"de Sitter Oddities"

work with:

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partially massless + shift symmetric scalars

non scalar bosonic particles in dS:

- massive $\quad m^2 > s(s-1)H^2$ Higuchi bound

gauge symmetries $\left\{ \begin{array}{l} \cdot \text{ massless/} \\ \text{partially massless} \end{array} \right.$ $\quad m^2 = [s(s-1) - t(t+1)]H^2$

depth $t = 0, \ldots, s-1$

$m^2 = 0 \leftrightarrow t = s-1$

$t = 0$ saturates Higuchi bound

eg $s = 1$

massive $\quad m^2 > 0 \quad \pm 1, 0$ helicities

massless $\quad t = 0 \quad m^2 = 0 \quad \pm 1$ helicities

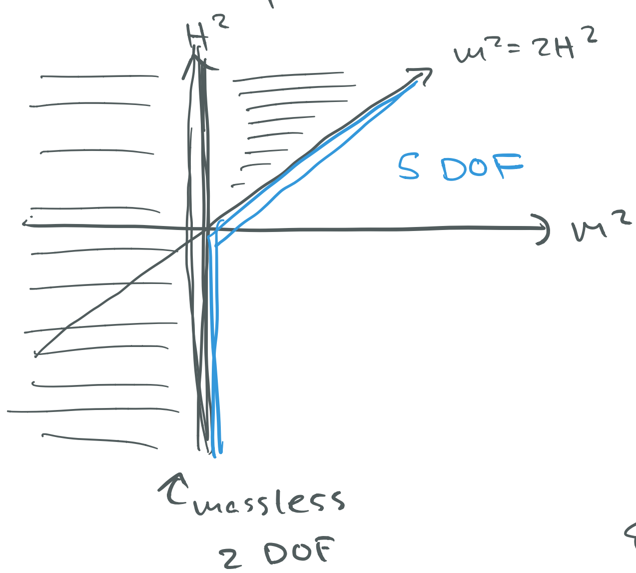
eg $s = 2$

massive $\quad m^2 > 2H^2 \quad \pm 2, \pm 1, 0$ helicities

$t = 0 \quad m^2 = 2H^2 \quad \pm 2, \pm 1$ helicities $\leftarrow$ Partially massless

massless $\quad t = 1 \quad m^2 = 0 \quad \pm 2$ helicities

Focus on spin-2



Free theory:

$$\mathcal{L} = \mathcal{L}^{(2)}_{EH} - \frac{m^2}{2}\left(h_{\mu\nu}h^{\mu\nu} - h^2\right)$$

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

when $m^2 = 2H^2$

$$\delta h_{\mu\nu} = \left(\nabla_\mu \nabla_\nu + H^2 g_{\mu\nu}\right)\alpha$$

invariant field strength:

$$F_{\mu\nu\lambda} = \nabla_\mu h_{\nu\lambda} - \nabla_\nu h_{\mu\lambda}$$

$$\mathcal{L} = -\frac{1}{4}\left(F^{\lambda\mu\nu}F_{\lambda\mu\nu} - 2F^{\lambda\mu}{}_{\mu}F_{\lambda\nu}{}^{\nu}\right)$$

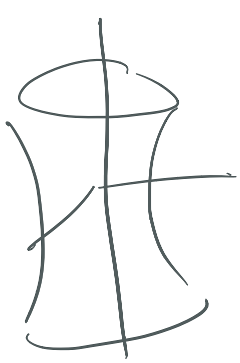
conserved charges $\longleftrightarrow$ "reducibility parameters"

$$\delta h_{\mu\nu} = 0 = \left(\nabla_\mu \nabla_\nu + H^2 g_{\mu\nu}\right)\alpha$$

embedding space X^A

$$\partial_A \partial_B \alpha = 0$$

$$\alpha = C_A X^A$$



pull back:

$$\alpha^A(x) = X^A(x)$$

- 5 conserved currents: $j_{\mu\nu}^{\ A} = F_{\mu\nu}^{\ \ \lambda} \nabla_\lambda \alpha^A$

$$\nabla^\mu j_{\mu\nu}^{\ A} = 0$$

- 5 conserved charges $Q^A = \oint_{S^2} \tilde{j}^A$

invariant charge: take the dS invariant norm

2 possibilities depending on whether norm is timelike or spacelike

Flat space limit

$$m^2 = 2H^2 \longrightarrow 0$$

$$\underset{\uparrow}{\mathcal{L}_{PM}} \rightarrow \underset{\pm 2}{\mathcal{L}^{(2)}_{EH}} + \underset{\pm 1}{\mathcal{L}_{EM}}$$

$\uparrow U(1)$ $\quad \delta A_\mu = \partial_\mu \Lambda$

$$\delta h_{\mu\nu} = \underline{\partial_\mu \xi_\nu} + \partial_\nu \xi_\mu$$

reducibility:

$$(\nabla_\mu \nabla_\nu + H^2 g_{\mu\nu})\alpha = 0 \longrightarrow \partial_\mu \partial_\nu \alpha = 0$$

$U(1)$
$\downarrow$
$\alpha = \text{const}$

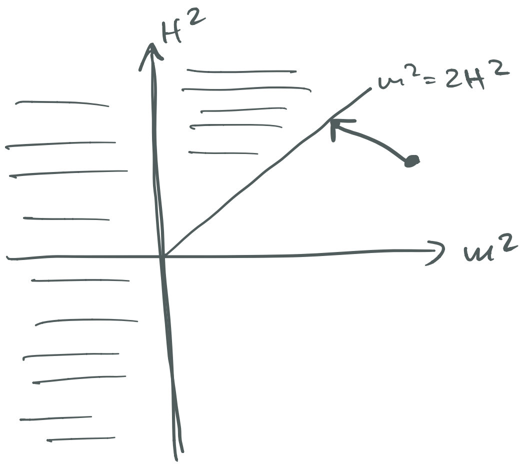
$\partial_\mu \alpha = \xi_\mu = \text{const}$

$\uparrow$ translations

2 invariant conserved charges:

mass, electric charge

spin-2



$m^2 > 2H^2$

$$\mathcal{L} = \mathcal{L}_{EH}^{(2)} - \frac{m^2}{2}\left(h_{\mu\nu}h^{\mu\nu} - h^2\right)$$

5 DOF

take $m^2 \to 2H^2$

$$\mathcal{L} = \mathcal{L}_{PM} - \frac{1}{2}(\partial\phi)^2 - \frac{m_s^2}{2}\phi^2$$

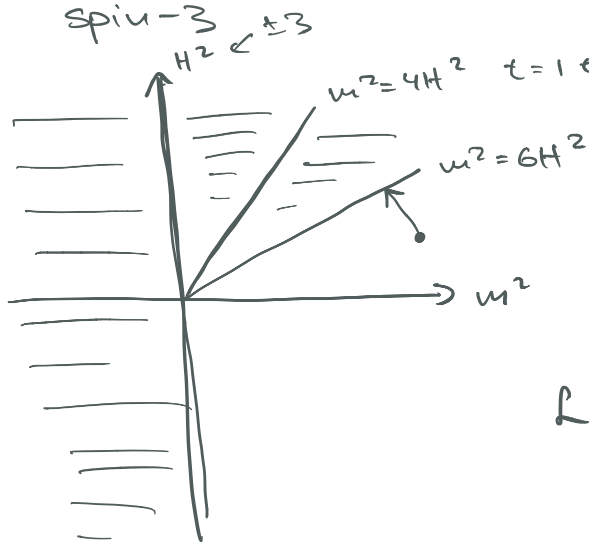
± 2
± 1 $\qquad\qquad 0$

$$m_s^2 = \underline{\underline{-4H^2}}$$

$$\delta h_{\mu\nu} = (\nabla_\mu \nabla_\nu + H^2 g_{\mu\nu})\alpha$$

embedding space ϕ $\to$ $\delta\Phi = \underline{\underline{C_A}} X^A$ $\leftarrow$ embedding space coords

spin-3



$t = 1 \leftarrow \pm 3, \pm 2$

$t = 0 \leftarrow \pm 3, \pm 2, \pm 1$

$\pm 3, \pm 2, \pm 1\, 0$

take $m^2 \to 6H^2$

$$\mathcal{L} = \mathcal{L}_{PM\,\text{spin-3}} - \frac{1}{2}(\partial\phi)^2 - \frac{m_s^2}{2}\phi^2$$

$$m_s^2 = -10H^2$$

$$\delta h_{\mu\nu\lambda} = \left(\nabla_{(\mu}\nabla_\nu\nabla_{\lambda)} + 4H^2 g_{(\mu\nu}\nabla_{\lambda)}\right)\alpha$$

$$\delta\Phi = C_{AB} X^A X^B$$

Generally in de Sitter:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{m_k^2}{2}\phi^2$$

$$m_k^2 = -k(k+3)H^2$$

$$\delta\Phi = C_{A_1\dots A_k}X^{A_1}\dots X^{A_k}$$

$\uparrow$ const, symm, traceless matrices

AdS: $m^2 = \frac{1}{L^2}k(k+3)$

dS:

Flat spacetime:

$$S = \int d^4x \left(-\frac{1}{2}(\partial\phi)^2\right)$$ free massless scalar

enjoys infinite number of shift sym:

$$\delta\phi = c + c_\mu x^\mu + c_{\mu\nu}x^\mu x^\nu + \dots$$

$$= \sum_{k=0}^{n} c_{\mu_1\dots\mu_k}x^{\mu_1}\dots x^{\mu_k}$$

Add interactions to preserve subset of sym:

- $k=0$ $\quad \delta\phi = c$

$$X = -\frac{1}{2}(\partial\phi)^2 \qquad \mathcal{L} = P(X)$$

$$\lim_{p\to 0} A(p) \propto p^\sigma \qquad \sigma = 1$$

- $k = 1$ $\quad \delta\phi = c_\mu x^\mu$

  - galileons $\rightarrow$ abelian
  - DBI action $\rightarrow$ non abelian $\quad \delta\phi = c_\mu x^\mu + c^\mu \phi \partial_\mu \phi$

  $\sigma = 2$

- $k = 2$ $\quad \delta\phi = c_{\mu\nu} x^\mu x^\nu$

  - "special galileon" $\quad$ Cheung et al 2014
    Hinterbichler + Joyce 2015

  $\sigma = 3$

- $k \geq 3$
