Quark masses:

An environmental impact statement

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Excited QCD 09

Zakopane, Poland

Tuesday, 10 February, 2009

Work discussed

- R. L. Jaffe, AJ, and I. Kimchi, `arXiv:0809.1647 [hep-ph]`, to appear in PRD (2009).

- Also (briefly) A. Adams, AJ, and D. O'Connell, `arXiv:0802.4081 [hep-ph]`

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Quark masses in the Standard Model

In the SM, quark masses

$$\mathcal{L}_{mass} = -\frac{v}{\sqrt{2}} \left(g_u \bar{u} u + g_d \bar{d} d \right)$$

depend on $g_{u,d}$ and on $v = \sqrt{\mu^2/\lambda}$, for Higgs potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi \right)^2$$

Note μ^2, λ, $g_{u,d}$ are all *free parameters* of the theory

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TOE's & landscapes

- Ideally, TOE would reproduce the SM at low energies *and* uniquely predict its parameters
- ...but some parameters *might* be **environmentally selected**

  cf. Carter '74; Barrow & Tipler '86
- **Bayes's theorem:**

$$p(\{\lambda_i\}|\text{observer}) \propto p(\text{observer}|\{\lambda_i\}) \times p(\{\lambda_i\})$$

- String theory requires **compactification** of extra dimensions
- It now seems this can be done consistently in *many* ways, leading to different low-energy parameters

  cf. review by Douglas & Kachru '06
- **Landscape** of string vacua might, through eternal inflation, produce a **multiverse**

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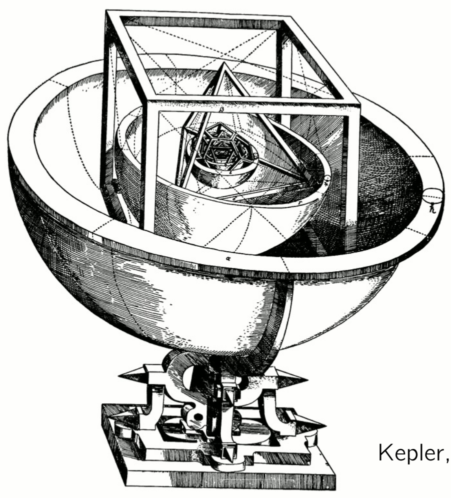
Fundamental vs. environmental quantities



Kepler, *Mysterium Cosmographicum* (1596)

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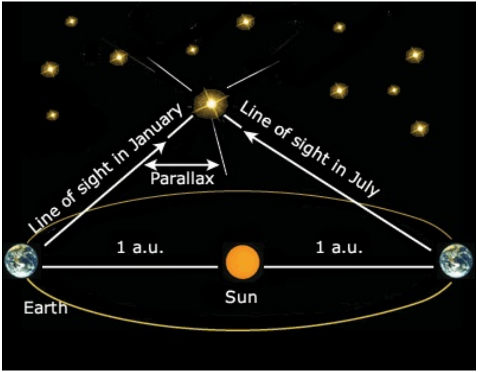
Naturalness

Geocentrism may be seen, in part, as a historical failure of *naturalness*:



Source: ESA website

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Naturalness, contd.

- Hierarchy ($\sim 10^6$) between Earth-Sun and Earth-star distances has an environmental explanation
- In the SM the cosmological constant Λ and Higgs μ^2 are dimensionful parameters, with unnaturally small values
- Many models proposed that could make μ^2 natural
- (**LHC** should have something to say about this soon)
- Weinberg '87 suggested an environmental explanation for the smallness of Λ
- First to *predict* $\Lambda > 0$ before it was measured by Riess et al. & Perlmutter et al. '98

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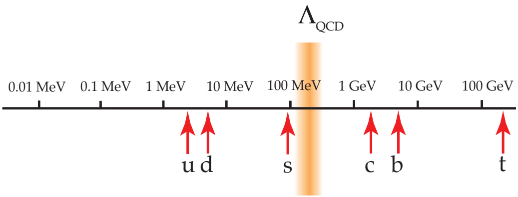
Environmental Higgs vev & Yukawas

- Agrawal, Barr, Donoghue & Seckel '98 propose environmental selection for Higgs v: $0 < v/v^{\oplus} \lesssim 5$, holding g_i's fixed
- Arkani-Hamed, Dimopoulos & Kachru '05 suggest only the *dimensionful* SM parameters (μ^2 and Λ) might scan significantly
- Only these are thought to be "technically unnatural"
- See Donoghue, Dutta & Ross '05; and Hall, Salem & Watari '07 for ideas about a **landscape** of Yukawas
- Quark masses in our world suggest **logarithmic** *a priori*:



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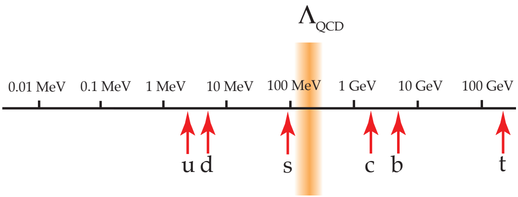

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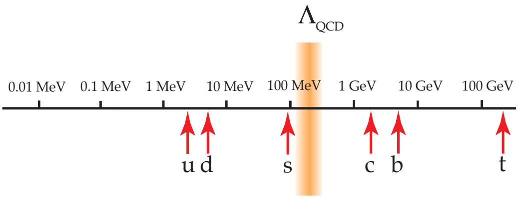

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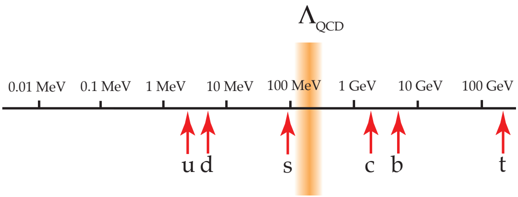

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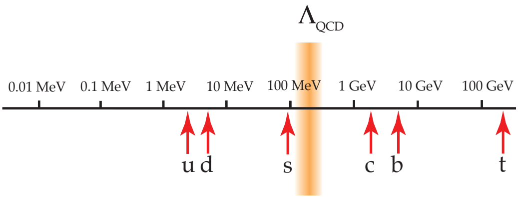

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Environmental constraint vs. environmental selection

- In the anthropic probability

$$p(\{\lambda_i\}|\text{observer}) \propto p(\text{observer}|\{\lambda_i\}) \times p(\{\lambda_i\}) \ ,$$

- we will focus on **environmental constraint**, given only by

$$p(\text{observer}|\{\lambda_i\})$$

- **Environmental selection** depends on unknown dynamics of the landscape giving *a priori* distribution

$$p(\{\lambda_i\})$$

- May think of this work as investigating relevance of QCD parameters in nuclear physics ...

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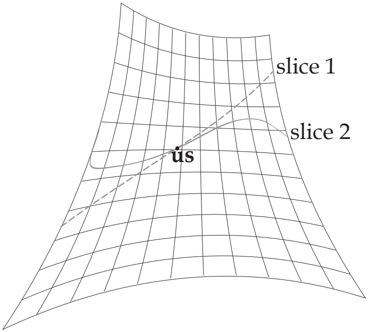
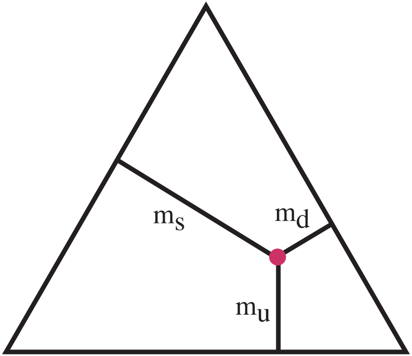
Our slice through the SM parameter space

- A superscript "$\oplus$" indicates value of parameter in our world
- Fix $m_e = m_e^{\oplus}$
- We **won't** hold $\alpha_s(M_Z)$ or $\alpha_s(M_{\text{GUT}})$ fixed
- Instead, we vary light quark masses and Λ_{QCD}, keeping average mass of lightest baryon flavor multiplet fixed to $M_N^{\oplus} = 940$ MeV.



Space of light quark masses

- For a fixed $m_u + m_d + m_s$, represent quark-mass space as interior of equilateral triangle



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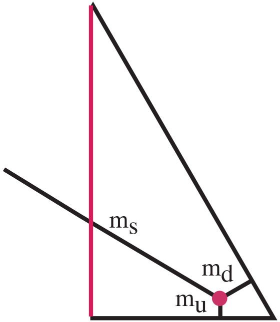
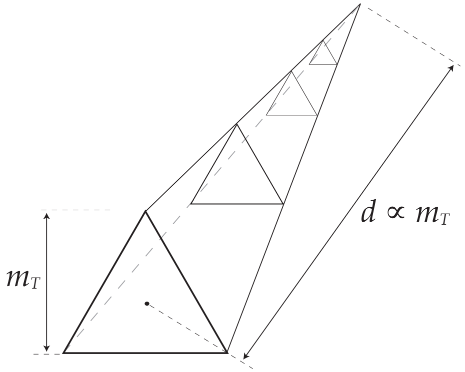
Space of light quark masses, contd.

- Insensitive to weak flavor structure, beyond assuming no accidental zeroes in CKM matrix
- In our world: $0 \lesssim m_u \lesssim m_d < m_s < \Lambda_{QCD}$



Space of light-quark masses, contd.

- Add an axis for the value of $m_T \equiv m_u + m_d + m_s$, producing a three-dimensional *prism*:



Quark mass dependence of nuclear interaction

- In χPT, $m_\pi \sim \sqrt{m_u + m_d}$, which is highly singular around zero quark masses
- Low-energy, non-relativistic action for isospin doublet $N = \begin{pmatrix} p \\ n \end{pmatrix}$:

$$\mathcal{L} = N^\dagger \left[i\partial_t + \nabla^2/(2m) \right] N - \frac{1}{2} \left[C_S \left(N^\dagger N \right)^2 + C_T \left(N^\dagger \sigma N \right)^2 \right] + \ldots$$

Kaplan, Savage & Wise '96, '98

- If $C_S \sim 1/m_\pi^2$, dependence of nuclear interaction on light quark masses would be severe (Donoghue '06, Damour & Donoghue '07)
- But $C_{S,T}$ are linearly related to the scattering lengths in the ${}^3S_1$ and ${}^1S_0$ channels

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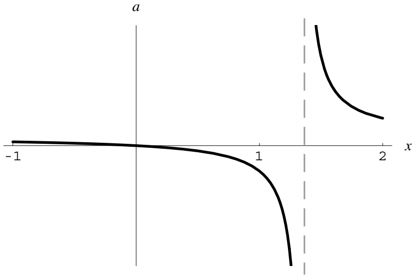
Scattering length

- E.g., for $V(\mathbf{r}) = -\frac{g}{r} e^{-\mu r}$; with $x \equiv gm/\mu$:



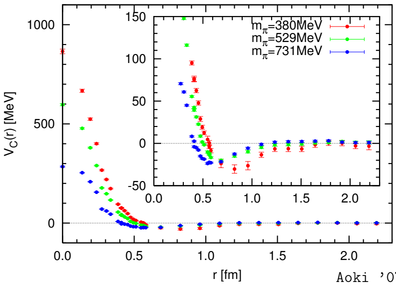
- Can't have $C_S \sim 1/m_\pi^2$ ("ineffective field theory")

Adams, AJ, O'Connell '08

Strength of nuclear interaction, contd.

- Attraction due mostly to $f_0(600)$ (a.k.a. σ) meson
- σ is largely a $\pi\pi$ resonance, with mass depending smoothly (and mildly) on m_π
  Alford & Jaffe '00; Hanhart, Pelaez & Rios '08
- In any event, we care more about bulk nuclear binding than about deuteron

Lattice results for nucleon-nucleon potential:



Aoki '07

Strong flavor violation in nuclear physics

- Expect, for scales M_i relevant to nuclear physics

$$\frac{\Delta M_i}{M_i^{\oplus}} \sim \frac{\Delta m_q}{\Lambda_{\mathrm{QCD}}^{\oplus}}$$

- Strong breaking of flavor $SU(2)$ and $SU(3)$ in QCD matters for nuclear structure mostly due to **sensitivity to baryon masses**
- *e.g.*, if $M_\Lambda \gtrsim M_N + 20$ MeV, then Λ doesn't appear in stable nuclei
- A 2% $SU(3)$ violation in baryon masses leaves almost *no trace* of the symmetry in nuclear structure!
- This feature can be understood qualitatively in Fermi gas model of nuclei
- We will keep baryon mass variations and mostly neglect changes to strength of nuclear interactions

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Organic chemistry

- By *atomic physics*, at least $Z = 1$ (**chemical hydrogen**) and $Z = 6$ (**chemical carbon**) needed for multiple bonds and hence complex molecules
- Stable $Z = 6$ usually also comes with stable $Z > 6$ (e.g., chemical nitrogen, oxygen, sulfur, etc.)
- Here we won't consider possible constraints from nucleosynthesis (cf. Hogan '06)
- We label universes with stable $Z = 1, 6$ **congenial**
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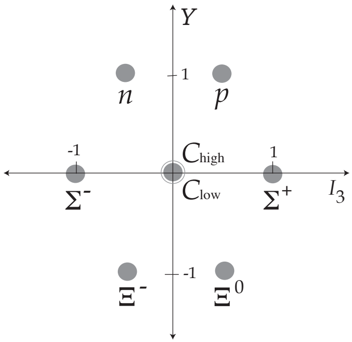
Baryon octet



- Eigenstates of total isospin are Λ ($I = 0$) and Σ^0 ($I = 1$)
- Mixing is small in our world ($C_{\mathrm{low}} \approx \Lambda$ and $C_{\mathrm{high}} \approx \Sigma^0$)

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Linear flavor $SU(3)$ breaking

- $H = H_{\rm QCD} + H_{\rm flavor} + H_{\rm EM}$, with

$$H_{\rm flavor} = \sum m_i \bar{q}_i q_i = m_0 \Theta^1_0 + m_3 \Theta^8_3 + m_8 \Theta^8_8 \ ,$$

- Treat $H_{\rm flavor}$ as a first-order perturbation

Baryon species	Flavor-dependent contribution	Electromagnetic correction (MeV)	Experimental (MeV)	Fitted (MeV)	Residual (MeV)
p	$\left(\frac{3F-D}{\sqrt{3}}\right) m_8 + (F+D)\, m_3$	$+0.63$	938.27	939.87	1.60
n	$\left(\frac{3F-D}{\sqrt{3}}\right) m_8 - (F+D)\, m_3$	-0.13	939.57	942.02	2.45
Ξ^0	$-\left(\frac{3F+D}{\sqrt{3}}\right) m_8 + (F-D)\, m_3$	-0.07	1314.83	1316.81	1.98
Ξ^-	$-\left(\frac{3F+D}{\sqrt{3}}\right) m_8 - (F-D)\, m_3$	$+0.79$	1321.31	1323.38	2.07
Σ^+	$\left(\frac{2D}{\sqrt{3}}\right) m_8 + 2F\, m_3$	$+0.70$	1189.37	1188.42	-0.96
Σ^-	$\left(\frac{2D}{\sqrt{3}}\right) m_8 - 2F\, m_3$	$+0.87$	1197.45	1197.21	-0.24
$C_{\rm high}$	$\left(\frac{2D}{\sqrt{3}}\right) \sqrt{m_8^2 + m_3^2}$	-0.21	1192.64	1191.82	-0.82
$C_{\rm low}$	$-\left(\frac{2D}{\sqrt{3}}\right) \sqrt{m_8^2 + m_3^2}$	$+0.21$	1115.68	1109.61	-6.07

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Fit to data, contd.

- $A_0 \equiv \langle H_{\rm QCD} \rangle + m_0 \langle \Theta_0^1 \rangle$ can be decomposed using the "pion-nucleon sigma term"
- Conflicting estimations. Following Gasser & Leutwyler, $m_0 \langle \Theta_0^1 \rangle = 368 \pm 101$ MeV
- Then $\langle H_{\rm QCD} \rangle = 783 \pm 101$ MeV
- Choice of slice makes us relatively insensitive to this uncertainty

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- Choice of slice makes us relatively insensitive to this uncertainty

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Fit to data, contd.

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Weizsäcker semi-empirical mass formula (SEMF)

$$M = \sum_i N_i m_i - a_V A + a_S A^{2/3} + a_C \frac{Z(Z-1)}{A^{1/3}} + a_A \frac{(A-2Z)^2}{A} - \frac{\delta(A,Z)}{A^{1/2}}$$

$$\delta(A,Z) = \begin{cases} +a_P & Z \text{ even, } A \text{ even} \\ 0 & A \text{ odd} \\ -a_P & Z \text{ odd, } A \text{ even} \end{cases}$$

Parameter	Term	Experimental value (MeV)
a_V	volume	15.56
a_S	surface	17.23
a_C	Coulomb	0.71
a_A	asymmetry	23.28
a_P	pairing	12

cf. Lilley, *Nuclear Phys.* '01

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Fermi gas model + quadratic Casimir correction

- **Qualitative features** of SEMF can be obtained in model of nucleus as **Fermi gas** under confining pressure
- Gives only *third* of empirical asymmetry term
- Note **deuteron** (I = 0) exists, but **dineutron** (I = 1) doesn't
- Account for extra asymmetry energy using flavor group's G^2:
  Nature prefers *corners* of weight diagrams
- For $SU(2)$, replace I_3^2 by $I(I+1)$
- For $SU(3)$ add G^2, plus function of A such that whole thing reduces to $I(I+1)$ in our world

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Stability analysis

When possible, for $Z = 1, 6$, we prefer to look at **analog nuclei** in our world with similar binding energies, up to Coulomb term

Check stability against

- **Fission**
- **Strong particle emission** (analogous to α-decay)
- **Weak nucleon emission**

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Weak nucleon emission

- In our world, nuclei with given A will β-decay down to bottom "valley of stability:"

$$\left.\frac{\partial M(A, I_3)}{\partial I_3}\right|_A = 0$$

- If a nucleon is too heavy, it might be emitted (in our world happens only to Λ in **hypernuclei**)
- *e.g.*, for heavy neutron,

$${}^{[A]}[Z] + e^- \rightarrow {}^{[A-1]}[Z-1] + n + \nu_e$$

- **One** *very* **light quark**: uncongenial: Like a world of Δ^{++}'s
- **Two light** $Q = -1/3$ **quarks:** uncongenial: no carbon (α-decay unstable)
- **Two light** $Q = 2/3$ **quarks:** uncongenial: helium and oxygen, but no hydrogen or carbon (fission unstable)
- **Two light quarks,** $Q = 2/3, -1/3$**:** Substantial area of congeniality
- **One light quark leading to two light baryons:** May produce an area of congeniality if the light baryons have different charge (e.g. $m_d \ll m_s \approx m_u$)

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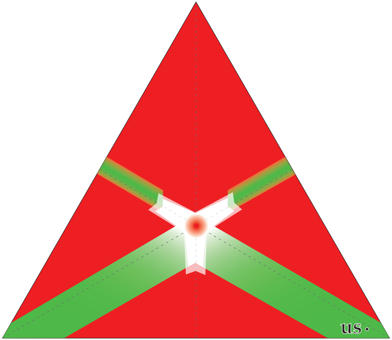
Congenial & uncongenial worlds, contd.

- For $m_T = m_T^{\oplus}$:



- Greater stability to weak nucleon emission than expected (**triton** might be stable even if proton and deuteron aren't)
- Lower green band about 29 MeV wide in $|m_d - m_u|$
- Notice we're not at the edge . . .

Congenial & uncongenial worlds, contd.

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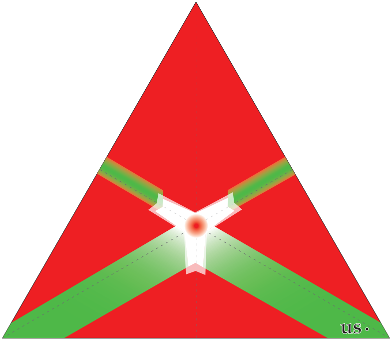

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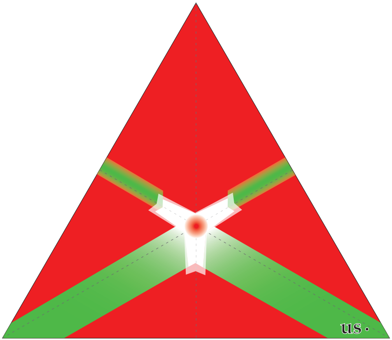

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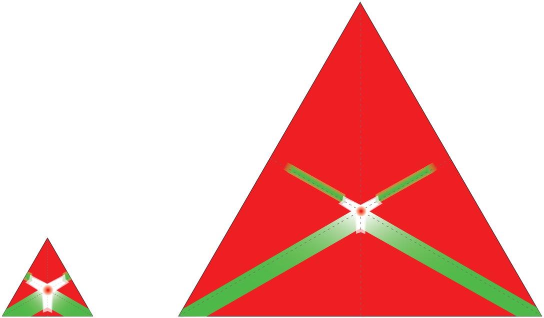
Congenial & uncongenial worlds, contd.

- As we vary $m_T \equiv m_u + m_d + m_s$ green and white regions keep their size



- For large m_T, upper green band stop when lightest decuplet baryon becomes lighter than all octet baryons

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Three light quarks

- In the flavor $SU(3)$ limit, the **dihyperon** is more likely to be stable
- Also, a very tightly bound **"arkon"** could make carbon unstable
- **Three light quarks,** $Q = 2/3, -1/3, -1/3$**:** Charge neutrality argues against congeniality
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Summary

- Take a particular slice through space of SM parameters relevant to nuclear physics
- Identify worlds on that slice for which organic chemistry is possible
- Classify those worlds as **congenial**
- Our world is not *quite* unique in being **congenial**, nor are we particularly close to an edge of **uncongeniality**.

- **Thank you!**

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