Schwinger DM production

- Dark photons as dark matter: Lorenzo’s talk
- Dark photons + Dark fermions/scalars:

  Schwinger production mechanism
- Dark fermions/scalars as dark matter

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(Arxiv:2309.xxxx)

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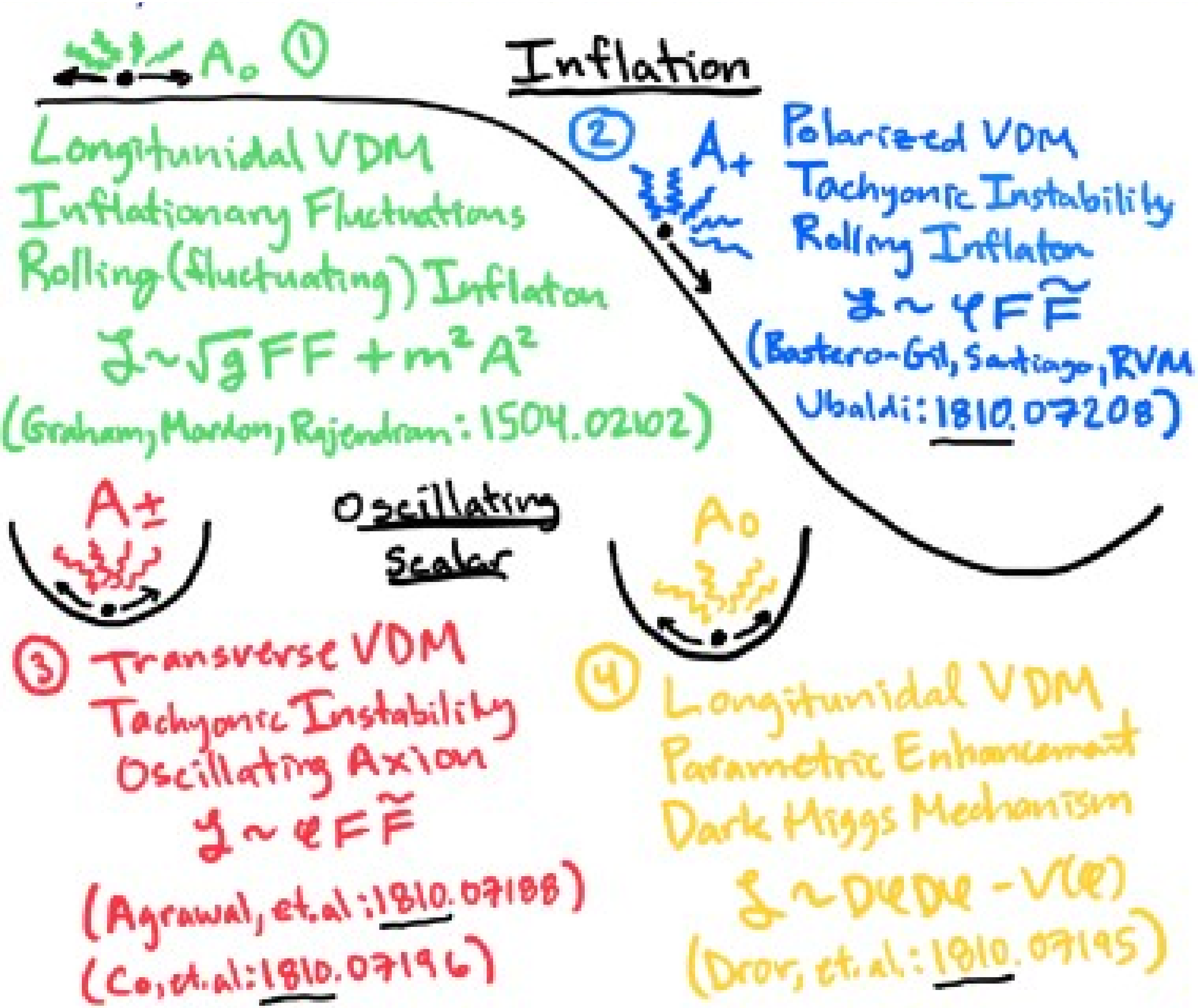
A_0 ①
Inflation
Longitunidal VDM
Inflationary Fluctuations
Rolling (fluctuating) Inflaton
$\mathcal{L} \sim \sqrt{g} FF + m^2 A^2$
(Graham, Mardon, Rajendran: 1504.02102)
② A_+
Polarized VDM
Tachyonic Instability
Rolling Inflaton
$\mathcal{L} \sim \varphi F\tilde{F}$
(Bastero-Gil, Santiago, RVM
Ubaldi: 1810.07208)
$A_\pm$
Oscillating Scalar
A_0
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Dark Higgs Mechanism
$\mathcal{L} \sim D\varphi D\varphi - V(\varphi)$
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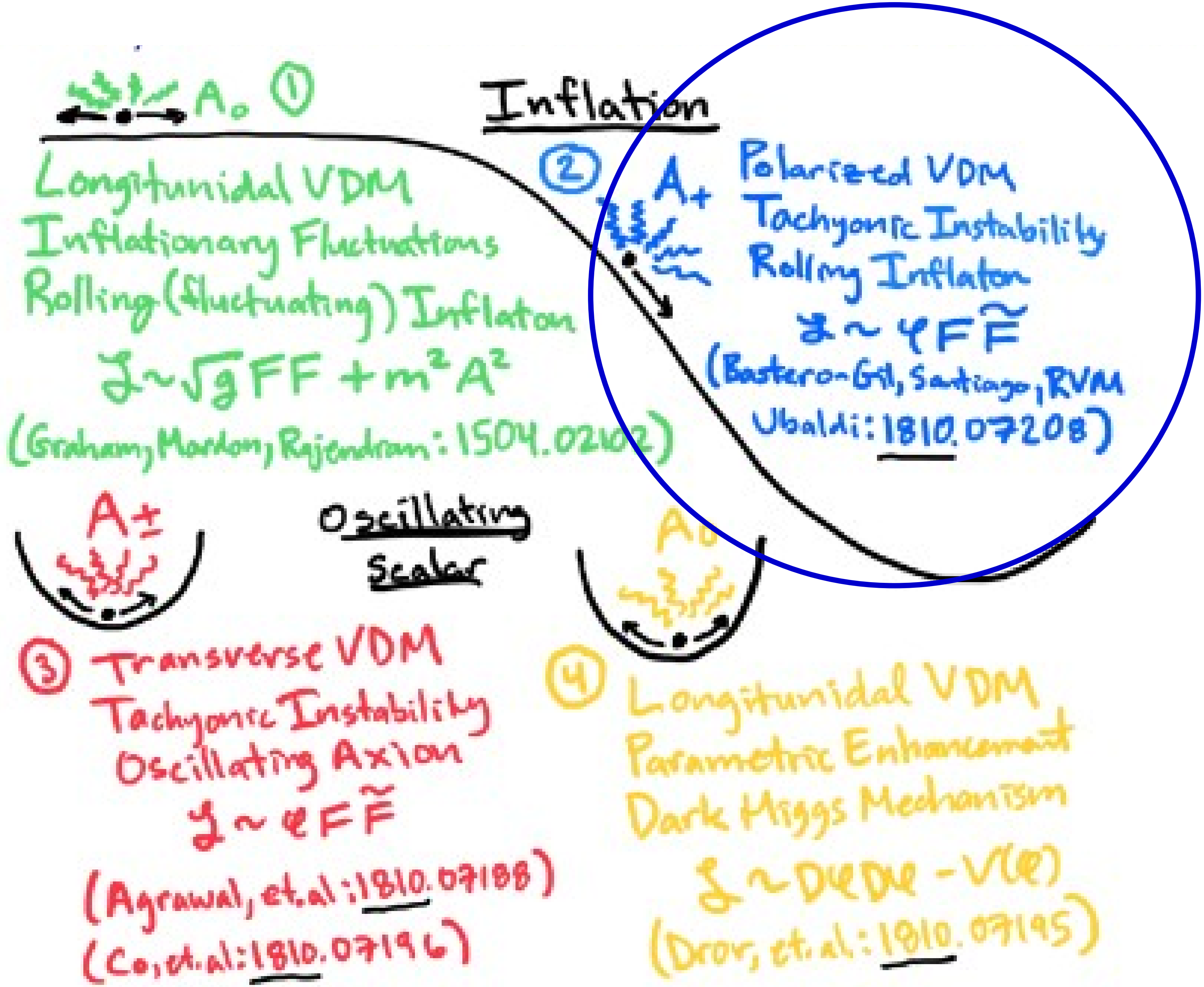
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Dark photons (vector) as Dark Matter

$$L=\frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_A^2 A_\mu A^\mu - \frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- SM+ ”hidden” U(1) : massive (light) vector (”dark photon”)
- ϕ : scalar singlet (axion like, inflaton,...)
- **Production:** inflation,reheating, ….

  Before Matter-Radiation equality $H < m_A$ ➡ Matter
- **Detection:** kinetic mixing

Dark photons (vector) as Dark Matter

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- Evolution equations during inflation

Longitudinal A:

$$\ddot{A}_L+\frac{3k^2+a^2m_A^2}{k^2+a^2m_A^2}H\dot{A}_L+\left(\frac{k^2}{a^2}+m_A^2\right)A_L=0$$

[Graham et al., Phys. Rev. D93 2015]

- **(Massive) Light field $m_A < H$** during inflation, superhorizon fluctuations, k/aH <<1, are "frozen"

$$\ddot{A}_L+H\dot{A}_L\simeq 0$$

- Constant amplitude of the spectrum by the end of inflation $\rho_{A_L}\sim m_A^2 A_L^2/a^2\propto a^{-2}$
- Re-entry, k/a > H, m : $\rho_{A_L}\sim m_A^2 A_L^2/a^2\propto a^{-4}$
- Late-time, k/a, H < m : $\rho_{A_L}\sim m_A^2 A_L^2/a^2\propto a^{-3}$

Matter

$$\frac{\Omega_L}{\Omega_c}=\sqrt{\frac{m_A}{6\times 10^{-6}\,\mathrm{eV}}}\left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2$$

Dark photons (vector) as Dark Matter

$$L=\frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_A^2 A_\mu A^\mu - \frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- Evolution equations during inflation

Transverse A: $$\ddot{A}_T + H\dot{A}_T + \left(\frac{k^2}{a^2} \mp \frac{k}{a}\frac{\alpha\dot{\phi}}{f} + m_A^2\right)A_T = 0$$

[Anber & Sorbo., Phys. Rev. D81 2010]

Negative squared frequency when $k/a < \alpha\dot{\phi}/f, m_A \ll H$

→ "Tachyonic" production: exponential enhancement of vector fluctuations

$$A_T \simeq \frac{e^{\pi\xi}}{2\sqrt{2\pi k\xi}}$$

$$\xi = \frac{\alpha\dot{\phi}}{2Hf} = \sqrt{\frac{\epsilon}{2}}\frac{\alpha}{f}m_P$$

Larger enhancement by the end of inflation when $\epsilon_H \simeq 1$

Mass can be Stueckelberg or Higgsed type and has negligible effects on tachyonic production mechanism as long as m << H

Dark Matter candidate

$$O(\mu eV) \leq m_A \leq O(GeV)$$

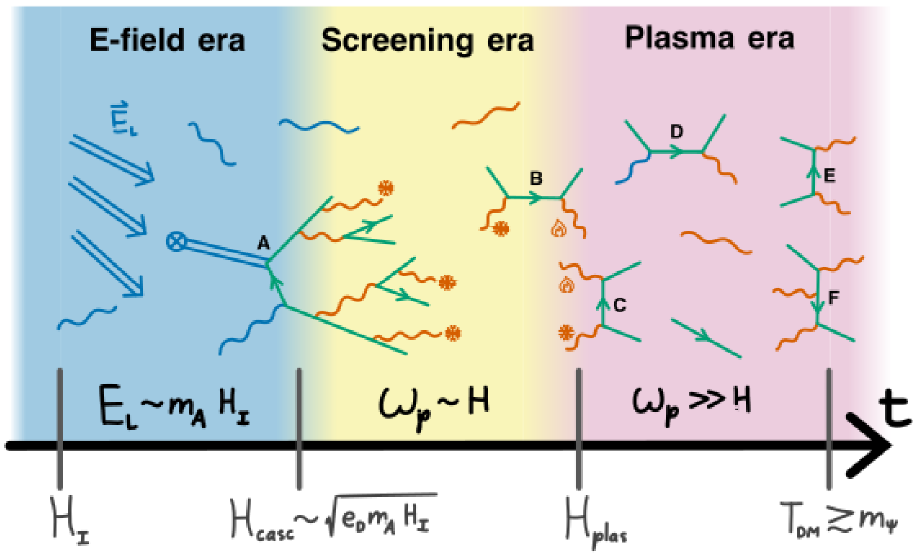
Dark photons + Dark fermions

$$L=\frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_A^2 A_\mu A^\mu + L_{DS}(A_\mu, \chi)$$

[Arvanitaki et al, JHEP 11 (2021)]

- **Longitudinal** A production during inflation

- After inflation: dark fermion production (electromagnetic cascade + plasma effects + scattering…)



- Relic abundance of **thermal** dark fermions
  + subdominant dark photons

- **Thermalization**:
  relatively large values of dark electric coupling

- **Freeze-out**: dark matter relic abundance 50 MeV <~ m_χ <~ 30 TeV

Dark photons + Dark fermions/scalars

$$L=\frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_A^2 A_\mu A^\mu - \frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu} + L(A_\mu, \chi)$$

- **Transverse** A production (m_A=0) during inflation

- **Schwinger production** of dark fermion/scalars: during inflation and until the Dark F/S becomes non-relativistic

- **No thermalization** of the DS: small values of dark electric coupling

- Dark matter relic abundance today: depending on model parameter values, it can be made up of dark photons, dark F/S, or a mixture of both….

- Even if m_A=0 during inflation, it can became massive later and become a good DM candidate

Schwinger effect during de Sitter expansion

[Kobayashi & Afshordi JHEP 10 (2014)]   [Hayashinake, Fujita & Yokoyama JCAP 1607 (2016)]

[Banyeres, Domenech & Garriga JCAP 1810 (2018)]

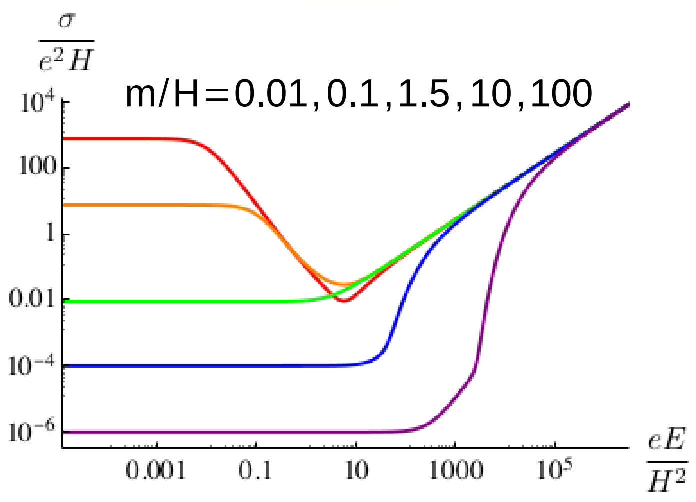
- Pair of charged particles production in presence of a ~ constant E field

- Inflation: production of a ~ constant E field + ~ constant rate of expansion H

- Electric field: $E_i = a\,E\,\delta_{iz}$ E~ constant

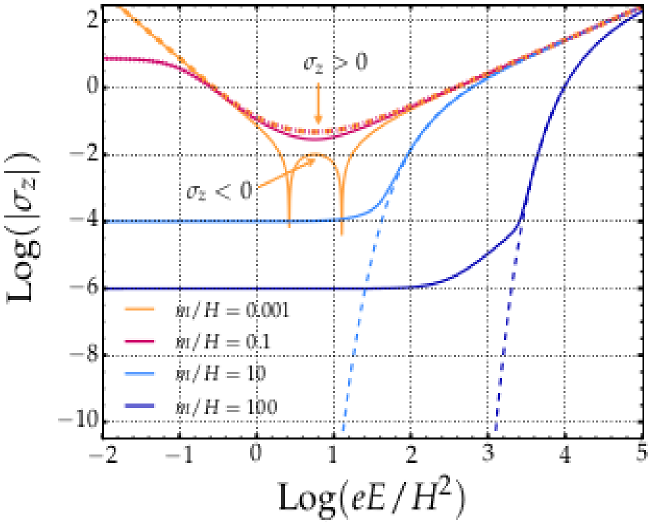
- Current $\langle J_i \rangle = a\,J\,\delta_{iz}$
- Conductivity $\sigma = J/E$, $\bar{\sigma} = \sigma/H$

Kobayashi & Afshordi:adiabatic subtraction



Scalar conductivity

Banyeres et al.: Pauli-Villars reg.



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- Strong field limit: $\sigma \propto e_D^3 \frac{E}{H} e^{-\pi m^2/(e_D E)}, \qquad e_D E/H^2 \gg 1, m/H$
- **Weak field** (scalars) limit: $\sigma \propto e_D^2 \frac{H^3}{m^2}, \qquad e_D E/H^2 \ll 1, m/H$

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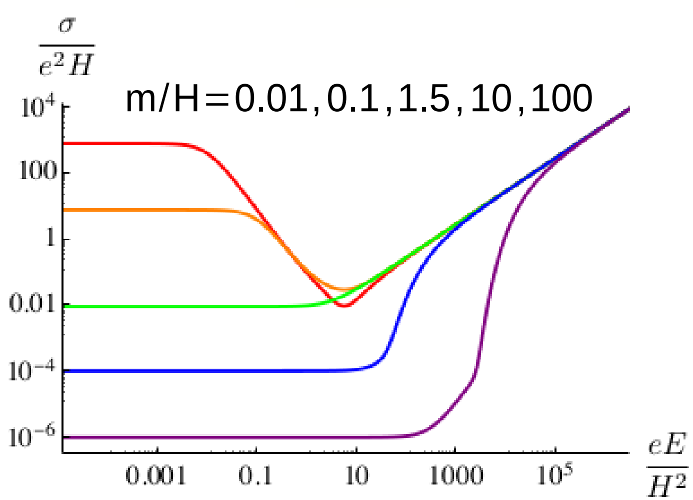

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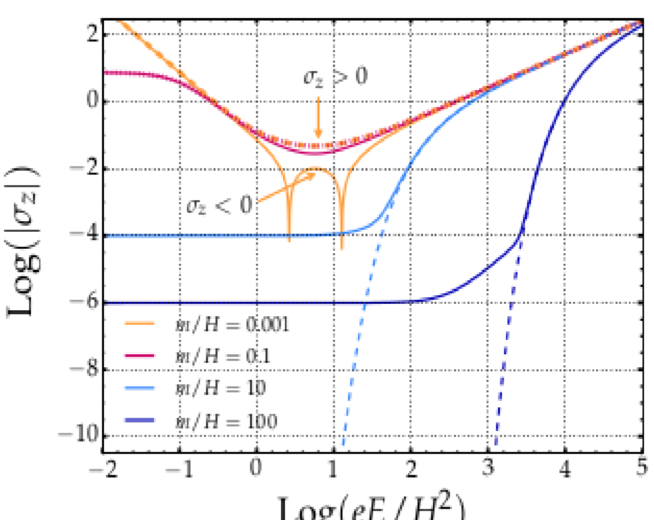

Schwinger effect during de Sitter expansion

- Weak field (scalars) limit: $\sigma \propto e_D^2 \frac{H^3}{m^2},$ $\quad e_D E/H^2 \ll 1, m/H$

- Particle production: gravitational or Schwinger ?

- Our scenario: conformal dark scalar/fermions ➡ no gravitational particle production

- $m_\chi \propto H^2, \quad \sigma \propto e_D^2 H, \quad \bar{\sigma} \propto e_D^2 \approx \text{Constant}$

- Energy densities during inflation (stress-energy tensor conservation)

Inflaton: $\dot{\rho}_\phi + 3H\langle\dot{\phi}^2\rangle = -\frac{\alpha\dot{\phi}}{f}\langle E\dot{B}\rangle$

Dark Vector: $\dot{\rho}_A + 4H\rho_A = +\frac{\alpha\dot{\phi}}{f}\langle E\dot{B}\rangle - \langle EJ\rangle$

Dark Scalar/Fermion: $\dot{\rho}_\chi + nH\rho_\chi = \langle EJ\rangle = \sigma\langle E^2\rangle$

n=3 Non Rel, n=4 Rel.

Schwinger effect during de Sitter expansion

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Weak coupling:
No backreaction

$$e_D \ll 10^2 \frac{\xi^{3/2}}{e^{\pi \xi}}, \quad \xi = \frac{\alpha \dot{\phi}}{2Hf} \sim O(1-3)$$

$$\bar{\sigma} \simeq 10^{-2} e_D^2$$

From inflation to reheating and radiation domination

Inflaton: $\rho_\phi(T_{RH}) = \epsilon_R^4 \rho_\phi^{end} = 3\epsilon_R^4 H_{end}^2 m_P^2$

Dark Vector: $\rho_A(T_{RH}) \simeq \rho_A^{end} \simeq 10^{-4} \frac{e^{2\pi\xi_{end}}}{\xi_{end}^3}$

Dark Scalar/Fermion: $\rho_\chi(T_{RH}) \simeq \rho_\chi^{end} \simeq \frac{2\bar{\sigma}}{n} \rho_A^{end}$

- Schwinger production during rad. domination, until dark particles become non-relativistic

$$\dot{\rho}_\chi + nH\rho_\chi = \sigma(t) 2\rho_A, \qquad \sigma(t) \propto a(t)^{-\alpha} \propto T^\alpha$$

- Dark particles become non-relativistic when physical momentum $q_\chi = m_\chi$

$$\dot{q}_\chi + H q_\chi = e_D E(t)$$

Redshift due to expansion

Increases due to electric field

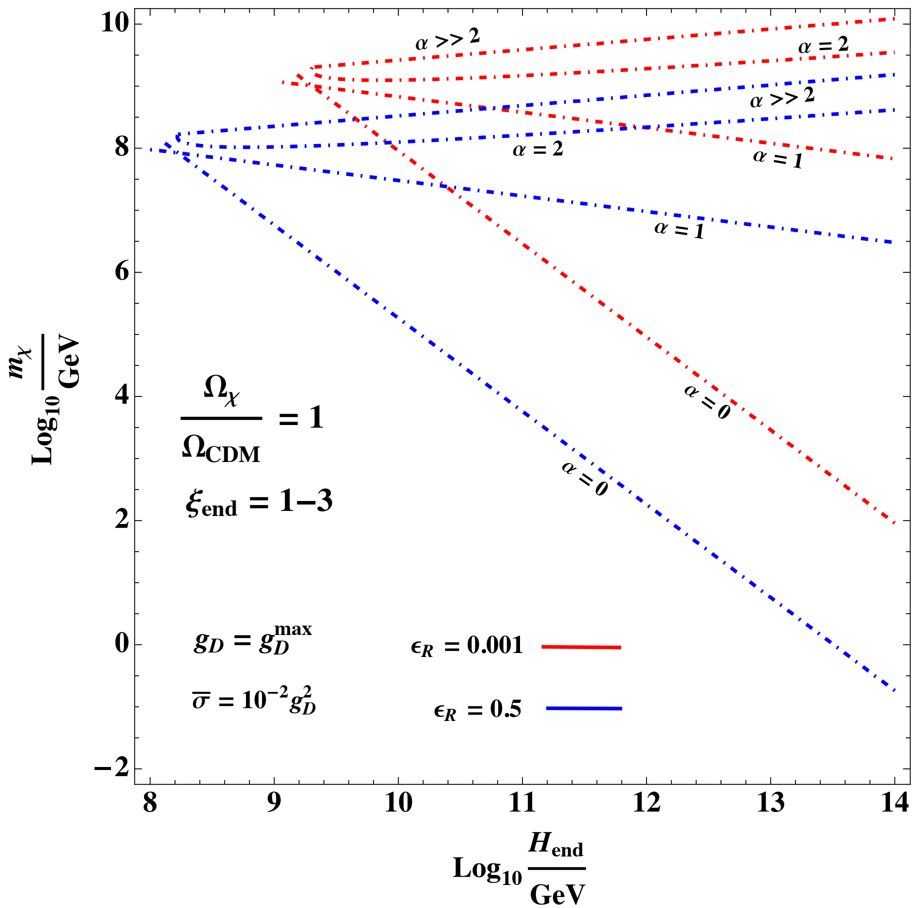
- They must become NR before Matter-Radiation Equality

$$e_D < 71\,\epsilon_R^2 \frac{\xi_{end}^{3/2}}{e^{\pi\xi_{end}}} \left(\frac{m_\chi}{H} - \frac{T_{MRE}}{T_{RH}} \right)$$

This also avoids thermalization in the DS

Relic abundance today: parameter space

$$\rho_\chi(T_0)=\rho_\chi(T_{MRE})\left(\frac{T_0}{T_{MRE}}\right)^3 \sim \bar{\sigma}_{RH}\rho_A^{RH}\left(\frac{T_0}{T_{RH}}\right)^3\left(\frac{m_\chi}{H_{end}}\right)^{\alpha-1} \quad \alpha\leq 2$$



Inflation:

$$\sigma=10^{-2}e_D^2 H$$

Rad. Dom. :

$$\sigma(t)=\sigma_{RH}(a_{RH}/a(t))^\alpha \propto T^\alpha$$

Summary

- Dark vectors/dark photons can be efficiently produced during inflation, and constitute a good dark matter candidate.

- Axion-like coupling inflaton-DP lead to production of transverse vectors, massless of very light during inflation, i.e., an aprox. constant electric field

- Massive Dark Scalars/Fermions are produced through the Swinger mechanism, and later become the dominant DM component

- The mechanism works in the weak e_D coupling regime (no thermalization of the DS), and for small conductivities (weak field regime, no backreaction in the inflationary sector)