# keV sterile neutrino dark matter: Dead or Alive?

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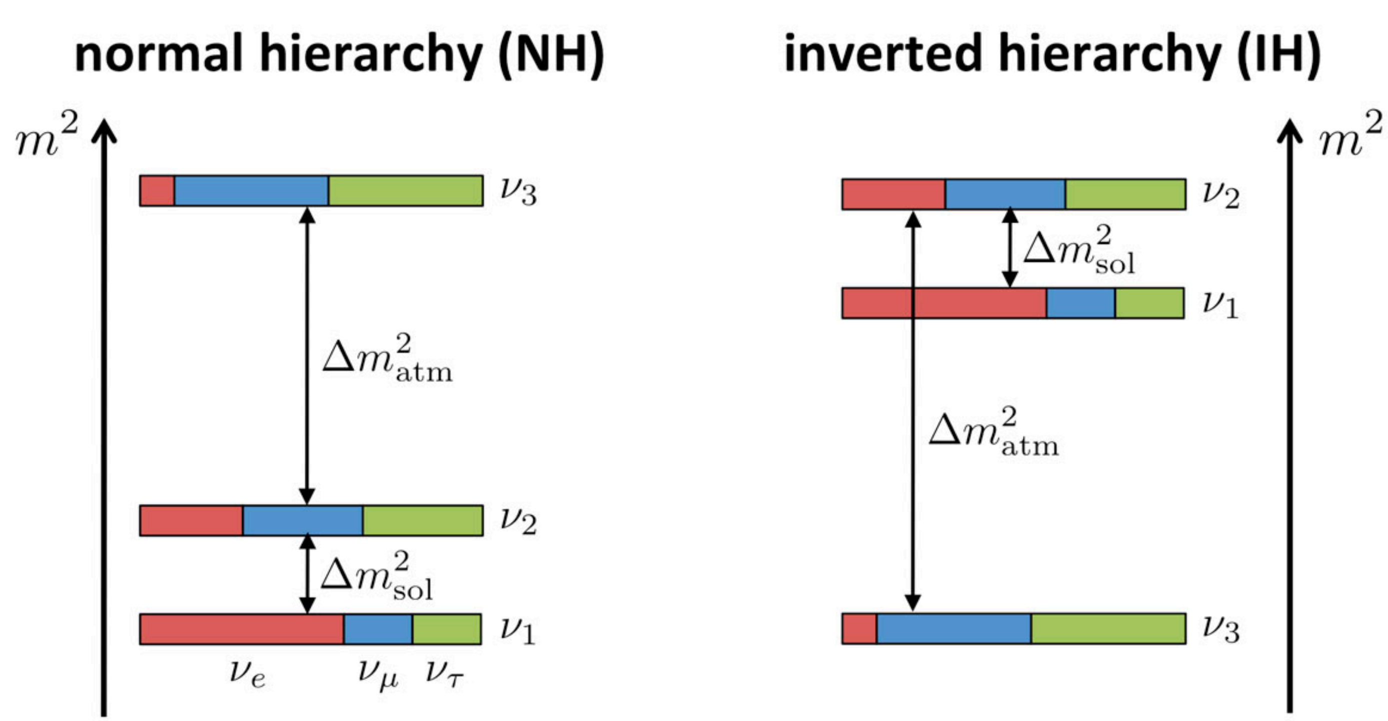
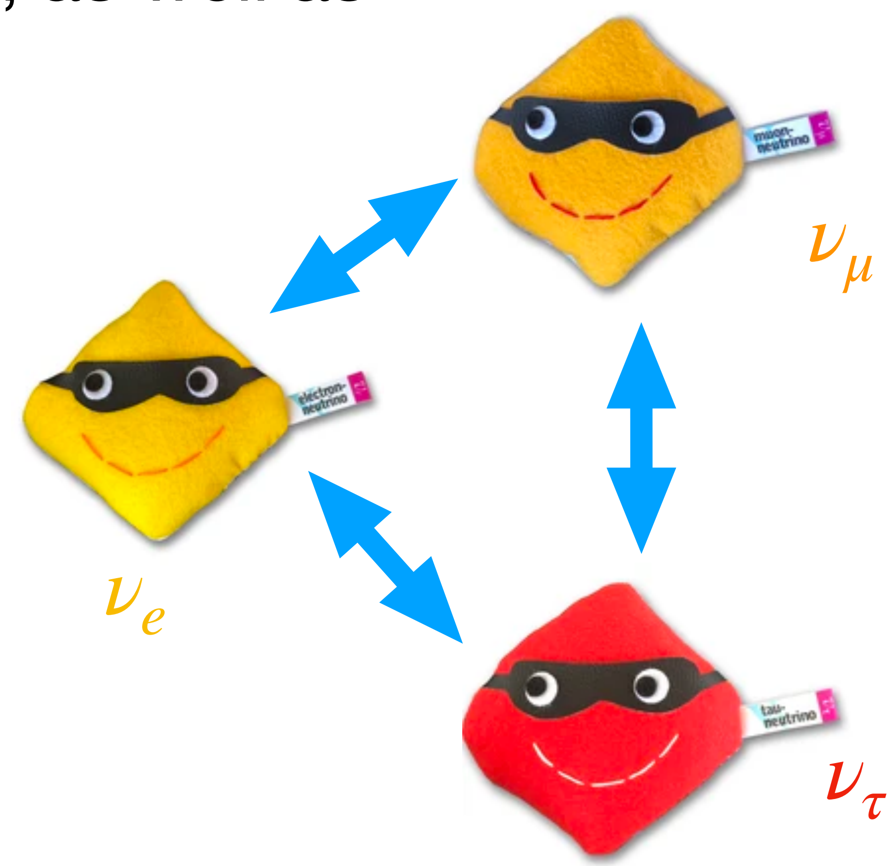
# The Standard paradigm…

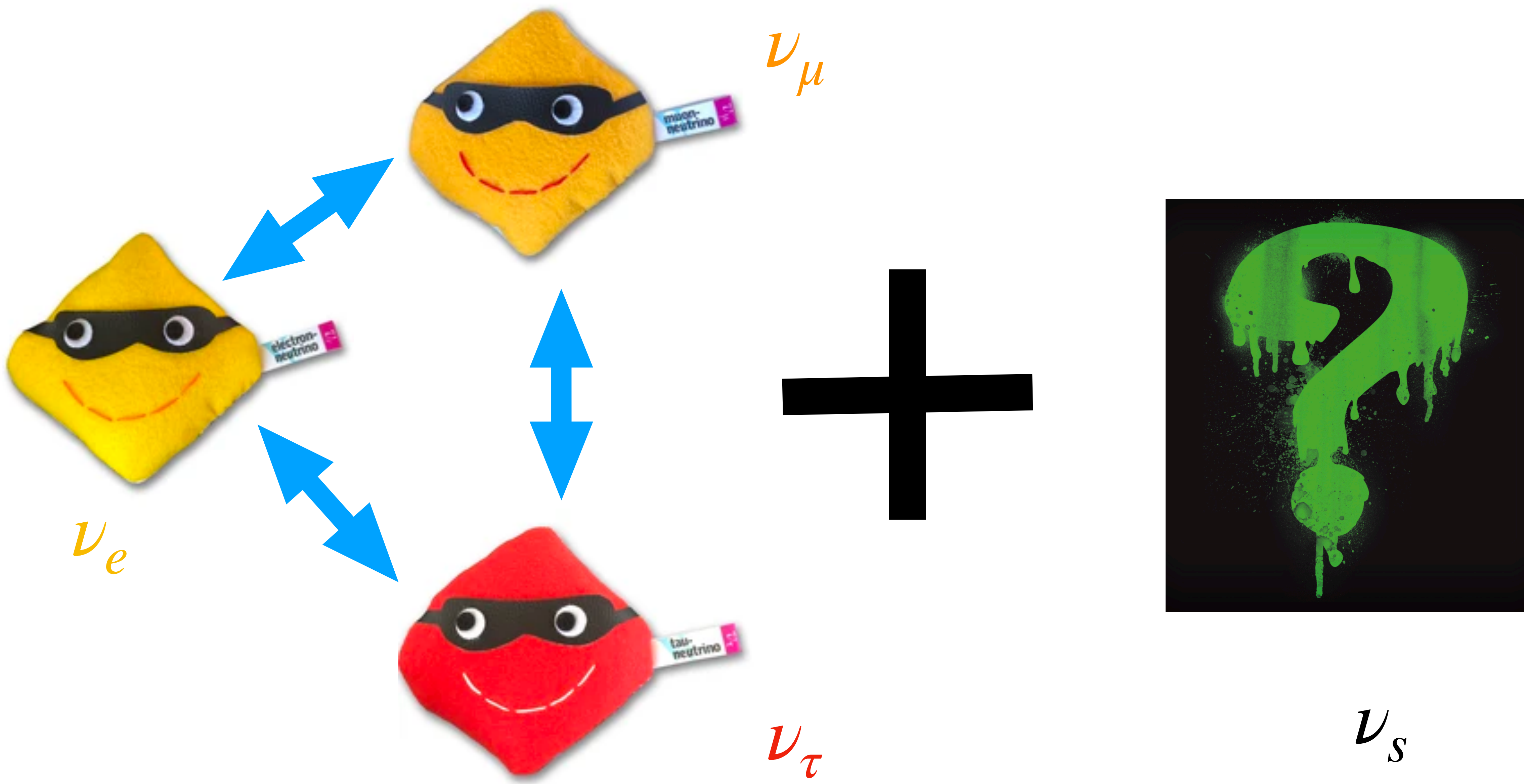
- Neutrinos are massive, and can change flavor.
- Neutrinos interact "weakly" with the rest, as well as with themselves.
- There are 3 active light neutrinos.




Credit: The Particle Zoo

# The sterile neutrino: the Riddler




Are there more of these ?

Four riddles:

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

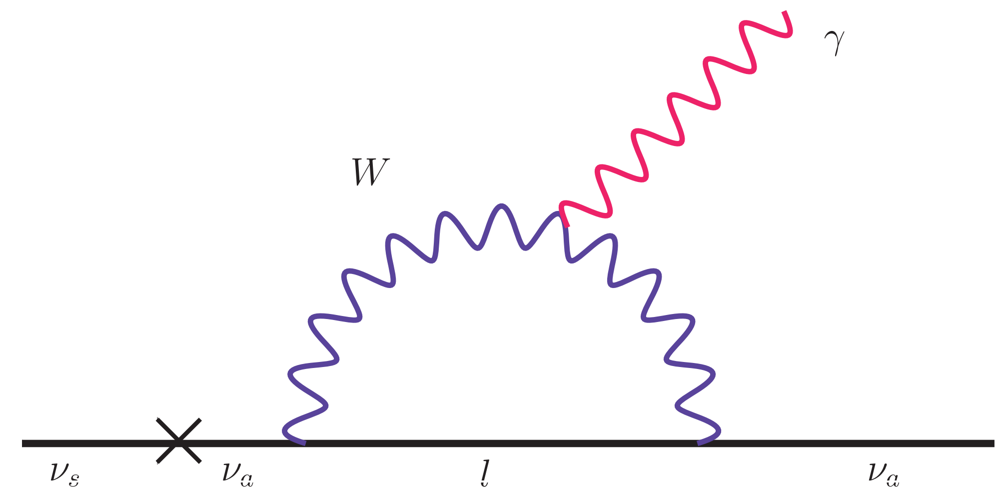
# Why do we like sterile neutrinos?


- 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), Dasgupta and Kopp (2021) for a detailed review

# Sterile neutrinos as Dark Matter

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

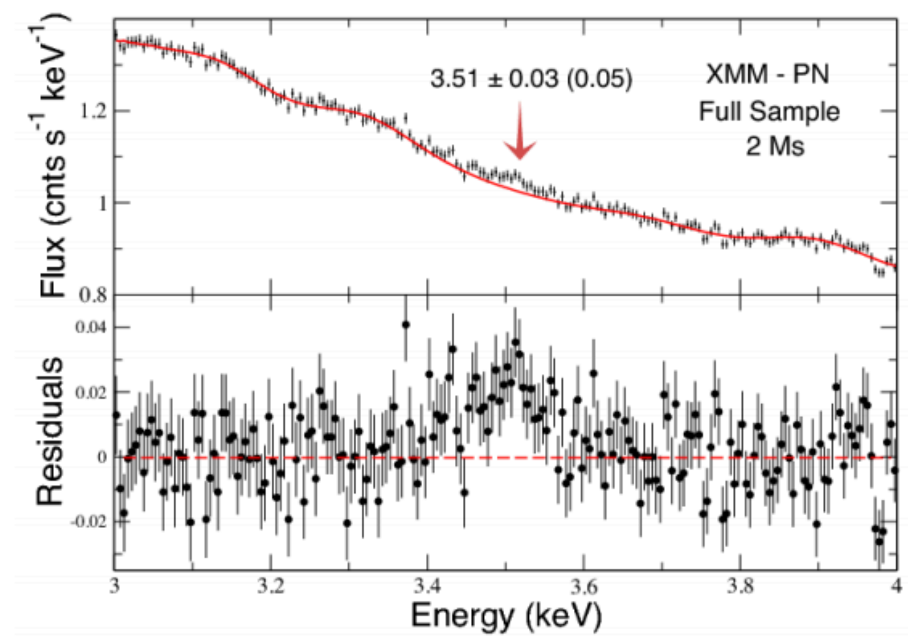



- Can be detected through 1-loop decay
  into photons: $\nu_s \to \nu_a \gamma$ .

- Decay rate $\Gamma \propto m_4^5 \sin^2 2\theta = 10^{-27} \left(\frac{\theta^2}{10^{-5}}\right) \left(\frac{m_4}{1\,\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$.

  Radiative decay detectable.

  Zatsepin and Smirnov, Yad. Fiz. 1978.
  Pal and Wolfenstein, PRD1982
  Abazajian, Fuller and Patel, PRD2001 + many more…




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

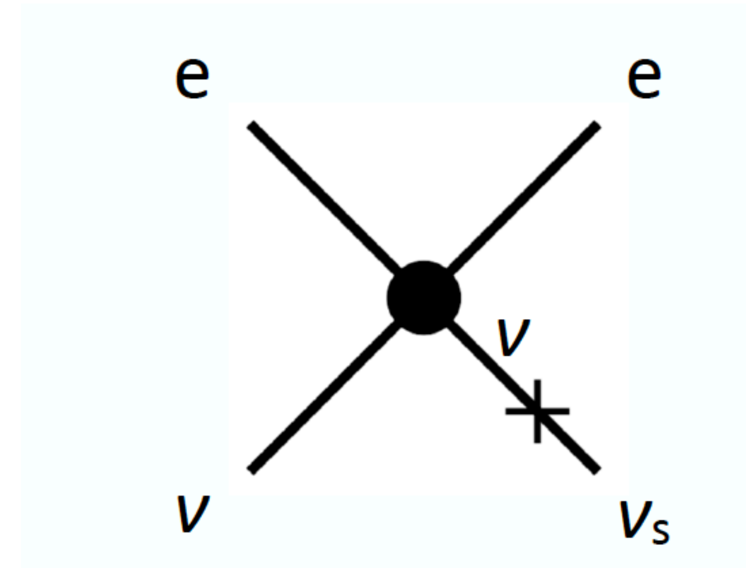
- Radiative decay leads to line at $E_\gamma = m_4/2$.

  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.

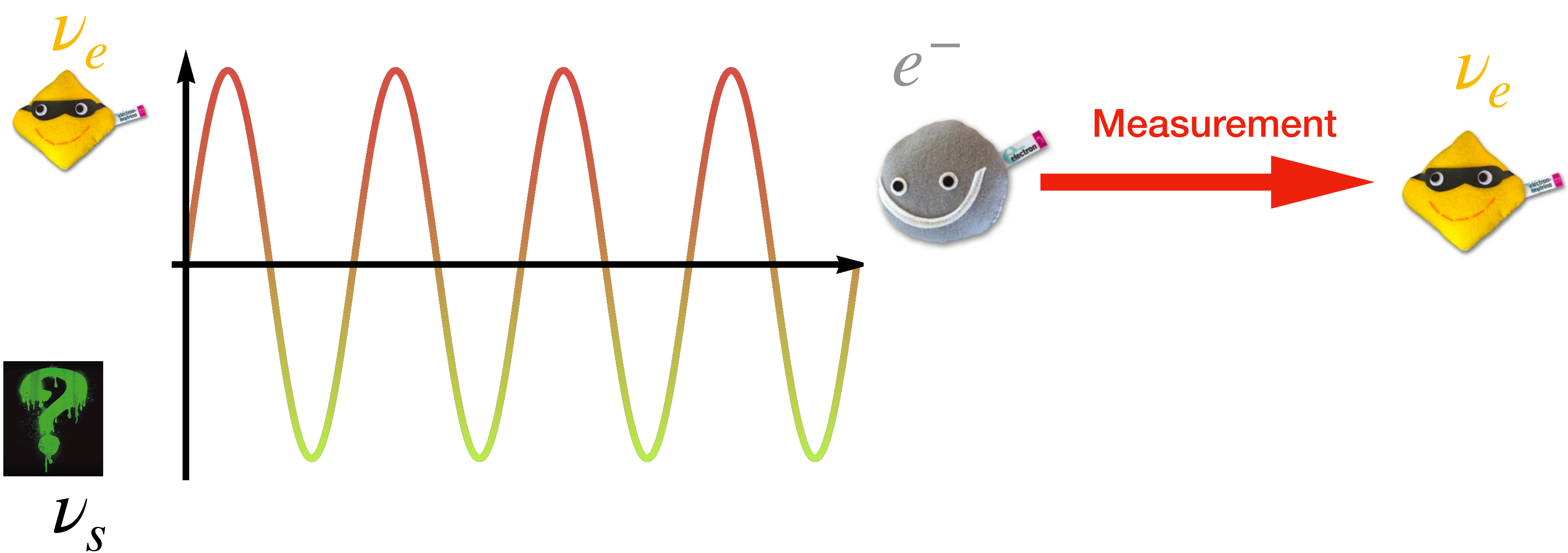
- But how do we produce these neutrinos?

# Production: the Dodelson-Widrow mechanism

- The $\nu_s$ cannot be in thermal equilibrium with SM particles before BBN.
- Must be produced non-thermally with $\theta \ll 1$.
- $\nu_a$ oscillates into $\nu_s$ before decoupling. Creates a non-thermal population of $\nu_s$.




Dodelson and Widrow, PRL1994.



# Production: the Dodelson-Widrow mechanism

$\nu_a$ oscillates into $\nu_s$ before decoupling. Creates a non-thermal population of $\nu_s$. 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

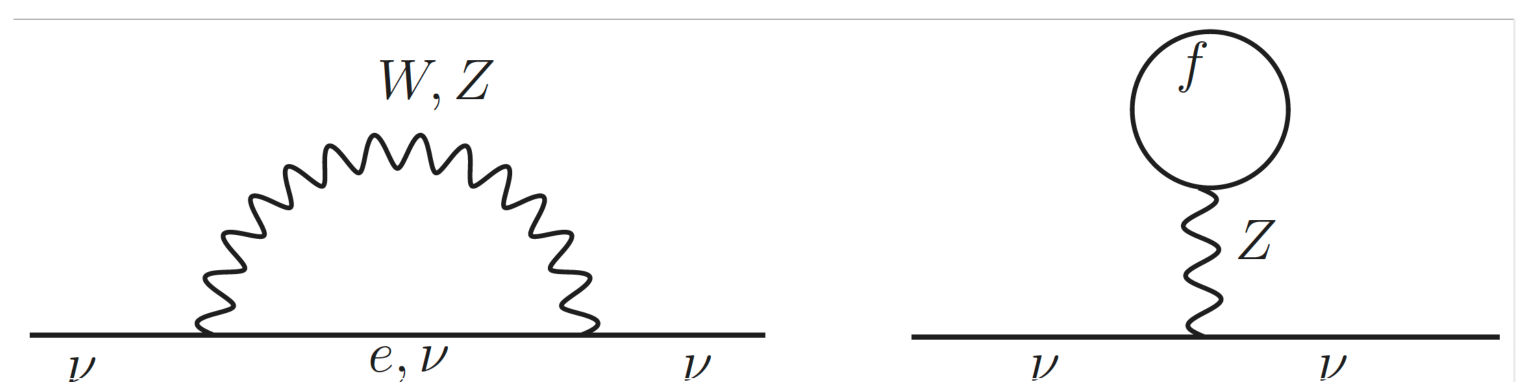
$\Delta = m_s^2/2E$

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

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

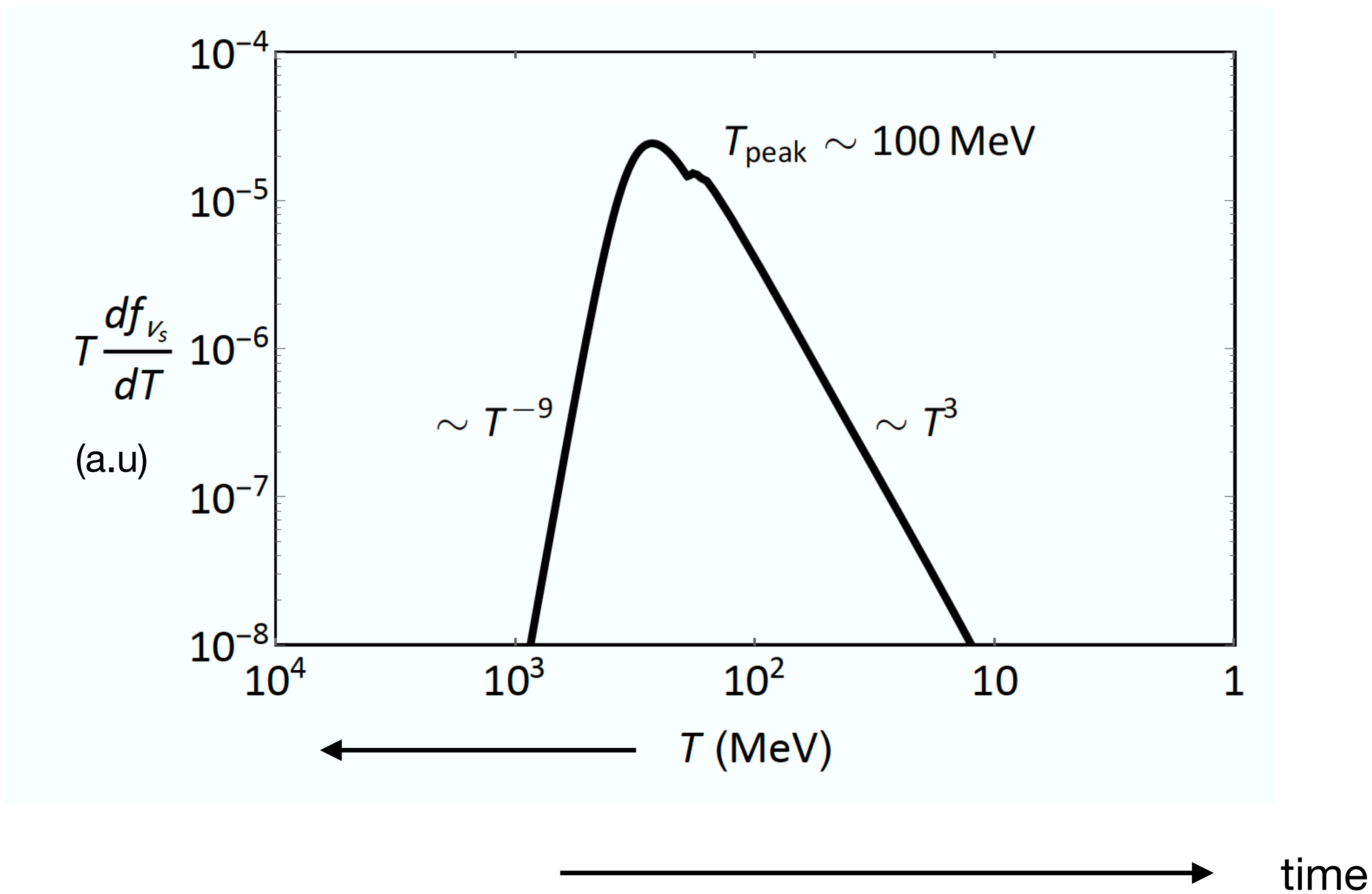
$$\langle P(\nu_a \to \nu_s)\rangle = \frac{1}{2}\frac{\Delta^2 sin^2 2\theta}{\Delta^2 sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta cos 2\theta - V)^2}$$

**SM**

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

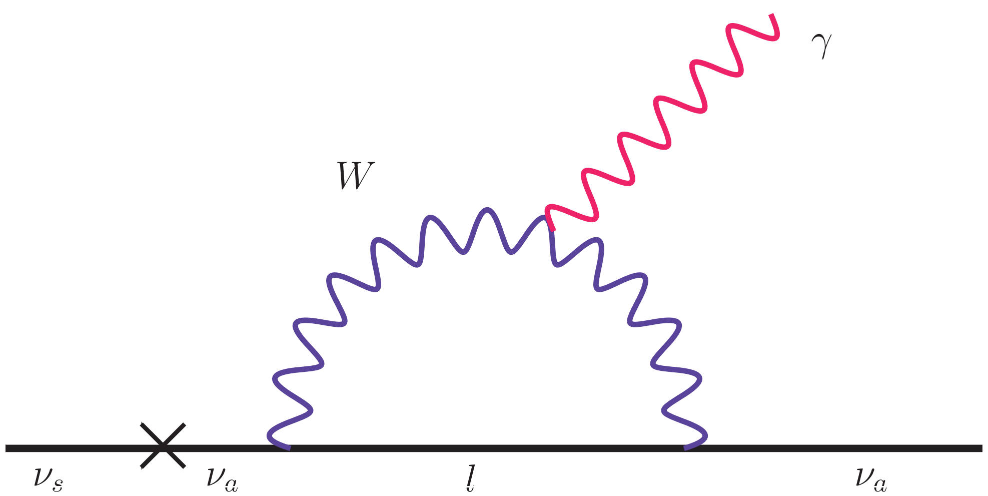
- Case 1: When $\Gamma \gg \Delta$, $\quad T\frac{df}{dT} \sim \frac{\Gamma}{H}\frac{\Delta^2}{\Gamma^2} \propto T^{-9}$
- Case 2: When $\Gamma \ll \Delta$, $\quad T\frac{df}{dT} \sim \frac{\Gamma}{H} \propto T^3$

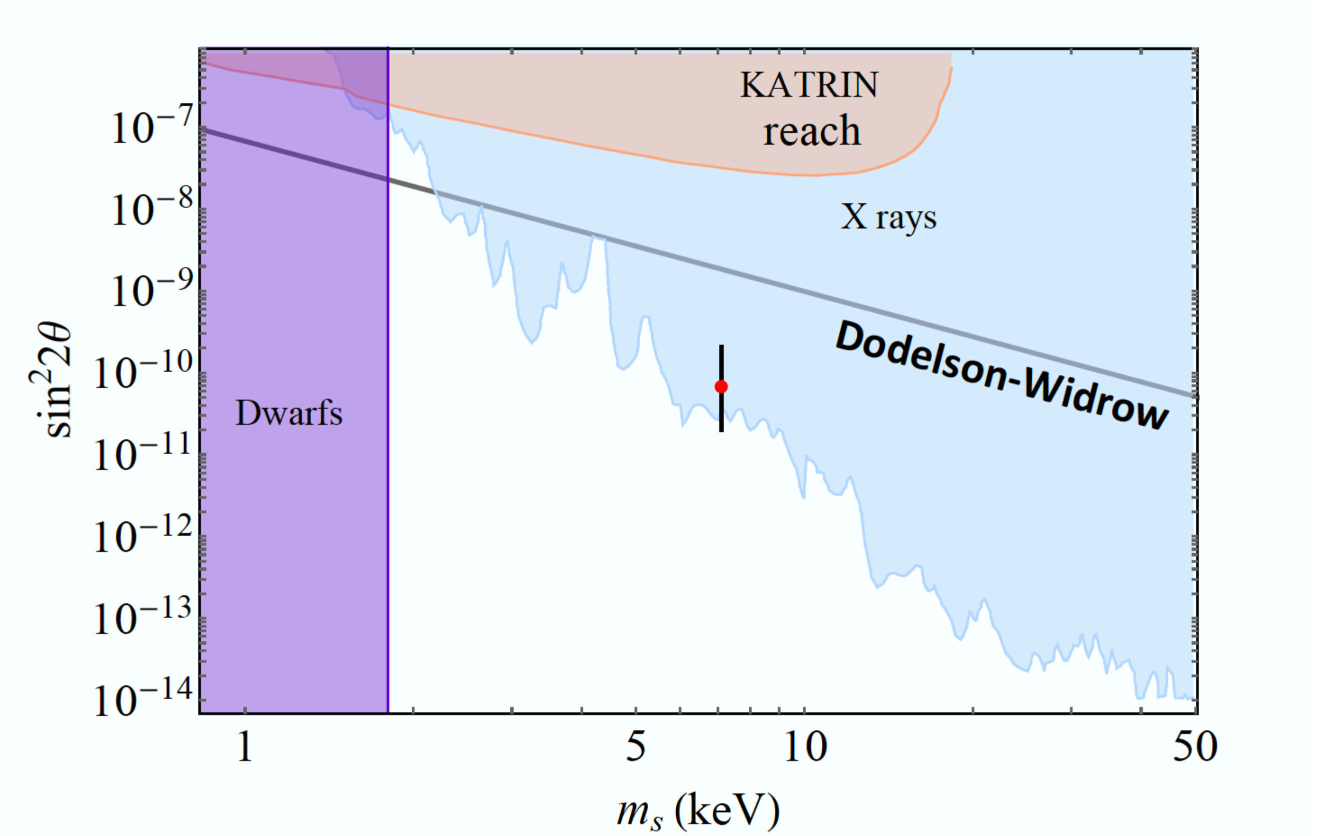
# The Dodelson-Widrow mechanism… contd




- $\nu_s$ 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, galaxy counts, Lyman alpha, strong lensing, 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?

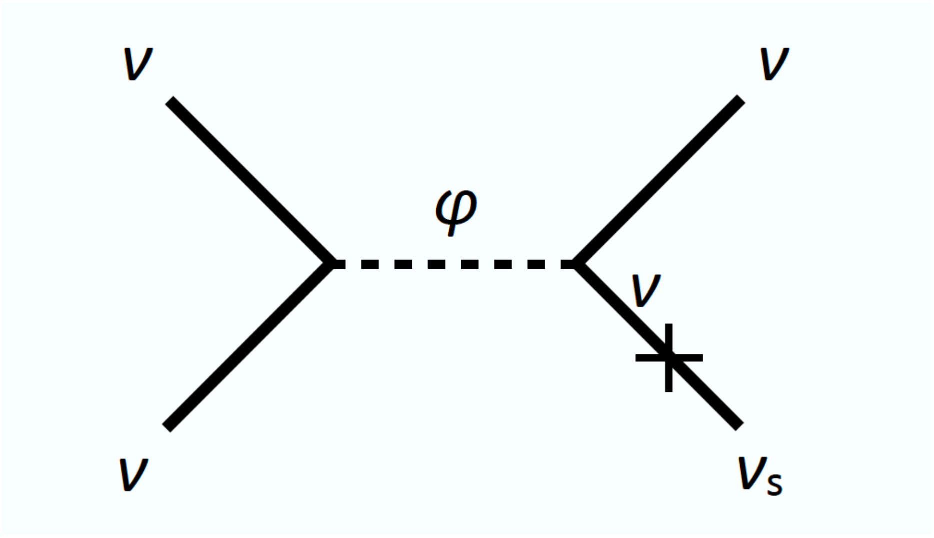
# Secret neutrino self-interactions

# Opening up the chamber of secret : NSSI

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

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

  $\varphi$ has lepton number.

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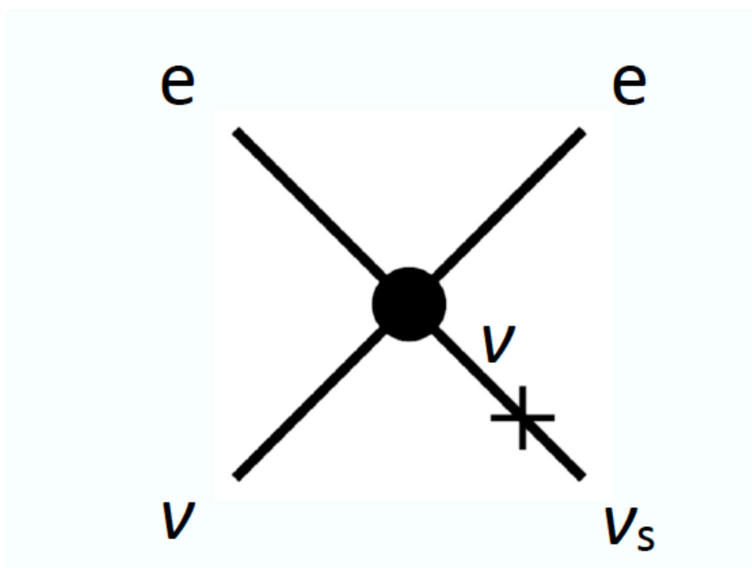
- Relic ~ (rate) X (mixing angle).

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

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

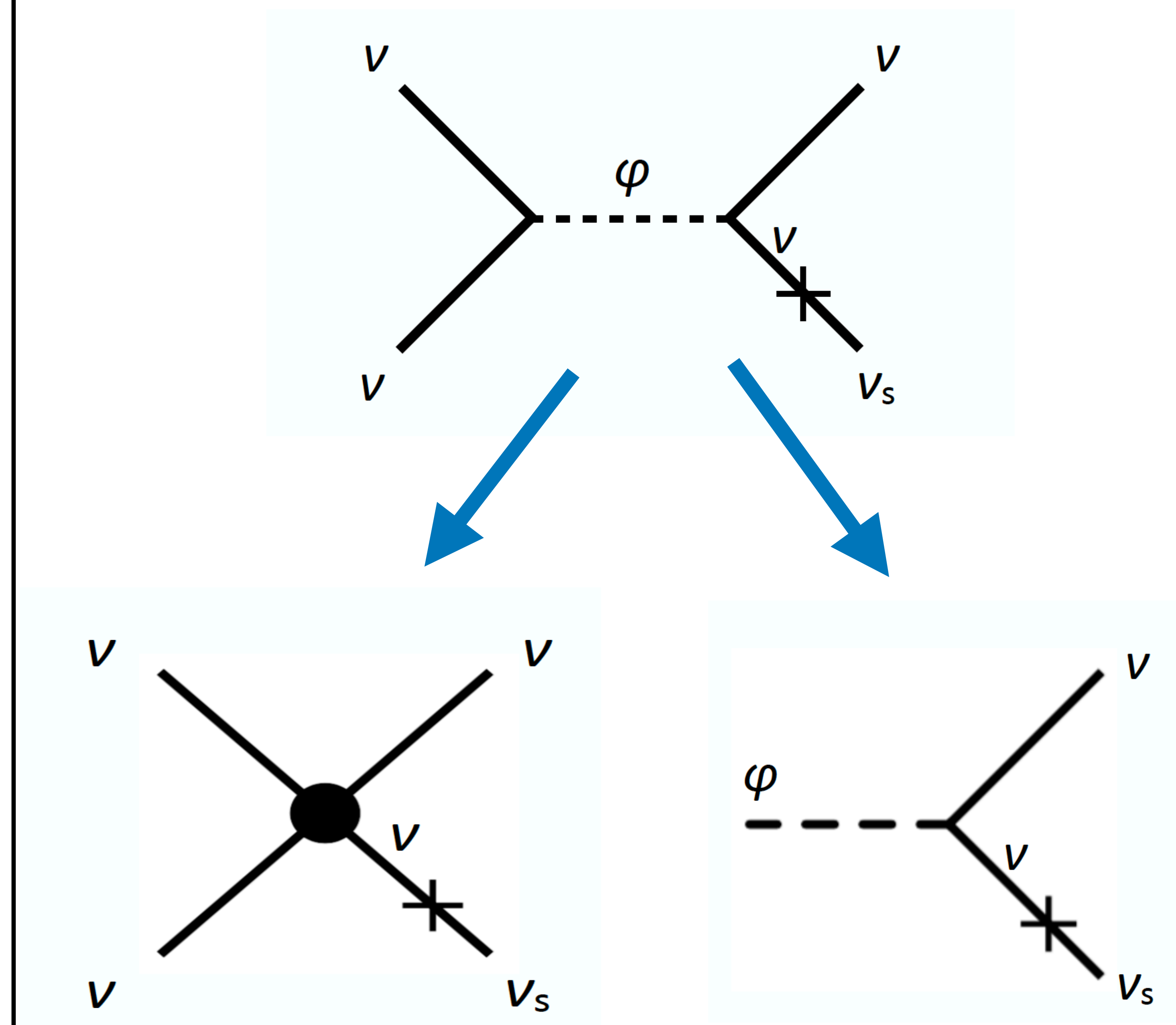
# What changes in the DW mechanism?

## S.M




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

## S.M + Self-Interactions




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

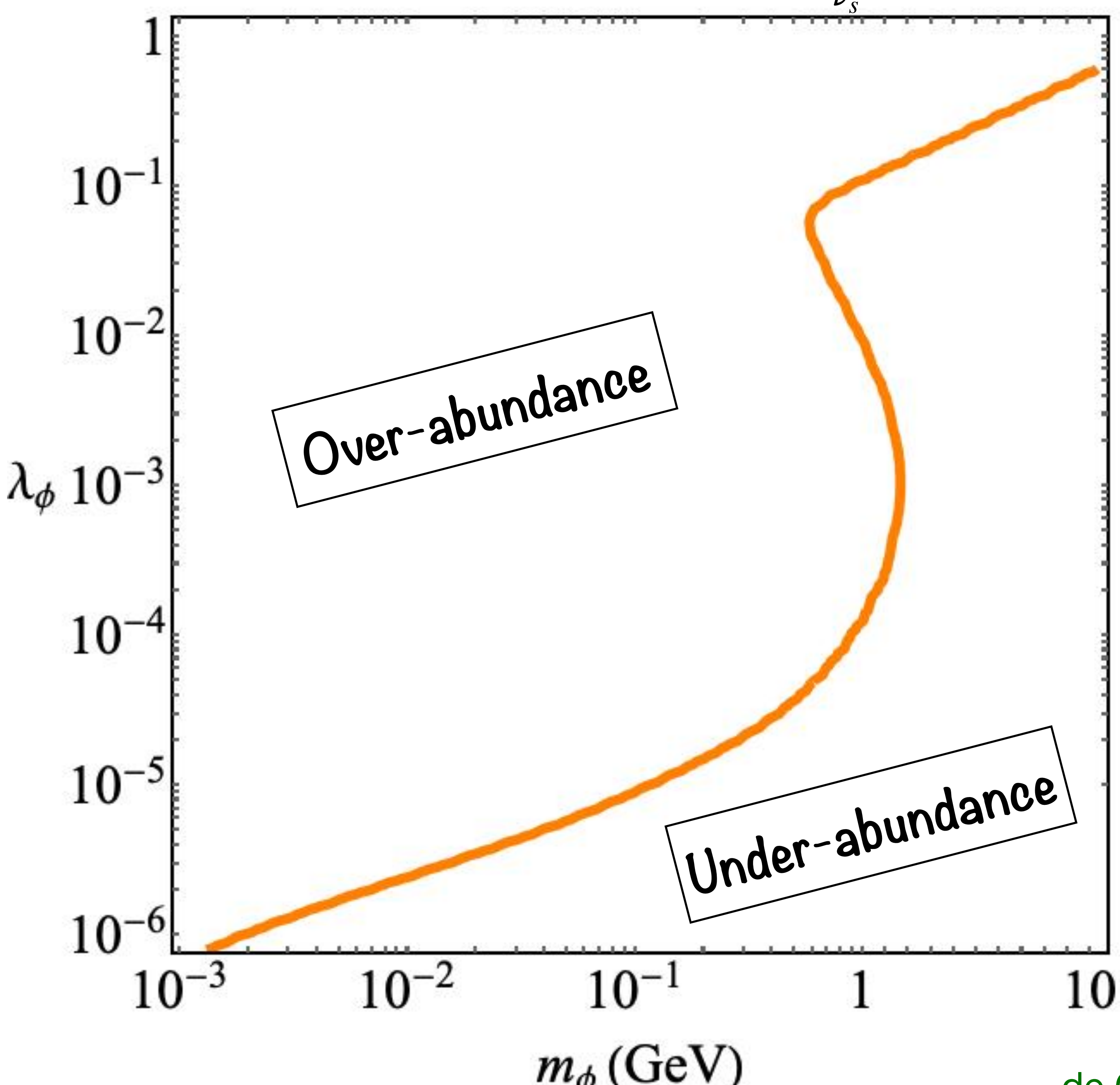
$$M_{\varphi} \lesssim T_{peak}$$

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

# 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?

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# 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. $t_{\varphi}$: When $T = m_{\varphi}$ , mediator cannot be produced on-shell for lower temperature

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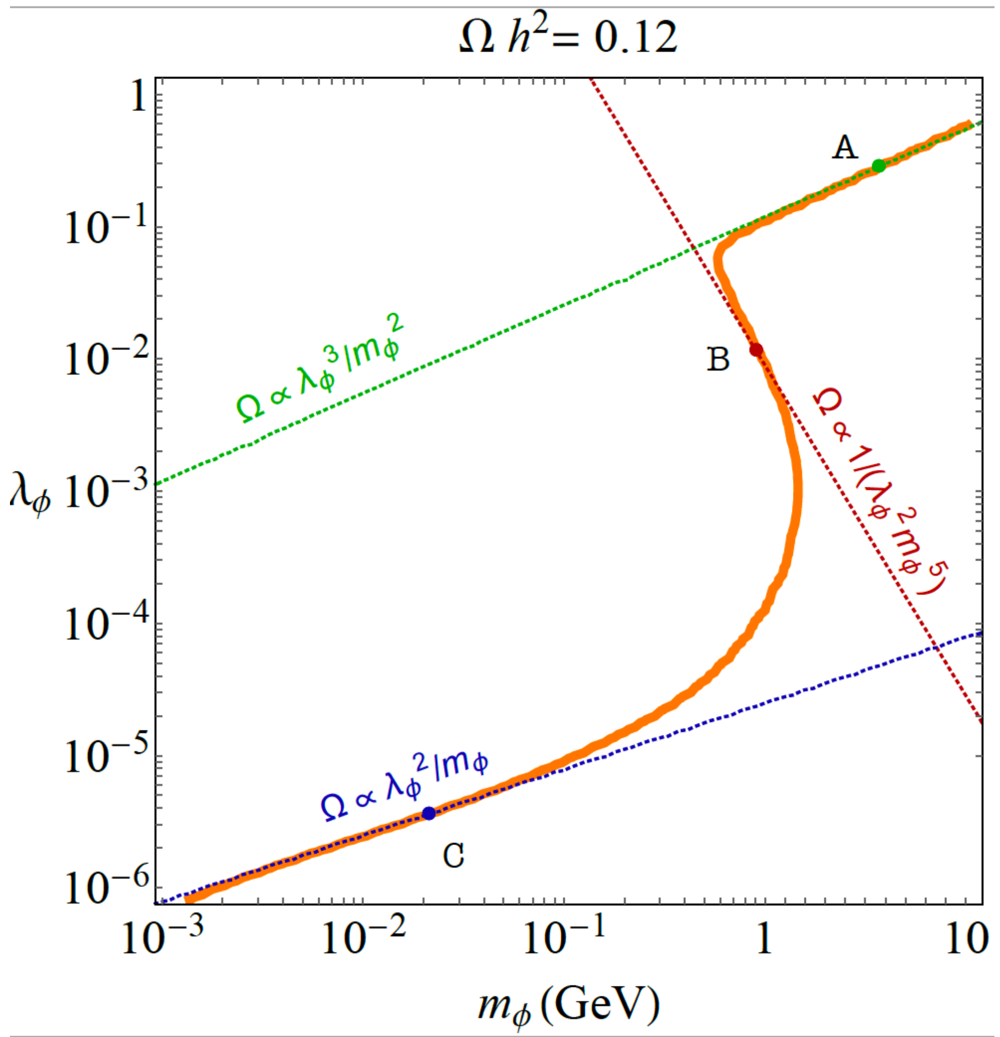
Cherry, Friedland, Shoemaker 1605.06506

# Explanation of Results

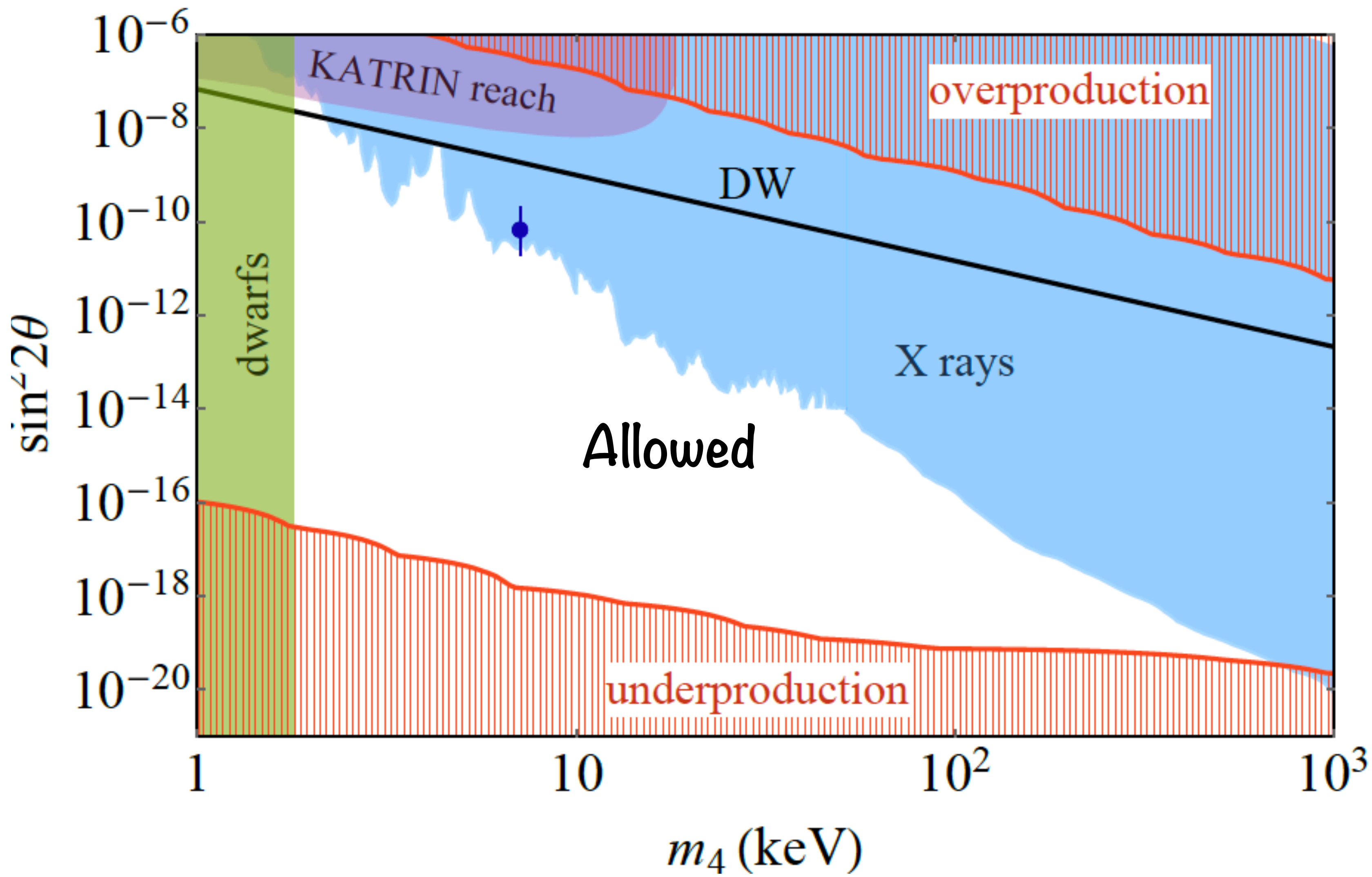



1. A: $t_\varphi < t_{\Delta=V} < t_{\Gamma=H}$. Production around $t_{\Delta=V}$ from scattering via an off-shell $\varphi$. Similar to the usual DW mech.

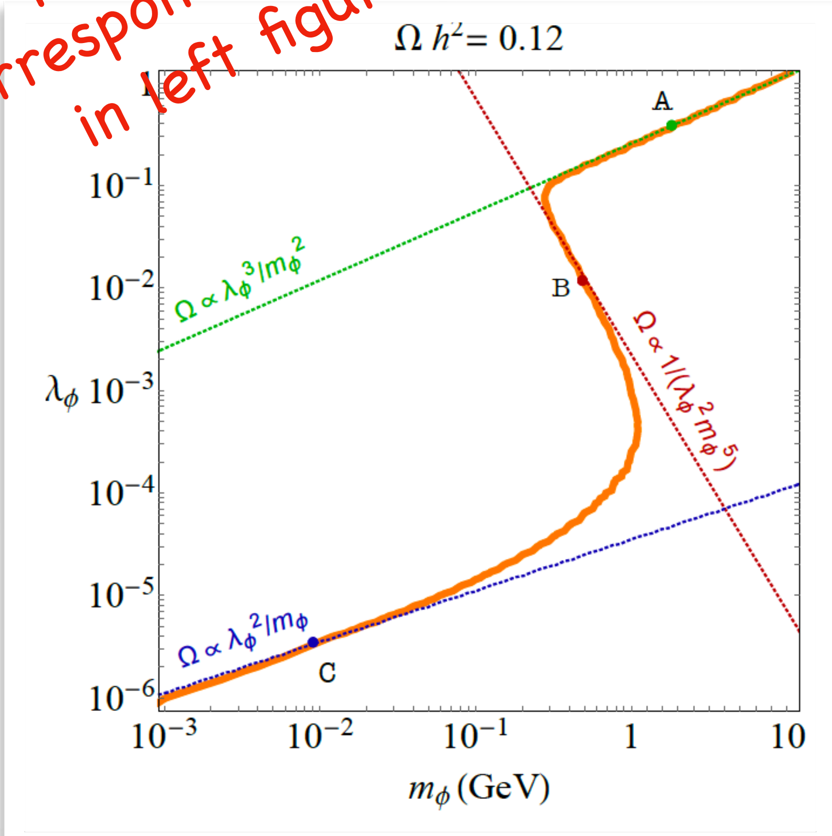
2. B: Intermediate mass, coupling: $t_\varphi < t_{\Gamma=H} < t_{\Delta=V}$ .Peak production happens in $(t_\varphi < t < t_{\Gamma=H})$ when $\theta_{\rm eff}$ is suppressed.

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

# Allowed Relic Density window




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

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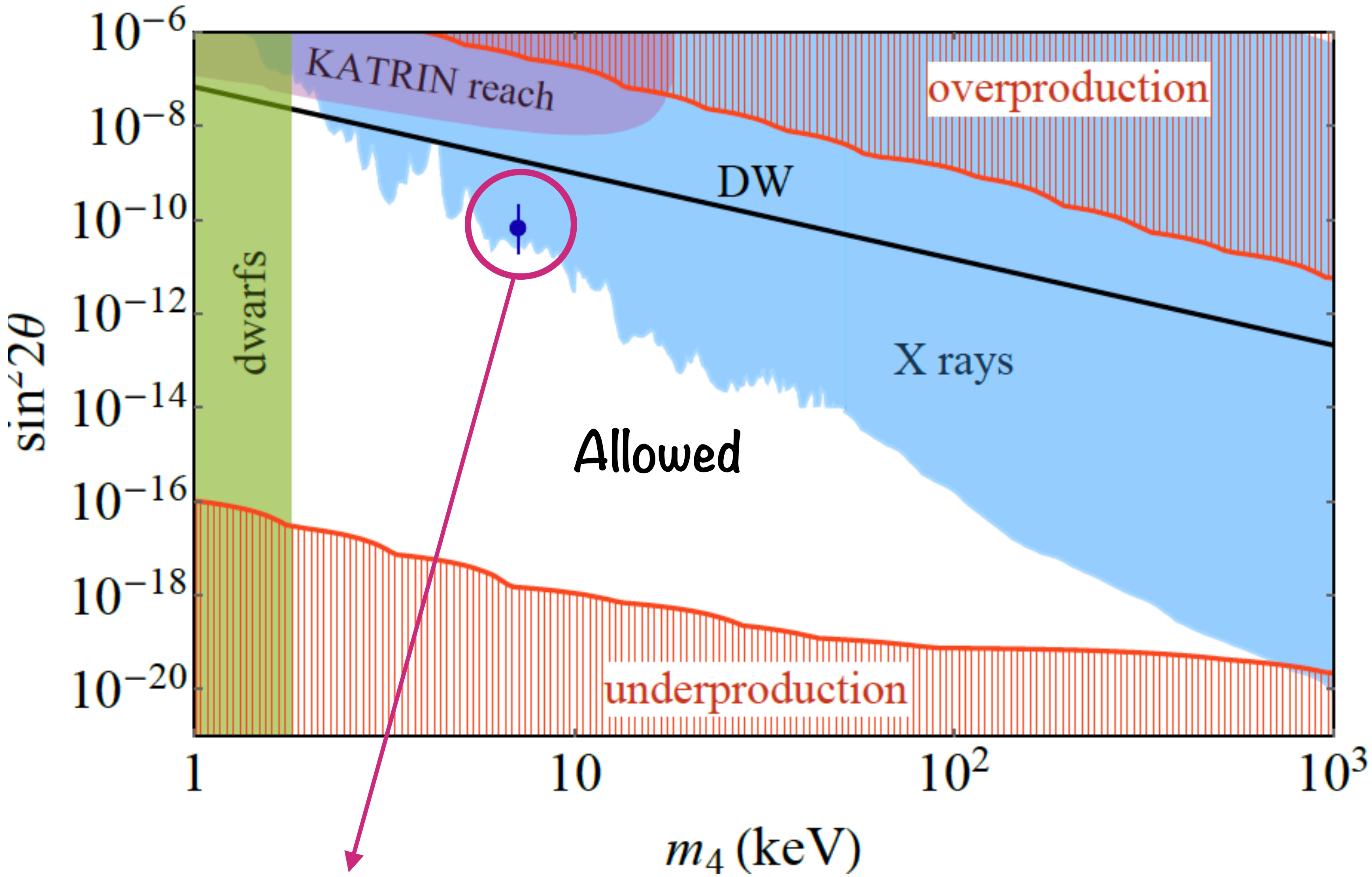
# Allowed Relic Density window

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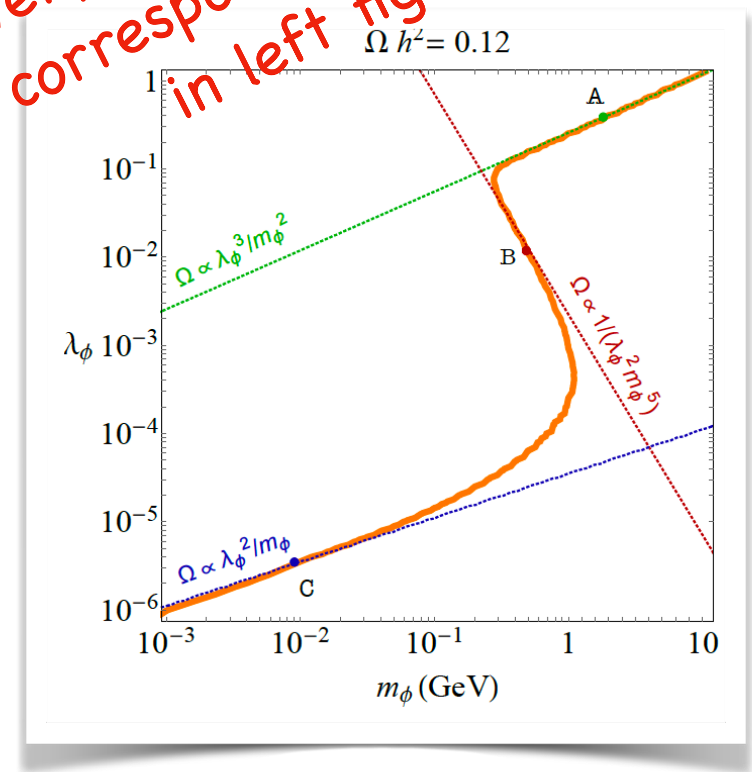


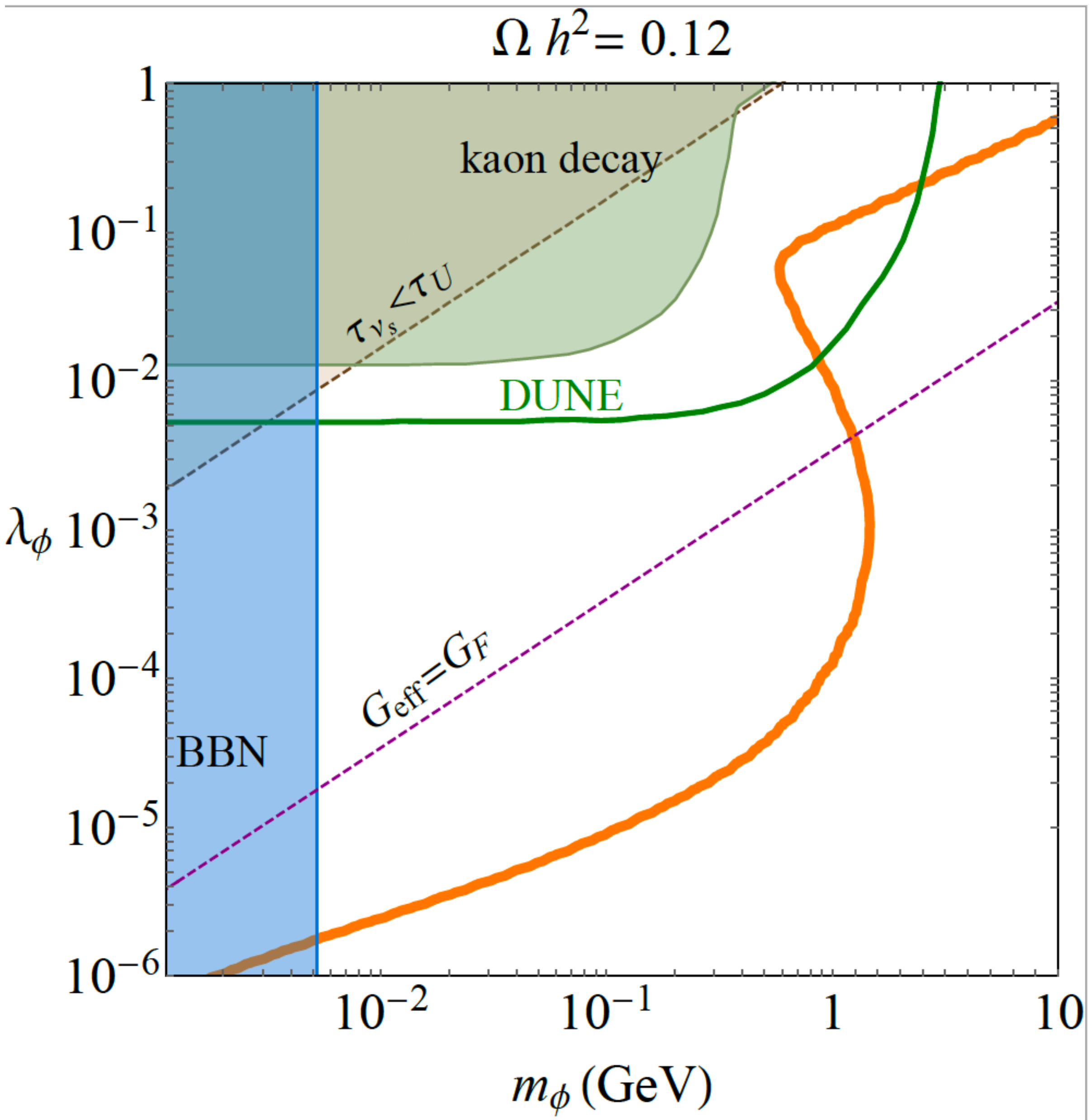

Can be used to satisfy the 3.5 keV X-ray line also ~

$m_{\nu_s} = 7.1\,\text{keV},\ sin^2 2\theta = 7\times 10^{-11}$ Bulbul et al. Astro. 2014+many more

# Experimental tests

# Lab based tests

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

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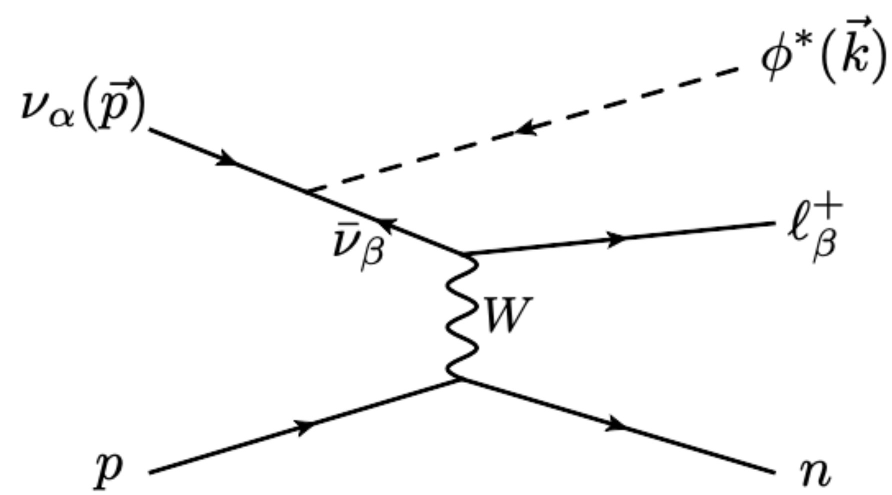
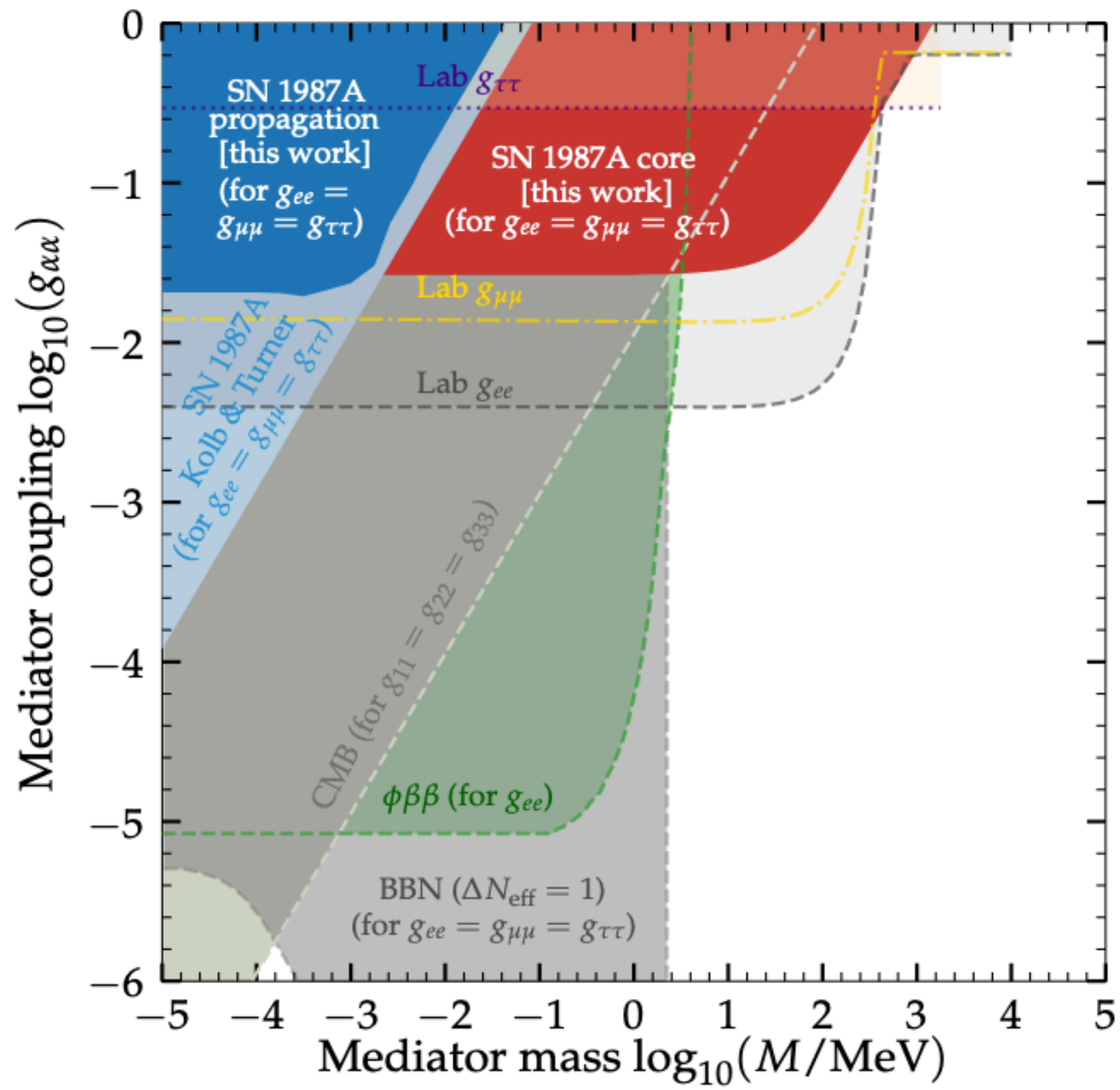
- Invisible Higgs decays, Z decays: $\lambda_\varphi < 0.7$.
- $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu$ . Bounds from $\text{Br}(K^- \to \mu^- 3\nu) < 10^{-6}$ .
- DUNE can look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$. Parameter space can be probed.




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

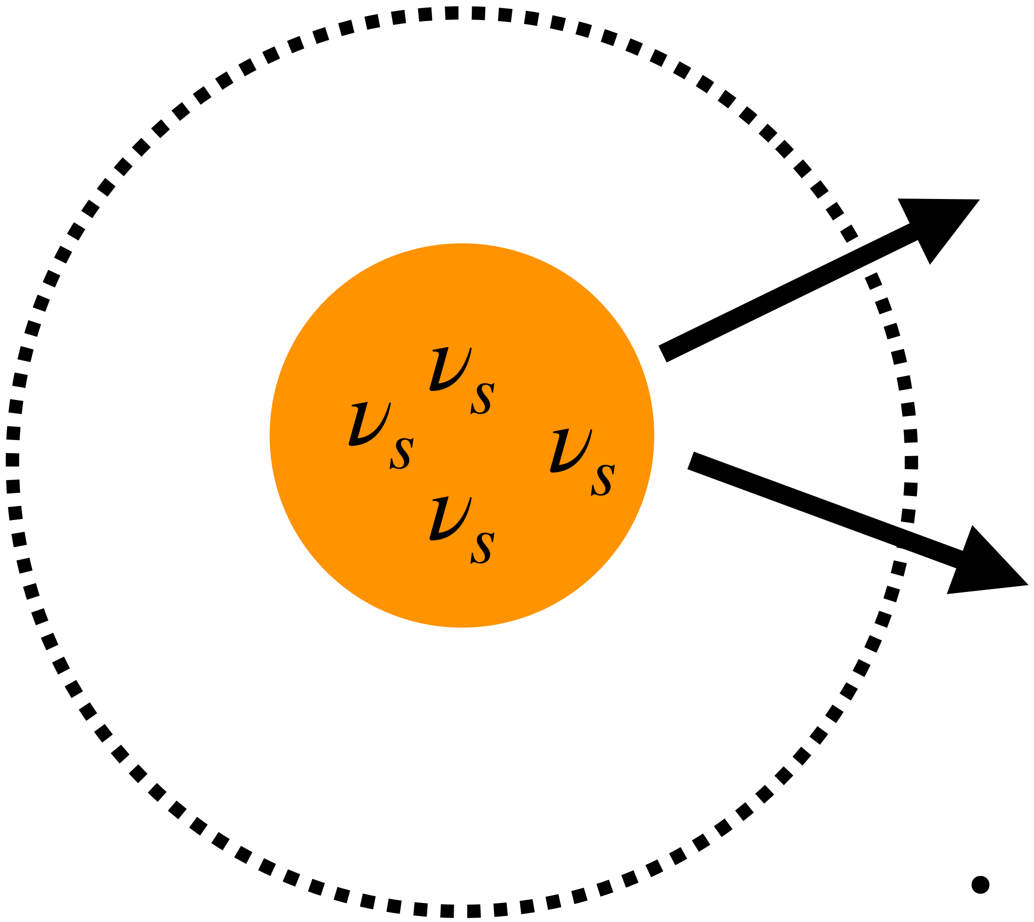
# Astro tests: Core-Collapse supernova constraints

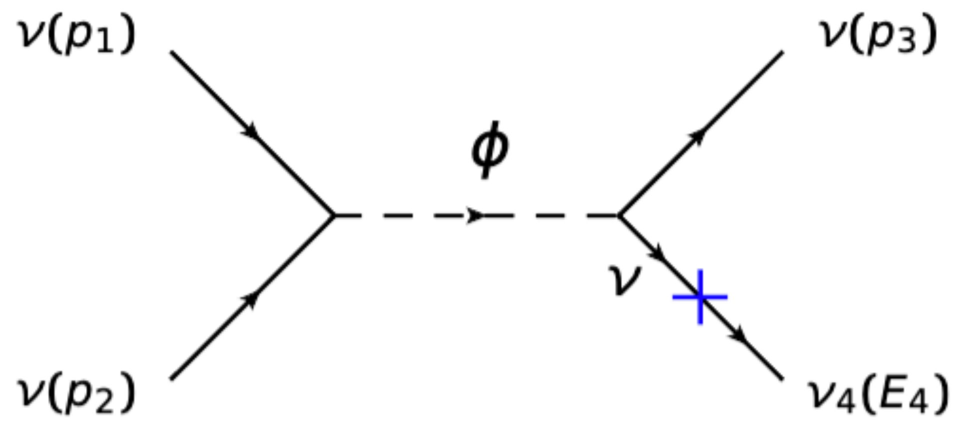



- Scatterings with the cosmic neutrino background could have down-scattered the neutrinos from SN1987A (blue shaded)
- Successful explosion could have been hindered (red shaded).
- Production of mediators, leading to cooling— less stringent bounds.

Bustamante, Shalgar, Tamborra, PRD 2021

# Supernova cooling bounds from sterile neutrinos



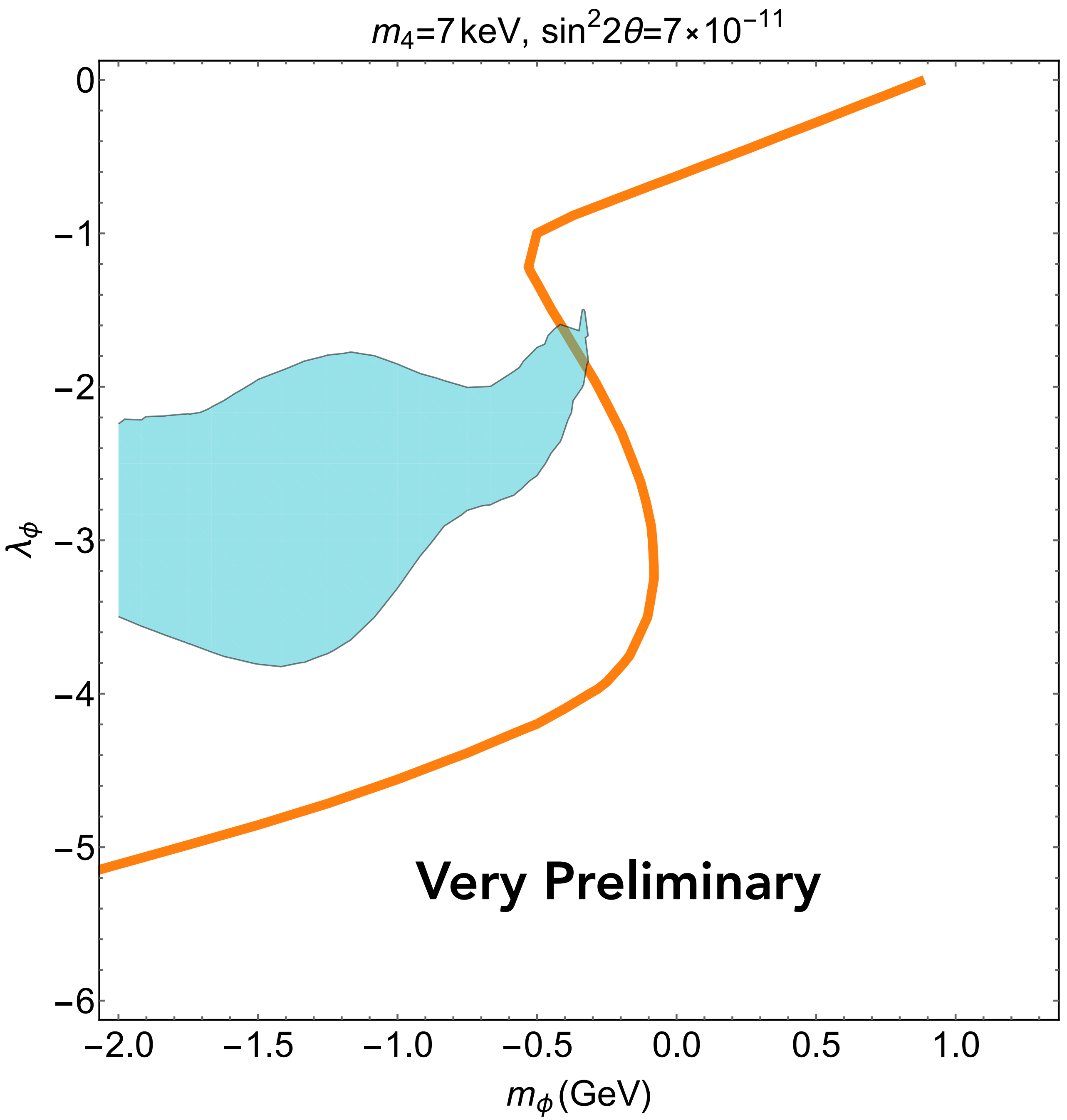




- $\nu_s$ can also be produced inside the SN core due to these new interactions, and lead to additional cooling channels.
- Bound : $L \lesssim 3 \times 10^{52}\,\mathrm{erg/s}$. Raffelt criterion.

$$L = \int d^3\vec{r} \int \frac{d^3\vec{p}_1}{(2\pi)^3} f_\nu(E_1, r) \int \frac{d^3\vec{p}_2}{(2\pi)^3} f_\nu(E_2, r) \frac{1}{4E_1 E_2} \int \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \int \frac{d^3\vec{p}_2}{(2\pi)^3 2E_4}$$
$$\times (2\pi)^4 \delta^4(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) |\mathcal{M}|^2 E_4 e^{-\tau(E_4, r)} \ ,$$

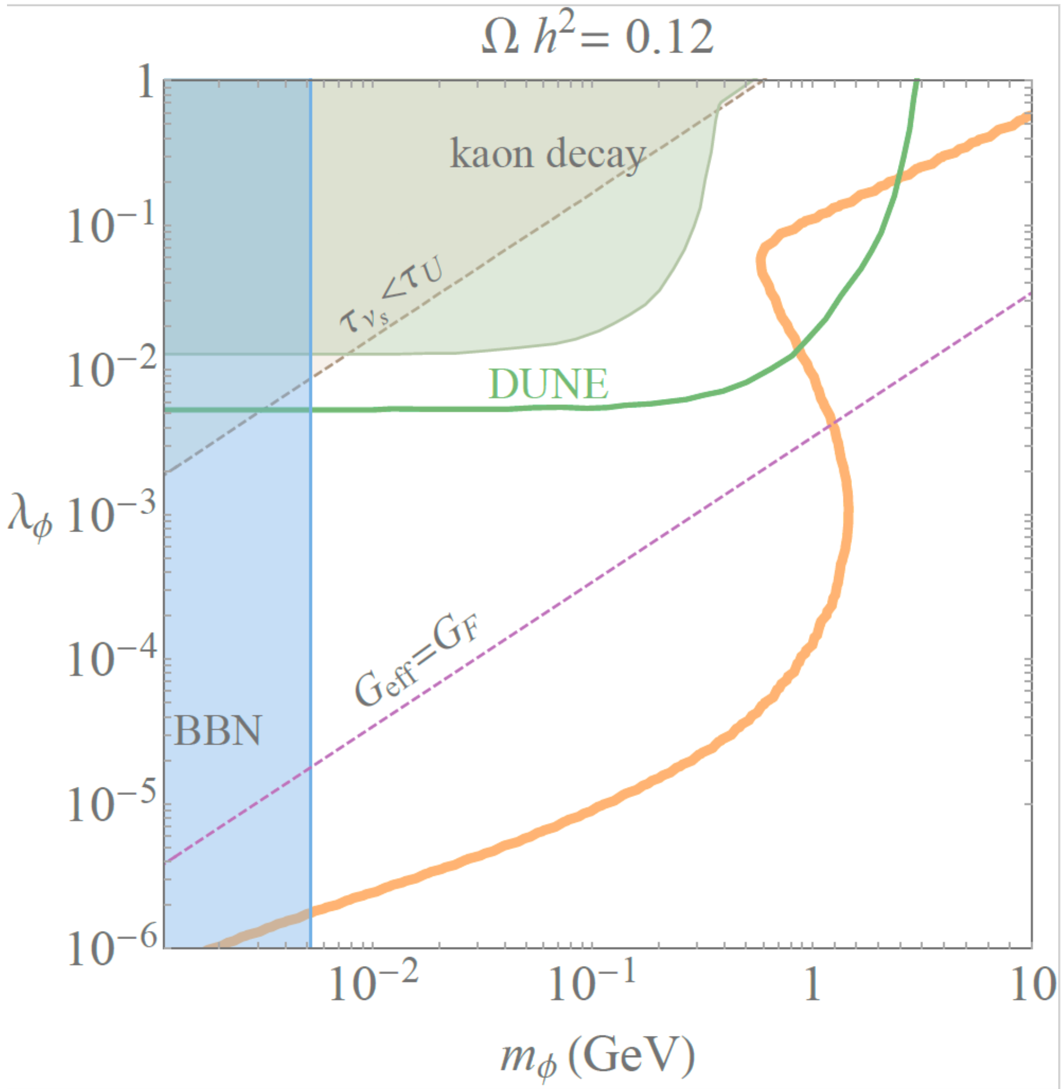
Chen, **MS**, Tuckler, Tangarife and Zhang, to appear

# Supernova cooling bounds




Can probe the parameter space for judicious choice of sterile mass and mixing.

Chen, **MS**, Tuckler, Tangarife and Zhang, to appear




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

**Cosmological Surveys**

# Low mass, low coupling limit

How do we evade BBN bounds? Relevant process $\phi \leftrightarrow \nu\nu$.

Partial thermalization of $\varphi$ before BBN, require feeble coupling to neutrinos.

Decay of $\varphi$ to keV $\nu_s$ before CMB


Negligible $\varphi$

$\varphi - \nu$
equilibrium

$\varphi \to \nu\nu_s$
decay

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

Energy density, lepton number conservation.

Entropy, lepton number conservation

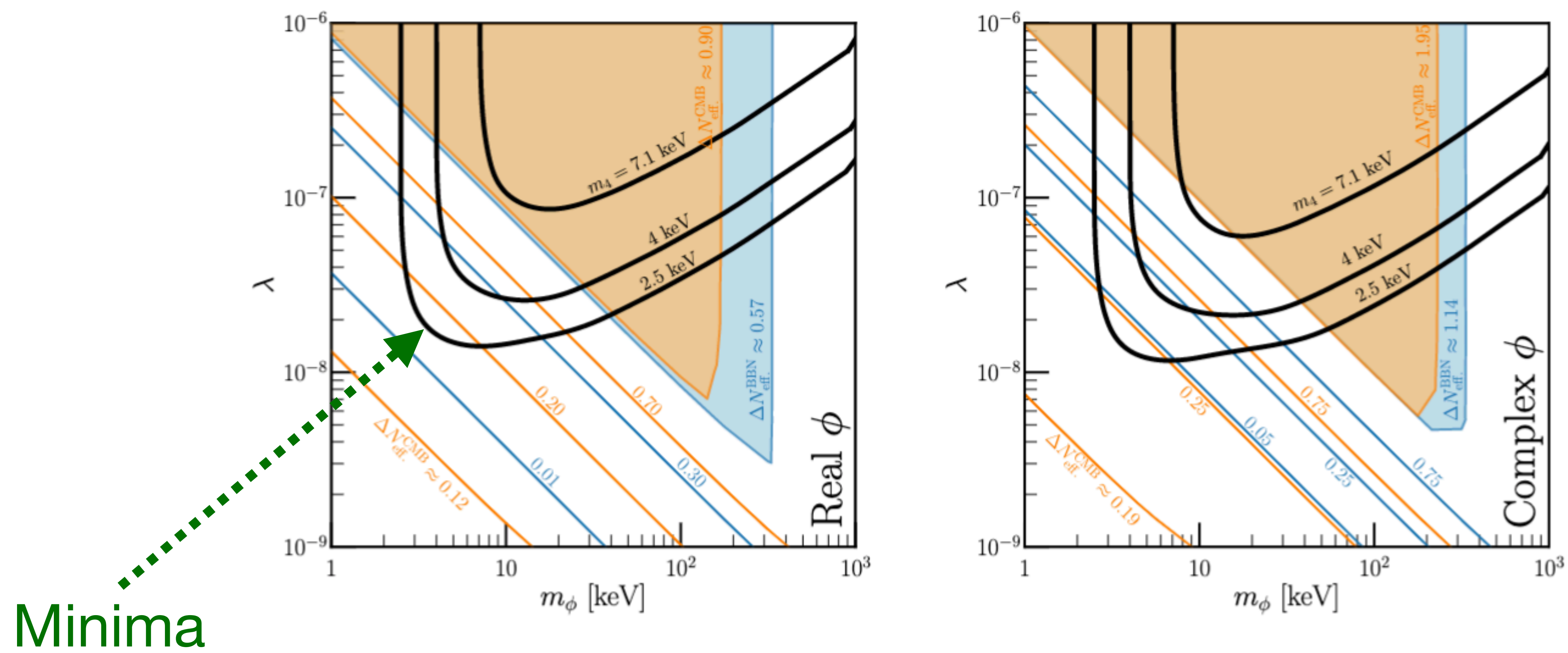
A chemical potential develops for neutrinos

Escudero, JCAP 2020

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

# Correlation with extra radiation

- Partial thermalization of $\varphi$ contributes to $N_{\rm eff}$ at BBN, and $\varphi$ decay to $N_{\rm eff}$ at CMB.
- As $m_\phi \to m_4$, larger values of $\lambda$ are required to compensate phase-space suppression of $\phi \to \nu\nu_s$
- Relic curves show a minima, can correlate DM relic with $N_{\rm eff}$ .




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

# Structure formation bounds evaded?

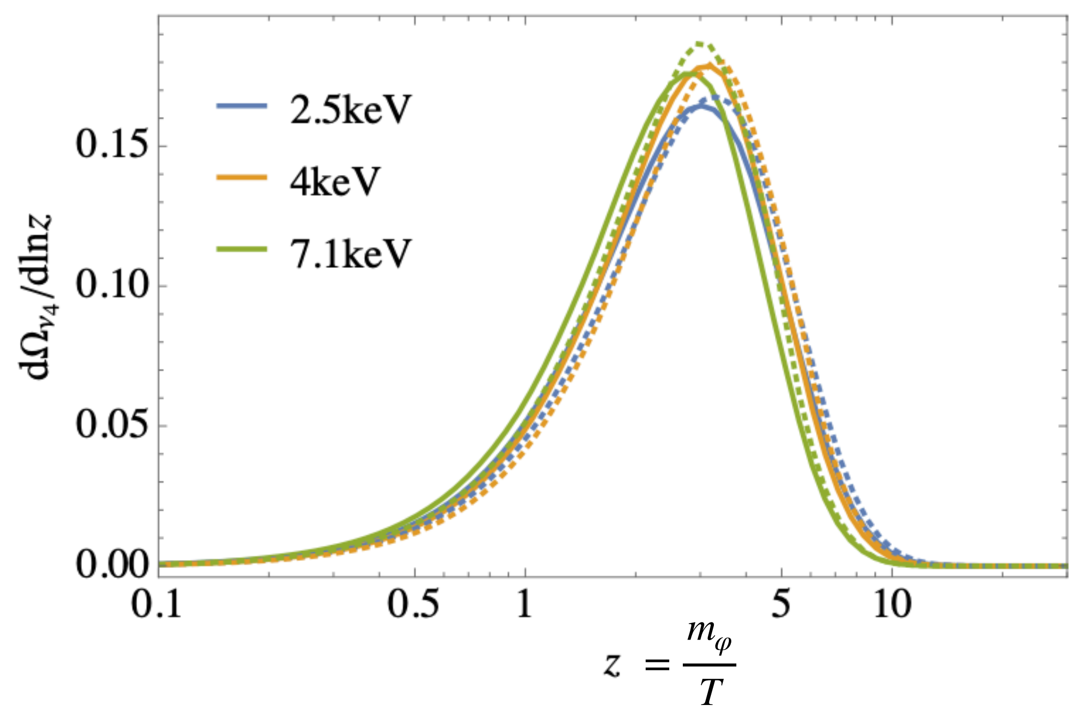



FIG. 5. Time dependence of S$\nu$DM, for three values of $m_4$ as labelled. The other parameters are chosen for producing the observed DM relic density. The solid (dashed) curves correspond to real (complex) scalar $\phi$ case.

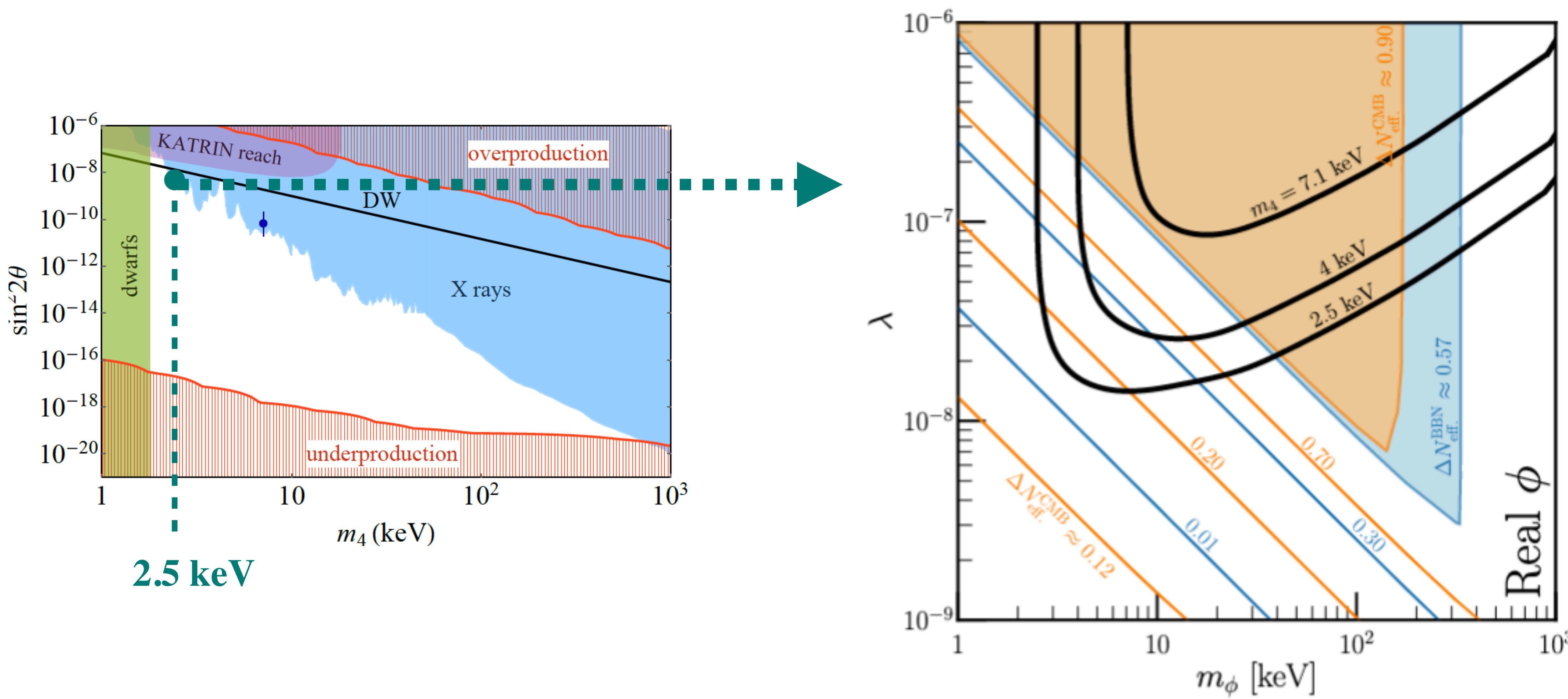
The DM is produced when $\varphi$ is non-relativistic and of the same order as the DM mass. Hence this is "colder than warm" DM.

$$L_{\rm fs} \propto L^0_{\rm fs} \times (v_{\rm prod}/c)$$

More conclusive work needed!

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

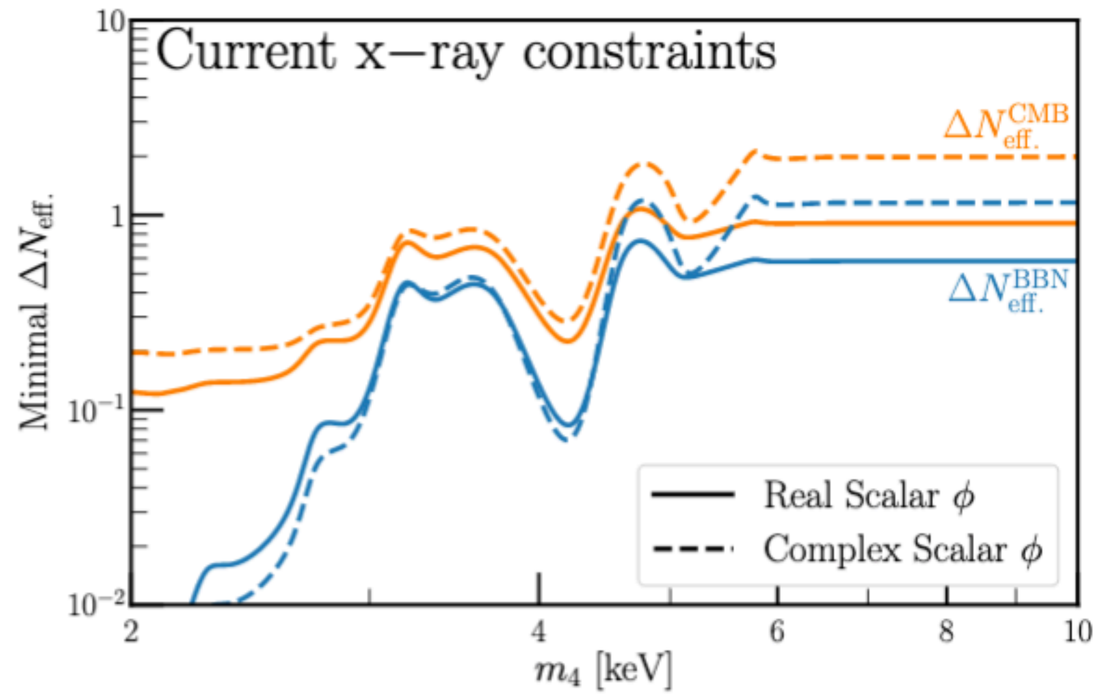
# The algorithm for deriving constraints




- 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 $N_{\rm eff}$




- Each point is for a maximum allowed mixing angle for a sterile neutrino mass.

- Corresponding minimum value of $\Delta N_{\rm eff}$ during BBN and CMB. For real scalar,

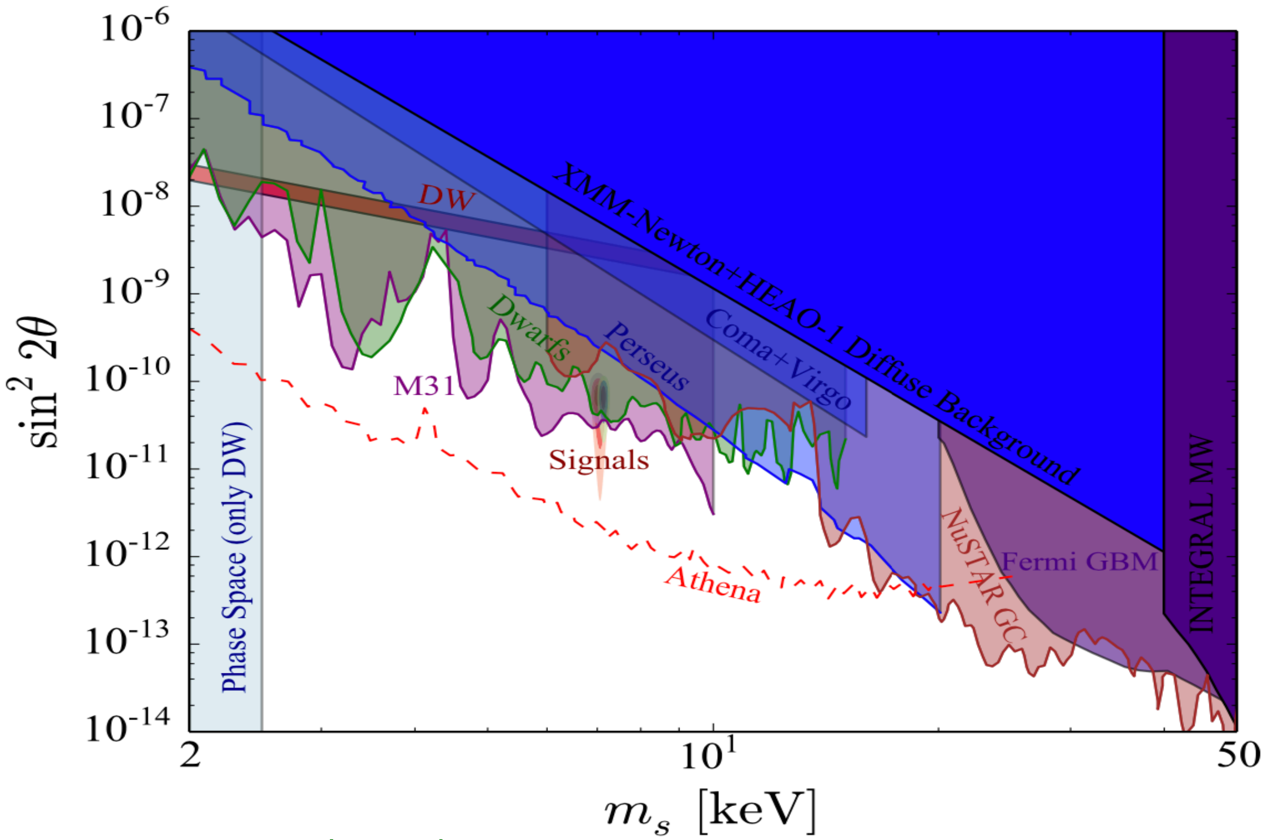
  $0 < \Delta N^{\rm eff}_{\rm BBN} < 0.57$

  $0.12 < \Delta N^{\rm eff}_{\rm CMB} < 0.9$

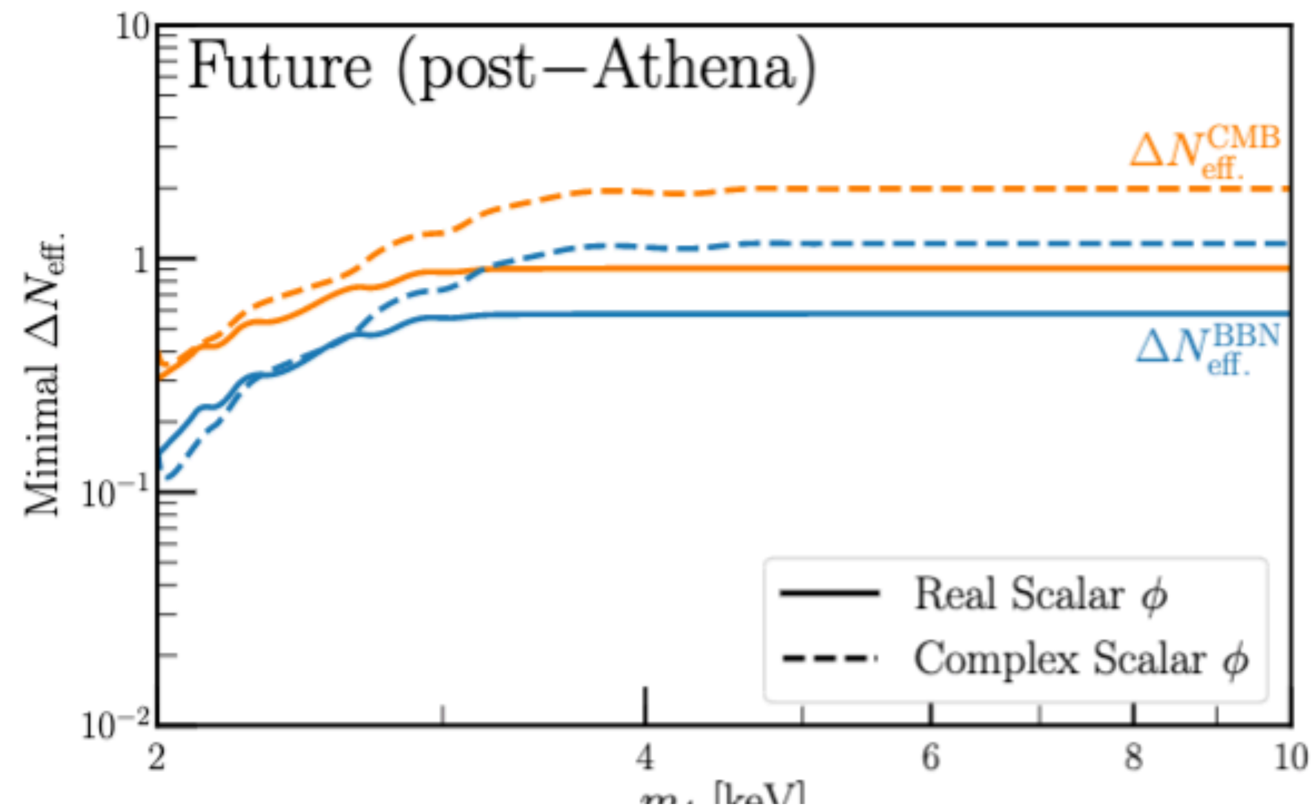
- This can put additional constraints from future cosmology surveys, like CMB-S4.

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

# Constraints from $N_{\text{eff}}$



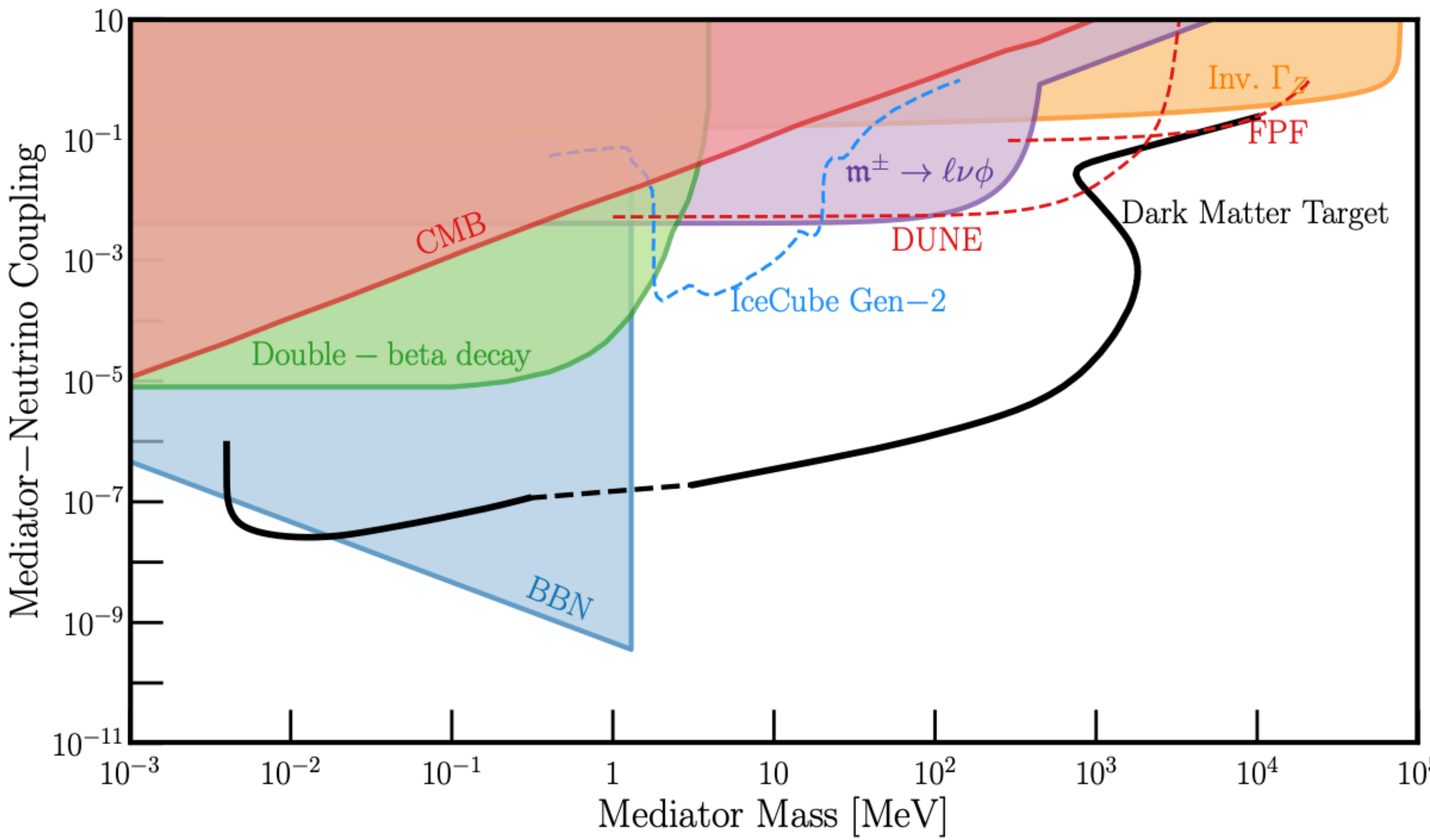

Abazajian (2017)




Stronger constraints from future surveys like Athena.

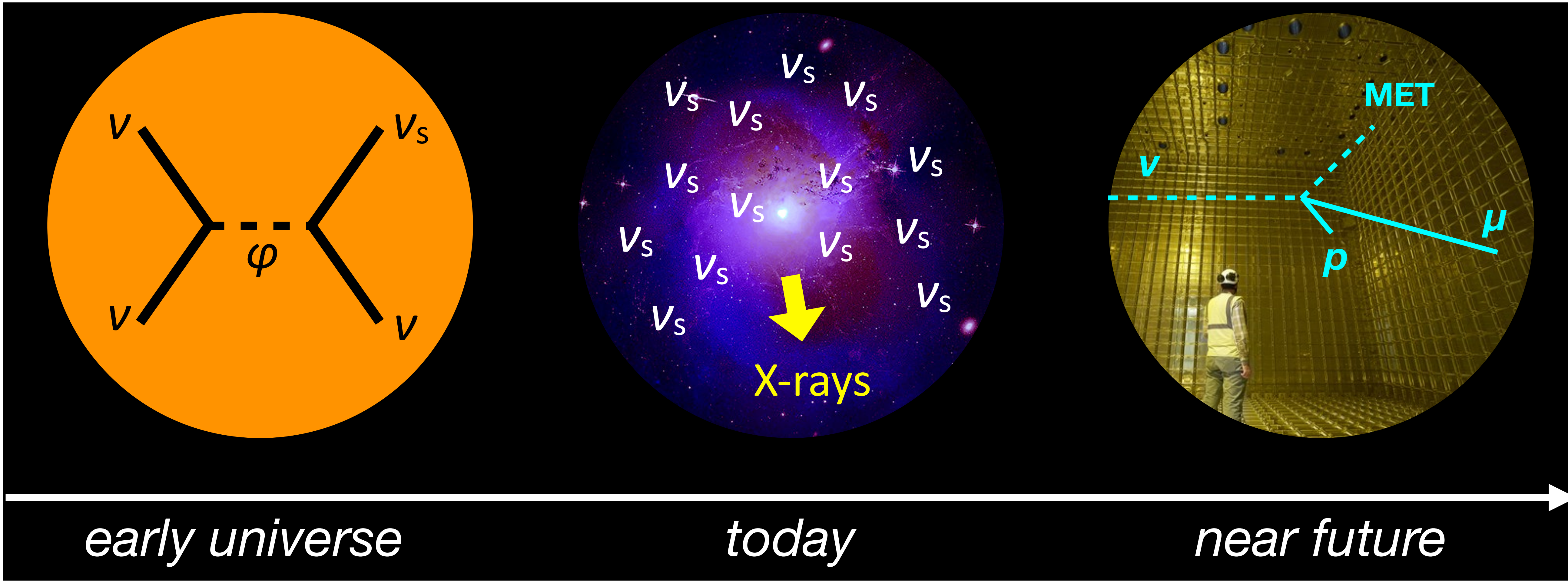
Kelly, **MS** and Zhang, PRL 2021

# Big Picture




Neutrino self-interactions, SNOWMASS 2021

# Summary




# 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 $\mp 1$, respectively. The most general renormalizable Lagrangian includes

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

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

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

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 $\alpha$ and $\beta$, $\lambda_T$ are scalar couplings between the triplet, the Higgs field and the *LeNCS* $\phi$, 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

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

Berryman, de Gouvêa, Kelly and Zhang PRD 2018

# Athena bounds

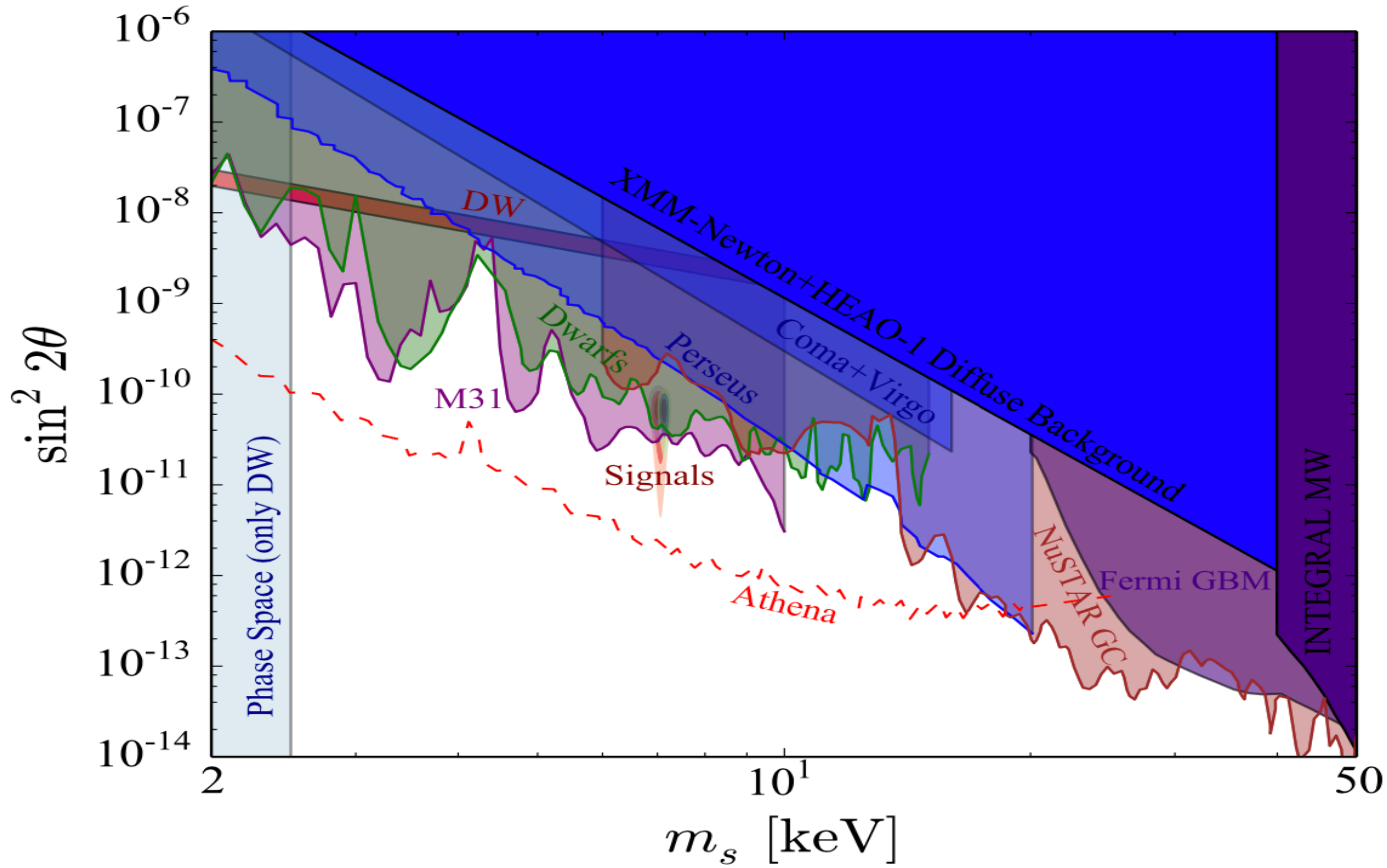
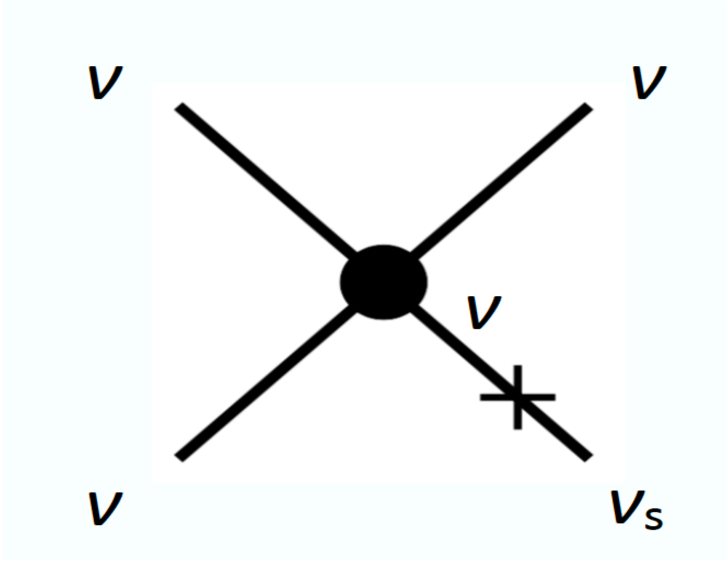
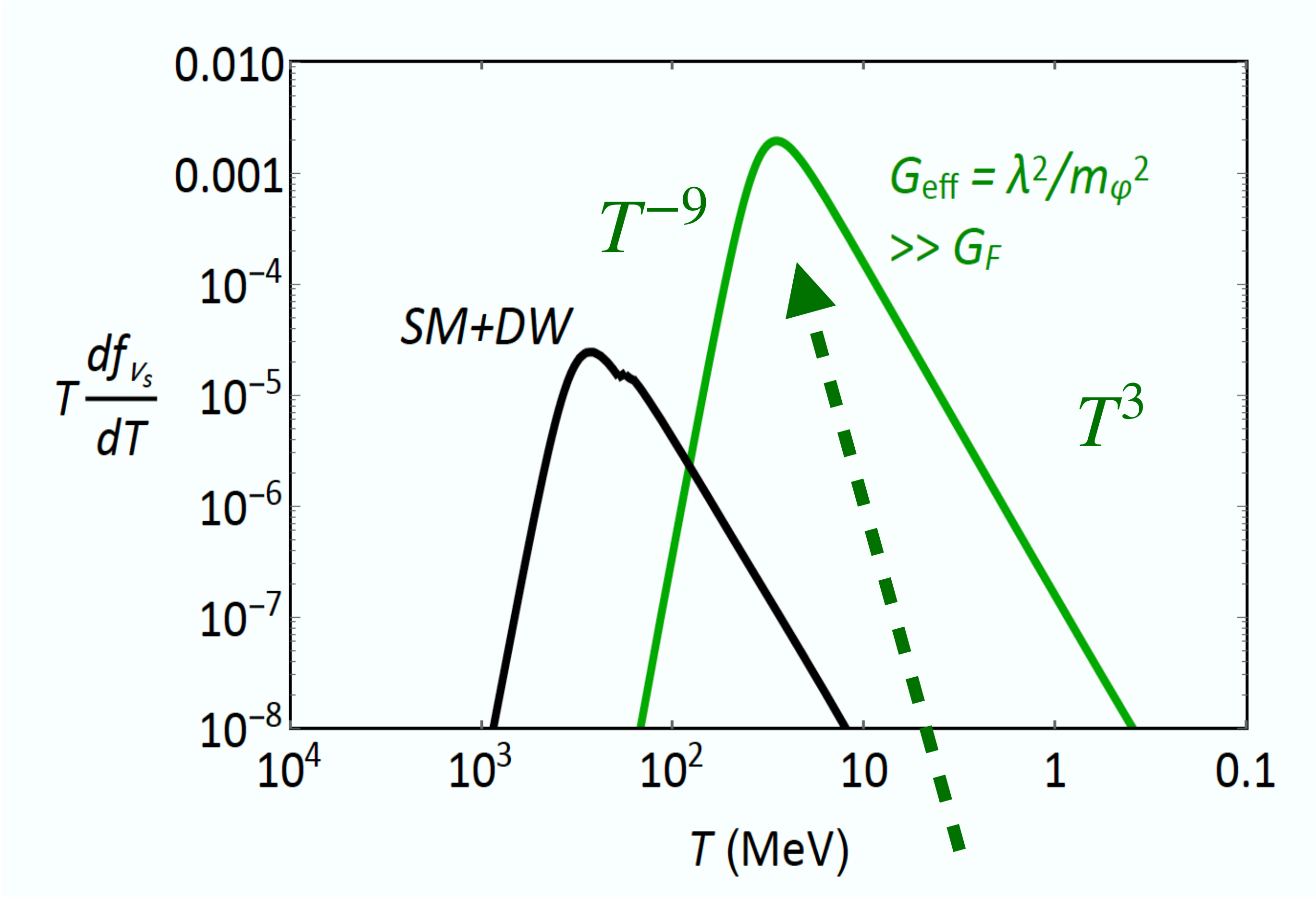



Figure 6: The full parameter space for sterile neutrino dark matter, when it comprises all of the dark matter, is shown. Among the most stringent constraints at low energies and masses are constraints from X-ray observations M31 Horiuchi et al. [134], as well as stacked dwarfs [204]. Also shown are constraints 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

$$m_\phi \gg T$$




- Similar to DW, except with a stronger interaction.

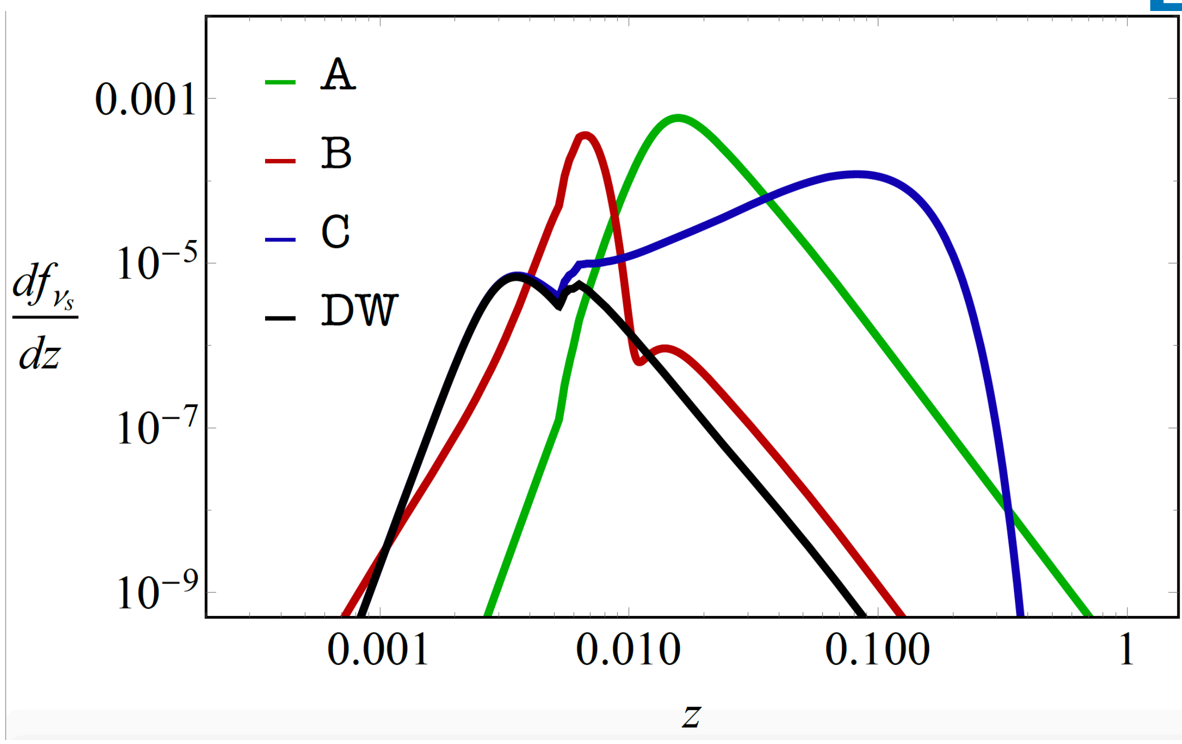
$$\Gamma_a \sim \frac{\lambda_\varphi^4}{m_\varphi^4} E T^4, \qquad V \sim -\frac{\lambda_\varphi^2}{m_\varphi^4} E T^4$$

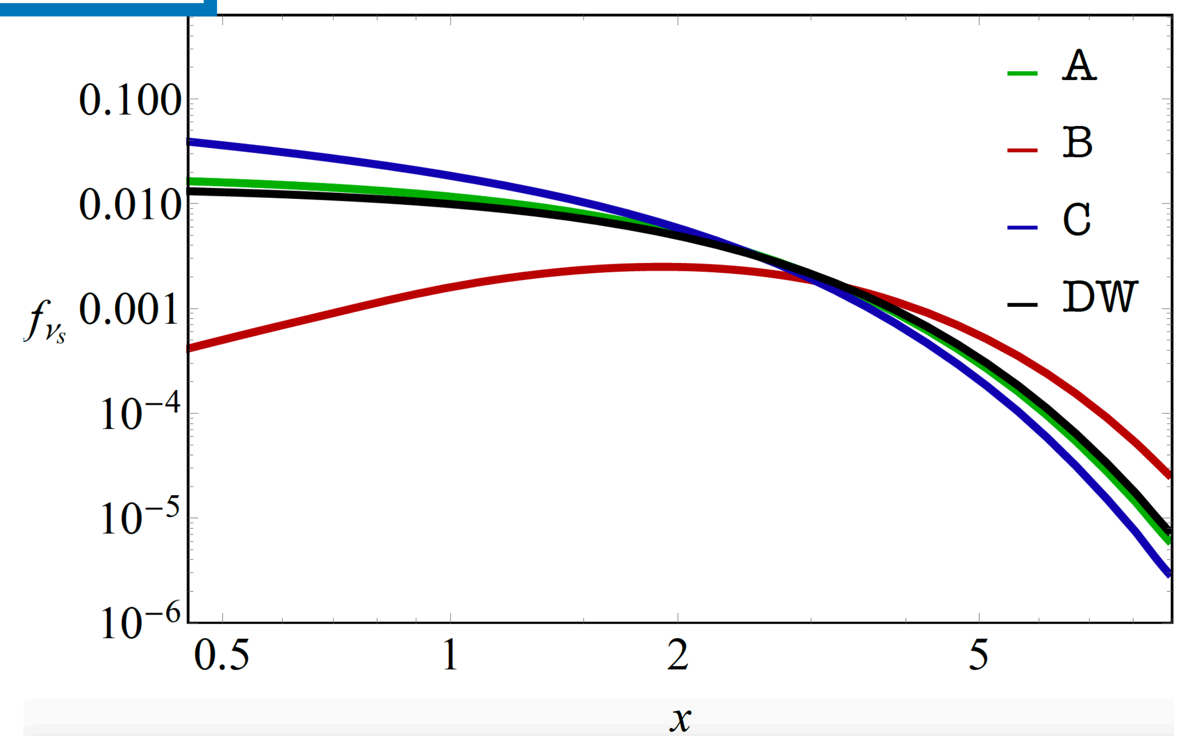
Production peaks at a lower temperature

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

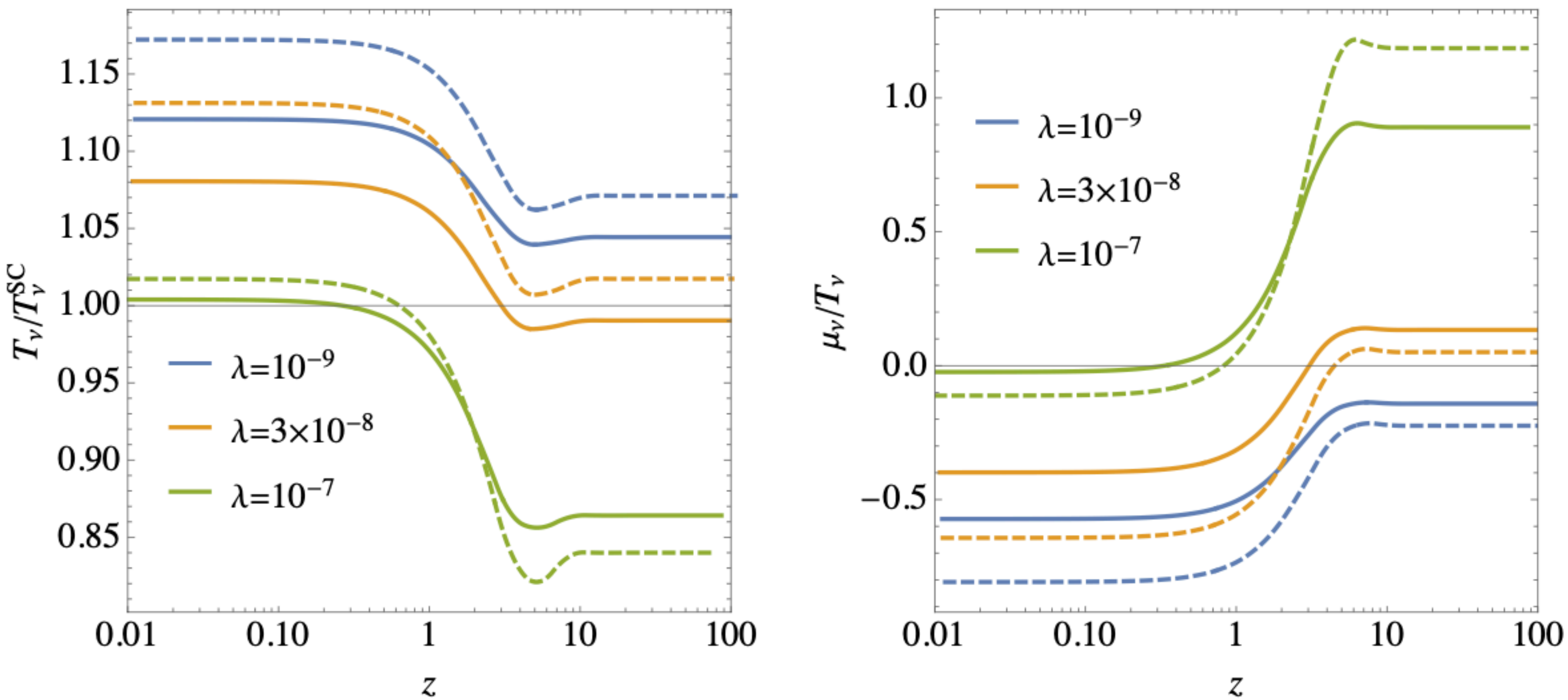
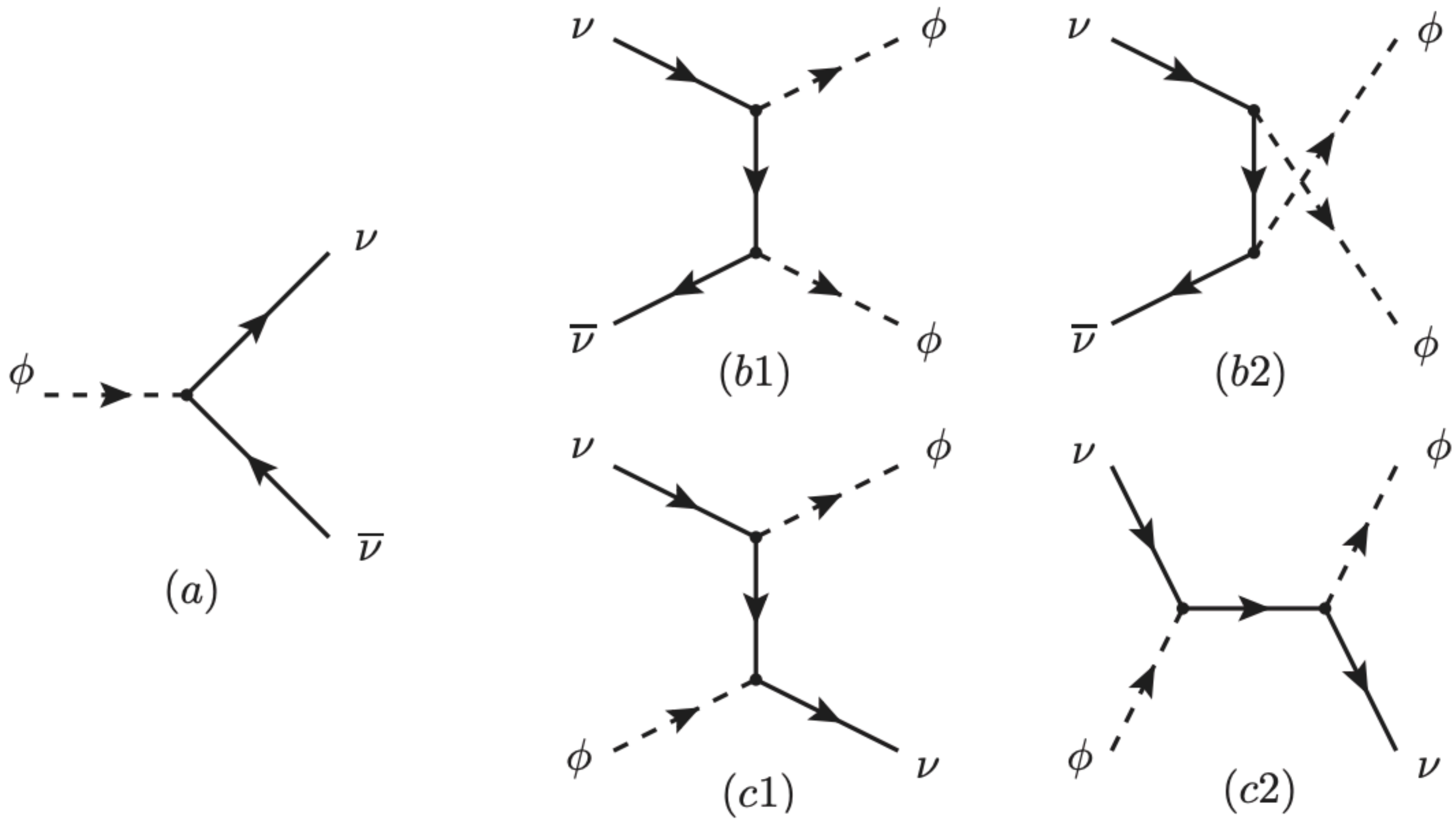



FIG. 4. Evolution of ratios $T_\nu(z)/T_\nu^{\rm SC}(z)$ and $\mu_\nu(z)/T_\nu(z)$ as functions of $z$ for three values of $\lambda_\phi$ and holding $m_\phi = 5\,\mathrm{keV}$ fixed. Solid (dashed) curves correspond to real (complex) scalar $\phi$ case.

# Contribution to extra radiation at BBN



# 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:

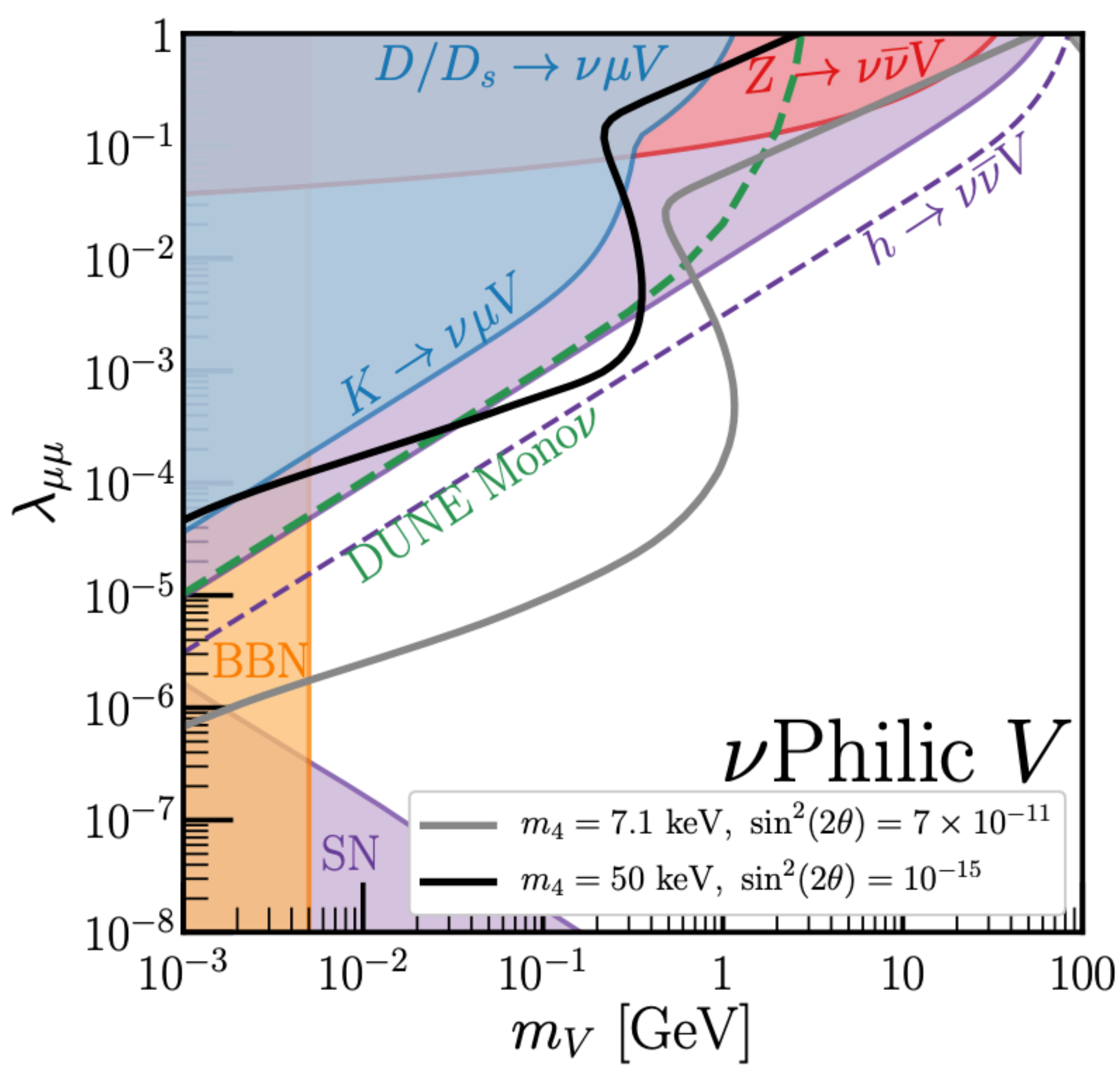
1. Neutrinophilic vector model.
2. $U(1)_{L_\mu - L_\tau}$
3. $U(1)_{B-L}$

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