INTERNATIONAL WORKSHOP
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Probing Reheating through UV Freeze-in Dark Matter at Lepton Colliders

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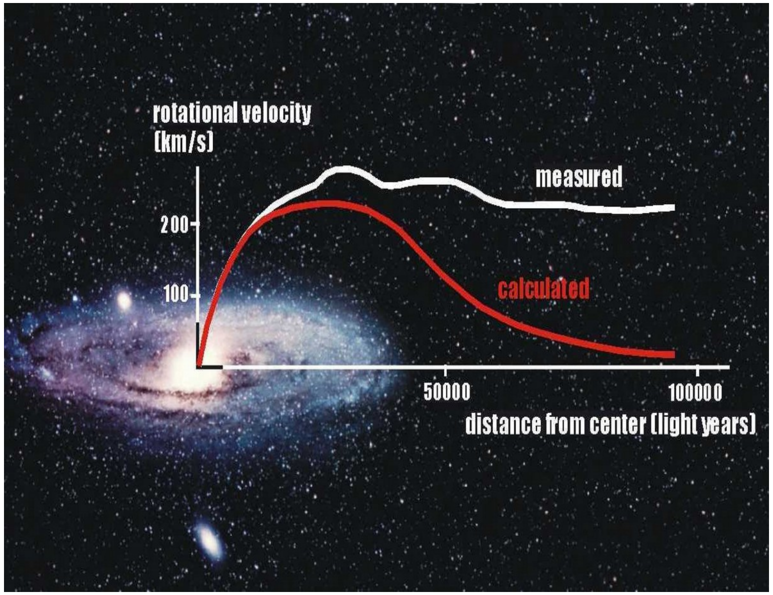
Based on **Phys. Lett. B 869 (2025) 139863** & **JHEP 07 (2025) 157**

Date : 8^{th} November, 2025

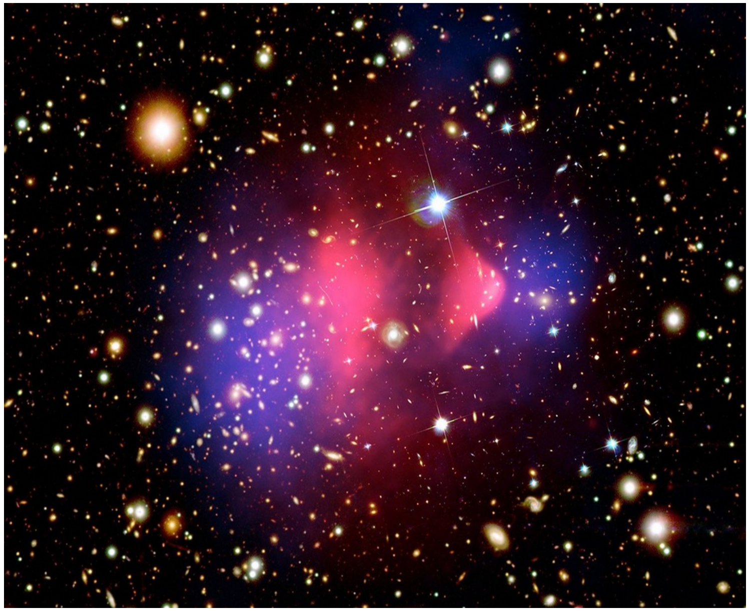
Evidences of Dark Matter:

Galaxy scale



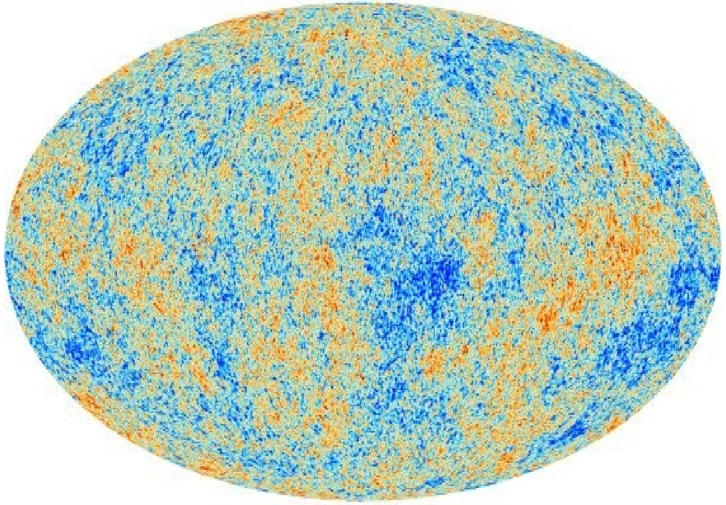
(Galaxy rotation curve)

Clauster scale



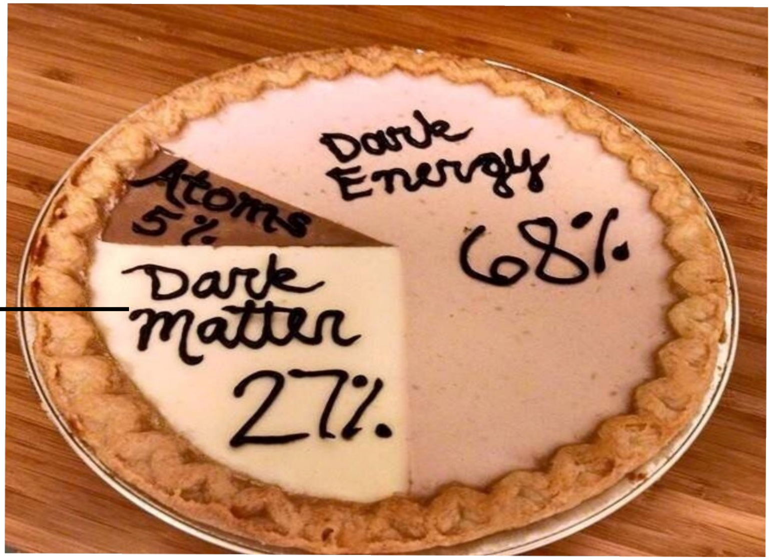
(X-ray imaging & gravitational lensing)

Cosmological scale



(Temperature anisotropy in CMB)

5 times more than the visible matter



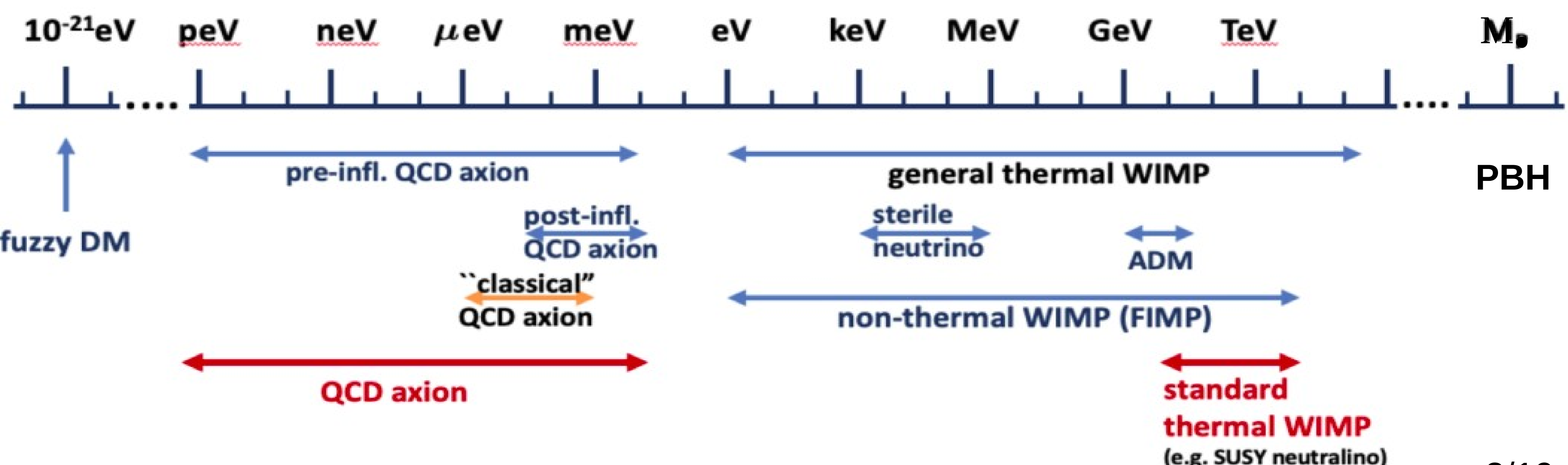
Dark Matter: knowns & unknowns

What we know

- Gravitational interaction
- Heavy and stable
- Electromagnetic charge neutral
- Cold/non-relativistic

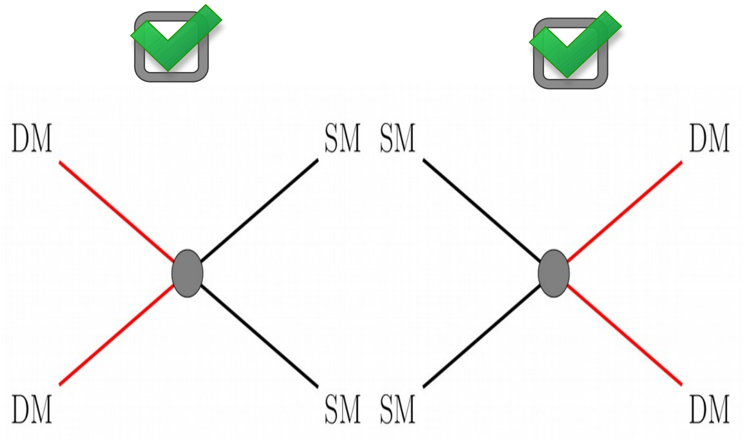
What we don't know

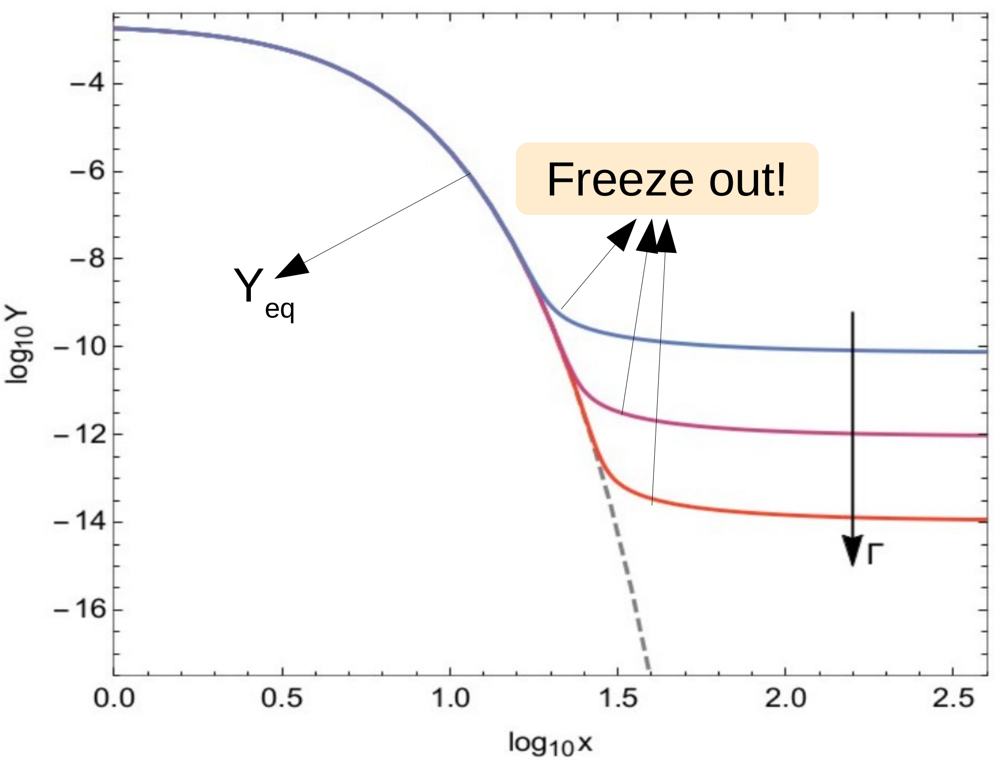
- Particle nature of DM
- Production mechanism
- Interaction with SM
- Single or multi-component



WIMP:

- DM is in thermal equlibrium with SM at T >> m_{DM}
- As T falls below DM mass, $n_{DM} \propto \exp(-m_{DM}/T)$
- When $\Gamma_{int} < H$, DM decouples from the thermal bath and the number density becomes constant.





Boltzmann Equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

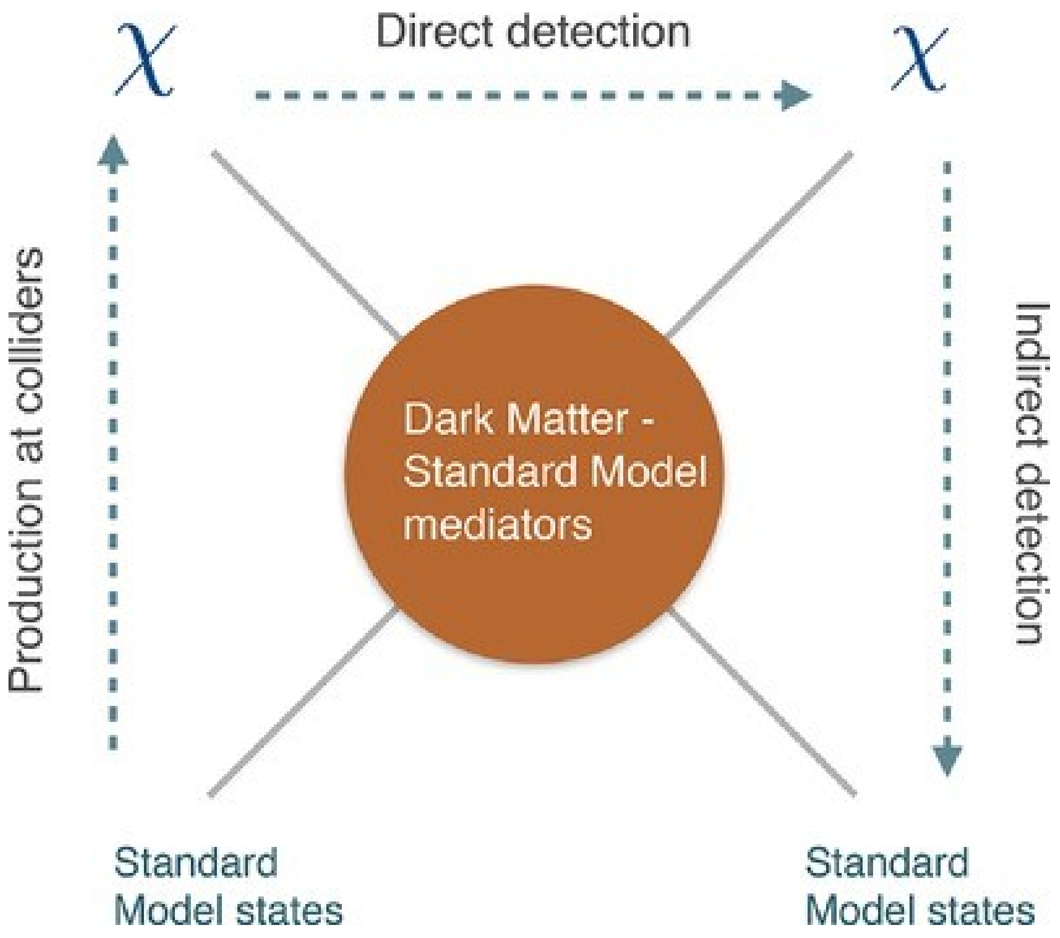
$$Y \equiv n/s \text{ and } x = m/T$$

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s}{Hx}(Y^2 - Y_{\rm eq}^2)$$

$$\Omega h^2 \simeq 0.12 \left(\frac{2 \times 10^{-9}}{\langle \sigma v \rangle} \right) \text{GeV}^{-2}$$

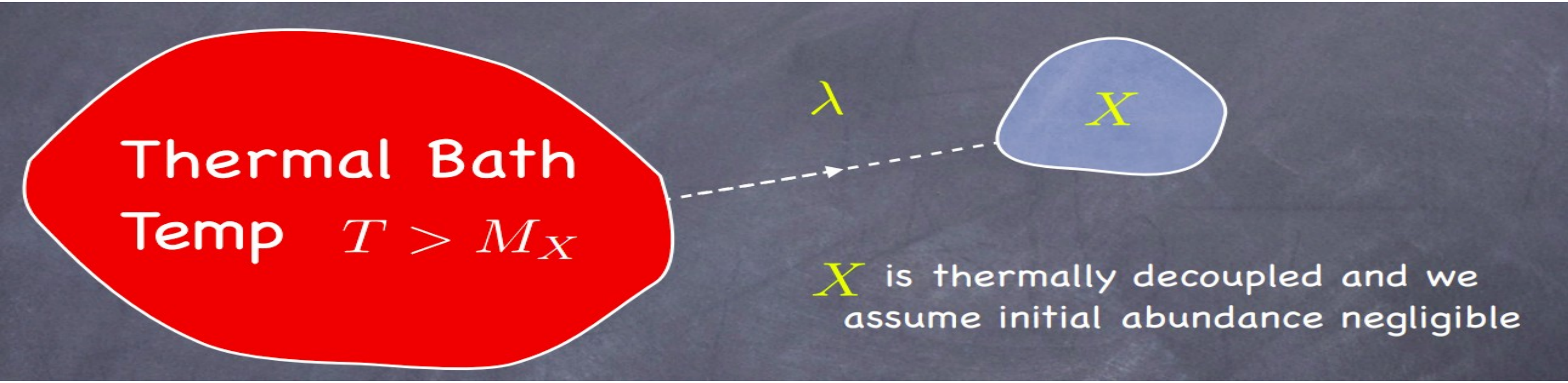
WIMP miracle!

WIMP searches:

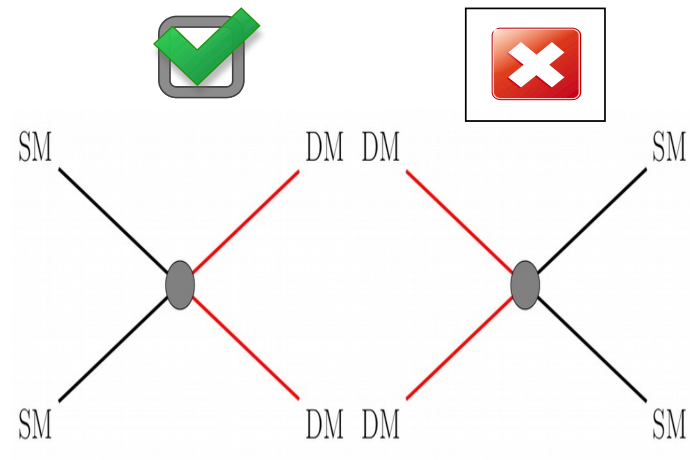


Null results from these experiments motivate us to look into other DM production mechanisms such as **Freeze-in** mechanism.

FIMP:



- DM is never in thermal equilibrium with the SM
- Initial DM abundance is vanishingly is small
- Produced via annihilation/decay of the bath particles
- Two categories: IR (0911.1120) & UV (1410.6157)



FIMP:

IR

- DM couples to SM via renormalizable interactions
- $\lambda \sim O(10^{-10})$ gives the corrrect DM relic abundance
- Dominant DM production happens at $T_{fi} \sim m_{DM}$
- Mild dependence on initial condition

UV

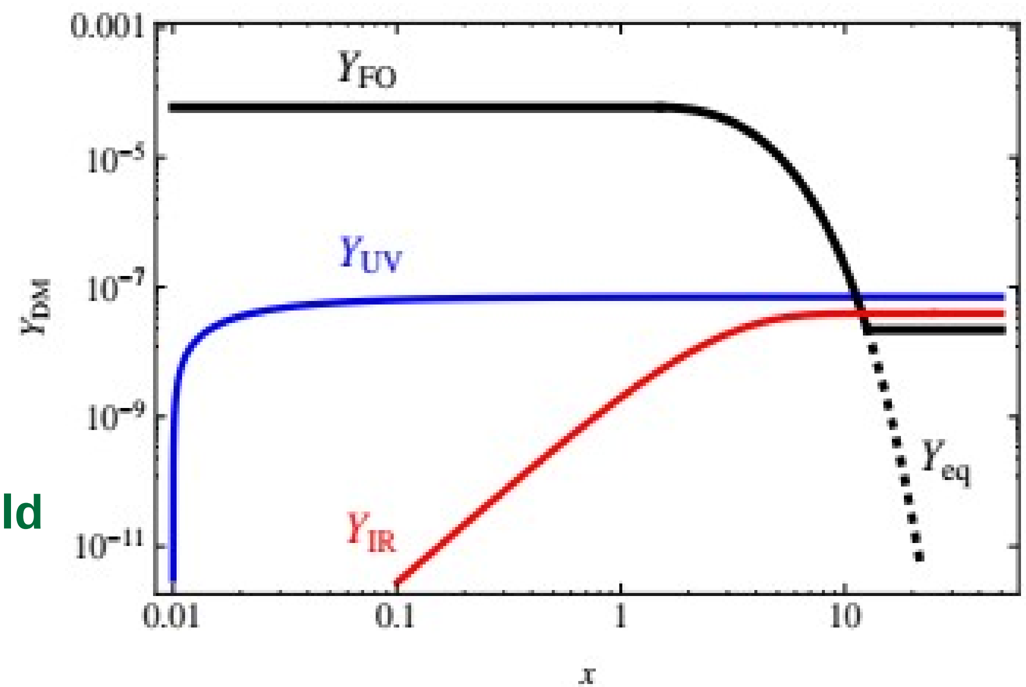
- DM couples to SM via non-renormalizable interactions
- DM yield is ∝ temperature
- Dominant DM production happens at $T_{fi} \sim T_{RH}$
- Strong dependence of initial conditions

Boltzmann Equation

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s}{Hx}(Y^2 - Y_{\rm eq}^2)$$

IR FIMP: Gradual increament of DM yield

UV FIMP: Immediate increament of DM yield



DM Effective Field Theory:

$$\mathcal{L}_{\rm eft} = \mathcal{L}_{\rm SM} + \sum_n \frac{c_n}{\Lambda^{(n-4)}} \mathcal{O}_{\rm SM-DM}$$

$$\mathcal{O}_{\rm DM-SM} \sim \mathcal{O}_{\rm DM} \mathcal{O}_{\rm SM}$$

$\mathcal{O}_{\rm SM}$ is constituted of SM fields
$\mathcal{O}_{\rm DM}$ is constituted with DM fields

This factorization assumes that DM does not possess any SM charges and vice versa

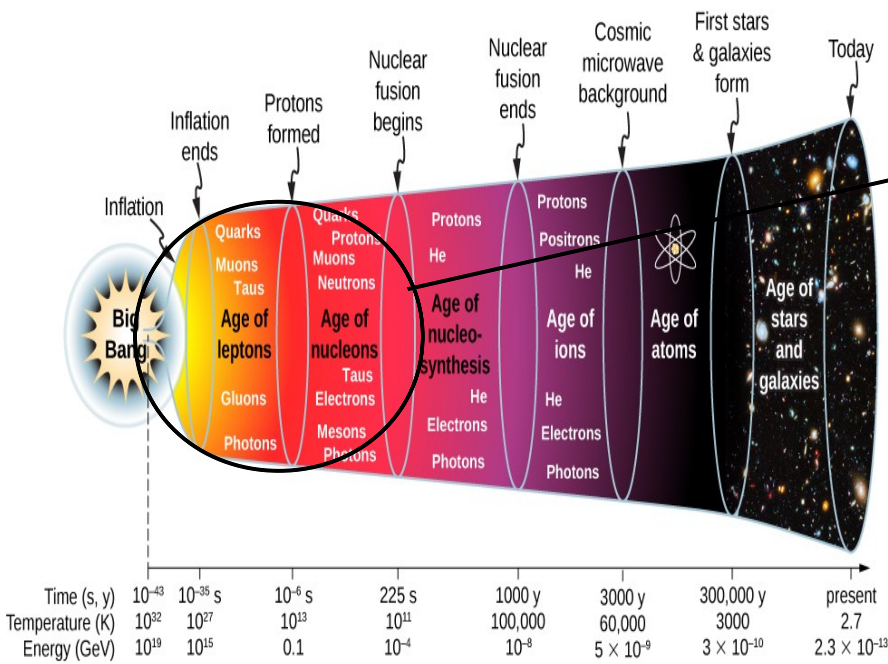
- DMEFT operators are Lorentz invariant
- Z_2 symmetry is imposed on DM for the stability
- Any operator would contain at least two DM particles

$$\mathcal{O}_2^s = \frac{1}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W^i_{\mu\nu}W^{i\mu\nu})\,\Phi^2 \sim F_{\mu\nu}F^{\mu\nu}\Phi^2$$

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

→ Photophilic Dark Matter

DM as a window to early universe:



Pre-BBN Cosmology

Inflation
$E \sim 10^{16}$ GeV
$t \sim 10^{-36}$ sec

BBN
$E \sim 4$ MeV
$t \sim 1$ sec

Massive Gap

Reheating dynamics

Non renormalizable interactions/ Effective theories

Direct Searches
Indirect searches
Collider searches

Early universe
T_{RH}

UV freeze-in DM
T_{RH}, m_{DM}, Λ_{NP}

DM experiments
m_{DM} and Λ_{NP}

Instantaneous reheating:

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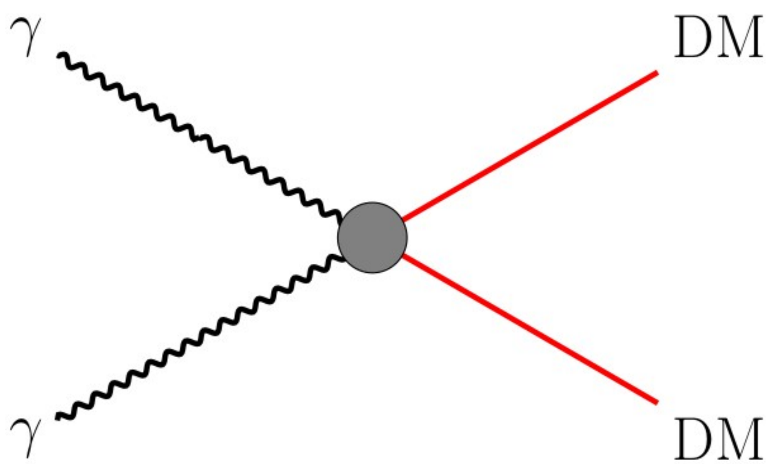
- Inflaton decays instantaneously: Inflationary dynamics absent
- Maximum temperature of the universe: Reheating temperature

From photophilic operators,

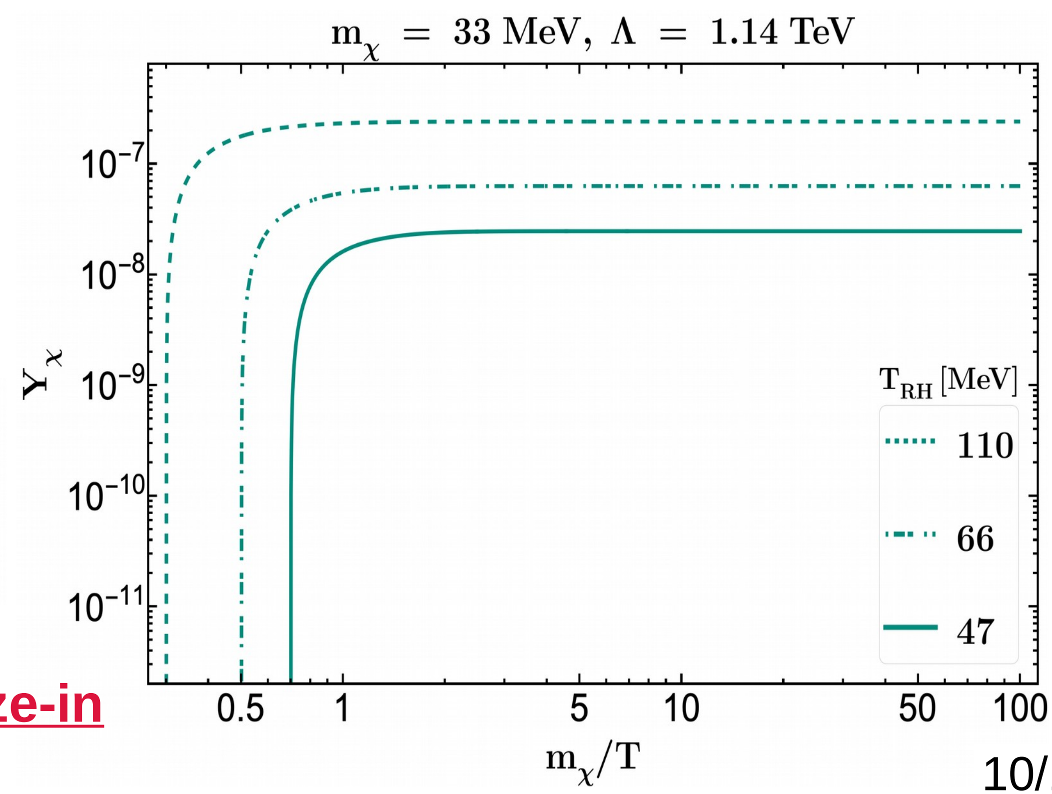


$$\left.\frac{\Gamma_{2\to 2}}{\mathrm{H}}\right|_{T=T_{\mathrm{RH}}} \sim \begin{array}{l} \dfrac{\mathscr{C}_0}{\sqrt{g_*(T)}}\left(\dfrac{m_\Phi}{1\ \mathrm{MeV}}\right)\left(\dfrac{T_{\mathrm{RH}}}{T_{\mathrm{BBN}}}\right)^2\left(\dfrac{1\ \mathrm{TeV}}{\Lambda}\right)^4 \\ \dfrac{\mathscr{C}_{1/2}}{\sqrt{g_*(T)}}\left(\dfrac{m_\chi}{1\ \mathrm{MeV}}\right)^3\left(\dfrac{T_{\mathrm{RH}}}{T_{\mathrm{BBN}}}\right)^2\left(\dfrac{1\ \mathrm{TeV}}{\Lambda}\right)^6 \end{array}$$

$$\mathscr{C}_0 \sim 1.39\times 10^{-1}\ ,\ \mathscr{C}_{1/2} \sim 8.94\times 10^{-16}$$

$$\Gamma_{2\to 2} = n_{\mathrm{eq}}\langle\sigma v\rangle_{\mathrm{DMDM}\to\gamma\gamma}$$

$$Y_{\mathrm{DM}}(T) \sim \frac{5\times 10^4\, M_{Pl}}{g_{*s}(T)\sqrt{g_*(T)}\,\pi^8}\left(\frac{T_{\mathrm{RH}}^5 - T^5}{\Lambda^6}\right)$$



Yield is maximum at T_{RH} >> T: **UV freeze-in**

Results:

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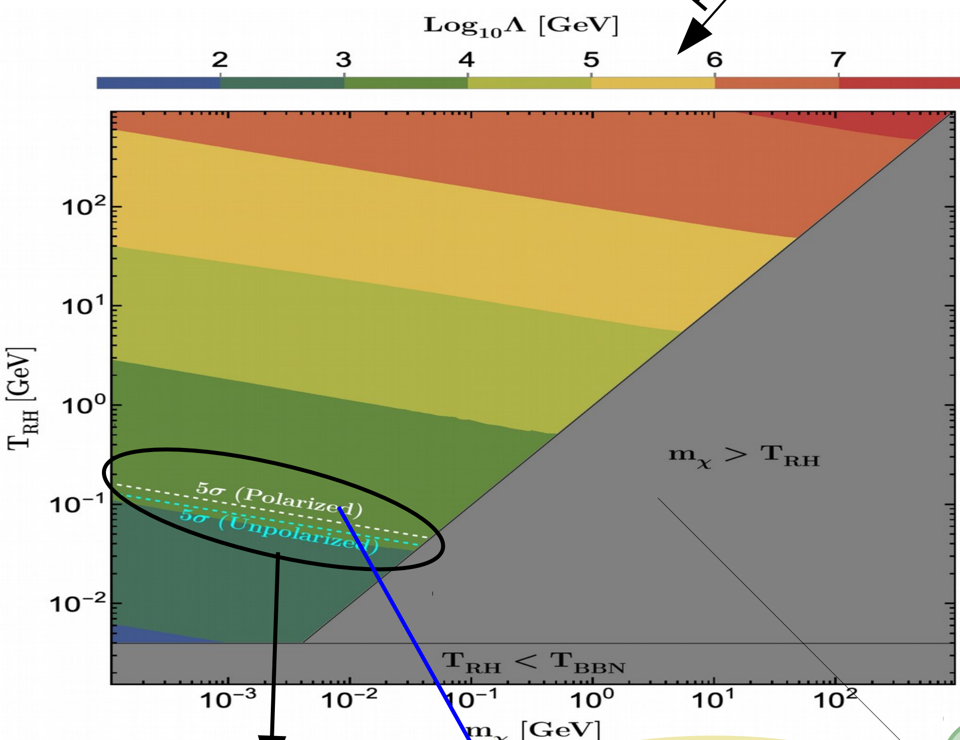
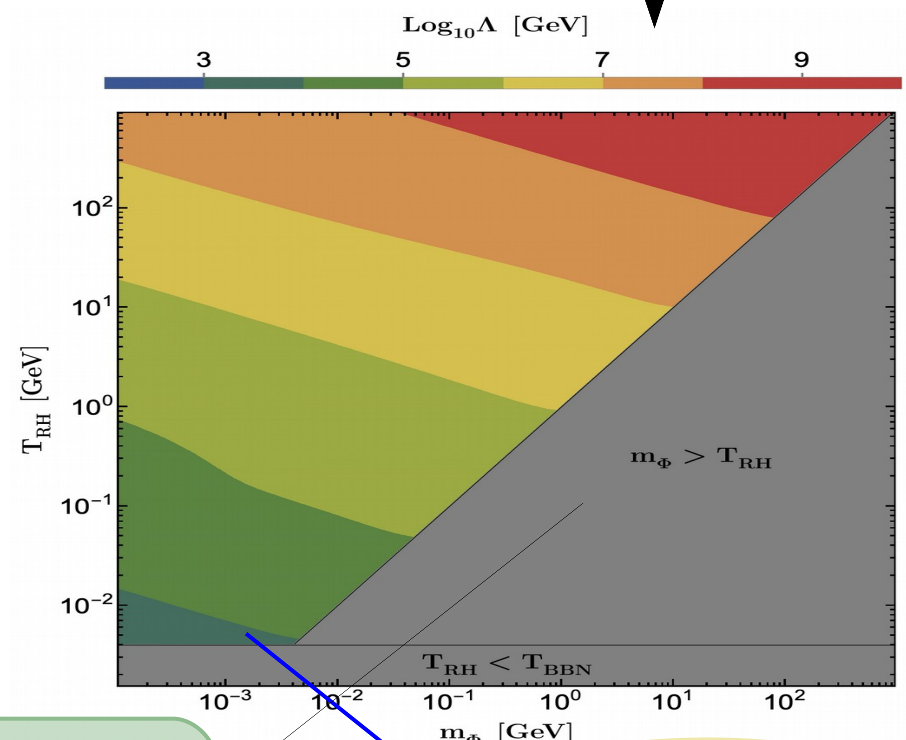
$$\Lambda \simeq \begin{cases} 5\,\mathrm{TeV}\,\left(\frac{m_\Phi}{1\,\mathrm{MeV}}\right)^{1/4}\left(\frac{T_{\rm RH}}{T_{\rm BBN}}\right)^{3/4} \\ 100\,\mathrm{GeV}\,\left(\frac{m_\chi}{1\,\mathrm{MeV}}\right)^{1/6}\left(\frac{T_{\rm RH}}{T_{\rm BBN}}\right)^{5/6} \end{cases}$$

Fermion DM

Scalar DM





Discovery limit at 1 TeV & 8 ab^{-1} ILC

$\Lambda \sim \mathcal{O}(1)$ TeV

Accessable via non-instantaneous reheating scenario

$\Lambda \sim \mathcal{O}(10)$ TeV

Event analysis:

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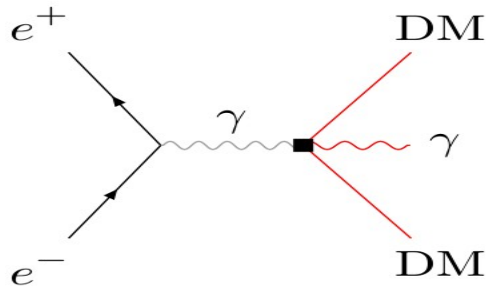
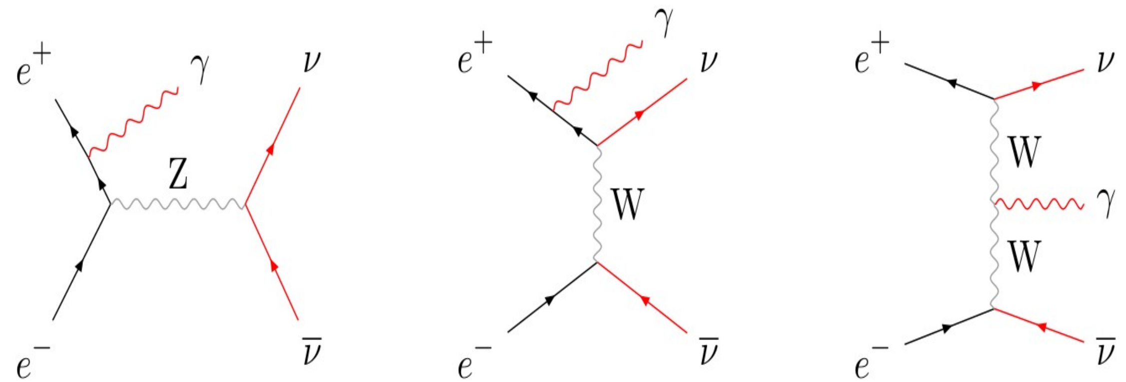
'Natural' Mono-photon signal



SM backgrounds



Missing energy

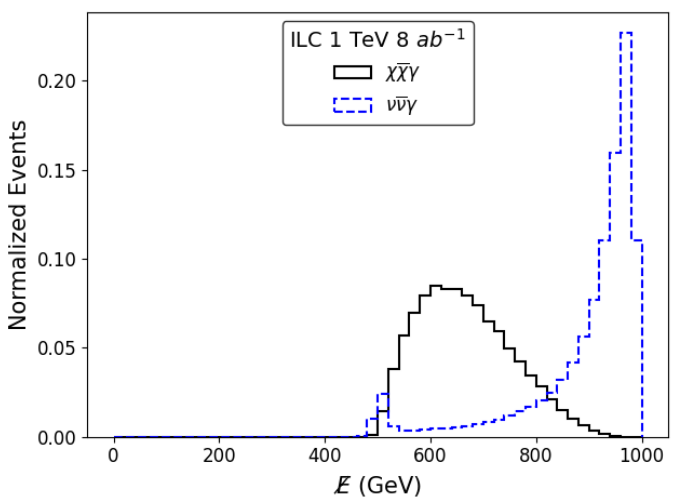
$$\not{E} = \sqrt{s} - \sum_i E_i$$

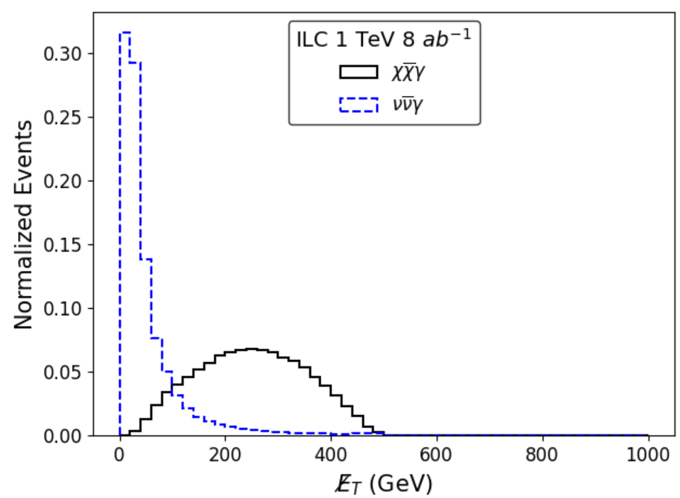
Missing transverse momentum

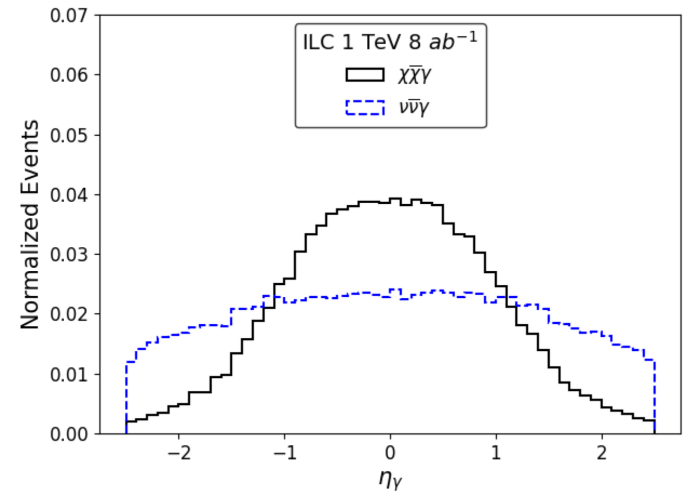
$$\not{E}_T = -\sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2}$$

Pseudorapidity

$$\eta_\gamma = -\ln\left[\tan\left(\frac{\theta_\gamma}{2}\right)\right]$$







Cut flows

$$\not{E}_T > 200.0 \text{ GeV}$$
$$\not{E} \in [525, 750] \text{ GeV}$$
$$|\eta_\gamma| < 1.0$$

97% bkg suppression

6 fold bkg suppression

Polarization	Signal	Background	Significance
Unpolarized	2395	219161	5.10
{-20%, +80%}	2778	40711	13.62
Benchmark: $\{m, \Lambda\}$ = {33.0 MeV, 1.14 TeV}			

Summary plot:

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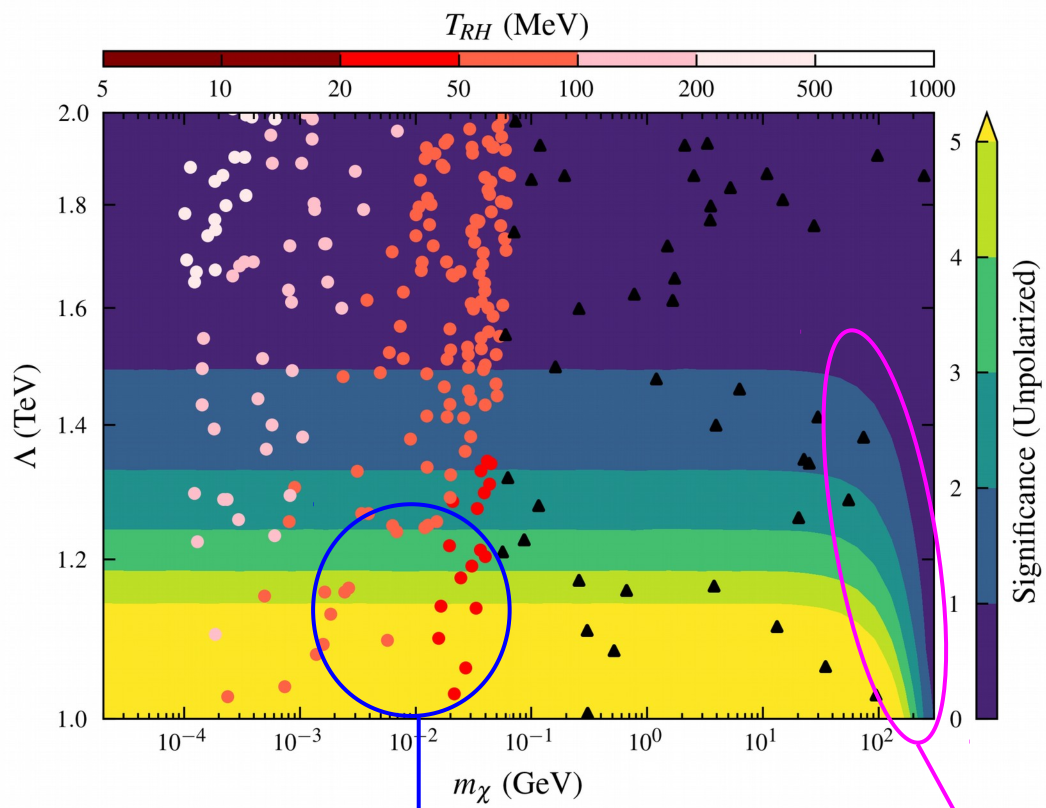
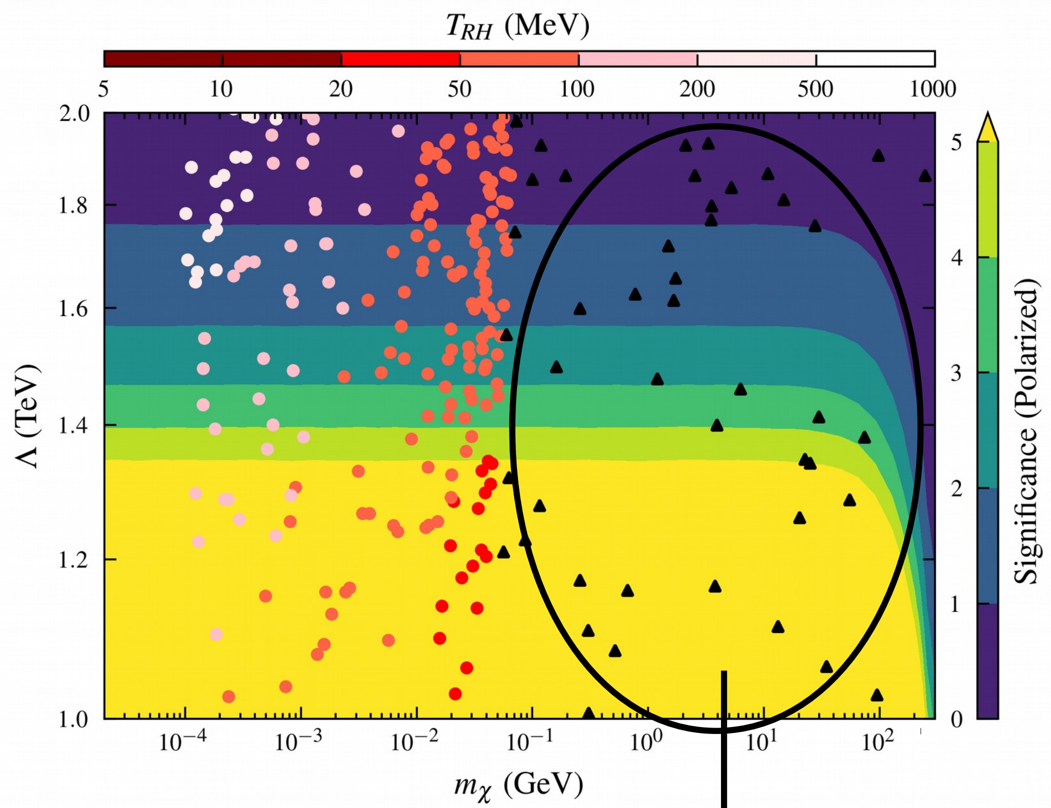
Fermionic DM

Unpolarized beam



Polarized beam



Low DM mass and low reheat teamperature ensure high signal significance

Kinematic suppression

Ruled out due to $T_{RH} < T_{BBN}$
Or $T_{RH} < m_{DM}$

Non-instantaneous reheating:

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- Decay of inflaton to SM radiation is a **continous** process
- Maximum temperature of the universe ≠ Reheating temperature

$$\mathcal{L}_{\rm int} \supset -\mu\phi|\Phi|^2 - y\phi\bar{\Psi}\Psi$$

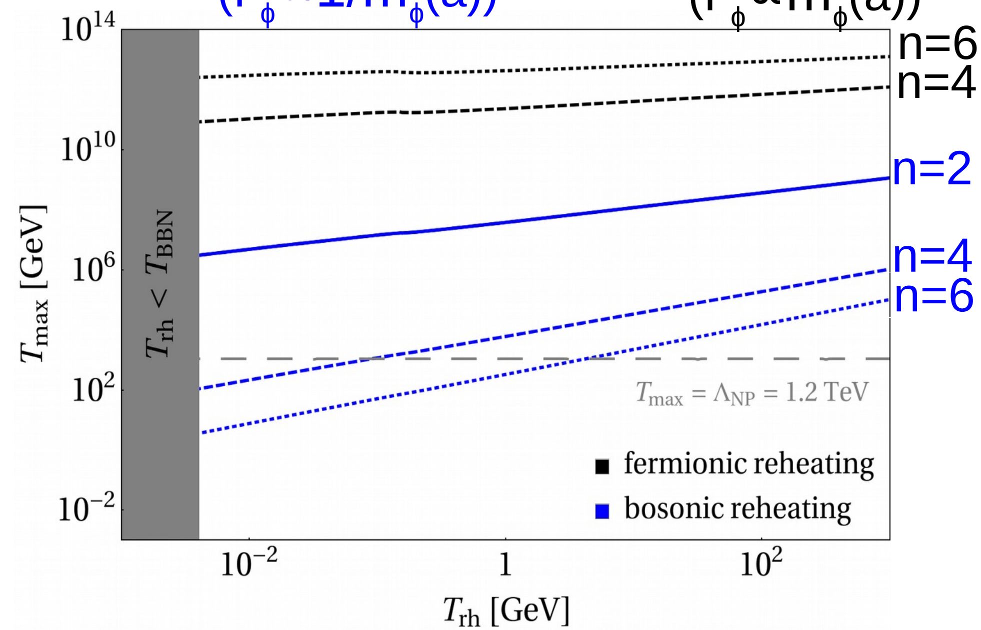
Bosonic ($\Gamma_\phi \propto 1/m_\phi(a)$)

Fermionic ($\Gamma_\phi \propto m_\phi(a)$)

Inflation oscillation

$$V(\phi) = \lambda \frac{\phi^n}{\Lambda_I^{n-4}}$$

$$\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + V'(\phi) = 0$$



Coupled differential equations

Inflaton: $\frac{d\rho_\phi}{dt} + \frac{6n}{2+n} H = -\frac{2n}{2+n}\Gamma_\phi \rho_\phi$

Radiation: $\frac{d\rho_R}{dt} + 4H\rho_R = +\frac{2n}{2+n}\Gamma_\phi \rho_\phi$

Dark matter: $\frac{d\rho_{\rm DM}}{dt} + 3H\rho_{\rm DM} = +\mathcal{C}_{\rm int} m_{\rm DM}$

$$H = \sqrt{\frac{\rho_\phi + \rho_R}{3M_{\rm PI}^2}} \qquad \mathcal{C}_{\rm int} \sim \frac{T^{2d-4}}{\Lambda^{2d-8}}$$

EFT validity: $\Lambda_{NP} > T_{max}$

Fermionic reheating: $T_{max} > O(10^{10})$ GeV

Bosonic reheating: $T_{max} \sim O(1)$ TeV for n= 4 and 6

Viable at colliders

Bosonic reheating and DM Yield:

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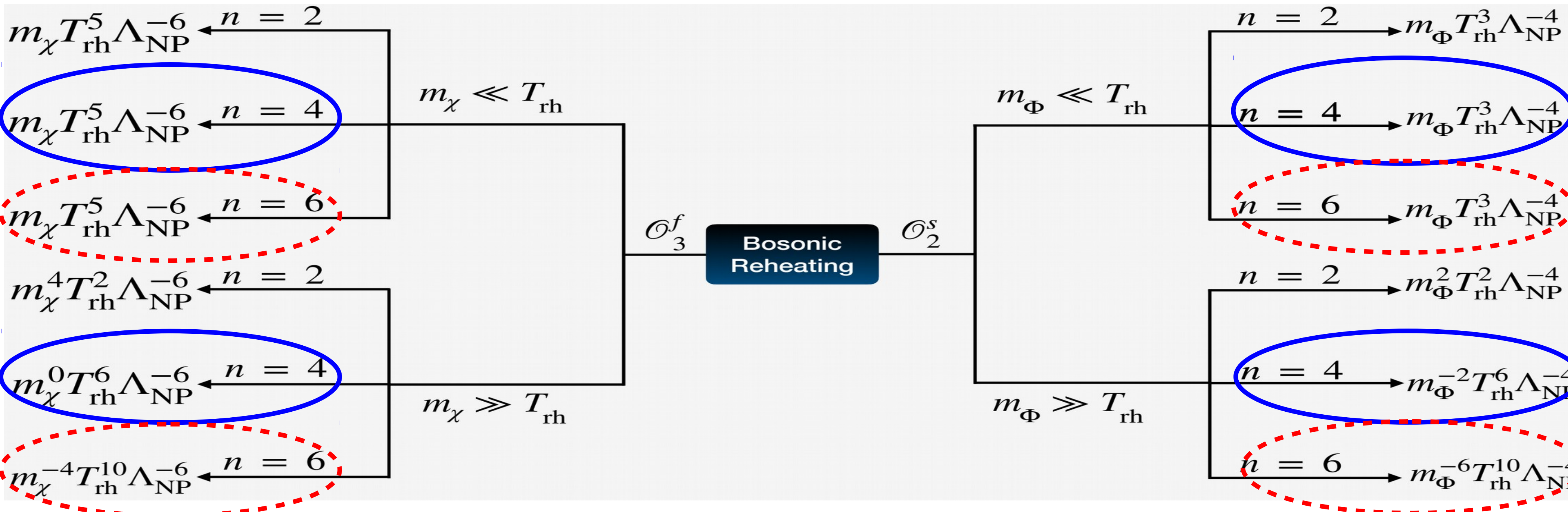
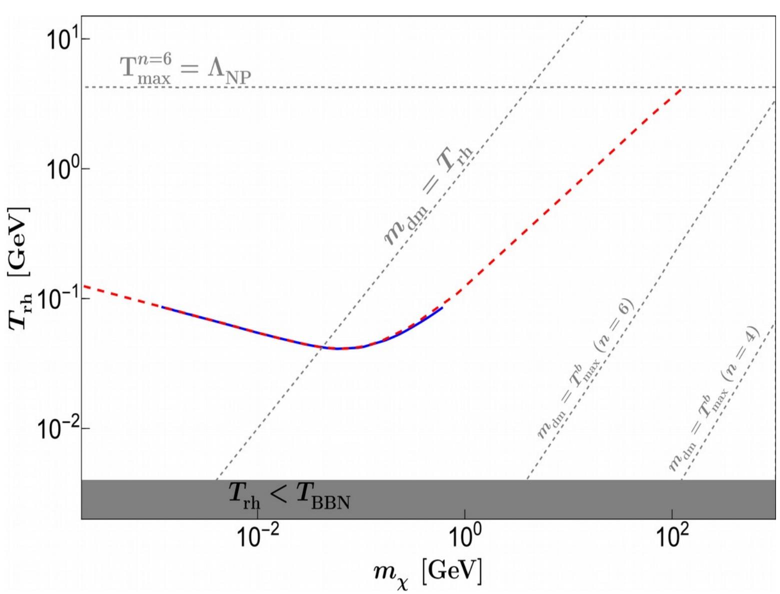
Fermionic DM

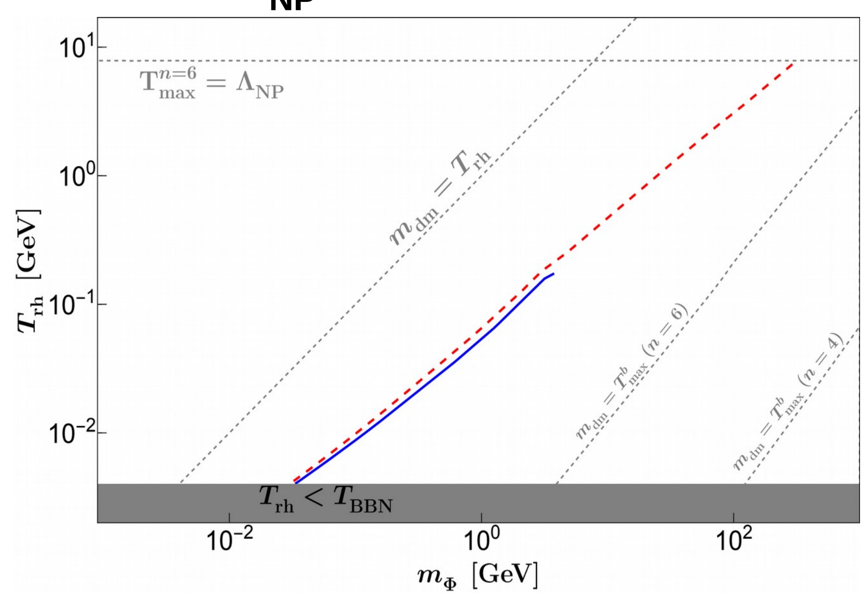
Scalar DM



$\Lambda_{\rm NP}$ = 1.2 TeV



$\Lambda_{\rm NP}$ = 2 TeV



Direct & Indirect searches:

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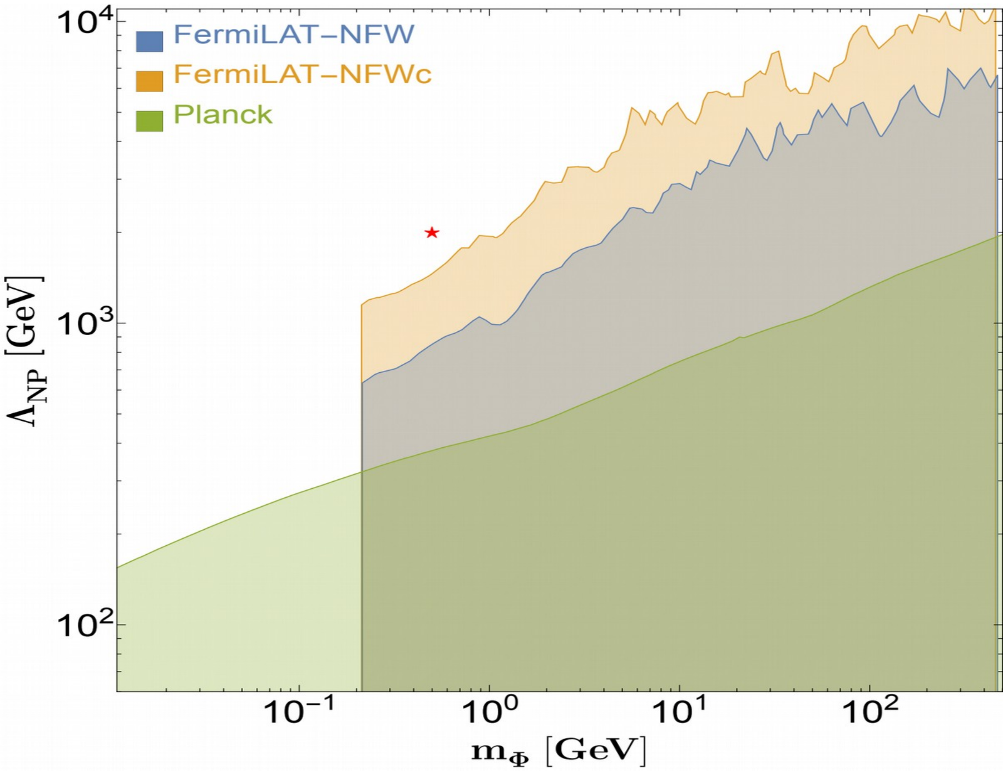
- The DM-electron scattering cross-section is a one loop photon mediated diagram therefore the cross-section is highly suppressed.

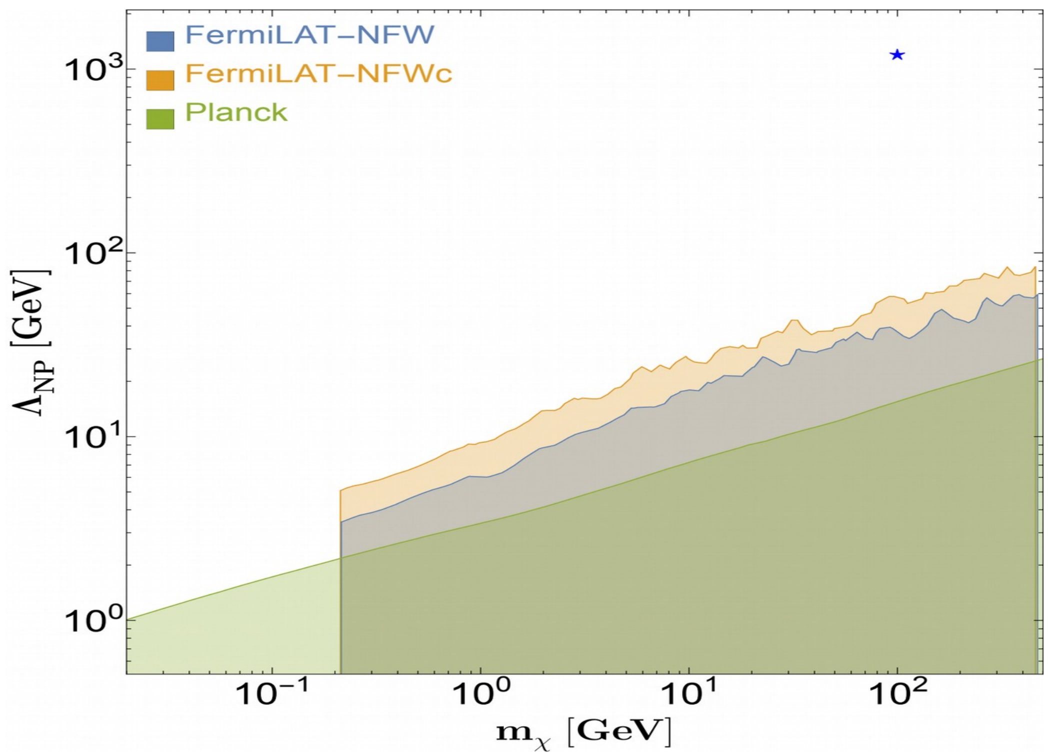
- Indirect search arises due to DM DM ⟶ γγ

Scalar DM



For $\Lambda_{NP} \leq 2$ TeV, $m_\phi > 1$ GeV is ruled out.

Fermionic DM



Two order magnetude relaxed compared to scalar DM.

OSE searches:

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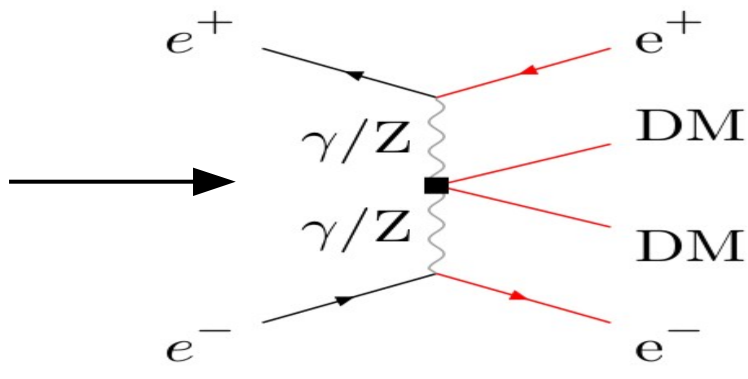
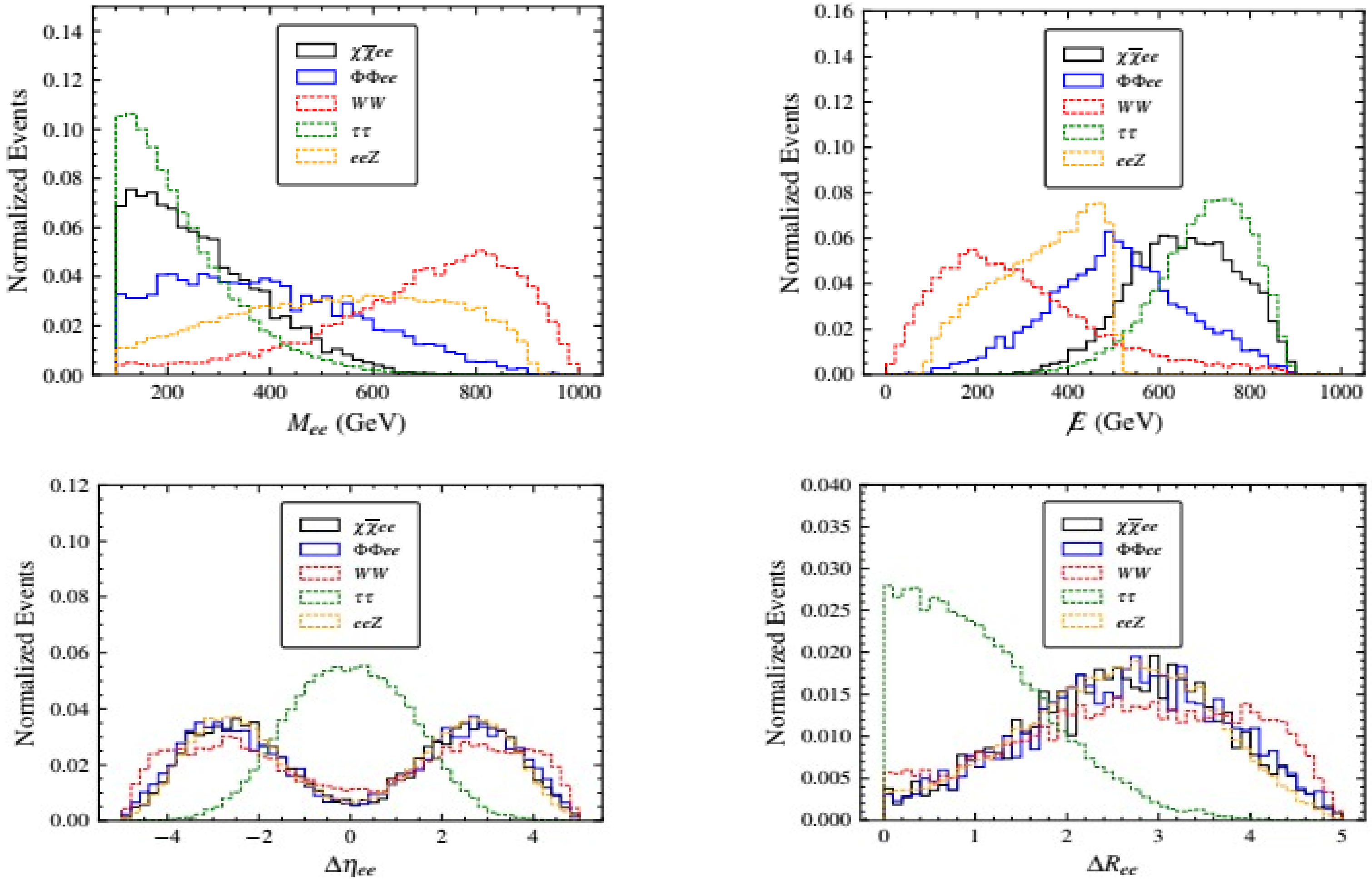
Signal:



SM backgrounds

i)WW
ii)τ τ
iii)eeZ



Results:

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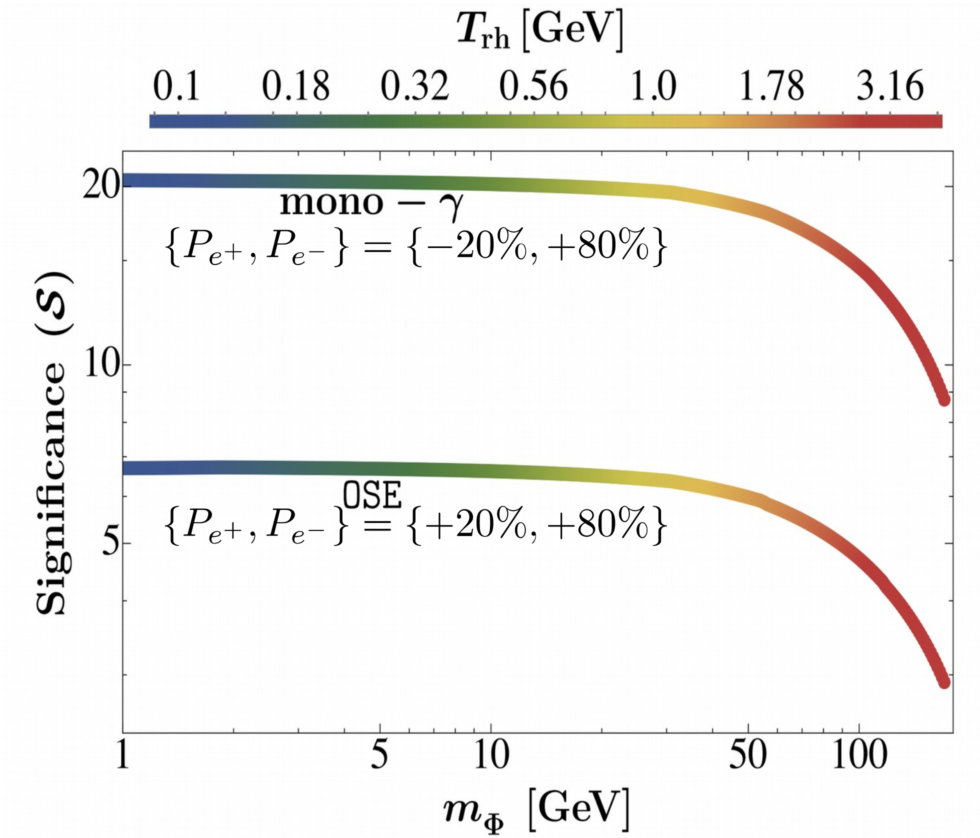
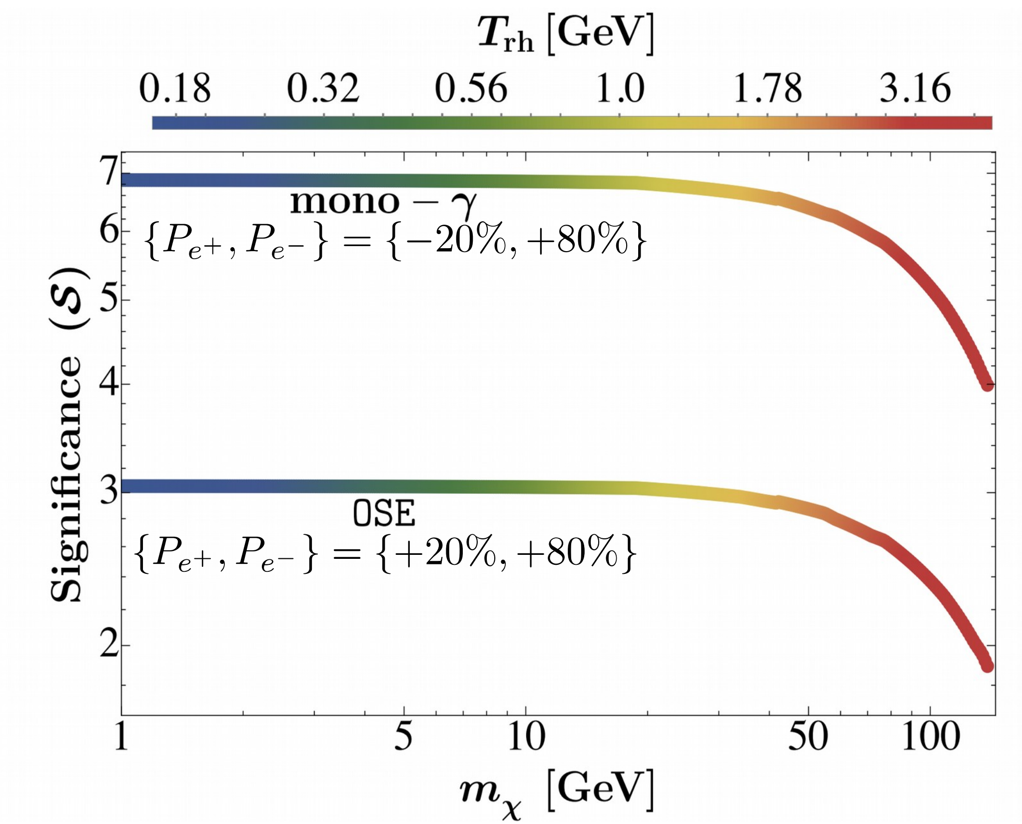
ILC: $\begin{cases} \sqrt{s} = 1 \text{ TeV} \\ \mathfrak{L}_{\text{int}} = 8 \text{ ab}^{-1} \end{cases}$

Scalar DM



Fermionic DM



Mono-γ signal proves to be more beneficial than OSE signal

Summary:

- UV freeze-in is a viable DM production mechanism that stongly depends on the initial conditions.

- Bosonic reheating is favourable for low temperature reheating scenario.

- Scalar DM, with dimension six operator, provides the allowed DM parameter space below 1 GeV DM mass, while for fermionic DM, the parameter space is much relaxed due to dimensionality.

- Natural mono-photon signal proves to be beneficial for dark matter searches at the colliders.

Thank you!