# A Warped Solution to the Strong CP Problem


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Pheno 5/10
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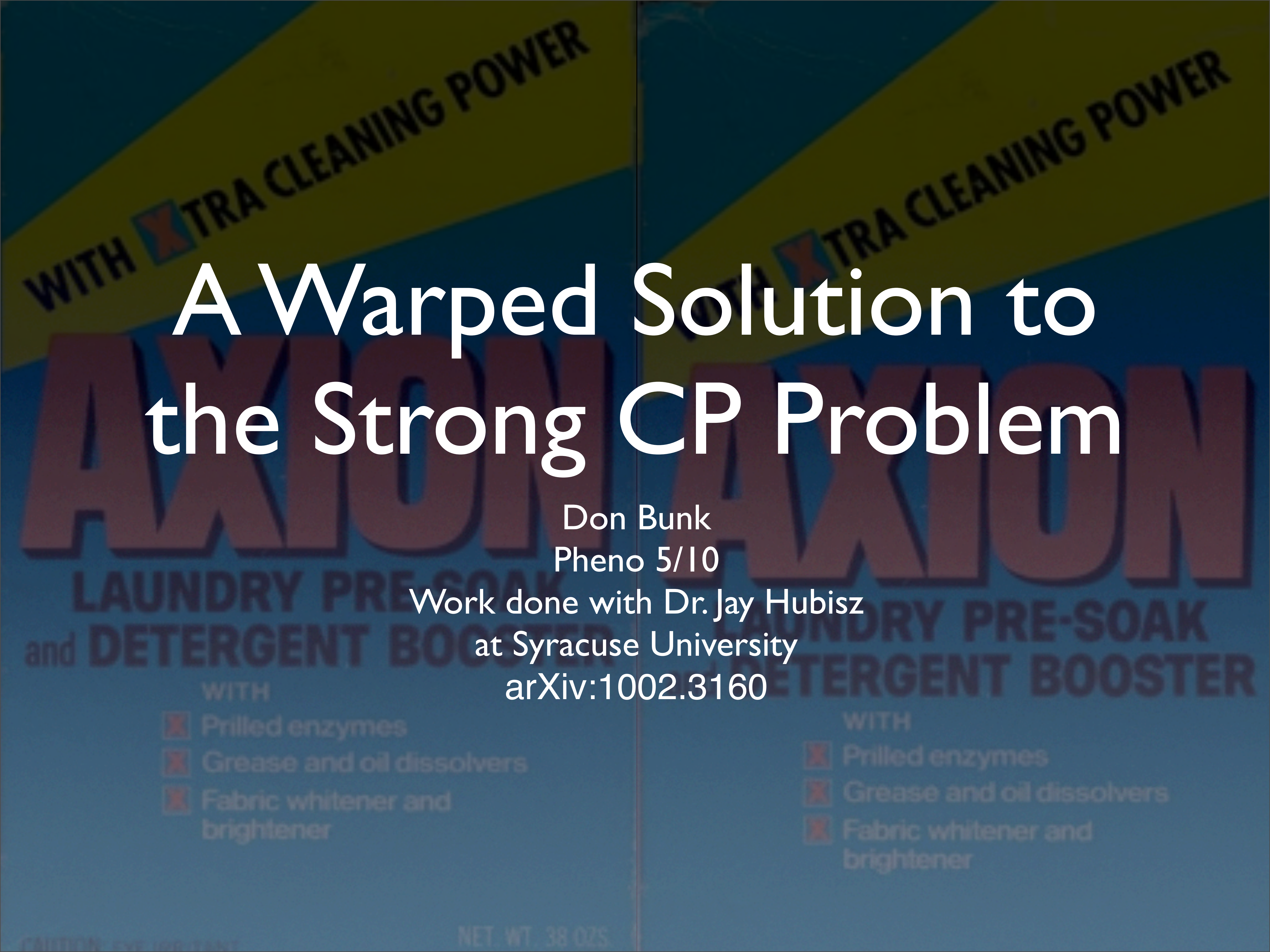


# Outline

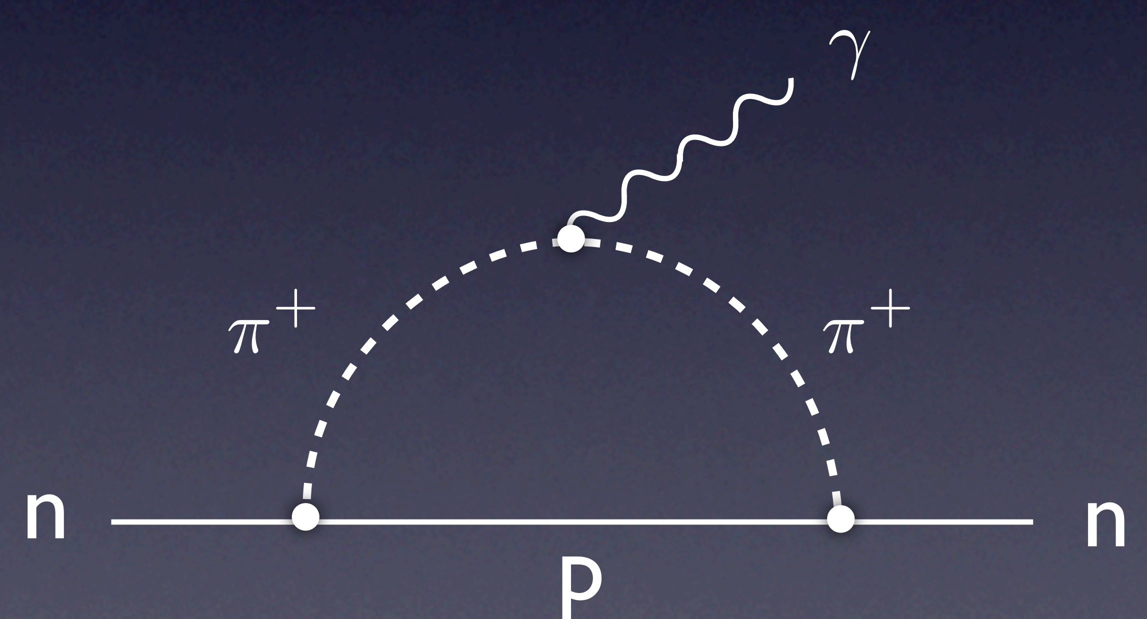
- The Strong CP problem and the Axion
- Warped model
- An Axion candidate for the Strong CP problem
- Phenomenology and constraints for Warped axion model

# The Strong CP problem

QCD violates CP:

$$\mathcal{L}_{QCD,CP} = \frac{\bar{\theta}}{32\pi^2} Tr G_{\mu\nu} \tilde{G}_{\mu\nu}$$ where $\bar{\theta} = \theta - arg|\mathbf{M}_q|$

Leading to a non-zero dipole moment for the neutron:




$$d_n = 3.2 \cdot 10^{-10} \bar{\theta} e\, cm < 6.3 \cdot 10^{-26} e\, cm$$

Why is $|\bar{\theta}| < 10^{-10}$ ? This is the Strong CP problem.

# The Axion

2 hints to a resolution:

1) The QCD vacuum energy is minimized at $\bar{\theta} = 0$
hence if $\bar{\theta}$ was a dynamical field it would relax to zero.

2) The theta term is actually a total derivative

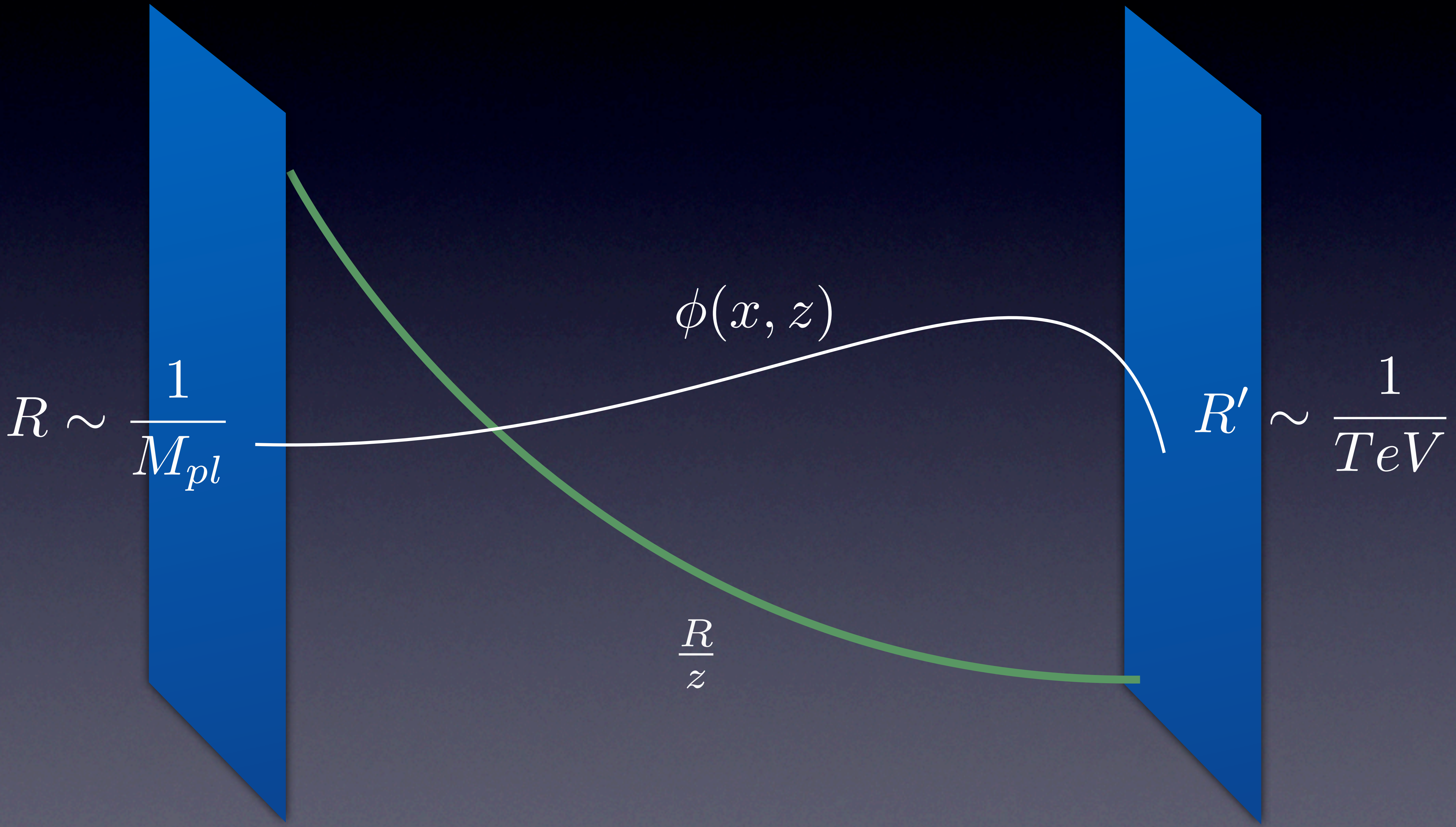
$$\bar{\theta} Tr \left( G_{\mu\nu} \tilde{G}^{\mu\nu} \right) \sim \bar{\theta} \partial_\mu J^\mu$$

If $\bar{\theta}$ was a field this would be the coupling from a spontaneously broken global symmetry $U(1)_{PQ}$

$$\mathcal{L} = \frac{a(x)}{f_{PQ}} \partial_\mu J^\mu{}_{PQ}$$

# RS Space

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

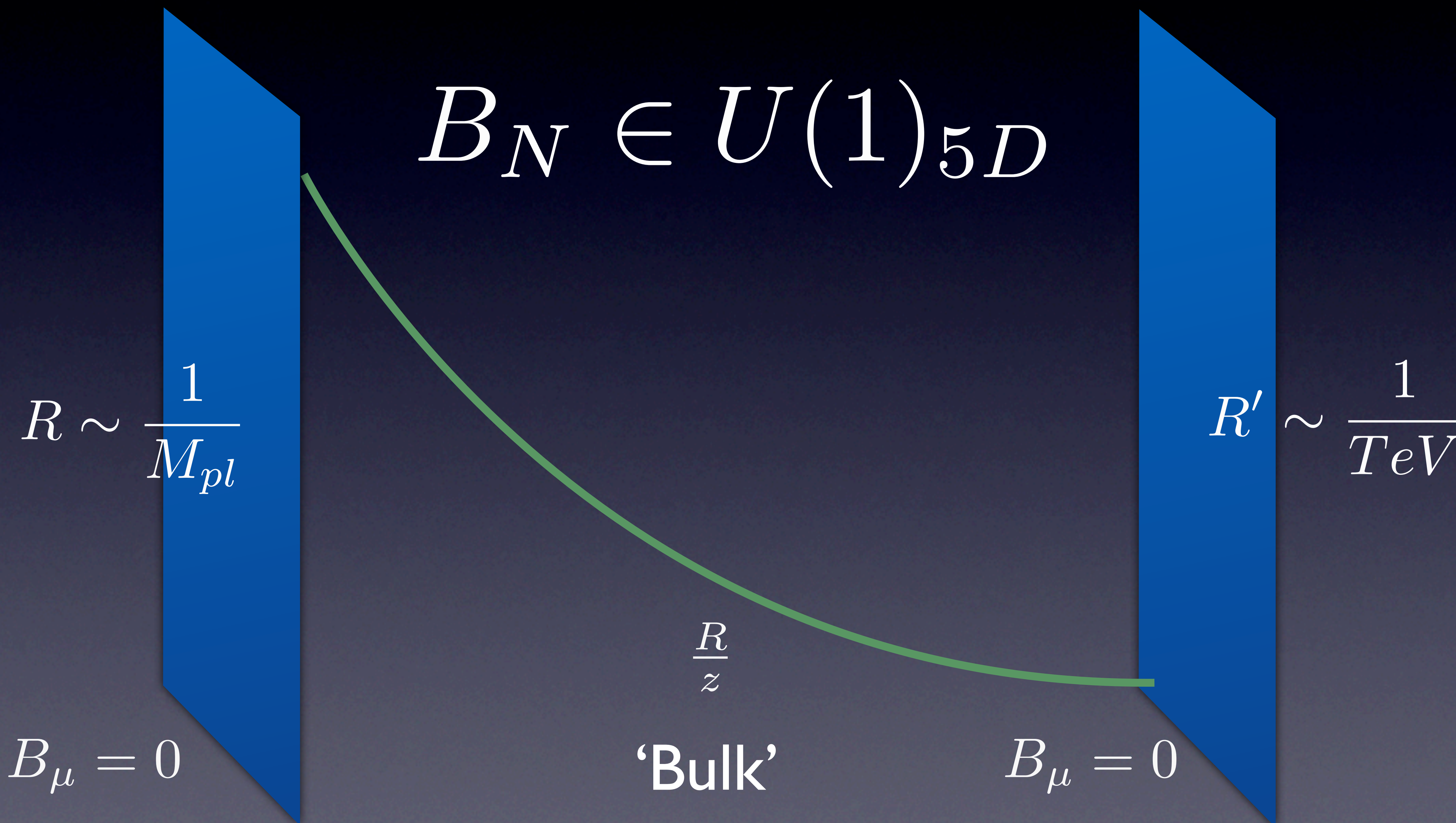



Randall, Sundrum hep-ph/9905221

# RS Space

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

$$B_N \in U(1)_{5D}$$




Choi hep-ph/0308024
Gripaios 0803.0497, 0704.3981, hep-ph/0611278

# The Setup

Starting point: U(1) gauge field ( not $U(1)_{PQ}$! )

$$S = \int d^5x\sqrt{g}\left[\frac{-1}{4}B^{MN}B_{MN} - \frac{1}{2}G(B_N)^2\right]$$

For $B_\mu|_{R,R'} = 0$ and $\partial_z\left(\frac{1}{z}B_5\right)|_{R,R'} = 0$ a massless mode survives:

$$S_{eff} = \int d^4x\left[\sum_{n=1}\left(\frac{-1}{4}B^{(n)}_{\mu\nu}B^{(n)\mu\nu} + \frac{1}{2}m^{(n)2}B^{(n)}_{\mu}B^{(n)\mu}\right) + \frac{1}{2}\partial_\mu B_5\partial^\mu B_5\right]$$

A residual subgroup remains that is global from the 4D perspective $B_5 \rightarrow B_5 + \partial_5\beta$

# Adding Fermions

$$S_{ferm} = \int d^5x \sqrt{g} \left[ \bar{\Psi} i \not{D} \Psi + m \bar{\Psi} \Psi \right]$$

To produce a chiral theory we need appropriate BC

For example for $\Psi_{5D} = \begin{pmatrix} \chi \\ \bar{\psi} \end{pmatrix}$

Choosing $\psi|_R = \psi|_{R'} = 0$

Yields $\Psi_{5D} = \begin{pmatrix} \chi_{(0)} \\ 0 \end{pmatrix} + \sum_{n=1} \begin{pmatrix} \chi_{(n)} \\ \bar{\psi}_{(n)} \end{pmatrix}$

# Coupling to $G \cdot \tilde{G}$

Introduce fermions that are charged under SM and $U(1)_{5D}$:

$$\Psi(z,x) \equiv \exp\left[iq \int_{z_0}^{z} dz' B_5(x,z')\right] \Psi'(z,x)$$

So that for $B_5 \to B_5 + \partial_z \beta(z)$, $\Psi' \to e^{iq\beta(z_0)} \Psi'$

Because of the chiral zero mode this symmetry is anomalous and produces the coupling:

$$\mathcal{L} = \frac{1}{f_{PQ}} B_5 \mathcal{A} \supset B_5 G \cdot \tilde{G}$$

With $f_{PQeff} = \dfrac{\sqrt{R}}{\sqrt{2} R' g_{5D}}$

# Suppressing higher dimensional operators

In general, higher dimensional operators can displace the axion from its CP-conserving value:

$$\mathcal{L}_{ax} \supset \frac{a}{f_{PQ}}\left[\frac{g_n}{M_{Pl}^n}\mathcal{O}^{n+4} + c_{QCD} G\cdot\tilde{G}\right]$$

For $c_{QCD}\langle G\cdot\tilde{G}\rangle \sim \Lambda_{QCD}^4$ and $\mathcal{O} \sim \mu$

$$g_n \lesssim 10^{-10}\left(\frac{\Lambda_{QCD}}{\mu}\right)^4\left(\frac{M_{Pl}}{\mu}\right)^n$$

Typically $\mu \sim f_{PQ} \sim 10^{9-12} GeV$ but in this case $\mu \sim TeV$

# Axion bounds

In general we need

$$10^9 GeV \leq f_{PQ} \leq 10^{12} GeV$$

$10^{12} GeV$ bound is from ‘Misalignment production’ contributing to the energy density of the universe

$$\Omega_{mis} h^2 \sim f_{PQ}$$

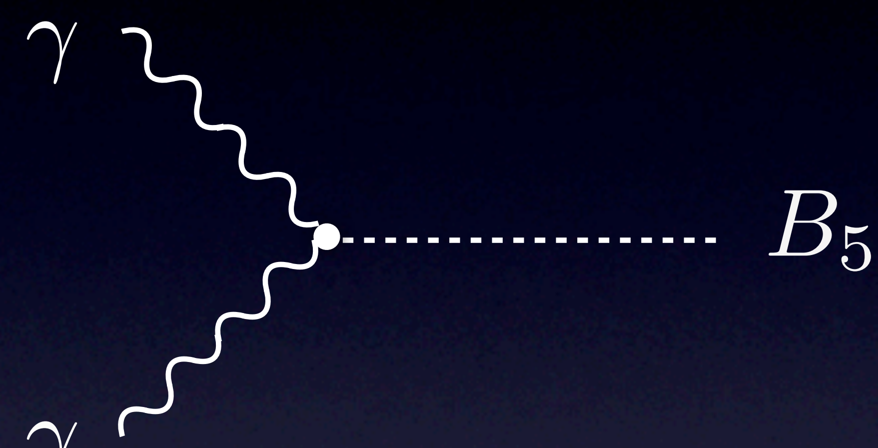
$10^9 GeV$ lower bound is from stellar cooling

$$\text{Luminosity} \sim \frac{1}{f_{PQ}^2}$$

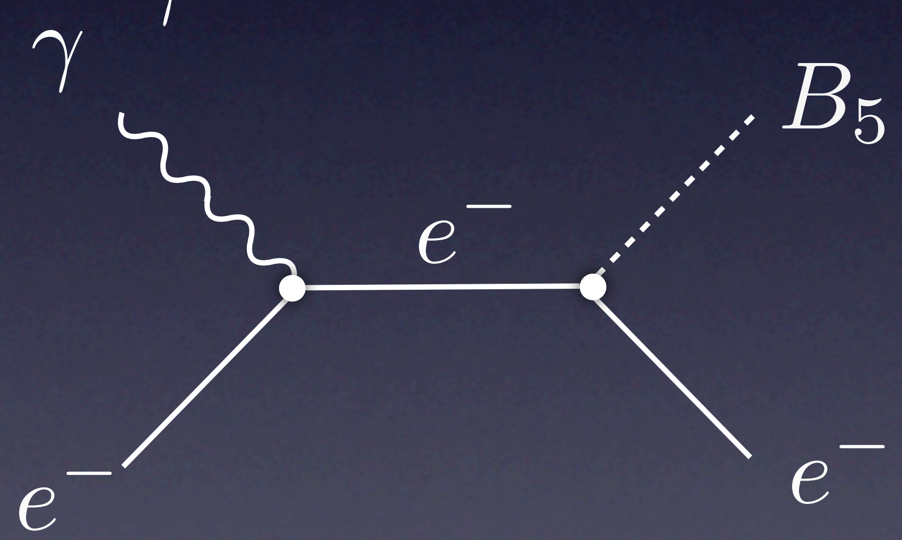
# Stellar Cooling

Typical interactions are suppressed by $f_{PQ}$

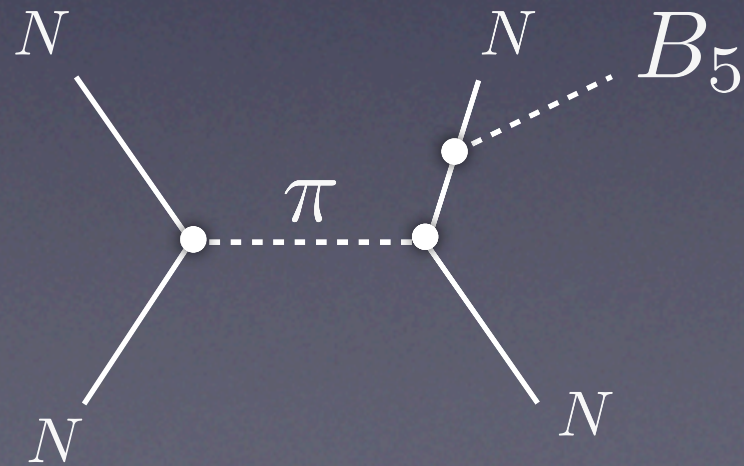
photon-axion




Compton



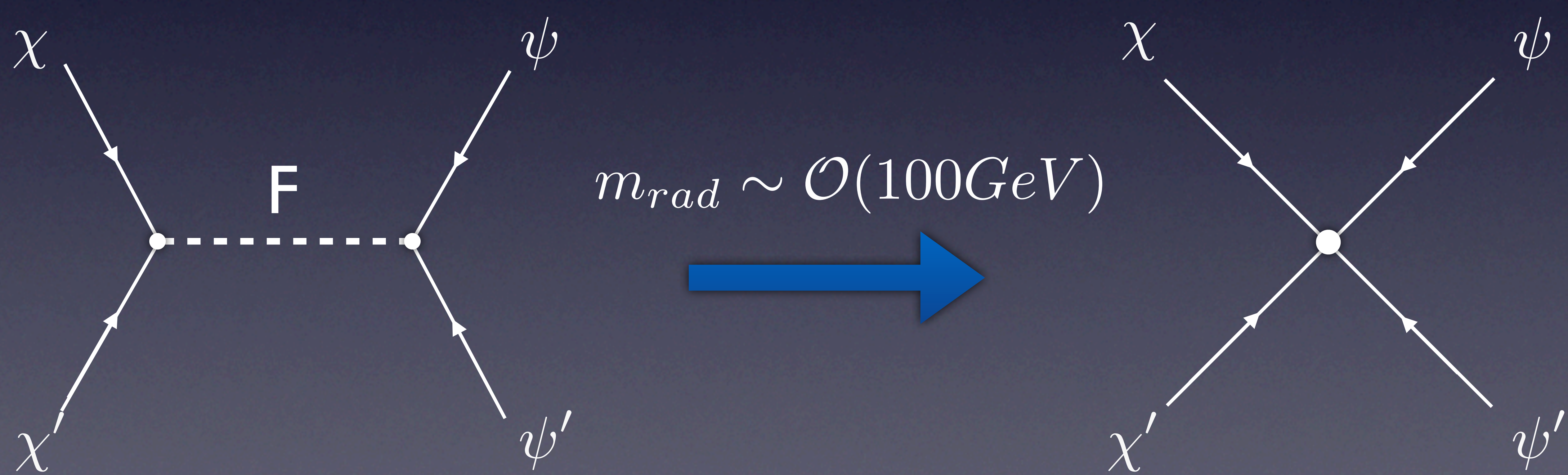

Bremsstrahlung



# Adding gravitational fluctuations

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(e^{-2F}\eta_{\mu\nu}dx^\mu dx^\nu + h_{\mu\nu}dx^\mu dx^\nu - (1+2F)^2 dz^2\right)$$

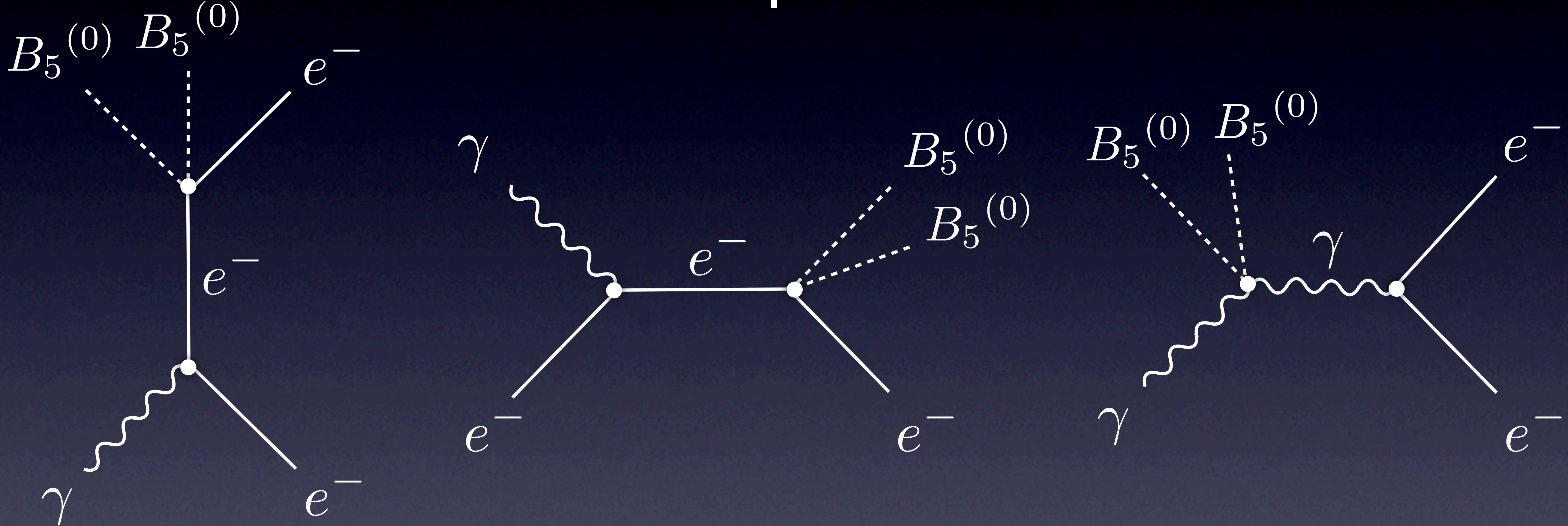
Effective vertices from integrating out the Radion:




$$\forall\ \chi, \chi', \psi, \psi'$$

# Stellar Cooling

For the sun Primakoff-like processes dominate



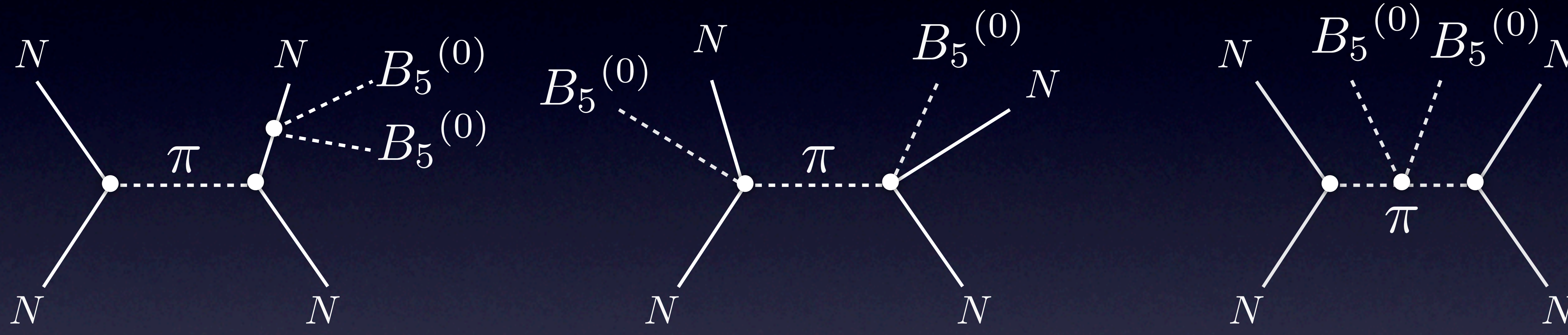

A conservative limit is given by $L_A < .2L_\odot$

For Sun $L_\gamma \approx 10^{33}\frac{erg}{s}$

Warped model $L_{B_5} \lesssim 10^{23}\frac{erg}{s}$

# Supernova type II Collapse

Bremsstrahlung-like dominate




Here the constraint is on neutrino burst duration.

SN 1987A: $(15 M_\odot)$

Experiment: $L_\nu \approx 10^{53} \frac{erg}{s}$

Warped model: $L_{B_5} \lesssim 10^{40} \frac{erg}{s}$

# Radion Phenomenology

$$\Gamma(r \to B_5 B_5) = \frac{1}{192\pi} \frac{m_r^3}{R'^2}$$

For light radions this decay dominates the width:

$$\Gamma_{tot} \approx \Gamma(r \to B_5 B_5)$$

And decreases photon branching ratio:

$$Br(r \to \gamma\gamma) \to \frac{1}{10} Br(r \to \gamma\gamma)$$

This is a significant modification since $\gamma\gamma$ is otherwise the most promising channel for the radion at the LHC.

# Conclusion

- Presented a U(1) gauge model in RS space
- Provides an axion candidate
- Naturally suppresses dangerous Planck-scale operators
- Evades known constraints