Minimal decaying dark matter: from cosmological tensions to neutrino constraints

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based on arXiv:2403.15543 (soon on JCAP)

The Dark Side of the Universe - Corfu

September 14, 2024

SFB 1258 Neutrinos Dark Matter Messengers

Cosmological tensions: A hint for something new?

?

H_0 S_8

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S_8 tension:

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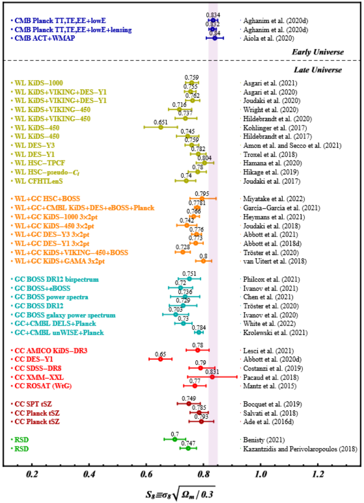

[Abdalla et. al., arXiv:2203.06142]

Decaying Cold Dark Matter

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$\rightarrow$ **Decaying Cold Dark Matter (DCDM)**

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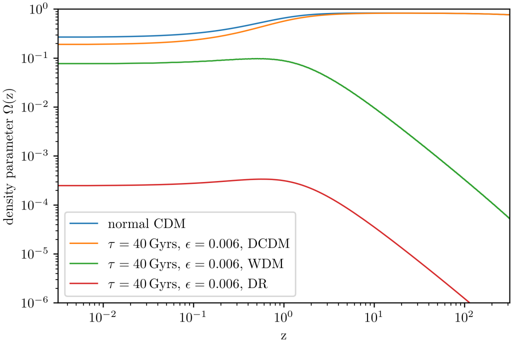
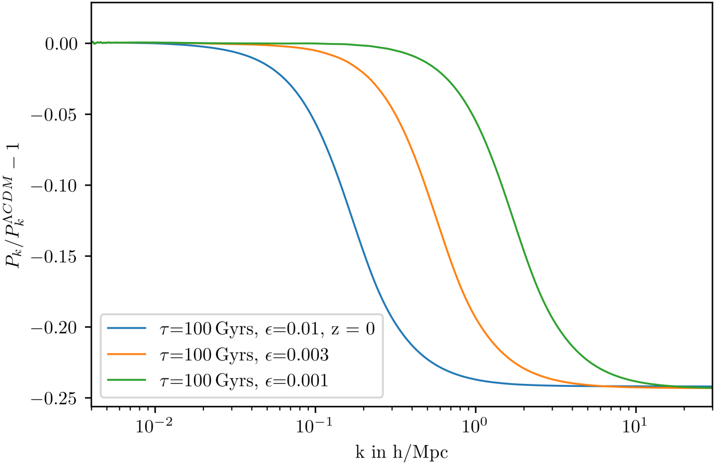
$$\dot{\bar{\rho}}_{\rm dcdm} = -3\mathcal{H}\bar{\rho}_{\rm dcdm} - a\Gamma\bar{\rho}_{\rm dcdm}$$
$$\dot{\bar{\rho}}_{\rm wdm} = -3(1+\omega)\mathcal{H}\bar{\rho}_{\rm wdm} + (1-\epsilon)a\Gamma\bar{\rho}_{\rm dcdm}$$
$$\dot{\bar{\rho}}_{\rm dr} = -4\mathcal{H}\bar{\rho}_{\rm dr} + \epsilon a\Gamma\bar{\rho}_{\rm dcdm}$$



Suppression through decay

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



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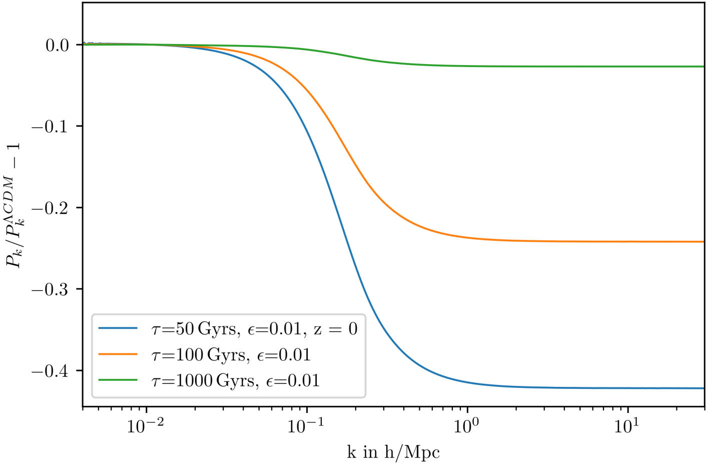


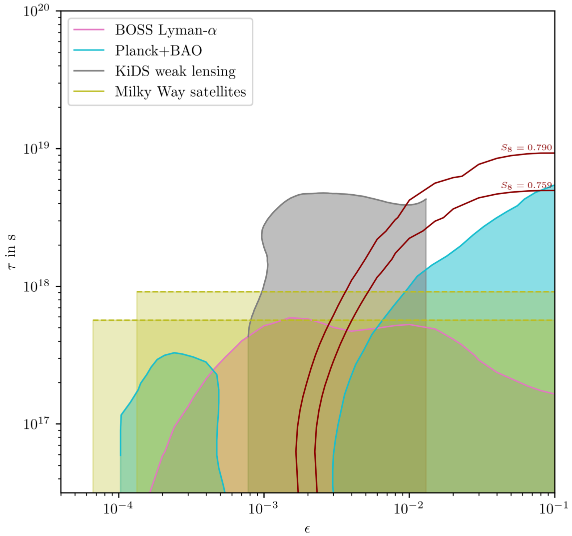
Cosmological Constraints

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]

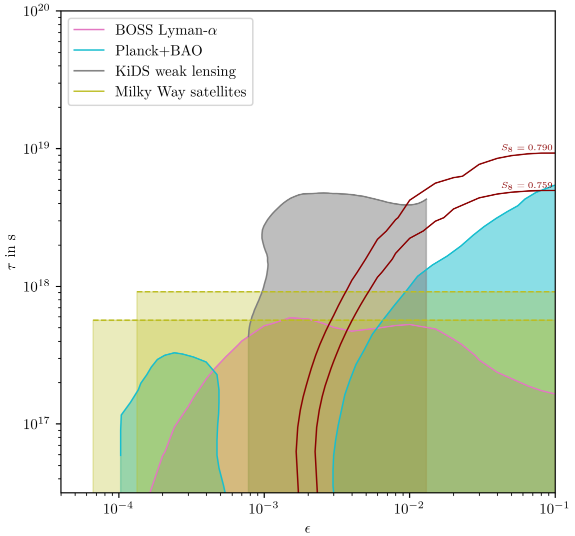
DM halo evolution
[DES Collab., arXiv:2201.11740]



Cosmological Constraints

singles out parameter space of interest to address S_8 tension:

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



A theoretical framework

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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
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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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L	**N**
$N_2 \rightarrow e^{i\alpha} N_2$	$N_2 \rightarrow e^{i\alpha} N_2$
$N_1 \rightarrow e^{i\alpha} N_1$	$N_1 \rightarrow e^{-i\alpha} N_1$

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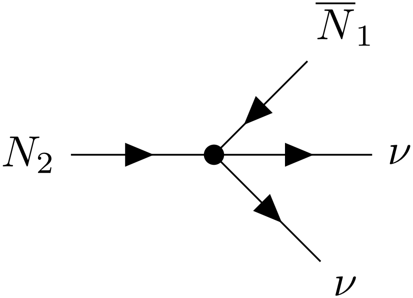
$$\Rightarrow \boxed{\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^4}\left(\bar{L}\tilde{H}P_R N_2\right)\left(\bar{L}\tilde{H}P_R N_1\right) + \text{h.c.}}$$

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

Recognizing DCDM

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



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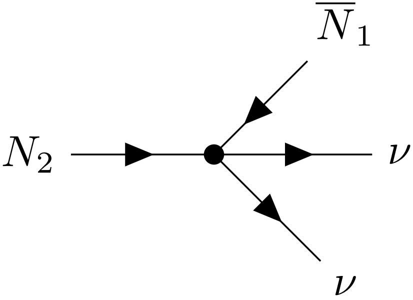


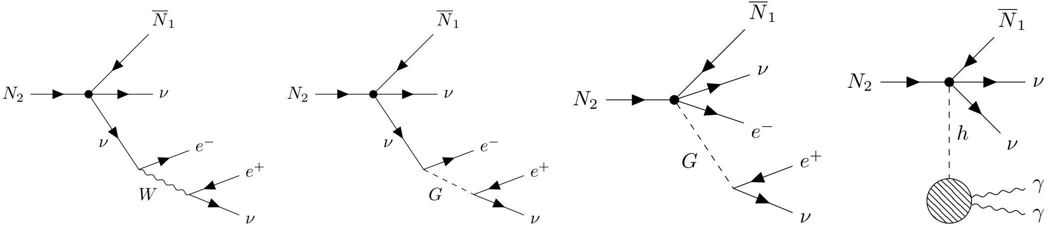
$$\Gamma_{N_2 \to N_1 \nu\nu} = \frac{v_{\text{EW}}^4}{1280\pi^3\Lambda^8}\,(\epsilon M)^5 = \frac{1}{\tau}$$

$\to \Lambda$ only dependent on model parameters ϵ, τ plus the DM mass M:

$$\Lambda = \left(\frac{v_{\text{EW}}^4}{1280\pi^3}\,\tau\,(\epsilon M)^5\right)^{1/8}$$

Visible particles?

- e^+e^- production possible via W and Goldstone boson, γ production via e^+e^- loop or Higgs loop



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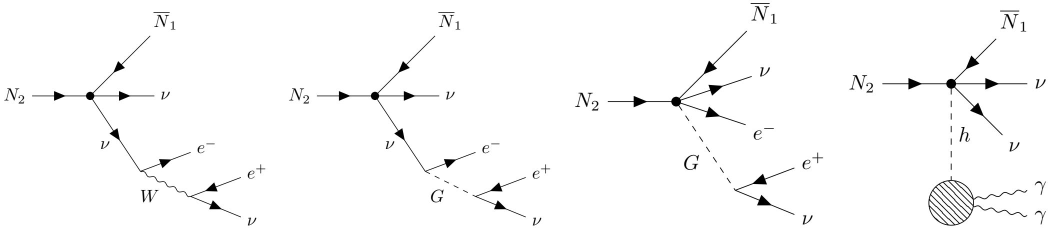

- heavily suppressed due to phase-space and small $(\epsilon M)/v_{\text{EW}}$

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:

$$D(\Omega) = \int \mathrm{d}\Omega \int \rho(l)\,\mathrm{d}l\,,$$

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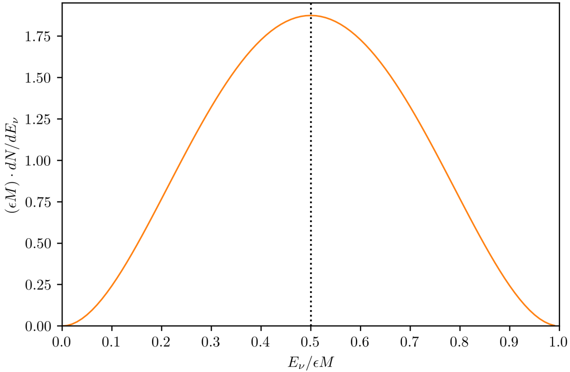
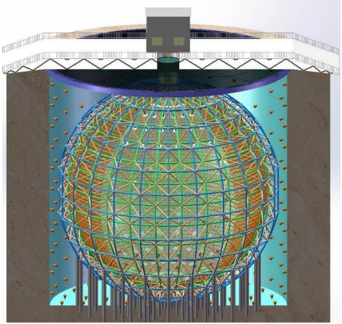


neutrino spectrum $\frac{dN}{dE_\nu}$ with $\langle E_\nu \rangle = \epsilon M/2$

Neutrino experiments

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

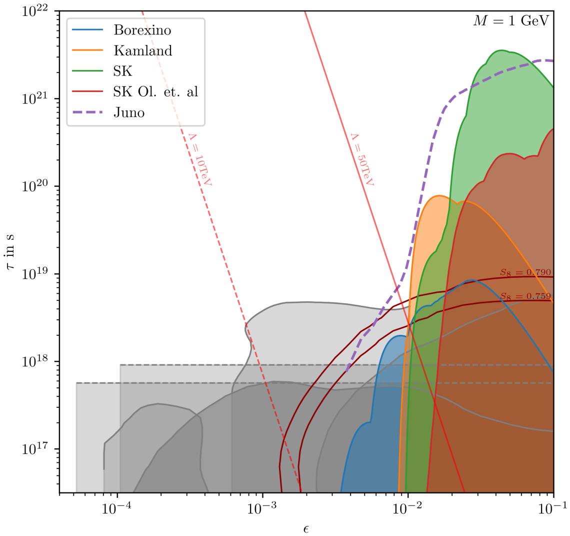


https://www.weltmaschine.de/neuigkeiten/neuigkeiten_archiv/2016/neutrinos_auf_der_goldwaage_das_juno_experiment/

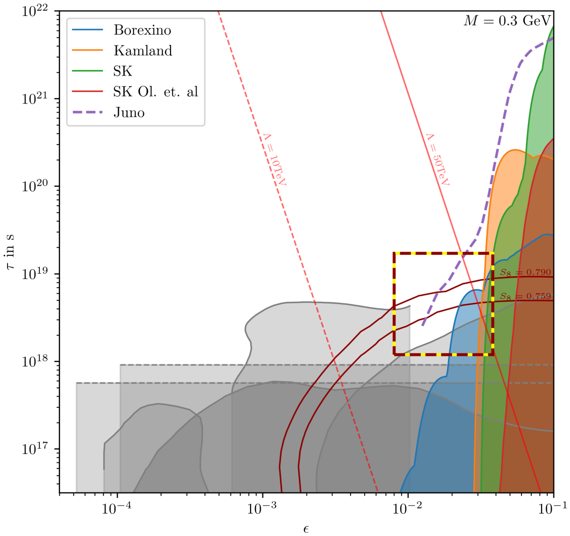
Measurement via inverse-β-decay: $\bar{\nu}_e + p \to e^+ + n$

Closing the window...

M = 1 GeV



M = 0.3 GeV



M = 0.3 GeV
Borexino
Kamland
SK
SK Ol. et. al
Juno
Λ = 10TeV
Λ = 50TeV
$S_8 = 0.790$
$S_8 = 0.759$
τ in s
ε
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

How to produce DM?

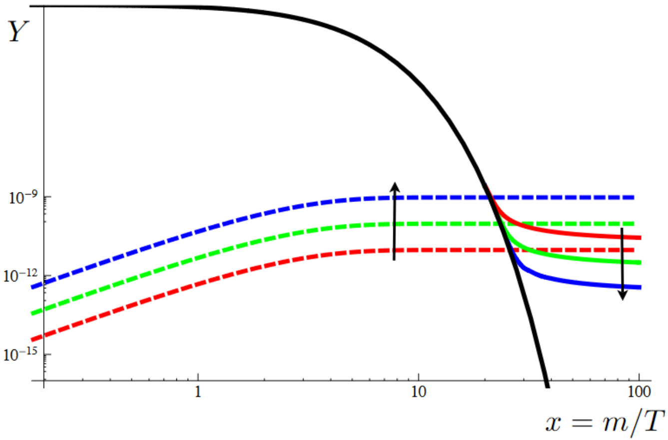
Freeze-out

vs.

Freeze-in

for typical scales

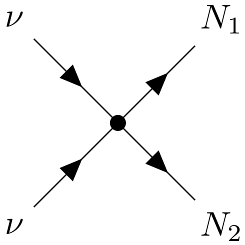
$\Lambda \sim$ TeV



[Hall et al., arXiv:0911.1120]

Freeze-in

- production after EW symmetry breaking via
  $\nu\nu \to N_1 N_2$, $\bar{\nu}\bar{\nu} \to \bar{N}_1 \bar{N}_2$



$50\% N_1$, $50\% N_2$

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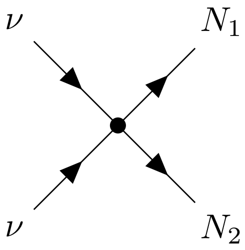
$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = \gamma_{N_1 N_2}$$



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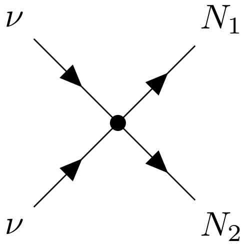
Temperature dependence!



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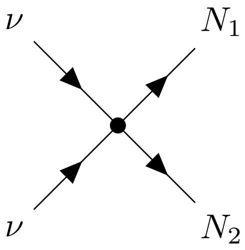

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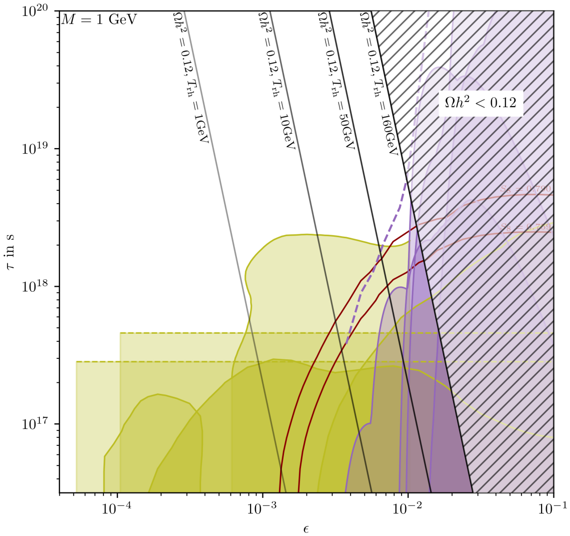
Temperature dependence!

- vary reheating temperature T_{rh} up to EW symmetry breaking $T < 160\text{GeV}$

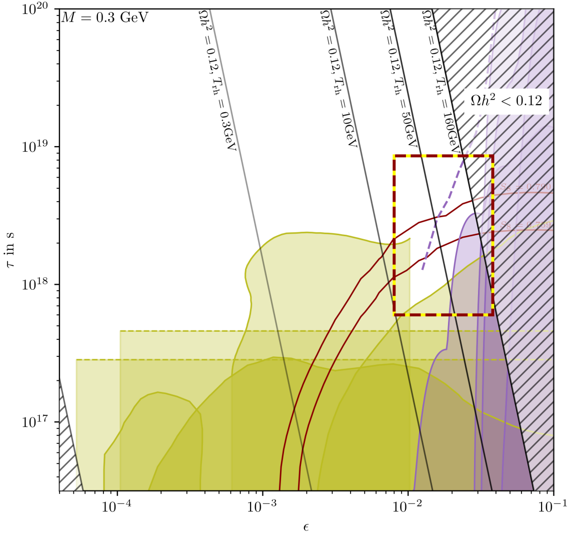
One window still closed,

M = 1 GeV



one window still open!

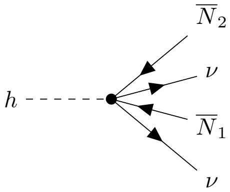
M = 0.3 GeV



Invisible Higgs decay

- $\Gamma_h^{SM} \simeq 3.2\text{MeV}$ with invisible BR $< 12\%$

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



Low-mass signatures

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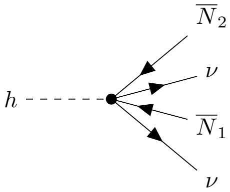
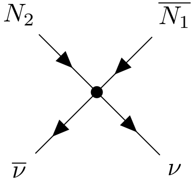


Neutrino-DM scattering

- limits from blazar TXS-0506+056 with $E_\nu \sim 290\,\mathrm{TeV}$ measured by IceCube
  [Ferrer, Herrera, Ibarra, arXiv:2209.06339]



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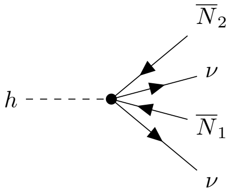

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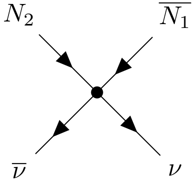

only relevant for very small M, ϵ, τ where EFT starts to become invalid

What comes next?

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

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1. New and/or improved **phenomenology**?
2. Connection to **neutrino masses**?
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 $M \lesssim 1\,\text{GeV}$
- Possible future testability: JUNO, Euclid

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Thank you for your attention!