A Song of D-branes and Fluxes

Wieland Staessens (JdC)

based on 1807.00620, 1807.00888 (1503.01015, 1503.02965 [hep-th])

with G. Shiu

Instituto de Física Teórica
UAM/CSIC
Madrid

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CSIC Consejo Superior de Investigaciones Científicas

UAM Universidad Autónoma de Madrid

Inflation in Type IIA

Guth, Linde, Mukhanov, Steinhardt, Starobinsky,...

- Inflationary epoch = cure for horizon problem and flatness problem
- nearly scale invariant, nearly Gaussian CMB data:

$$n_s - 1 = 2\eta - 6\epsilon, \; r = 16\epsilon$$

  in agreement with slow-roll single scalar field w/ potential V

$$\epsilon \equiv \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \qquad |\eta| \equiv \left|M_{Pl}^2 \frac{V''}{V}\right| \ll 1 \qquad \text{during inflation}$$

- Challenge for String Theory: Inflaton candidate + potential?

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reviews: Baumann (2009); Baumann-McAllister (2009,2014); Westphal (2014); ...

- Inflation in String Theory tied with Moduli Stabilization

Type IIB

D3/7-brane position moduli Burgess et al ('01), Dvali et al ('01), Dasgupta et al ('02)
Hebecker et al ('12), Ibáñez et al ('14-'15-'16), ...

Kähler Moduli (e.g. Fibre) Cicoli-Burgess-Quevedo ('08) (Cicoli, Shukla)

Kähler Axions (aligned natural, N-flation, monodromy, kinetic alignment)
Kim-Nilles-Peloso ('04), Dimopoulos et al ('05), Silverstein-Westphal-(McAllister) ('08)
Marchesano-Shiu-Uranga ('14)
Blumenhagen-Plauschinn ('14)
Hebecker-Krause-Witkowski ('14)

Type IIA

Inflaton	Source	Potential
Volume ρ	NS-flux & RR-flux	$\rho^{-3,3-p}$
Dilaton s	NS-flux & RR-flux & O6/D6	$s^{-2,-3,-4}$
B_2-axion	RR-flux	$b^{1,2,3}$
C_3-axion		

- Note: flux stabilization $\rightsquigarrow$ only linear combination C_3-axions stabilized
DeWolfe-Giryavets-Kachru-Taylor (2005), Cámara-Font-Ibáñez (2005)

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B_2-axion	RR-flux	$b^{1,2,3}$	Axion Monodromy ↯ Baume-Palti ('16), Valenzuela ('16)
C_3-axion	D6	Abhinc	

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Stringy Axions & Effective Decay Constant

w/ Shiu-Ye 1503.01015, 1503.02965 [hep-th]

- Type II String Theory compactifications Blumenhagen-Körs-Lüst-Stieberger ('06); Ibañez-Uranga ('12)
  $\rightsquigarrow$ Closed string axions a^i from dim. red. of p-forms $C_{(p)}$ on $\mathcal{M}_{1,3} \times \mathcal{X}_6/\Omega\mathcal{R}$
  ($C_{(p)} \in$ RR-forms + NS 2-form in Type II)

$$a^i \equiv (2\pi)^{-1} \int_{\Sigma^i} C_{(p)}, \qquad p-\text{cycle } \Sigma^i \subset \mathcal{X}_6, \qquad i \in \{1, \ldots, \begin{matrix} h_{11} \\ h_{21}+1 \end{matrix} \}$$

- Type II String Theory compactifications w/ D-branes
  $\rightsquigarrow$ 4d EFT with mixing axions + fermions (anomaly cancellation) (Dudas' talk)
  Aldazabel-Franco-Ibáñez-Rábadan-Uranga ('01)

$$\mathcal{S}^{\rm eff}_{axion} = \int \left[\frac{1}{2} \sum_{i,j=1}^{N} \mathcal{G}_{ij} (\mathrm{d}a^i - k^i A) \wedge \star_4 (\mathrm{d}a^j - k^j A) - \frac{1}{8\pi^2} \left(\sum_{i=1}^{N} r_i a^i \right) \mathrm{Tr}(G \wedge G) + \mathcal{L}_{gauge} + \mathcal{L}_\psi \right]$$

metric mixing ($\mathcal{G}_{ij}$) — $U(1)$ mixing $k^i \neq 0$ — anomalous coupling

- Diagonalisation of kinetic and potential terms
  $\Rightarrow$ effective decay constant $f_{\rm eff}$ with moduli dependence

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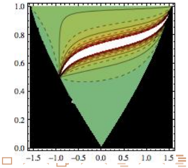
θ

$\sqrt{\frac{\mathcal{G}_{22}}{\mathcal{G}_{11}}}$



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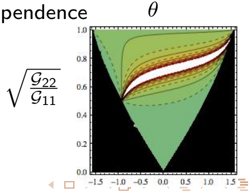

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From UV (Fermions) to IR (Infladrons)

Shiu-W.S. (1807.00620, 1807.00888)

- Integrating out $U(1) \rightsquigarrow 4\psi$ interactions (N-JL): $\frac{q_L q_R}{2M_{st}^2}\left[(\overline{\psi}\psi)^2 + (\overline{\psi}i\gamma^5\psi)^2\right]$
- θ-vacuum of $SU(N)$ YM breaks $U(1)$ explicitly
  - ⋆ Instanton-induced effective fermion interactions 't Hooft ('76) Callan-Dashen-Gross ('78)

$$\mathcal{L}_{\text{'t Hooft}} = C\, e^{-\frac{8\pi^2}{g^2}+i\theta} \det(\overline{\psi}_L\psi_R) + h.c.$$

    at strong coupling for $SU(N) \rightsquigarrow$ effective fermion mass
  - ⋆ Fermion Confinement $\Rightarrow$ Fermion condensate ($\langle\overline{\psi}_L\psi_R\rangle_\theta \neq 0$) Casher (1979)
    4ψ interactions $\rightsquigarrow$ fermion mass $M \sim -\frac{1}{M_{st}^2}\langle\overline{\psi}_L\psi_R\rangle_\theta$
- $E < \Lambda_s$: bound state $\overline{\psi}\psi$ $\rightarrow$ EFT for composite scalar $\Phi(x) = \sigma(x)e^{i\frac{\eta}{f}}$
  Weinberg ('79)
- mass spectrum in vacuum

$f_\xi \ll f$	$f_\xi \sim f$	$f \ll f_\xi$
$\downarrow$	$\downarrow$	$\downarrow$
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  $$V = -\mu^2\Phi^\dagger\Phi + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \Lambda_s^2\left(\kappa e^{i\frac{\xi}{f_\xi}+i\theta}\det(\Phi) + \kappa e^{-i\frac{\xi}{f_\xi}-i\theta}\det(\Phi^\dagger) + M\Phi + M\Phi^\dagger\right)$$

  Set by the $U(1)$ symmetries in the model with spurions $e^{i\theta}$ and M
- mass spectrum in vacuum

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$$V = -\mu^2\sigma^2 + \frac{\lambda}{2}\sigma^4 + 2\kappa\Lambda_s^2\,\sigma\,\cos\left(\frac{\eta}{f} + \frac{\xi}{f_\xi} + \theta\right) + 2\Lambda_s^2 M\,\sigma\,\cos\frac{\eta}{f}$$

with vacuum $\langle\sigma\rangle = f \sim \Lambda_s$, $\langle\eta\rangle = 0 = \langle\xi\rangle$

- mass spectrum in vacuum

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- mass spectrum in vacuum massive (σ, η) = INFLADRONS

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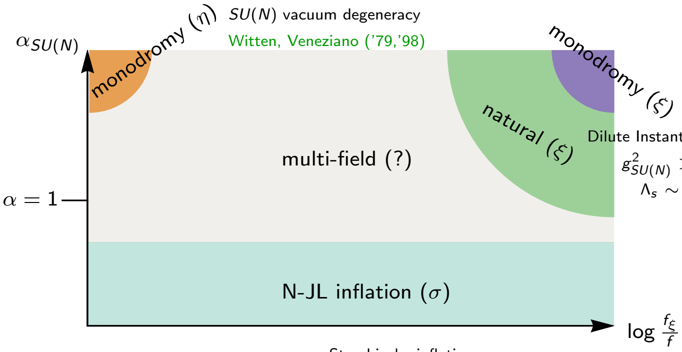
Phases of Axion Inflation

Shiu-W.S. (1807.00888)

$SU(N)$ vacuum degeneracy
Witten, Veneziano ('79,'98)



Dilute Instanton Gas
$g^2_{SU(N)} > 0.8$ @ $M_{\rm string}$
$\Lambda_s \sim f \sim 10^{16}$ GeV

$\sim$ Starobinsky inflation
strongly coupled 4ψ interactions
see talk @ StringPheno 2016
see also Inagaki-Odintsov-Sakamoto ('15-'17)

Natural-like Inflation

Shiu-W.S. (1807.00620, 1807.00888)

$\xi =$ inflaton candidate

with $f \ll f_\xi$ and $m_\xi \ll m_\eta < m_\sigma$

Viable inflationary model requires control over corrections:

(1) perturbative QFT corrections constrained by perturbative $U(1)$ symmetry
Weinberg ('79), Coleman-Weinberg ('73), Hill-Salopek ('92)

(2) back-reaction of heavy infladrons on inflationary trajectory
see e.g. Stewart ('94), Lazarides-Panagiotakopoulos ('95), Lyth-Stewart ('96), Dong-Horn-Silverstein-Westphal('11)

(3) Pert. & Non-pert. gravitational corrections

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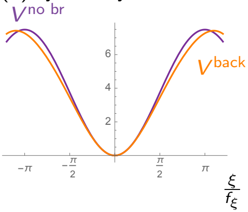

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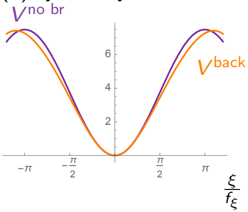

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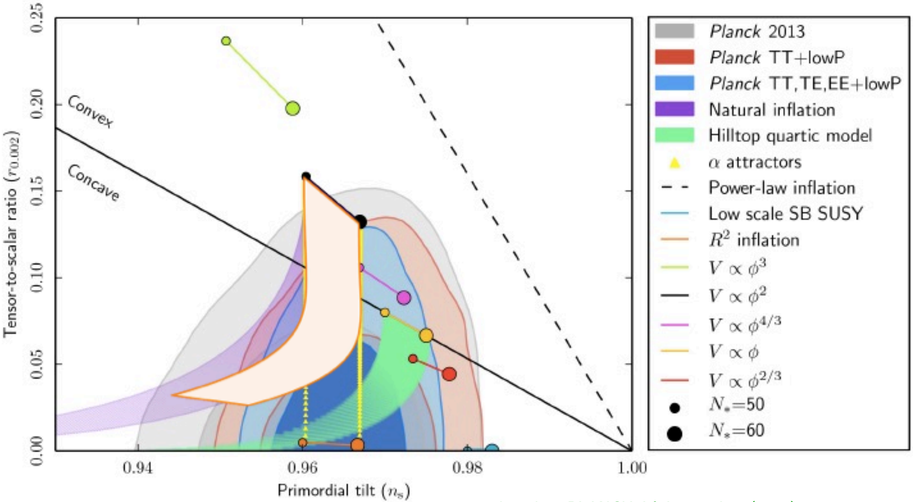

based on PLANCK A&A 594, A20 (2016)

Constraints from Gravity

Shiu-W.S. (1807.00620)

- $U(1)$ symmetry constrains perturbative corrections involving gravitons
  $\rightarrow$ one-loop corrections in terms of $\frac{V_{\rm per}}{M_{Pl}^4}, \frac{V'_{\rm per}}{M_{Pl}^3}, \frac{V''_{\rm per}}{M_{Pl}^2}$ Smolin (1980)

- Axionic wormholes with metric $ds^2 = dr^2 + a^2(r)d\Omega_3^2$ and $a(0) > M_{st}^{-1}$

$$S_{AW} = \int \sqrt{g_E}\Big[-\frac{M_{Pl}^2}{2}R_E - \underbrace{\frac{f_\xi^2}{2}g_E^{mn}\partial_m\xi\partial_n\xi}_{\text{Giddings-Strominger ('88)}} + \underbrace{\frac{1}{2}g_E^{mn}\partial_m\sigma\partial_n\sigma - \frac{\sigma^2}{2}g_E^{mn}\partial_m\eta\partial_n\eta + V_{\rm per}(\sigma)}_{\text{Abbott-Wise ('89)}}\Big]$$

axion charge $w_\xi \gg 1$ axion charge $w_\eta \gg 1$

$\downarrow$ $\downarrow$

$\mathcal{S}_{GS} \sim w_\xi \frac{M_{Pl}}{f_\xi} \gg 1$ $\mathcal{S}_{AW} \sim w_\eta^{4/3}\lambda^{1/3} \gg 1$

Gravit. Instanton corrections highly suppressed Montero-Uranga-Valenzuela ('15) Hebecker-Mangat-Theissen-Witkowski ('16)

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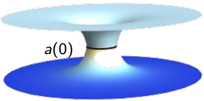

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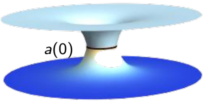

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Conclusions and Outlook

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- Rich UV theory with mixing axions, gauge dof and fermions
  $\rightsquigarrow$ rich IR theories in terms of axions and infladrons
- $\neq$ phase of gauge theories $\rightsquigarrow \exists \neq$ inflationary models (natural, monodromy, Starobinsky)
- QFT corrections under control, back-reaction gives flattened potential, Gravitational corrections under control

Open issues

☞ Full String Theory construction including moduli stabilisation

Conlon (2006), Cicoli-Dutta-Maharana (2014), Blumenhagen-(Font-Fuchs-)Herschmann-Plauschinn(-Sekiguchi-Wolf) (2014/15),...

☞ Verification of WGC and other swampland conjectures

Vafa ('05), Arkani-Hamed-Motl-Nicolis-Vafa ('06), Ooguri-Vafa ('06), Cornell, Hamburg, Harvard, Heidelberg, Madison, Madrid, Münich ...

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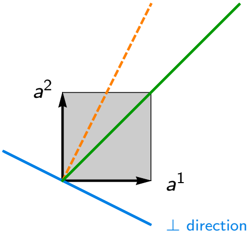
Dziękuję ci bardzo

Thank you very much

Effective Action & Effective Decay Constant

- Geometric picture of axion moduli space



- different from N-enhancement mechanisms: $f_{\text{eff}} \sim N^p f$ with p $\geq 1/2$,
Dimopoulos-Kachru-McGreevy-Wacker (2005), Choi-Kim-Yung (2014), Bachlechner-Long-McAllister (2014/15), Junghans (2015)

Chiral Symmetry Breaking & Mass Generation

- Global $U(1)$ symmetry $J^\mu_{U(1)} = q_+ \overline{\psi}\gamma^\mu\psi + q_- \overline{\psi}\gamma^\mu\gamma^5\psi$ is broken by gauge instantons & Yukawa-coupling (4ψ-coupling) in θ-vacuum

$$\partial_\mu J^\mu_{U(1)} = -q_- \frac{1}{16\pi^2}\mathrm{Tr}(\varepsilon^{\mu\nu\rho\sigma} G_{\mu\nu} G_{\rho\sigma}) + 2q_- M\overline{\psi} i\gamma^5\psi$$

- Shift symmetry $\xi \to \xi + \varepsilon_\xi$ is broken by gauge instantons

$$\partial_\mu J^\mu_\xi = \frac{1}{8\pi^2}\mathrm{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu}), \qquad J^\mu_\xi = f_\xi^2 \partial^\mu \xi.$$

- $U(1)_{\mathrm{chiral}} \times U(1)_\xi$ as spurion symmetries with (θ, M) as spurion fields:

$$U(1)_{\mathrm{chiral}}: \begin{array}{l} \Phi \to e^{2i\alpha q_-}\Phi, \\ \theta \to \theta + 2\alpha q_-, \\ M \to e^{-2i\alpha q_-} M \end{array} \qquad U(1)_\xi: \begin{array}{l} \xi \to \xi + \varepsilon, \\ \theta \to \theta + \varepsilon. \end{array}$$

2 separate mass-generating terms:

$$V = V_1(\xi - i \ln\det(\Phi) - \theta) + V_2(M\Phi + M^\dagger\Phi^\dagger)$$

Natural-like Inflation

$\xi =$ inflaton candidate

with $f \ll f_\xi$ and $m_\xi \ll m_\eta < m_\sigma$

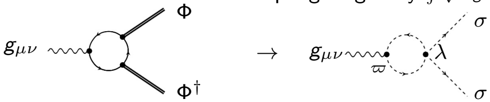
Viable inflationary model requires control over perturbative QM corrections:

Weinberg ('79)

- Non-renormalizable corrections have to be compatible with $U(1)$ symmetries:
  - ⋆ derivative terms: $M_{UV}^{-4} \left|\partial\Phi^\dagger\partial\Phi\right|^2$, $M_{UV}^{-2}|\Phi|^2\left|\partial\Phi\right|^2$
  - ⋆ potential & mixed terms

  $\Rightarrow$ additionally suppressed by powers of $\frac{f}{f_\xi} \sim 10^{-3}$
- Loop-corrections for perturbative Φ-interactions
  - ⋆ 1-loop effective action $V^{1-loop} \sim (-\mu^2 + 3\lambda|\Phi|^2)^2 \left\{\ln\left(\frac{-\mu^2+3\lambda|\Phi|^2}{\Lambda_r^2}\right) - \frac{3}{2}\right\}$ Coleman-Weinberg ('73)

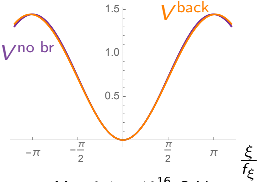
    $\rightsquigarrow$ proper resummation using Callan-Symanzik equation for $V_{\rm eff}$ maintains vacuum structure
  - ⋆ Induced non-minimal coupling to gravity $\int\sqrt{-g}\,\varpi|\Phi|^2 R$ Hill-Salopek ('92)



Solving RGE for $\varpi \rightarrow$ IR-fixed point $\varpi = 0$ Voloshin-Dolgov ('82)

Back-reacting infladrons

- (σ, η)-backreaction on inflationary potential $\rightsquigarrow$ flattening for ξ-potential



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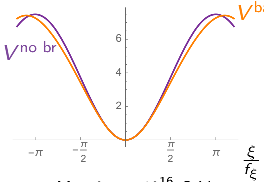

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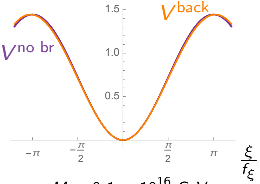

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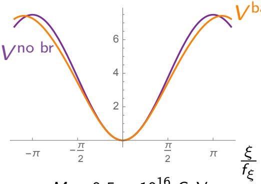

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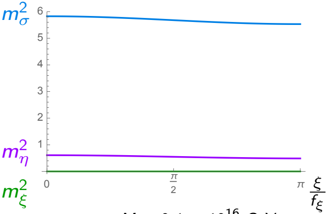

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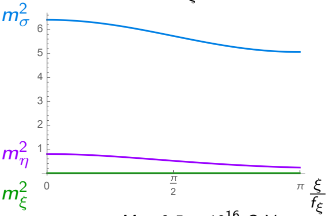

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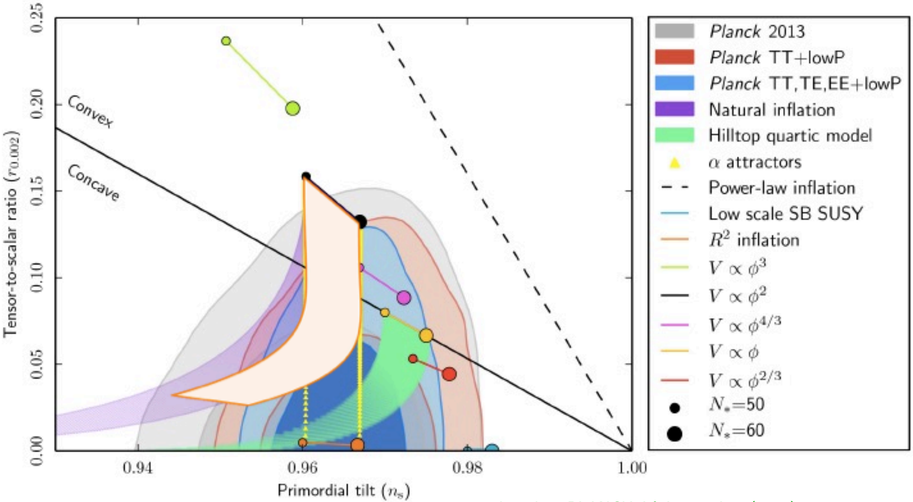

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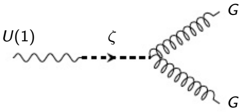
Consistency & 4-Fermion Couplings

w/ Shiu-Ye 1503.01015, 1503.02965 [hep-th]

- $U(1)$ gauge invariance requires presence of chiral fermions ψ



- Integrating out massive $U(1)$ boson
  $\rightsquigarrow$ 1 axion ξ + 1 non-Abelian gauge group + chiral fermions

$$\mathcal{S} = \int \frac{1}{2} d\xi \wedge \star_4 d\xi - \frac{1}{8\pi^2} \frac{\xi}{f_\xi} \mathrm{Tr}(G \wedge G) - \frac{\mathcal{C}}{f_2^2} \underbrace{\mathcal{J}_\psi \wedge \star_4 \mathcal{J}_\psi}_{4-fermion} + \mathcal{L}_\psi$$

- Work out infrared vacuum for 1 generation ψ

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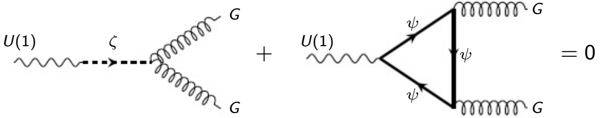

"reversed" GS mechanism

Aldazabel-Franco-Ibáñez-Rábadan-Uranga ('01)

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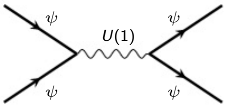
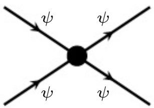


$\Longrightarrow$



+ global $U(1)_{\mathrm{anom}}$

N-JL type couplings: $\frac{q_L q_R}{2M_{st}^2}\left[(\overline{\psi}\psi)^2 + (\overline{\psi}i\gamma^5\psi)^2\right]$

Nambu-Jona-Lasinio ('61)

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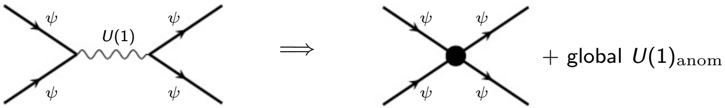

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