Opening the chamber of secrets to revive sterile neutrino dark matter

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HIDDeN & ASYMMETRY Webinar

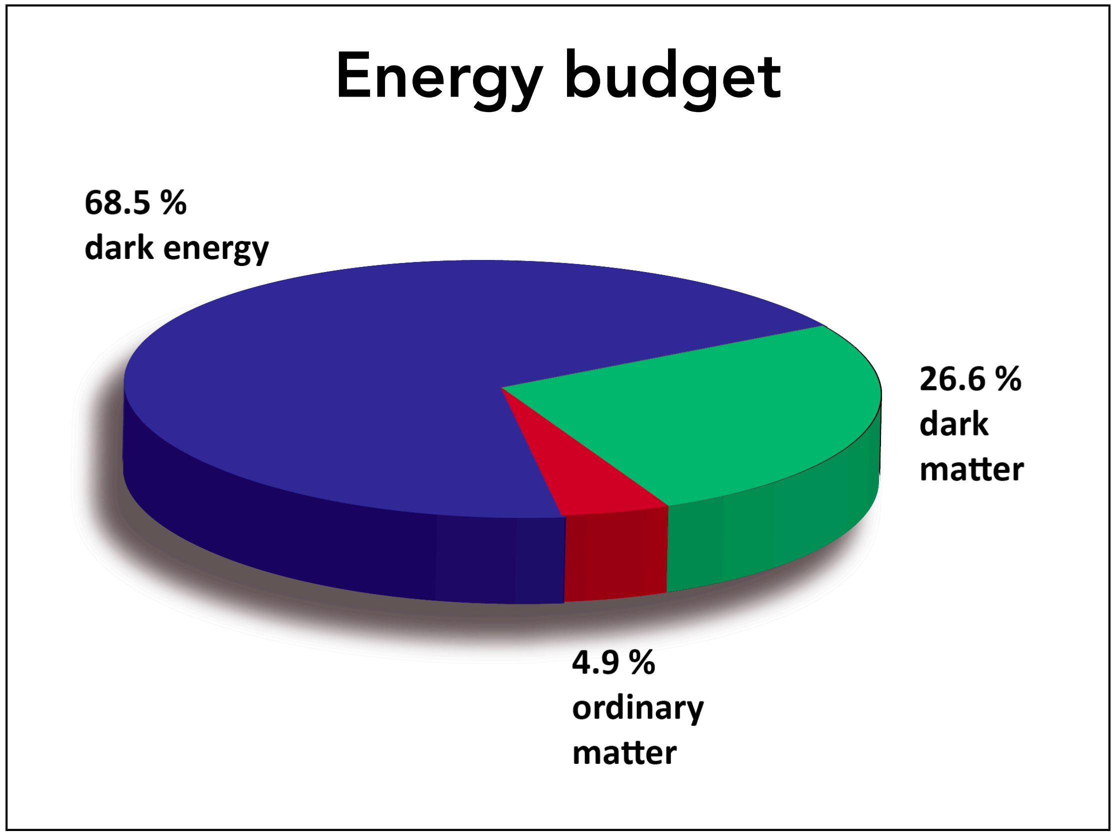
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature

The Standard Model of Particle Physics

QUARKS	**UP** mass 2,3 MeV/c^2 charge ⅔ spin ½ u	**CHARM** 1,275 GeV/c^2 ⅔ ½ c	**TOP** 173,07 GeV/c^2 ⅔ ½ t	**GLUON** 0 0 1 g	**HIGGS BOSON** 126 GeV/c^2 0 0 H
QUARKS	**DOWN** 4,8 MeV/c^2 -⅓ ½ d	**STRANGE** 95 MeV/c^2 -⅓ ½ s	**BOTTOM** 4,18 GeV/c^2 -⅓ ½ b	**PHOTON** 0 0 1 γ	
LEPTONS	**ELECTRON** 0,511 MeV/c^2 -1 ½ e	**MUON** 105,7 MeV/c^2 -1 ½ μ	**TAU** 1,777 GeV/c^2 -1 ½ τ	**Z BOSON** 91,2 GeV/c^2 0 1 Z	
LEPTONS	**ELECTRON NEUTRINO** <2,2 eV/c^2 0 ½ ν_e	**MUON NEUTRINO** <0,17 MeV/c^2 0 ½ ν_μ	**TAU NEUTRINO** <15,5 MeV/c^2 0 ½ ν_τ	**W BOSON** 80,4 GeV/c^2 ±1 1 W	

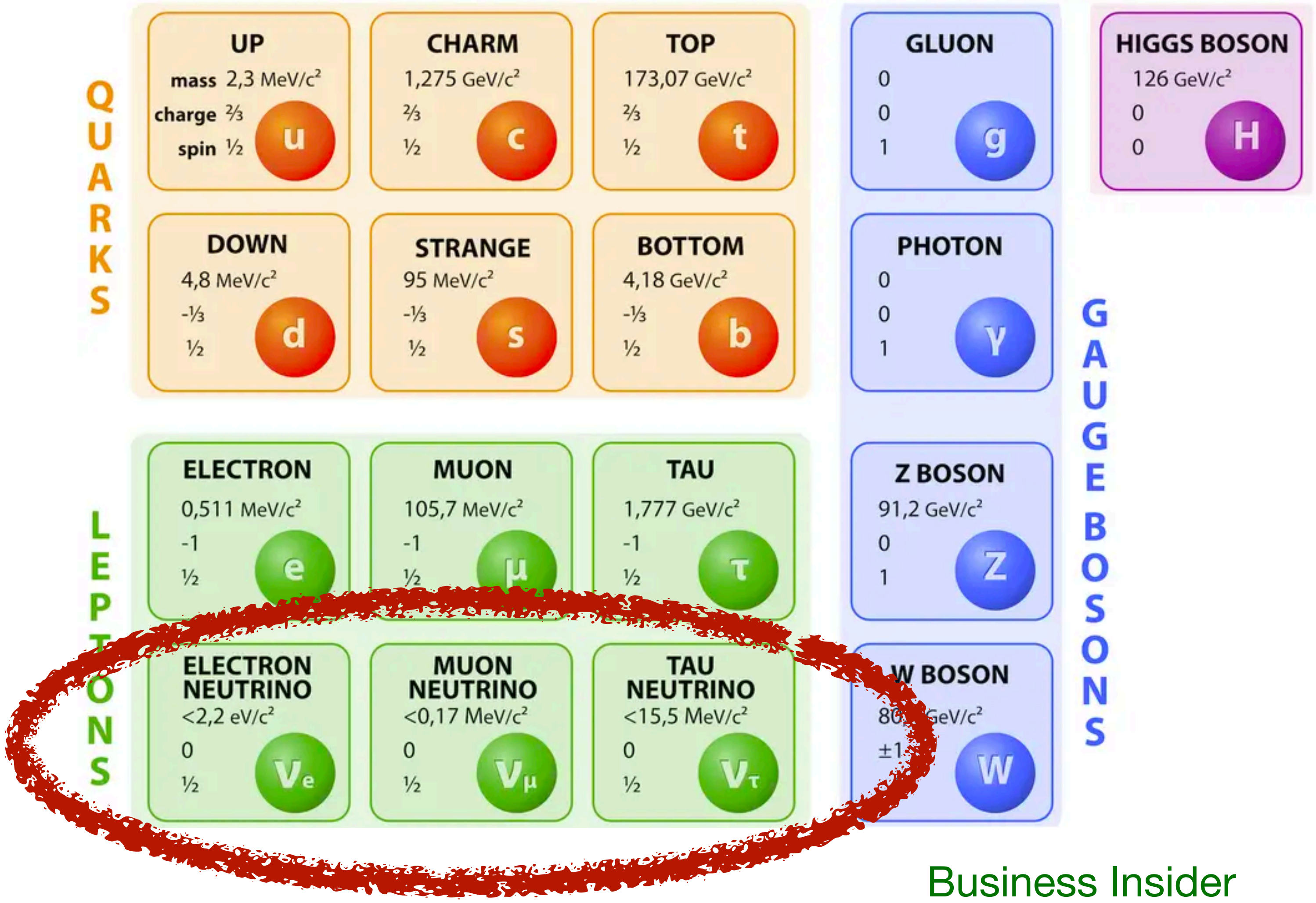


Business Insider

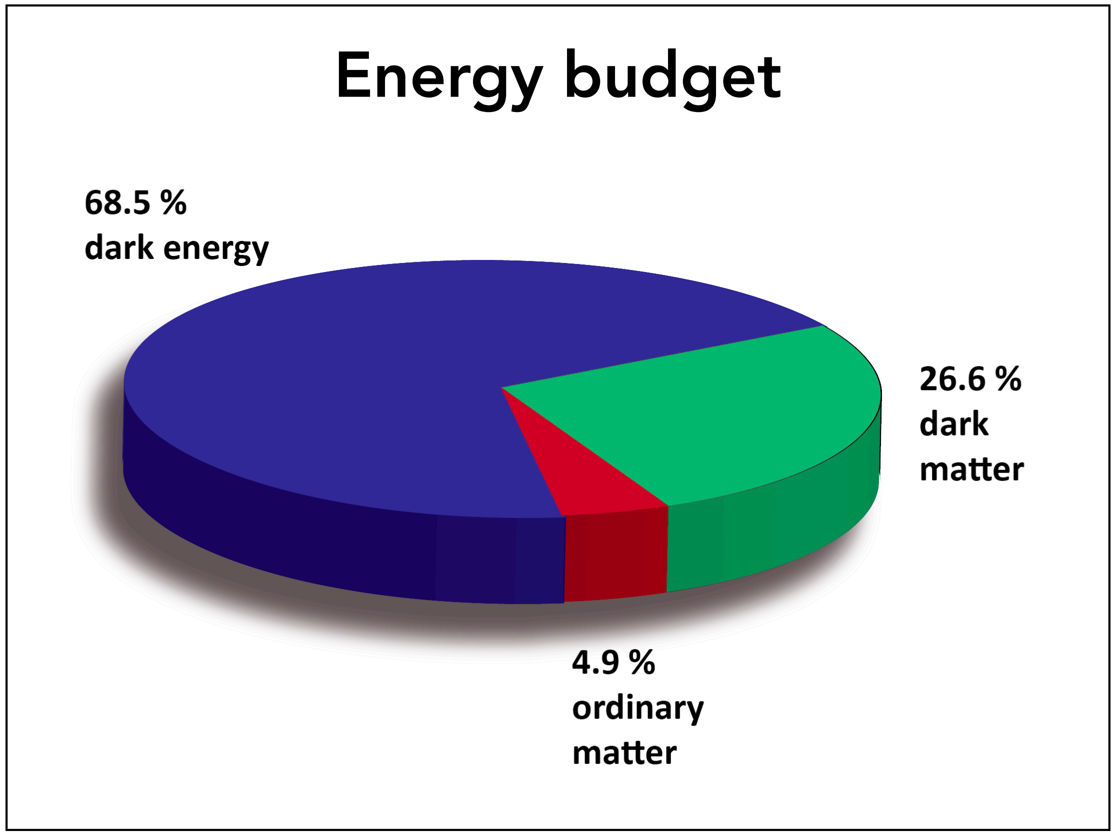
Major unanswered questions:

- Why are neutrinos massive?
- What composes the 95% of the energy budget of the Universe?
- Why is our Universe matter-antimatter asymmetric?

The Standard Model of Particle Physics



Business Insider



Major unanswered questions:

- Why are neutrinos massive?
- What composes the 95% of the energy budget of the Universe?
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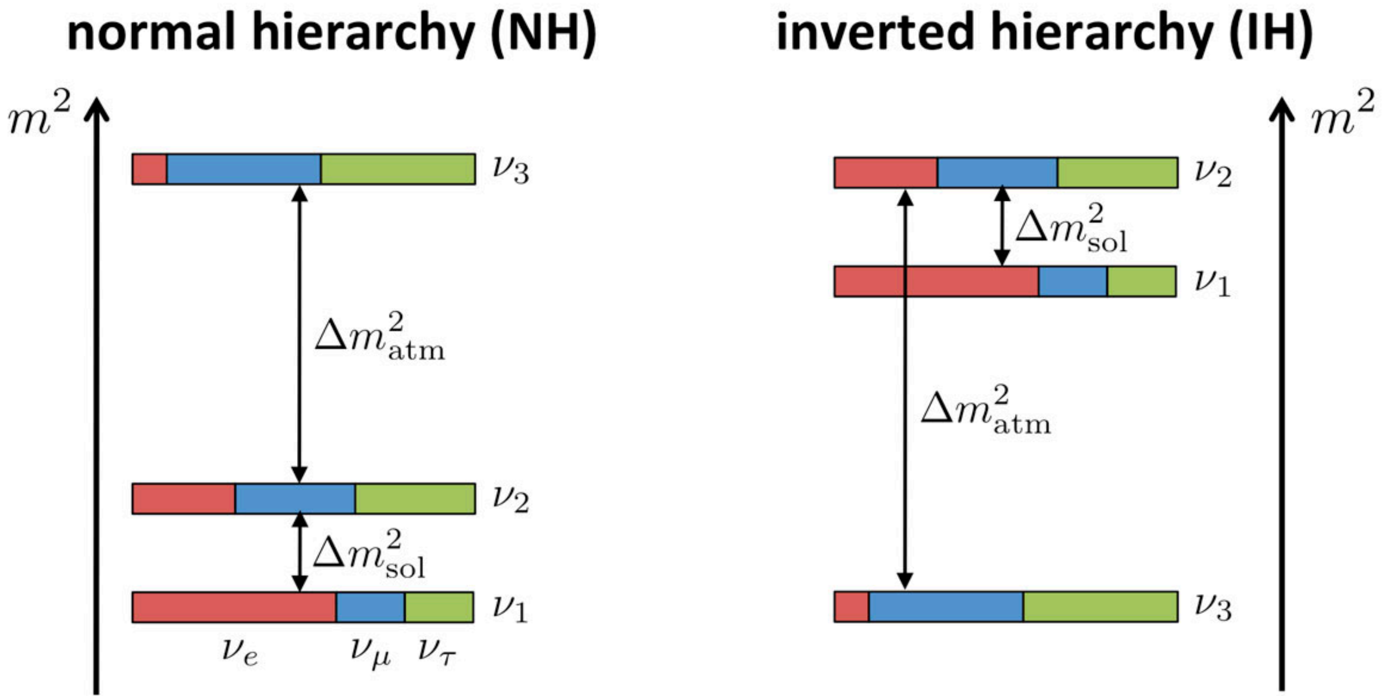
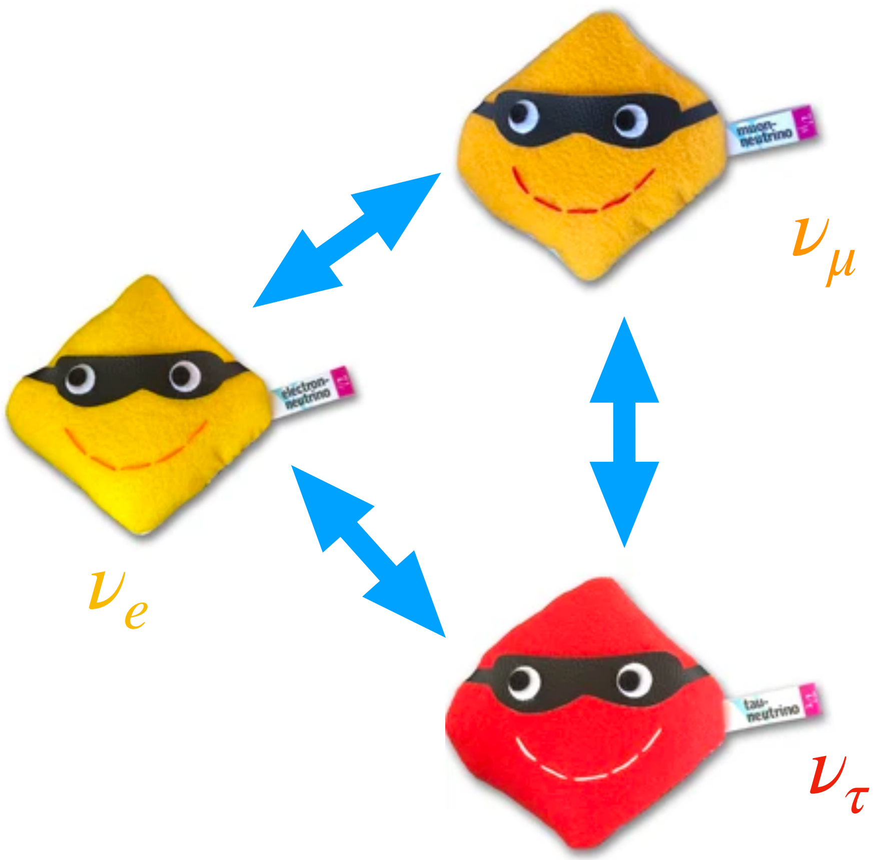
What we know so far...

- Neutrinos are massless within the SM.
- Nature wants neutrinos to be massive.



Mass ordering yet unknown

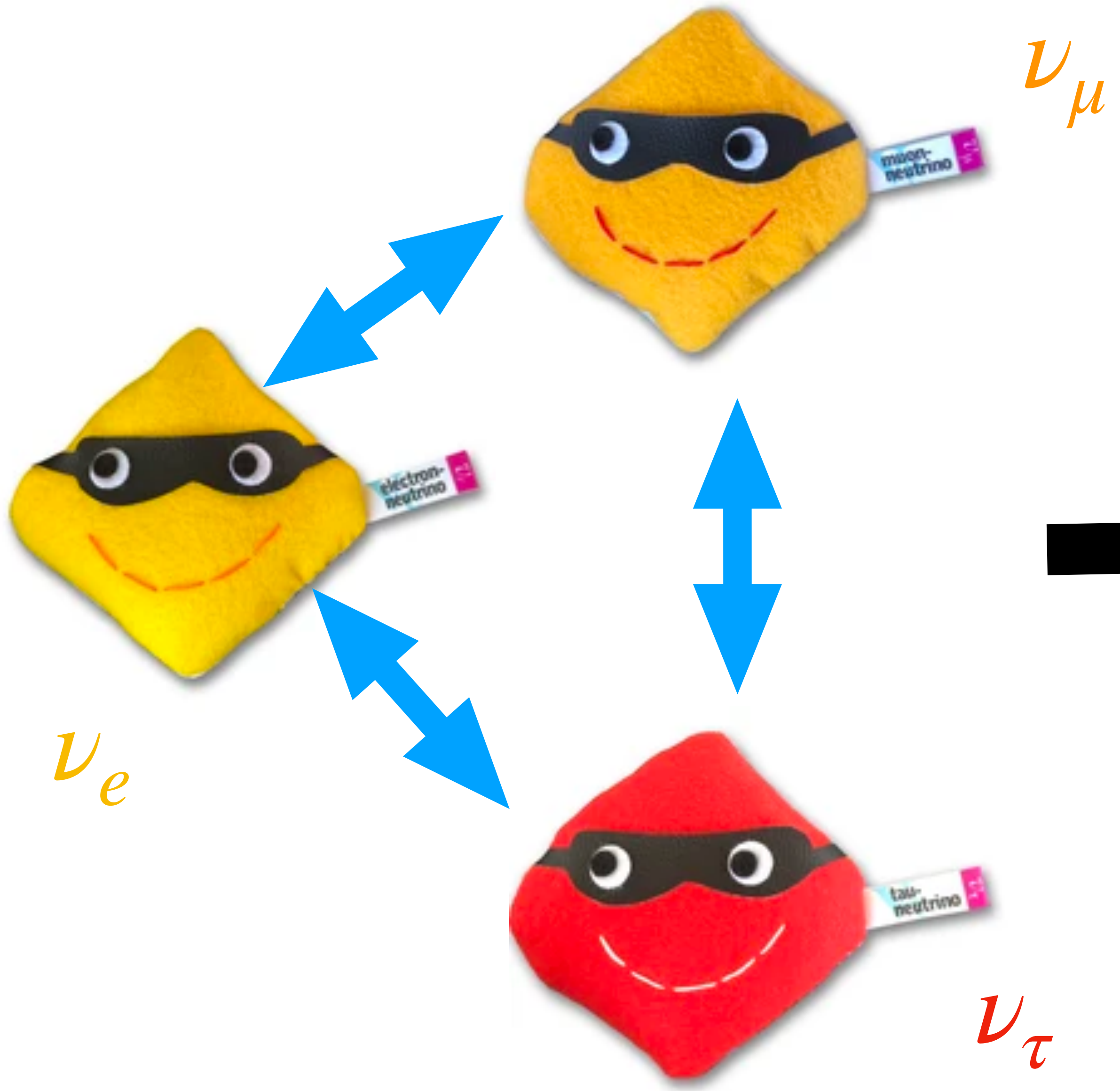
Credit: The Particle Zoo



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

The sterile neutrino - the Riddler

Can there be more neutrinos?



+

ν_s

Are there more of these ?

Three directions:

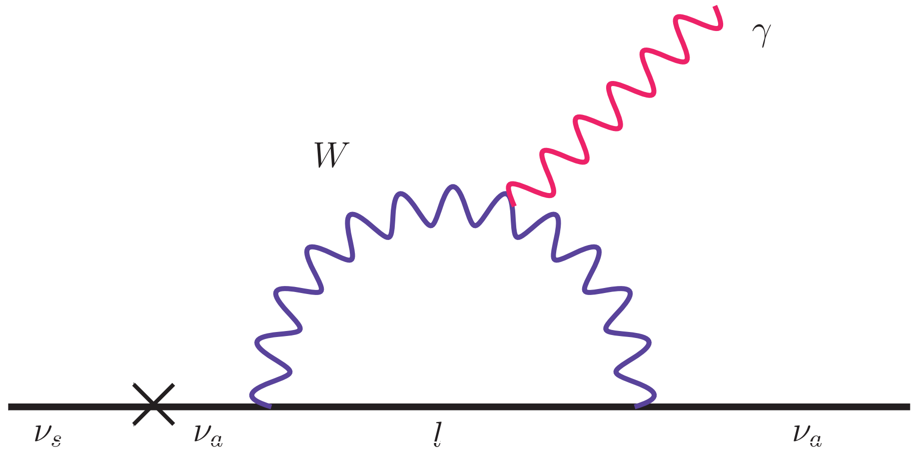
1. Neutrino mass.
2. Short baseline anomalies. (eV masses)
3. Cosmology. (mostly keV onwards)

Why do we like sterile neutrinos?

- Sterile neutrinos by definition have no gauge interactions within the SM.
- 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



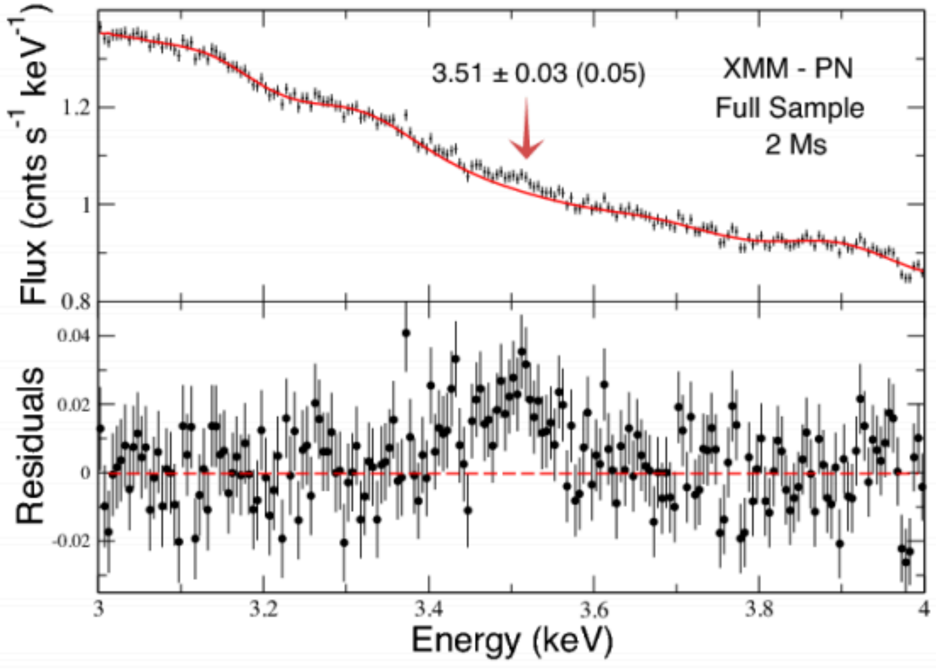
- Extra keV mass eigenstate $\nu_4 = \cos\theta\,\nu_s + \sin\theta\,\nu_a$

- 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 $E_\gamma = m_4/2$.

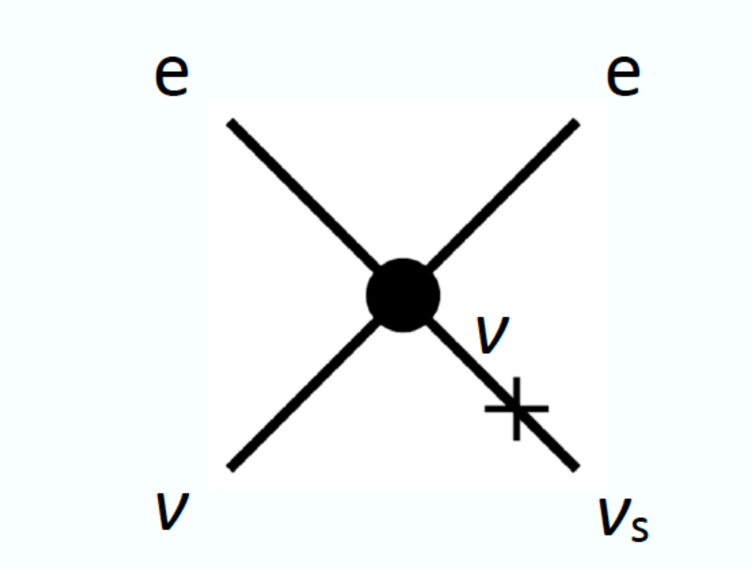
  Hints of a line at $E = 3.55\,\mathrm{keV}$? Sterile neutrino at 7.1 keV?

  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.

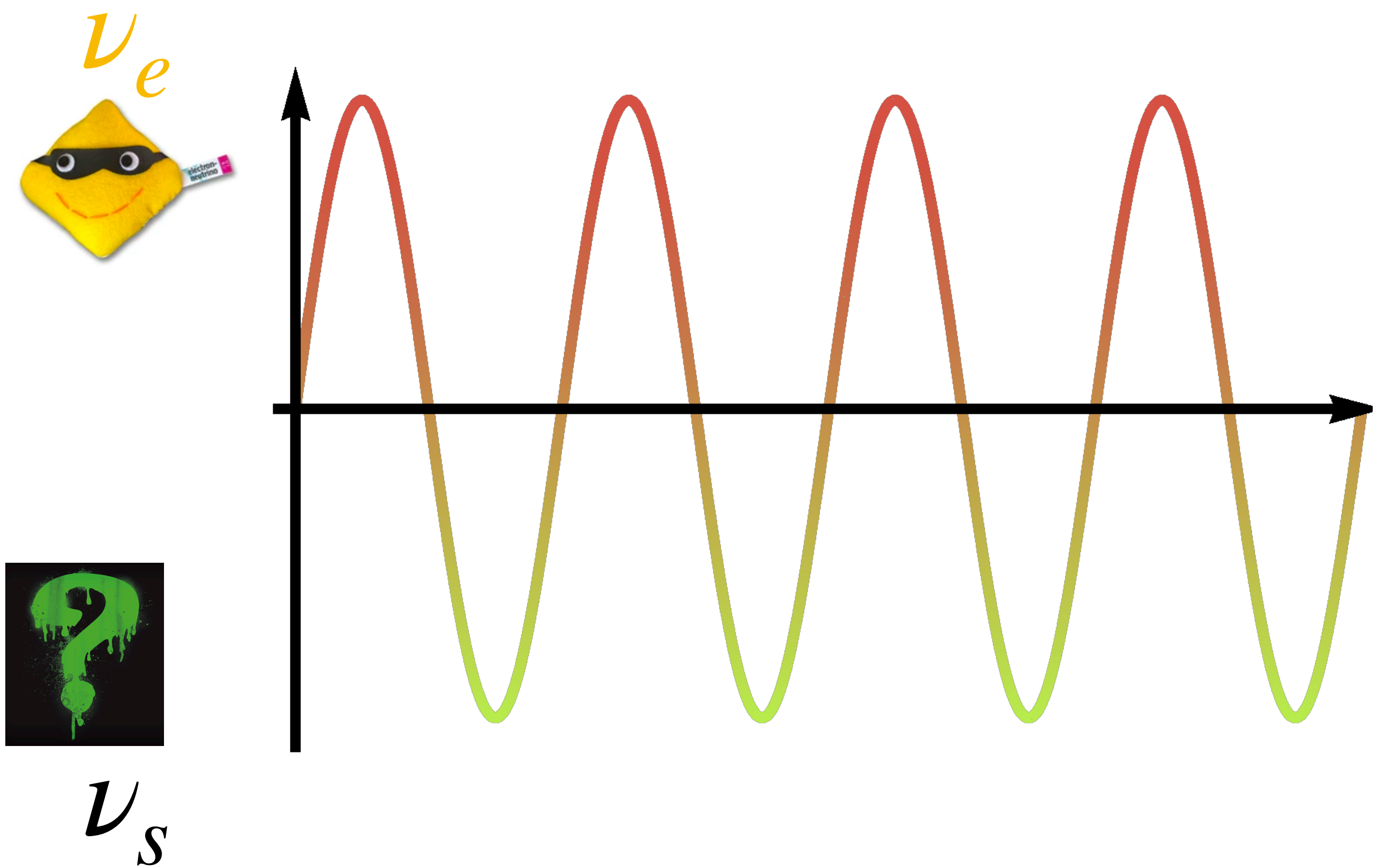
- But how do we produce these neutrinos?

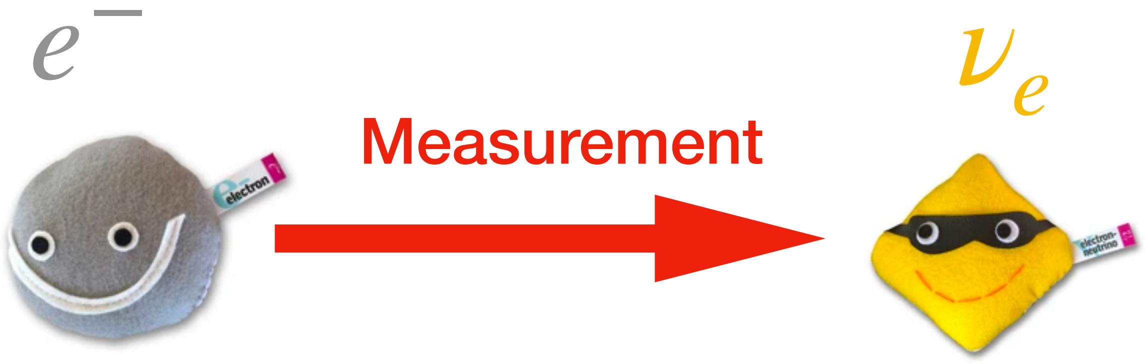
Production: the Dodelson-Widrow mechanism

- The 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

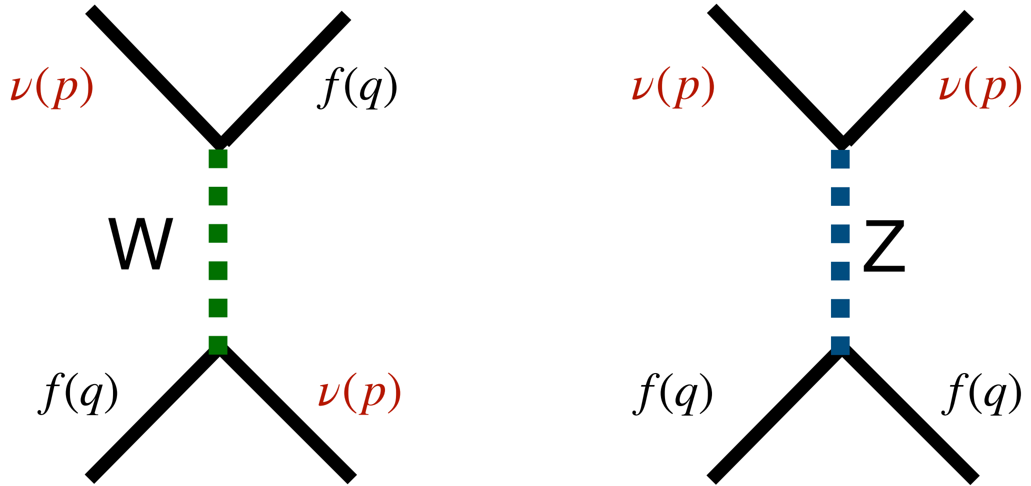
$\Delta = m_s^2/2E$

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

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

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

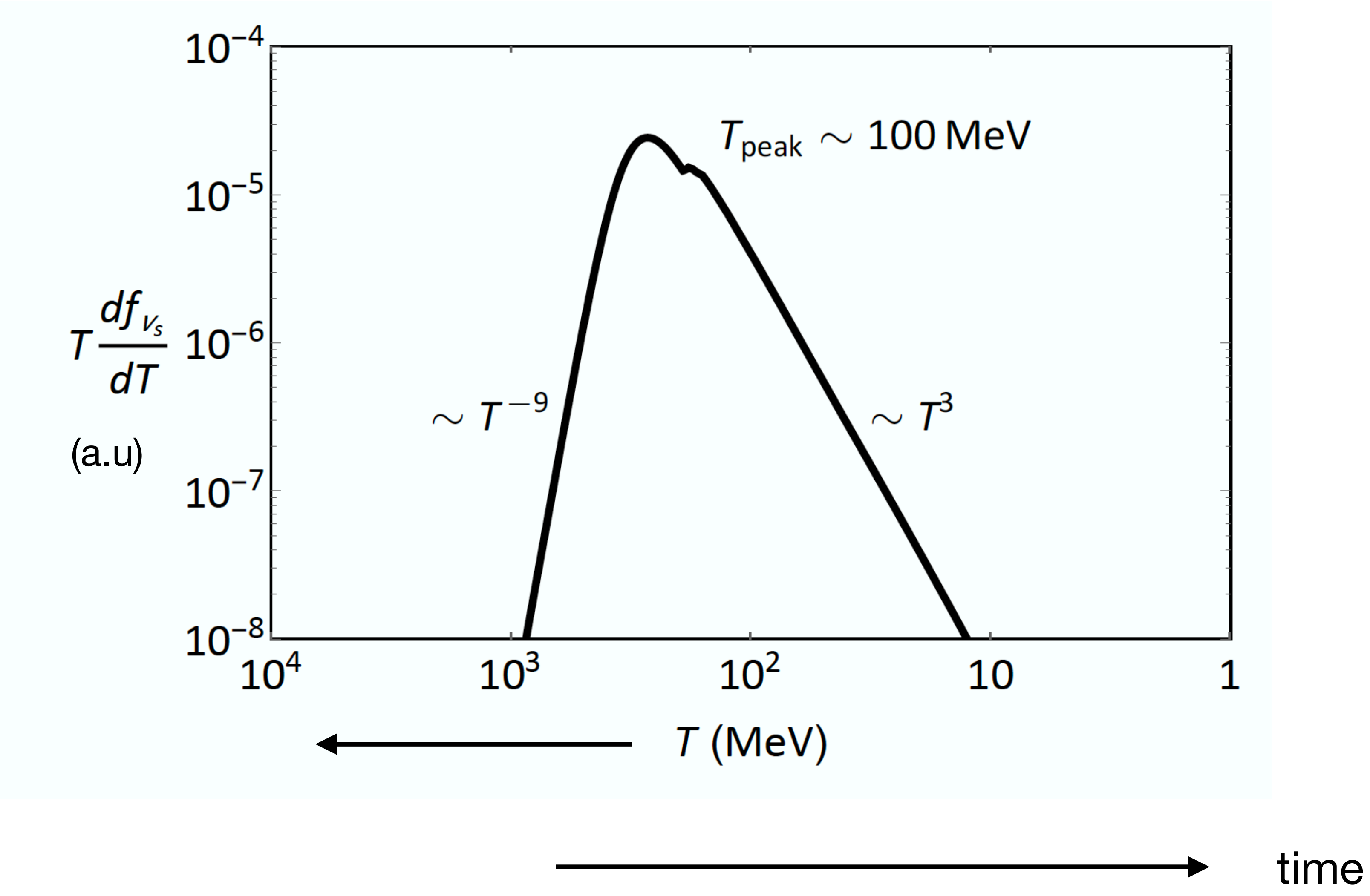
SM

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

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

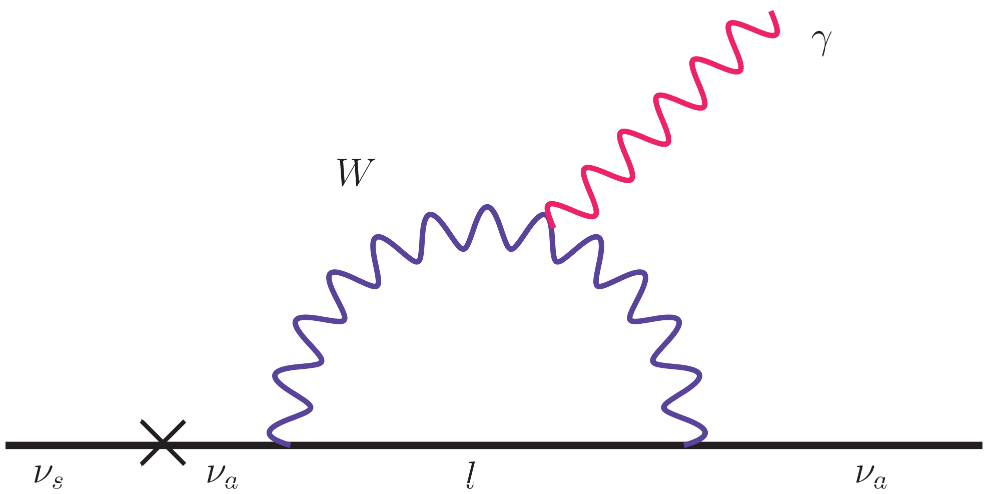
- Case 2: When $\Gamma \ll \Delta$, $T\frac{df}{dT} \sim \frac{\Gamma}{H} \propto T^3$

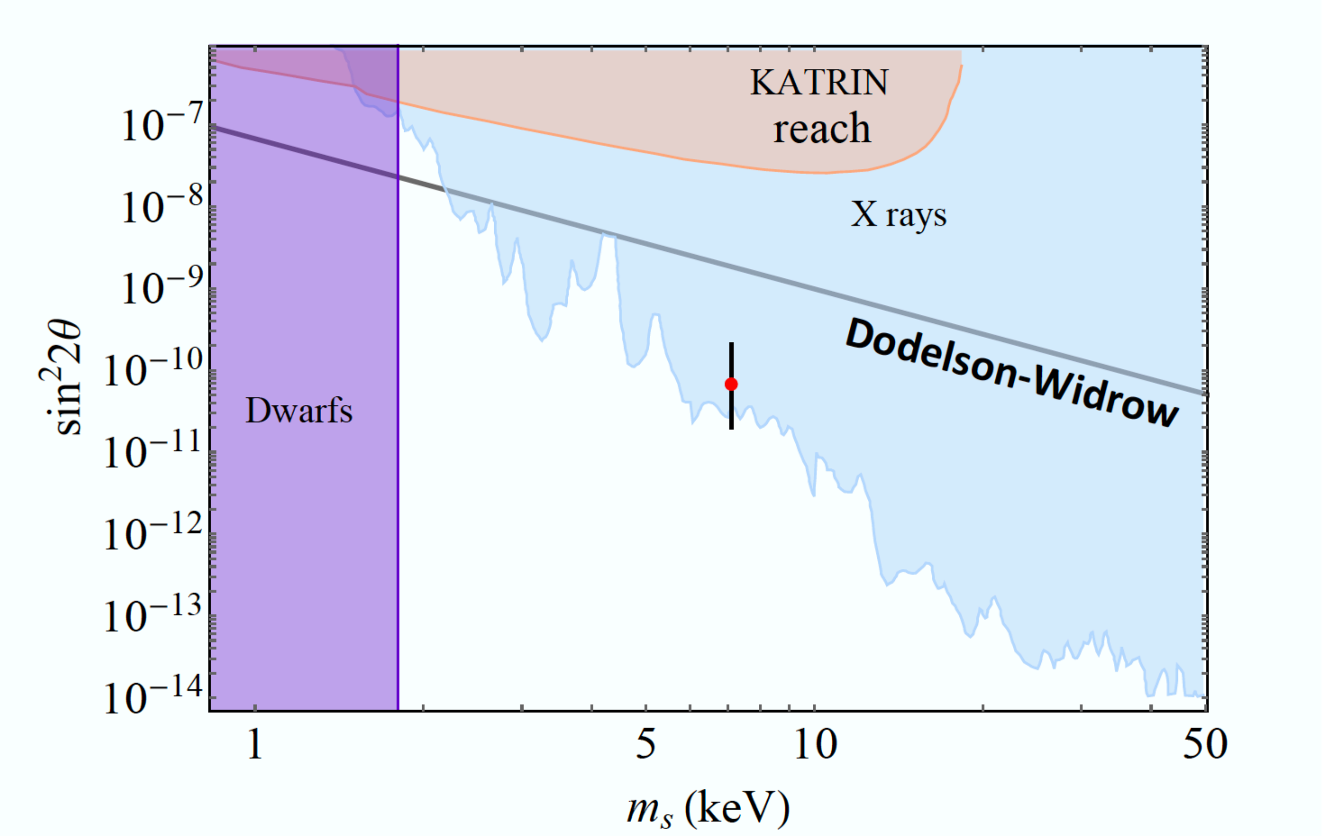
The Dodelson-Widrow mechanism… contd



- 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



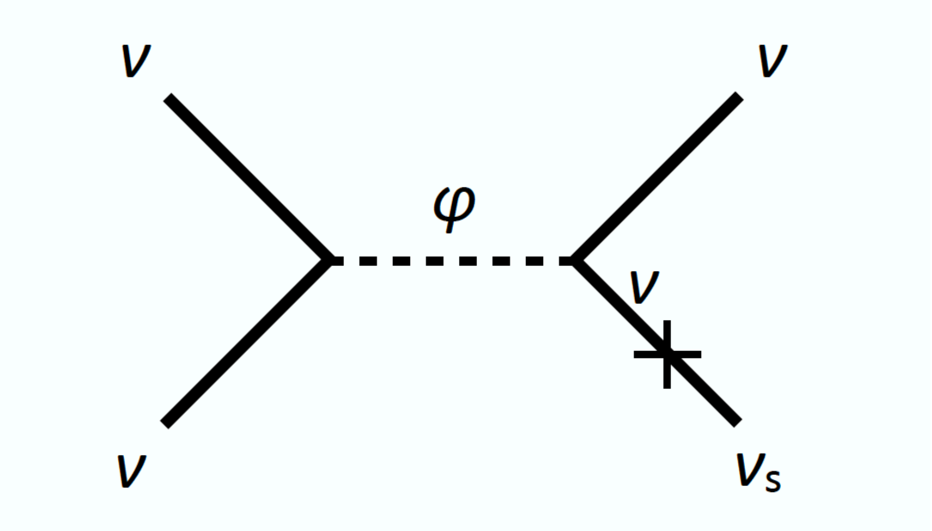


- Ruled out by X-ray bounds and phase-space considerations (Tremaine-Gunn, galaxy counts, Lyman alpha, strong lensing, etc.).
- A finite lepton asymmetry (Shi-Fuller Mechanism) can help. Required lepton asymmetry difficult to constrain. Shi and Fuller, PRL 1999, Fuller, Abazajian and Patel PRD 2001
- Can we open up parameter space without introducing a lepton asymmetry?

Secret neutrino self-interactions

Secret neutrino self-interactions

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



- Model building aspect?
  Consider

$$\mathscr{L}_\nu = \frac{y}{\Lambda^2}(LH)^2\varphi^* \xrightarrow{\text{EWSB}} \lambda_\varphi \nu_a \nu_a \varphi^*$$

  φ has lepton number.

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

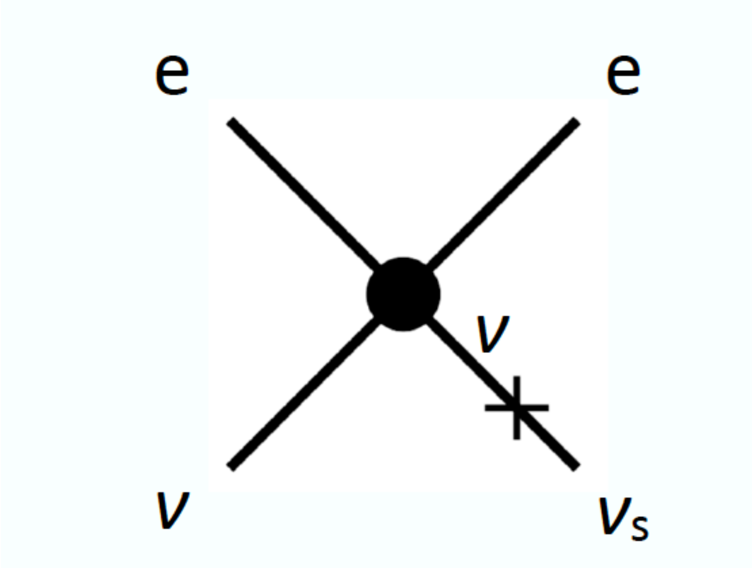
$$\boxed{T\frac{\partial}{\partial T} f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H} \ \langle P(\nu_a \rightarrow \nu_s)\rangle \ f_{\nu_a}}$$

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

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

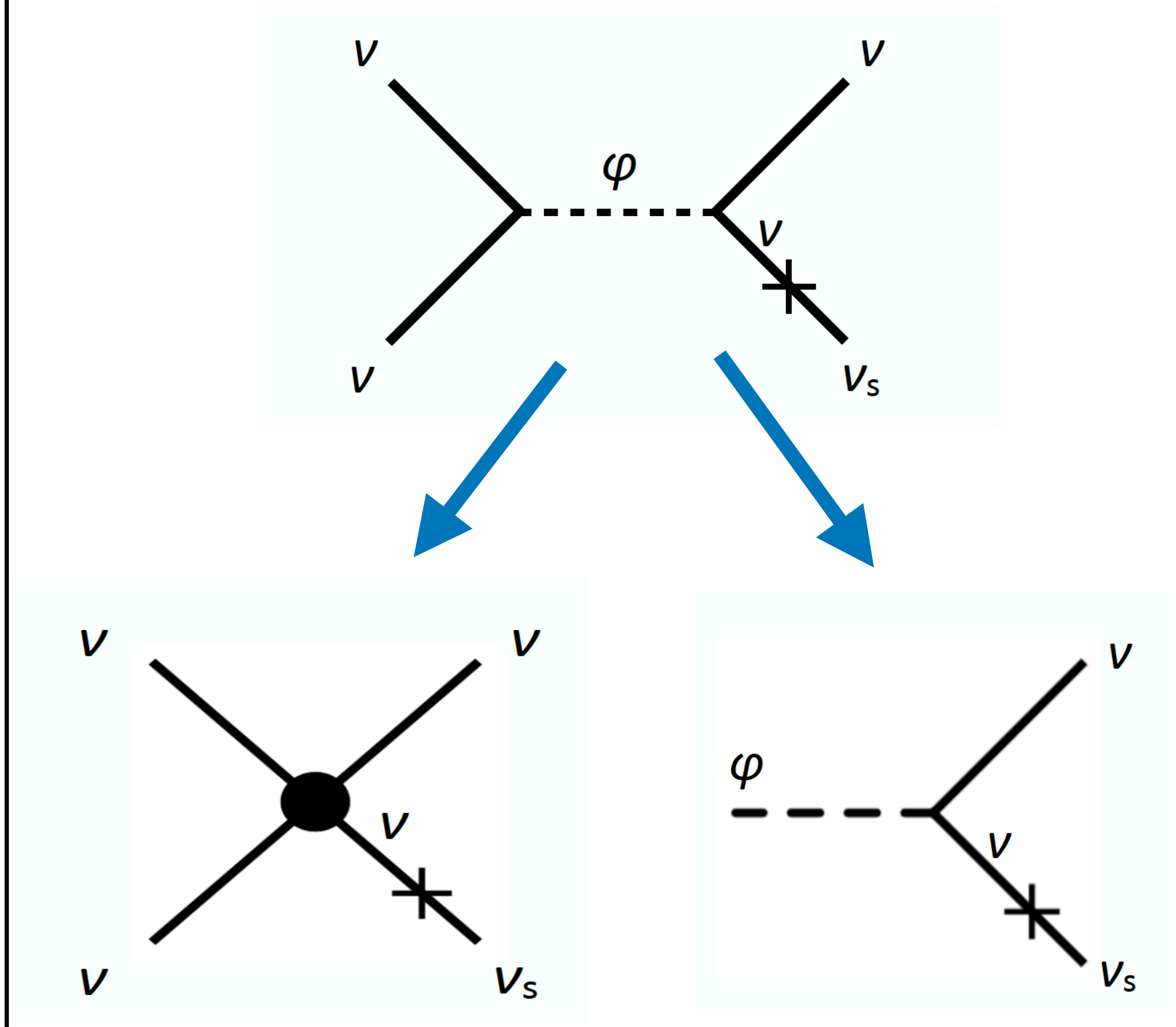
What changes in the DW mechanism?

S.M



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

S.M + Self-Interactions



$M_\varphi > T_{peak}$

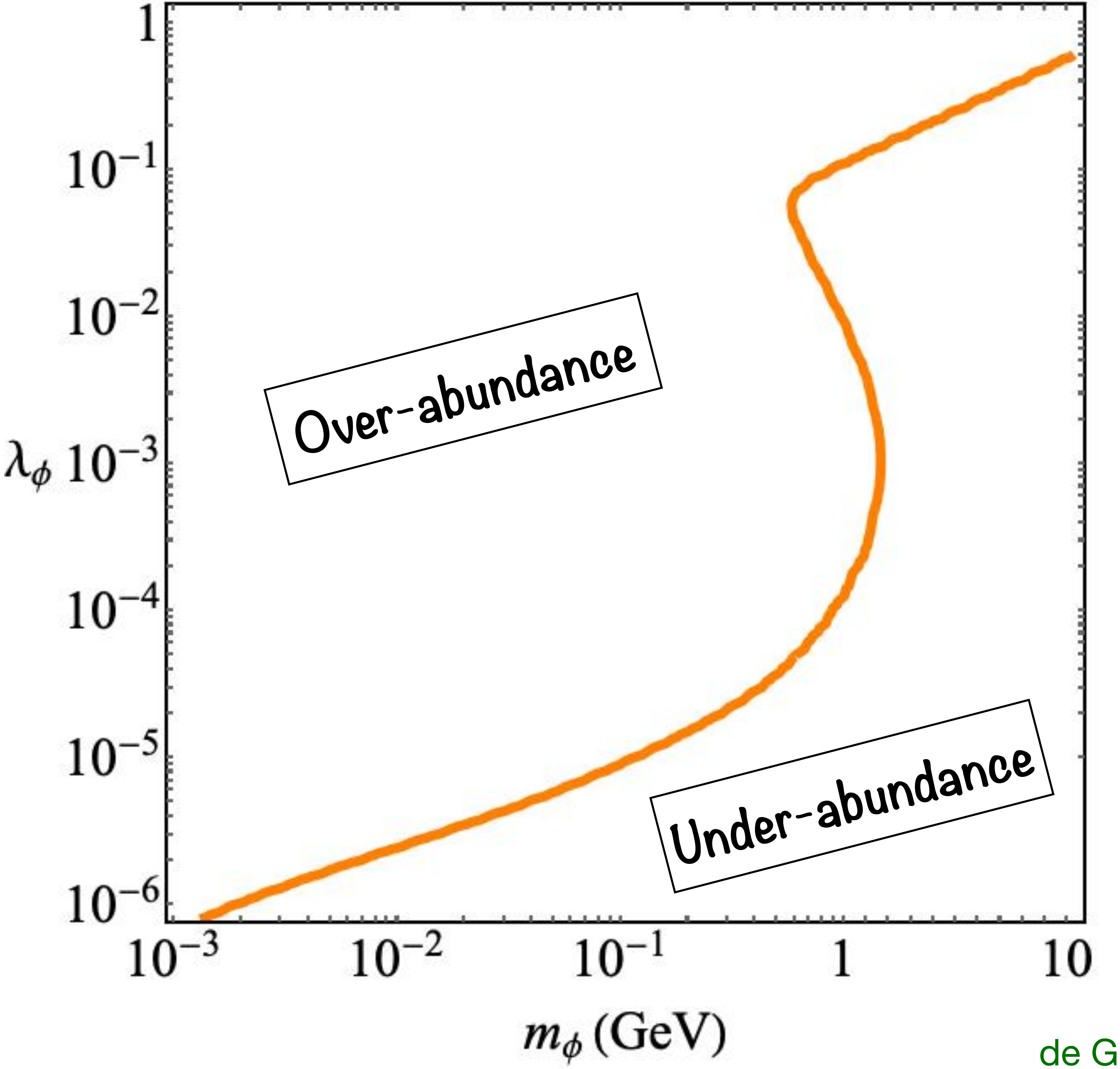
$M_\varphi \lesssim T_{peak}$

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

Numerical estimates

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

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



Not a monotonic dependence! Why?

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

Numerical and analytical estimates

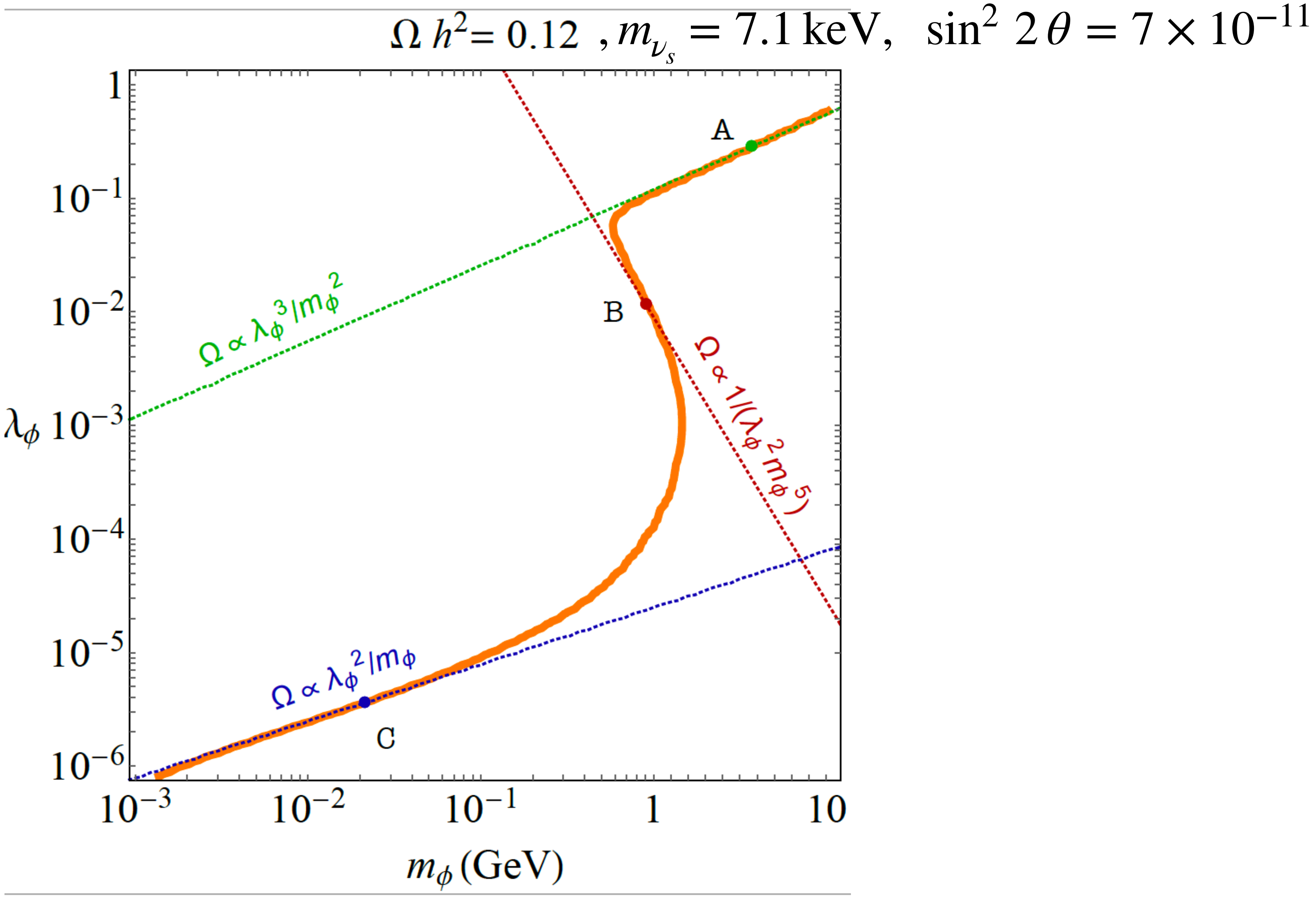
$$T\frac{\partial}{\partial T}f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H}\,\frac{1}{2}\,\frac{\Delta^2\sin^2 2\theta}{\Delta^2\sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta\cos 2\theta - V)^2}f_{\nu_a}$$

- 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 not suppressed.
3. t_φ: When $T = m_\varphi$, mediator cannot be produced on-shell for lower temperature

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

Explanation of Results

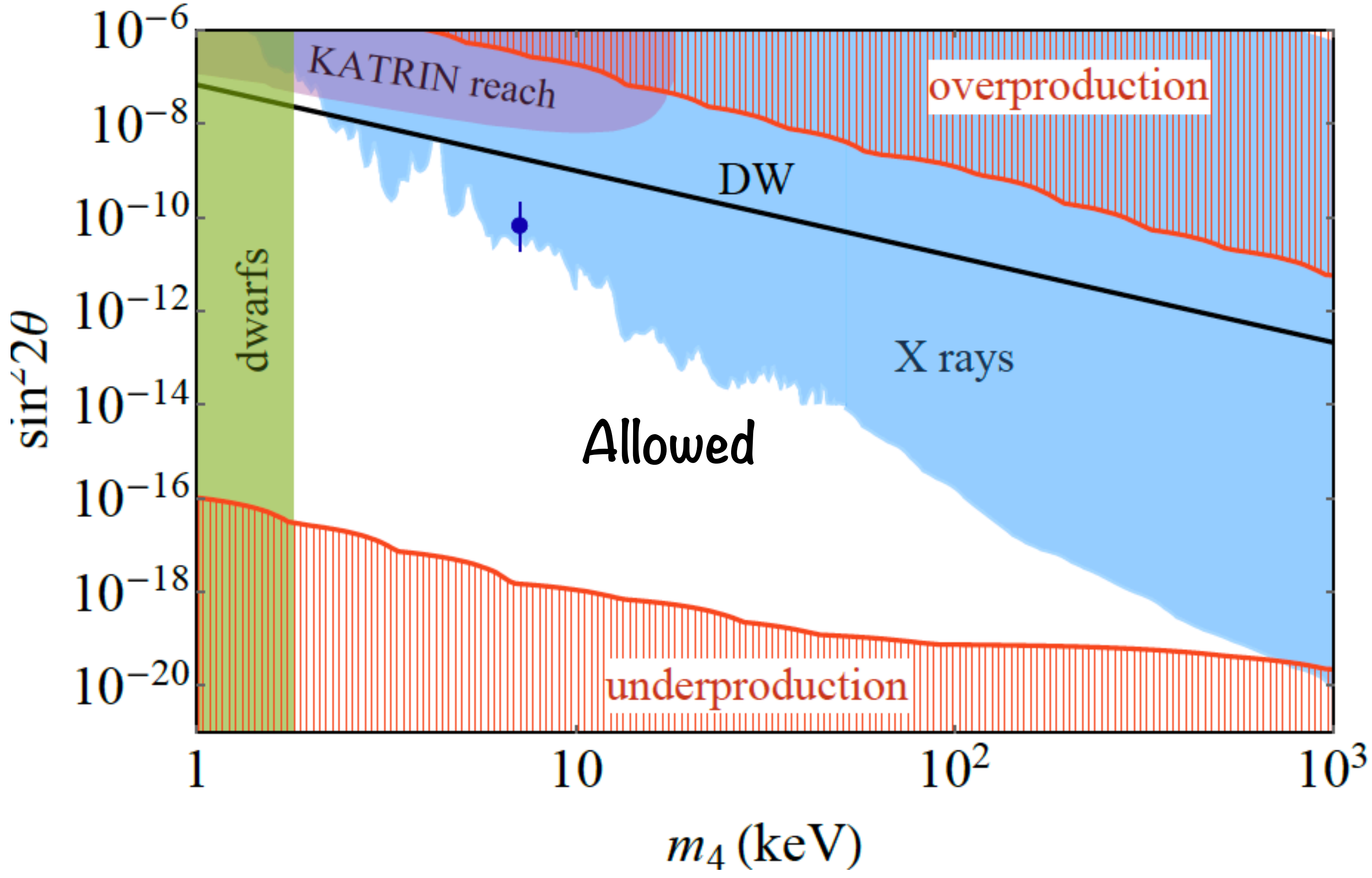

$\Omega\, h^2 = 0.12\ , m_{\nu_s} = 7.1\,\mathrm{keV},\ \ \sin^2 2\theta = 7\times 10^{-11}$

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.

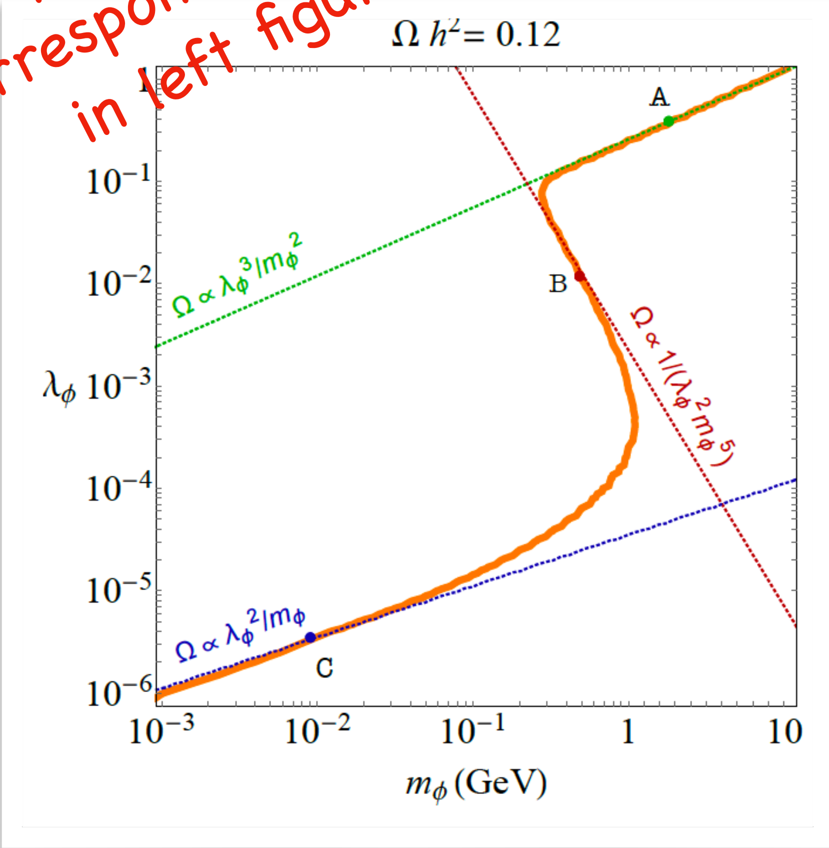
2. B: Intermediate mass, coupling: $t_\varphi < t_{\Gamma=H} < t_{\Delta=V}$ .Peak production happens in $(t_\varphi < t < t_{\Gamma=H})$ when θ_{eff} is suppressed.

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

Allowed Relic Density window

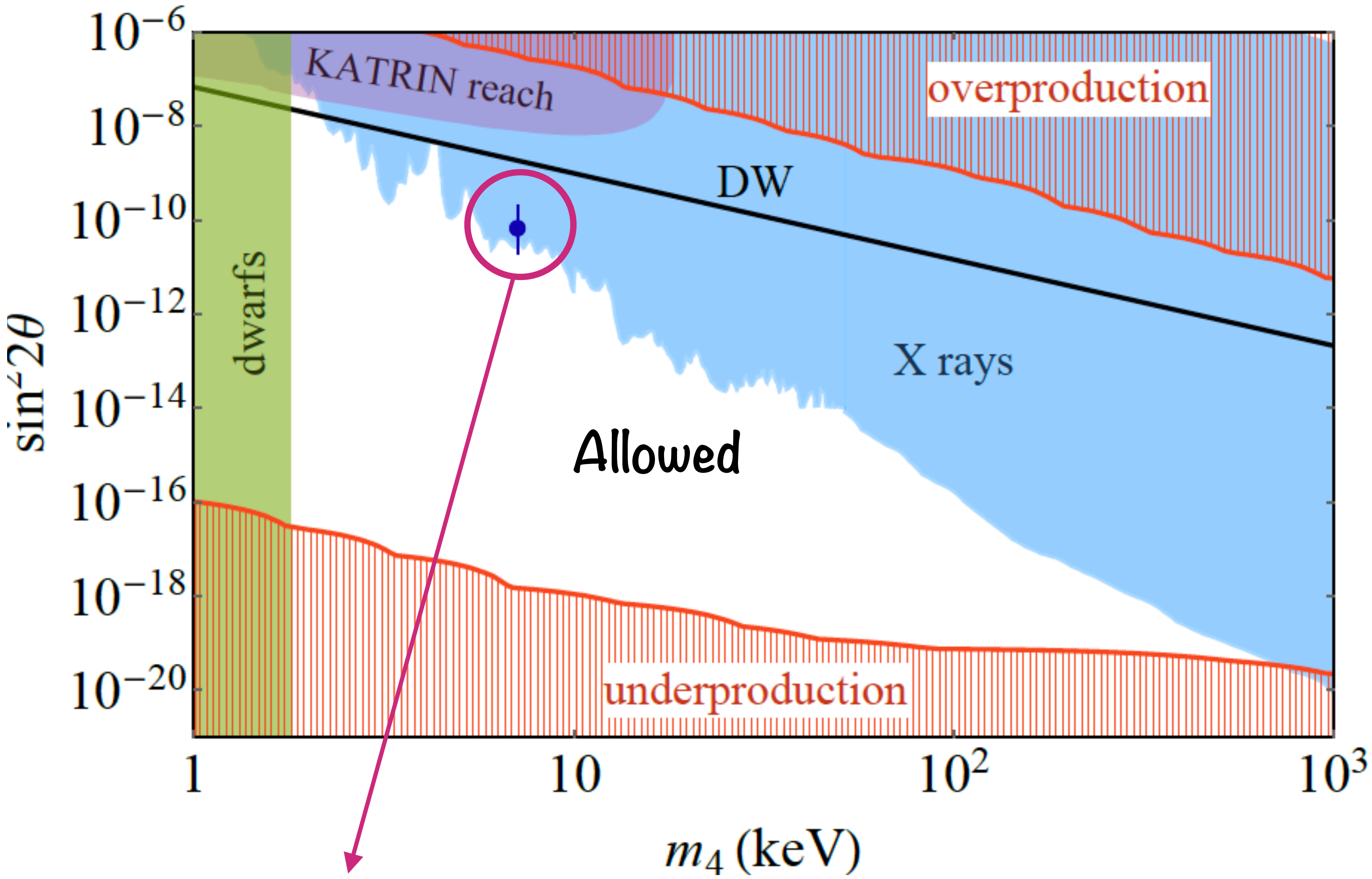


Every point in this plane corresponds to a line in left figure



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

Allowed Relic Density window



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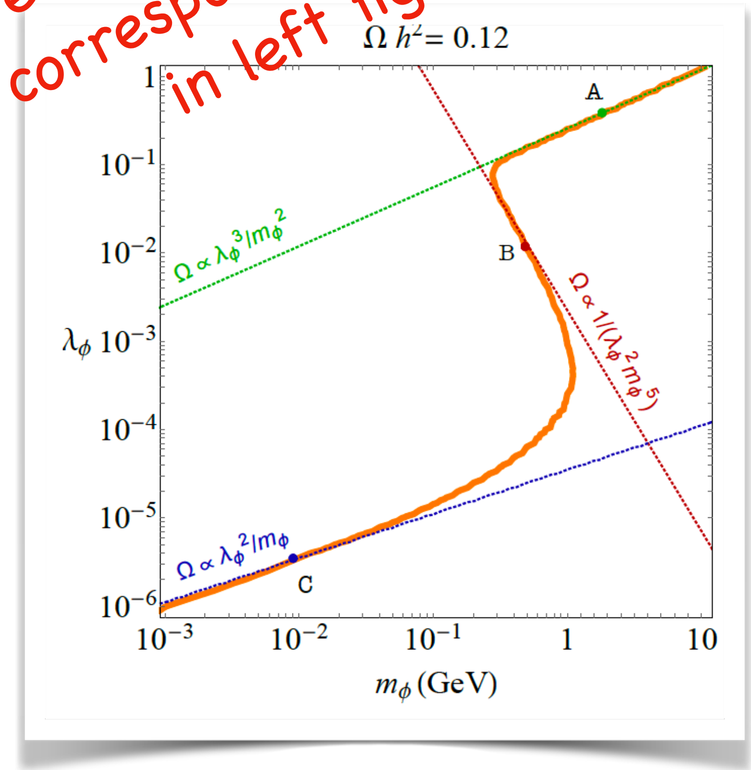


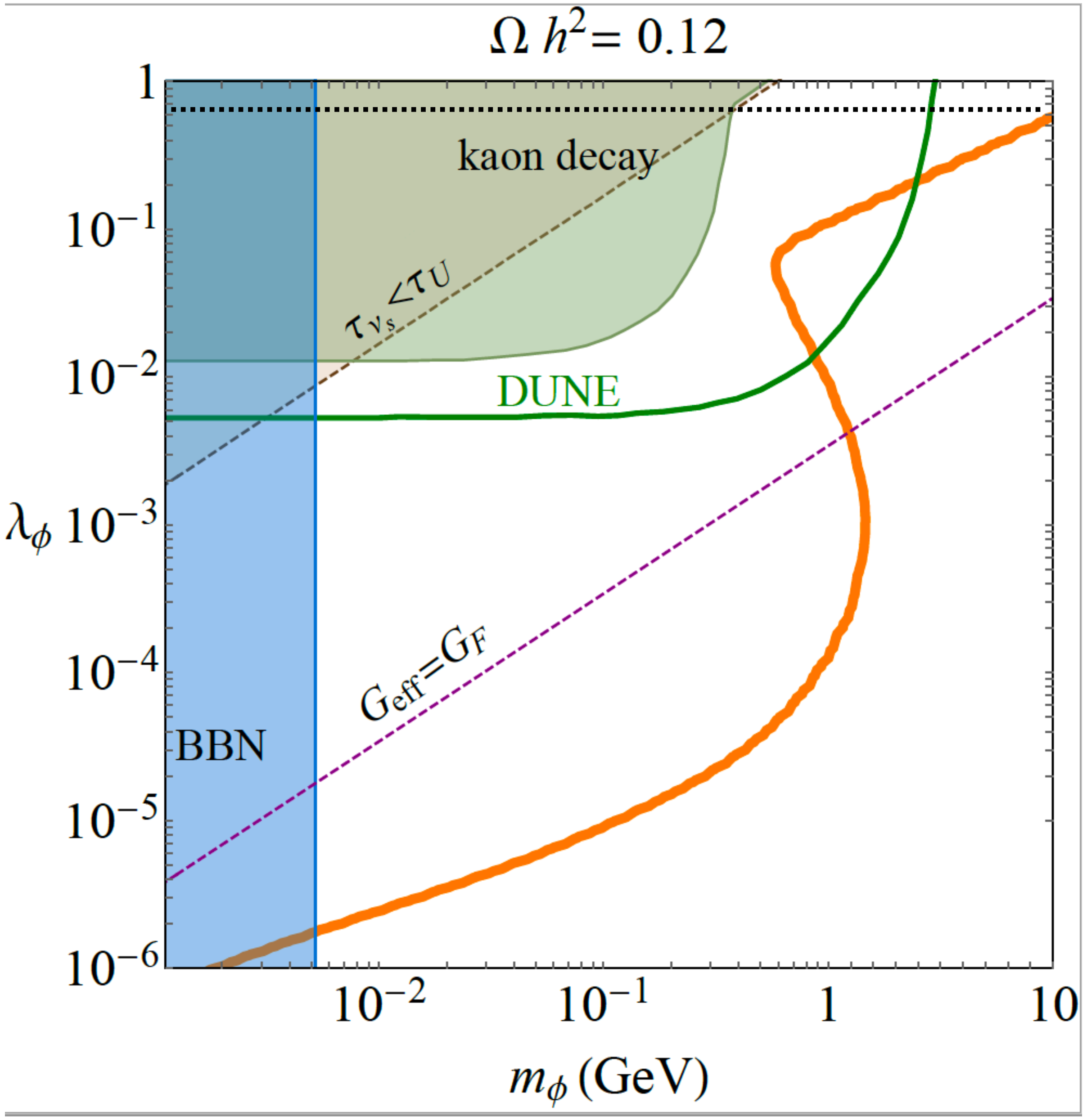
Can be used to satisfy the 3.5 keV X-ray line also ~

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

Experimental tests

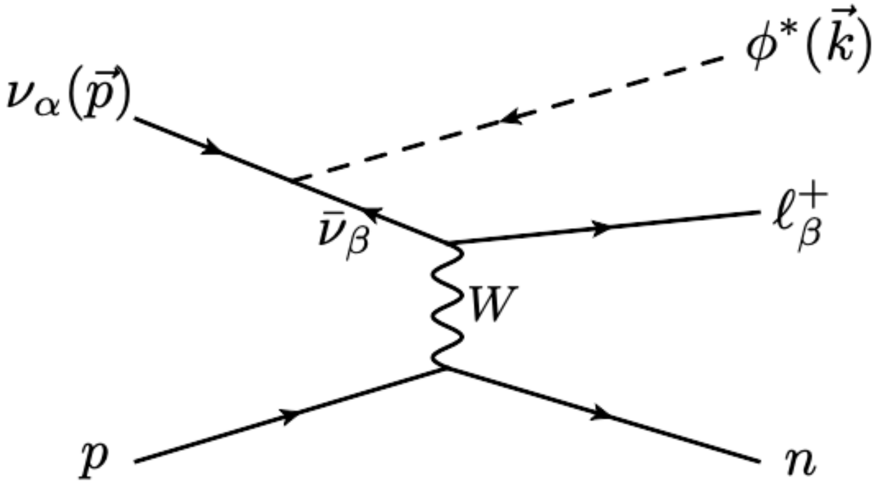
Lab based tests

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



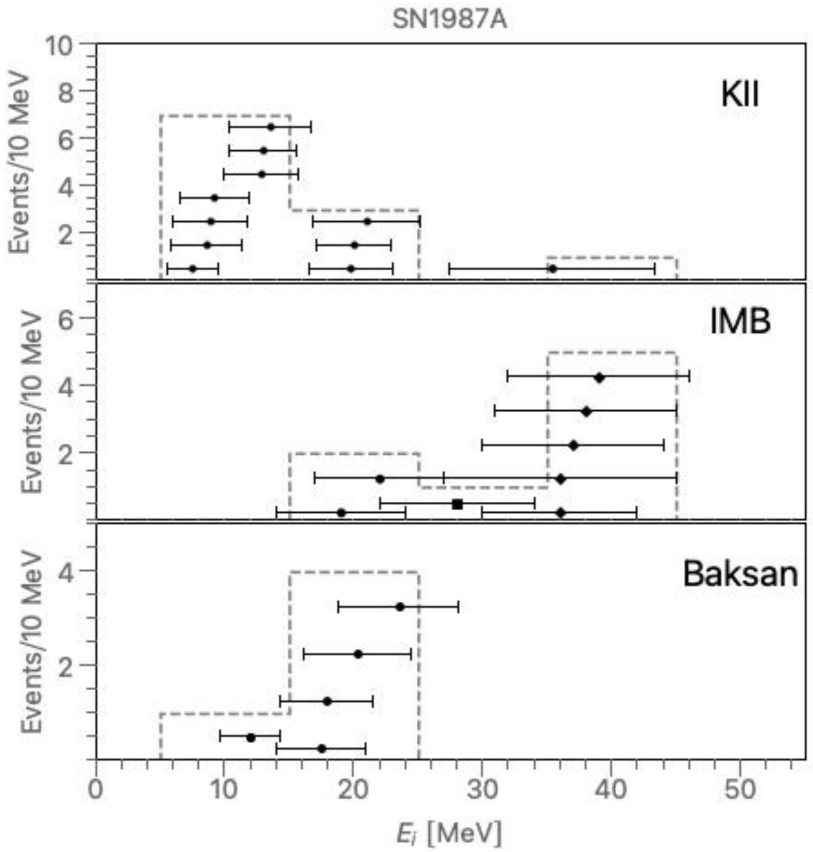
de Gouvêa, **MS**, Tangarife and Zhang PRL 2020

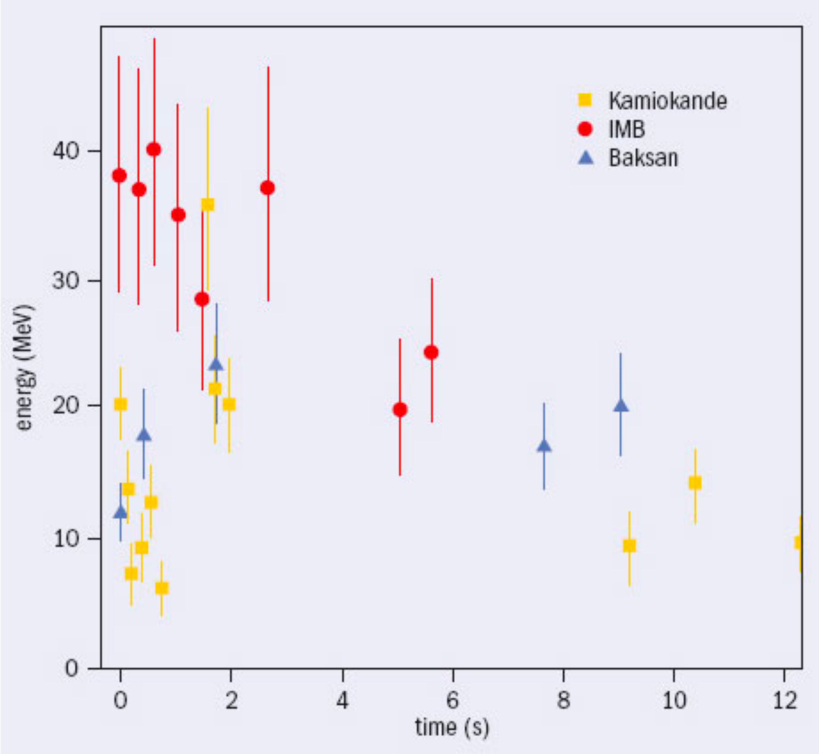
- Invisible Higgs decays, Z decays
- $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu\,.$
  Bounds from $\mathrm{Br}(K^- \to \mu^- 3\nu) < 10^{-6}\,.$
- Look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi.$
  Parameter space can also be probed through missing energy.



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

Astro tests: supernova cooling bounds



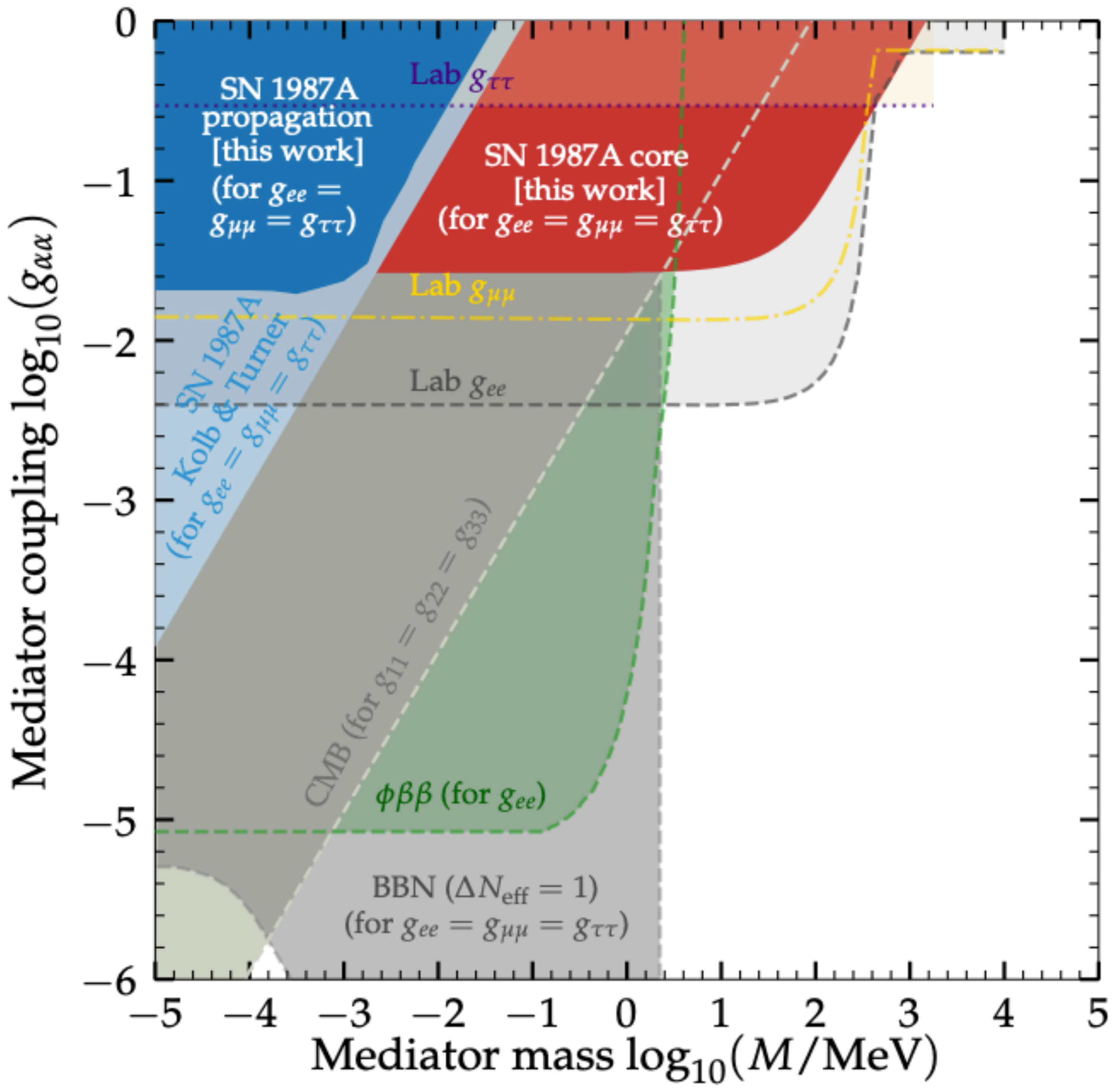


- Around 30 neutrinos of energy $\mathcal{O}(10)$ MeV observed from SN1987A for a period of 10s or so.
- New modes of energy loss due to weakly coupled particles.
- If $\mathscr{L}_x > \mathscr{L}_\nu \sim 10^{52}\,\mathrm{erg/s}$, then duration of neutrino burst is reduced from 10s.

Raffelt criterion.

- Alternation of the neutrino events.

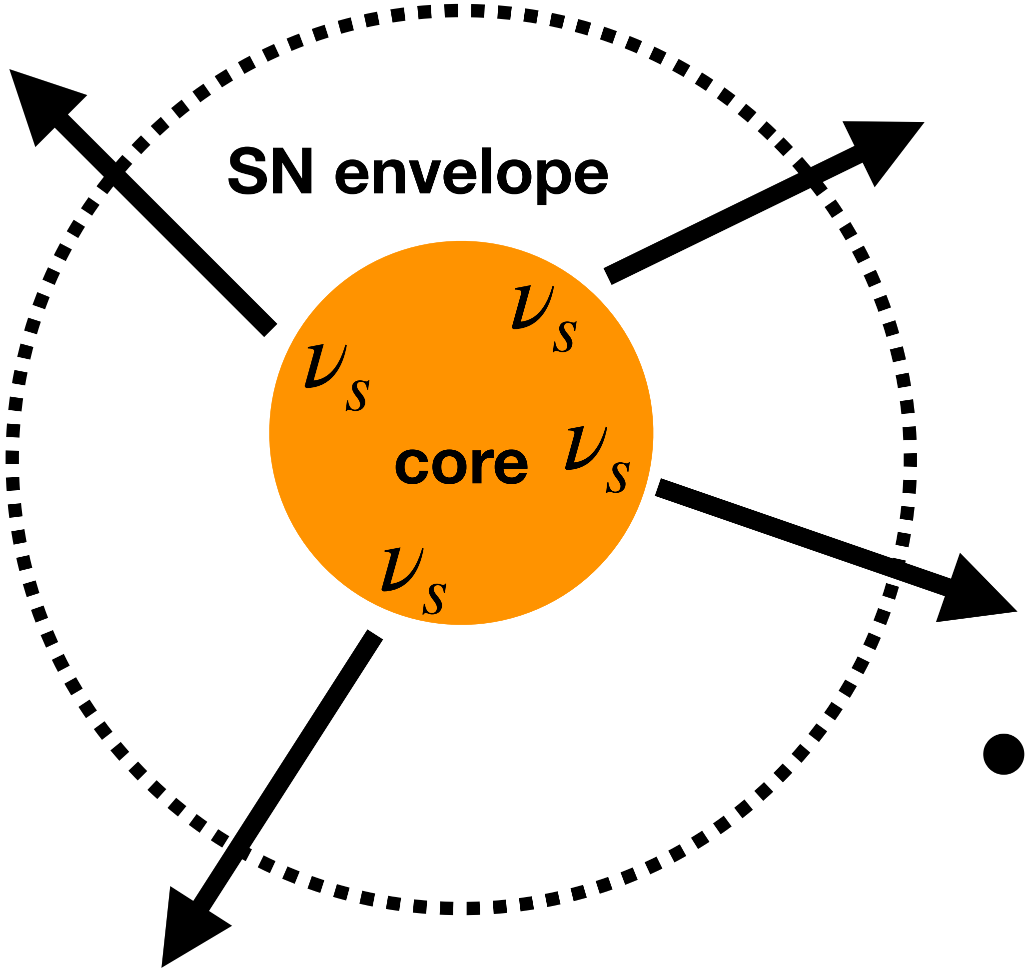
Astro tests: Core-Collapse supernova constraints

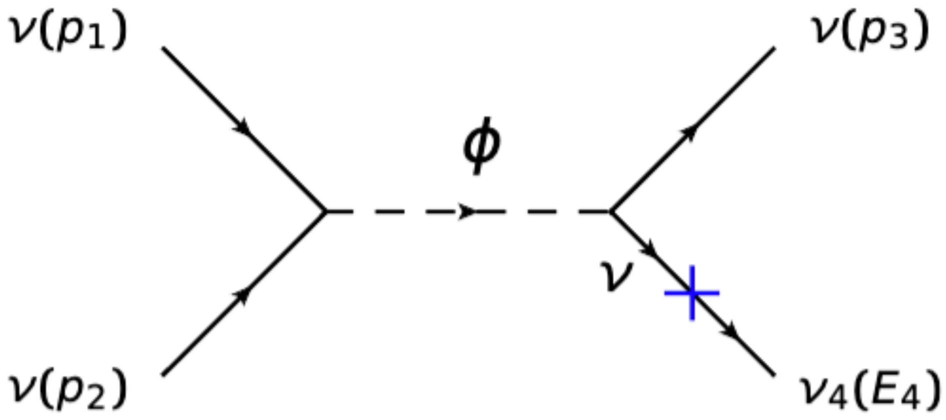


- Scatterings with the cosmic neutrino background could have down-scattered the neutrinos from SN1987A (blue shaded)
- Successful explosion could have been hindered (red shaded).
- Production of mediators, leading to cooling— less stringent bounds.

Neutrino self-interactions, snowmass white paper 2022, **MS** et al.

Astro tests: supernova cooling bounds





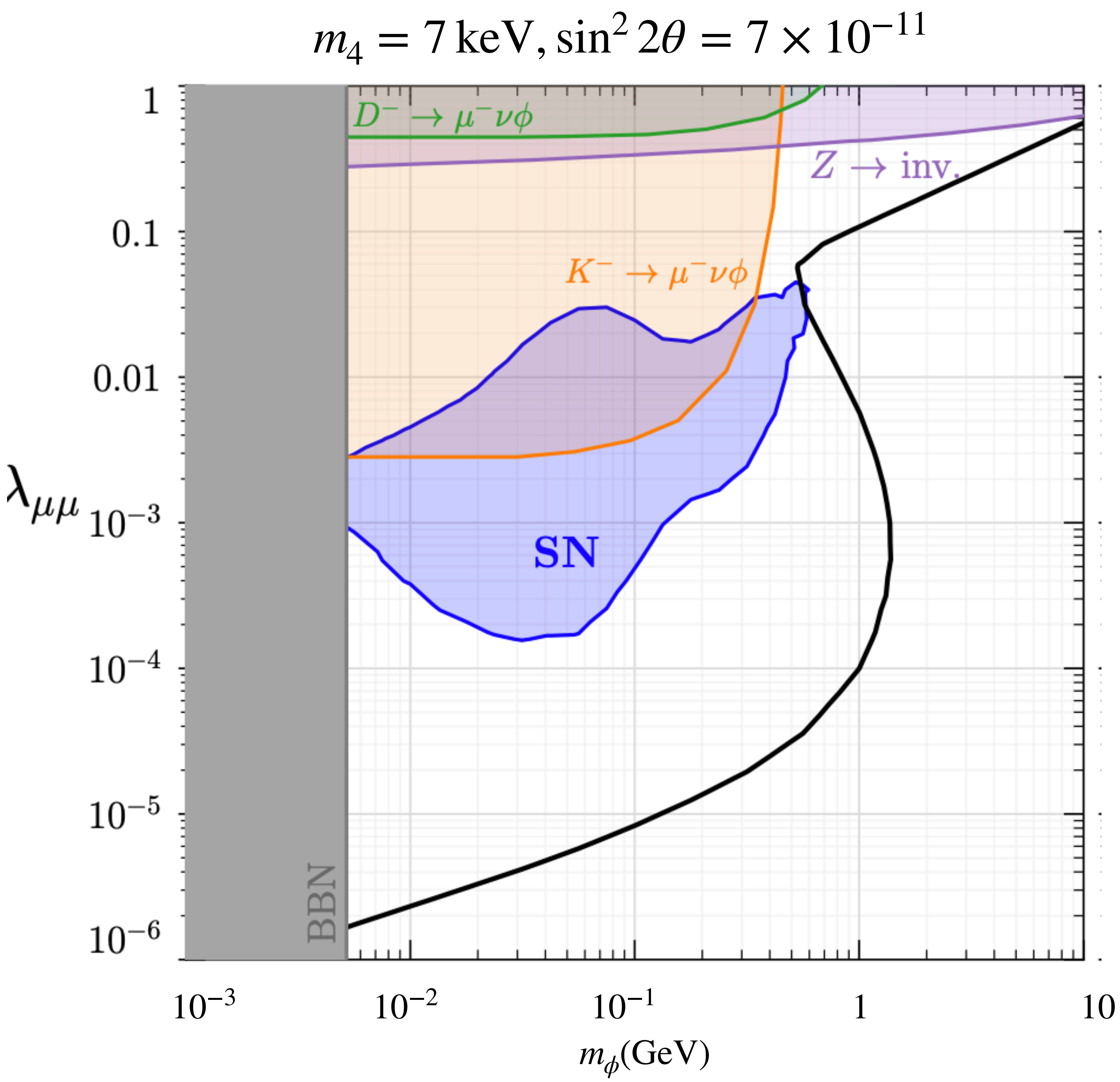
- ν_s can also be produced inside the SN core due to these new interactions, and lead to additional cooling channels.

$$L = \int d^3\vec{r} \int \frac{d^3\vec{p}_1}{(2\pi)^3} f_\nu(E_1, r) \int \frac{d^3\vec{p}_2}{(2\pi)^3} f_\nu(E_2, r) \frac{1}{4E_1E_2} \int \frac{d^3\vec{p}_3}{(2\pi)^3 2E_3} \int \frac{d^3\vec{p}_2}{(2\pi)^3 2E_4}$$
$$\times (2\pi)^4 \delta^4(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) |\mathcal{M}|^2 E_4 e^{-\tau(E_4, r)} \ ,$$

$$\boxed{L_{\nu_s} > L_\nu = 10^{52}\,\mathrm{erg/s}}$$

Chen, **MS**, Tuckler, Tangarife and Zhang, JCAP (2022)

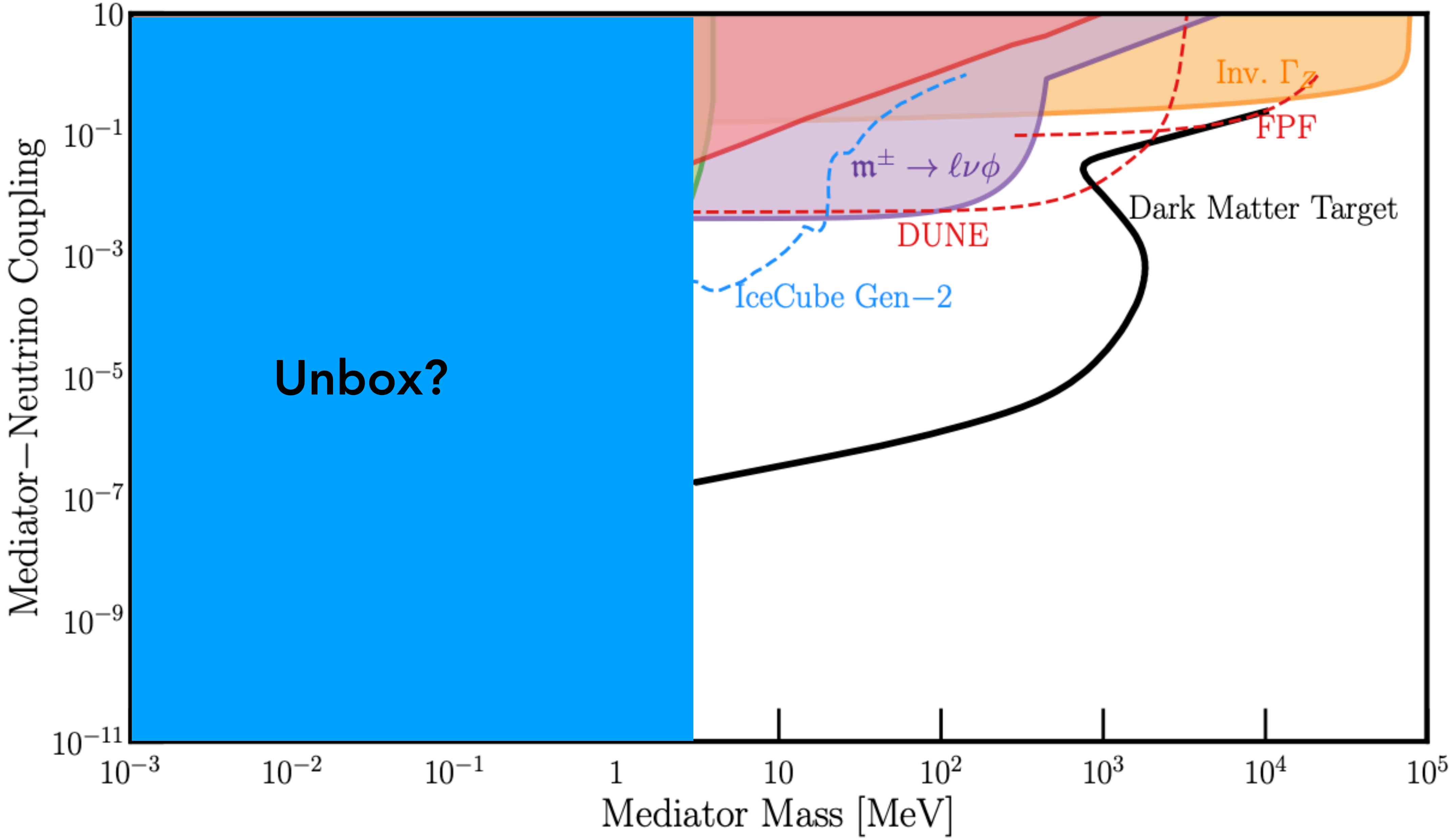
Supernova cooling bounds

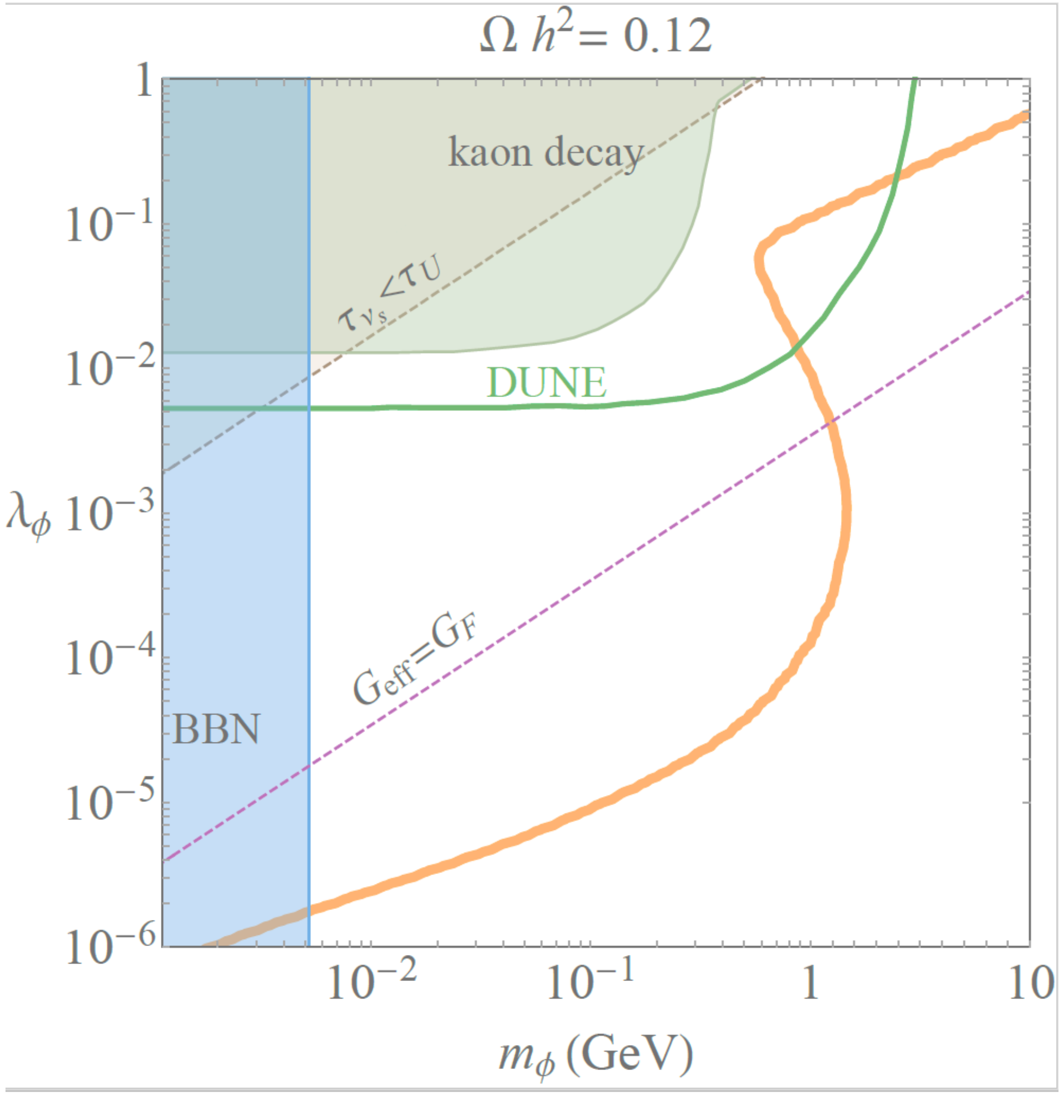


Can probe the parameter space for judicious choice of sterile mass and mixing.

Chen, **MS**, Tuckler, Tangarife and Zhang, JCAP 2022

Big picture


Unbox?
Inv. Γ_Z
FPF
$\mathfrak{m}^{\pm} \to \ell\nu\phi$
Dark Matter Target
DUNE
IceCube Gen−2
Mediator−Neutrino Coupling
10
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
Mediator Mass [MeV]



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

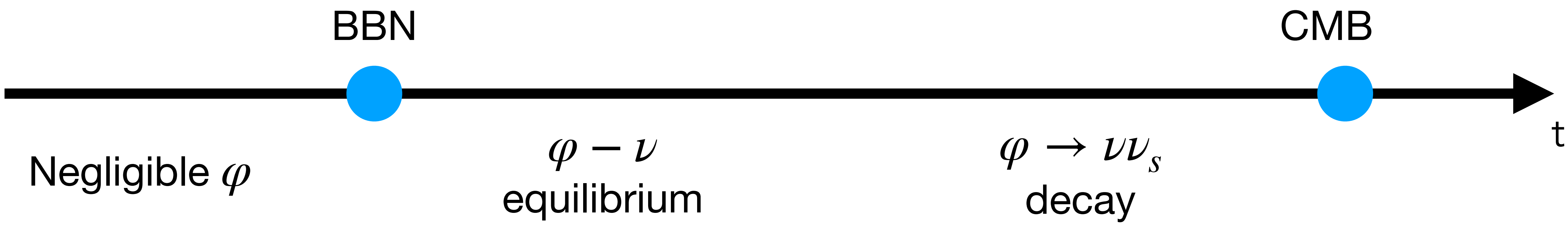
Cosmological Surveys

Low mass, low coupling limit

How do we evade BBN bounds? Relevant process $\phi \leftrightarrow \nu\nu$. Dominates over $2 \leftrightarrow 2$ processes.

Partial thermalization of φ before BBN, require feeble coupling to neutrinos.

Decay of φ to keV ν_s before CMB



BBN

CMB

t

Negligible φ

$\varphi - \nu$
equilibrium

$\varphi \to \nu\nu_s$
decay

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

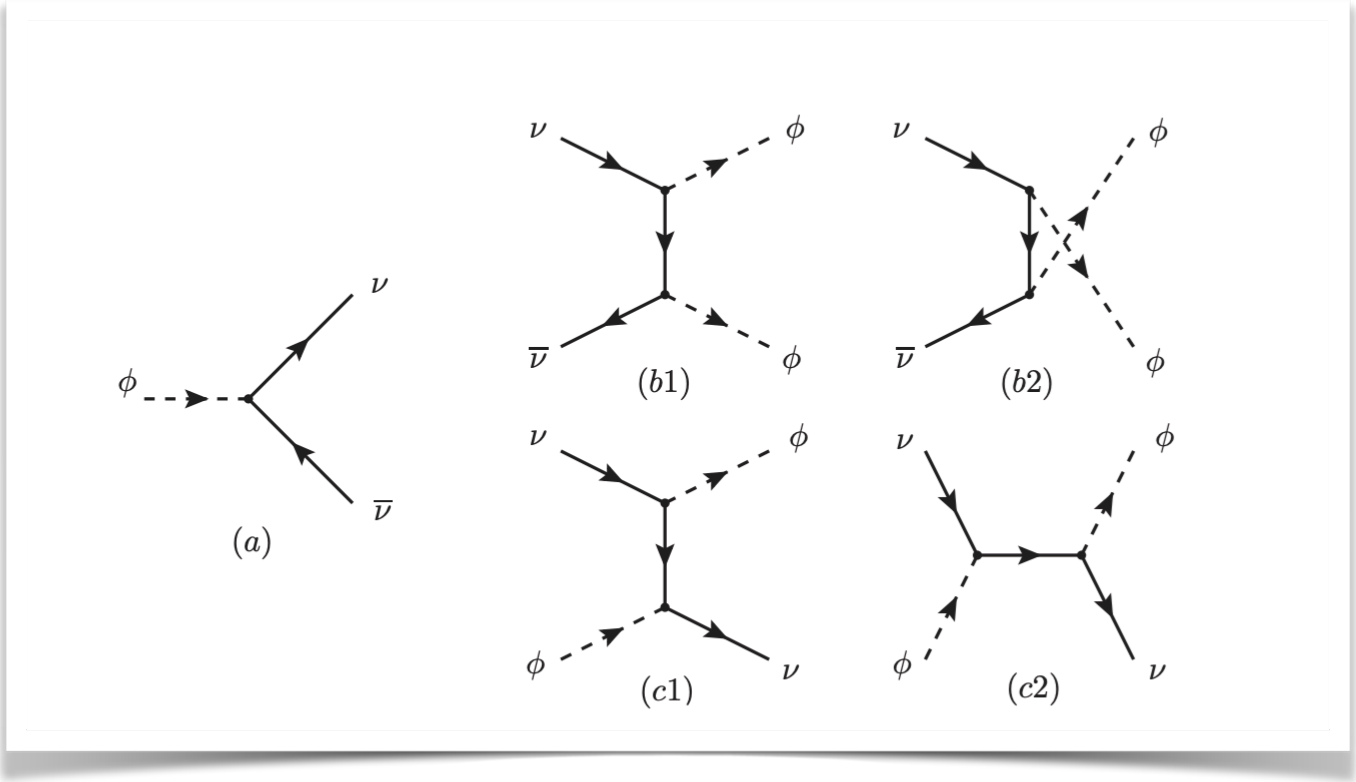
Energy density, lepton number conservation.

Entropy, lepton number conservation

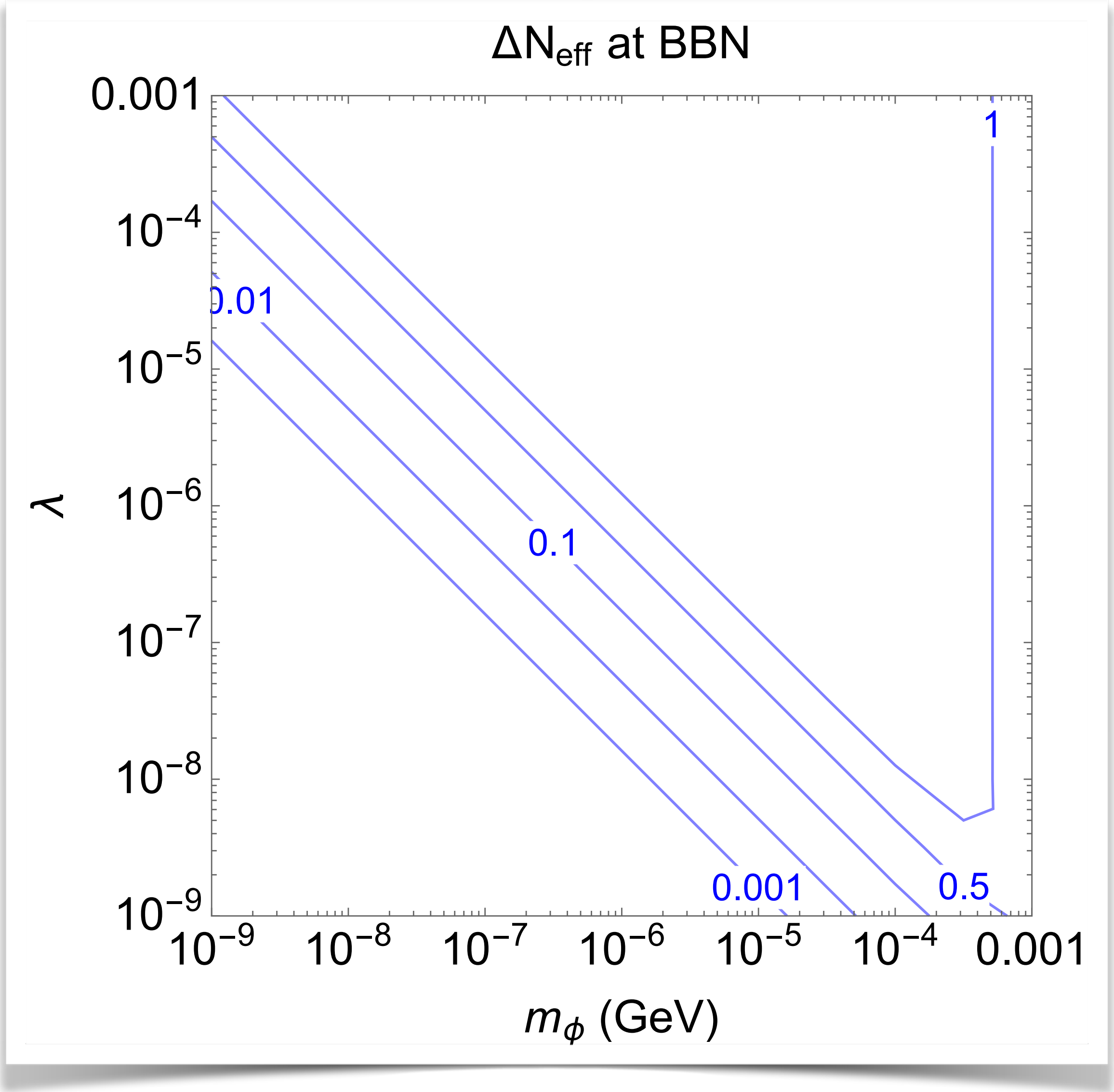
Escudero, JCAP 2020

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

Contribution to extra radiation at BBN



Huang, Ohlsson, Zhou, PRD 2018



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

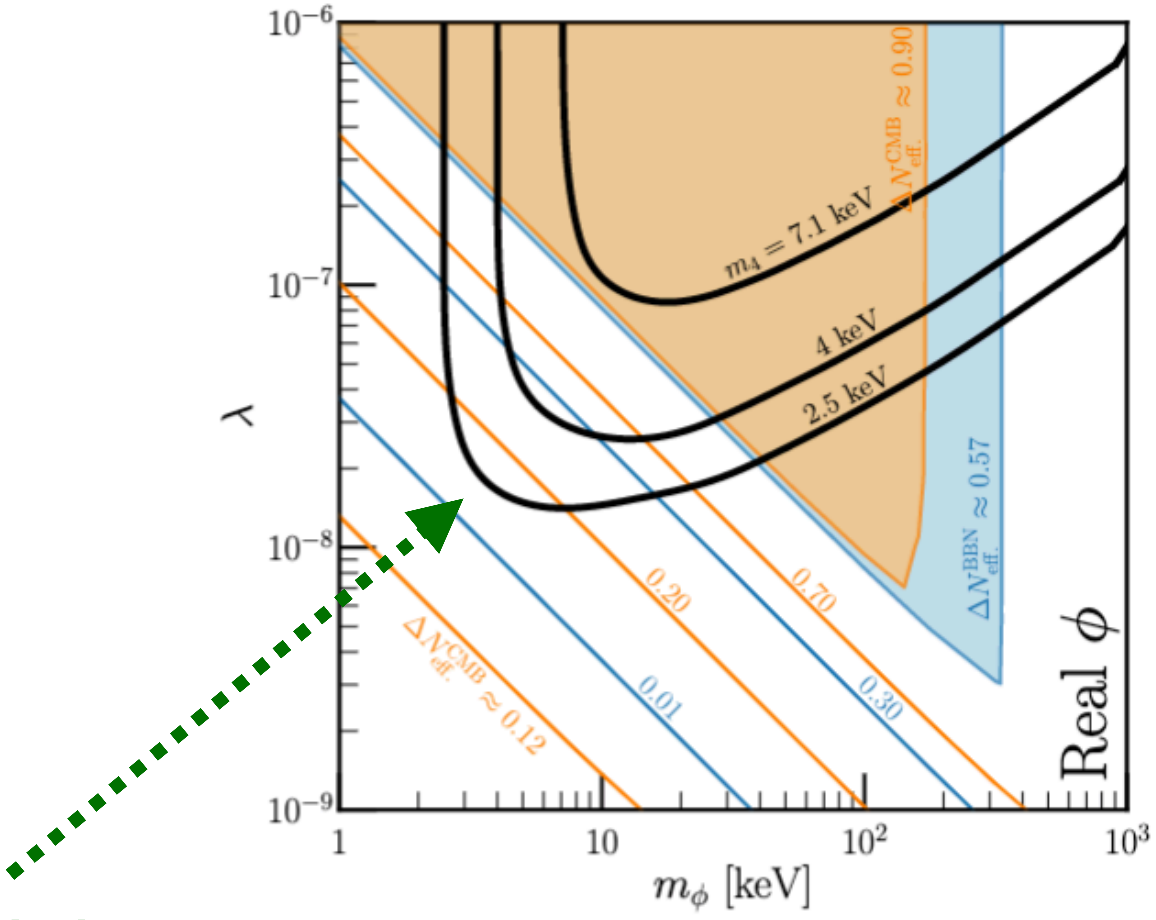
For low mass ϕ, processes like $\phi \leftrightarrow \nu\nu$ become relevant. This explains the wedge like feature.

Correlation with extra radiation

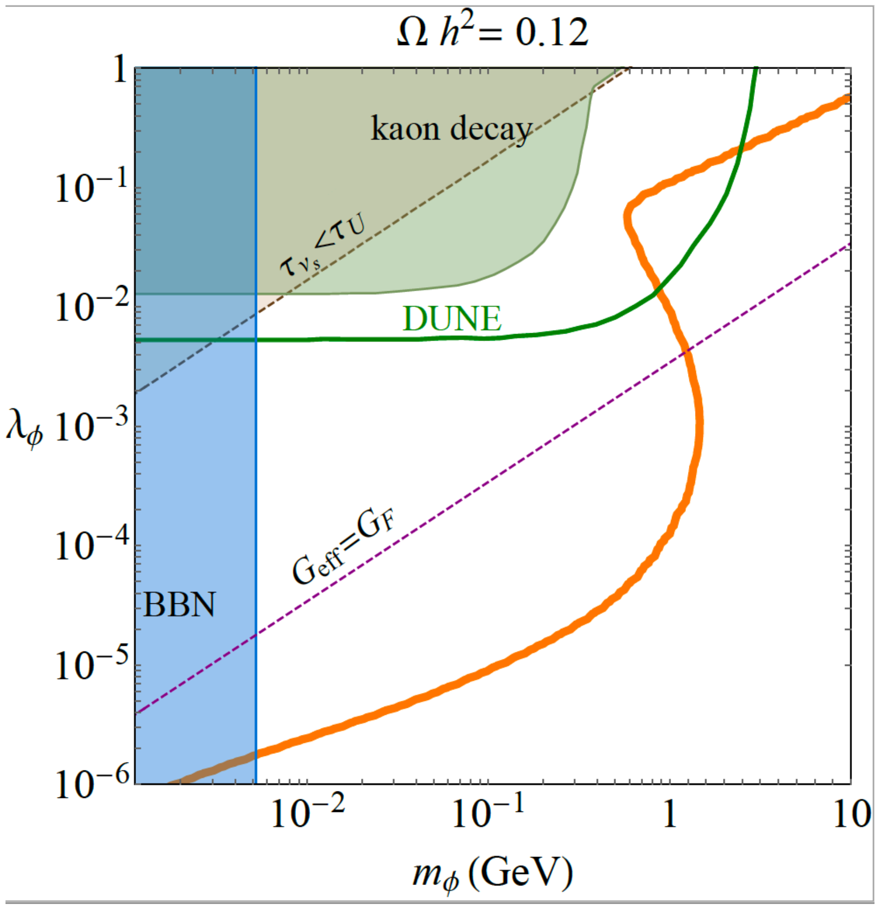
- Partial thermalization of φ contributes to $N_{\rm eff}$ at BBN, and φ decay to $N_{\rm eff}$ at CMB.

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

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



Minima



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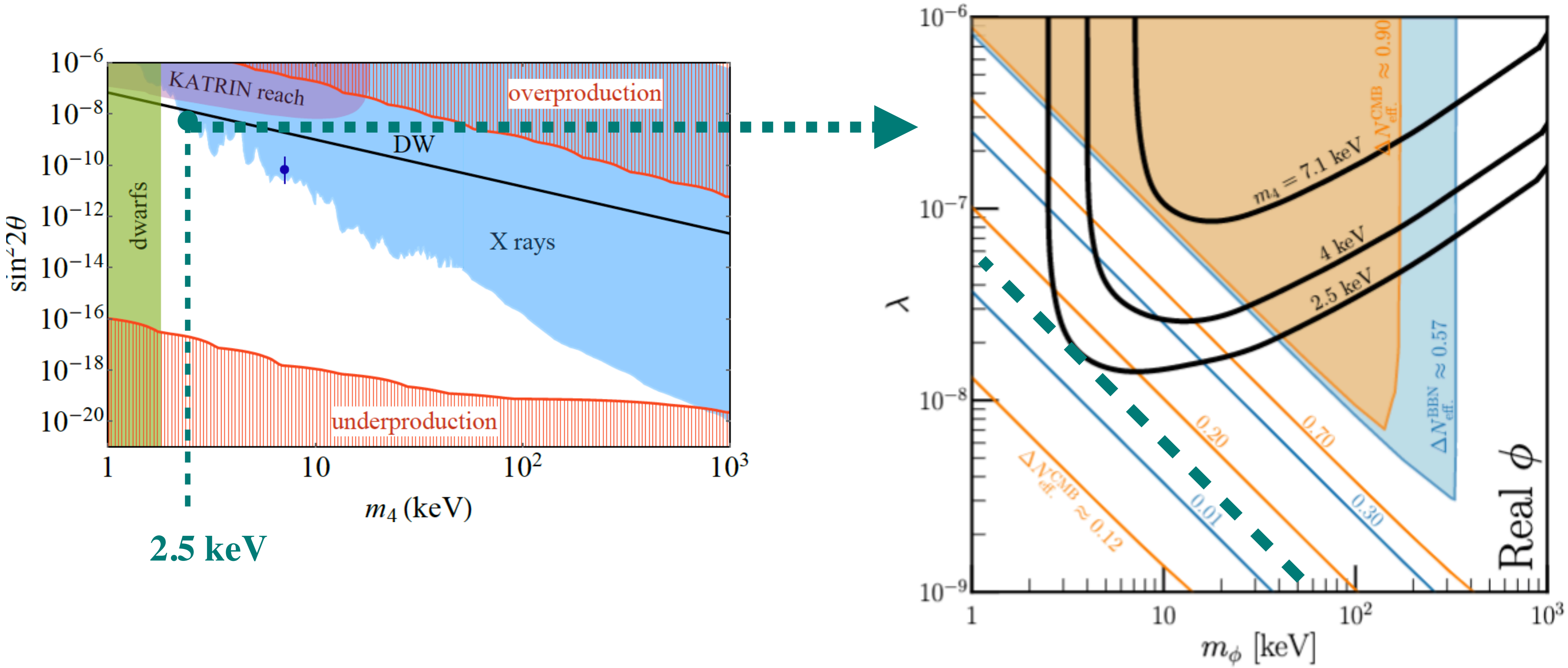
The algorithm for deriving constraints



- 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 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.

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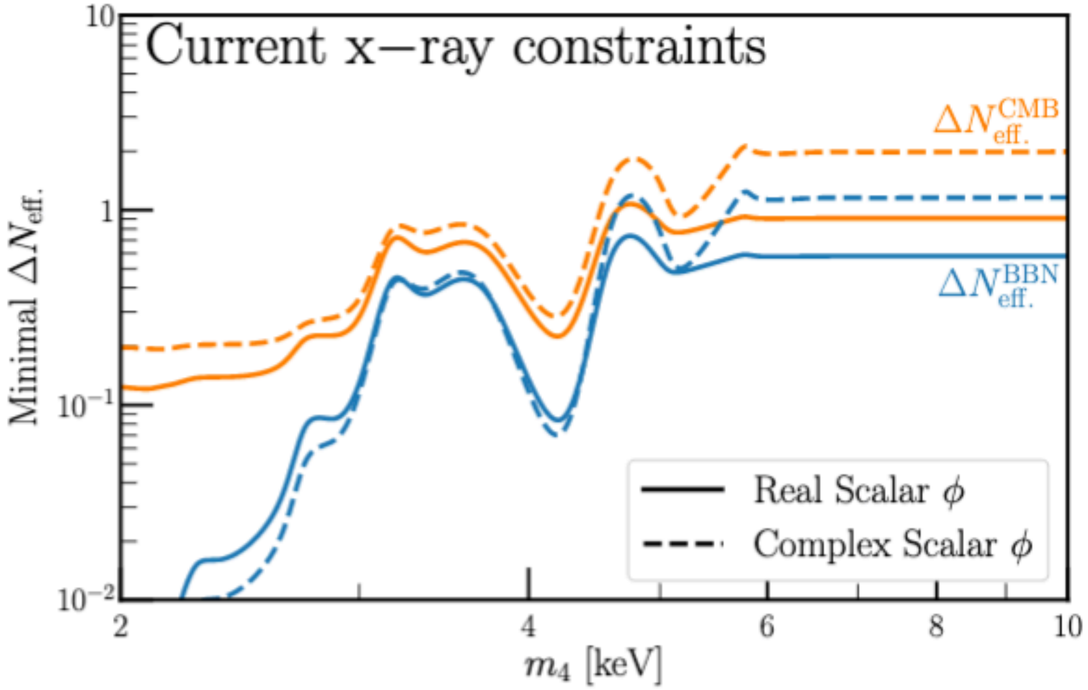
Constraints from N_{eff}

Minimal ΔN_{eff} probe



- Each point is for a maximum allowed mixing angle for a sterile neutrino mass.
- Corresponding minimum value of ΔN_{eff} during BBN and CMB. For real scalar, $0 < \Delta N^{\text{eff}}_{\text{BBN}} < 0.57$

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

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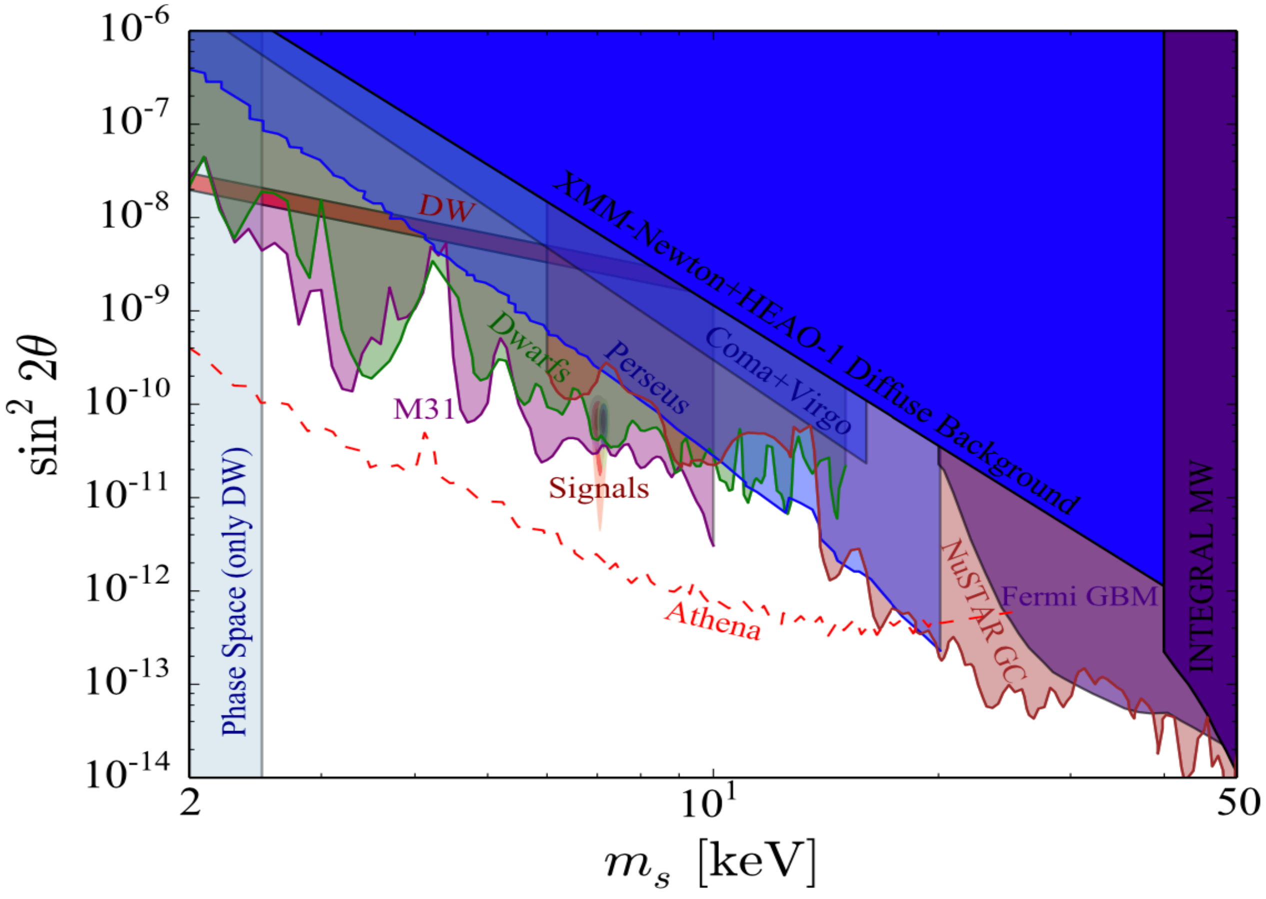
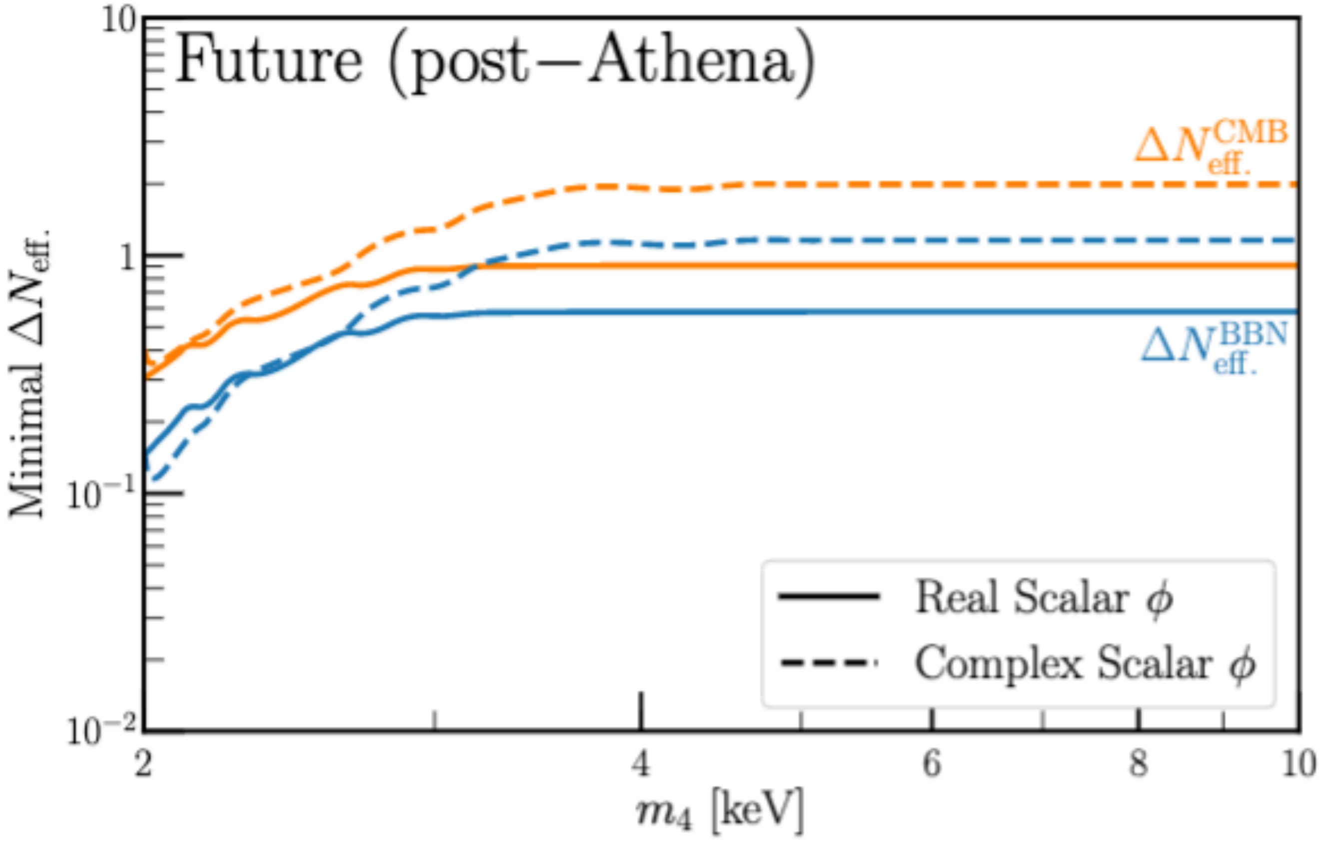
Constraints from $N_{\rm eff}$



Abazajian (2017)



Stronger constraints from future surveys like Athena.

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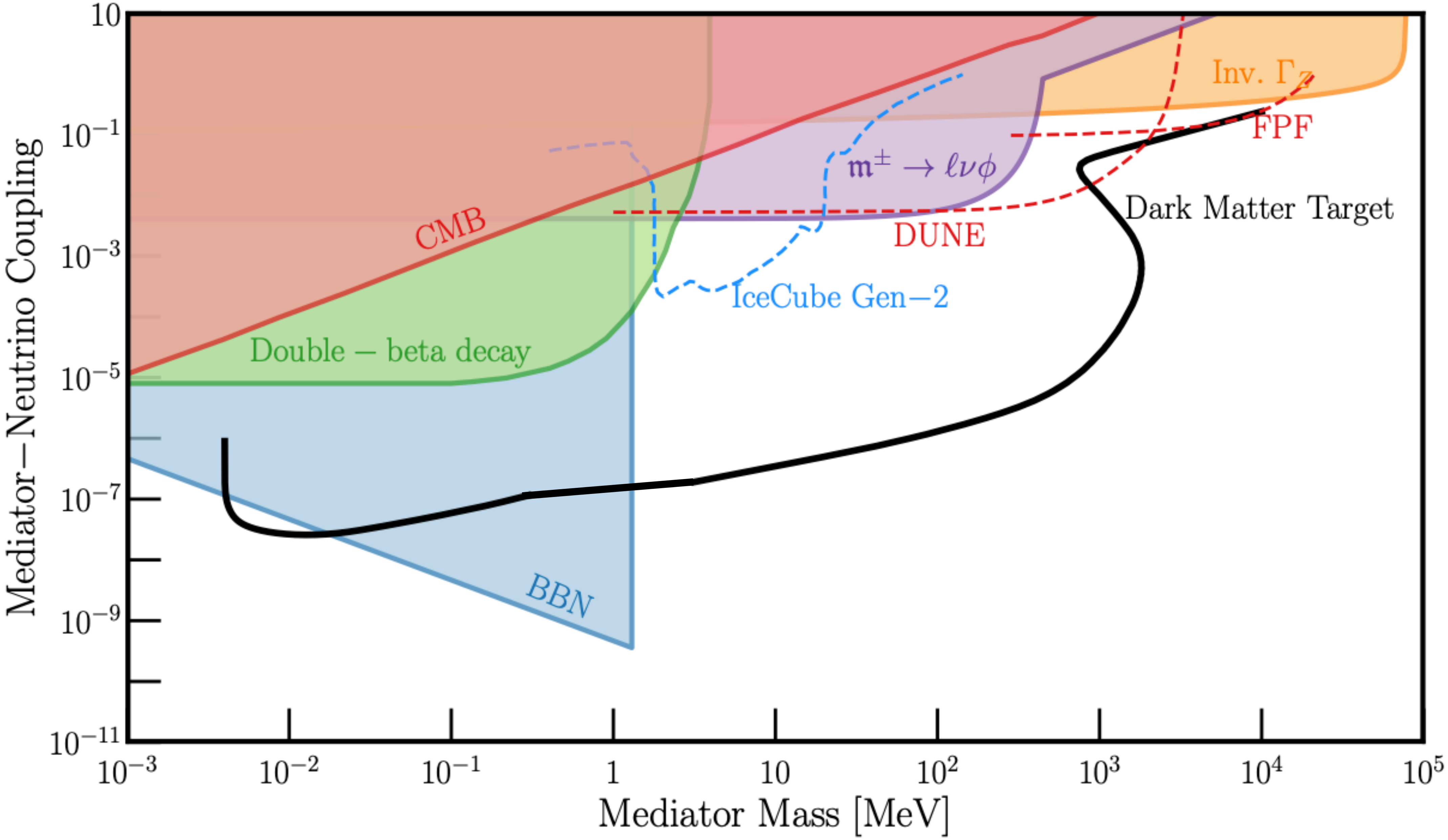
Big Picture - unboxed



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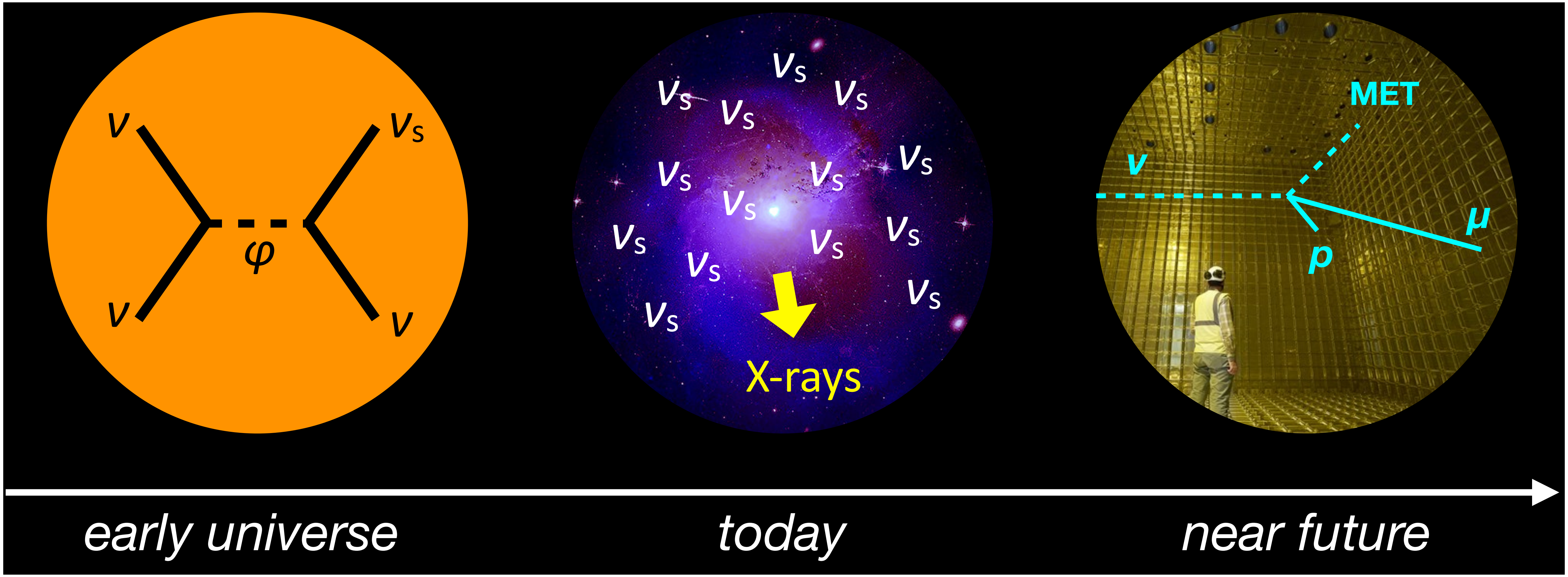
Summary

- keV sterile neutrinos are excellent warm dark matter candidates. Can be produced non-thermally through a mixture of oscillations and collisions.
- Vanilla scenario is in tension with X-ray bounds+ phase space bounds.
- Introduce secret interactions among active neutrinos. Can be used to efficiently produce sterile neutrino DM in the early Universe.
- Leaves imprints in the lab, in astrophysical objects as well as in the early Universe.
- Can be cornered from all possible directions with upcoming experiments.
- This will be an exciting decade for sterile neutrino dark matter theories.

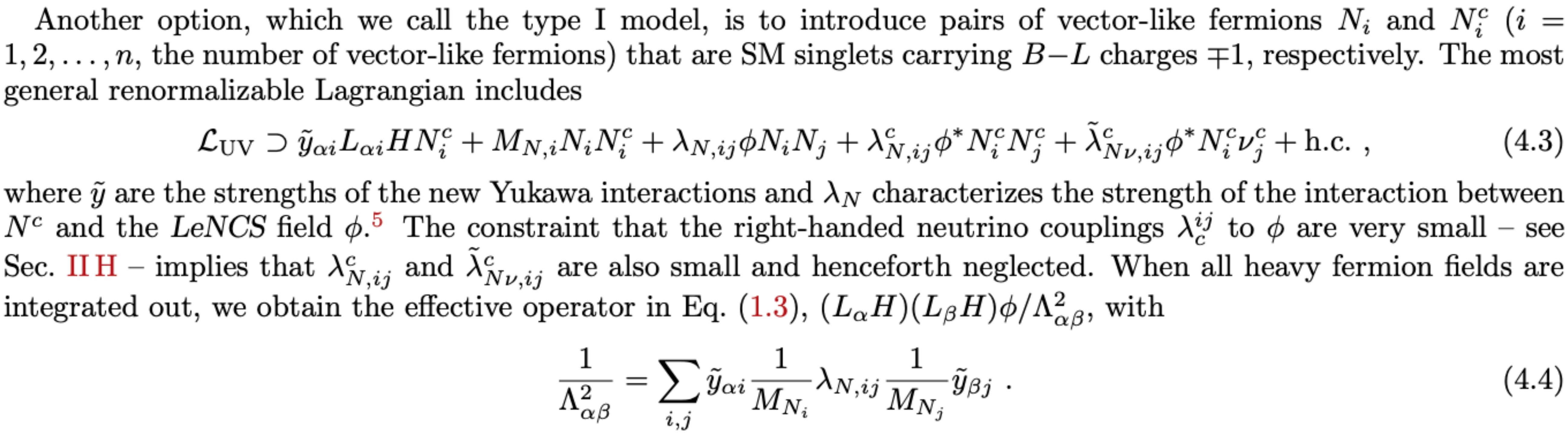
Summary



Thank you!

BACKUP

Backup: UV Completion

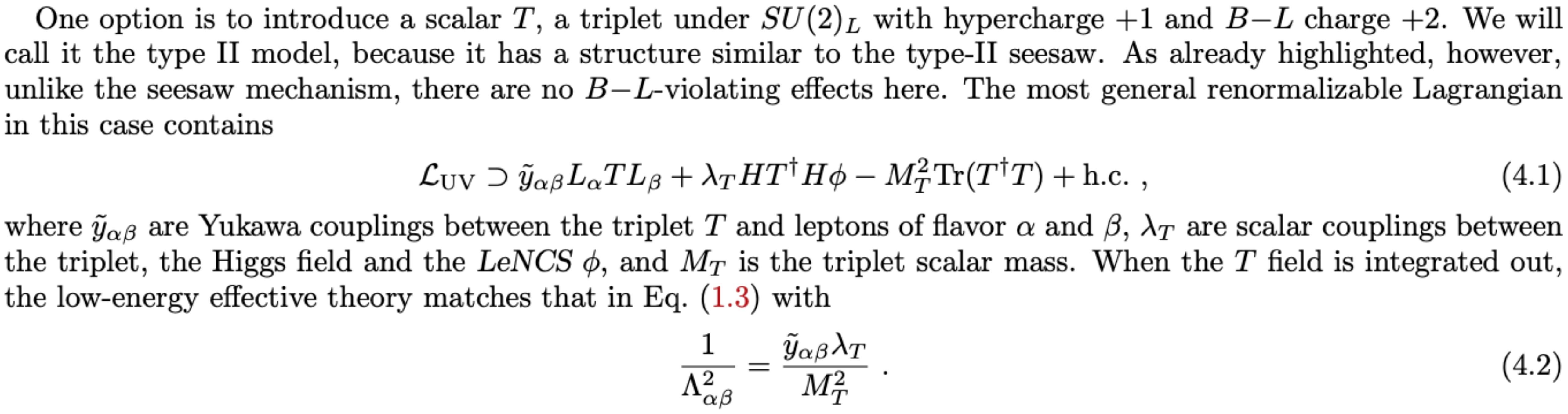


Another option, which we call the type I model, is to introduce pairs of vector-like fermions N_i and N_i^c ($i = 1, 2, \ldots, n$, the number of vector-like fermions) that are SM singlets carrying $B-L$ charges ∓ 1, respectively. The most general renormalizable Lagrangian includes

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

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

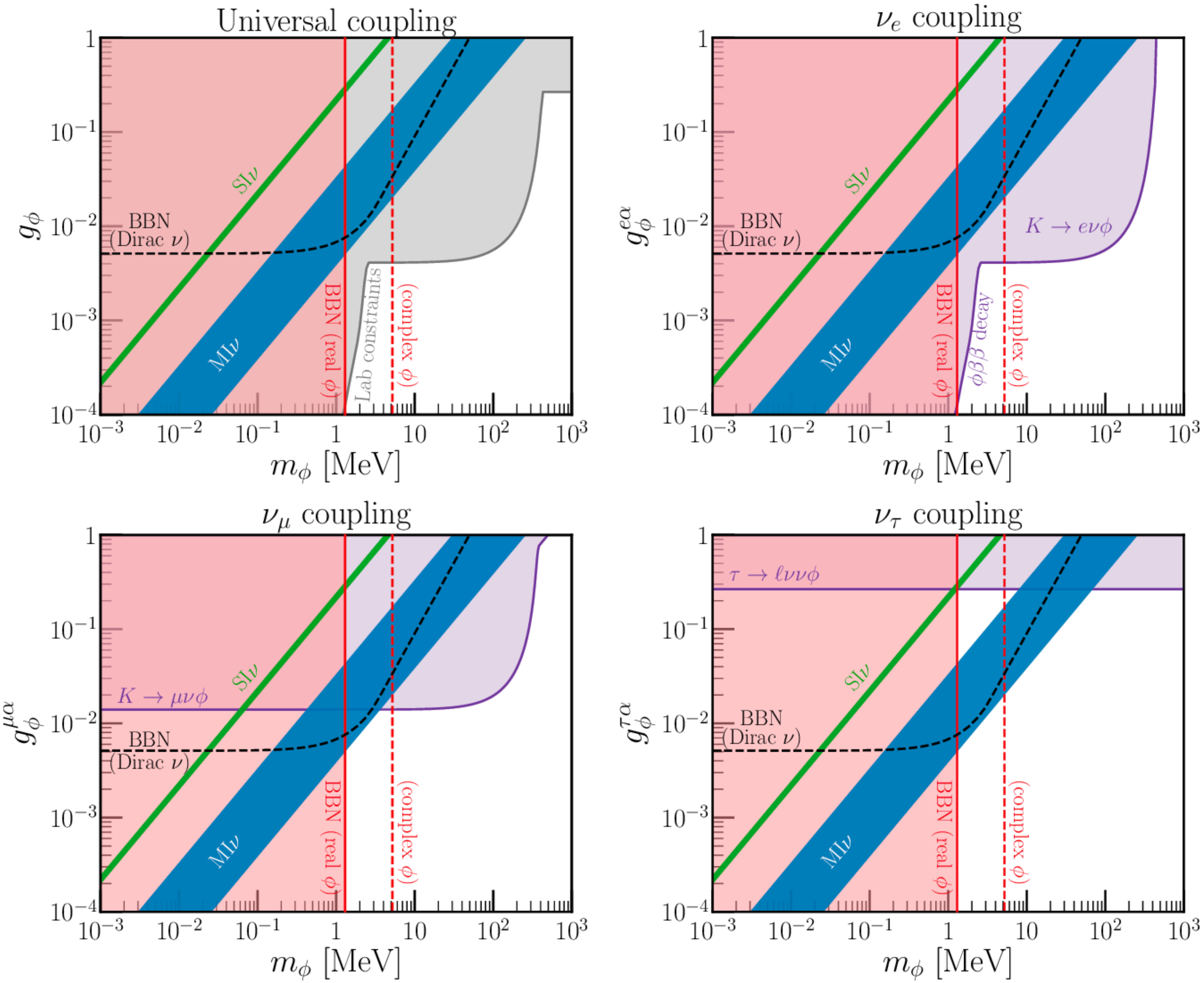
$$\mathcal{L}_{\rm UV} \supset \tilde{y}_{\alpha\beta} L_\alpha T L_\beta + \lambda_T H T^\dagger H \phi - M_T^2 {\rm Tr}(T^\dagger T) + \text{h.c.}\ , \tag{4.1}$$

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

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

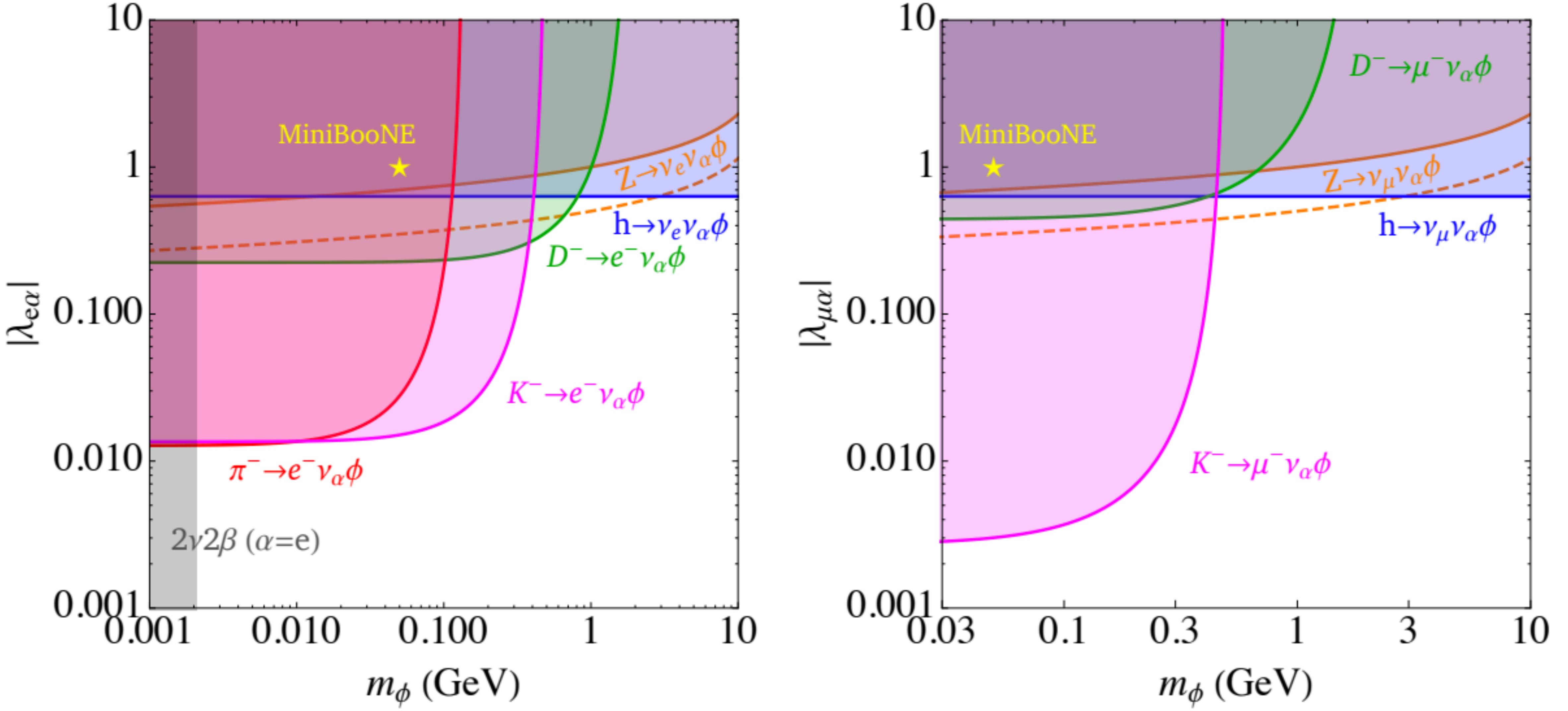
Berryman, de Gouvêa, Kelly and Zhang PRD 2018

Self-interaction bounds



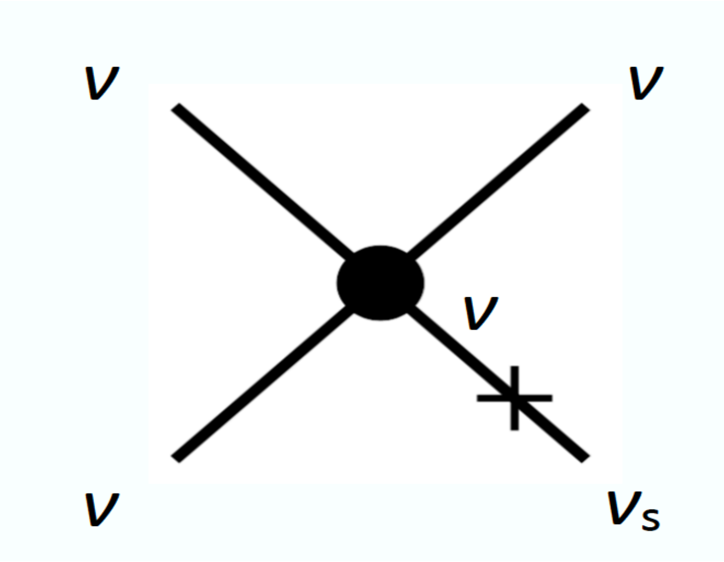
Berryman, de Gouvêa, Kelly and Zhang PRD2018
Blinov, Kelly, Krnjaic and McDermott, PRL2018

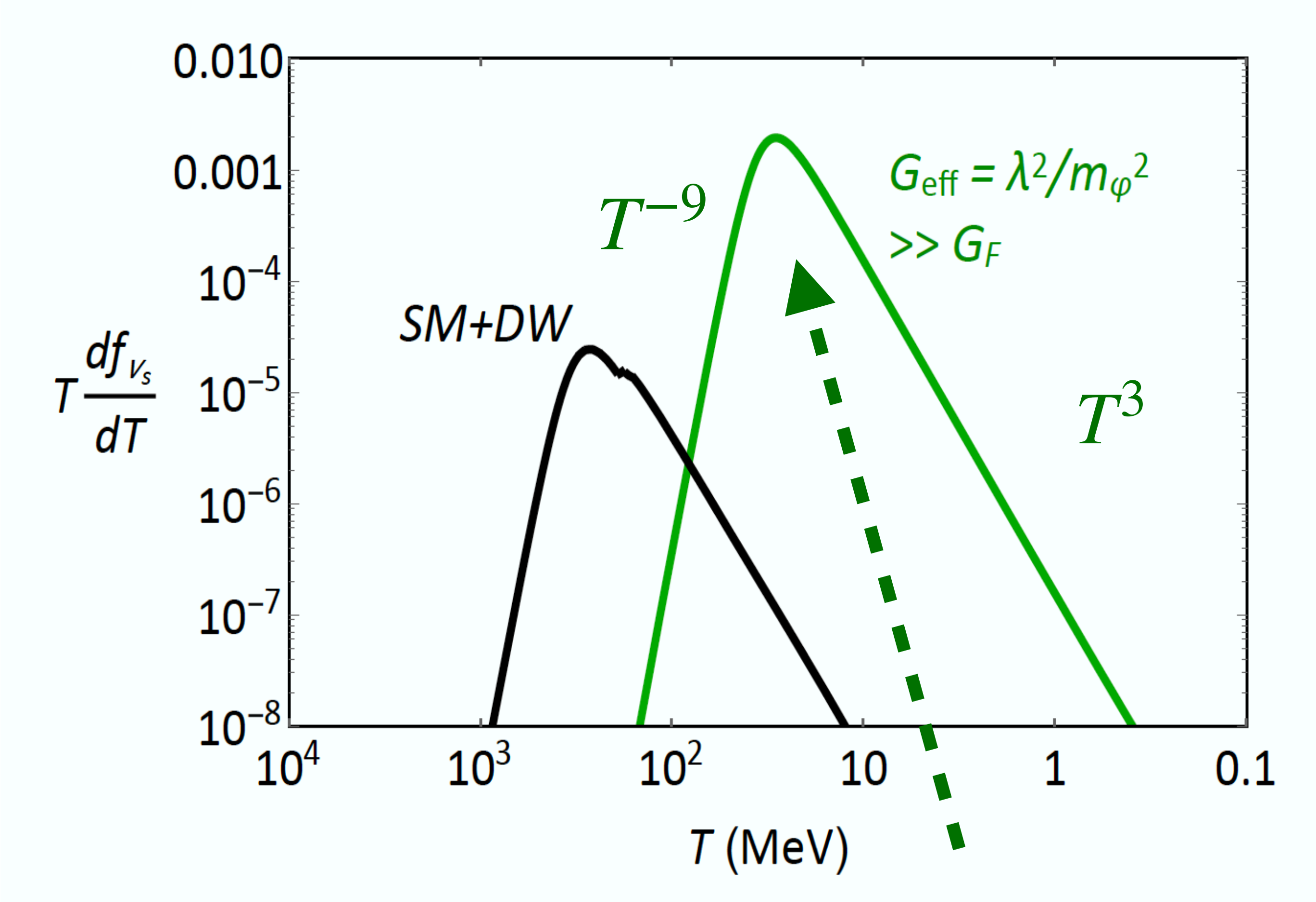
Self-interaction bounds



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

$m_\phi \gg T$





- Similar to DW, except with a stronger interaction.

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

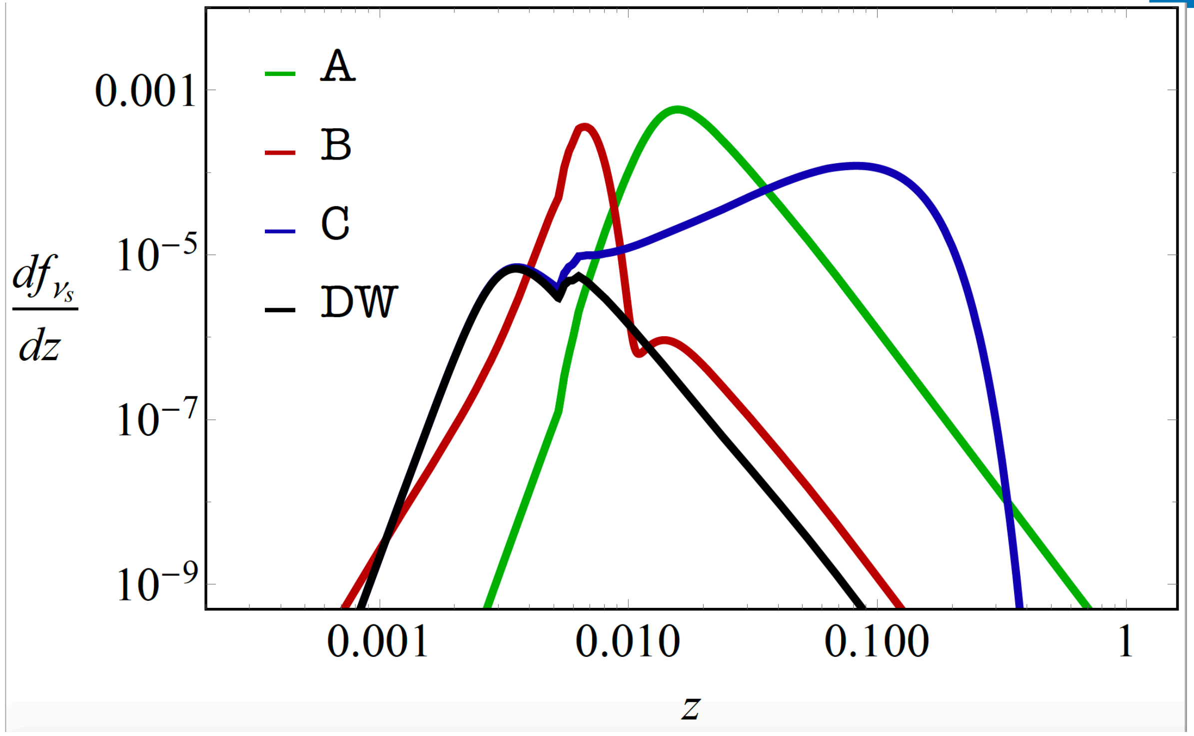
Production peaks at a lower temperature

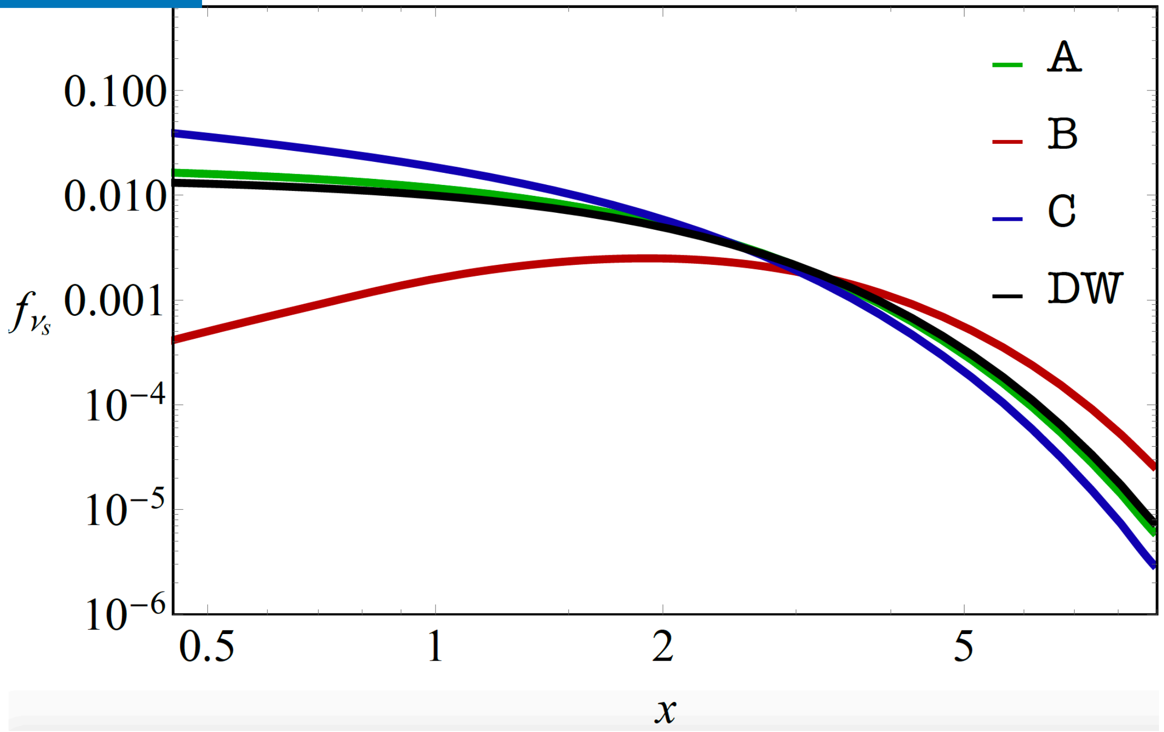
de Gouvêa, MS, Tangarife and Zhang PRL 2020

Neutrino Spectra

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

$$x = \frac{p}{T}$$





- Free streaming length: $\lambda_{\mathrm{FS}} = \int_0^t dt \frac{v(t)}{a(t)} \simeq 1.2\,\mathrm{Mpc} \left(\frac{1\,\mathrm{keV}}{m_4}\right) \left(\frac{\langle x \rangle}{3.15}\right)$

Structure formation bounds evaded?

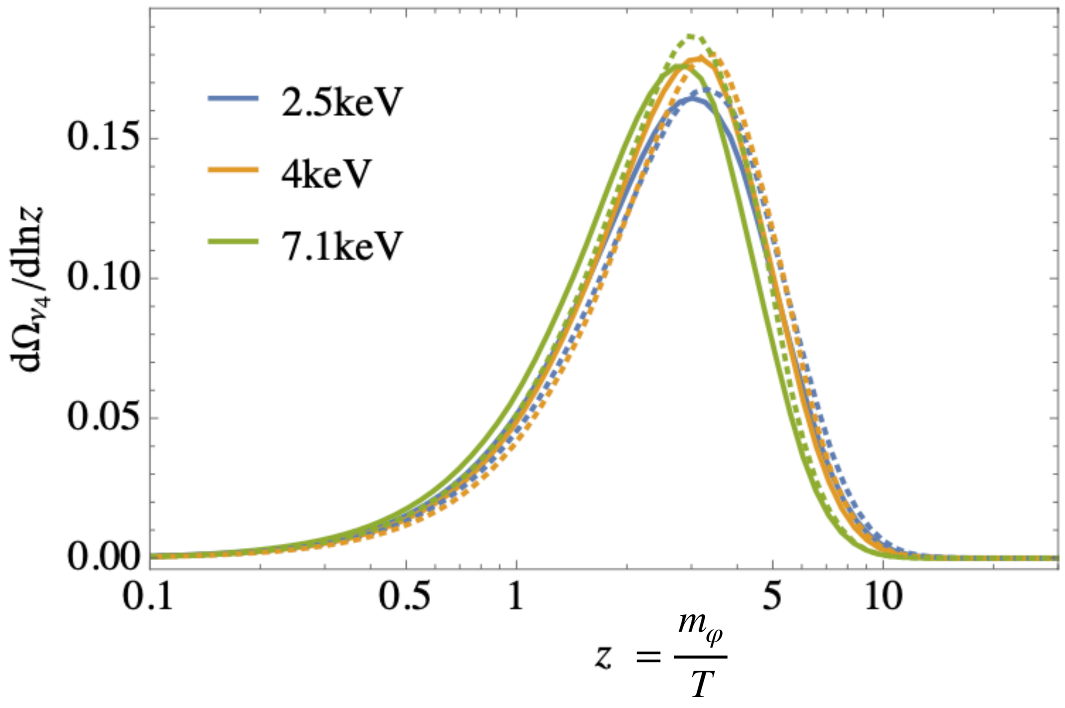


FIG. 5. Time dependence of SνDM, for three values of m_4 as labelled. The other parameters are chosen for producing the observed DM relic density. The solid (dashed) curves correspond to real (complex) scalar ϕ case.

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

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

More conclusive work needed!

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Chemical potential

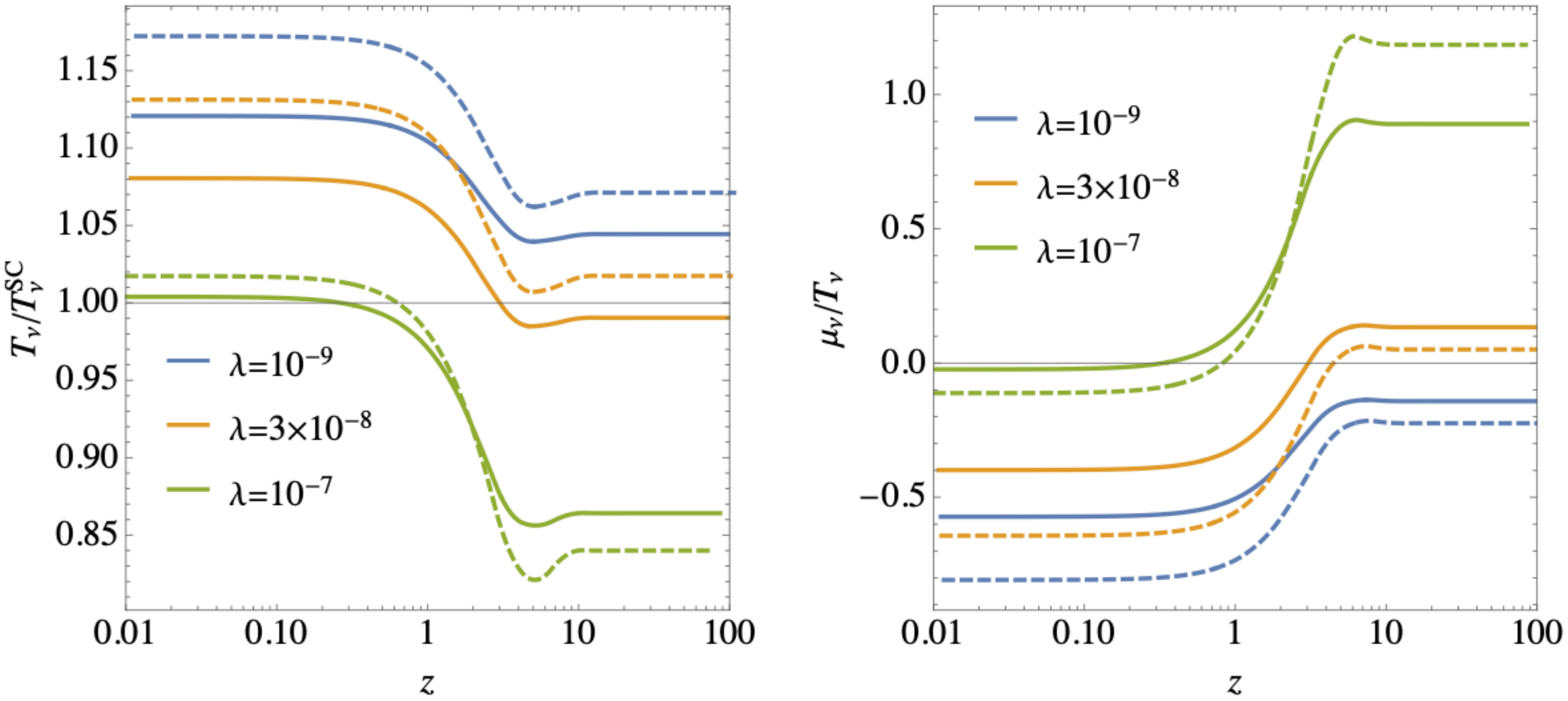

FIG. 4. Evolution of ratios $T_\nu(z)/T_\nu^{\mathrm{SC}}(z)$ and $\mu_\nu(z)/T_\nu(z)$ as functions of z for three values of λ_ϕ and holding $m_\phi = 5\,\mathrm{keV}$ fixed. Solid (dashed) curves correspond to real (complex) scalar ϕ case.

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. $U(1)_{B-L}$

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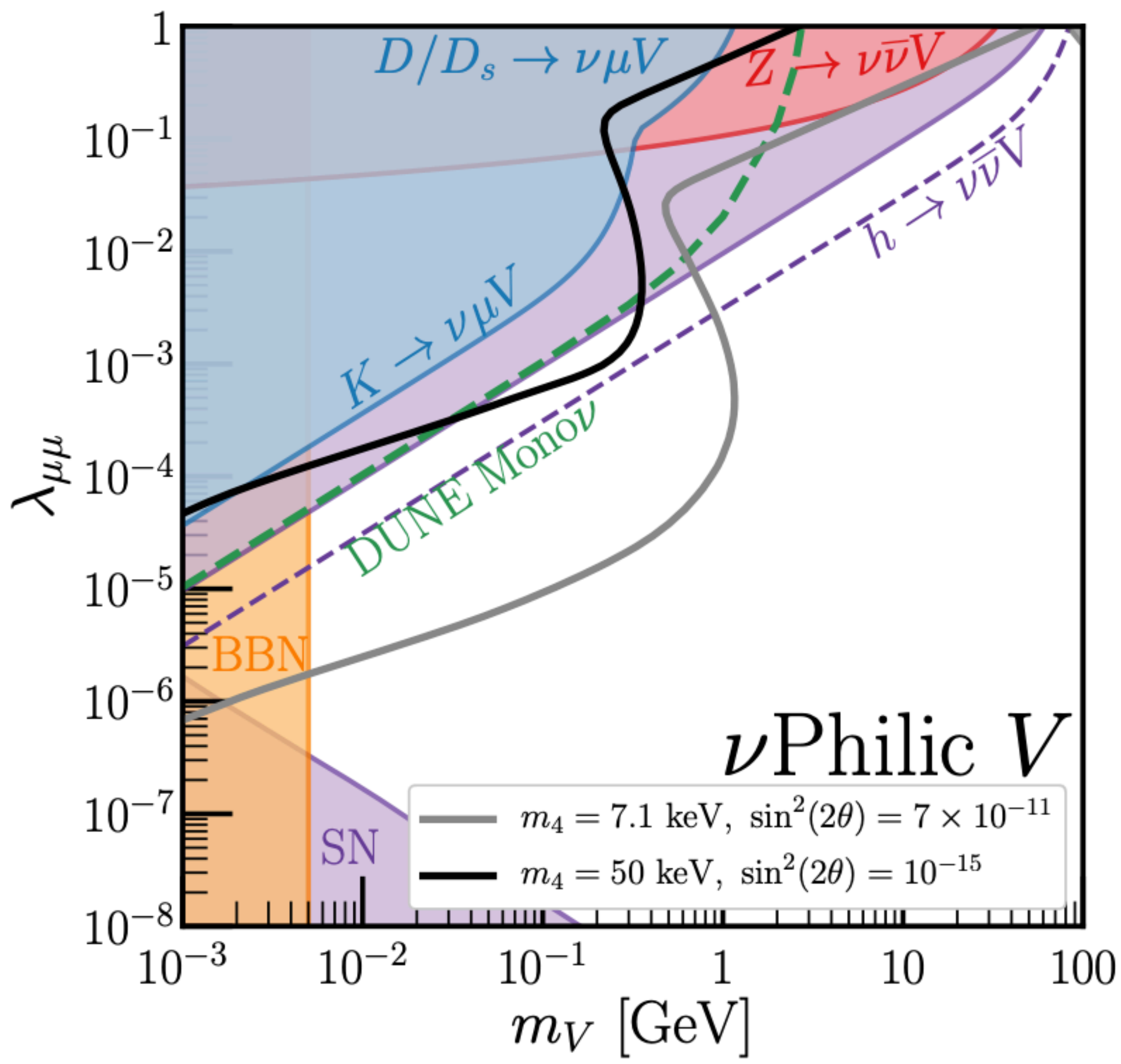
Neutrinophilic vector

Consider the vector equivalent of the neutrinophilic interaction.

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



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.

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