

Dark Matter Searches as Probes of Reheating at Future (Linear) Colliders

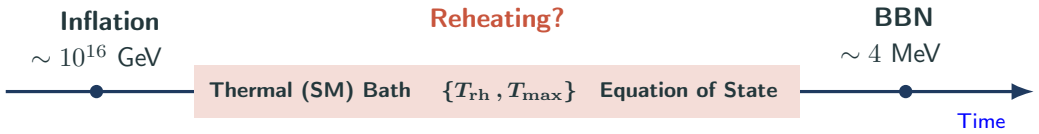
Abhik Sarkar

LPSC Grenoble and IIT Guwahati

PLB 869 (2025) 139863 • JHEP 07 (2025) 157 • arXiv 2509.14340

International Workshop on Future Linear Colliders 2026 (LCWS2026)

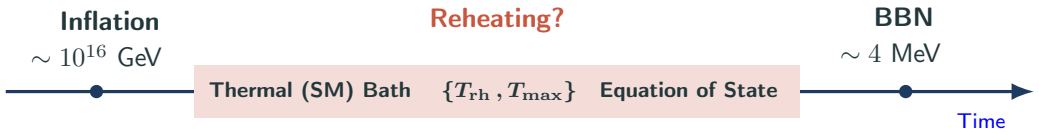
The Least Known Stretch of Cosmic History



What do we know?

- CMB indicates towards inflation.
- ^{4}He, ^{2}H, ^{3}He $\rightarrow$ hot bath at BBN.
- Therefore, $T_{\rm rh} > T_{\rm BBN} \simeq 4$ MeV.

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The Connection

$$(\Omega h^2)_{\rm DM} \xrightarrow[\text{reheating}]{\text{during}} T_{\rm rh}$$

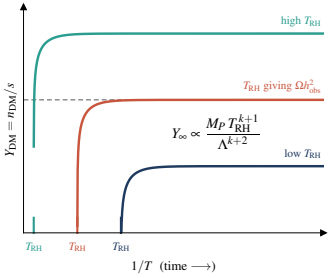
Dark Matter (DM) relic produced during reheating carries "memory" of the epoch.

If future colliders measure the DM-SM interaction, can it tell us about $T_{\rm rh}$?

Two Ways Dark Matter can Remember Reheating

Ultraviolet (UV) Freeze-in

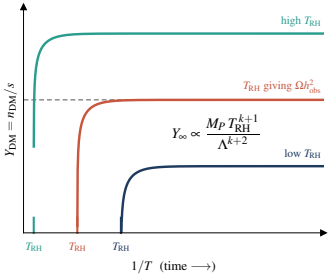
- Feeble, non-renormalizable coupling.
- Relic density set near the highest temperature achieved by the bath.



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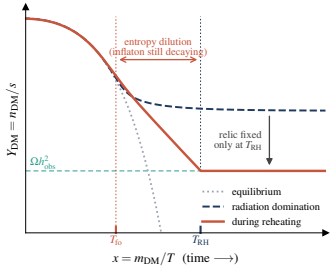
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Freeze-out during Reheating

- Thermal decoupling while inflaton still dominates the energy density.
- Relic diluted by entropy injection.



(Very) Brief Outline of Reheating

Perturbative Reheating in One Slide

Inflaton oscillates in a monomial potential.

$$V(\Phi) = \lambda \frac{\Phi^n}{\Lambda_\Phi^{n-4}}, \quad \Lambda_\Phi \leq 10^{16} \text{ GeV}$$

and decays perturbatively to the SM bath:

$$\mathcal{L} \supset \underbrace{-\mu\, \Phi |\varphi|^2}_{\text{bosonic}} \quad \text{or} \quad \underbrace{-y\, \Phi \bar{\Psi} \Psi}_{\text{fermionic}}$$

Time evolution tracked by scale factor, a.

End of Reheating : $\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$

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Temperature Evolution

- Bath temperature during reheating:

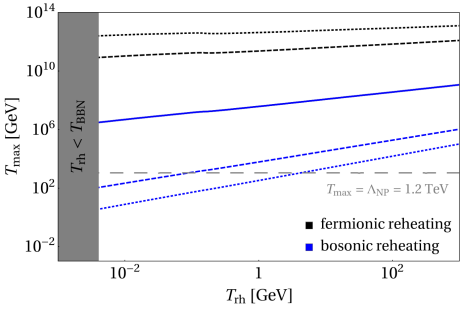
$$T(a) \simeq T_{\rm rh} \left(\frac{a_{\rm rh}}{a}\right)^\alpha, \begin{cases} \alpha_{\rm b} = \frac{3}{2(n+2)} \\ \alpha_{\rm f} = \frac{3(n-1)}{2(n+2)} \end{cases}$$

- Highest temperature of the bath:

$$T_{\rm max} \simeq T(a_I) \gg T_{\rm rh}$$

- $\{T_{\rm rh}\,, T_{\rm max}\} \longrightarrow n\,, \Gamma_\Phi$ dependent, and, DM inherits that dependence.

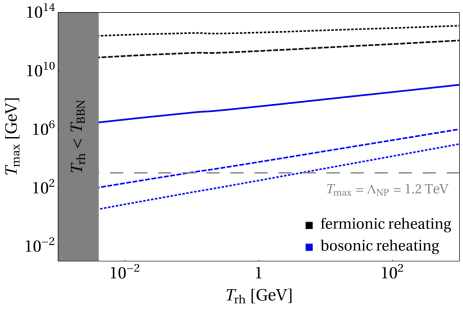
The Effective Scale Selects the Reheating Scenario



Solid / Dashed / Dotted $\longrightarrow$ $n = 2, 4, 6$

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Solid / Dashed / Dotted $\longrightarrow$ $n = 2, 4, 6$

Validity Criteria

- The theory must hold in the early Universe, i.e. $\Lambda > T_{\rm max}$.
- The theory must also be valid at colliders, i.e. $\Lambda > \sqrt{\hat{s}}$.
- Fermionic reheating: $T_{\rm max} \gg$ TeV, for all $n \Rightarrow \Lambda$ out of reach.

Bosonic reheating with $n = 4, 6$; MeV-scale $T_{\rm rh}$ keeps $\Lambda \sim \mathcal{O}$(TeV).

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UV Freezing-in Dark Matter

Why FIMPs Evade Detection? and the Loophole

UV freeze-in through a dim-d operator,
DM yield grows with bath temperature:

$$Y_{\rm DM} \propto \frac{M_P\, T^{k+1}}{\Lambda^{k+2}}, \qquad k = 2(d-5)$$

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Most DM is made at the hottest moment.
Instantaneous reheating, DM with $(d = 7)$:

$$\Lambda \simeq 100\ \text{GeV} \left(\frac{m_{\rm DM}}{\text{MeV}}\right)^{1/6} \left(\frac{T_{\rm rh}}{T_{\rm BBN}}\right)^{5/6}$$

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The Usual Story

High $T_{\rm rh}$ $\rightarrow$ Huge Λ $\rightarrow$ ~~Detection~~

The Loophole

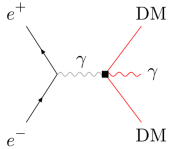
Low $T_{\rm rh}$ + Light DM $\rightarrow$ $\Lambda \sim$ TeV,
while still out of equilibrium $(\Gamma/H \ll 1)$.

A detection friendly FIMP points to a low reheating temperature scenario.

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Preferred Interactions: FIMP Suppression + Collider Detection

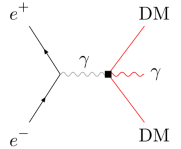
$$\mathcal{O}_3^f = \frac{1}{\Lambda^3}\left(B_{\mu\nu}B^{\mu\nu} + W^i_{\mu\nu}W^{i\mu\nu}\right)\bar{\chi}\chi$$



- Same operator: $\gamma\gamma \to \chi\bar{\chi}$ in the bath and $e^+e^- \to \chi\bar{\chi}\gamma$ at lepton colliders.

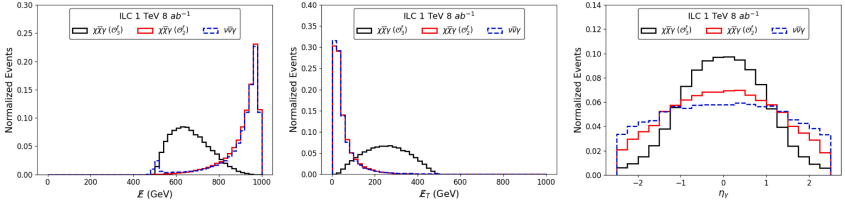
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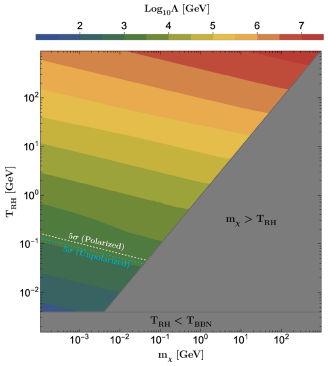


- Same operator: $\gamma\gamma \to \chi\bar{\chi}$ in the bath and $e^+e^- \to \chi\bar{\chi}\gamma$ at lepton colliders.
- ISR photons look like $\nu\bar{\nu}\gamma$. Vertex photons have distinct $\not{E}_T$ and $\not{E}$.

Black: Vertex γ **Red: ISR γ** **Blue: $\nu\bar{\nu}\gamma$**



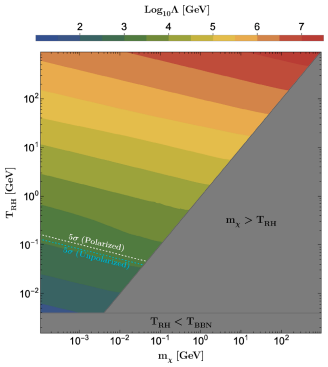
Instantaneous ($T_{\rm max} = T_{\rm rh}$) vs Non-Instantaneous ($T_{\rm max} \gg T_{\rm rh}$)



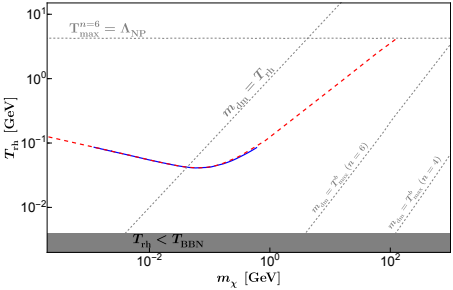
- $\Lambda \sim$ TeV $\longrightarrow$ MeV $T_{\rm rh}$, sub-GeV DM.

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Instantaneous ($T_{\rm max} = T_{\rm rh}$) vs Non-Instantaneous ($T_{\rm max} \gg T_{\rm rh}$)



- $\Lambda \sim$ TeV $\longrightarrow$ MeV $T_{\rm rh}$, sub-GeV DM.



- Bosonic, $\Lambda = 1.2$ TeV, $n = 4$, $n = 6$.
- DM heavier than $T_{\rm rh}$ is now viable.

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Mono-$\gamma + \not{E}$ Signal: Role of Beam Polarization

Cutflow (ILC 1 TeV 8 ab^{-1})

Cut	$\chi\bar{\chi}\gamma$	$\nu\bar{\nu}\gamma$	$\mathcal{S}$
Basic	4422	18 101 325	1.04
$\mathcal{C}_1$	2957	725 945	3.47
$\mathcal{C}_2$	2694	289 420	5.00
$\mathcal{C}_3$	2395	219 161	**5.10**

Benchmark: $m_\chi = 33$ MeV, $\Lambda = 1.14$ TeV
ILC: $\sqrt{s} = 1$ TeV, $\mathfrak{L}_{\rm int} = 8$ ab^{-1}

Cuts
$$\begin{cases} \mathcal{C}_1 : \not{E}_T > 200 \text{ GeV} \\ \mathcal{C}_2 : 525 \text{ GeV} < \not{E} < 750 \text{ GeV} \\ \mathcal{C}_3 : -1.0 < \eta_\gamma < 1.0 \end{cases}$$

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Polarization Effects

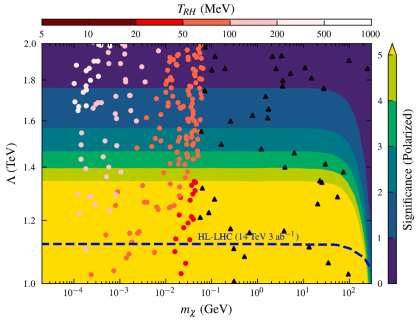
$\{P_{e^+}, P_{e^-}\}$	$\chi\bar{\chi}\gamma$	$\nu\bar{\nu}\gamma$	$\mathcal{S}$
$\{0\%, 0\%\}$	2395	219 161	5.10
$\{+20\%, +80\%\}$	2010	55 052	8.52
$\{-20\%, +80\%\}$	2778	40 711	**13.6**
$\{+20\%, -80\%\}$	2774	453 639	4.11
$\{-20\%, -80\%\}$	2003	303 079	3.63

Polarizing to RH e^- cuts the W-exchange $\nu\bar{\nu}\gamma$ background ($\sim 5\times$). Signal grows.

Polarization: $5.10\sigma \rightarrow 13.6\sigma$

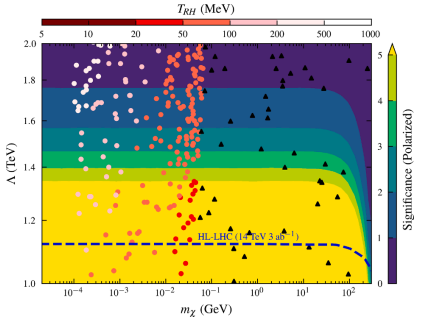
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What Reheating History does Collider Suggest?

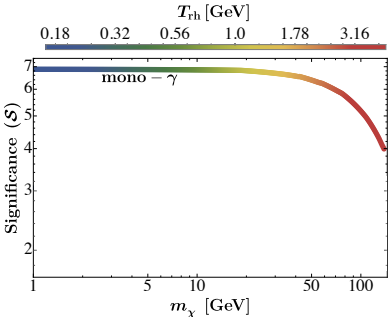


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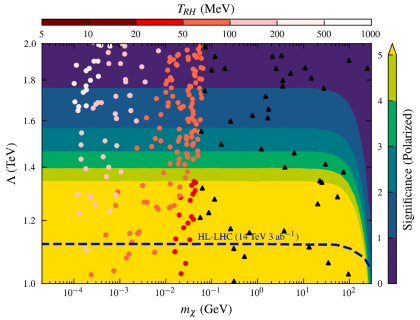


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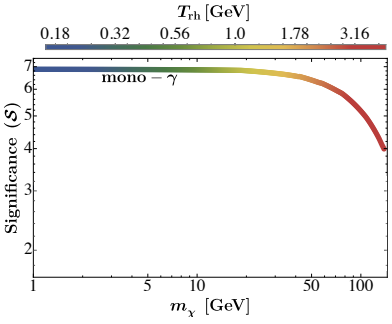


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- Required $T_{\rm rh}$: sub-GeV to few GeV.

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- Required $T_{\rm rh}$: sub-GeV to few GeV.

Signal $\to \Lambda$; relic $\to \{T_{\rm rh}, m_\chi\}$: a discovery selects a band of reheating histories.

Freezing-out during Reheating

WIMPs that remember reheating

$$\boxed{\mathcal{O}_2^s = \frac{1}{\Lambda^2} \sum_i (\bar{\ell}_L^i H e_R^i)\, \phi^2}$$

If DM (ϕ) freezes-out during reheating:

$$\Omega h^2 \;\propto\; \frac{6}{2+n} \frac{m_\phi \Lambda^4}{T_{\rm rh}} \left(\frac{T_{\rm rh}}{T_{\rm fo}}\right)^4$$

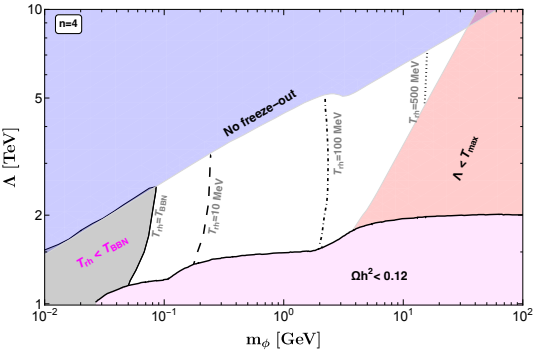
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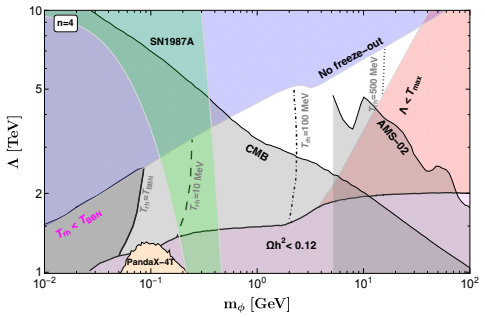
Entropy injection $\Longrightarrow$ smaller $\langle\sigma v\rangle$ (larger Λ) can saturate the observed relic density.



With $n = 4$; Thick Black: Standard Freeze-Out

MeV-GeV leptophilic WIMP, excluded in standard cosmology, is revived by low $T_{\rm rh}$.

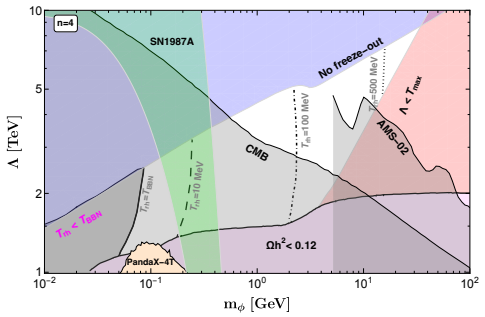
Constraining the Parameter Space, Further!



- **CMB** ($\phi\phi \to \ell^+\ell^-$), provides the strongest limit for low mass DM, excludes $T_{\rm rh} \lesssim 25$ MeV scenarios.
- **AMS-02** ($\phi\phi \to e^+e^-$), e^+ flux.
- **SN1987A** cooling. DM produced ($e^+e^- \to \phi\phi$) carry away energy.

arXiv:2509.14340, Bhattacharya, Ghosh, Mondal, and Sarkar

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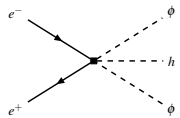


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WIMP: Small wedge survives for $\Lambda \gtrsim 2$ TeV and $m_\phi \approx \mathcal{O}(\text{GeV})$.

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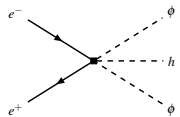
Mono-Higgs: Characteristic Signature of the Operator



- After EWSB: contact $e^+e^-h\phi\phi$ vertex. Signal grows with $\sqrt{s}$.
- $\boldsymbol{S}: h \to b\bar{b}$; $\boldsymbol{B}: \nu\bar{\nu}h\,, \nu\bar{\nu}$ + jets.

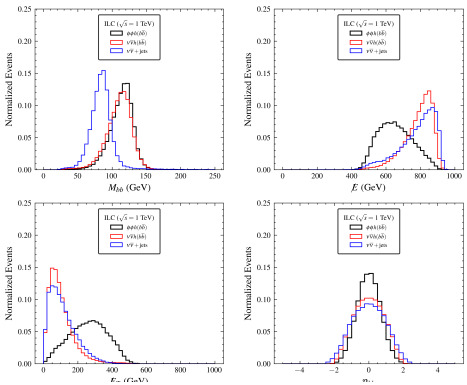
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Cuts
$$\begin{cases} \mathcal{C}_1 : |M_{bb} - m_h| < 25 \text{ GeV} \\ \mathcal{C}_2 : \not{E}_T > 265 \text{ GeV} \\ \mathcal{C}_3 : \not{E} < 670 \text{ GeV} \end{cases}$$



Black: Signal ($m_\phi = 5$ GeV, $\Lambda = 2.5$ TeV)

arXiv:2509.14340, Bhattacharya, Ghosh, Mondal, and Sarkar

Polarization Tuning Helps Once Again!

Cross Sections (fb, ILC 1 TeV)

$\{P_{e^+}, P_{e^-}\}$	$\phi\phi h$	$\nu\bar{\nu}h$	$\nu\bar{\nu}jj$
Unpolarised	0.159	120.8	512.0
$\{+20\%, +80\%\}$	0.184	29.7	139.5

- Choice of RH e^- polarization suppresses the W-exchange backgrounds.
- The Yukawa-like operator flips chirality: signal *grows* for same-sign polarization.

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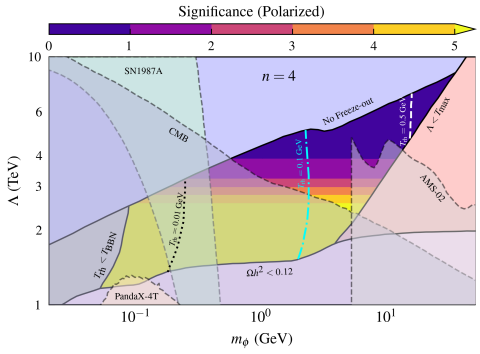
$\{P_{e^+}, P_{e^-}\}$	S	B	$\mathcal{S}$
Unpolarised	173	9218	1.80
$\{+20\%, +80\%\}$	200	2324	**4.15**

arXiv:2509.14340, Bhattacharya, Ghosh, Mondal, and Sarkar

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Mono-γ (previous): best $\{-,+\}$.
Mono-h (current): best $\{+,+\}$.
The optimal polarization configuration follows the concerned operator structure.

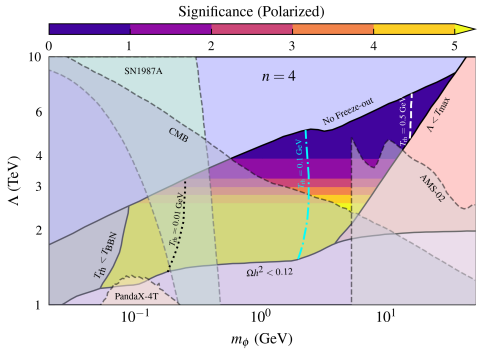
Reach Over the Viable WIMP Wedge



- Lower $T_{\rm rh} \Rightarrow$ Smaller $\Lambda \Rightarrow$ Larger signal. Signal flat in DM mass.
- For $T_{\rm rh} \gtrsim 500$ MeV $\Rightarrow$ Weak signal.

arXiv:2509.14340, Bhattacharya, Ghosh, Mondal, and Sarkar

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An observed mono-h excess could favour freeze-out during reheating. $25\ \text{MeV} \lesssim T_{\rm rh} \lesssim \mathcal{O}(100)$ MeV.

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Summary & Conclusion

Summing it Up

- Low-scale reheating makes TeV-suppressed DM operators both cosmologically viable and possibly visible at future high-energy e^+e^- machines.
- **FIMP:** UV freeze-in. Natural mono-γ separates cleanly from $\nu\bar{\nu}\gamma$ background. $> 5\sigma$ with polarized beams, tied to $T_{\rm rh}$ and inflaton potential (n).
- **WIMP:** Entropy dilution revives an excluded leptophilic scenario. Searches like mono-h may observe $\sim 4\sigma$ excess in the surviving wedge.
- **Polarization** is essential for DM searches. $\sim 2\times$ significance improvement, and optimal polarization choice reflects the operator's chirality.
- Operators presented are a proof of concept: the method carries over to other (possibly better) DM models, search channels and colliders.

Can DM discovery turn into a probe of the pre-BBN Universe? Requires more scrutiny.

THANK YOU!

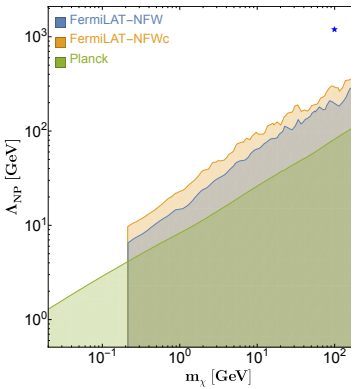
For any questions or discussion in future, feel free to contact me: asarkar@lpsc.in2p3.fr

Some Additional Information

Assumptions Behind the Reheating Picture

- Perturbative inflaton decay; tiny couplings ($\mu/M_P \lesssim 10^{-27}$) keep preheating inefficient.
- Non-perturbative effects (resonance, fragmentation for $n \geq 4$) could shift $T_{\rm rh}$ and $T_{\rm max}$. Need lattice-based calculations. Also assumes instantaneous thermalization of the bath.
- Standard radiation domination after reheating is assumed, no further entropy injection.
- (Very) crude EFT validity criteria: $\Lambda > T_{\rm max}$ (early Universe) and $\Lambda > \sqrt{s}$ (collider).

Photophilic Dark Matter: Direct & Indirect Detection



Indirect Detection

Same operator gives $\chi\bar{\chi} \to \gamma\gamma$ today. Fermi-LAT and Planck (CMB) excludes $\Lambda \lesssim \mathcal{O}(100)$ GeV. TeV-scale Λ is safe.

Direct Detection

Generates $\chi N(e) \to \chi N(e)$, at one loop. SIDD cross section, $\sigma_{\rm SI} \leq 10^{-51}$ cm^2, far beyond current DD sensitivity reach.

JHEP 07 (2025) 157, Barman, Bhattacharya, Jahedi, Pradhan, and Sarkar