Gauge-fixing, Gribov copies and gluonic correlation functions

Axel Maas

28th of February 2008
Schladming Winter School 2008
Schladming, Austria

UNI GRAZ

Overview

- What is a Gribov copy?
  - The structure of configuration space

Supported by the DFG and the FWF

Overview

- What is a Gribov copy?
  - The structure of configuration space
- The lattice and Gribov copies
  - How can one fight them?

Supported by the DFG and the FWF

Overview

- What is a Gribov copy?
  - The structure of configuration space
- The lattice and Gribov copies
  - How can one fight them?
- Impact on gluonic correlation functions in Landau gauge
  - The quest for the infrared properties
- Summary

Supported by the DFG and the FWF

Gauge-fixing

- QCD is a gauge theory with a Lie-algebra-element valued gauge-field $A_\mu = \tau^a A_\mu^a$

Gauge-fixing

- QCD is a gauge theory with a Lie-algebra-element valued gauge-field $A_\mu = \tau^a A_\mu^a$
  - Gauge transformations change the gauge fields, but leave physics invariant: Gauge orbits

Gauge-fixing

- QCD is a gauge theory with a Lie-algebra-element valued gauge-field $A_\mu = \tau^a A_\mu^a$
  - Gauge transformations change the gauge fields, but leave physics invariant: Gauge orbits
- Correlation functions are in general gauge-dependent
  - Gauge-fixing is required

UNI GRAZ

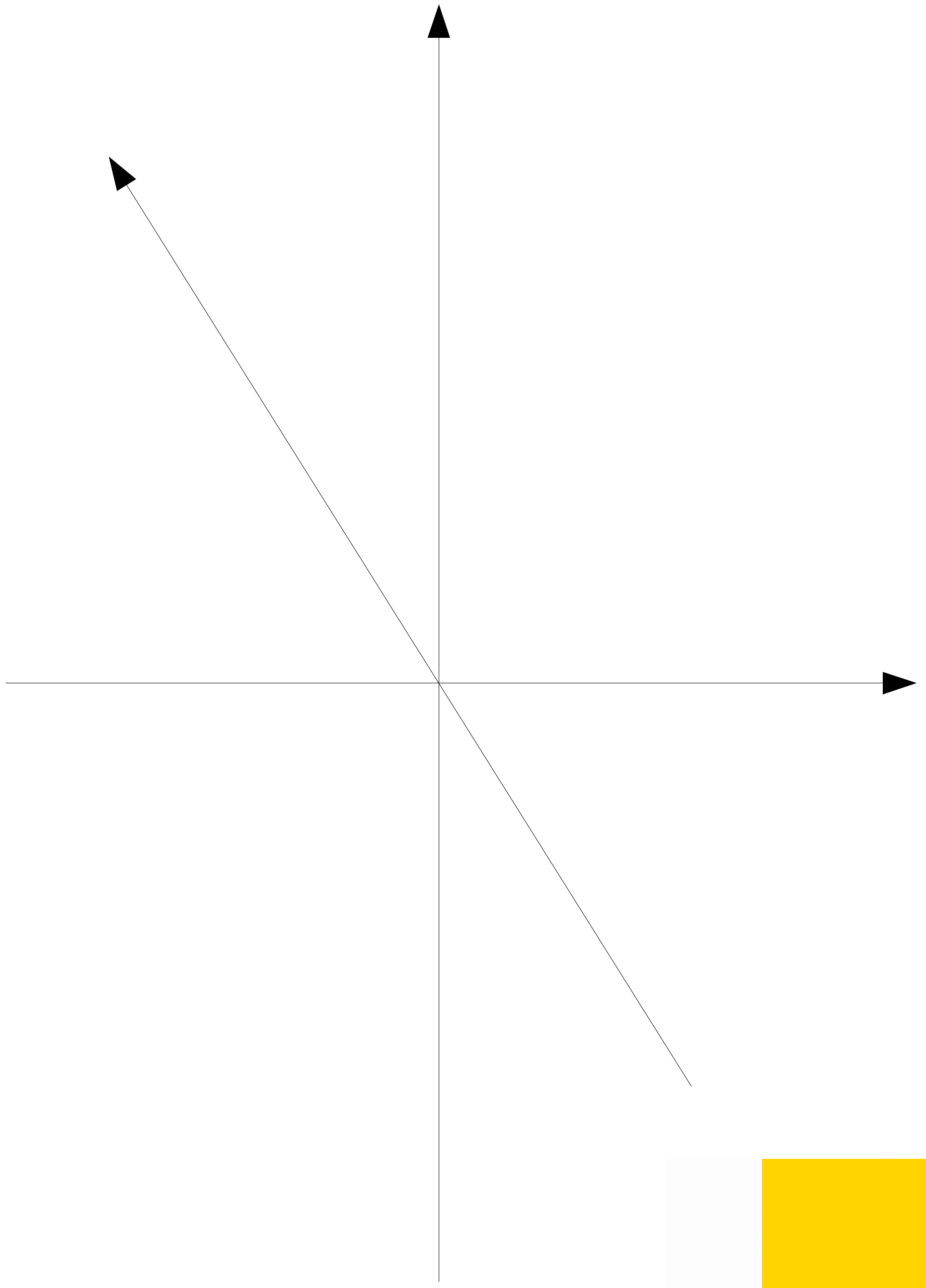
Gauge-fixing

- QCD is a gauge theory with a Lie-algebra-element valued gauge-field $A_\mu = \tau^a A_\mu^a$
  - Gauge transformations change the gauge fields, but leave physics invariant: Gauge orbits
- Correlation functions are in general gauge-dependent
  - Gauge-fixing is required
- Gauge-dependent quantities are interesting
  - Manifestation of confinement mechanism
    - Gribov-Zwanziger scenario
    - Topologial mechanisms

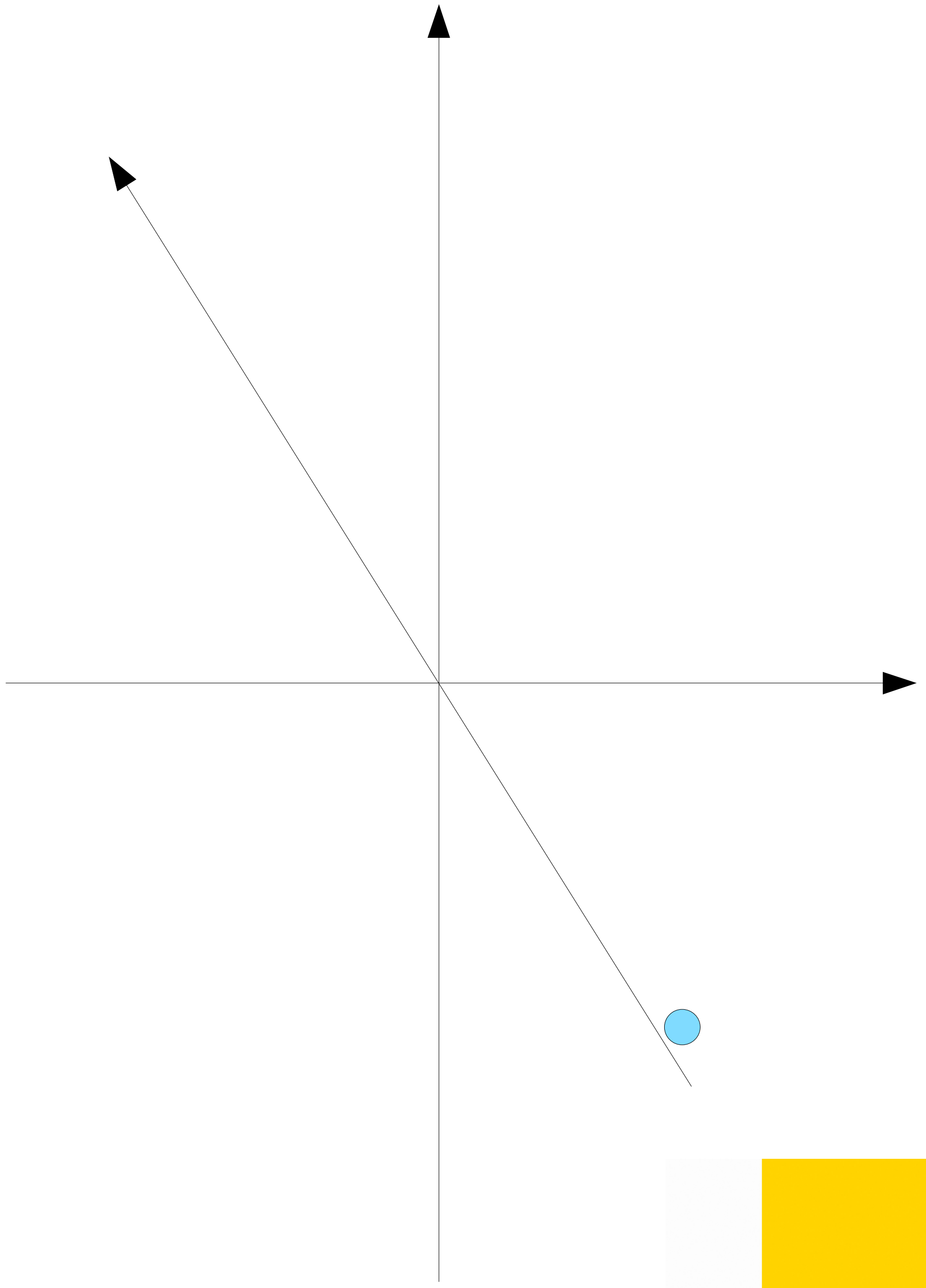
Gauge-fixing

- QCD is a gauge theory with a Lie-algebra-element valued gauge-field $A_\mu = \tau^a A_\mu^a$
  - Gauge transformations change the gauge fields, but leave physics invariant: Gauge orbits
- Correlation functions are in general gauge-dependent
  - Gauge-fixing is required
- Gauge-dependent quantities are interesting
  - Manifestation of confinement mechanism
    - Gribov-Zwanziger scenario
    - Topologial mechanisms
- Need of a well-defined gauge-fixing

Configuration space (artist's view)

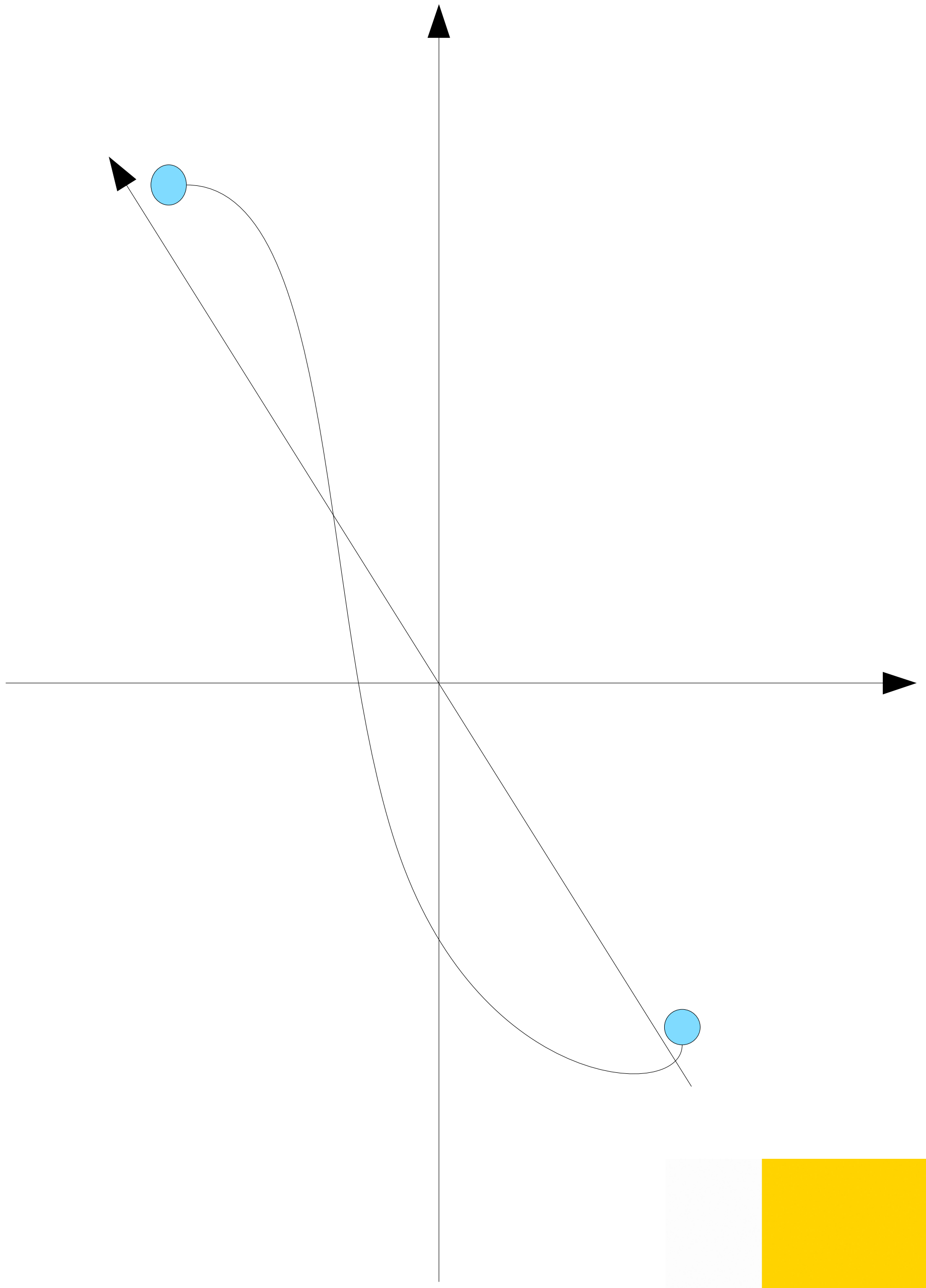


Configuration space (artist's view)



Configuration space (artist's view)

- Gauge fields not unique
  - Gauge transformation does not change physics



Unique gauge-fixing [For an introduction: Sobreiro & Sorella, 2005]

- In perturbation theory: Local gauge condition
  - Landau gauge: $\partial_\mu A_\mu^a = 0$

Unique gauge-fixing [For an introduction: Sobreiro & Sorella, 2005]

- In perturbation theory: Local gauge condition
  - Landau gauge: $\partial_\mu A_\mu^a = 0$
- Sufficient for perturbation theory

Unique gauge-fixing

[For an introduction: Sobreiro & Sorella, 2005]

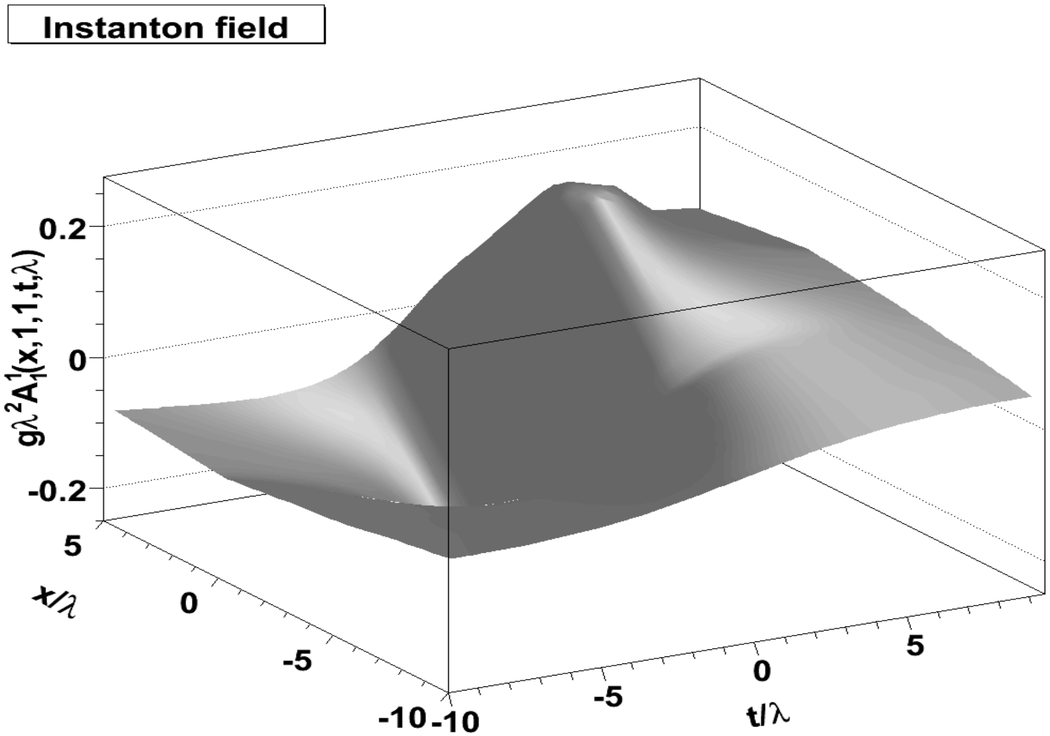
- In perturbation theory: Local gauge condition
  - Landau gauge: $\partial_\mu A_\mu^a = 0$
- Sufficient for perturbation theory
- Insufficient beyond perturbation theory
  - There are gauge-equivalent configurations which obey the same local gauge-condition

Unique gauge-fixing

[For an introduction: Sobreiro & Sorella, 2005]

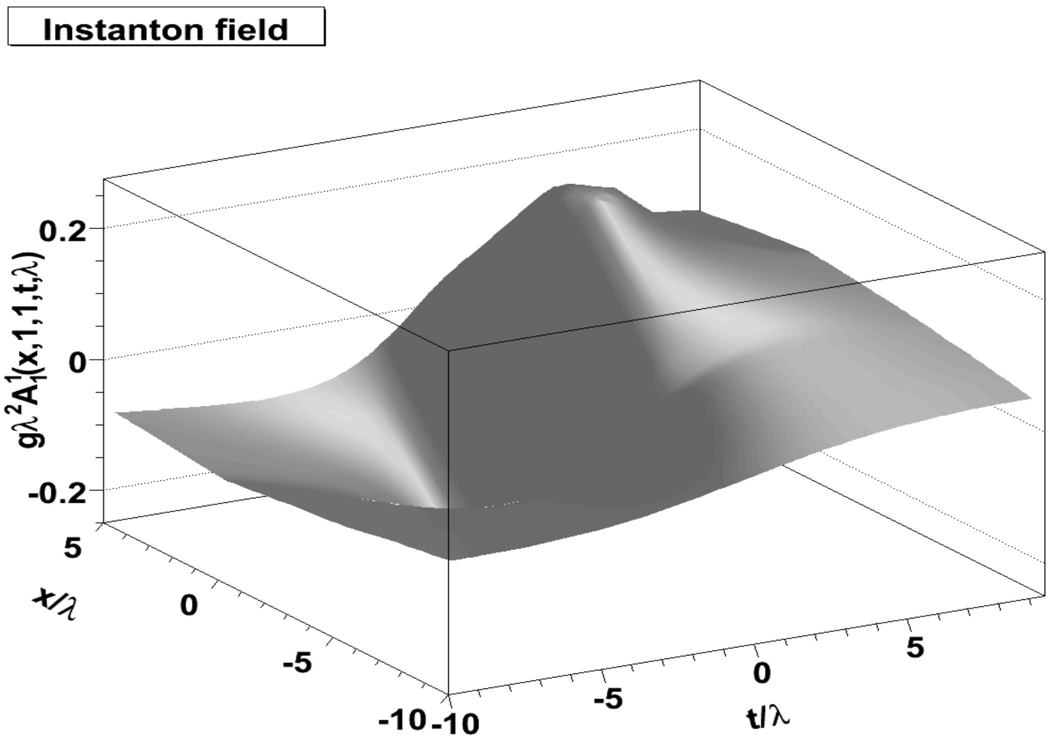
- In perturbation theory: Local gauge condition
  - Landau gauge: $\partial_\mu A_\mu^a = 0$
- Sufficient for perturbation theory
- Insufficient beyond perturbation theory
  - There are gauge-equivalent configurations which obey the same local gauge-condition
- There are no known local gauge conditions, which lead to a unique gauge configuration
  - Non-local conditions possible, but impractical outside lattice gauge theory

Example: Instanton [Maas, EPJC 2006]



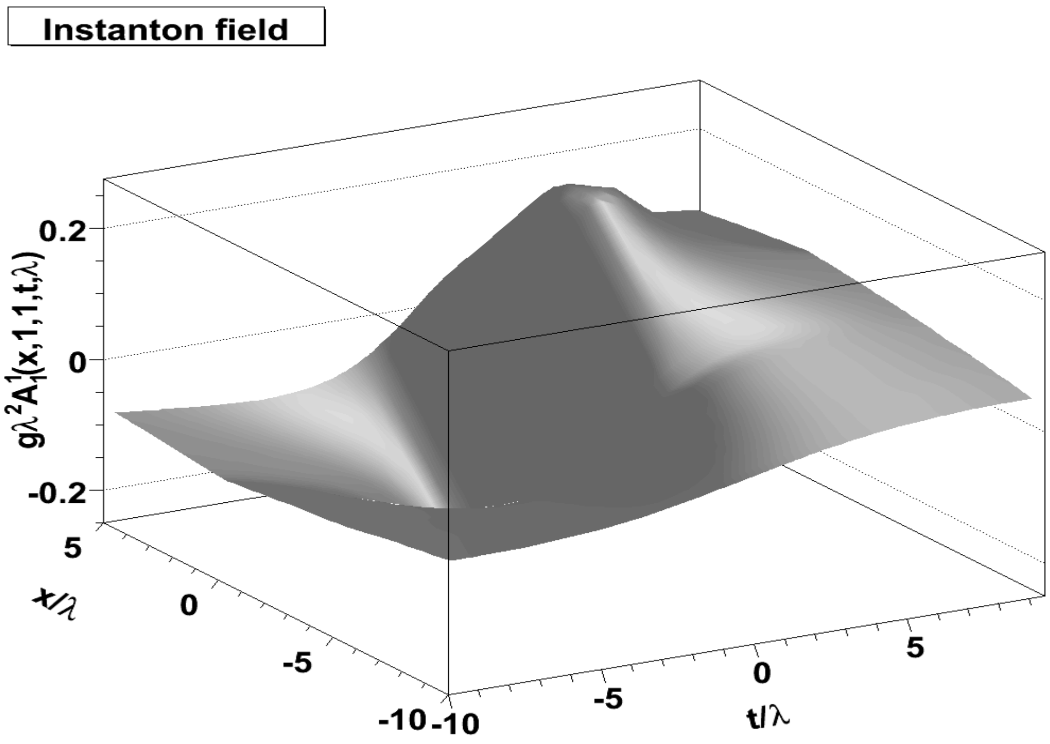
- Instanton field configuration is $A_\mu^a(r,\lambda)=2r_\nu\eta_{\nu\mu}^a/(g(r^2+\lambda^2))$

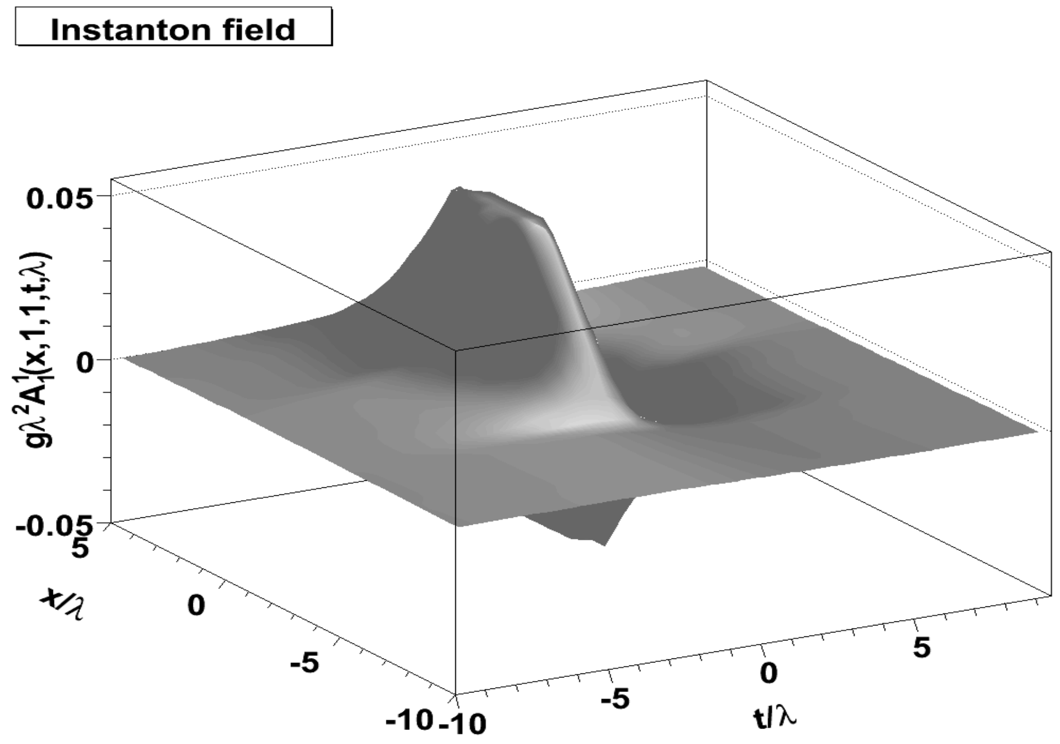
Example: Instanton [Maas, EPJC 2006]



- Instanton field configuration is $A_\mu^a(r,\lambda)=2\mathrm{r}_\nu \eta_{\nu\mu}^a/(g(r^2+\lambda^2))$
  - It is a Landau-gauge configuration, satisfying $\partial_\mu A_\mu^a=0$

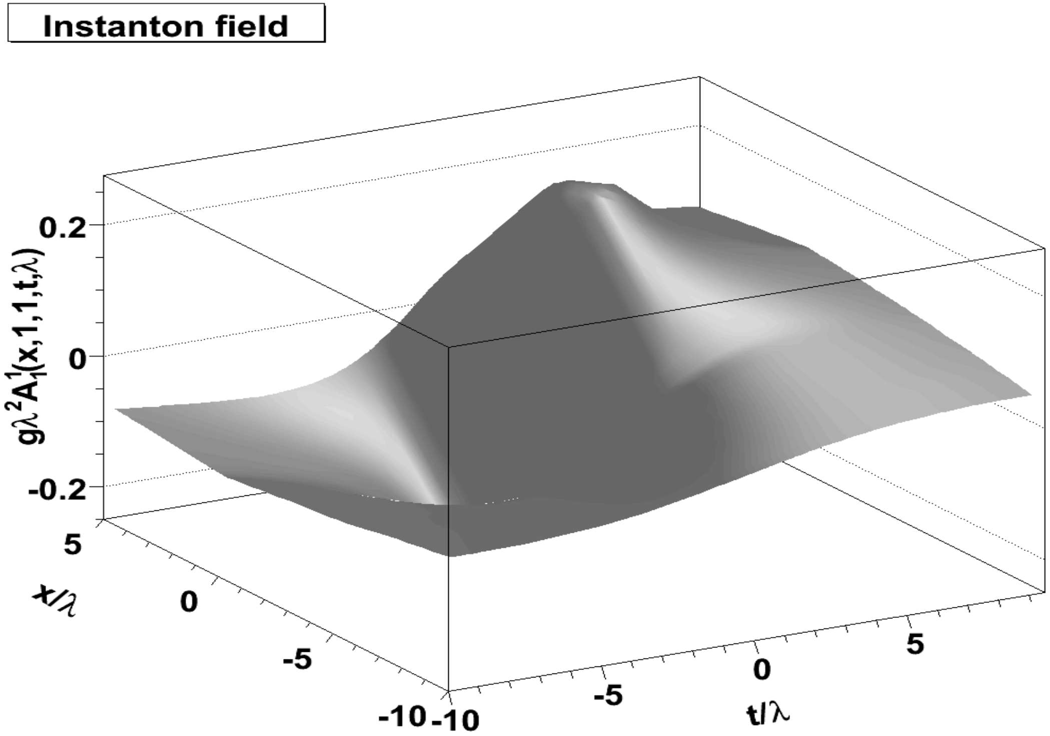
Example: Instanton [Maas, EPJC 2006]

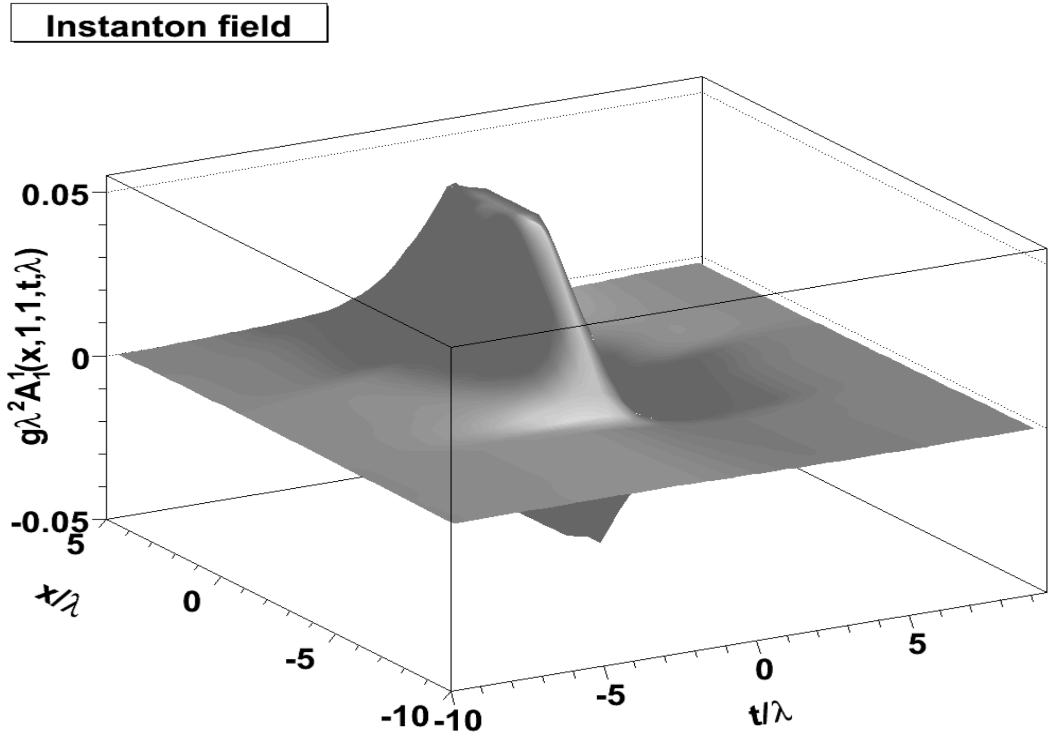




- Gauge transformation to $A_\mu^a(r,\lambda)=-2r_\nu \eta_{\nu\mu}^a \lambda^2/(gr^2(r^2+\lambda^2))$

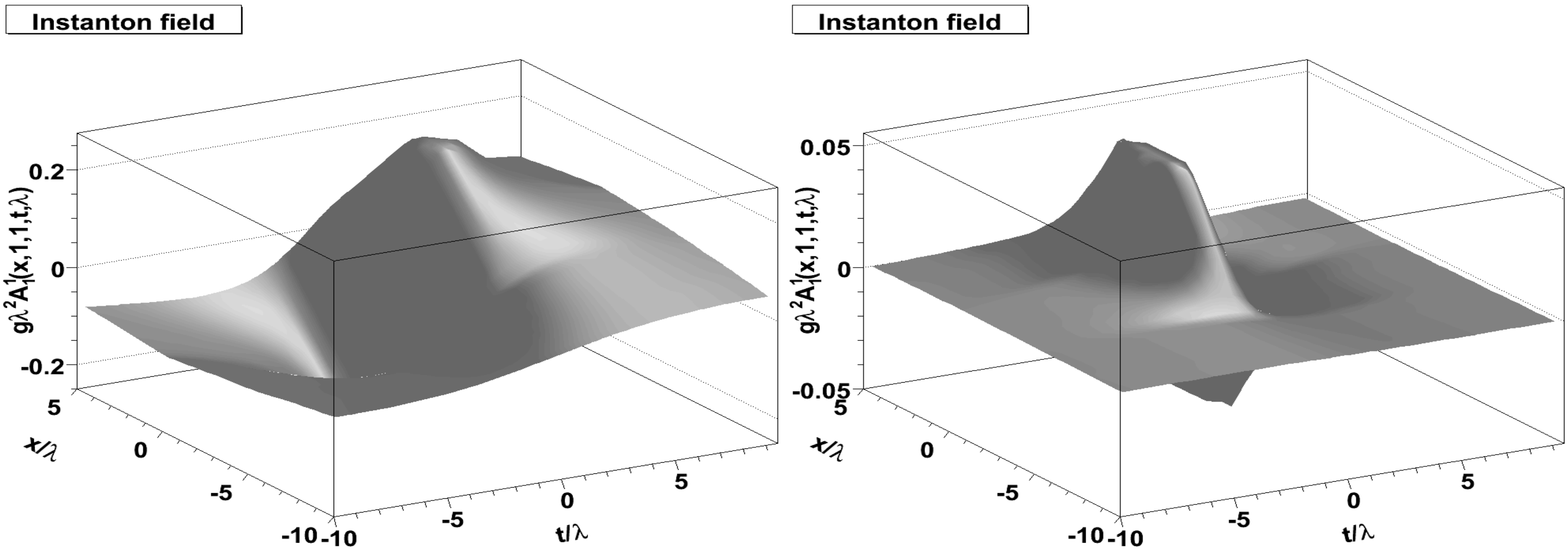
Example: Instanton [Maas, EPJC 2006]





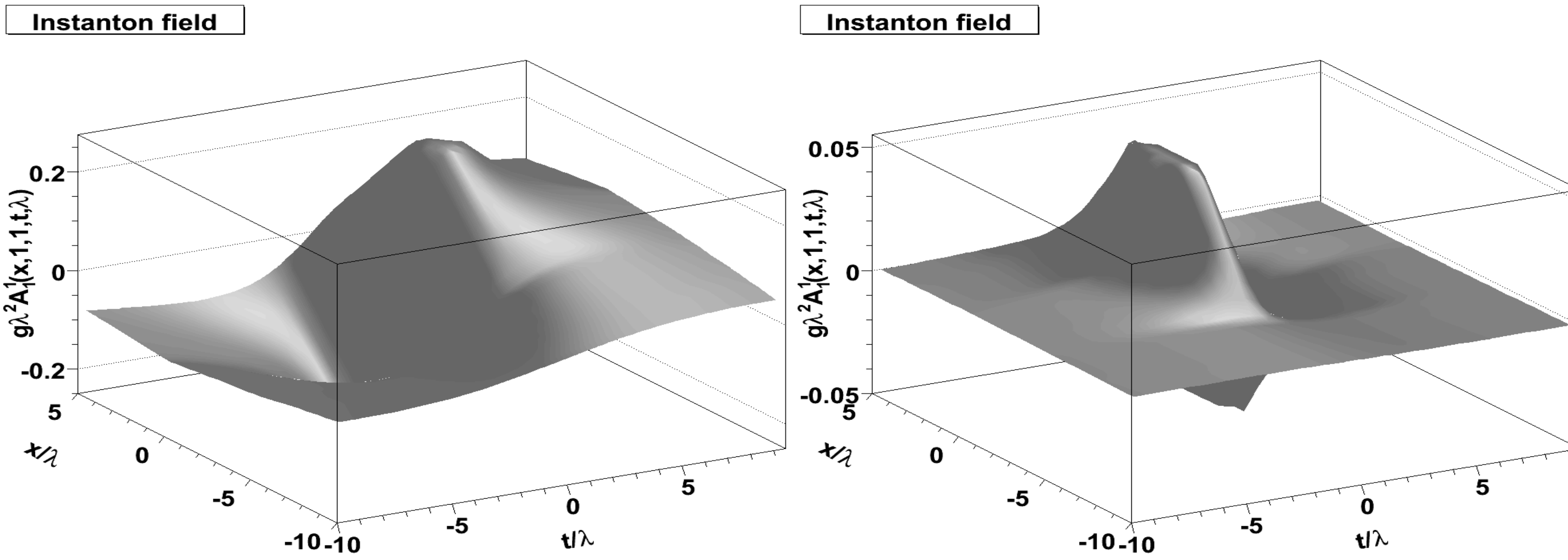
- Gauge transformation to $A_\mu^a(r,\lambda)=-2\mathrm{r}_\nu\eta_{\nu\mu}^a\lambda^2/(gr^2(r^2+\lambda^2))$
  - It is still a Landau gauge configuration!

Example: Instanton [Maas, EPJC 2006]



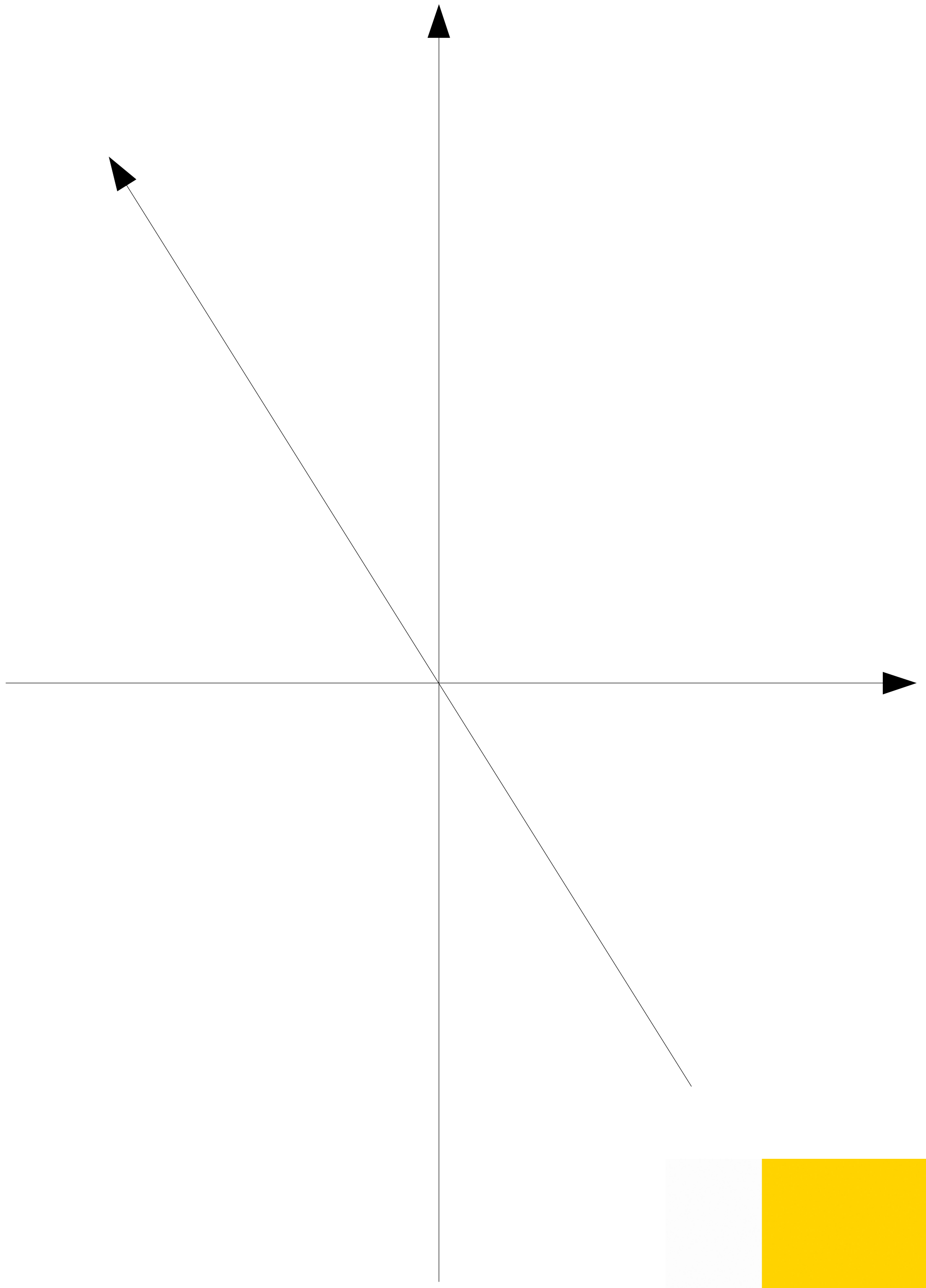
- Gauge transformation to $A_\mu^a(r,\lambda)=-2r_\nu\eta^a_{\nu\mu}\lambda^2/(gr^2(r^2+\lambda^2))$
  - It is still a Landau gauge configuration!
  - Gribov copy

Example: Instanton [Maas, EPJC 2006]



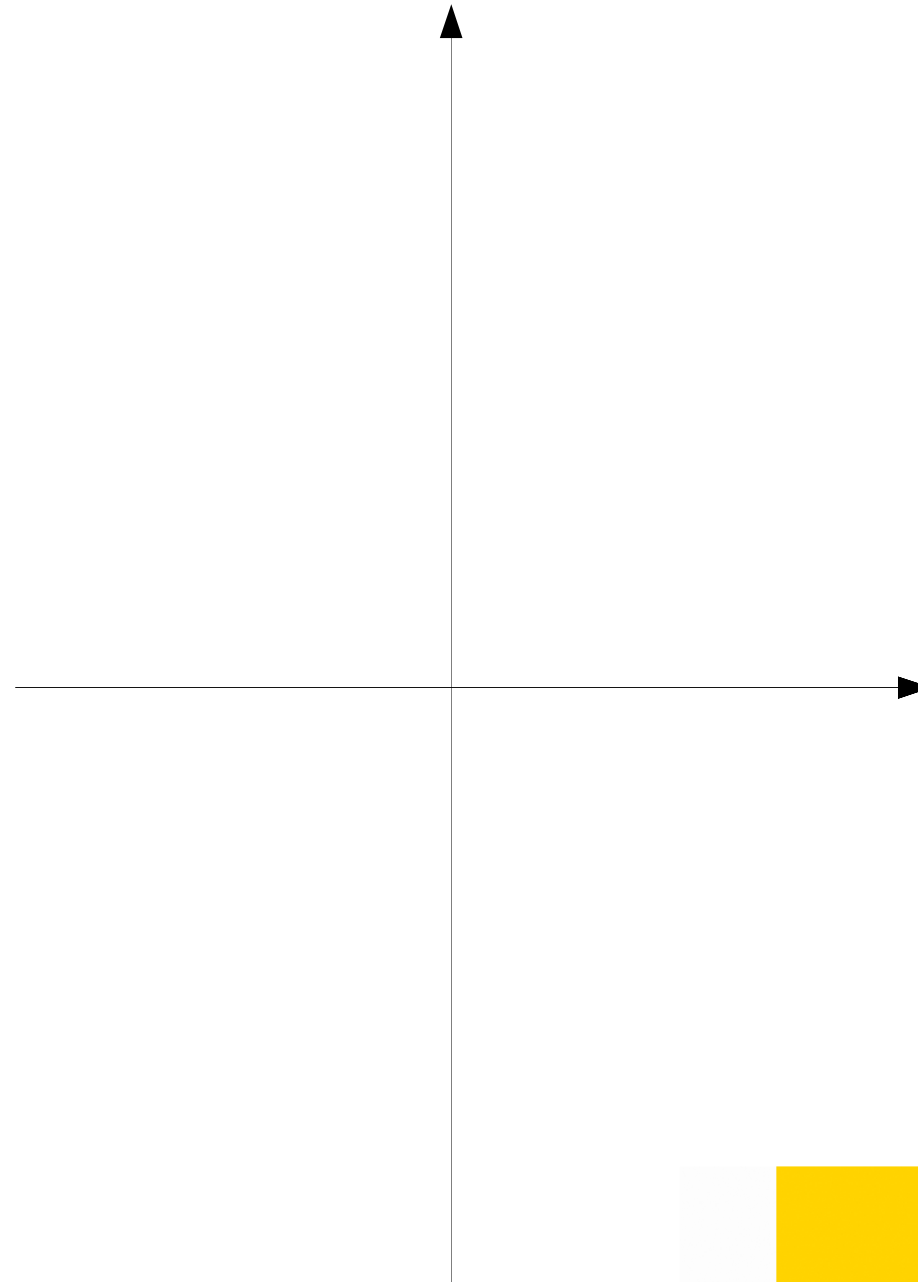
- Gauge transformation to $A_\mu^a(r,\lambda) = -2 r_\nu \eta_{\nu\mu}^a \lambda^2 / (g r^2 (r^2 + \lambda^2))$
  - It is still a Landau gauge configuration!
  - Gribov copy
  - Non-perturbative: Depends on $1/g$

Configuration space (artist's view)



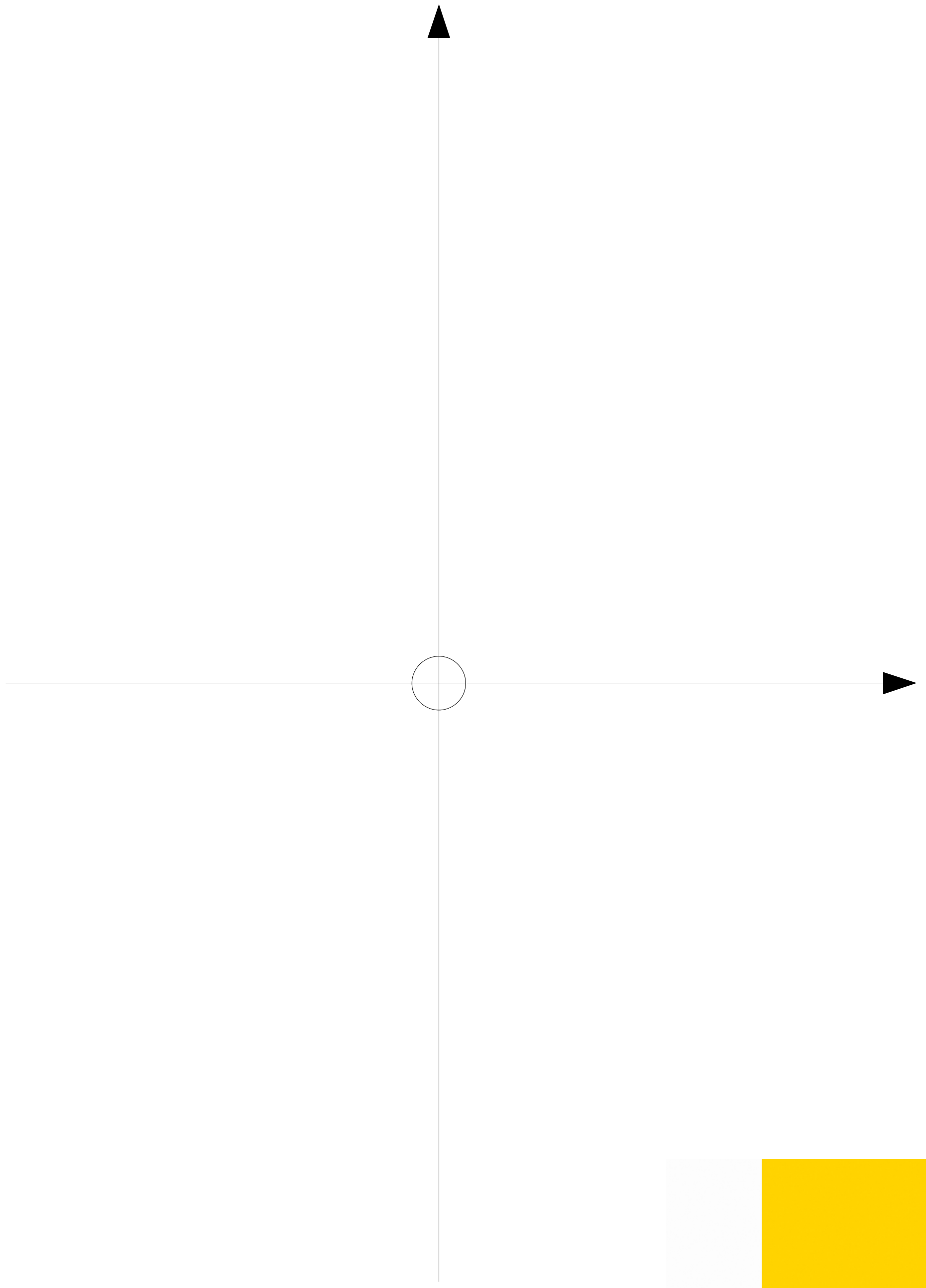
Configuration space (artist's view)

- Impose Landau gauge condition
  - Reduces configuration space to a hypersurface



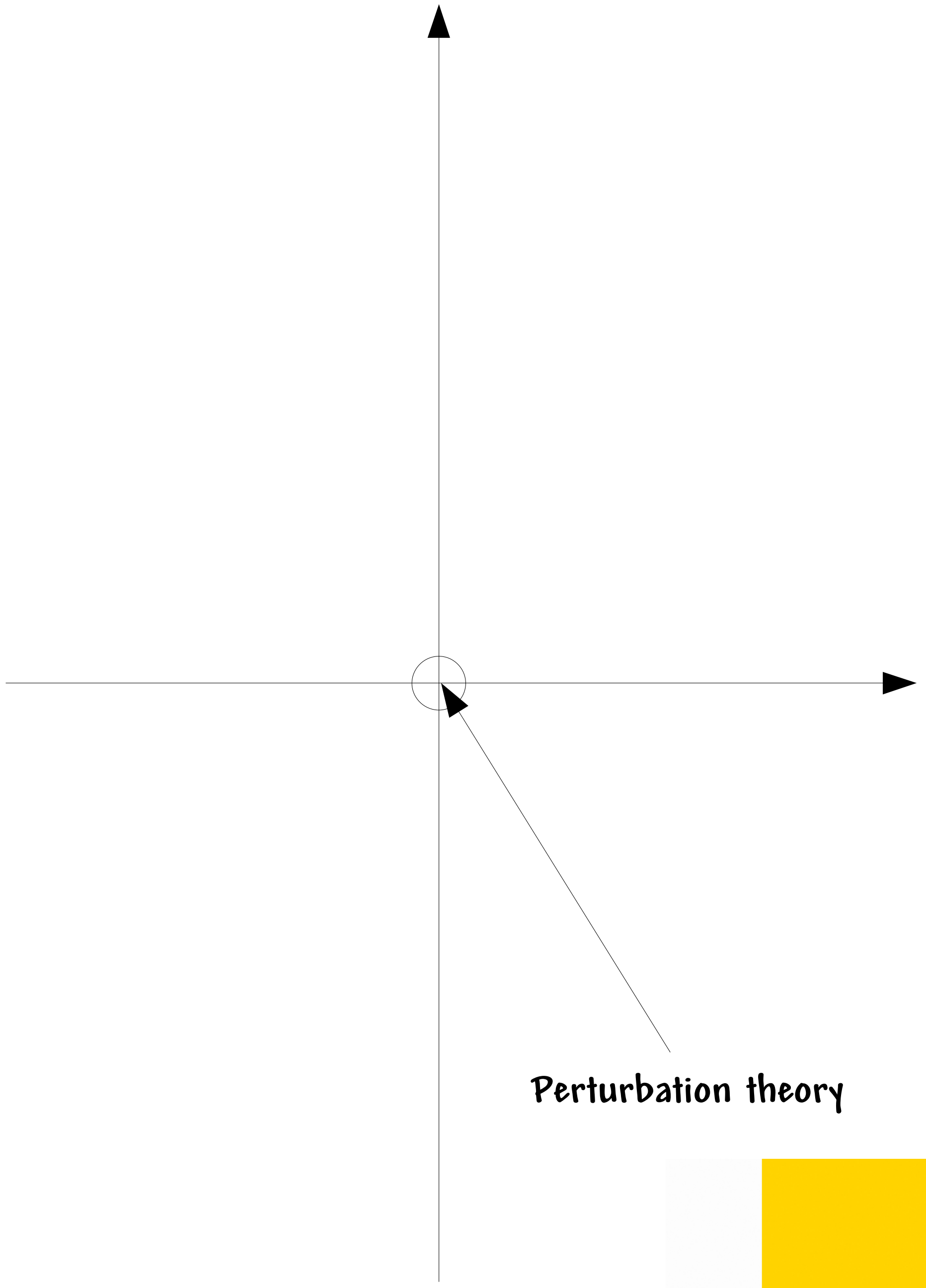
Configuration space (artist's view)

- Local gauge condition is sufficient near the origin
  - Small field fluctuations



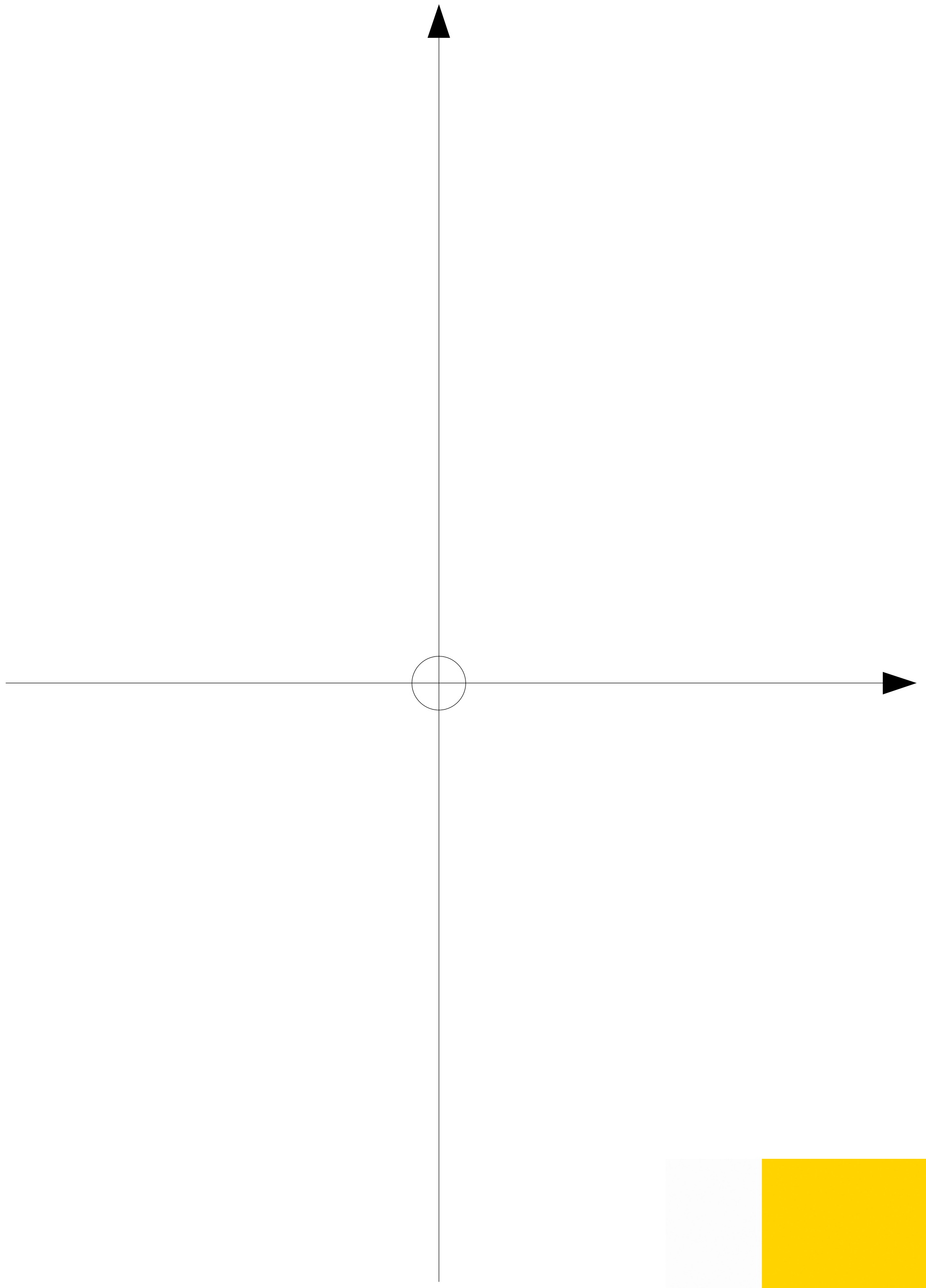
Configuration space (artist's view)

- Local gauge condition is sufficient near the origin
  - Small field fluctuations
  - Domain of perturbation theory



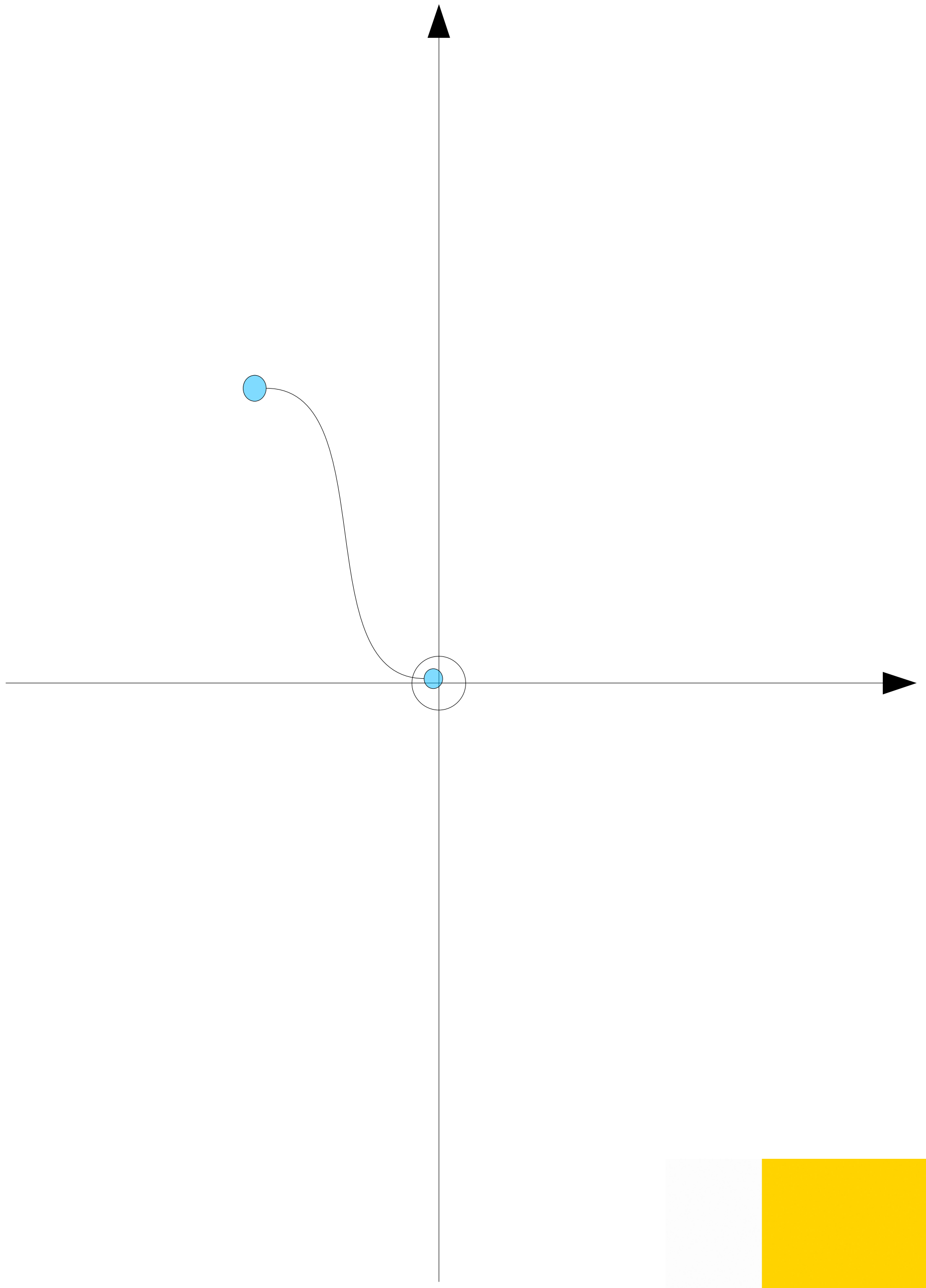
Configuration space (artist's view)

- Non-perturbative calculations probe all of configuration space



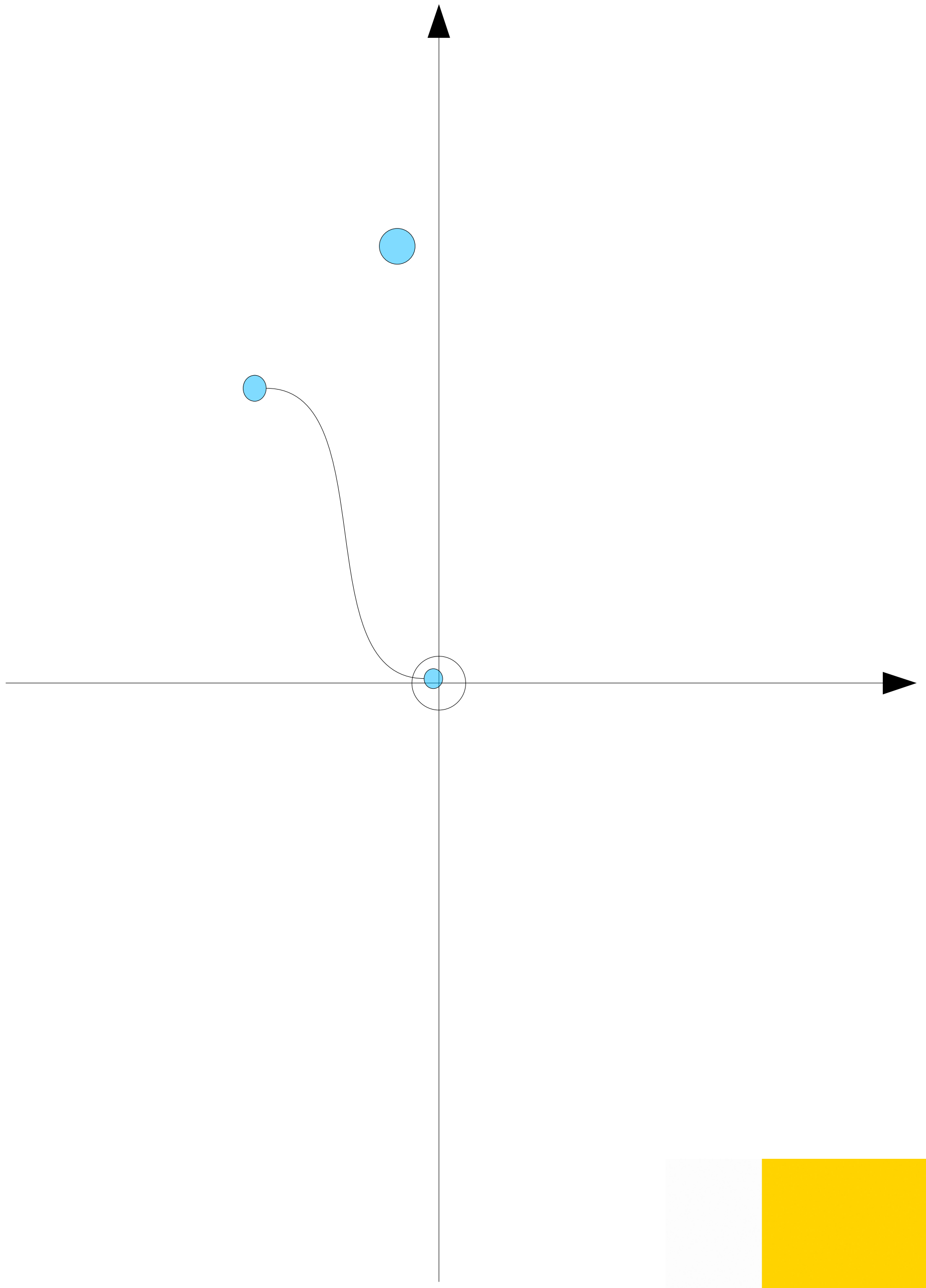
Configuration space (artist's view)

- Non-perturbative calculations probe all of configuration space
  - Gauge fields not small anymore
  - Local gauge condition no longer sufficient to single out one copy



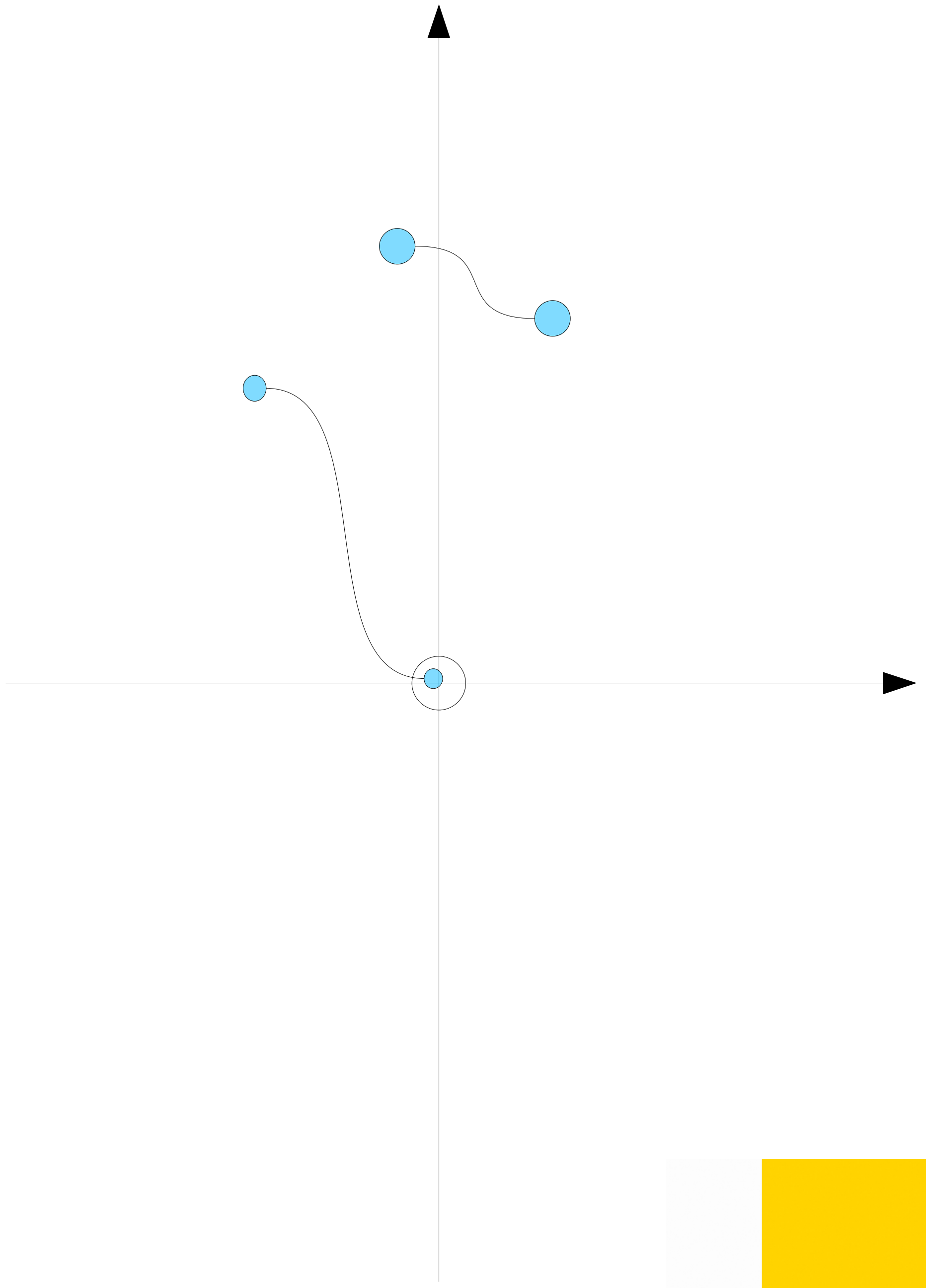
Configuration space (artist's view)

- Non-perturbative calculations probe all of configuration space
  - Gauge fields not small anymore
  - Local gauge condition no longer sufficient to single out one copy
  - The instanton is already outside perturbation theory



Configuration space (artist's view)

- Non-perturbative calculations probe all of configuration space
  - Gauge fields not small anymore
  - Local gauge condition no longer sufficient to single out one copy
  - The instanton is already outside perturbation theory
  - As is its gauge copy



Remedy: Additional constraints

- Non-local supplemental conditions required

Remedy: Additional constraints

- Non-local supplemental conditions required
  - Supply Landau gauge by the requirement that [Zwanziger 1993...2003]

    $$\int d^d x\, A_\mu^a(x)\, A_\mu^a(x)$$

    is an absolute minimum wrt gauge transformations

UNI GRAZ

Remedy: Additional constraints

- Non-local supplemental conditions required
  - Supply Landau gauge by the requirement that [Zwanziger 1993...2003]

    $$\int d^d x\, A_\mu^a(x)\, A_\mu^a(x)$$

    is an absolute minimum wrt gauge transformations

    - Sufficient

Remedy: Additional constraints

- Non-local supplemental conditions required
  - Supply Landau gauge by the requirement that [Zwanziger 1993...2003]

    $$\int d^d x\, A_\mu^a(x)\, A_\mu^a(x)$$

    is an absolute minimum wrt gauge transformations
    - Sufficient
    - Well-defined perturbative limit: Ordinary Landau gauge

Remedy: Additional constraints

- Non-local supplemental conditions required
  - Supply Landau gauge by the requirement that [Zwanziger 1993...2003]

    $$\int d^d x\, A_\mu^a(x) A_\mu^a(x)$$

    is an absolute minimum wrt gauge transformations
    - Sufficient
    - Well-defined perturbative limit: Ordinary Landau gauge
    - Equivalent: Take the gauge field configuration which minimizes the integral of the gluon propagator in momentum space along the gauge orbit

Remedy: Additional constraints

- Non-local supplemental conditions required
  - Supply Landau gauge by the requirement that [Zwanziger 1993...2003]

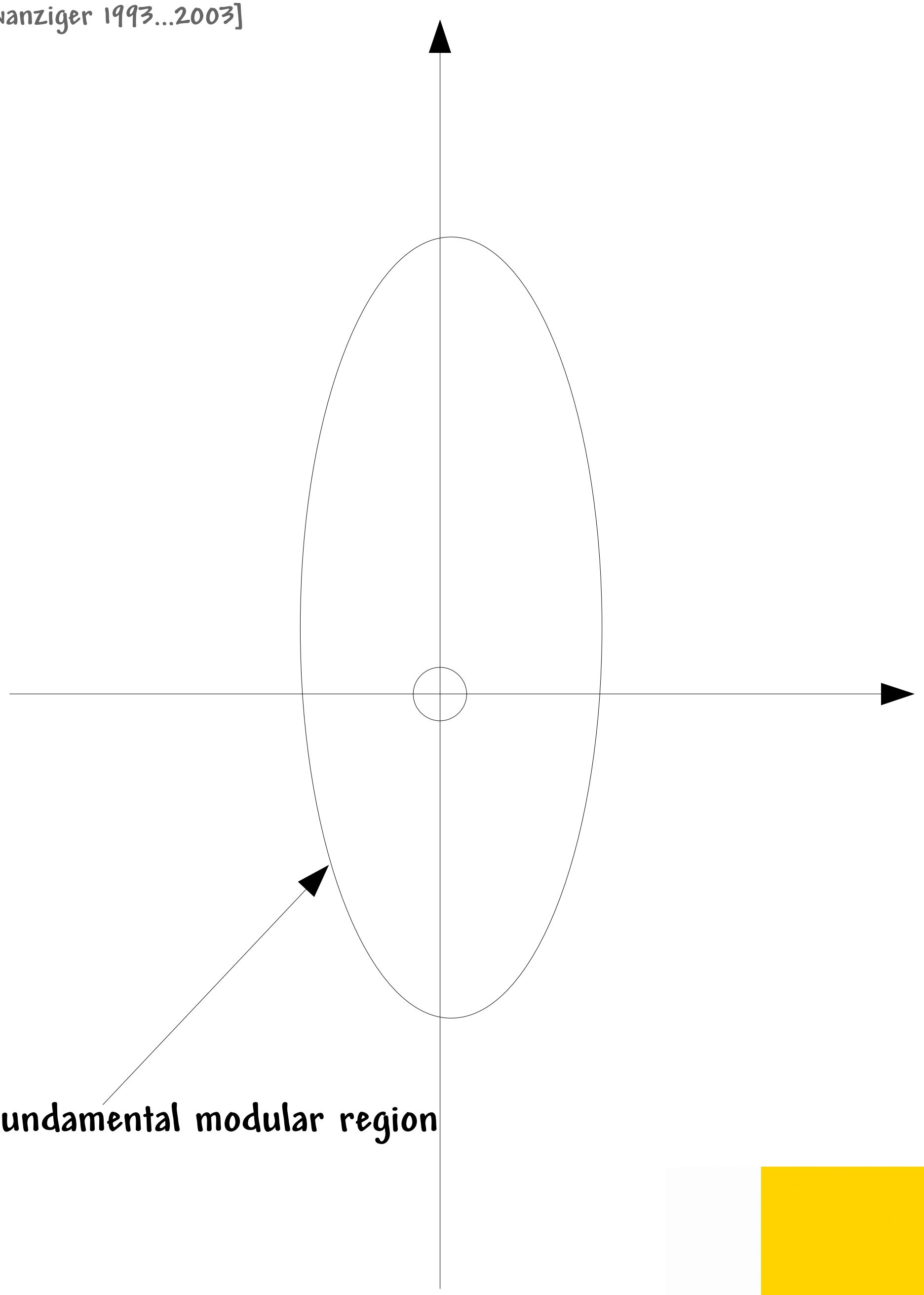
    $$\int d^d x\, A_\mu^a(x)\, A_\mu^a(x)$$

    is an absolute minimum wrt gauge transformations
    - Sufficient
    - Well-defined perturbative limit: Ordinary Landau gauge
    - Equivalent: Take the gauge field configuration which minimizes the integral of the gluon propagator in momentum space along the gauge orbit
- Becomes a hard problem: Spin-glass class

UNI GRAZ

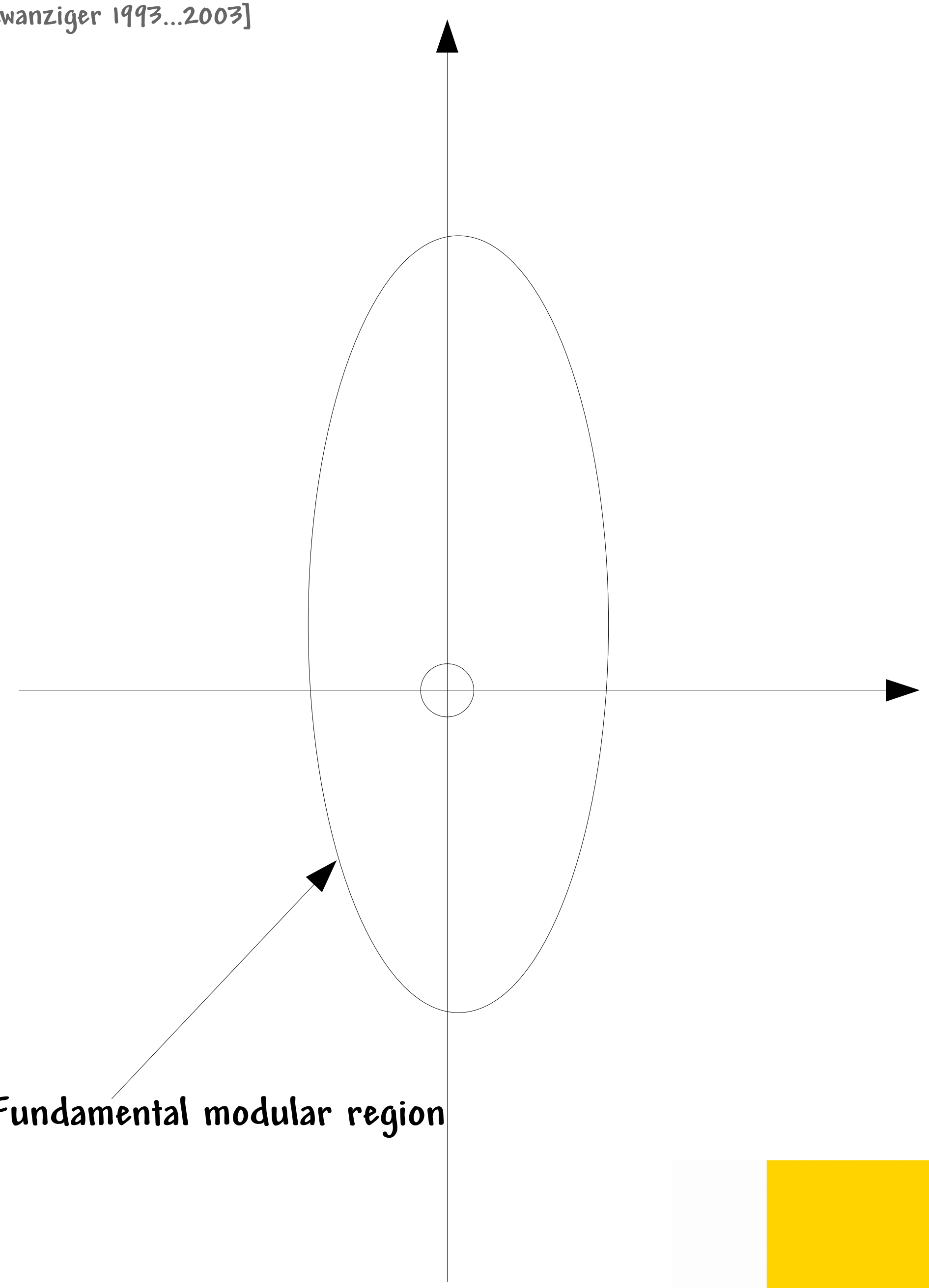
Configuration space (artist's view) [Zwanziger 1993...2003]

- Requiring additionally an absolute minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ defines the fundamental modular region



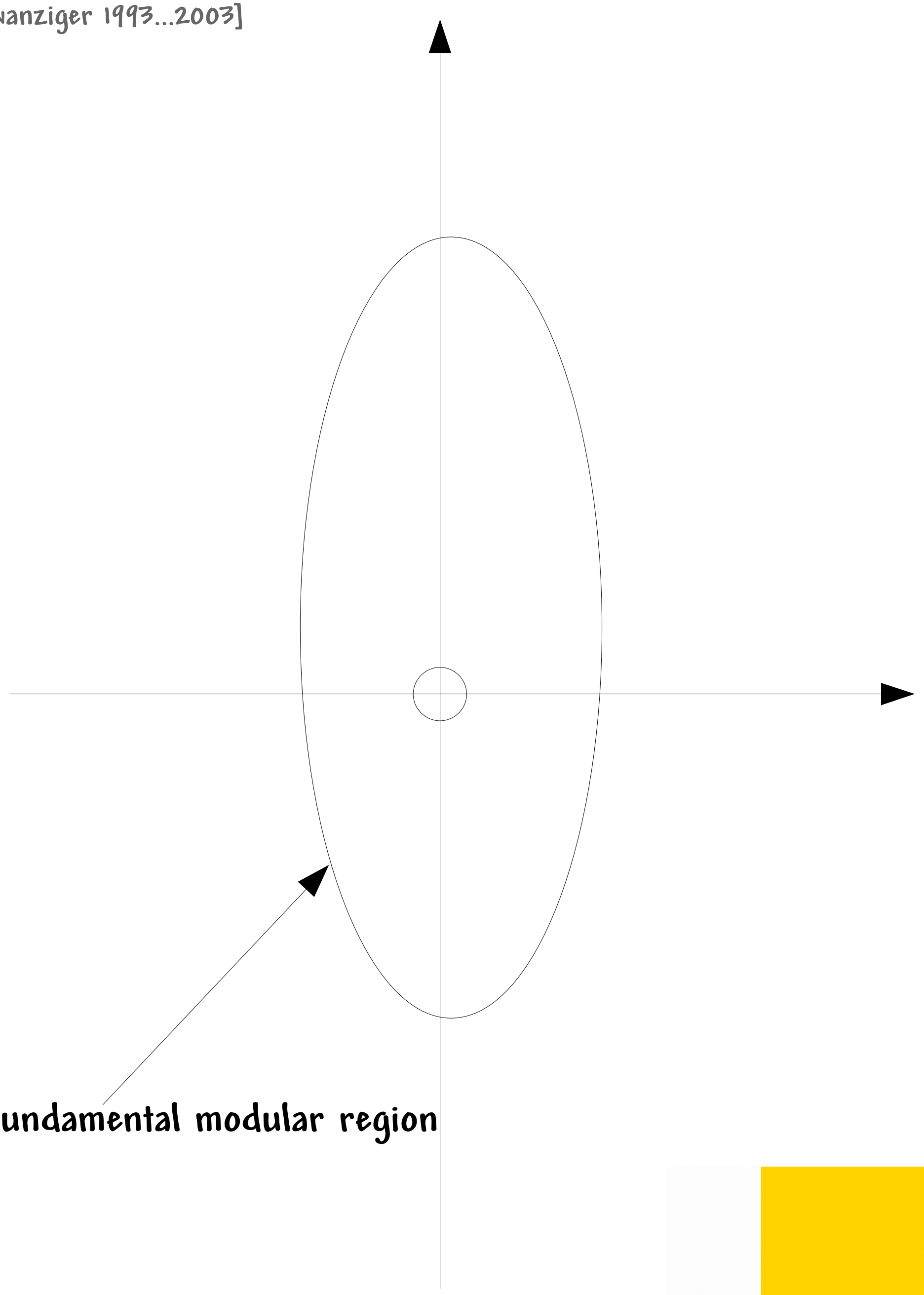
Configuration space (artist's view) [Zwanziger 1993...2003]

- Requiring additionally an absolute minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ defines the fundamental modular region
- Inside this region is one and only one representative of all physically equivalent field configurations



Configuration space (artist's view) [Zwanziger 1993...2003]

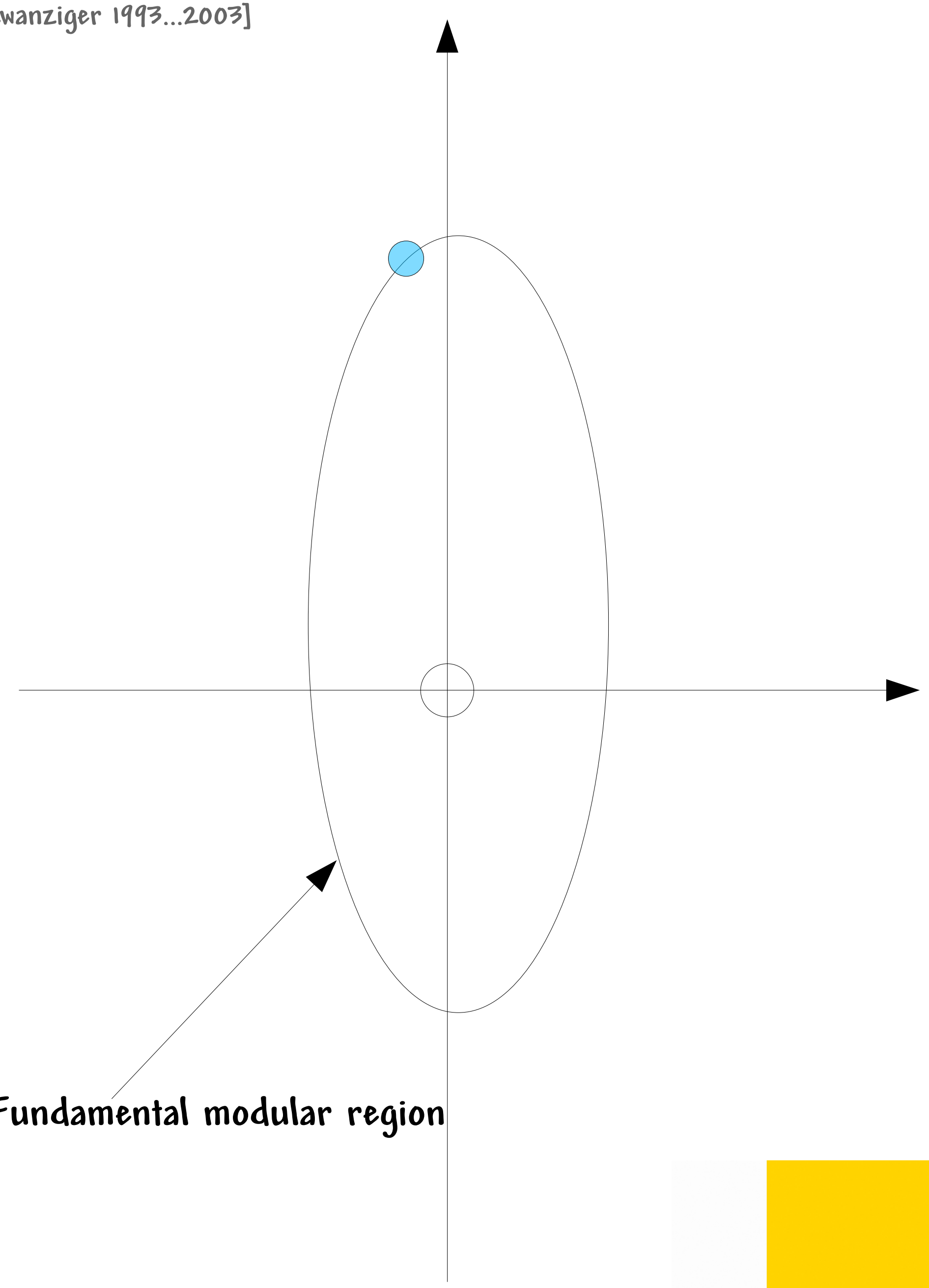
- Requiring additionally an absolute minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ defines the fundamental modular region
- Inside this region is one and only one representative of all physically equivalent field configurations
- It encloses the origin and the domain of perturbation theory
- It is compact



Configuration space (artist's view) [Zwanziger 1993...2003]

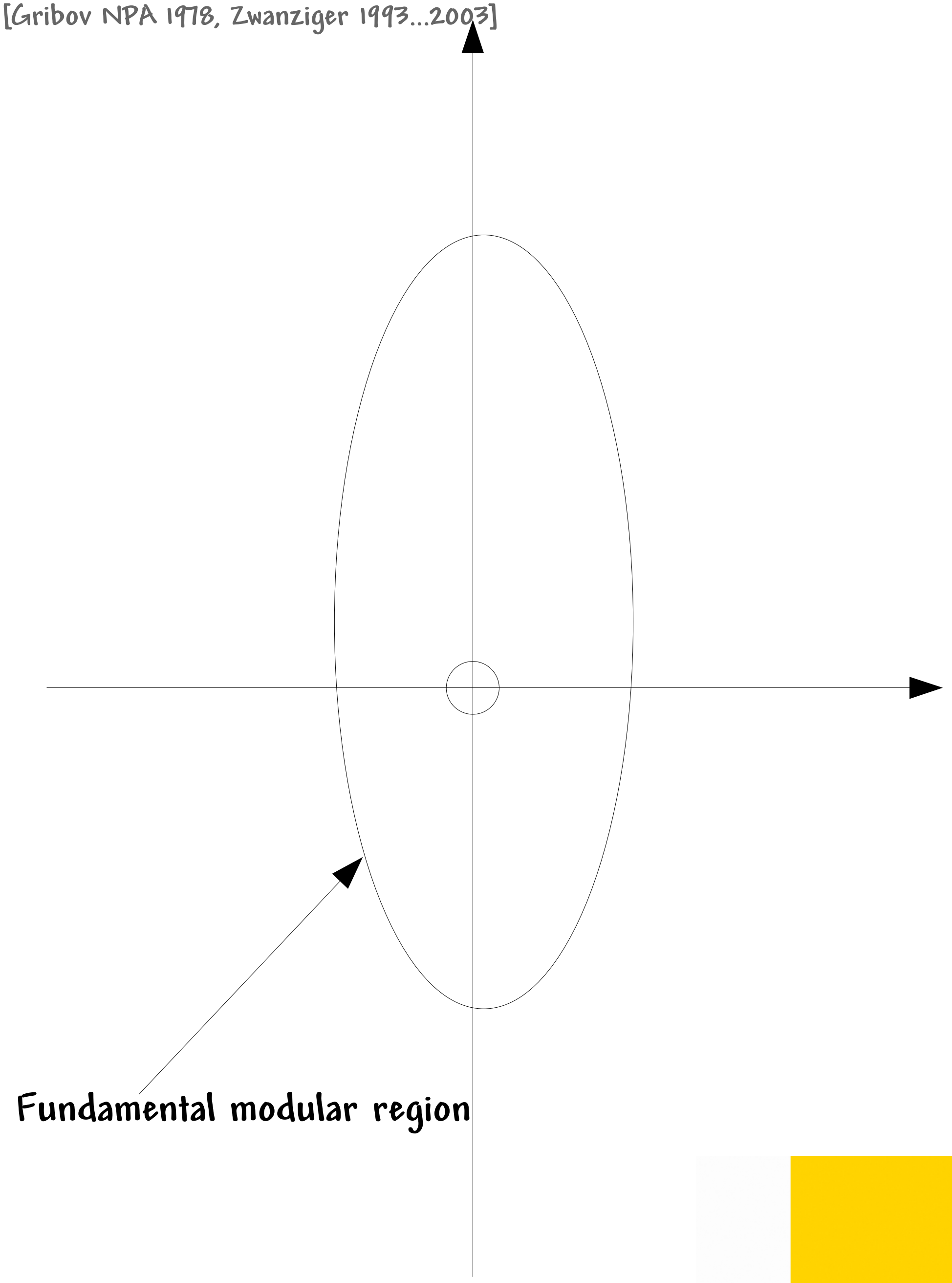
- Requiring additionally an absolute minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ defines the fundamental modular region
- Inside this region is one and only one representative of all physically equivalent field configurations
- It encloses the origin and the domain of perturbation theory
- It is compact
- The instanton lies on its boundary

  [Maas, EPJC 2006]



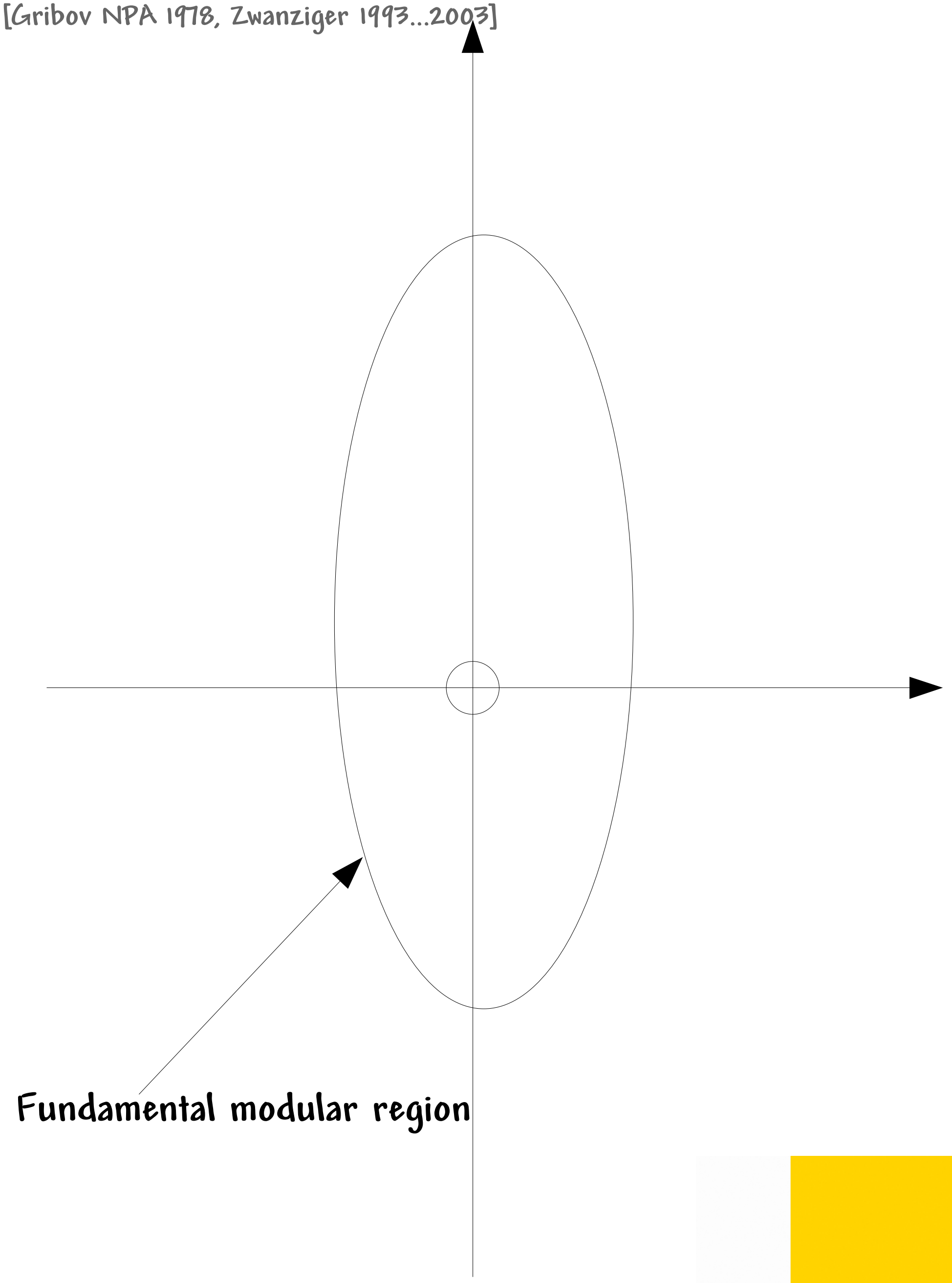
Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

- Finding a local minimum of $\int d^d x A_\mu^a(x) A_\mu^a(x)$ is much simpler



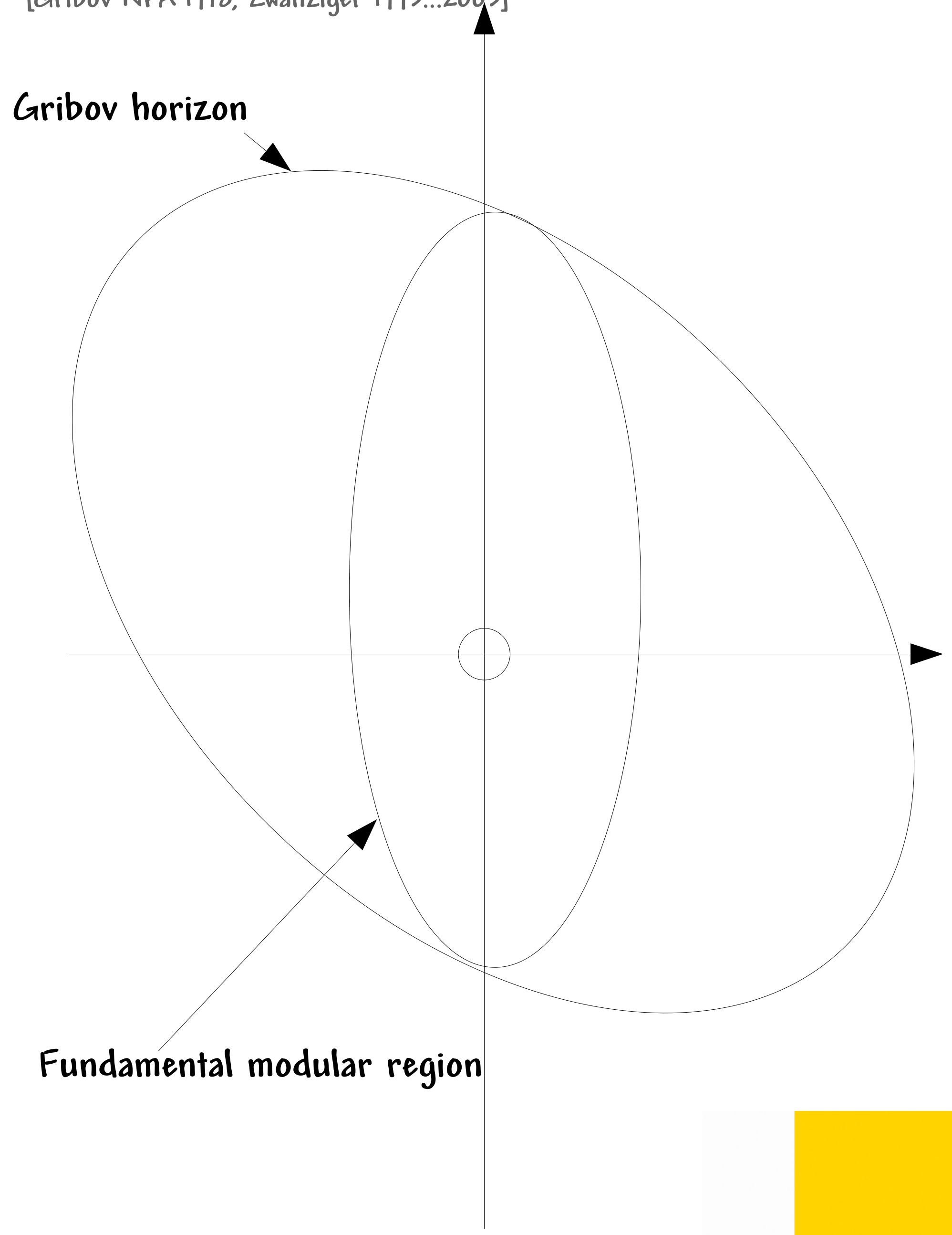
Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

- Finding a local minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ is much simpler
- It is also rather simple to find a local minimum, which in addition is characterized by the positive semi-definiteness of the Faddeev-Popov operator
  - In Landau-gauge defined as $-\partial_\mu(\partial_\mu - g A_\mu)$



Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

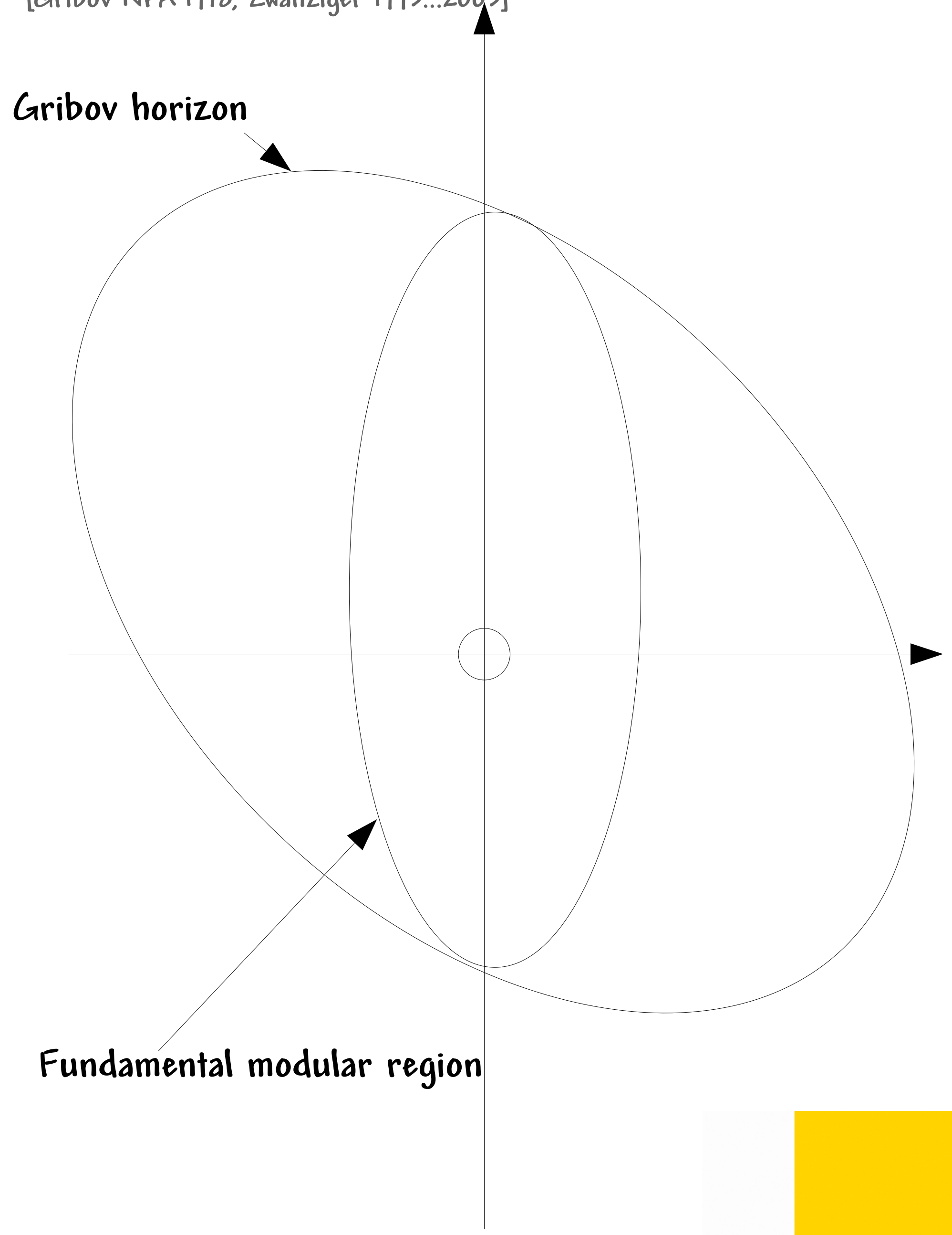
- Finding a local minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ is much simpler
- It is also rather simple to find a local minimum, which in addition is characterized by the positive semi-definiteness of the Faddeev-Popov operator
  - In Landau-gauge defined as $-\partial_\mu(\partial_\mu - g A_\mu)$
- This defines the first Gribov region, enclosed by the Gribov horizon



UNI GRAZ

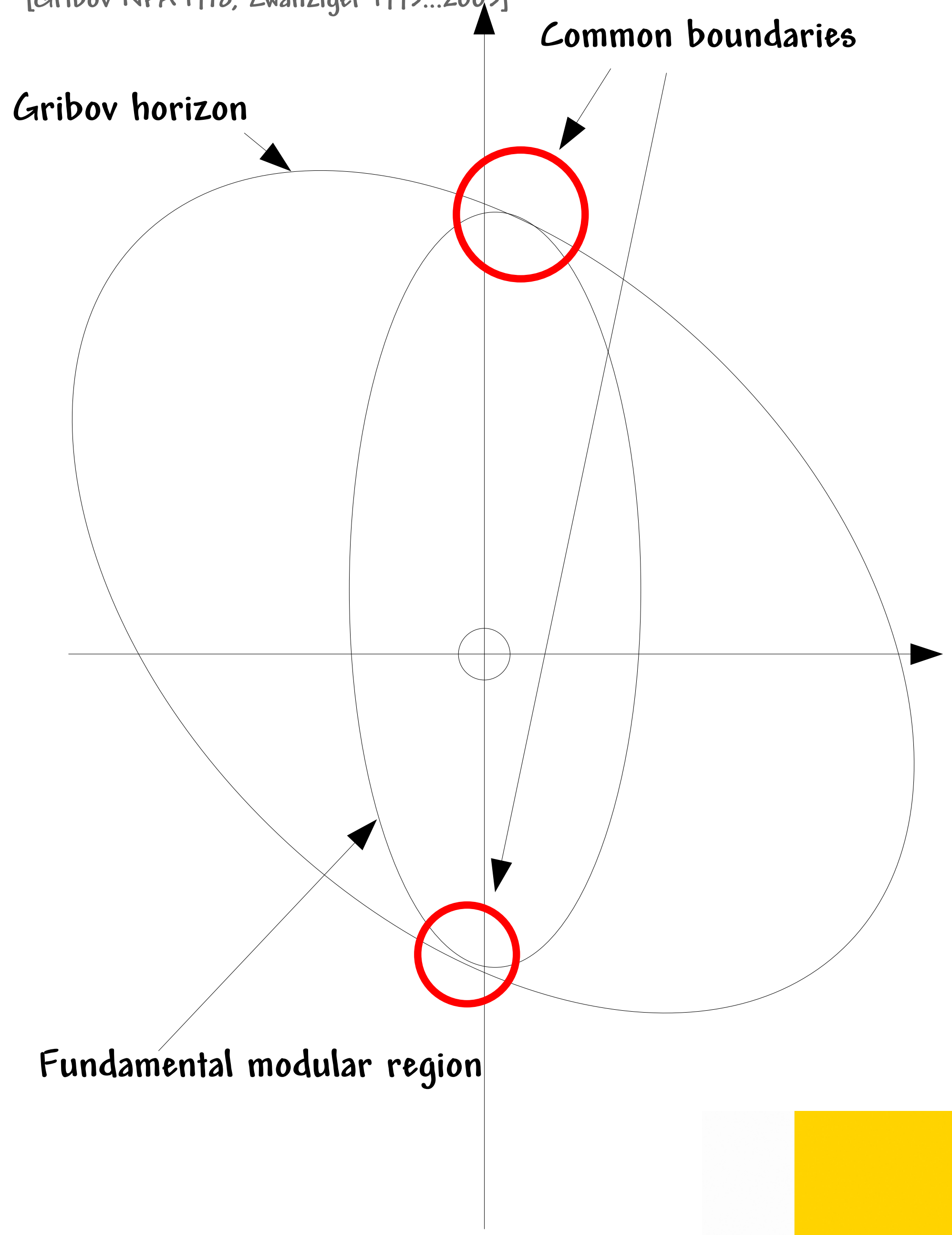
Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

- Finding a local minimum of $\int d^d x\, A_\mu^a(x) A_\mu^a(x)$ is much simpler
- It is also rather simple to find a local minimum, which in addition is characterized by the positive semi-definiteness of the Faddeev-Popov operator
    - In Landau-gauge defined as $-\partial_\mu(\partial_\mu - g A_\mu)$
- This defines the first Gribov region, enclosed by the Gribov horizon
- It encloses the fundamental modular region and is compact and convex



Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

- Both have partly a common boundary
  - From this fact the Gribov-Zwanziger scenario of confinement is constructed

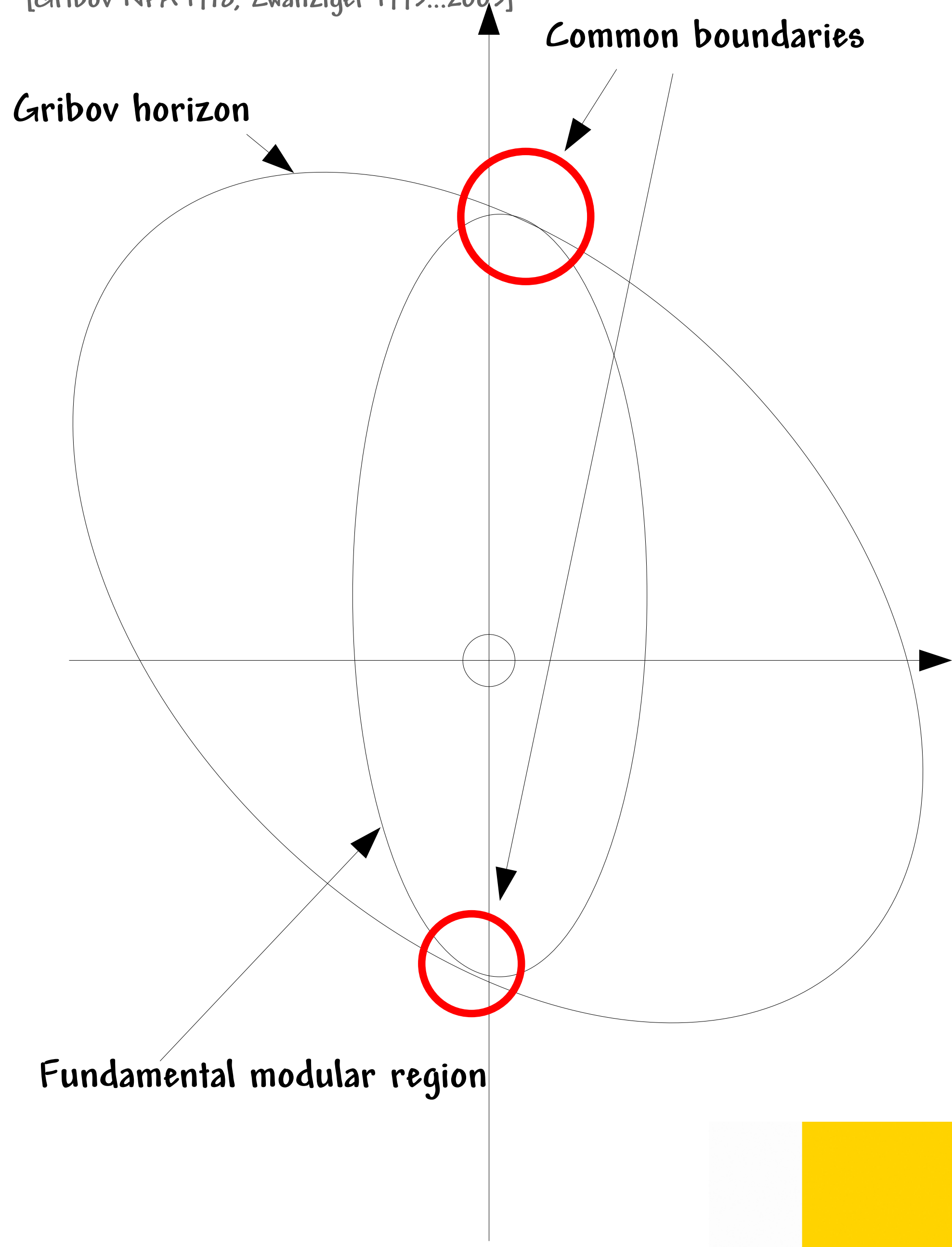


Configuration space (artist's view) [Gribov NPA 1978, Zwanziger 1993...2003]

- Both have partly a common boundary
  - From this fact the Gribov-Zwanziger scenario of confinement is constructed
- Zwanziger-conjecture: [Zwanziger PRD 2003]

$$<O>_{Gribov\,reg.} = <O>_{Fund.\,mod.\,reg.}$$

  - If O is a finite product
  - If the volume is infinite
  - Could solve the problem



Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem

Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem
  - Minimize $\sum_{x,\mu}(1-\Re(tr(\exp(i A_\mu(x)))))$

Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem
  - Minimize $\sum_{x,\mu}(1-\Re(tr(\exp(i A_\mu(x)))))\sim\sum_x A_\mu^a(x) A_\mu^a(x)+O(a^2)$

Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem
  - Minimize $\sum_{x,\mu}(1-\Re(tr(\exp(i A_\mu(x)))))\sim\sum_x A_\mu^a(x)A_\mu^a(x)+O(a^2)$
    - Guarantees to be inside the first Gribov horizon

Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem
  - Minimize $\sum_{x,\mu}(1-\Re(tr(\exp(i A_\mu(x)))))\sim\sum_x A_\mu^a(x) A_\mu^a(x)+O(a^2)$
    - Guarantees to be inside the first Gribov horizon
- In practice a finite volume: Need to find the absolute minimum

Gauge-fixing on the lattice

- Take the requirement of finding an absolute minimum literally by recasting (Landau-) gauge-fixing into a minimization problem
  - Minimize $\sum_{x,\mu}(1-\Re(tr(\exp(i A_\mu(x)))))\sim\sum_x A_\mu^a(x)A_\mu^a(x)+O(a^2)$
    - Guarantees to be inside the first Gribov horizon
- In practice a finite volume: Need to find the absolute minimum
  - Numerically highly complicated and unsolved
    - Various approximate approaches have been developed
      - Mostly used: Restart algorithms
      - Here: Evolutionary algorithm

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations
  - Randomly generated, but still to local Landau gauge inside the first Gribov horizon

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix existing ones
  - Take two, which belong to the more successful population
    - Lower minimum of the gauge-fixing functional
  - Create a new one, by taking half the elements from one and the other one from the other
    - Random, which element is from which

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix/change existing ones
    - Create a new gauge transformation by changing a copy of a successful gauge transformation randomly at a random number of points in space-time – point mutations

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix/change existing ones and discard ineffective ones
  - The half of the ancestor generation with the hightes local minima
  - This half is replaced by the new/mixed/changed ones

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix/change existing ones and discard ineffective ones to get a new generation

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix/change existing ones and discard ineffective ones to get a new generation
- Repeat, until no improvement is found in a new generation

Evolutionary algorithm [Maas, unpublished]

- Interpret a gauge transformation as the genetic code
- Begin with a population of gauge transformations to local Landau gauge into the first Gribov region
- Add new gauge transformations and mix/change existing ones and discard ineffective ones to get a new generation
- Repeat, until no improvement is found in a new generation
- Not guaranteed to find the absolute minimum
  - But a very successful approach in many applications
  - Requires for optimization more knowledge on the shape of local and absolute minima

Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists

Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists
- Measure the difference D between the shallowest and deepest minimum found
  - Correlates acceptable with the impact on correlation functions

Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists
- Measure the difference D between the shallowest and deepest minimum found
  - Correlates acceptable with the impact on correlation functions
- Dependence on volume, discretization and dimensionality

Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists
- Measure the difference D between the shallowest and deepest minimum found
  - Correlates acceptable with the impact on correlation functions
- Dependence on volume, discretization and dimensionality
  - Number of Gribov copies grows exponentially with volume

    [Zwanziger 1993...2003]

Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists
- Measure the difference D between the shallowest and deepest minimum found
  - Correlates acceptable with the impact on correlation functions
- Dependence on volume, discretization and dimensionality
  - Number of Gribov copies grows exponentially with volume [Zwanziger 1993...2003]
  - Nearly no measurable impact of Gibov copies in 2d [Maas, unpublished]

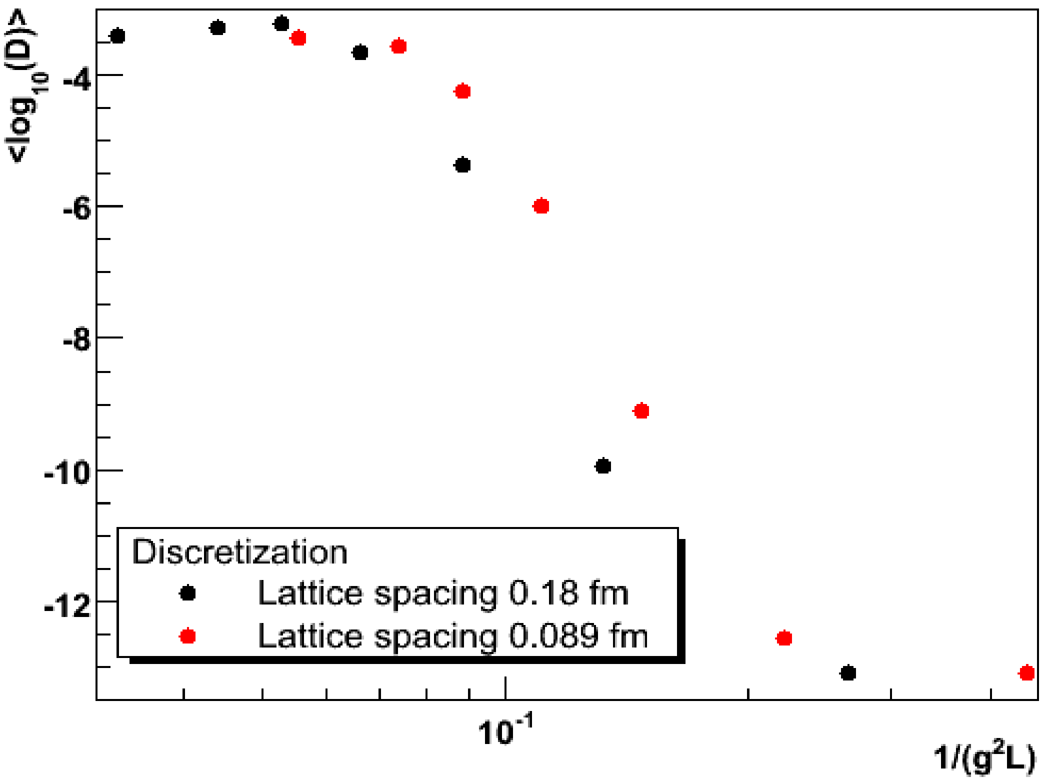
Artifact-dependence of Gribov-copies

- Correct solution unknown - no reliable measure of gauge-fixing quality exists
- Measure the difference D between the shallowest and deepest minimum found
  - Correlates acceptable with the impact on correlation functions
- Dependence on volume, discretization and dimensionality
  - Number of Gribov copies grows exponentially with volume [Zwanziger 1993...2003]
  - Nearly no measurable impact of Gibov copies in 2d [Maas, unpublished]
  - Significant impact in 3d and higher dimensions
    - 3d results here for the sake of computing time

UNI GRAZ

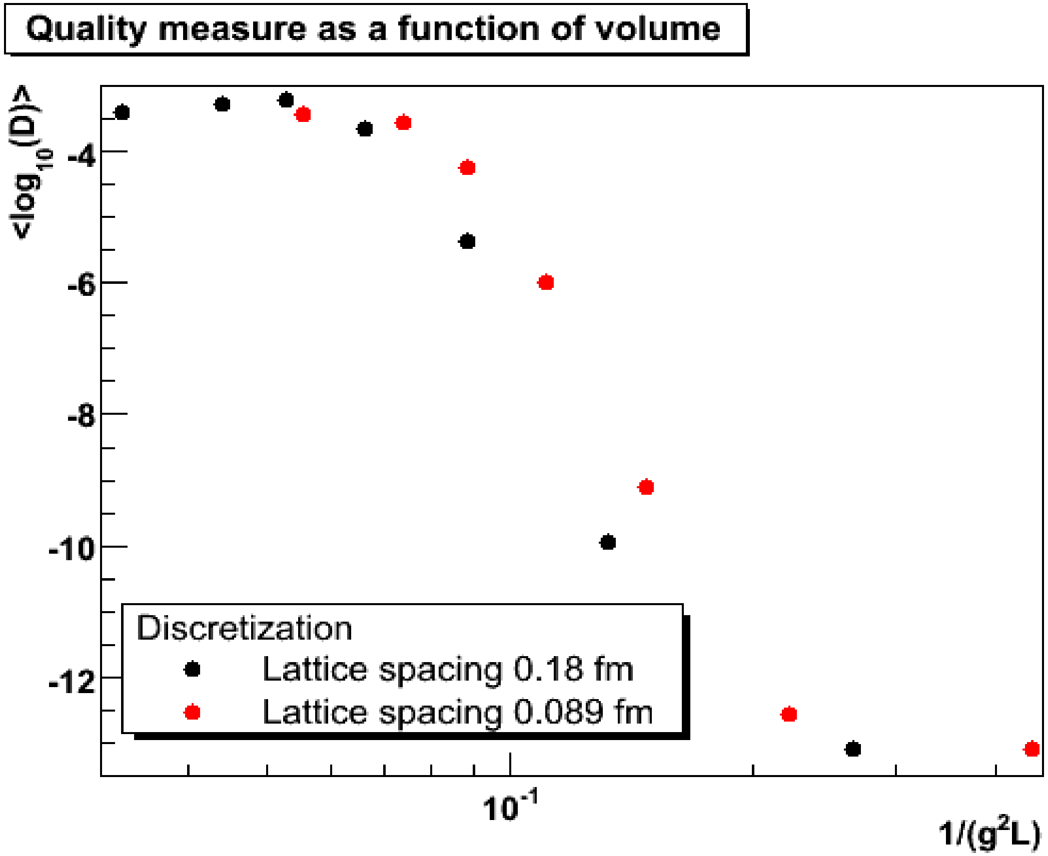
Artifact-dependence of Gribov copies [Maas, unpublished]

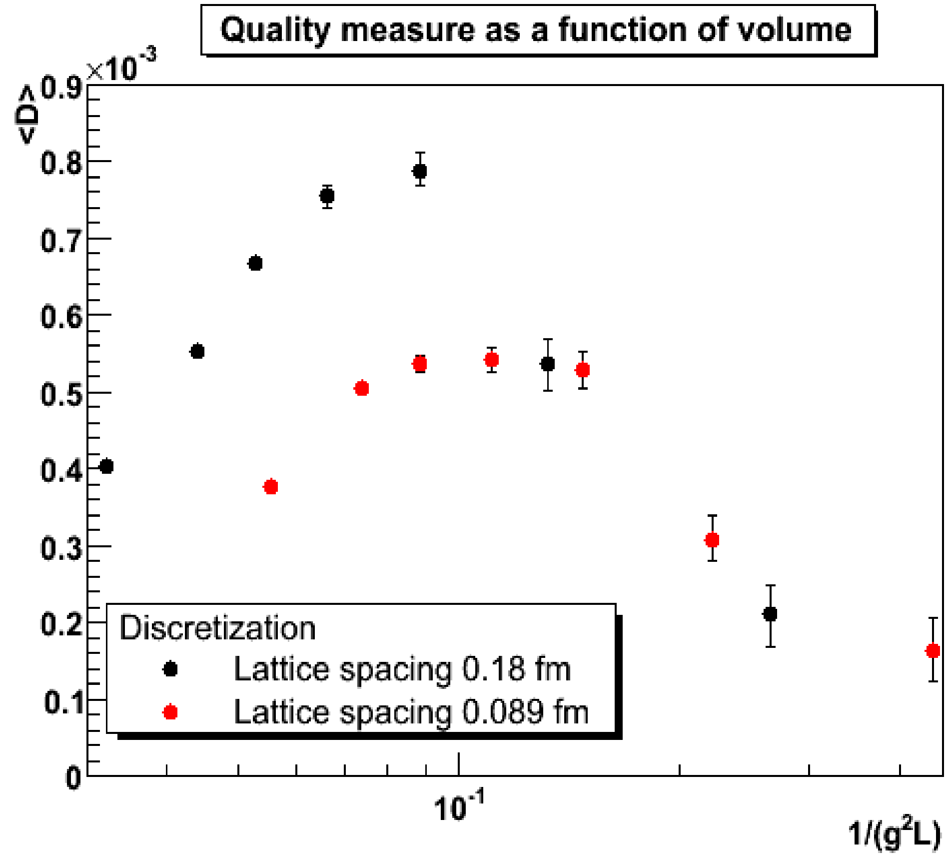
Quality measure as a function of volume



- Strong increase with volume
- Small impact of discretization

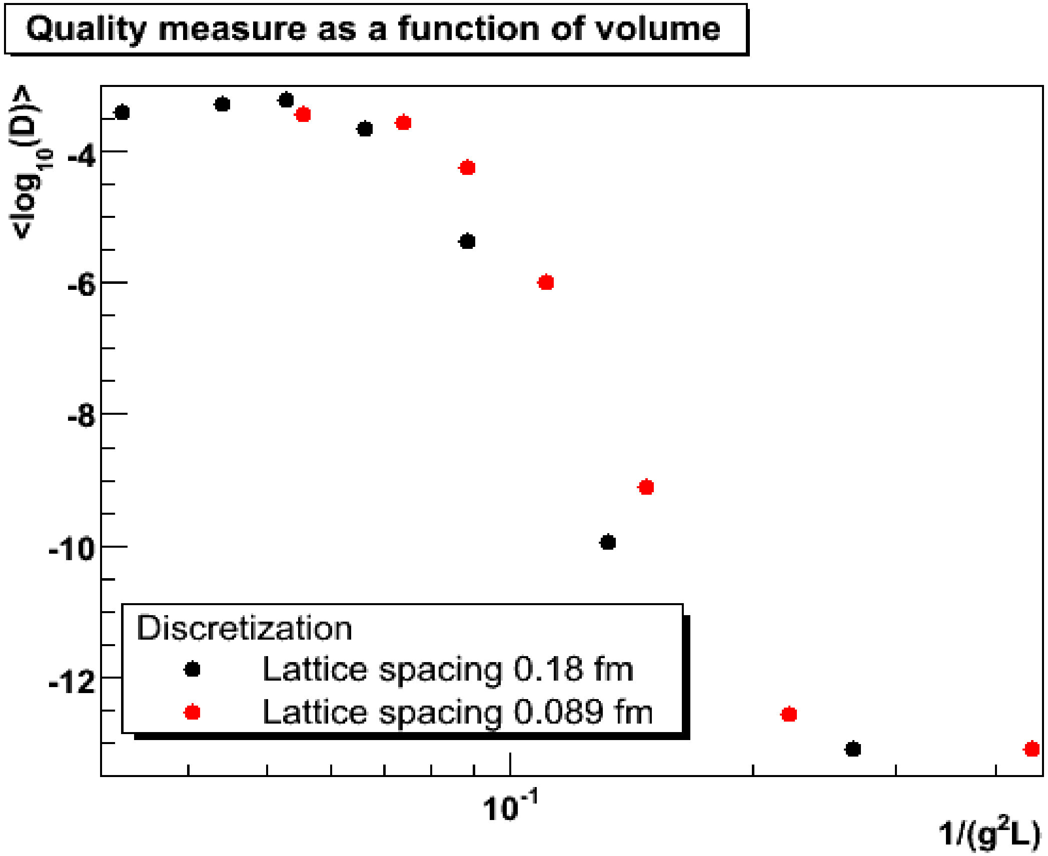
Artifact-dependence of Gribov copies [Maas, unpublished]

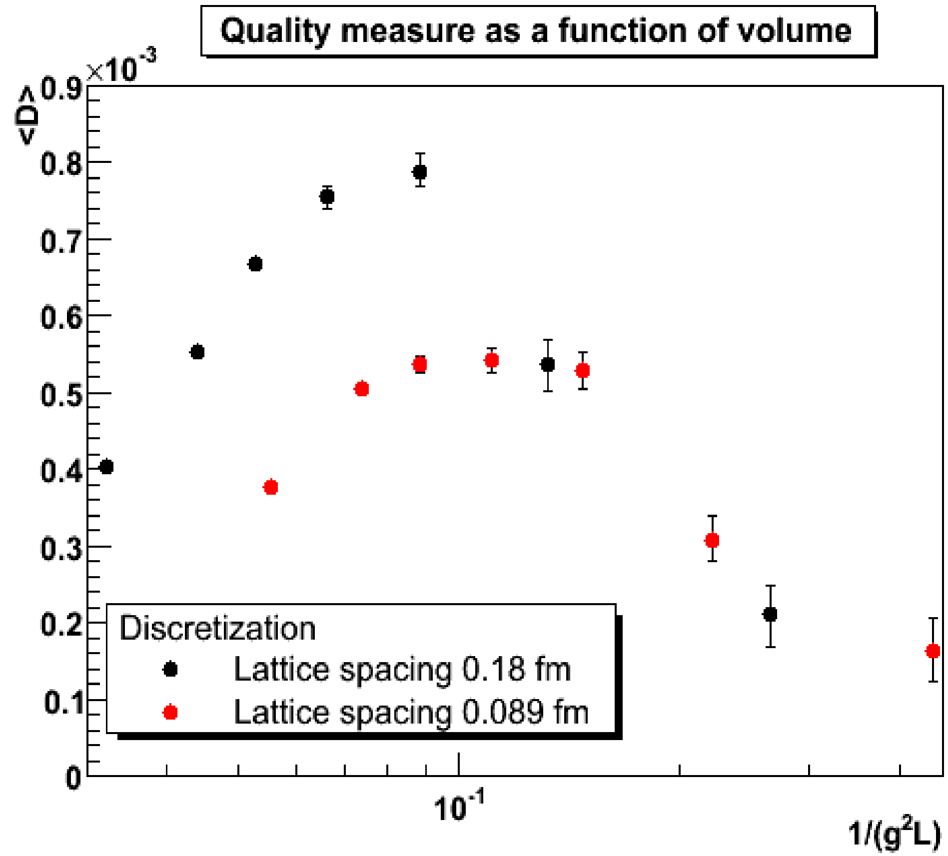




- Strong increase with volume
- Small impact of discretization
- Impact seems to be reduced weakly at large volume

Artifact-dependence of Gribov copies [Maas, unpublished]





- Strong increase with volume
- Small impact of discretization
- Impact seems to be reduced weakly at large volume
  - Onset of the applicability of the Zwanziger conjecture?

Impact on the propagators

- Propagators are the (inverse) 2-point function
  - Product of two field operator – Zwanzigers conjecture applies

Impact on the propagators

- Propagators are the (inverse) 2-point function
  - Product of two field operator - Zwanzigers conjecture applies
- Important quantities
  - Describe gluons
  - Confinement and other non-perturbative information are encoded

Propagators [Introduction: Alkofer & von Smekal, 2001]

- In Landau gauge: Gluon and one auxiliary field: Ghost

Propagators

[Introduction: Alkofer & von Smekal, 2001]

- In Landau gauge: Gluon and one auxiliary field: Ghost
- Gluon:

$$D^{ab}_{\mu\nu}(x-y) = \ < A^a_\mu(x) A^b_\nu(y) >$$

$$D_{\mu\nu}(p) = (\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) \frac{Z(p)}{p^2}$$

Propagators

[Introduction: Alkofer & von Smekal, 2001]

- In Landau gauge: Gluon and one auxiliary field: Ghost
- Gluon:

$$D_{\mu\nu}^{ab}(x-y) = \langle A_\mu^a(x) A_\nu^b(y) \rangle$$

$$D_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right)\frac{Z(p)}{p^2}$$

- Ghost:

$$D_G^{ab}(x-y) = \langle \bar{c}^a(x) c^b(y) \rangle$$

$$D_G(p) = \frac{-G(p)}{p^2}$$

Propagators [Introduction: Alkofer & von Smekal, 2001]

- In Landau gauge: Gluon and one auxiliary field: Ghost

- Gluon:

$$D^{ab}_{\mu\nu}(x-y) = \; < A^a_\mu(x) A^b_\nu(y) >$$

$$D_{\mu\nu}(p) = (\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) \frac{Z(p)}{p^2}$$

- Ghost:

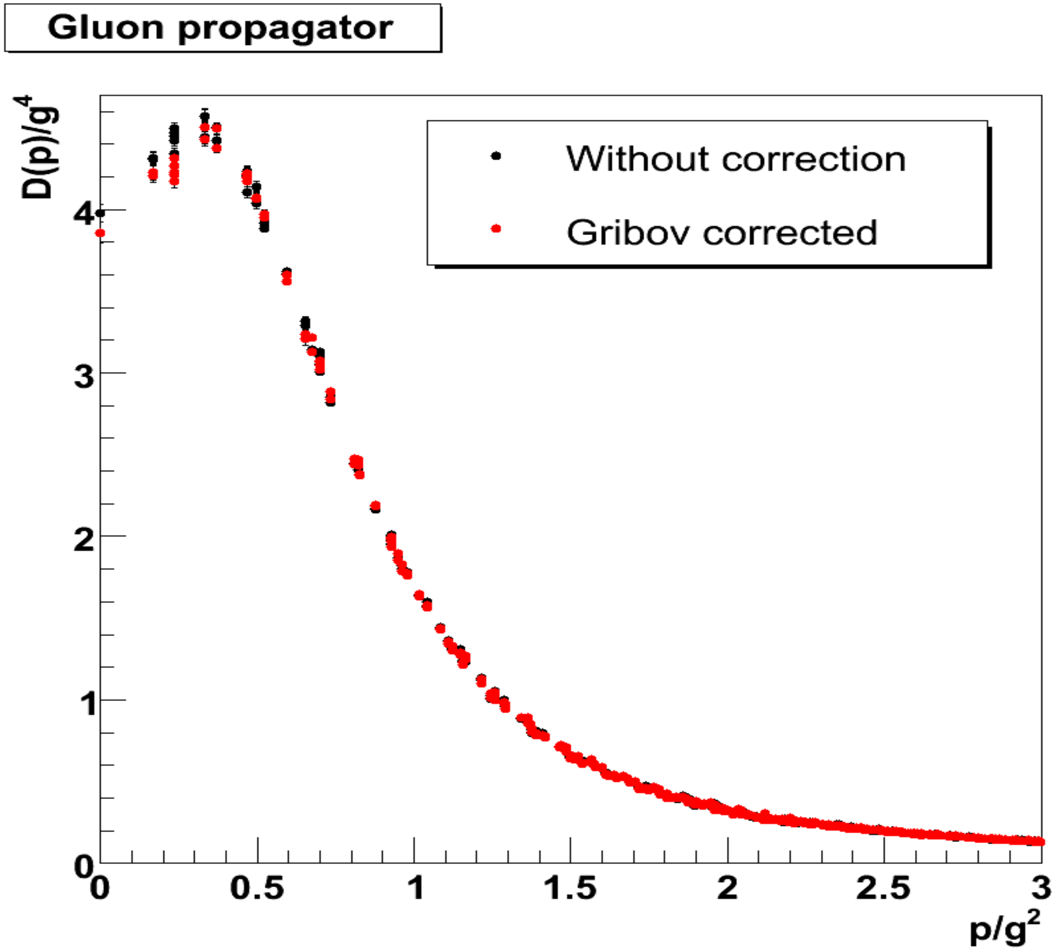
$$D^{ab}_G(x-y) = \; < \bar{c}^a(x) c^b(y) >$$

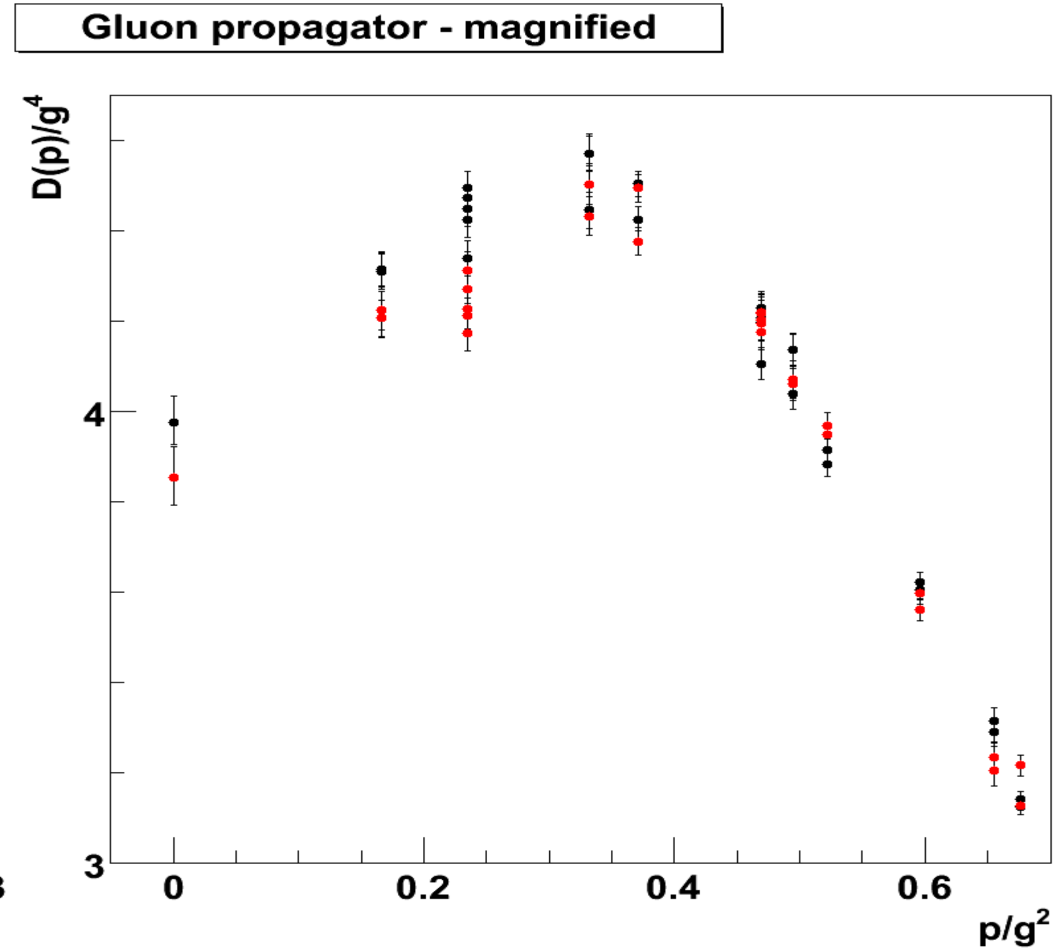
$$D_G(p) = \frac{-G(p)}{p^2}$$

- Ghost linked to the Faddeev-Popov operator

$$D^{ab}_G(x-y) \; \sim \; < (\partial_\mu D^{ab}_\mu)^{-1} > \; = \; < (\partial_\mu (\delta^{ab} \partial_\mu - g f^{abc} A^c_\mu))^{-1} >$$

Impact on the gluon propagator [40³, beta=4.24, Maas, unpublished]

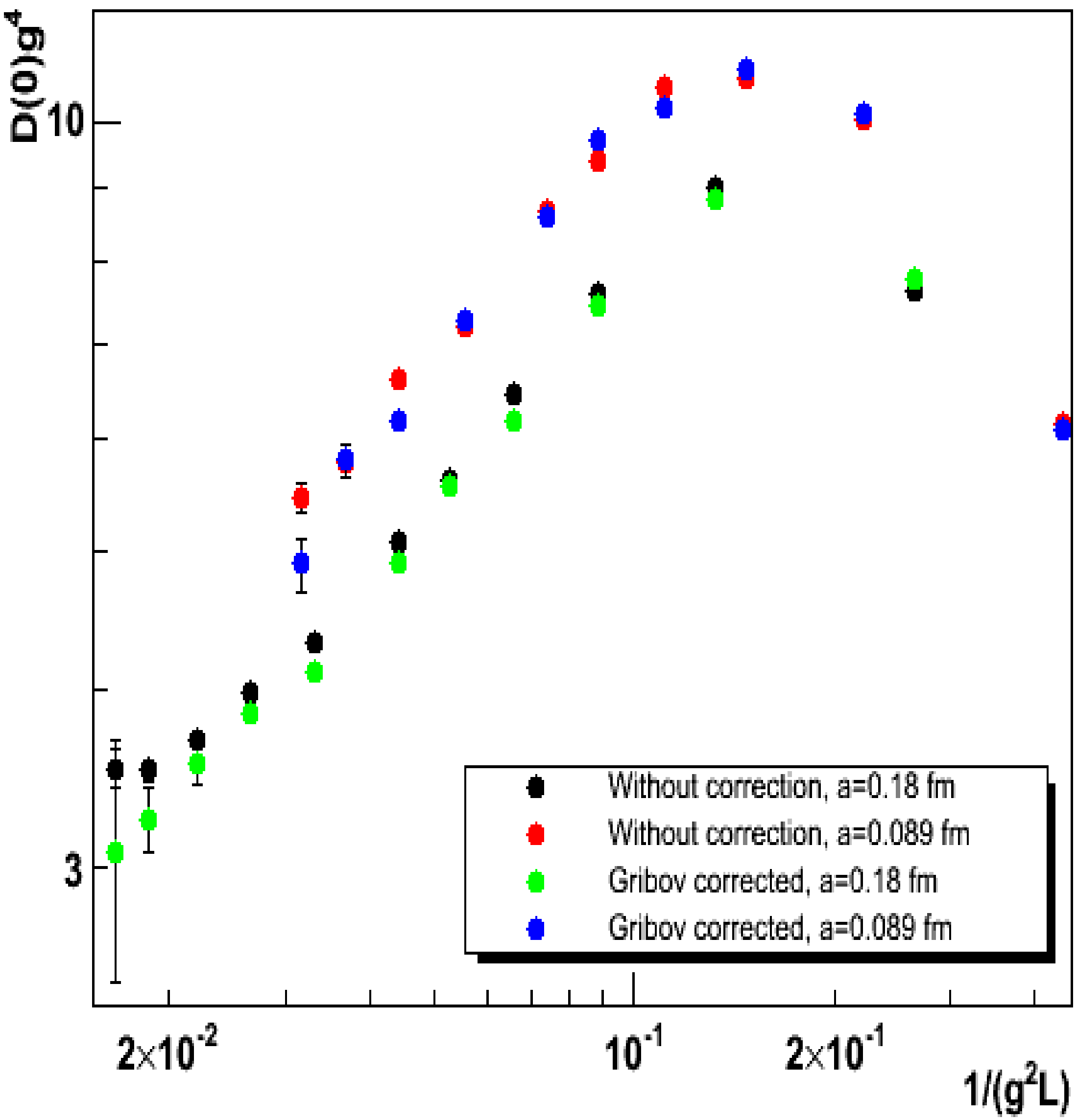




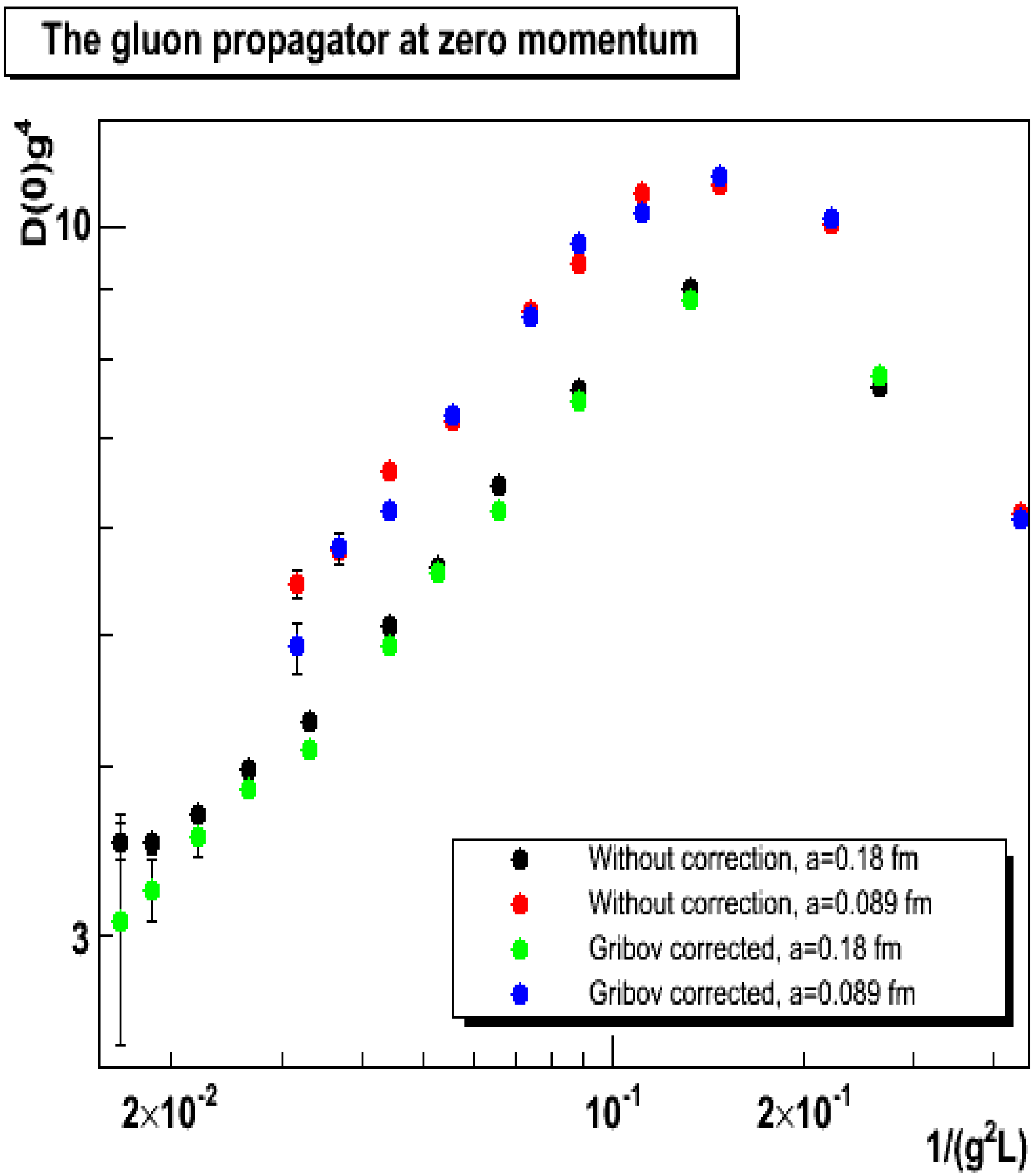
- Small effect
  - Most pronounced in the far infrared, and decays with increasing momentum

Impact on the gluon propagator [Maas, unpublished]

The gluon propagator at zero momentum

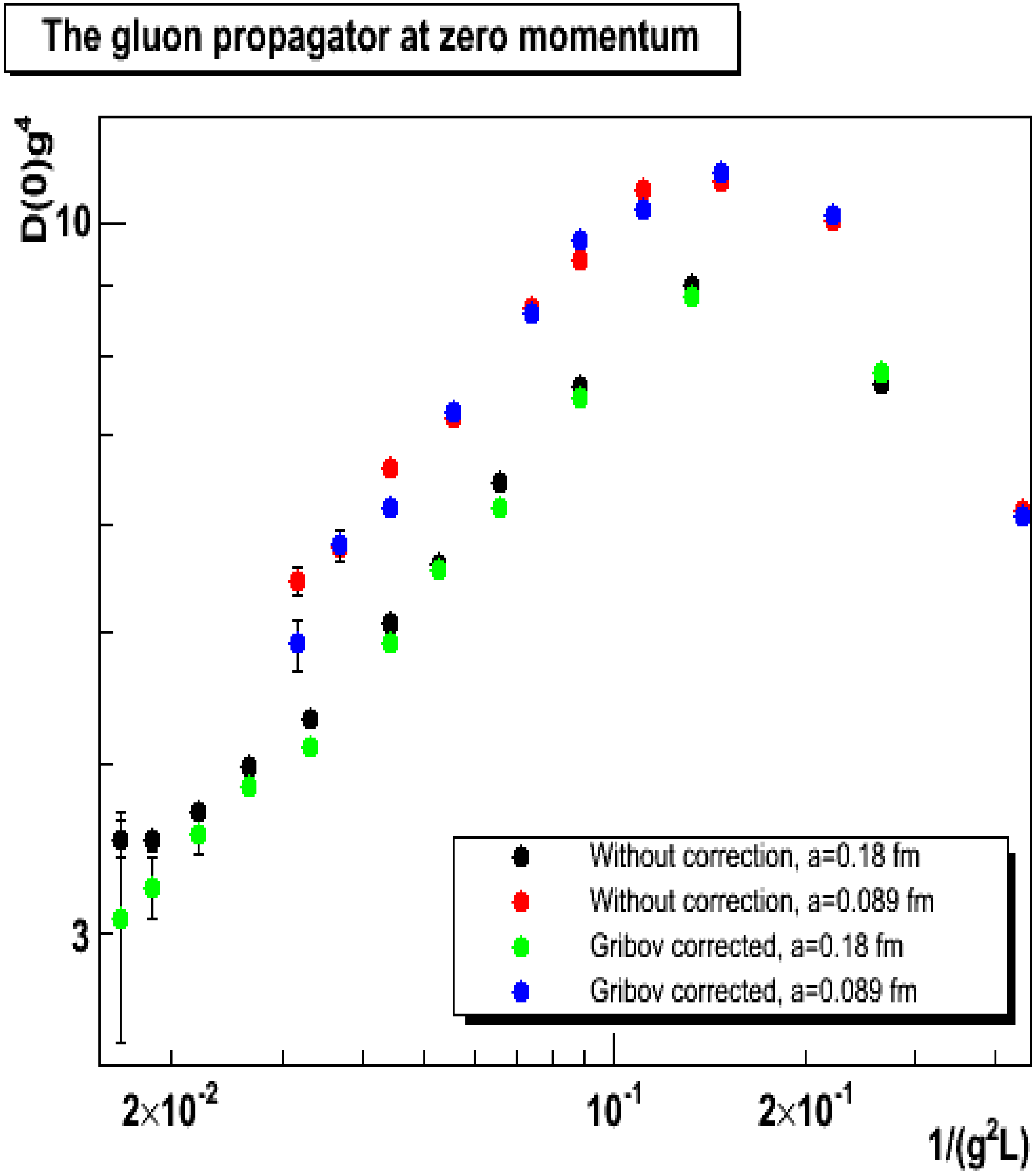


Impact on the gluon propagator [Maas, unpublished]



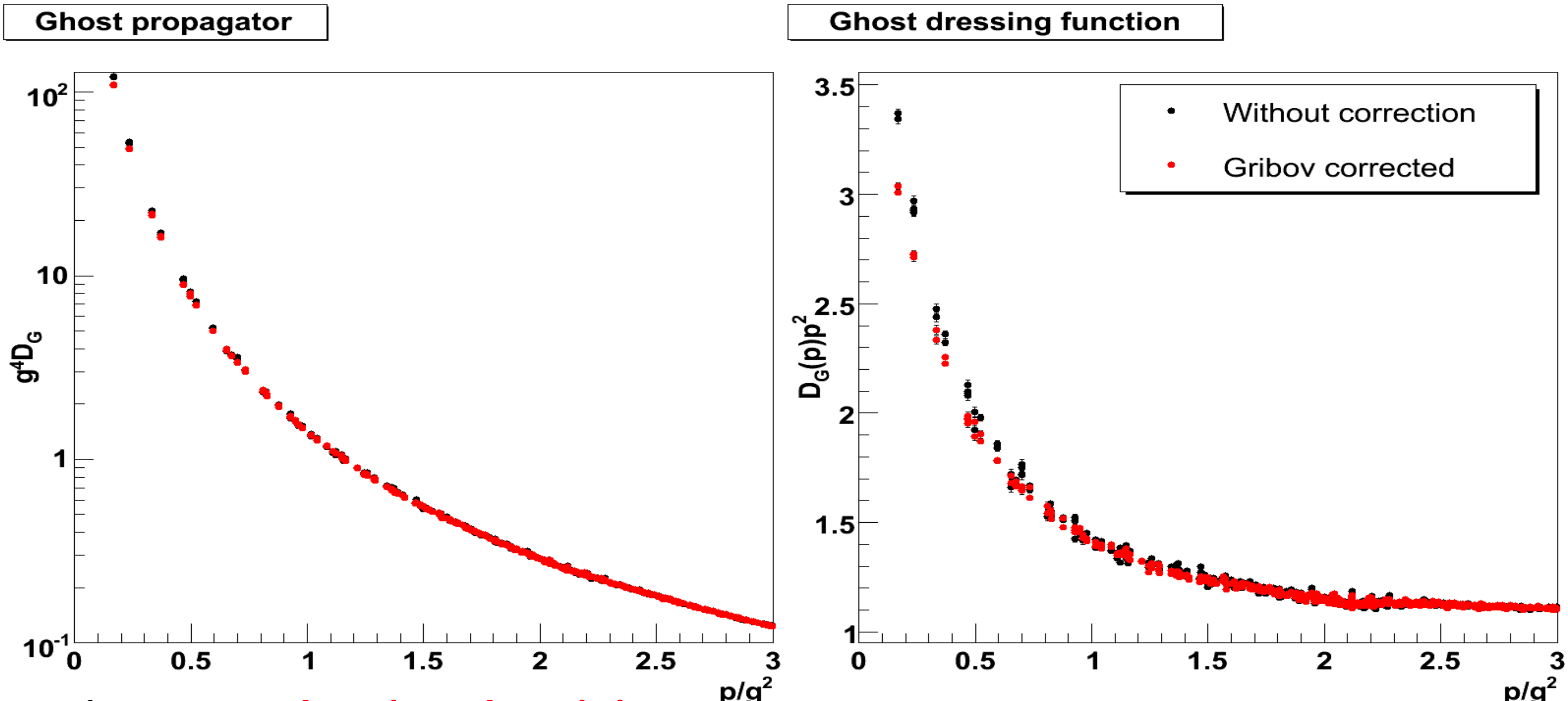
- Changes the asymptotic behavior of the gluon propagator at zero momentum

Impact on the gluon propagator [Maas, unpublished]



- Changes the asymptotic behavior of the gluon propagator at zero momentum
- Could decide the question, whether the gluon propagator is vanishing at zero momentum
  - Important question in the removal of gluons from the physical spectrum

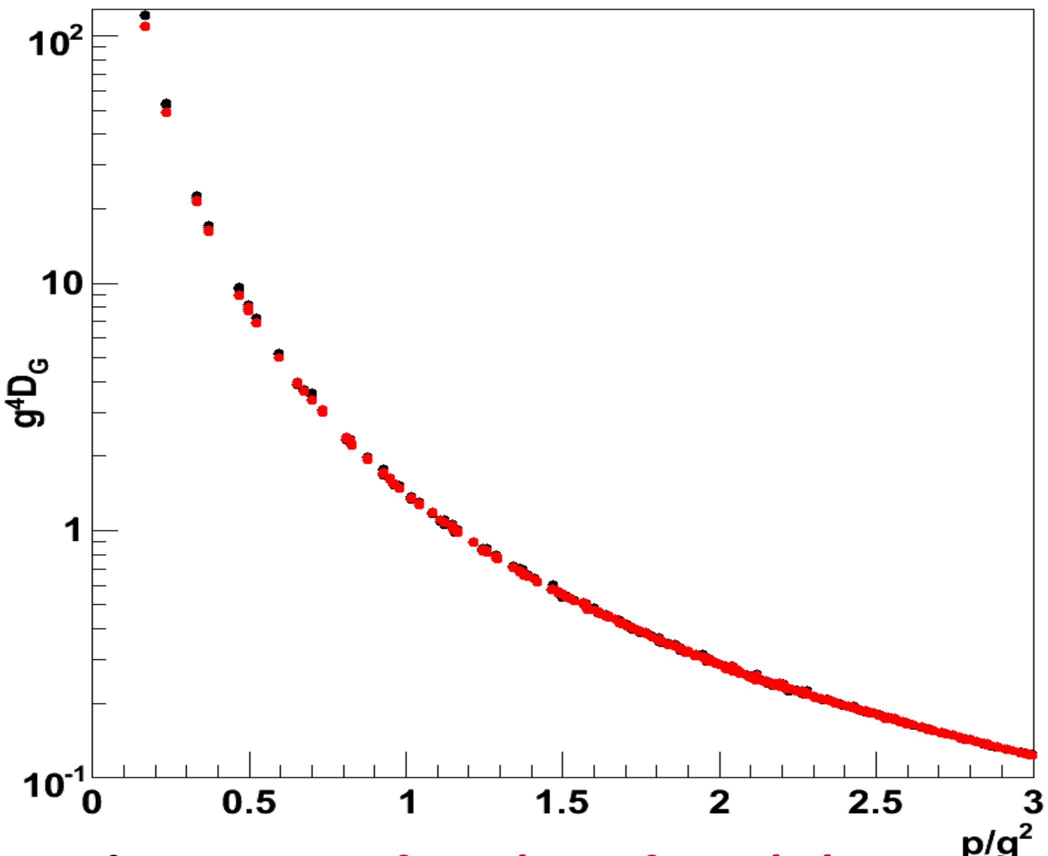
Impact on the ghost propagator [40^3, beta=4.24, Maas, unpublished]



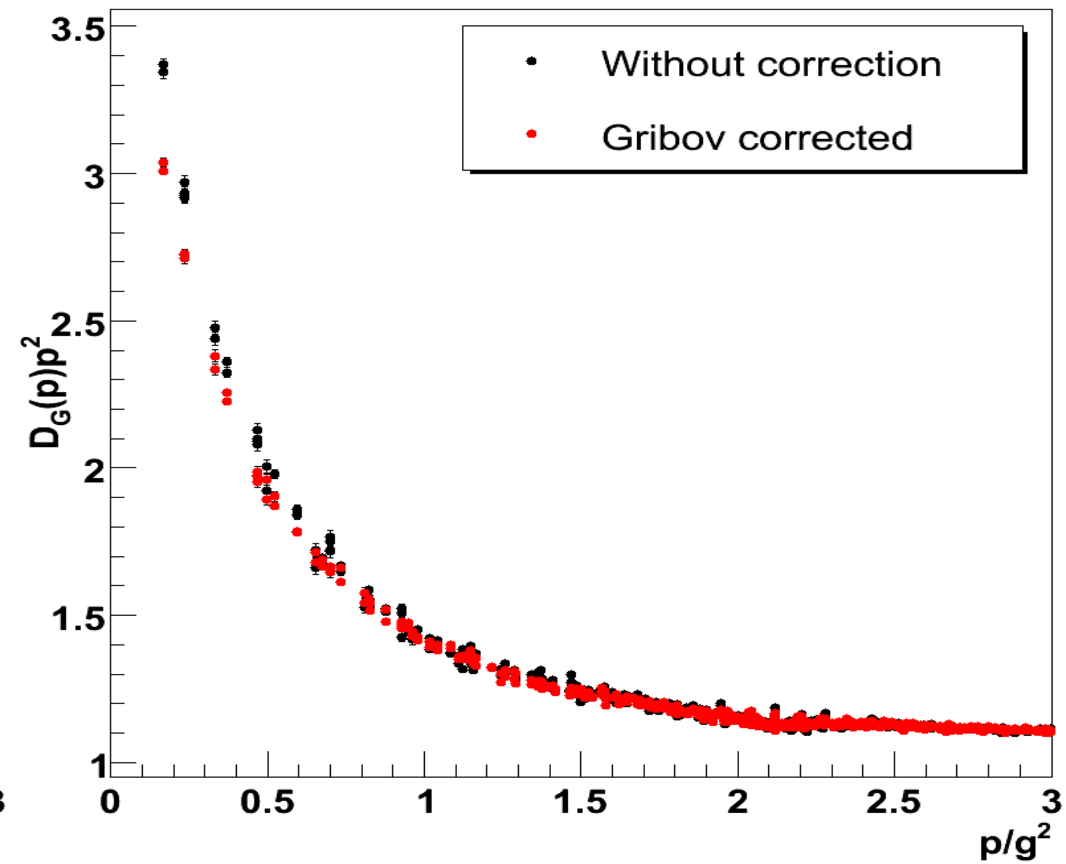
- Seems to soften the infrared divergence

Impact on the ghost propagator [40^3, beta=4.24, Maas, unpublished]

Ghost propagator



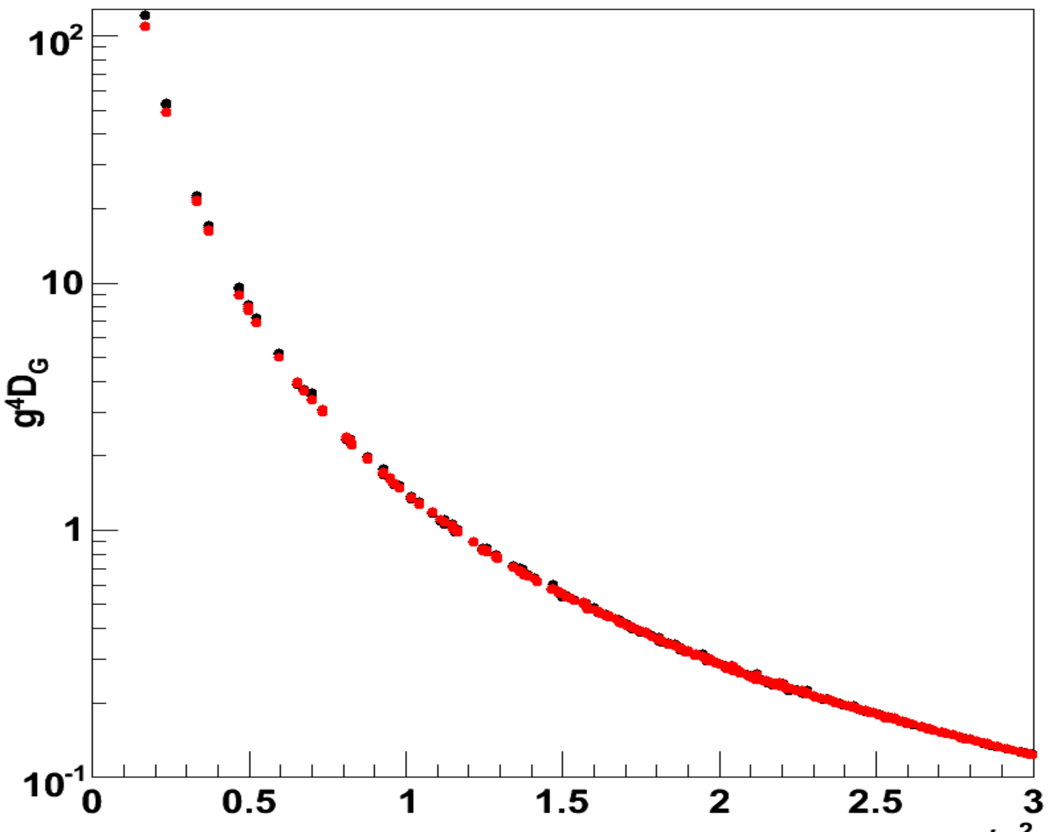
Ghost dressing function



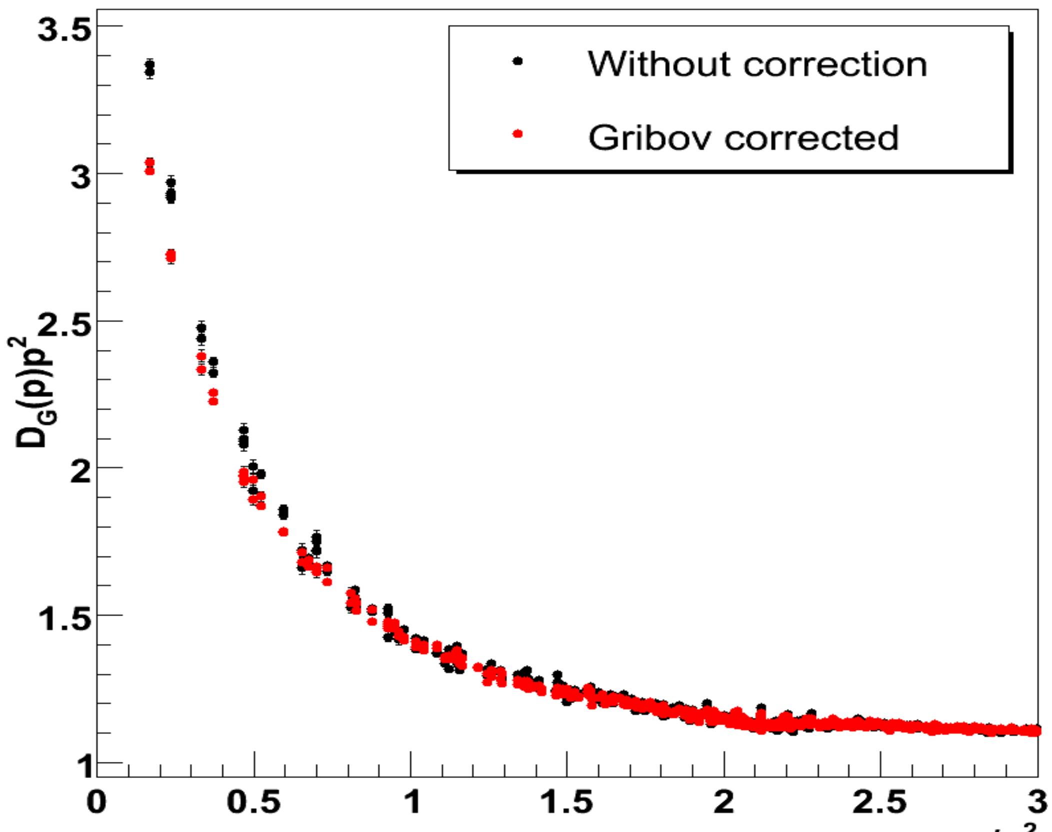
- Seems to soften the infrared divergence
- Impact rate depends likely non-montonically on the volume

Impact on the ghost propagator [40^3, beta=4.24, Maas, unpublished]

Ghost propagator



Ghost dressing function



- Seems to soften the infrared divergence
- Impact rate depends likely non-montonically on the volume
- Asymptotic limit? - The ghost propagator is not a finite product of gluon field operators: Zwanzigers conjecture may not apply!

Summary

- Gribov copies are a general problem in local gauges
  - No complete and rigorous solution known
  - Even the measurement of success is a non-trivial problem

Summary

- Gribov copies are a general problem in local gauges
  - No complete and rigorous solution known
  - Even the measurement of success is a non-trivial problem
- Affects gauge-dependent correlation functions
  - Relevant to study, e.g., confinement scenarios

Summary

- Gribov copies are a general problem in local gauges
  - No complete and rigorous solution known
  - Even the measurement of success is a non-trivial problem
- Affects gauge-dependent correlation functions
  - Relevant to study, e.g., confinement scenarios
- May be decisive in our understanding of the infrared physics of the (intrinsically gauge-dependent) quark and gluon degrees of freedom