Approximate Symmetries of the Standard Model for Elementary Particle Interactions and Their Implications for Particle Physics and Cosmology

Mark Wise, Nov 5 2021, Karlsruhe Germany

OUTLINE

Julius Wess1934-2007

Much of his research was focussed on aspects of symmetry in particle physics.

Supergauge Transformations in Four-Dimensions #1

J. Wess (Karlsruhe U.), B. Zumino (CERN) (1974)

Published in: *Nucl.Phys.B* 70 (1974) 39-50, In *Ferrara, S. (ed.): Supersymmetry, Vol. 1*, 13-24,

DOI cite 3,370 citations

Consequences of anomalous Ward identities #2

J. Wess (CERN and Karlsruhe U.), B. Zumino (CERN) (1971)

Published in: *Phys.Lett.B* 37 (1971) 95-97

DOI cite 2,849 citations

Structure of phenomenological Lagrangians. 1. #3

Sidney R. Coleman (Harvard U.), J. Wess (New York U.), Bruno Zumino (New York U.) (1969)

Published in: *Phys.Rev.* 177 (1969) 2239-2247

DOI cite 2,144 citations

Structure of phenomenological Lagrangians. 2. #4

Curtis G. Callan, Jr. (Harvard U.), Sidney R. Coleman (Harvard U.), J. Wess (New York U.), Bruno Zumino (New York U.) (1969)

Published in: *Phys.Rev.* 177 (1969) 2247-2250

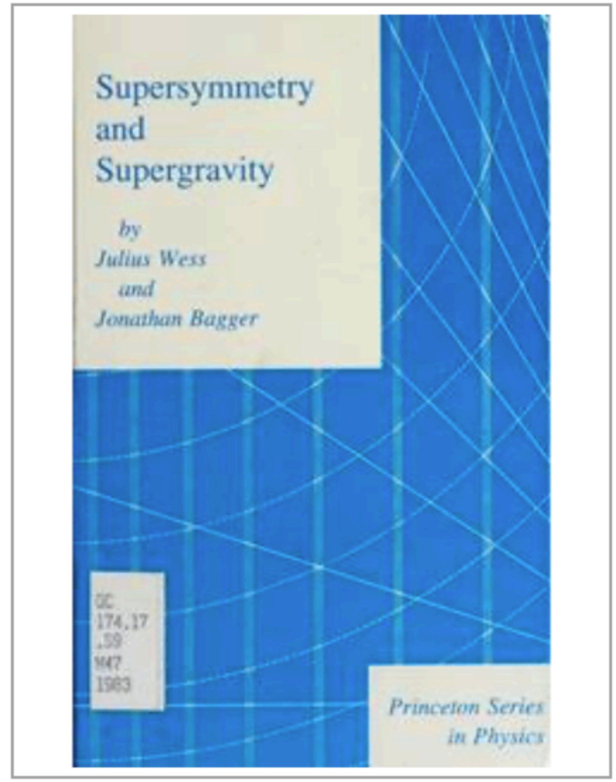
DOI cite 1,900 citations

A Lagrangian Model Invariant Under Supergauge Transformations #5

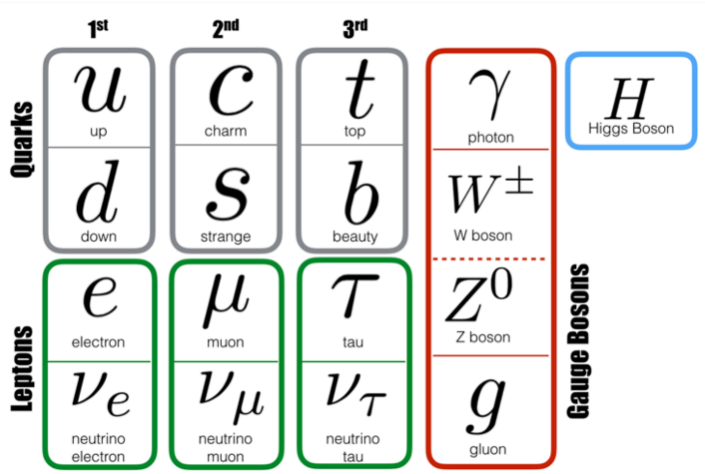
J. Wess (Karlsruhe U.), B. Zumino (CERN) (Dec, 1973)

Published in: *Phys.Lett.B* 49 (1974) 52, IN *FERRARA, S. (ED.): SUPERSYMMETRY, VOL. 1*, 77-79. (PHYS. LETT. B49 (1974) 52-54) AND CERN GENEVA - TH. 1794 (83,REC.JAN.74) 9 P. (SEE BOOK INDEX)

DOI cite 1,711 citations

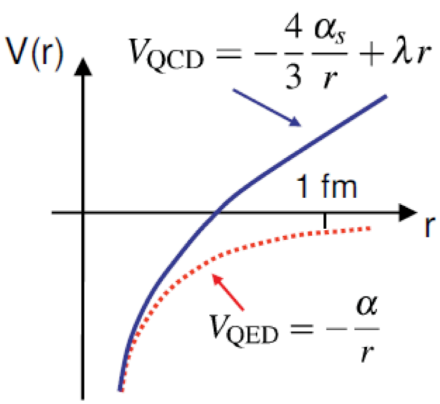


STANDARD MODEL OF PARTICLE PHYSICS



Strong weak and Electromagnetic interactions $SU(3) \times SU(2) \times U(1)_Y$

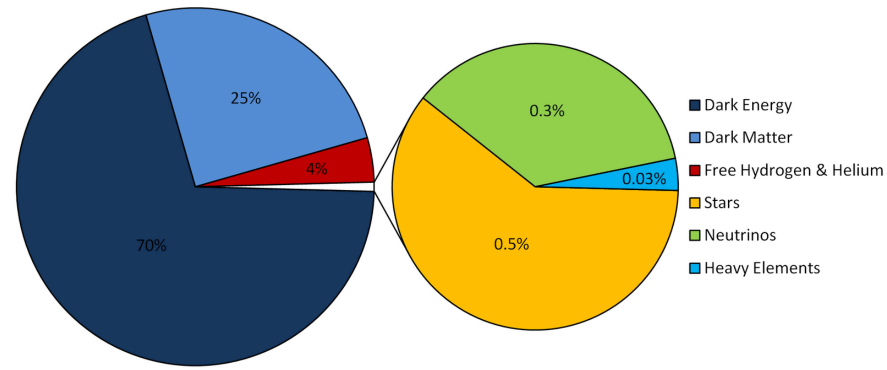
Classical General Relativity



Don't observe quarks observe Hadrons

$$\pi^+ \sim u\bar{d}$$
$$p \sim uud$$
$$B^- \sim b\bar{d}$$
$$\Lambda_b \sim bud$$
$$\Upsilon \sim b\bar{b}$$

STANDARD MODEL OF COSMOLOGY



Standard Model of Particle Physics with Classical General Relativity

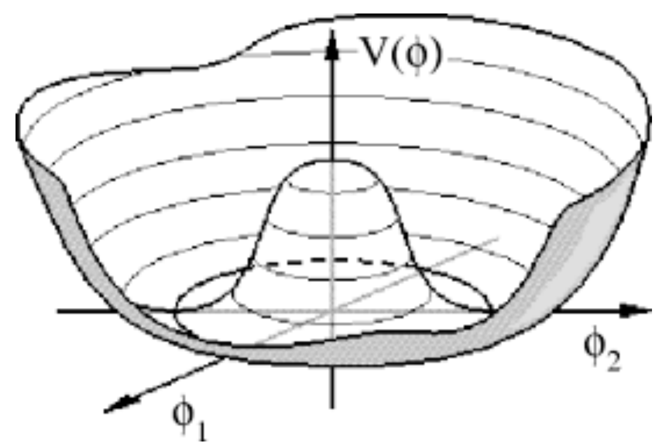
Primordial Gaussian energy density perturbations

Dark Energy = A cosmological Constant

Dark Matter an new massive particle that is non-relativistic today

Effective Field Theory For Pions and Kaons (Chiral Perturbation Theory)

QCD theory of quarks interacting with gluons. Notation q=(u,d,s), $m_q/\Lambda_{QCD} << 1$. Approximate flavor Symmetries of the theory arise in the limit that $m_q \to 0$ ($m_q/\Lambda_{QCD} << 1$). $SU(3)_L X SU(3)_R$ ($q_L \to Lq_L$, $q_R \to Rq_R$), spontaneously broken to $SU(3)_V$ (V=L=R) by vacuum expectation value of quark bilinears. Derive effective theory for interactions of 8 pseudo-Goldstone bosons, π, K, η. Expand effective Lagrangian for strong interactions π, K, η in derivatives (momentum) and insertions of the light quark mass matrix. Approximate flavor symmetries arise not because quark masses are almost equal ($m_u/m_d \sim 1/2$). Strange quark mass not small enough that one can have confidence that it will always work well at low orders. Conserved s→u current j_L^μ matrix elements for weak semileptonic kaon decays, V_{us} .



S. Weinberg, Phys. Rev. **166** (1968) 1568.
S. Coleman, J. Wess and B. Zumino, Phys. Rev. **177** (1968) 2239.
C. Callan, S. Coleman, J. Wess and B. Zumino, Phys. Rev. **177** (1968) 2247.

Heavy Quark Effective Theory

For very heavy quarks Q, $m_Q >> \Lambda_{QCD}$, in a meson or baryon that contains other light degrees of freedom (q, g) the interactions of the heavy quark with the light degrees of freedom involve momentum transfers of order the scale of non-perturbative strong interactions .. Changes in heavy quark four-velocity $\Delta v \sim \Lambda_{QCD}/m_Q \to 0$ as $m_Q \to \infty$. Strong interactions of heavy quark independent of its mass and spin in the limit $m_Q \to \infty$ and so there is a spin flavor $SU(4)$ symmetry for charm and bottom quarks of the same four-velocity. For a given non zero spin of the light degrees of freedom hadrons come in degenerate doublets with spin $s = s_\ell \pm 1/2$.

Weak semileptonic decays $B \to D^{(*)} e \bar{\nu}_e$ used to determine V_{cb}

Has implications for Hadronic Spectrum $m_{\Lambda_b} - m_B = m_{\Lambda_c} - m_D + \mathcal{O}(\Lambda^2_{QCD}/m_Q)$. Here $\mathcal{O}(\Lambda^2_{QCD}/m_Q) \simeq -20\mathrm{MeV}$

Can cancel out some corrections $\Delta L \sim \frac{1}{2m_Q}\bar{Q}_v D^2 Q_v + \frac{g}{2m_Q}\bar{Q}_v \sigma_{\alpha\beta} Q_v G^{\alpha\beta}$ $Q_v = exp[-im_Q v \cdot x]Q$

$$m_{\Lambda_b} - \bar{m}_B = m_{\Lambda_c} - \bar{m}_D + \mathcal{O}(\Lambda^2_{QCD}/m_Q^2) \qquad \bar{m}_D = (3m_{D*} + m_D)/4 \qquad \Delta m = \frac{g}{m_Q}\mathbf{s}_\ell \cdot \mathbf{s}_Q$$

Cancelled magnetic moment correction to masses

Tetraquarks two Heavy Quarks

Baryons and tetraquarks with two very heavy quarks Q have a large negative contribution to their mass

$$V(r) = -\frac{2}{3}\frac{\alpha_s(m_Q \mathrm{v}_{\mathrm{rel}})}{r} \qquad \text{diquark} \qquad \mathrm{BE} \sim \alpha_s(m_Q \mathrm{v}_{\mathrm{rel}})^2 m_Q, \quad r \sim \frac{1}{\alpha_s(m_Q \mathrm{v}_{\mathrm{rel}}) m_Q}$$

Ground state tetraquarks with two very heavy quarks decay weakly $T_{QQ\bar{q}\bar{q}} \to M_{Q\bar{q}} + M_{Q\bar{q}}$ or $B_{QQq} + \bar{B}_{\bar{q}\bar{q}\bar{q}}$ forbidden

Several papers find that tetraquarks with two heavy bottom quarks are stable and deeply bound (not molecules) $BE \sim 100 - 200\mathrm{MeV}$

Cornell potential for diquark $V_{\Phi_{bb}}(r) = -\frac{2}{3}\left(\frac{0.3}{r}\right) + \frac{1}{2}(0.2\mathrm{GeV}^2)r$ Implies radius $\langle r^2 \rangle = 3.2\mathrm{GeV}^{-2}$

Small compared to typical hadronic size $1/(300\ \mathrm{MeV})^2 \sim 11\mathrm{GeV}^{-2}$

Heavy quark-diquark symmetry is one way to estimate the tetra quark masses if you knew the masses of the baryons containing two heavy quarks. Lattice and more phenomenological quark model type methods exist now.

$$m_{T_{QQ\bar{q}\bar{q}}} - m_{B_{Qqq}} = m_{B_{QQq}} - m_{M_{Q\bar{q}}} + \mathcal{O}(\Lambda_{QCD}^2/m_Q)$$

Finding Baryons and tetra quarks with two heavy bottom quarks

Baryon with two heavy charm quarks discovered at LHCb in 2017 using mode

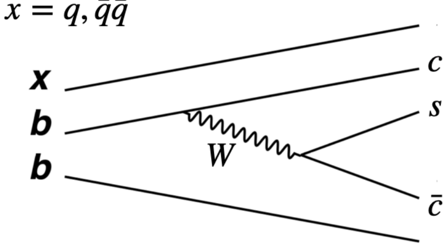
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ In our notation $B_{ccu} \to B_{cud} K^- \pi^+ \pi^+$

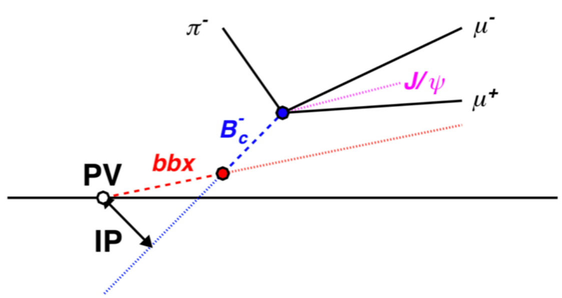
Harder to detect baryons with two heavy bottom quarks using exclusive modes

For example suppose use $\Xi_{bb}^0 \to B^- \Lambda_c$ Branching ratio guess $\sim 10^{-3}$

$Br(\Lambda_c^+ \to p K^- \pi^+) \sim 10^{-3}$ $Br(B^- \to J/\psi K^-) \sim 10^{-3}$ $Br(J/\psi \to \mu^+ \mu^-) \sim 10^{-1}$

$x = q, \bar{q}\bar{q}$





$Br(B_{bbq} \to \bar{B}_c + X) \simeq 10^{-2}$ $\mathrm{Br}\left(\bar{B}_c \to J/\psi \pi^- \to \mu^+ \mu^- \pi^-\right) \simeq 2 \times 10^{-4}.$

Scale Invariance of de Sitter Space-time

Flat Metric $ds^2 = -dt^2 + dx^i dx^i$ empty space

Symmetries, time translations $t \to t' = t + d$ spatial translations $x^i \to x'^i = x^i + c^i$

rotations $x^i \to x'^i = R^{ij} x^k, \quad RR^T = I$ etc

Scalar field $\phi(t, \mathbf{x}) = \int d^3 x e^{i\mathbf{k}\cdot\mathbf{x}} \tilde{\phi}(t, \mathbf{k})$ $\langle \tilde{\phi}(t, \mathbf{k}) \tilde{\phi}(t, \mathbf{k}') \rangle = P_\phi(t, k)(2\pi)^3 \delta(\mathbf{k} + \mathbf{k}')$

Delta function translation invariance power spectrum only dependent on magnitude of wave vector rotational invariance.

Our future de Sitter metric $ds^2 = -dt^2 + e^{2Ht} dx^i dx^i$ cosmological constant, scale factor $a(t) = e^{Ht}$

Metric no longer invariant under time translations.

$t \to t' = t + d, \; x^i \to x'^i = \lambda x^i, \quad \lambda = e^{-Hd}$ at infinite time just spatial scale invariance

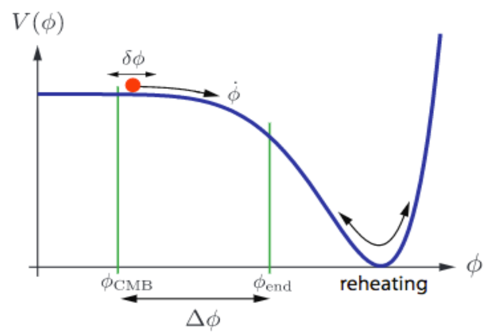
Scalar field $\phi(t, \mathbf{x}) = \int d^3 k e^{i\mathbf{k}\cdot\mathbf{x}} \tilde{\phi}(t, \mathbf{k}), \quad \mathbf{q} = \mathbf{k}/a(t)$ physical wave vector

$\langle \tilde{\phi}(\infty, \mathbf{k}) \tilde{\phi}(\infty, \mathbf{k}') \rangle = P_\phi(k)(2\pi)^3 \delta(\mathbf{k} + \mathbf{k}'), \quad P_\phi(\mathbf{k}) \propto 1/k^3$ scale invariance

Also Larger Conformal Invariance

Conjectured Inflationary Era

$q = k/a$



During inflation scalar fluctuations in curvature $P_\zeta(k, ; t_{\rm infl} \to \infty) \propto \dfrac{1}{k^3}$ scale invariance

Very Small k $\tilde{\delta}_\rho(\mathbf{k}; t_0) \propto \tilde{\delta}_\zeta(\mathbf{k}; t_{\rm infl}) k^2 \implies P_\rho(k; t_0) \propto \dfrac{k^2 k^2}{k^3} = k$

Write power spectrum today $P_\rho(k, ; t_0) \propto k^{n_s}$, $n_s = 0.9655 \pm 0.0062$ (68 % CL, *Planck* TT+lowP)

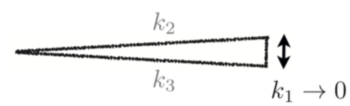
More generally (k not small) $\tilde{\delta}_\rho(\mathbf{k}; t_0) = \tilde{\delta}_\rho(\mathbf{k}; t_{\rm infl}) k^2 T(k)$ Transfer function cuts off large k non-Gaussianities $\langle \tilde{\phi}(\infty, \mathbf{k}_1), \ldots, \tilde{\phi}(\infty, \mathbf{k}_n) \rangle_c = P_\phi^{(n)}(\mathbf{k}_1, \ldots, \mathbf{k}_n)(2\pi)^3 \delta(\mathbf{k}_1 + \ldots + \mathbf{k}_n)$

scale invariance $P_\phi^{(n)}(\lambda \mathbf{k}_1, \ldots, \lambda \mathbf{k}_n) = \lambda^{3-3n} P_\phi^{(n)}(\mathbf{k}_1, \ldots, \mathbf{k}_n)$

e.g local non-Gaussianity $P_\zeta^{(3)}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) \propto \left[\left(\frac{1}{k_1^3}\right)\left(\frac{1}{k_2^3}\right) + \left(\frac{1}{k_1^3}\right)\left(\frac{1}{k_3^3}\right) + \left(\frac{1}{k_2^3}\right)\left(\frac{1}{k_3^3}\right) \right]$

Fixed by conformal invariance but not scale invariance alone

squeezed limit of three-point correlation $q = |\mathbf{k_1}| = |\mathbf{k_3} + \mathbf{k_2}| << |\mathbf{k_{3,2}}| \simeq k$



eg. consistent with scale invariance $P_\zeta^{(3)} \propto \dfrac{k^{-s}}{q^{3-s} k^3}$ s=0 local non-Gaussianity

$s \propto m^2/H^2$ m mass of additional light scalar in some inflationary model

compressed Limit of Four Point Correlation $\mathbf{k_1} \simeq -\mathbf{k}_2 \quad k \simeq k_{1,2} \qquad \mathbf{k_3} \simeq -\mathbf{k}_4 \quad k' \simeq k_{3,4}$

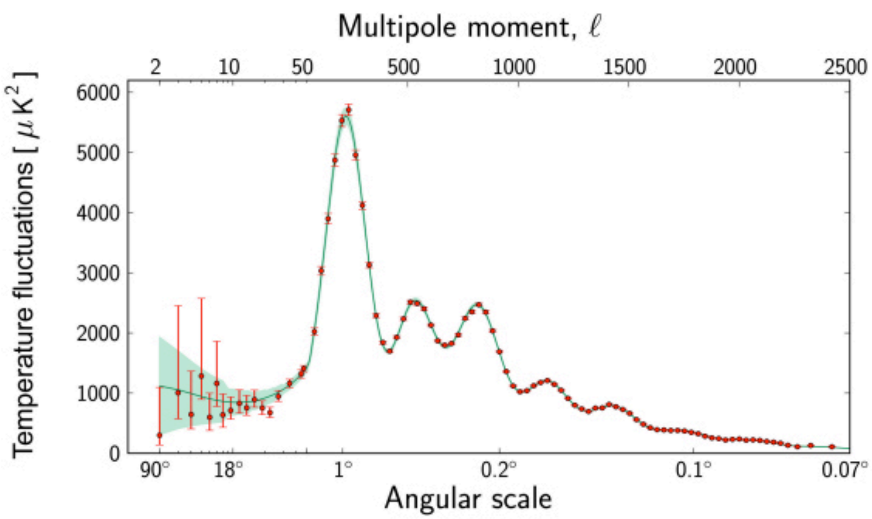
$q = |\mathbf{k}_1 + \mathbf{k}_2| = |\mathbf{k}_3 + \mathbf{k}_3| << k, k'$

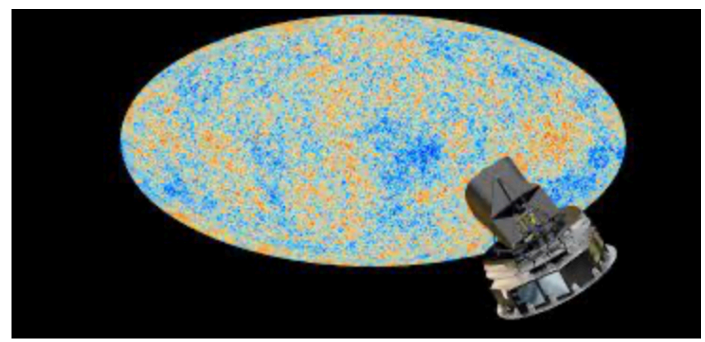
eg. consistent with scale invariance $P_\zeta^{(4)} \propto \dfrac{(kk')^{-s}}{q^{3-2s}(kk')^3}$

Constraints on non Gaussianity from CMB

$$P_\zeta^{(3)} \sim f_{NL} P_\zeta^{(2)} P_\zeta^{(2)} \qquad f_{NL} < 10$$

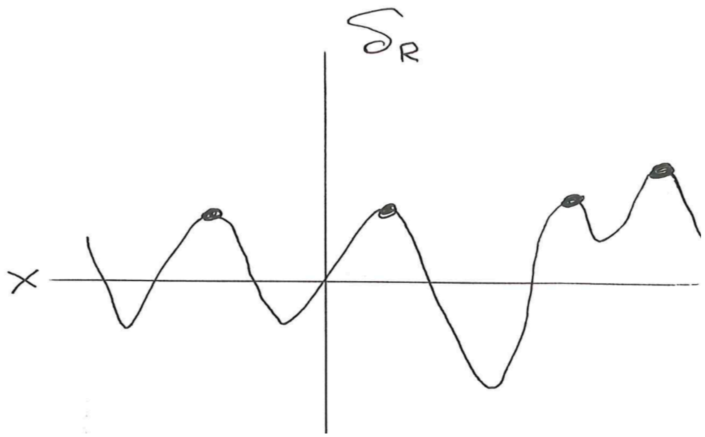
$$P_\zeta^{(4)} \sim \tau_{NL} P_\zeta^{(2)} P_\zeta^{(2)} P_\zeta^{(2)}$$





Galaxies

Average mass density fluctuations over a sphere of radius R $\tilde{\delta}_{\rho,R}(\mathbf{k}) = W(kR)\tilde{\delta}_{\rho}(\mathbf{k})$

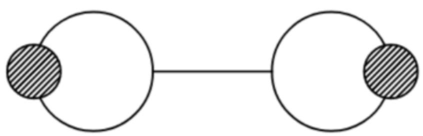


Galaxies don't trace the mass

$$\delta_g(\mathbf{x}) = b_1\delta_\rho(\mathbf{x}) + b_2\left(\delta_\rho(\mathbf{x})^2 - \langle(\delta_\rho(\mathbf{x}))^2\rangle\right) + \ldots$$

Composite field renormalized + new term in bias expansion

New contributions to $\langle\delta_g(\mathbf{x})\delta_g(\mathbf{y})\rangle$ that go as $b_2 b_1\langle\delta_\rho(\mathbf{x})^2\delta_\rho(\mathbf{y})\rangle_c$ $b_2^2\langle\delta_\rho(\mathbf{x})^2\delta_\rho(\mathbf{y})^2\rangle_c$

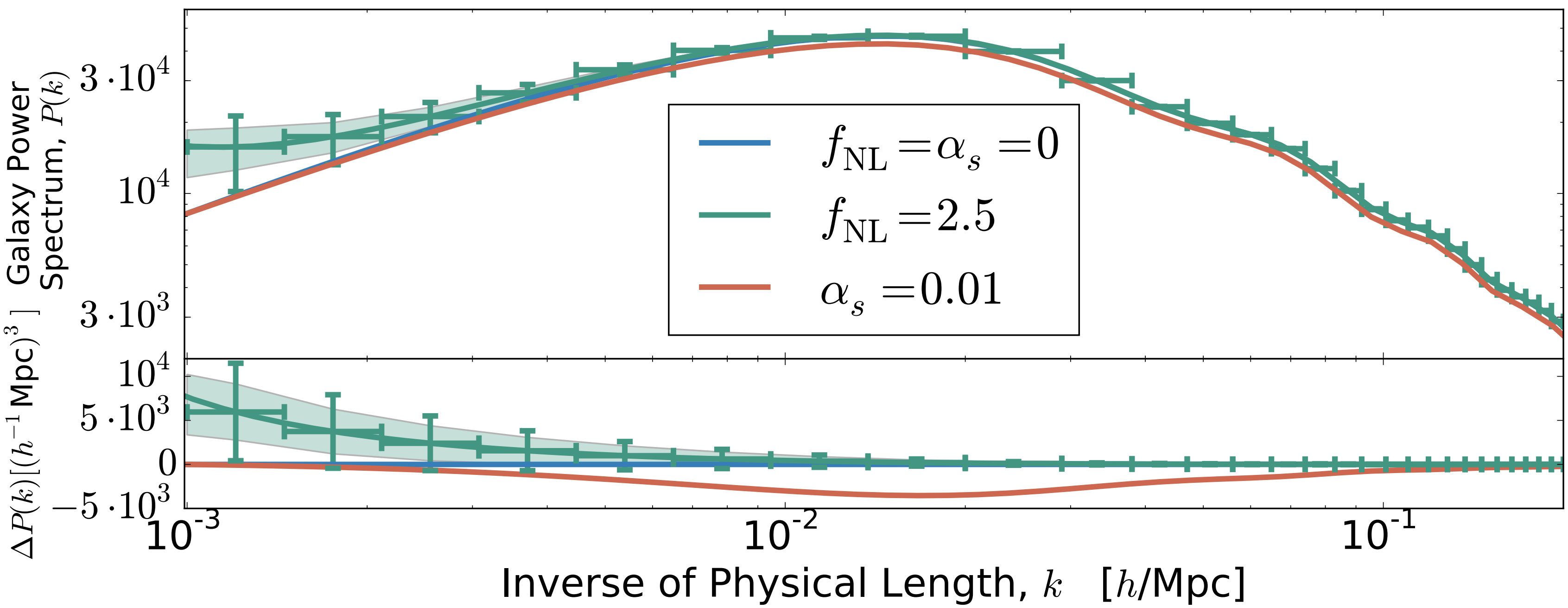


$$P_g(q) \sim b_2^2\left[\int\frac{d^3k}{(2\pi)^3}T(k)^2(k^2)^2W(kR)^2(1/k^3)\right]^2 1/q^3 \qquad s = 0$$

In a model but in model independent approach square brackets replaced by new coupling c that is fit to data

$$P_g(q) \sim c/q^3$$

SPHEREx



Galaxy Power Spectrum, $P(k)$
$\Delta P(k)\,[(h^{-1}\,\mathrm{Mpc})^3]$
$f_{\rm NL}=\alpha_s=0$
$f_{\rm NL}=2.5$
$\alpha_s=0.01$
$3\cdot10^4$
10^4
$3\cdot10^3$
10^4
$5\cdot10^3$
0
$-5\cdot10^3$
10^{-3}
10^{-2}
10^{-1}
Inverse of Physical Length, k [h/Mpc]

Conclusions / Outlook

It is likely that hadrons containing two bottom quarks and two anti-quarks light quarks are stable with respect to the strong interactions. Their binding energy is large, 100-200 MeV so they are not molecules (a weakly bound pair of $\bar{B}$ mesons). Hadrons with two heavy bottom quarks, may be seen soon at LHCb using an inclusive method but we won't know if their mass or if they are baryons or tetraquarks.

When we observe baryons with two bottom quarks and measure their mass we will know the masses of tetra quarks with two bottom quarks using heavy quark symmetry. Already Lattice and some quark model type estimates.

Upcoming large Galaxy Surveys: Euclid, Wfirst, SPHEREx, etc may observe primordial non-Gaussianity. That could teach us about particles that have masses around the Hubble constant (or less) during inflation and couple to derivatives of the inflaton field, or about symmetries that play a role in the dynamics that generates the primordial density perturbations.