Inflationary Schwinger Dark Matter Production

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(1810.07208, 2103.12145, 2311.09475, 2311.15137, + ongoing)

Motivation / Punchline

DM

WIMPs

non-thermal

dark vectors

oscillating scalars

inflaton + dark $U(1)$

background EM fields during inflation → magnetogenesis

↳ vector dark matter

(Graham, Mardon, Rajendran: 1504.02102)

(RVM, et. al: 1810.07208, 2103.12145)

dark Schwinger production of charged particles

↳ dark scalar DM ⇒ $0.1\,eV - 10^{15}\,GeV$

↳ 'sterile neutrino' DM ⇒ $100\,eV - 10^{15}\,GeV$

↳ multi-comp. DM

↳ Interesting pheno ?

(2312.15137, 2311.09435)

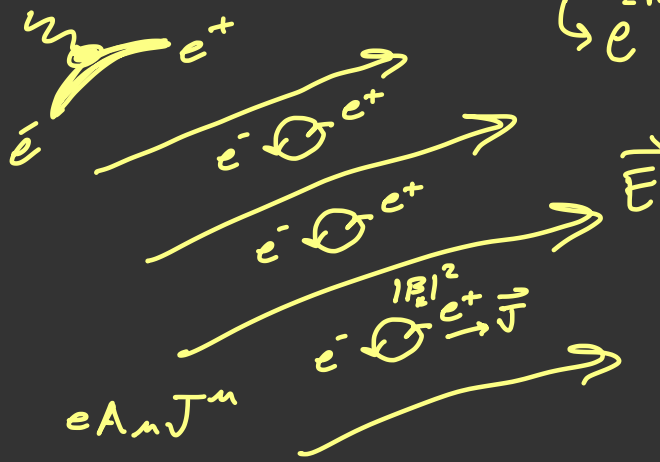
Inflationary Schwinger Dark Matter Production

- Schwinger effect long been known (Schwinger 1951)

↳ pairs of (charged) particles and anti-particles (e^+e^-) created by background E-field

↳ Requires strong E-field in Minkowski

↳ Exponentially suppressed by particle mass $\to e^{-m^2/eE}$



- Background gauge field leads to time-dependent dispersion relation

$$\ddot{q}_k + \omega_k^2 q_k = 0$$

$$\Downarrow \quad \omega_k^2 < 0$$

particle production

- During inflation the exp. of space leads to time dependence $\Rightarrow$ Particle production

↳ Requires breaking of conformal sym.

$$m \neq 0$$

or coupling to gravity / inflaton

- In Schwinger + Inflation both expansion and the E-field contribute to induced charged current

- Leads to novel effects in charged PP
- can generate an induced current even with weak E-fields
- Can have PP even in $m \to 0$ (conformal) limit in fermion or scalar sector
- Allows for light DM which is typically difficult from inflation

- Schwinger effect utilized in inflationary magnetogenesis scenarios
  ↳ primordial magnetic fields
- Also potential applications to reheating

Can inflationary Schwinger be used to generate DM relic abundance?

Schwinger Effect in de-Sitter Space

- Starting point is "dark QED" action in dS space

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{\text{charged}}(A, \chi) \right] - g_D A_\mu J_\chi^\mu$$

(χ can be scalar or fermion 'dark electrons')

$D_\mu = \partial_\mu + i g_D A_\mu + \Gamma_\mu$

- Also need $\mathcal{L}_{\text{source}}(A, \psi)$ to provide BG E-field
- The induced current is given by

$$\frac{2\mathcal{I}}{2A_\mu} = \partial_\nu F^{\mu\nu} = J_\chi^\mu$$

- Induced current will be in direction of E-field which we take to be z-direction
- One can directly compute $\langle J_z \rangle$
- Current and E-field related by

$$\langle J_z \rangle = \sigma \langle E_z \rangle = \sigma E$$

σ: conductivity can be computed in terms of ratios

E: constant background E-field

$$\lambda \equiv \frac{g_0 E}{H^2}, \quad \bar{m}_x \equiv \frac{m_x}{H}$$

- $\langle J_z \rangle$ is formally divergent $\Rightarrow$ Renorm.
  (some discrepancies in literature)
  ↳ negative currents ?

- Need a 'source' to maintain constant background E-field (due to expansion)
  ↳ various mechanisms possible

- With σ and E can compute energy density of Schwinger produced χ during inflation

- From conservation of energy-momentum $\nabla_\mu T^{\mu\nu} = 0$

$$\dot{\rho}_\chi + n H \rho_\chi = \langle E \cdot J \rangle = \sigma E^2$$

$n=3$ $n=4$ ↑ Hubble damping

- Can integrate energy evolution equation to obtain

$$\boxed{\rho_\chi \simeq \frac{\bar{\sigma}}{n} E^2 = \frac{2}{n} \bar{\sigma} \rho_E} \quad \left(\bar{\sigma} \equiv \frac{\sigma}{H}\right)$$

- To avoid backreaction on E-field requires $\rho_\chi \ll \rho_E \Rightarrow \bar{\sigma} < 1$

- We see the energy density in χ is prop to ρ_E, but suppressed by $\bar{\sigma}$

- Energy density in dark sector dominated by E-field during inflation
- Suppression by $\bar{F}$ can be compensated for by redshifting effects after inflation
- For large enough m_X, X can make up part or even all of the DM ($m_X \gg m_A$)

  ($m_A \gtrsim 10^{-10}$ eV)
- To compute relic abundance, need to know how ρ_X and ρ_E evolve
- We assume ρ_X and ρ_E evolve independently $\Rightarrow$ no-thermalization

$\Downarrow$

upper bound on dark gauge coupling

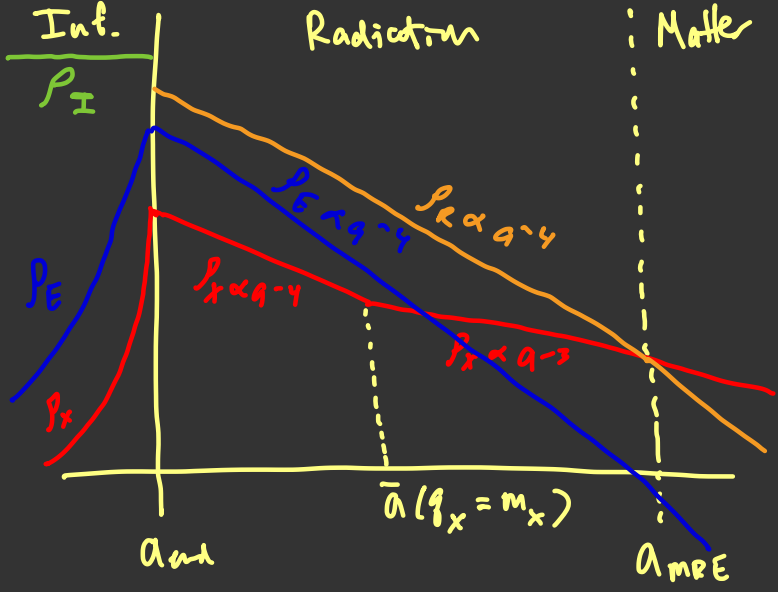
Cosmic Evolution and Relic Abundance

- At the end of inflation we have
- $\rho_I^{end} = 3 H_{end}^2 M_{Pl}^2$ • $\rho_E^{end} = \frac{1}{2} E_{end}^2$
- $\rho_R = \epsilon_R^4 \rho_I^{end}$ • $\rho_X^{end} = \frac{\bar{\sigma}}{\Lambda} E_{end}^2$
  $= \frac{\pi^2}{30} g_*(T_{RH}) T_{RH}^4$
- Need to ensure the hierarchy

$$\rho_I^{end} \gg \rho_R \gg \rho_E^{end} \gg \rho_X^{end}$$

$\downarrow$ $\epsilon_R < 1$ $\downarrow$ H_{max} $\downarrow$ $\bar{\sigma} < 1$

- No BR on inflaton $\rho_E^{end} \ll \rho_I^{end}$
  $\Rightarrow E/H_{end}^2 < 10^9$
- The A and X energy density spectra which is peaked at small scales
  ↳ can avoid isocurvature constraints



- The energy density today in X

$m_X < H_{end}$

$$\rho_X(T_0) = \left(\frac{T_0}{T_{RH}}\right)^3 \left(\frac{m_X}{H_{end}}\right) \frac{\sigma}{4} E^2$$

$m_X > H_{end}$

$$\rho_X(T_0) = \left(\frac{T_0}{T_{RH}}\right)^3 \frac{\sigma}{3} E^2$$

- Can now examine contours of

$$\frac{\Omega_X}{\Omega_{CDM}} = \frac{\rho_X(T_0)}{\rho_{CDM}} = 1$$

- See results slides

Summary

$M_X < M_{end}$: $0.1\,eV \lesssim m_X \lesssim 10^{12}\,GeV$

$M_X > M_{end}$: $100\,GeV \lesssim m_X \lesssim 10^{15}\,GeV$

Ongoing Work

- Computing current in de-Sitter
- Backreaction and reheating effects

Future Work

- Exploring phenomenology
- Multi-component feebly interacting DM

EXTRA

Generating Dark E-fields During Inflation

- Need a 'source' to maintain constant E-field during inflation due to dilution from expansion

  → Various possibilities from VDM production mechanisms

  - couplings to metric: $m_A^2 g_{\mu\nu} A^\mu A^\nu, R A^\mu A_\mu$
  - coupling to inflaton: $\phi F F$, $\phi F \tilde{F}$

- VDM production mechanism must generate background E-field ($\dot{A}$) with coherence length

$$\lambda \sim H^{-1}$$

- Recent mechanism based on ϕF^2 can generate necessary E-field during inflation $\Rightarrow$ works for $m_A = 0$

(1810.07208, 2103.12145 : MBG, JS, LV, RVM)

- Utilizes the source lagrangian

$$\mathcal{L}_{source} = (\partial_\mu \varphi)^2 - V(\phi) + \frac{\alpha}{f}\varphi F\tilde{F}$$

$$\tilde{F} = \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$$

- This leads to EOM for transverse modes

$$\ddot{A}_\pm + H(1+\delta)\dot{A}_\pm + \left(\frac{k^2}{a^2} + \frac{\alpha}{f}\dot{\phi}\frac{k}{a}\right)A_\pm = 0$$

where we have use $E = \frac{1}{a}\dot{A}_\pm$

- In limit of small conductivity (weak field) we can ignore this correction and find (in conformal time)

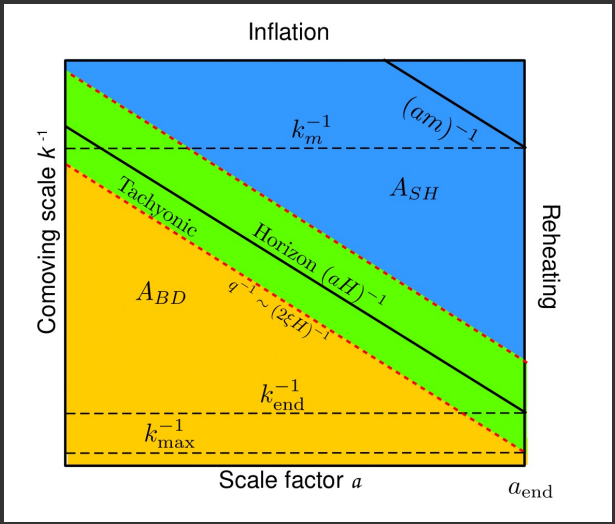
$$\frac{d^2 A_\pm}{d\tau^2} + \omega^2(k,\tau) = 0$$

$$\omega^2(k,\tau) = k^2 \pm \frac{2k\xi}{\tau}$$

$$\xi = \frac{\alpha\dot{\phi}}{2Hf}$$

- When $\omega^2 < 0$ there is a tachyonic mode.

- This occurs when $\frac{\dot{n}}{n} = g \sim H$
- Leads to exponential production of dark vector modes $\Rightarrow$ high occupation number
- Coherence length $l \sim H^{-1}$
- Classical background E-field within each Hubble patch



Phenomenology of DM sector

- Dark sector may or may not couple to SM

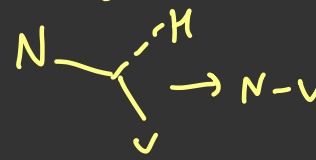
  dark vector A

  dark scalar φ

  dark fermion N
  ↳ "sterile neutrino"

"kinetic mixing portal" $\epsilon F^{\mu\nu} A_{\mu\nu}$ (photon (γ)) 

"Higgs portal" $\lambda \varphi^2 H^2$ 

"neutrino portal" $y N H \nu$ 

- Working on exploring different portals
- Even if no DM-SM coupling there is a lot of potential phenomenology
  - ↳ structure
  - ↳ superradiance
  - ↳ lensing
  - ↳ gravitational waves
- Studying $\mathcal{O}$ in detail for fermion and scalar χ
- Constructing explicit UV models during inflation