# Scale hierarchies in particle physics and cosmology

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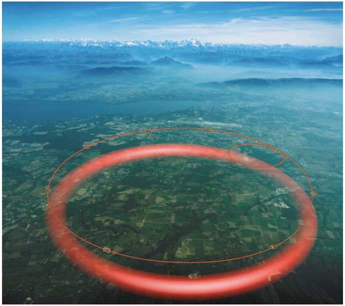
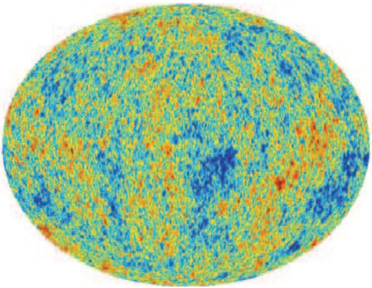
# A fundamental theory of Nature

- should describe both particle physics and cosmology





# Problem of scales

- describe high energy SUSY extension of the Standard Model

  unification of all fundamental interactions

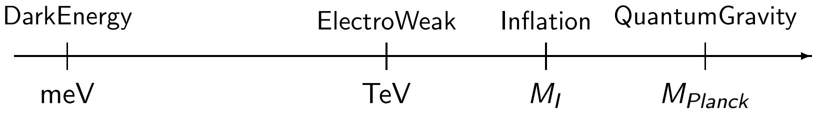
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

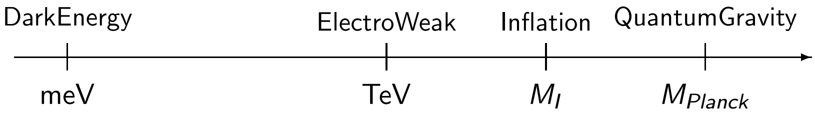
- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides $M_{Planck}$ :



# Problem of scales




1. possible connections
   - $M_I$ could be near the EW scale, such as in Higgs inflation

     but large non minimal coupling to explain
   - $M_{Planck}$ could be emergent from the EW scale

     in models of low-scale gravity and TeV strings

   2 extra dims at submm $\leftrightarrow$ meV: interesting coincidence with DE scale

   $M_I \sim TeV$ is also allowed by the data since cosmological observables are dimensionless in units of the effective gravity scale

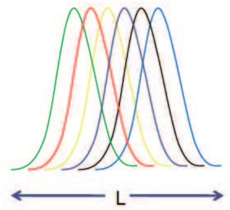
   I.A.-Patil '14 and '15
2. they are independent [10]

$N$ particle species $\Rightarrow$ lower quantum gravity scale : $M_*^2 = M_p^2/N$

Dvali '07, Dvali, Redi, Brustein, Veneziano, Gomez, Lüst '07-'10

derivation from: black hole evaporation or quantum information storage

Pixel of size $L$ containing $N$ species storing information:




localization energy $E \gtrsim N/L \rightarrow$

Schwarzschild radius $R_s = N/(LM_p^2)$

no collapse to a black hole : $L \gtrsim R_s \Rightarrow L \gtrsim \sqrt{N}/M_p = 1/M_*$

# Cosmological observables

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations $\mathcal{R}$)

$$\mathcal{P}_\mathcal{R} = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22$$

$\epsilon$ ← $-\dot{H}/H^2$

Power spectrum of primordial tensor anisotropies $\mathcal{P}_t = 2\frac{H^2}{\pi^2 M_*^2}$

$\Rightarrow$ tensor to scalar ratio $r = \mathcal{P}_t/\mathcal{P}_\mathcal{R} = 16\epsilon$

measurement of $\mathcal{A}$ and $r \Rightarrow$ fix the scale of inflation

$$H \text{ in terms of } M_* \quad : \quad \frac{H}{M_*} = \left(\frac{\pi^2 \mathcal{A}\, r}{2 \times 10^{10}}\right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$$

# Cosmological obs without assumption on scales

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations $\mathcal{R}$)

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{8\pi^2 M_{*s}^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22 \quad ; \quad M_{*s}^2 = M_p^2 / N_s$$

$\epsilon \leftarrow -\dot{H}/H^2$ no of scalars coupled to $T_\mu^\mu$ (→ $N_s$)

Power spectrum of primordial tensor anisotropies

$$\mathcal{P}_T = 2\frac{H^2}{\pi^2 M_{*T}^2} \quad ; \quad M_{*T}^2 = M_{*s}^2 / N_T \leftarrow \text{no of tensor modes}$$

$\Rightarrow$ tensor to scalar ratio $r = \mathcal{P}_T / \mathcal{P}_{\mathcal{R}} = 16\epsilon N_T \quad \Rightarrow$

- $H$ in terms of $M_*$ : $\dfrac{H}{M_{*T}} = \left(\dfrac{\pi^2 \mathcal{A}\, r}{2 \times 10^{10}}\right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$
- deviation for the tensor spectral index : $n_T = 2\epsilon = -\dfrac{r}{8}\dfrac{1}{N_T}$

# Extra species as Kaluza-Klein states

$D = 4 + n$ extra dims of size average size $R \Rightarrow$

fundamental gravity scale $M_s^{2+n} R^n = M_{Pl}^2$

$N_T$ = all graviton KK states with mass less than $H \Rightarrow N_T \simeq (HR)^n$

$$M_{*T} = M_{Pl}/\sqrt{N_T} = M_s (M_s R)^{n/2}/(HR)^{n/2} = M_s (M_s/H)^{n/2}$$

$$H = M_{*T}\Upsilon = M_s (M_s/H)^{n/2}\Upsilon \quad \Rightarrow \quad H = M_s \Upsilon^{2/(n+2)}$$

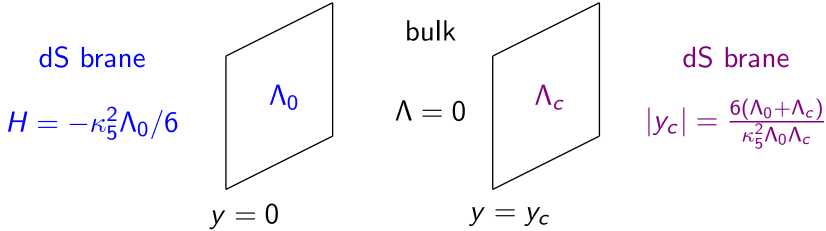
$\Rightarrow H \sim$ 1-3 orders of magnitude less than $M_s$ for $0.001 \lesssim r \lesssim 0.1$

as low as near the EW scale

# A brane-world model

5D brane-world realisation: empty bulk with two boundary dS branes

$$ds^2 = \frac{(1 + H|y|)^2}{H^2\tau^2}\left(-d\tau^2 + dx_1^2 + dx_2^2 + dx_3^2\right) + dy^2$$




$\Rightarrow$ keeping $H$ fixed one can make $y_c$ large, so that $H^2 \gg 1/y_c^2$ [4]

# impose independent scales: proceed in 2 steps

1. SUSY breaking at $m_{SUSY} \sim$ TeV

   with an infinitesimal (tuneable) positive cosmological constant

   Villadoro-Zwirner '05

   I.A.-Knoops, I.A.-Ghilencea-Knoops '14, I.A.-Knoops '15

2. Inflation in supergravity at a scale different than $m_{SUSY}$ [21]

# Toy model for SUSY breaking

Content (besides $N = 1$ SUGRA): one vector $V$ and one chiral multiplet $S$

with a shift symmetry $S \to S - ic\omega \leftarrow$ transformation parameter

String theory: compactification modulus or universal dilaton

$s = 1/g^2 + ia \leftarrow$ dual to antisymmetric tensor

Kähler potential $K$: function of $S + \bar{S}$

string theory: $K = -p \ln(S + \bar{S})$

Superpotential: constant or single exponential if R-symmetry $W = ae^{bS}$

$\int d^2\theta W$ invariant

$b < 0 \Rightarrow$ non perturbative

# Scalar potential

$$\mathcal{V}_F = a^2 e^{\frac{b}{l}} l^{p-2} \left\{ \frac{1}{p}(pl - b)^2 - 3l^2 \right\} \qquad l = 1/(s + \bar{s})$$

Planck units

no minimum for $b < 0$ with $l > 0$ $(p \leq 3)$

but interesting metastable SUSY breaking vacuum

when R-symmetry is gauged by $V$ allowing a Fayet-Iliopoulos (FI) term:

$$\mathcal{V}_D = c^2 l(pl - b)^2 \qquad \text{for gauge kinetic function } f(S) = S$$

- $b > 0$: $\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$ SUSY local minimum in AdS space at $l = b/p$
- $b = 0$: SUSY breaking minimum in AdS $(p < 3)$
- $b < 0$: SUSY breaking minimum with tuneable cosmological constant $\Lambda$

In the limit $\Lambda \approx 0$ $(p = 2)$ $\Rightarrow$

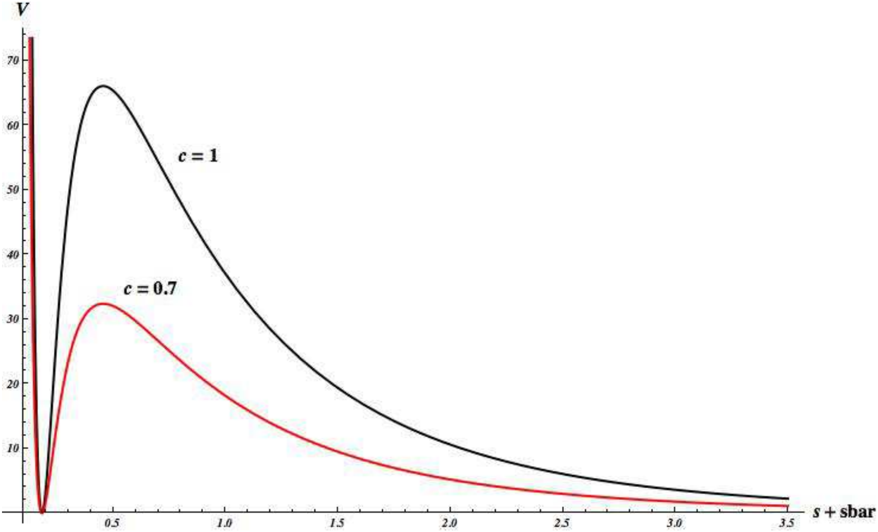
$b/l = \alpha \approx -0.183268$

$\frac{a^2}{bc^2} = 2\frac{e^{-\alpha}}{\alpha}\frac{(2-\alpha)^2}{2+4\alpha-\alpha^2} + \mathcal{O}(\Lambda) \approx -50.6602$

physical spectrum:

massive dilaton, $U(1)$ gauge field, Majorana fermion, gravitino

All masses of order $m_{3/2} \approx e^{\alpha/2} l a \leftarrow$ TeV scale


V
70
60
50
40
30
20
10
c = 1
c = 0.7
0.5
1.0
1.5
2.0
2.5
3.0
3.5
s + sbar

# Properties and generalizations

- Metastability of the ground state: extremely long lived

  $l \simeq 0.02$ (GUT value $\alpha_{GUT}/2$) $m_{3/2} \sim \mathcal{O}(TeV) \Rightarrow$

  decay rate $\Gamma \sim e^{-\mathcal{B}}$ with $B \approx 10^{300}$

- Add visible sector (MSSM) preserving the same vacuum

  matter fields $\phi$ neutral under R-symmetry

  $K = -2\ln(S+\bar{S}) + \phi^\dagger\phi \quad ; \quad W = (a + W_{MSSM})e^{bS}$

  $\Rightarrow$ soft scalar masses non-tachyonic of order $m_{3/2}$ (gravity mediation)

- R-charged fields can be added in the hidden sector

  needed for anomaly cancellation (important constraint)

- Toy model classically equivalent to

  $K = -p\ln(S+\bar{S}) + b(S+\bar{S}) \quad ; \quad W = a$ with $V$ ordinary $U(1)$

# Properties and generalizations

- Consider a simple (anomaly free) variation of the model with the above $K$ and $W$, gauge kinetic function $f = 1$ and $p = 1$

  $\Rightarrow$ tuning still possible but scalar masses of neutral matter tachyonic

  possible solution: add a new field $Z$ in the 'hidden' SU̸SY sector

  $\Rightarrow$ one extra parameter

- alternatively: add an $S$-dependent factor in Matter kinetic terms

  $K = -\ln(S+\bar{S}) + (S+\bar{S})^{-\nu} \sum \Phi\bar{\Phi}$ for $\nu \gtrsim 2.5$

  $\Rightarrow$ similar phenomenology

- distinct features from other models of SUSY breaking and mediation
- gaugino masses at the quantum level

  $\Rightarrow$ suppressed compared to scalar masses and A-terms

# A realistic model

$$K = -\ln(S+\bar{S}) + b(S+\bar{S}) + Z\bar{Z} + \sum \Phi\bar{\Phi}$$

$$W = a\,(1+\gamma Z) + W_{MSSM}(\Phi)$$

$$f = 1 \quad , \quad f_A = 1/g_A^2$$

Existence of tunable dS vacuum + non-tachyonic soft scalar masses

$\Rightarrow 0.5 \leq \gamma \lesssim 1.7$

- main properties remain with $\mathrm{Re} z, F_z \neq 0$
- soft scalar masses: $m_0 \approx B_0 \sim \mathcal{O}(m_{3/2})$
- trilinear scalar couplings: $A_0 = B_0 + m_{3/2}$

gaugino masses appear to vanish since $f_A$ are constants

however in the gauged R-symmetry representation they don't

# Kähler transformation and gaugino masses

$$K = -\ln(S+\bar{S}) + Z\bar{Z} + \sum \Phi\bar{\Phi}$$

$$W = [a\,(1+\gamma Z) + W_{MSSM}(\Phi)]\, e^{bS}$$

$$f_A = 1/g_A^2 + \beta_A S \quad ; \quad \beta_A = \frac{b}{8\pi^2}(T_{R_A} - T_{G_A})$$

$S$-dependent contribution: needed to cancel the $U(1)_R$ anomalies

$\Rightarrow$ generate non-vanishing gaugino masses!

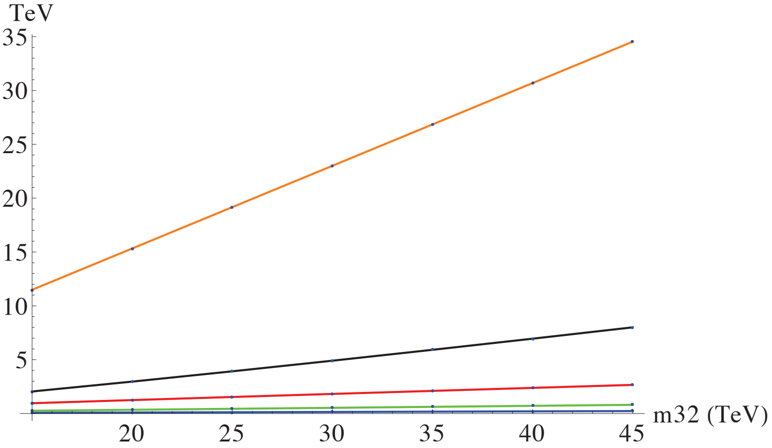
resolution of the puzzle: 'anomaly' mediation contribution

due to super-Weyl-Kähler and sigma-model anomalies

$$m_{1/2} = -\frac{g^2}{16\pi^2}\left[(3T_G - T_R)m_{3/2} + (T_G - T_R)K_\alpha F^\alpha + 2\frac{T_R}{d_R}(\log\det \underbrace{K|''_R}_{=\,0})_{,\alpha} F^\alpha\right]$$

difference in $K_S$ is accounted by difference in $f$

# Typical spectrum




The masses of sbottom squark (yellow), stop (black), gluino (red), lightest chargino (green) and lightest neutralino (blue) as a function of the gravitino mass. The mass of the lightest neutralino varies between $\sim$ 40 and 150 GeV

# Identify the dilaton shift with a global SM symmetry

**I.A.-Knoops to appear**

A combination of Baryon and Lepton number

containing the matter parity $(-)^{B-L}$

- $B-L$: anomaly free in the presence of 3 R-handed neutrinos
- $3B-L$: forbids all dim-4 and dim-5 operators violating $B$ or $L$

  anomalies cancel by a Green-Schwarz mechanism

  $S$-dependant gauge kinetic functions
- one extra parameter: the unit of charge for SM fields

  or equivalently the $U(1)$ gauge coupling
- similar phenomenology with lighter stop quark $\gtrsim 1.5$ GeV [10] [26]

# Starobinsky model of inflation

$$\mathcal{L} = \frac{1}{2}R + \alpha R^2$$

Lagrange multiplier $\phi \Rightarrow \mathcal{L} = \frac{1}{2}(1+2\phi)R - \frac{1}{4\alpha}\phi^2$

Weyl rescaling $\Rightarrow$ equivalent to a scalar field with exponential potential:

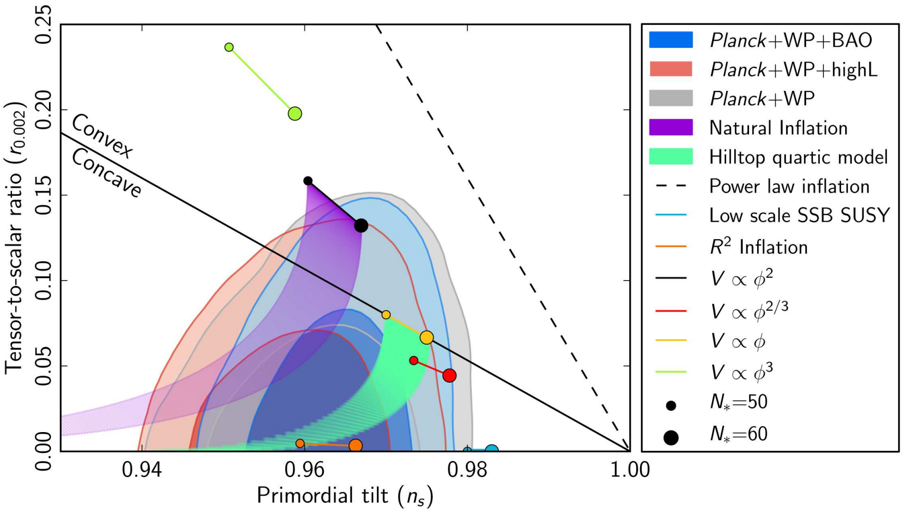
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

Note that the two metrics are not the same

supersymmetric extension:

add D-term $\mathcal{R}\bar{\mathcal{R}}$ because F-term $\mathcal{R}^2$ does not contain $R^2$

$\Rightarrow$ brings two chiral multiplets



0.00
0.05
0.10
0.15
0.20
0.25
Tensor-to-scalar ratio ($r_{0.002}$)
0.94
0.96
0.98
1.00
Primordial tilt ($n_s$)
Convex
Concave
*Planck*+WP+BAO
*Planck*+WP+highL
*Planck*+WP
Natural Inflation
Hilltop quartic model
Power law inflation
Low scale SSB SUSY
$R^2$ Inflation
$V \propto \phi^2$
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^3$
$N_*$=50
$N_*$=60

# SUSY extension of Starobinsky model

$$K = -3 \ln(T + \bar{T} - C\bar{C}) \quad ; \quad W = MC(T - \frac{1}{2})$$

- $T$ contains the inflaton: $\mathrm{Re}\, T = e^{\sqrt{\frac{2}{3}}\phi}$
- SUSY is broken during inflation with $C$ the goldstino superfield

$\rightarrow$ model independent treatment in the decoupling sgoldstino limit

$C \equiv X_{NL}$ constrained superfield satisfying $X_{NL}^2 = 0 \Rightarrow$

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

Rocek-Tseytlin '78, Lindstrom-Rocek '79, Komargodski-Seiberg '09

# Non-linear SUSY in supergravity

I.A.-Dudas-Ferrara-Sagnotti '14, I.A.-Markou '15

$$K = -3\log(1 - X\bar{X}) \equiv 3X\bar{X} \quad ; \quad W = f\,X + W_0 \qquad X \equiv X_{NL}$$

$$\Rightarrow \quad V = \frac{1}{3}|f|^2 - 3|W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2$$

- $V$ can have any sign    contrary to global NL SUSY
- NL SUSY in flat space $\Rightarrow f = 3\,m_{3/2}M_p$
- Dual gravitational formulation: $(\mathcal{R} - 6W_0)^2 = 0$

  ↖ chiral curvature superfield
- Minimal SUSY extension of $R^2$ gravity

# Non-linear Starobinsky supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

$$K = -3\ln(T + \bar{T} - X_{NL}\bar{X}_{NL}) \quad ; \quad W = M\, X_{NL}\, T + f\, X_{NL} + W_0 \qquad \Rightarrow$$

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 - \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\phi}(\partial a)^2 - \frac{M^2}{18}e^{-2\sqrt{\frac{2}{3}}\phi}a^2$$

- axion $a$ much heavier than $\phi$ during inflation, decouples:

  $m_\phi = \frac{M}{3}e^{-\sqrt{\frac{2}{3}}\phi_0} << m_a = \frac{M}{3}$

- inflation scale $M$ independent from NL-SUSY breaking scale $f$

  $\Rightarrow$ compatible with low energy SUSY

# Conclusions

Consistent framework for particle phenomenology and cosmology

at least 3 very different scales (besides $M_{Planck}$)

electroweak, dark energy, inflation

their origins may be connected or independent

- $\not{S}$USY with infinitesimal (tuneable) +ve cosmological constant

  interesting framework for model building incorporating dark energy
- Inflation models at a hierarchically different third scale

  sgoldstino-less supergravity models of inflation