

Taming the dark photon production via a non-minimal coupling to gravity

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Response to Capanelli et al., PRL 133 (2024)

Outline

PART 1: THE PROBLEM

- Dark photons with non-minimal couplings
- Runaway production [Capanelli et al. 2024]

PART 2: UV COMPLETION

- Unitarity constraints
- Scalar coupling (ξ_1) & Tensor coupling (ξ_2)
- Universal bound: $|\xi_i| \ll m_a^2/H^2$

PART 3: RESOLUTION

- Numerical analysis with Claude AI
- Runaway = EFT breakdown artifact

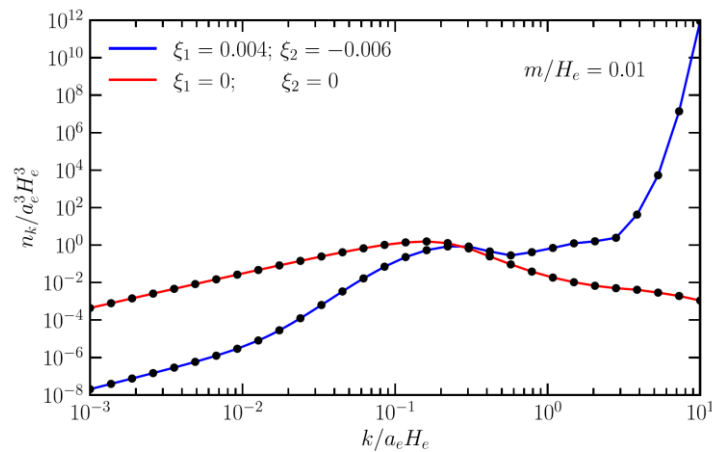
Dark Photon with Non-Minimal Couplings

- Action: $S = \int d^4x \sqrt{|g|} \left(-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_A^2 g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_1 R g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_2 R^{\mu\nu} A_\mu A_\nu \right)$
 - ξ_1, ξ_2 : Non-minimal couplings (required by EFT)
 - Time-dependent effective masses

$$m_t^2 = m_A^2 - \xi_1 R - \frac{1}{2} \xi_2 R - 3\xi_2 H^2,$$

$$m_x^2 = m_A^2 - \xi_1 R - \frac{1}{6} \xi_2 R + \xi_2 H^2.$$
- Important for particle production during inflation

The Runaway Problem



Capanelli et al., Runaway Gravitational
Production of Dark Photons, PRL 133 (2024)

- High-momentum modes: explosive growth
- Tens of orders of magnitude increase
- Ghost, gradient, superluminal instabilities observed

Conclusion: "No obvious solution"

Is this a fundamental problem?

Our Approach

- Observation:
 - Couplings ξ_1, ξ_2 come from effective theory
 - Must examine UV completion
- Strategy:
 - Build UV-complete models
 - Derive constraints on couplings
 - Examine production within the allowed parameter space
- Does runaway persist in fundamental theory?

Unitarity Constraint

- Process: $AA \rightarrow GG$ (dark photon \rightarrow gravitons)
- High-energy amplitude: $|\mathcal{A}| \propto |\xi_{1,2}| \frac{E^4}{m_A^2 M_{\text{Pl}}^2}$
- Perturbative unitarity breaks down at: $p_{\text{max}} \lesssim \frac{\sqrt{m_A M_{\text{Pl}}}}{|\xi_{1,2}|^{1/4}}$
- Critical observation: $p_{\text{max}} \rightarrow 0$ as $m_A \rightarrow 0$
 $\Rightarrow \xi_i \rightarrow 0$ (required by gauge invariance!)
 $\Rightarrow \xi_i$ cannot be fundamental constants

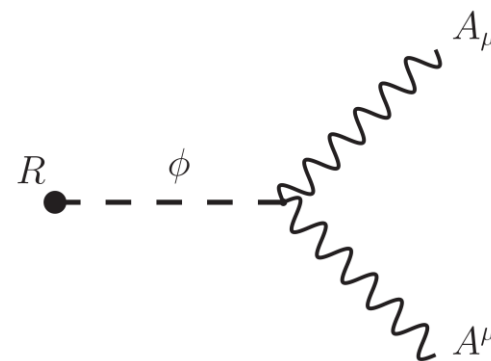
UV Completion 1: Scalar Coupling

- Setup: $\mathcal{L}_{sc} = \overline{D_\mu \Phi} D^\mu \Phi - \frac{1}{2} \xi R |\Phi|^2 - V(\Phi)$

- Higgs mechanism:

$$\langle \Phi \rangle = v/\sqrt{2} \rightarrow m_A = gv$$

Physical scalar mass: m_s



- Integrate out heavy scalar ($m_s \gg p$) $\Rightarrow \mathcal{L}_{\xi_1} = -\frac{1}{2} \xi \frac{m_A^2}{m_s^2} R A_\mu A^\mu$, $\xi_1 = \xi \frac{m_A^2}{m_s^2}$

- Validity conditions:

- Momentum: $p \ll m_s$

- Curvature: $|\xi R|/2 \ll m_s^2$

- During inflation ($R = -12H^2$): $|\xi_1| \ll \frac{1}{6} \frac{m_A^2}{H^2}$

UV Completion 2: Tensor Coupling

- 5D Kaluza-Klein model: $S = \int d^5x \frac{1}{\hat{\kappa}^2} \sqrt{|\hat{g}|} \hat{R} + \int d^5x \sqrt{|\hat{g}|} \mathcal{L}_{\text{mat}} \delta(x_5)$
 - Extra dimension compactified (radius r)
 - massive KK graviton modes
 - Localized gravity term with parameter ϵ

$$S_{\text{loc}} = \epsilon \int d^5x \frac{1}{\kappa^2} \sqrt{|\hat{g}|} R(\hat{g}_{\mu\nu}) \delta(x_5)$$

- Integrate out KK modes $\Rightarrow \mathcal{L}_{\xi_2} \simeq -\epsilon \frac{m_A^2}{m_1^2} R_{\mu\nu} A^\mu A^\nu$, $\xi_2 = 2\epsilon \frac{m_A^2}{m_1^2}$

- Validity: $p \lesssim m_1$ (below KK scale) $p_{\text{max}} \lesssim \frac{m_A}{\sqrt{|\xi_2|}}$

- Same constraint: $|\xi_{1,2}| \ll \frac{m_A^2}{H^2}$

$$M_{\text{Pl}}^2/2 = r/\hat{\kappa}^2 + \epsilon/\kappa^2$$

$$\hat{g}_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu} + \dots$$

$$h_{\mu\nu}(x, x_5) = \sum_n h_{\mu\nu}^n(x) \exp\left(i \frac{2\pi n x_5}{r}\right)$$

$$m_n = 2\pi n/r$$

Universal Pattern

- Form-factor behavior in ANY UV completion:
where M = mass of integrated-out state $\xi_i \propto \frac{m_A^2}{p^2 - M^2 + \mathcal{O}(H^2)}$
- High-energy behavior: $\xi_i(p) \rightarrow m_A^2/p^2$ (NOT constant!)
- Universal Constraint: for ξ_i constant from $p = 0$ to $p \sim H$: \rightarrow Require $M \gg H$
- $|\xi_i| \ll m_A^2/H^2$
- This is STRONGER than unitarity bound!

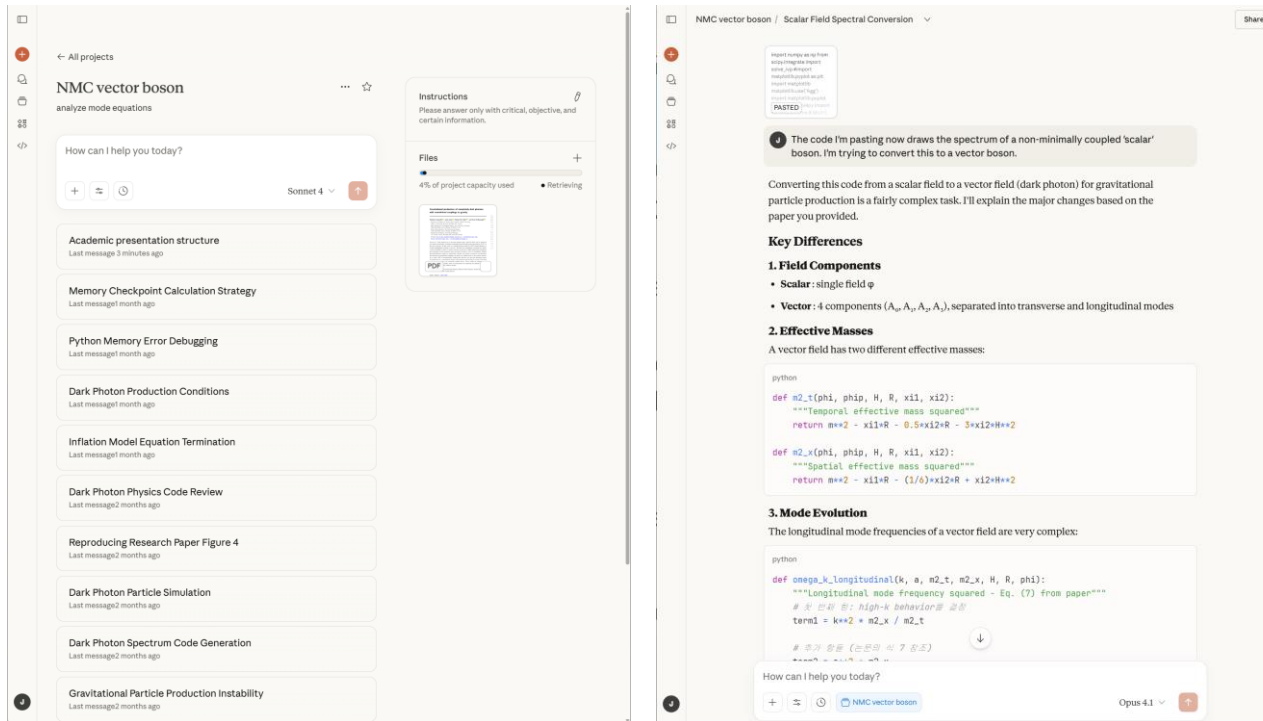
Numerical Verification

- Reproduce the known results + EFT validity boundary
- Modern computational tools:
 - AI-assisted development
 - High-performance computing
- Leveraging state-of-the-art technology

AI-Assisted Programming

- Large Language Models (LLMs):
 - Conversational AI trained on code and text
 - (e.g., ChatGPT, Claude, Gemini)
- Key capability: Natural language \leftrightarrow Code translation
- We used Claude AI by Anthropic

Conversational Programming



※ translated into English

- Starting point:
"The code I'm pasting now draws the spectrum of a non-minimally coupled 'scalar' boson. I'm trying to convert this to a vector boson."
- Equation modifications
- Implementation guidance
- Working solver
- Physics problem → Code through dialogue

- Process: Problem → AI suggestion → Test → Refine → Problem ..(×100s)

NMC vector boson / Dark Photon Production Conditions

No, you idiot. Then there will be nodes that don't calculate.

Oh, right! I thought that was stupid.

today:

- 4 nodes × 64 processes = **256 processes**
- k value 256 → each process is responsible for 1

If you set mpiprocs=32:

- 4 nodes × 32 processes = **128 processes**
- k value 256 → 2 per process, **but only 32 cores are used on each node**
- **The remaining 32 cores are idle!**

Correct solutions:

1. Reduce the number of k values

```
python  
  
k_values = np.linspace(-3, 1, 128) # 256개 → 128개  
# 그러면 256로 나눠서 128개 k값을 나눠서 처리
```

2. Code memory optimization

```
python  
  
# tolerance 문제로 메모리 사용량 줄이기  
rtol=1e-8, atol=1e-10  
  
# 시간 절약 줄이기  
[0, 400000] # 700000 대신
```

3. Reduce the phi0 value

```
python  
  
phi0 = 2.3 # 2.5 대신 조금 줄이기
```

I think reducing the number of k values to 128 would be the cleanest solution!

Retry

No, you idiot, the value of k can't be less than the number of processes.

Oh, right! I was so confused.

Current situation:

- 256 MPI processes
- 16 k values (`np.linspace(-3, 1, 16)`)

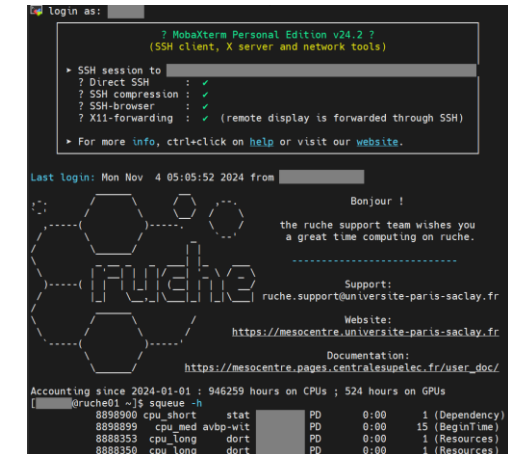
How can I help you today?

Caveats

- Important notes:
 - ⚠ AI has randomness and makes mistakes
 - ⚠ Physics understanding required
 - ⚠ Tool to accelerate, not replace thinking
- Critical thinking + AI = Efficient workflow

High-Performance Computing

- the use of supercomputers and computer clusters to solve advanced problems (wikipedia)
- Independent equations for each k
→ All solved simultaneously
- High-resolution spectrum efficiently
- ruche cluster (Paris-Saclay), Nurion (KISTI), ...



```
login as:
? MobaXterm Personal Edition v24.2 ?
(SSH client, X server and network tools)

> SSH session to :
? Direct SSH :
? SSH compression :
? SSH-browser :
? X11-forwarding : (remote display is forwarded through SSH)

> For more info, ctrl+click on help or visit our website.

Last login: Mon Nov 4 05:05:52 2024 from
Bonjour !
the ruche support team wishes you
a great time computing on ruche.

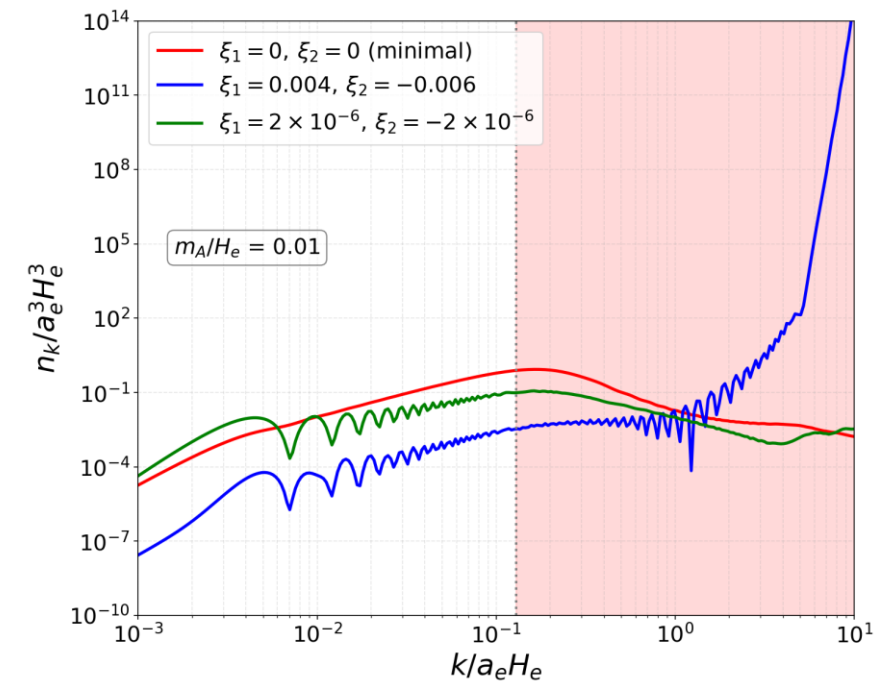
Support:
ruche.support@universite-paris-saclay.fr
Website:
https://mesocentre.universite-paris-saclay.fr
Documentation:
https://mesocentre.pages.centralsupelec.fr/user_doc/

Accounting since 2024-01-01 : 946259 hours on CPUs ; 524 hours on GPUs
[~] ruche01 ~$ squeue -h
      8898900 cpu_short      stat      PD      0:00      1 (Dependency)
      8898899 cpu_med avbp-wit PD      0:00     15 (BeginTime)
      8888353 cpu_long      dort      PD      0:00      1 (Resources)
      8888350 cpu_long      dort      PD      0:00      1 (Resources)
```



Numerical Results

- Reproduced Capanelli et al. ($\xi_1=0.004$, $\xi_2=-0.006$): Runaway confirmed
- Our addition - EFT validity boundary:
 $p > m_A / \sqrt{|\xi_2|} \simeq 0.1 H_e$
 \rightarrow Runaway occurs OUTSIDE valid regime!



Physical Interpretation

- What's really happening?
- Effective theory approach:
 - Assume $\xi_i = \text{constant}$
 - Extrapolate to high k
 - Find runaway production
- UV-complete theory:
 - $\xi_i(k) \propto 1/k^2$ (form-factor)
 - Already decreasing at high k
 - Runaway suppressed

⇒ The runaway is an ARTIFACT

⇒ Not real physics, but EFT breakdown signal

Conclusions

- Key insight: Non-minimal couplings must come from UV completion
→ Form-factor behavior $\xi_i(k) \propto 1/k^2$
- Universal constraint: $|\xi_i| \ll m_A^2/H^2$
- Runaway appears only where EFT breaks down
- Dark photon production with non-minimal couplings is theoretically consistent