Adventures with Stringy Axions

Wieland Staessens

based on 16xx.xxxxx (1503.01015, 1503.02965 [hep-th])

with G. Shiu

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Stringpheno 2016,

IFT-UAM/CSIC, 23 June 2016

Axions in a Nutshell

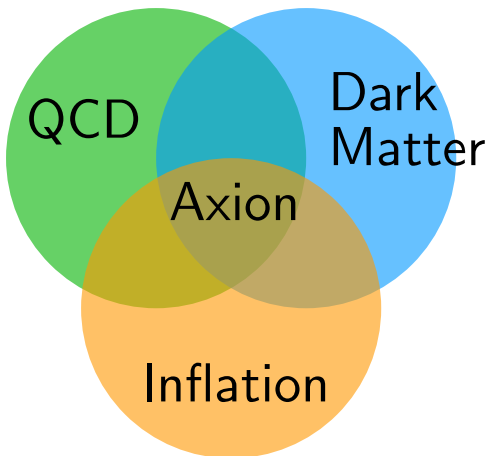
Peccei-Quinn, Wilzcek, Weinberg (1977), KSVZ (1979), DFSZ (1979) ,
Freese-Frieman-Olinto (1990), . . .

axion: CP-odd $\mathbb{R}$ scalar with $a \to a + \varepsilon$, broken by nonpert. effects

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \Lambda^4 \left[1 - \cos\frac{a}{f_a}\right] \quad \Rightarrow \quad m_a^2 \sim \frac{1}{f_a^2}$$

$\rightsquigarrow$ suitable building blocks for particle physics + cosmology

Axions in a Nutshell



QCD-axion: f_a constraint by exp. searches
& DM considerations

QCD axion window 10^9 GeV $< f_a <$ 10^{12} GeV

Inflationary axion: $f_a > M_{Pl}$
due to slow roll conditions

String Theory: plethora of axions from KK compact. of p-forms
see e.g. Witten (1984), Banks-Dine-Fox-Gorbatov (2003), Svrček-Witten (2006)

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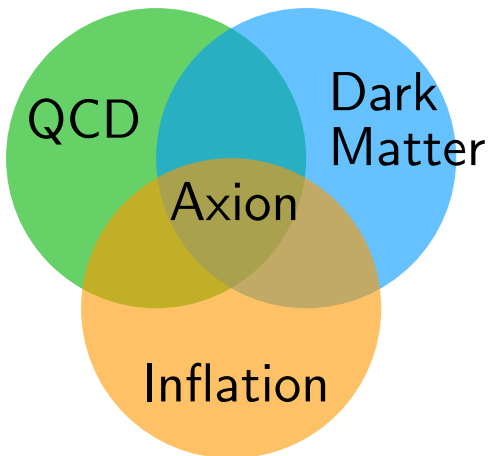

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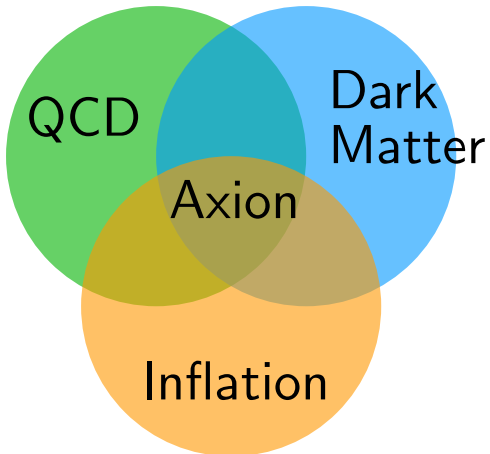

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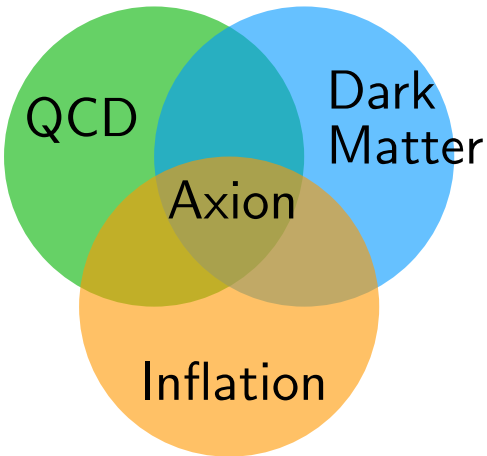

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Cracking the QCD Nut

☞ Question: Does String Theory allow QCD axion?

$\rightsquigarrow$ Answers within Type IIA with intersecting D6-branes

QCD axion $\rightsquigarrow$ open string axions

- ⋆ within chiral multiplet @ intersection point of two D-branes
- ⋆ construct DFSZ models

  Honecker-WS (2013), Ecker-Honecker-WS (2014, 2015)

  Escobar-Marchesano-Ruiperez-WS (work in progress)

$\rightsquigarrow$ Alternative & Complementary approaches

- ⋆ construct KSVZ models

  see e.g. Buchbinder-Constantin-Lukas ('14) for HE
- ⋆ closed string axions in LVS with $M_s \sim 10^{12}$ GeV

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Inflation and Stringy Axions

- natural inflation Freese-Frieman-Olinto ('90)
  - ⋆ pert. shift symmetry $\rightarrow$ ~~dim 6 operators~~
  - ⋆ Nonpert. effects $\rightarrow V_{inf} \sim \Lambda^4 \left[1 - \cos \frac{a}{f_a}\right]$
- strong UV sensitivity of Large Field Inflation Lyth ('96)
  $\rightarrow$ need for UV complete theory with quantum gravity = String Theory

But $\exists$ no-go theorems and arguments forbidding $f > M_{Pl}$ (1 axion)
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$\rightsquigarrow$ multiple axions: N-flation (2005), aligned natural inflation (2004), axion monodromy (2008, 2014), kinetic mixing (2015) (McAllister)

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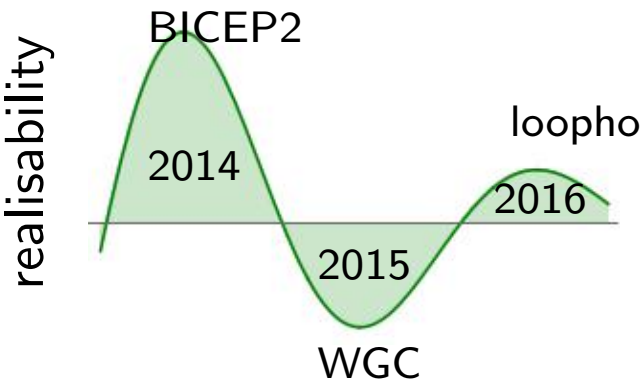

loopholes (Blumenhagen)

(generalised) WGC: kinematic constraints on f_a for multiple axions??
(Shiu,Hebecker,Reece,Baume,Montero, Mangat,Valenzuela,Witkowski,Rompineve . . .)

GAME OF INFLATONS

All inflationary models: inflaton = fundamental scalar

reviews: Baumann (2009), Baumann-McAllister (2009,2015), Westphal (2014)

☞ Question: Can inflaton be a composite scalar?

Other: Evans-French-Kim('10),(Bezrukov-)Channuie-Joergensen-Sannino('11/'12),Inagaki-Odintsov-Sakamoto('15), Angeluova-Suranyi-Wijewardhana('15/'16)

Here: EFT for stringy axions $\rightsquigarrow$ Nambu-Jona-Lasinio (NJL) models + explore inflationary models from strong dynamics

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Stringy Axions and NJL models

Stringy Axions and Stückelberg-mechanism

Ibáñez-Uranga('12), Blumenhagen-Lüst-Theisen('13), Blumenhagen-Cevtič-Langacker-Shiu('05), Grimm-Louis ('05), Grimm-Lopes ('11), Kerstan-Weigand ('11), Grimm-Louis ('04), Jockers-Louis ('05), Haack-Krefl-Lust-Van Proeyen-Zagermann ('06)

- 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)

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

Kinetic terms for p-forms $C_{(p)} \in \rightsquigarrow$ kinetic terms for a^i

- Stack of N D-branes on $\mathcal{M}_{1,3} \times \Sigma^i \rightsquigarrow U(N)$ gauge theory in $4+p$ dim
  Reduction of D-brane CS-action $\rightsquigarrow$ couplings for a^i
  - ⋆ $C_3 \wedge \mathrm{Tr}(G \wedge G) \rightarrow$ anomal. coupling $a^i Tr(G \wedge G)$
  - ⋆ $C_5 \wedge F \rightarrow$ Stückelberg-coupling $(da^i - k^i A)^2$ under U(1)
- Subset of axions are eaten by anomalous $U(1)$'s $\rightsquigarrow$ $U(1)$'s survive as global symmetries
  Ibáñez,Quevedo,Marchesano,Rabadán,Uranga,Ghilencea,Irges,Antoniadis, Kiritsis,Rizos,Coriano,Anastasopoulos,Bianchi,Dudas, ...

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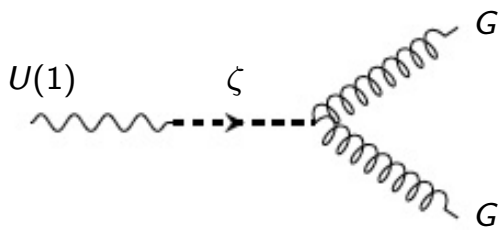
The road to NJL Models

Shiu-WS-Ye('15), Shiu-WS (work in progress)

- $U(1)$ gauge invariance: $A \to A + \mathrm{d}\chi$, $a \to a + k\chi$

$$\mathcal{S}_{EFT} = \int \left[-\frac{M_{st}^2}{2} |\mathrm{d}a - kA|^2 - \frac{1}{4g_{U(1)}^2}|F|^2 - \underbrace{\frac{1}{8\pi^2} a\,\mathrm{Tr}(\,G \wedge G)}_{\text{not } U(1) \text{ invariant}} \right]$$



- @ intersection of two D-brane stacks with $U(N) \times U(1)$
  $\rightsquigarrow$ chiral matter in bifund. rep.

- EFT for generation-indep. $U(1)$ charges:

$$\mathcal{L} = -\frac{M_{st}^2}{2}|da - kA|^2 - \frac{1}{4g_{U(1)}^2}|F|^2 + i\sum_{i=1}^{N_f} \overline{\psi}_L^i \partial\!\!\!/ \psi_L^i + i\sum_{i=1}^{N_f} \overline{\psi}_R^i \partial\!\!\!/ \psi_R^i$$

$$+ \sum q_L \overline{\psi}_L^i A\!\!\!/ \psi_L^i + \sum q_R \overline{\psi}_R^i A\!\!\!/ \psi_R^i + \text{coupling to } U(N) \text{ \& gravity}$$

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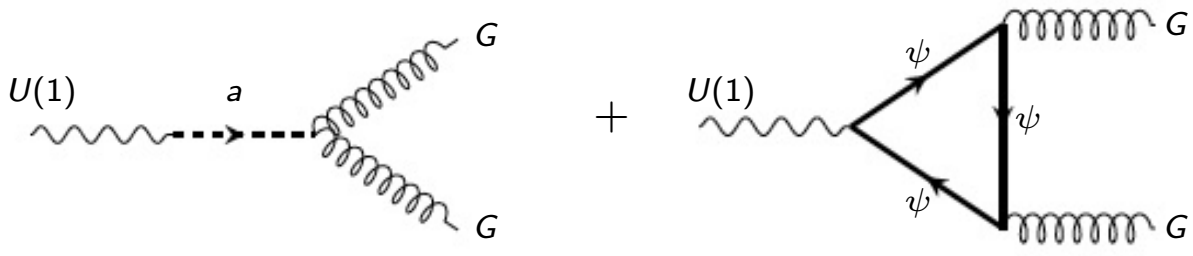
$+$ chiral fermions ψ



Antoniadis-Kiritsis-Rizos ('02)

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

"reversed" GS mechanism

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Toy Model with intersecting D6-branes

- Literature: Plethora of chiral $U(1)$'s with $q_R = 0$ or $q_L = -q_R$
- For our purposes: $sgn(q_L) = sgn(q_R)$ and $q_L \neq q_R$

$\rightsquigarrow$ Set of 3 D6-branes wrapping three-cycles on $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2 \times \Omega\mathcal{R})$

Cvetič-Shiu-Uranga('01)

- 1 massless $U(1)_0$ + 2 massive $U(1)_1^{\perp}$ and $U(1)_2^{\perp}$
  Antoniadis-Kiritsis-Rizos('02), Ibáñez-Uranga('12)
- (SUSY) chiral spectrum
- Local model can be "globalised" by introducing additional D6-branes $\uparrow\uparrow \Omega\mathcal{R}\mathbb{Z}_2^{(i)}$ and/or fluxes

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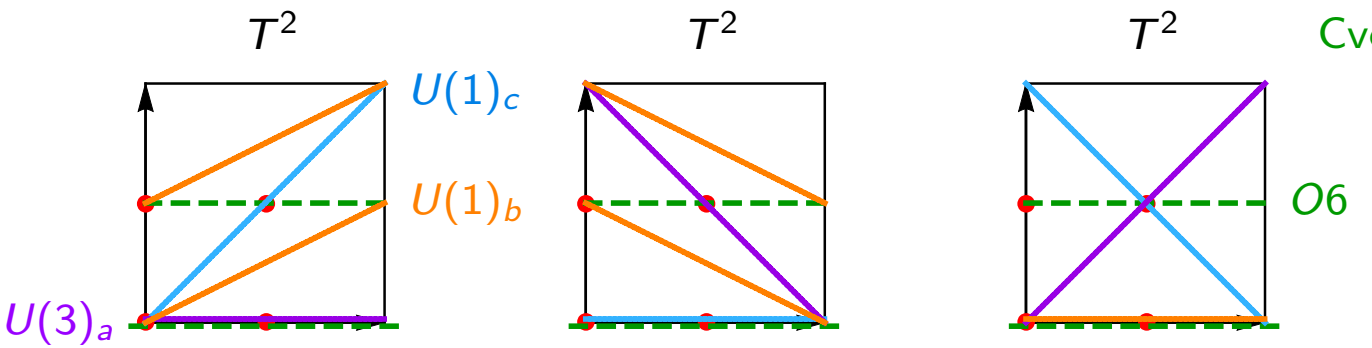

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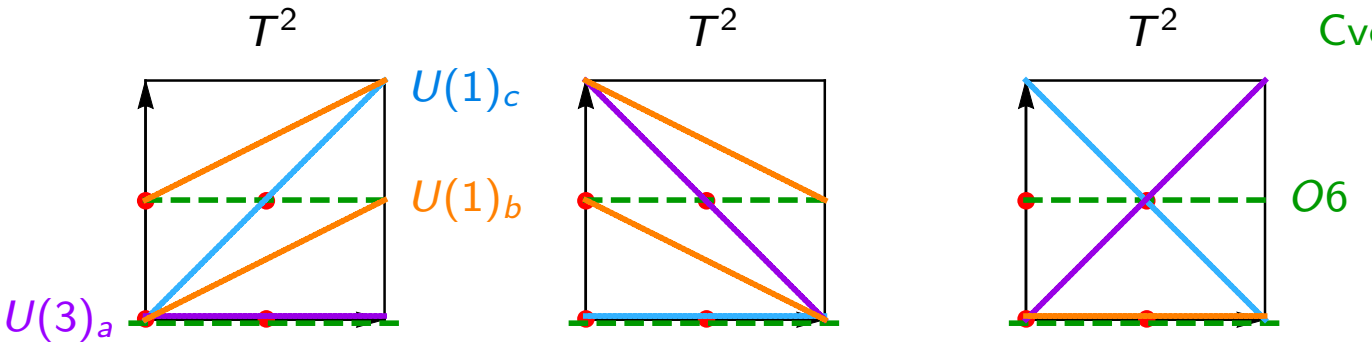

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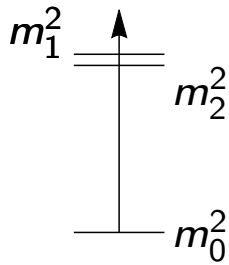

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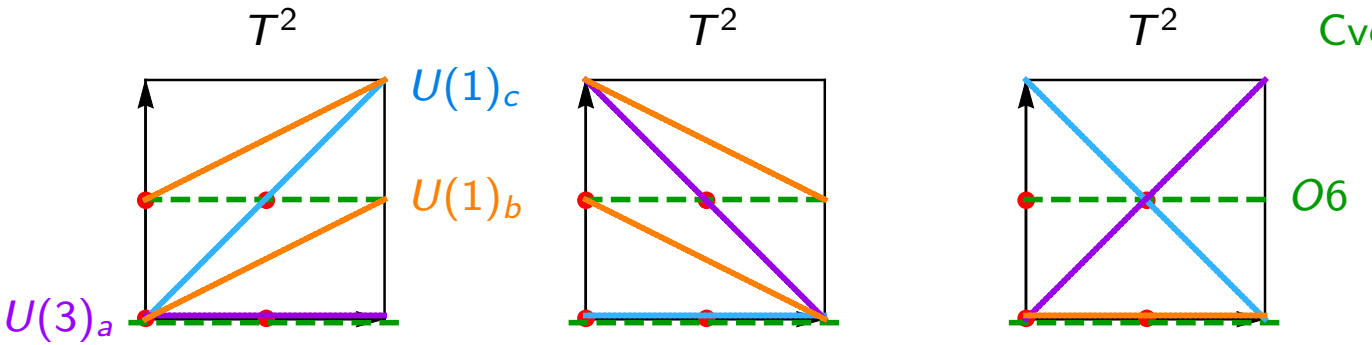

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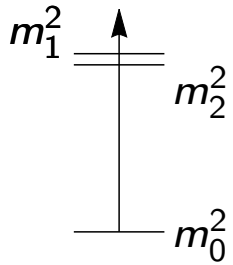

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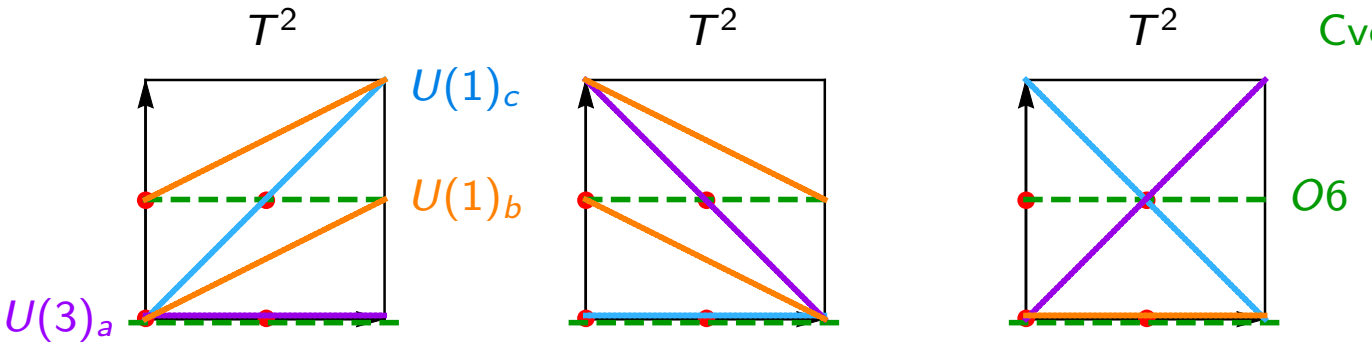

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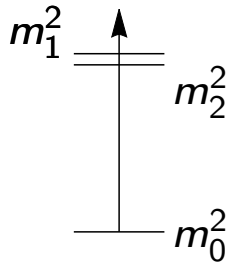

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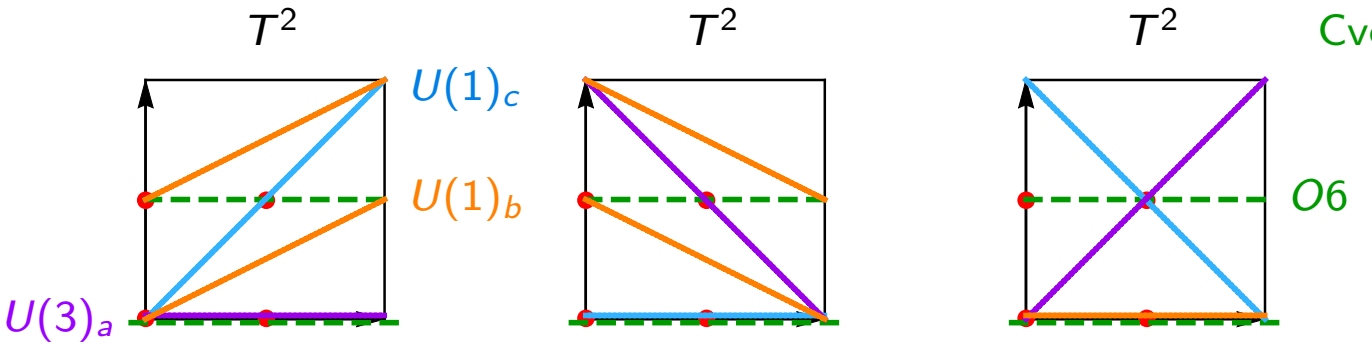

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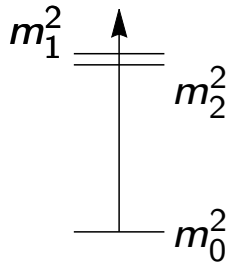

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Shiu-WS-Ye('15), Shiu-WS(work in progress)

- Integrating out Stückelberg $U(1)$ by solving Lorenz gauge condition:

$$A \sim \frac{1}{M_{st}^2}\left(q_L \overline{\psi}_L^i \Gamma \psi_L^i + q_R \overline{\psi}_R^i \Gamma \psi_R^i\right)$$

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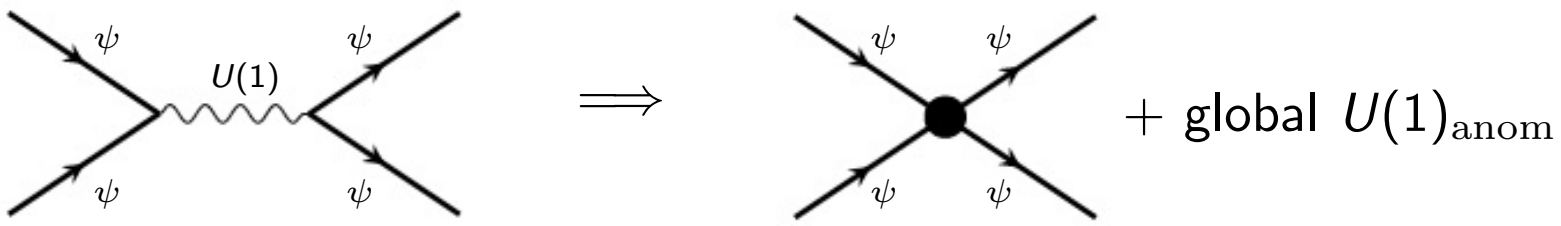

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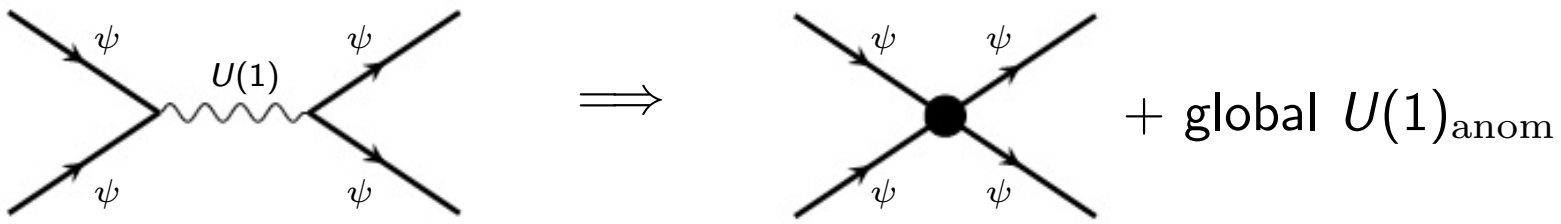

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$$\mathcal{L}_{4\psi} = \frac{q_L q_R}{2M_{st}^2}\sum_{i,j=1}^{N_f}\left[\underbrace{(\overline{\psi}^i\psi^j)(\overline{\psi}^j\psi^i) - (\overline{\psi}^i\gamma^5\psi^j)(\overline{\psi}^j\gamma^5\psi^i)}_{\text{typical NJL interactions}}\right] + \frac{1}{2M_{st}^2}\sum_{i\neq j}\left[q_L^2 V_L^\mu V_{L,\mu} + q_R^2 V_R^\mu V_{R,\mu}\right]$$

Nambu-Jona-Lasinio ('61)

$$V_*^\mu = \overline{\psi}_*\gamma^\mu\psi_*$$

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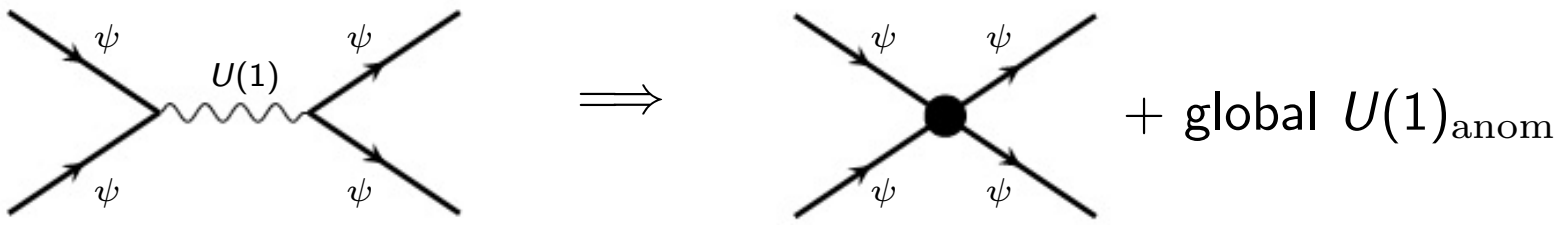

$+$ global $U(1)_{\text{anom}}$

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NJL & Dynamical Mass Generation

Nambu-Jona-Lasinio ('61), review: Vogl-Weise ('91)

- NJL $= U(1)_{\text{chiral}}$ invariant 4ψ-interactions $\quad \psi \to e^{i\alpha\gamma^5}\psi$

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  - ⋆ Nambu-Goldstone-phase : $\langle\overline{\psi}\psi\rangle \neq 0 \rightsquigarrow \exists\ m_\psi = -\frac{q_L q_R}{M_{st}^2}\langle\overline{\psi}\psi\rangle$ and ~~$U(1)_{\text{chiral}}$~~

NG-phase requires satisfied self-consistency condition:

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- Verify minimum in NG-phase in large N limit Gross-Neveu ('74), Dudas('93)
  - ⋆ auxiliary fields (σ, π): $\begin{pmatrix} \sigma \\ \pi \end{pmatrix} \to \begin{pmatrix} \cos 2\alpha & \sin 2\alpha \\ -\sin 2\alpha & \cos 2\alpha \end{pmatrix} \begin{pmatrix} \sigma \\ \pi \end{pmatrix}$

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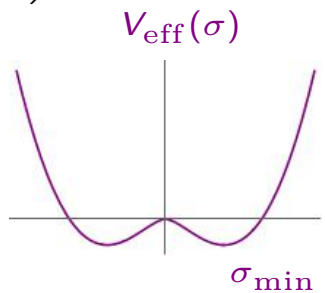
  - ⋆ effective potential $V_{\rm eff}(\sigma) = \frac{1}{2g^2}\sigma^2 - 2N \int \frac{d^4p}{(2\pi)^4} \ln\left(1 + \frac{\sigma^2}{p^2}\right)$

    $\rightsquigarrow$ minimum: $\frac{dV_{\rm eff}}{d\sigma}\Big|_{\sigma=\sigma_{\rm min}} = 0 \to$ GAP eq

    $V_{\rm eff}(\sigma_{\rm min}) < 0$



- Bound (scalar) states: (Salpeter-Bethe ('51) or poles of $G^{(4)}_{4\psi}$)
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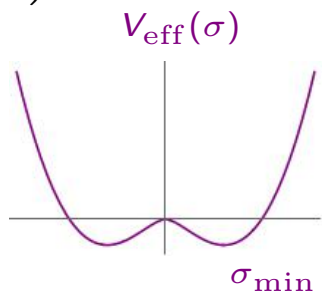

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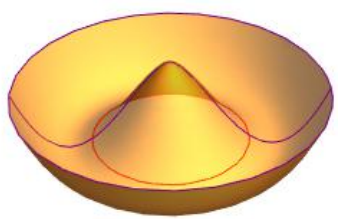

First Inflationary Steps

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- Using auxiliary fields (σ, π): NJL-model $\longrightarrow$ Higgs-Yukawa system

$$\mathcal{L}_{HY} = \mathcal{L}_{\rm kin} - y\,\overline{\psi}(\sigma + i\gamma^5\pi)\psi - \frac{1}{2}m^2(\sigma^2+\pi^2) - \frac{\lambda}{4}\left(\sigma^2+\pi^2\right)^2$$

for specific RGE-solution $y(t), m(t), \lambda(t)$ $\rightsquigarrow$ equivalent models
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- Coupling to gravity $\longrightarrow$ conformal coupling: $\frac{\xi}{2}R(\sigma^2+\pi^2)$ with $\xi = \frac{1}{6}$
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$\rightsquigarrow$ RG-invariant $V^{\rm eff}$ (dropping massless π) Inagaki-Odintsov-Sakamoto ('15)

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- Using auxiliary fields (σ, π): NJL-model $\longrightarrow$ Higgs-Yukawa system

$$\mathcal{L}_{HY} = \mathcal{L}_{\rm kin} - y\,\overline{\psi}(\sigma + i\gamma^5\pi)\psi - \frac{1}{2}m^2(\sigma^2+\pi^2) - \frac{\lambda}{4}\left(\sigma^2+\pi^2\right)^2$$

for specific RGE-solution $y(t), m(t), \lambda(t)$ $\rightsquigarrow$ equivalent models
Bardeen-Hill-Lindner (1990), Harada-Kikukawa-Kugo-Nakano (1994)

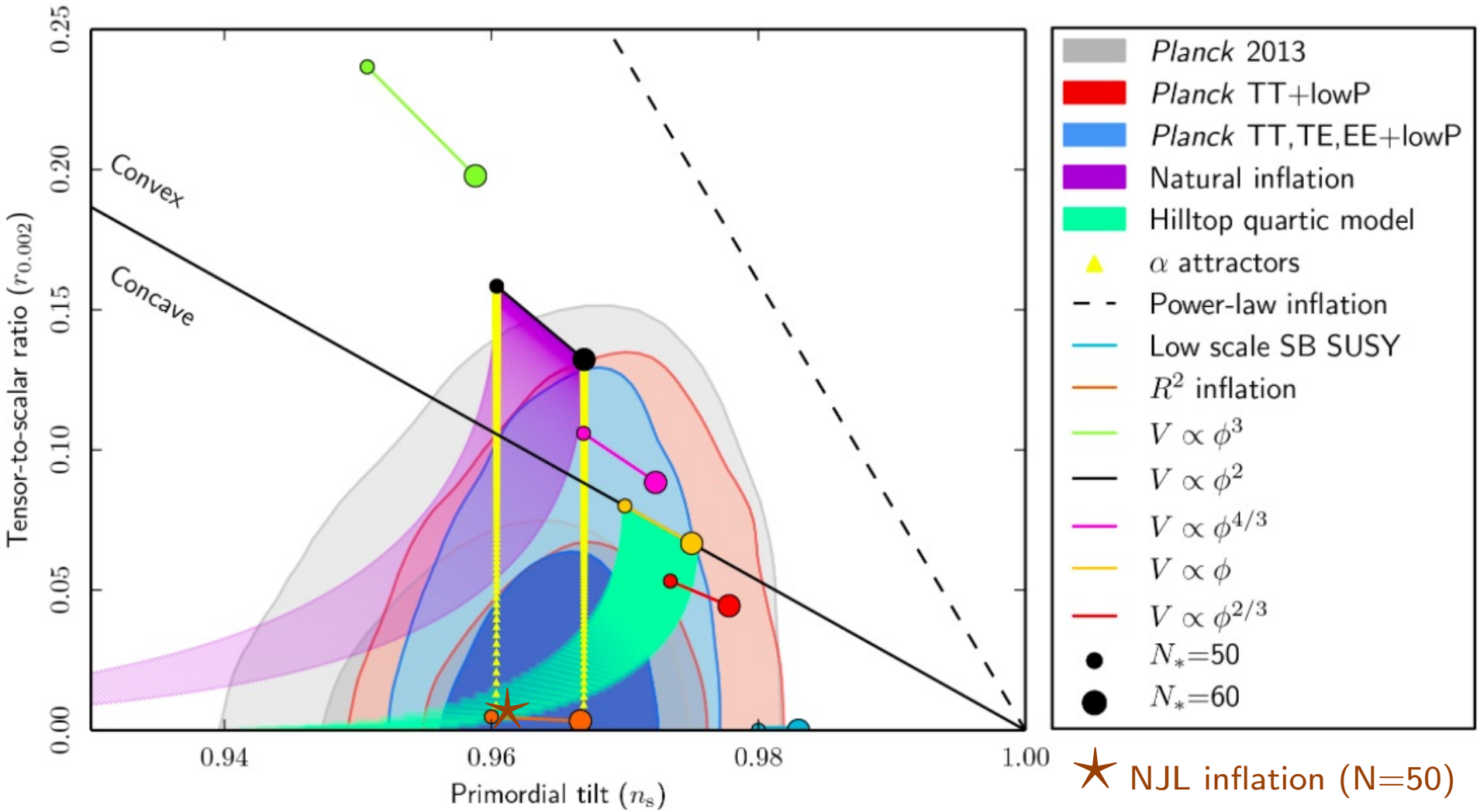
- Coupling to gravity $\longrightarrow$ conformal coupling: $\frac{\xi}{2}R(\sigma^2+\pi^2)$ with $\xi = \frac{1}{6}$
Hill-Salopek (1991)

$\rightsquigarrow$ RG-invariant $V^{\rm eff}$ (dropping massless π) Inagaki-Odintsov-Sakamoto ('15)

$$V^{\rm RGE}_{(\sigma,\pi)} = \frac{1}{1+\frac{D}{6}(\sigma^2)^{1/(1+\frac{\alpha}{\alpha_c})}}\left(\frac{B}{2}\sigma^2 + \frac{C}{4}(\sigma^4)^{1/(1+\frac{\alpha}{\alpha_c})}\right)$$

$\rightsquigarrow$ compatible with Planck 2015 data:
$n_s = 0.961$, $r = 0.0083$ @ weak coupling $\alpha \ll 1$

First Inflationary Steps



★ NJL inflation (N=50)

First Inflationary Hurdles

- consistency with density fluctuations $\rightarrow$ very weak coupling $\alpha \sim 10^{-12}$
  $\rightsquigarrow$ strong geometric constraint on "compact" space
  $\left(R_2/R_1 \sim 5 \times 10^7 \text{ for } T^2\right)$

- Strong $SU(N)$ dynamics can spoil (σ, π) set-up: 't Hooft (1976)
  - $SU(N)$ gauge instantons produce ~~$U(1)$~~ coupling $\kappa \det(\overline{\psi}(1+\gamma^5)\psi) + h.c.$
  - $m_\pi^2 \sim |\kappa|^2 < m_\sigma^2 = 4m_\psi^2 + m_\pi^2 \quad \rightsquigarrow \quad \pi =$ inflaton ?

- $\exists$ remaining closed string axions coupling to $SU(N)$ can play rôle of inflaton or spoil inflation?

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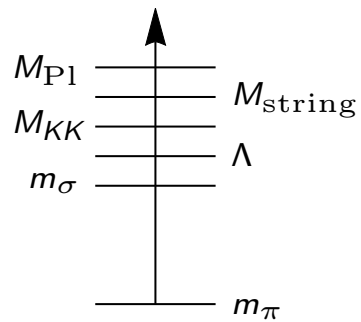

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- ☞ Set-up spoiled by $SU(N)$ strong dynamics??
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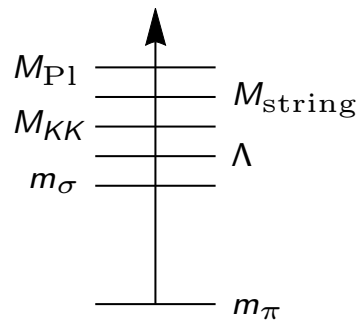

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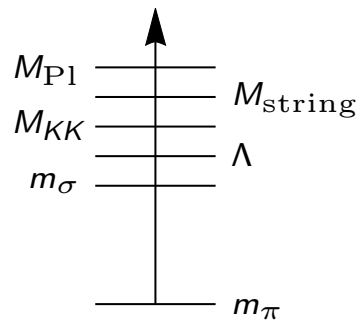

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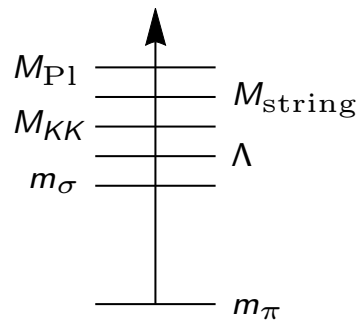

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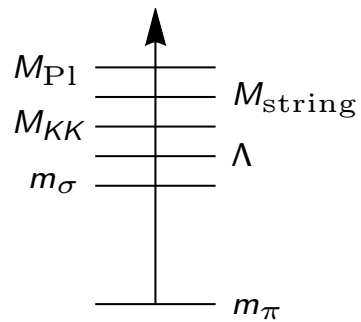

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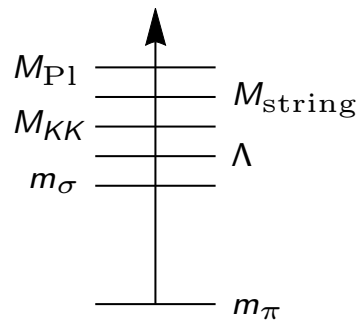

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Ευχαριστώ πολύ

Effective Potential

Gross-Neveu ('74) + textbooks

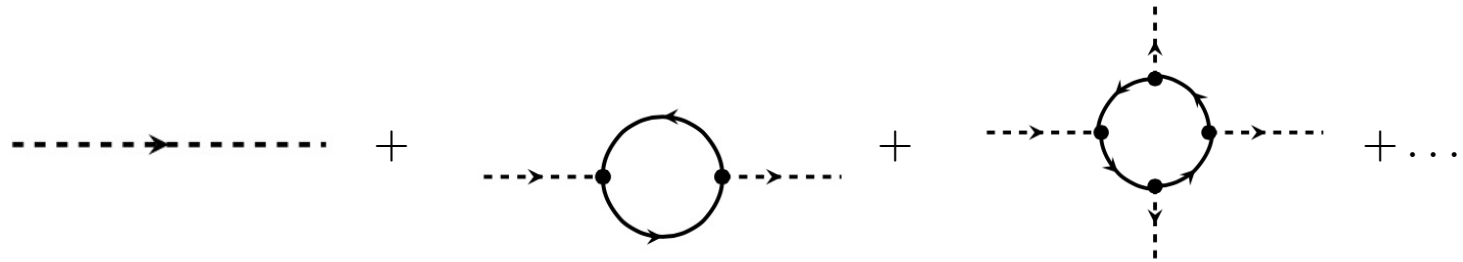
- effective action Γ is Legendre-transform of generating functional $W[J]$ for connected Green's functions:

$$\Gamma[\sigma] = \int d^4x\, \sigma(x) J(x) - W[J]$$

- $V_{\rm eff}(\sigma)$ is effective potential for classical field $\sigma = \langle vac|\hat{\sigma}|vac\rangle$ arising from effective action $\Gamma[\sigma]$
- $\Gamma[\sigma]$ is generating functional for 1PI n-point functions

☞
$$V_{\rm eff}(\sigma) = \sum_{n=2}^{\infty} \frac{1}{n!} \sigma^n \underbrace{\tilde{\Gamma}^{(n)}(0,0,\ldots,0)}_{\text{amputated 1 PI}}$$

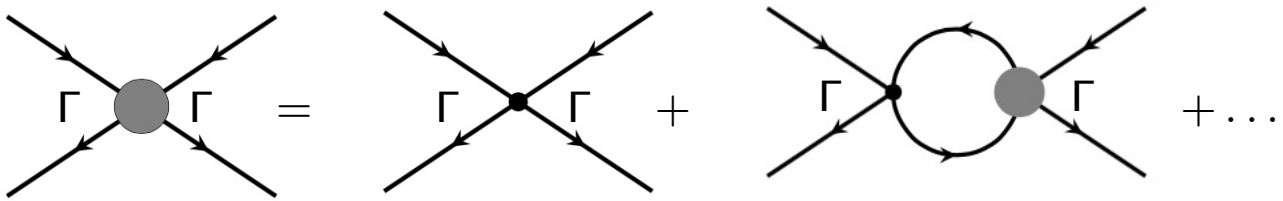
$$= V_{\rm cl}(\sigma) + V_{1-\rm loop}(\sigma) = \frac{1}{2g^2}\sigma^2 - iN \sum_{n=1}^{\infty} \int \frac{1}{2n} \left(\frac{\sigma^2}{p^2}\right)^n$$

$V_{\rm eff} =$  $+ \ldots$

Bethe-Salpeter bound states

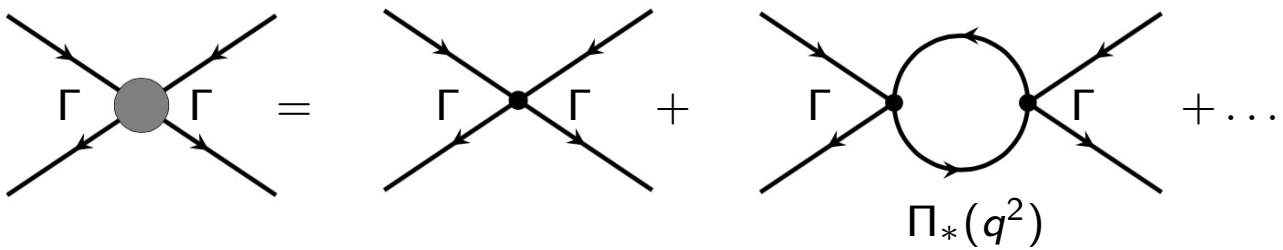
Buballa ('04) + textbooks

- Bethe-Salpeter: presence of bound states assuming mass gap as poles in the Green function



- Modern day formulation: search for poles in T-matrix for 4ψ interactions:

$$T_{4\psi} = \frac{g^2}{1 - g^2 \Pi_{4\psi}(q^2)}$$



R^2-type Inflation

Baumann-McAllister ('15)

- Non-minimally coupled inflation:

$$\mathcal{S} = \int dvol_4 \left[\frac{M_{Pl}^2}{2} \left(1 + \xi \frac{\varphi^2}{M_{Pl}} \right) R - \frac{1}{2} (\partial\varphi)^2 - V(\varphi) \right]$$

perform a conformal rescaling of $g_{\mu\nu}$ & for $\xi \gg 1$

$\rightsquigarrow$ canonically normalised inflaton $\frac{\phi}{M_{Pl}} = \sqrt{\frac{3}{2}} \ln(1 + \frac{\xi\varphi^2}{M_{Pl}^2})$

- $V(\varphi) = \frac{\lambda}{4}\varphi^4 \rightsquigarrow$ Starobinsky's R^2-inflation
- Gauged NJL models Inagaki-Odintsov-Sakamoto ('15)
  - ⋆ Composite scalar σ couples conformally to gravity: Hill-Salopek ('92)

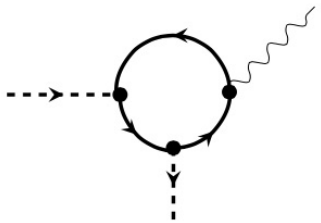
$$\mathcal{L} = \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2} m_\sigma^2 s^2 - \frac{\lambda}{4}\sigma^4 - \xi\sigma^2 R + \ldots, \qquad \xi = \frac{1}{6}(\text{IR fixed point})$$

  - ⋆ @ weak coupling for $SU(N) \rightarrow \phi \sim \sinh^{-1}(\sigma) - \tanh^{-1}\left(\frac{\sigma}{\sqrt{1+\sigma^2}} \right)$

Non-minimal coupling to gravity

Hill-Salopek ('92)

- Coupling ψ to gravity $\rightsquigarrow$ coupling of σ to gravity
  - ⋆ minimal coupling: $\sqrt{g}\left[g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - m_\sigma^2\sigma^2\right]$
  - ⋆ induced coupling: $\xi R\sigma^2$



- upon RG analysis: $\xi = \frac{1}{6} \rightarrow$ attractive IR fixed point for $\mu > m_\sigma$
- possibly only approximate scale-invariance when $\exists$ scale-breaking effects @ composite scale Λ

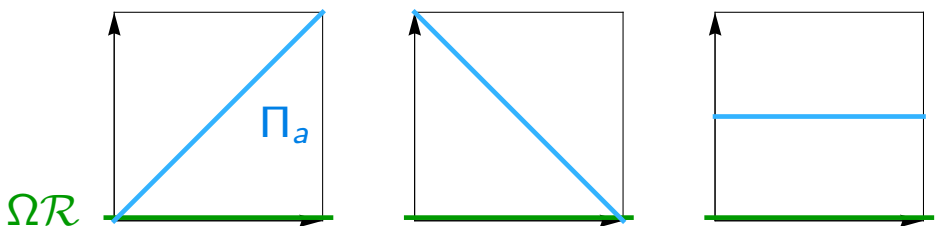
Axions & String Theory: Example

reviews: Blumenhagen-Cvetič-Langacker-Shiu ('05); Blumenhagen-Körs-Lüst-Stieberger ('06); Ibañez-Uranga ('12)

e.g. Type IIA D6-branes on $CY_3/\Omega\mathcal{R} \rightsquigarrow \Sigma^i = \Sigma^i_+ + \Sigma^i_-$

$$\int_{\Sigma^i_-} C_{(5)} \wedge F \neq 0 \qquad \rightsquigarrow \qquad \text{Stückelberg coupling for } a^i$$

$T^6/\Omega\mathcal{R}$ with 4 $\Omega\mathcal{R}$-even 3-cycles $\underbrace{\Sigma_+^{i=0,1,2,3}}_{\text{4 axions } a^i}$ and 4 $\Omega\mathcal{R}$-odd 3-cycles $\Sigma_-^{i=0,1,2,3}$



$$\Pi_a = \underbrace{\Sigma^0_+ - \Sigma^3_+}_{\Downarrow} + \underbrace{\Sigma^1_- - \Sigma^2_-}_{\Downarrow}$$

$$a^0 F_a \wedge F_a \qquad (da^1 - A_a)^2$$
$$-a^3 F_a \wedge F_a \qquad (da^2 + A_a)^2$$