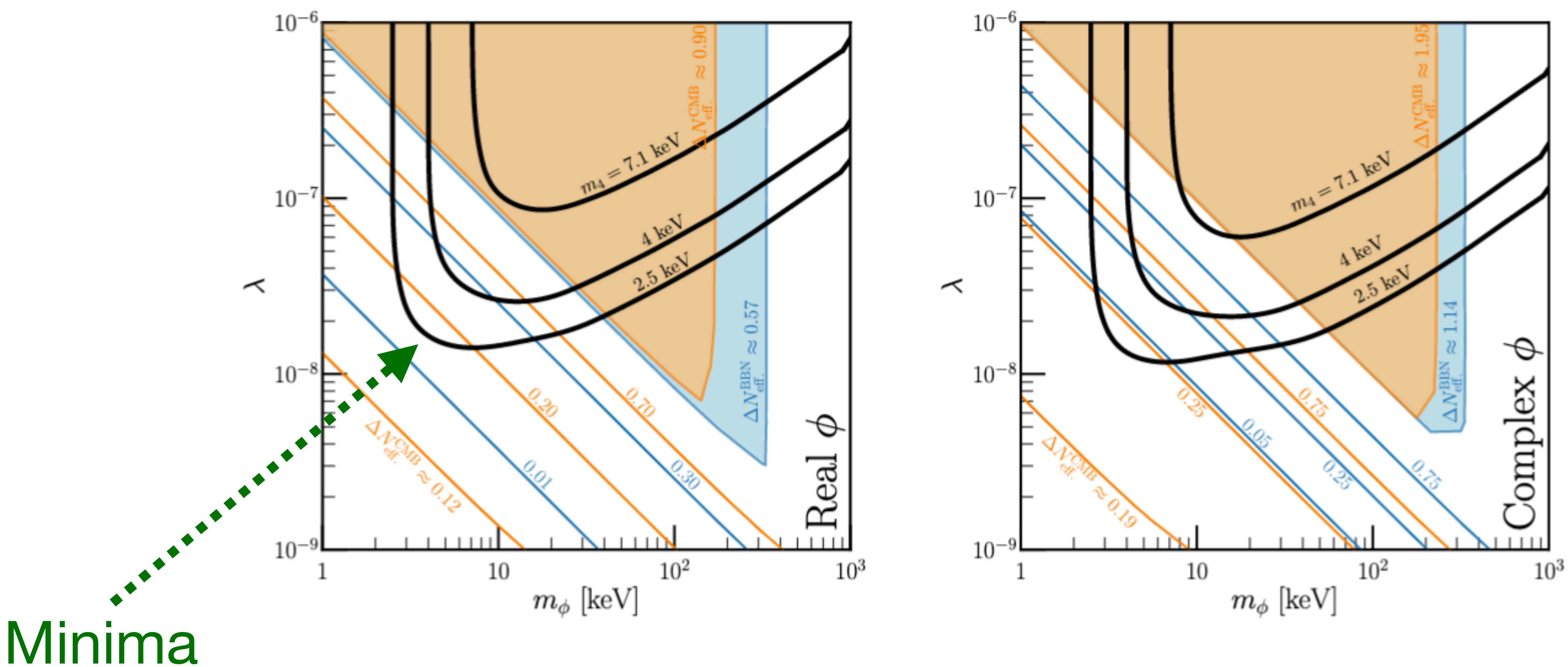
Kelly, **MS** and Zhang, PRL 2021

Correlation with extra radiation

- Partial thermalization of φ contributes to $N_{\rm eff}$ at BBN, and φ decay to $N_{\rm eff}$ at CMB.

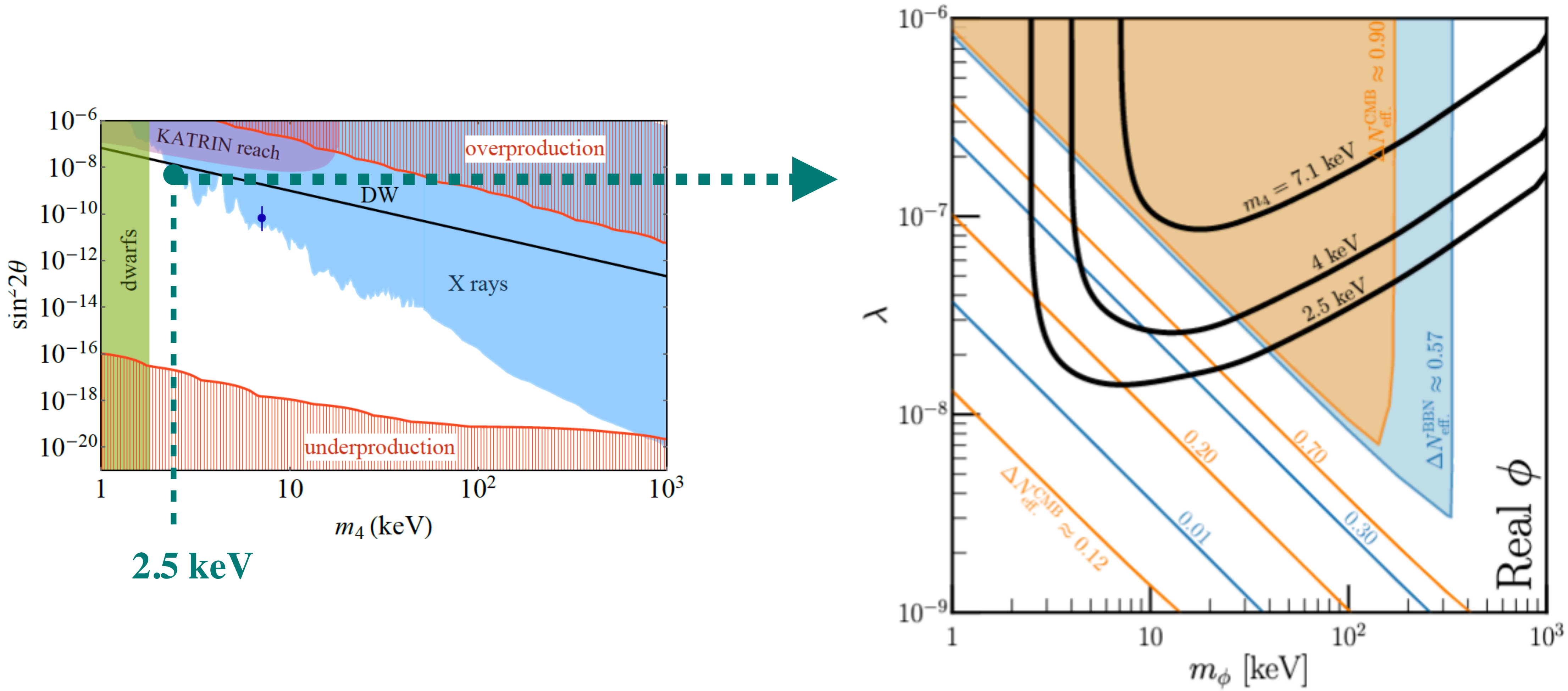
- Relic curves show a minima, can correlate DM relic with $N_{\rm eff}$.

- As $m_\phi \to m_4$, larger valyes of λ are required to compensate phase-space suppression of $\phi \to \nu\nu_s$



Kelly, **MS** and Zhang, PRL 2021

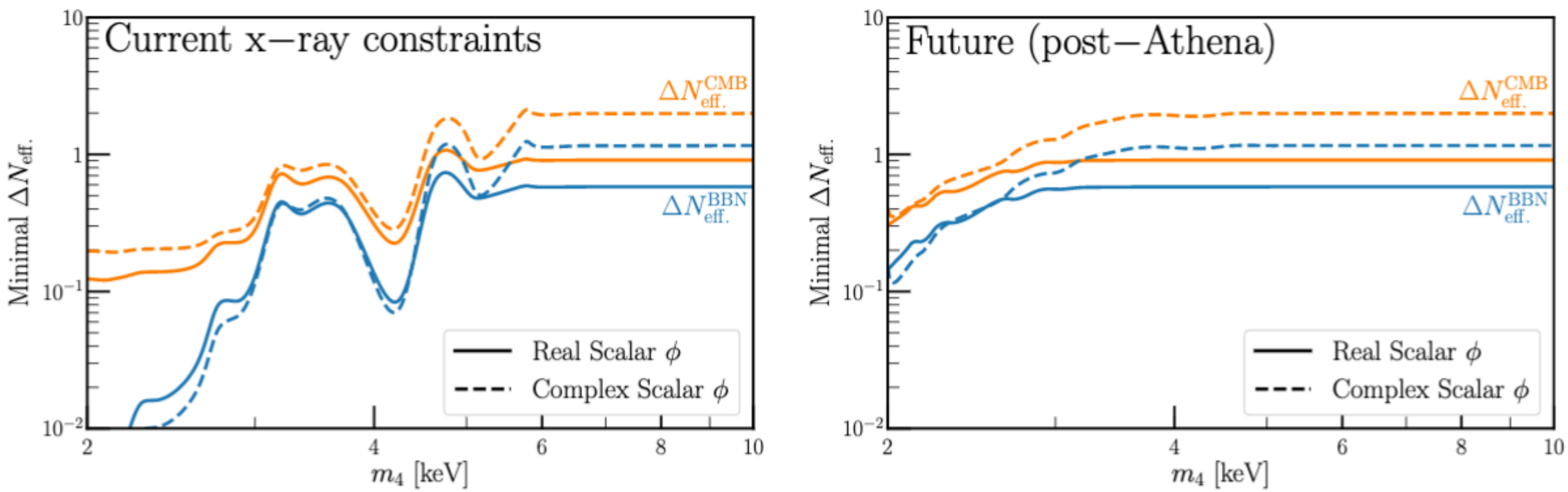
The algorithm for deriving constraints



- Consider the maximum allowed mixing angle for each sterile neutrino mass.
- For a given sterile neutrino mass, and the maximum allowed mixing angle, choose the minima of the curve corresponding to a minimum value of $\Delta N^{\rm eff}_{\rm BBN}$ and $\Delta N^{\rm eff}_{\rm CMB}$.
- This gives a target $\Delta N^{\rm eff}$ to probe these models.

Kelly, **MS** and Zhang, PRL 2021

Constraints from $N_{\rm eff}$

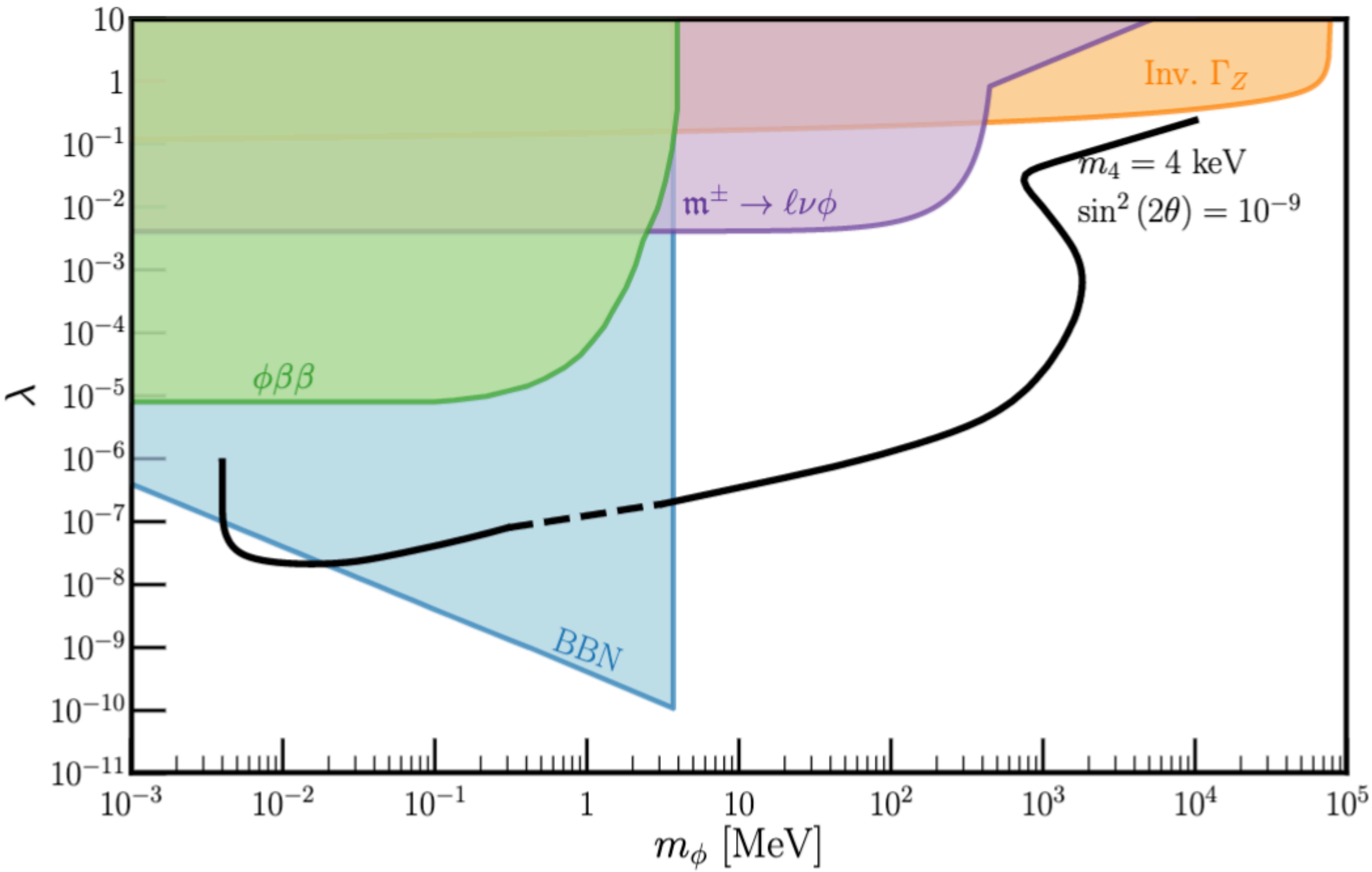


- Consider the maximum allowed mixing angle for each sterile neutrino mass.
- Corresponding minimum value of $N_{\rm eff}$ during BBN and CMB. For real scalar, $0 < \Delta N_{\rm BBN}^{\rm eff} < 0.57$

  $0.12 < \Delta N_{\rm CMB}^{\rm eff} < 0.9$
- This can put additional constraints from future cosmology surveys, like CMB-S4.

Kelly, **MS** and Zhang, PRL 2021

Big Picture



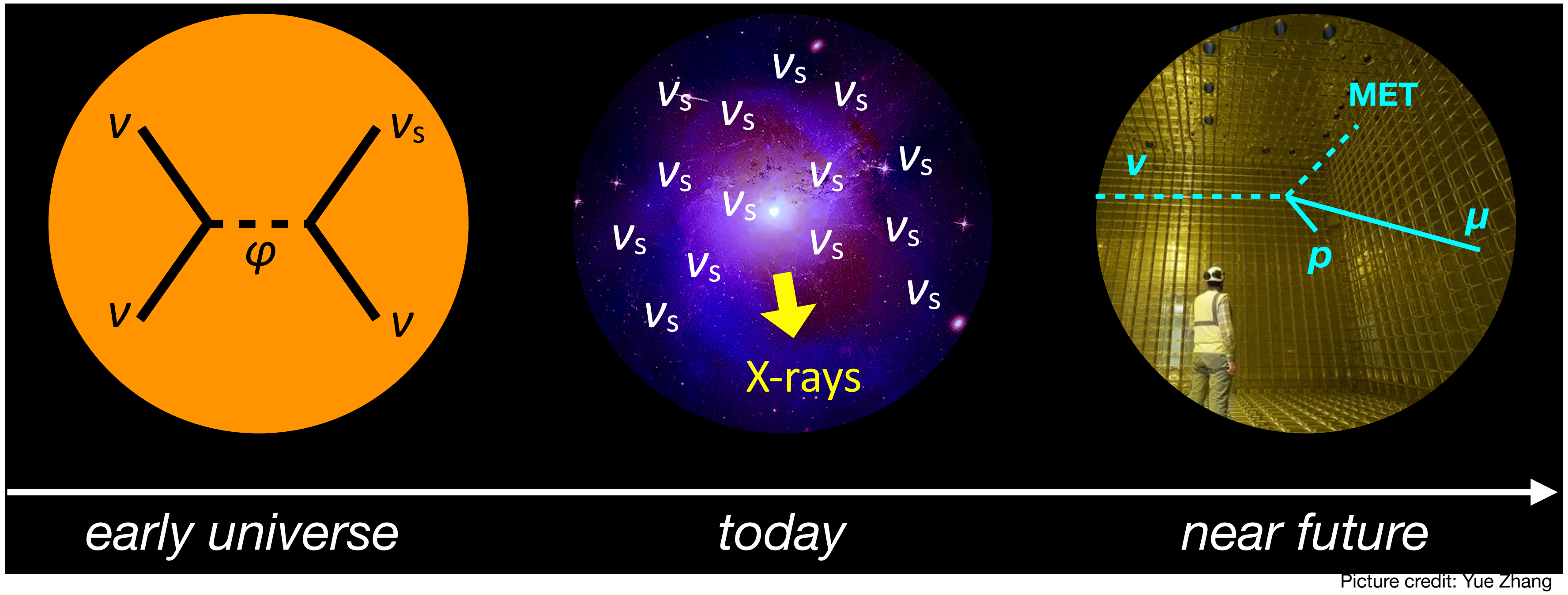
Kelly, **MS** and Zhang, PRL 2021

Summary

- A model with the SM appended with sterile neutrinos, and a new interaction among the SM neutrinos, much stronger than weak interactions. Mediator masses can vary from a few keV to GeVs.

- Sterile neutrinos can be produced non-thermally via freeze-in, using new interactions. Stronger interactions helps alleviate tensions with DW mechanism.
  Can be used as a candidate model for the 3.5 keV line.

- Can be probed using current and upcoming neutrino experiments.



Picture credit: Yue Zhang

Thank you!

BACKUP

Backup: UV Completion

Another option, which we call the type I model, is to introduce pairs of vector-like fermions N_i and N_i^c ($i = 1, 2, \ldots, n$, the number of vector-like fermions) that are SM singlets carrying $B-L$ charges ∓ 1, respectively. The most general renormalizable Lagrangian includes

$$\mathcal{L}_{\rm UV} \supset \tilde{y}_{\alpha i} L_{\alpha i} H N_i^c + M_{N,i} N_i N_i^c + \lambda_{N,ij} \phi N_i N_j + \lambda^c_{N,ij} \phi^* N_i^c N_j^c + \tilde{\lambda}^c_{N\nu,ij} \phi^* N_i^c \nu_j^c + \text{h.c.} \; , \tag{4.3}$$

where $\tilde{y}$ are the strengths of the new Yukawa interactions and λ_N characterizes the strength of the interaction between N^c and the *LeNCS* field ϕ.[5] The constraint that the right-handed neutrino couplings λ_c^{ij} to ϕ are very small – see Sec. II H – implies that $\lambda^c_{N,ij}$ and $\tilde{\lambda}^c_{N\nu,ij}$ are also small and henceforth neglected. When all heavy fermion fields are integrated out, we obtain the effective operator in Eq. (1.3), $(L_\alpha H)(L_\beta H)\phi/\Lambda^2_{\alpha\beta}$, with

$$\frac{1}{\Lambda^2_{\alpha\beta}} = \sum_{i,j} \tilde{y}_{\alpha i} \frac{1}{M_{N_i}} \lambda_{N,ij} \frac{1}{M_{N_j}} \tilde{y}_{\beta j} \; . \tag{4.4}$$

One option is to introduce a scalar T, a triplet under $SU(2)_L$ with hypercharge $+1$ and $B-L$ charge $+2$. We will call it the type II model, because it has a structure similar to the type-II seesaw. As already highlighted, however, unlike the seesaw mechanism, there are no $B-L$-violating effects here. The most general renormalizable Lagrangian in this case contains

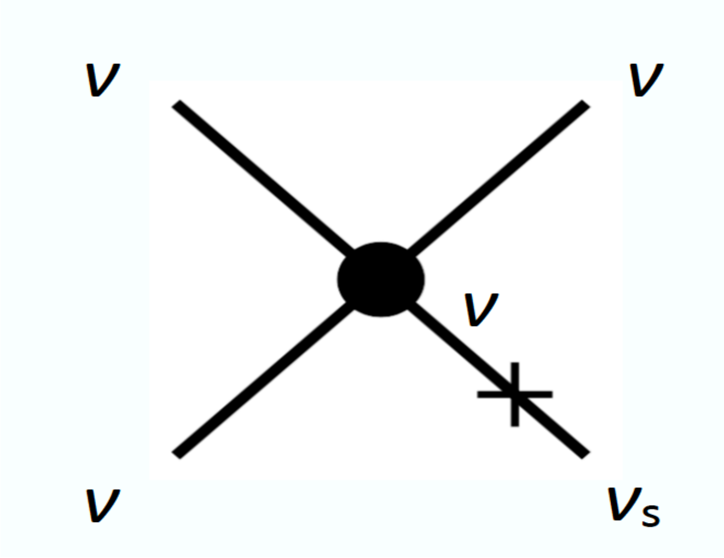
$$\mathcal{L}_{\rm UV} \supset \tilde{y}_{\alpha\beta} L_\alpha T L_\beta + \lambda_T H T^\dagger H \phi - M_T^2 \text{Tr}(T^\dagger T) + \text{h.c.} \; , \tag{4.1}$$

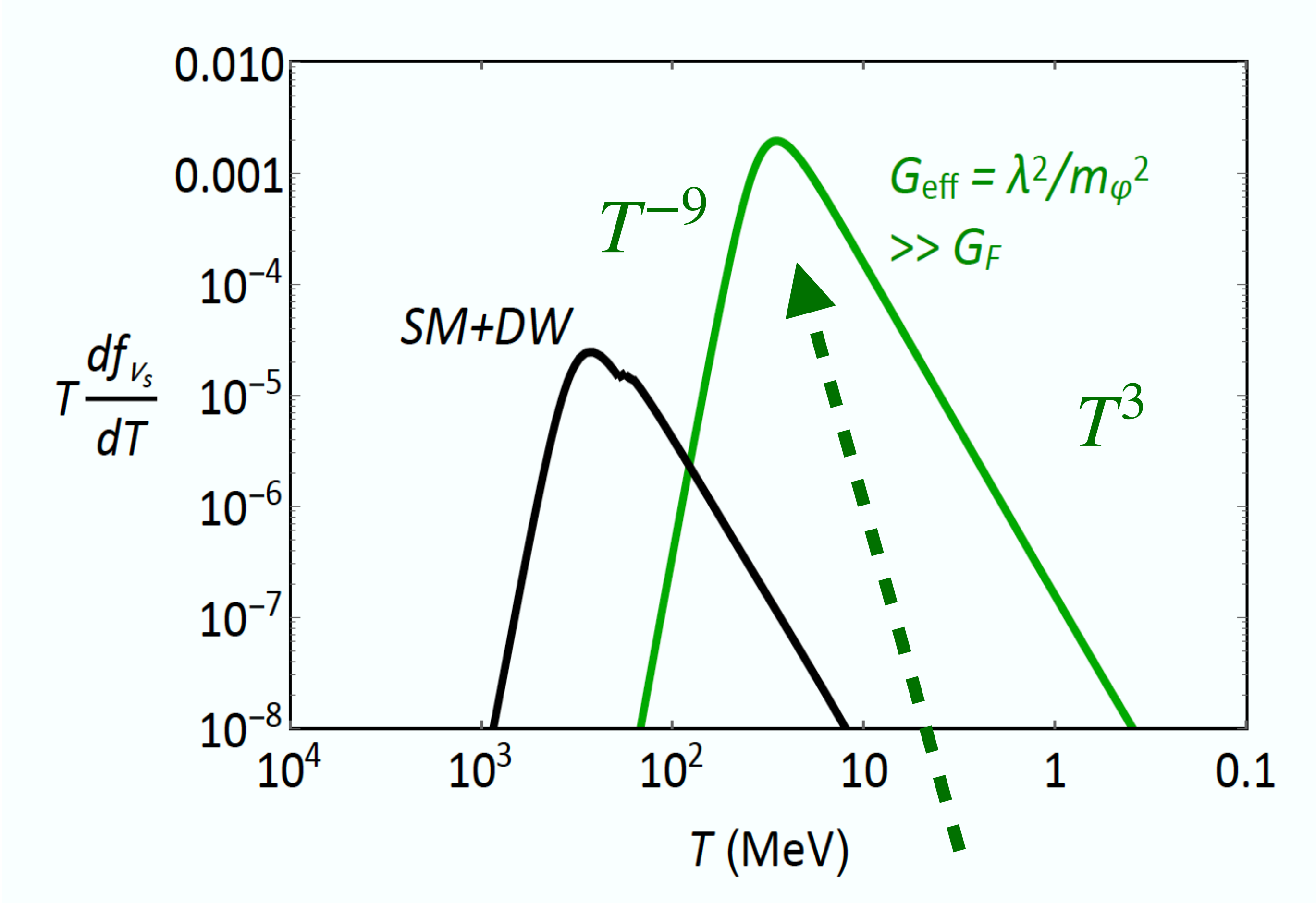
where $\tilde{y}_{\alpha\beta}$ are Yukawa couplings between the triplet T and leptons of flavor α and β, λ_T are scalar couplings between the triplet, the Higgs field and the *LeNCS* ϕ, and M_T is the triplet scalar mass. When the T field is integrated out, the low-energy effective theory matches that in Eq. (1.3) with

$$\frac{1}{\Lambda^2_{\alpha\beta}} = \frac{\tilde{y}_{\alpha\beta}\lambda_T}{M_T^2} \; . \tag{4.2}$$

Berryman, de Gouvêa, Kelly and Zhang PRD 2018

$$m_\phi \gg T$$





- Similar to DW, except with a stronger interaction.

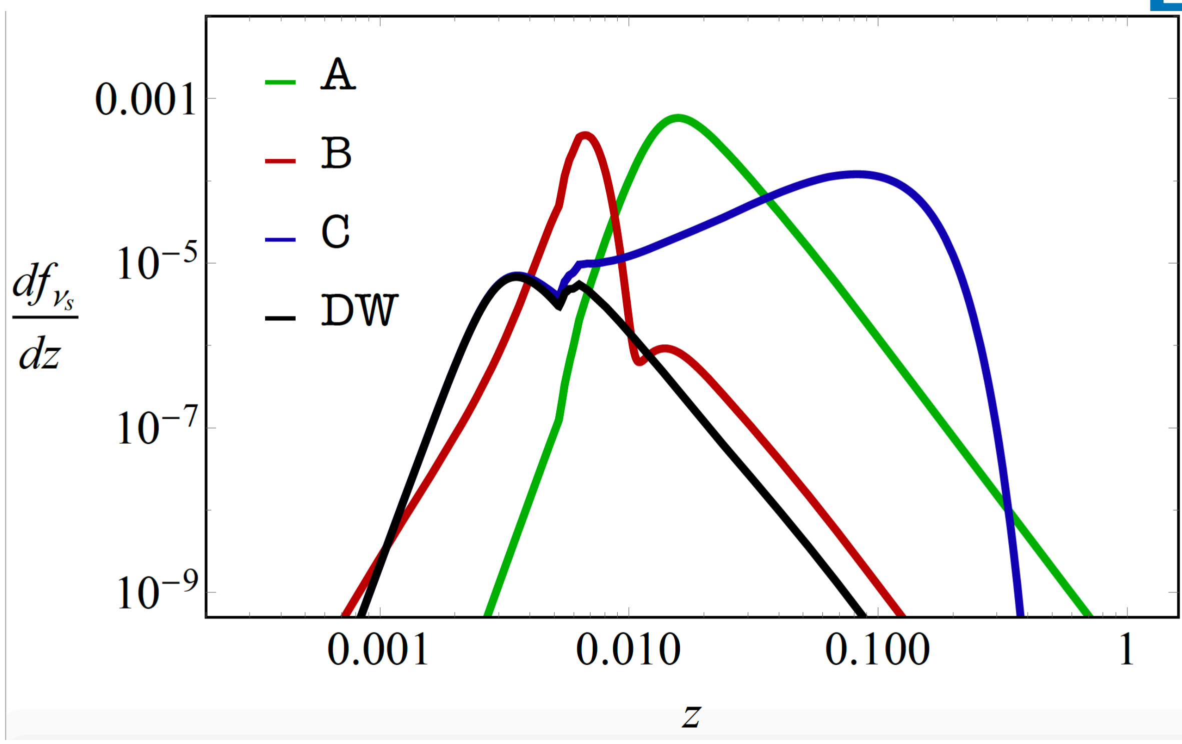
$$\Gamma_a \sim \frac{\lambda_\varphi^4}{m_\varphi^4} E T^4, \qquad V \sim -\frac{\lambda_\varphi^2}{m_\varphi^4} E T^4$$

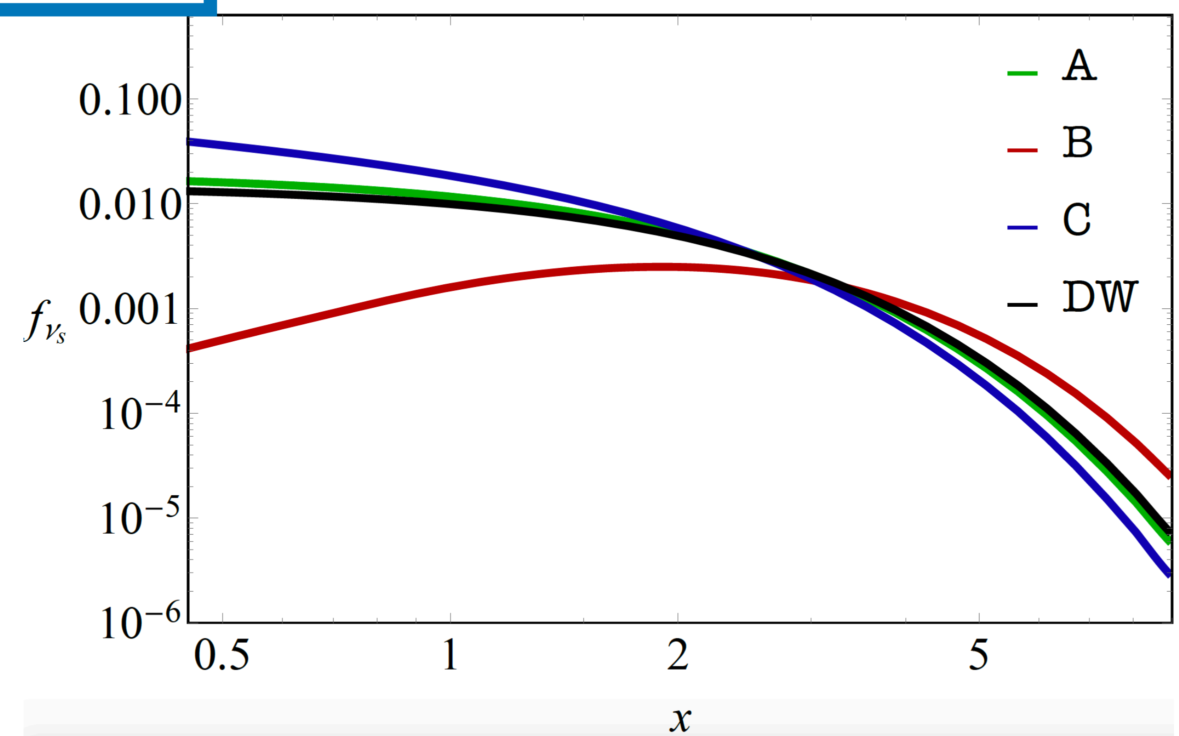
Production peaks at a lower temperature

de Gouvêa, MS, Tangarife and Zhang PRL 2020

Backup: Neutrino Spectra

$$z = \frac{1\,\mathrm{MeV}}{T}$$
$$x = \frac{p}{T}$$





- Free streaming length: $\lambda_{\rm FS} = 1.2\,\mathrm{Mpc}\left(\frac{1\,\mathrm{keV}}{m_4}\right)\left(\frac{\langle x\rangle}{3.15}\right)$

Backup: Chemical potential

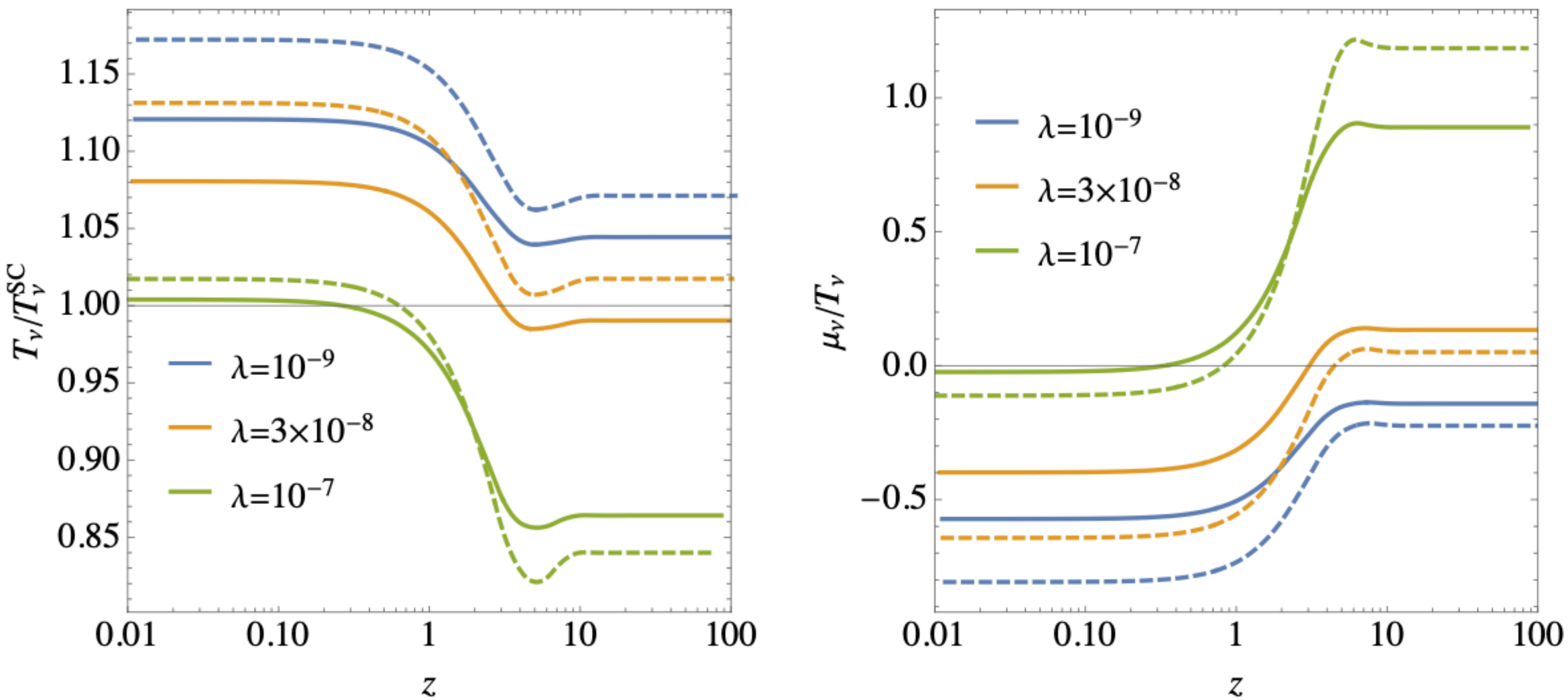


FIG. 4. Evolution of ratios $T_\nu(z)/T_\nu^{\rm SC}(z)$ and $\mu_\nu(z)/T_\nu(z)$ as functions of z for three values of λ_ϕ and holding $m_\phi = 5\,{\rm keV}$ fixed. Solid (dashed) curves correspond to real (complex) scalar ϕ case.

Backup: Structure formation

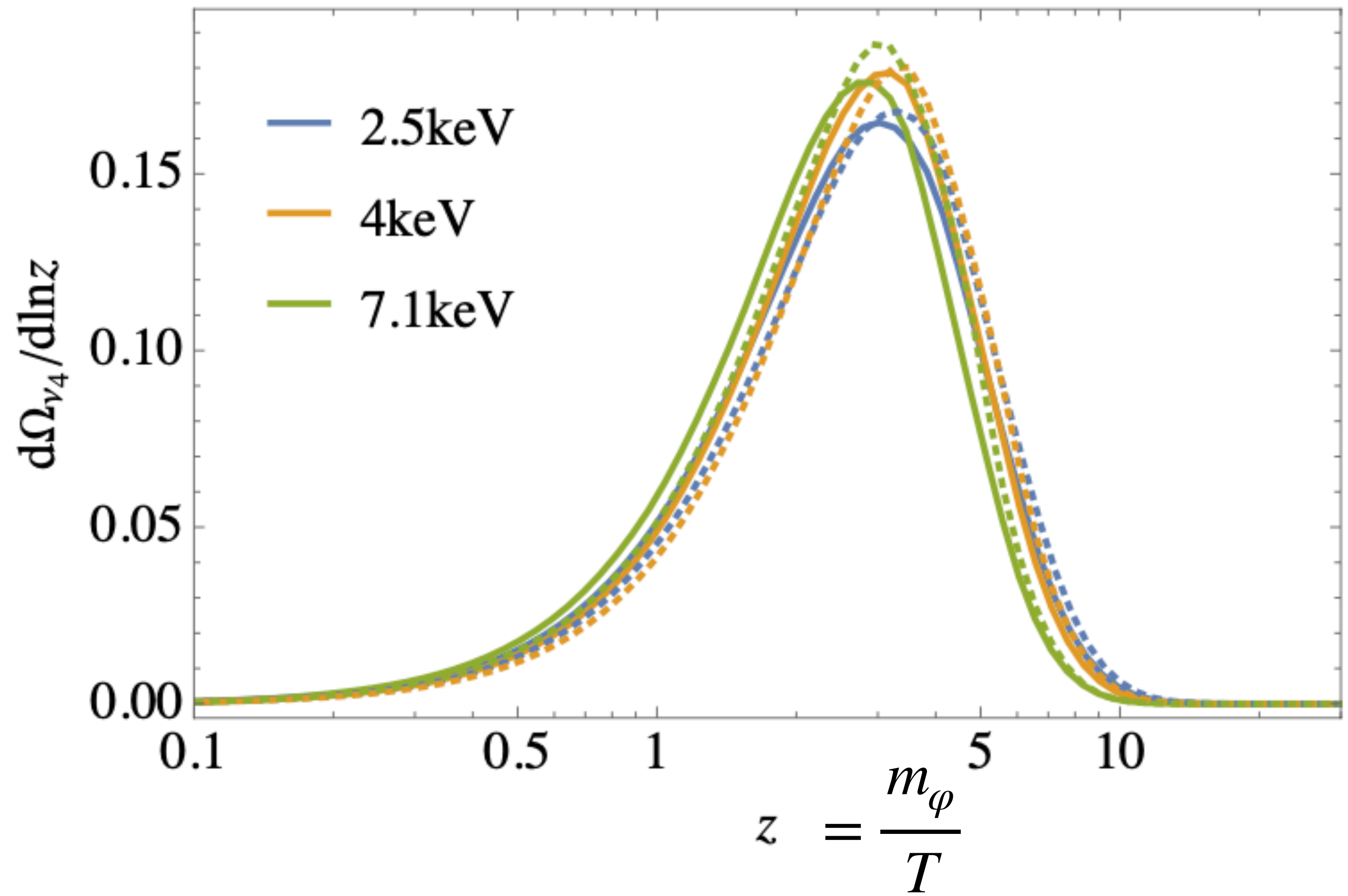


FIG. 5. Time dependence of SνDM, for three values of m_4 as labelled. The other parameters are chosen for producing the observed DM relic density. The solid (dashed) curves correspond to real (complex) scalar ϕ case.

The DM is produced when φ is non-relativistic and of the same order as the DM mass. Hence this is "warmer" DM

Athena bounds

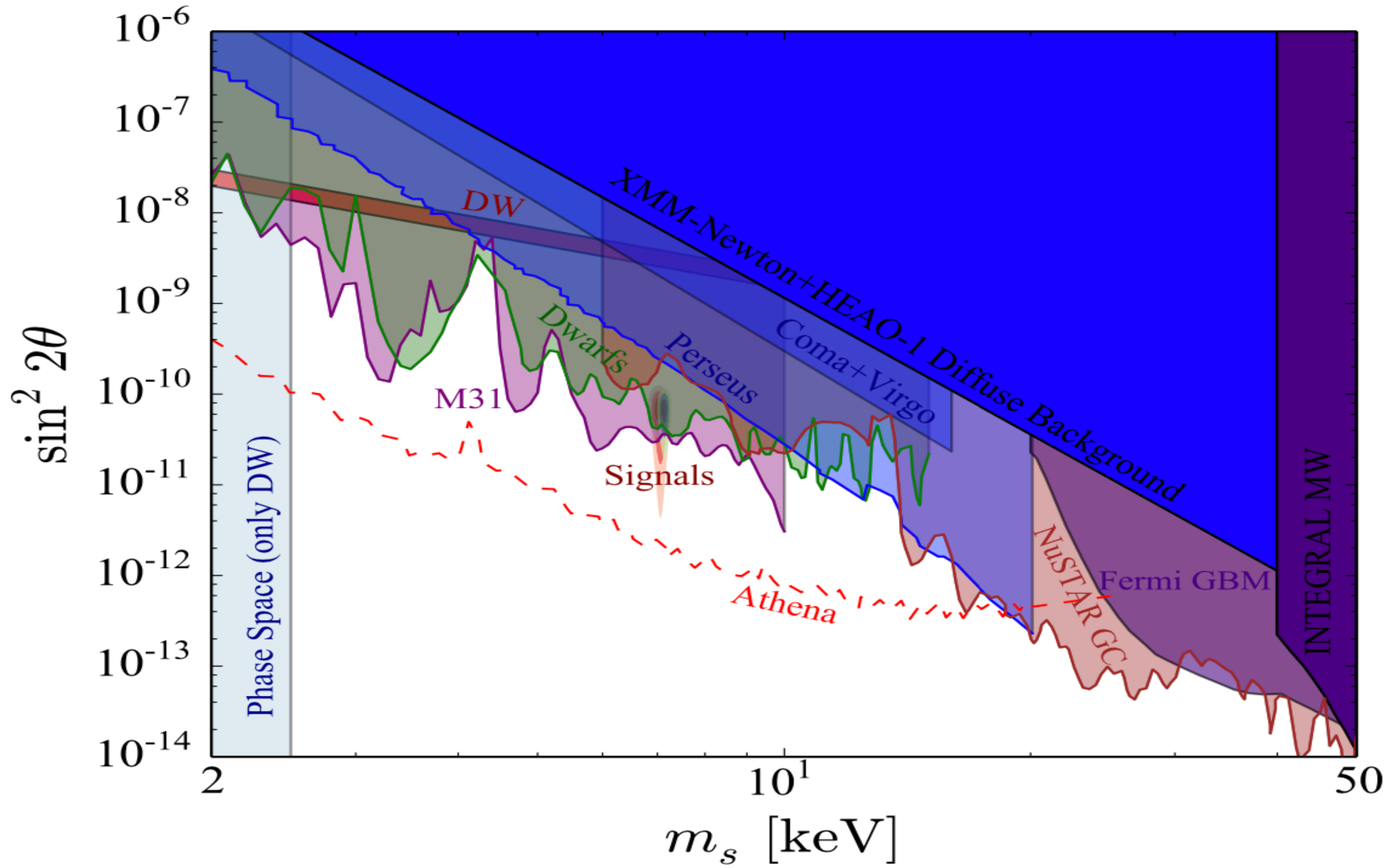


Figure 6: The full parameter space for sterile neutrino dark matter, when it comprises all of the dark matter, is shown. Among the most stringent constraints at low energies and masses are constraints from X-ray observations M31 Horiuchi et al. [134], as well as stacked dwarfs [204]. Also shown are constraints from the diffuse X-ray background [197], and individual clusters "Coma+Virgo" [208]. At higher masses and energies, we show the limits from Fermi GBM [206] and INTEGRAL [207]. The signals near 3.55 keV from M31 and stacked clusters are also shown [29, 30]. The vertical mass constraint only directly applies to the Dodelson-Widrow model being all of the dark matter, labeled "DW," which is now excluded as all of the dark matter. The Dodelson-Widrow model could still produce sterile neutrinos as a fraction of the dark matter. We also show forecast sensitivity of the planned *Athena X-ray Telescope* [209].

See Abazajian (2017) for a detailed review

What about vector mediators?

- The same chain of arguments can be used for vector mediators as well.
- Bounds can be stronger, due to presence of longitudinal d.o.f of massive vector boson.
- Here we consider three of the most popular vector models:

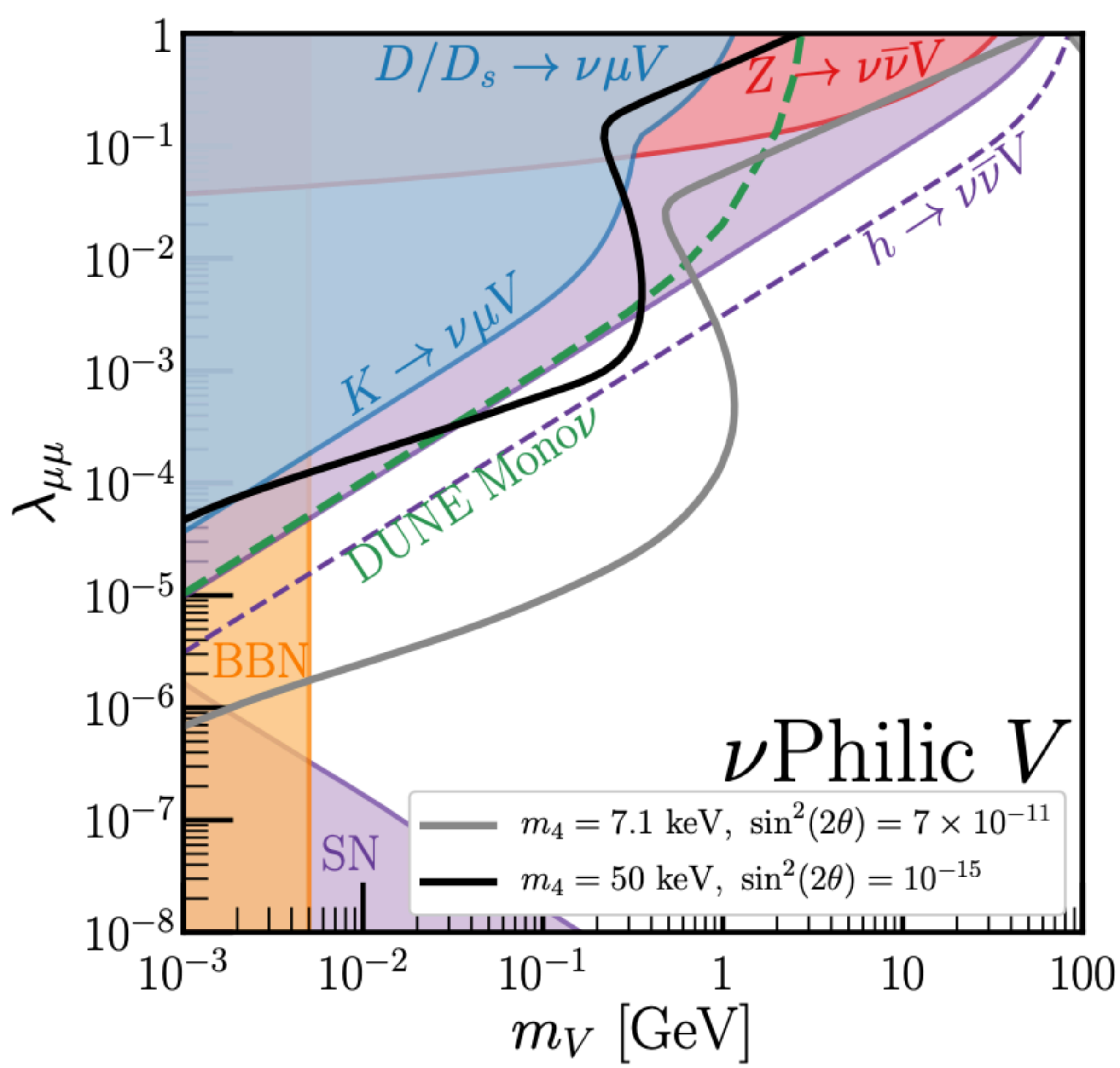
1. Neutrinophilic vector model.
2. $U(1)_{L_\mu - L_\tau}$
3. $U(1)_{B-L}$

Kelly, **MS**, Tangarife and Zhang, PRD 2020

Neutrinophilic vector

Consider the vector equivalent of the neutrinophilic interaction.

$$\mathscr{L} = \frac{1}{\Lambda^2}(\overline{L}_\alpha i\sigma_2 H^*)\gamma_\mu (H^T i\sigma_2 L_\beta)V^\mu \rightarrow \lambda_{\alpha\beta}\overline{\nu}_\alpha \gamma^\mu \nu_\beta V^\mu$$



Bounds :

1. Invisible Higgs decay.
2. Z boson decay width.
3. Exotic meson decays.
4. SN cooling bounds.
5. Accelerator neutrino bounds.
6. BBN bounds.

Kelly, **MS**, Tangarife and Zhang, PRD 2020