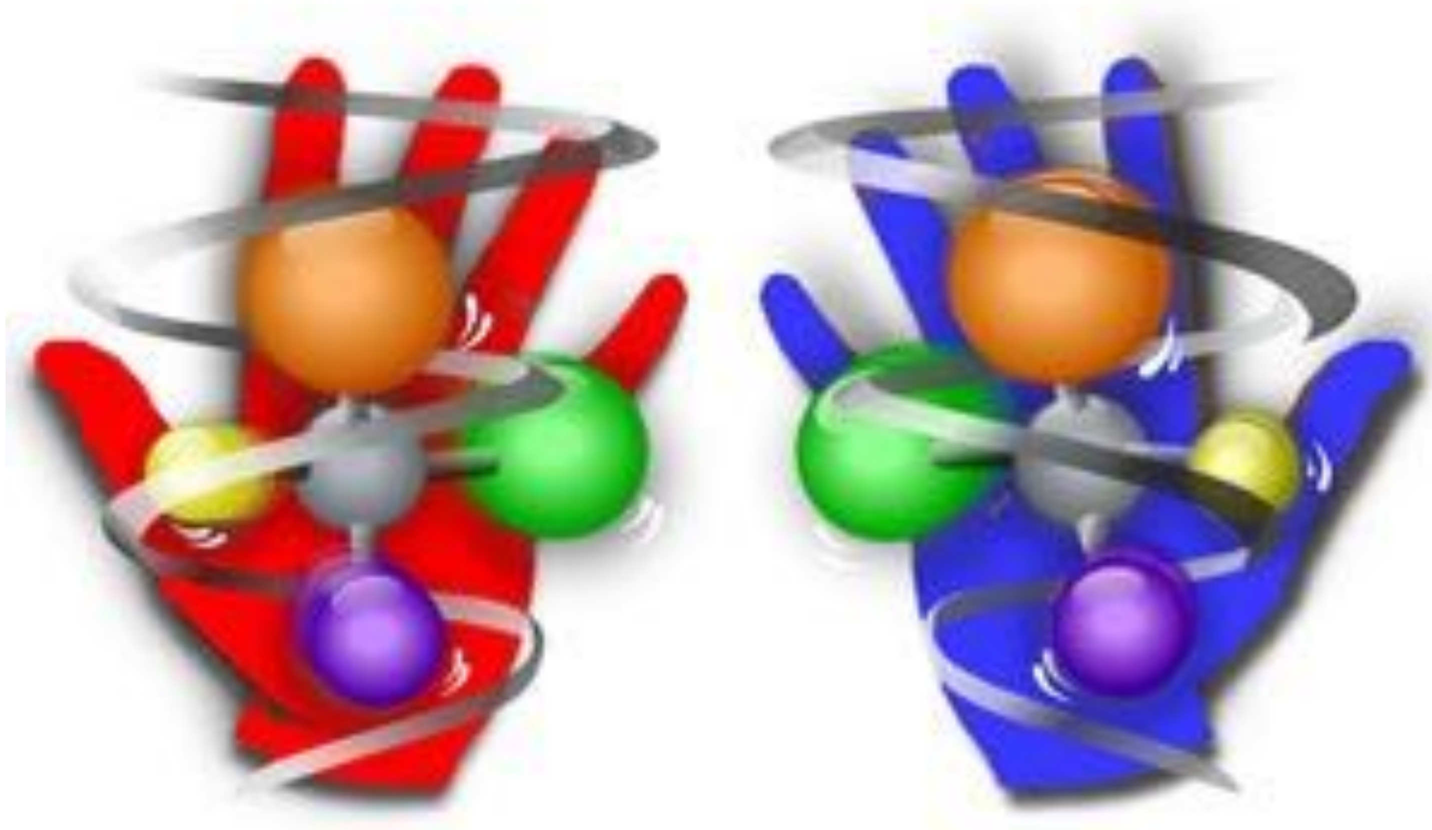
# Exotic Mirror Fermions from Chiral Gauge Theories



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…mirror fermions in the SM which only interact with normal matter non-locally through gauge field topology

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Devise a nonperturbative (lattice) regulator for chiral gauge theories.



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Without understanding renormalization we do not understand how short distance physics can decouple from the theory

…maybe there is exotic physics needed to make the SM work that is partly hidden from us and unsuspected?

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What happens if you give the doublers large masses to decouple them?

*You break the gauge symmetry.*

Chiral symmetry — forbids mass
Renormalization — requires mass

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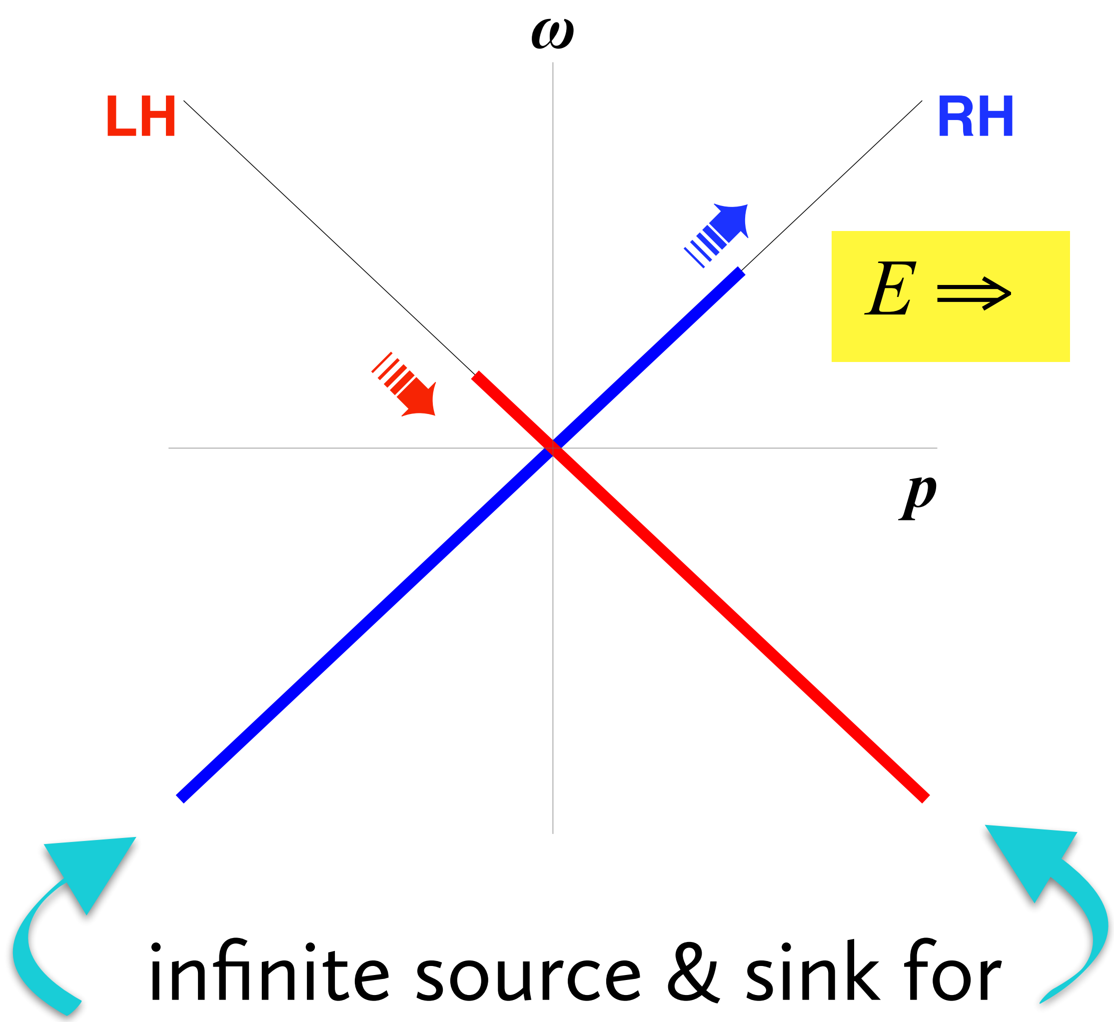


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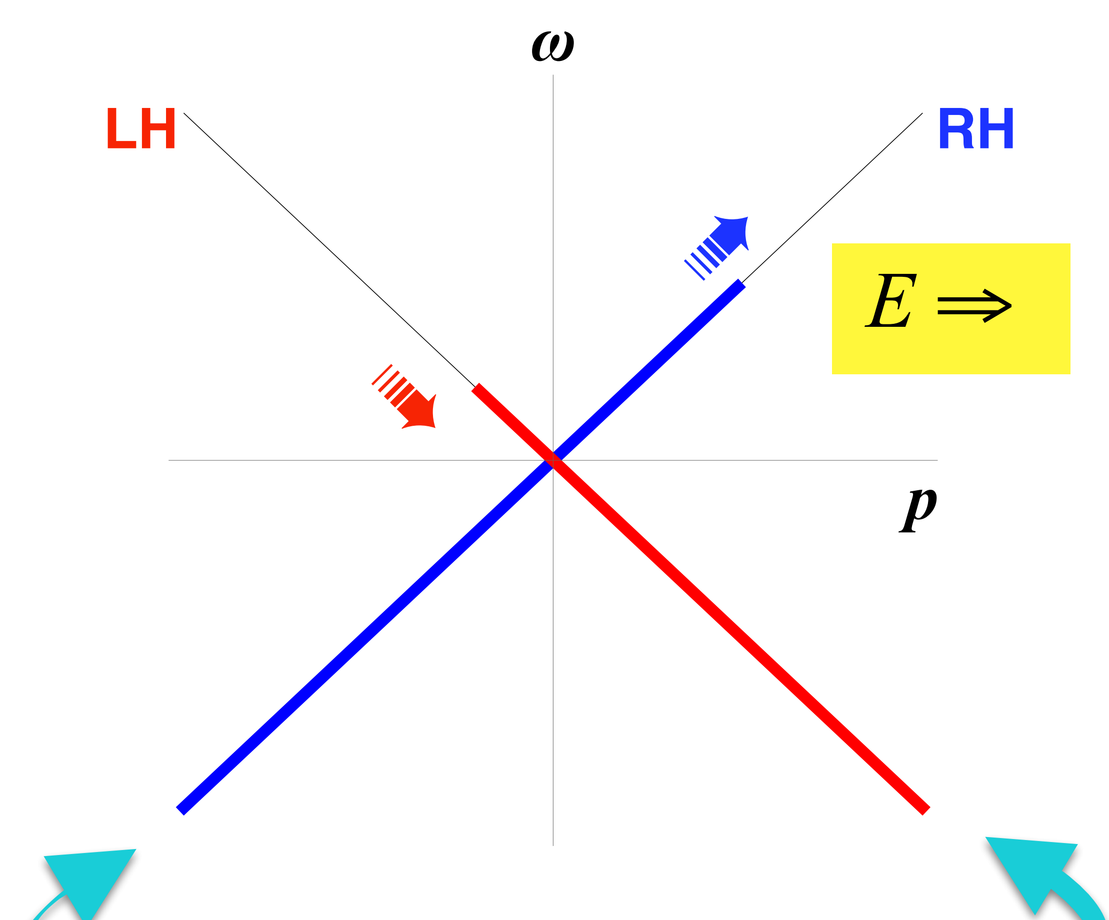



infinite source & sink for fermions

$$dp = qE\,dt$$

$$dn_R = +\frac{dp}{2\pi} \qquad dn_L = -\frac{dp}{2\pi}$$

$$\frac{dn_5}{dt} = \frac{qE}{\pi}$$

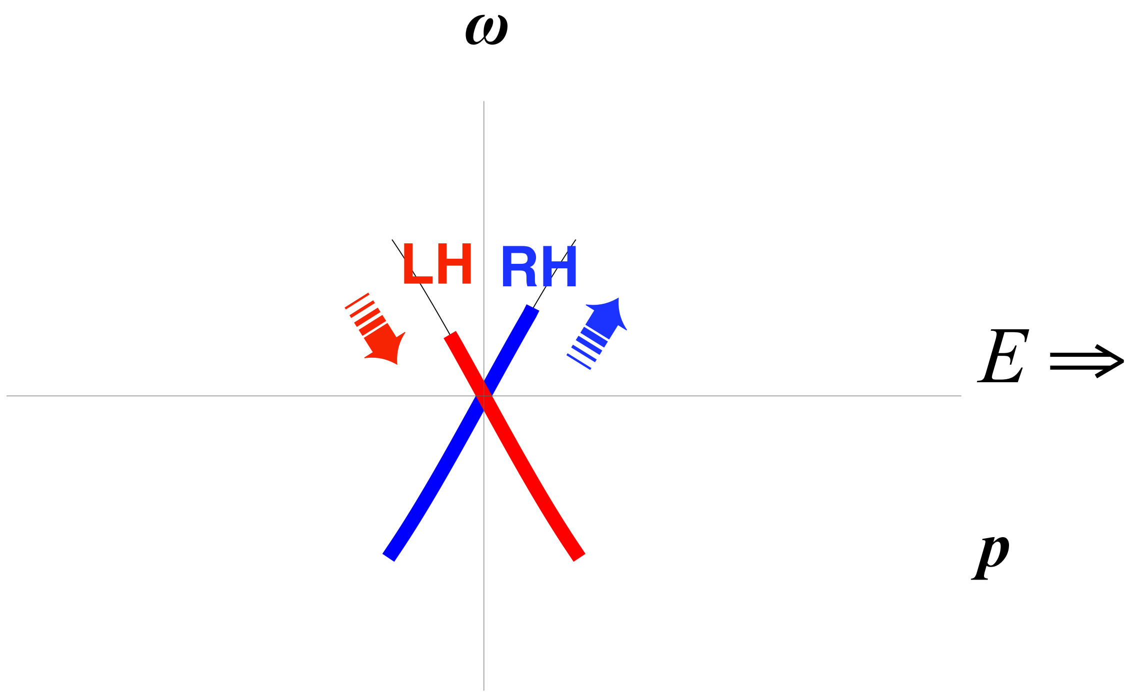
d=1+1 anomaly

$$\partial_\mu j_5^\mu = \frac{q}{2\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$


In the continuum, the Dirac sea is filled…but is a Hilbert Hotel which always has room for more

## **Not so on the lattice**:

Can reproduce continuum physics for long wavelength modes…



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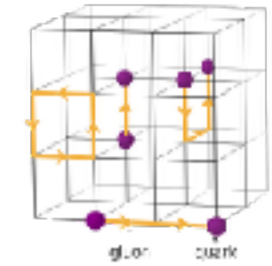

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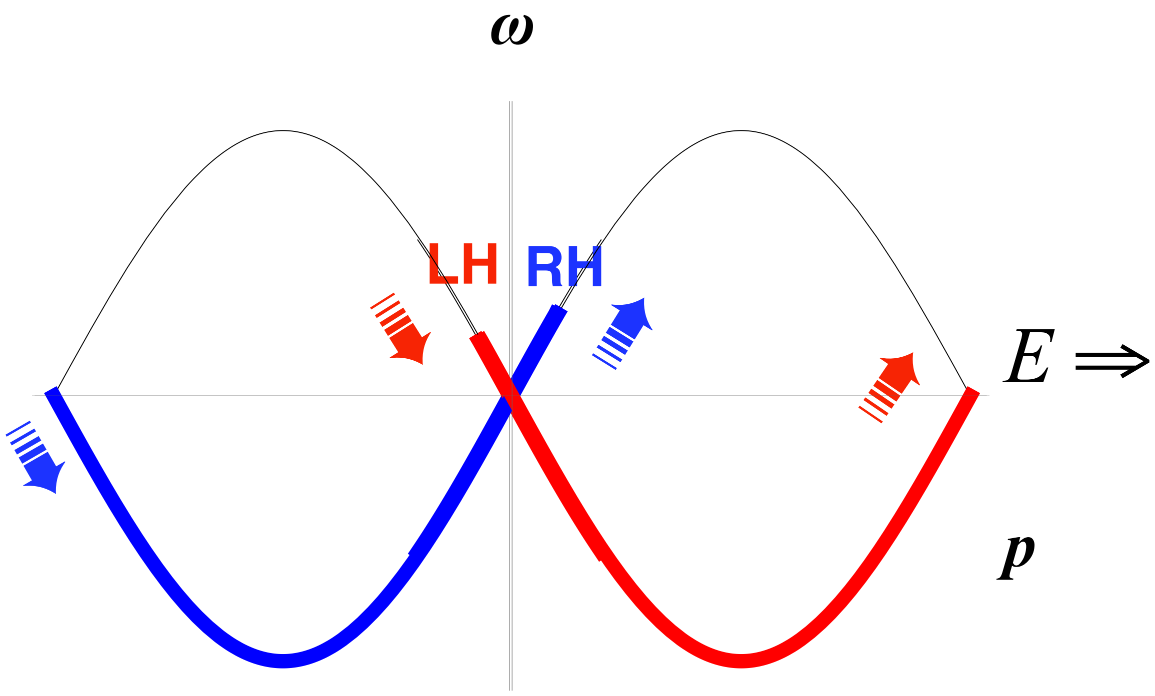


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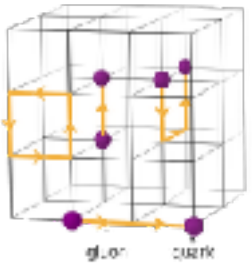

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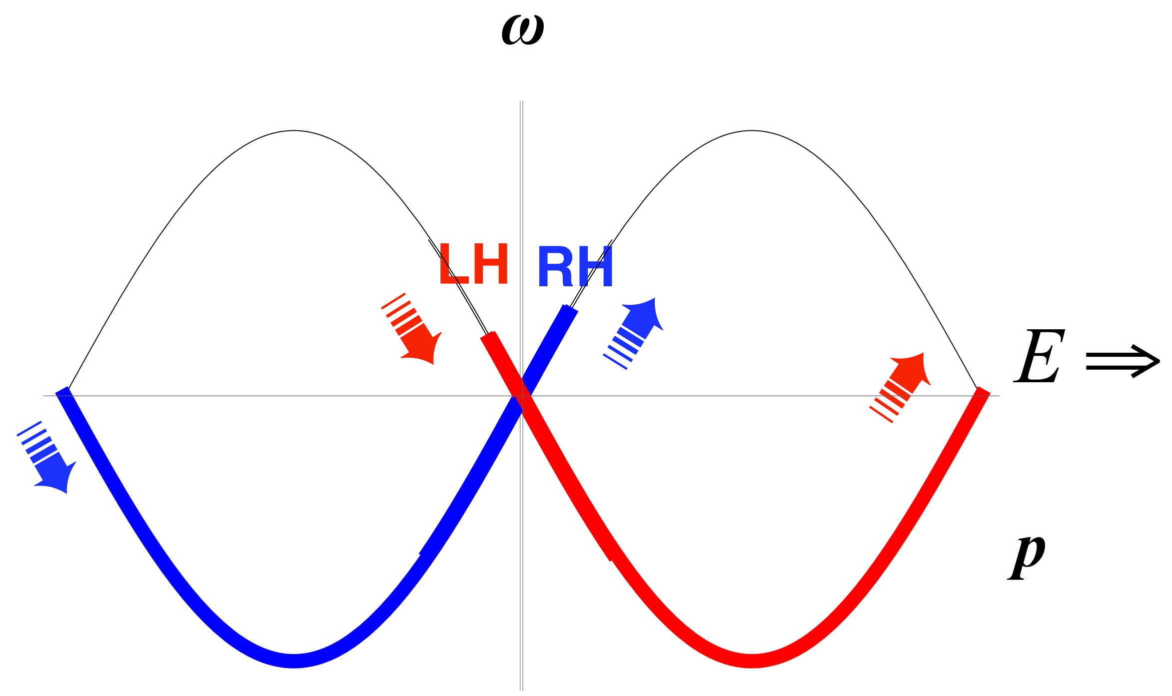


$$\partial_\mu j_5^\mu = 0$$

<u>anomalous symmetry</u> in the continuum

must be

<u>explicitly broken symmetry</u> on the lattice

# The Nielsen-Ninomiya Theorem:

*The Euclidian fermion action:*

$$S = \int_{-\pi/a}^{\pi/a} \frac{d^{2k}p}{(2\pi)^4}\, \overline{\Psi}_{-\mathbf{p}} \tilde{D}(\mathbf{p}) \Psi(\mathbf{p})$$

*cannot have a kinetic operator D satisfying all four of the following properties simultaneously:*

1. $\tilde{D}(\mathbf{p})$ is a periodic, analytic function of $p_\mu$; $\Leftarrow$ regulated, local
2. $D(\mathbf{p}) \propto \gamma_\mu p_\mu$ for $a|p_\mu| \ll 1$; $\Leftarrow$ Dirac @ long wavelength
3. $\tilde{D}(\mathbf{p})$ invertible everywhere except $p_\mu = 0$; $\Leftarrow$ No doubling of flavors
4. $\{\Gamma, \tilde{D}(\mathbf{p})\} = 0$. ($\Gamma = \gamma_5$) $\Leftarrow$ respects a chiral symmetry

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Advances in the 1990s showed us how to break global chiral symmetry in just the right way for QCD…but will be problematic when chiral symmetry is gauged!

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Lattice covariant derivatives

$$\mathcal{L} = \bar{\psi}\left(\not{D} + m + aD^2\right)\psi$$

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- Break the symmetries explicitly at the lattice cutoff (m~ 1/a) !
- Fine tune the hell out of the theory to find chiral symmetry in the continuum...magically, the anomaly is reproduced as a byproduct
- **Lost**: the benefits of chiral symmetry - multiplicative mass renormalization, non-mixing of operators...
- ...and a particularly disturbing way to deal with **gauged** chiral symmetries

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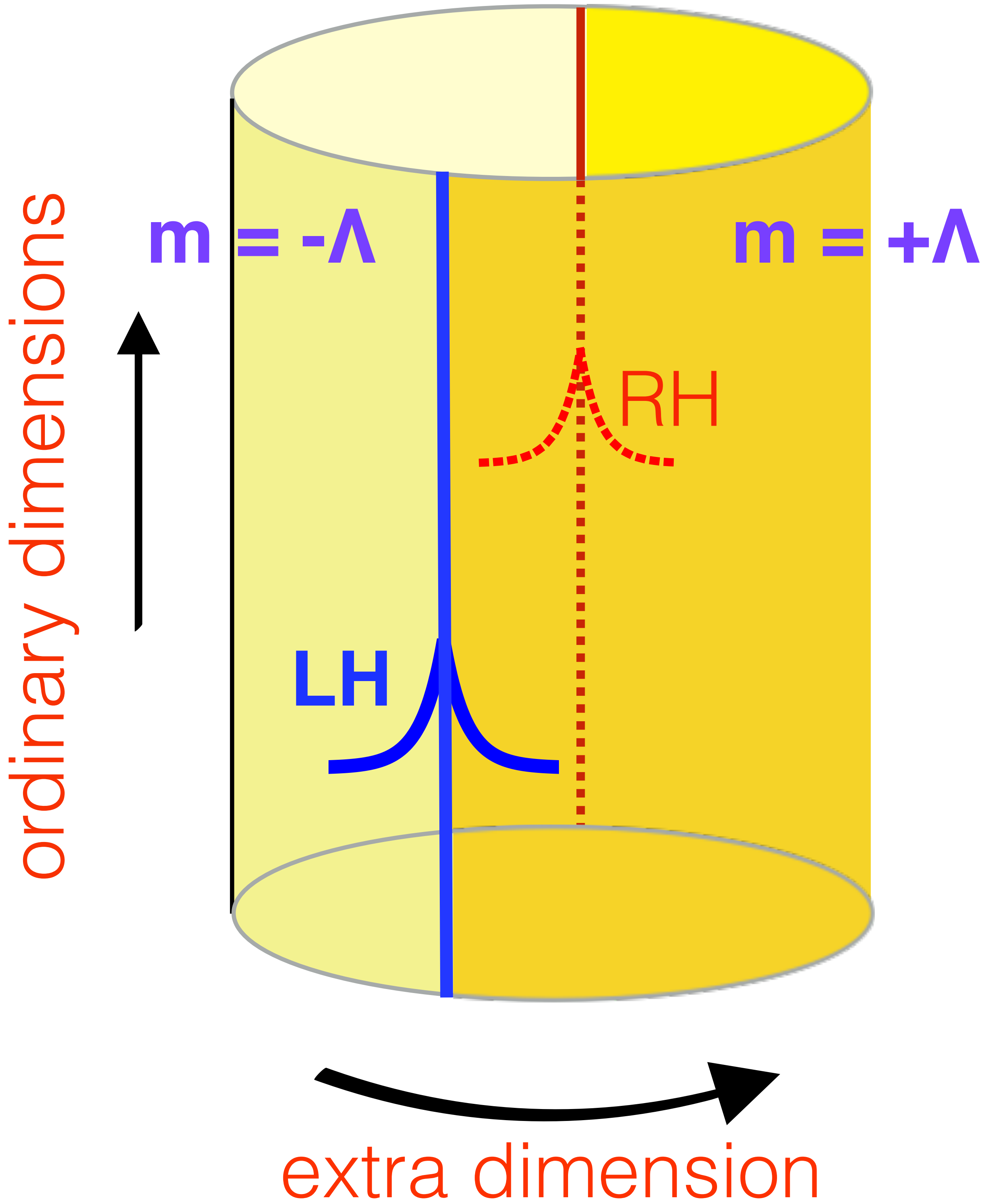


- Introduce a compact extra dimension
- 5d fermion has heavy positive mass on one side, negative on the other
- Chiral massless states appear at the mass defects; other modes are heavy
- Gauge fields do not depend on extra dimension
- Low energy theory looks like a single massless favor with chiral symmetry

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They decouple completely except for induced Chern-Simons term:
(For now: 5d background gauge fields)

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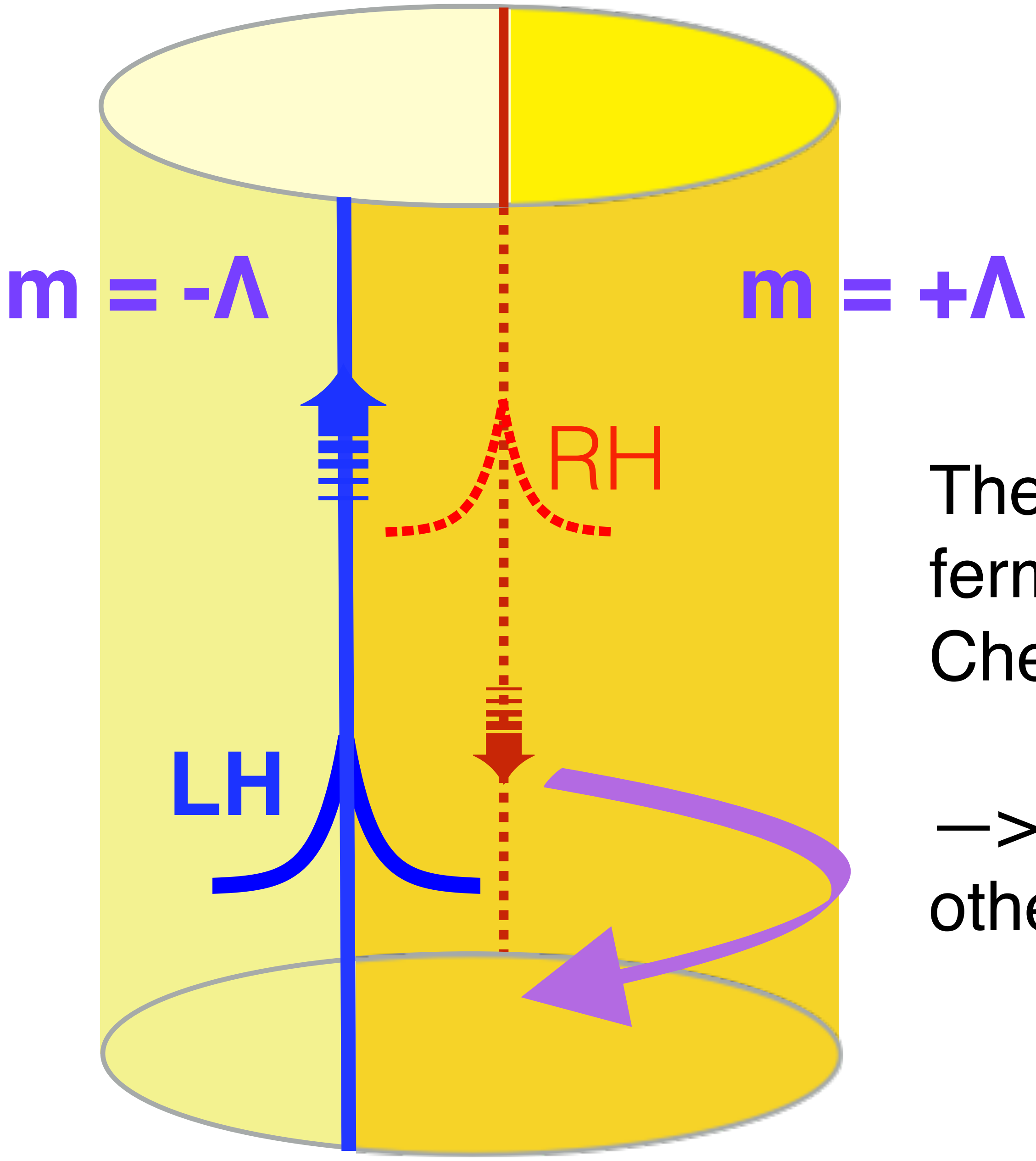
Bulk current explains anomalous disappearance of charge on one defect and reappearance on the other
= anomalous chiral symmetry violation

This is what is called a topological insulator these days by condensed matter theorists

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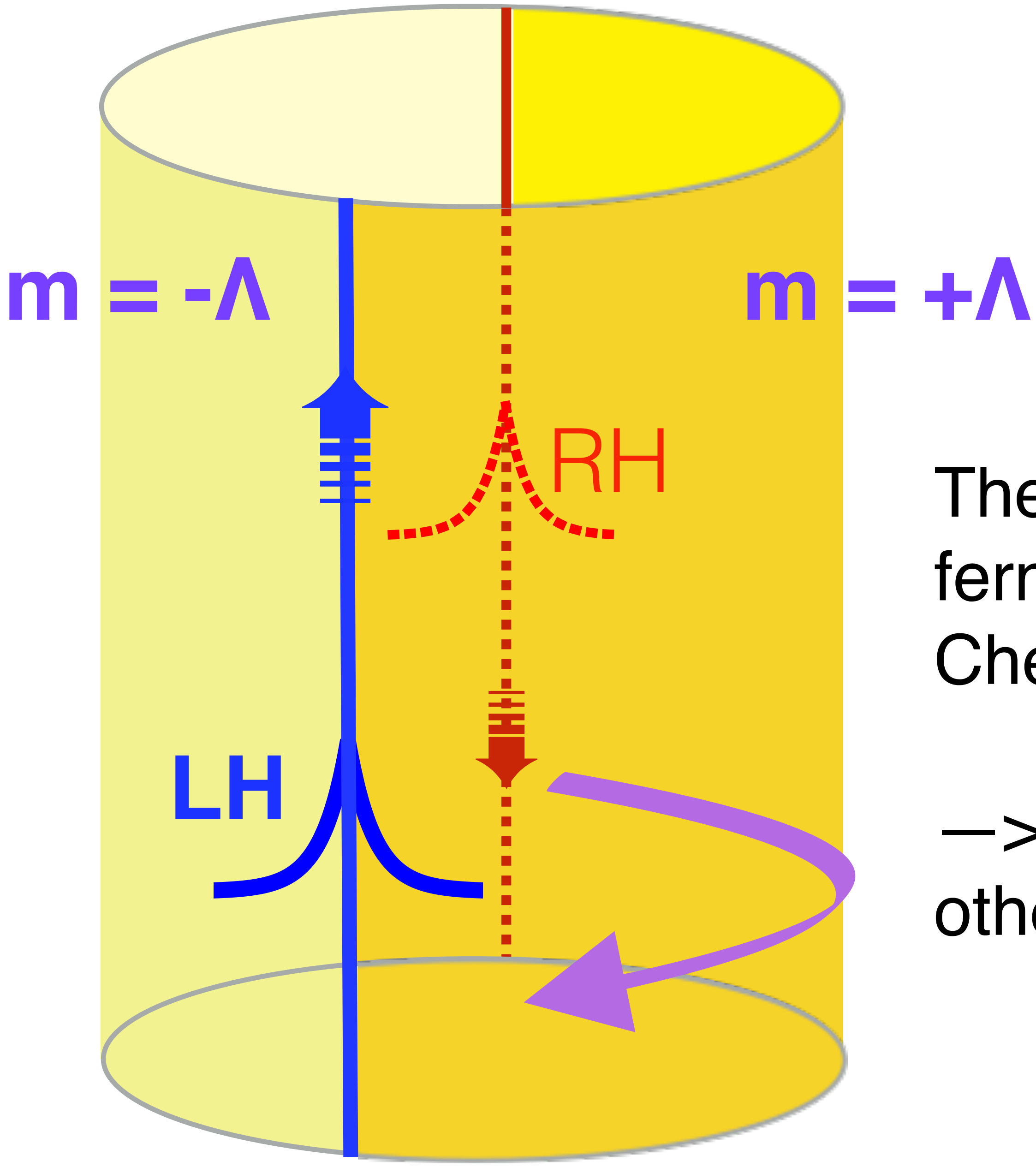


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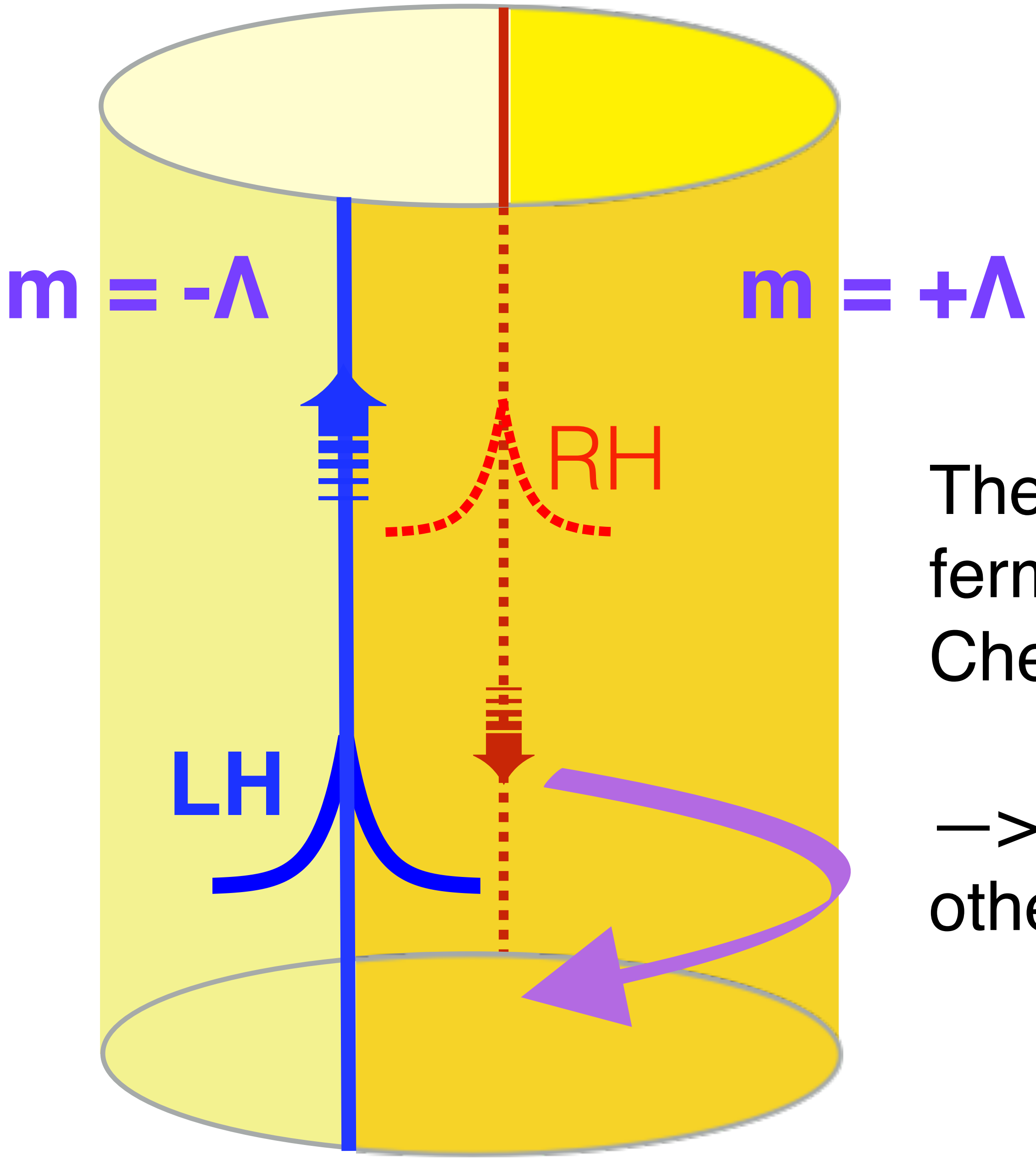
Can construct the exact 4d effective theory in this limit (the “overlap operator”).

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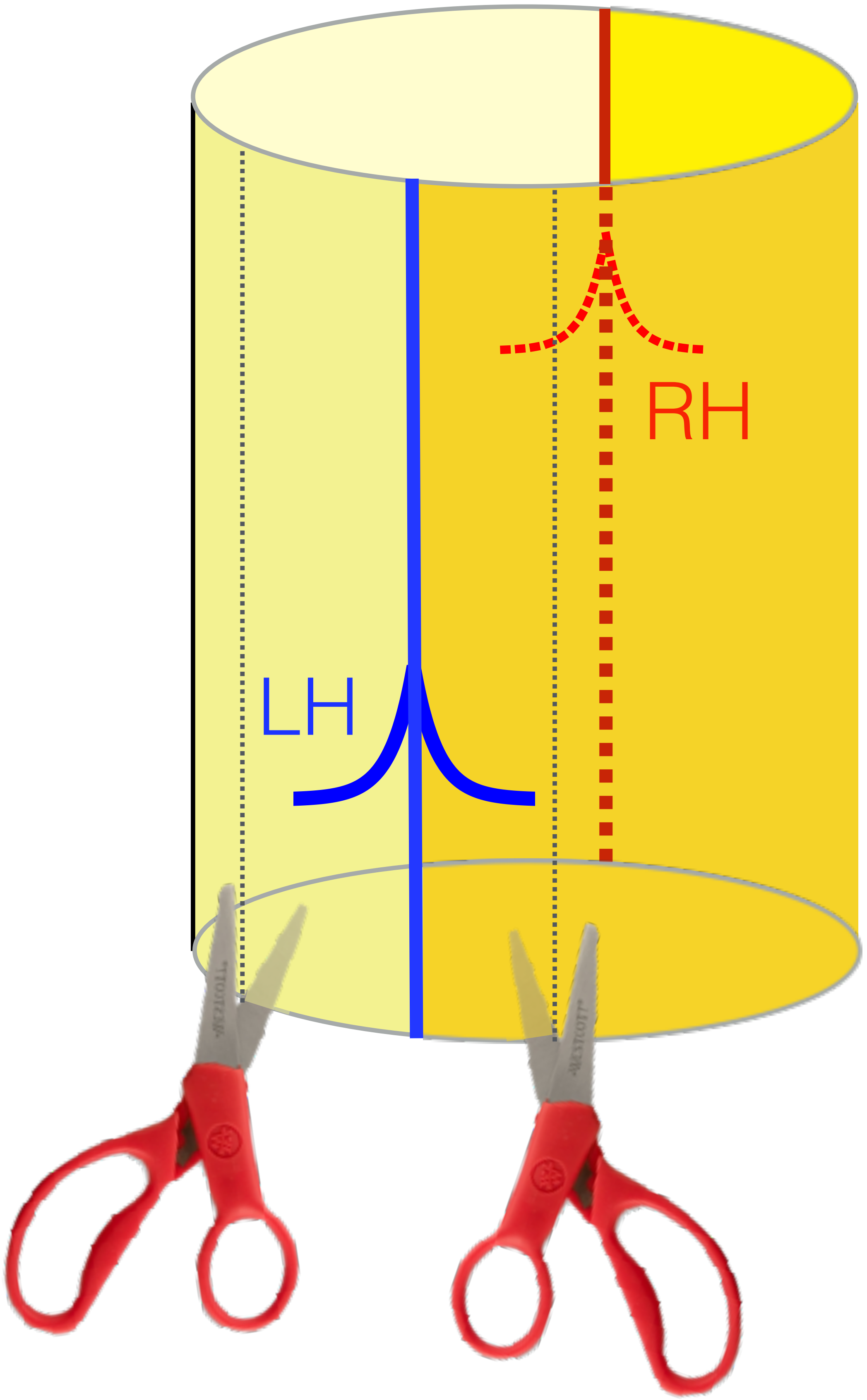
**Can this construction be used for chiral gauge theories?**

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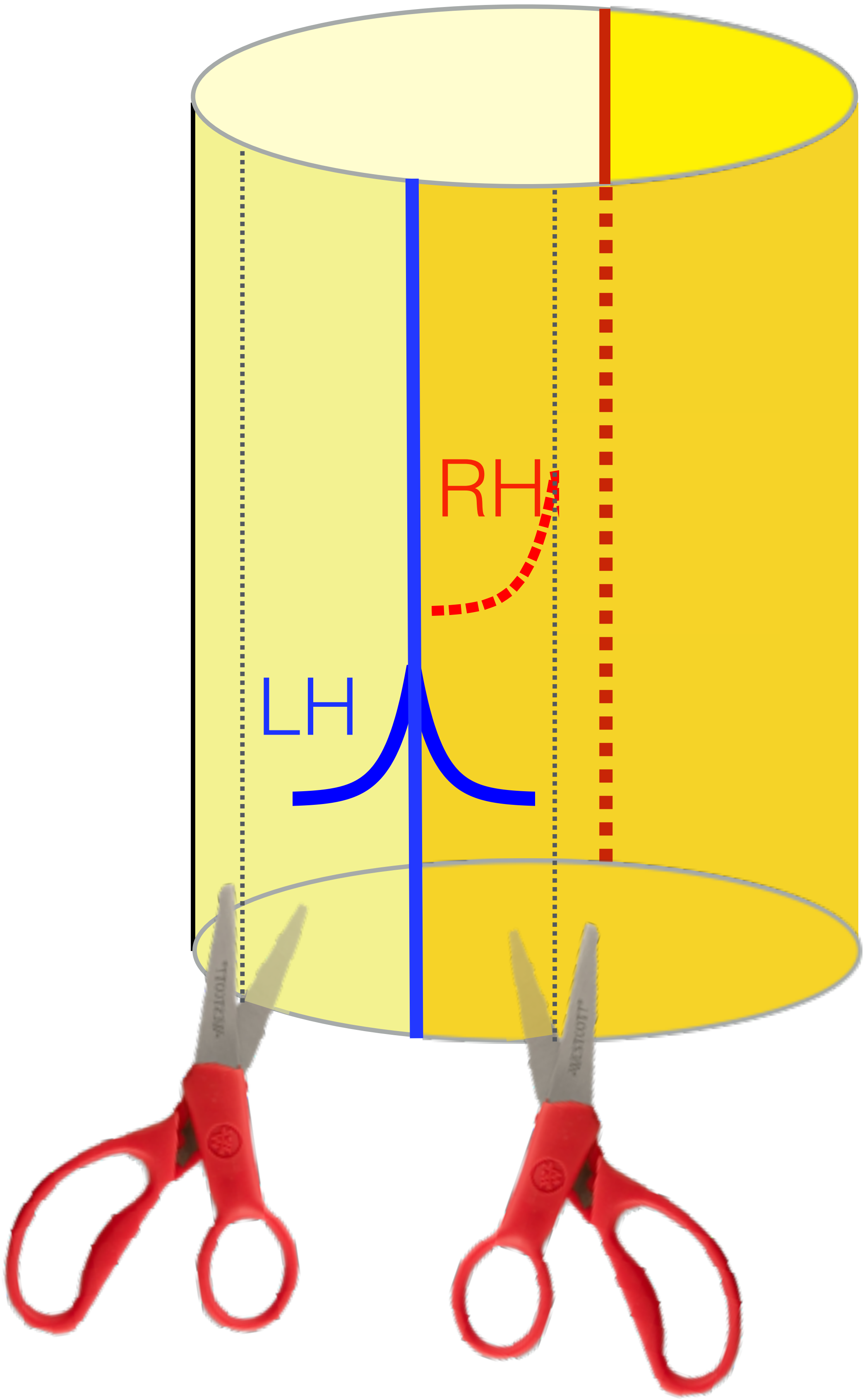


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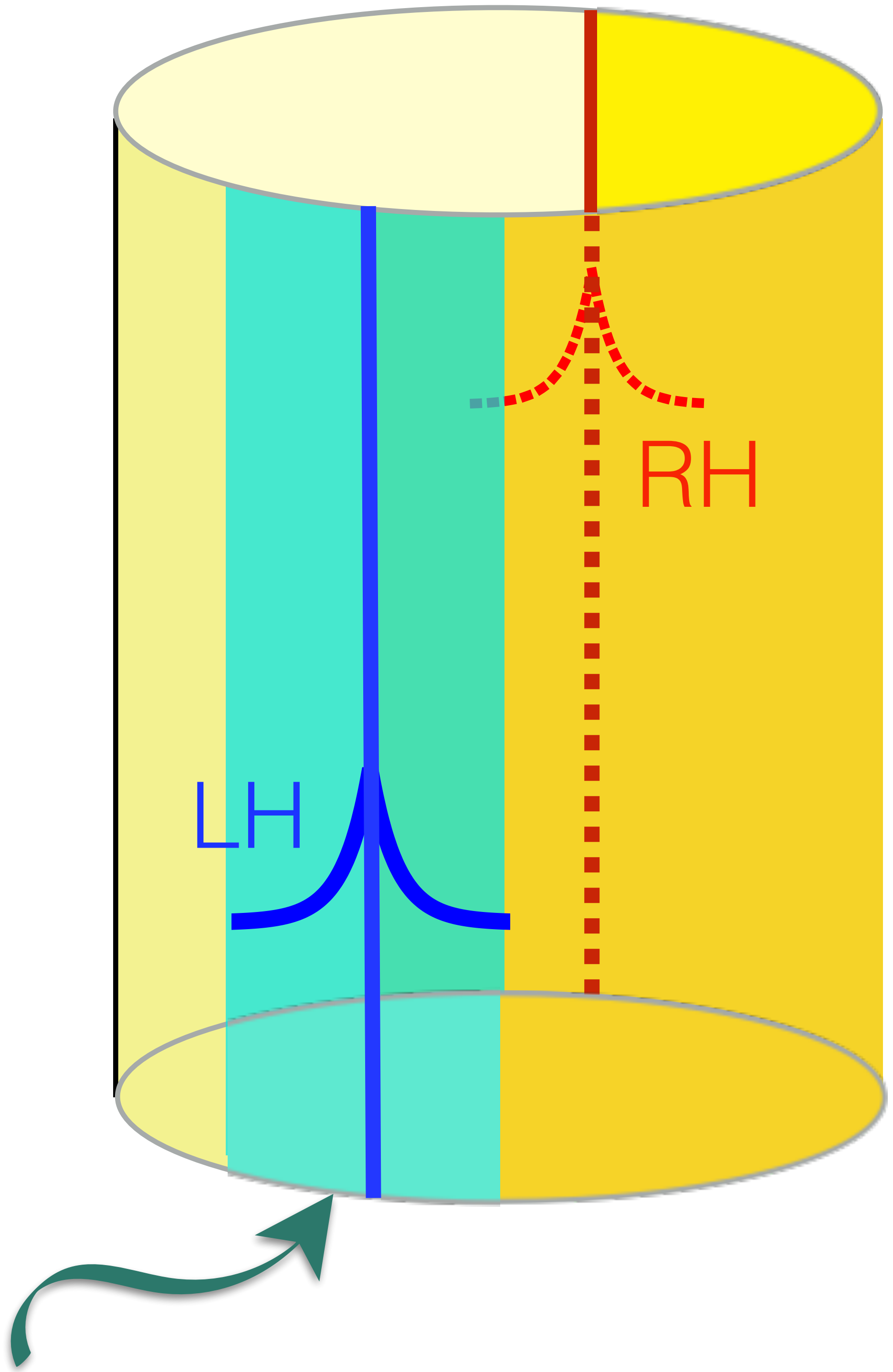


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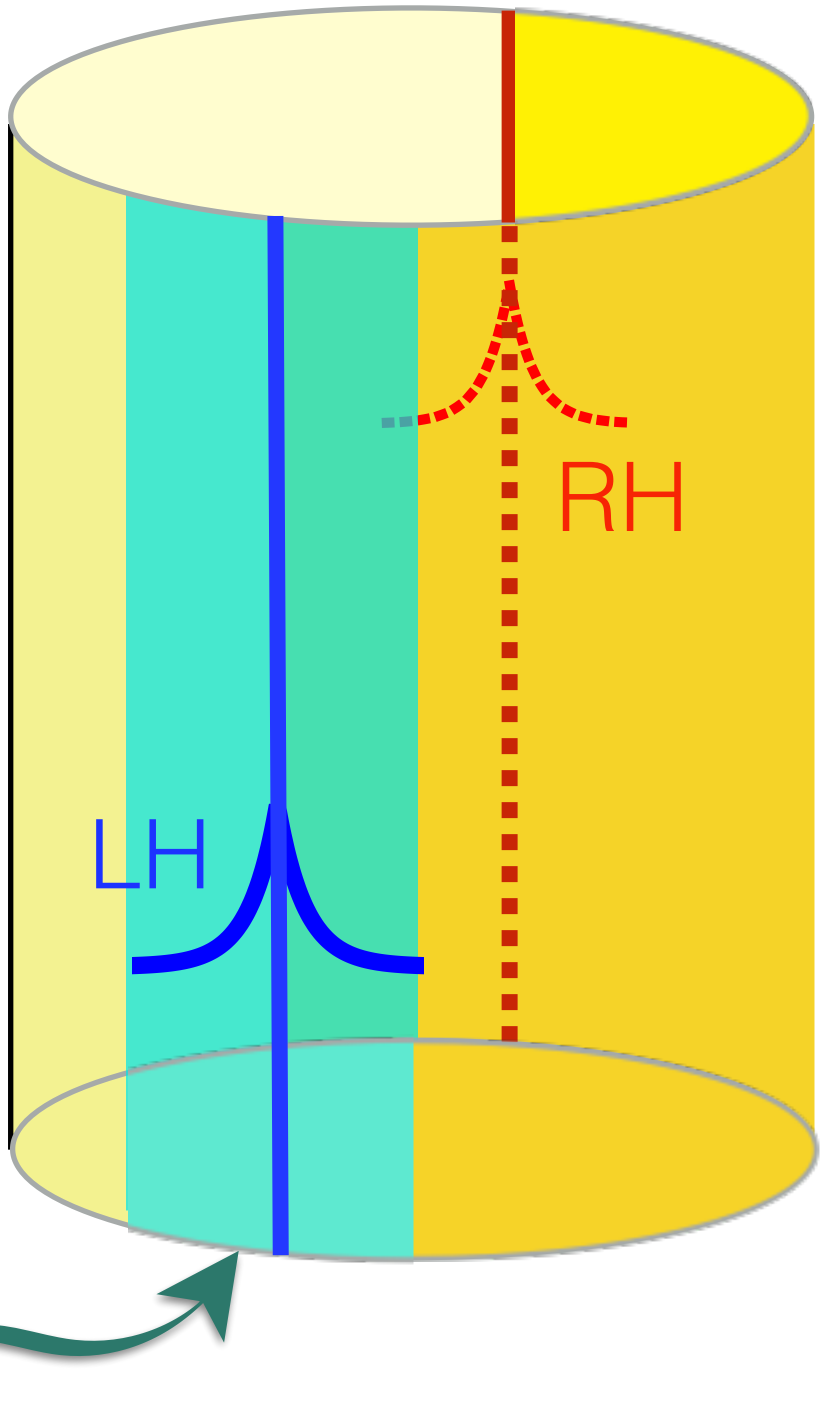


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*No: The 5d kinetic term allows fermions to "hop" in the extra dimension; localizing the gauge field would explicitly break gauge symmetry.*

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Dorota Grabowska, D.B.K.

- Phys.Rev.Lett. 116 211602 (2016) [arXiv:1511.03649]
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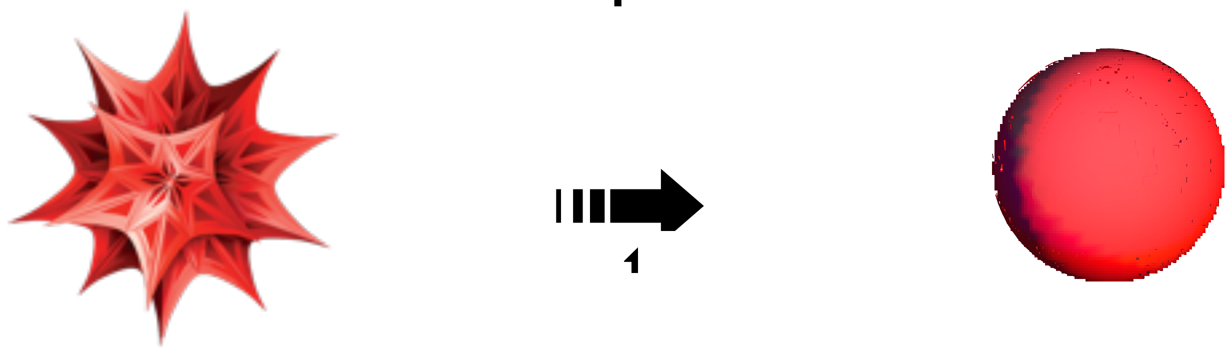

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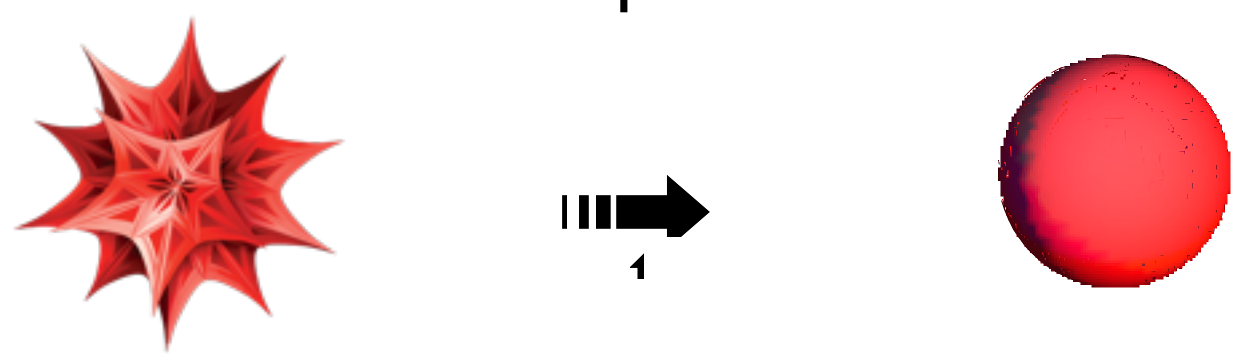

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4d world

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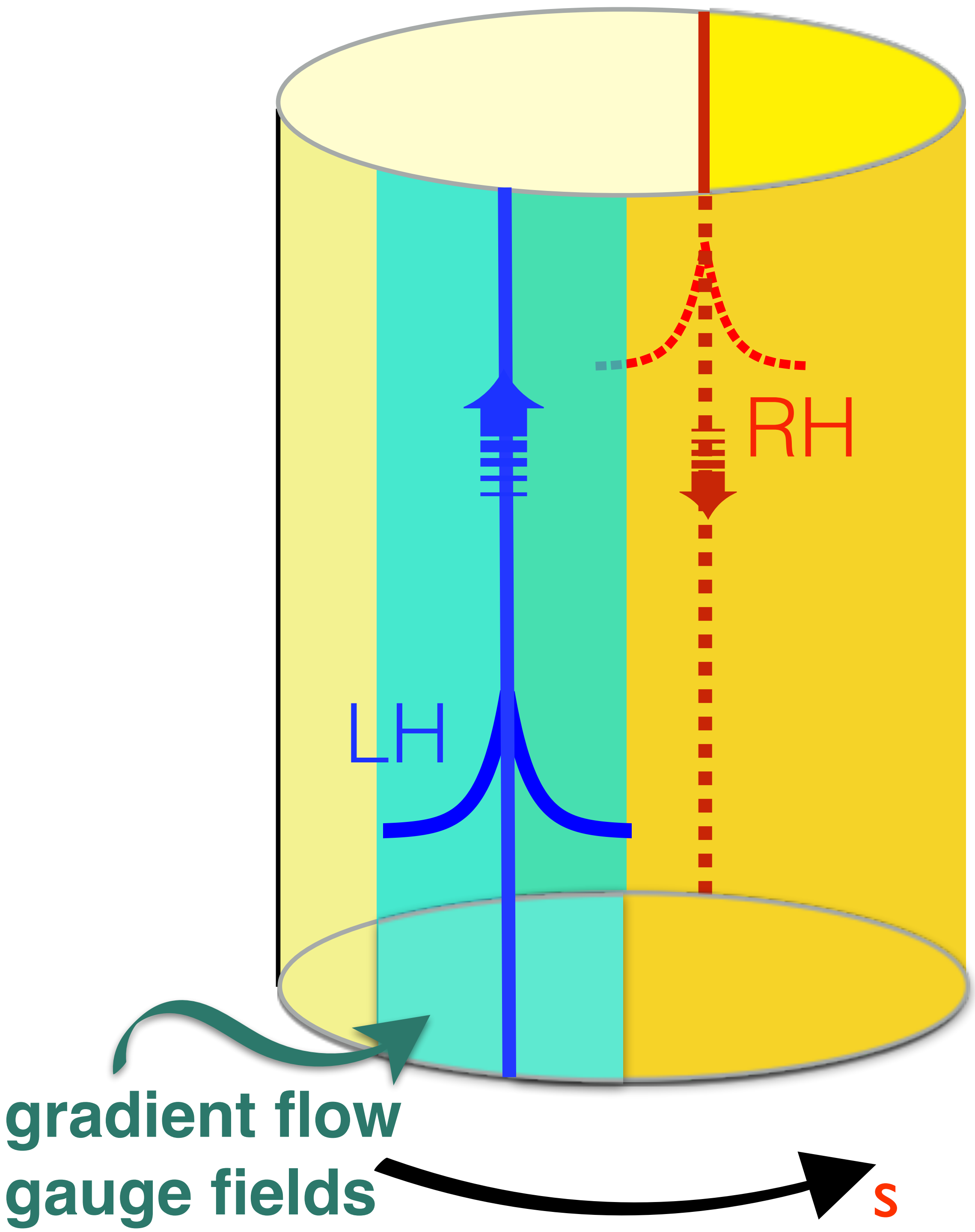
*This will allow λ(p) to be localized near t=0 while maintaining gauge invariance*

*Combining gradient flow gauge fields with domain wall fermions:*



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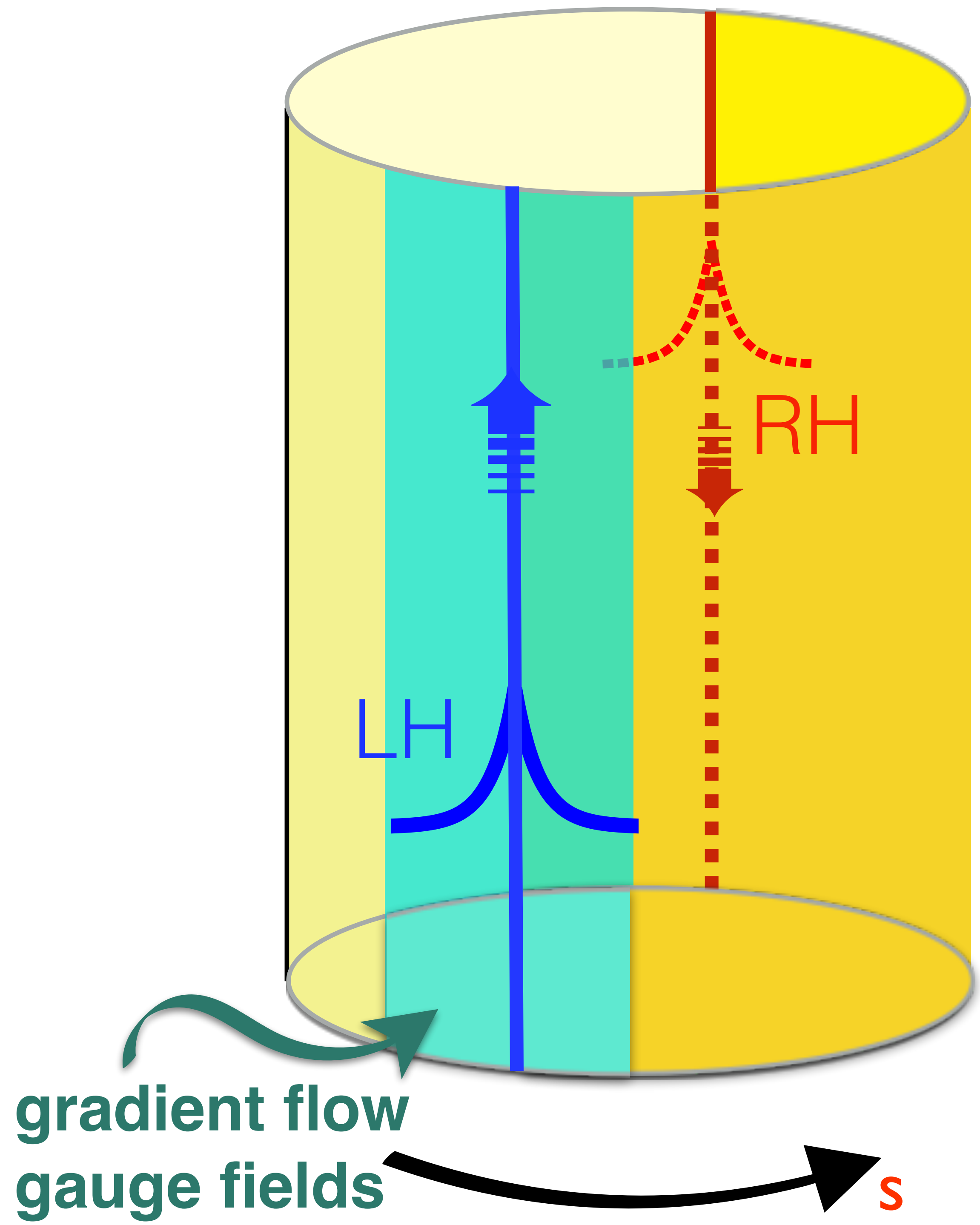

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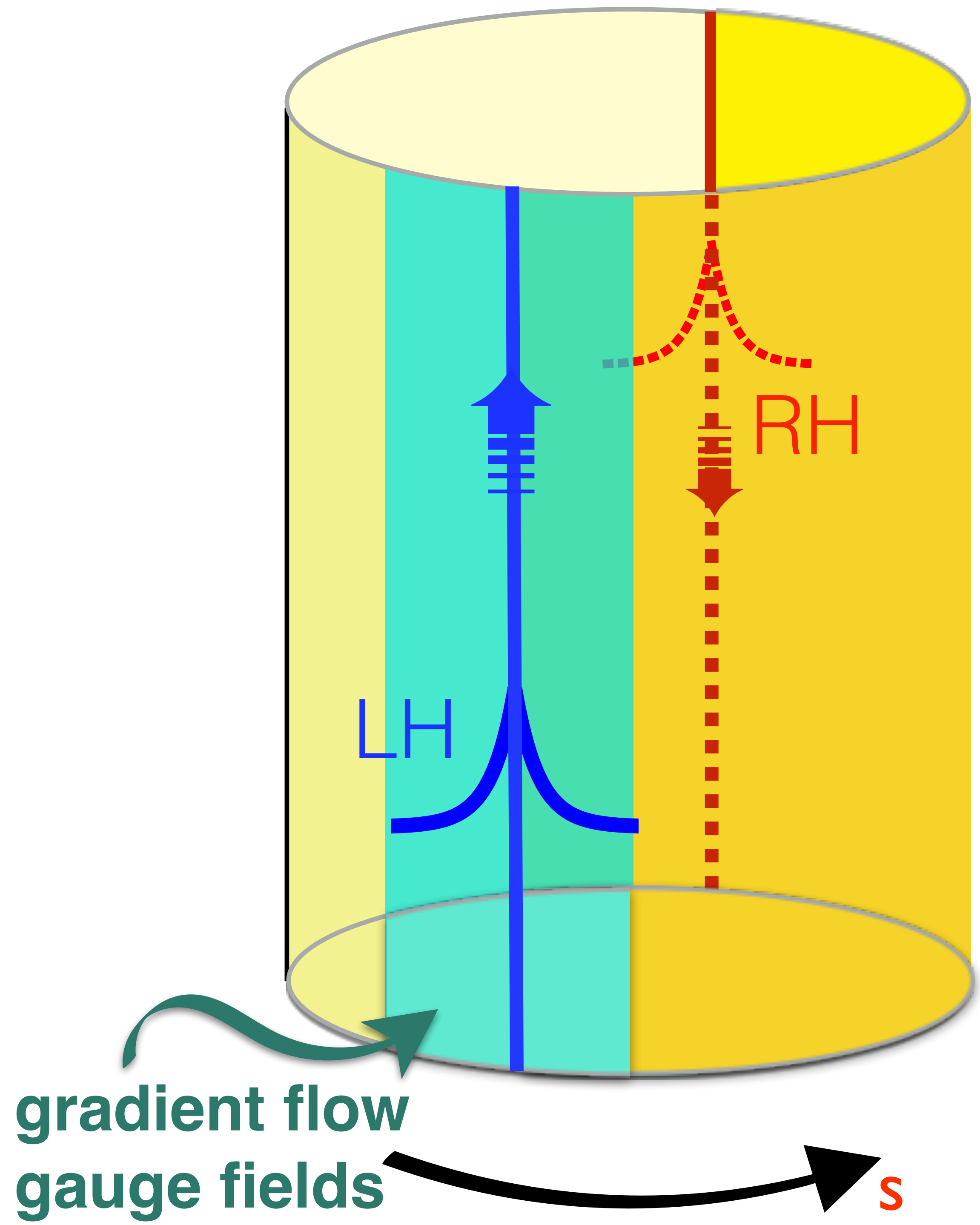

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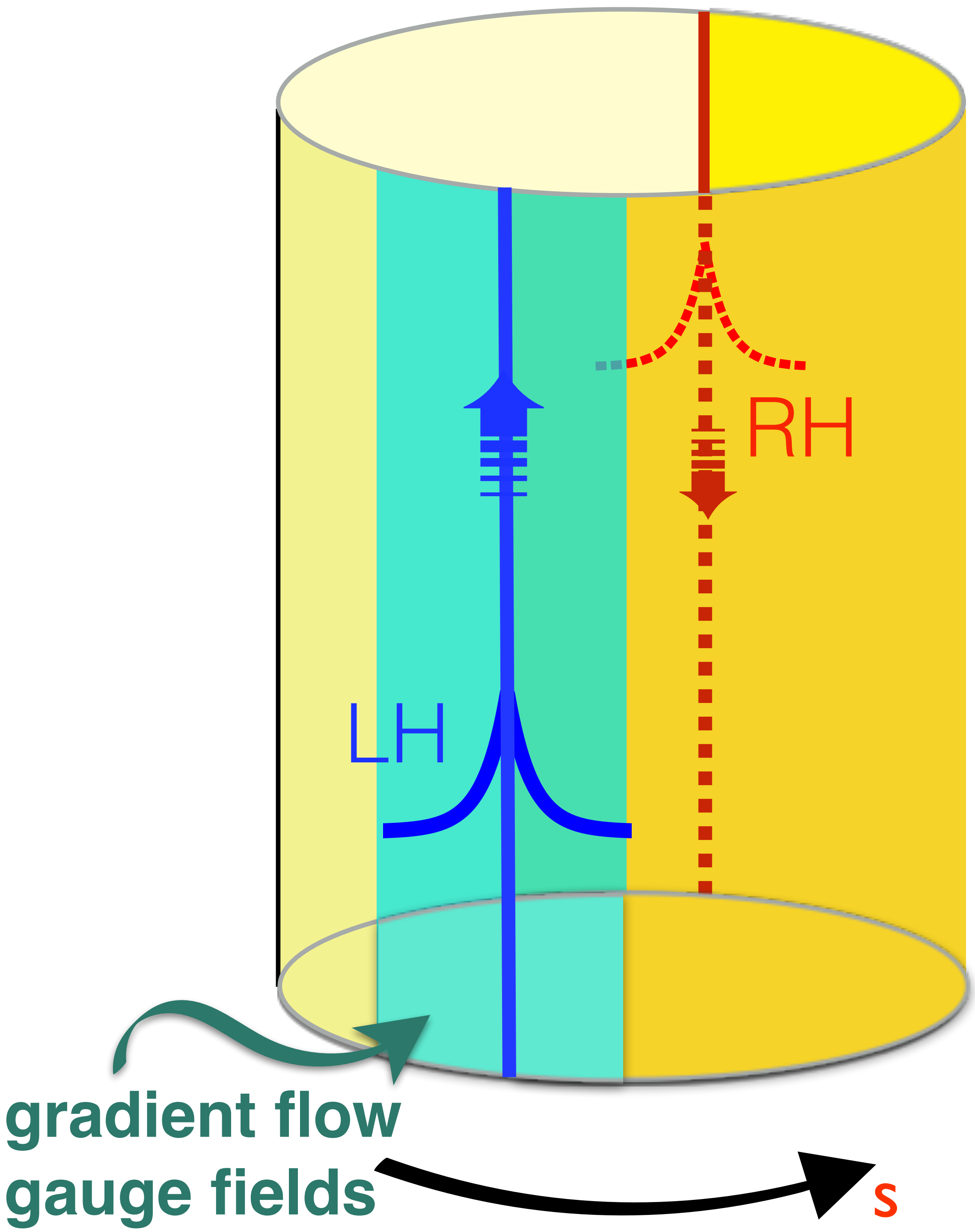

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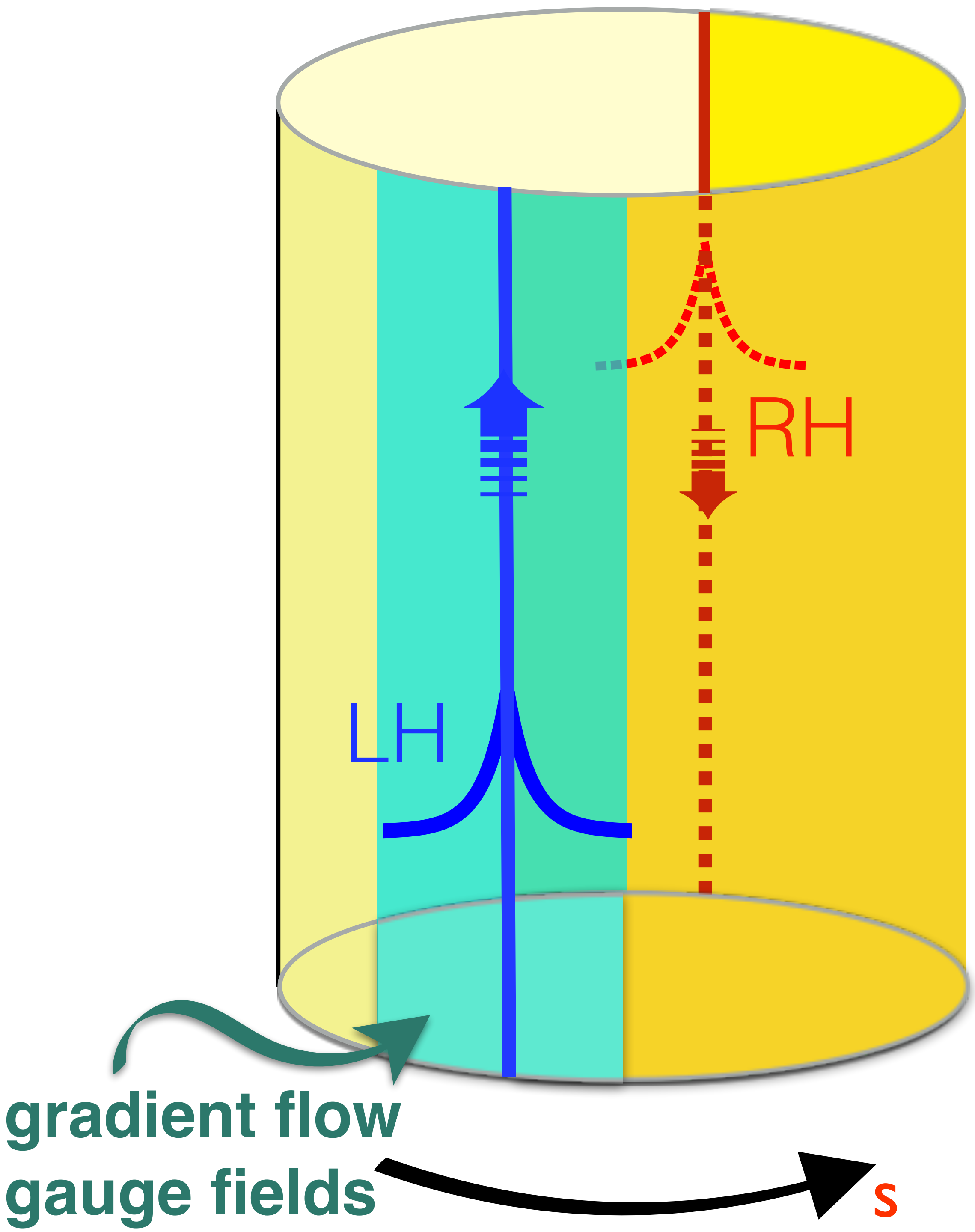

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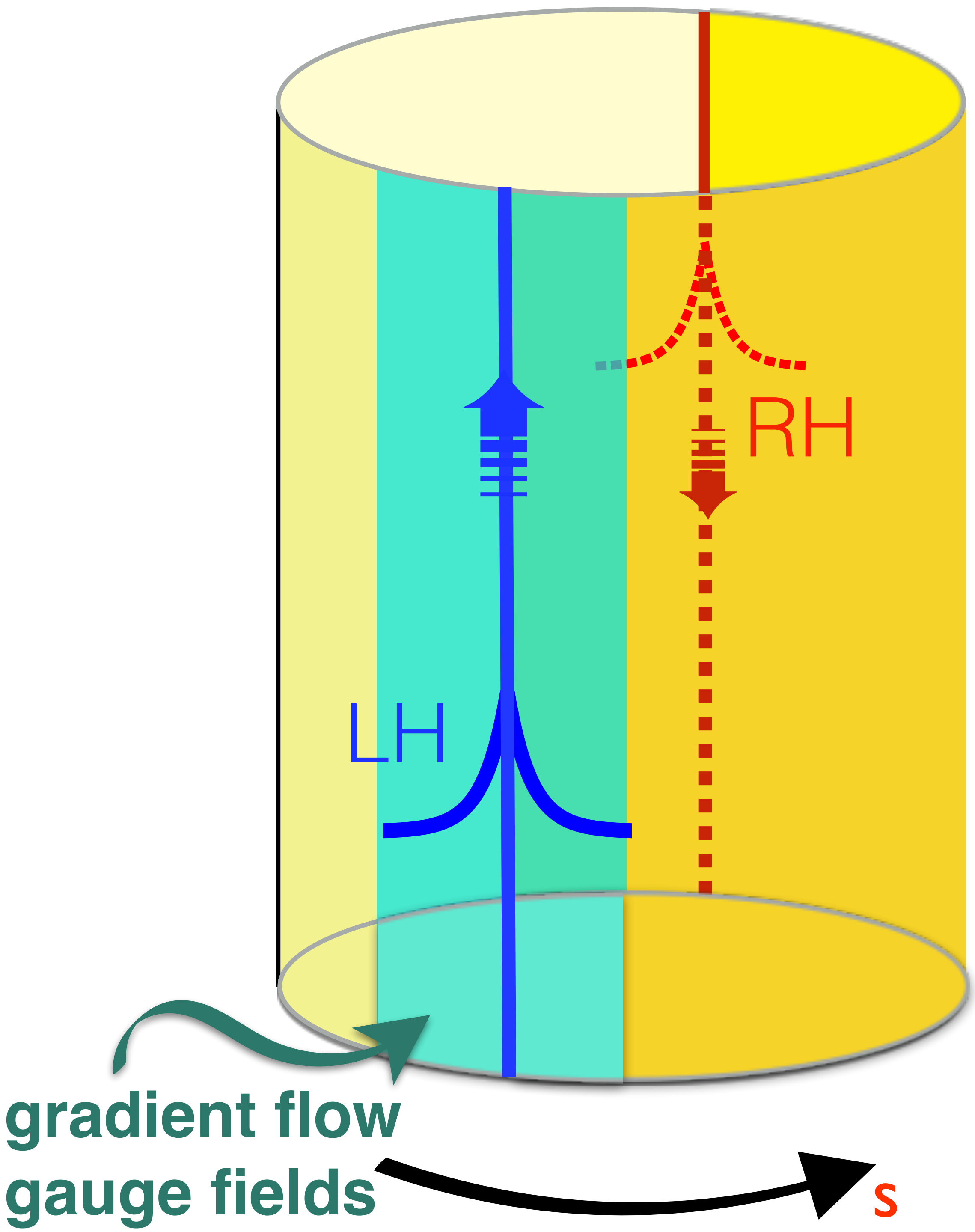

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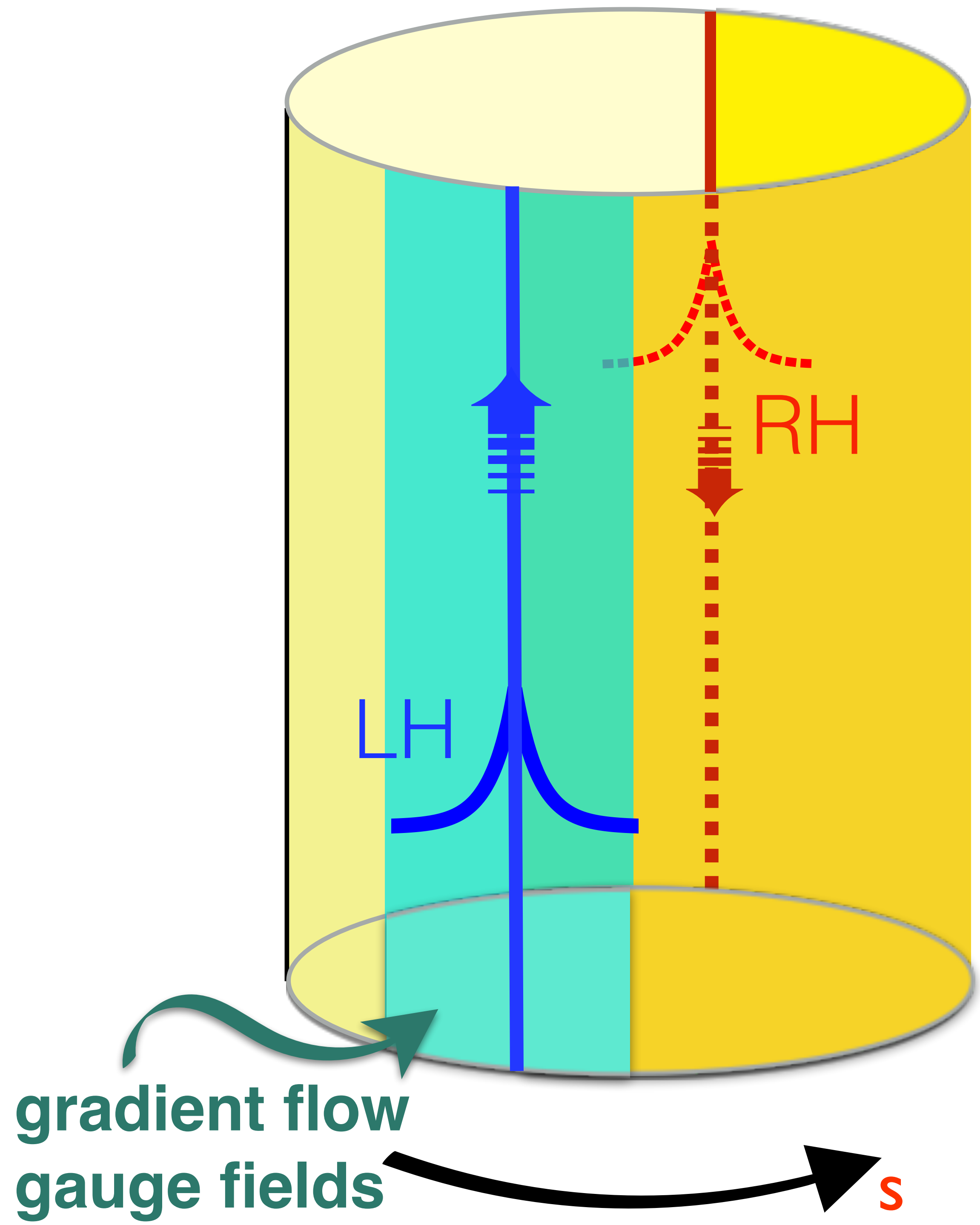

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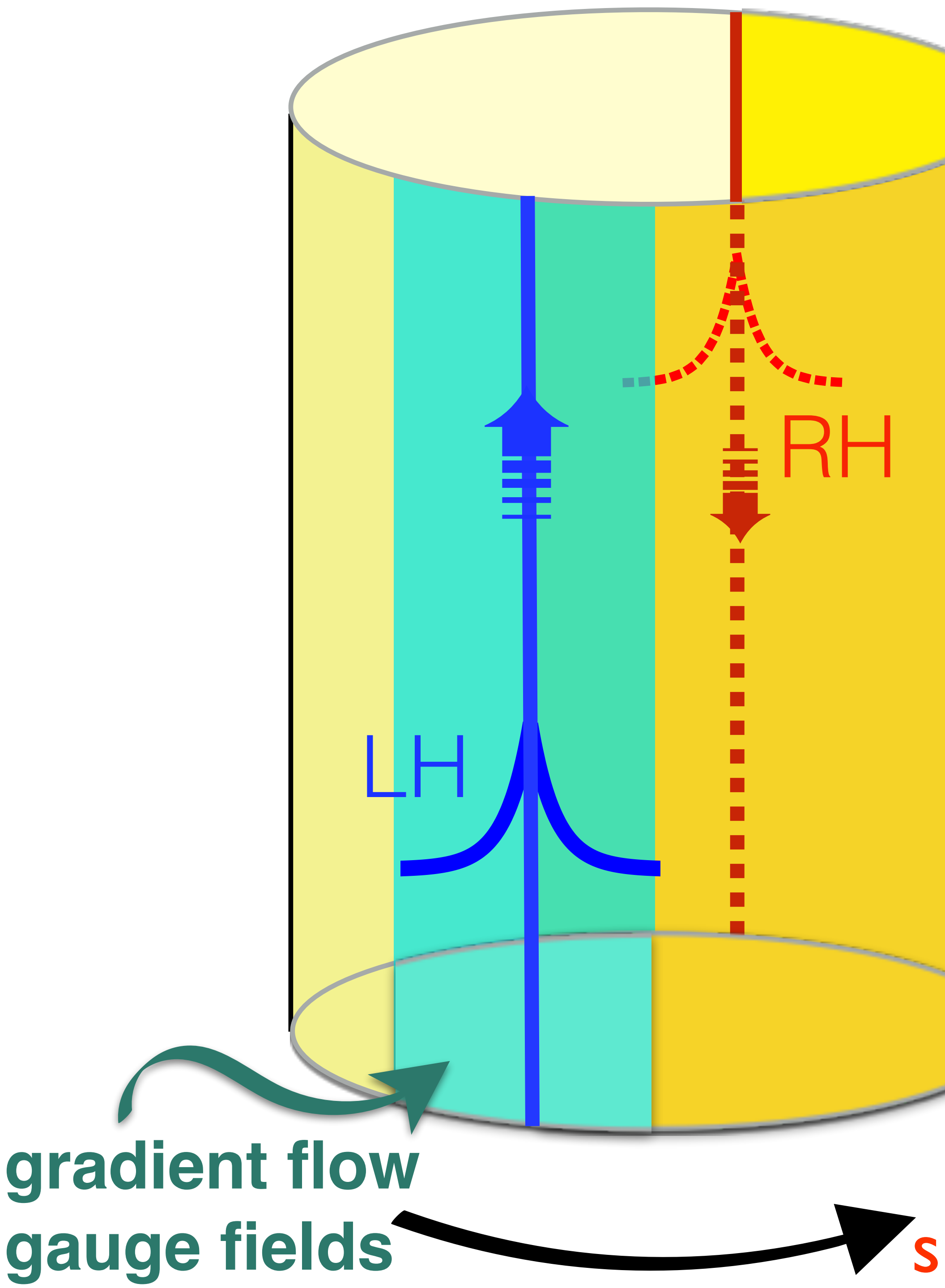

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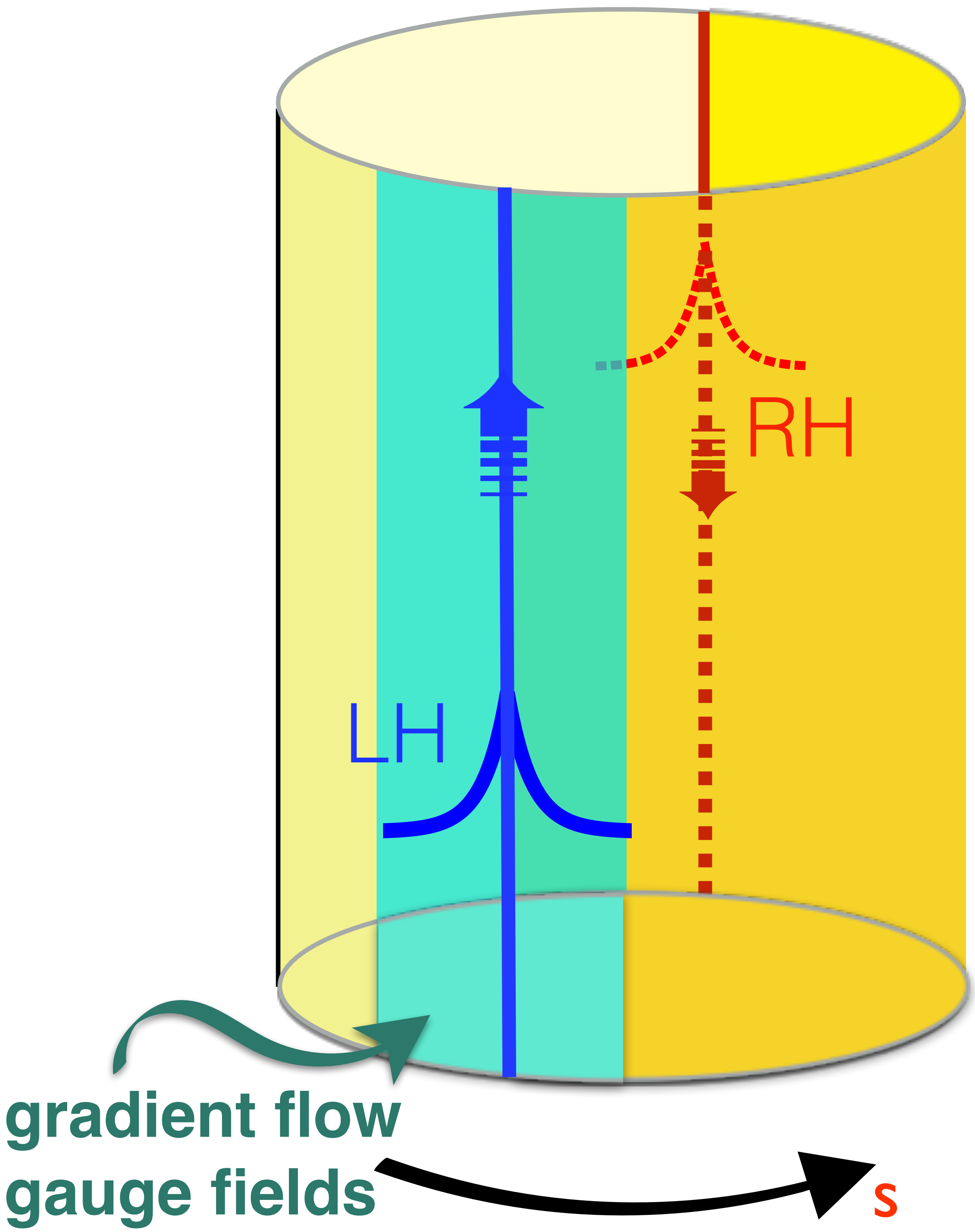

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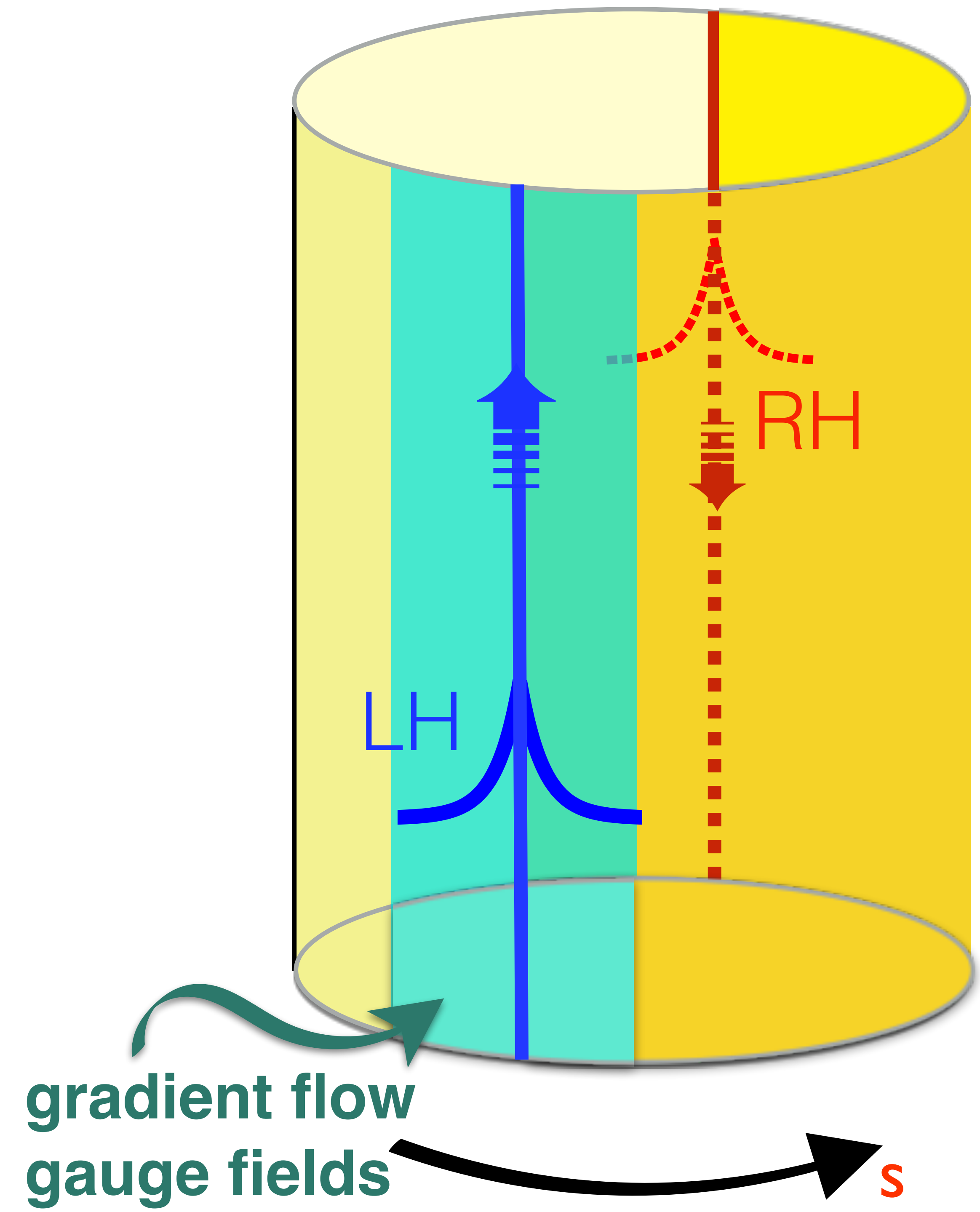
- method fails when theory is anomalous (a good thing)



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- quantum gauge field $A_\mu(x)$ lives at defect at s=0 where LH fermions live
- gauge field $\mathbf{A}_\mu(x,s)$ defined as solution to gradient flow equation with BC: $\mathbf{A}_\mu(x,0) = A_\mu(x)$
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- RH mirror fermions behave as if with very soft form factor… "Fluff"…and decouple from gauge bosons as $s \to \infty$
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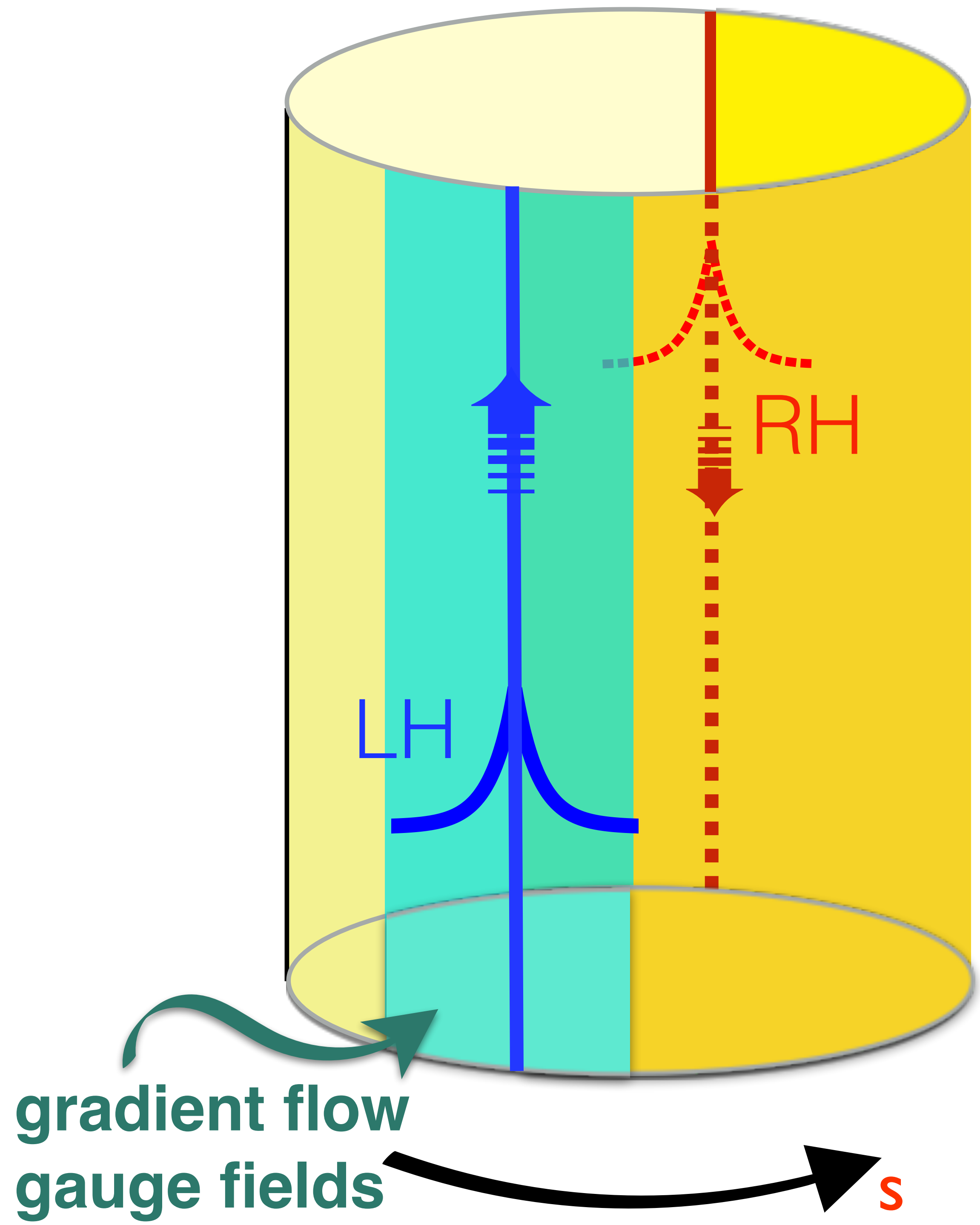

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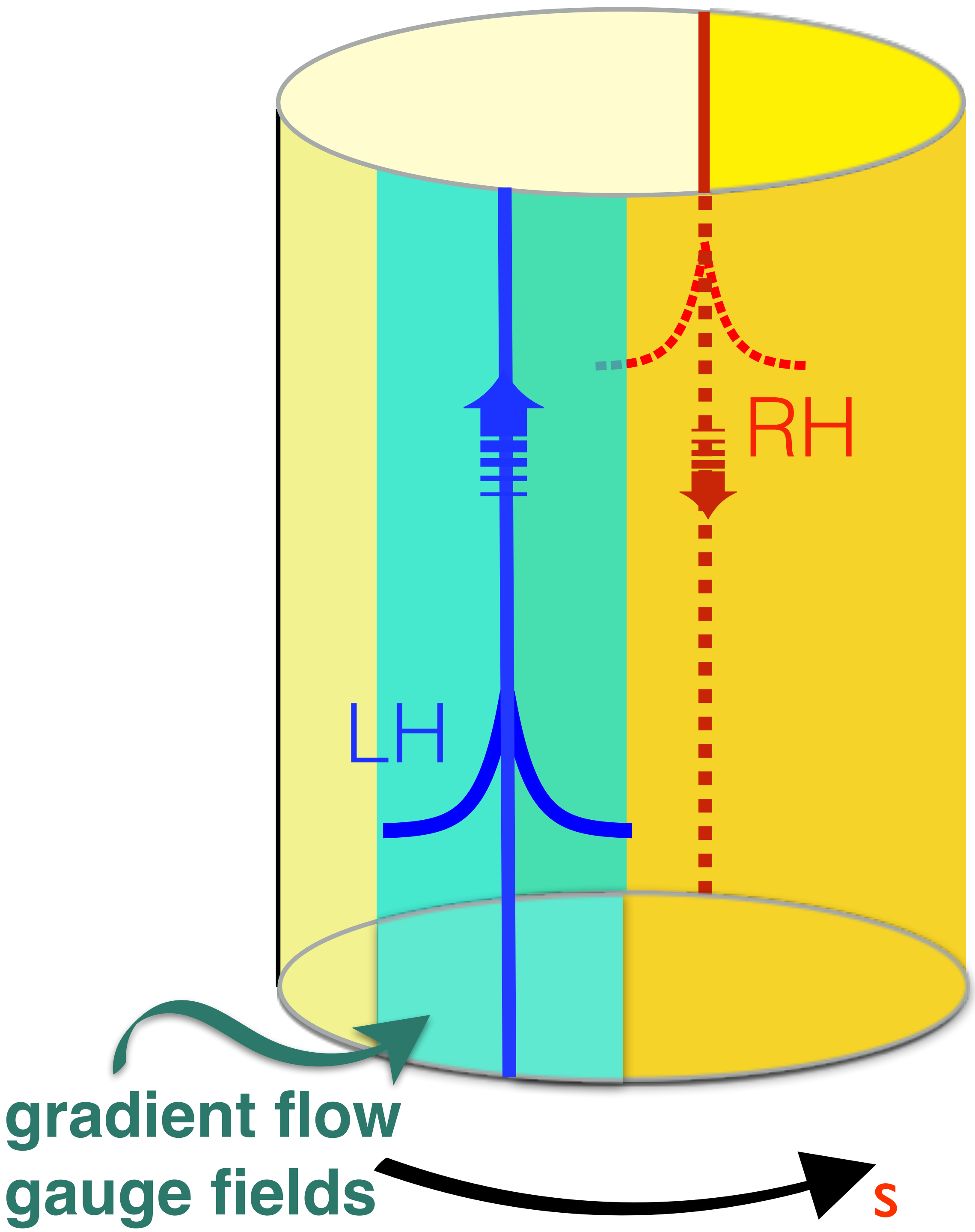
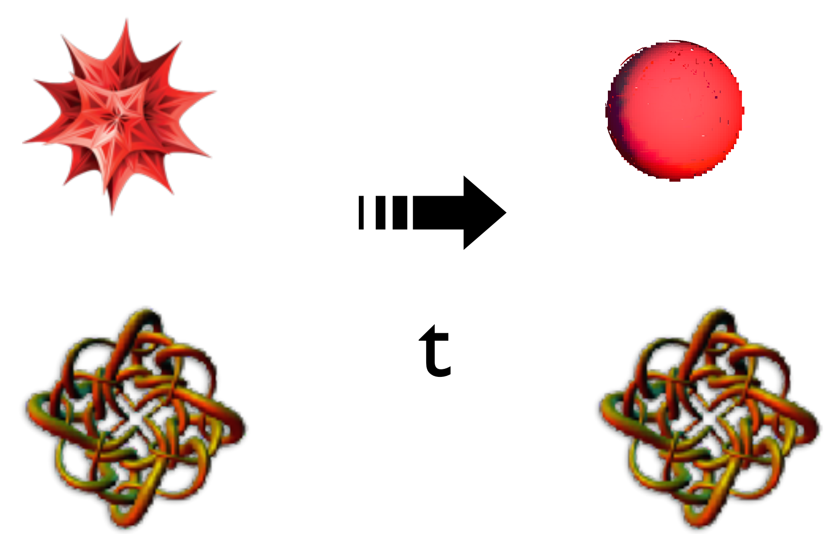


# Decoupling mirror fermions as soft fluff in a gauge invariant way:

- 🙂 Can show that this could only lead to a local 4d quantum field theory if the fermion representation has no gauge anomalies
- 🤔 ...exp(-p²s) form factors are a problem in Minkowski spacetime!...but can take $s \to \infty$ limit first before lattice spacing $a \to 0$ using the overlap operator method. OK theory?
- 😳 gradient flow doesn't damp out instantons, which can induce interactions with fluff

$$\frac{\partial \bar{A}_\mu(x,t)}{\partial t} = -D_\nu \bar{F}_{\mu\nu}$$



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Should we take Fluff seriously? What is its phenomenology? Can it explain the strong CP problem or have other effects? Does it have similarly soft gravitational interactions?

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- Implications/viability not well understood!
- **What could go wrong throwing away locality?**