



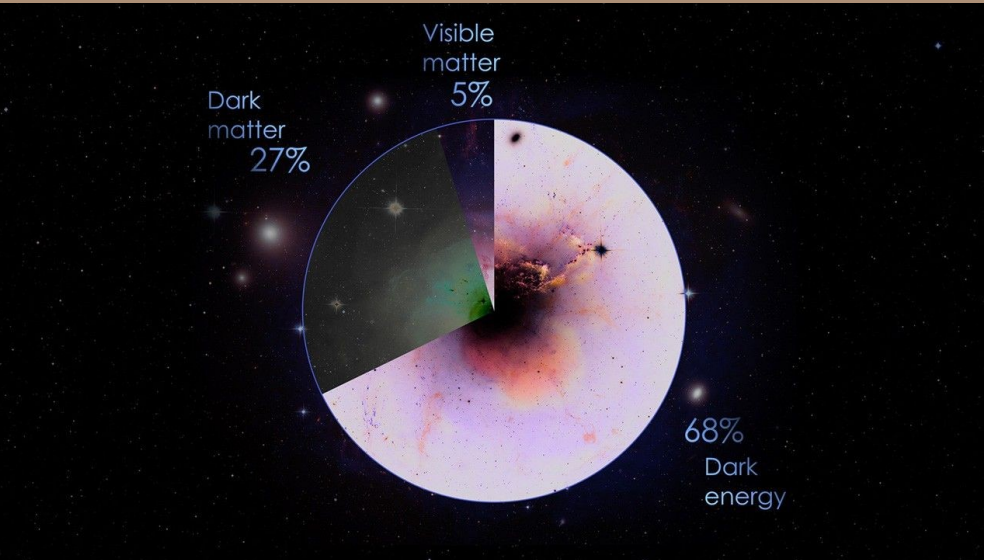
Light non-thermal Dark Matter production from post-Inflationary dynamics

Based on PRD 106 (2022) 4, 043519 ; JCAP 04 (2026) 047

Avirup Ghosh
Postdoctoral Fellow
University of Melbourne



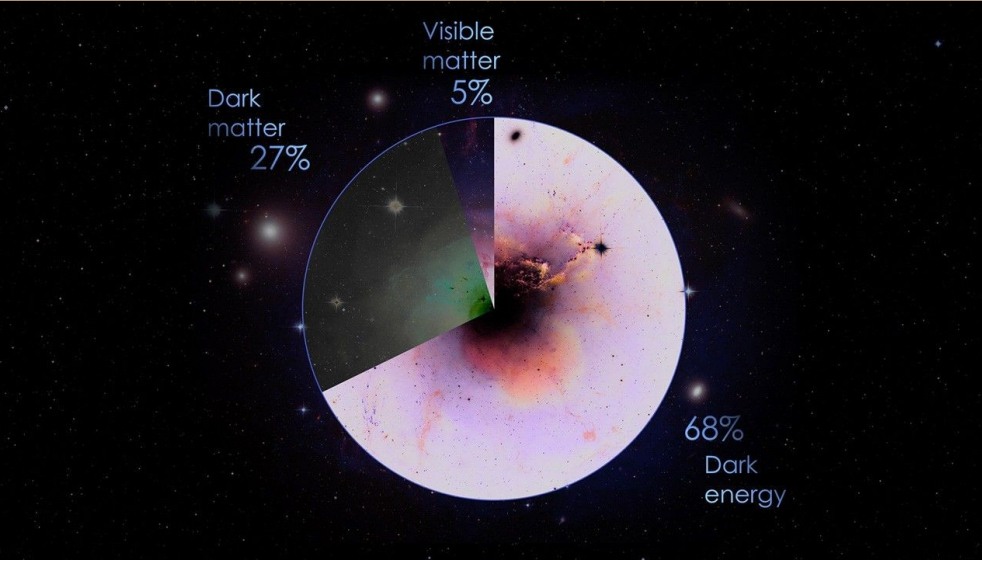
Evidences of dark matter (DM)



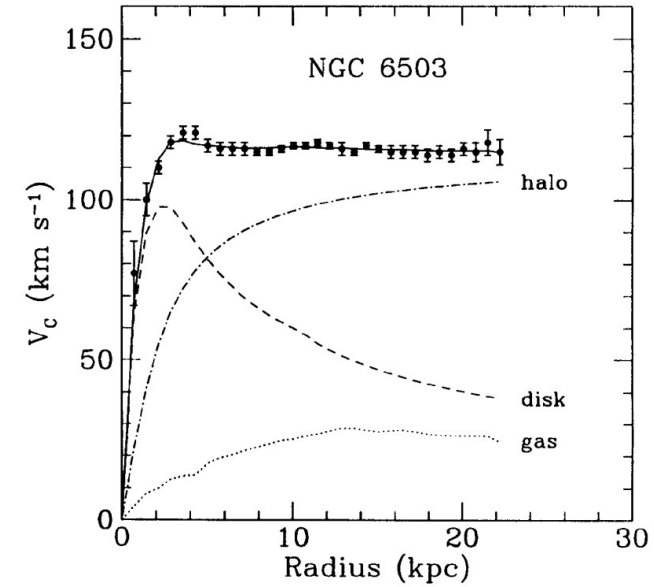
[<https://science.nasa.gov/dark-matter/>]



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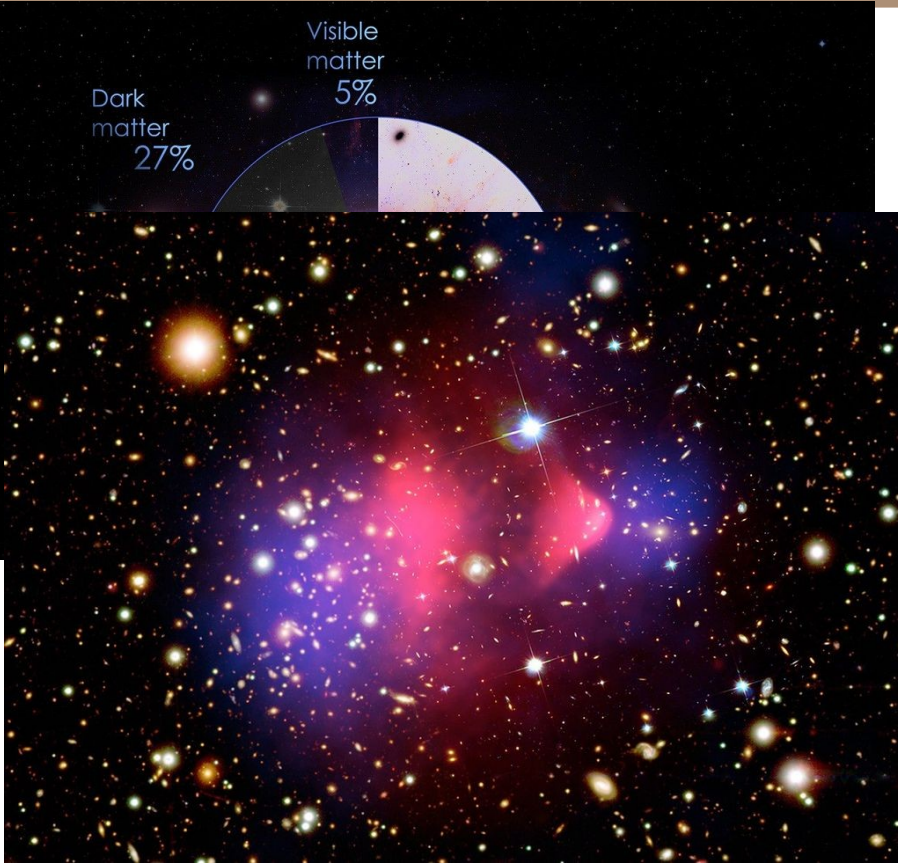
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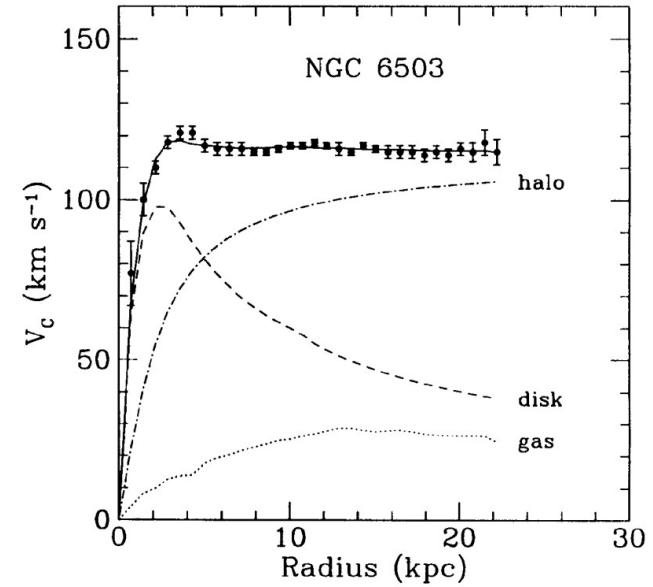
[K Freese EAS Publ.Ser.'2009]

Galaxy Rotation Curve

Evidences of dark matter (DM)



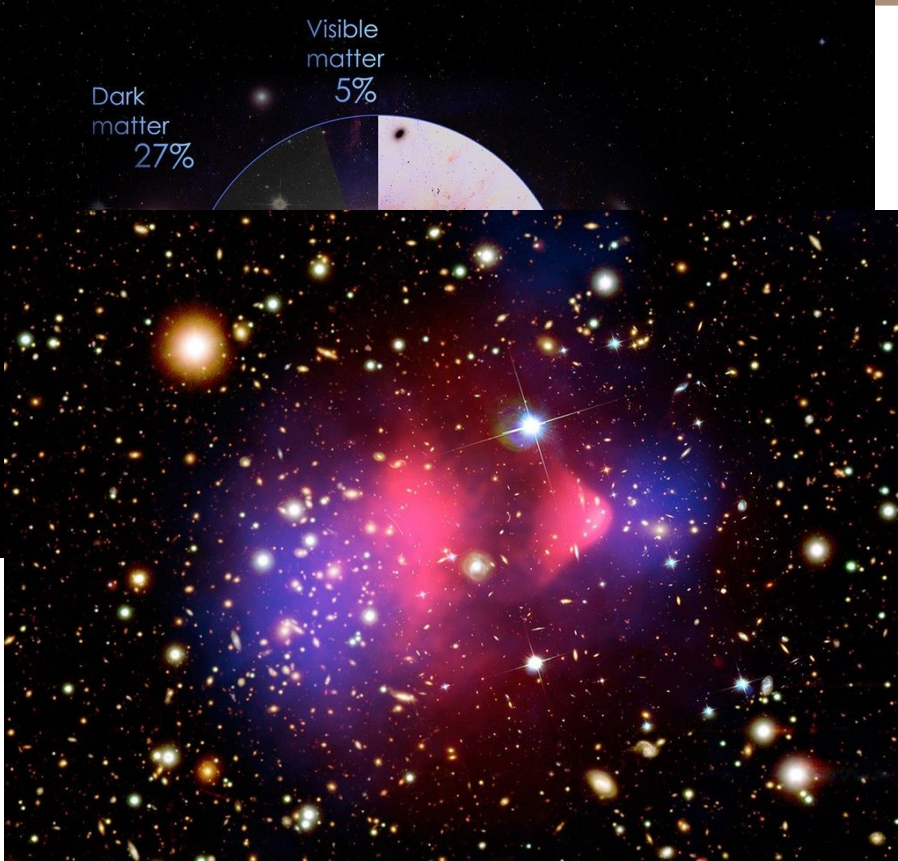
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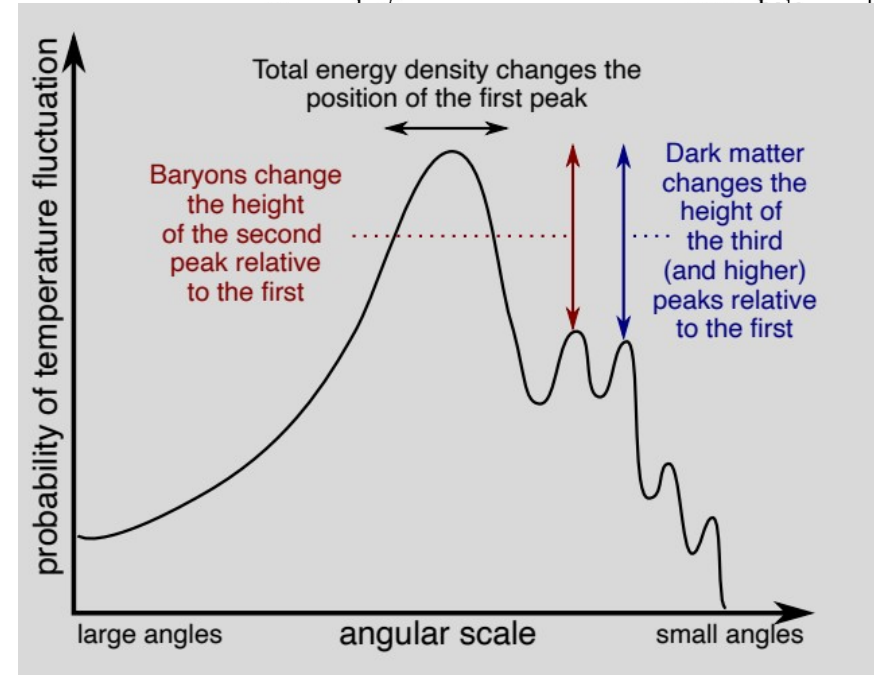
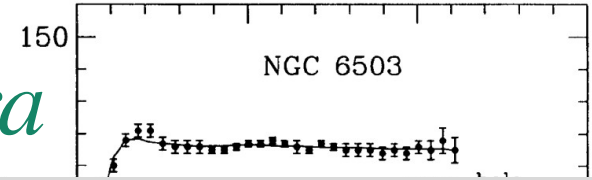
Bullet Cluster

Evidences of dark matter (DM)



[<https://science.nasa.gov/dark-matter/>]

CMB Spectra



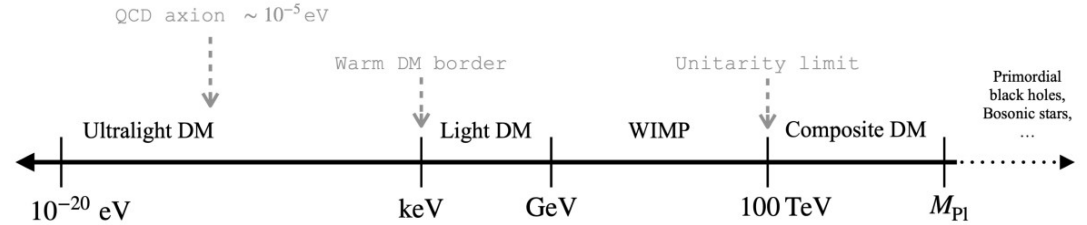
[C Balazs Astrophysics'2026]

Thermal WIMPs as particle dark matter



[K Tuominen Symmetry'2021]

- Allowed mass range for particle dark matter extends ~50 orders of magnitude

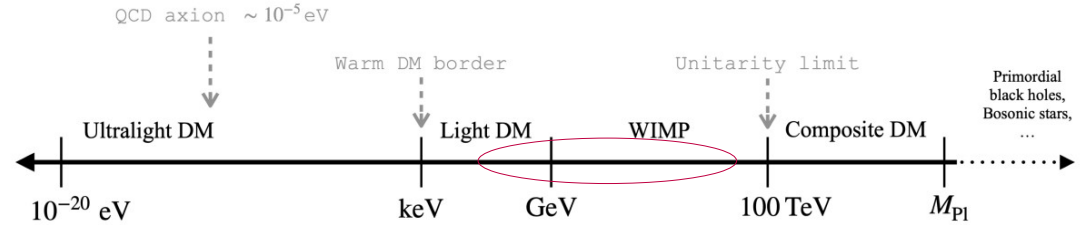


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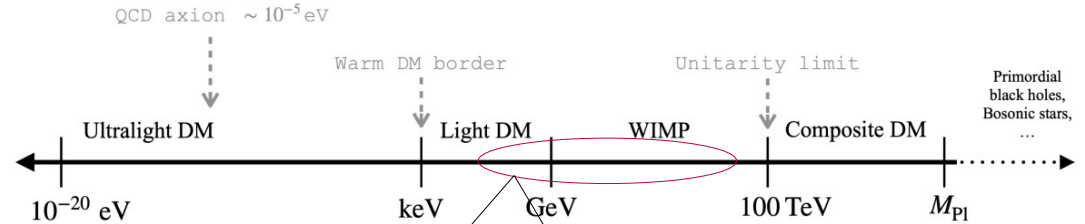


Thermal WIMPs as particle dark matter

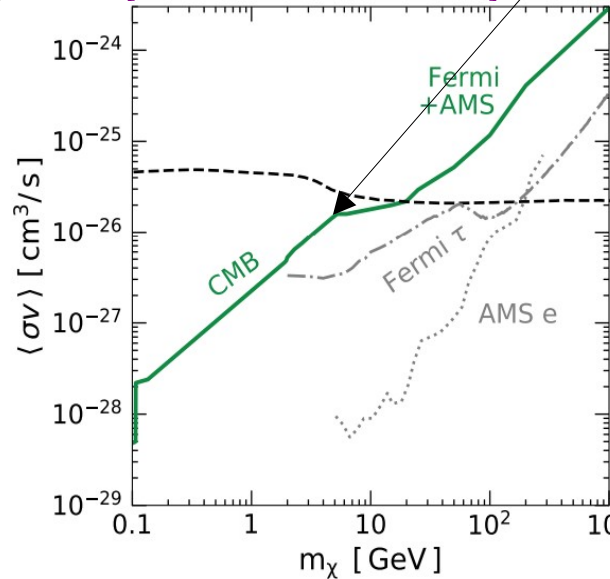


- Allowed mass range for particle dark matter extends ~ 50 orders of magnitude
- Most focus has been given to MeV-TeV scale thermal WIMPs
- Strong CMB and direct-detection constraints on sub-GeV WIMPs
- Alternative *non-thermal* production mechanisms for sub-GeV dark matter are needed

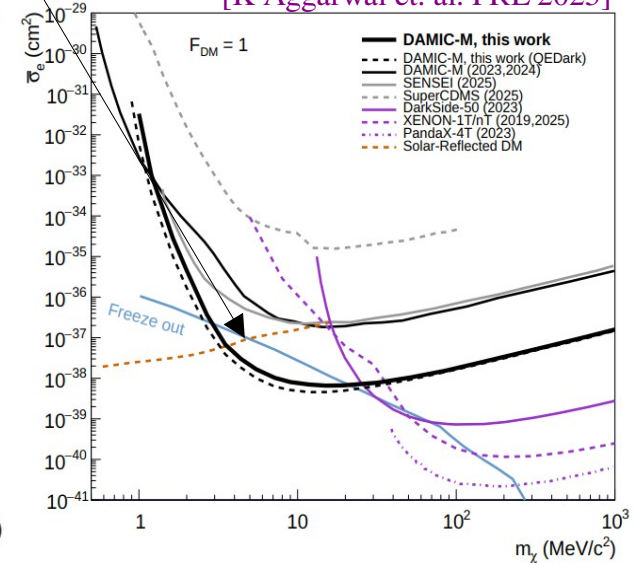
[K Tuominen Symmetry'2021]



[RK Leane et. al. PRD'2018]



[K Aggarwal et. al. PRL'2025]



Cosmological Inflation and post-inflationary reheating



- **Inflation:** An era of exponential expansion at the beginning of the Universe

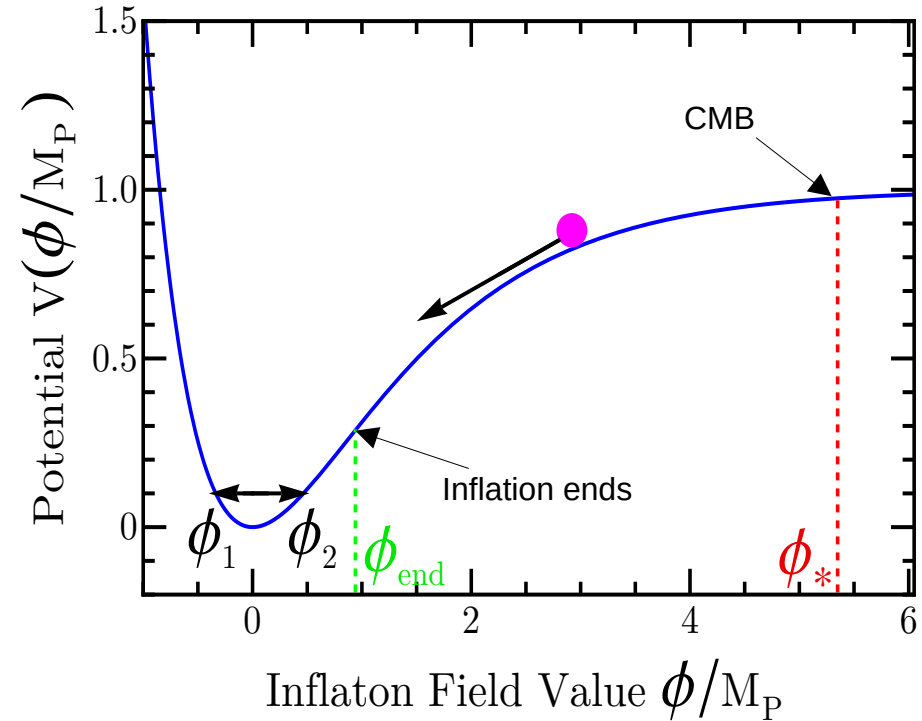
[AA Starobinsky PLB'1980, AH Guth PRD'1981, AD Linde PLB'1982]

- Provides explanations for:

- * Large-scale homogeneity and isotropy of the Universe
- * Seeds for late-time structure formation

- Post-inflationary *reheating* era:

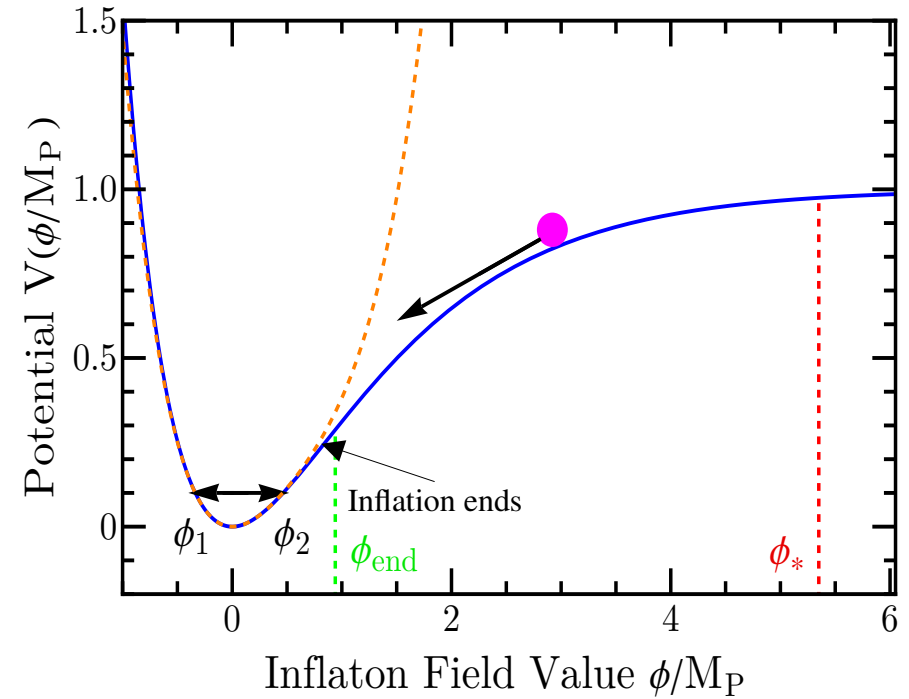
- * Energy of the oscillating inflaton field is transferred to SM radiation to set the stage for Radiation Dominated (RD) era before Big-Bang Nucleosynthesis (BBN)



Cosmological Inflation and post-inflationary reheating



- Around minimum inflaton potential is well approximated by $V(\phi) = \sum c_n \phi^n$

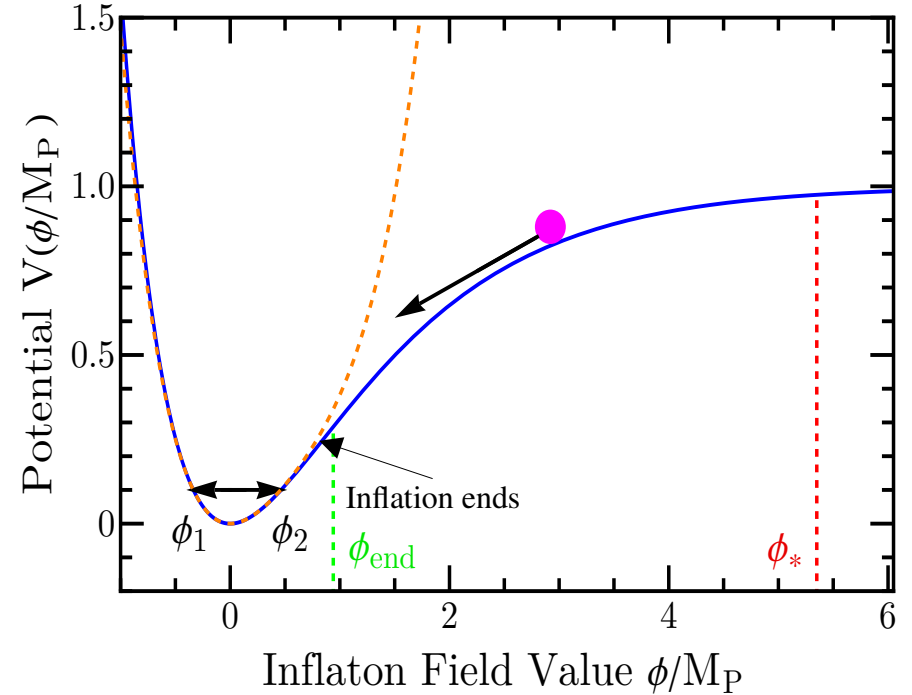


Cosmological Inflation and post-inflationary reheating



- Around minimum inflaton potential is well approximated by $V(\phi) = \sum c_n \phi^n$
- Inflaton field evolves as *damped oscillator*
[MAG Garcia et. al. JCAP'2021]:

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





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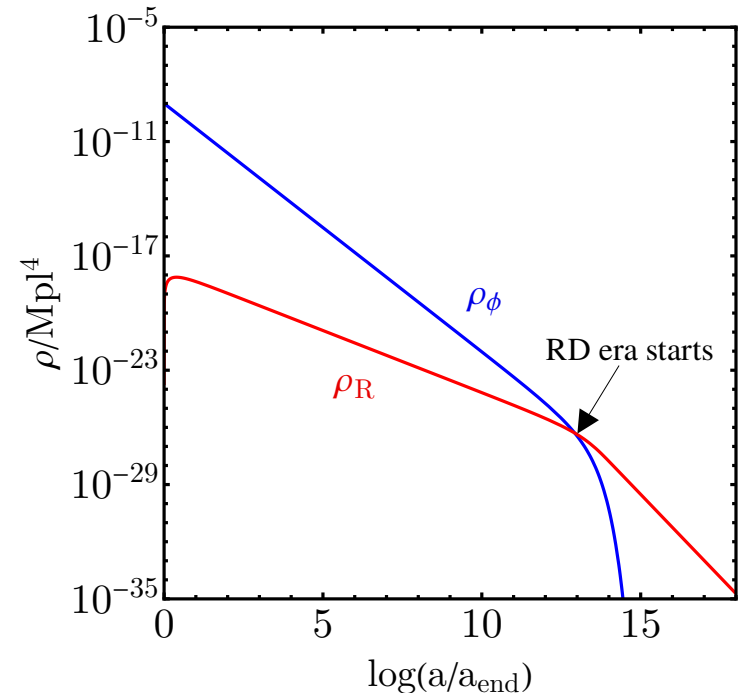
- In terms of inflaton energy density ρ_ϕ

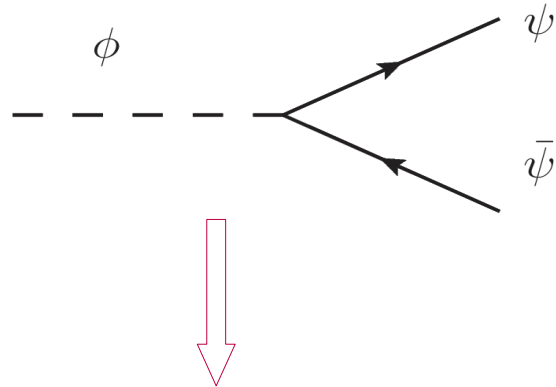
$$\dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = -\Gamma_\phi(\rho_\phi + P_\phi) \rightarrow P_\phi \approx \frac{(n-2)}{(n+2)} \rho_\phi$$

& the radiation energy density ρ_R

$$\dot{\rho}_R + 4H\rho_R = \Gamma_\phi(\rho_\phi + P_\phi)$$

- Inflaton may also couple to other fields (e.g., dark matter)
[R Allahverdi et. al. PRL'2002, DJH Chung PRD'2003, T Moroi et. al. JHEP'2021]





- We consider a fermionic DM ψ coupled to ϕ :

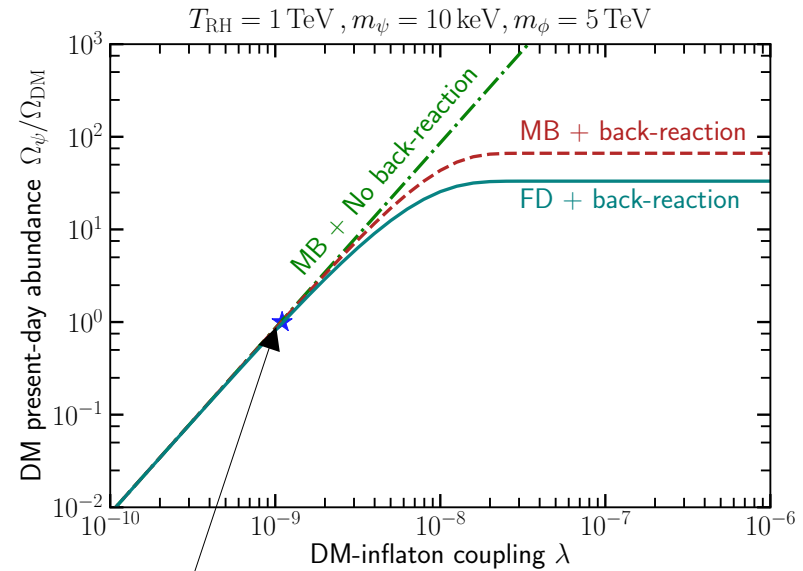
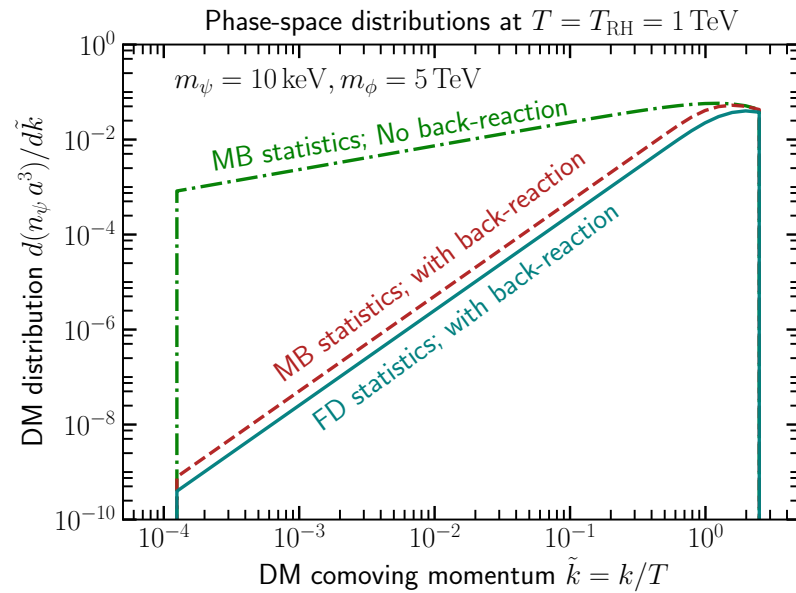
$$\mathcal{L} \supset -\mu_H \phi H^\dagger H - \lambda \phi \bar{\psi} \psi - \frac{1}{2} m_\phi^2 \phi^2$$

- In addition to ρ_ϕ and ρ_R we have solve for n_ψ also

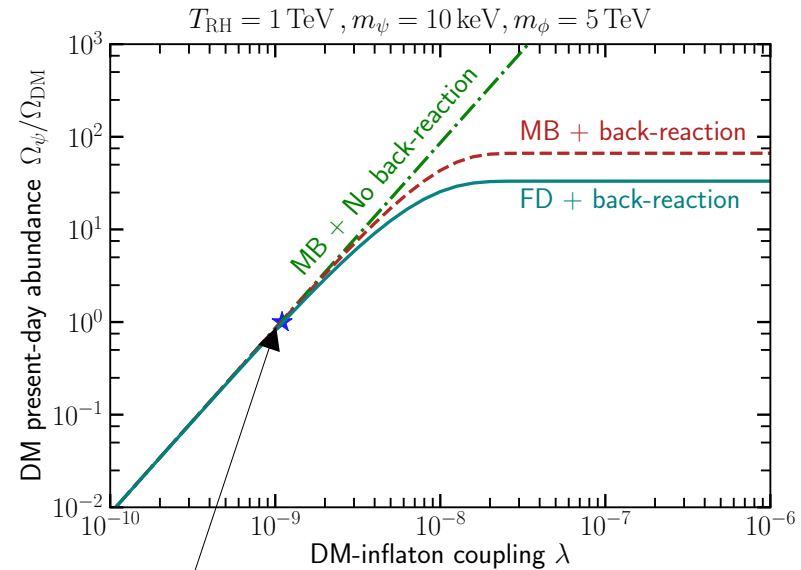
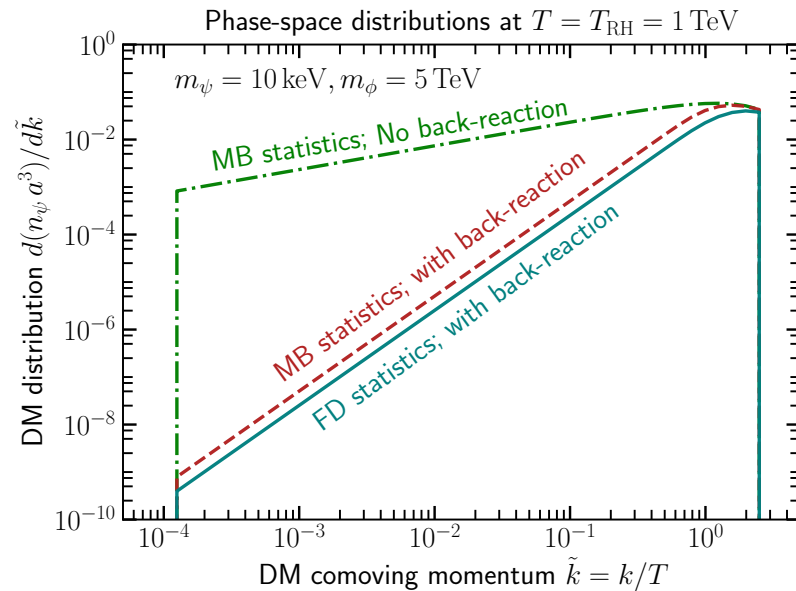
- For this we solve Boltzmann eq. for ψ distribution (PSD) f_ψ :

$$\frac{\partial f_\psi}{\partial t} - H k \frac{\partial f_\psi}{\partial k} = f_\psi^{\text{coll}}(k, t)$$

$$f_\psi^{\text{coll}} = 2\Gamma_\psi n_\phi(t) \left(\frac{2\pi^2}{p_\psi^2} \right) \delta(k - p_\psi) \begin{cases} 1 & \text{[MB Statistics; No back-reaction]} \\ 1 - f_\psi^2 & \text{[MB Statistics+back-reaction]} \\ (1 - f_\psi)^2 - f_\psi^2 & \text{[FD Statistics+back-reaction]} \end{cases}$$



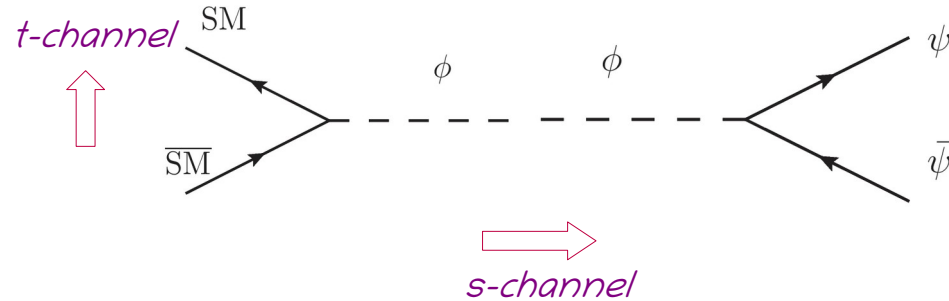
- Correct relic density **does not require FD statistics and back-reactions** to include



- Correct relic density **does not require** FD statistics and back-reactions to include
- **Is this all to it?**



- **No**; inflaton couples to both SM and DM
- Inflaton mediated scatterings between SM and DM are inevitable
- s-channel: changes DM no. density



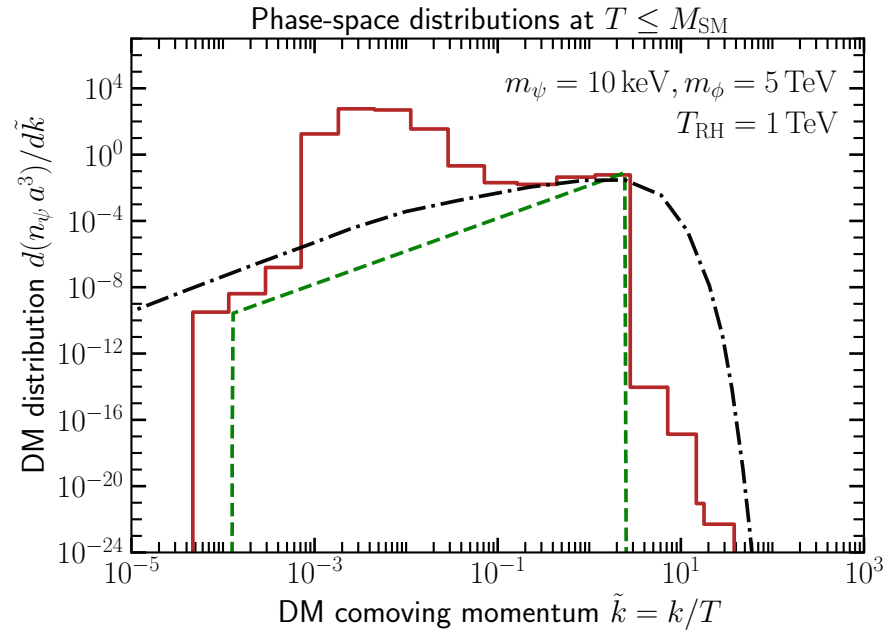
t-channel: transfer energy between DM & SM

- One needs to solve Boltzmann eq. at the phase-space distribution level:

$$\frac{\partial f_\psi}{\partial t} - H p_1 \frac{\partial f_\psi}{\partial p_1} = C(E_1, t)$$

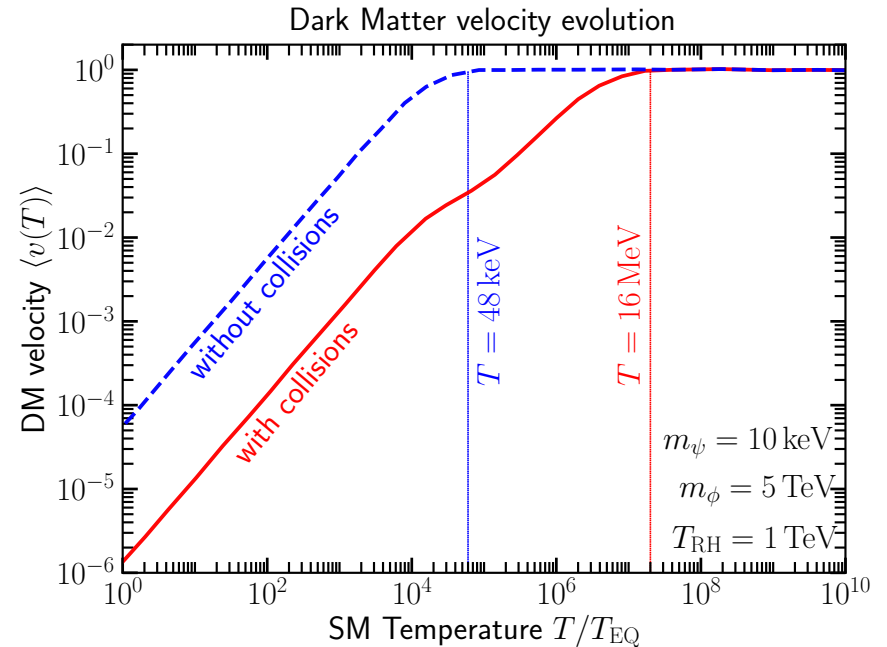
[K Ala-Mattinen et. al. PRD'2022]

$$C(E_1, t) = -\frac{1}{2 E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \int \frac{d^3 p_3}{(2\pi)^3 2E_3} \int \frac{d^3 p_4}{(2\pi)^3 2E_4} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) |M|^2 (f(E_1, t) f(E_2, t) - f(E_3, t) f(E_4, t))$$



- Increases the DM no. density by a factor of ~ 60
- Decreases the Free-streaming length by a factor of ~ 40

$$\lambda_{\text{FSH}} = \int_{t_{\text{dec}}}^{t_{\text{EQ}}} \frac{\langle v(t) \rangle}{a(t)} dt$$





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- **No** $\Rightarrow$ it can couple to spectator fields which are coupled to both DM and SM; and carries energy of the inflaton initially
- These are called **Reheatons** $\Rightarrow$ SM + DM



- Does **Inflaton** necessarily couple to both SM and DM?
- **No** $\Rightarrow$ it can couple to spectator fields which are coupled to both DM and SM; and carries energy of the inflaton initially
- These are called **Reheats** $\Rightarrow$ SM + DM
- We consider a **Z' Reheaton** within $U(1)_D$ extended SM $\Rightarrow$ spin-1 **Reheaton** for the first time

$$S = \int d^4x \sqrt{-g} \left[-\frac{M_P^2}{2} \left(1 + \frac{\xi_\Phi \Phi^\dagger \Phi}{M_P^2} + \frac{\xi_H H^\dagger H}{M_P^2} \right) R + (\tilde{D}_\mu \Phi)^\dagger (\tilde{D}^\mu \Phi) + (D_\mu H)^\dagger (D^\mu H) \right. \\ \left. - V(\Phi, H) - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} B_Y^{\mu\nu} + \bar{\chi} i \not{D} \chi - m_\chi \bar{\chi} \chi \right],$$

$$\tilde{D}_\mu \Phi = \partial_\mu \Phi - i g_D Z'_\mu \Phi$$

Inflaton Reheaton

$$V(\Phi, H) = \frac{\lambda_H}{2} \left(H^\dagger H - \frac{v_H^2}{2} \right)^2 + \frac{\lambda_\Phi}{2} \left(\Phi^\dagger \Phi - \frac{v_D^2}{2} \right)^2 + \lambda_{\Phi H} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_D^2}{2} \right)$$



- During initial phases of rapid inflaton oscillations only Z' and Φ quanta are produced for $\lambda_{\Phi H} \ll g_D$
- The equations for transverse and longitudinal components of Z' follows Lamé equations

$$\frac{d^2 \vec{A}_T}{d\tau^2} + \overbrace{(k^2 + m_A^2)}^{\omega_T^2} \vec{A}_T = 0$$

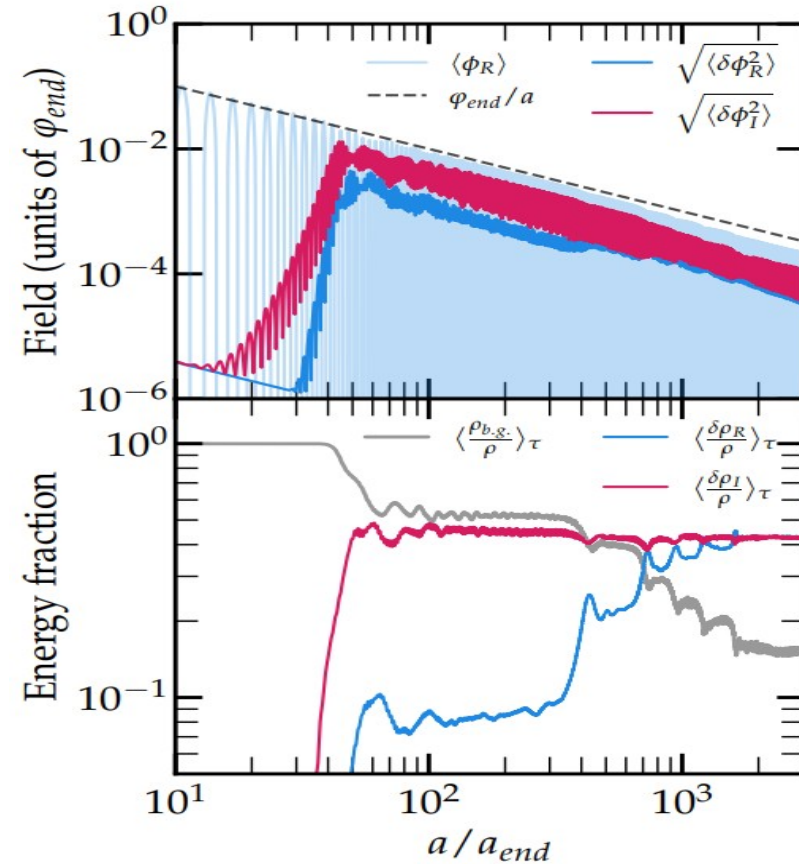
Y Ema et. al. JCAP' 2017

EI Sfakianakis et. al. PRD'2019

$$\frac{d^2 A_L}{d\tau^2} + \overbrace{\left[k^2 + m_A^2 - \frac{k^2}{k^2 + m_A^2} \left(\frac{1}{m_A} \frac{d^2 m_A}{d\tau^2} - \frac{3}{k^2 + m_A^2} \left(\frac{dm_A}{d\tau} \right)^2 \right) \right]}^{\omega_L^2 = \omega_T^2 - \Delta} A_L = 0$$

$\downarrow$
 $m_A^2(\tau) = g_D^2 a^2(\tau) \langle \phi_R^2(\tau) \rangle$

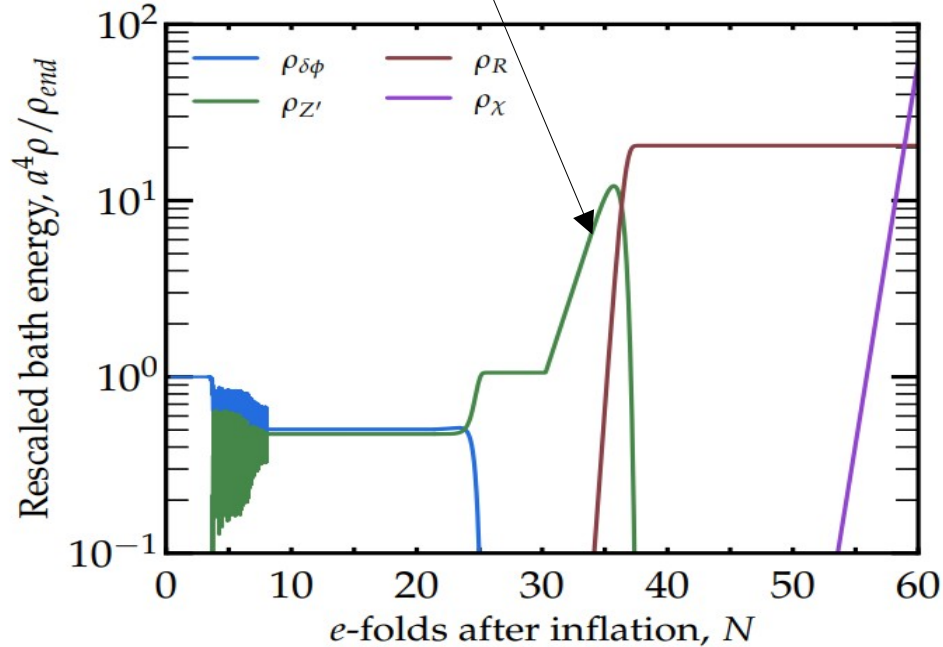
- In the near global limit $g_D^2 \leq \lambda_\Phi$ only longitudinal modes are enhanced $\Rightarrow$ **Parametric Resonance** J. A. Dror et. al. PRD'2019



Non-thermal DM from Reheaton



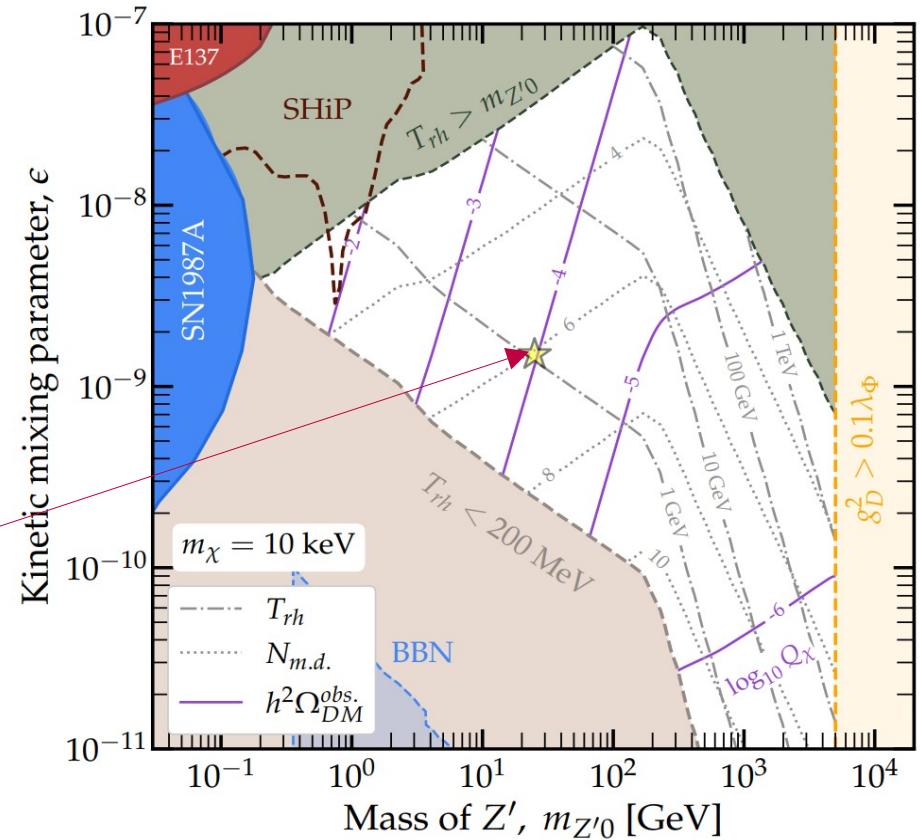
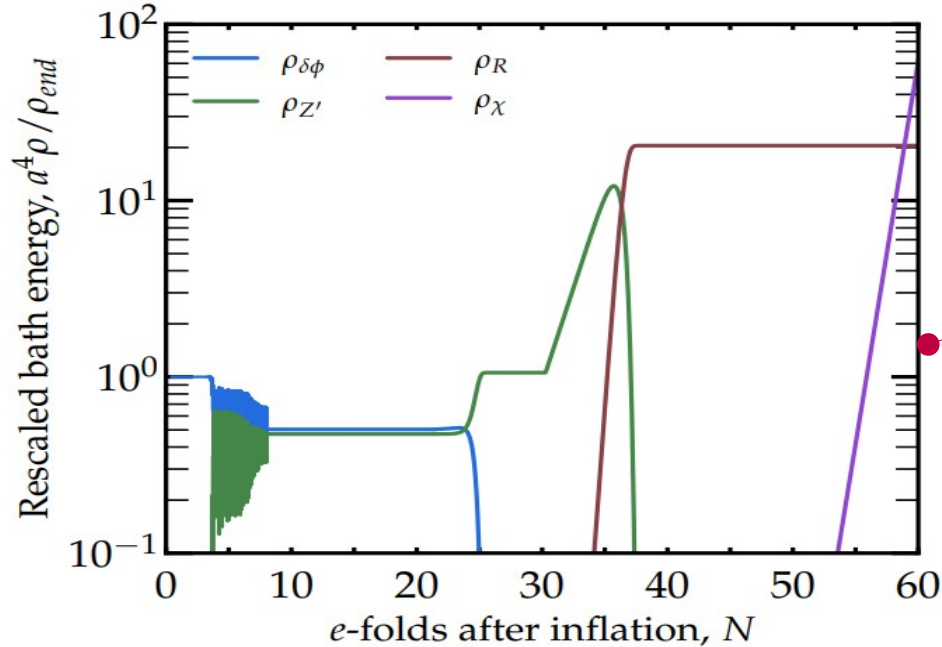
- Z' decays to SM and DM
- Z' remains non-thermal prior to decay
- Z' behaves like matter for long enough time



Non-thermal DM from Reheaton



- Z' decays to **SM** and **DM**
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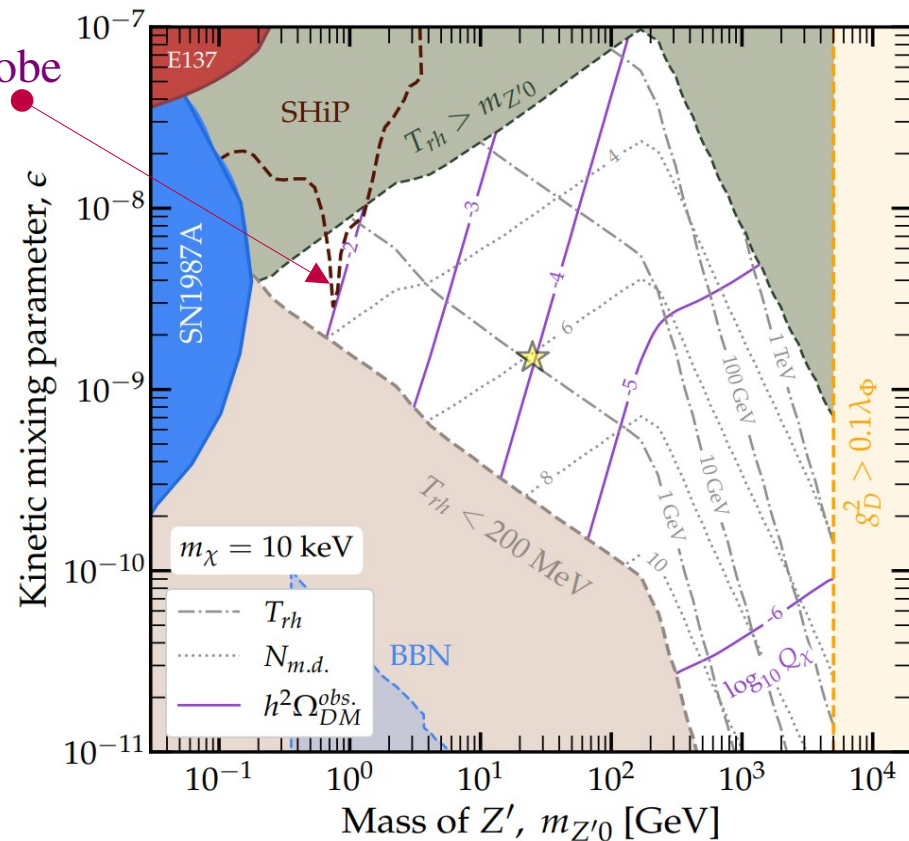
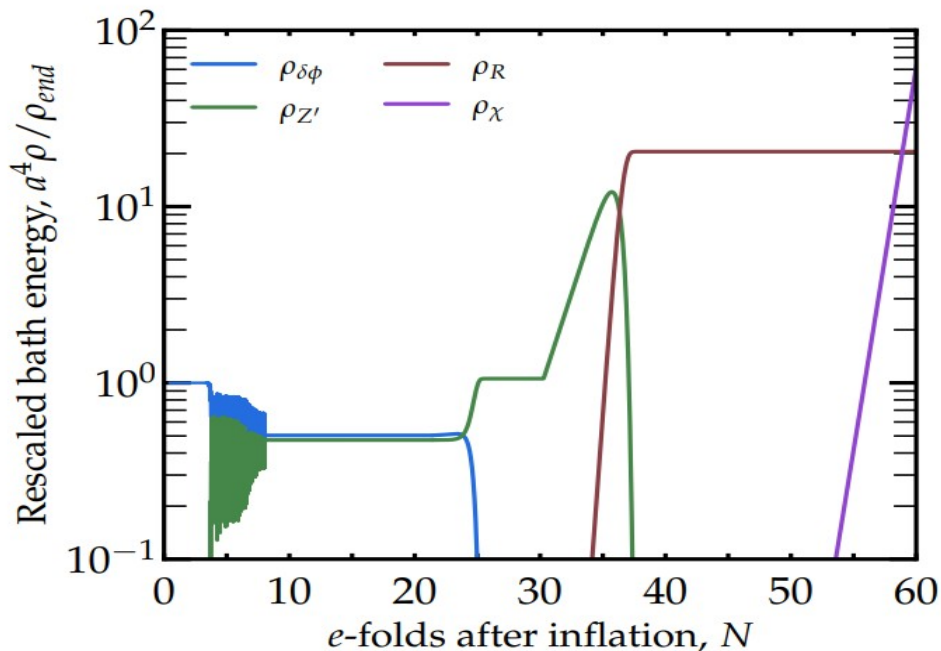


Non-thermal DM from Reheaton



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Accelerator Probe



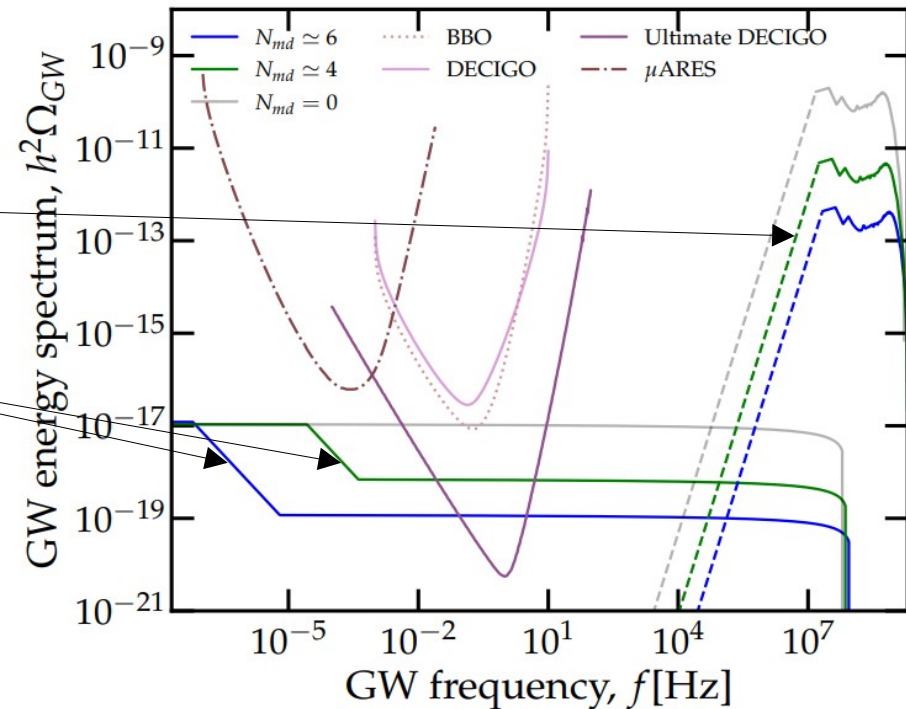


- Z' production is **non-perturbative**

→ Gives rise to high-frequency Gravitational Waves (GW)

- Matter-like Z' modifies the inflationary GW spectrum (Intermediate Matter Domination [IMD])

- Lies within the sensitivity range of several proposed GW detectors



Conclusion



- During transfer of energy of the inflaton to SM, dark sector particles may also be produced
- Even in absence of direct coupling, DM can interact with SM via inflaton mediated process
 - ⇒ can reduce **free streaming length** and allow **lower DM** masses
- Inflaton energy may be transferred to SM via **spin-1 reheaton** that can also produce DM
- **Reheaton** may give rise to intermediate matter-domination (IMD) prior to BBN
 - ⇒ impact inflationary **GW spectrum** in an observable way
 - ⇒ May also leave imprints in **SHiP**

A blue pen with a silver tip, positioned diagonally, writing the text "Thank you!" in a cursive script.

Thank you!