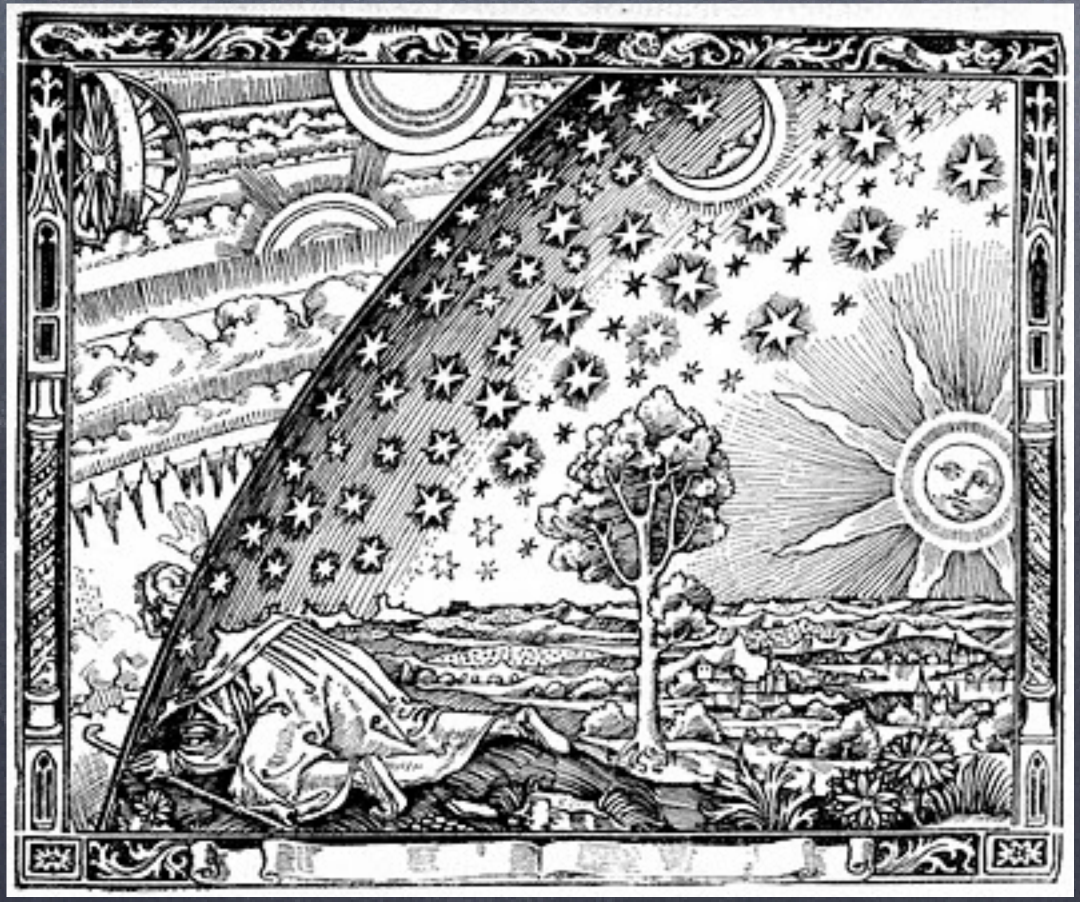
Adam Falkowski

Introduction to Physics beyond the Standard Model

Part 4: Reasons for Physics Beyond the Standard Model

Osaka University, 21 May 2014



Plan

The Standard Model is not the ultimate theory
Coupling to gravity implies it breaks down at the Planck scale of order 10^19 GeV

Yet we have very good reasons to think that Standard Model, and it breaks down below the Planck Scale

- **Esthetic Reasons:**
  certain puzzling aspects of the Standard Model that hint at a deeper explanation via new physics

- **Phenomenological Reasons:**
  observations that require new physics beyond the Standard Model

Esthetic Reasons

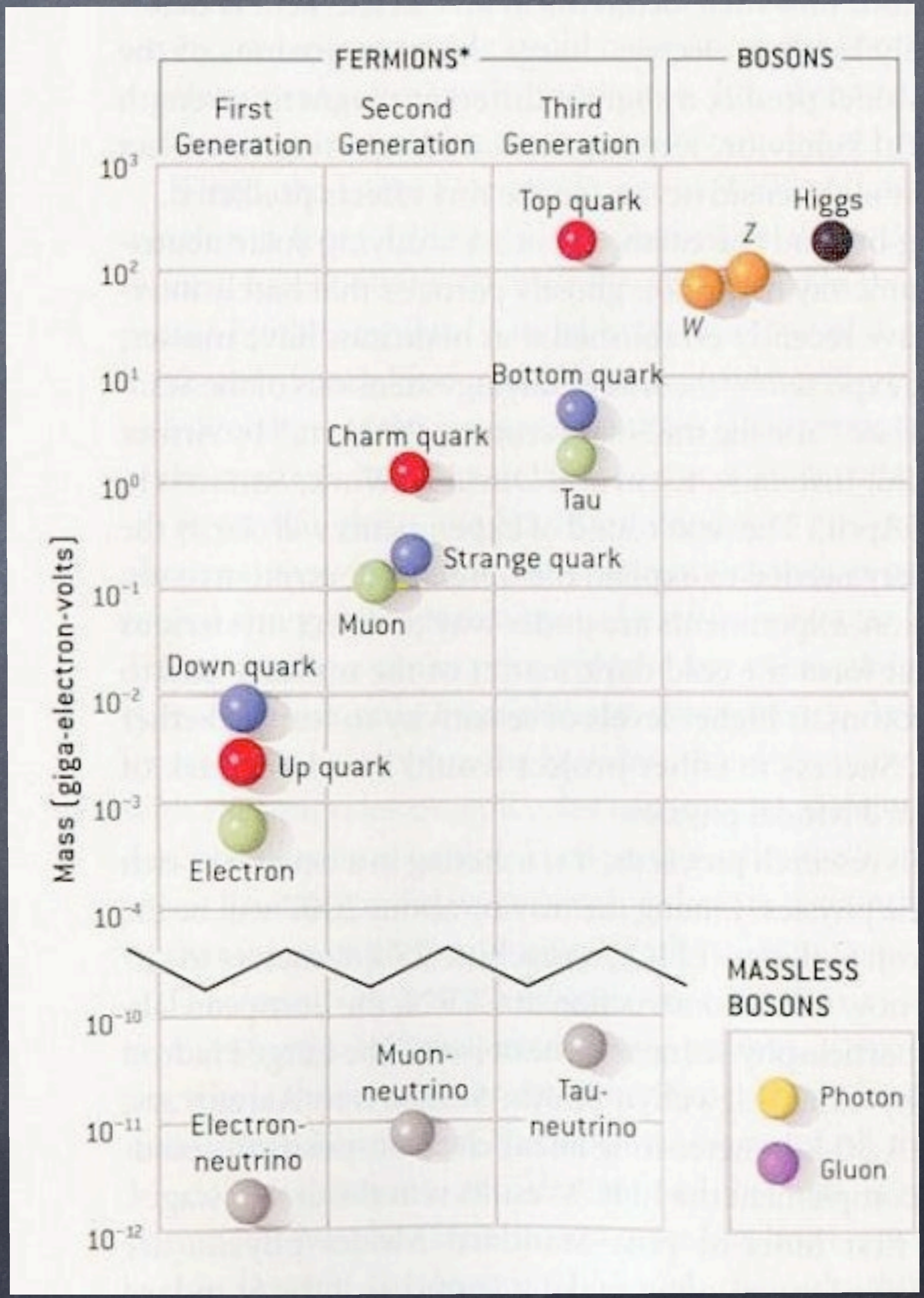
Esthetic Reasons
For Physics Beyond the Standard Model

- Fermion generation structure and mass/mixing hierarchies
- Vacuum metastability
- Gauge coupling unification
- Strong CP problem
- Naturalness problem

Fermion mass and mixing hierarchies

Fermion generation puzzles

- Why 3 generations = carbon copies with different masses but exactly the same interactions?
- Why masses of quarks and leptons are so different? Is there a pattern?
- Why quark mixing matrix is hierarchical? Is there a pattern?



Fermion generation puzzles

- Why 3 generations = carbon copies with different masses but exactly the same interactions?
- Why masses of quarks and leptons are so different? Is there a pattern?
- Why quark mixing matrix is hierarchical? Is there a pattern?

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda \sim 0.2$$

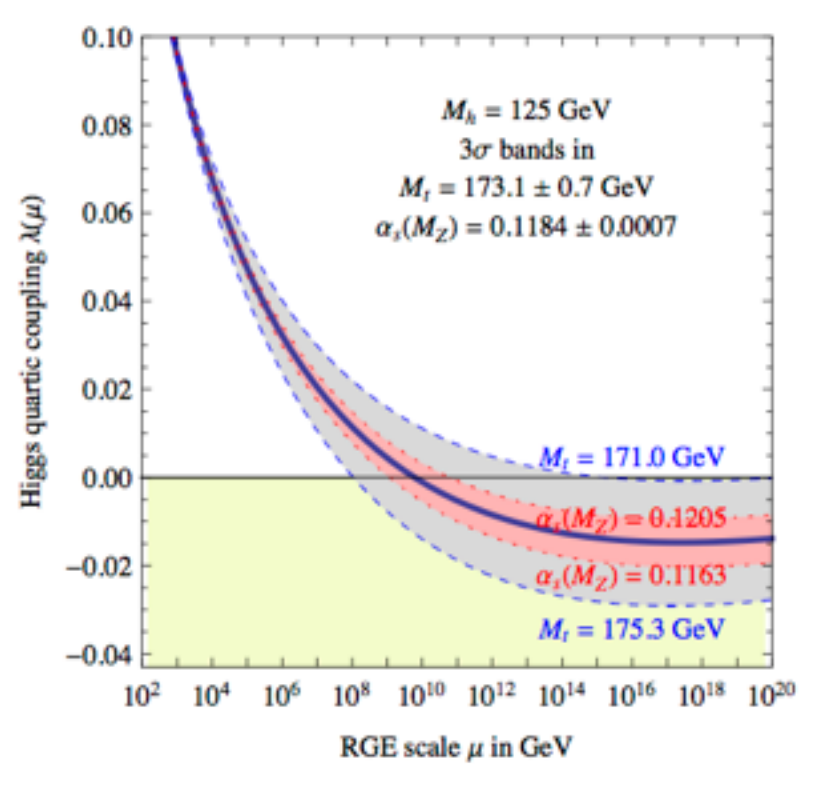
but, maybe it's just so...

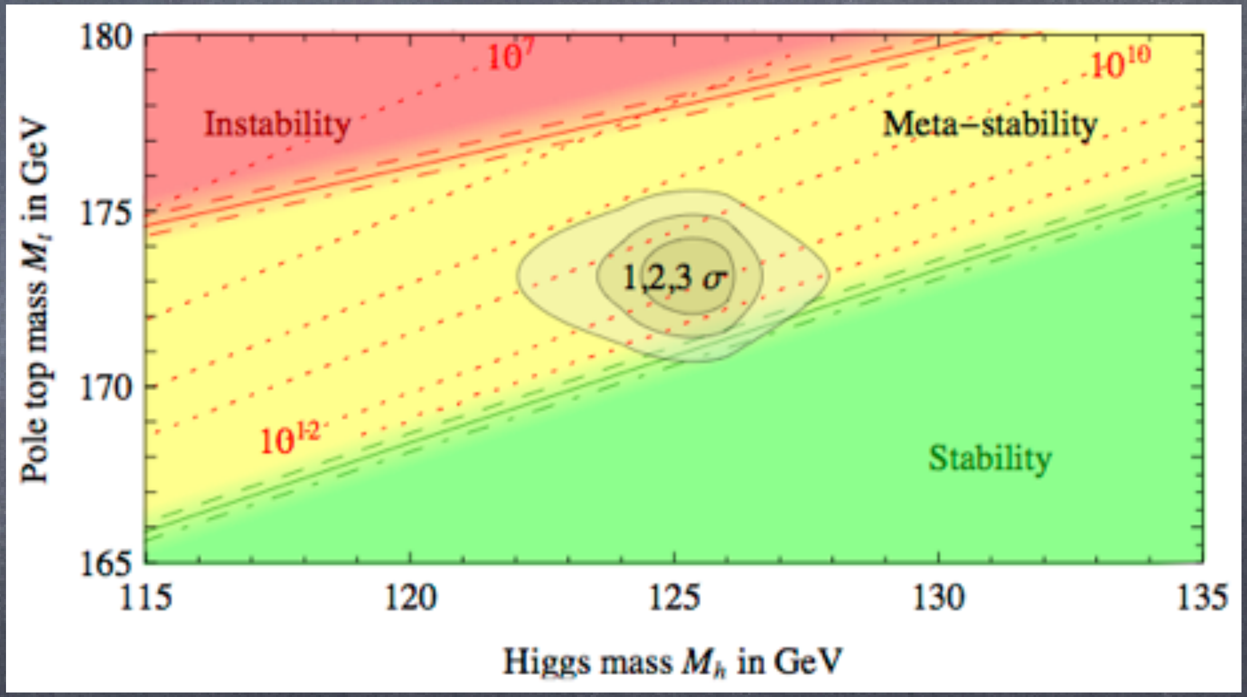
Vacuum Metastability

Esthetic Reasons - Vacuum Metastability

- Higgs potential develops another deeper minimum at large field values

Degrassi et al.
1205.6497





Esthetic Reasons - Vacuum Metastability

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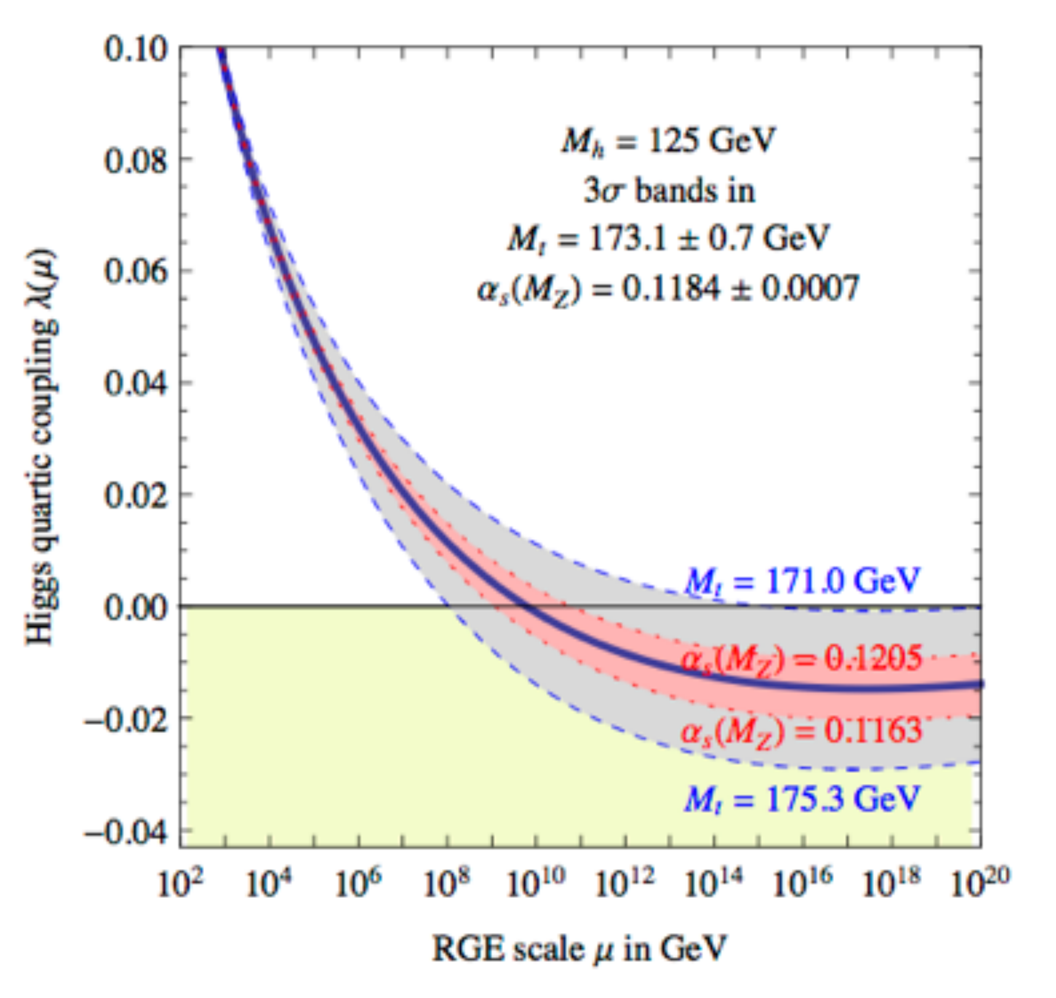
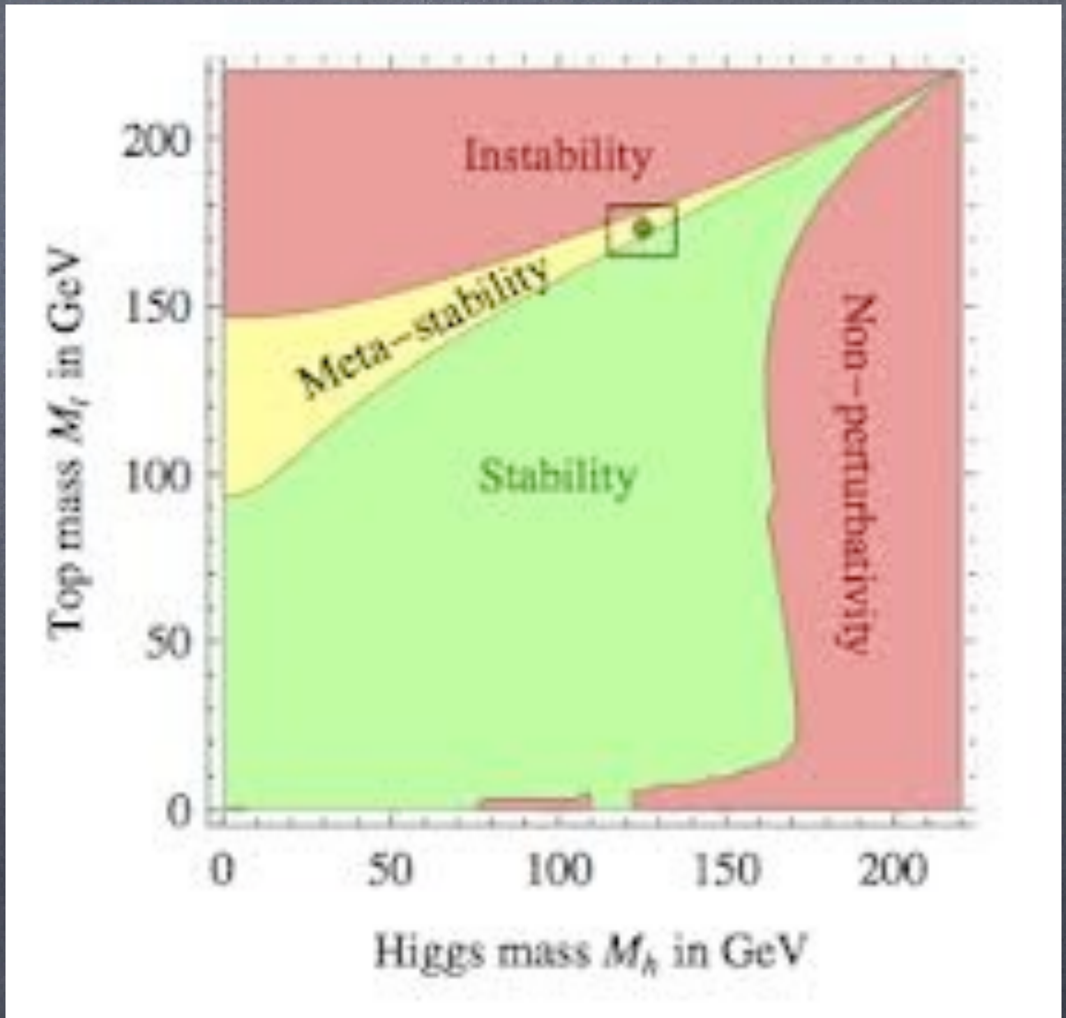


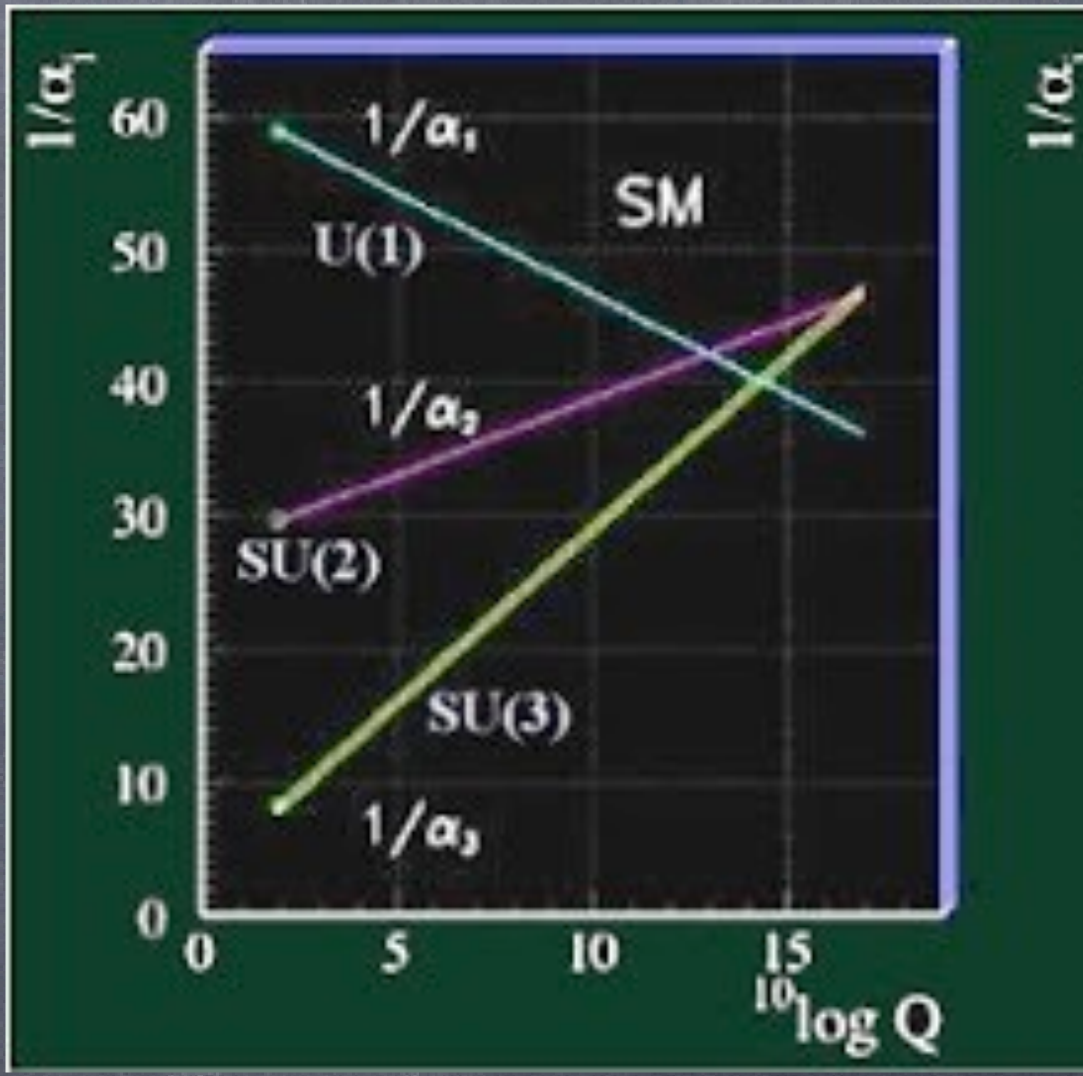


but, maybe nature does not care about our sense of security?

Gauge Coupling Unification

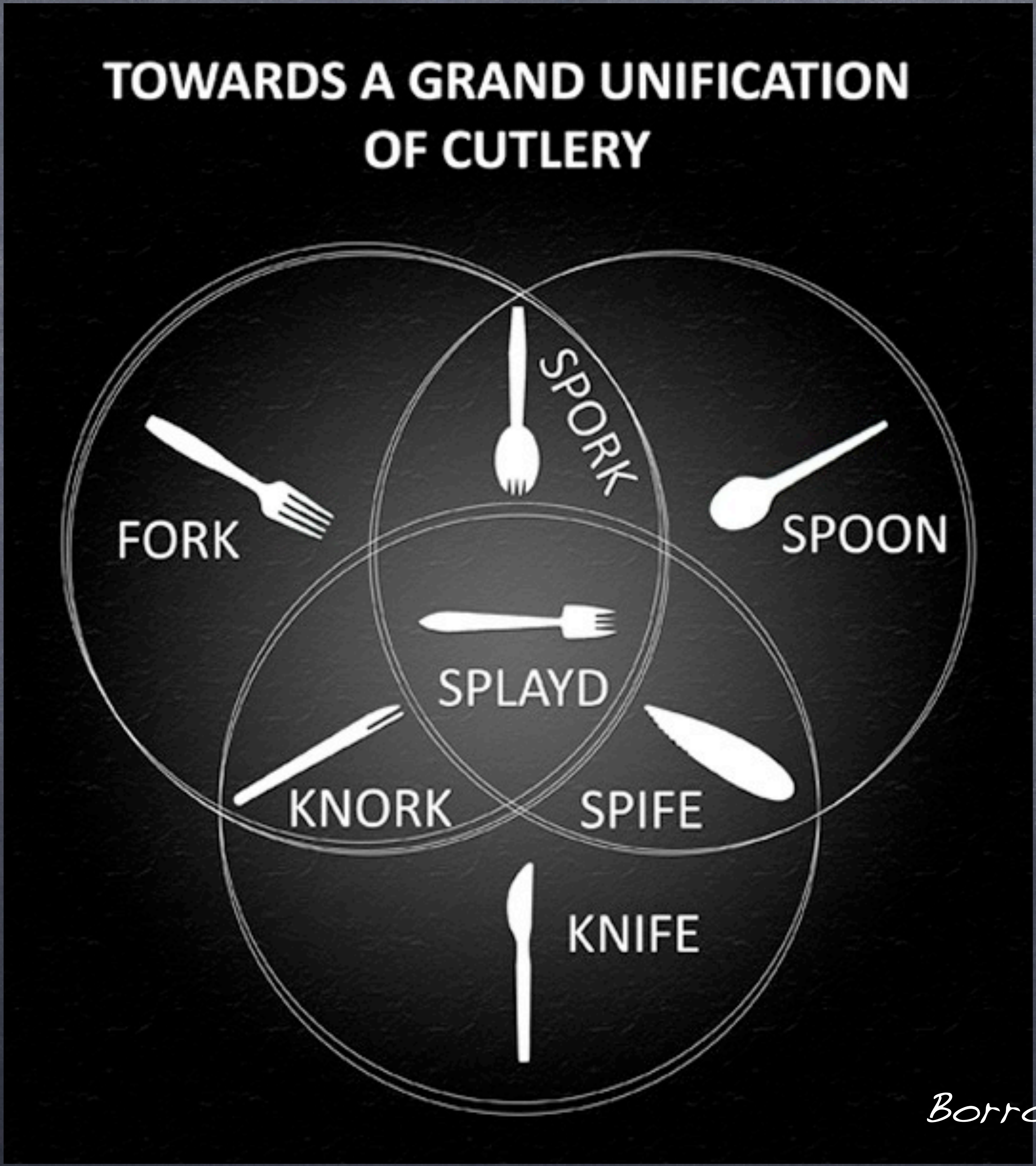
Gauge couplings unification

- 3 coupling constants in the Standard Model evolve with energy scale
- They approximately unify (within 20%) at energies near 10^14 GeV
- This may be explained by a larger local symmetry, for example SU(5) or SO(10)
- Also, explains electric charge quantization



Borrowed from L.Motl blog

Grand unification



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Quantum numbers unification

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3
d^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
$l = \begin{pmatrix} \nu \\ e \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
e^c	$\mathbf{1}$	$\mathbf{1}$	1

$$\mathbf{5} = \begin{pmatrix} l \\ d^c \end{pmatrix} \qquad \mathbf{10} = \begin{pmatrix} q \\ u^c \\ e^c \end{pmatrix}$$

$$\Psi = \begin{pmatrix} \bar{d}_R \\ \bar{d}_B \\ \bar{d}_G \\ e^- \\ \nu_e \end{pmatrix}_L$$

$$\chi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{u}_G & -\bar{u}_B & -u_R & -d_R \\ -\bar{u}_G & 0 & \bar{u}_R & -u_B & -d_B \\ \bar{u}_B & -\bar{u}_R & 0 & -\bar{u}_G & -d_G \\ u_R & u_B & \bar{u}_G & 0 & -e^+ \\ d_R & d_B & d_G & e^+ & 0 \end{pmatrix}_L$$

but, maybe it's all just accident?

Strong CP Problem

Esthetic Reasons - Strong CP Problem

- The local symmetries of the Standard Model allow for one more renormalizable term (19th parameter θ)
- This term violates P and CP
- Its effect would be to produce an electric dipole moment for the neutron

$$G^a_{\mu\mu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$$

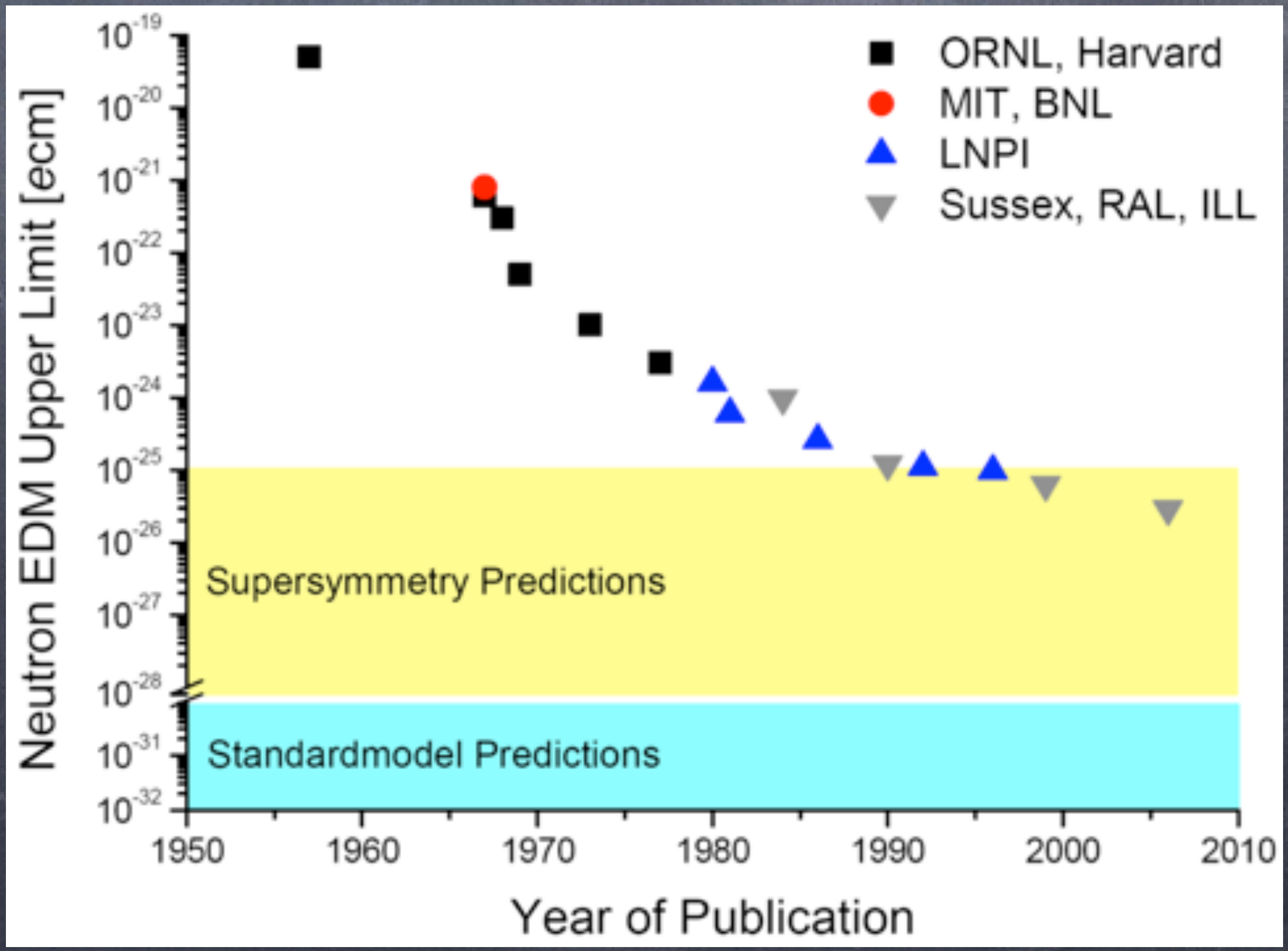
$$\mathcal{L}_{\rm kin} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a}$$

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

Strong CP Problem

$$d_n \sim \theta \frac{m_u m_d}{m_u + m_d} \frac{e}{\Lambda^2_{\mathrm{QCD}}} \sim \theta \cdot 6 \cdot 10^{-17} e \cdot \mathrm{cm}$$

- The effect of θ would be to produce an electric dipole moment for the neutron
- Current bounds on neutron EDM imply θ≲10^-9



Naturalness Problem

Esthetic Reasons - Naturalness Problem

- Instability of Higgs mass against radiative corrections suggests new states at 100 GeV

Coleman-Weinberg potential

$$V_{\rm CW} = \frac{1}{32\pi^2}{\rm Str}\left\{M^2(|H|)\Lambda^2 - \frac{1}{2}M^4(|H|)\left(\log[\Lambda^2/M^2(|H|)] - \frac{1}{2}\right)\right\}$$

In particular, the top SM quark contributes:

$$\mathcal{L}_{\rm top} = -\, y_t |H| \bar{t}t \quad \Rightarrow \quad M(|H|) = y_t |H|$$

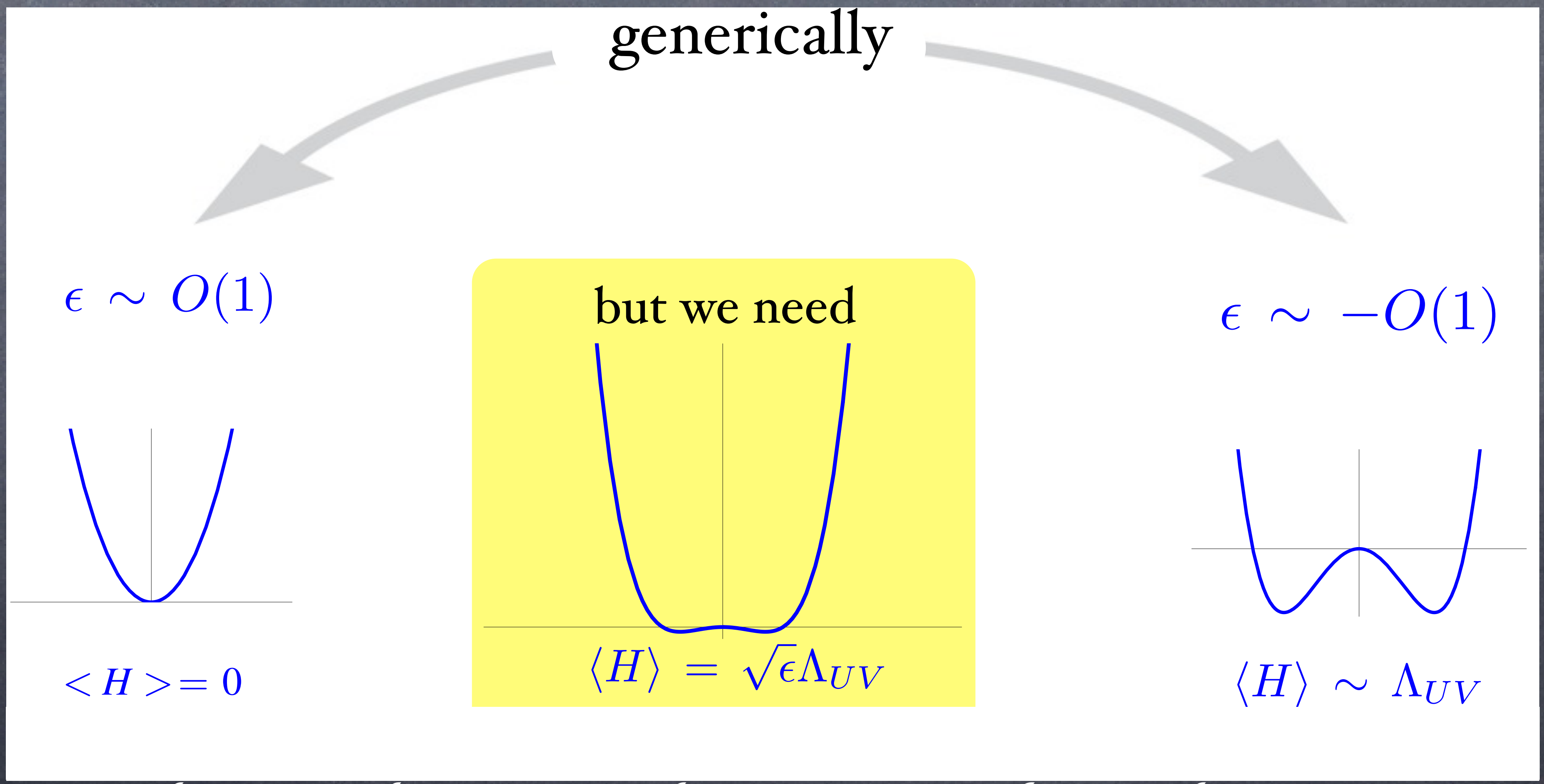
$$V_{\rm CW} = -\,\frac{3\cdot 4}{32\pi^2} y_t^2 \Lambda^2 |H|^2 + \ldots$$

$$\lambda v^2 \sim \frac{\Lambda^2}{\pi} \quad \Rightarrow \quad v \sim \Lambda$$

Generically, Higgs vev (and Higgs mass) parametrically close to the cut-off of the theory, unless other contributions to Higgs potential approximately cancel the top contributions

Esthetic Reasons - Naturalness Problem

- Instability of Higgs mass against radiative corrections suggests new states at 100 GeV



but, maybe nature does not care about our notion of naturalness....

Well at least in one other case it seems so....

Phenomenological Reasons

Phenomenological Reasons
For Physics Beyond the Standard Model

- Neutrino Oscillations
- Dark Matter in the Universe
- Inflation
- Baryon Asymmetry

Neutrino Oscillations

Pheno Reasons - Neutrino Oscillations

- In the Standard Model, there is left-handed but no right-handed neutrinos. Therefore neutrinos are massless by construction

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3
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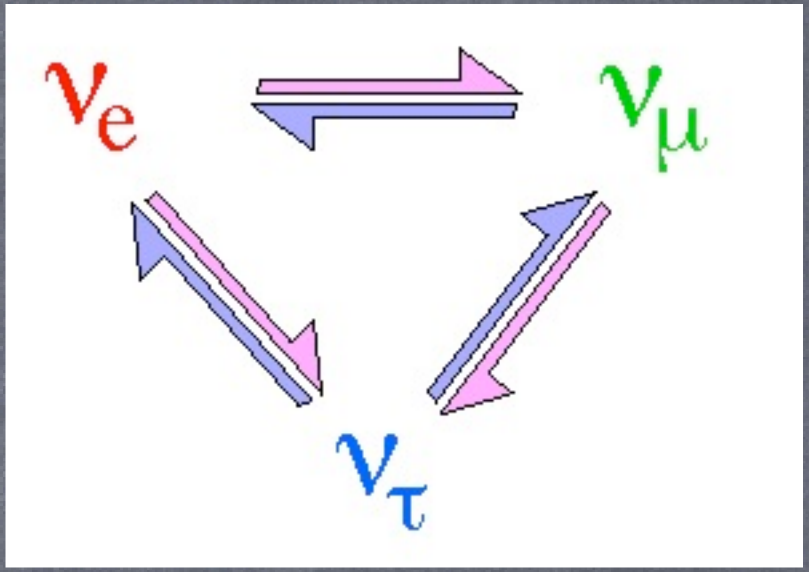
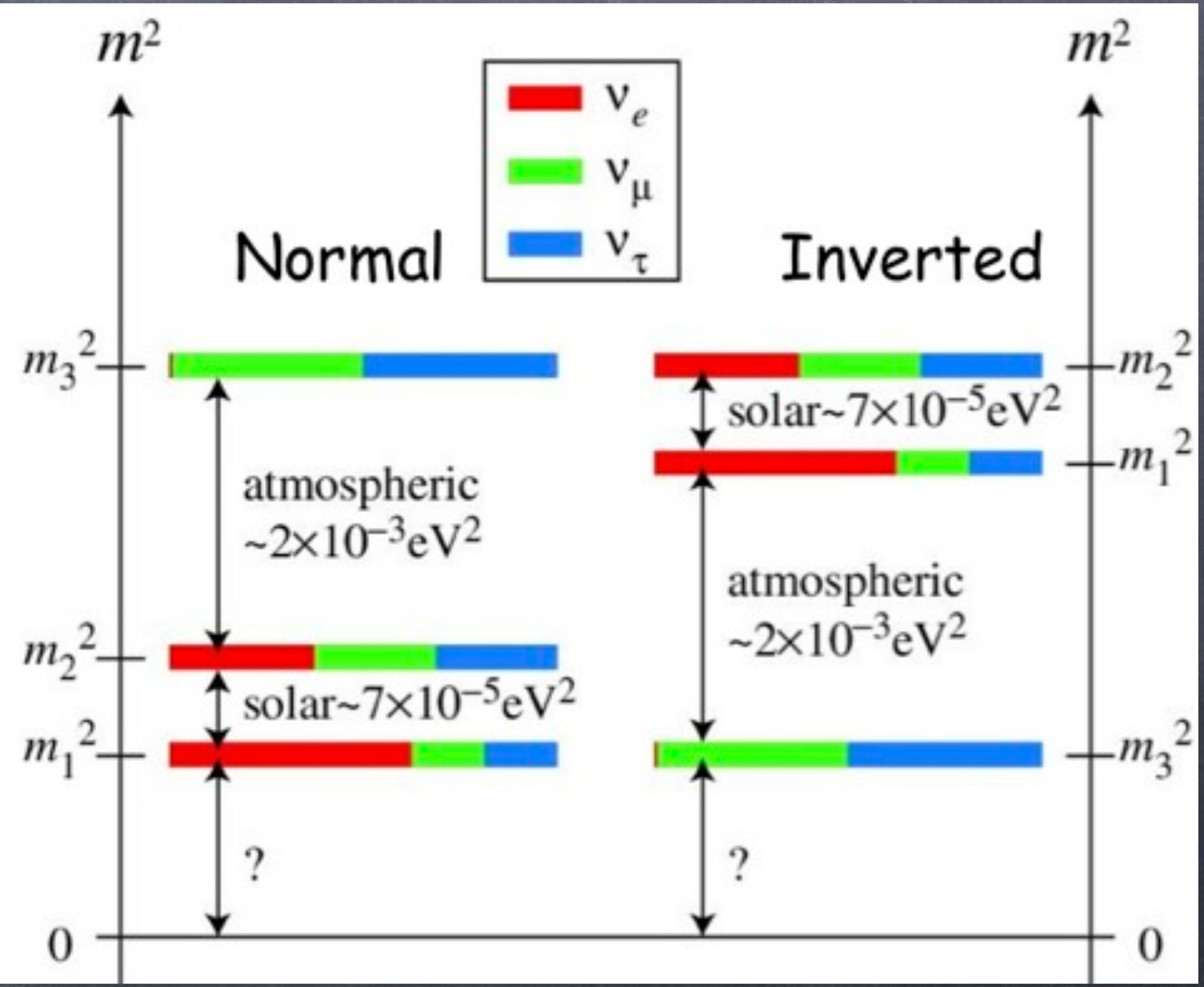
Neutrino Oscillations



- It was discovered back in the 90s that neutrino oscillate = neutrino of different flavors change into one another
- This happens when mass eigenstates are different than flavor eigenstate
- Implies at least 2 neutrinos have masses



Neutrino Oscillations

- Trivial to add a singlet right-handed neutrino νc and write new Yukawa couplings
- But neutrino masses are so much smaller the we suspect a different mechanism is in play

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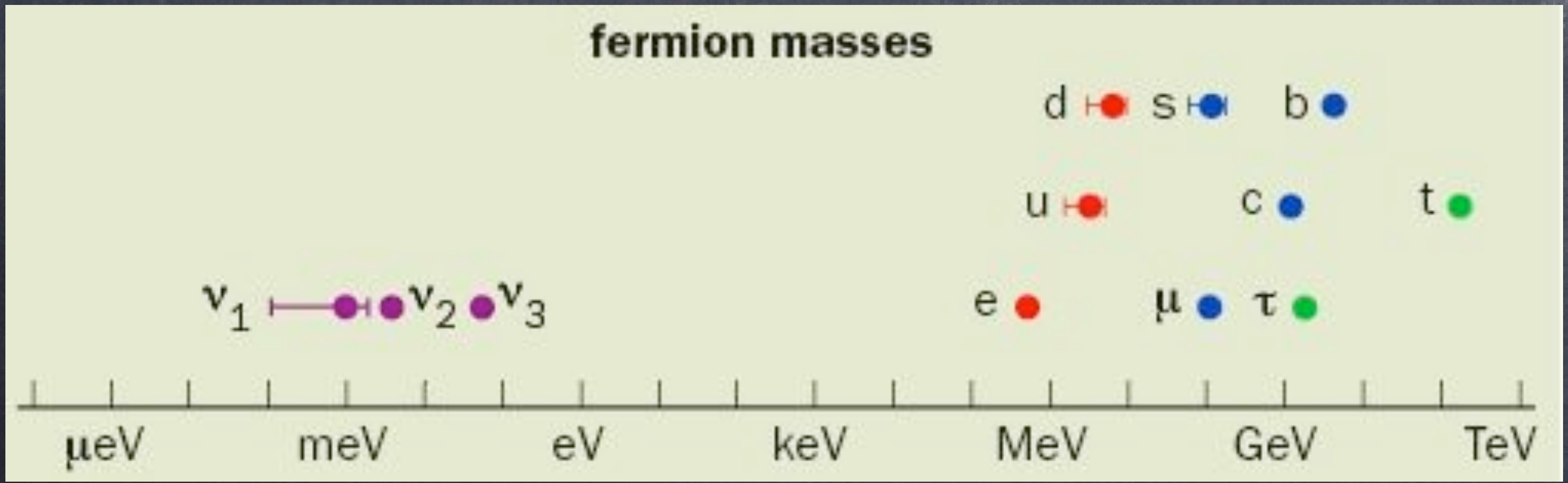
$l = \begin{pmatrix} \nu \\ e \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
e^c	$\mathbf{1}$	$\mathbf{1}$	1
ν^c	1	1	0

$$\Delta\mathcal{L} = -H\ lY_\nu \nu^c \rightarrow \frac{v}{\sqrt{2}} \nu Y_\nu \nu^c$$



Neutrino Oscillations

- But neutrino masses are so much smaller the we suspect a different mechanism is in play
- Neutrino masses probably signal the presence of non-renormalizable operator beyond the SM

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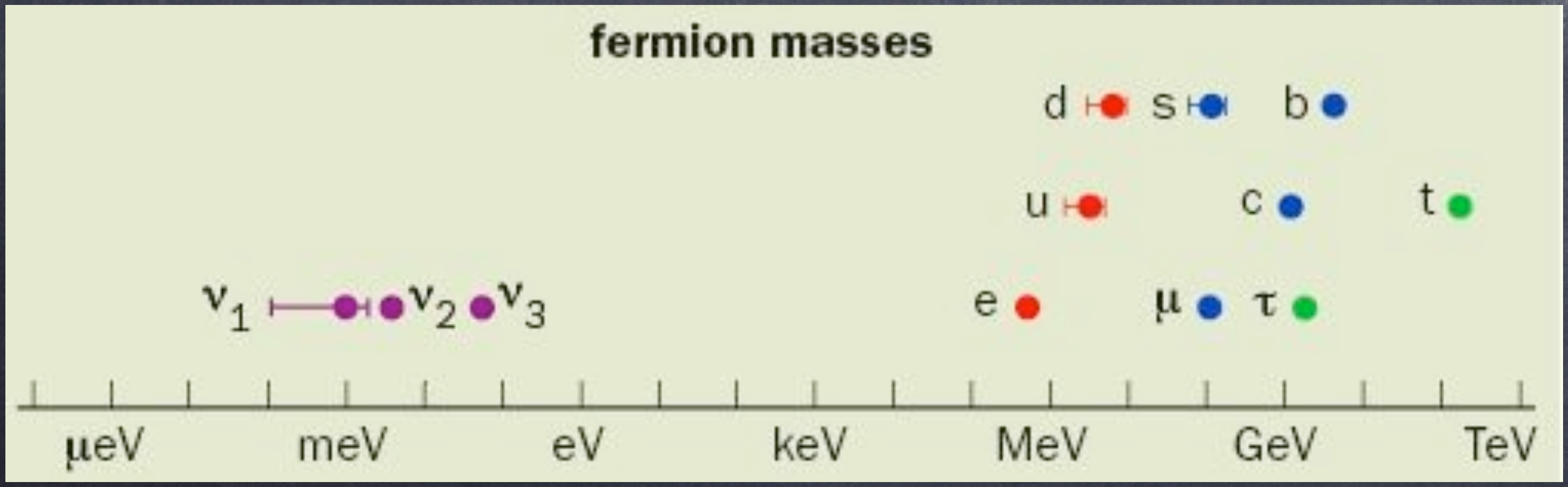
$$\Delta L = -\frac{1}{\Lambda}(Hl)Y_\nu(Hl) \rightarrow -\frac{v^2}{2\Lambda}\nu Y_\nu \nu$$



Dark Matter

Pheno Reasons - Dark matter

Several independent pieces of evidence

- Galactic rotation curves
- Gravitational lensing
- CMB fluctuation spectrum

Taken together, no doubt dark matter is out there in some form

The Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

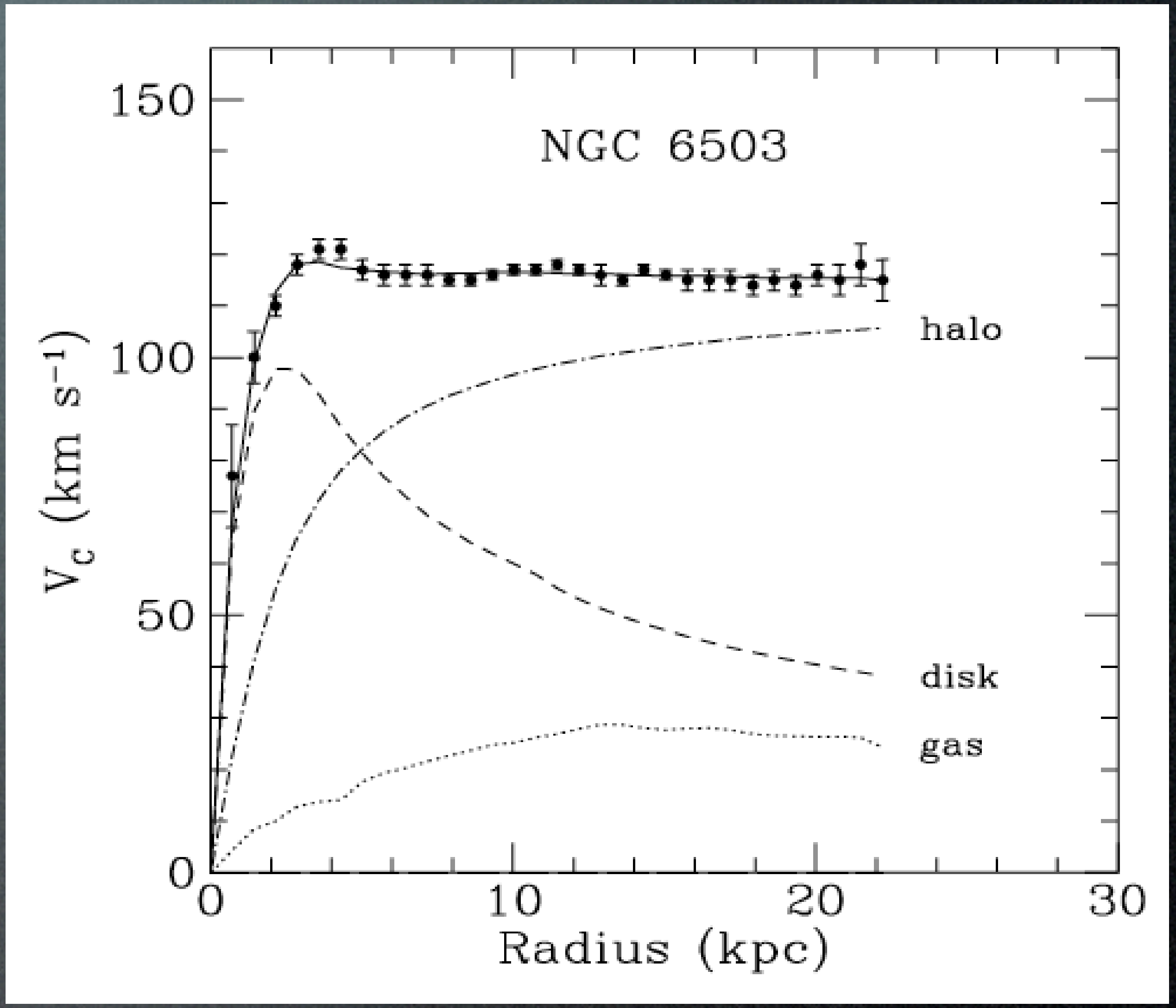
'centrifugal' 'centripetal'

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

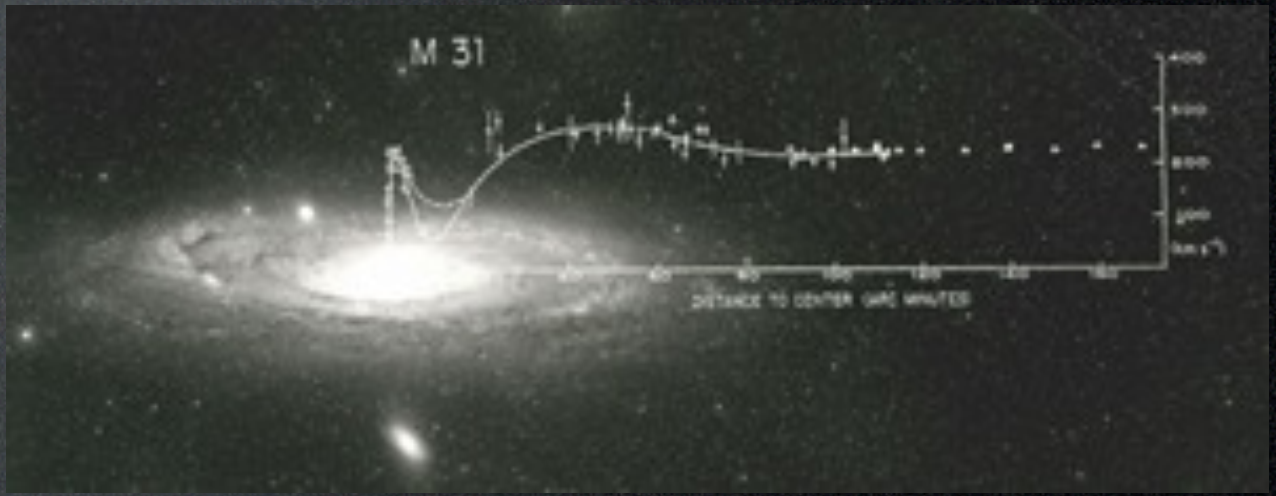
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_M \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



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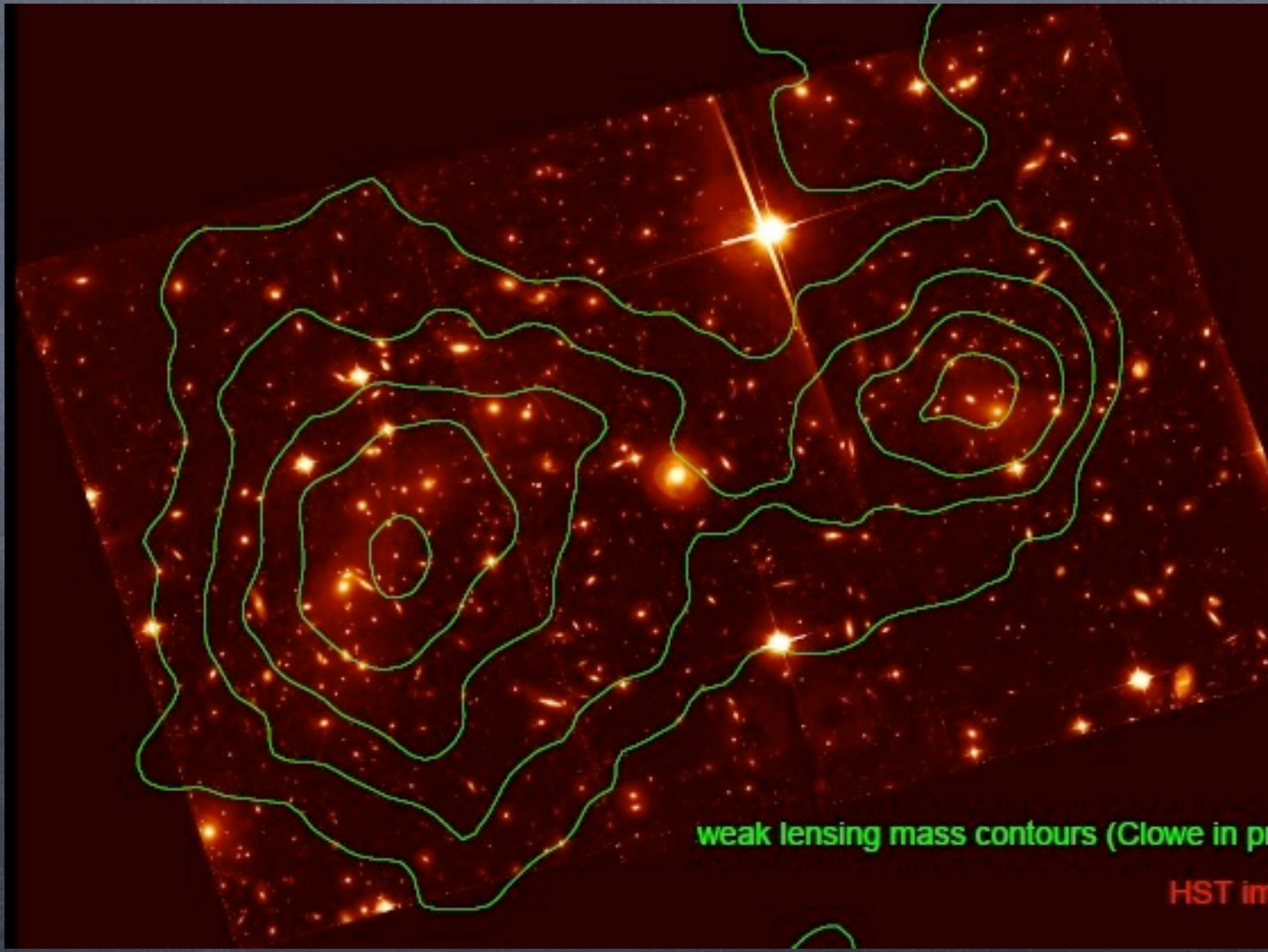
Gravitational Lensing

Strong Lensing

Weak Lensing



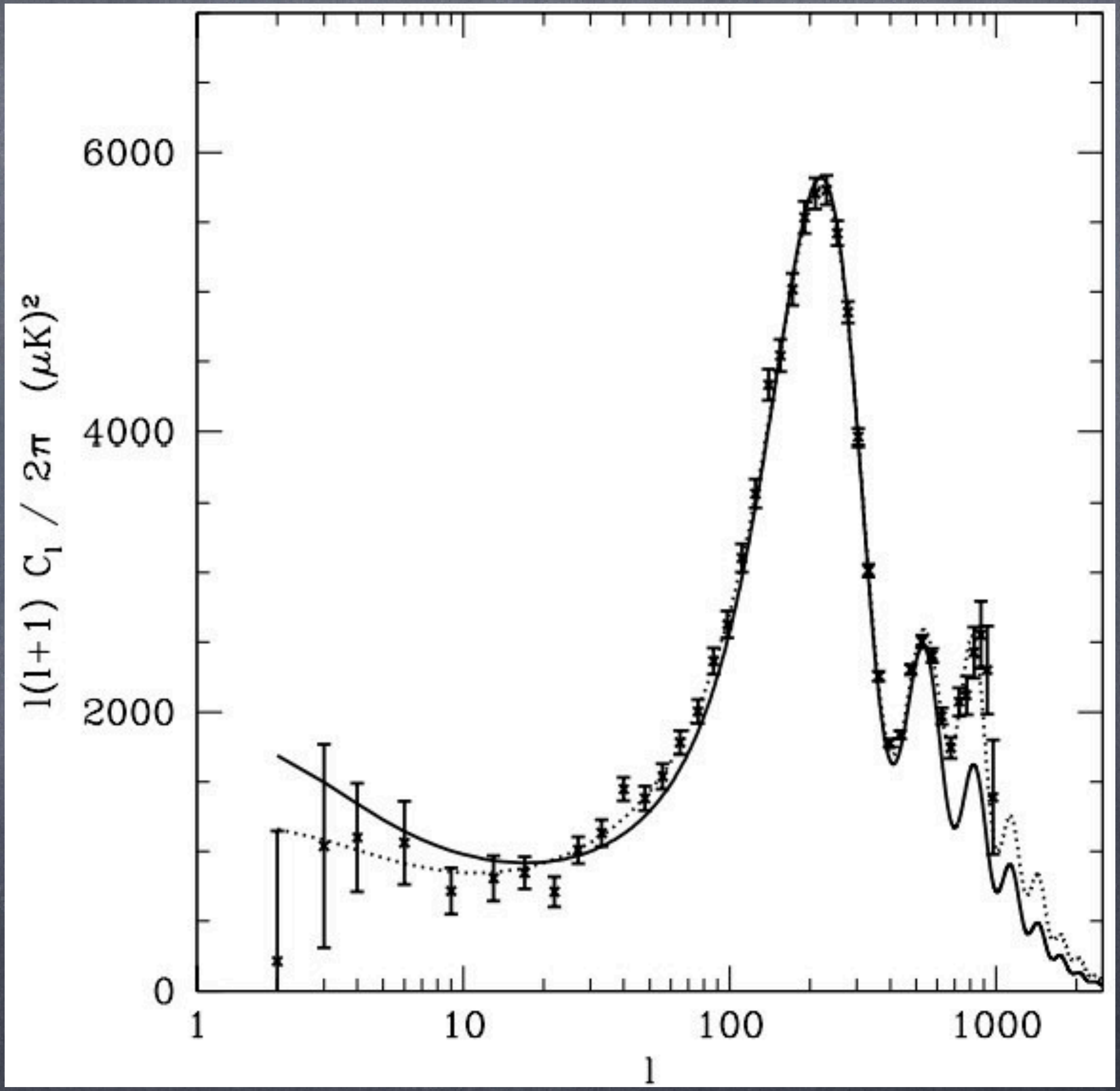
Gravitational Lensing

Strong Lensing

Weak Lensing

Dark Matter from CMB

- Allows one to understand now present day galaxies are compatible with order 10^-5 fluctuations at last scattering surface
- Dark matter predicts even-numbered CMB peaks are enhanced, and odd-numbered are suppressed



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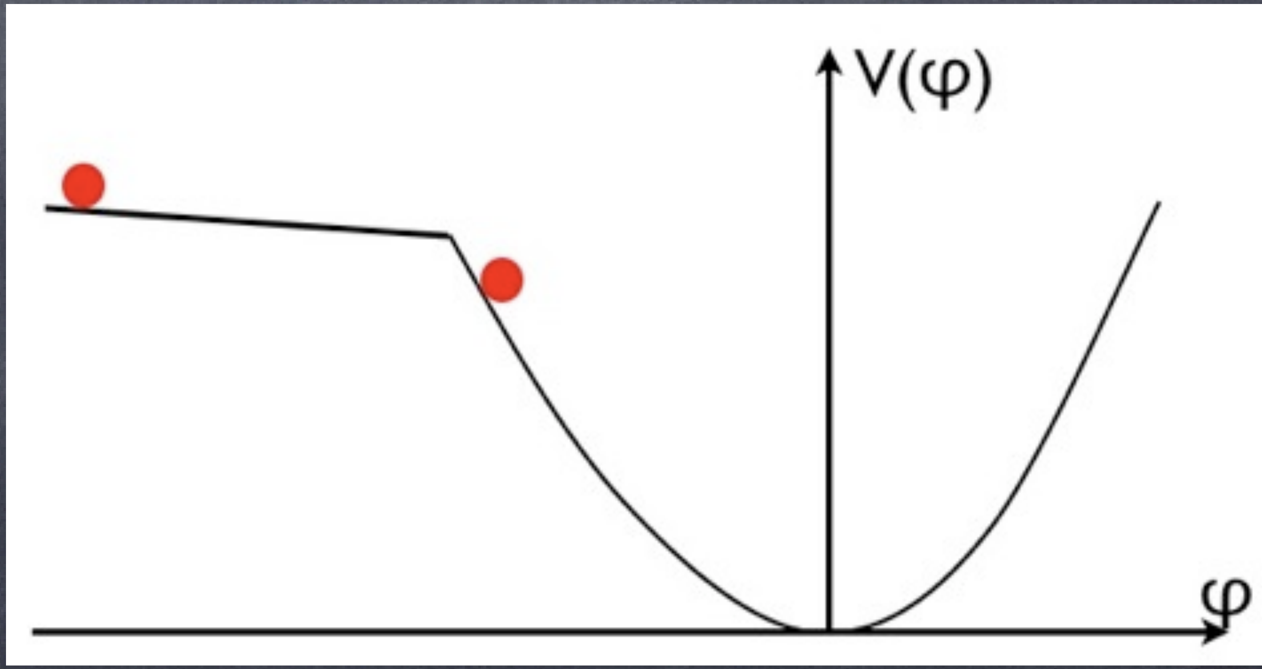
Dark Matter from CMB

Parameter	*Planck*		*Planck*+lensing		*Planck*+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048

Inflation

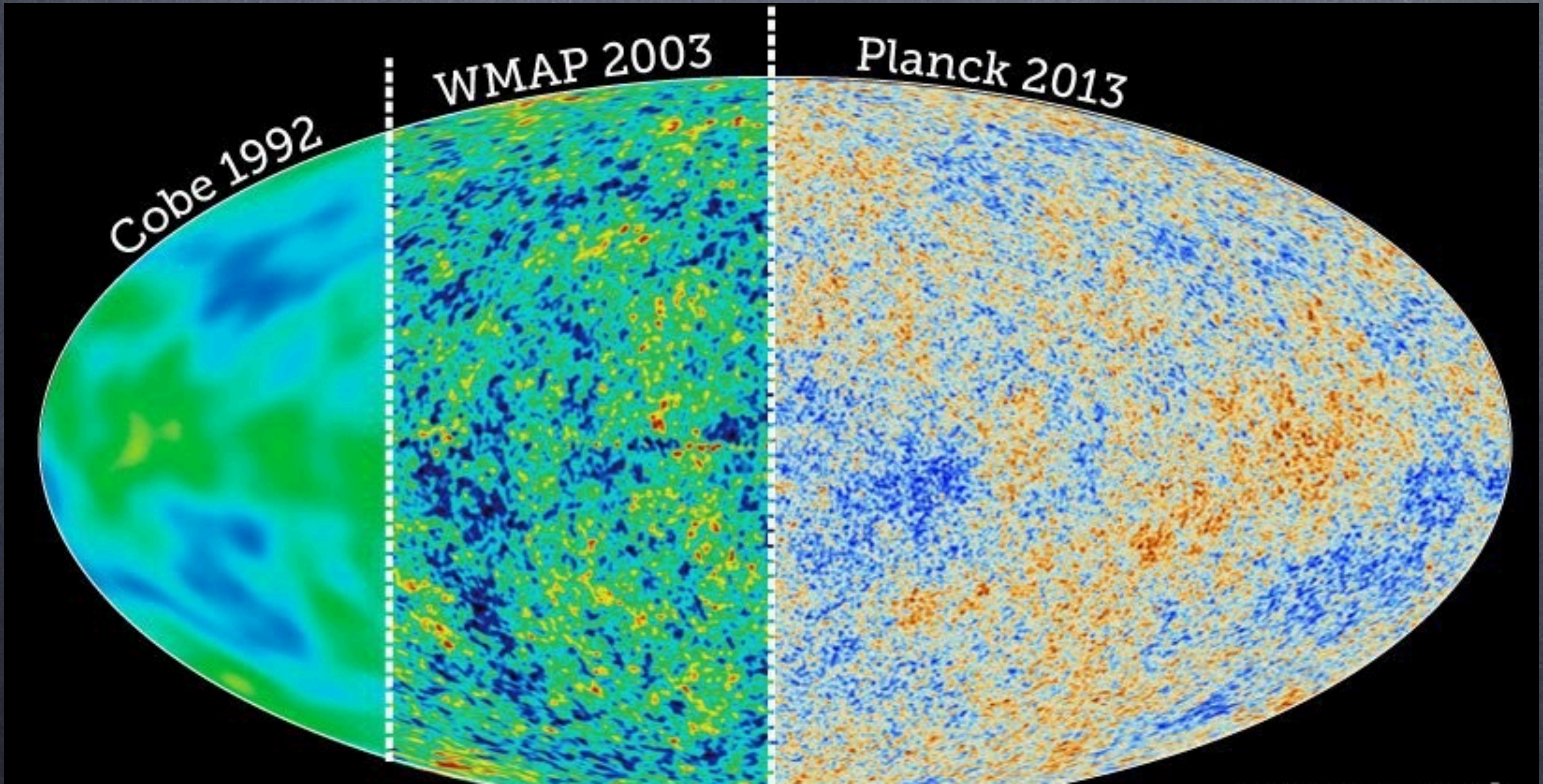
Inflation

- Universe is very homogenous, and on average flat
- Temperature of cosmic microwave background at opposite parts of the sky is correlated
- We think these regions of the sky were once causally connected, and then blown apart via superluminal expansion == inflation
- Simplest model is the one with a scalar field slowly rolling down the potential hill



Inflation

- Quantum fluctuations of the inflaton field should seed density perturbations in the matter of the universe
- These can be seen at their early stage of the evolution in the CMB



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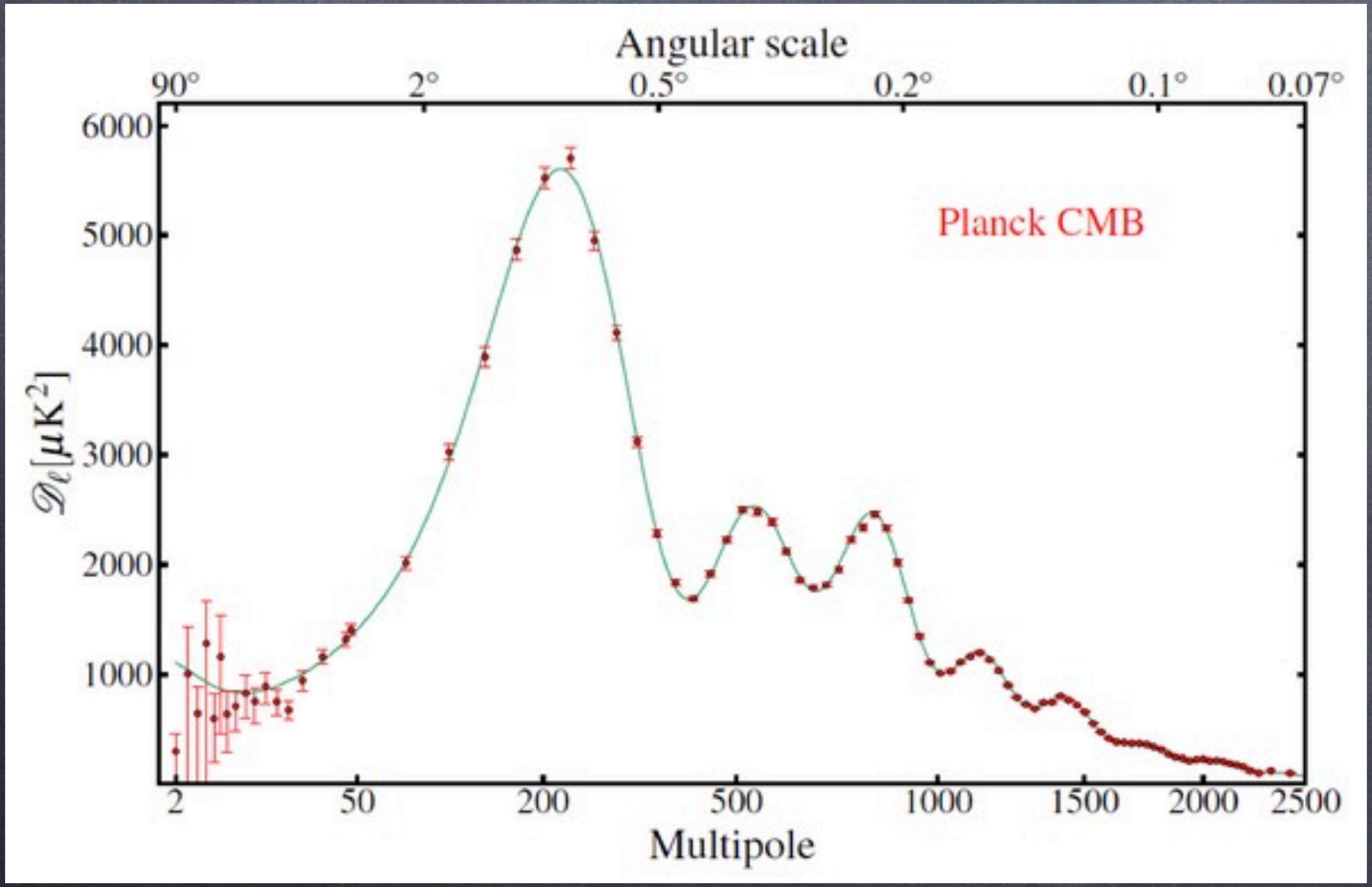
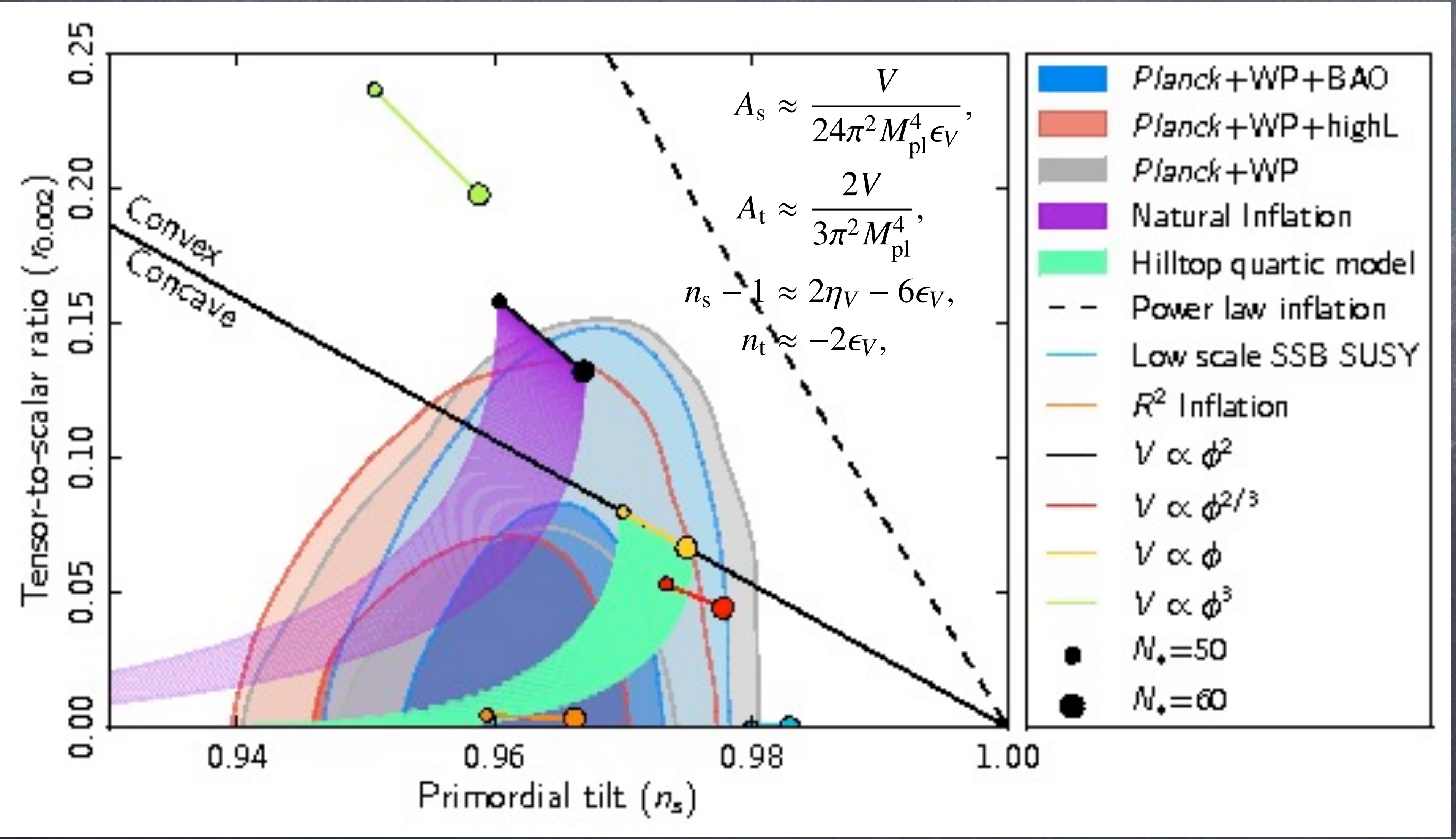


Inflation

- Zeroth order prediction is scale-invariant spectrum of perturbation

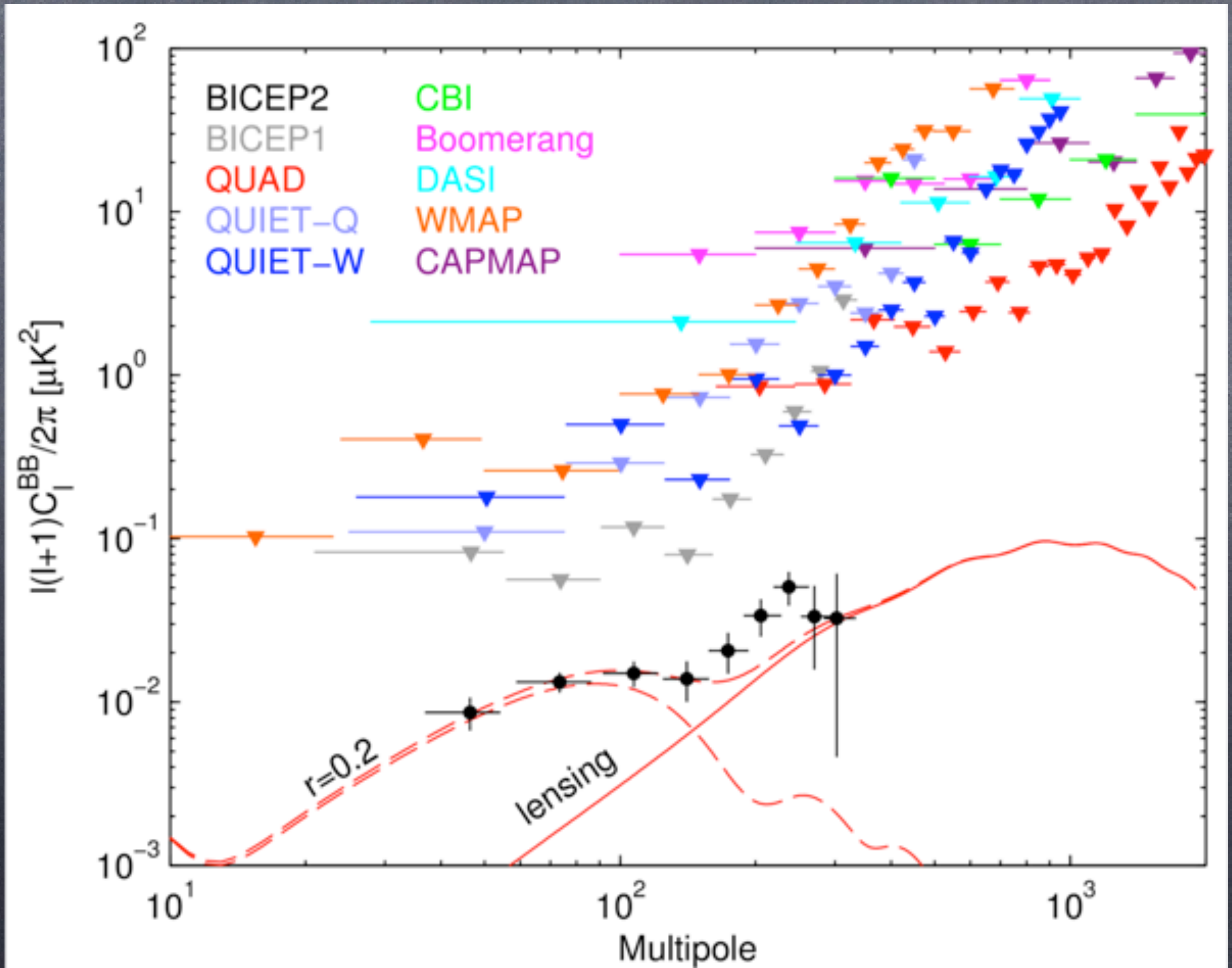
- Due to inflaton rolling down the potential hill, there should be small departure from scale invariance, that is spectral index less than 1



Inflation

- High-scale inflation predicts another kind of effect == tensor modes, due to gravitational waves propagating during inflation

- Discovery possible, but not yet established



Baryon Asymmetry

Baryon asymmetry

- Today, the universe consists of matter and almost no anti-matter
- Inflation must have wiped out any original baryon asymmetry and make the universe matter-antimatter symmetric
- Some mechanism operating during subsequent evolution must have produced the small baryon asymmetry (of order 10^-10)
- After matter and anti-matter annihilated away, the small asymmetry became the matter we see around

Baryon asymmetry

- Sakharov conditions: needs C and CP violation, as well as departure from thermal equilibrium
- All these conditions satisfied in the Standard Model
- But, CP violation in the CKM matrix is too small to explain the observed asymmetry
- There must be another source of CP violation from beyond the Standard Model.