# Dodelson-Widrow mechanism in the presence of neutrino self-interactions

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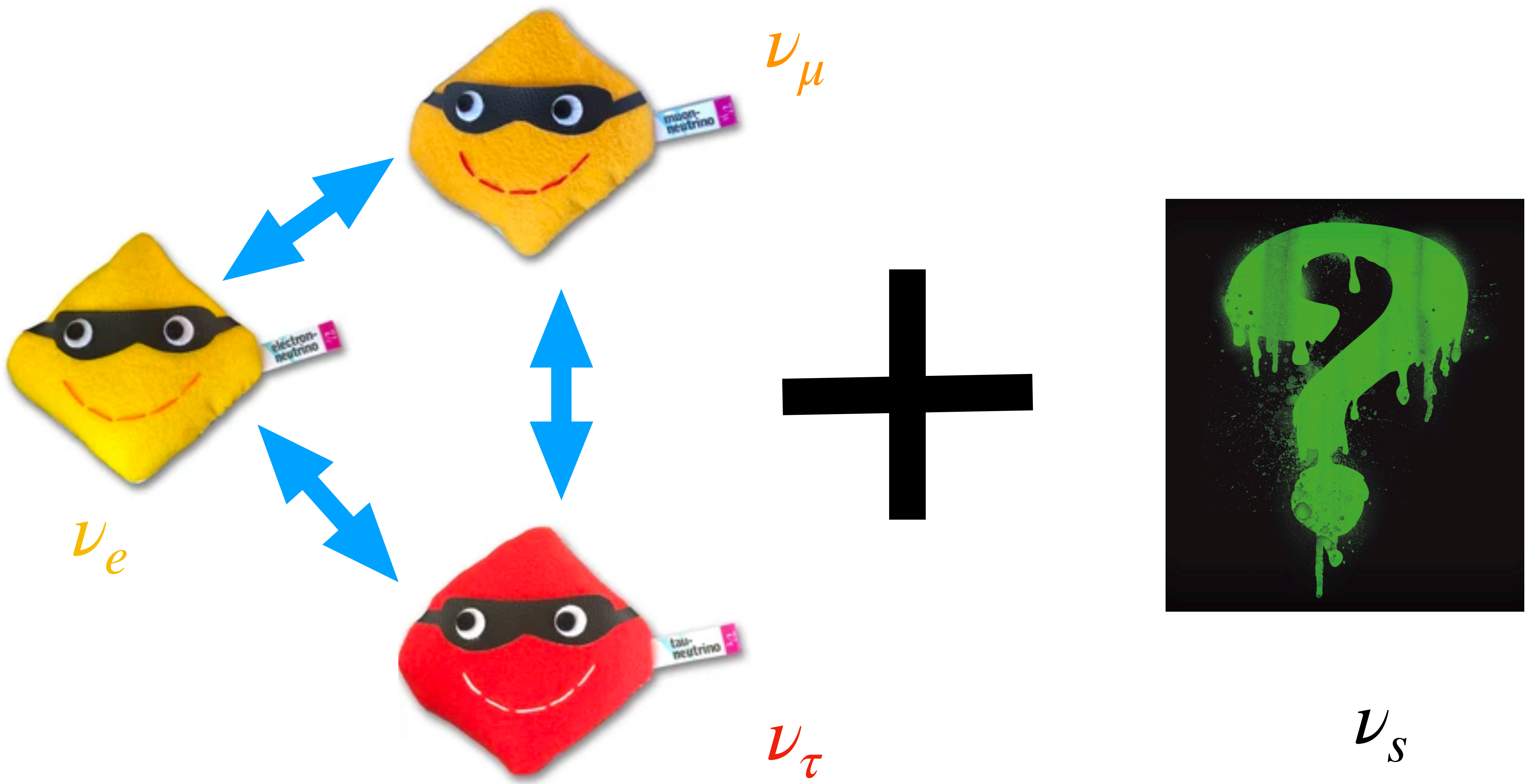
Northwestern University

# The sterile neutrino




Are there more of these ?

Four suspects:

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

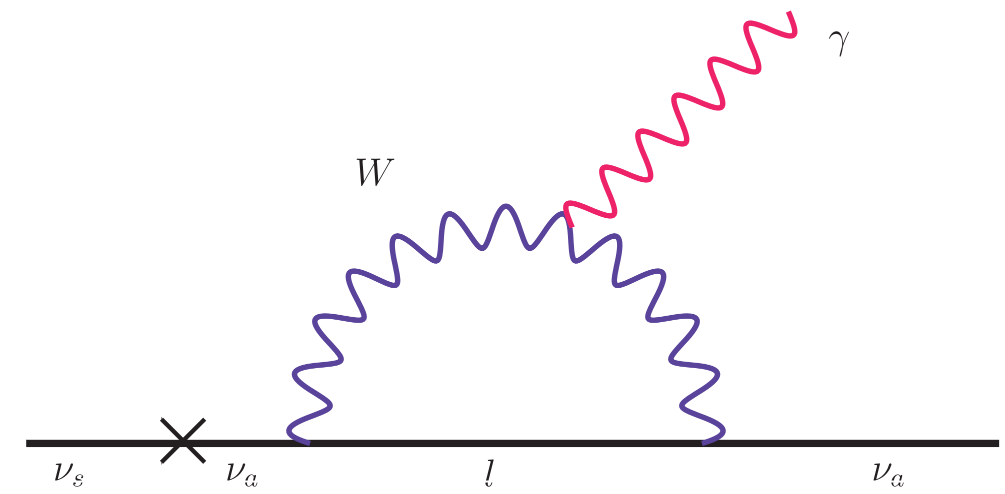
# Sterile neutrino: the riddler neutrino


- 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

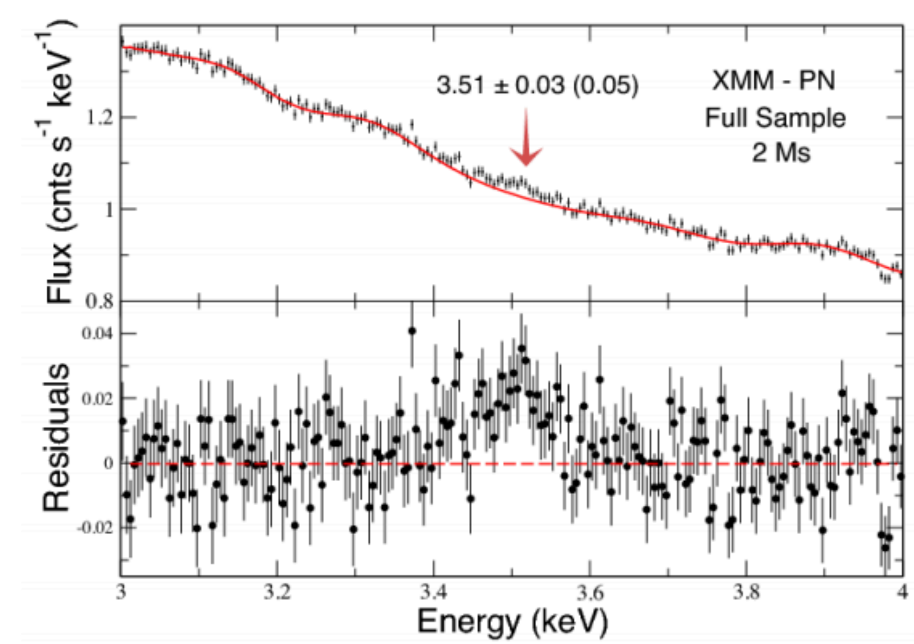
- 4th mass eigenstate $\nu_4 = cos\theta\, \nu_s + sin\theta\, \nu_a$




- 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…



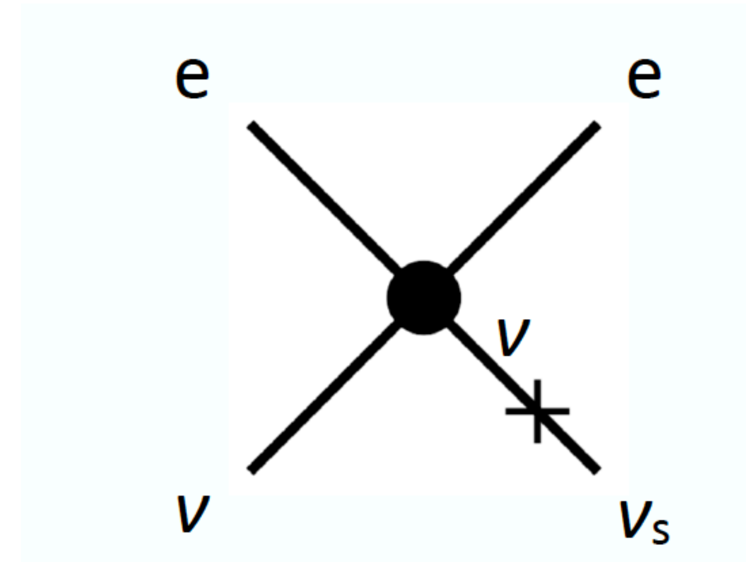

- Non-observation puts bound on $m_4 - sin\,2\,\theta$ plane.

- Radiative decay leads to line at $E_\gamma = m_4/2$.
Hints of a line at $m_4 = 7.1\,\mathrm{keV}$?– 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.

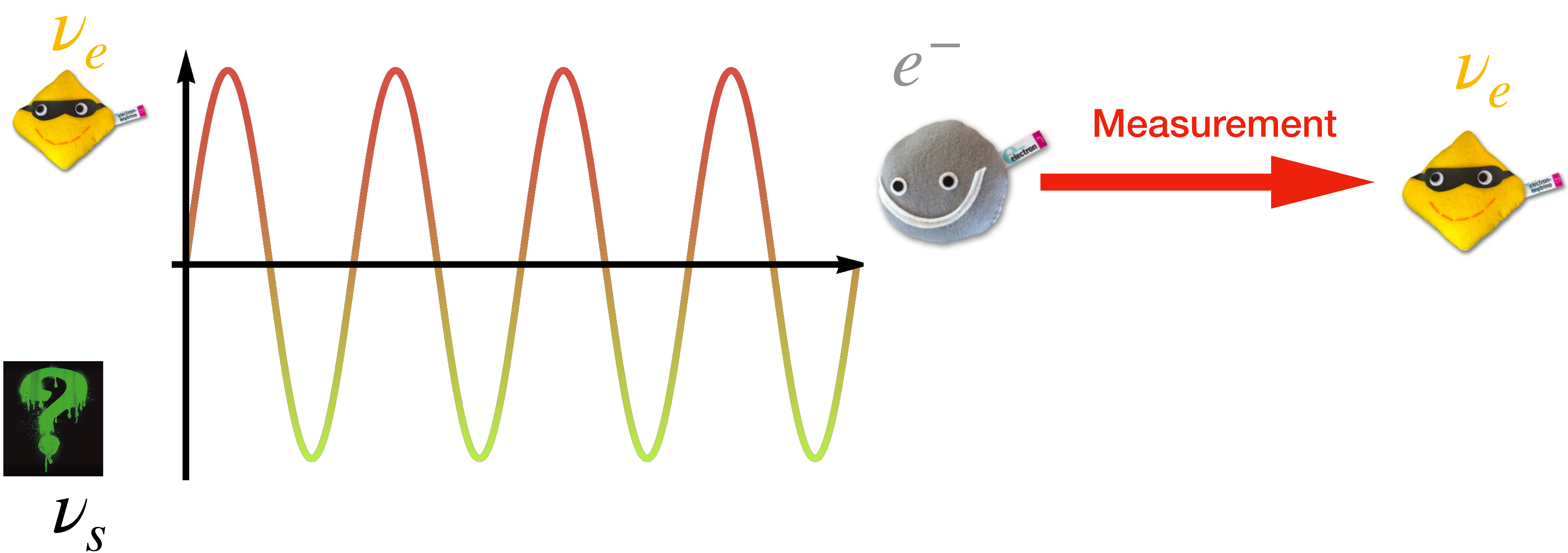
- But how do we produce these neutrinos?

# 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

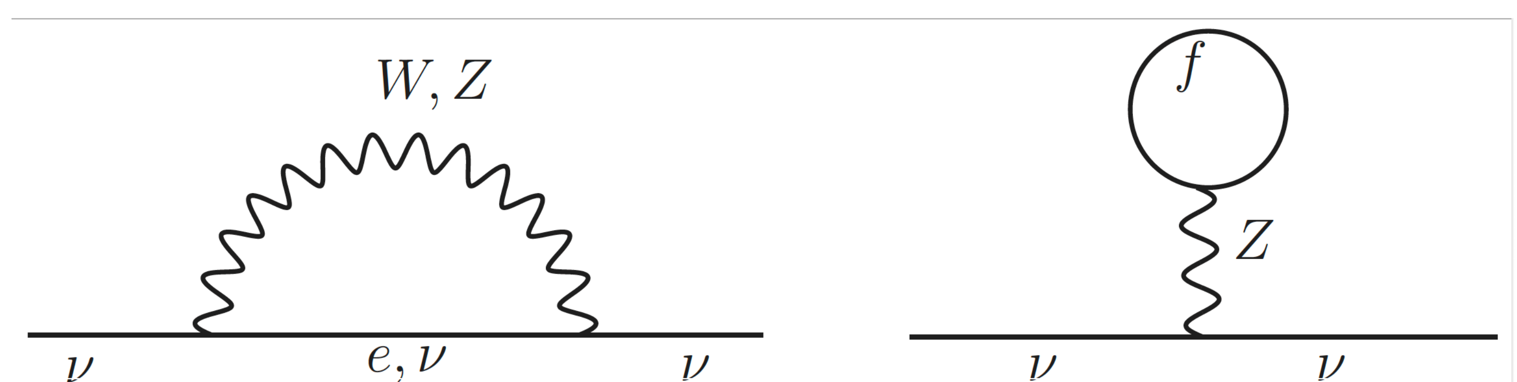
$\Delta = m_s^2/2E$

Quantum Zeno damping

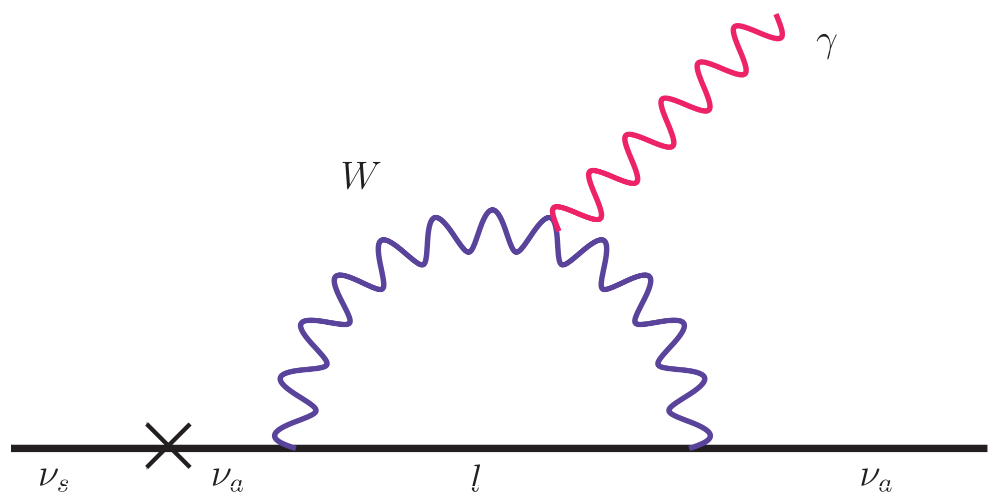
Matter potential $V = V_T + V_D$

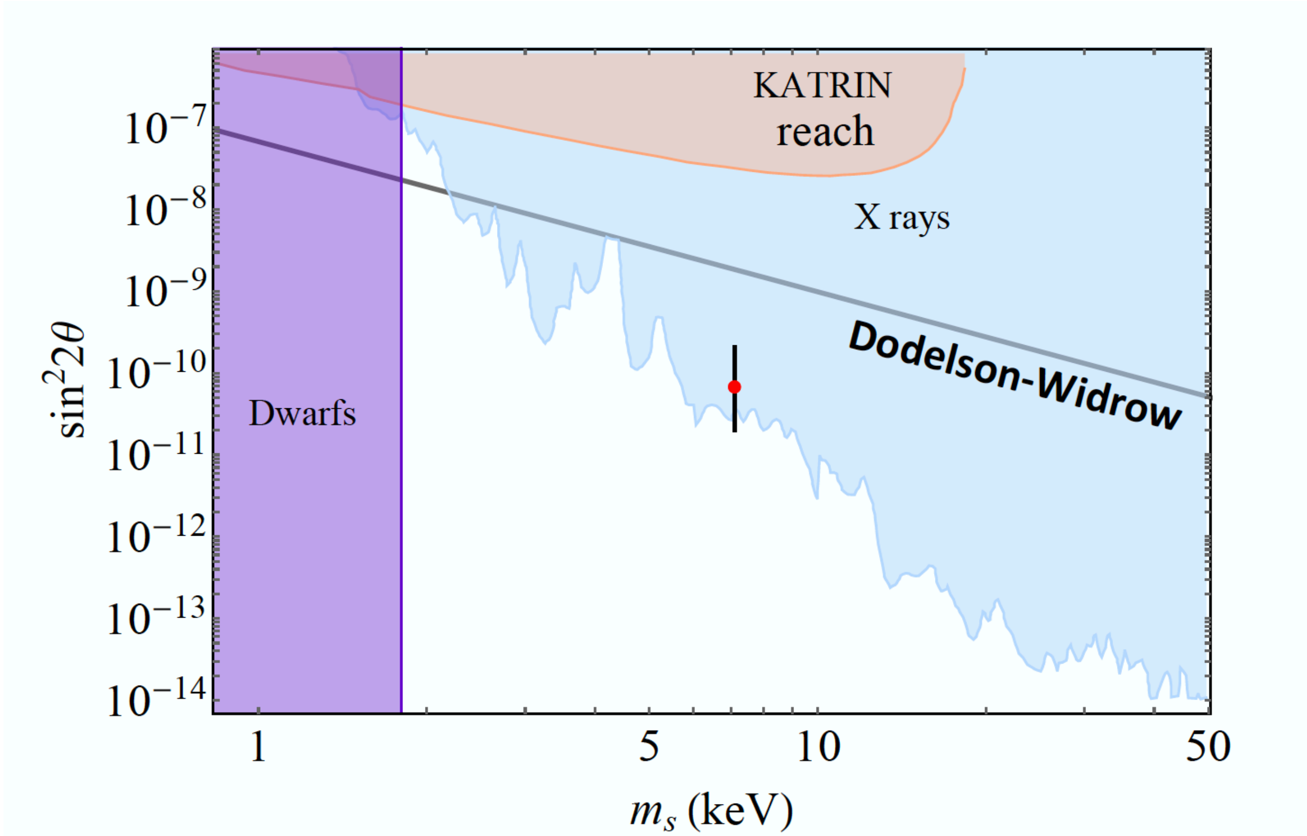
Finite temperature: $V_T \propto T$

Finite density: $V_D \propto n_f$



# The Dodelson-Widrow mechanism…constrained




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

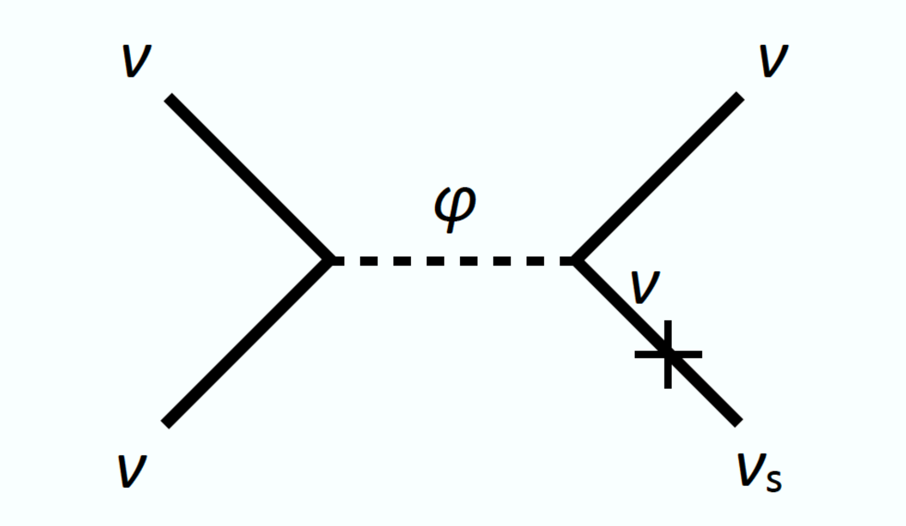
- A finite lepton asymmetry (Shi-Fuller Mechanism) can help. Required lepton asymmetry difficult to constrain. Shi and Fuller, PRL 1999, Fuller, Abazajian and Patel PRD 2001

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

# Opening up the chamber of secret : NSSI

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

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

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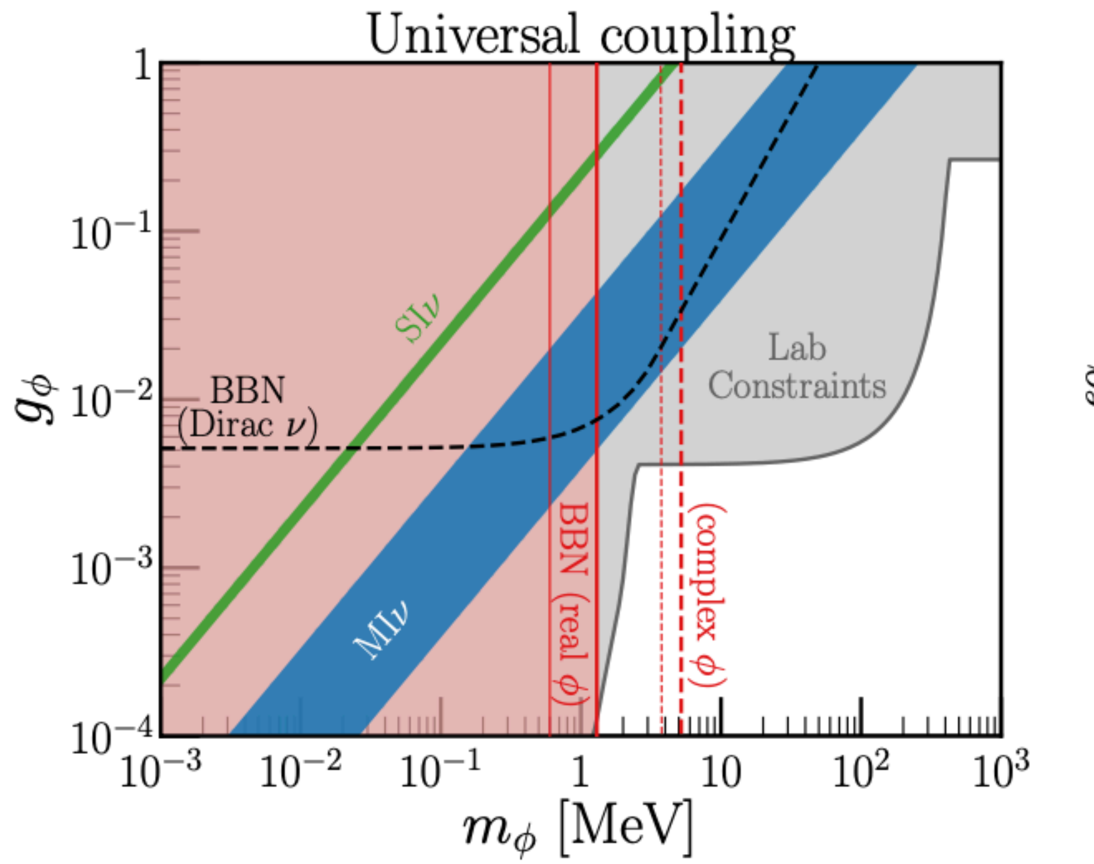
- Relic ~ (rate) X (mixing angle).

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

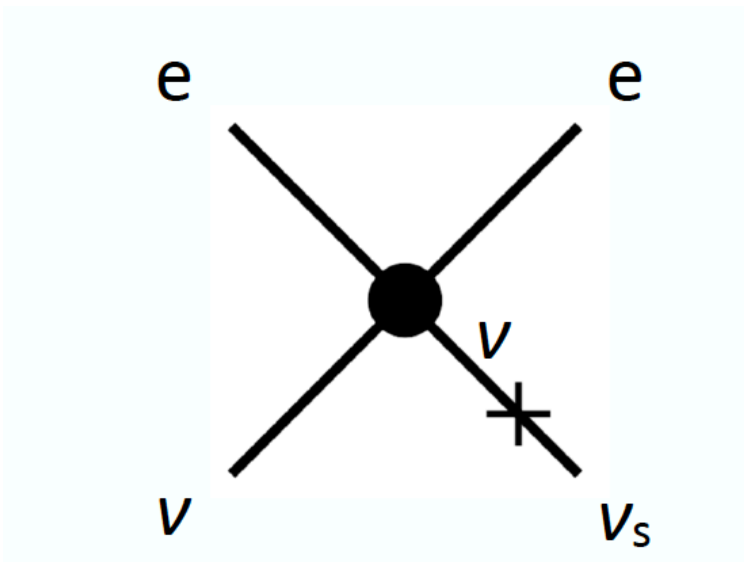
- This opens up new production channels for sterile neutrino DM.




Blinov, Kelly, Krnjaic and McDermott, PRL2018

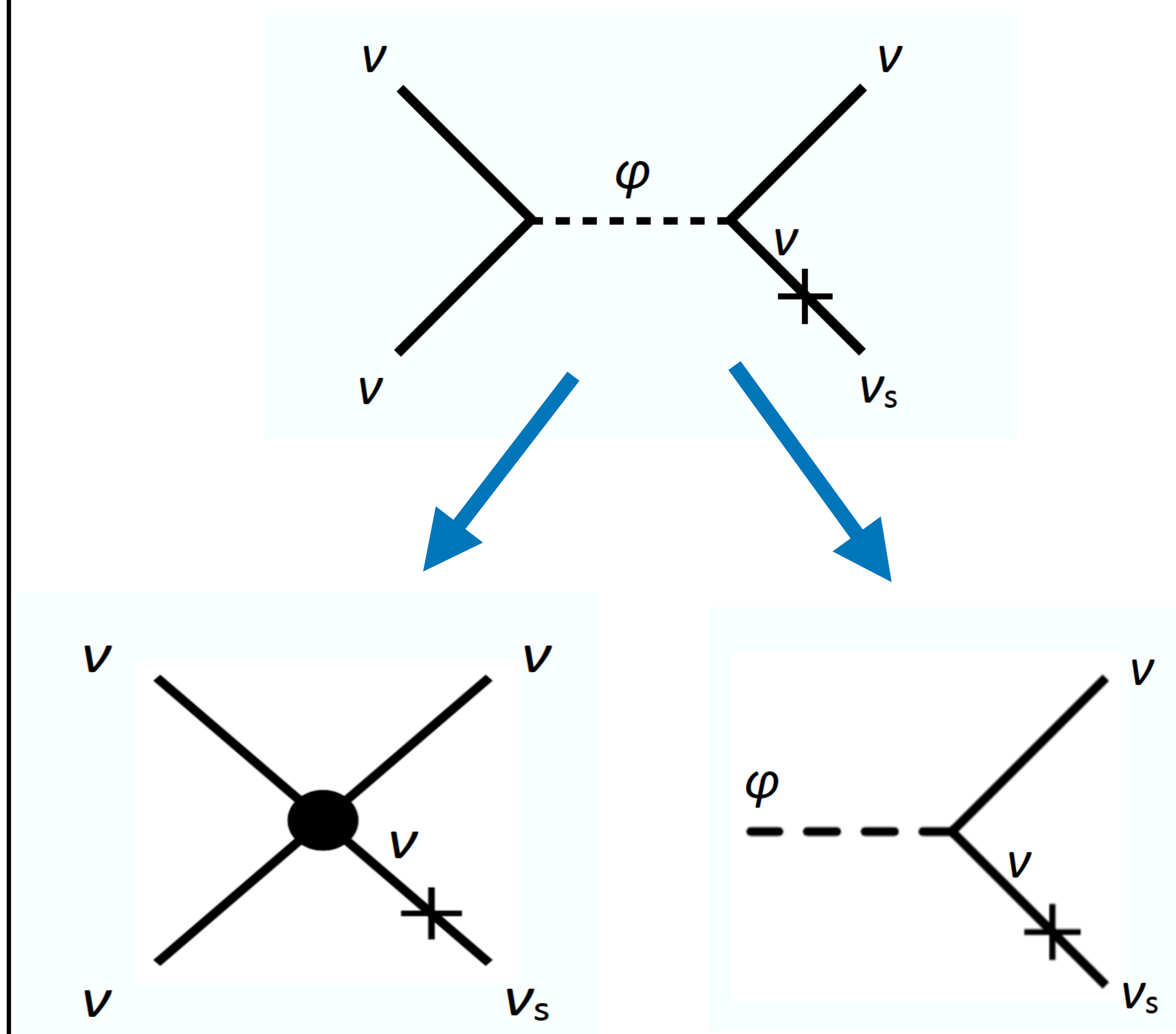
# What changes in the DW mechanism?

## S.M




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

## S.M + Self-Interactions



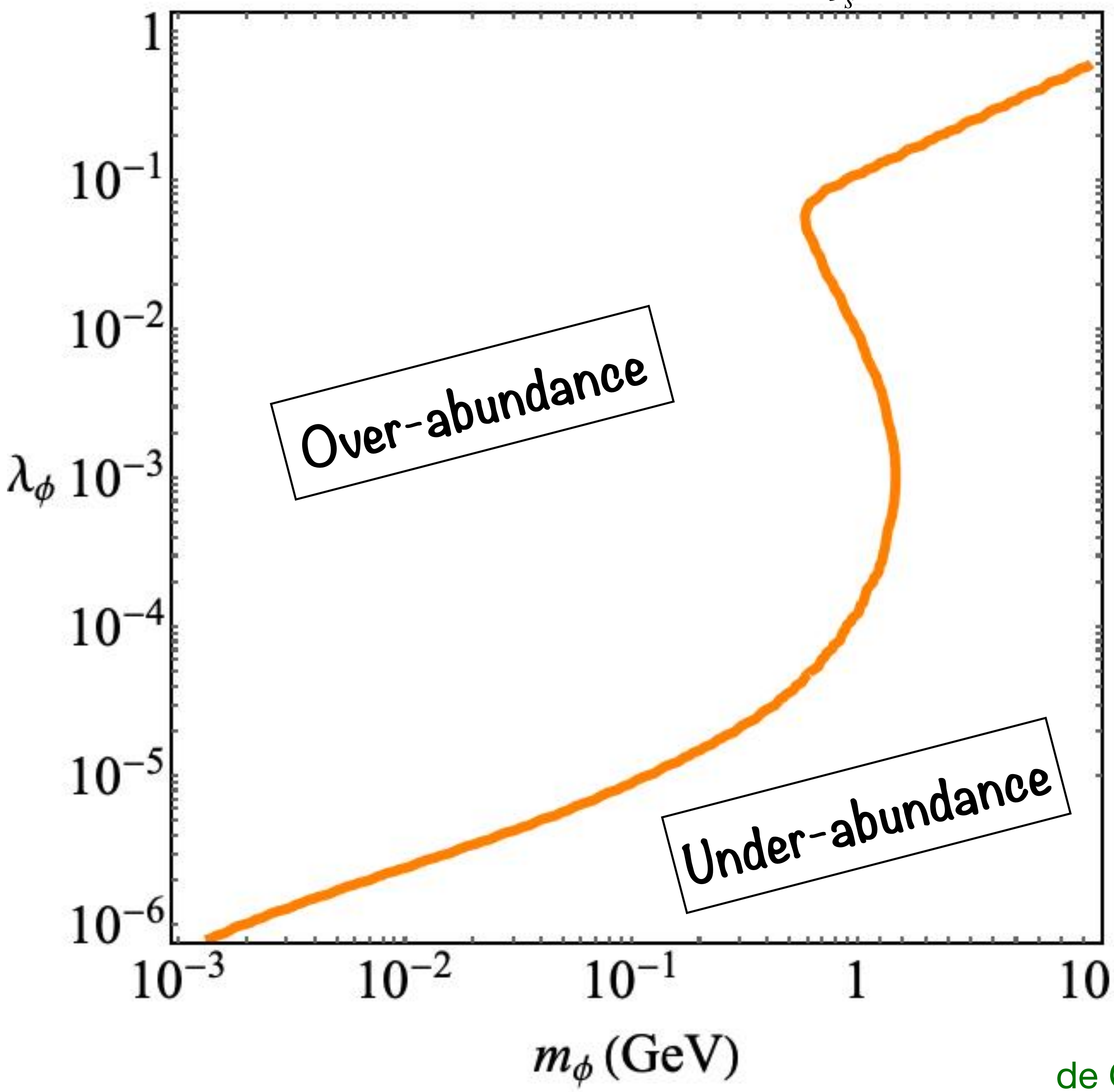

$M_{\varphi} > T_{peak}$

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

# Numerical estimates

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

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




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

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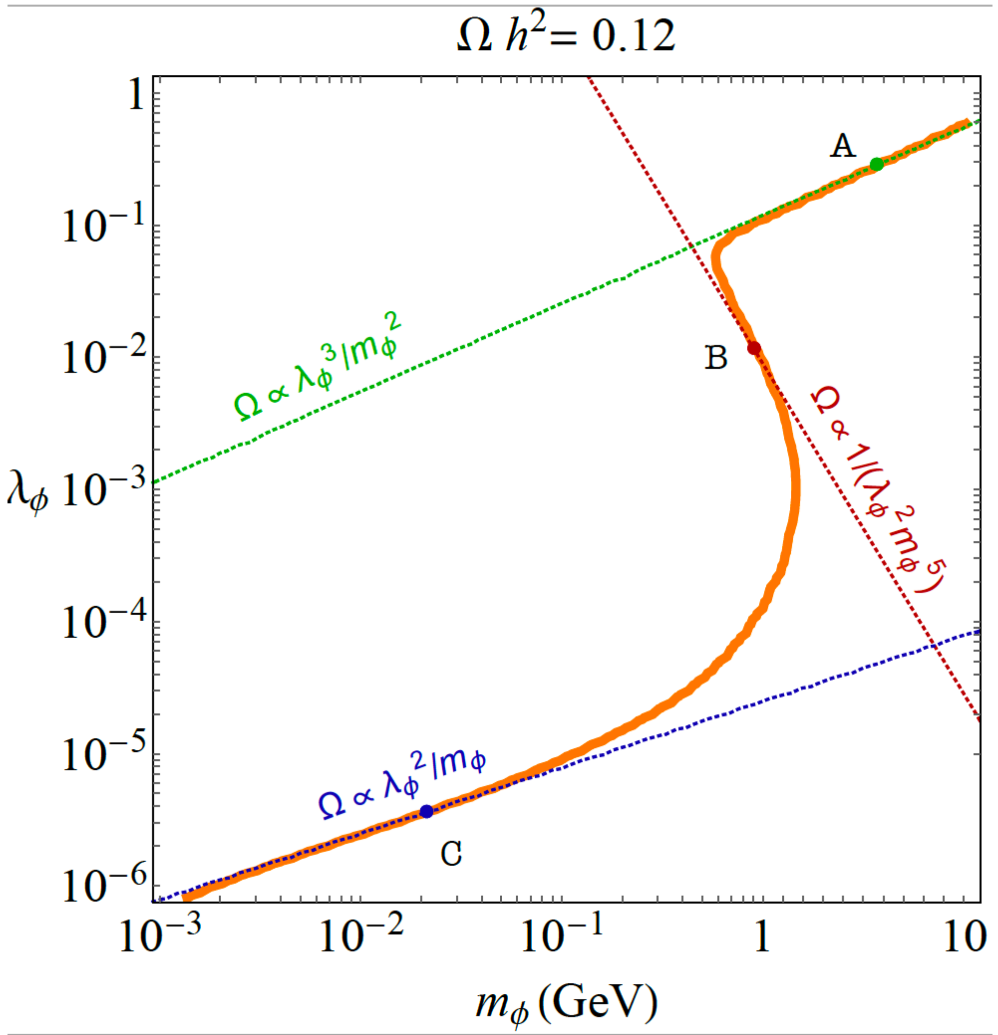
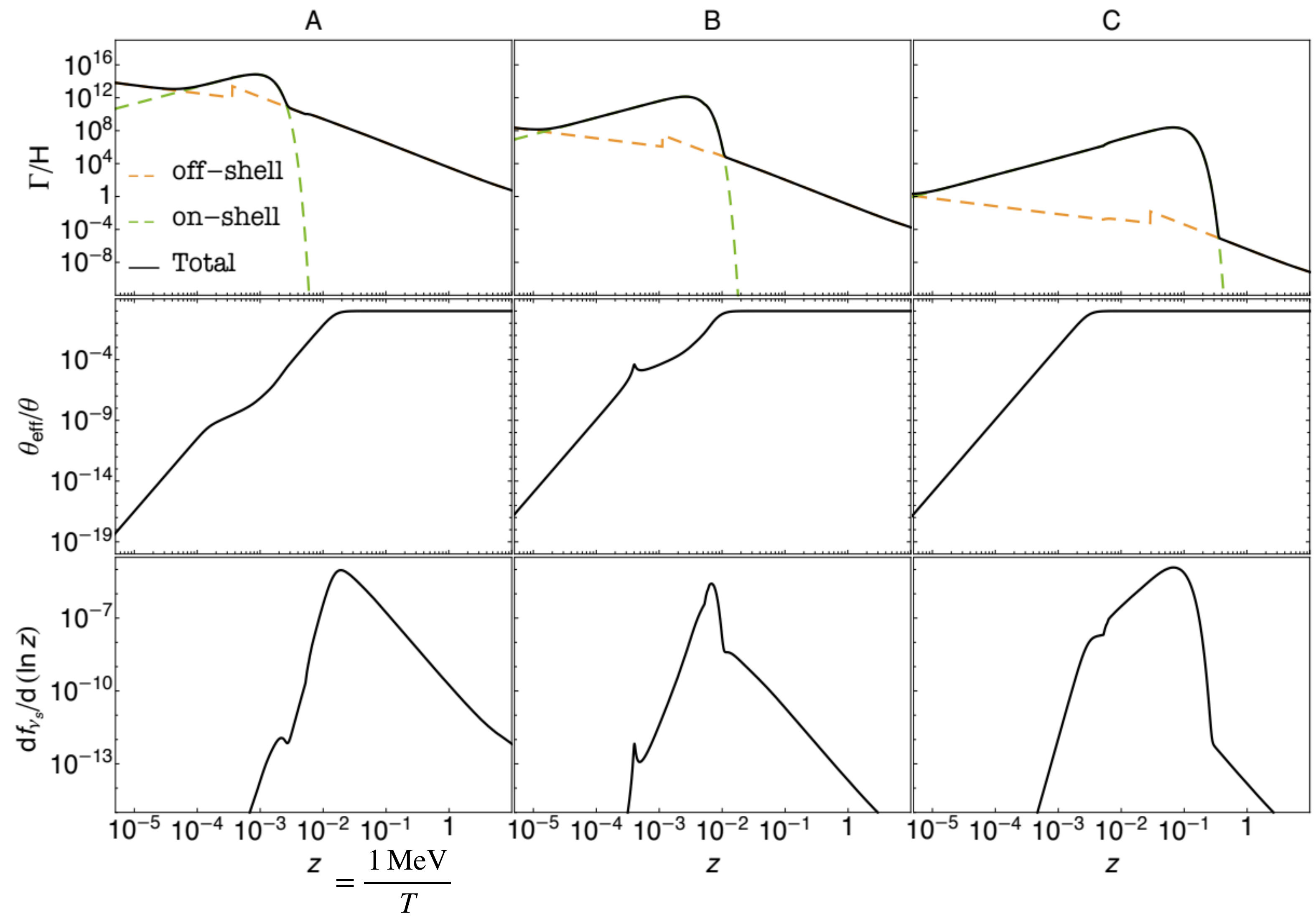
Cherry, Friedland, Shoemaker 1605.06506

# Explanation of Results



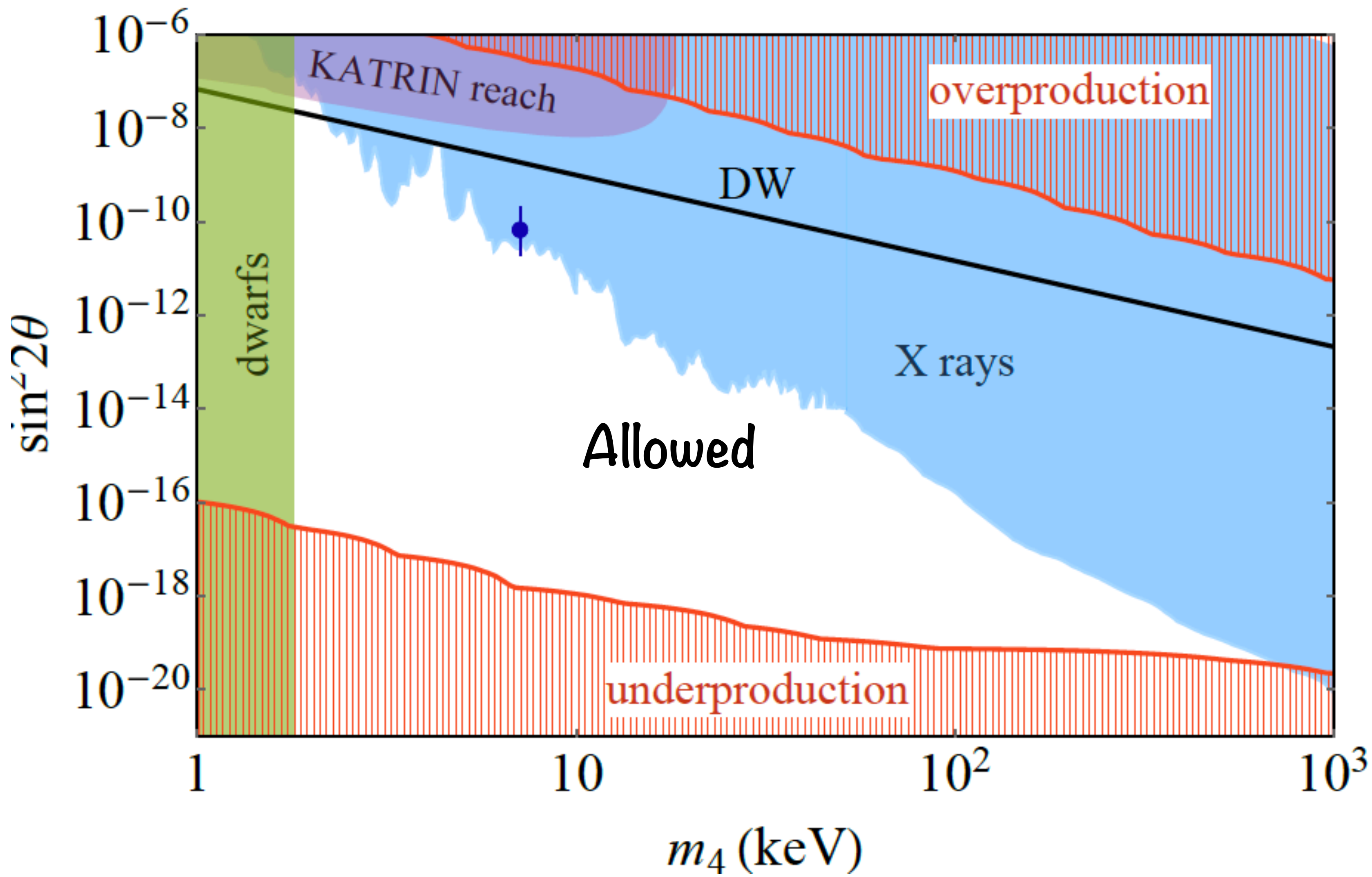




1. A: $t_\varphi < t_{\Delta=V} < t_{\Gamma=H}$. Production around $t_{\Delta=V}$ from scattering via an off-shell $\varphi$. Similar to the usual DW mech.

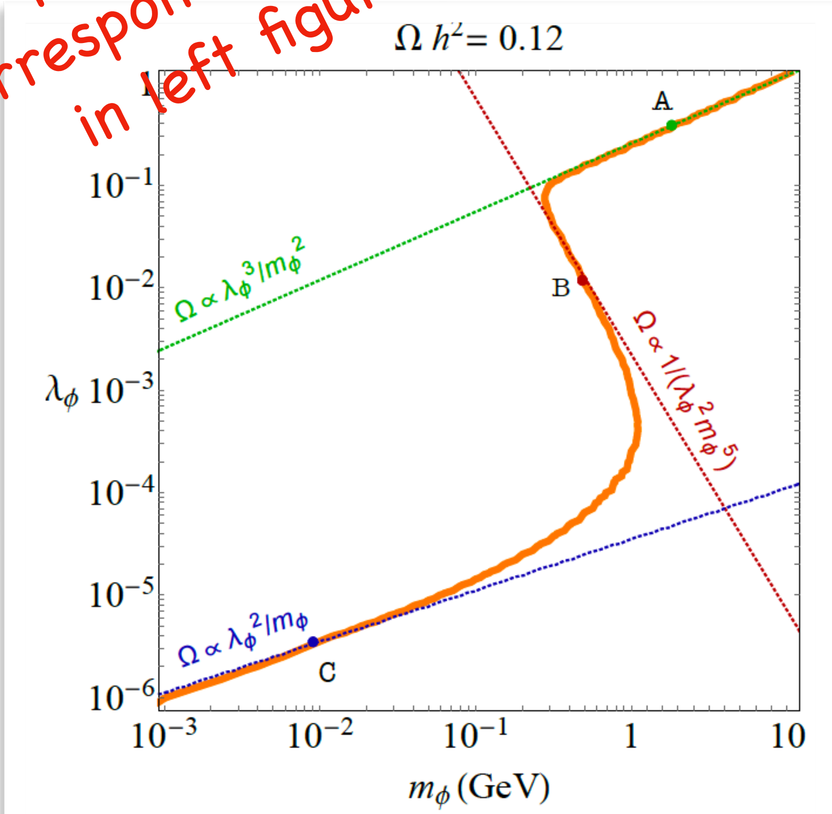
2. B: Intermediate mass, coupling: $t_\varphi < t_{\Gamma=H} < t_{\Delta=V}$ .Peak production happens in $(t_\varphi < t < t_{\Gamma=H})$ when $\theta_{\rm eff}$ is suppressed. Production through scattering via on-shell $\varphi$.

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

# Allowed Relic Density window




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

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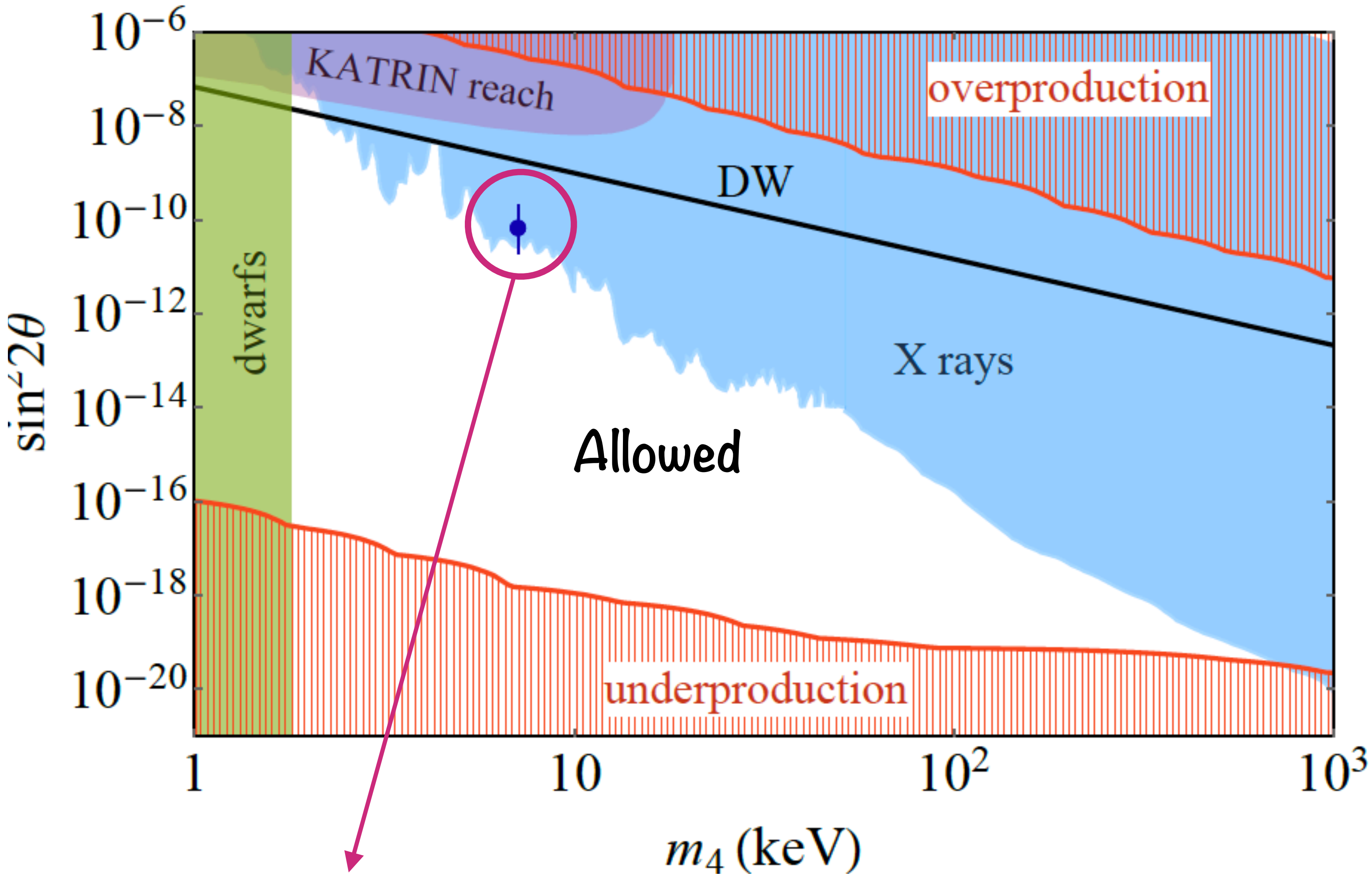


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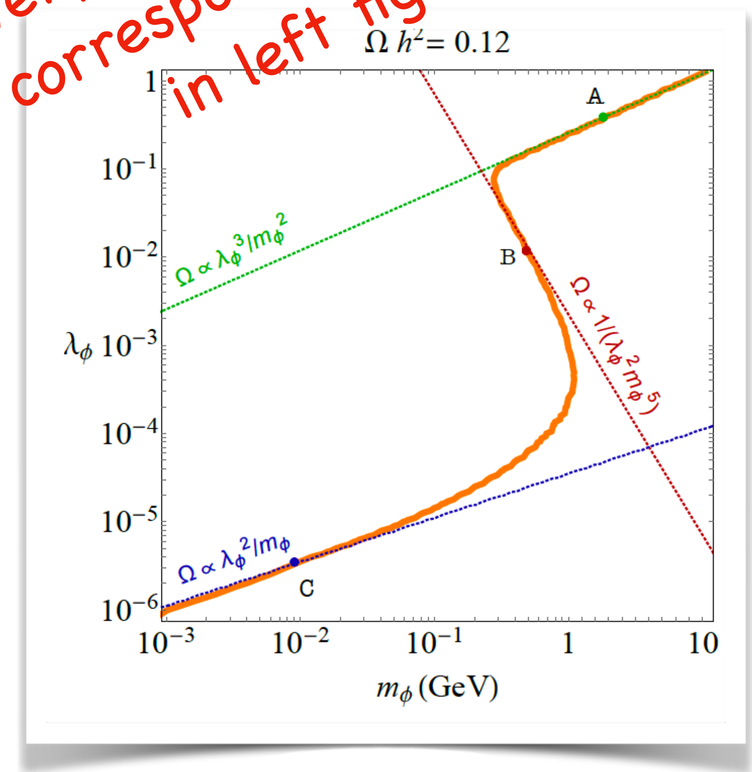
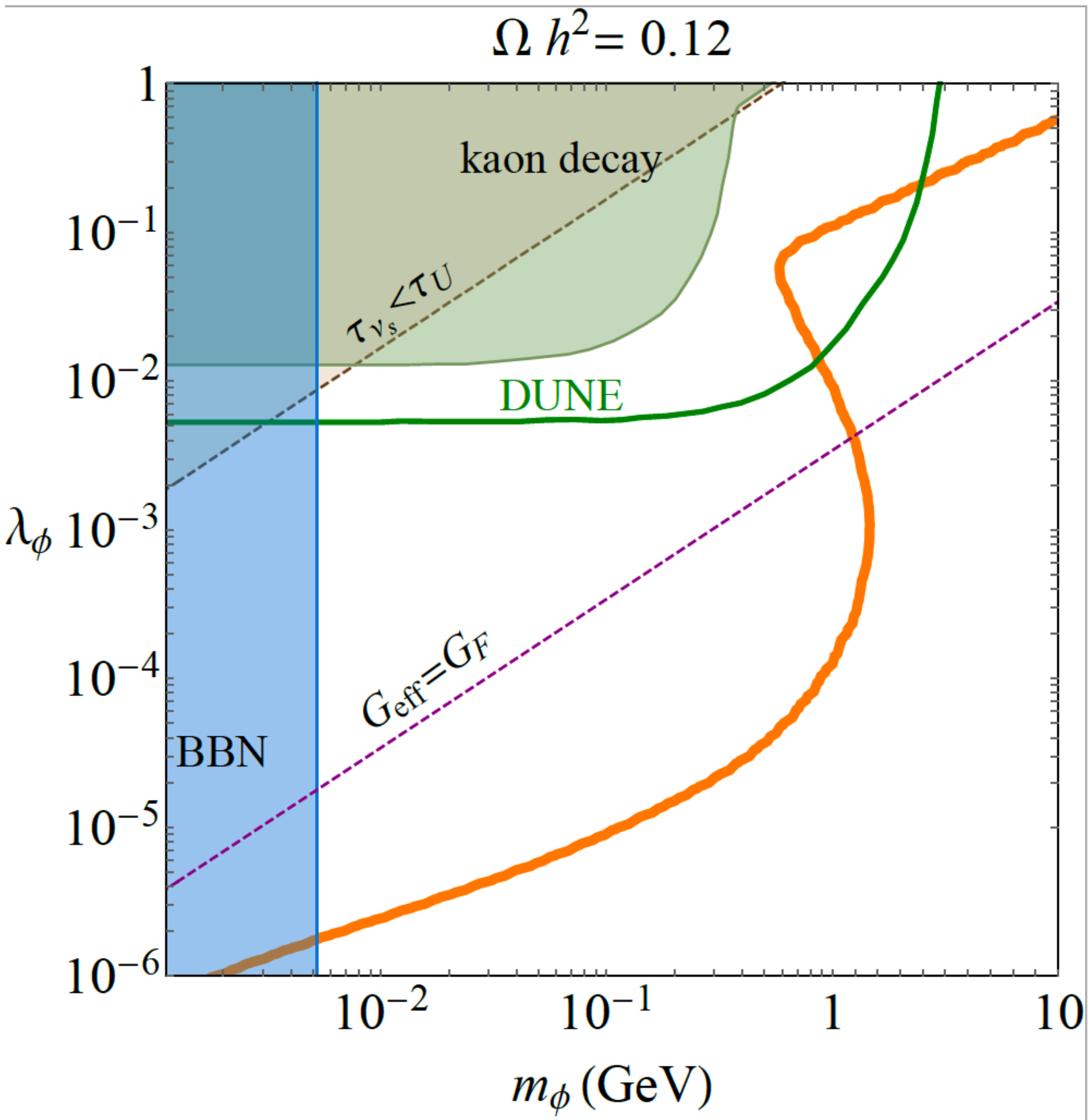



Can be used to satisfy the 3.5 keV X-ray line also ~

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

# Experimental tests

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

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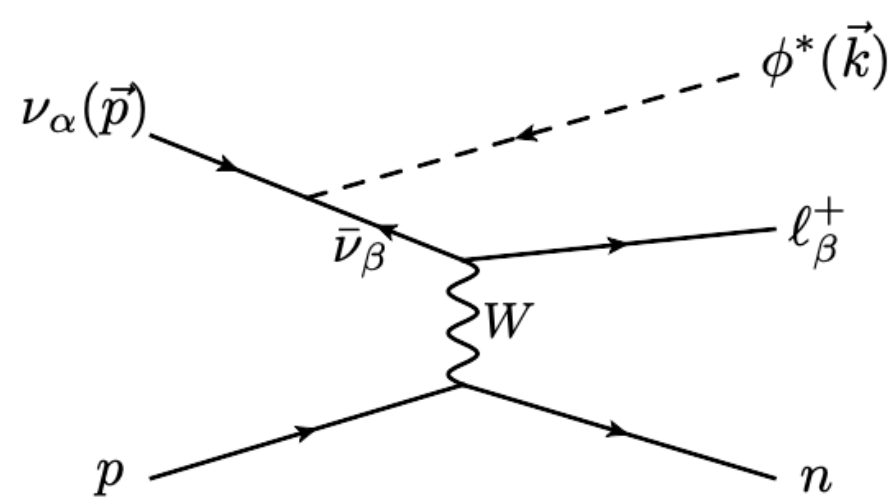
- Interested in range $1\,\mathrm{MeV} \leq m_\varphi \leq 10\,\mathrm{GeV}$
- $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu\,.$ Bounds from $\mathrm{Br}(K^- \to \mu^- 3\nu) < 10^{-6}\,.$
- BBN bounds on $m_\varphi$.
- DUNE can look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$.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



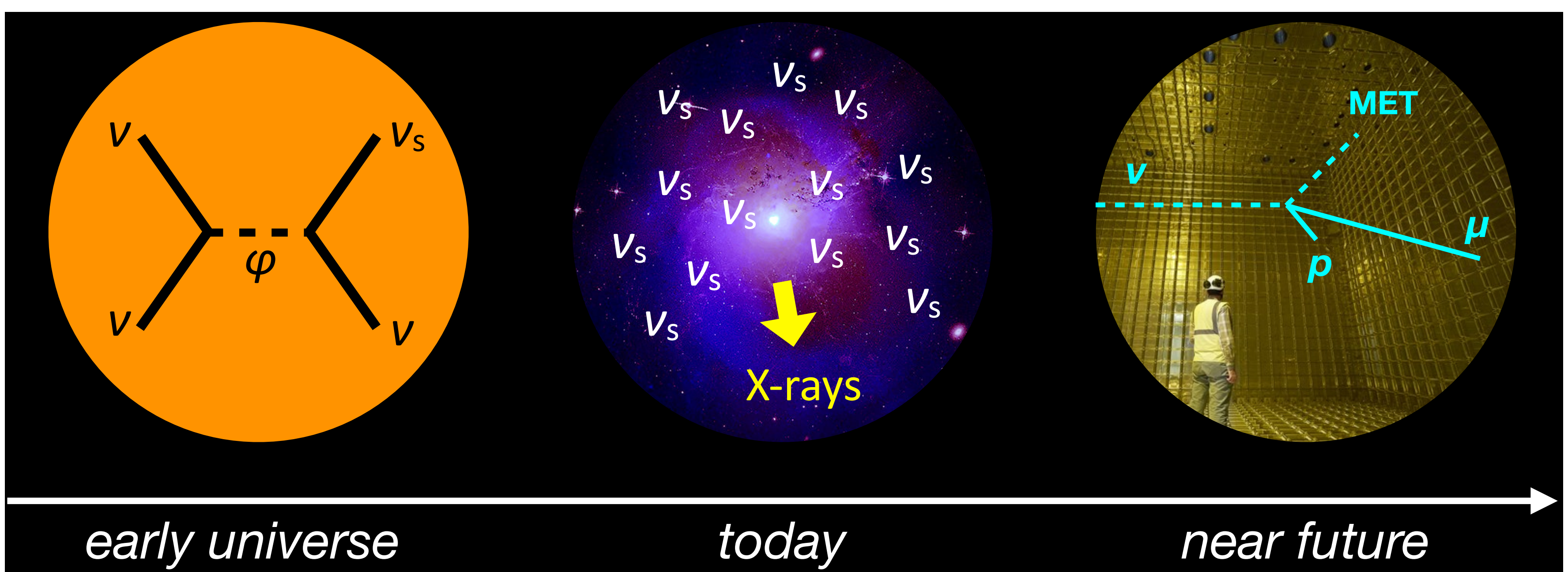

Berryman, de Gouvêa, Kelly and Zhang PRD2018
Blinov, Kelly, Krnjaic and McDermott, PRL2018

# 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!**