The Impact of Plasma Non-Linearities on Dark Matter Searches

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1 Line

Heating A Plasma is Hard

Dark Photon Dark Matter

1) Well Motivated

- **Common in any extra dimensional theory**
- **We've seen massive vectors before**

2) Very restricted interactions - Kinetic Mixing

- **Acts like a photon but with a smaller α**

What does it look like?

Dark Photon Dark Matter

- **Dark Matter is non-relativistic (it's clumped up)**

$$v_{\text{now}} \sim 10^{-3}$$

- **A massive vector at rest is all Electric field**

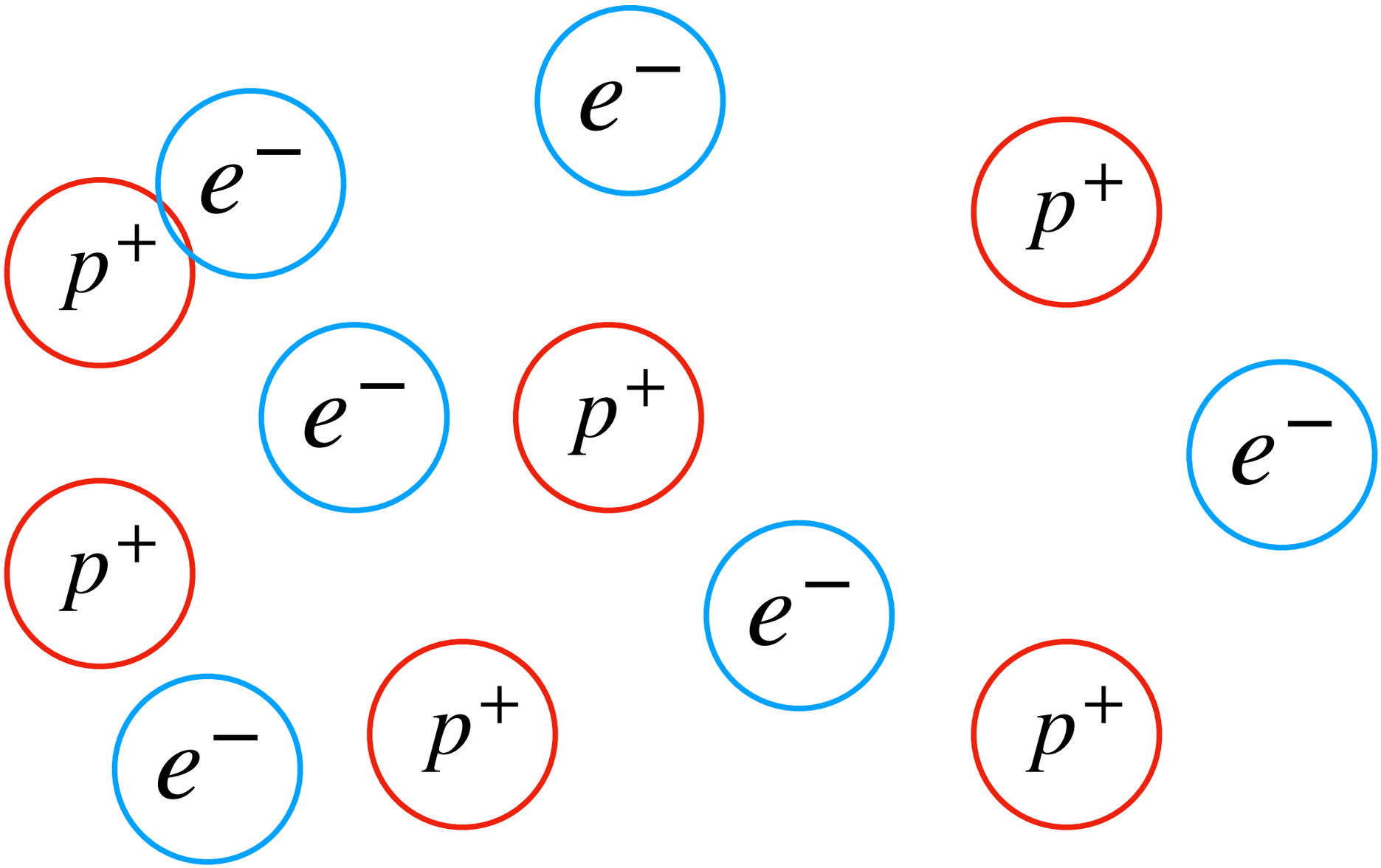
$$\vec{E} = E_0 \cos\left(m_{DM} t\right) \hat{u}$$

What does it look like?

Looking for dark matter is as simple as looking for an oscillating electric field!

E.g. A leading experimental proposal is using a (very good) antenna to look for this E field

Early Universe Plasma



Early Universe Plasma

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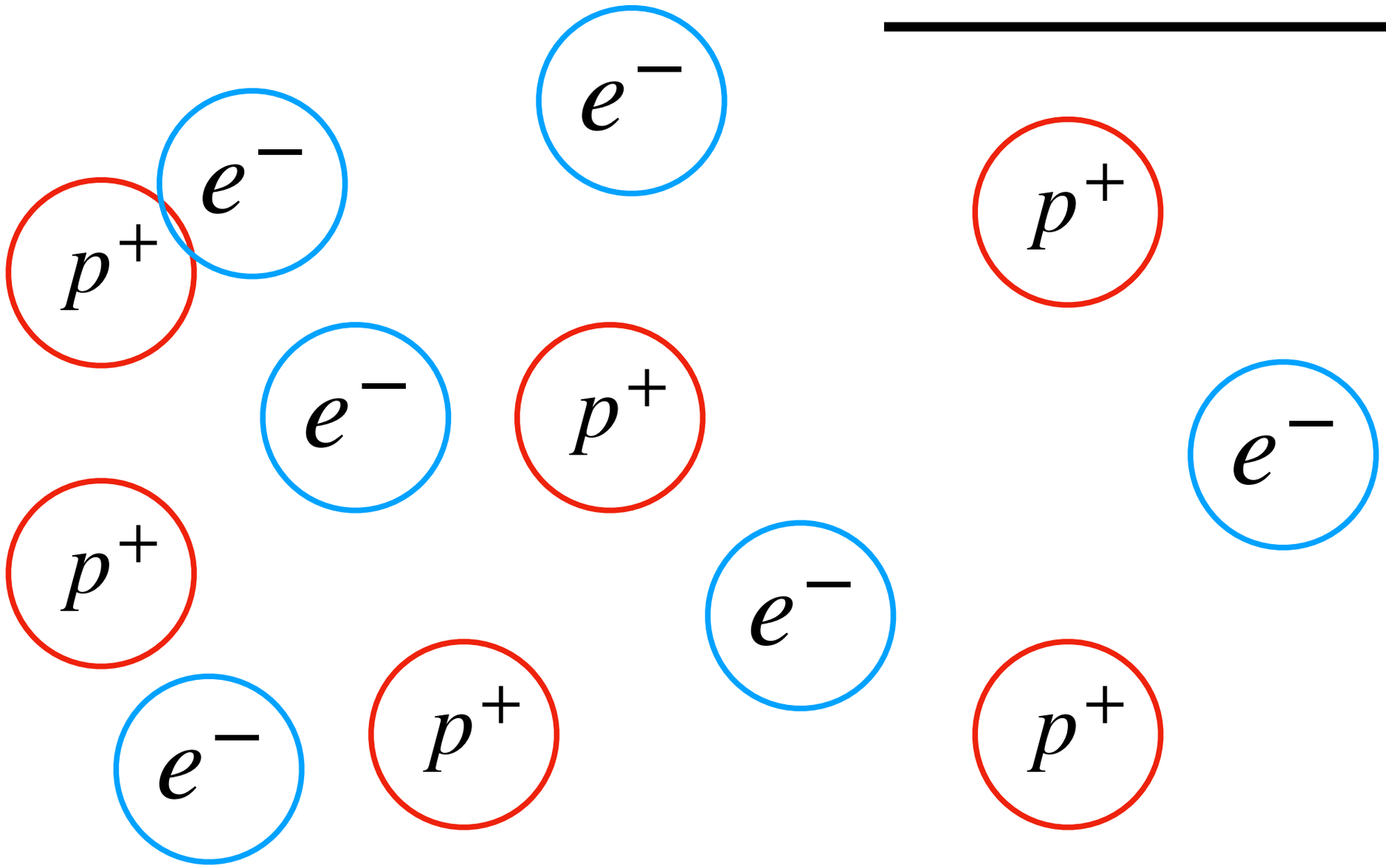

Early Universe Plasma

Famously plasmas oscillate at plasma frequency

Like a swing, if frequencies match the amplitude grows a lot!

Early Universe Plasma

Too much energy in plasma and model is excluded

μ and y distortions - $\Delta\rho \lesssim 10^{-4,-5}\rho_\gamma$

If the plasma frequencies match, inject energy until the above occurs and you are excluded!

Early Universe Plasma

Too much energy in plasma and model is excluded

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If the plasma frequencies match, inject energy until the above occurs and you are excluded!

Non-linearities push you off resonance when

$$\Delta\rho \sim \rho_{e^-}^{K.E.} \sim 10^{-10}\rho_\gamma$$

Early Universe Plasma

A swing

$$\partial_t^2\phi + \omega^2 \sin\phi \approx \partial_t^2\phi + \omega^2\phi - \lambda\phi^3 = J\cos(\omega t)$$

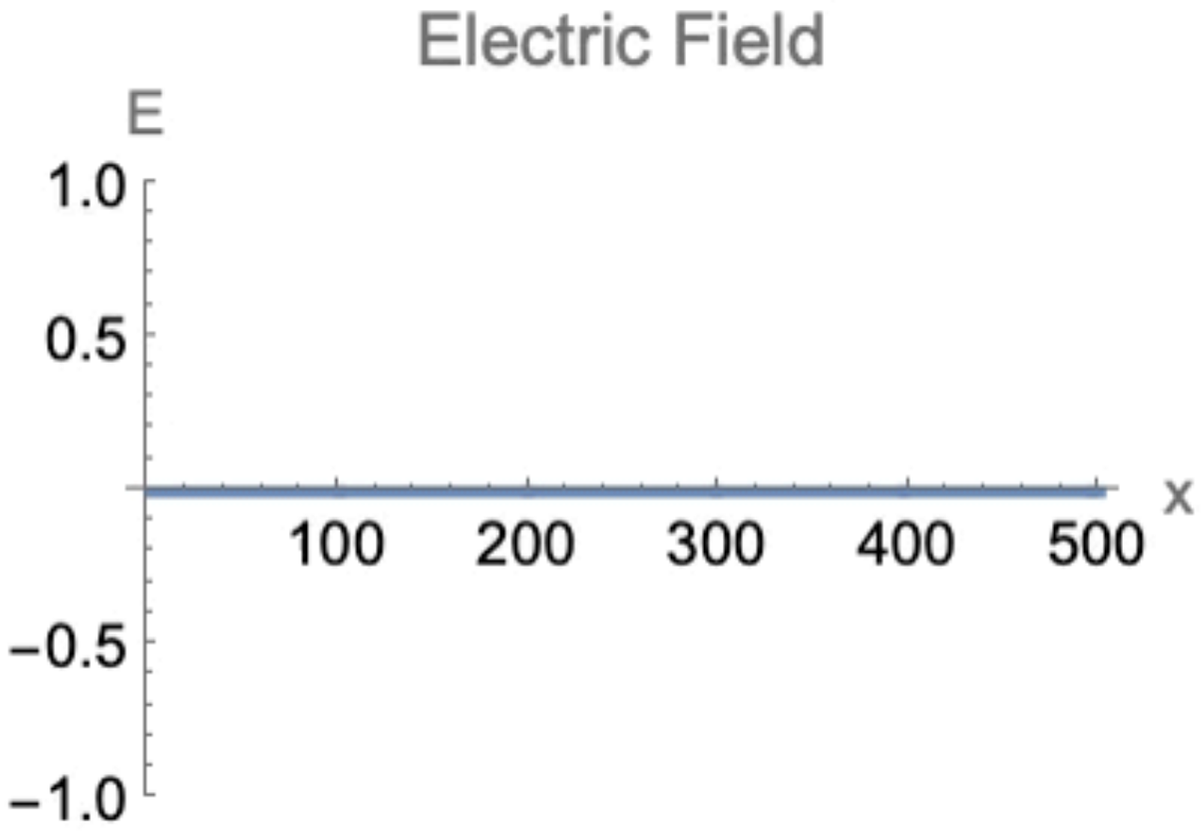
ϕ grows linearly with time until it goes off resonance because of non-linear term

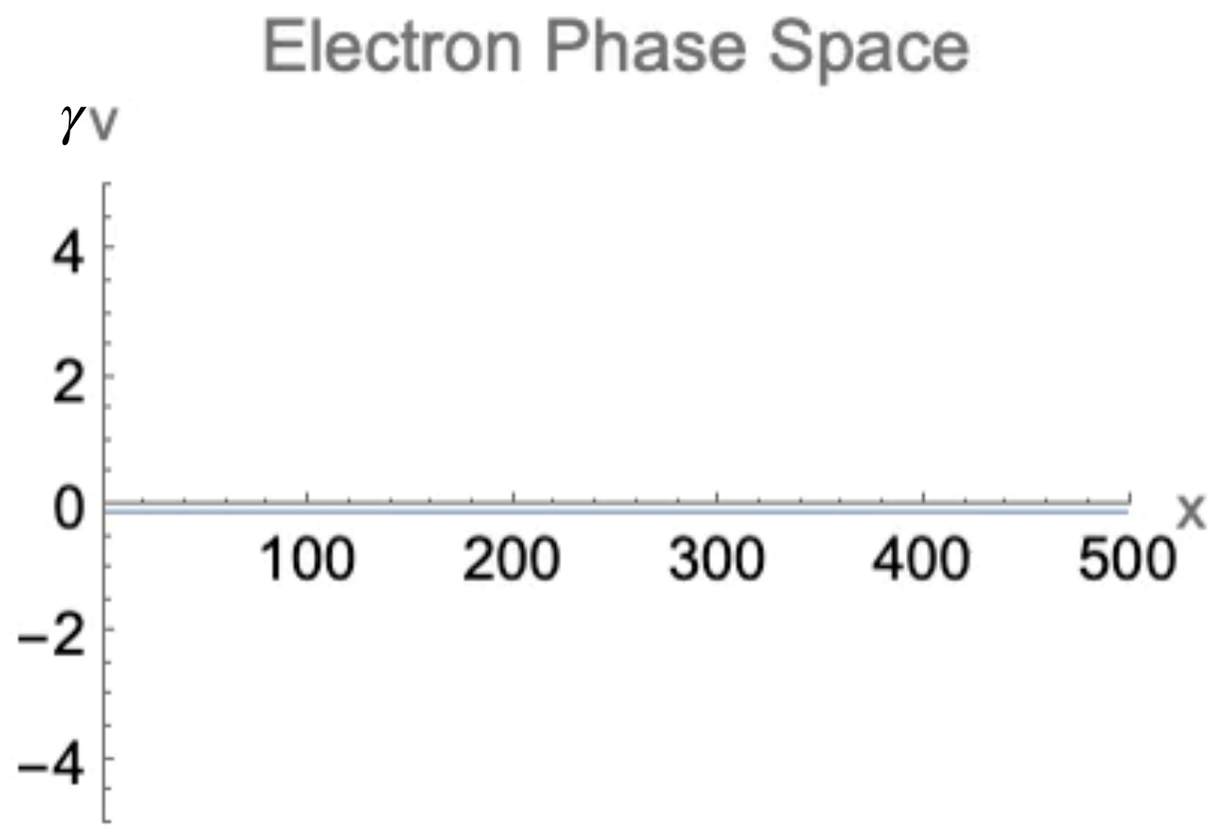
$$\omega_{\text{eff}}^2 = \omega^2 - 3\lambda\phi^2$$

Numerical Simulation

Theory is hard - Pictures/Videos are easy

Step 1 - Write Mathematica Code





Numerical Simulation

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Step 1 - Write Mathematica Code

- **Grows as expected**
- **Eventually growth stops - off resonance**
- **Additional surprise - fragments!**

Numerical Simulation

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Step 1 - Write Mathematica Code

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Step 2 - Write better C code

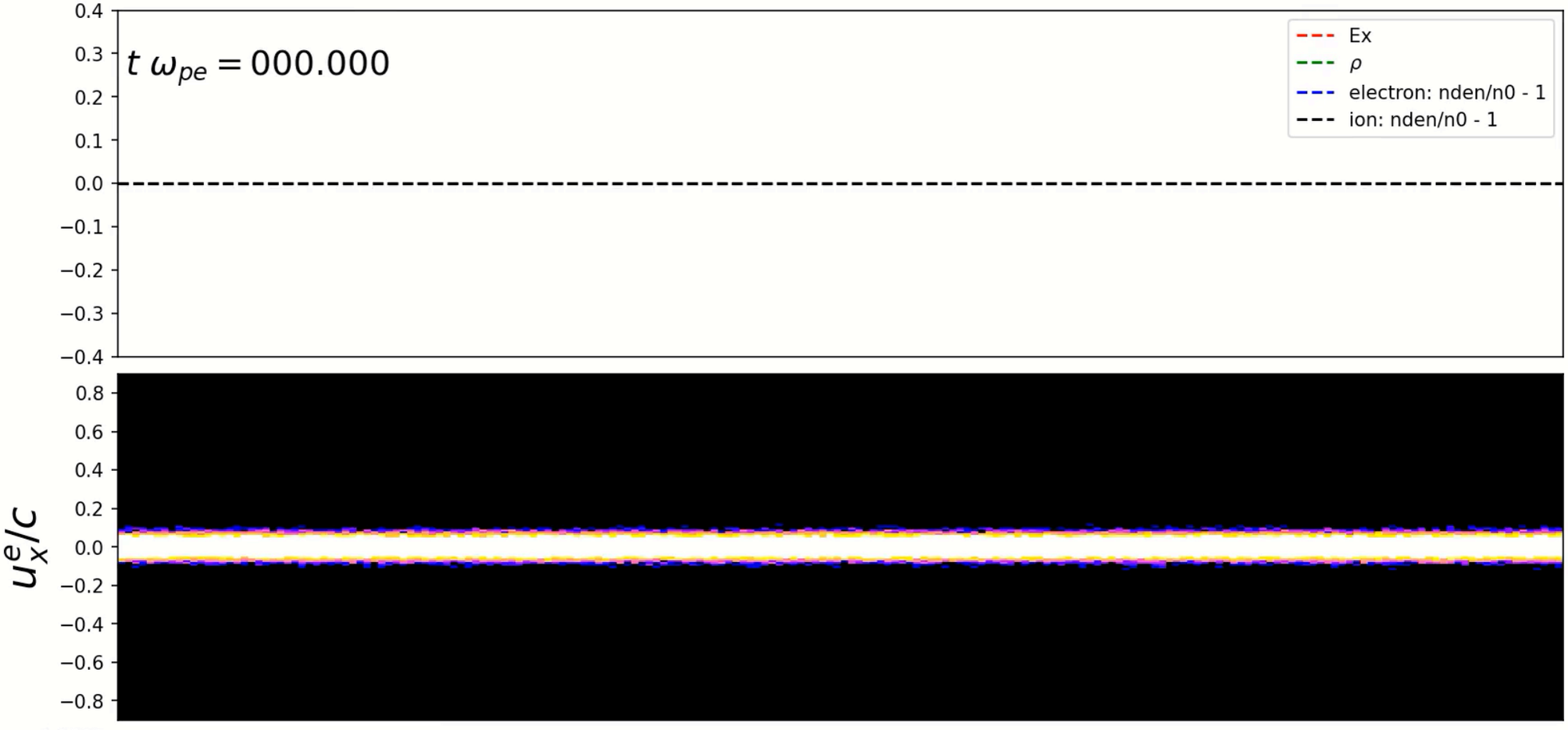
Step 3 - Realize why people do this for a living

Step 4 - Ask an expert for help

Numerical Simulation

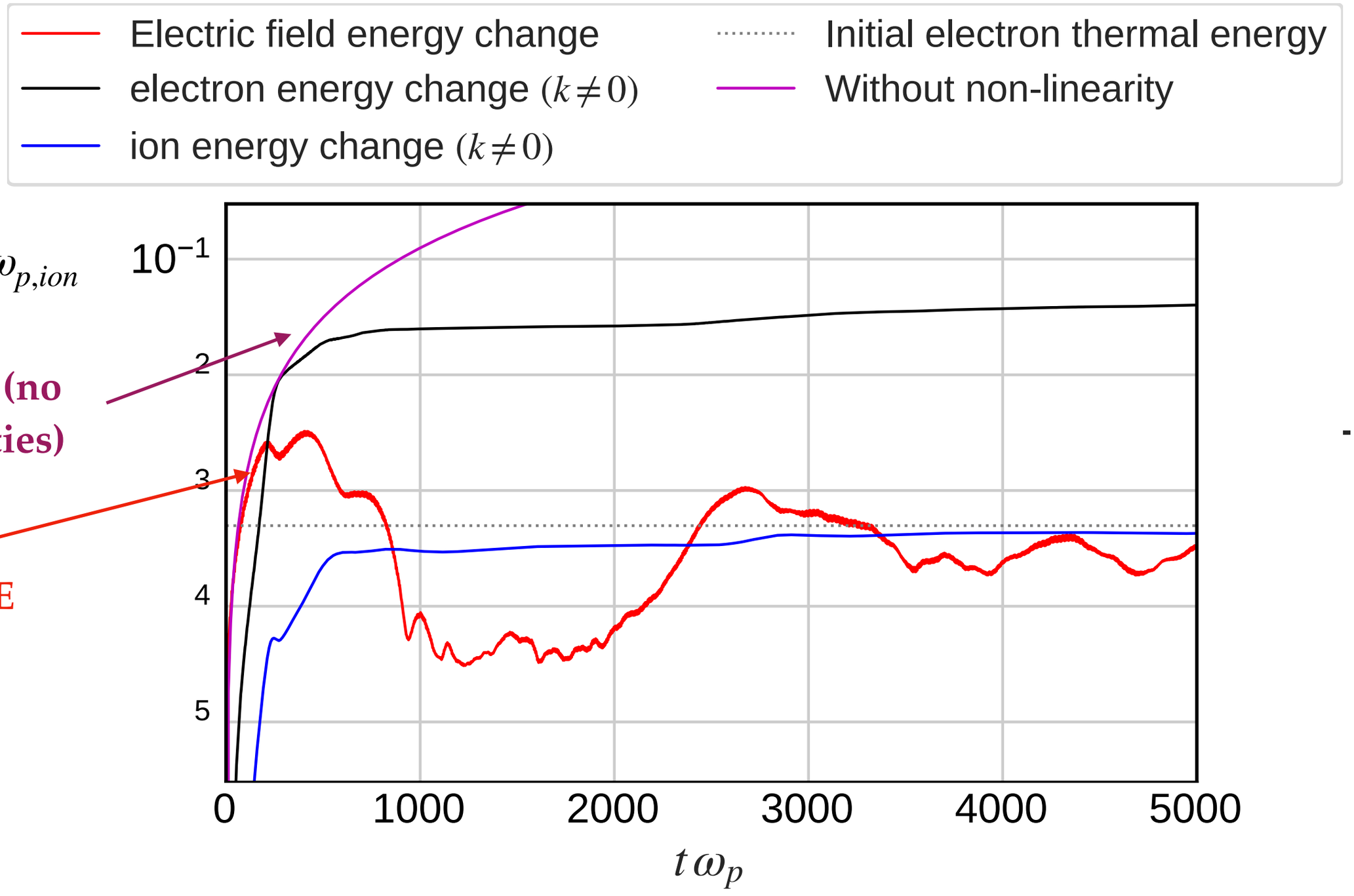
Large Electric Field Limit

1. **Initial instability from acoustic waves**
2. **Acoustic waves die off and a mess remains**



Numerical Simulation

Large Electric Field Limit



Stops at $t \sim 1/\omega_{p,ion}$

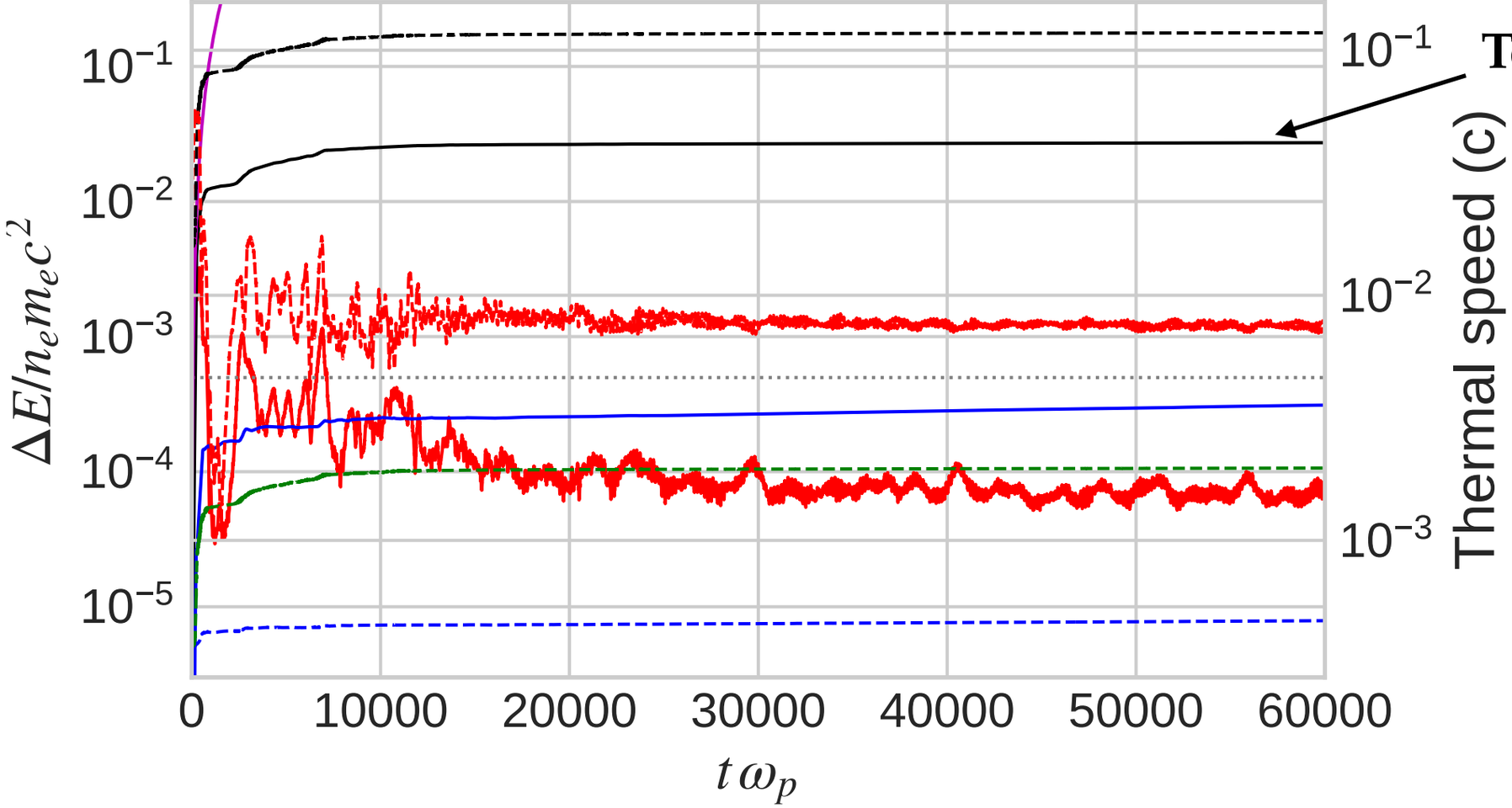
Analytic E (no nonlinearities)

Numerical E

Numerical Simulation

Large Electric Field Limit

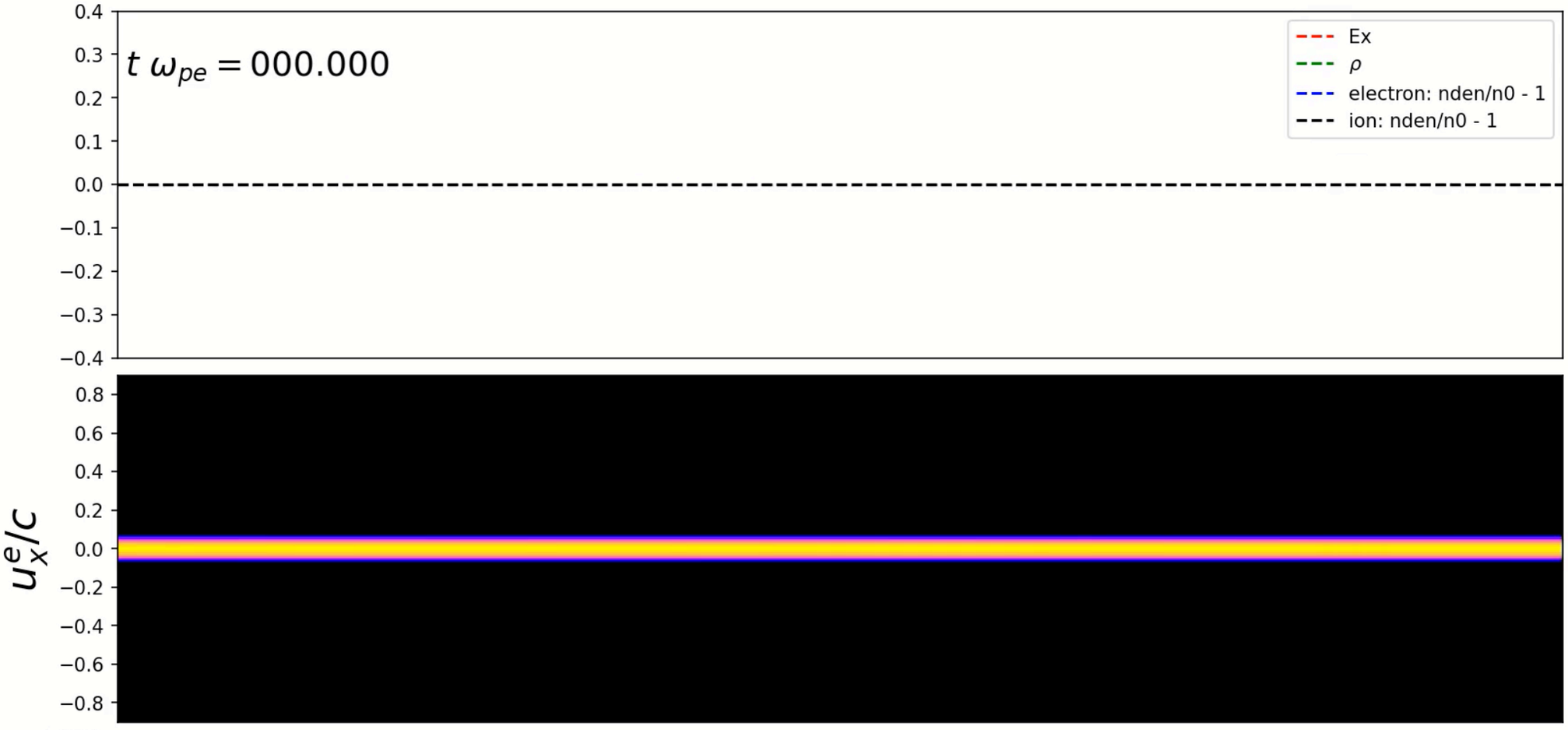
Electric energy change
electron thermal energy change
ion thermal energy change
Initial electron thermal energy
Without non-linearity
electron thermal speed
ion thermal speed
sound speed/2
electron average speed



Numerical Simulation

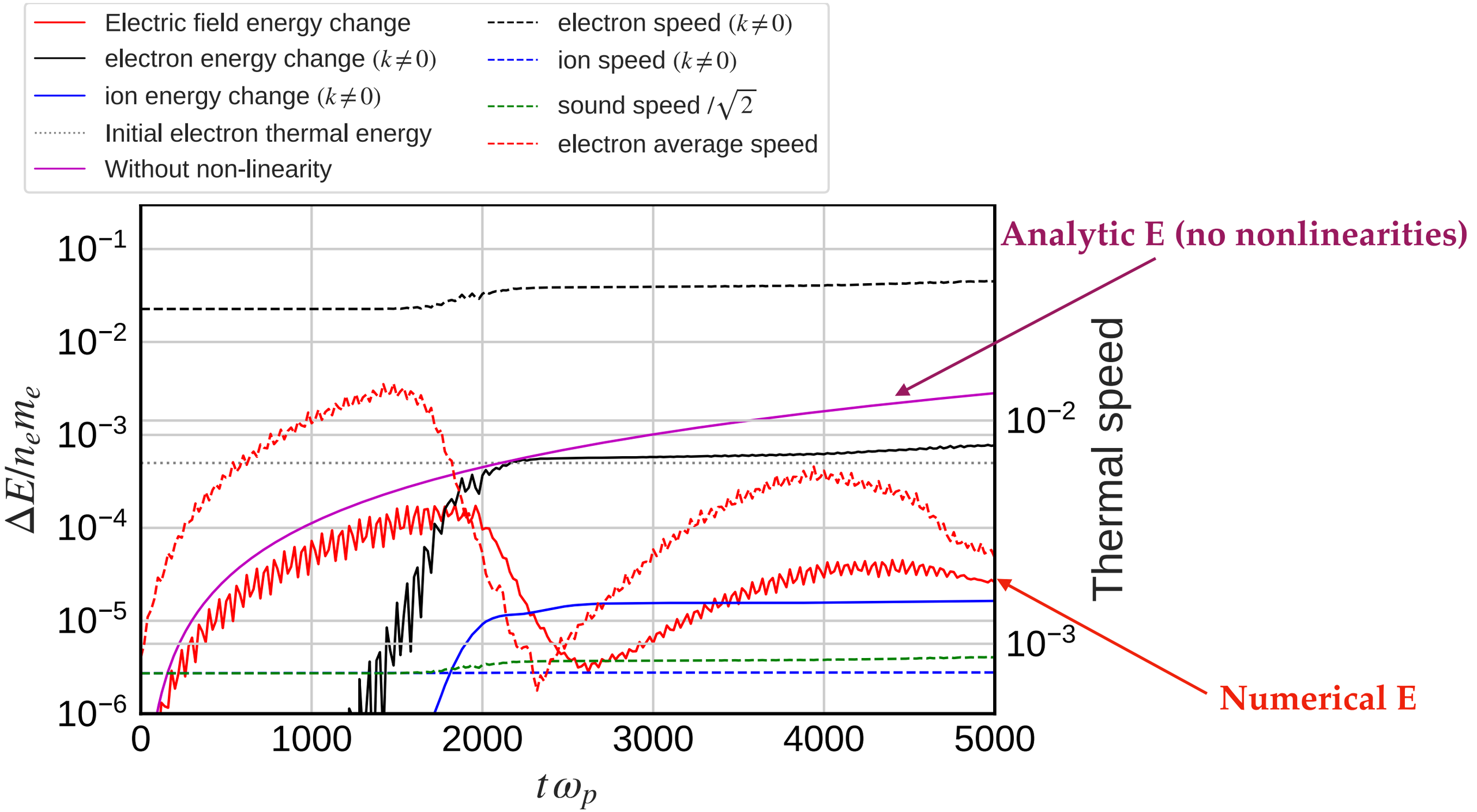
Small Electric Field Limit

1. **Starts to grow**
2. **Stops when acoustic waves (charge neutral) are important**
3. **Acoustic waves die off and a mess remains**



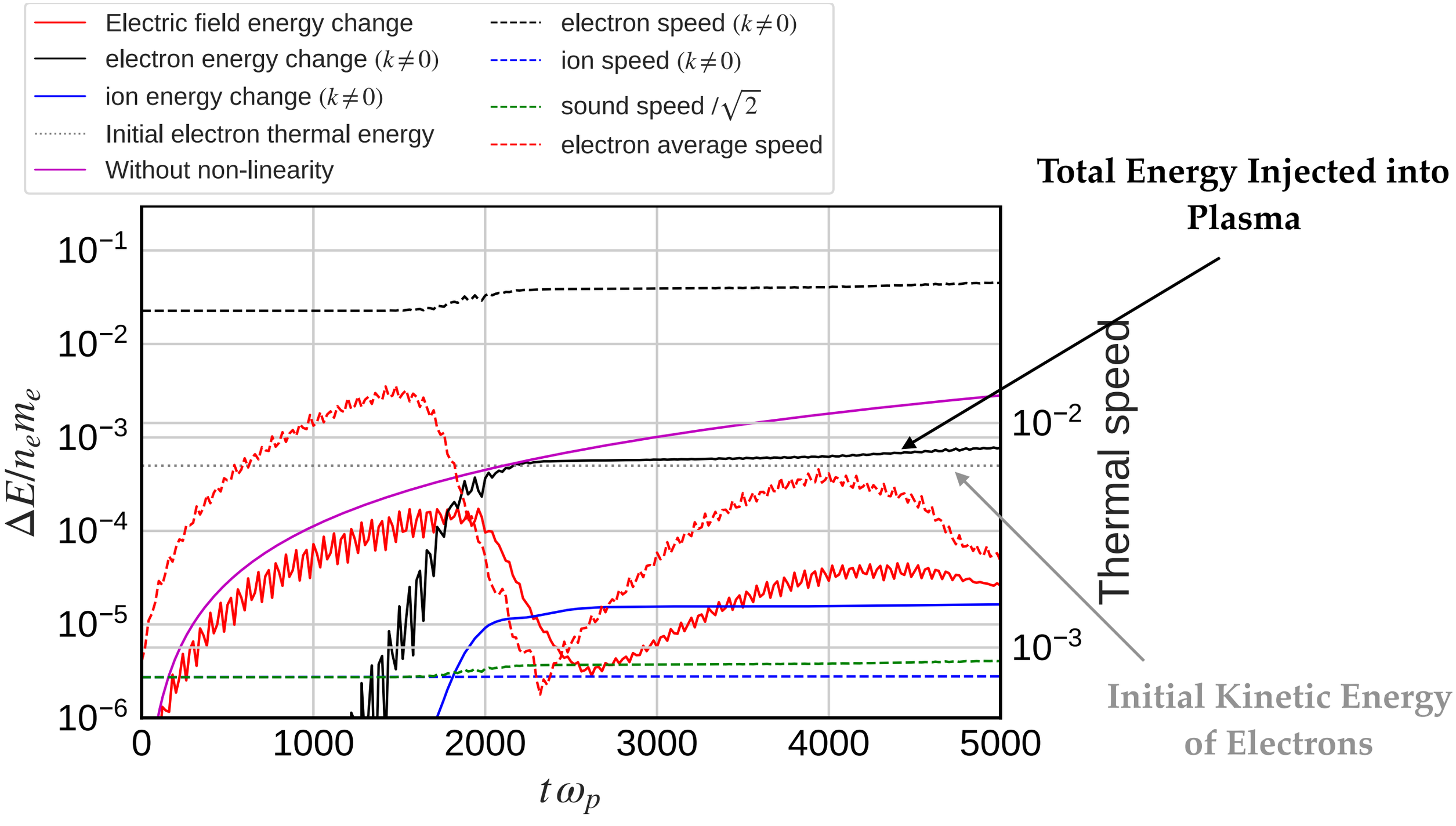
Numerical Simulation

Small Electric Field Limit



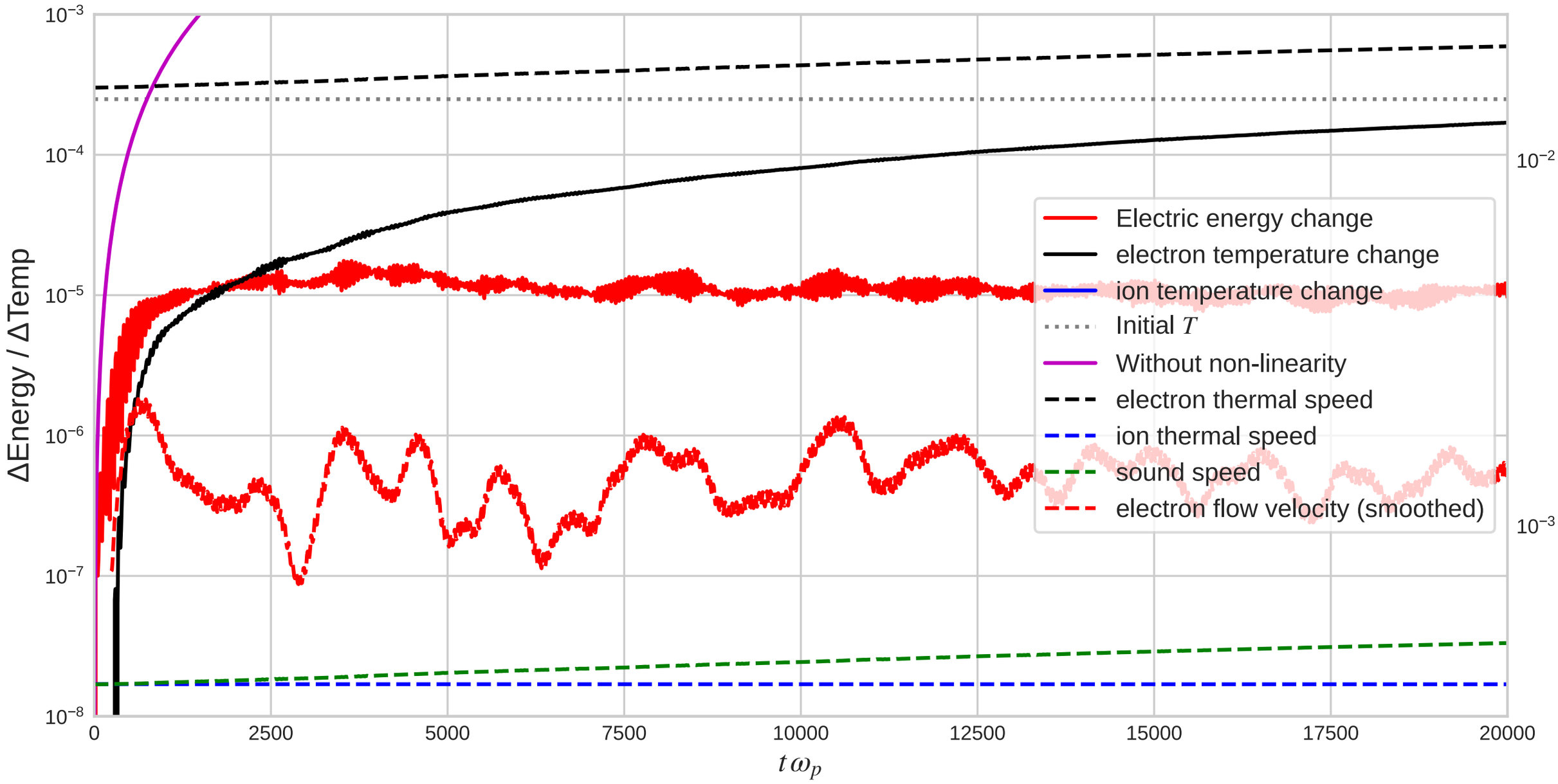
Numerical Simulation

Small Electric Field Limit



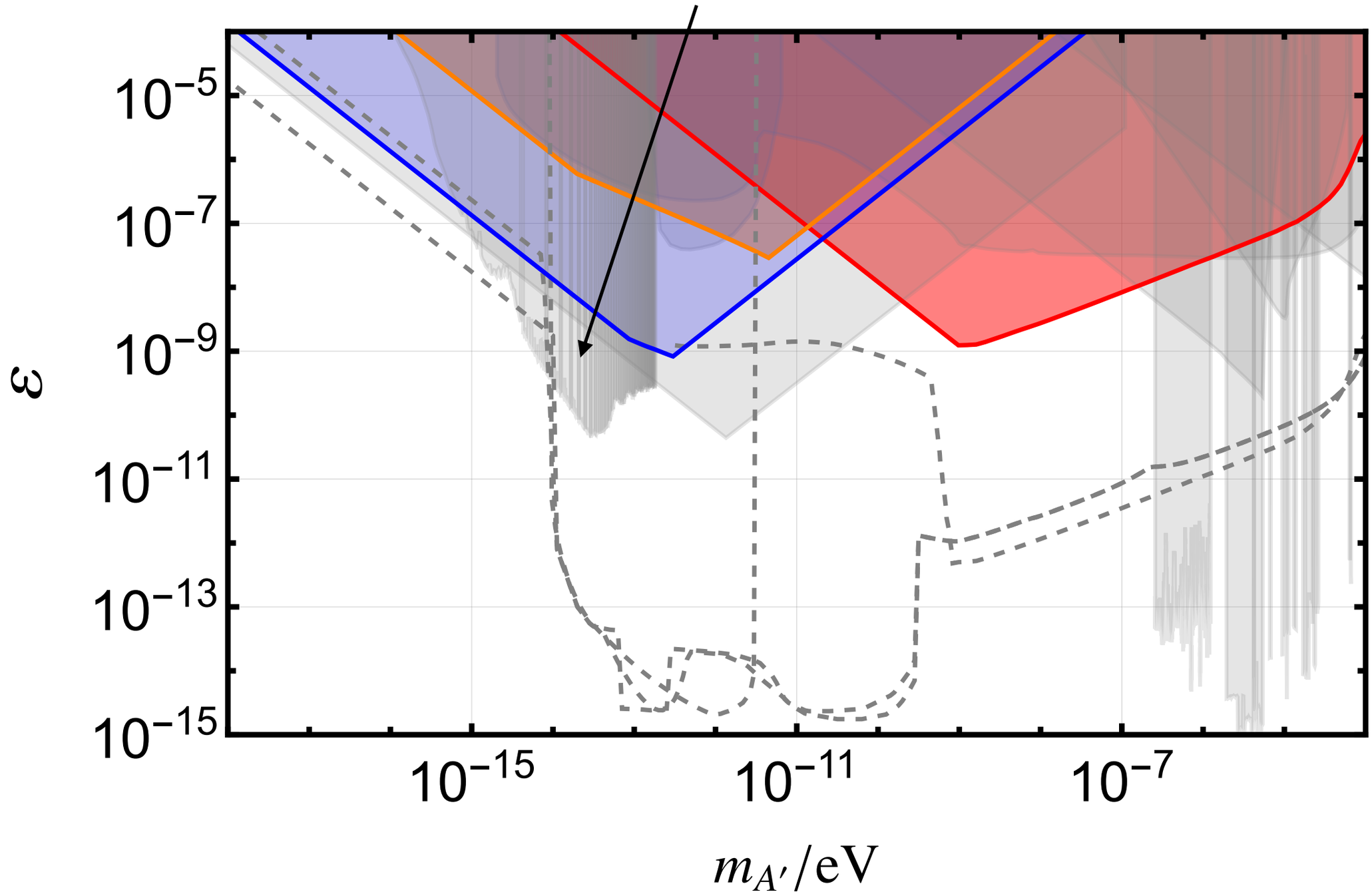
Numerical Simulation

Even Smaller Electric Field Limit



Limits

Experimental/Lab-based bounds are now the world's leading constraints on dark photon dark matter



Conclusion

Plasma Physics is complicated!

- **Numerically - Energy deposition is capped at kinetic energy of electrons**
  - **Annoying for energy deposition constraints**
  - **Full 3D simulations need to be done to capture the proper final state**
- **Perhaps there are other cool new ways to look for the presence of a background oscillating electric field with plasmas**