Challenges in particle physics and cosmology

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SEENET-MTP online Seminar on Theoretical Physics

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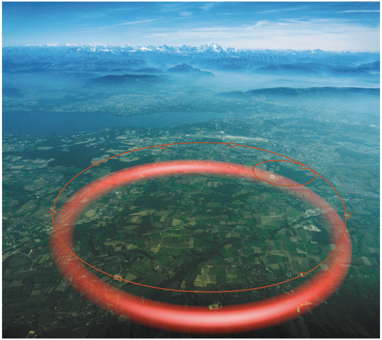
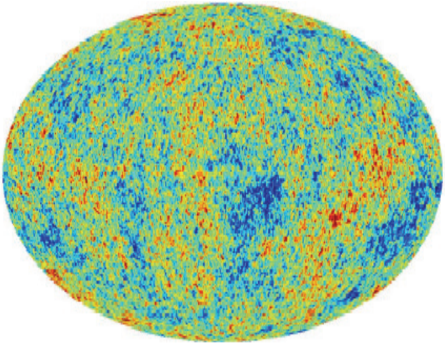
Challenge for a fundamental theory of Nature

describe both particle physics and cosmology [12] [17]





- Particle physics studies phenomena at very short distances
  structure of matter and fundamental forces
  particle accelerators are the today microscopes [4]
- Cosmology studies phenomena at very large distances
  evolution of the Universe at early times after the Big Bang
  measurement of temperature fluctuations in the sky [6]
- However observations from very far come from the very past
  when Universe was very small and very hot
  governed by the laws of particle physics [8]

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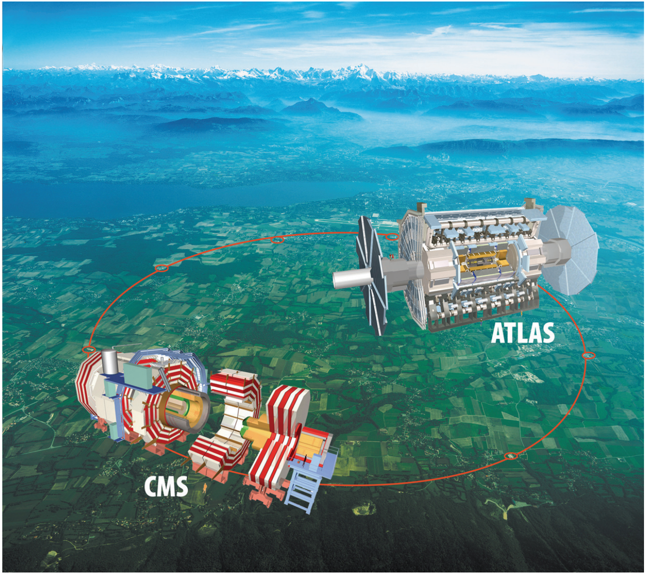
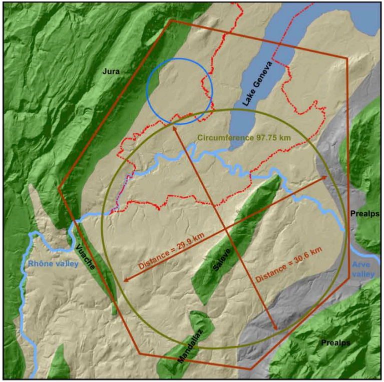
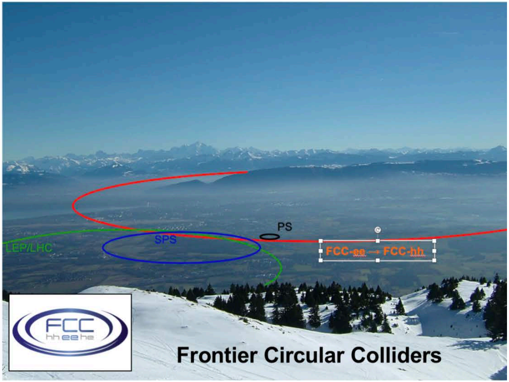
The large Hadron Collider (LHC) at CERN
the world's most powerful microscope

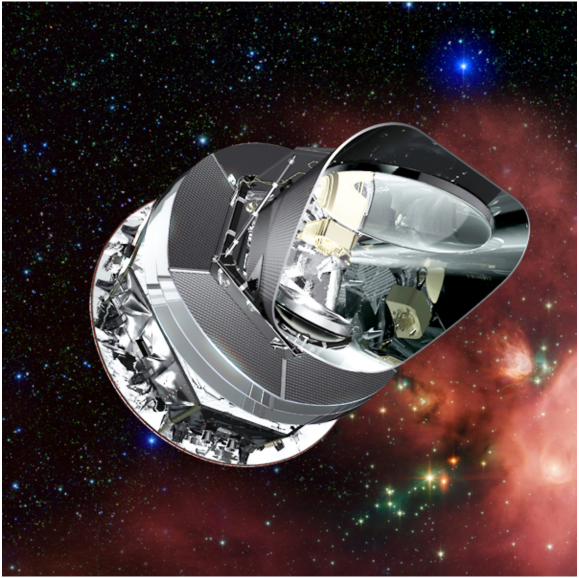


Frontier Circular Colliders (FCC) [3]

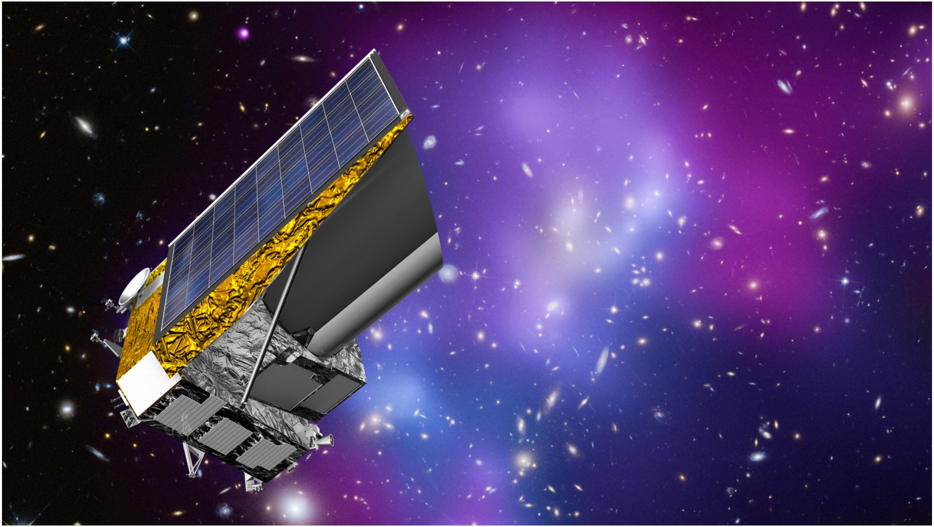




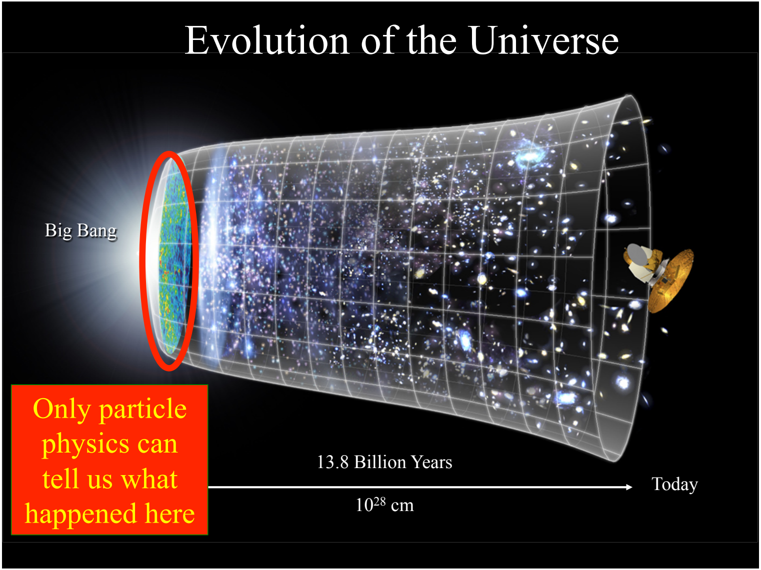
Planck satelite experiments
Cosmic Microwave Background (CMB) anisotropies



The Golden age of cosmology: From Planck to Euclid ESA Mission [3]



Accelerator experiments and cosmological observations: complementary information for the fundamental theory



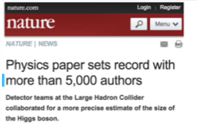
Standard Model of particle physics : accurate description of microphysics at present energies

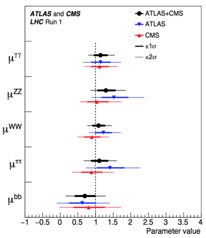
Higgs: ATLAS+CMS Combination

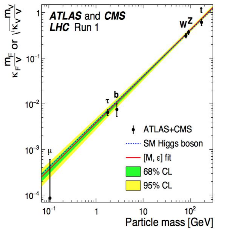
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

The Run-1 Higgs Legacy!

arXiv:1606.02266 /
JHEP 1608 (2016) 045
5153 authors!!







The newly found boson has properties as expected for a Standard Model Higgs

Signal strength/SM:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\ ^{+0.04}_{-0.04}\,(\text{expt})\ ^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

Standard Model of electroweak + strong forces

- Quantum Field Theory Quantum Mechanics + Special Relativity
- Principle: gauge invariance $U(1) \times SU(2) \times SU(3)$

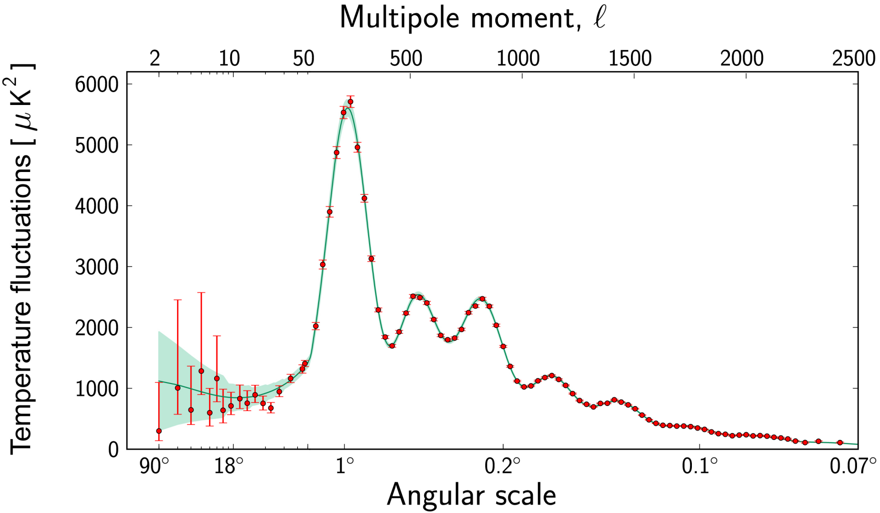
Very accurate description of physics at present energies 17 parameters

1. mediators of gauge interactions (vectors): photon, $W^{\pm}$, Z + **8 gluons**
2. matter (fermions): (leptons + quarks) $\times$ 3

   electron, positron, neutrino (up, down) **3 colors**
3. Brout-Englert-Higgs sector: new scalar(s) particle(s)

François Englert and Peter Higgs: Nobel Prize 2013

Standard Model of cosmology : ΛCDM [2] [26] [27]



James Peebles: Nobel Prize 2019

Dark energy: Nobel Prize 2011

© The Nobel Foundation. Photo: U. Montan

Saul Perlmutter

Prize share: 1/2

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Brian P. Schmidt

Prize share: 1/4

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Adam G. Riess

Prize share: 1/4

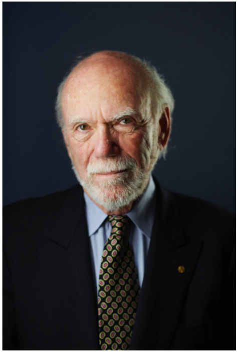
Gravitational waves: start a new era of astronomy

The Nobel Prize in Physics 2017

© Nobel Media AB. Photo: A. Mahmoud

Rainer Weiss

Prize share: 1/2



© Nobel Media AB. Photo: A.Mahmoud

Barry C. Barish

Prize share: 1/4

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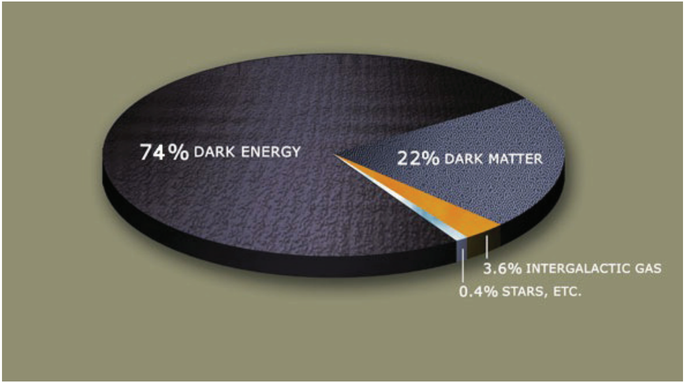
Kip S. Thorne

Prize share: 1/4

What our Universe is made of ?

- Ordinary matter: only a tiny fraction $\lesssim 5\%$
- Non-luminous (dark) matter: $\sim 25\%$

  if new 'stable' particle $\Rightarrow$ beyond the Standard Model of PP

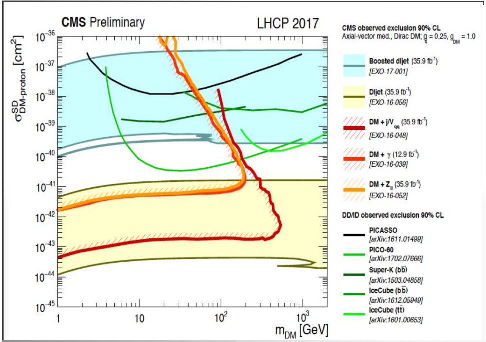


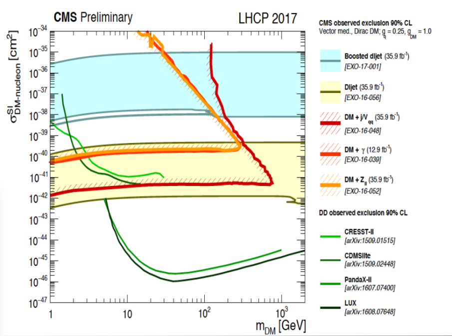
Comparison with Direct Detection

No signal seen in any of the "mono"-signals so far -> limits

Axial-vector mediator and
Spin-dependent direct limits

Vector mediator and
Spin-independent direct limits





Mono-jet/V searches are typically the most sensitive ones

90% CL limits

Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

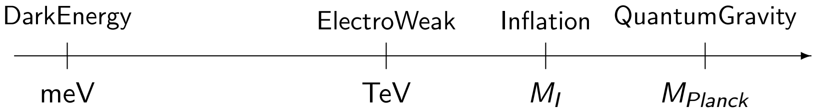
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant [21]

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter) [23] [27]

$\Rightarrow$ 3 very different scales besides M_{Planck} : [31]



Supersymmetry: every particle has a superpartner with spin differ by 1/2

A well motivated proposal

addressing several open problems of the Standard Model

- natural elementary scalars
- realise unification of the three Standard Model forces
- natural dark matter candidate (lightest supersymmetric particle)
- addressing the hierarchy problem
- prediction of light Brout-Englert-Higgs ($\lesssim 130$ GeV)
- soft UV behavior and important ingredient of string theory

But no experimental indication of any BSM physics at LHC

It is likely to be there at some (more) fundamental level

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	$E_T^{\rm miss}$	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ 2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ 1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ 1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<Δm($\tilde{b}_1,\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ Forbidden 0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 0.55	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_2, \tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.64	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 1.0	m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 0.66	Pure Wino	ATLAS-CONF-2021-015
						$\tilde{\chi}^\pm_1$ 0.21	Pure higgsino	ATLAS-CONF-2021-015
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1, \tilde{\chi}^0_{1,2}\to tbs, \tilde{\chi}^\pm_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$ 0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: March 2021

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $Z' \to ZH$ model B	0-2 e, μ	1-2 b	Yes	139	Z' mass 3.2 TeV	$g_V = 3$	ATLAS-CONF-2020-043
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	ATLAS-CONF-2021-012
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	ATLAS-CONF-2021-012
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med} 3.1 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	ATLAS-CONF-2021-006
	Pseudo-scalar med. 2HDM+a	0 e, μ	2 b	Yes	139	m_{med} 520 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-006
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	y=0.4, λ=0.2, $m(\chi)$=10 GeV	1812.09743
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥ 2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	ATLAS-CONF-2021-008
	Scalar LQ 3rd gen	0 e, μ	≥ 2 j, ≥ 2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥ 2e, μ, ≥ 1τ	≥ 1 j, ≥ 1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥ 1τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ	≥ 2 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	singlet, κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	139	N^0 mass 790 GeV		20008.07949
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho \;\Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\Rightarrow\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

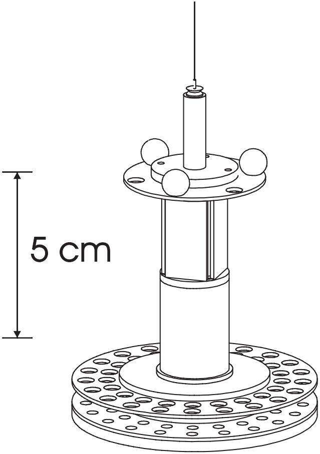
  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$ [17]

Newton's law is valid down to distances 0.05 mm

Adelberger et al. '06



de Sitter spacetime

vacuum solution of Einstein equations with +ve cosmological constant

and maximal symmetry: 10 isometries like flat space

$SO(4,1)$ vs Poincaré E_4

hyperboloid from 5 dimensions: $-y_0^2 + \vec{y}^2 = \frac{1}{H^2}$

$$R_{\mu\nu\lambda\rho} = H^2(g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}) \qquad R = 12H^2 = 4\Lambda$$

Flat slicing: $ds^2 = -dt^2 + e^{2Ht}d\vec{x}^2$ exponential expansion

FRW with flat 3-space and scale factor $a(t) = e^{Ht}$

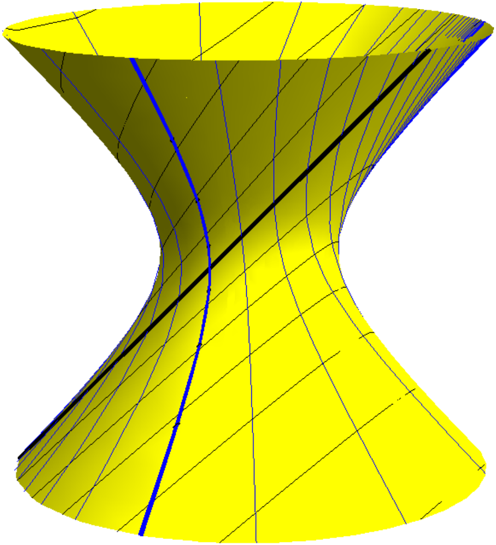
isometries: 3 space translations, 3 rotations, 1 scale, 3 special conformal

e.g. scale: $\vec{x} \to \omega^2\vec{x}$ and $t \to t - \omega/H$

Closed slicing: $ds^2 = -dt^2 + \frac{1}{H^2}ch^2Ht\, d\Omega_3^2 \leftarrow$ unit sphere S^3

Open slicing: $ds^2 = -dt^2 + \frac{1}{H^2}sh^2Ht\, dH_3^2 \leftarrow$ unit hyperbolic H^3 [26]

de Sitter spacetime



de Sitter spacetime: static coordinates

$$ds^2 = -(1 - H^2 r^2) dt^2 + \frac{dr^2}{1 - H^2 r^2} + r^2 d\Omega_2^2 \quad \leftarrow \text{ unit sphere } S^2$$

describes 1/4 of the spacetime

Observed Universe: homogeneous, isotropic and (spacially) flat

$\Rightarrow$ all regions causally connected in the past

But in contradiction with Einstein's equations

observed universe has a huge number of causally disconnected regions

Inflation proposal:

postulates an exponentially expanding period in early times

a small region becomes fast exponentially large

$\Rightarrow$ explains homogeneity, isotropy and flatness problems

it needs 50-60 e-foldings of expansion at least [39]

It predicts also small anisotropies from slight deviation from de Sitter space

temperature/density perturbations from quantum fluctuations [12] [17]

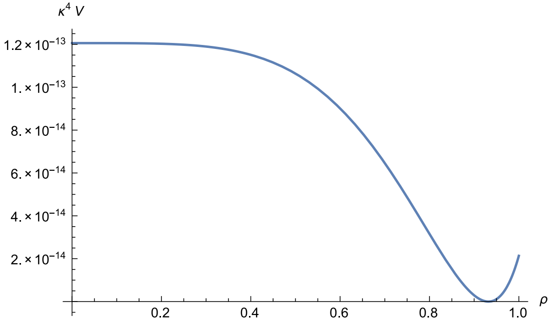
Inflation:

Theoretical paradigm consistent with cosmological observations [12]

But phenomelogical models with not real underlying theory [17]

introduce a new scalar field that drives Universe expansion at early times

Inflaton potential



slow-roll region with V', V'' small compared to the de Sitter curvature

Swampland de Sitter conjecture

String theory: vacuum energy and inflation models

related to the moduli stabilisation problem

Difficulties to find dS vacua led to a conjecture:

$$\frac{|\nabla V|}{V} \geq c \quad \text{or} \quad \min(\nabla_i \nabla_j V) \leq -c' \quad \text{in Planck units } G_N = 8\pi$$

with c, c' positive order 1 constants Ooguri-Palti-Shiu-Vafa '18

Dark energy: forbid dS minima but allow maxima

Inflation: forbid standard slow-roll conditions

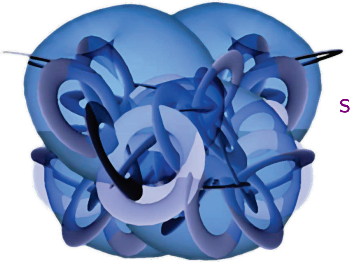
Assumptions: heuristic arguments, no quantum corrections

debate on the validity of the conjectures [31]

String moduli

String compactifications from 10/11 to 4 dims $\rightarrow$ scalar moduli

arbitrary VEVs: parametrize the compactification manifold



size of cycles, shapes, . . . , string coupling

- $N = 1$ SUSY $\Rightarrow$ complexification: scalar + i pseudoscalar $\equiv \phi_i$
- Low energy couplings: functions of moduli

Moduli stabilization

If moduli massless $\rightarrow$ inconsistent

long range forces, cosmological production, accelerators

Outstanding problem: moduli stabilization

- avoid experimental conflict
- fix their VEVs $\Rightarrow$ compute low energy couplings

Generate moduli potential: - preserving SUSY / - after SUSY breaking via

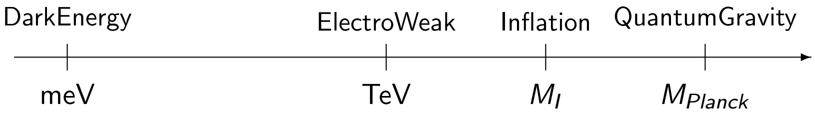
• non-perturbative effects or by

• turn-on fluxes: constant field-strengths of generalized gauge potentials

gauge fields: internal magnetic fields

generalization: higher rank antisymmetric tensors [28]

Problem of scales: connections



Direct connection of inflation and supersymmetry breaking:

identify the inflaton with the partner of the goldstino

Goldstone fermion of spontaneous supersymmetry breaking

longitudinal (spin-1/2) helicity of the massive spin-3/2 gravitino

while accommodating observed vacuum energy

Inflation in supergravity: main problems

Inflaton: part of a chiral superfield X [37]

together with a 2-component fermion and a (pseudo) scalar

- slow-roll conditions: the eta problem

  $|\eta| = |V''/V| << 1$ in Planck units $G_N = 8\pi \Rightarrow$

  fine-tuning of the inflaton potential $V_F \propto e^K$

  Kähler potential

  canonically normalised field: $K = X\bar{X} \Rightarrow \eta = 1 + \dots$ [38]

- trans-Planckian initial conditions $\Rightarrow$

  break validity of Effective Field Theory from gravitational corrections

- stabilisation of the (pseudo) scalar companion of the inflaton

- moduli stabilisation, de Sitter vacuum, ...

Starobinsky model of inflation

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

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

Rescaling the metric to the Einstein frame $\Rightarrow$

equivalent to a scalar field with exponential potential:

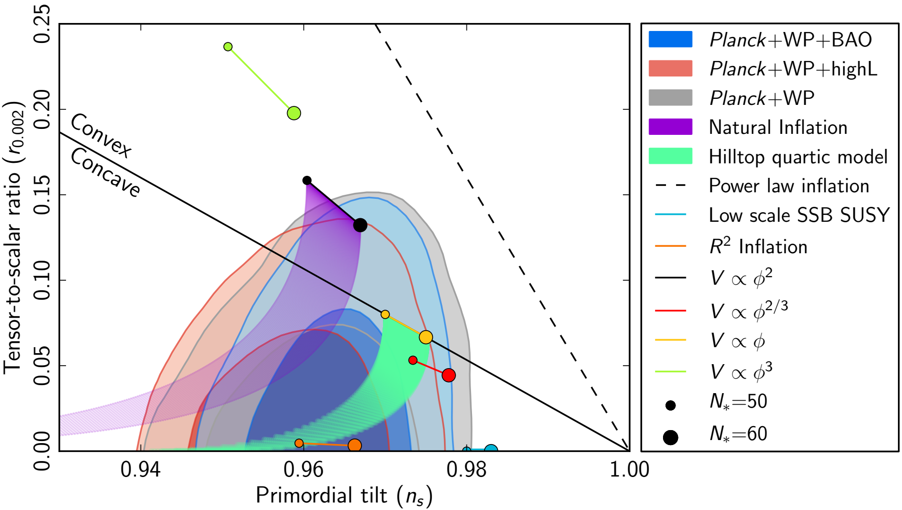
$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

supersymmetric extension: need two Lagrange multipliers

$\Rightarrow$ two chiral superfields

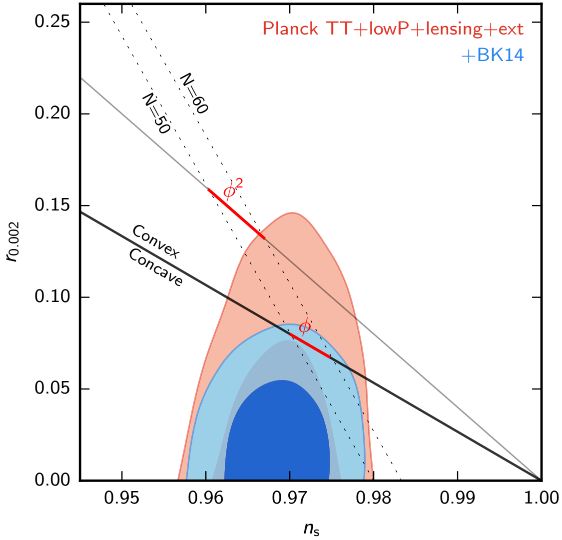
one contains the inflaton ϕ and the other the goldstino [36]

Goldstone fermion of spontaneous supersymmetry breaking


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

Combined results from Planck/BISEP2/Keck Array

P. A. R. Ade et al., Phys. Rev. Lett. 116, 031302 (2016)



Non-linear Starobinsky supergravity

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

Non-linear supersymmetry limit: one field decouples:

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

- no eta-problem but

  initial conditions require trans-planckian values for ϕ $(\phi > 1)$

- pseudoscalar a much heavier than ϕ 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 supersymmetry breaking scale

  $\Rightarrow$ compatible with low energy supersymmetry [32]

Inflation from supersymmetry breaking

I.A.-Chatrabhuti-Isono-Knoops '16, '17, '19

Inflaton : supersymmetric partner of the goldstino

in the presence of an abelian $U(1)$ gauge symmetry

R symmetry: rotates the fermionic coordinates of superspace by a phase

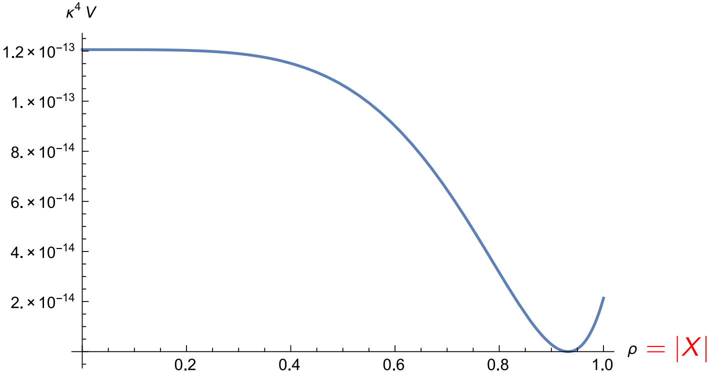
- η vanishes to lowest order $\Rightarrow$ no η-problem [32]

  (superpotential linear in the goldstino superfield X)
- gauge R-symmetry: pseudoscalar companion absorbed by the $U(1)_R$
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  no large field initial conditions
- vacuum energy at the minimum:

  tuned between gravitational and gauge contributions

R-symmetry restored during inflation



maximum at the origin with η due to

a correction to the kinetic terms depending on one parameter $A > 0$ [32] [41]

$$K = X\bar{X} + A(X\bar{X})^2$$

Predictions

slow-roll parameters (neglecting $U(1)_R$ gauge interactions)

$$\eta = \frac{V''}{V} = -4A + \mathcal{O}(\rho^2)$$
$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = 16A^2\rho^2 + \mathcal{O}(\rho^4) \simeq \eta^2\rho^2 << |\eta|$$

η naturally small since A is a correction

inflation starts with an initial condition for $\phi = \phi_*$ near the maximum

and ends when $|\eta| = 1$

$\Rightarrow$ number of e-folds $N = \int_{end}^{start} \frac{V}{V'} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\rm end}}{\rho_*}\right)$

Planck '15 data : $\eta \simeq -0.02 \Rightarrow N \gtrsim 50$ naturally [26]

CMB anisotropies

Density petrurbations characterised by:

- an amplitude $A_s \sim \mathcal{O}(10^{-9})$
- and a spectral index $n_s \simeq 0.96$

($n_s = 1$ corresponds to a scale invariant spectrum)

Primordial gravitational waves have (yet) not been observed

tensor-to-scalar ratio of amplitudes $r \equiv A_g/A_s \lesssim 0.015$

Predictions

$$\text{amplitude of density perturbations} \quad A_s = \frac{\kappa^2 H_*^2}{8\pi^2 \epsilon_*}$$

$$\text{spectral index} \quad n_s \simeq 1 + 2\eta_*$$

$$\text{tensor} - \text{to} - \text{scalar ratio} \quad r = 16\epsilon_*$$

Planck '15 data : $\eta_* \simeq -0.02,\ A_s \simeq 2.2 \times 10^{-9},\ N \gtrsim 50$

$$\Rightarrow r \lesssim 10^{-4},\ H_* \lesssim 10^{12}\ \text{GeV}$$

Question: can a 'nearby' minimum exist with a tiny +ve vacuum energy?

Answer: Yes [38]

need an extra correction to the kinetic terms

Microscopic model

- Explicit examples within field theory/supergravity
- Derive these models in string theory?

interesting open problem

part of a more general research in supergravity and string theory

realising supersymmetry deformations, gauged R-symmetry

and Fayet-Iliopoulos D-terms

Cribiori-Farakos-Tournoy-Van Proeyen '18

I.A.-Jiang-Lacombe '19; I.A.-Derendinger-Tartaglino Mazzucchelli '19

I.A.-Derendinger-Jiang-Tartaglino Mazzucchelli '20

Conclusions

Challenges in fundamental theories of particle physics and cosmology

- Origin of very different scales
- Role and breaking scale of supersymmetry in Nature
- Origin of inflation and nature of the inflaton field

  another fundamental scalar or an effective degree of freedom?
- Nature of dark energy   cosmological constant or a dynamical field?

General class of models with inflation from supersymmetry breaking:

Identify the inflaton with the superpartner of the goldstino

- direct connection of supersymmetry and inflation scales
- R-symmetry restored during inflation $\Rightarrow$ fixes the initial conditions
- avoids all supergravity problems of inflation