Minimal decaying dark matter: from cosmological tensions to neutrino constraints

Lea Fuß, Mathias Garny, Alejandro Ibarra
based on arXiv:2403.15543

The Dark Matter Landscape: From Feeble to Strong Interactions (MITP)

August 30, 2024

SFB 1258 Neutrinos Dark Matter Messengers

Outline

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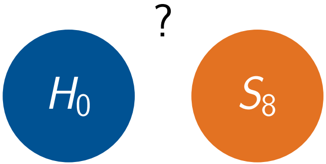
Cosmological tensions: A hint for something new?



S_8 tension:

persistent tension of $2 - 3\sigma$ between early and late universe measurements in the clustering on small scales

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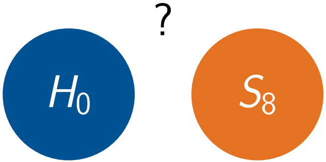

$$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$$

$$\sigma_R^2 = \int_0^\infty \frac{dk}{k}\Delta_m(k)\tilde{W}_R(k)^2$$

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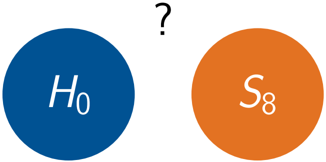

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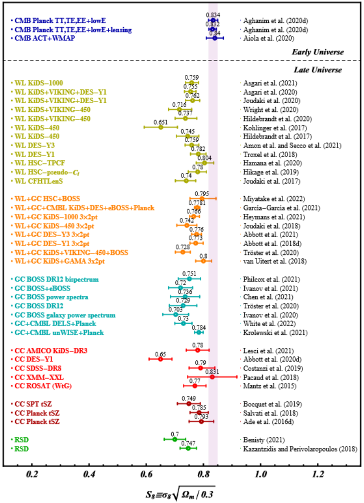

[Abdalla et. al., arXiv:2203.06142]

Decaying Cold Dark Matter

DM model that generates suppression on small scales
→ **Decaying Cold Dark Matter (DCDM)**

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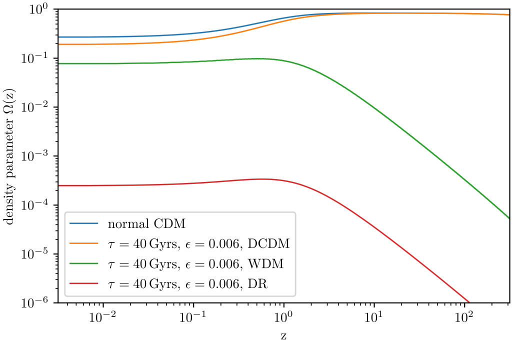
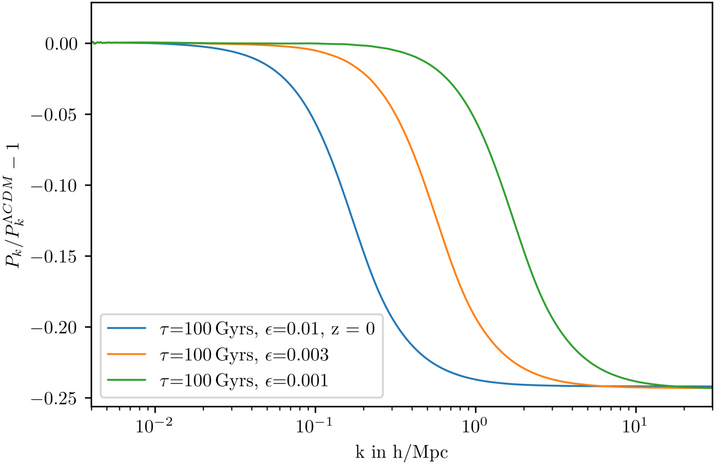
$$\begin{aligned}
\dot{\bar\rho}_{\mathrm{dcdm}} &= -3\mathcal{H}\bar\rho_{\mathrm{dcdm}} - a\Gamma\bar\rho_{\mathrm{dcdm}} \\
\dot{\bar\rho}_{\mathrm{wdm}} &= -3(1+\omega)\mathcal{H}\bar\rho_{\mathrm{wdm}} \\
&\quad + (1-\epsilon)a\Gamma\bar\rho_{\mathrm{dcdm}} \\
\dot{\bar\rho}_{\mathrm{dr}} &= -4\mathcal{H}\bar\rho_{\mathrm{dr}} + \epsilon a\Gamma\bar\rho_{\mathrm{dcdm}}
\end{aligned}$$



Suppression through decay

- Compute power spectrum with modified CLASS code for DCDM from [Abellan, Murgia, Poulin, arXiv:2102.12498]



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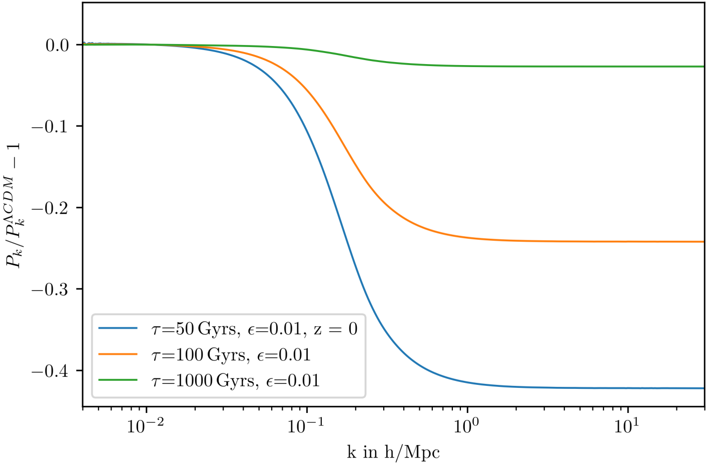


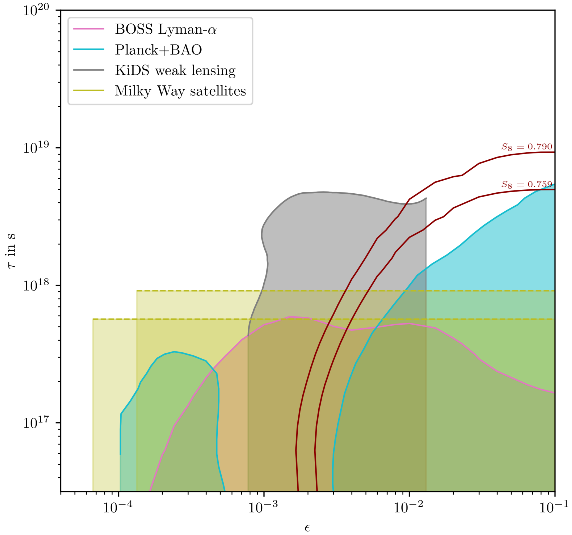
Cosmological Constraints

Lyman-α forest
[LF, Garny, arXiv:2210.06117]

CMB and BAO
[Simon et al., arXiv:2203.07440]

Weak lensing shear data
[Bucko et al., arXiv:2307.03222]

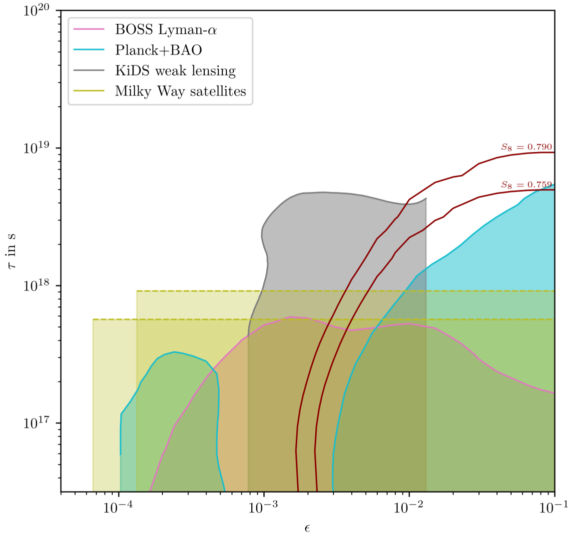
DM halo evolution
[DES Collab., arXiv:2201.11740]



Cosmological Constraints

singles out parameter space of interest to address S_8 tension:

- $\tau \sim 10^{18}\,\mathrm{s} \sim 100\,\mathrm{Gyrs}$
- $\epsilon \sim 10^{-2}$



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I. Cosmological model

II. Theoretical model building

III. New phenomenology

  - Neutrinos
  - Production via freeze-in
  - Low-mass signatures

IV. Outlook and Summary

A theoretical framework

Question: *How can such a model be realized theoretically?*

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Can DM decay instead into neutrinos?

Minimal approach: as few ingredients as possible

- 2 new fermionic particles N_1 and N_2 as DM
- SM neutrinos as "DR"
- described by effective interaction

The challenge

What we want:
(for S_8)

decay into neutrinos
with $\tau \sim 10^{18}\,\mathrm{s}$

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with $\tau \gtrsim 10^{26} - 10^{30}$ s

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Challenge!

$\Rightarrow$ coupling to SM visible particles needs to be suppressed around 10 orders of magnitude

New symmetries

easiest operators:

$$\mathcal{L} \sim (\bar{L} N_1)(\bar{N}_2 L) + \text{h.c.}$$
$$\mathcal{L} \sim (\bar{L} N_1)(\bar{N}_2^c L) + \text{h.c.}$$

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impose 2 U(1) symmetries:

L	**N**
$N_2 \to e^{i\alpha} N_2$	$N_2 \to e^{i\alpha} N_2$
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$$\Rightarrow \boxed{\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^4} \left(\bar{L} \tilde{H} P_R N_2\right) \left(\bar{L} \tilde{H} P_R N_1\right) + \text{h.c.}}$$

with $\tilde{H} = \left(\frac{v_{\text{EW}} + h - iG^0}{\sqrt{2}}, -G^-\right)$

Recognizing DCDM

after electroweak symmetry breaking: $\boxed{\mathcal{L}_{\mathrm{eff}} = \frac{v_{\mathrm{EW}}^2}{2\Lambda^4}\,\bar{\nu} P_R N_2\,\bar{\nu} P_R N_1 + \mathrm{h.c.}}$

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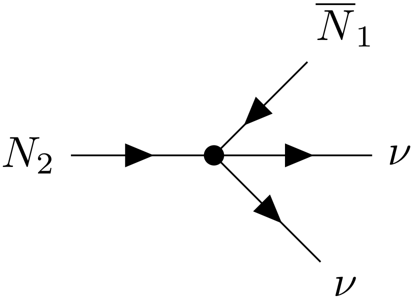

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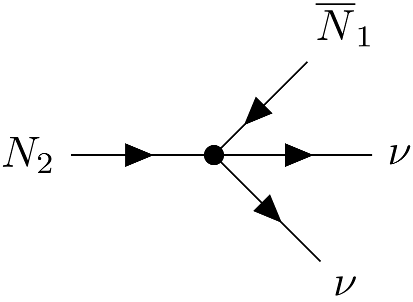

$$\Gamma_{N_2 \to N_1 \nu\nu} = \frac{v_{\text{EW}}^4}{1280\pi^3\Lambda^8}\,(\epsilon M)^5 = \frac{1}{\tau}$$

→ Λ only dependent on model parameters ϵ, τ plus the DM mass M:

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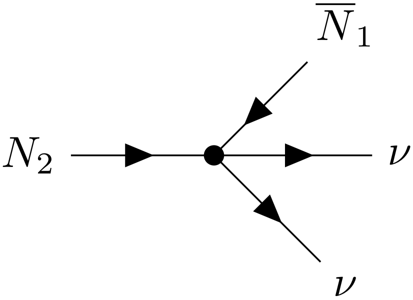

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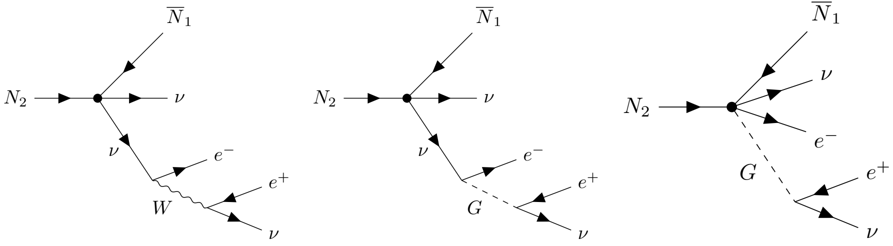
What we wanted!

Charged particles?

- e^+e^- production possible via W and Goldstone boson



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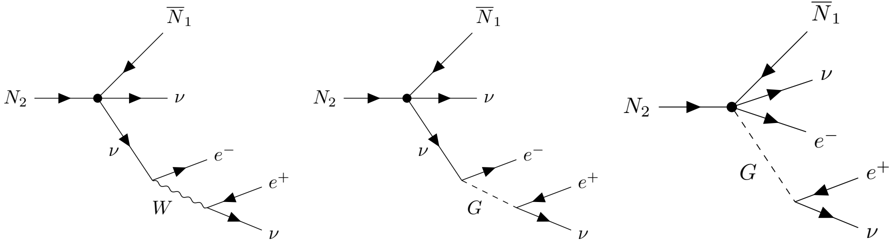
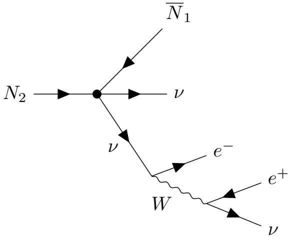


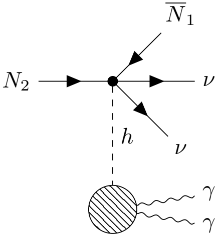
- diagrams heavily suppressed with branching ratio scaling as

$$\frac{\Gamma_{N_2 \to \bar{N}_1 \nu\nu e^+ e^-}}{\Gamma_{N_2 \to \bar{N}_1 \nu\nu}} \propto \frac{(\epsilon M)^4}{v_{\mathrm{EW}}^4}$$

Photons?

- γ production via previous diagram or Higgs loop





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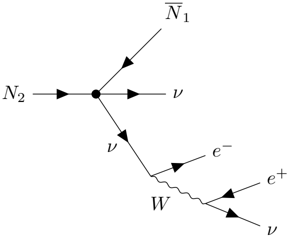

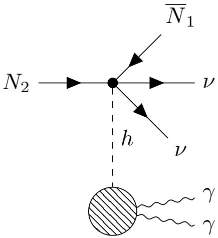

- similarly suppressed with branching ratio

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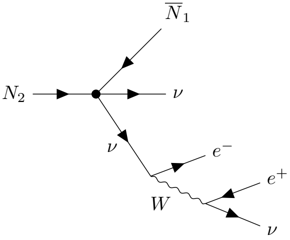

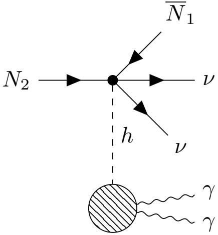

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$\Rightarrow$ **We solved the challenge!**

Adjusting for a 3-body decay

$$\boxed{\text{DCDM} \rightarrow \text{WDM} + \text{DR} + \text{DR}}$$

- now: momentum distribution

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Adjusting for a 3-body decay

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- now: momentum distribution
- important effect given by perturbations capturing the heating of WDM instead of background evolution
- scale ϵ (3-body) to a new ϵ' (2-body) that produce the same perturbations

$\Rightarrow$ small re-scaling with $\epsilon'(\epsilon) = \sqrt{\frac{13}{21}}\epsilon + \mathcal{O}(\epsilon^2) \approx 0.79\epsilon$

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A new neutrino flux

diffuse neutrino flux induced by N_2 decay:

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} \simeq \frac{1}{4\pi}\frac{1}{\tau M}\frac{1}{3}\frac{\mathrm{d}N}{\mathrm{d}E_\nu}D(\Omega)$$

D-factor:

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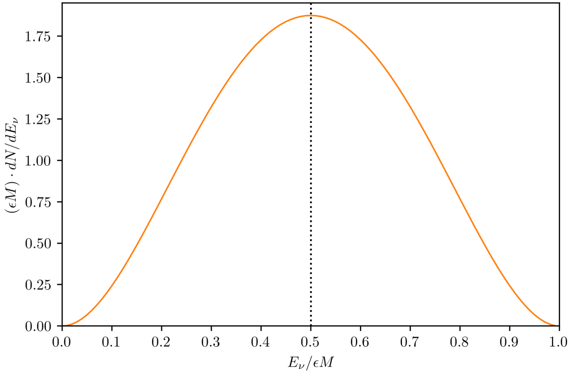
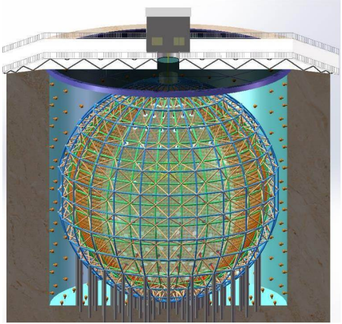


neutrino spectrum $\frac{\mathrm{d}N}{\mathrm{d}E_\nu}$ with $\langle E_\nu \rangle = \epsilon M/2$

Neutrino experiments

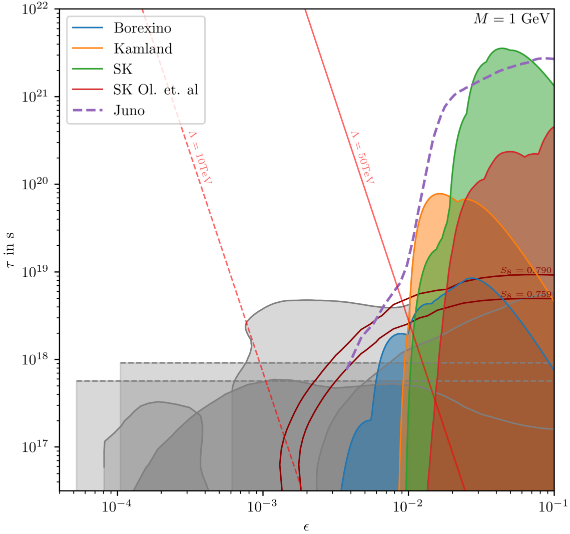
- Borexino $(1.8 - 16.8\ \text{MeV})$
  [Borexino Collab., arXiv:1909.02422]
- KamLAND $(8.3 - 30.8\ \text{MeV})$
  [KamLAND Collab., arXiv:2108.08527]
- Super-Kamiokande $(9.3 - 200\ \text{MeV})$
  [SK Collab., arXiv:2109.11174;
  Olivares-Del Campo et al., arXiv:1711.05283]
- JUNO $(2.75 - 100\ \text{MeV})$
  [Akita et al., arXiv:2206.06755]


https://www.weltmaschine.de/neuigkeiten/neuigkeiten_archiv/2016/neutrinos_auf_der_goldwaage_das_juno_experiment/

Measurement via inverse-β-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

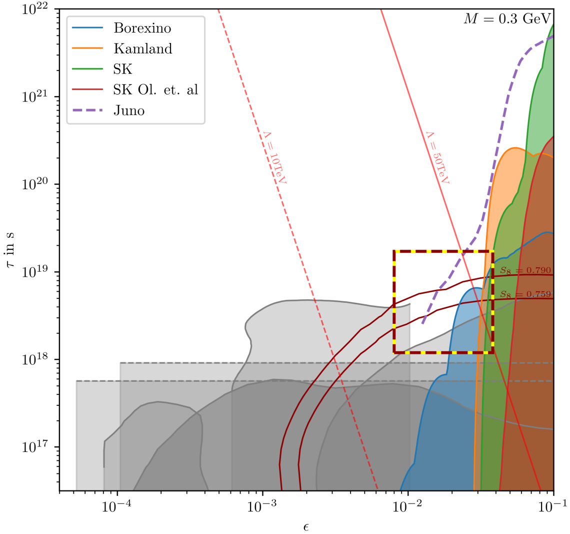
Closing the window...

$M = 1\,\mathrm{GeV}$



...but opening it again!

$M = 0.3\,\text{GeV}$



How to produce DM?

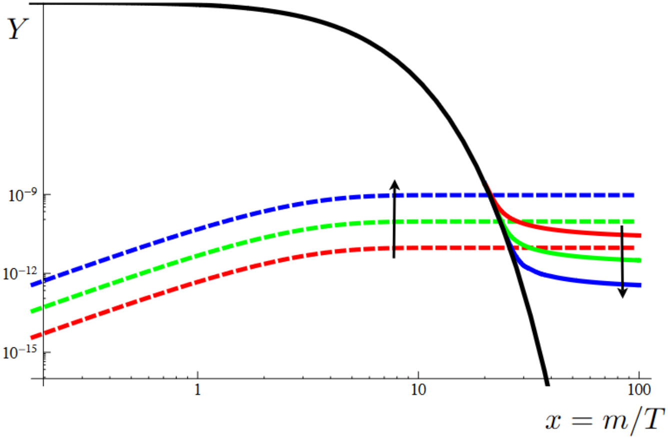
Freeze-out

vs.

Freeze-in

for typical scales

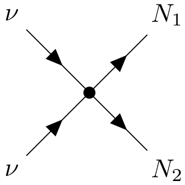
$\Lambda \sim \text{TeV}$



[Hall et al., arXiv:0911.1120]

Freeze-in...

- effective interaction can also produce DM after EW symmetry-breaking: $\nu\nu \rightarrow N_1 N_2$, $\bar{\nu}\bar{\nu} \rightarrow \bar{N}_1 \bar{N}_2$



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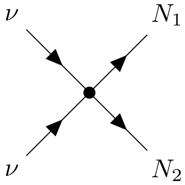

$$\frac{\mathrm{d}Y}{\mathrm{d}x} \propto x^4 \gamma_{N_1 N_2}$$

leads to 50% N_1, 50% N_2

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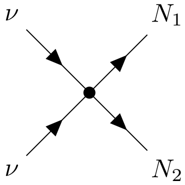

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- depends strongly on temperature!

...after reheating

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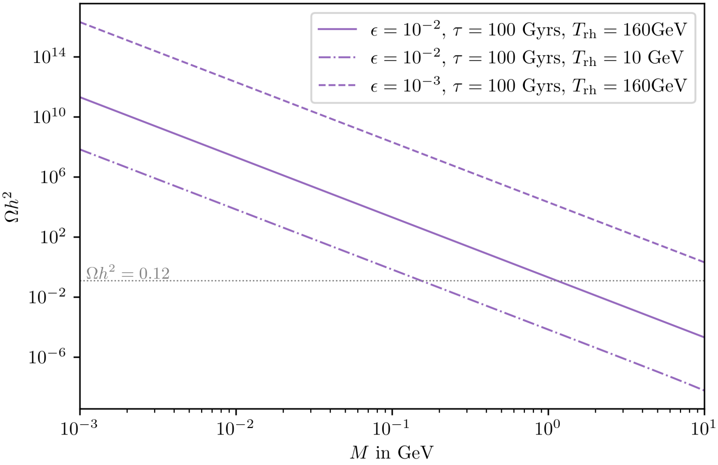
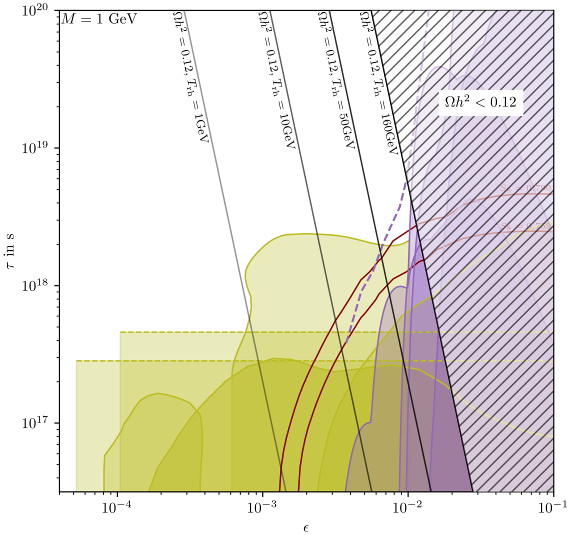


One window still closed,

M = 1 GeV



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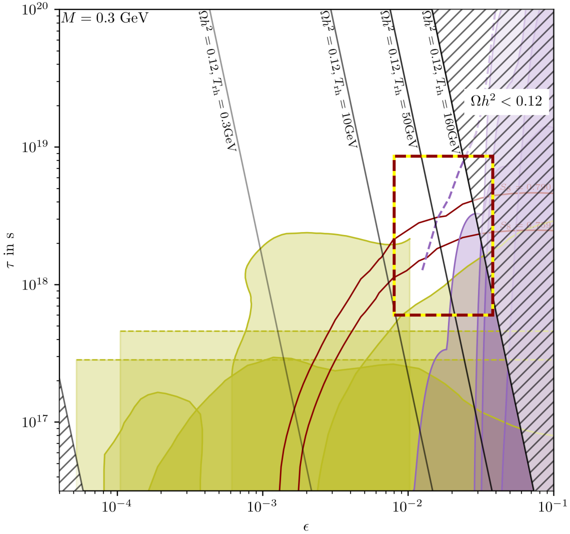
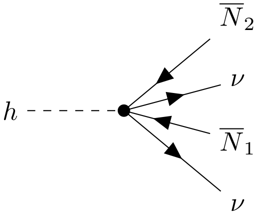


Invisible Higgs decay

1. **Invisible Higgs decay**



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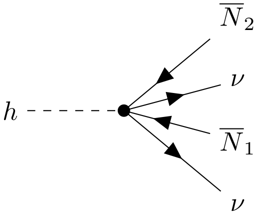

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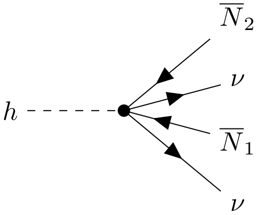
$$\Gamma_{\mathrm{h}}^{\mathrm{inv}} = \frac{1}{4 m_h} \frac{v_{\mathrm{EW}}^2}{30 \pi^5 \Lambda^8} \left(\frac{m_h}{4}\right)^8$$

$$\approx 1.37 \cdot 10^{-20} \mathrm{MeV} \left(\frac{\mathrm{MeV}}{\epsilon M}\right)^5 \left(\frac{100\ \mathrm{Gyrs}}{\tau}\right)$$



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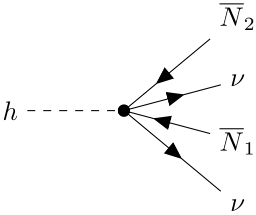
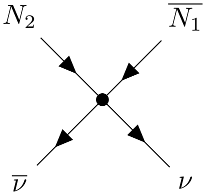


- small effect only relevant at very small M, ϵ and τ

Neutrino scattering

2. **Neutrino-DM scattering**

- typical constraints at **low** neutrino energies from CMB/LSS



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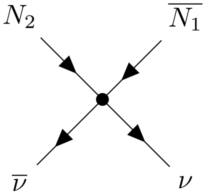
- typical constraints at **low** neutrino energies from CMB/LSS
- cross section boosted at **high** energies
- limits from blazar TXS-0506+056 with $E_\nu \sim 290\,\text{TeV}$ measured by IceCube [Ferrer, Herrera, Ibarra, arXiv:2209.06339]



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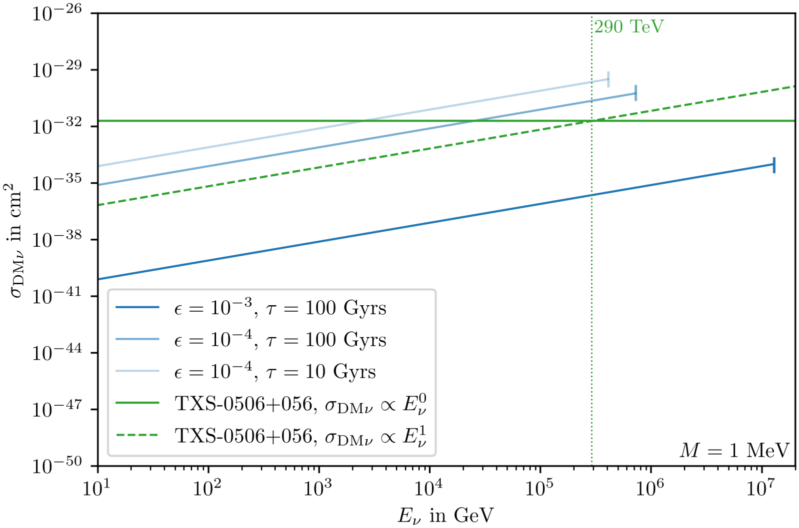
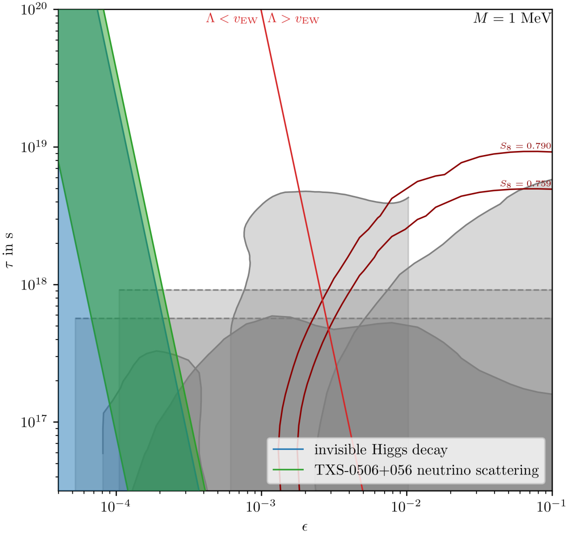
Help from high energy sources



Low Mass Constraints

- neutrino-DM scattering: constraints only shown for $\sqrt{s} < \Lambda$
- invisible Higgs decay: constraints in $\Lambda < v_{EW}$ regime

$\Rightarrow$ limit of EFT description



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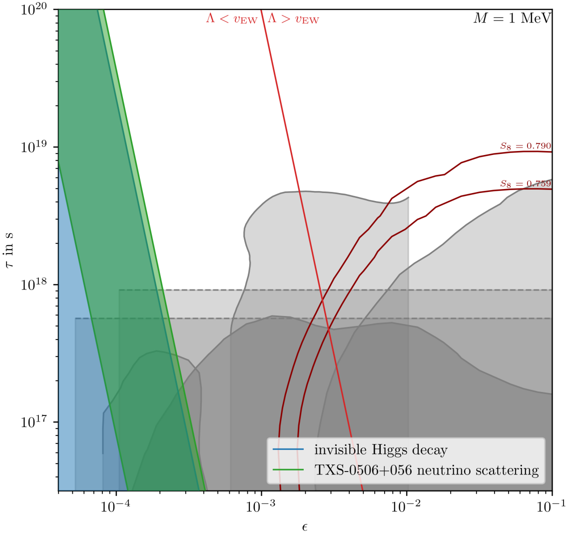

Outline

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One step further: going to a **UV complete theory**

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3. Natural explanation for the mass splitting between N_1 and N_2?

Summary

- Found minimal and effective realization of decaying DM that opens up new phenomenology
- Complementary constraints from cosmology, neutrino experiments, and freeze-in production
- Window in parameter space where all constraints and lower S_8 are satisfied for $M \lesssim 1\,\mathrm{GeV}$
- Possible future testability: JUNO, Euclid (?)

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Thank you for your attention!