Dark QED from Inflation

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In collaboration with A. Arvanitaki, S. Dimopoulos, D. Racco, O. Simon and J.O. Thompson

INT workshop: Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

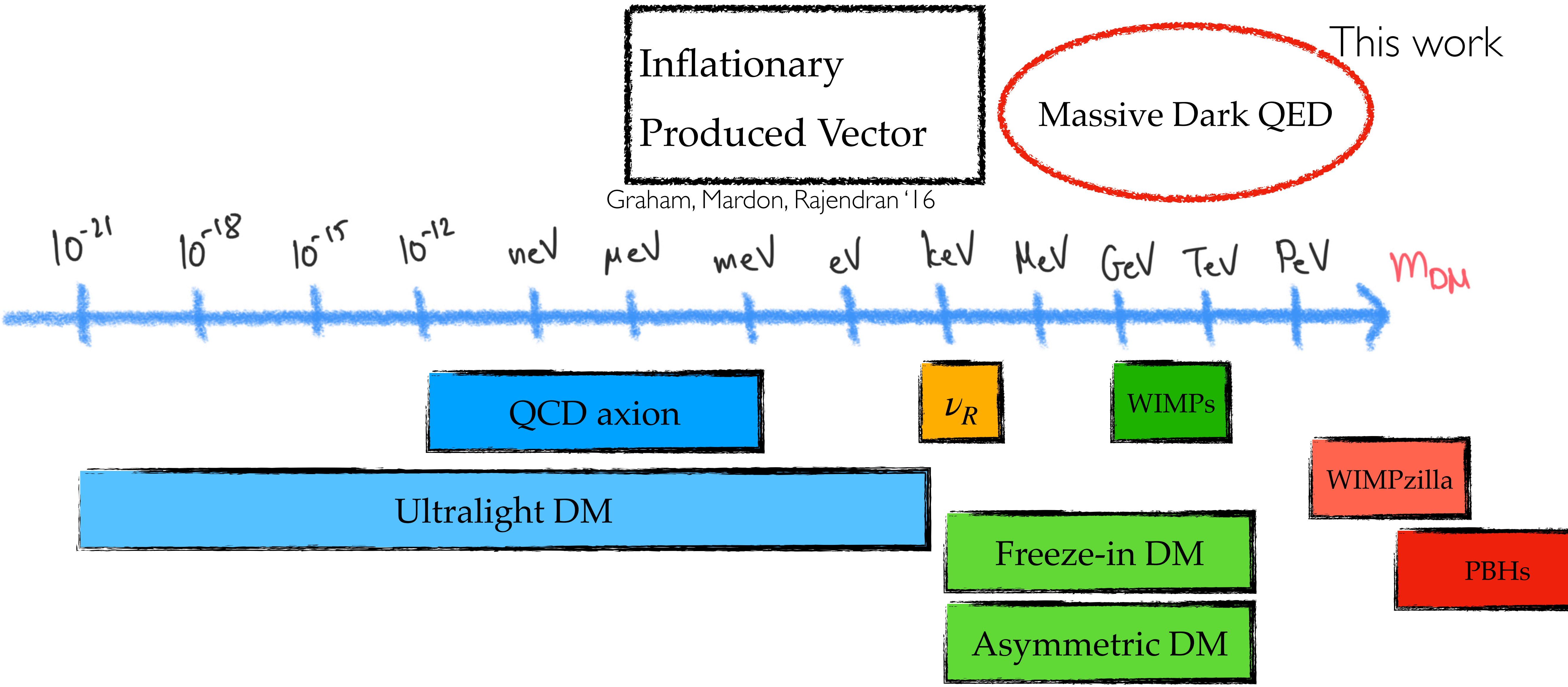
Outline

Motivation

Review of Gravitational Particle Production

Dark QED

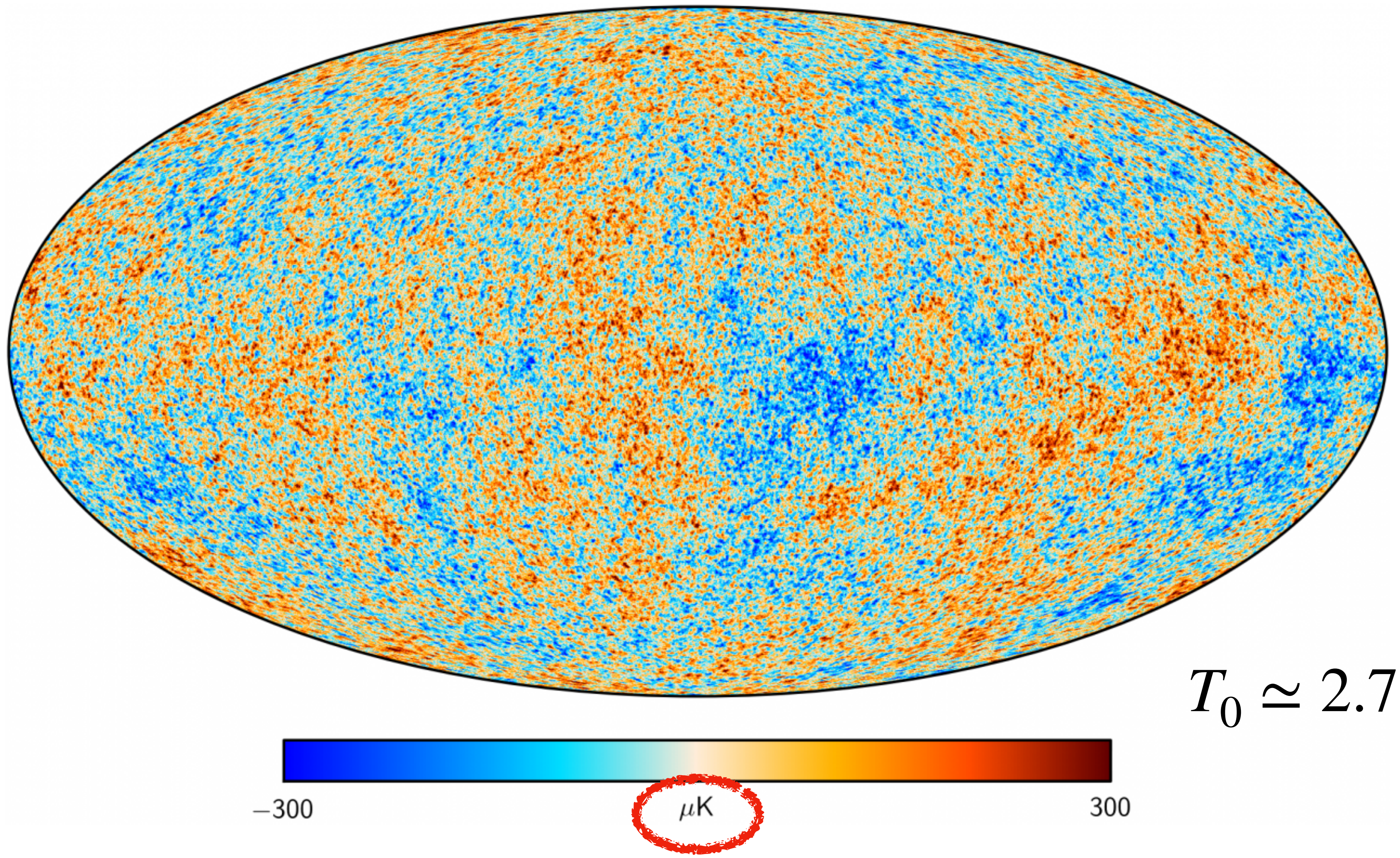
Why care about production mechanism?



Many mechanisms rely on non-gravitational interactions

Production mechanisms can guide experimental searches

Why Inflation?



$T_0 \simeq 2.7$ K

Sources Particles - Time dependent background

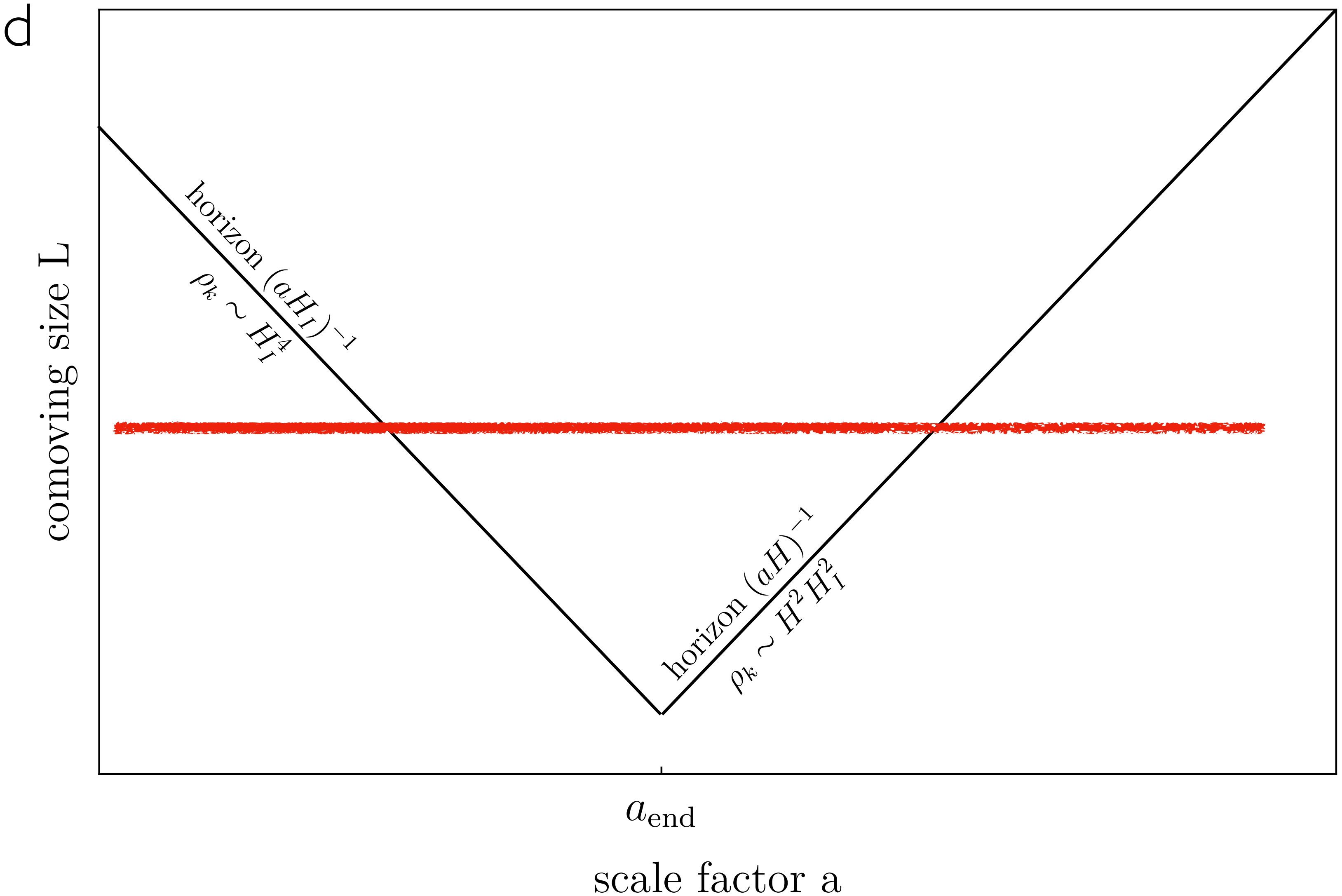
Irreducible contribution to any sector - just gravity!

Can account for totality of DM

Gravitational Particle Production

['39 Schrödinger; '69 Parker; ''77 Gibbons, Hawking; '79 Birrell, Davies; '87 Ford; …]

$|0\rangle_k$ → Let it be stretched



Subhorizon evolution is instantaneous

Radiation Era → New Vacuum

$${}_k\langle 0' | 0 \rangle_k \neq 1$$

Particle Production!

Formally: Solve EoM, choose Bunch-Davies vacuum, stitch to Radiation Era States

$$|0\rangle \to \alpha\,|0'\rangle + \beta\,|n\rangle$$

Gravitational Particle Production

General Point: There needs to be some violation of scale invariance.

Scalar or tensor: $\chi'' + \left(k^2 - \frac{a''}{a}\right)\chi = 0$

Fermion: $(i\gamma^\mu \partial_\mu - a(\eta) m)\,\psi = 0$

T Vector: $\vec{A}_T'' + (k^2 + a(\eta)^2 m^2)\vec{A}_T = 0$

Example: At $H = m_\psi$ energy density is $\rho_\psi \sim m_\psi^4$

$$\frac{\Omega_\psi}{\Omega_{DM}} \sim 2\left(\frac{m_\psi}{10^9\ \mathrm{GeV}}\right)$$

[Chung Kolb Riotto ('98)
Kuzmin, Tkachev ('99)
Chung et al. (2011)]

Goes to 0 as $m_\psi \to 0$: Conformal Invariance

Horizon exit: $$\frac{\mathrm{d}\rho}{\mathrm{d}\log k} = \mathcal{C}\left(\frac{H_I}{2\pi}\right)^4$$

m^2/H_I^2 for fermions/T vectors

Maximal for scalars

Gravitational Production of Vectors

[Graham, Mardon, Rajendran '16]

Massless is conformally coupled, no production

Massive: Transverse modes like fermions, but **longitudinal** like scalars

$$A_L = \frac{k}{m_{A'}}\phi, \text{ for } k \gg m_{A'} \qquad\qquad \phi'' + 3H\phi' \simeq 0$$

$$\phi = \text{const} \qquad \Rightarrow \qquad \rho_\phi = m_\phi^2 \phi^2 = \text{const}$$

Unique for vectors: Energy density redshifts while superhorizon because of the norm

$$\rho_{A'} \sim m_{A'}^2 A'^\mu A'_\mu \sim m_{A'}^2 g^{ij} |A'_L|^2 \text{ and } g^{ij} \propto a^{-2}$$

Gravitational Production of Vectors

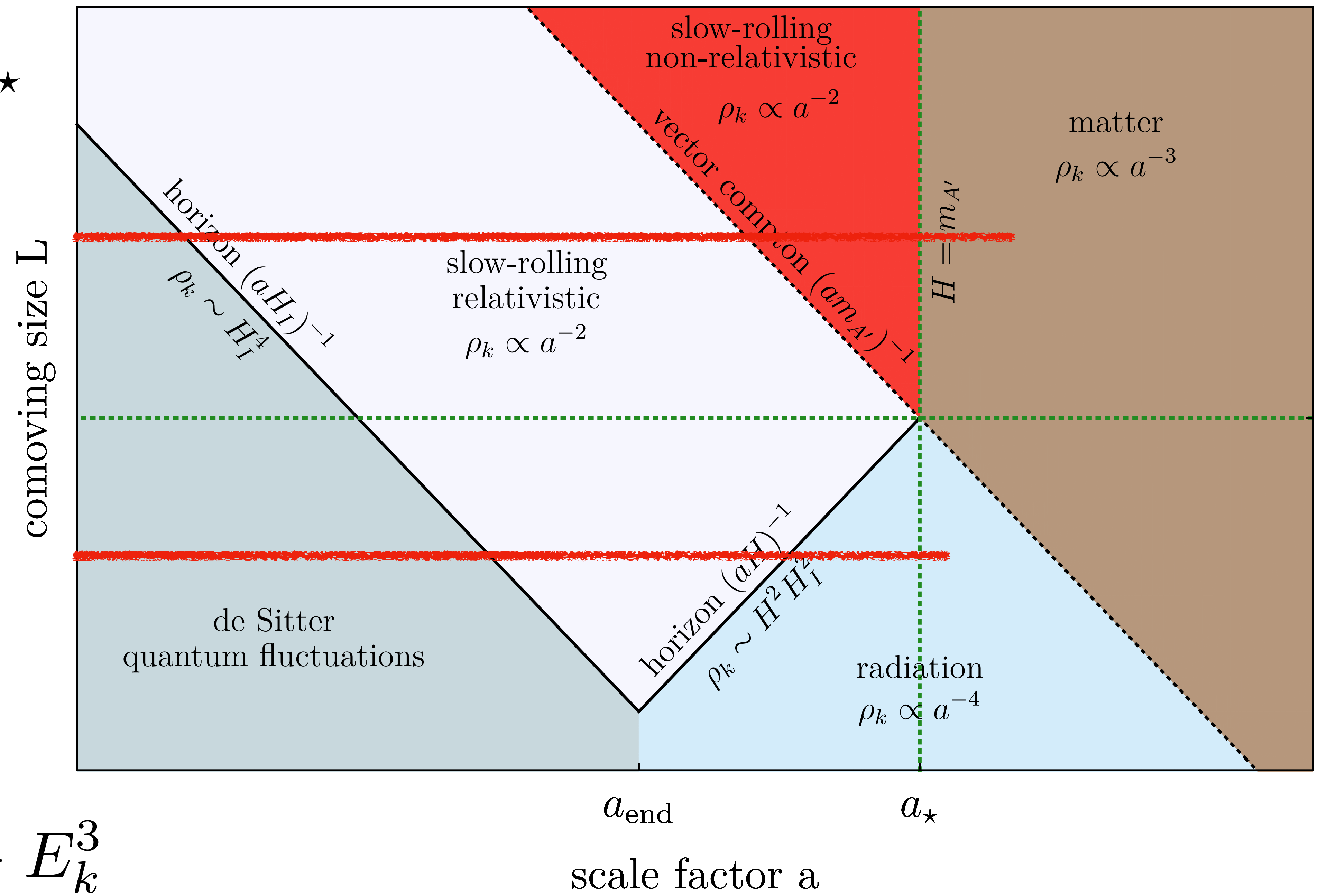
[Graham, Mardon, Rajendran '16]

At $a_\star$ all modes $k > k_\star$ contribute the same

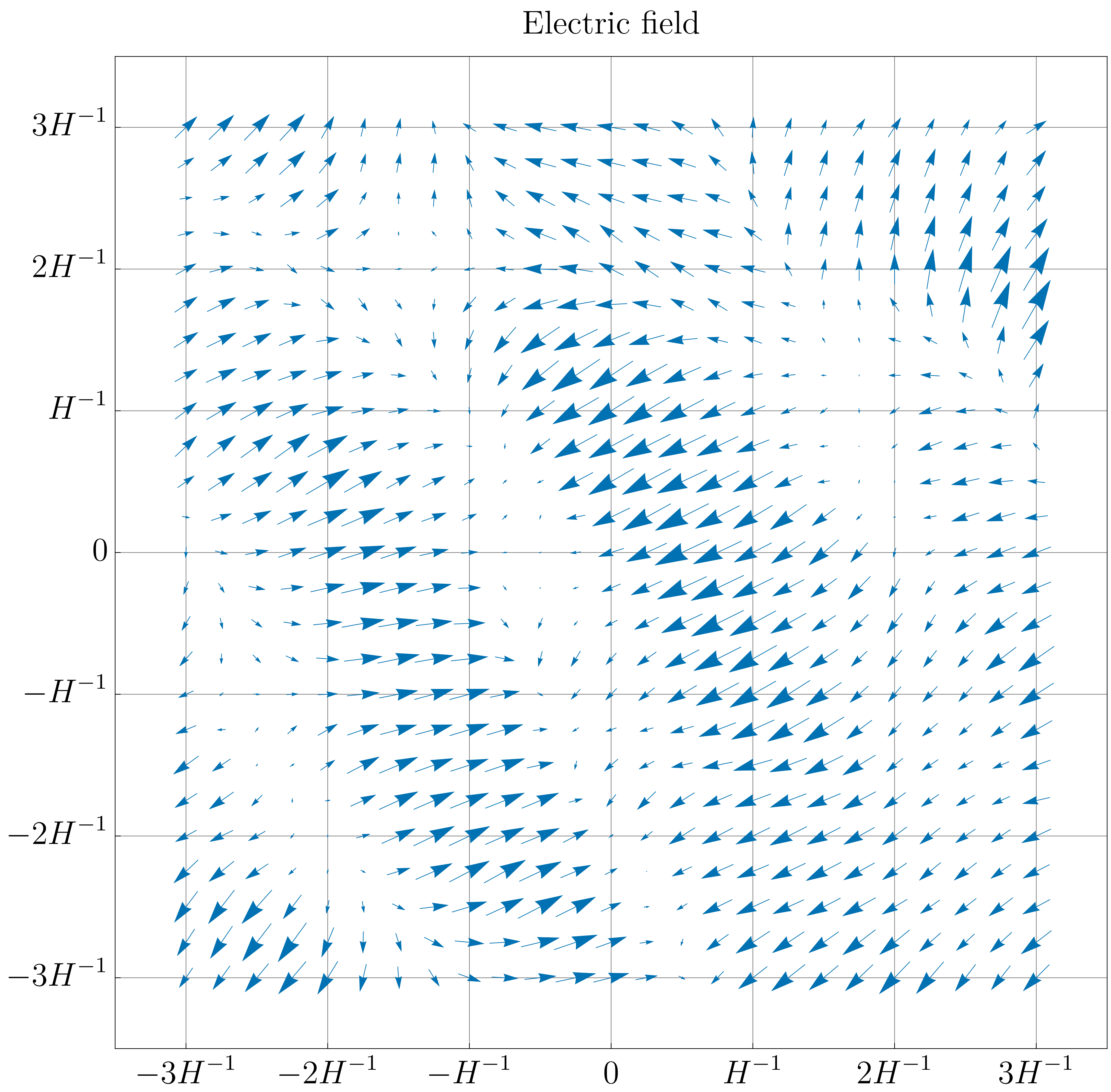
Mode entering when $H \sim m_{A'}$ dominates

$$E_k \sim H$$
$$\rho_k \sim H^2 H_I^2$$
$$n_k \sim H H_I^2$$

Non thermal: $n_k \gg E_k^3$



$$\frac{\Omega_{A'}}{\Omega_{DM}} = \left(\frac{m_{A'}}{6 \times 10^{-6}\,\mathrm{eV}}\right)^{1/2} \left(\frac{H_I}{10^{14}\ \mathrm{GeV}}\right)^2$$



Electric field
$3H^{-1}$
$2H^{-1}$
H^{-1}
0
$-H^{-1}$
$-2H^{-1}$
$-3H^{-1}$
$-3H^{-1}$
$-2H^{-1}$
$-H^{-1}$
0
H^{-1}
$2H^{-1}$
$3H^{-1}$

Important Takeaways

- Breaking of scale invariance necessary for production
- "Cold" state, many photons, low energies
- Coherent states, large classical electric fields

But what if there is a sector?

Interactions

- Conformal Invariance breaking because of β-function
  - Expecting a number density $\propto \beta^2$

[Adler, Collins Duncan '77; Dolgov '93…]

- Interactions change evolution
  - Strong electric fields seed particles
  - Thermalization

Our focus

Dark QED

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

Massive vector + fermion

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu} + \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_{\psi}\right)\psi - e_D A'^{\mu}\bar{\psi}\gamma_{\mu}\psi$$

Two regimes

- Light dark photon $m_{A'} \ll m_{\psi}$. QED-like
- Heavy dark photon $m_{A'} \gg m_{\psi}$

Longitudinal dark photons produced by inflation

Fermion production suppressed

Dark QED

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

- Initially: very cold, very populous coherent state of A_L

$$\rho_k \sim H^2 H_I^2 \qquad n_k \sim H H_I^2 \qquad \frac{n_k}{H^3} \sim \left(\frac{H_I}{H}\right)^2 \gg 1$$

- Large coherent electric field $E_L = m_{A'} H_I$

Mismatch!

- Thermal number density

$$n_{\text{thermal}} \sim \rho^{3/4} \sim (H H_I)^{3/2} \qquad \frac{n_{\text{thermal}}}{H^3} \sim \left(\frac{H_I}{H}\right)^{3/2}$$

Thermalization needs total number changing processes!

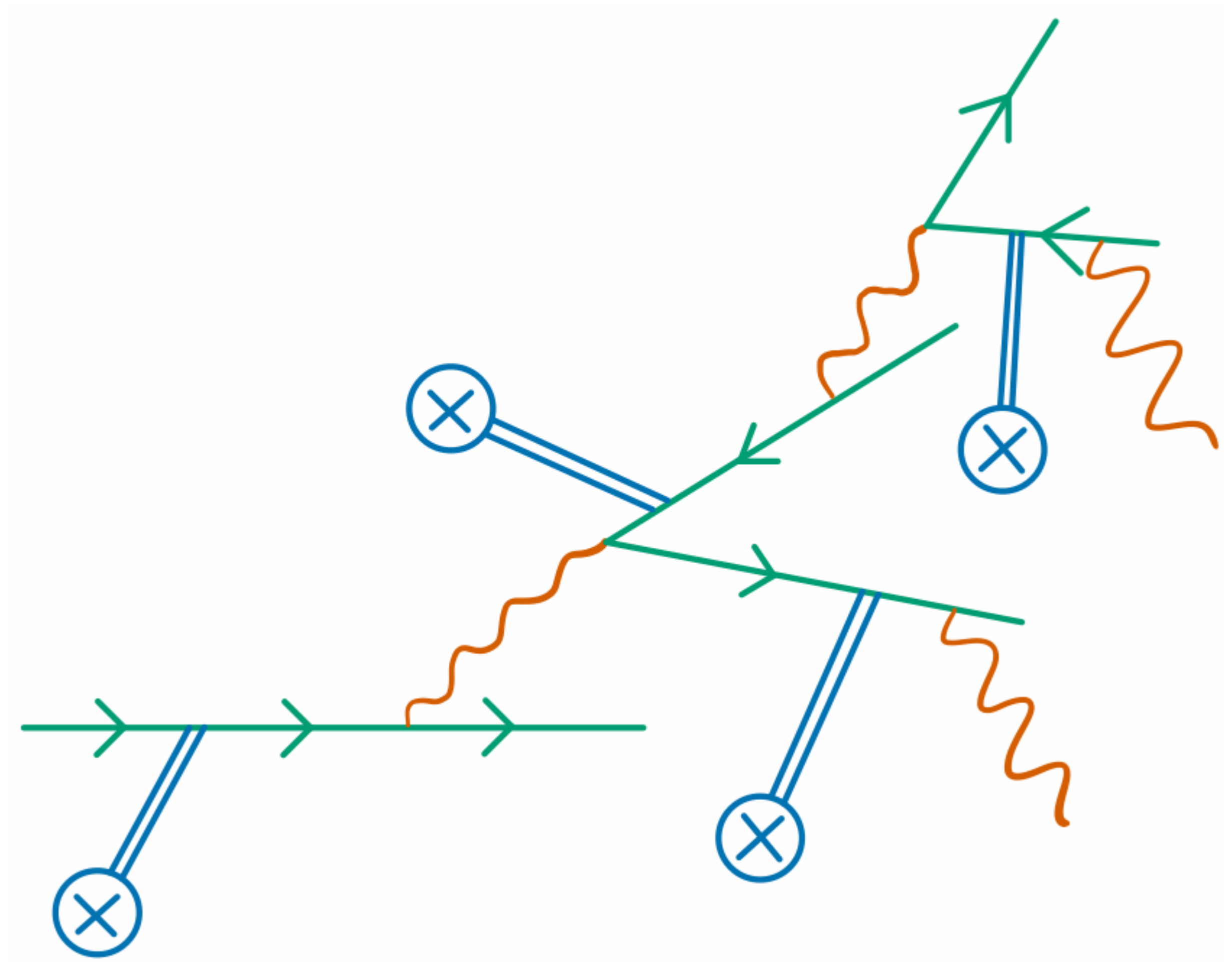
Strong field QED

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

- If $m_\psi^2 \lesssim e_{\rm D} E_L \sim e_{\rm D} m_{A'} H_I$ ⟶ Strong-field coherent processes

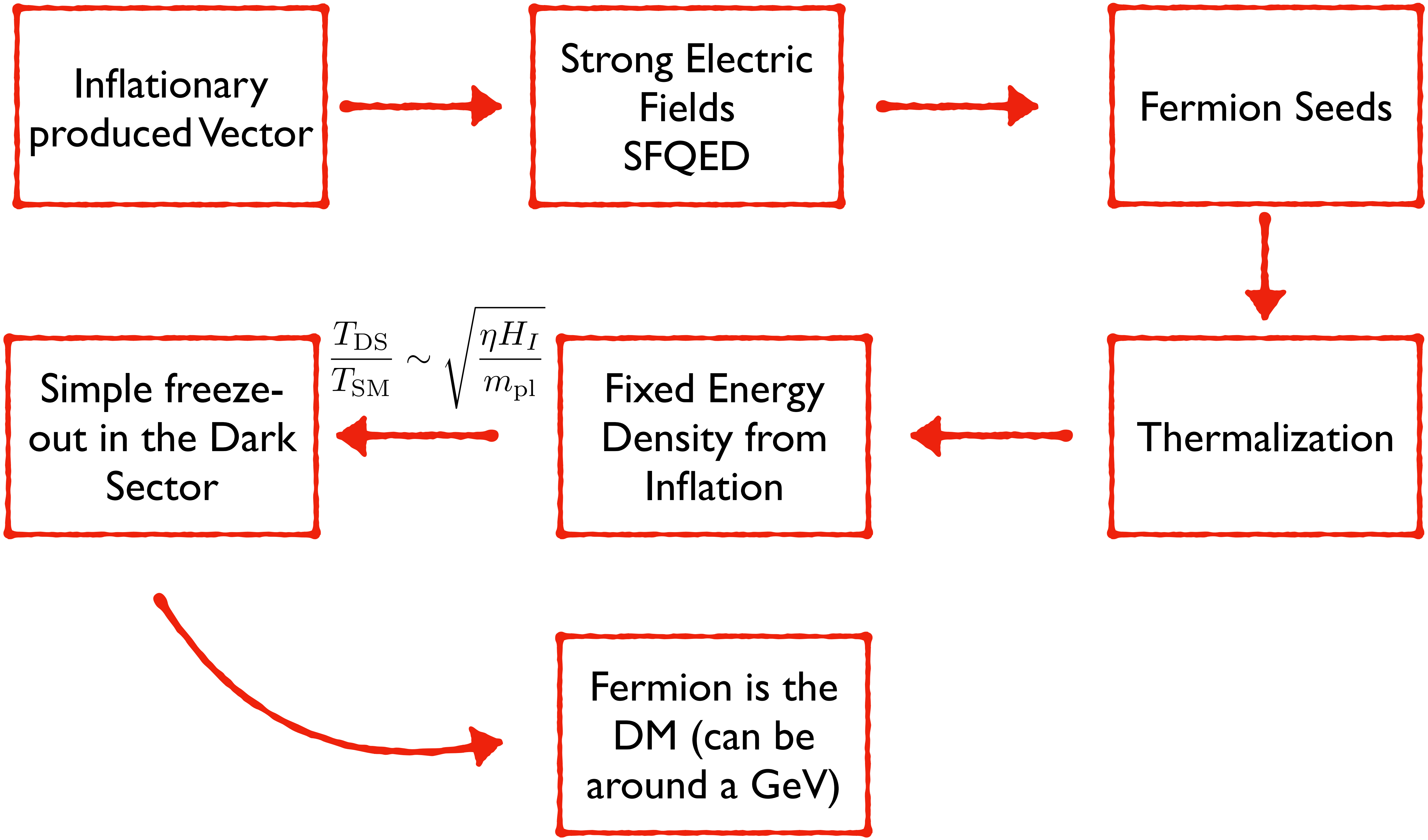
- Schwinger pair production
- Electromagnetic Cascades

- The first fermion seeds
- Number changing already!

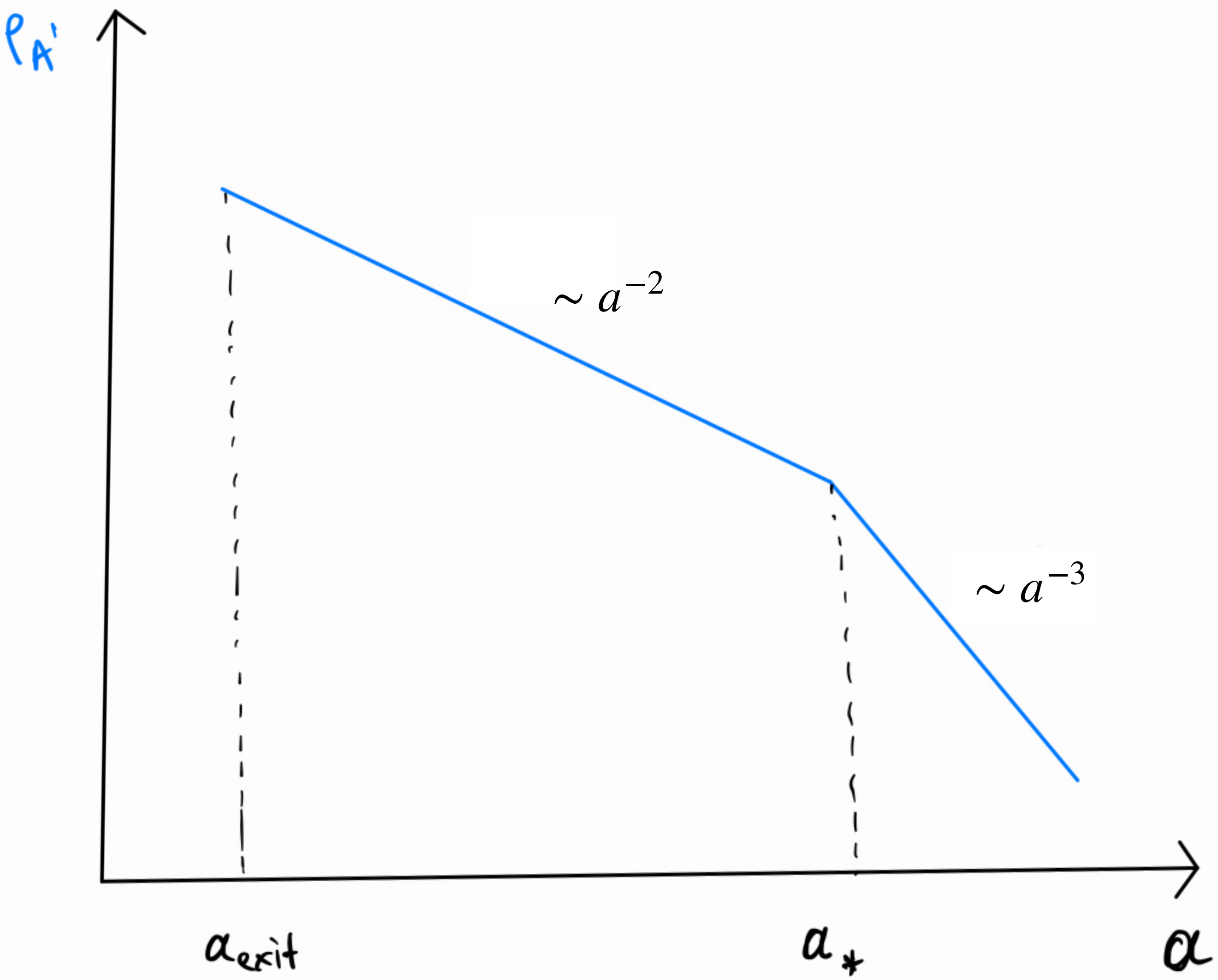


Executive Summary

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

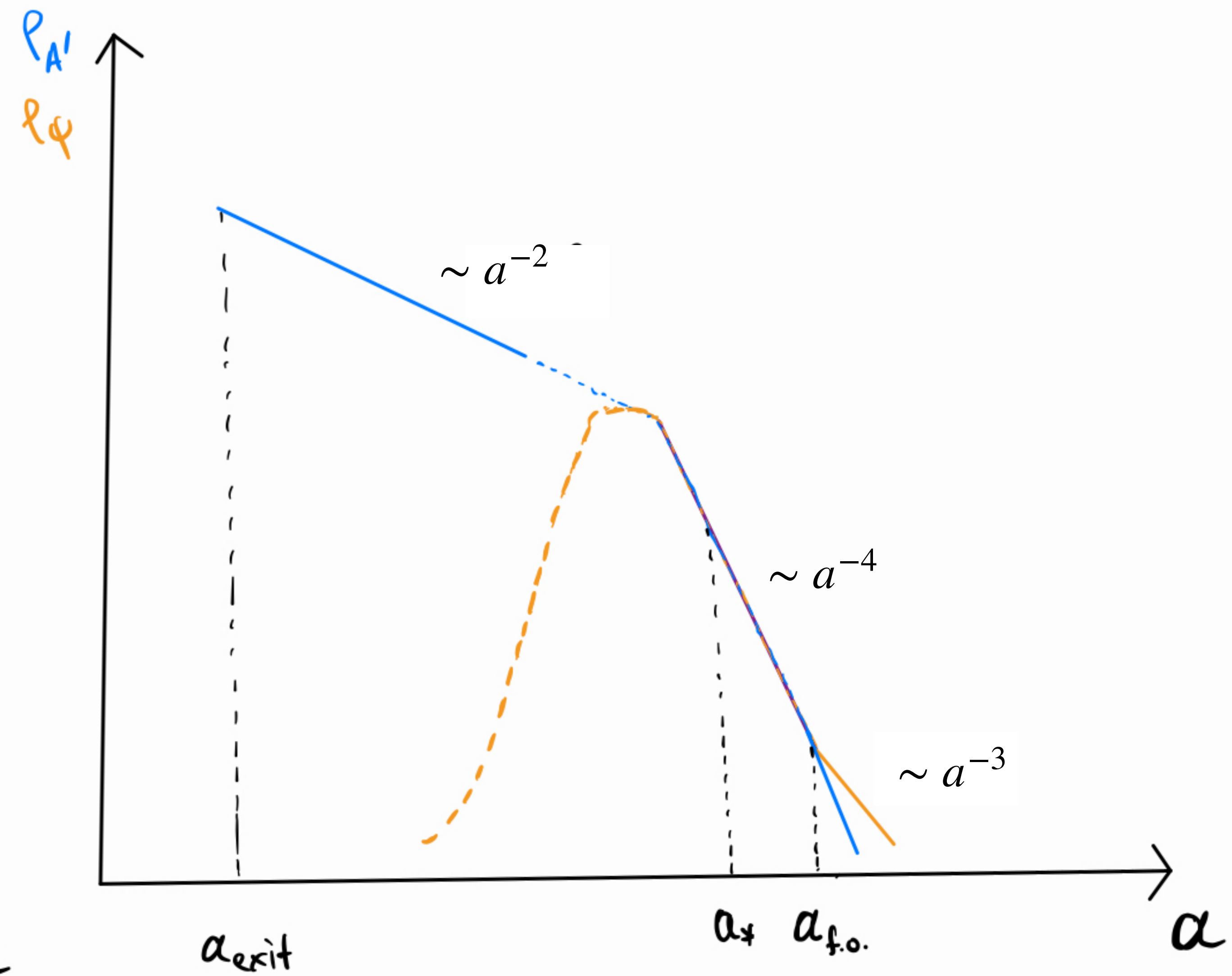


[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]



Pure Dark Photon

[Graham, Mardon, Rajendran '16]



Dark QED

Relic Abundance

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

- Simple: Dark sector is colder than SM. Fixed energy density

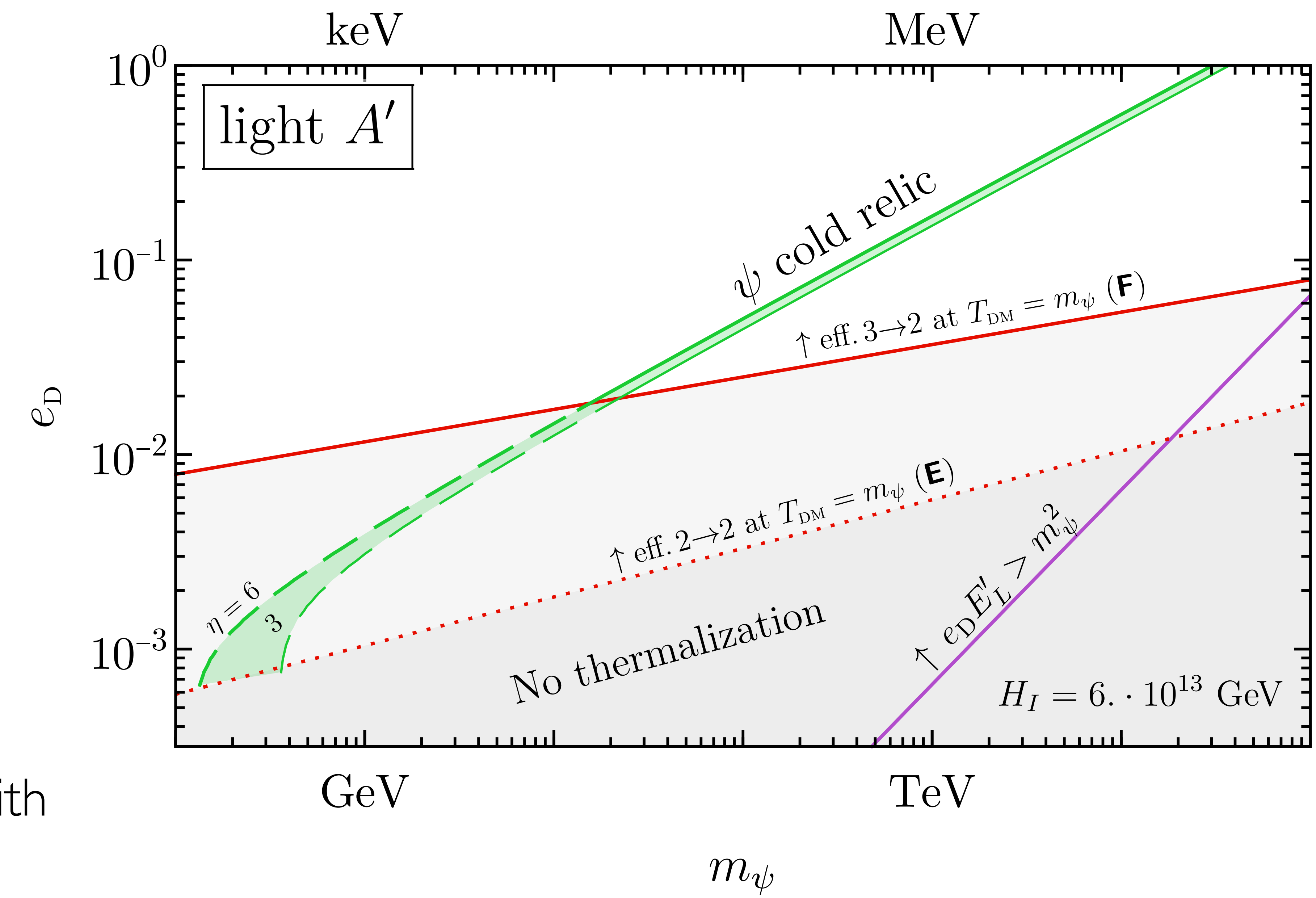
$$\rho_{\rm dark} \sim \eta^2 H^2 H_I^2$$

$$\rho_{\rm SM} \sim H^2 m_{\rm pl}^2$$

$$T_{\rm DS} \sim \sqrt{\frac{\eta H_I}{m_{\rm pl}}} T_{\rm SM}$$

- Standard freeze-out with $m_{\rm pl,eff} = \eta H_I$

$m_{A'} = 10^{-6} m_\psi$

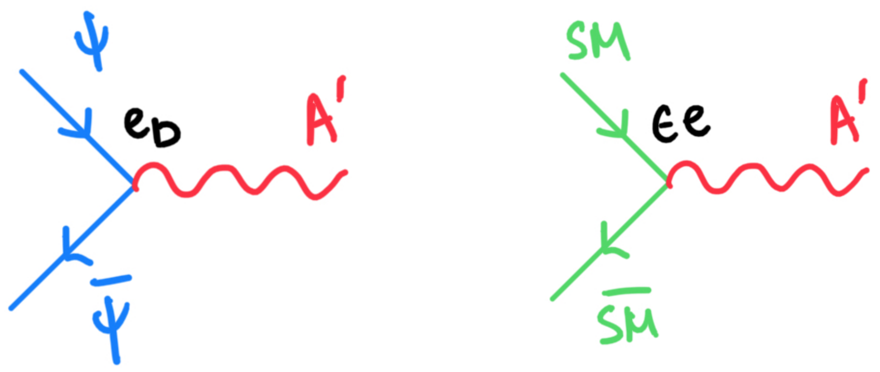


Signatures

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

- Galactic Halos
  - Self-Interactions can thermalize profile
  - Look for deviations
  - Does not constrain this mechanism now, but may in the future

- Kinetic Mixing
  - $\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$
  - Dark fermion - SM scattering
  - Look for it in Direct Detection



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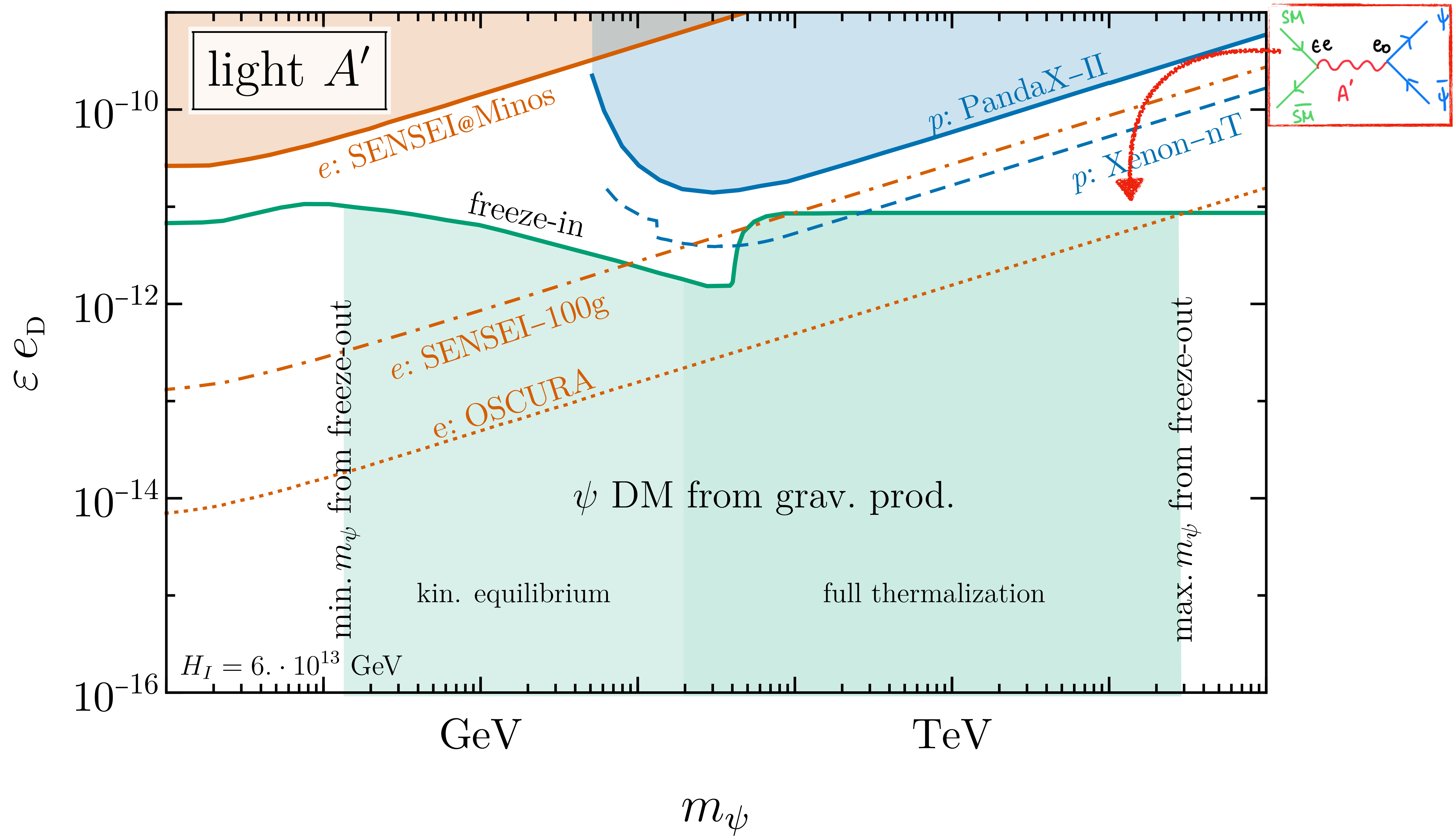


Summary

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

- Interactions can significantly affect the preferred parameter space of inflationary produced particles, **even if their free-theory abundances are negligible.**

- Dark QED not only **changes the DM candidate**, its mass is also **~10 orders of magnitude different** from the free theory predictions.

- The prediction of Dark QED is fermionic DM in the range
  - **500 MeV — 30 TeV**, for a light mediator
  - **O(200 MeV)**, for a heavy mediator

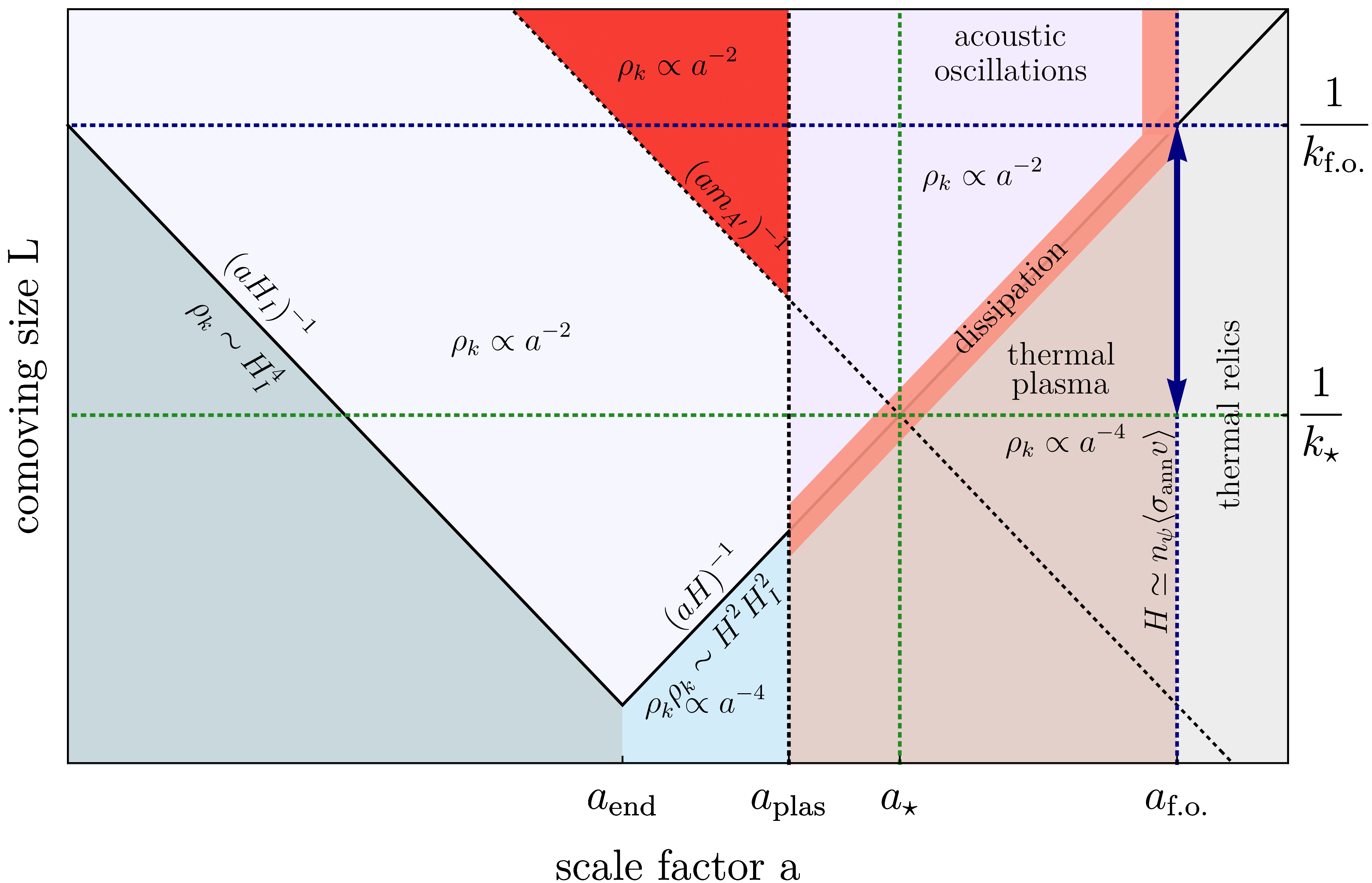
For the highest inflationary scale $H_I = 6 \times 10^{13}$ GeV

- Can look for in **Direct Detection** experiments even below freeze-in. Potential hint for inflation.

Backup

Dark QED from Inflation

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]



$H = m_{A'}$ no longer special

Fermions freeze-out

Su[illegible] Dissipation [illegible] collisions [illegible] Plasma [illegible]aters

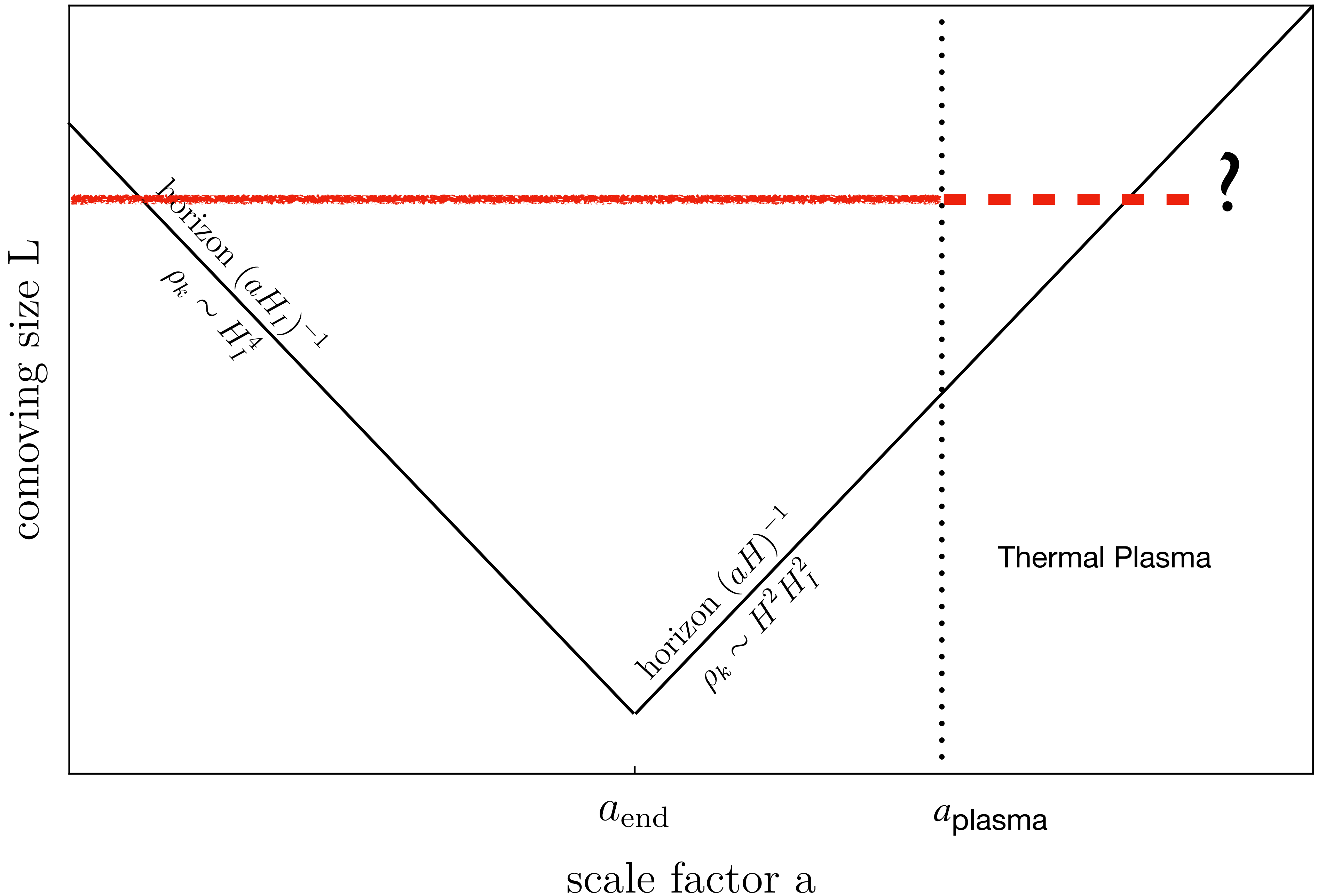
All contribute the same

All remaining SH modes become very damped

Logarithmic factor

Superhorizon modes

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]



Plasma Effects

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]

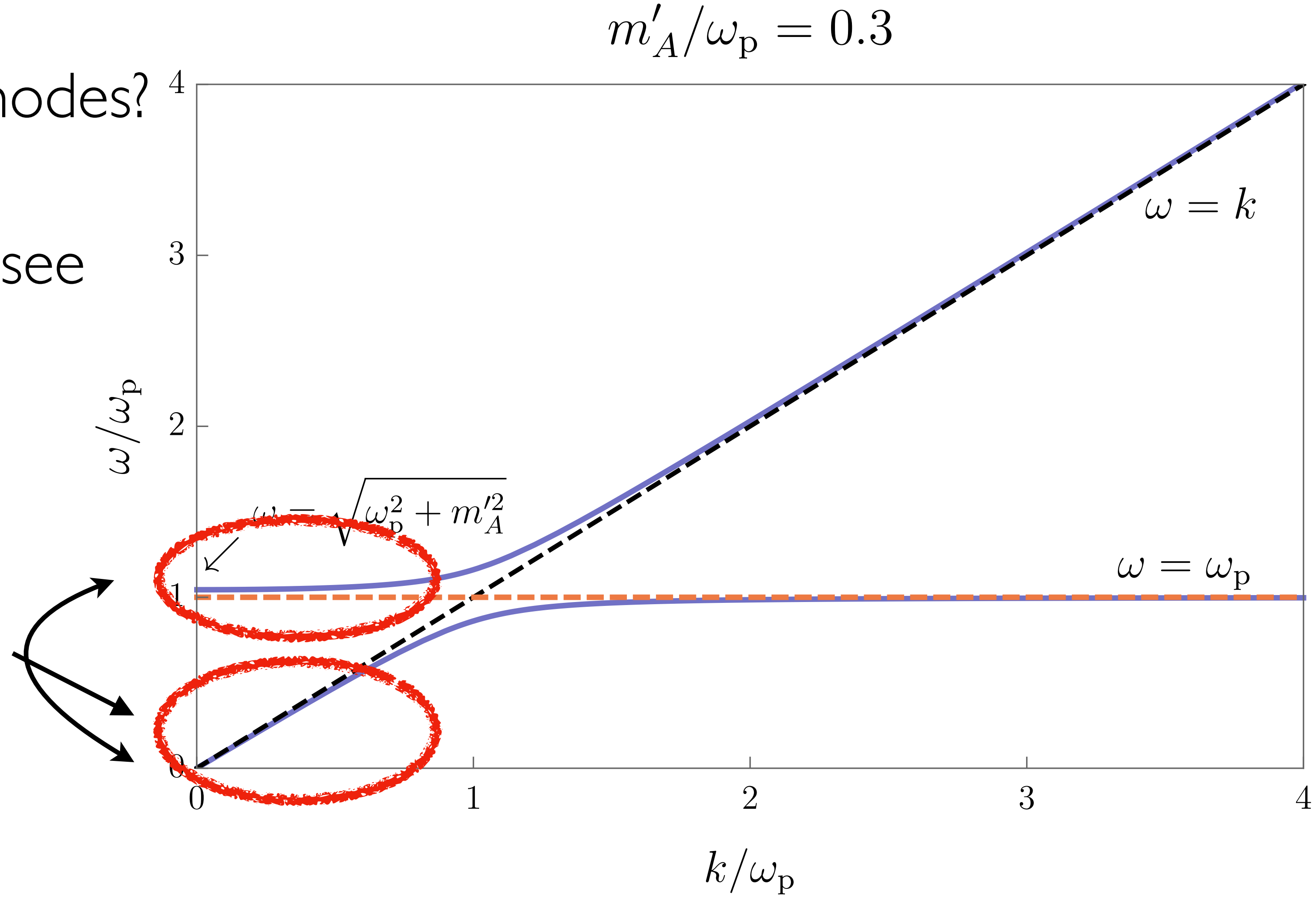
What happens to the rest of the modes?

- Remaining superhorizon modes see a Proca plasma

$$\omega_{\rm p} \sim e_{\rm D} T \gg m_{A'}$$

Which branch do we get?

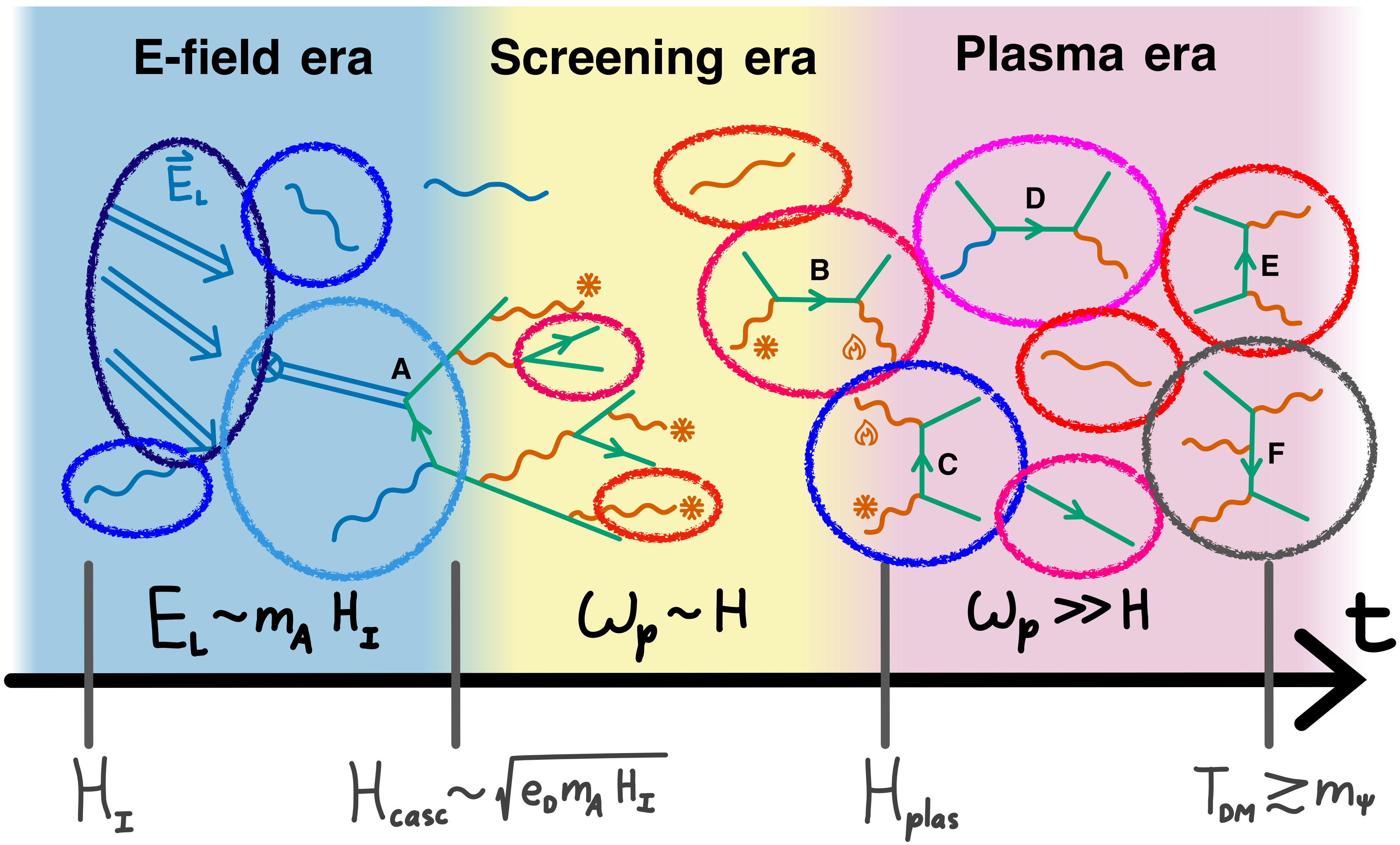
This one



- Initial Conditions: A_L is almost constant when produced
  - Proca EoM: $m^2_{A'} A'_L \simeq J$ Unique non-QED solution!
  - Solution can be found analytically in FRW
  - Mode oscillates when k enters the horizon

Towards thermalization

[Arvanitaki, Dimopoulos, **MG**, Racco, Simon, Thompson]



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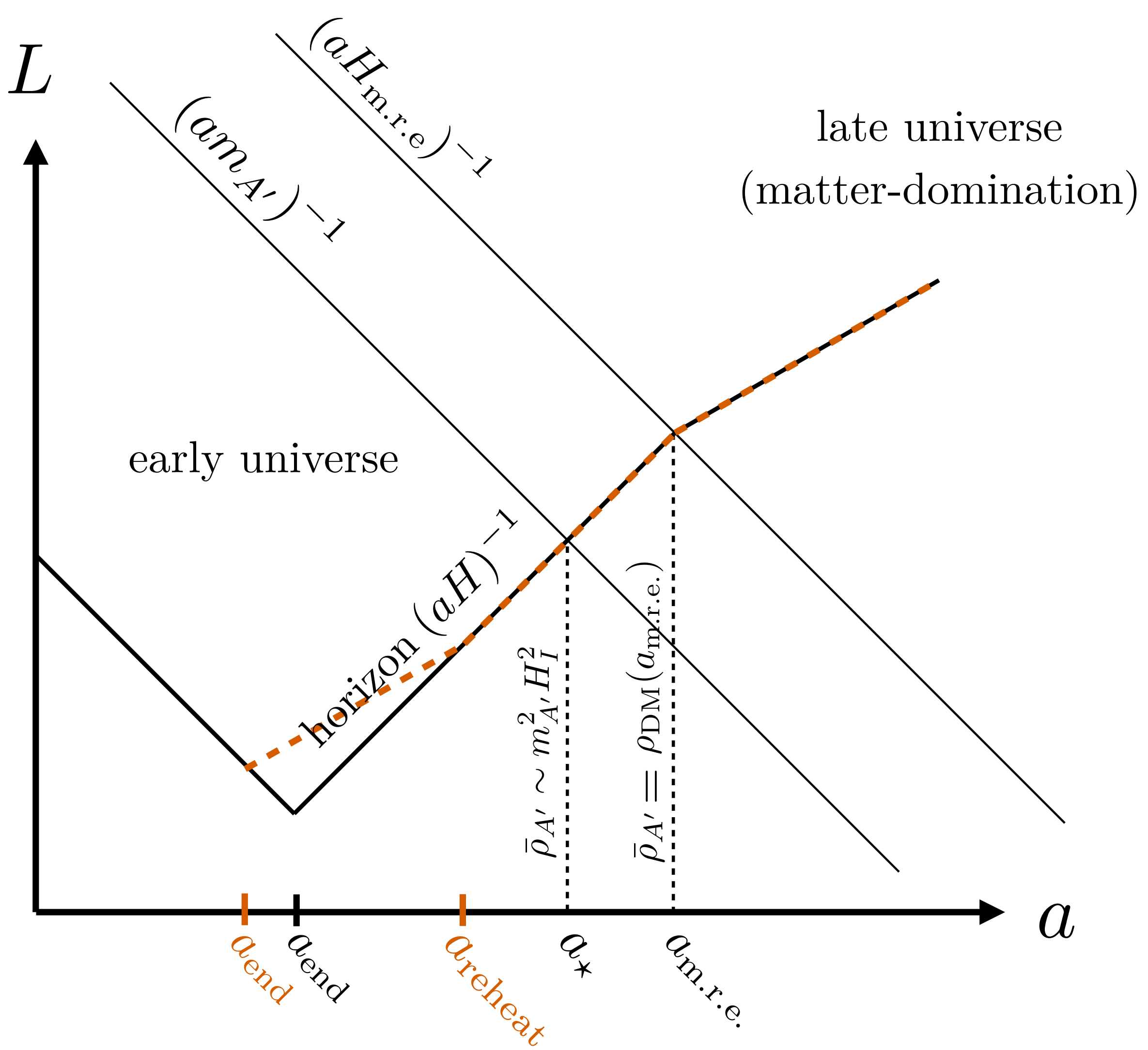
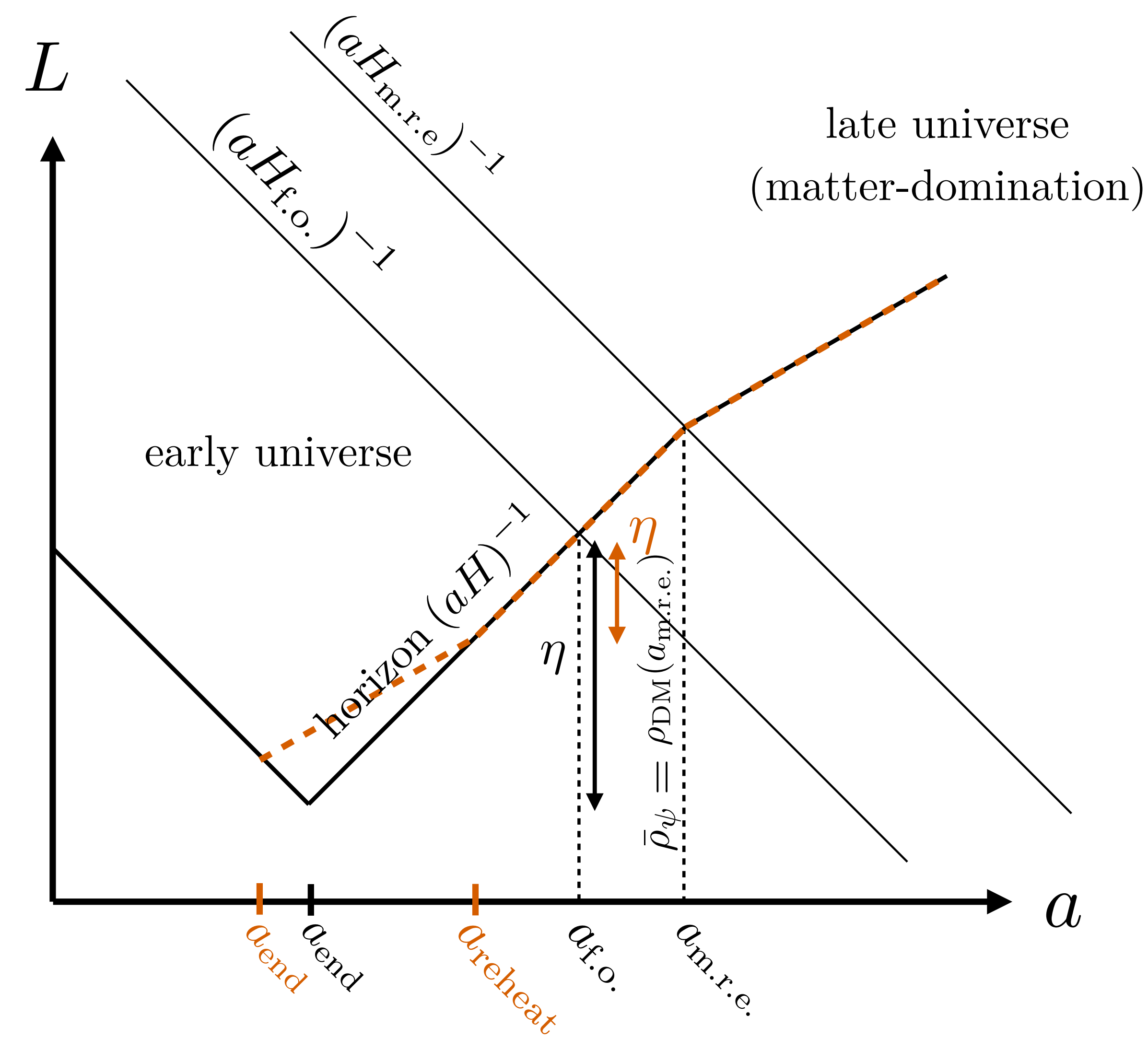
Effects of Reheating (I)





Effects of Reheating (II)

Gravitational Freeze-in dominates for instantaneous reheating

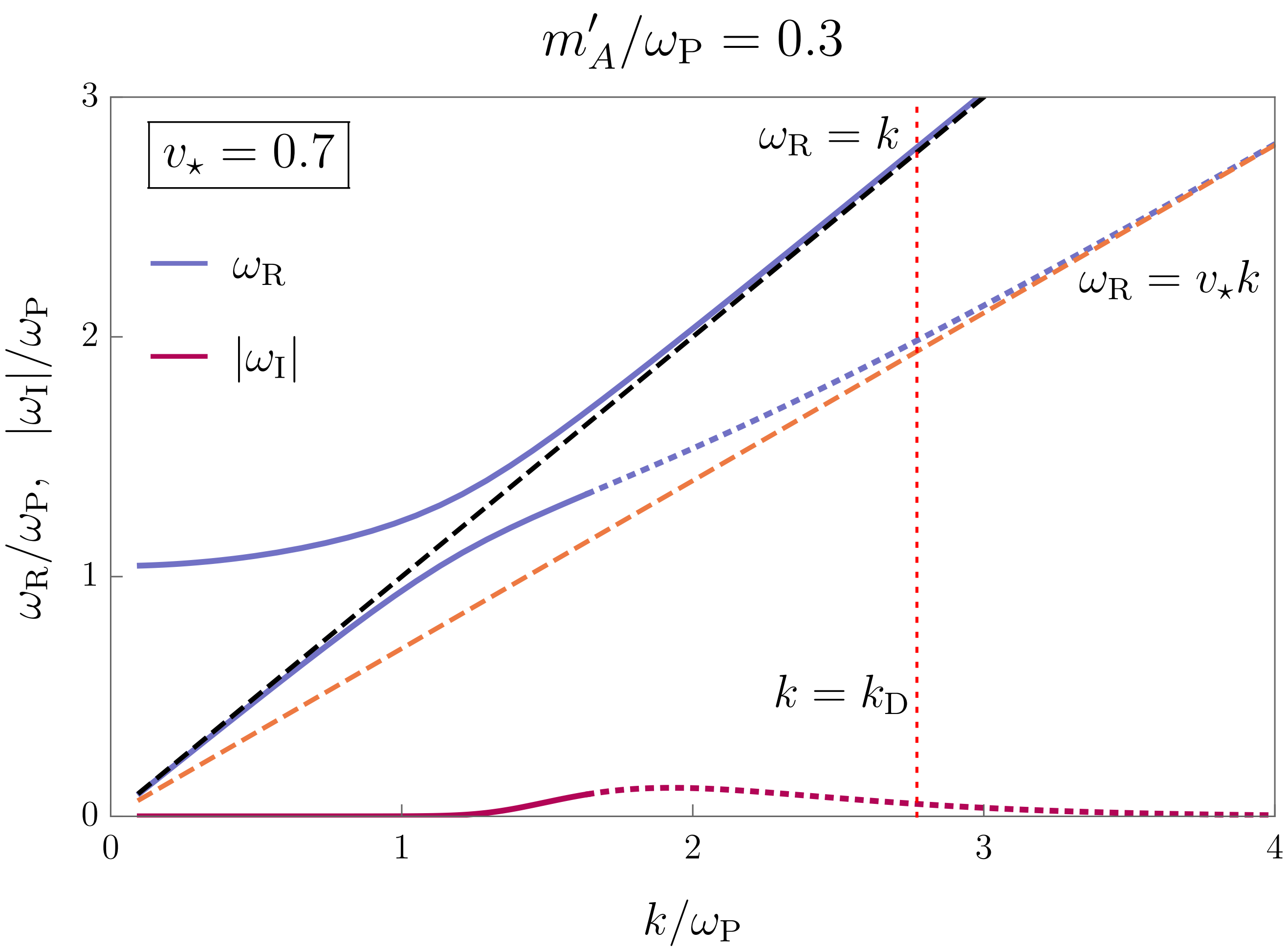
$$\frac{\rho_{\rm inj,gr}}{\rho_{\rm DS}} \simeq 0.24 \frac{T_{\rm rh}^3}{H_I^2 m_{\rm pl} \eta^2} \qquad \frac{T_{\rm rh}}{T_{\rm insta}} \simeq 0.54 \eta^{2/3} \left(\frac{H_I}{6 \times 10^{13}\ \rm GeV} \right)^{1/6}$$

About ~2 for η~6

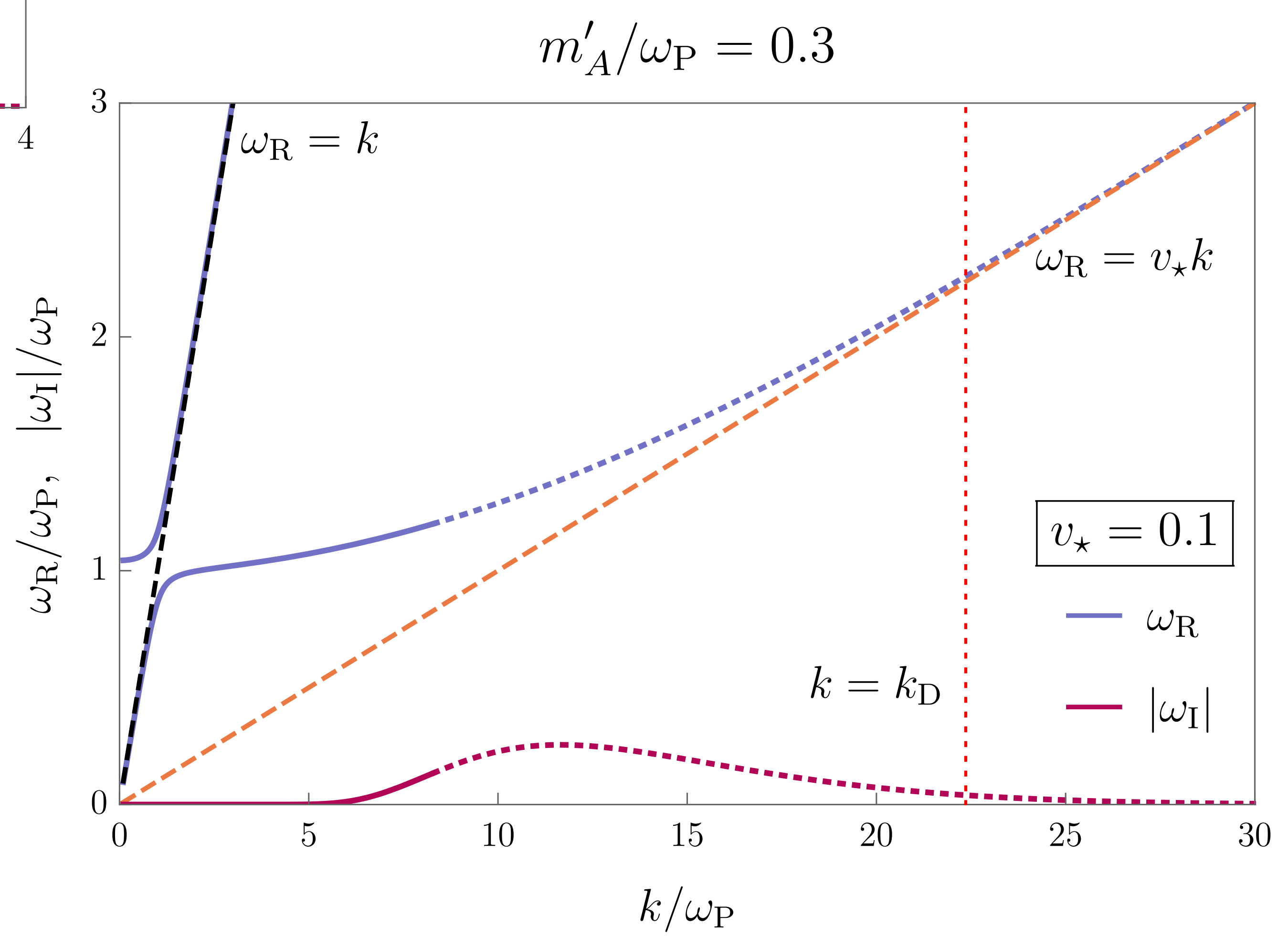
Direct Inflaton decays

$$\frac{m_\phi}{H_I} \lesssim 3 \times 10^{-2} \eta^2 \left(\frac{H_I}{\Gamma_\phi} \right)^{2/3} \qquad y \lesssim 7.1 \left(\frac{H_I}{m_\phi} \right)^{5/4} \quad \text{for Yukawa} \quad \Gamma_\phi = \frac{y^2 m_\phi}{8\pi}$$

Thermal effects

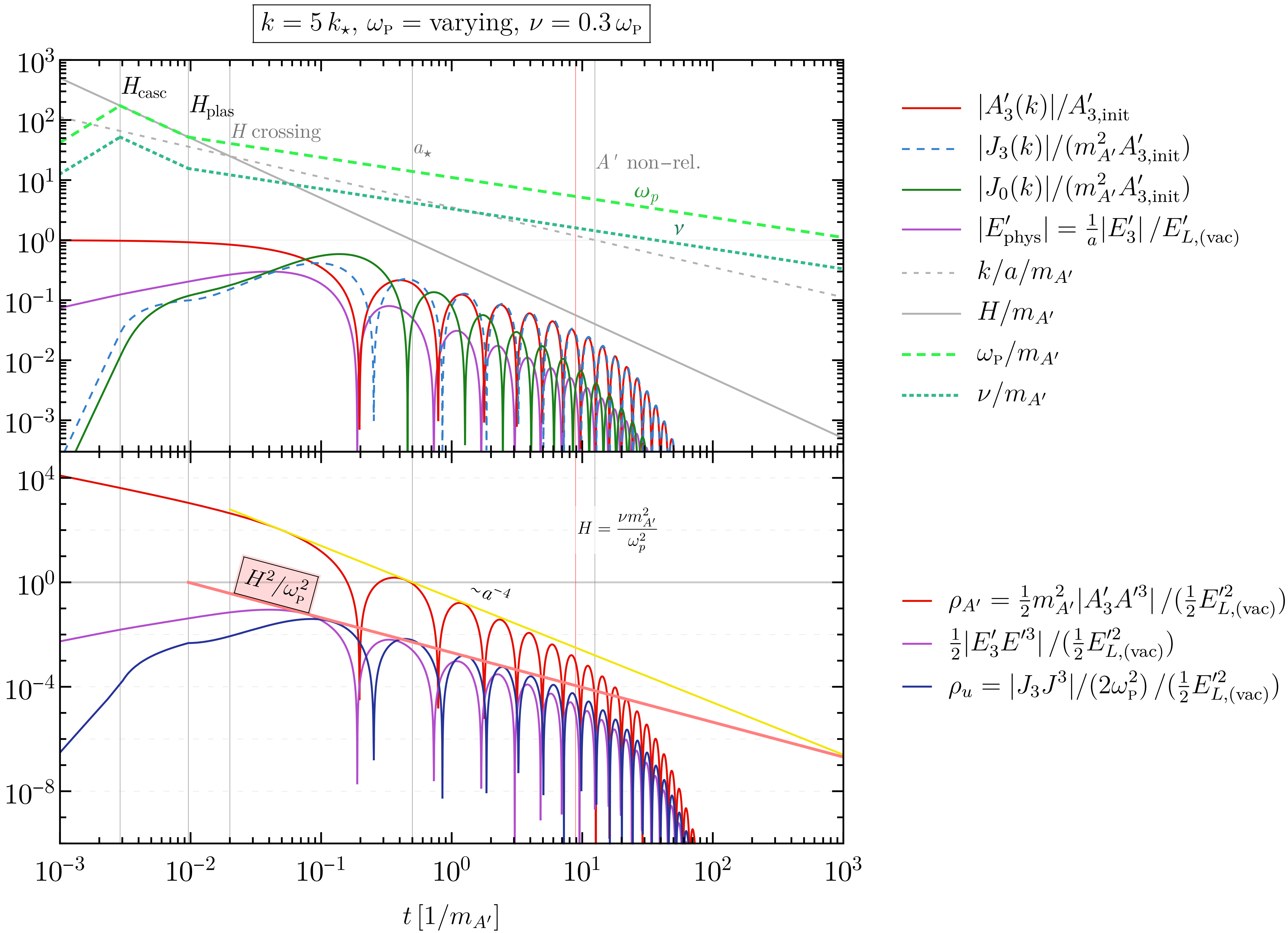


Dispersion relations in hot relativistic plasma



Plasma Effects

Time evolution before freeze-out



Plasma Effects

EoM to $\mathcal{O}(k^2)$

$$\partial_t^2 A_3' + H\left(1+\frac{2k^2}{m_{A'}^2 a^2}\right)\partial_t A_3' + \left(\frac{k^2}{a^2}+m_{A'}^2\right)A_3' = J_3 - 2H\frac{ik}{m_{A'}^2}J_0$$

$$\frac{\mathrm{d}J_3}{\mathrm{d}t} = -\omega_{\mathrm{P}}^2\left(1-\frac{k^2}{m_{A'}^2 a^2}\right)\partial_t A_3' + \omega_{\mathrm{P}}^2\frac{ik}{m_{A'}^2}J_0 + \frac{\dot{n}_\psi}{n_\psi}J_3$$

$$\partial_t J_0 + 3HJ_0 - \frac{ik}{a^2}J_3 = 0.$$

Zero momentum: $J_3(t) = -\omega_{\mathrm{p}}^2\left[A_3'(t) - A_3'(t_{\mathrm{init}})\right]$

Solution:

$$A_3'(t) = \frac{\omega_{\mathrm{P}}^2}{m_{A'}^2+\omega_{\mathrm{P}}^2}A'_{3,\mathrm{init}} + \mathcal{A}t^{1/4}J_{1/4}\left(t\sqrt{\omega_{\mathrm{P}}^2+m_{A'}^2}\right) + \mathcal{B}t^{1/4}Y_{1/4}\left(t\sqrt{\omega_{\mathrm{P}}^2+m_{A'}^2}\right)$$

Frozen!

Plasma Effects

Superhorizon to first order in momentum

$$\partial_t^2 J_3 + 3H\partial_t J_3 + \frac{k^2\omega_{\rm P}^2}{a^2(m^2+\omega_{\rm P}^2)} J_3 = 0$$

Oscillates when k enters

After fermion freeze-out

$$\ddot{\tilde{A}}_3 + \frac{1}{2\tau}\dot{\tilde{A}}_3 + \tilde{A}_3 = \left(\frac{\tau_{\rm np}}{\tau}\right)^{3/2}, \quad \tau > \tau_{\rm np}, \tag{E.14}$$

where dots denote derivatives with respect to τ. Since $H_{\rm np} \ll m_{A'}$, $\tau \gg 1$, so that this equation has the simple solution

$$\tilde{A}_3(\tau) = \left(\frac{\tau_{\rm in}}{\tau}\right)^{3/2} + \frac{3\sin(\tau-\tau_{\rm in})}{2\tau^{1/4}\tau_{\rm in}^{3/4}} - \frac{9\cos(\tau-\tau_{\rm in})}{64\tau^{5/4}\tau_{\rm in}^{3/4}}. \tag{E.15}$$

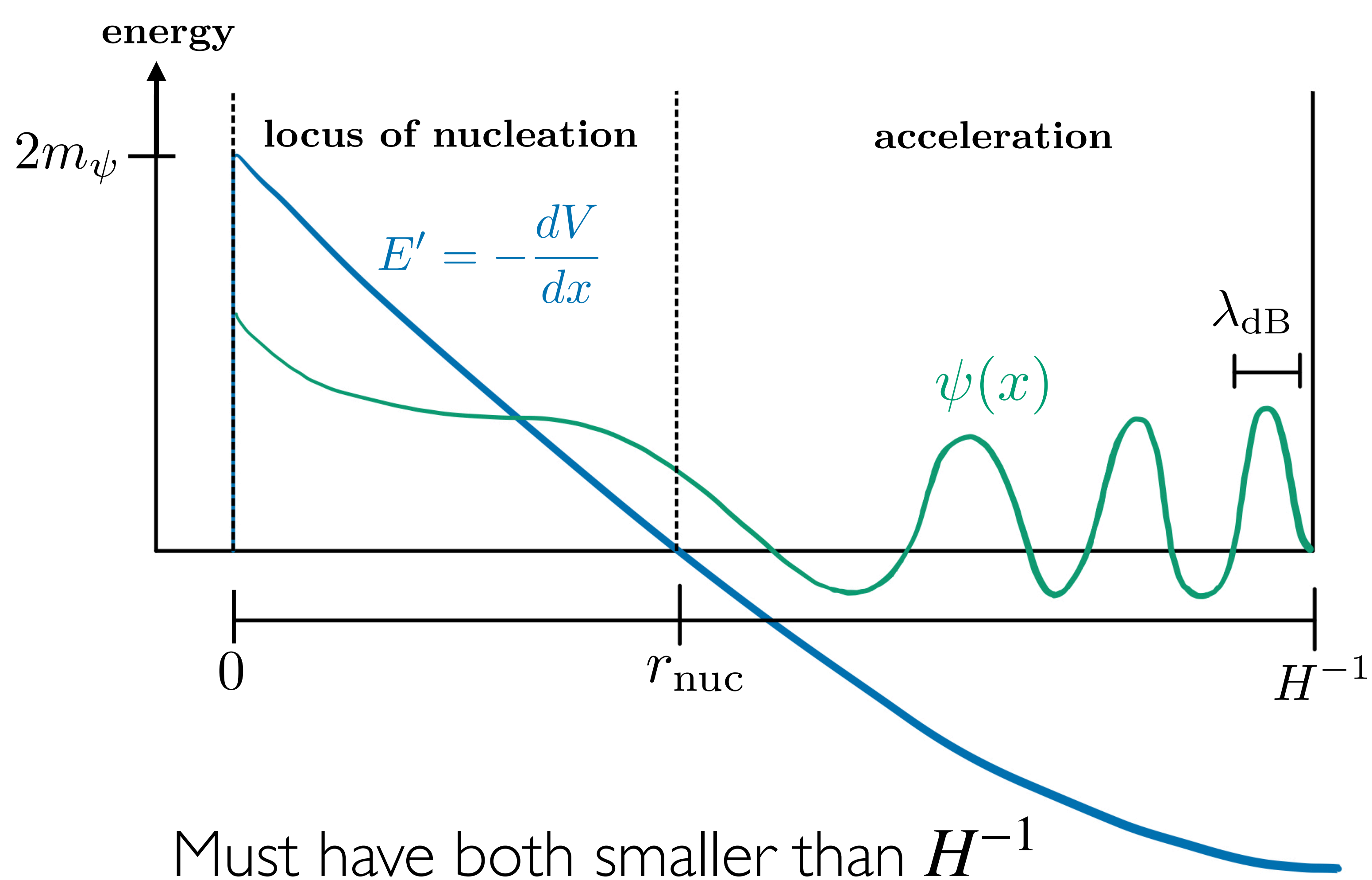
Back-reaction at horizon exit

Current observable: $$|J_{\rm phys}| = e_{\rm D}^2 H_I |E_{\rm phys}|^2 \log\left(\frac{H_I}{m_\psi}\right)$$

Back-reaction: $$\frac{|J_{\rm phys}||E_{\rm phys}|H_I^{-1}}{H_I^4} \sim e_{\rm D}^2 \left(\frac{m_{A'}}{H_I}\right)^2 \log\left(\frac{H_I}{m_\psi}\right)$$

Hayashinaka et al. (2016)

Strong Field QED



$$r_{\rm nuc} \simeq \frac{m_\psi}{e_{\rm D}|E'|}$$

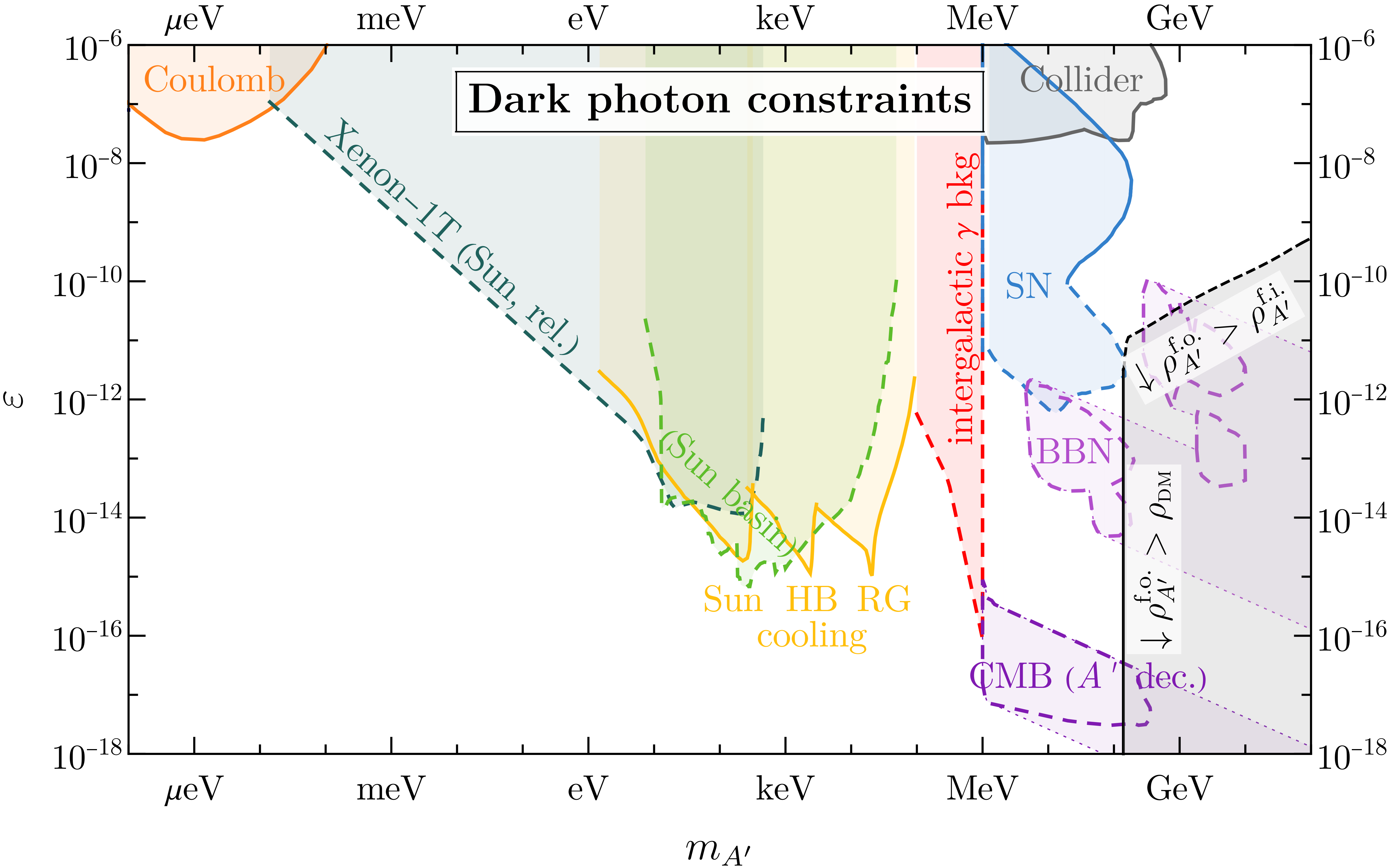
$$\lambda_{\rm dB} = \frac{H}{e_{\rm D}|E'|}$$

Must have both smaller than H^{-1}

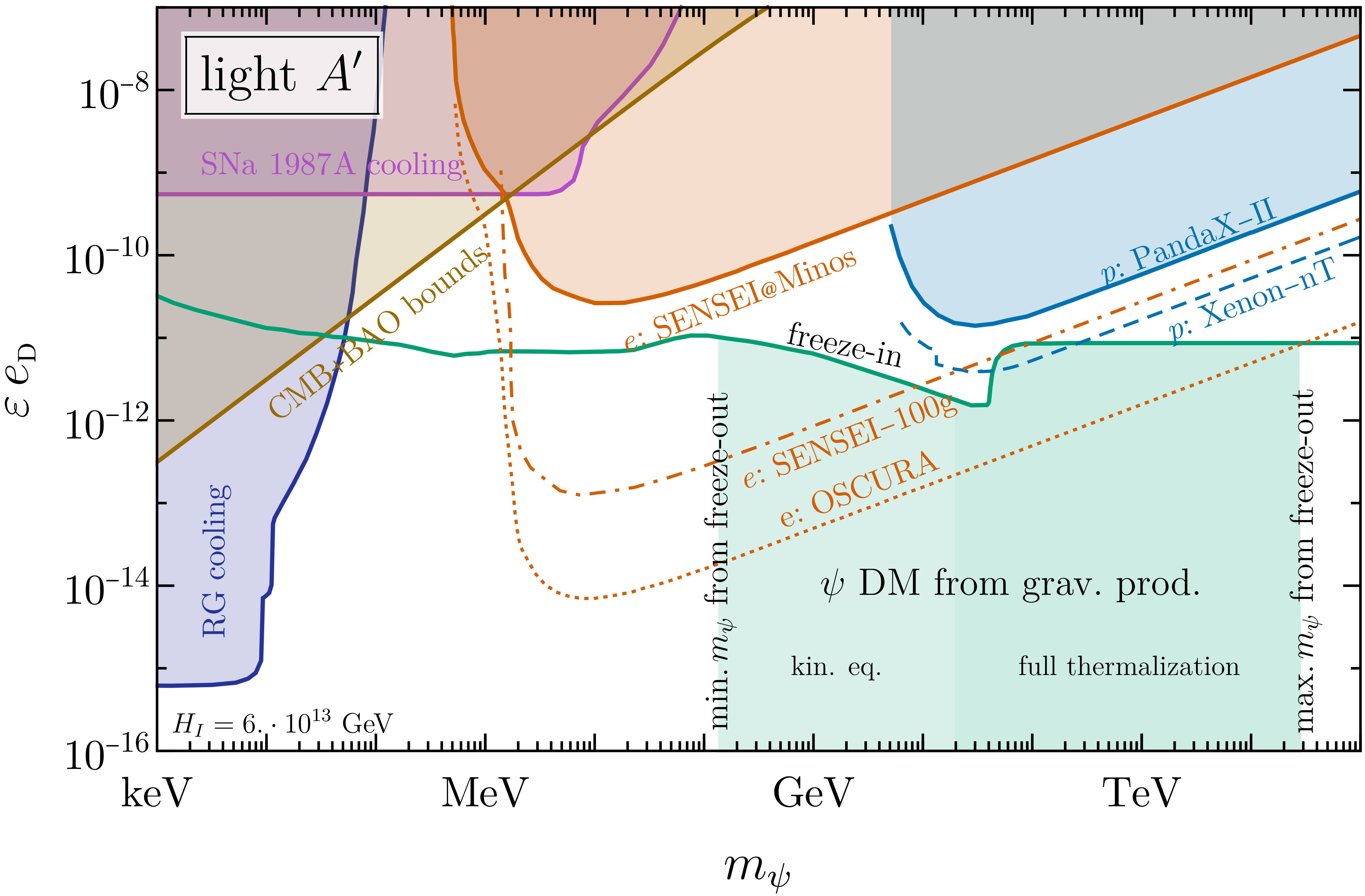
Below the mass of the fermion, the de Broglie requirement is stronger.

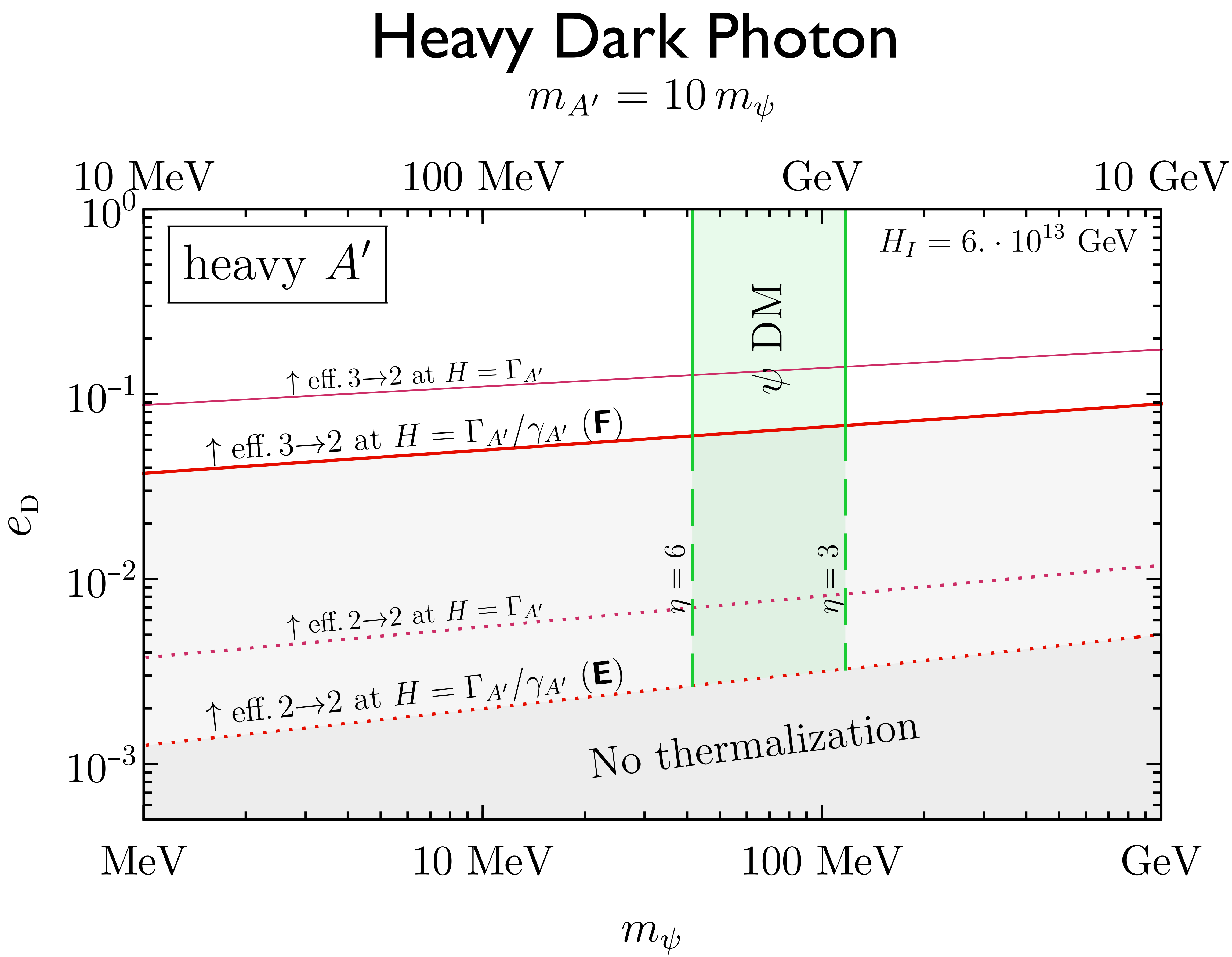
Coincidentally, that's when Strong Field processes become efficient anyway.

Photon Parameter Space



Wide Parameter Space





Heavy Dark Photon
$m_{A'} = 10\, m_\psi$
10 MeV
100 MeV
GeV
10 GeV
10^0
10^{-1}
10^{-2}
10^{-3}
heavy A'
$H_I = 6. \cdot 10^{13}$ GeV
ψ DM
↑ eff. 3→2 at $H = \Gamma_{A'}$
↑ eff. 3→2 at $H = \Gamma_{A'}/\gamma_{A'}$ (F)
↑ eff. 2→2 at $H = \Gamma_{A'}$
↑ eff. 2→2 at $H = \Gamma_{A'}/\gamma_{A'}$ (E)
$\eta = 6$
$\eta = 3$
No thermalization
e_D
MeV
10 MeV
100 MeV
GeV
m_ψ

Dependence on H_I

For lower H_I the total available energy drops

Equivalently, the Dark Sector is colder $$T_{\rm DS} \sim \sqrt{\frac{\eta H_I}{m_{\rm pl}}} T_{\rm SM}$$

Light Dark Photon: $m_\psi = (\eta H_I)^{-1/4}$

Heavy Dark Photon: $m_\psi = (\eta H_I)^{-3/2}$

Classical Stochastic Electric Field

$$F'_{0i} = \frac{m_{A'}^2 a^2}{k^2 + m_{A'}^2 a^2} \partial_0 A'_i.$$

The size of the physical dark electric field measured by a cosmological observer is

$$|\vec{E}'_{\rm phys}| = \frac{\sqrt{{F'_{0i}}^2}}{a}.$$

Power Spectrum $$\mathcal{P}_{E'_{\rm phys}}(k,a) \approx \frac{m'^2_{A'} H_I^2}{(2\pi)^2} \times \begin{cases} k^2/a^2H^2, & k/a < H, \\ a^2H^2/k^2, & k/a > H. \end{cases}$$

Coherence length $k \sim aH$

The amplitude is constant and the direction is random.

$$\langle E'^2_{\rm phys}(a) \rangle \approx \frac{m_{A'}^2 H_I^2}{(2\pi)^2} \left(\int_{-\infty}^{\ln(aH)} d\ln k \frac{k^2}{a^2H^2} + \int_{\ln(aH)}^{\infty} d\ln k \frac{a^2H^2}{k^2} \right) = \frac{m_{A'}^2 H_I^2}{(2\pi)^2}.$$

SFQED

$$\mathcal{W}_{\text{Schwinger}} \sim e_{\text{D}}^2 |\vec{E}'|^2 \exp\left(-\frac{\pi E'_{\text{crit}}}{|\vec{E}'|}\right) \qquad E'_{\text{crit}} \equiv \frac{m_\psi^2 c^3}{e_{\text{D}} \hbar} = \frac{m_\psi c^2}{e_{\text{D}} \lambda_{\text{C}}};$$

$$W_{\text{pair}} \sim \frac{\alpha_{\text{D}} m_\psi^2}{\omega_{A'}} \cdot \begin{cases} \chi \exp\left(-\frac{8}{3\chi}\right), & \chi \ll 1, \\ \chi^{2/3}, & \chi \gg 1. \end{cases}$$

$$W_{\text{rad}} \sim \frac{\alpha_{\text{D}} m_\psi^2}{\omega_\psi} \cdot \begin{cases} \chi, & \chi \ll 1, \\ \chi^{2/3}, & \chi \gg 1. \end{cases}$$

$$\chi = \frac{\sqrt{-f^\mu f_\mu}}{E'_{\text{crit}}} \gtrsim 1 \qquad \sqrt{-f^\mu f_\mu} = \frac{1}{m_\psi} \sqrt{\frac{1}{a^2} (p^0 \vec{E}' + \vec{p} \times \vec{B}')^2 - (\vec{E}' \cdot \vec{p})^2} = |\vec{E}'_{\text{rest}}|$$