

The Inflationary Schwinger Effect and Dark Matter Production

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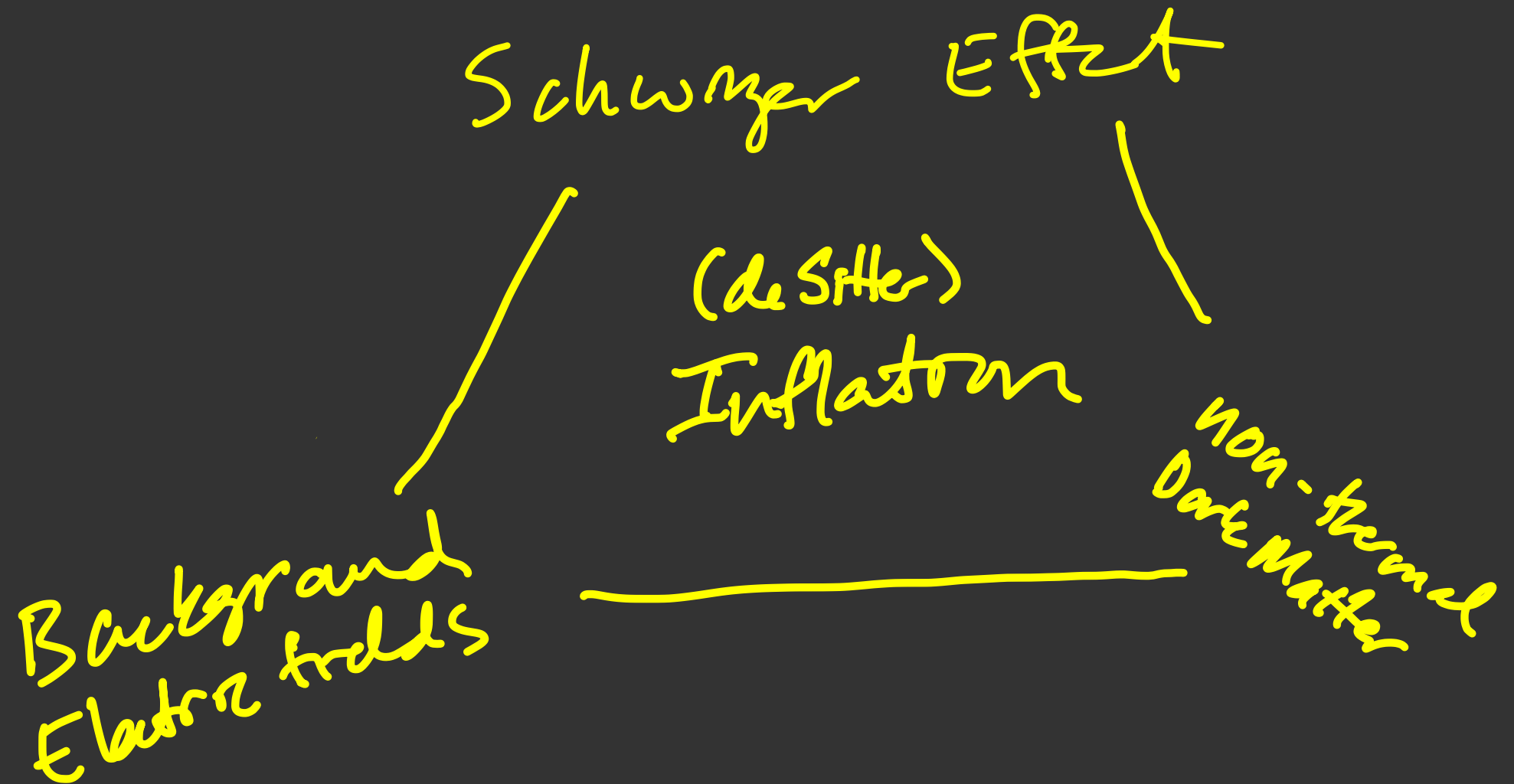
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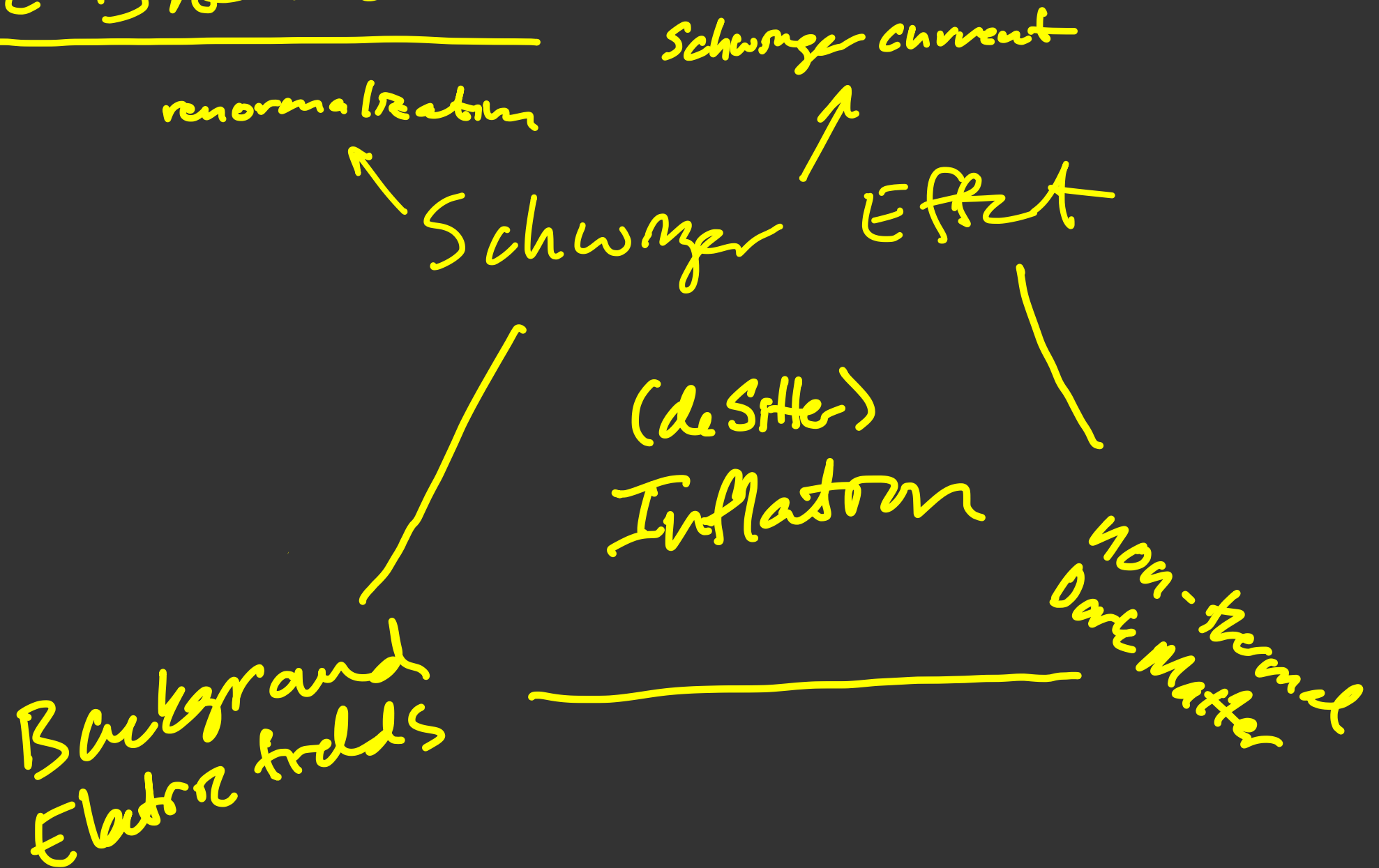
In collaboration with: Mar Bastero-Gil, Antonio Torres Manso,
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Based on:
1810.07208
2103.12145
2311.09475
2312.15137
2503.01981
2508.14973

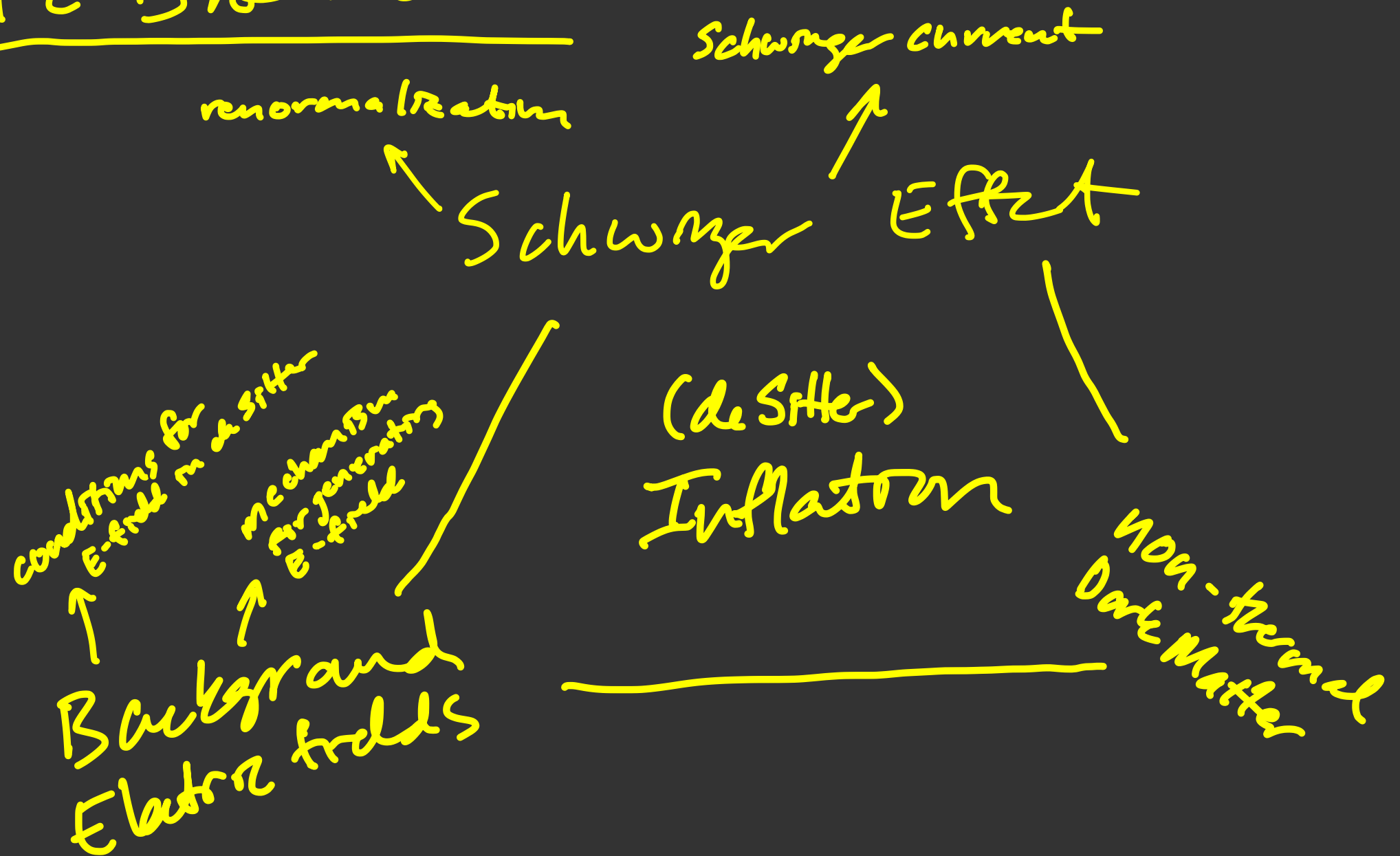
The B16 Picture



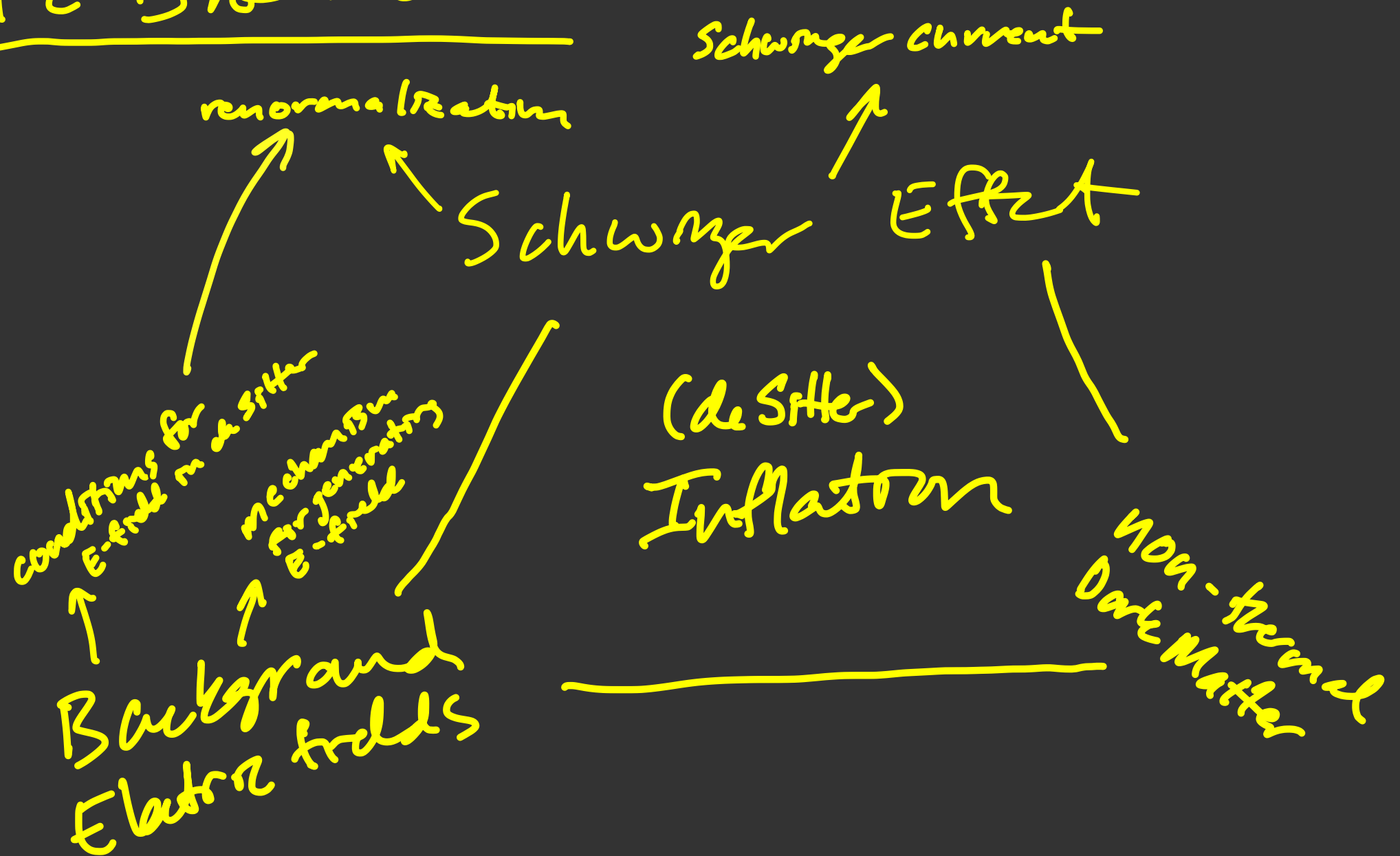
The Big Picture



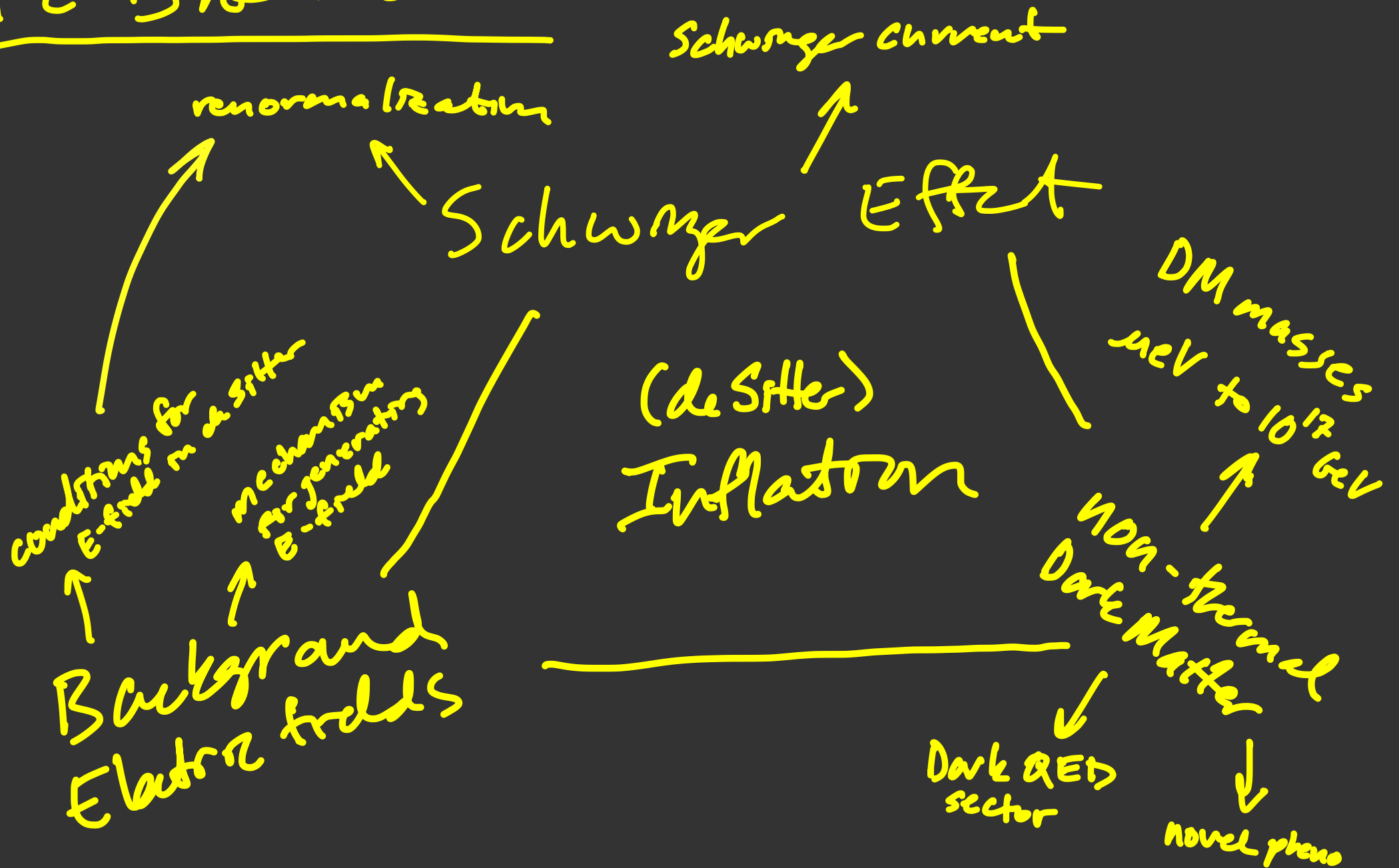
The B16 Picture



The B16 Picture

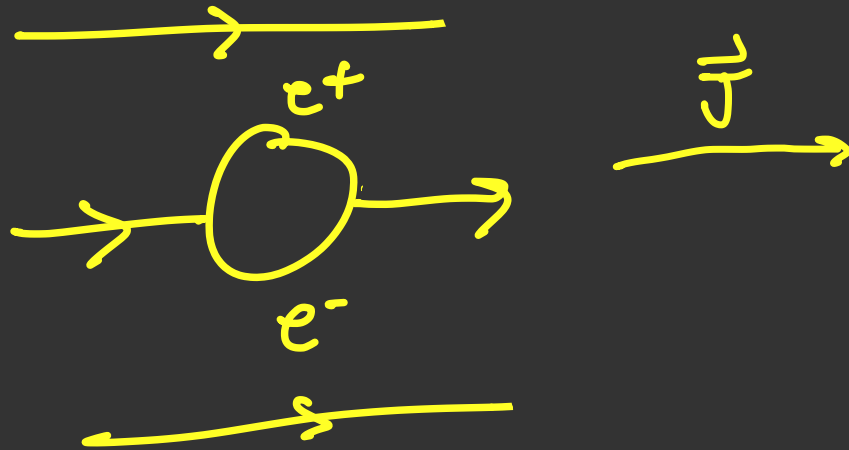


The B16 Picture



The Schwinger Effect (Minkowski)

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



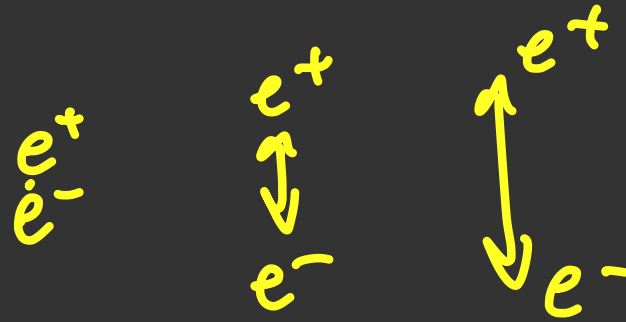
- First anticipated in 1936 by Euler and Heisenberg well before QED

- Firmly established in 1951 by Schwinger $\Rightarrow$ Schwinger effect

- Has not been experimentally observed (graphene analogs) since very large E-fields are needed $E \gg m_e^2$ ($J \propto e^{-m_e^2/eE}$)

The Schwinger Effect (de Sitter)

- In Schwinger + Inflation both expansion and H 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 $m \rightarrow 0$ (conformal) limit in fermion or scalar sector
- Allows for light DM which is typically difficult from inflation

Applications/Motivations

- 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?

Renormalized Lagrangian and Schwinger Current

- Starting with the renormalized QED Lagrangian in de Sitter with classical gauge field and quantized charged particles

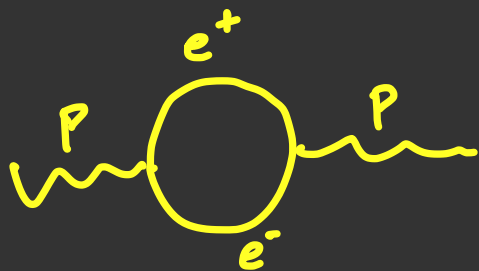
$$\left(S = - \int d^4x \sqrt{-g} \mathcal{L} \right)$$

↑
on dS

$$\mathcal{L} = -\frac{1}{4}(1 + \delta_3)(F_{\mu\nu})^2 - \frac{1}{2}m_A^2 A_\mu A^\mu - A_\mu J^\mu + \dots$$

conserved
charge
current

- Note we only need one counterterm δ_3 (since A_μ is classical) associated with the vacuum polarization diagram



- The only loop diagram in the theory



no internal photon lines

- 2 point function implies the photon is dynamical
↳ EOM

Renormalized Schwinger Current

- Gauge configuration for classical constant E-field

$$A_\mu = \frac{E}{H^2 \tau} \delta_\mu^z.$$

$$(1 + \delta_3) \partial^\mu F_{\mu\nu} - m_A^2 A_\nu = J_\nu$$

$$\frac{\delta I}{\delta A_\mu}$$

Computed many times in literature

$$\partial^\mu F_{\mu\nu} - m_A^2 A_\nu = \langle J_\nu \rangle_{\text{reg}} + 2aHE\delta_\nu^z\delta_3$$

- Physical renormalized current

$$\langle J_z \rangle_{\text{ren}} = \langle J_z \rangle_{\text{reg}} + 2aHE\delta_3$$

↳ should be UV and IR finite and always positive

- Found to be IR divergent in previous calculations

1408.4141 → Kobayashi et al. (minimally coupled scalar) 1603.04165 → Yokoyama et al. (fermion)

1809.08977 → Garriga et al.

WHY?

- This would imply a large negative current (opposite to E) for light charged fermions ???

Renormalized Schwinger Current

- Of course need a (physical) renormalization condition to fix δ_3
- For classical A_μ , we take the on-shell renormalization condition (OSRC)

$$\Pi(p^2 = -m_A^2) = 0$$

→ pole at $p^2 = m_A^2$

→ residue $-i$

↳ $e^2 \Pi(p^2)$ coefficient of $-i(p^2 g^{\mu\nu} - p^\mu p^\nu)$ in the sum of all 1PI contributions to the photon 2-pt function

- $\Pi(p^2)$ defined by Π to all orders
- OSRC fixes counterterm

$$\delta_3 = -e^2 \Pi(-m_A^2).$$

- Taking $m_A = 0$ reproduces previous calculations
↓ $(\log m_c / \mu)$
negative IR divergence

Background E-fields During Inflation (RVM, d.d.: 2508.14973)

- In flat space the E-field is generated by a massless photon
- In de Sitter a constant background E-field generated by a massless photon is not consistent with the EOM

- Action in de Sitter $\Rightarrow$ for massless photon

$$S = - \int d^4x \sqrt{-g} \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

- Gauge field configuration that produces constant E-field $\Rightarrow$

$$A_\mu = \frac{E}{H^2 \tau} \delta_\mu^z$$

- Does not satisfy EOM $\Rightarrow$

$$g^{\alpha\mu} \partial_\alpha F_{\mu\nu} = -2H^2 \tau^2 \frac{E}{H^2 \tau^3} \delta_\nu^z = -\underline{2H^2 A_\nu} \neq 0$$

Background E-fields During Inflation

- A simple solution is to add a photon mass to the lagrangian

$$S = - \int d^4x \sqrt{-g} \left(\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_A^2 A_\mu A^\mu \right) \text{ where}$$

$$m_A^2 = -2H^2,$$

- Photon mass m_A^2 acts as a 'source term' which breaks conformal invariance
- Provides a tadpole condition necessary to compensate for the exponential expansion of space

In dS photon cannot be massless for constant E-field

- Fixes the counterterm

$$\delta_3 = -e^2 \Pi(2H^2)$$

↪ calculate in dS

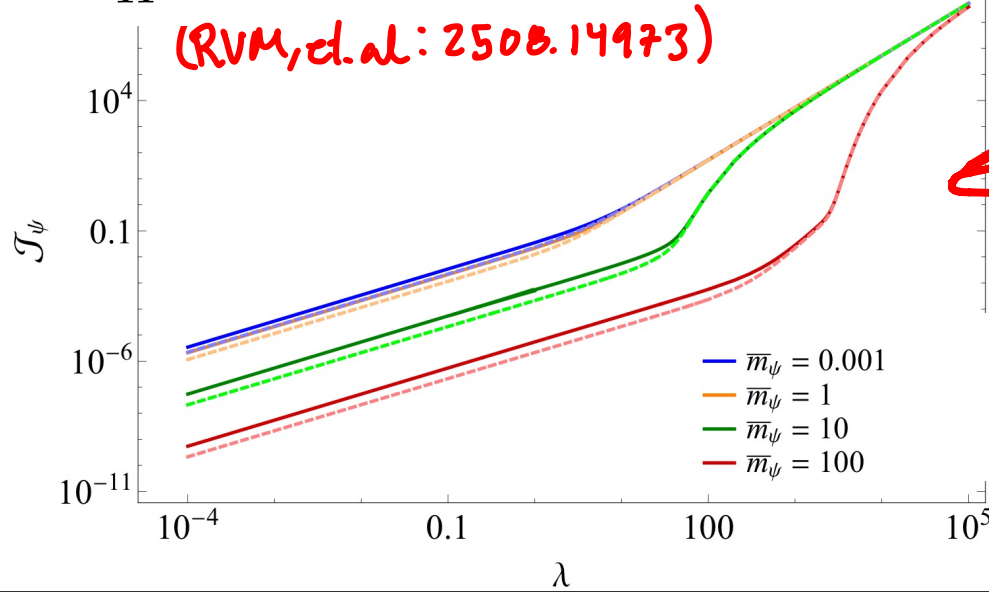
cures IR
divergence!

The Schwinger Current

$$\mathcal{J}_\phi \equiv \frac{\langle J_z^\phi \rangle_{\text{ren}}}{aeH^3}$$

$$\mathcal{J}_\psi \equiv \frac{\langle J_z^\psi \rangle_{\text{ren}}}{aeH^3}$$

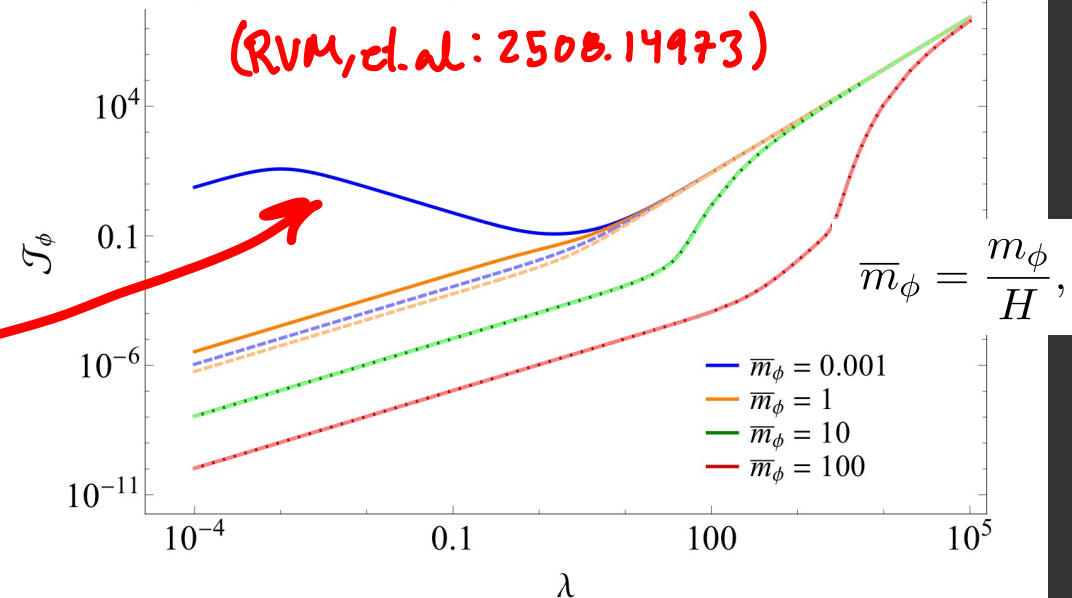
$$\bar{m}_\chi \equiv \frac{m_\chi}{H},$$



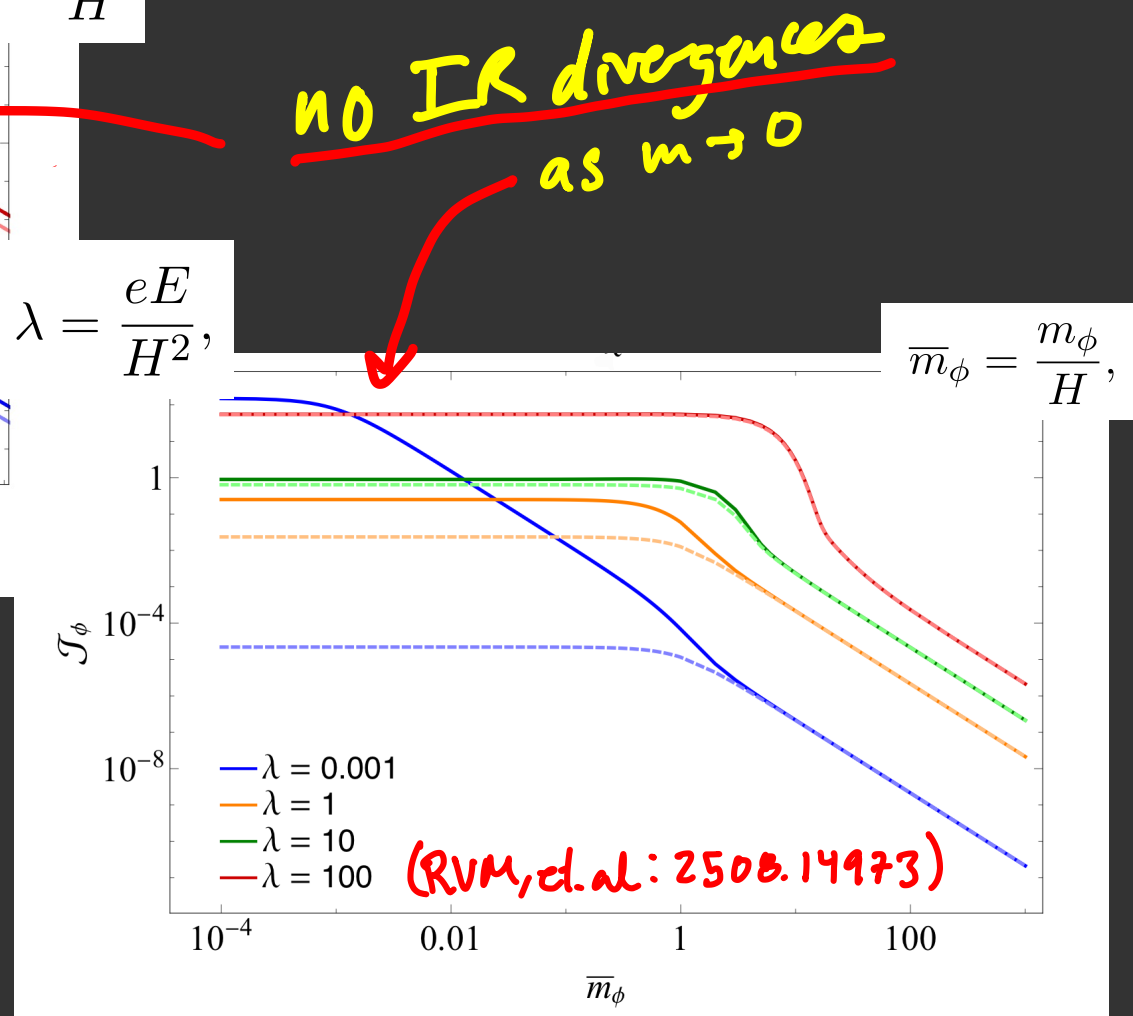
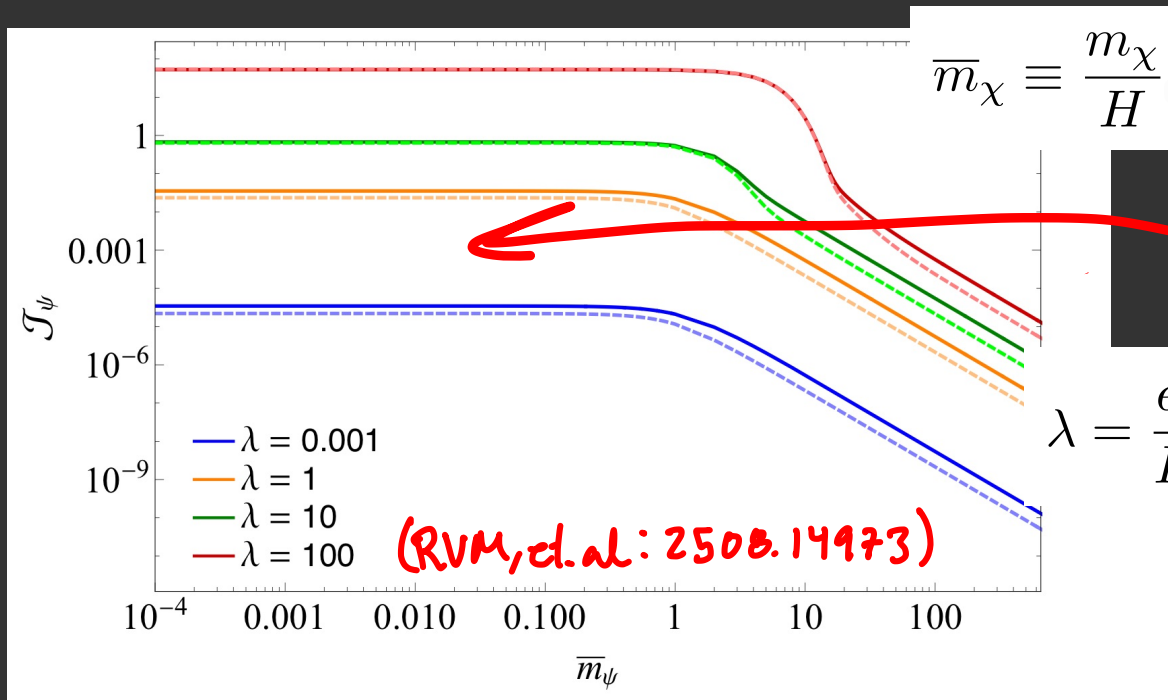
$$\lambda = \frac{eE}{H^2},$$

The current for a conformal scalar has same behavior as fermions

IR 'Hyperconductivity' for massless minimally coupled scalar as $\lambda \rightarrow 0$



The Schwinger Current



- previous calculations had spurious IR divs introduced by their renormalization procedure

Inflationary Schwinger Dark Matter Production

- Starting from dark QED lagrangian can derive evolution equation for dark charged particles χ

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

(conductivity)

$$\sigma = \frac{J}{E} \quad \bar{\sigma} \equiv \frac{\sigma}{H}$$

$\ll 1 \rightarrow$
no backreaction

- Can solve to find energy density of χ at end of inflation $\longrightarrow$

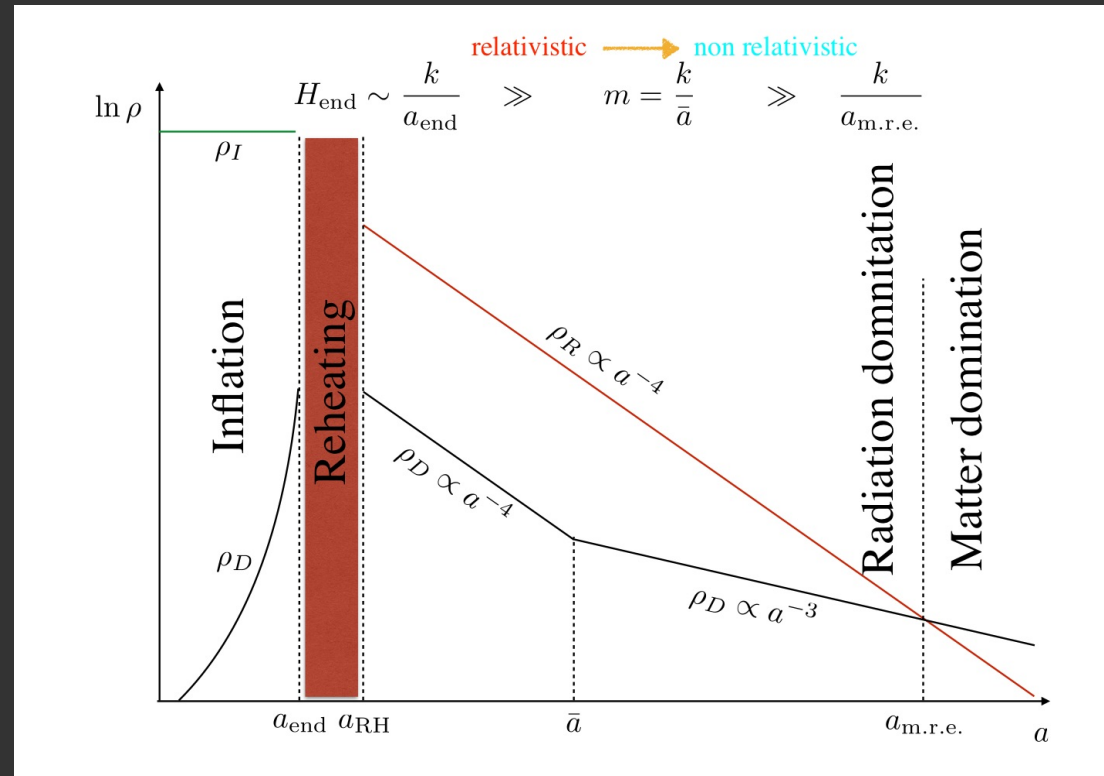
$$\rho_{\chi}^{\text{end}} \equiv \rho_{\chi}(\tau_{\text{end}}) \simeq \frac{\bar{\sigma}}{n} E^2 = \frac{\bar{\sigma}}{n} 2\rho_E^{\text{end}}$$

- The energy density of the dark charged particles at the end of inflation given by energy density in E-field suppressed by $\sigma/H \ll 1$

Cosmic Evolution of Energy Density

- For small dark gauge coupling the dark sector does not thermalize

- Negligible coupling to SM
 $\Downarrow$
cosmic evolution is determined by redshifting



- Energy density of A and X today

$$m_\chi < H_{\text{end}}$$

$$m_\chi > H_{\text{end}}$$

$$\rho_A(T_0) = \left(\frac{T_0}{T_{\text{RH}}} \right)^3 \left(\frac{m_A}{H_{\text{end}}} \right) \rho_E^{\text{end}}.$$

$$\rho_\chi(T_0) = \left(\frac{T_0}{T_{\text{RH}}} \right)^3 \left(\frac{m_\chi}{H_{\text{end}}} \right) \frac{\bar{\sigma}}{2} \rho_E^{\text{end}},$$

$$\rho_\chi(T) = \frac{\bar{\sigma}_{\text{end}}}{3} E^2 \left(\frac{T}{T_{\text{RH}}} \right)^3,$$

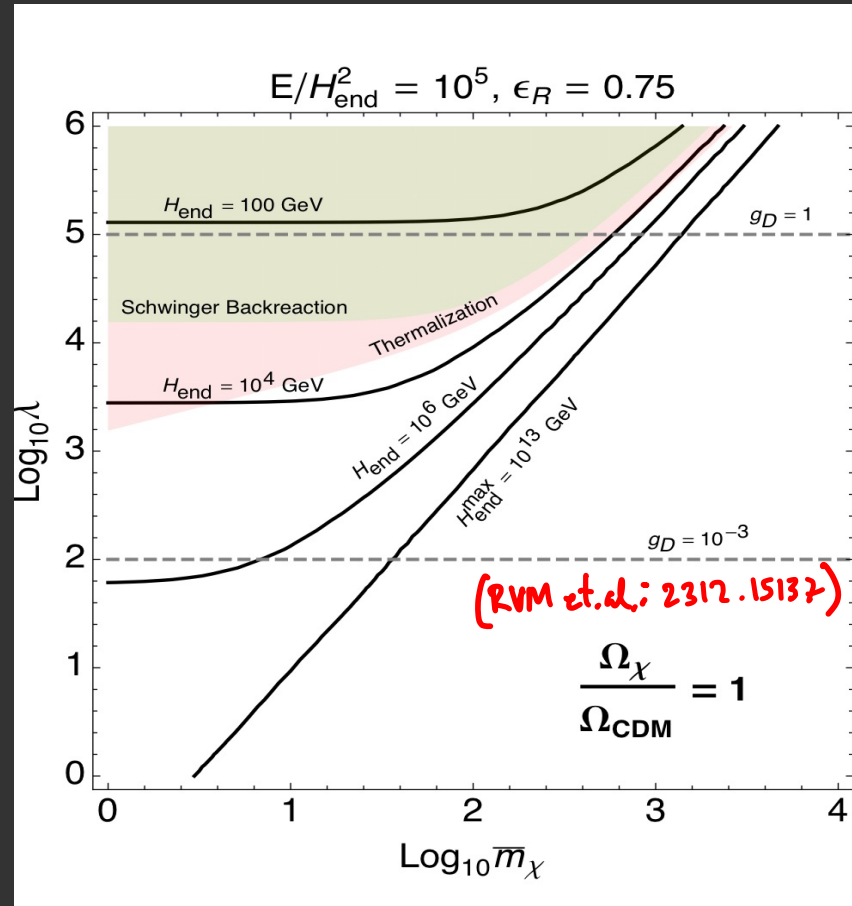
Dark Matter Relic Abundance (Heavy)

- Taking $m_A \ll m_\chi$, dark electrons make up all DM

- Strong field regime $\lambda > 1$

$$\lambda = \frac{eE}{H^2},$$

$$\overline{m}_\chi \equiv \frac{m_\chi}{H}$$



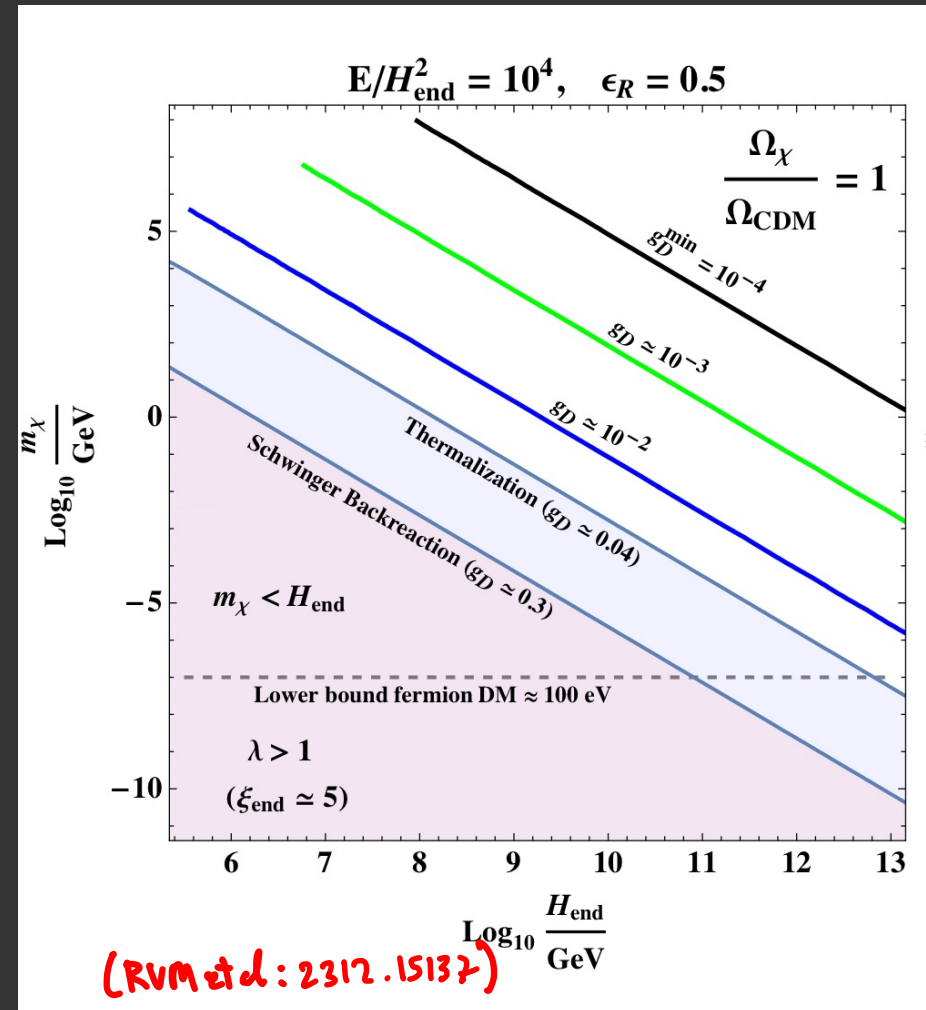
$$m_\chi > H_{\text{end}}$$

- Can obtain DM as heavy as $\sim 10^{17} \text{ GeV}$

Dark Matter Relic Abundance (Light)

- Can obtain scalar DM as light as 0.1 eV
- Fermion dark matter as light as 100 eV (astro lower bound)
- In weak field regime can obtain DM as light as 10^{-2} GeV

$$m_\chi < H_{\text{end}}$$



Generating a Background E-field in de Sitter

- So far have said nothing about how to generate E-field
- Need a 'source' to maintain constant E-field during inflation due to dilution from expansion

- Various possibilities from vector production mechanisms

couplings to metric
 $M_A^2 g_{\mu\nu} A^\mu A^\nu, R A^\mu A_\mu$

coupling to inflaton
 $\mathcal{L}FF, \mathcal{L}F\tilde{F}$

- Vector production mechanism must generate background E-field ($\vec{A}$) with coherence length $\lambda \sim H^{-1}$



Generating a Background E-field in de Sitter

- This can be done via an axion like coupling to ϕ

RVM et al. $\begin{cases} 1810.07208 \\ 2103.12145 \end{cases}$

$$S = - \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial_\mu \phi \partial^\mu \phi + V(\phi) + \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu + \frac{\alpha}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \right]$$

$$f \gtrsim \frac{\alpha}{10\sqrt{2}} M_{Pl}$$

Inflaton

$$\rightarrow \ddot{\phi} + 3H\dot{\phi} + V' = \frac{\alpha}{4f} F \tilde{F} \approx 0 \text{ no BR}$$

Transverse

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

Longitudinal

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

↳ only for $m_A \approx 0$ during inflation (Graham, Mardon, Rajendran: 1504.02102)

Tachyonic Transverse Modes

- In conformal time we have a harmonic oscillator for $A_{\pm}$

$$\left[\frac{\partial^2}{\partial \tau^2} + \omega^2(k, \tau) \right] A_{\pm}(k, \tau) = 0$$

$$\omega^2(k, \tau) = k^2 + 2k \frac{\xi}{\tau} + \frac{\bar{m}^2}{\tau^2} = k^2 - 2k\xi aH$$

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

Instability parameter ξ

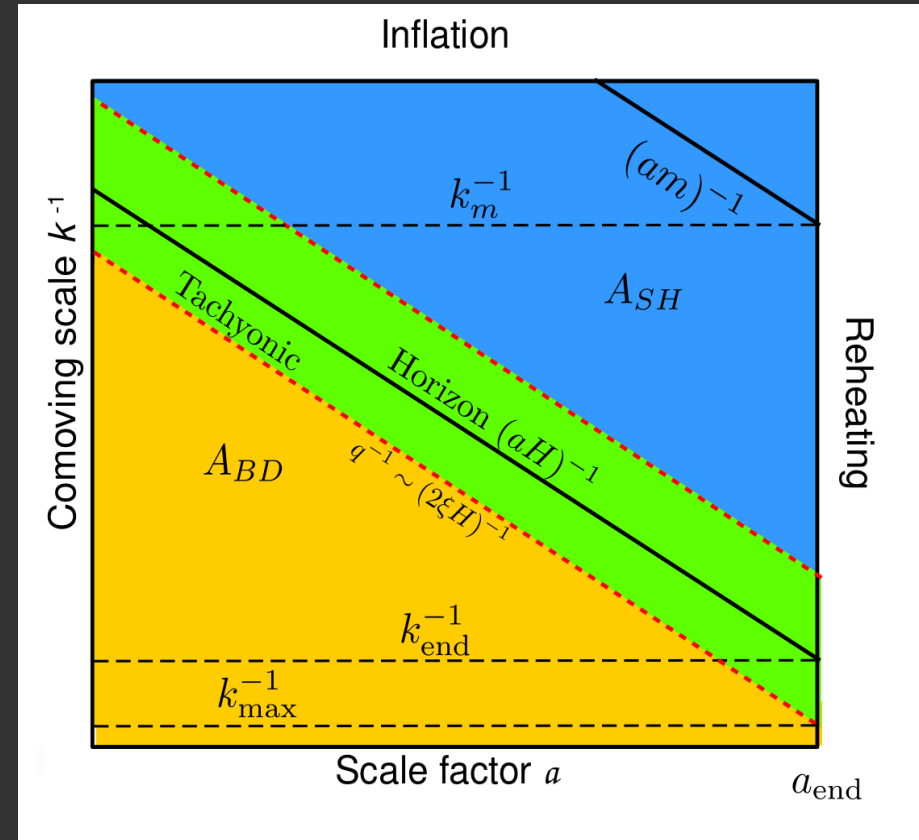
- When $\omega^2(k, \tau) < 0$ this leads to a tachyonic instability (only for A_+ or A_-)

- Occurs when $\frac{u}{a} = g \sim H \Rightarrow \underline{\lambda \equiv g^{-1} H^{-1}}$

- Leads to exponential production of A_+ ($\xi > 0$)

$$A_+(k, \tau)_{\text{WKB}} \simeq \frac{1}{\sqrt{2k}} \left(\frac{-k\tau}{2\xi} \right)^{1/4} \underline{e^{\pi\xi - 2\sqrt{-2\xi k\tau}}}$$

$$\left(\frac{1}{8\xi} < -k\tau < 2\xi \right)$$



Classical (Helical) Background E-field

- So we have A_+ modes with very high occupation number (classical) with coherence length $\ell \sim H^{-1}$



Classical background E-field
within each Hubble patch



- Since production depends exponentially on $\dot{\phi}$ (via $\mathcal{E}$) maximum production occurs just at the end of inflation
- Since only A_+ is produced, the E-field is helical

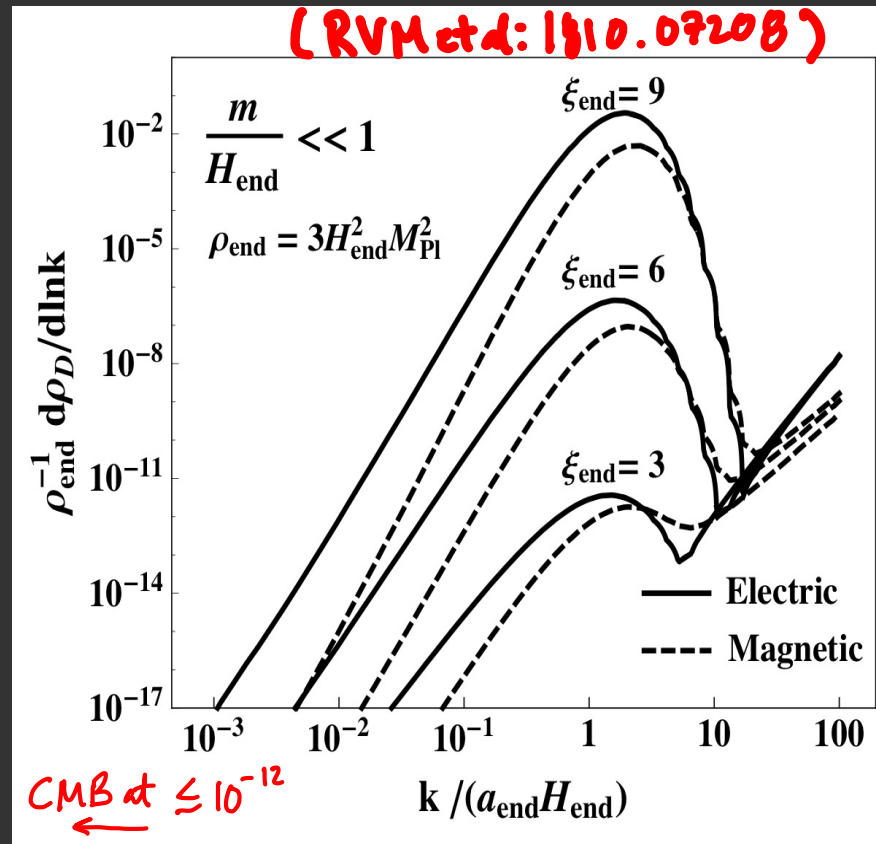
Energy Density (power) Spectrum at a_{end}

- At the end of inflation the dark photon has an energy density spectrum peaked at $k \sim a_{\text{end}} H_{\text{end}}$
- Power suppressed at CMB scales
- Integrate to find total energy density

$$\begin{aligned}\rho_D &= \frac{1}{4\pi^2 a^4} \int_0^\infty dk k^2 \left(|\partial_\tau A_+(k, \tau)|^2 + (k^2 + a^2 m^2) |A_+(k, \tau)|^2 \right) \\ &= \frac{1}{2a^4} \int d \ln k \left(\mathcal{P}_{\partial_\tau A_+}(k, \tau) + (k^2 + a^2 m^2) \mathcal{P}_{A_+}(k, \tau) \right) \\ &= \langle (\partial_\tau A_+)^2 \rangle + \langle A_+^2 \rangle = \frac{1}{2} \langle \vec{E}^2 + \vec{B}^2 \rangle. \quad \mathbf{E} \gg \mathbf{B}\end{aligned}$$

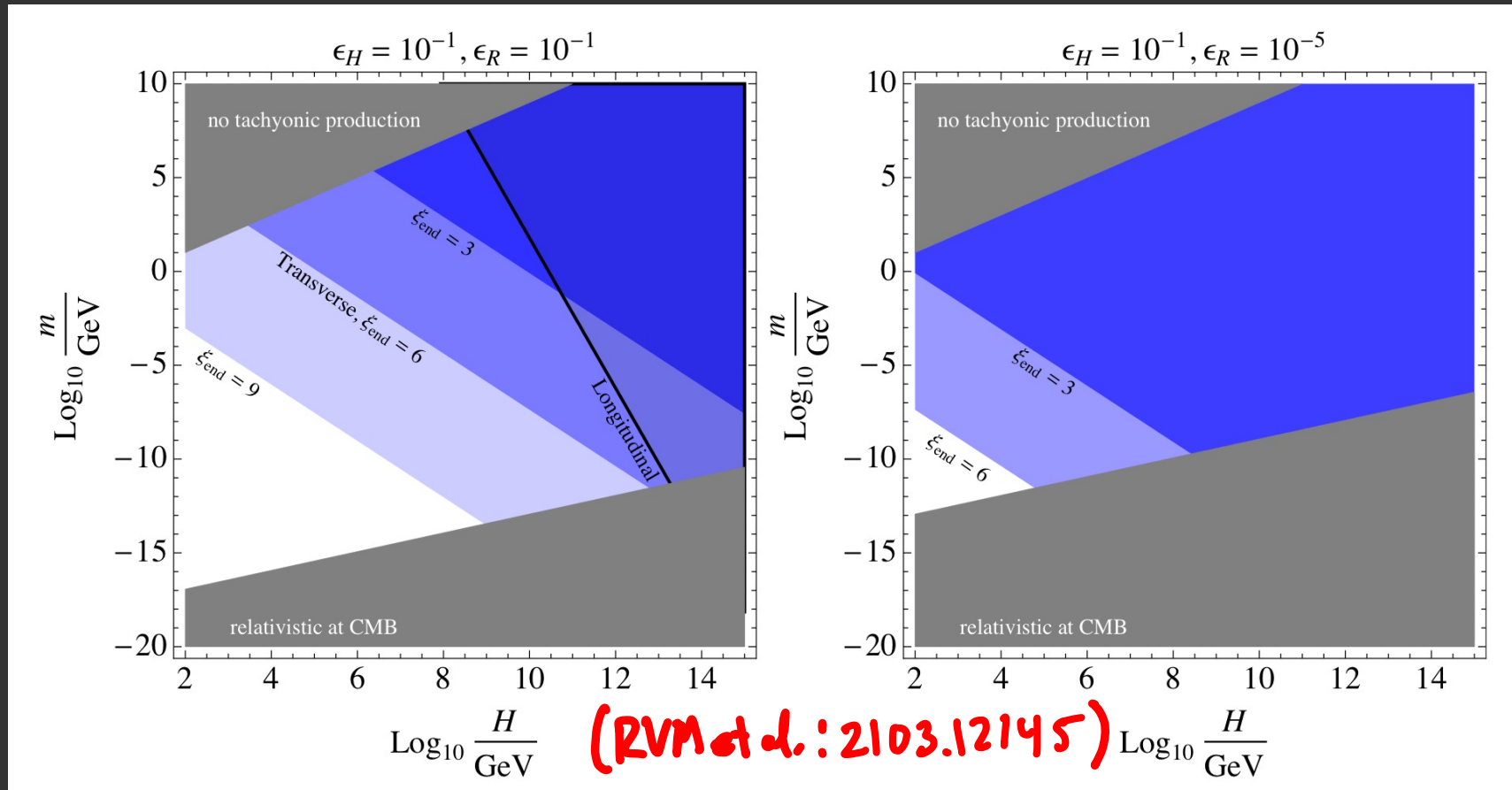


$$\rho_D(a_{\text{end}}) \equiv \rho_D^{\text{end}} \approx 10^{-4} \frac{e^{2\pi\xi_{\text{end}}}}{\xi_{\text{end}}^3} H_{\text{end}}^4$$



Dark Photon Dark Matter Relic Abundance

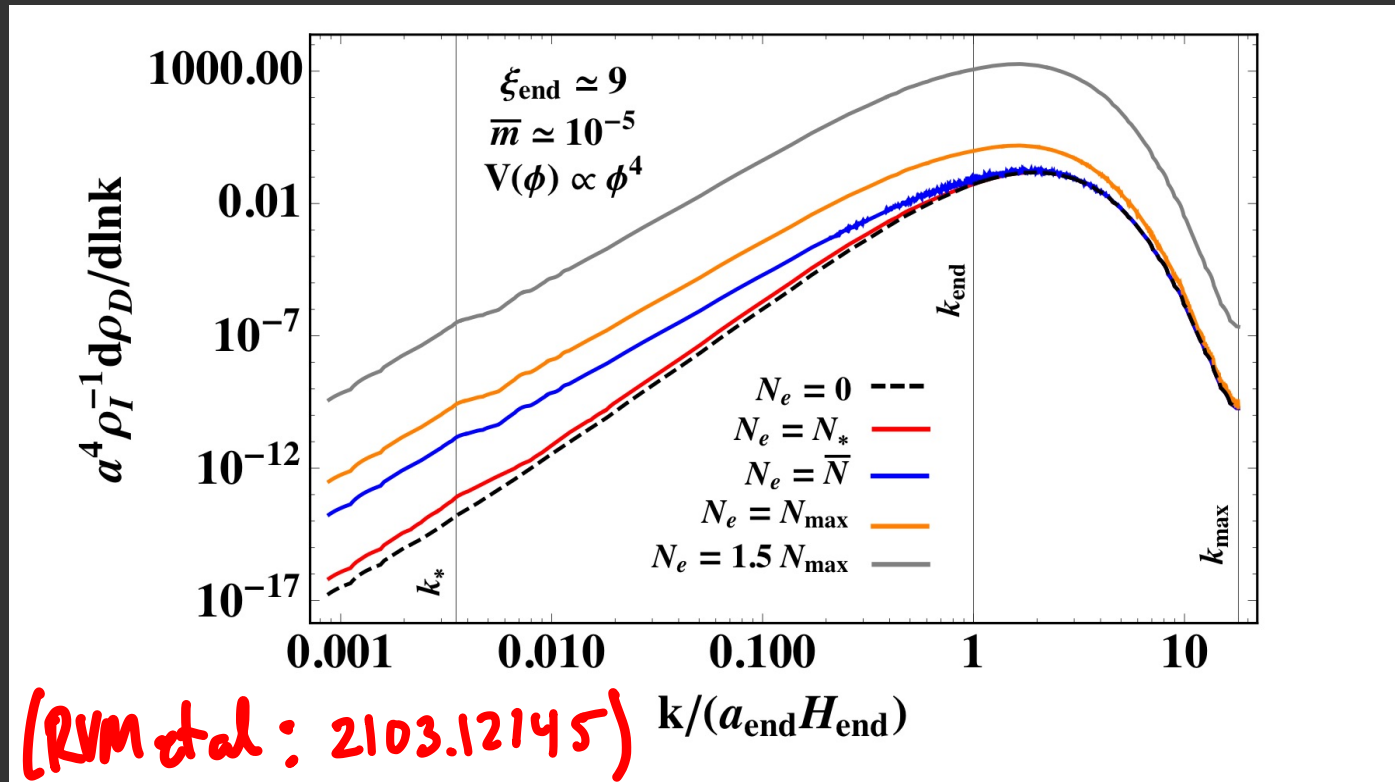
- In regions of parameter space dark photon can make up all DM



- Can obtain dark photon DM for masses $\sim$ meV - 10 TeV

Energy Density (power) Spectrum Today

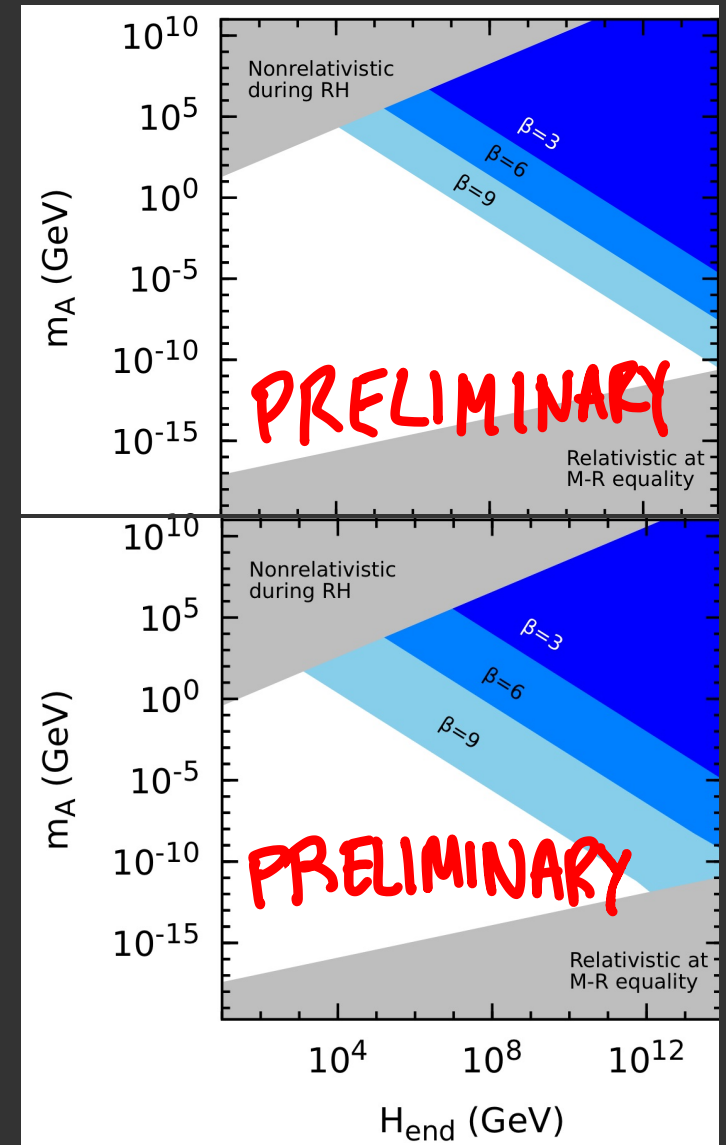
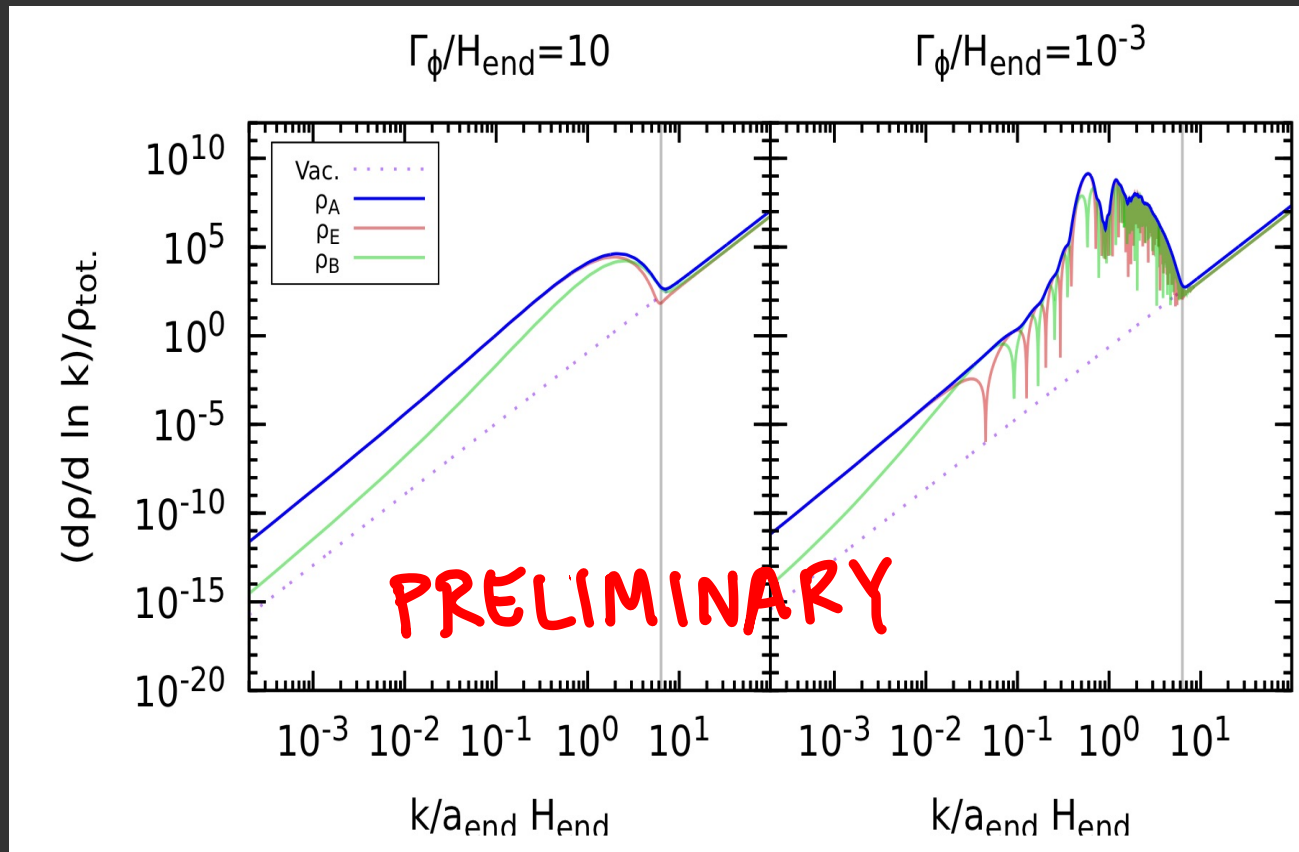
- Peak in spectrum survives cosmic evolution to today



- Today DM 'clumps' on physical scales $l_{\text{today}} \sim \text{cm} - 100 \text{ km}$

Reheating Effects (Ongoing)

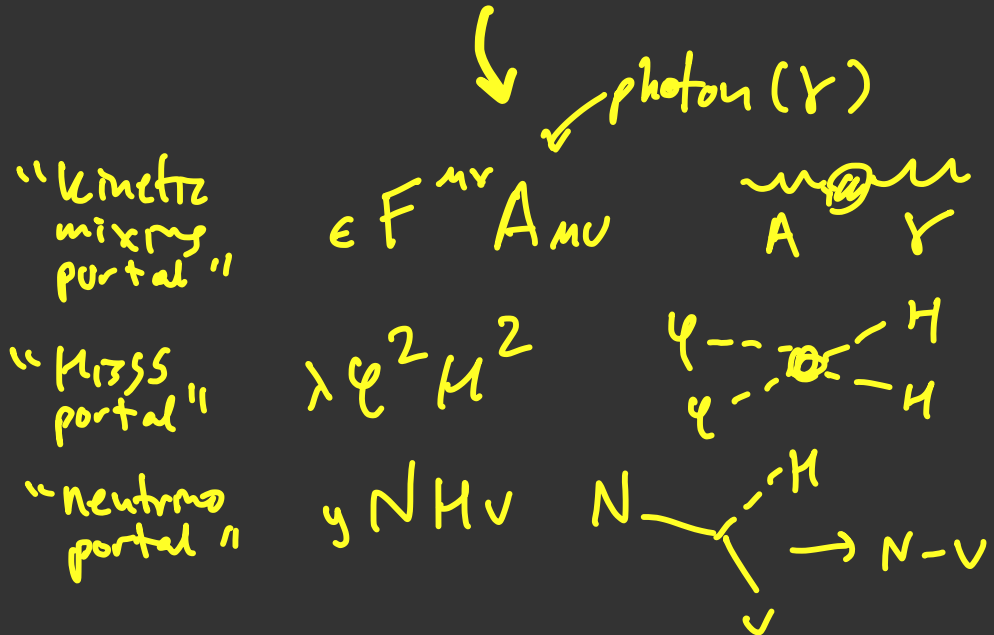
- Reheating affects the power spectrum and the DM parameter space



Potential Phenomenology of DM sector (Future)

- Dark sector may or may not couple to SM

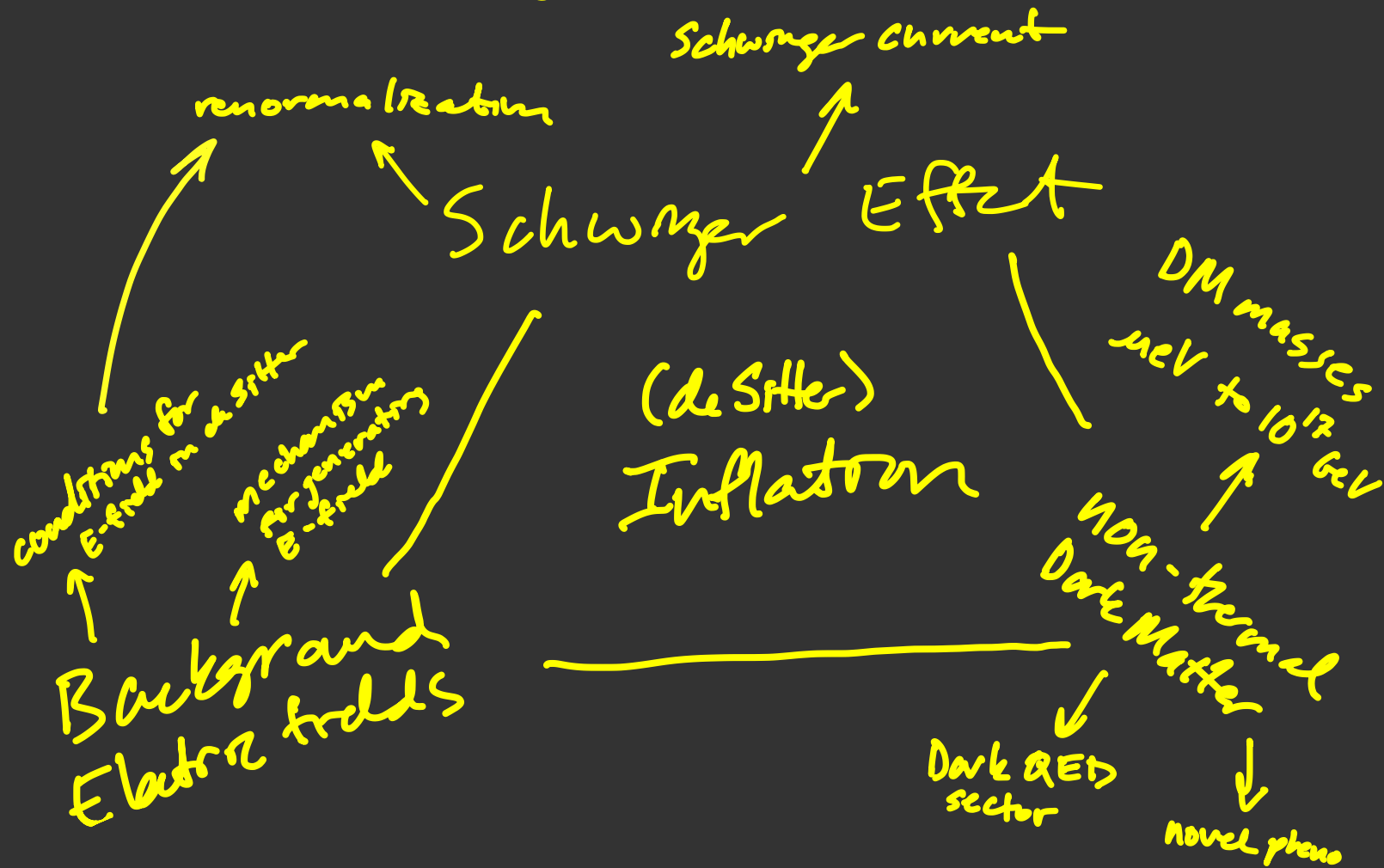
- Multi-component self interacting dark matter (vector, scalar, fermion)



- Even if no DM-SM coupling there is a lot of potential phenomenology
 ↳ structure, superradiance, lensing, gravitational waves

- Polarized dark matter?

Summary / Conclusions



THANK YOU!

EXTRA

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Computing the Counter term δ_3

- Our calculation of $\langle T_2 \rangle_{\text{reg}}$ agrees with previous results

$$\langle T_2 \rangle_{\text{reg}} \sim \ln\left(\frac{\Lambda^2}{H^2}\right) + \text{Finite} \rightarrow \text{how to define?}$$

- This result is exact and non-perturbative
- UV log divergent, but IR finite and > 0
- Encodes full dependence on $\lambda \equiv \frac{cE}{H^2}$, $\bar{m} \equiv \frac{m}{H}$
including curvature effects (de Sitter)

Computing the Counter term δ_3

- We expect all of these properties to hold in $\langle T \rangle_{\text{ren}}$ once the log divergence in $\langle T \rangle_{\text{reg}}$ is removed with δ_3
- In principle δ_3 (linear in λ) should be computed on the Shell and include full m dependence $\Rightarrow$ ~~Angular~~
- Taking Monkowskie limit in loop integral including the electron propagator $\Rightarrow (k^2 - m^2)^{-1}$
- Evaluating Π_{00} we obtain the standard QED result which depends on p^2 of photon

Computing the Counter term δ_3

(RVM et.al: 2503.01981, 2508.14973)

$$\delta_3^\phi = -e^2 \Pi(2H^2) = \left(\frac{e}{12\pi}\right)^2 \left[-3 \ln\left(\frac{\Lambda^2}{H^2}\right) + 3 \ln\left(\frac{m_\phi^2}{H^2}\right) \right. \\ \left. + 6\left(2\frac{m_\phi^2}{H^2} + 1\right)^{3/2} \coth^{-1}\left(\sqrt{2\frac{m_\phi^2}{H^2} + 1}\right) - 12\frac{m_\phi^2}{H^2} - 8 \right],$$

$$\delta_3^\psi = \frac{e^2}{36\pi^2} \left[-3 \ln\left(\frac{\Lambda^2}{H^2}\right) + 3 \ln\left(\frac{m_\psi^2}{H^2} + 3\right) + 6\left(\frac{m_\psi^2}{H^2} + 3\right) \right. \\ \left. - 6\left(\left(\frac{m_\psi^2}{H^2} + 3\right) - 1\right) \sqrt{2\left(\frac{m_\psi^2}{H^2} + 3\right) + 1} \coth^{-1}\left(\sqrt{2\left(\frac{m_\psi^2}{H^2} + 3\right) + 1}\right) - 5 \right],$$