

# Chromo-Weibel instabilities in an expanding Quark Gluon Plasma \*

Maximilian Attems

Institute for Theoretical Physics, TU Vienna

Collaborators: Anton Rebhan, Michael Strickland

September 22, 2011

---

\*“ Dans la vie, rien n'est à craindre, tout est à comprendre.” Marie Curie

# Hard Expanding Loops (HEL)

## Hard Expanding Loops (HEL)

Stages of the Little Big Bang

Momentum Anisotropy

Weibel instabilities

Scales QGP

Hard (Thermal) Loops - Boltzmann - Vlasov

## Plasma Instabilities

HEL 3D+3V Check

Expanding 3D+3V Abelian plasma

Expanding 3D+3V non-Abelian plasma

Expanding 3D+3V non-Abelian plasma

Conclusions

Backup

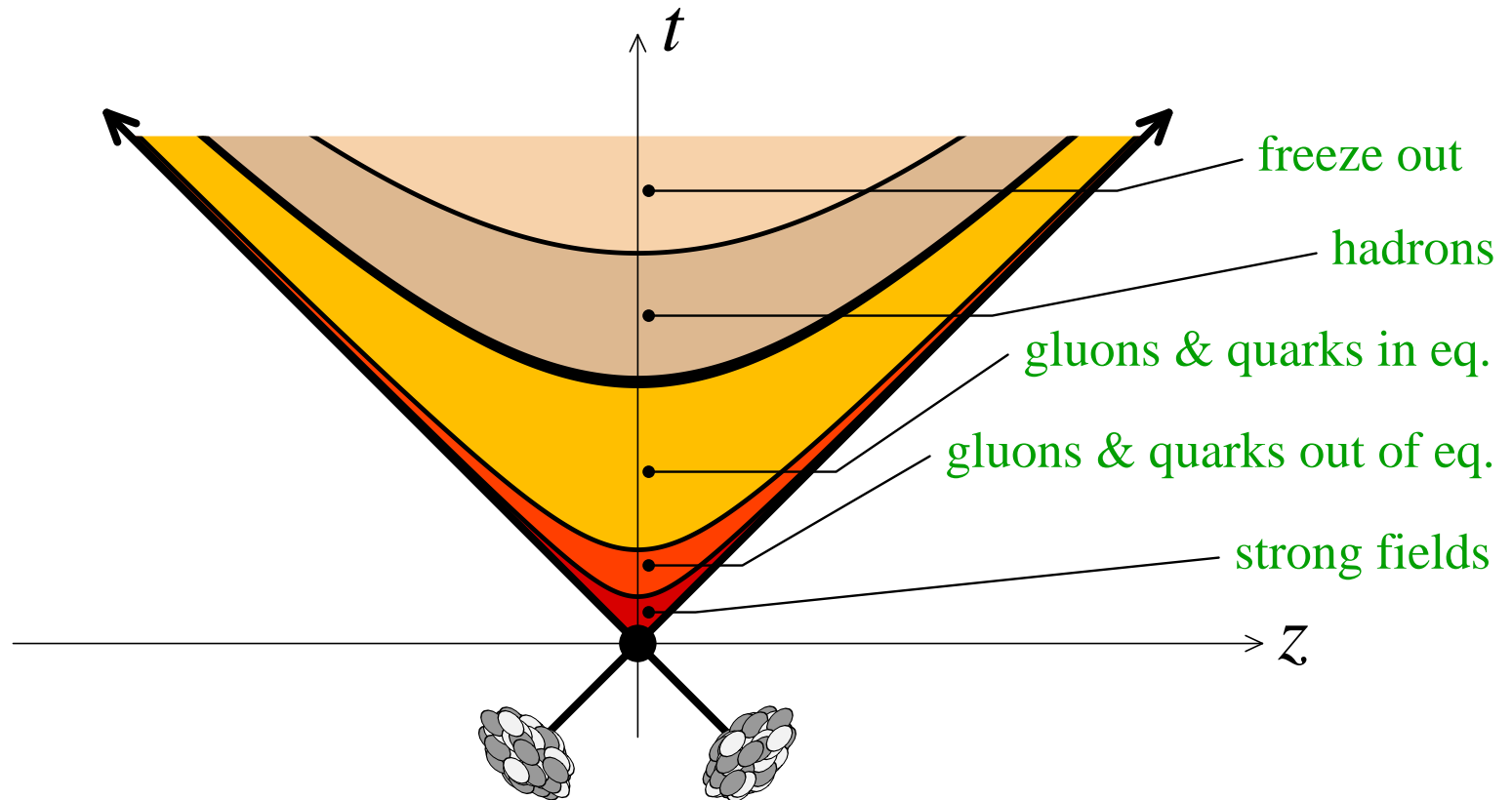
Hard Expanding  
Loops (HEL)

Stages of the  
Little Big Bang  
Momentum  
Anisotropy  
Weibel instabilities  
Scales QGP  
Hard (Thermal)  
Loops -  
Boltzmann -  
Vlasov

Plasma  
Instabilities

# Stages of the Little Big Bang

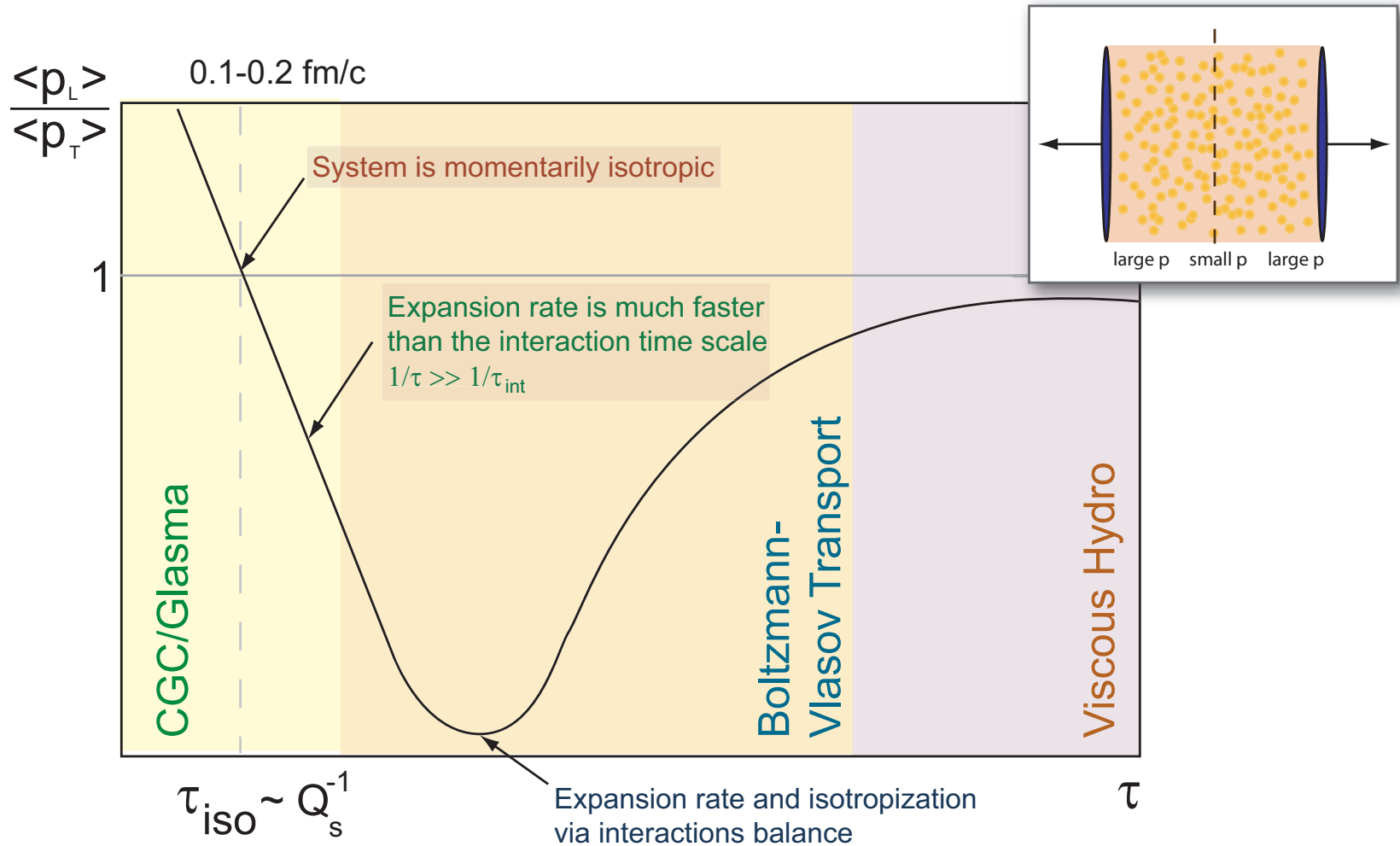
Hard Expanding  
Loops (HEL)  
Stages of the  
Little Big Bang  
Momentum  
Anisotropy  
Weibel instabilities  
Scales QGP  
Hard (Thermal)  
Loops -  
Boltzmann -  
Vlasov  
Plasma  
Instabilities



[Gelis 2010] Illustration of the stages of a heavy ion collision.

# Momentum Anisotropy

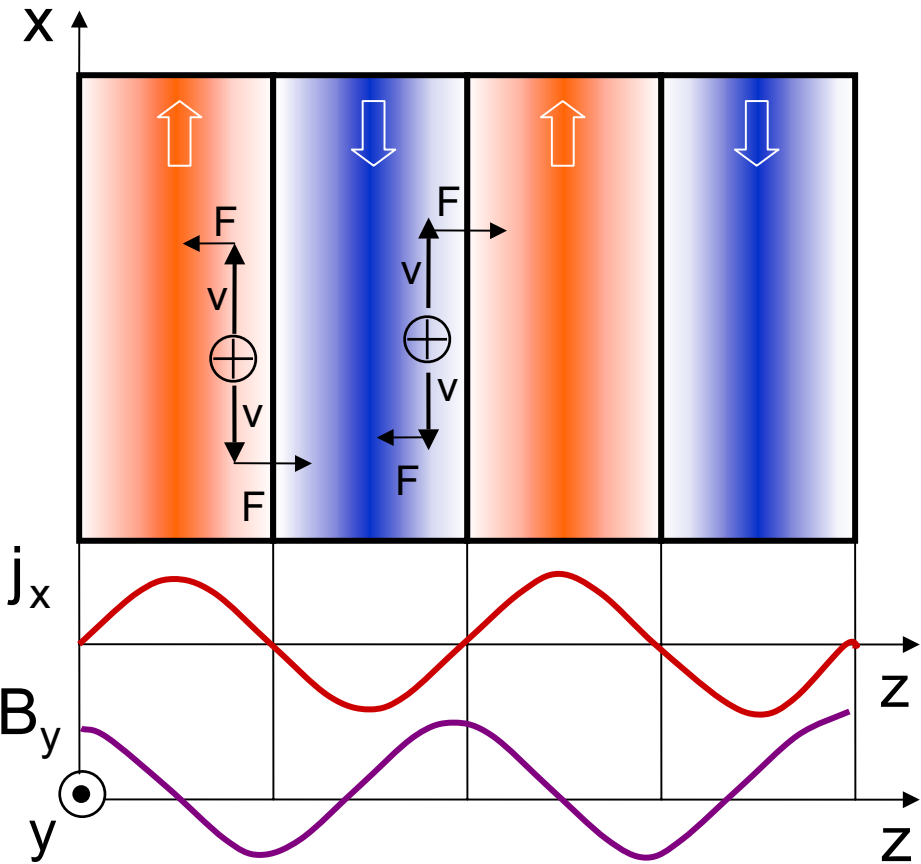
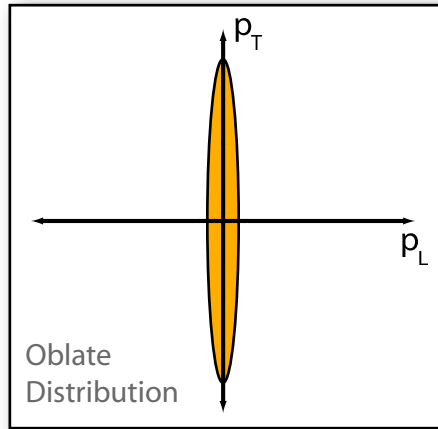
- Hard Expanding Loops (HEL)
- Stages of the Little Big Bang
- Momentum Anisotropy
- Weibel instabilities
- Scales QGP
- Hard (Thermal) Loops - Boltzmann - Vlasov
- Plasma Instabilities



[Strickland 2004]: Momentum space anisotropy time dependence at the early stages of a heavy ion collision

# Weibel instabilities

- Hard Expanding Loops (HEL)
- Stages of the Little Big Bang
- Momentum Anisotropy
- Weibel instabilities**
- Scales QGP
- Hard (Thermal) Loops - Boltzmann - Vlasov
- Plasma Instabilities



[Strickland 2006]: Illustration of the mechanism of filamentation instabilities.

# QED Plasma

Hard Expanding  
Loops (HEL)

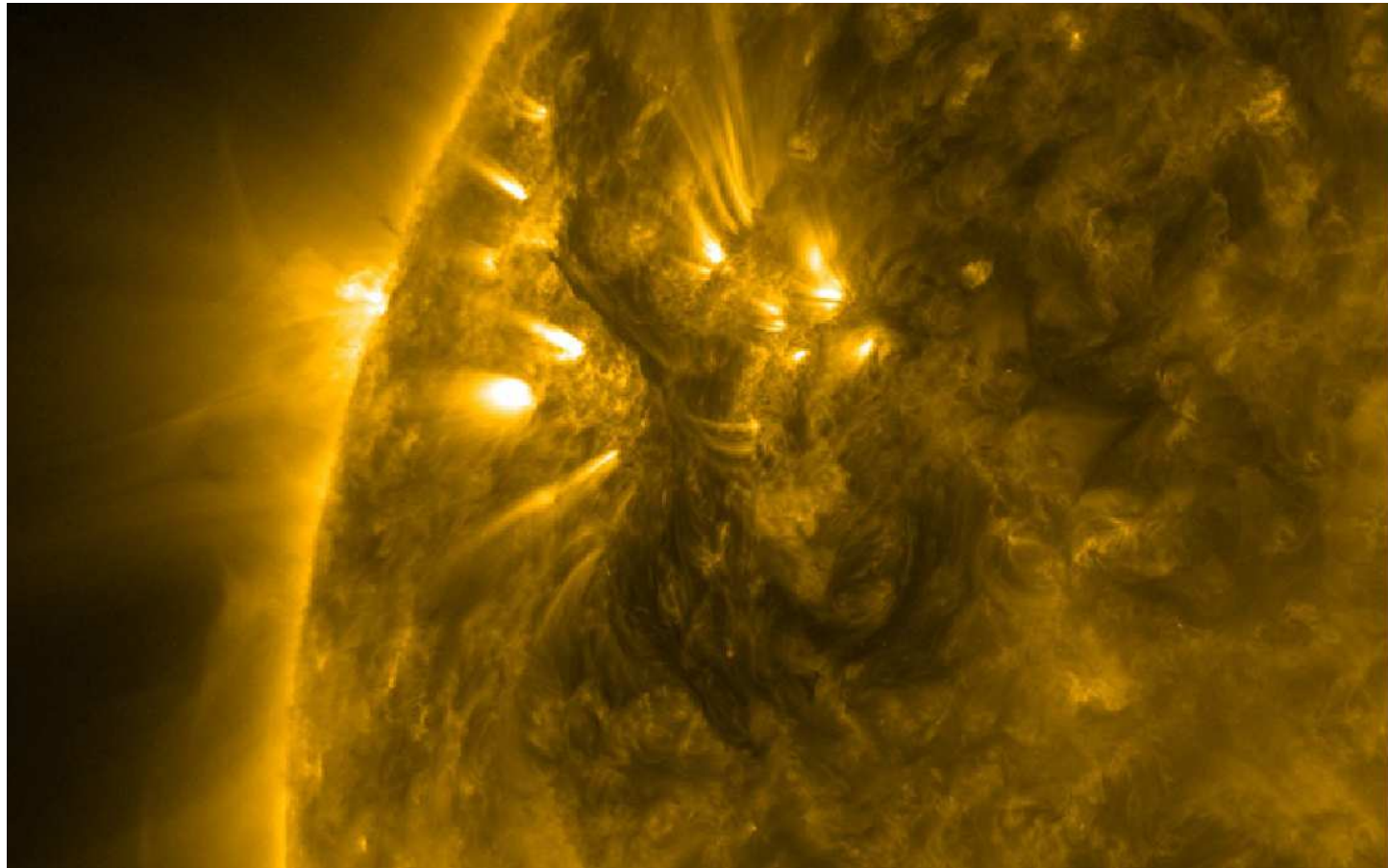
Stages of the  
Little Big Bang  
Momentum  
Anisotropy

Weibel instabilities

Scales QGP  
Hard (Thermal)  
Loops -  
Boltzmann -  
Vlasov

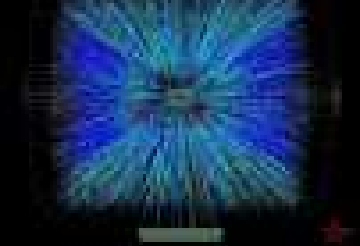
Plasma  
Instabilities

---



Filaments and active solar region from NASA's Solar Dynamics Observatory

# Scales of weakly coupled QGP



## Hard Expanding Loops (HEL)

Stages of the  
Little Big Bang  
Momentum  
Anisotropy  
Weibel instabilities

## Scales QGP

Hard (Thermal)  
Loops -  
Boltzmann -  
Vlasov

Plasma  
Instabilities

- $T$ : energy of hard particles
- $gT$ : thermal masses, Debye screening mass, Landau damping, **plasma instabilities** [Mrowczynski 1988, 1993, ..]
- $g^2T$ : magnetic confinement, color relaxation, rate for small angle scattering
- $g^4T$ : rate for large angle scattering,  $\eta^{-1}T^4$

# Hard (Thermal) Loops - Boltzmann - Vlasov

Assuming free streaming, one solves the gauge covariant Boltzmann-Vlasov equation

$$v \cdot D \partial f_a(\mathbf{p}, \mathbf{x}, t) = g v_\mu F_a^{\mu\nu} \partial_\nu^{(p)} f_0(\mathbf{p}, \mathbf{x}, t) \quad (1)$$

coupled to Yang-Mills equation

$$D_\mu F_a^{\mu\nu} = j_a^\nu = g \int \frac{d^3 p}{(2\pi)^3} \frac{p^\mu}{2p^0} \delta f_a(\mathbf{p}, \mathbf{x}, t) \quad (2)$$

in the HTL approximation

$$g A_\mu \ll |\mathbf{p}_{hard}| \quad (3)$$

in comoving coordinates  $ds^2 = d\tau^2 - d\mathbf{x}_\perp^2 - \tau^2 d\eta^2$  .

Hard Expanding  
Loops (HEL)

Stages of the  
Little Big Bang  
Momentum  
Anisotropy  
Weibel instabilities  
Scales QGP

Hard (Thermal)  
Loops -  
Boltzmann -  
Vlasov

Plasma  
Instabilities



# Plasma Instabilities

## Hard Expanding Loops (HEL)

Stages of the Little Big Bang

Momentum Anisotropy

Weibel instabilities

Scales QGP

Hard (Thermal) Loops - Boltzmann - Vlasov

## Plasma Instabilities

HEL 3D+3V Check

Expanding 3D+3V Abelian plasma

Expanding 3D+3V non-Abelian plasma

Expanding 3D+3V non-Abelian plasma

Conclusions

Backup

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

Expanding 3D+3V

non-Abelian

plasma

Conclusions

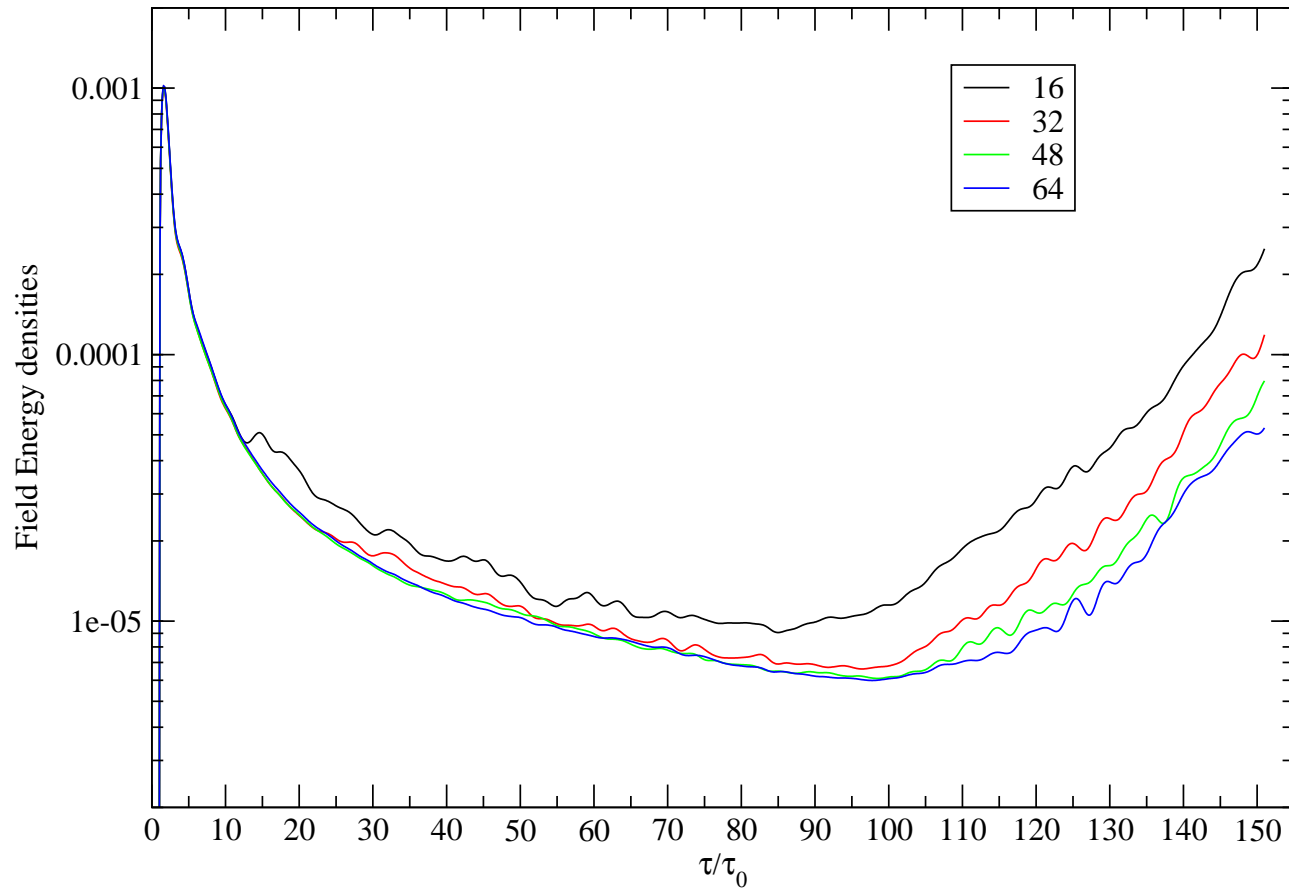
Backup

# HEL 3D+3V Check

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities  
HEL 3D+3V  
Check

Expanding 3D+3V  
Abelian plasma  
Expanding 3D+3V  
non-Abelian  
plasma  
Expanding 3D+3V  
non-Abelian  
plasma  
Conclusions  
Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]  
Preliminary runs from the HEL 3d IC "stable nodes".

# HEL 3D+3V Check

Hard Expanding  
Loops (HEL)

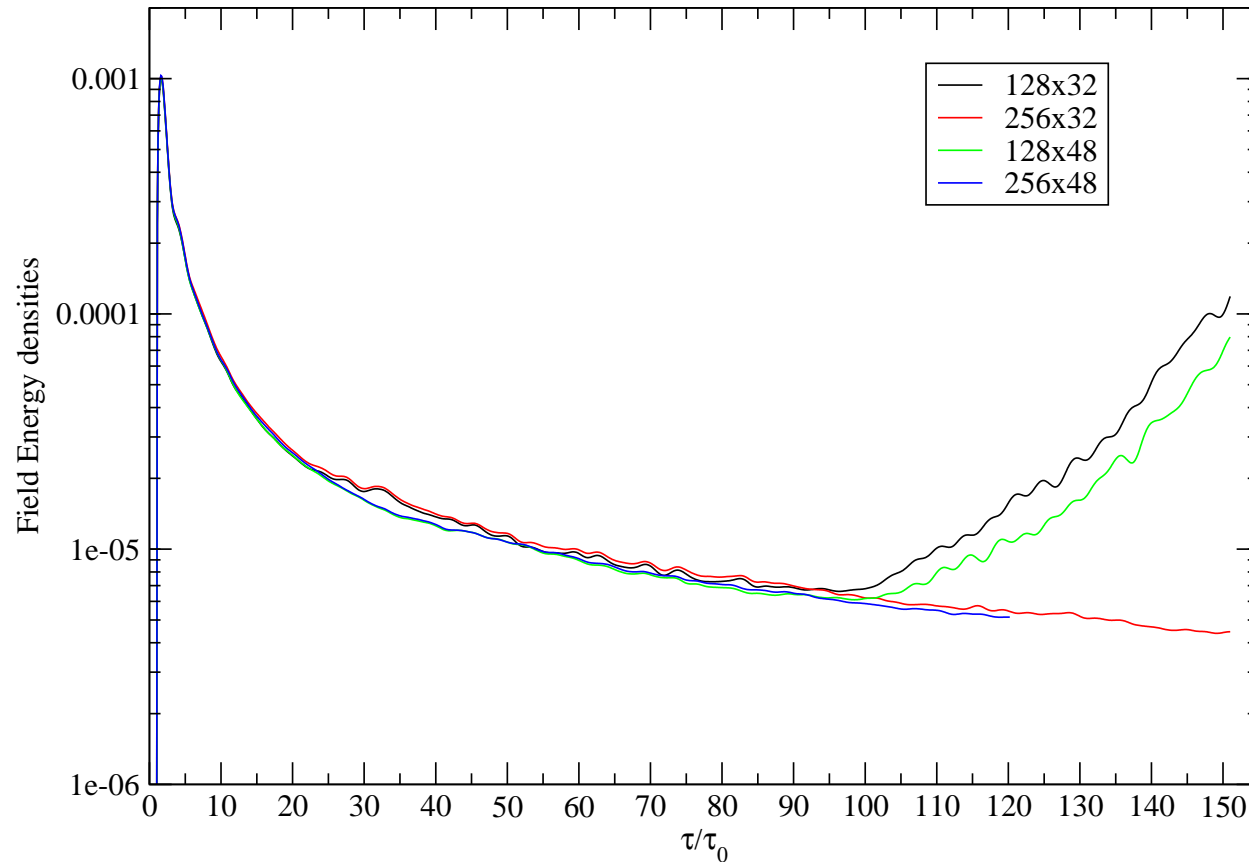
Plasma  
Instabilities  
HEL 3D+3V  
Check

Expanding 3D+3V  
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions  
Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "stable nodes".

# Expanding 3D+3V Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V  
Check

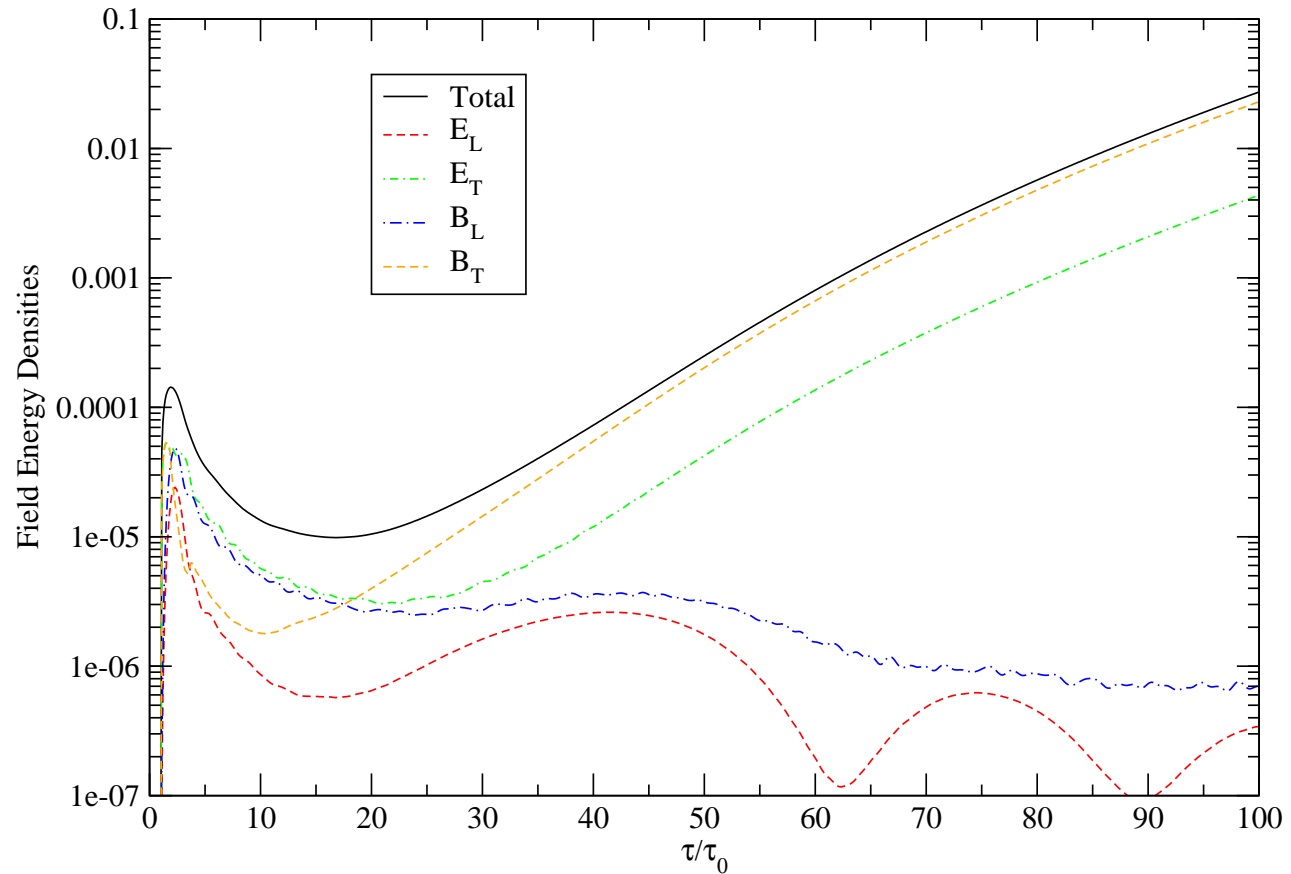
Expanding 3D+3V  
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions

Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "transverse current".

# Expanding 3D+3V Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

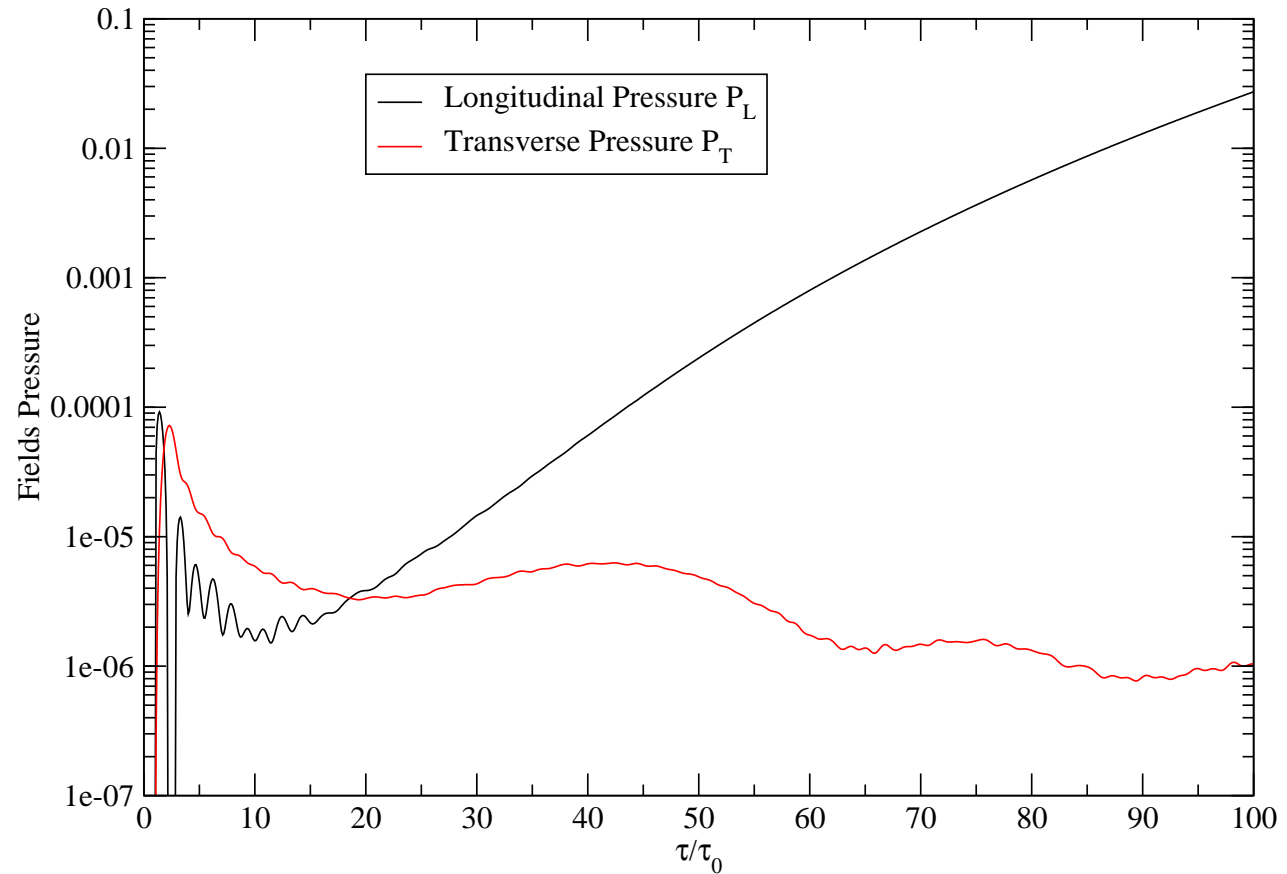
HEL 3D+3V  
Check

Expanding 3D+3V  
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions  
Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "transverse current".

# Expanding 3D+3V Abelian/non-Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

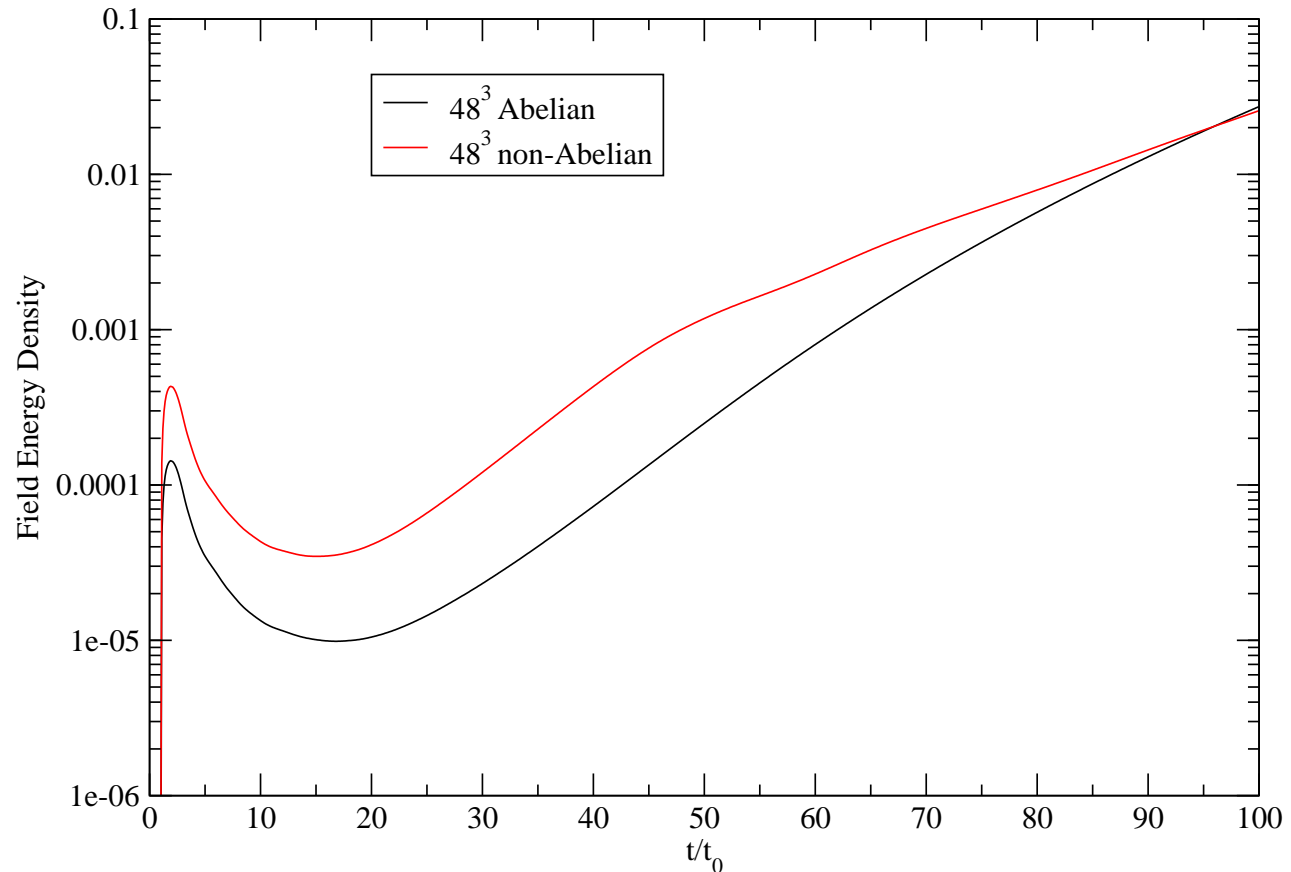
HEL 3D+3V  
Check

Expanding 3D+3V  
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions  
Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "transverse current".

# Expanding 3D+3V non-Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

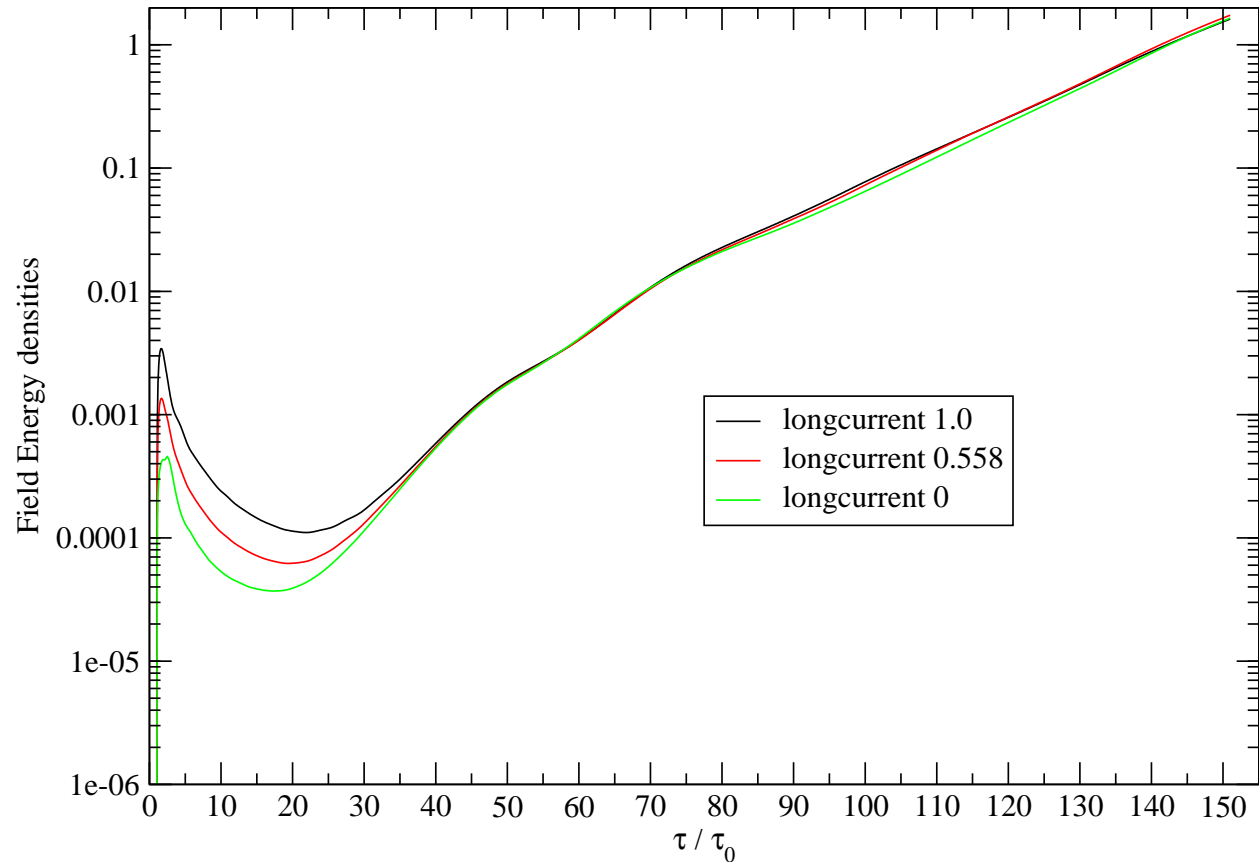
Expanding 3D+3V  
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions

Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "transverse current".

# Expanding 3D+3V non-Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

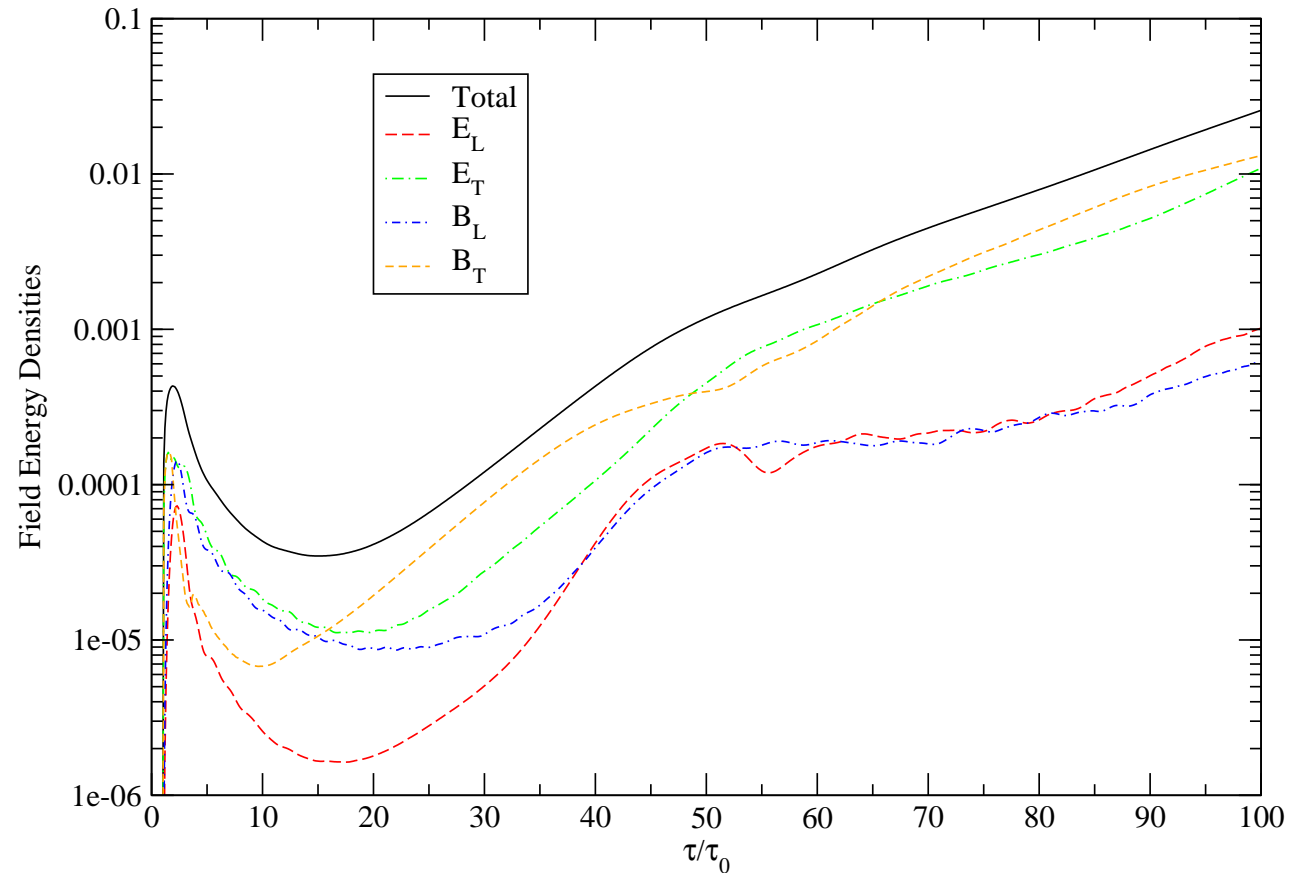
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions

Backup



[Attems, Rebhan, Strickland arXiv:1110.XXXX]

Preliminary runs from the HEL 3d IC "transverse current".



# Conclusions

Non-abelian plasma instabilities play a significant role in a weakly coupled Quark Gluon Plasma at high  $T$ .

Chromo-Weibel instabilities are an important candidate process accelerating isotropization and thermalization of the Quark Gluon Plasma fireball maybe already at LHC.

The previous 1D HEL code has been extended to full 3D+3V parallel MPI-code with improved "transverse current" initial conditions. This significantly reduces the onset time of chromo-Weibel instabilities in the expanding setup.

Final results including a scan of our parameter space are being computed on the Vienna Scientific Cluster.

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

Expanding 3D+3V

non-Abelian

plasma

Conclusions

Backup

# Backup - Expanding 1D+3V non-Abelian plasma



Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

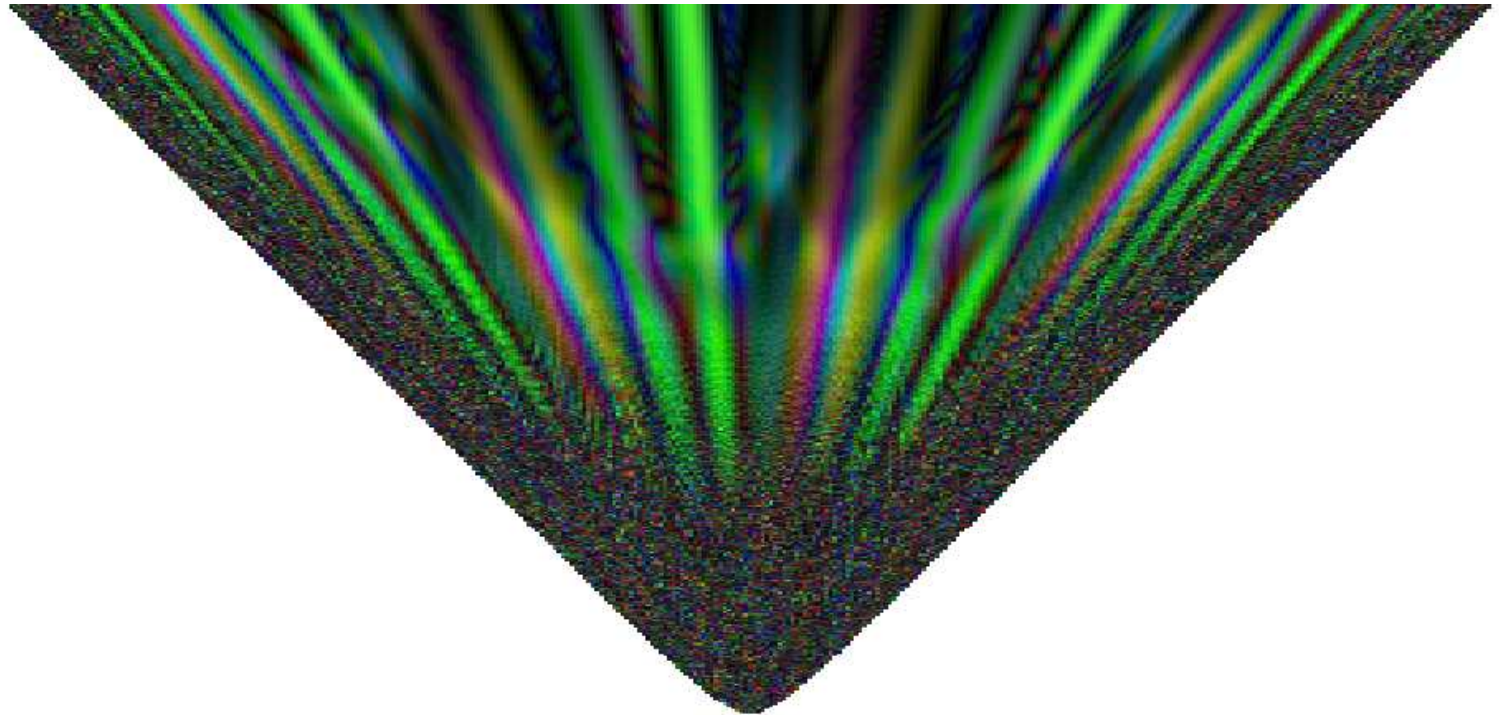
Expanding 3D+3V

non-Abelian

plasma

Conclusions

Backup



[Strickland 2008] Visualization of the space-time development of color correlations in a non-Abelian plasma instabilities in Bjorken expansion.

# Backup - Equation of motions

## Conjugate Momenta

$$\tau^{-1} \partial_\tau \Pi_i = j^i - D_j F^{ji} - D_\eta F^{\eta i}. \quad (4)$$

$$\tau \partial_\tau \Pi^\eta = j_\eta - D_i F^i_\eta, \quad (5)$$

## Gauss law constraint

$$\tau j^\tau = D_\eta \Pi^\eta - ig[A^i, \Pi_i], \quad (6)$$

with

$$\Pi^i \equiv \tau \partial_\tau A_i, \quad \Pi^\eta \equiv \frac{1}{\tau} \partial_\tau A_\eta. \quad (7)$$

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

Expanding 3D+3V

non-Abelian

plasma

Conclusions

Backup

# Backup - Unstable transverse modes

## Hard Expanding Loops (HEL)

### Plasma Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

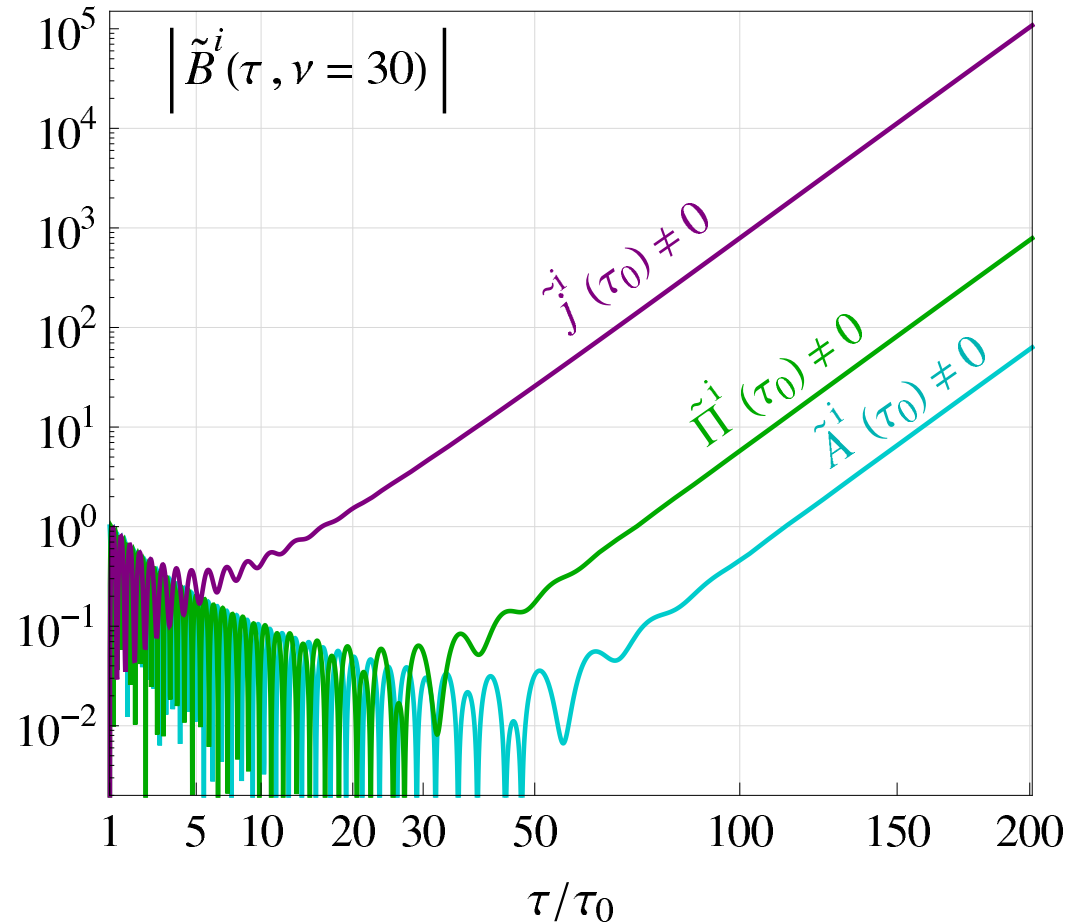
Expanding 3D+3V

non-Abelian

plasma

### Conclusions

Backup



[Rebhan, Steineder 2009] Influence of different initial conditions for a specific mode with  $\nu = 30$ .

# Backup

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

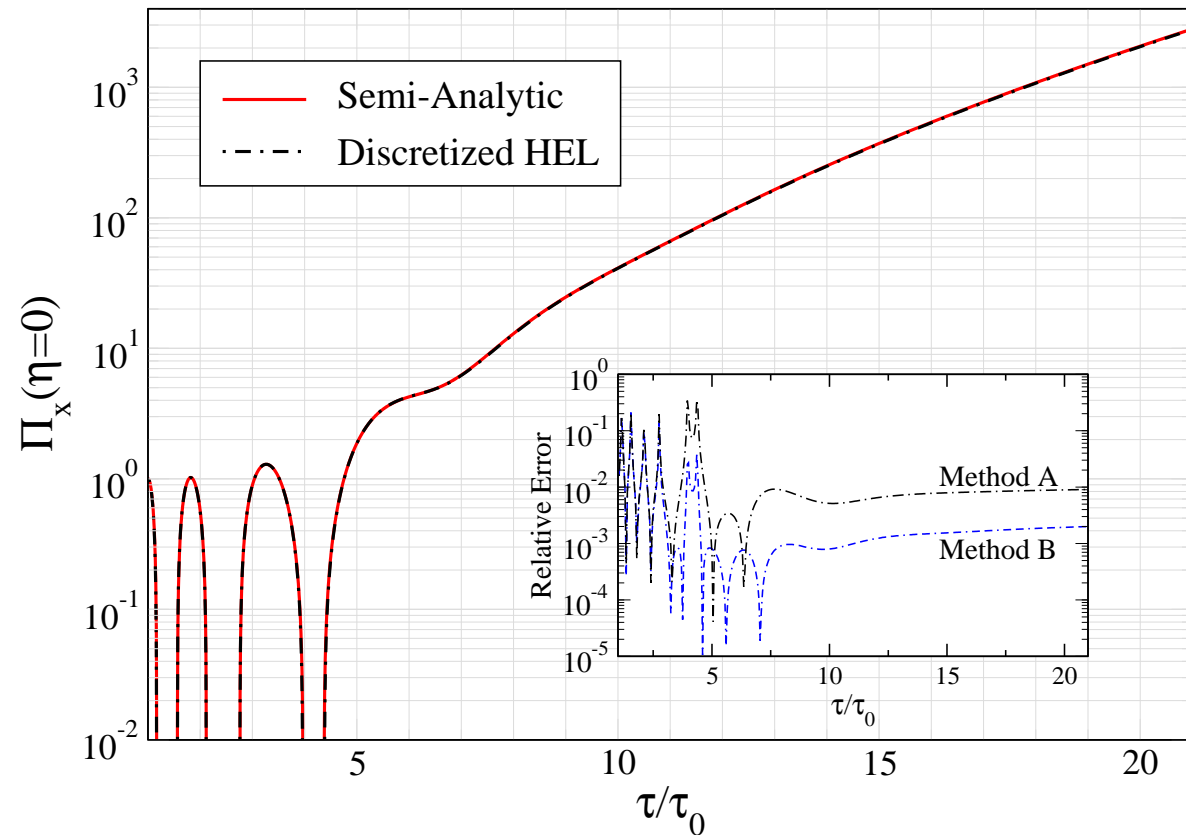
non-Abelian  
plasma

Expanding 3D+3V

non-Abelian  
plasma

Conclusions

Backup



[Rebhan, Strickland, Attems 2008] The proper-time evolution of the canonical field momentum of a single Abelian mode in comparison with [Romatschke, Rebhan 2006].

# Expanding 1D+3V non-Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

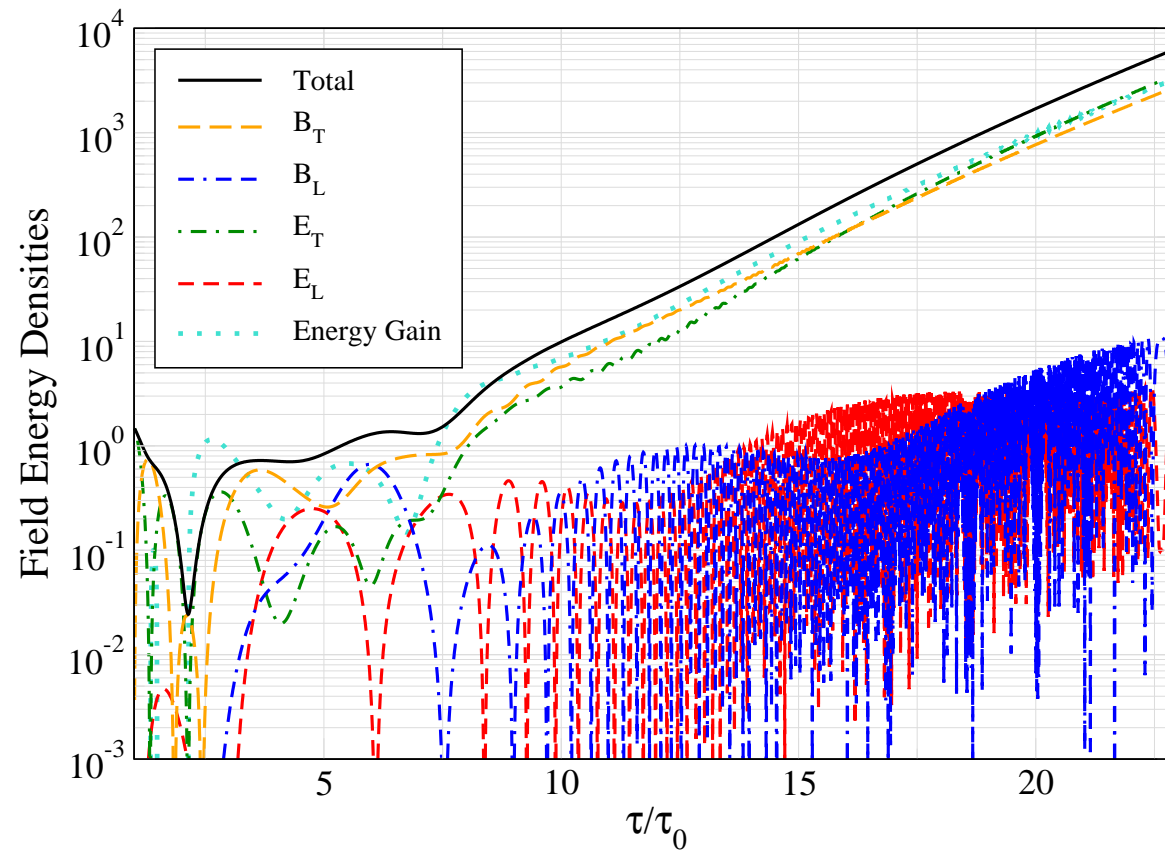
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions

Backup



[Rebhan, Strickland, Attems 2008] The proper-time dependence of the chromo-field energy densities from a run with a single non-Abelian mode seeded with random noise.

# Backup - Expanding 1D+3V Abelian plasma

Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

Abelian plasma

Expanding 3D+3V

non-Abelian

plasma

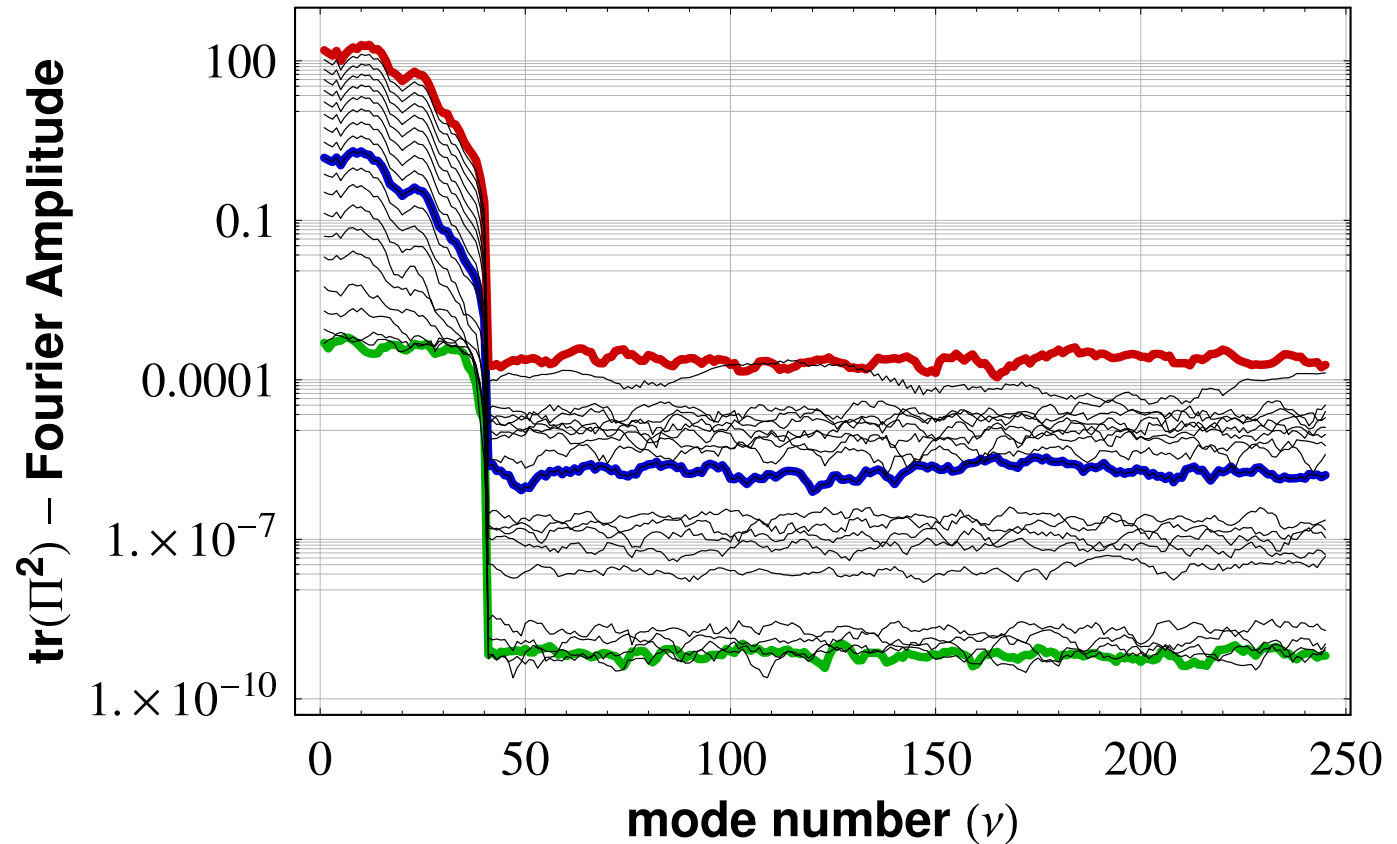
Expanding 3D+3V

non-Abelian

plasma

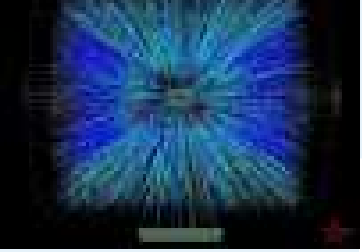
Conclusions

Backup



[Rebhan, Strickland, Attems 2008] Fourier spectrum of the color-traced conjugate field momentum obtained from Abelian run with FGM initial conditions.

# Backup - Expanding 1D+3V non-Abelian plasma



Hard Expanding  
Loops (HEL)

Plasma  
Instabilities

HEL 3D+3V

Check

Expanding 3D+3V

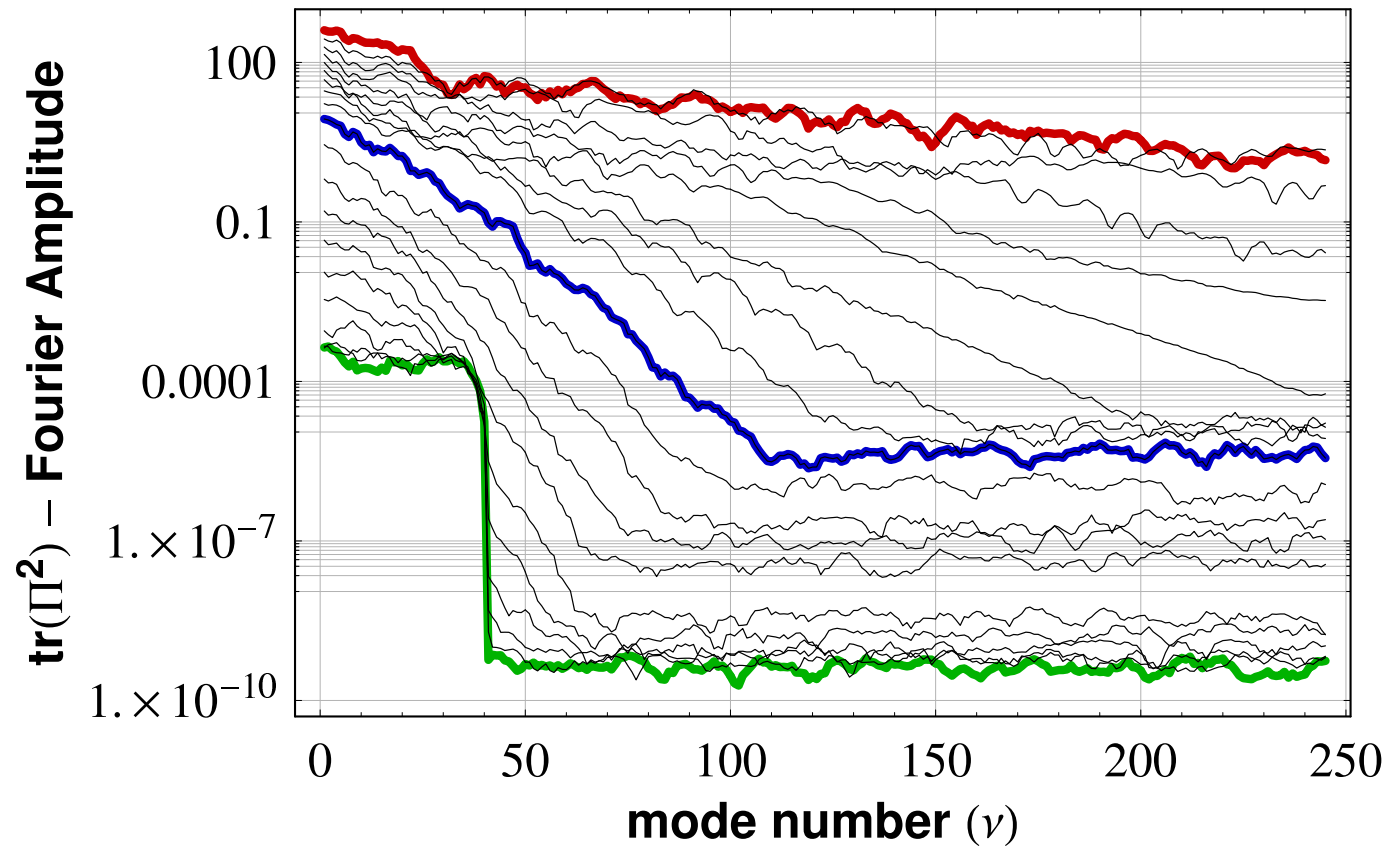
Abelian plasma

Expanding 3D+3V  
non-Abelian  
plasma

Expanding 3D+3V  
non-Abelian  
plasma

Conclusions

Backup



[Rebhan, Strickland, Attems 2008] Fourier spectrum of the color-traced conjugate field momentum obtained from non-Abelian run with FGM initial conditions.