Nonperturbatively Regulating Chiral Gauge Theories

DMG and David B. Kaplan

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Motivation: Lattice Regulate Chiral Gauge Theory

Big Question 1: Do chiral gauge theories (χGT) make sense beyond perturbation theory?

- Only known χGT is the Standard Model Electroweak sector
- What are the requirements to have a well-defined χGT

Big Question 2: What are the properties of strongly interacting chiral gauge theories?

- High energy extensions of the Standard Model

To answer these, must first find a nonperturbative regulator.

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- Gauge symmetries **allow** fermion mass term

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Chiral Theory (Electroweak)

- **Complex** fermion representation
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Is this a technical issue or indicative of new physics and thus a problem with the Standard Model?

Technical Question: Define Measure for χGT

Observables are calculated by integrating over gauge fields with some measure

$$\langle F(A) \rangle = \frac{\int [DA] e^{-S(A)} \Delta(A) F(A)}{\int [DA] e^{-S(A)} \Delta(A)}$$

- F(A) is the observable
- S(A) is gauge action (Maxwell or Yang Mills)
- Δ(A) is due to fermions

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- Δ(A) is due to fermions
  - Δ(A) for Dirac fermion is well-known

$$\Delta_{DF}(A) = \det \not{D}(A)$$

  - But it is not well know how to define Δ(A) for chiral fermion

$$\Delta_{\chi F} \Delta^*_{\chi F} = \Delta_{DF}$$

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What is the fermionic contribution to the measure for χGT?

- Need definition so that effective action is local and analytic

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Dirac operator eigenvalues

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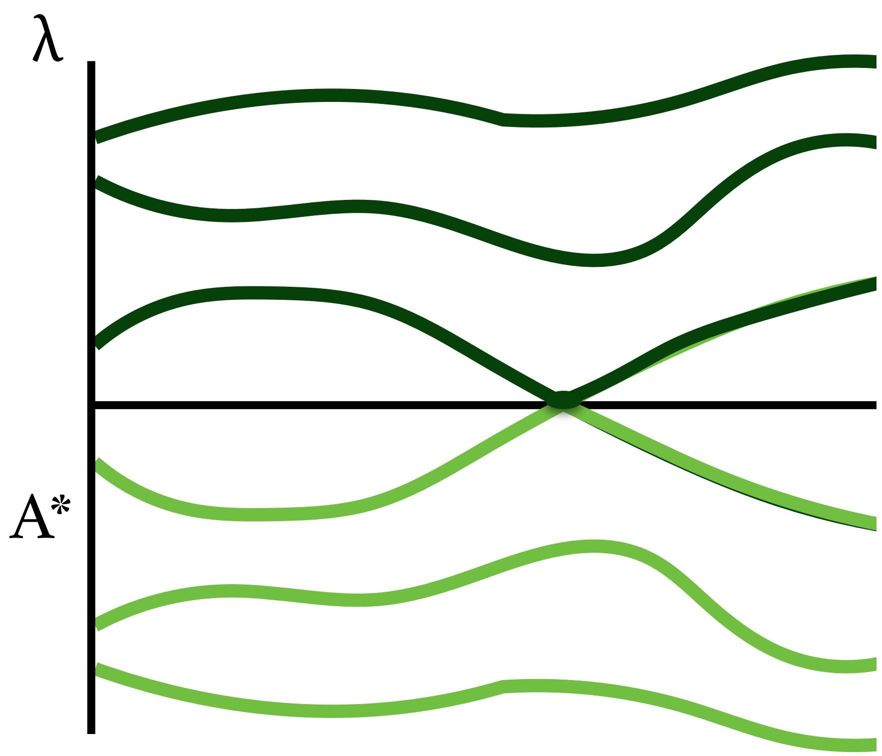

$$\Delta_{\chi F}(A) = \prod_{\lambda_j > 0} \lambda_j$$

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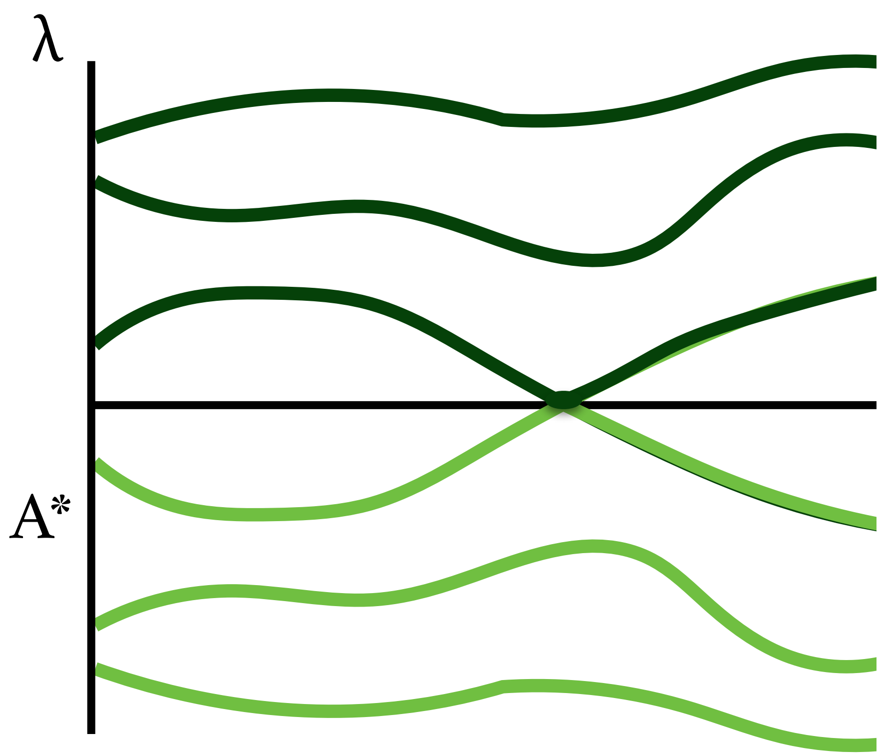

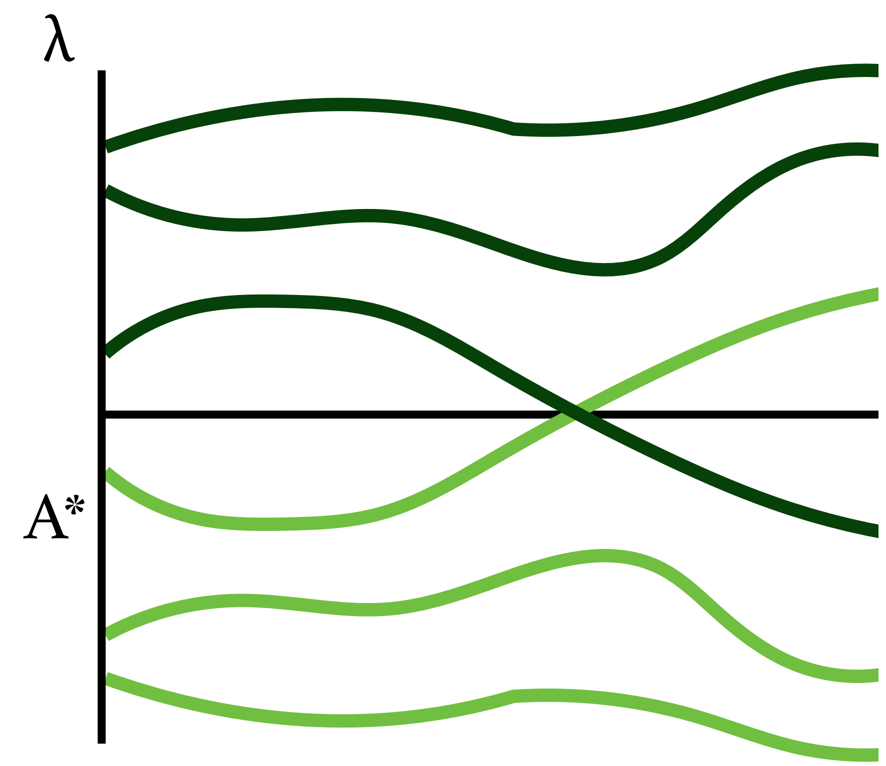

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$$\Delta_{\chi F}(A) = \prod_{\lambda_j(A^*) > 0} \lambda_j$$

Motivation: Lattice Regulate Chiral Gauge Theory

Continuum Field Theory

- Theories with chiral symmetries can have anomalies

- Standard Model contains global anomalies

- Chiral gauge theories only well-behaved if no gauge anomalies

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Lattice Field Theory

- No anomalies in system with finite degrees of freedom
- Lattice must explicitly break global chiral symmetry to reproduce anomaly
- Lattice must somehow distinguish anomalous and anomaly-free gauge theories

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How does one construct a lattice theory that has the correct continuum behavior?

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Choice A: Explicit Gauge Violation

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- Gauge invariance must be restored in continuum limit
- Sensible continuum limit only exists for anomaly-free theories

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We will go with Choice B

For our construction, only anomaly-free theories are local

Steps to Define Measure for χGT

Basic building block is Dirac fermion, in order to have well-defined eigenvalue problem

1. Global chiral symmetry (massless Dirac fermions)

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3. Mechanism for distinguishing anomalous versus anomaly free fermion representation

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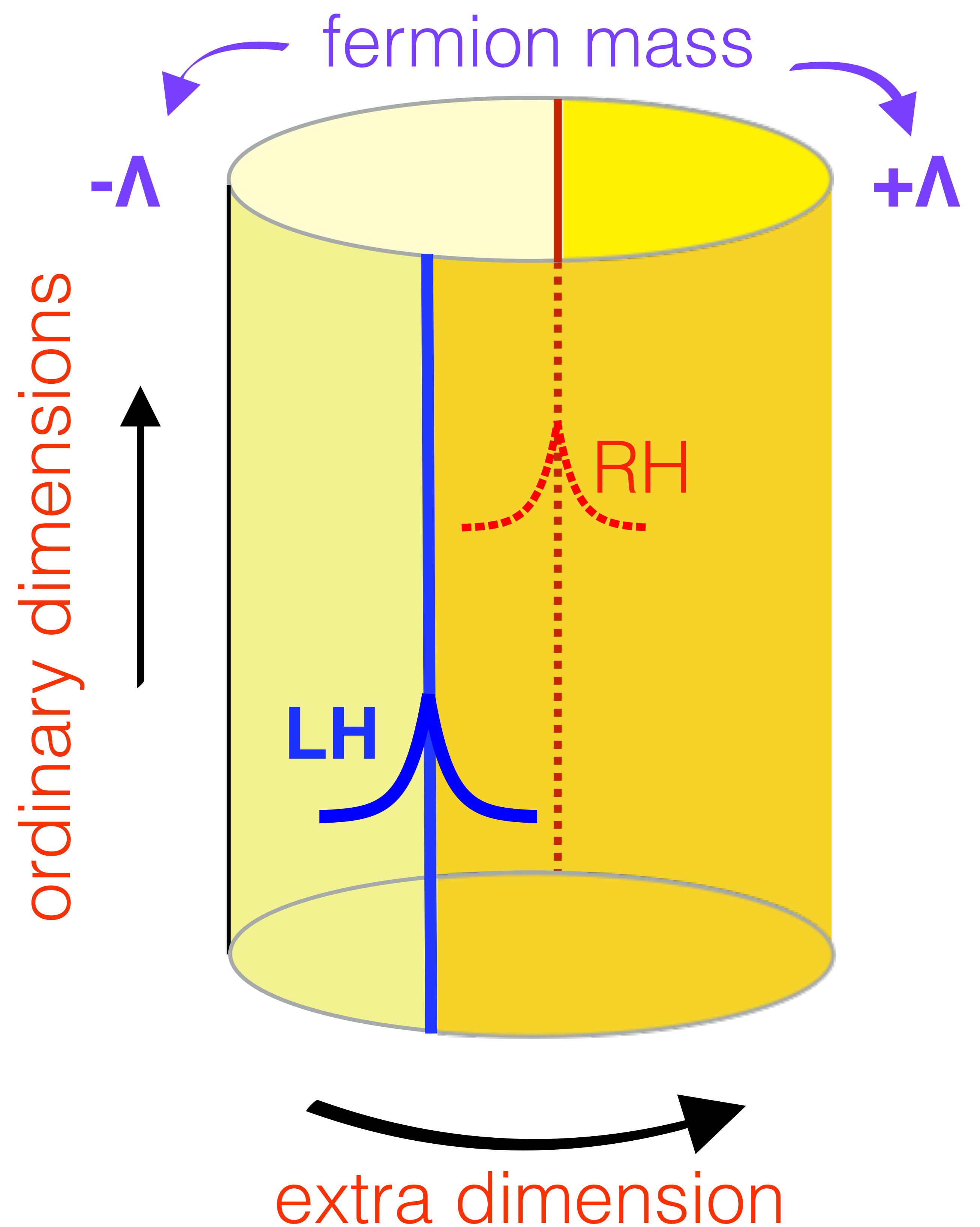
Global Chiral Symmetries

Domain Wall Fermions (DWF)

(Kaplan, '92)

- Introduce extra (compact) dimension, x_5
- Fermion mass depends on x_5
- Massless modes localized on mass defects
- Gauge fields independent of x_5
- Anomaly due to bulk fermions carrying charge between mass defects
- Condensed matter physicists would call this a topological insulator



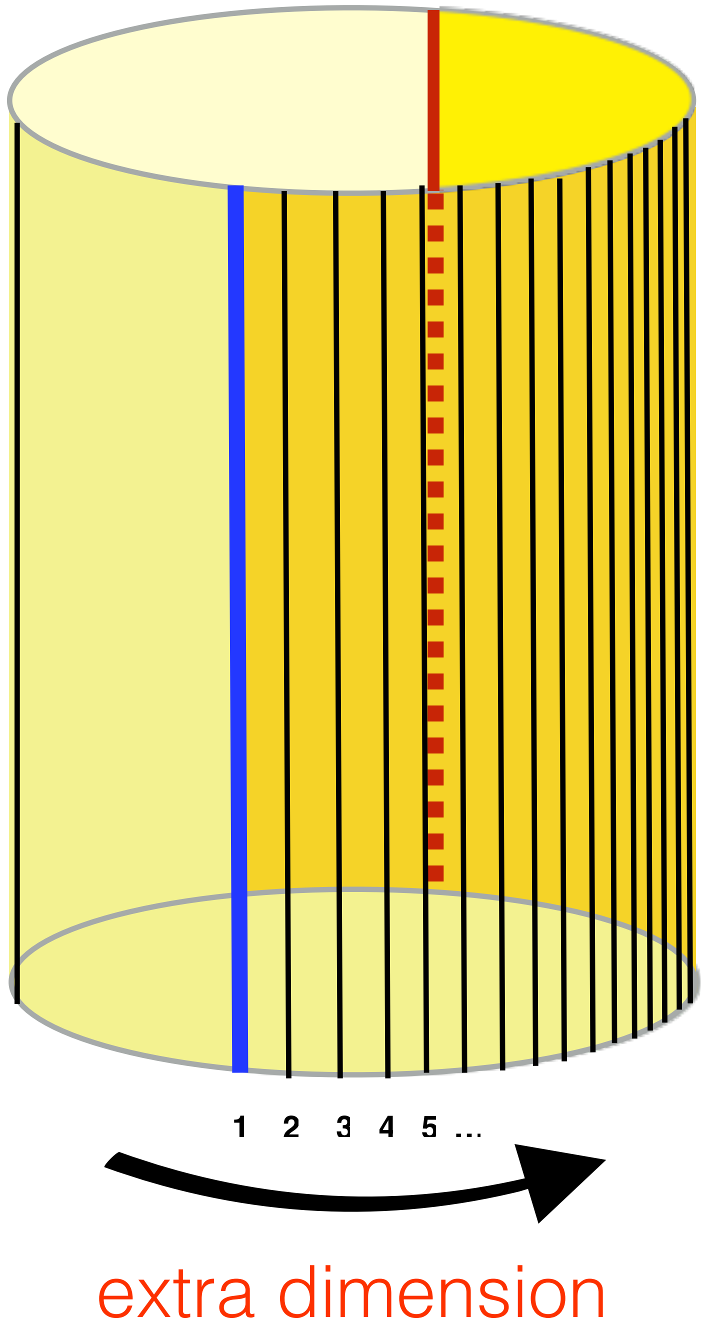
Global Chiral Symmetries

DWF always give rise to a vector gauge theory

- DWF 5d action is equivalent to action for an infinite number of 4d fermions
- If discretize extra dimension, x_5 is a flavor quantum number

$$\overline{\psi}\gamma_5\partial_5\psi \rightarrow \overline{\psi}_n\gamma_5\left(\psi_{n+1} - \psi_n\right)$$

Every flavor must be in same gauge group representation



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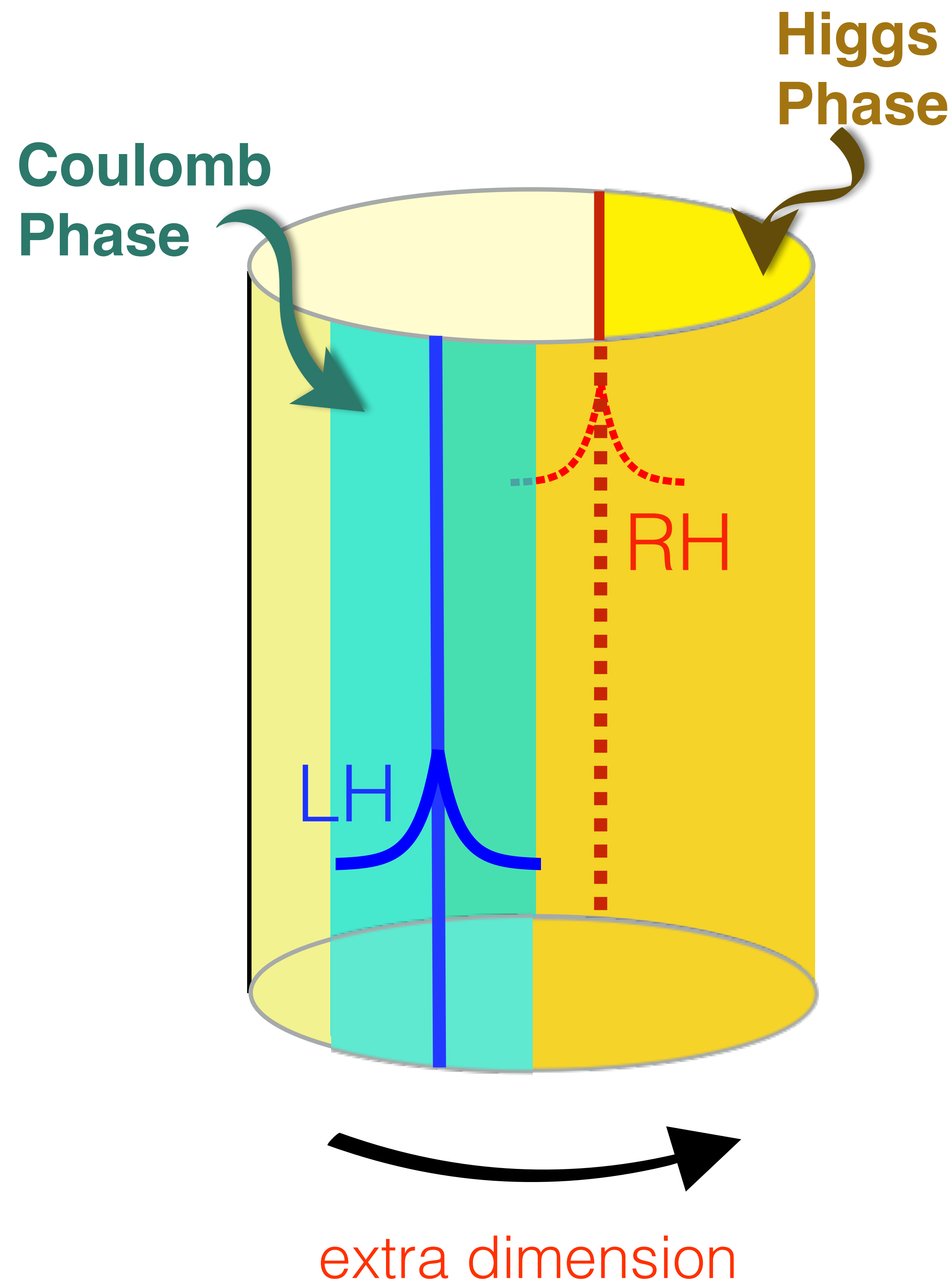
Gauged Chiral Symmetries (Previous Attempt)

Idea: Localize Gauge Fields at one defect

- Waveguide Model
- Gauge fields **depend** on x_5
- Need spontaneous symmetry breaking to preserve gauge invariance
- New RH mode appears at location of SSB
- Spectrum has **Dirac** fermions

  Golterman, Jansen, Vink 1993



Gauged Chiral Symmetries (New Attempt)

New Idea: Localize gauge fields around one defect via smearing
(DMG and Kaplan, '1511)

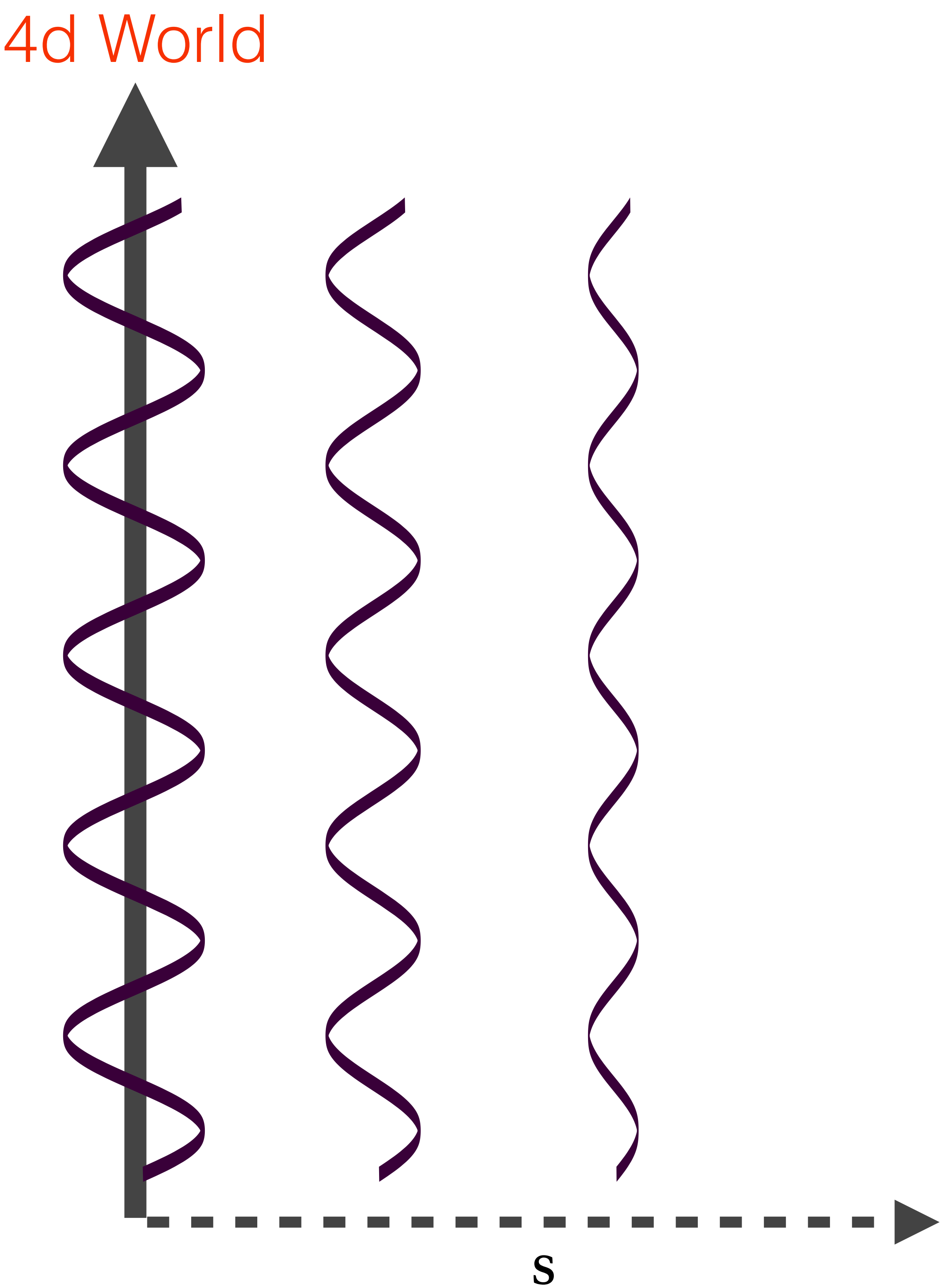
Smeared Gauge Fields (Narayanan and Neuberger, '06; Lüscher, '11, etc)

- Utilizes extra dimension
- Start with any gauge field, A_μ
- Extend gauge field into the bulk via particular flow equation

Flow Eq: $\partial_s \bar{A}_\mu = D_\nu \bar{F}_{\nu\mu}$ BC: $\bar{A}_\mu(x,0) = A_\mu(x)$

  - Behaves like heat equation
  - **Damps out high momentum modes**

Flow Equation: 2d/3d QED Example



Write A_μ in terms of gauge and physical degree of freedom

$$\bar{A}_\mu = \partial_\mu \bar{\omega} + \epsilon_{\mu\nu} \partial_\nu \bar{\lambda}$$

Flow Eqs.

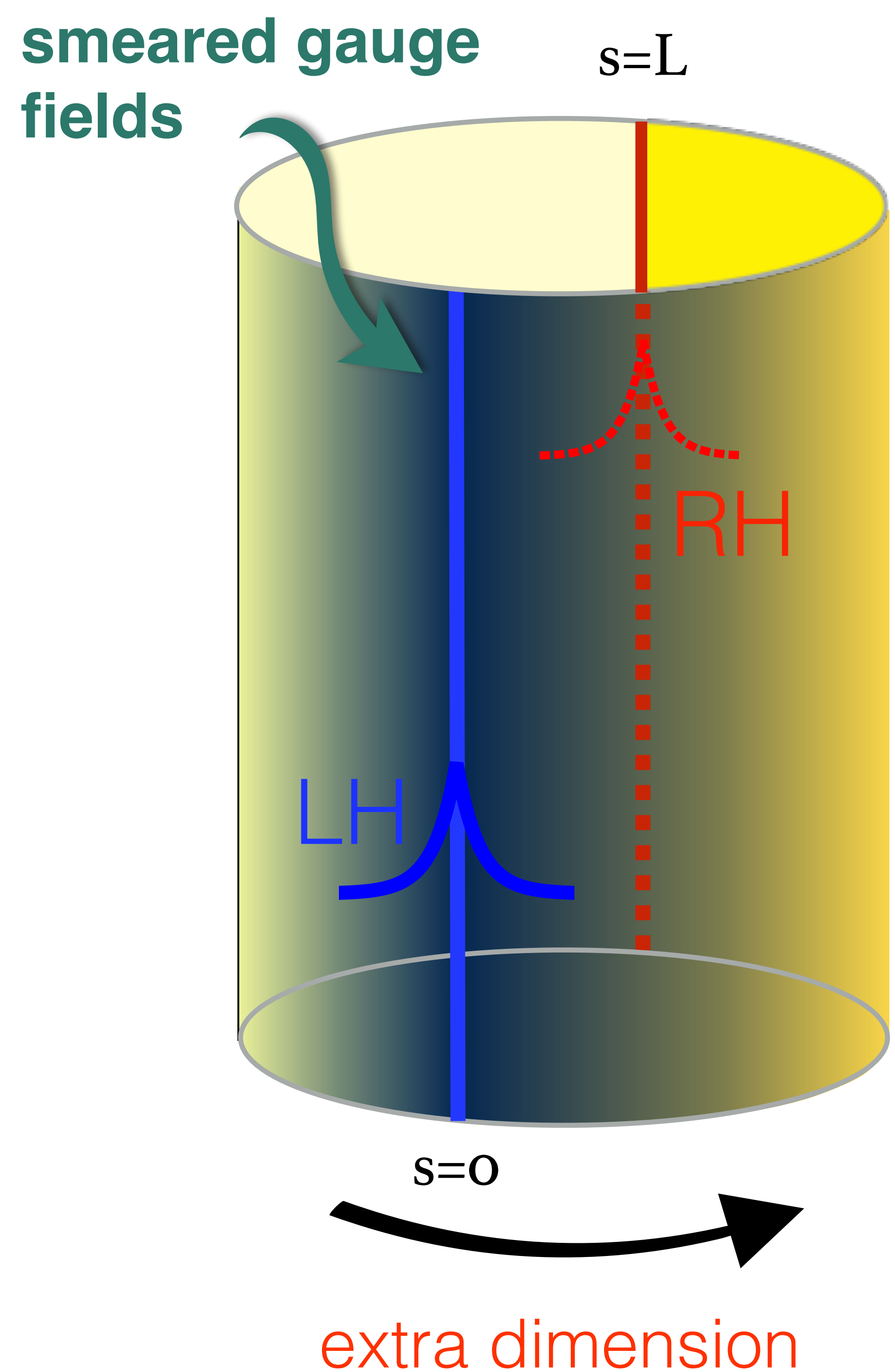
$$\partial_s \bar{\lambda} = \Box \bar{\lambda} \qquad \partial_s \bar{\omega} = 0$$

Flow in extra dimension damps out high momenta modes

Combine Domain Wall Fermions and Smearing

New Idea: Localize gauge fields at one defect via smearing

- Gauge field at s= 0 is quantum gauge field $A_\mu(x)$
- Bulk gauge field $\bar{A}_\mu(x,s)$ obeys flow equation
- Flow is symmetric around s=0
- RH modes have soft form factor coupling to physical degrees of freedom



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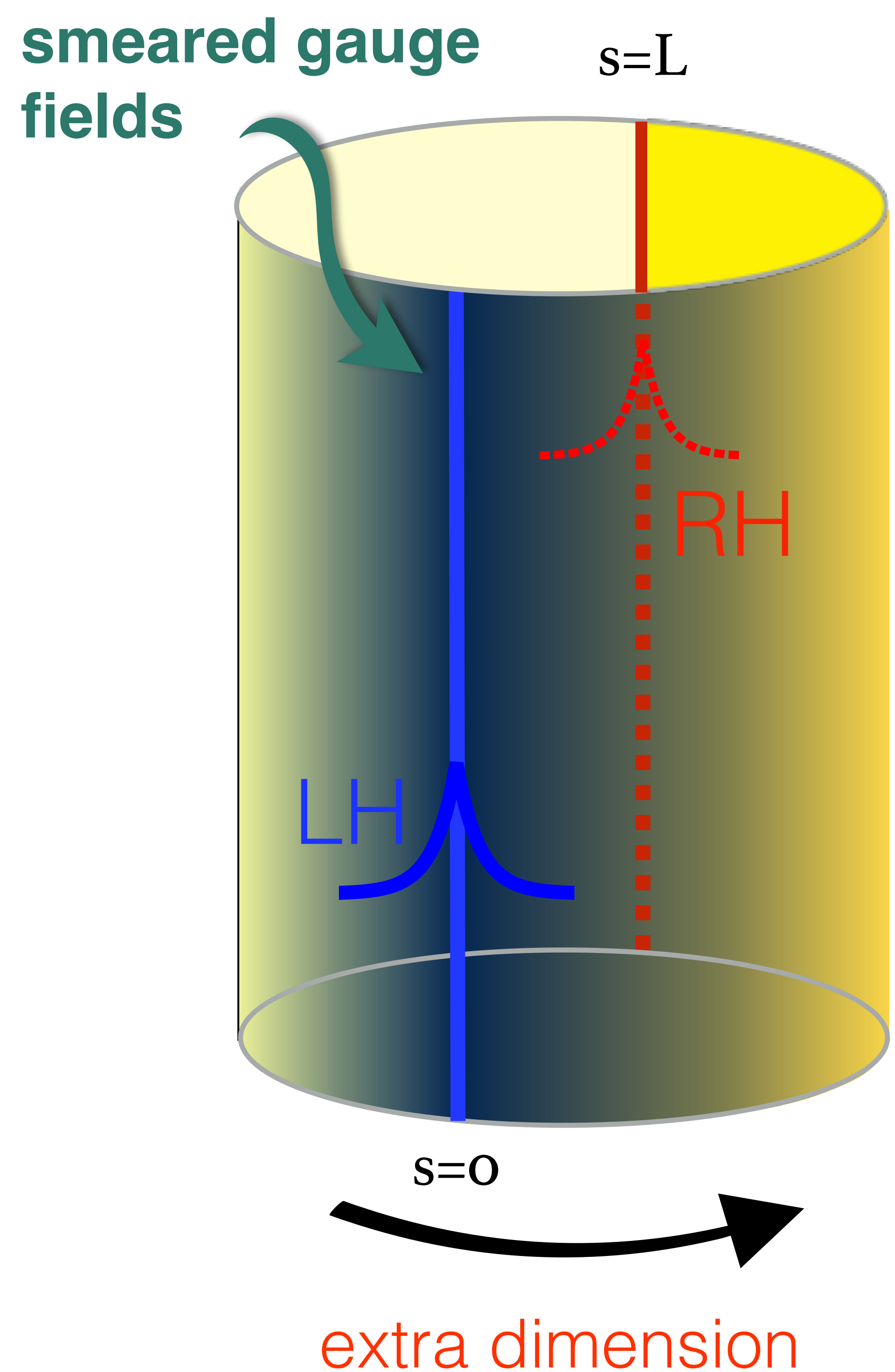
$$e^{-\xi p^2 L/\Lambda}$$



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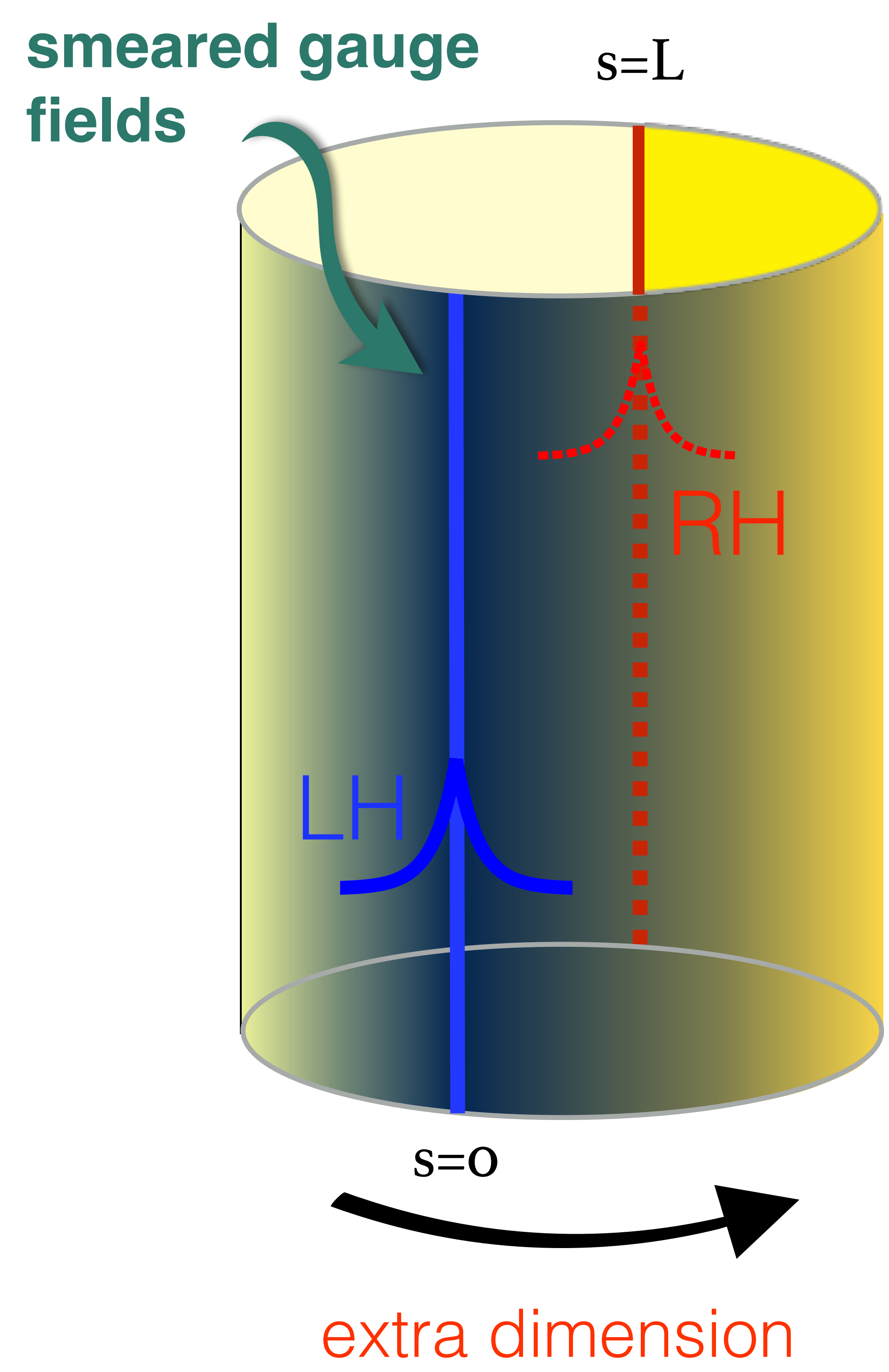
Photon Momentum   Wall separation



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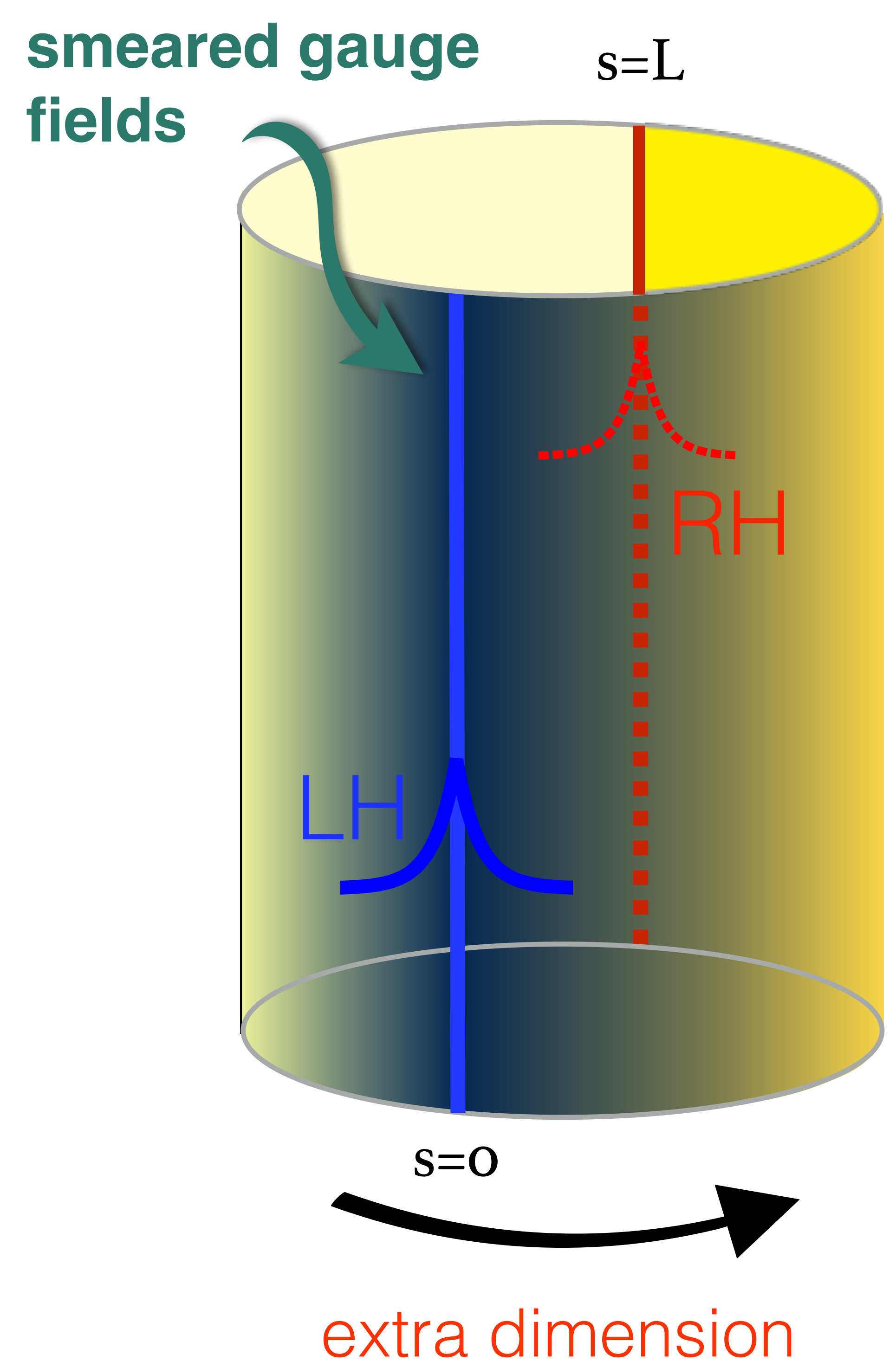
Flow parameter

Bulk fermion mass



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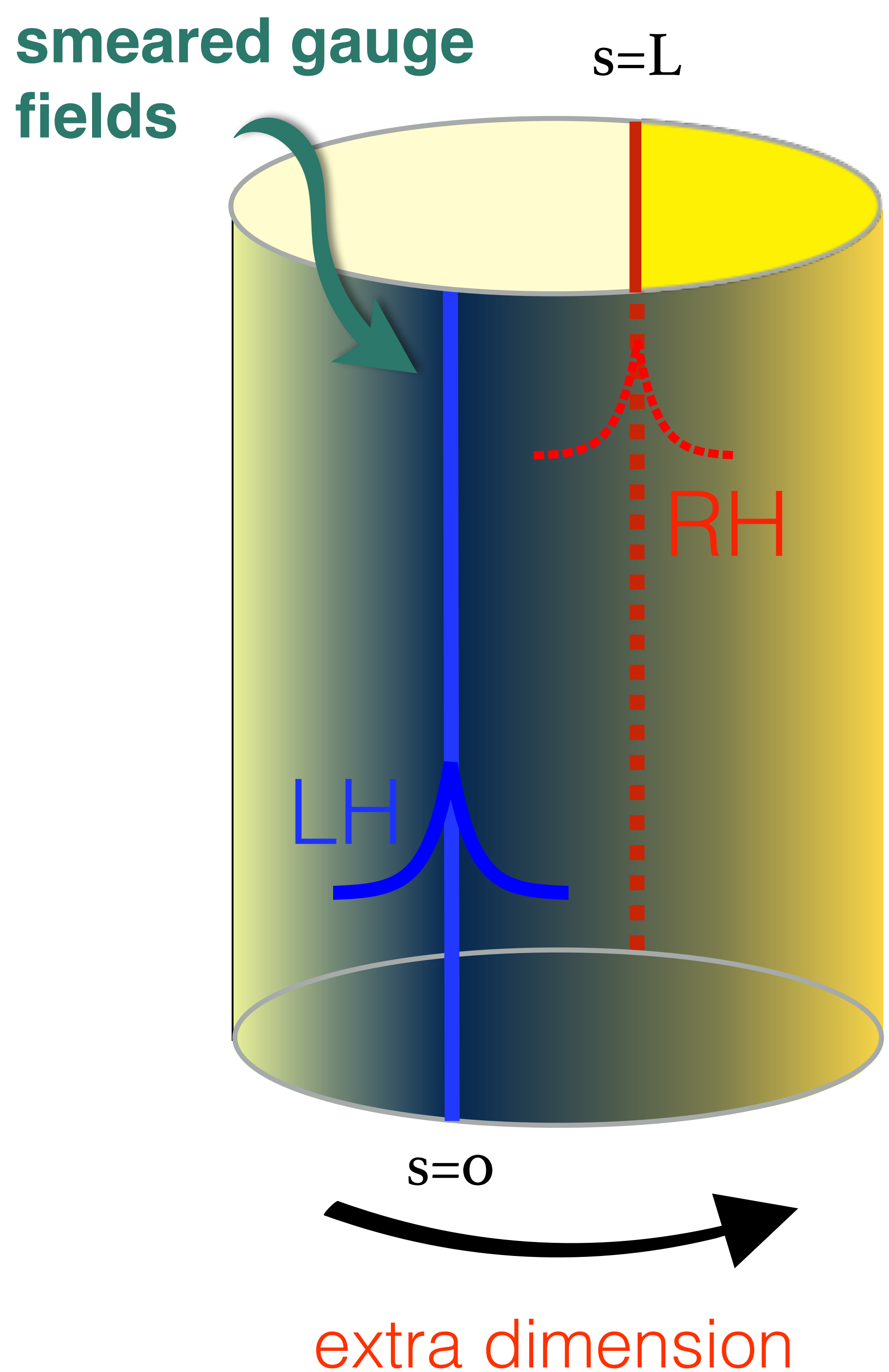
- LH and RH modes couple equally to gauge degrees of freedom



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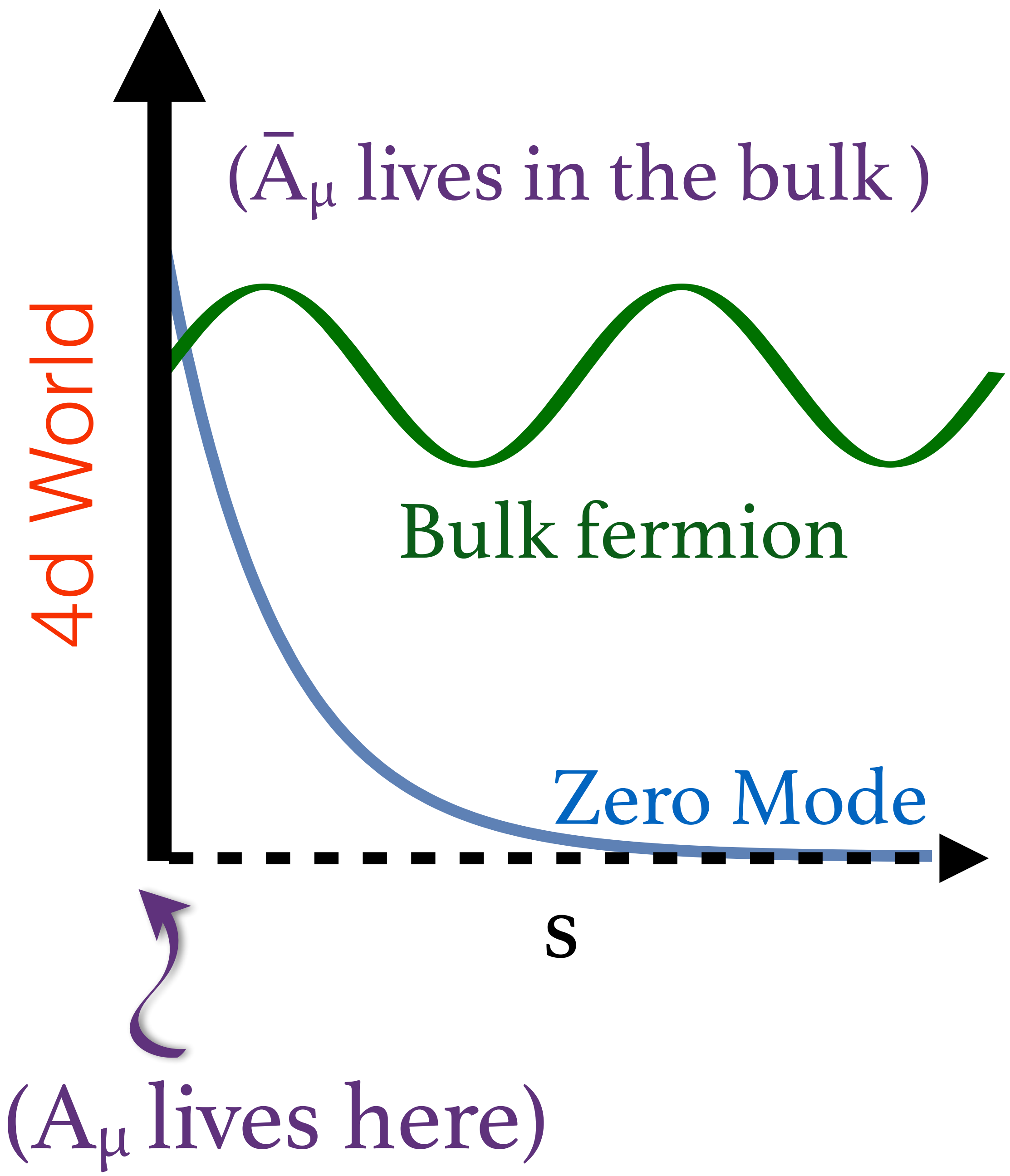
Anomalies and Callan-Harvey Mechanism (Callan and Harvey, '84)

Integrating out bulk fermions generates a Chern-Simons term



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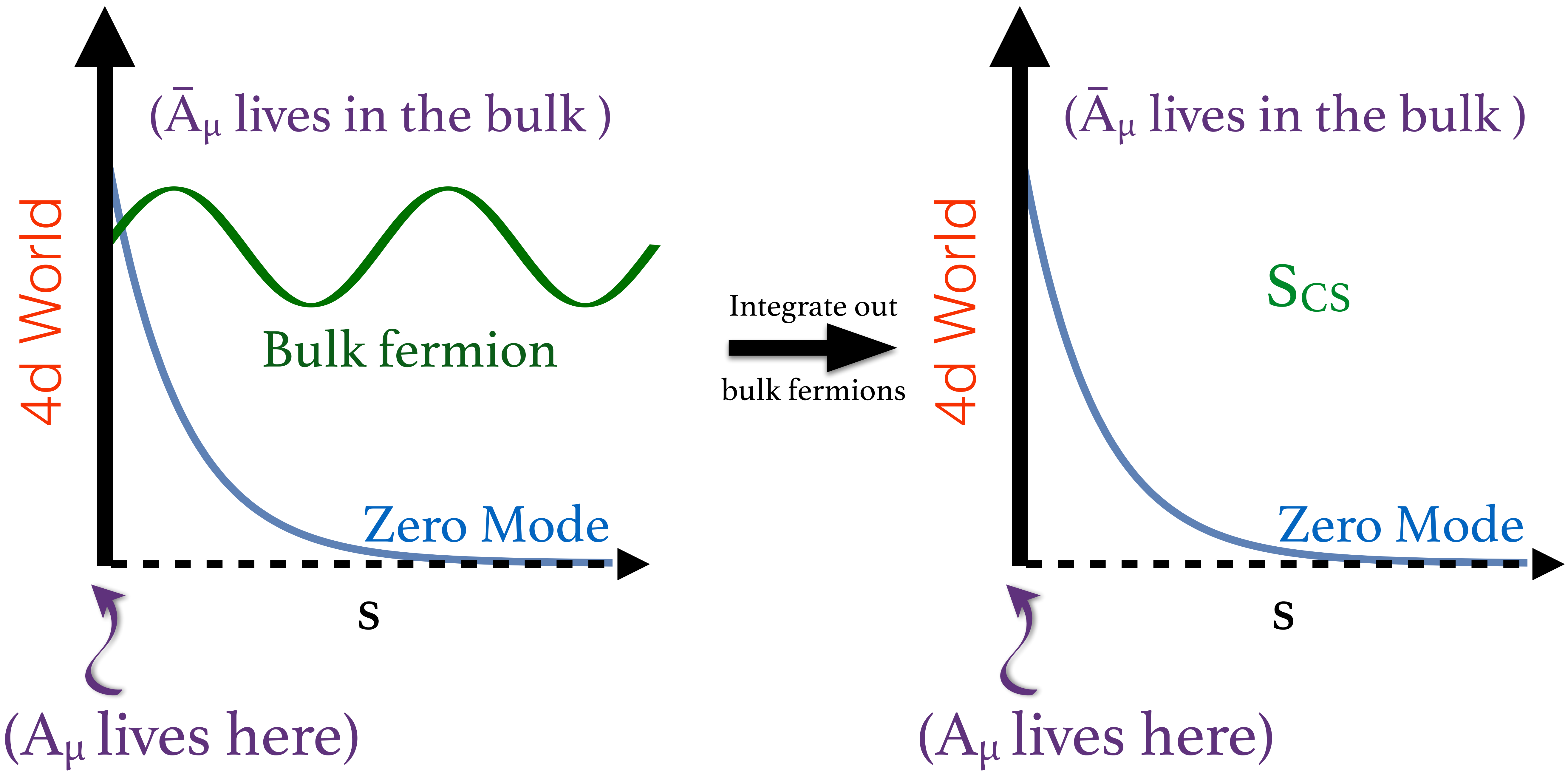

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- Integrating out bulk fermions generates a Chern-Simons term
- In 3 dimensions, the Chern Simons action is

$$S_3^{\mathrm{bulk}} = c_3 \frac{\Lambda}{|\Lambda|} \int \left(\epsilon(s) - 1\right) \mathrm{Tr}\left(\bar{F}\bar{A} - \frac{1}{3}\bar{A}^3\right)$$

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Fermion Contribution

CS only depends on sign of domain wall mass

Pauli Villars Contribution

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Fermion Contribution

Pauli Villars Contribution

- This approximation is only valid far away from domain wall

Anomalies and Callan-Harvey Mechanism

- Consider 3 dimensional QED with flowed gauge fields

$$S_3^{\text{bulk}} = 2e^2 c_3 \frac{\Lambda}{|\Lambda|} \int dx^2 dy^2 \left(\frac{\partial_\mu \partial_\alpha}{\Box} A_\alpha(x) \right) \Gamma(x-y) \left(\frac{\partial_\mu \partial_\beta}{\Box} \epsilon_{\beta\gamma} A_\gamma(y) \right)$$

  - No gauge field in 3rd dimension

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- Effective two point function is nonlocal

$$\Gamma(r) = \left(\delta^2(r) - \frac{\mu^2}{4\pi} e^{-\mu^2 r^2/4} \right) \qquad \mu \equiv \sqrt{\frac{\Lambda}{\xi L}}$$

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Serves as an IR cutoff

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Anomaly Cancellation and Nonlocality

- DWF with flowed gauge fields gives rise to a nonlocal 2d theory

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$$\sum_i e_i^2 \frac{\Lambda_i}{|\Lambda_i|}$$

- The theory is local if this prefactor vanishes

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This is exactly equivalent to the requirement that the chiral fermions be in an anomaly free representation

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1. Global chiral symmetry (massless Dirac fermions)
    - Domain Wall Fermions
2. Decouple mirror fermions
    - Smeared Gauge Fields
3. Mechanism for distinguishing anomalous versus anomaly free fermion representation
    - Theory is local if fermions are in an anomaly free representation

Proposal for Chiral Gauge Theory Measure

Recall that the goal is to be able to define a chiral fermion measure

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Our proposal:

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One factor for each species of fermion

5d Dirac operator with flowed gauge field

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- Mirror fermions decouple for large wall separation
- Target d-dimensional theory is local if fermions are in an anomaly free representation
- Effective action is what one would expect for chiral fermion (did not show here)

Open Questions

Open Question 1: What is the behavior of topological gauge configurations

- Do the mirrors decouple from topological gauge configurations?
- Can the Standard Model particles exchange energy and momenta with the mirror fermions

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- Is the S matrix unitary?
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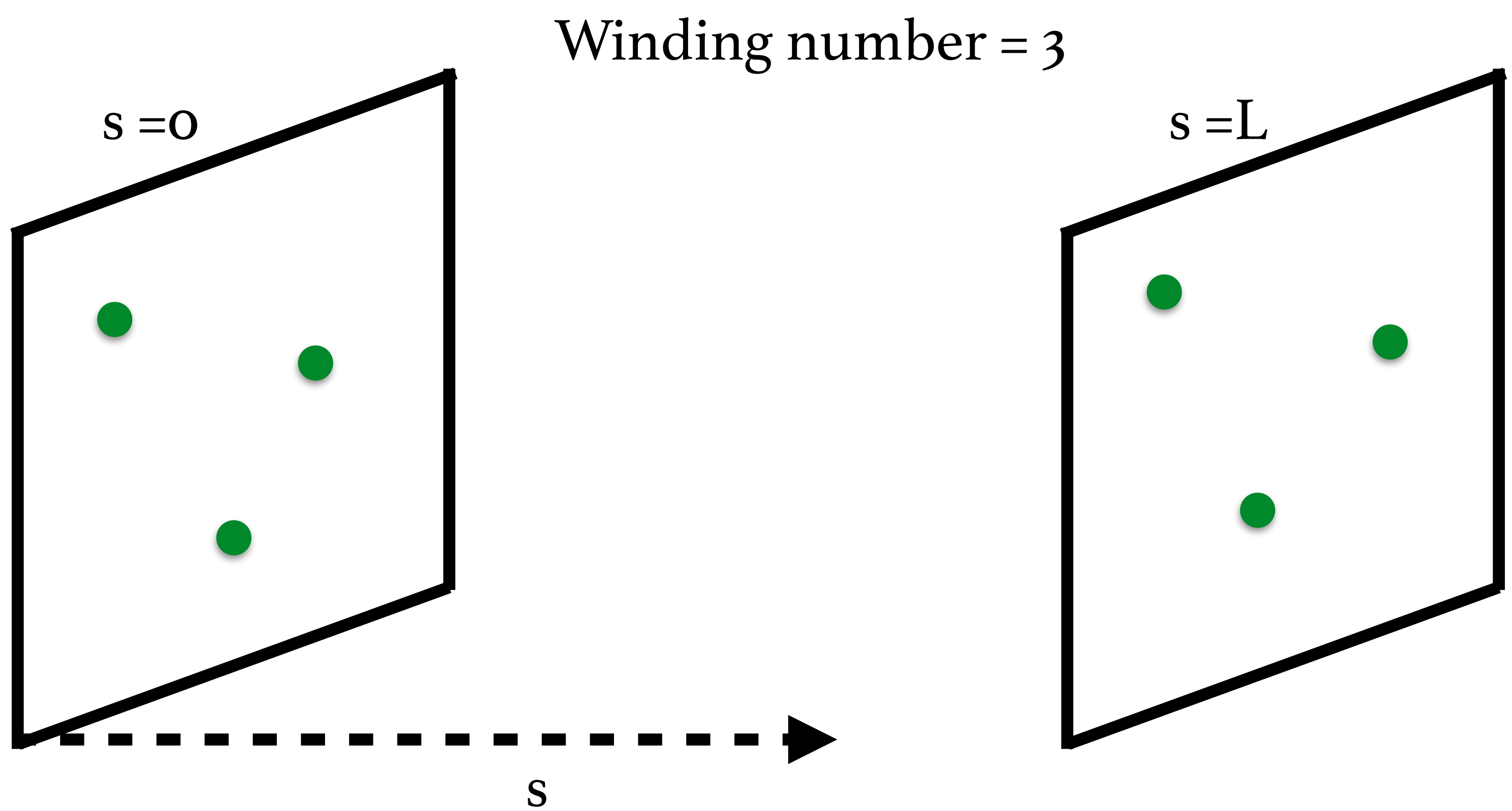
Topological Gauge Configurations - Weak Coupling



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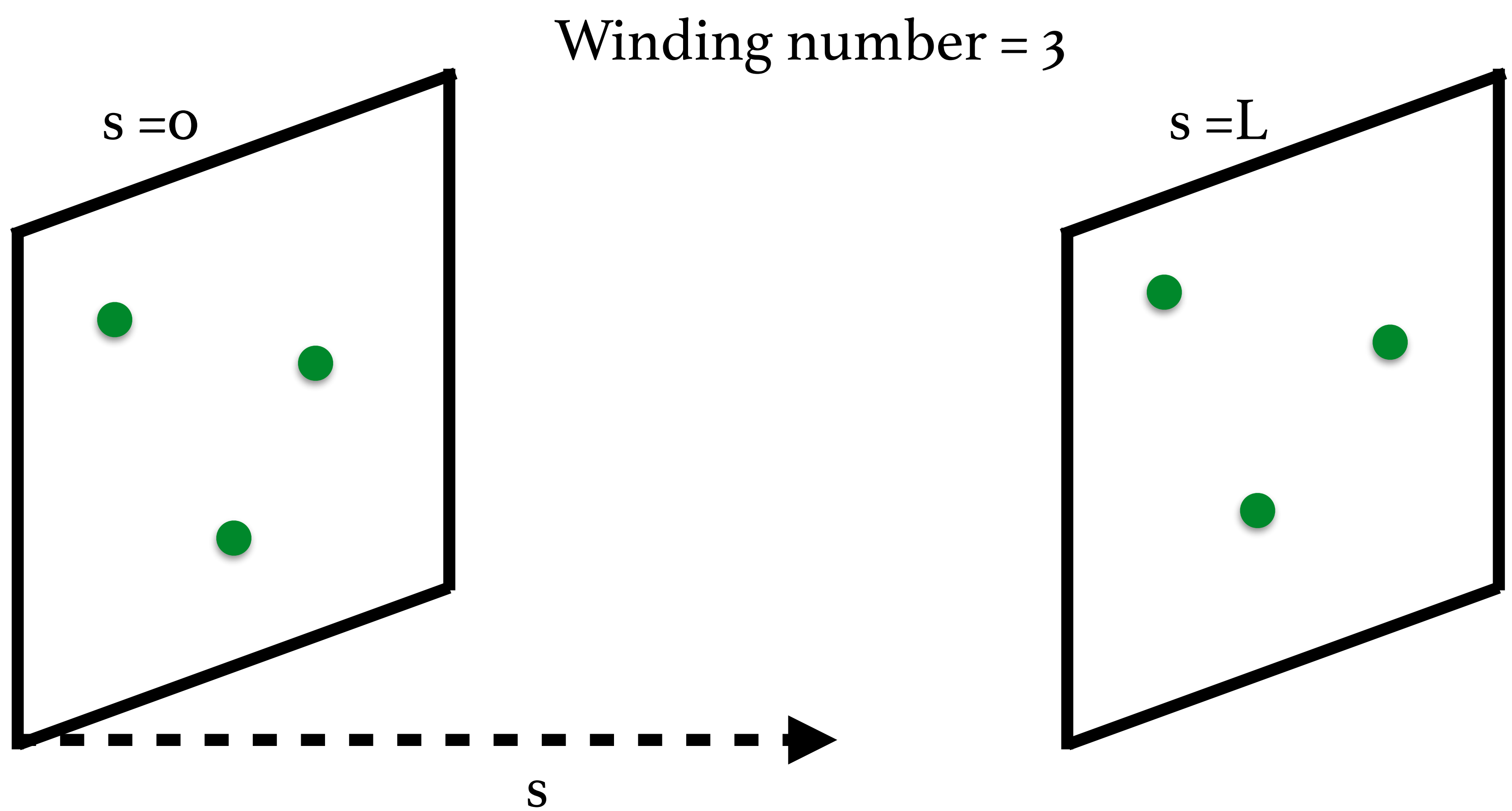
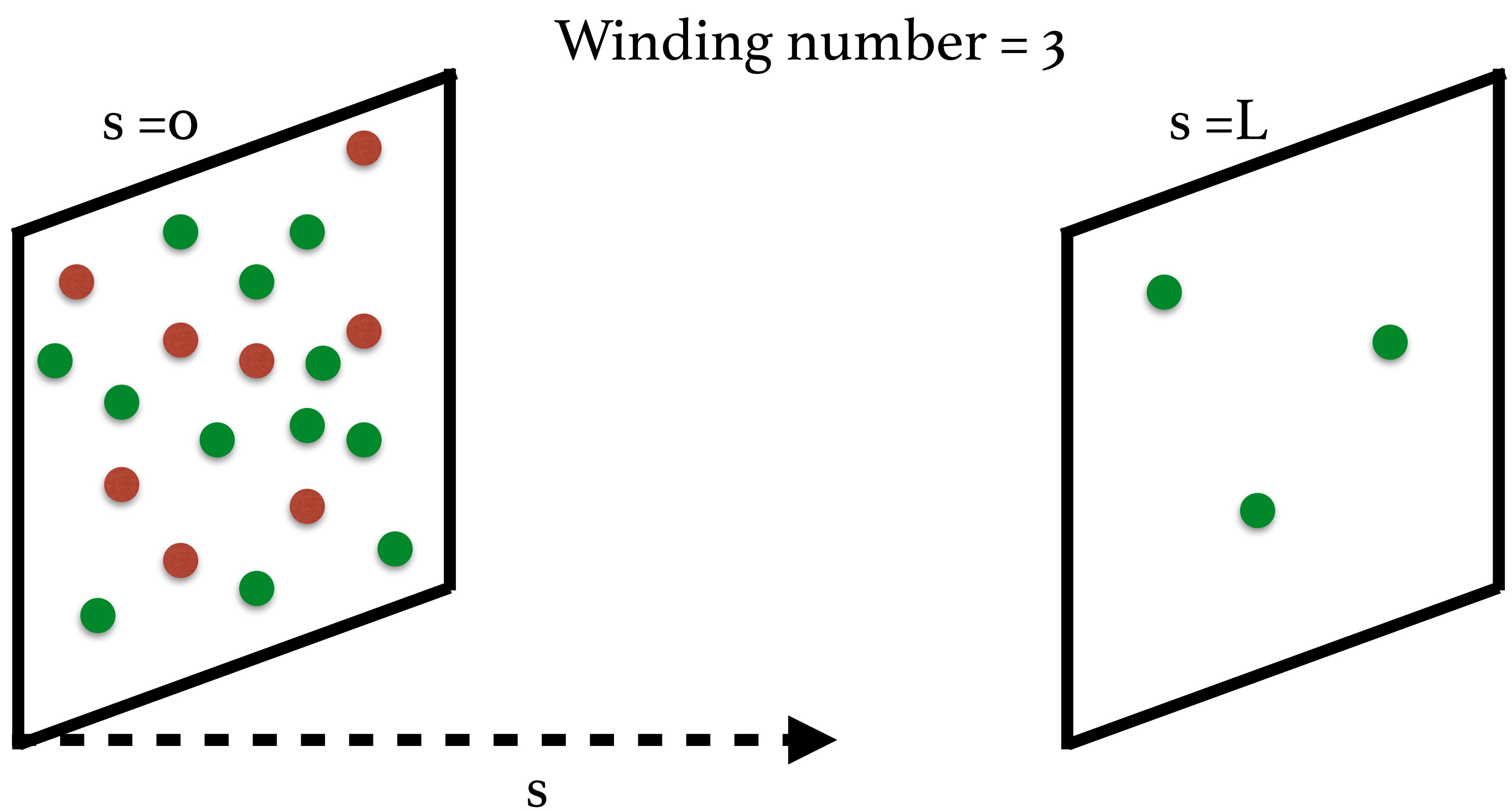


At weak coupling, instanton contribution is most important

- Flow does not affect location of instantons
- Correlation between location of instantons on the two boundaries allows for exchange of energy/momentum
- Highly suppressed process, so difficult to observe

Topological Gauge Configurations - Strong Coupling



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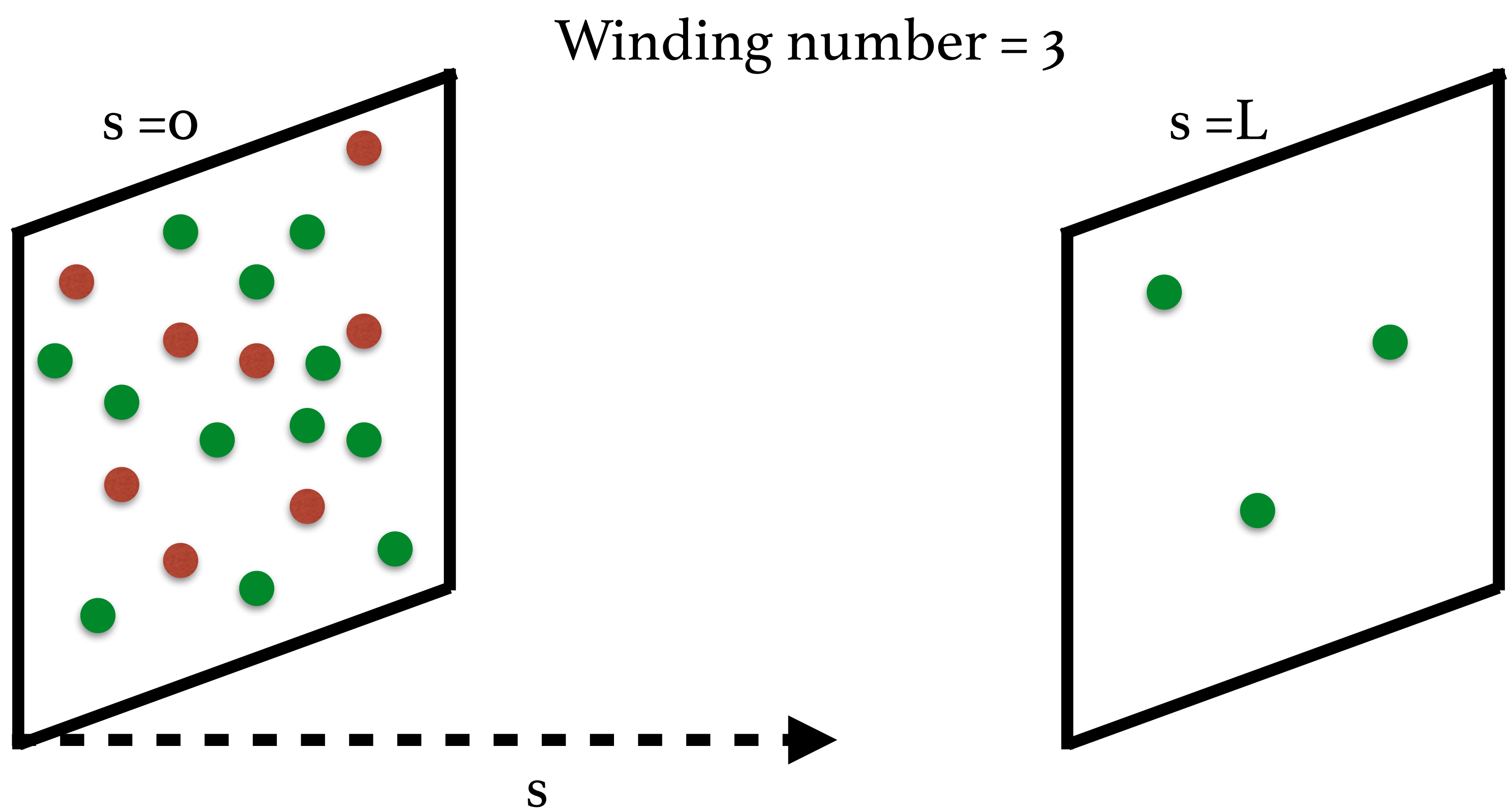

At strong coupling, need to include instanton-anti instanton pairs

- I-A pairs DO NOT satisfy equations of motion
- If flow for sufficiently long time, all pairs will annihilate
- If no correlation between location of instantons on the two boundary, standard fermions and Fluff do not exchange energy/momentum

Summary

- Proposal for fermion measure for chiral gauge theory

$$\Delta(A) = \prod_i \frac{\det\left[\not{D}(\bar{A}) - \Lambda_i \epsilon(s)\right]}{\det\left[\not{D}(\bar{A}) - \Lambda_i\right]} \qquad \partial_s \bar{A}_\mu = \frac{\xi \epsilon(s)}{|\Lambda|} D_\nu \bar{F}_{\nu\mu}$$

  - Combines domain wall fermions and gauge field smearing
  - Local theory if chiral fermion representation is anomaly free
  - Mirror fermions decouple due to exponentially soft form factors to gauge fields

Summary

- Proposal for fermion measure for chiral gauge theory

$$\Delta(A) = \prod_i \frac{\det\left[\not{D}(\bar{A}) - \Lambda_i \epsilon(s)\right]}{\det\left[\not{D}(\bar{A}) - \Lambda_i\right]} \qquad \partial_s \bar{A}_\mu = \frac{\xi \epsilon(s)}{|\Lambda|} D_\nu \bar{F}_{\nu\mu}$$

  - Combines domain wall fermions and gauge field smearing
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- Important open questions remain about this proposal
- Is there Fluff hiding in the Standard Model?