STRINGY COSMOLOGY & THE LHC

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New Frontiers in Physics ICFP 2012

10-16 June 2012, Kolymbari, Crete, Greece

CERN · Universitas Osloensis MDCCCXI · Forskningsrådet

OUTLINE

- MOTIVATION: CURRENT STATUS OF COSMOLOGICAL & COLLIDER (LHC) DATA ON DARK SECTOR OF UNIVERSE
- GENERIC ASPECTS OF STRING COSMOLOGIES - THE ROLE OF MODULI FIELDS
- DILATON DOMINANCE IN EARLY UNIVERSE
- MODIFICATION OF DARK MATTER ABUNDANCES vs STANDARD COSMOLOGY

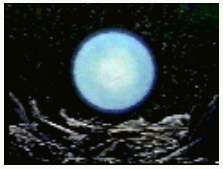
- LHC SEARCHES OF SUPERSYMMETRY AND DILATON COSMOLOGIES
- LORENTZ & CPT VIOLATING STRINGY COSMOLOGIES & THE OBSERVED BARYON ASYMMETRY IN THE UNIVERSE – D-FOAM
- D-FOAM & THE UNIVERSE DARK SECTOR

THE DARK SECTOR OF THE UNIVERSE

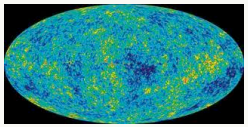
Current Energy Budget of the Cosmos

Observations from:

Supernovae Ia



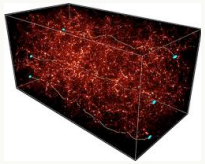
CMB



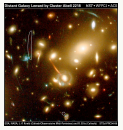
Baryon Acoustic Oscillations

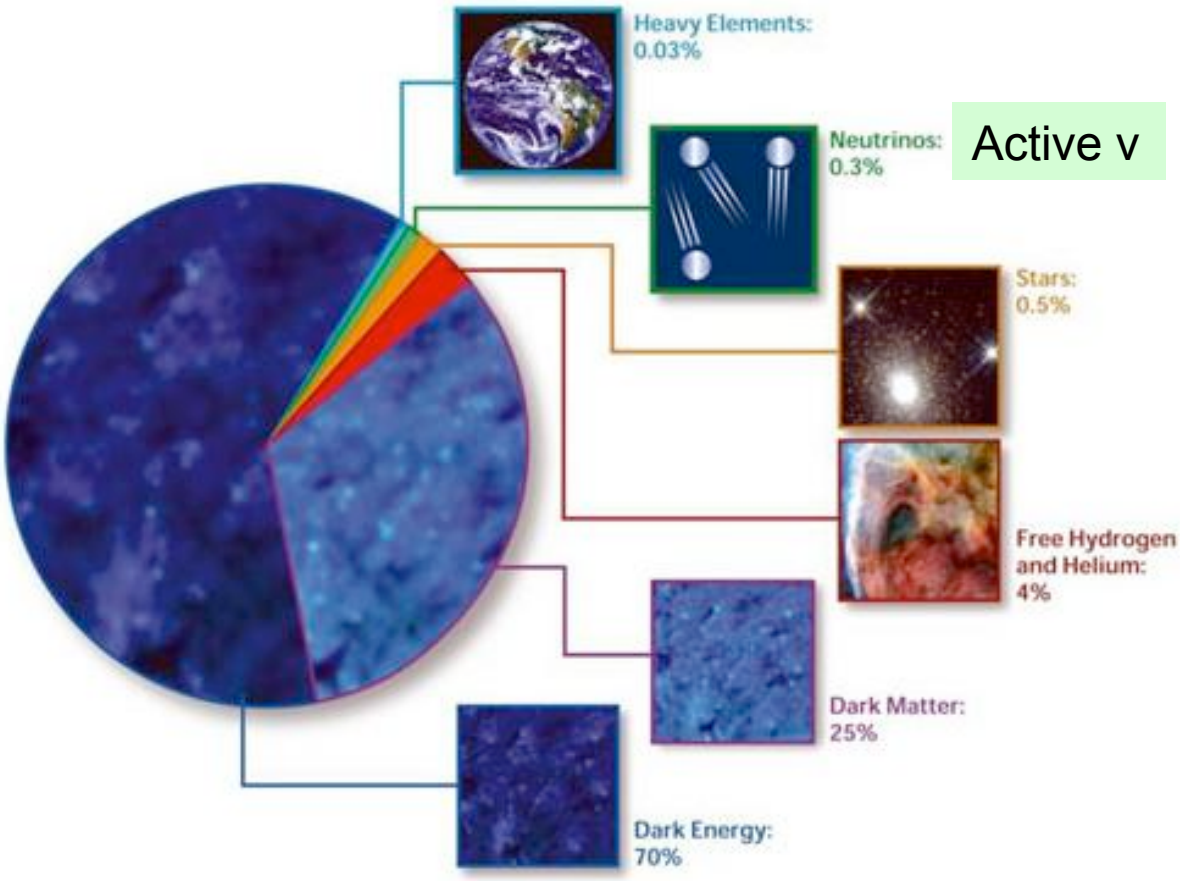
Galaxy Surveys

Structure Formation data



Strong & Weak lensing





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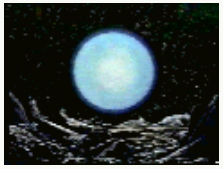

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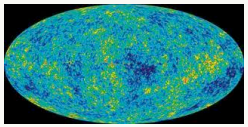

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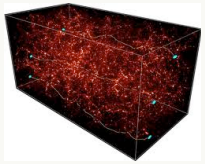

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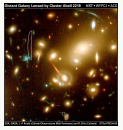

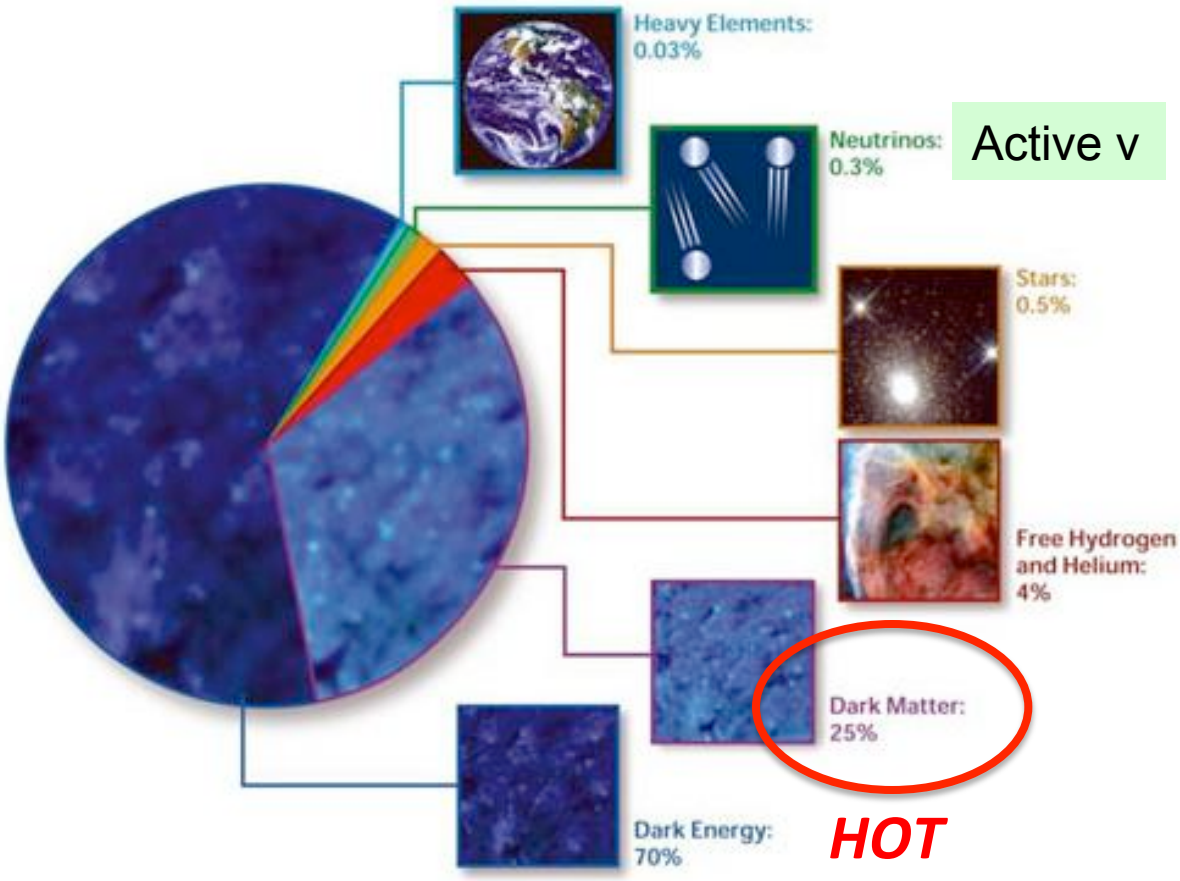

HOT

WARM

COLD

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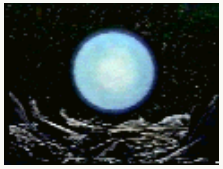

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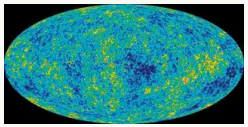

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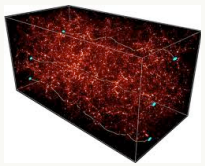

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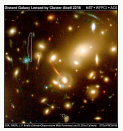

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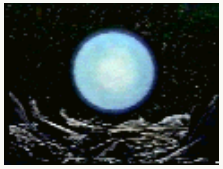

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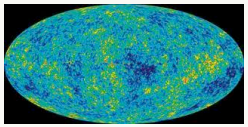

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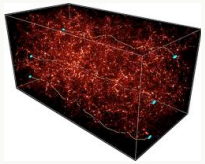

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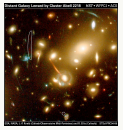

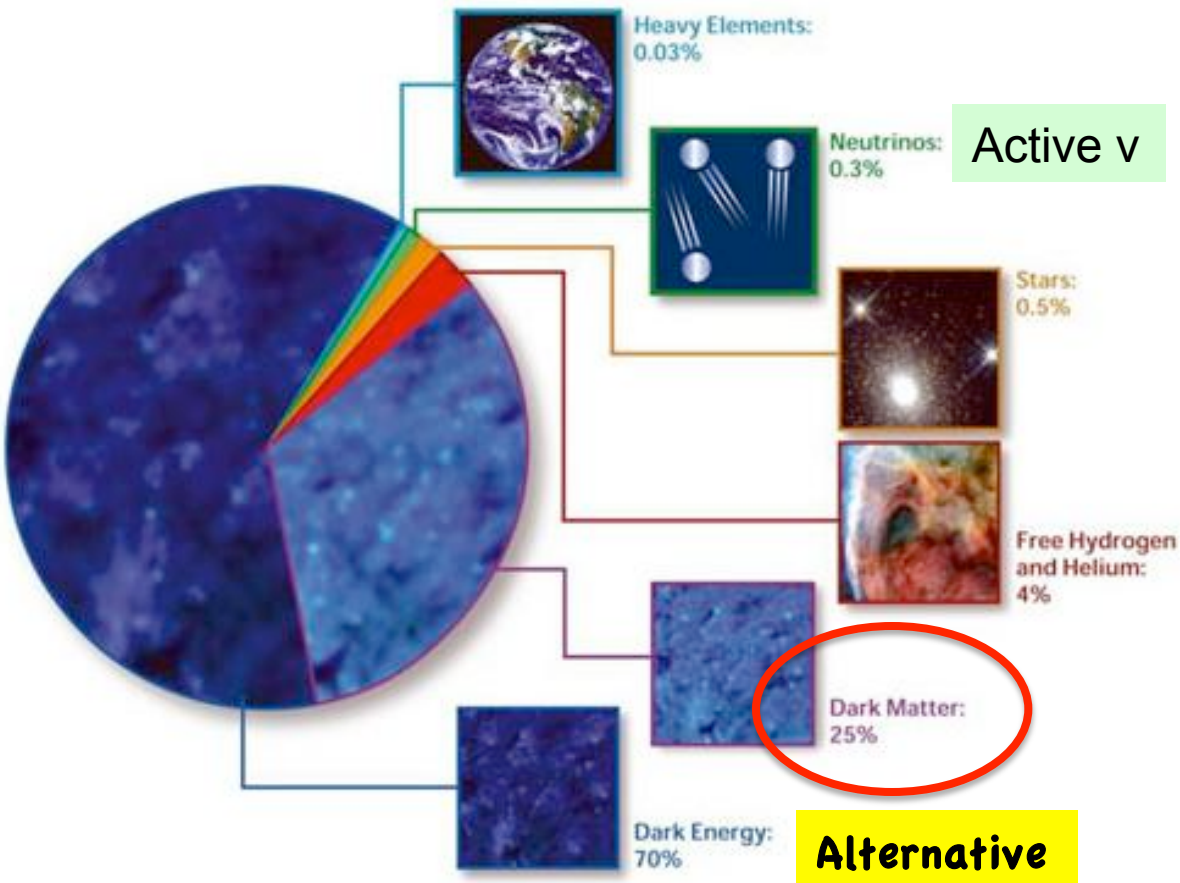

Alternative theories of Gravity?

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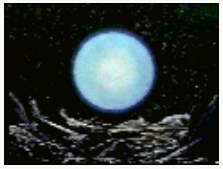

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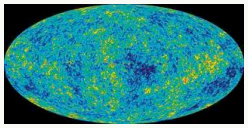

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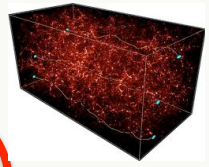

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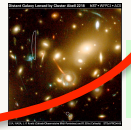

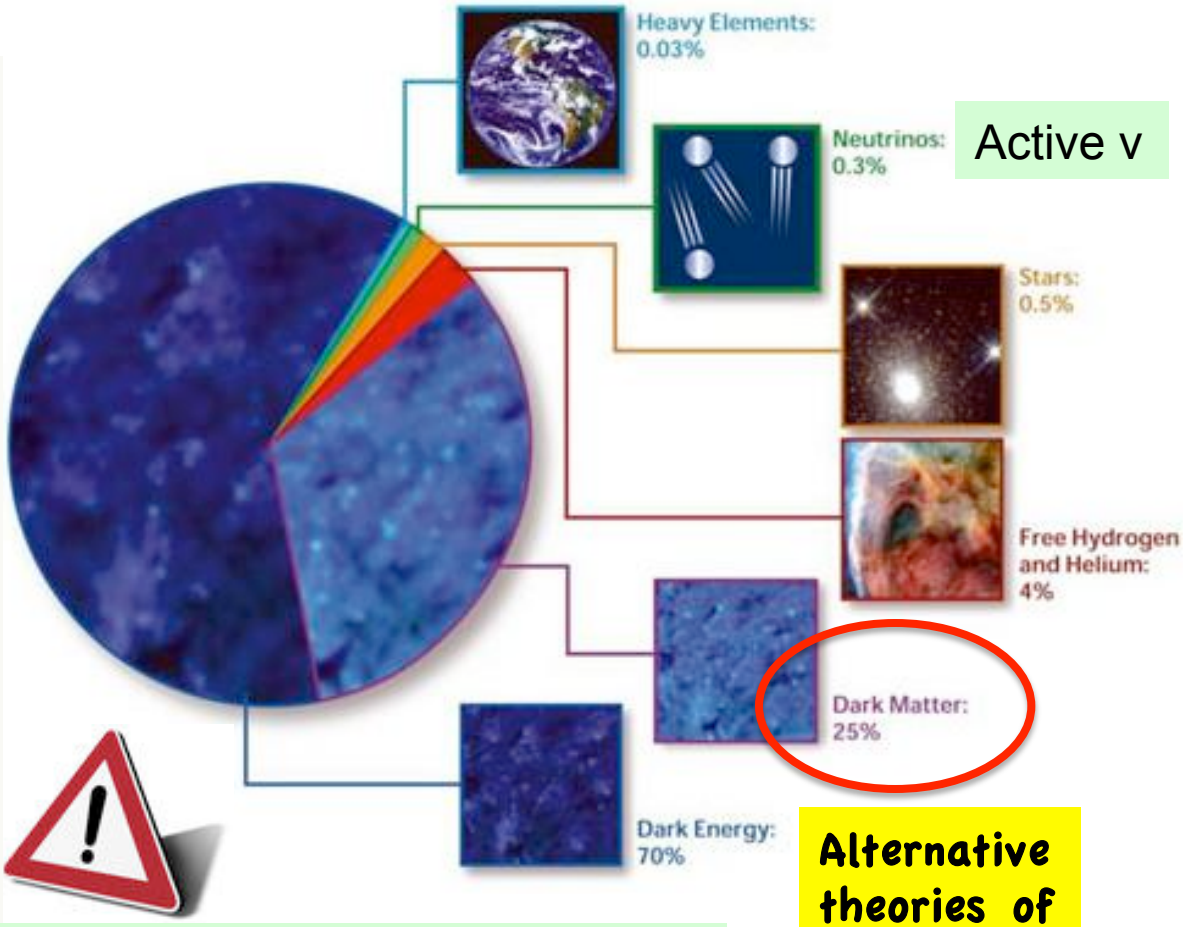

Rule out simplest Alternative Gravity Models ?

Alternative theories of Gravity?

Several Candidates for Dark Matter (DM) – NO CONCRETE EXPLANATION YET!

PARTICLE PHYSICS CANDIDATES:

SUSY PARTNERS – MODEL DEPENDENT
(LSP: **Neutralinos**, Gravitinos …)
AXIONS
STERILE (LIGHT keV) NEUTRINOS in νMSM
D-MATTER (STRINGY) …

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SUSY PARTICLE SPECTRUM

(□ = superpartners)

spin $\frac{1}{2}$	spin 0	spin 1	spin $\frac{1}{2}$
quark q_L, q_R	squark $\tilde{q}_L$, $\tilde{q}_R$	W_3, B	$\tilde{W}_3$, $\tilde{B}$
lepton ℓ_L, ℓ_R	slepton $\tilde{\ell}_L$, $\tilde{\ell}_R$	$W^\pm$	$\tilde{W}^\pm$
higgsino $\tilde{H}_1$, $\tilde{H}_2$	Higgs H_1, H_2	gluino g	gluino $\tilde{g}$

graviton (spin 2) ↔ gravitino (spin 3/2)

charginos

$\tilde{W}^\pm$, $\tilde{H}^\pm$ $\Longleftrightarrow$ $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$

$\tilde{B}$, $\tilde{W}_3$, $\tilde{H}_1$, $\tilde{H}_2$ $\Longleftrightarrow$ $\tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0$

neutralinos

- *R*-parity: $R = (-1)^{3(B-L)+2s}$ →
  - ***R*-parity conservation hinted but *not required* by proton stability**
  - **not a fundamental symmetry**

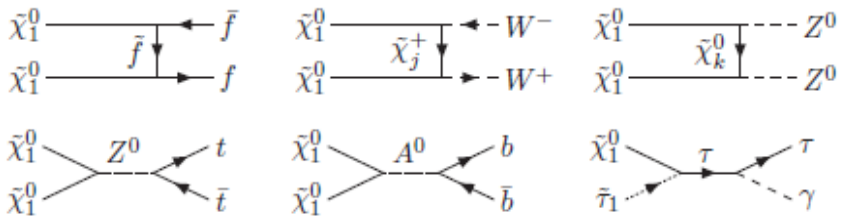
***R*=** { **+1, for SM particles**; **−1, for superpartners**

- If *R*-parity is conserved:
  - **SUSY-partners are always produced in pairs (*R* is a multiplicative quantum number)**
  - **Lightest SUSY-particle (LSP) is stable**
    - **should be colorless and neutral**
    - **weakly interacting → escapes the detector undetectable → *large missing energy***
    - **dark matter candidate**

Neutralino dark matter

Neutralino mass matrix in bino–wino–higgsino basis $\psi_j^0 = (-i\lambda', -i\lambda^3, \psi_{H_1}^0, \psi_{H_2}^0)$ is

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$



M_1, M_2: the U(1) and SU(2) gaugino masses, μ: higgsino mass parameter, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, $s_\beta = \sin\beta$, $c_\beta = \cos\beta$ and $\tan\beta = v_2/v_1$ ($v_{1,2}$ v.e.v. of Higgs fields $H_{1,2}$).

Matrix diagonalized by unitary mixing matrix N,

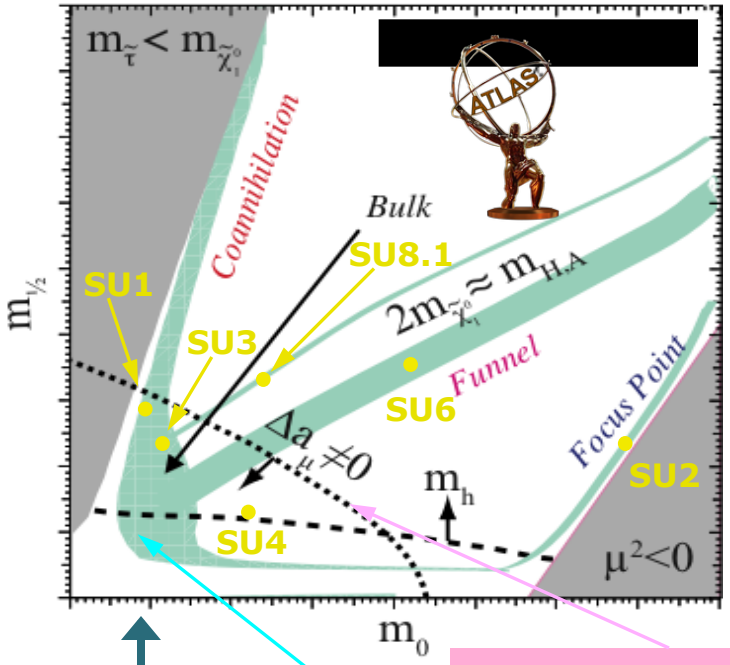
$N^* \mathcal{M}_N N^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$, where $m_{\tilde{\chi}_i^0}$, $i = 1, ..., 4$, are the (non-negative) masses of the physical neutralino states with $m_{\tilde{\chi}_1^0} < ... < m_{\tilde{\chi}_4^0}$. The lightest neutralino is then:

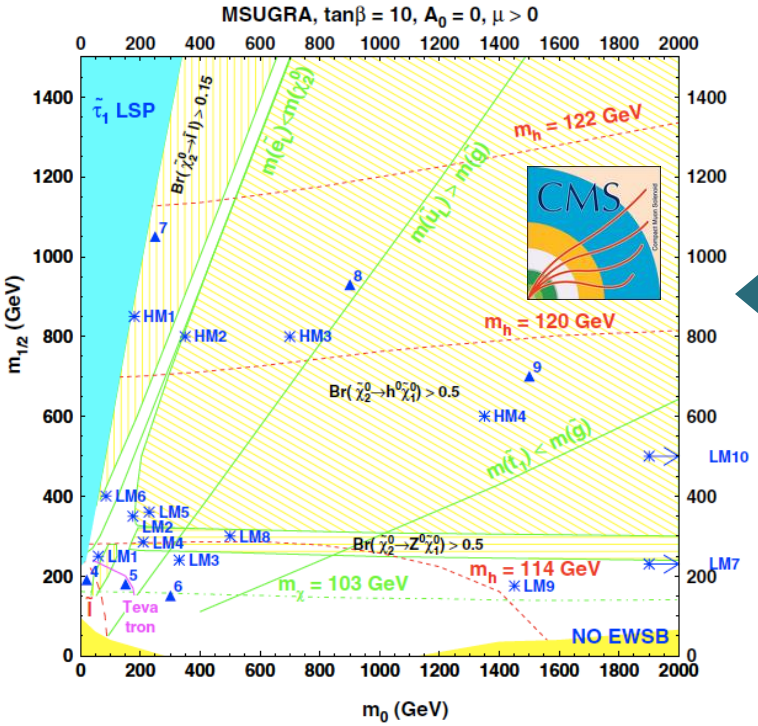
$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2 \,.$$

SUSY model framework

- **Minimal SuperSymmetric Standard Model (MSSM) contains >100 free parameters**
  → assume specific physically-motivated model (Э gravity) for systematic studies
- **Simplest: minimal SuperGravity (mSUGRA)**
  - **local SUSY with soft breaking mediated by gravitational interactions**
  - **universal masses and couplings at GUT scale**
    → 5 free parameters: m_0, $m_{1/2}$, tanβ, A_0, sgn(μ)

qualitative picture – no mass scale





Benchmark points for detailed studies

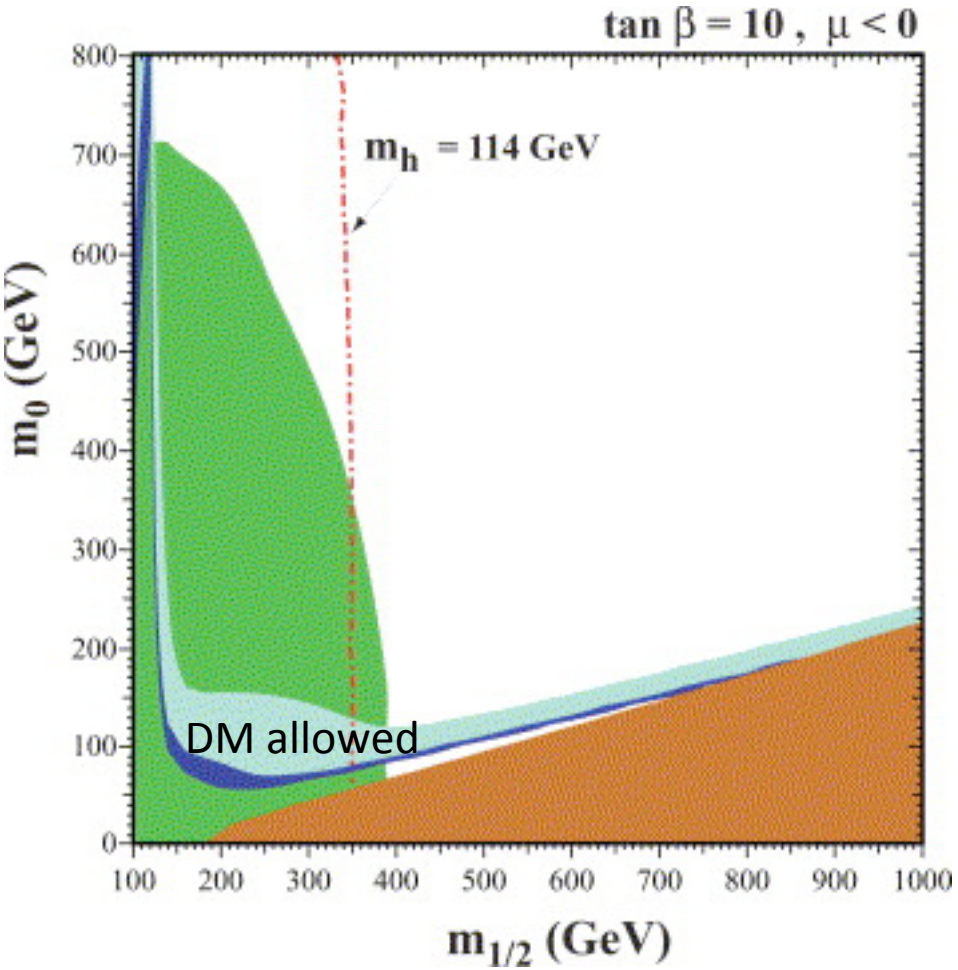
$(g-2)_\mu$ measurements

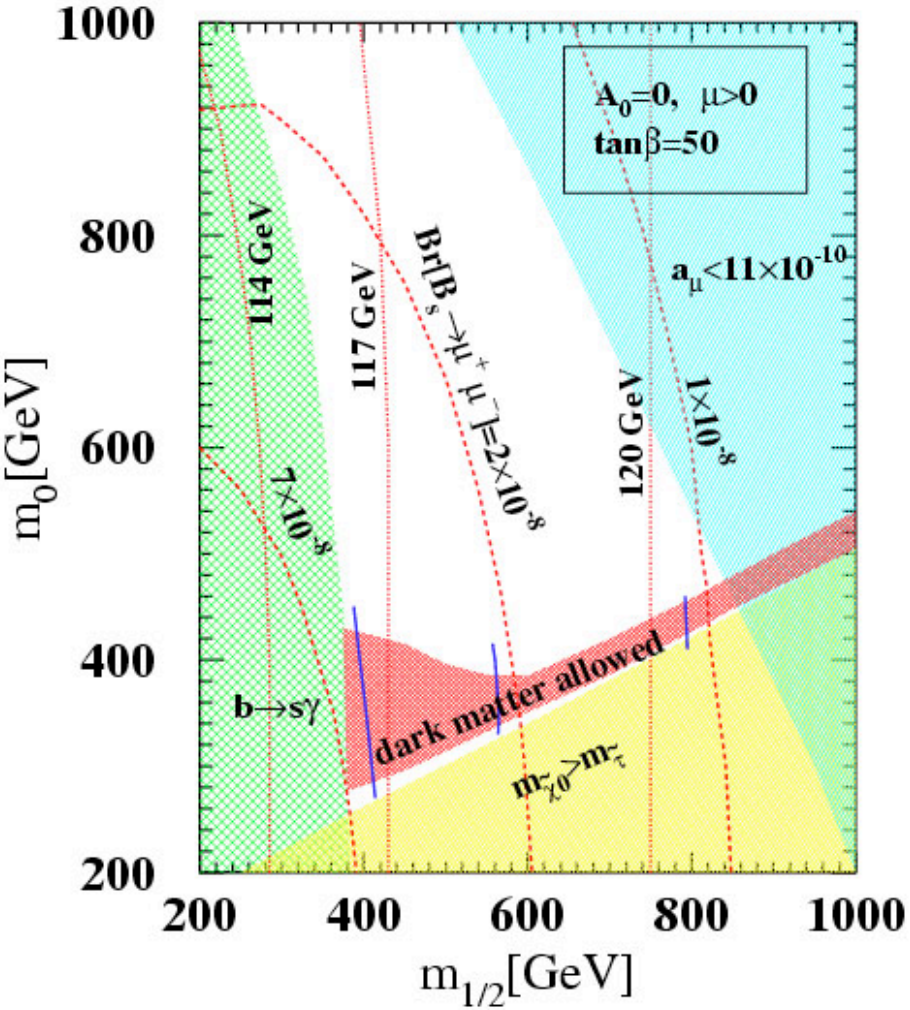
WMAP constraints on neutralino relic density

Other models also investigated *(not presented here)*

- **GMSB: gauge messengers; light gravitino LSP**
- **AMSB: anomalies in SUGRA $\mathcal{L}$; no flavour problem**

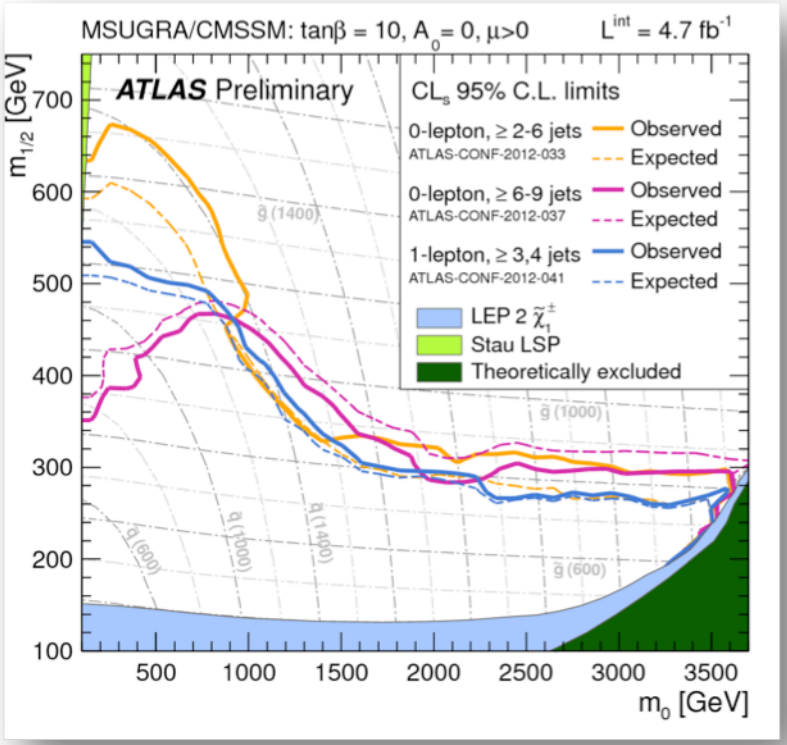
COSMOLOGICALLY-ALLOWED MSSM REGIONS

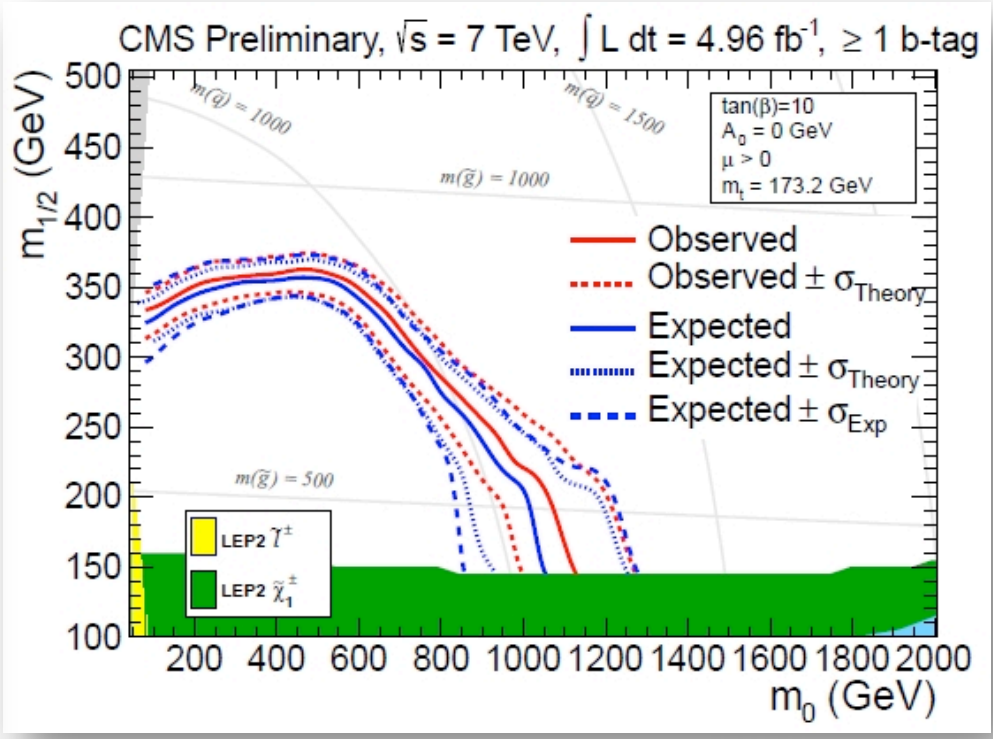




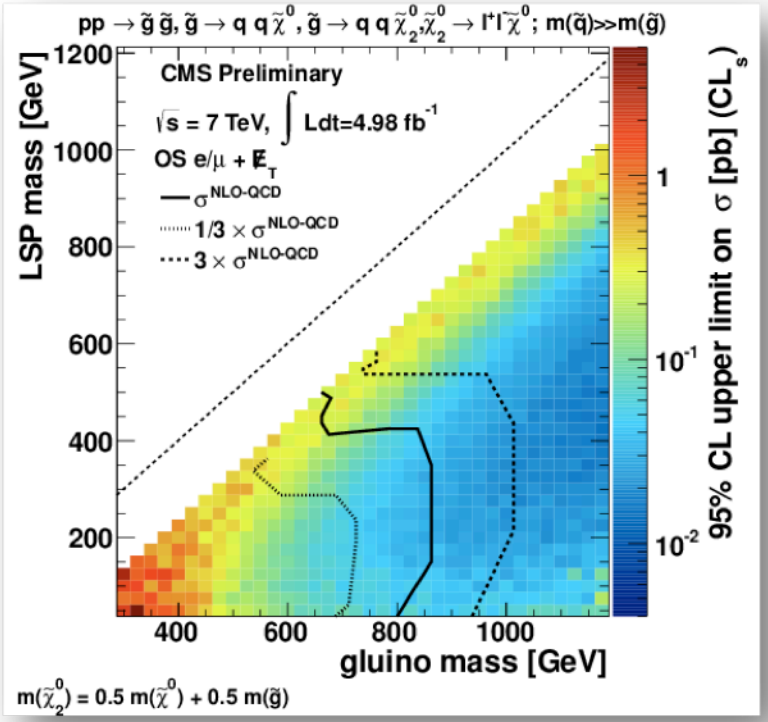
Several Candidates for Dark Matter (DM)–NO CONCRETE EXPLANATION YET !

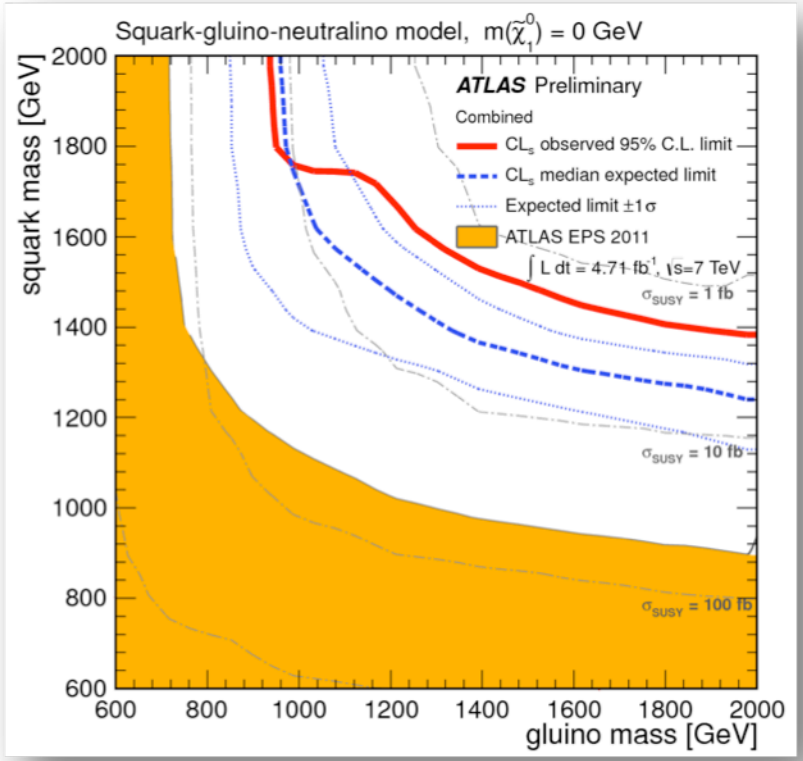
LHC SEARCHES FOR MSSM: SEEM TO RULE OUT @ PRESENT COSMOLOGICALLY-ALLOWED REGIMES FOR SUSY DM



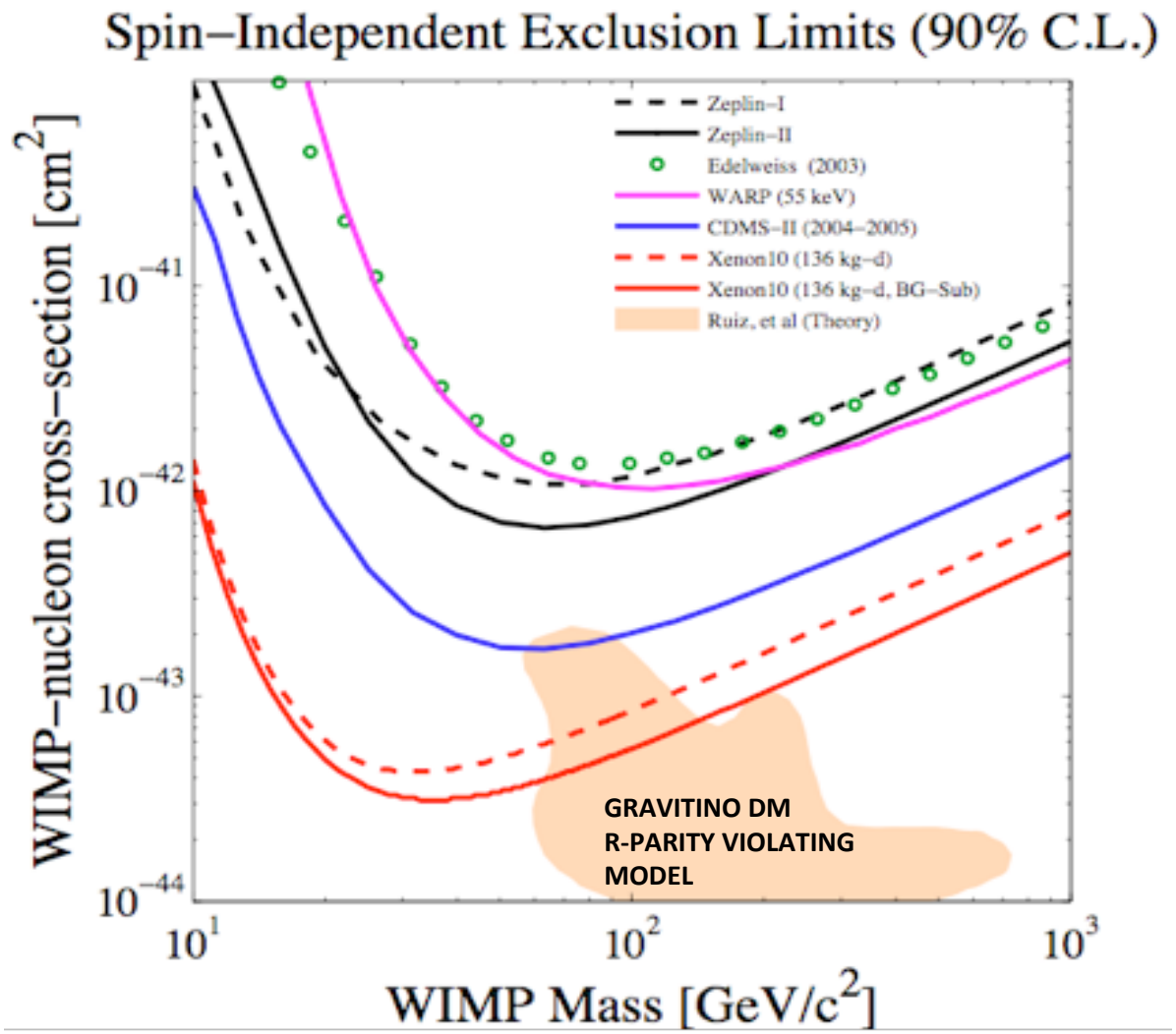


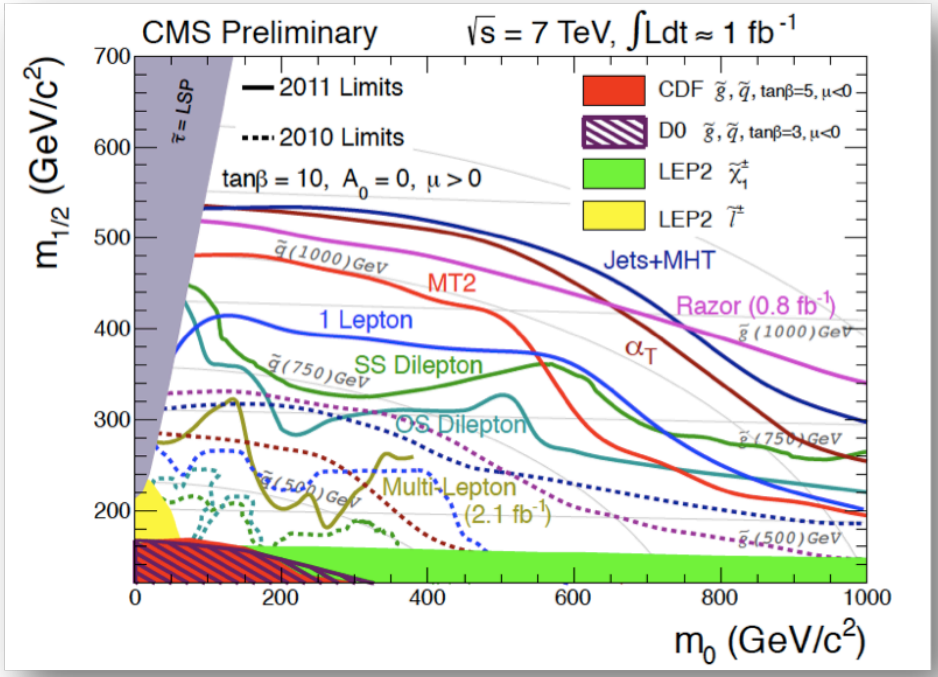
SUSY EXCLUSION PLOTS @ LHC



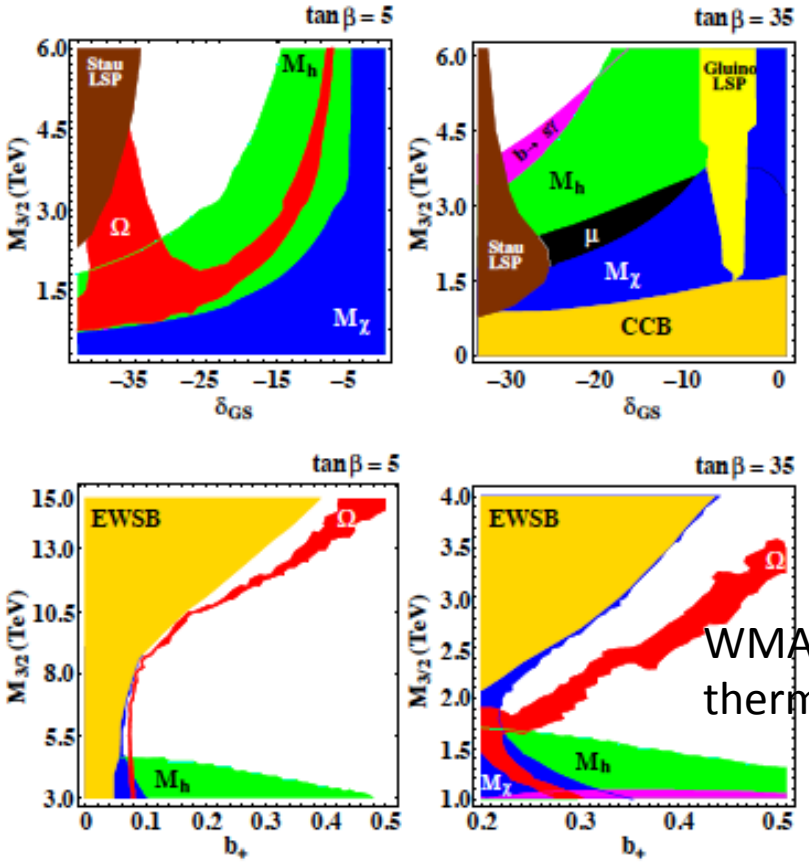


DIREDCT DM SEARCHES: ALSO CONSTRAIN STRONGLY SUSY DM





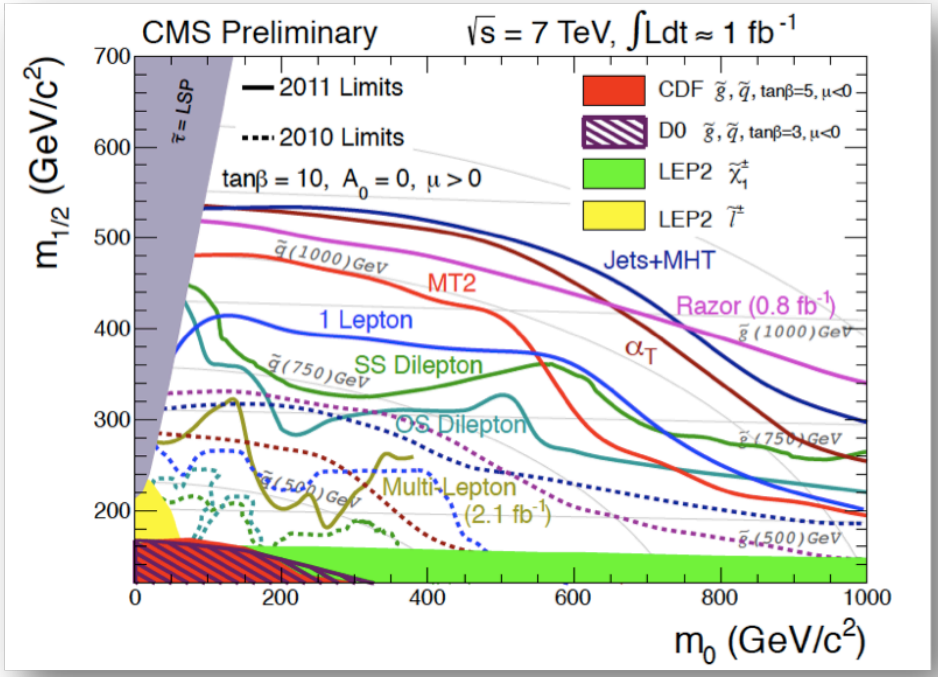
SO.... IS minimal SUSY ruled out as Dark Matter CANDIDATE?



MOTIVATION FOR STUDYING ...STRINGY COSMOLOGIES

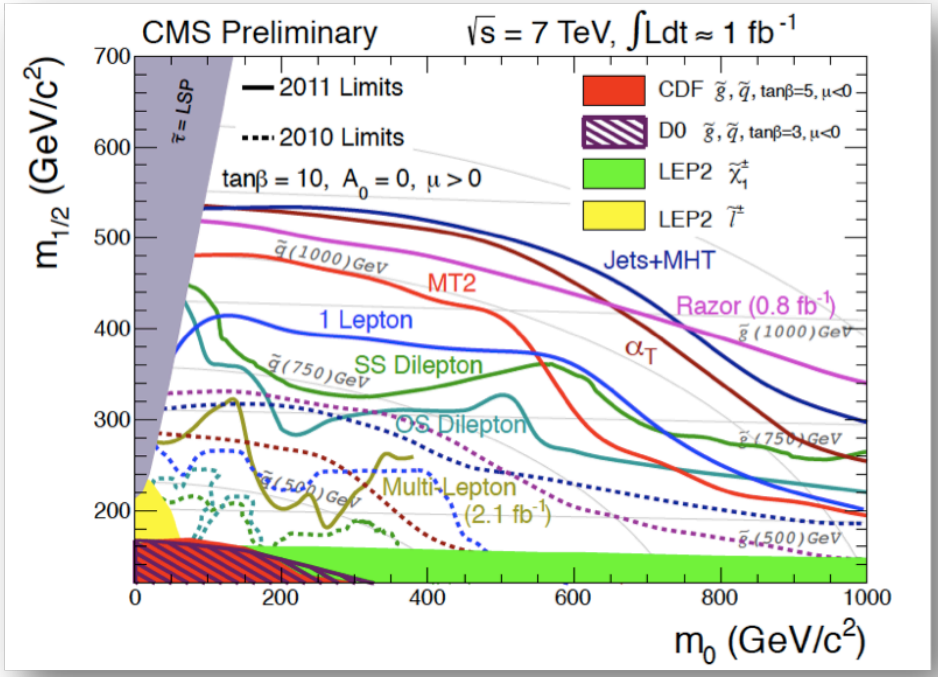
WMAP allowed thermal DM

Non-thermal DM characterises several stringy models, e.g. Heterotic Strings → very different parameter spaces for SUSY .... WMAP constraints can be evaded



MOTIVATION FOR STUDYING …STRINGY COSMOLOGIES

Running Dilaton or Moduli Fields in *String Cosmology* increase cosmologically allowed parameter space & push even minimal SUSY partner masses higher ….



MOTIVATION FOR STUDYING ...STRINGY COSMOLOGIES

This Talk

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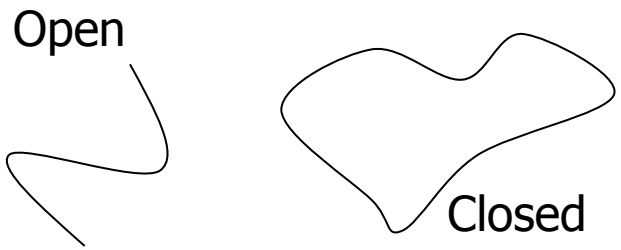
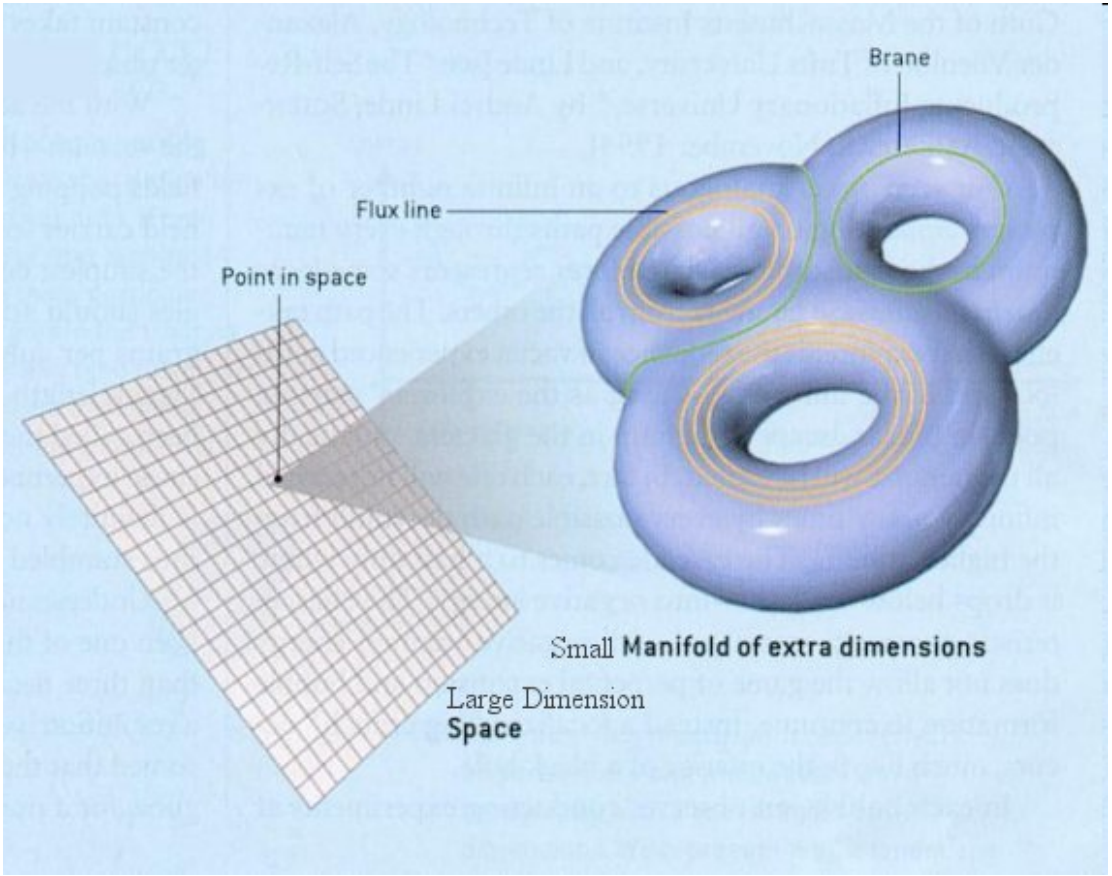
What is String Theory?

Fundamental Excitations are not point-like but one-dimensional (strings)



ONE VERSION :
Strings live in Large Four space-time dimensions but have extra dimensions ``Curled-up'' in small-size but of complicated Geometry spaces



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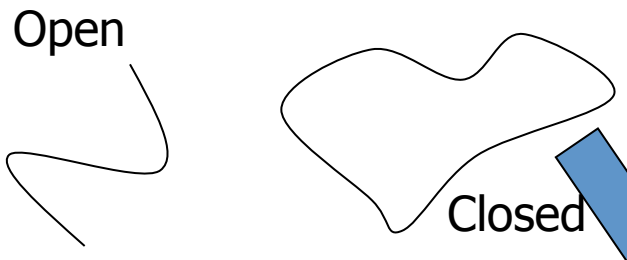

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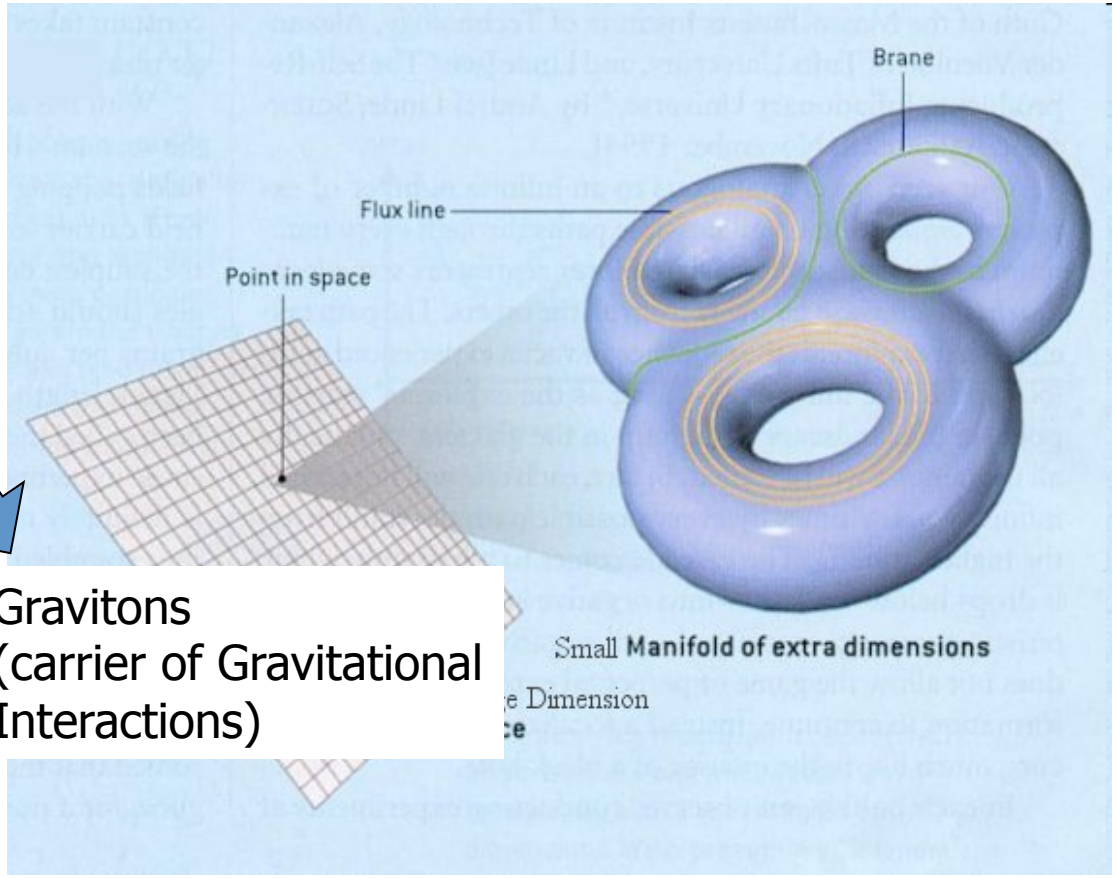

Gravitons
(carrier of Gravitational Interactions)

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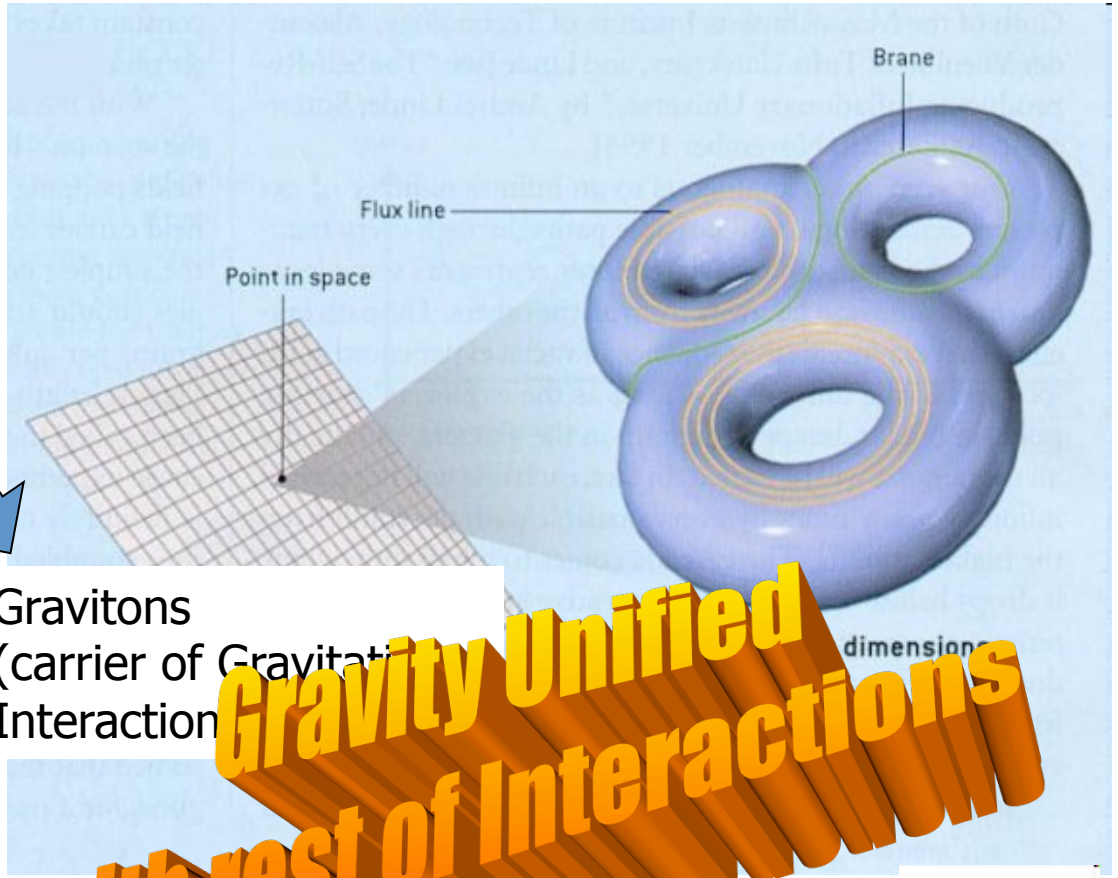
Open

Closed



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Gravitons
(carrier of Gravitati
Interaction

Gravity Unified with rest of Interactions

STRING MODULI FIELDS

SCALAR FIELDS WITH POTENTIAL FUNCTIONS CHARACTERIZED BY CONTINUOUS FAMILIES OF GLOBAL MINIMA
– Their expectation value labels STRING BACKGROUNDS

STRING MODULI INCLUDE:

(i) THE DILATON FIELD, Φ, WHOSE STABILIZED <Φ> is ASSOCIATED WITH THE STRING COUPLING $g_s = e^{<\Phi>}$ → **4-d Gauge couplings**

We shall consider*: non-stabilized dilatons in Non-Equilibrium Cosmologies & study (dilution) effects on Dark Matter (DM) if Dilaton dominance at DM decoupling → effects on Collider Searches for Supersymmetry*

Lahanas, NEM, Nanopoulos
Lahanas , Spanos

(ii) SCALAR FIELDS ASSOCIATED WITH **EXTRA** DIMENSIONS with **no classical** potential (i.e. generated by string loop corrections, suppressed by powers of g_s and with **Planck scale suppressed couplings** to matter. The expectation values of the moduli classically describe the ***size*** and ***configuration*** of the ***curled up extra dimensions***.

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Acharya, Kane, Kuflik …

STRING MODULI FIELDS

SCALAR FIELDS WITH POTENTIAL FUNCTIONS CHARACTERIZED BY CONTINUOUS FAMILIES OF GLOBAL MINIMA
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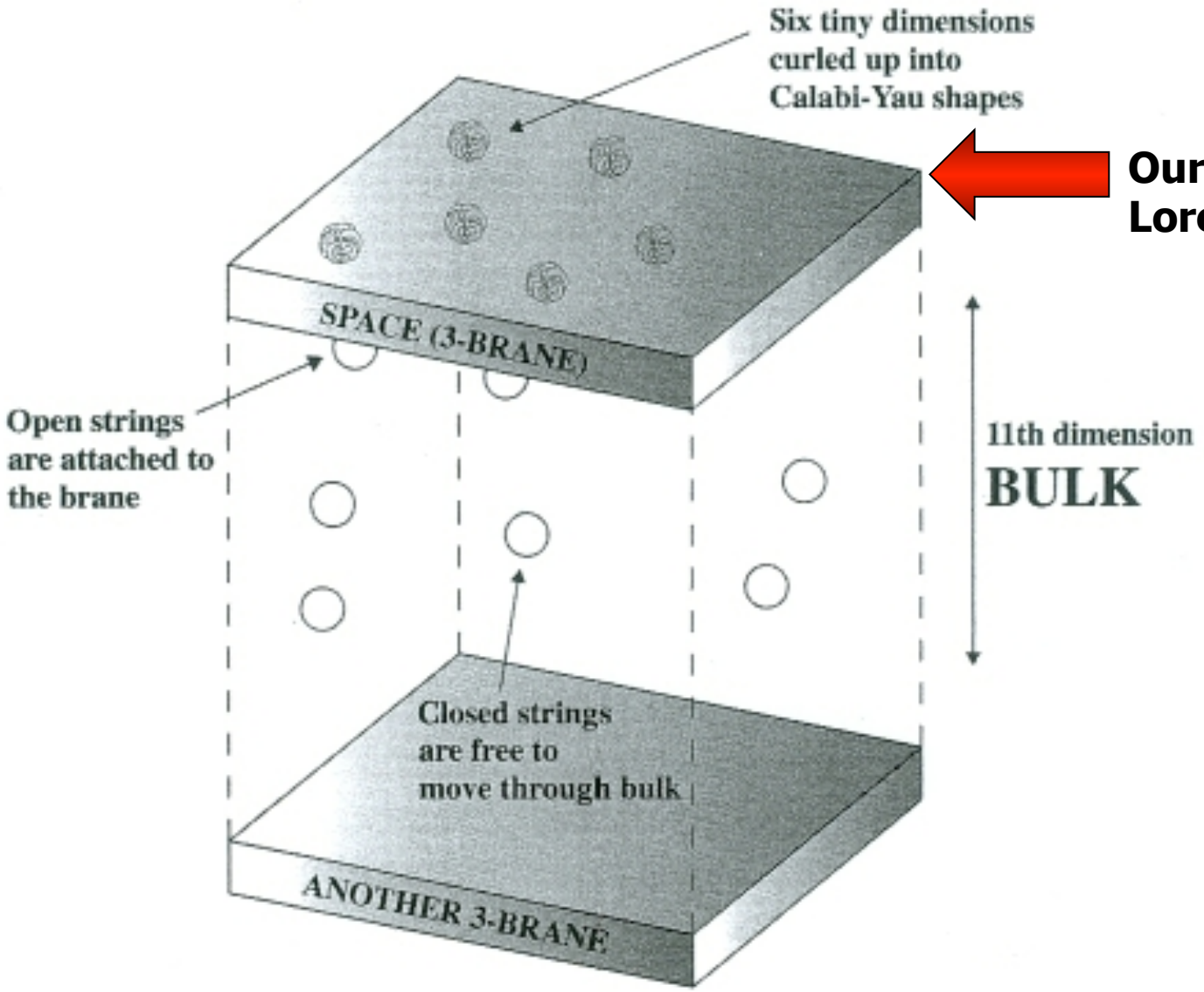

Our Universe
Lorentz Invariant

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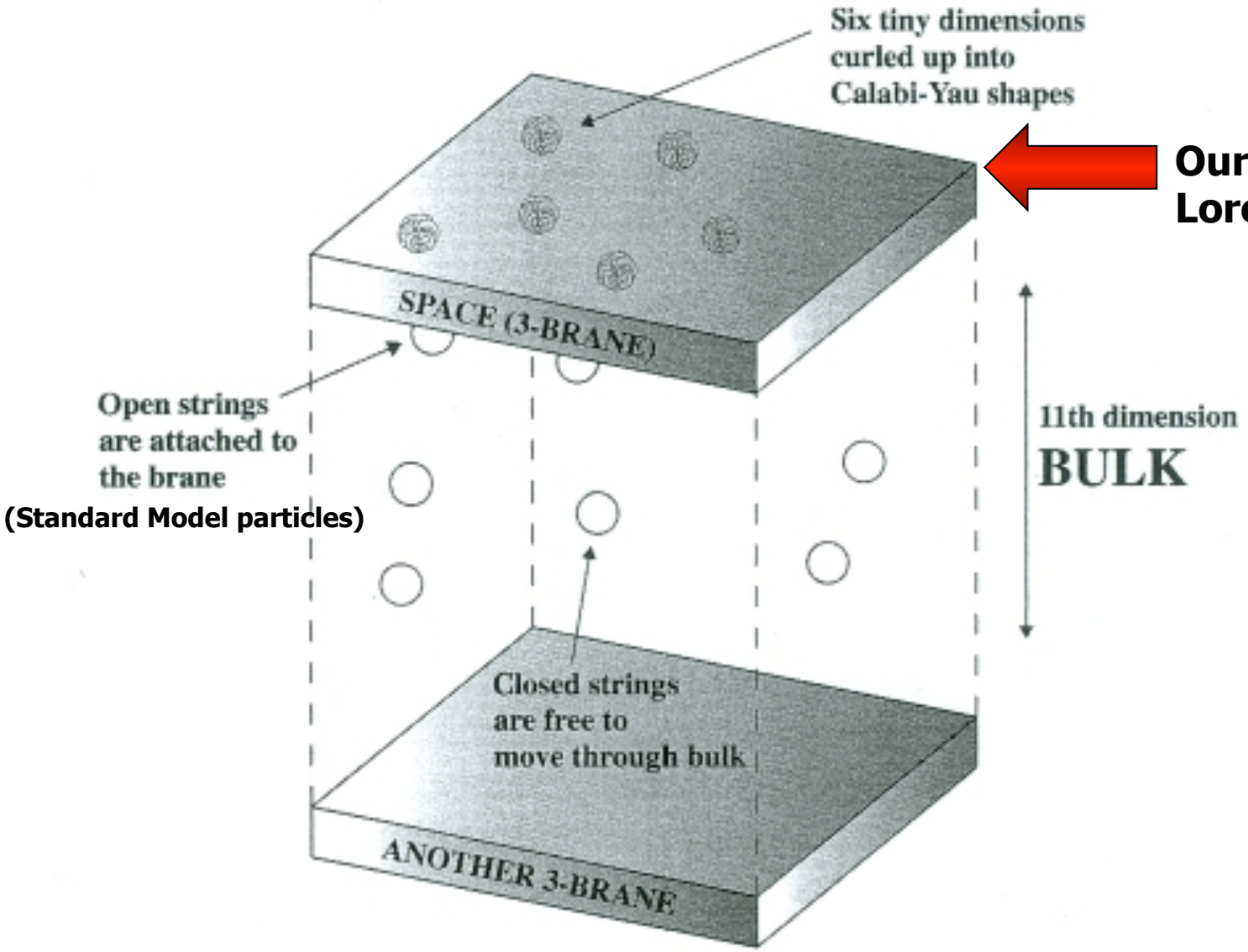

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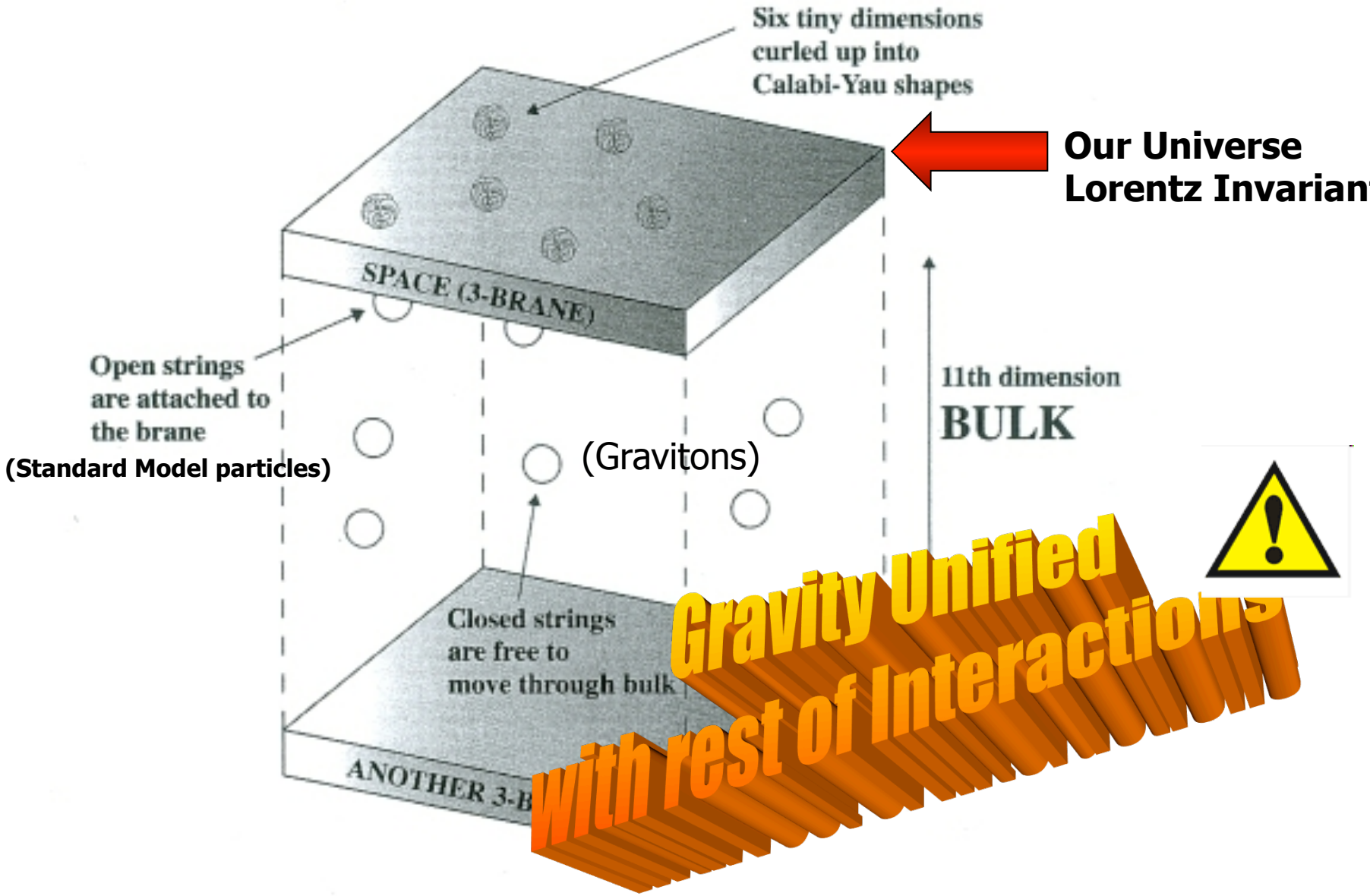

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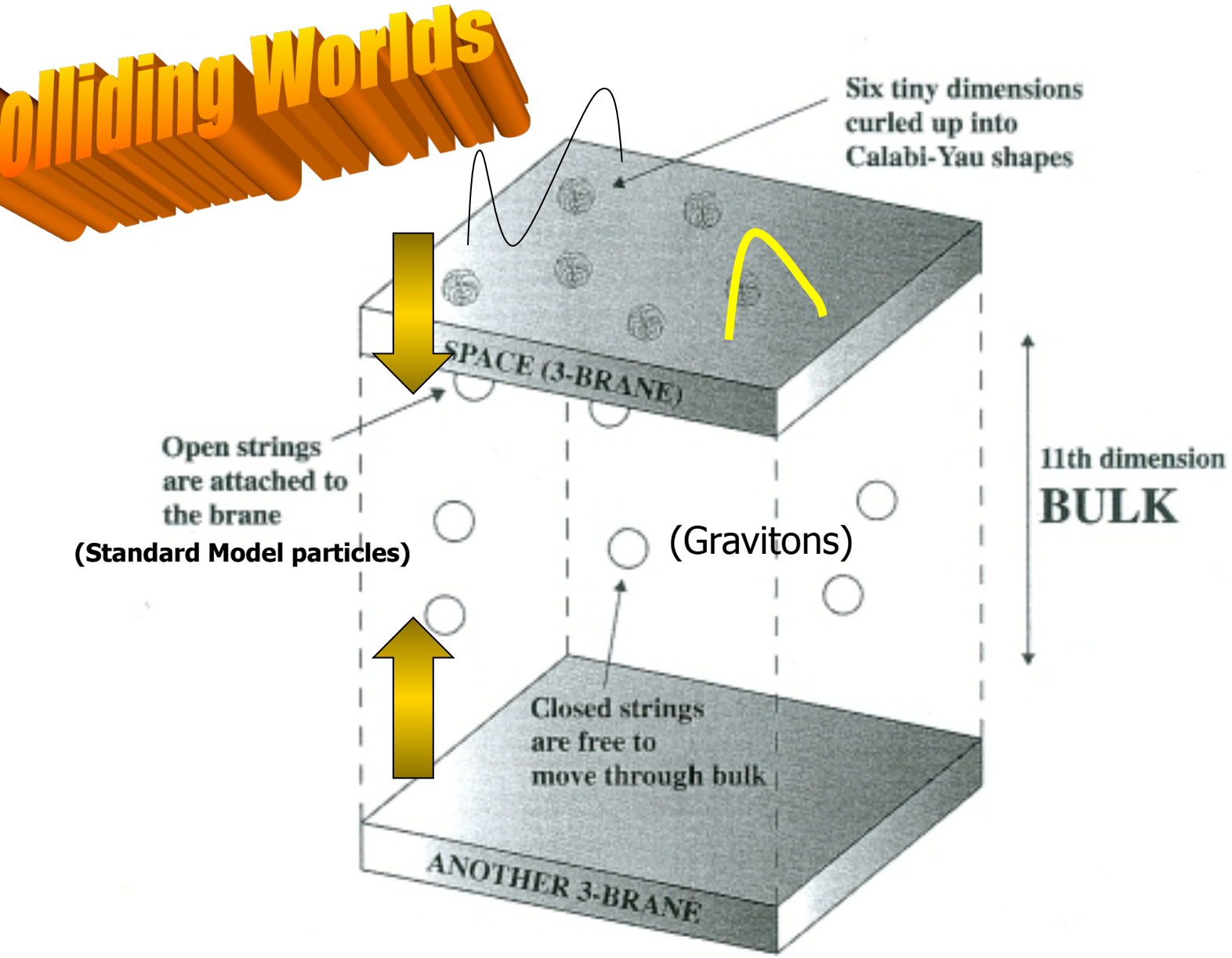

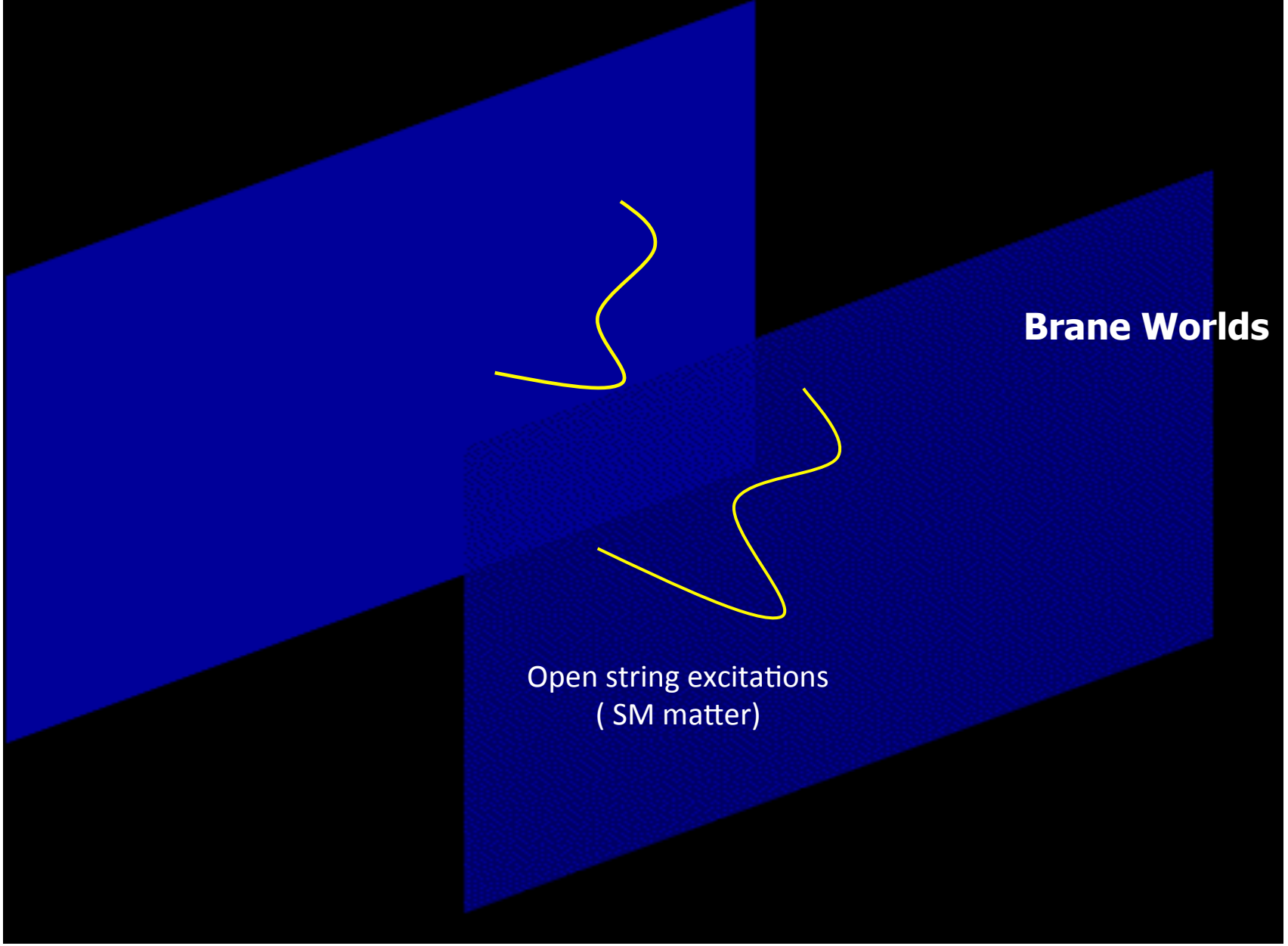

Colliding & Bouncing Brane world Cosmology

ANTOHER VERSION: COLLIDING BRANE WORLDS :

Moving Brane Worlds

Target-space Supersymmetry Breaking,

Brane Collision (Bounce)
World-sheet Conformal Invariance violation
Restoration by:
Liouville Dressing,
Non-equilibrium strings
Non-trivial time dependent
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COLLIDING BRANE WORLDS:

BRANE RECOIL (BOUNCE)-INDUCED
DEPARTURES FROM CONFORMAL INVARIANCE
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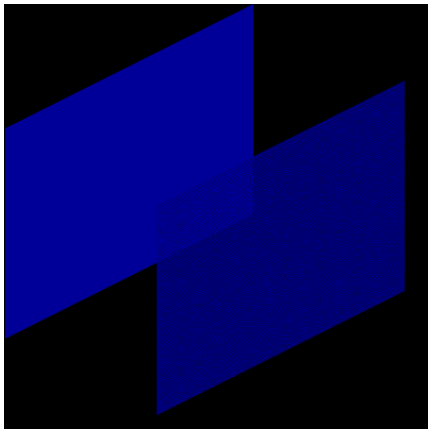

$$\mathcal{V}_{\rm recoil} = \int_{\partial\Sigma} U_J X^0 \Theta_\varepsilon(X^0) \partial_n X^J \ ,$$
$$J = \text{BULK index},$$

DILATON IN THIS CASE:

Liouville – mode φ dressing → restoration of world-sheet conformal invariance :

$$\Phi(\varphi) = Q(\varphi)\,\varphi$$

GLOBALLY DESTABILIZED DILATON
….Relevant for Cosmology

``Running'' Central charge deficit in identical Brane-Worlds recoil case:

$$Q^2 = \frac{(\vec{U}_J^2)^2}{t^2 + t_P^2}$$

$$\varphi = -\sqrt{2}\,t$$

$$t = \text{Minkowski time}$$

Gravanis, NEM

Φ → constant
$t >> t_P$
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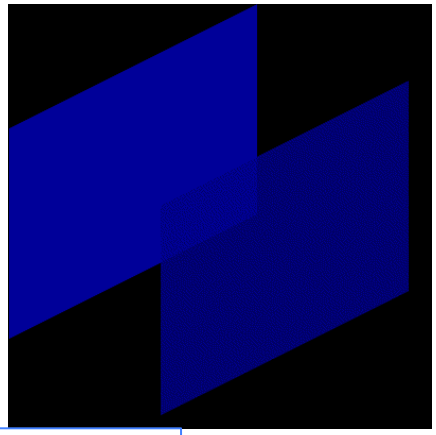

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Bulk Recoil velocity of Brane World,
non-conformal, anomalous dimension - $\varepsilon^2/2$

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Basic Liouville Equation-Relaxation

$$\frac{d^2}{d\varphi^2}g^i + Q(\varphi)\frac{d}{d\varphi}g^i = \beta^i + \dots$$

$$\varphi = -\sqrt{2} \times (\text{FRW time})$$

Background fields:
$G_{\mu\nu}$, A_μ, Ψ …

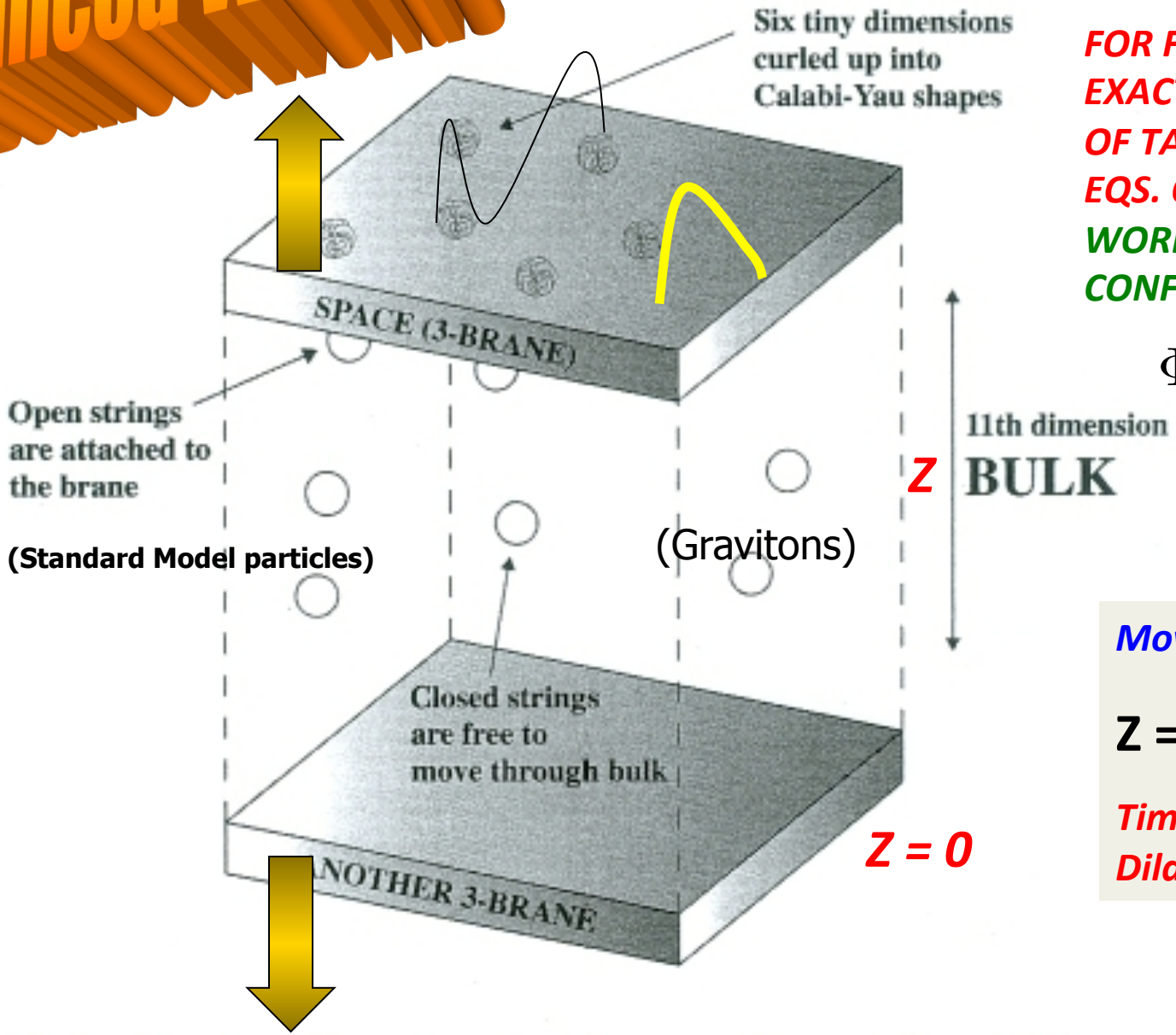
World-Sheet Renormalization Group (wsRG) of g^i

NEAR A world sheet RG FIXED POINT: near equilibrium, e.g. late Universe

TIME-DEPENDENT DILATONS IN ADIABATICALLY MOVING (BOUNCED) BRANES:

Bounced Worlds

Rizos, NEM



FOR FIXED Z WARPED E.D.:
EXACT SOLUTIONS
OF TARGET SPACE
EQS. OF MOTION =
WORLD-SHEET
CONFORMAL INVARIANCE

$$\Phi(Z) = \phi_0 \ln|Z|, \qquad \phi_0 < 0$$

Moving Branes:

Z = U t → Φ = Φ(t)

Time-dependent
Dilaton backgrounds

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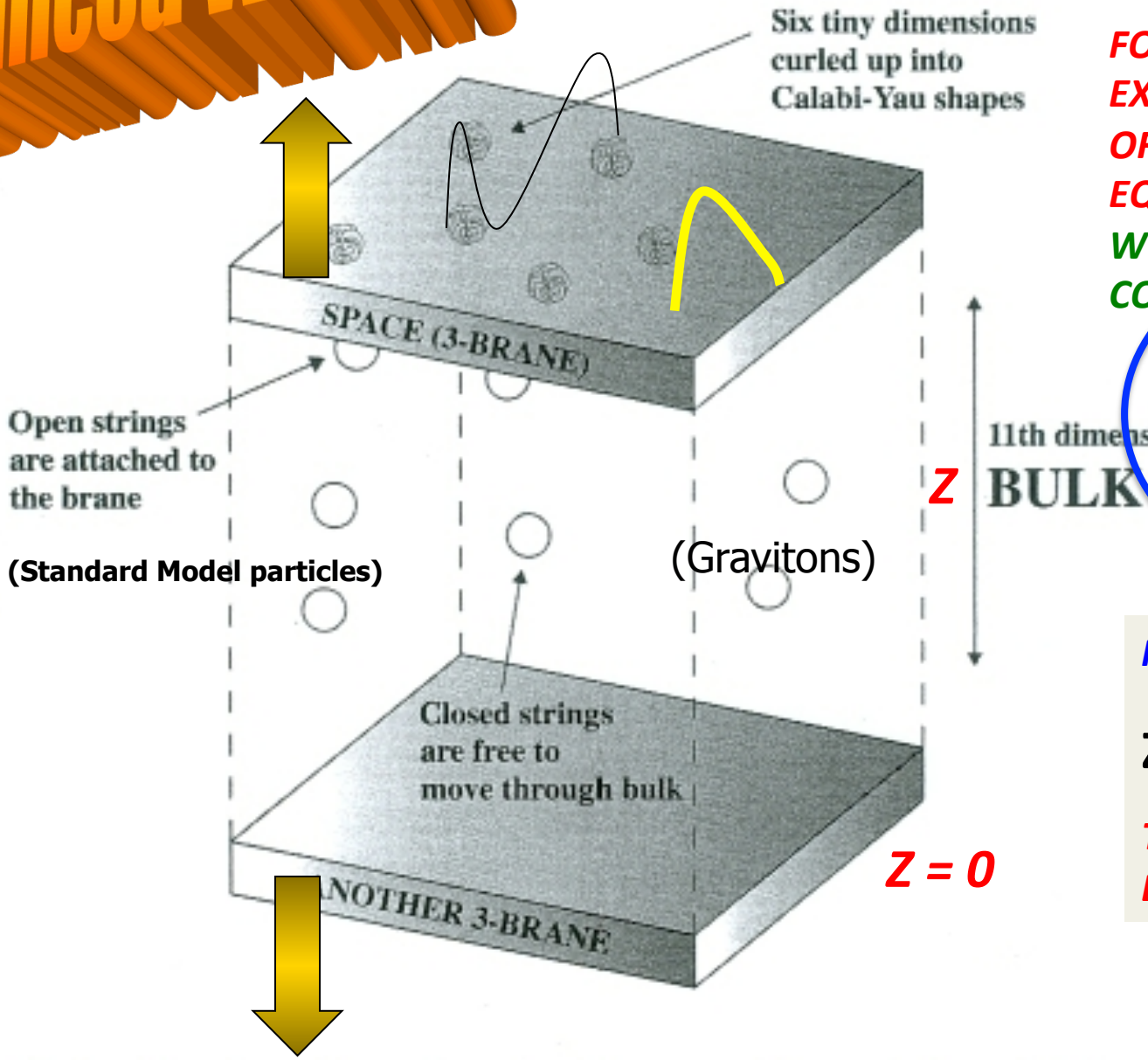

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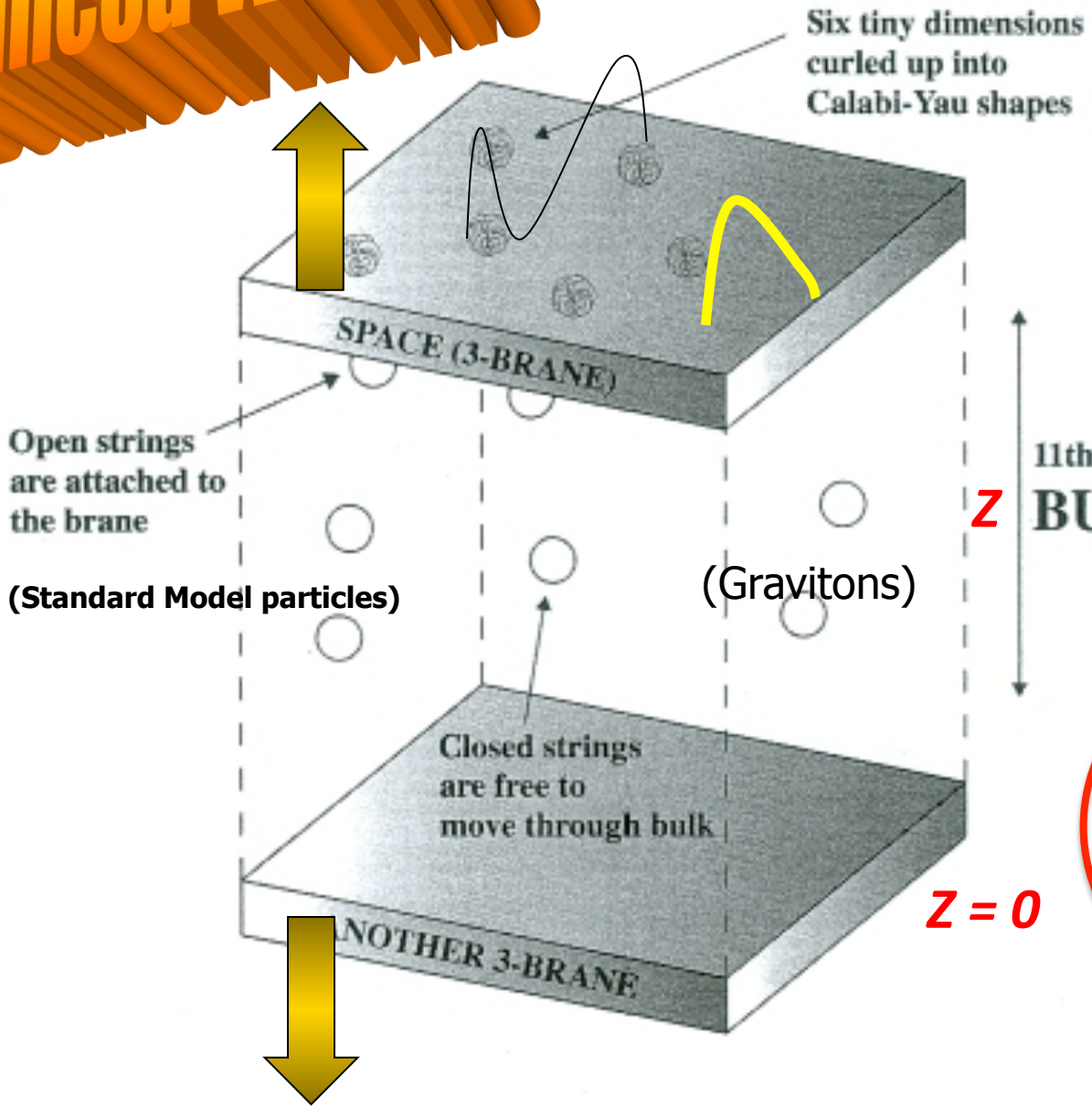

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GENERIC ASPECTS OF DILATON COSMOLOGIES

NON-TRIVIAL DILATON EFFECTIVE 4-d ACTIONS IN STRING FRAME

$$\mathcal{S}^{(4)} = \frac{1}{2\,\alpha'}\int d^4x\sqrt{-G}\left(e^{\Psi(\phi)}\,R(G) + Z(\phi)(\nabla\phi)^2 + 2\alpha' V(\phi)\right) + \dots$$

$$-\frac{1}{16\pi}\int d^4x \int \sqrt{G}\,\frac{1}{\alpha(\phi)}\,F^2_{\mu\nu} + \mathcal{S}_{\rm matter}[\phi, G_{\mu\nu}, {\rm matter}]$$

Including String Loops: $e^{\Psi[\phi]} = c_0\,e^{-2\phi} + c_1 + c_2\,e^{2\phi} + \dots\ , \quad Z(\phi) = 4 + \dots$

$$V(\phi) = 2Q^2\,e^{-2\phi} + \text{string loop corrections}$$

Canonically Normalize Einstein term by redefining graviton (Einstein Frame)

$$G_{\mu\nu} \to g_{\mu\nu} = (e^{-2\phi} + \dots)\,G_{\mu\nu} \quad \to \quad \mathcal{S}^{(4)}_E = \frac{1}{2\,\alpha'}\int d^4x\sqrt{-g_E}\,R(g_E) + \dots$$

Assume FRW Cosmic backgrounds, and define FRW time

$$(e^{-\phi} + \dots)\,dt = dt_E \quad \to \quad ds^2 = -dt_E^2 + a^2(t_E)\,h^{ij}\,dx_i dx_j$$

$$V(\phi) \quad \to \quad V_E(\phi) = 2Q^2\,e^{+2\phi} + \text{string loop corrections}$$

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EQUATIONS OF MOTION FOR THE DILATON UNIVERSE

Off-Shell Liouville Equations: $\left(\rho_\phi = (\dot\phi)^2 + V(\phi)/2\ ,\ p_\phi = (\dot\phi)^2 - V(\phi)/2\ \right)$

$$3H^2 = \rho_m + \rho_\phi + \frac{e^{2\phi}}{2}\mathcal{J}_\phi\ ,$$

$$2\frac{dH}{dt_E} = -\rho_m - \rho_\phi - p_m - p_\phi + a^{-2}(t_E)\mathcal{J}_{ii}\ , \qquad i = 1,2,3,$$

$$\frac{d^2\phi}{dt_E^2} + 3H\frac{d\phi}{dt_E} + \frac{1}{4}\frac{\partial V}{\partial\phi} + \frac{1}{2}(\rho_m - 3p_m) = -\frac{3\ \mathcal{J}_{ii}}{2\ a^2} - \frac{e^{2\phi}\mathcal{J}_\phi}{2}\ ,$$

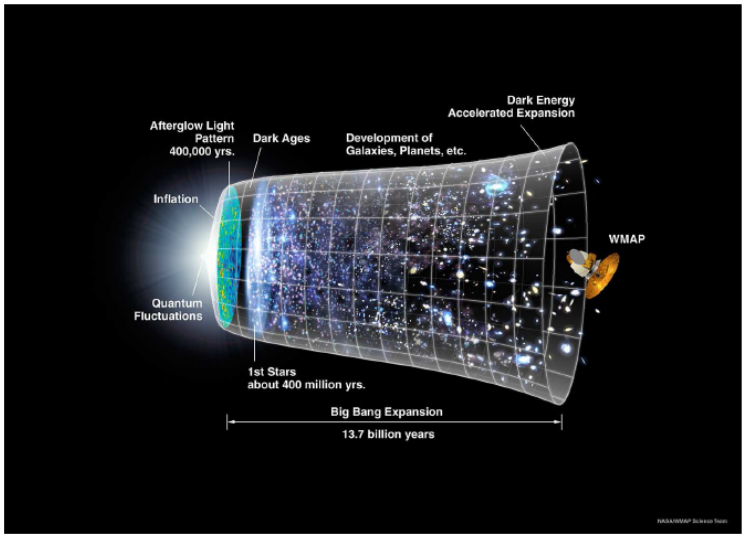
$$\mathcal{J}_\phi = e^{-2\phi}(\ddot\phi - \dot\phi^2 + Qe^\phi\dot\phi), \quad \mathcal{J}_{ii} = 2a^2\left(\ddot\phi + 3H\dot\phi + \dot\phi^2 + (1-q)H^2 + Qe^\phi(\dot\phi + H)\right)\ .$$

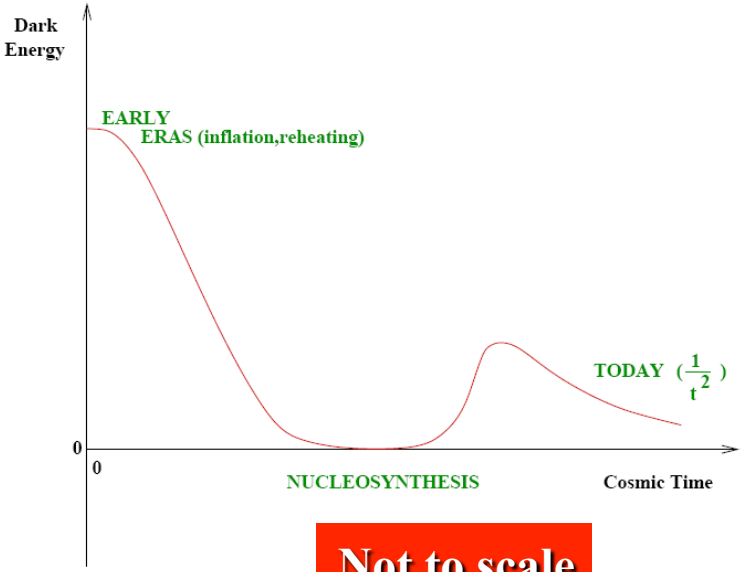
Matter (non) Conservation equations:

$$\dot\rho_m + 3H(\rho_m + p_m) + \dot Q(\partial V(\phi))/2\partial Q - \dot\phi(\rho_m - 3p_m) = 6(H + \dot\phi)a^{-2}\mathcal{J}_{ii}$$

In our bouncing Universe case: $$Q^2 = \frac{(\vec{U}_J^2)^2}{t^2 + t_P^2} \ll 1 \to \dot Q \sim \frac{1}{t^2} \ll Q$$

EVOLUTION OF A LIOUVILLE UNIVERSE





Not to scale

In Liouville string (Non-Equilibrium, off-shell) Dark Energy Models, Dilaton Dark Energy may be negligible at NUCLEOSYNTHESIS epoch.

Conformal Field Theory (Logarithmic CFT, in brane recoil models) $\longrightarrow$ asymptotic scaling with cosmic time $\sim 1/t^2$ (E.Gravanis, N.M.) .

NB: Cosmic Time $\Longleftrightarrow$ world-sheet Renormalizartion Group (RG) local Scale (Liouville mode), Irreversible (Zamolodchikov C-theorem) !

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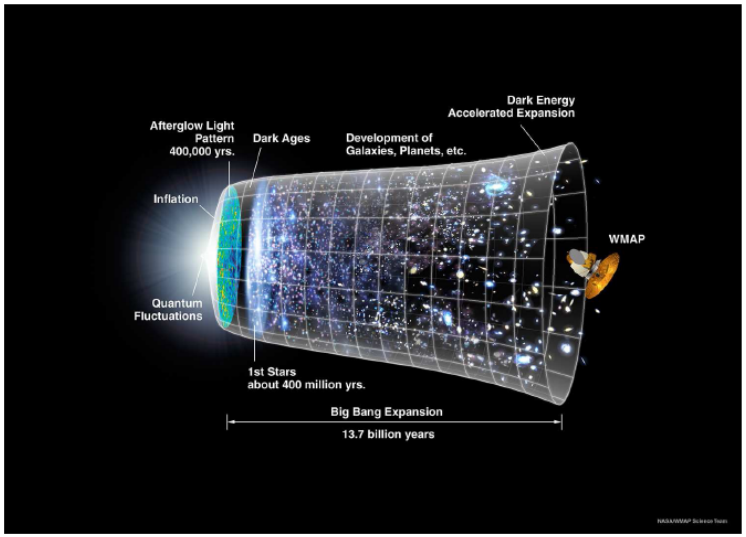

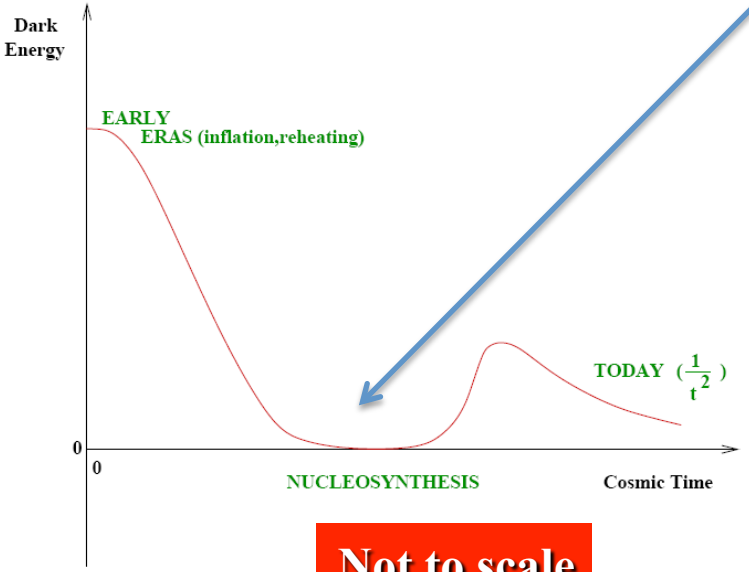

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DILATON EFFECTS ON DM

ASSUME DILATON DOMINANCE DURING DM DECOUPLING

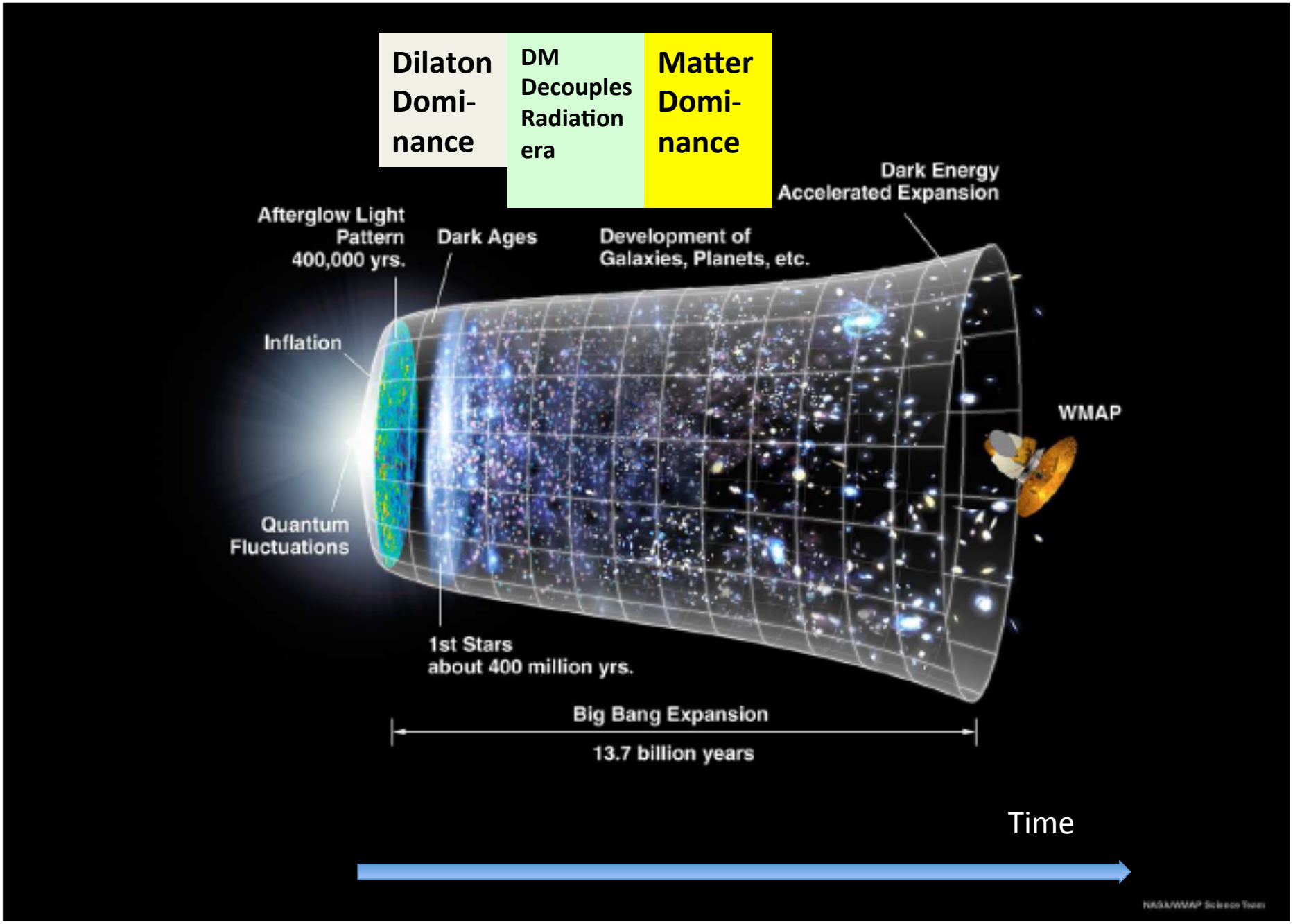
ASSUME DILATON POTENTIAL IS EXPONENTIAL WITH $\Phi \approx \mathrm{Ln}\,(a(t))$
BUT SUCH THAT DILATON MASS VERY LOW SO DECAY IS PROHIBITED

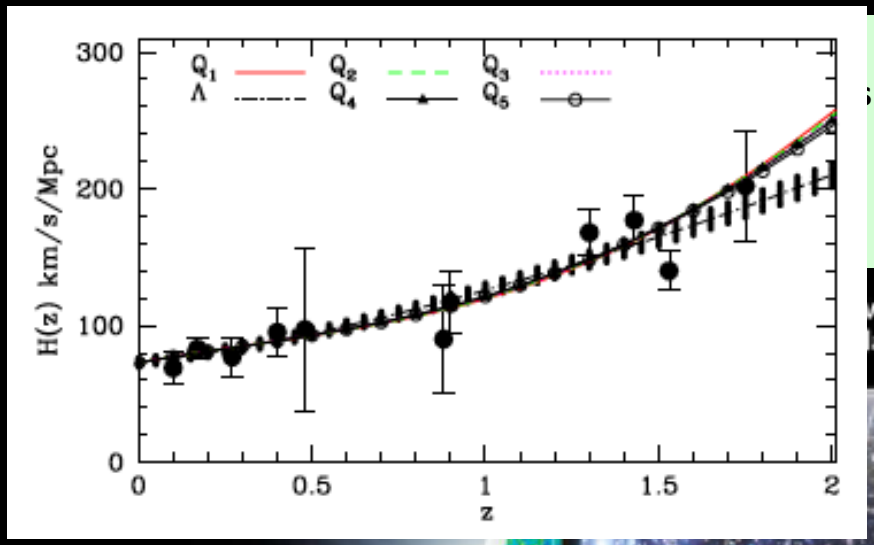
BOTH FEATURES GUARANTEED IN LIOUVILLE MODEL OF COLLIDING BRANE WORLDS

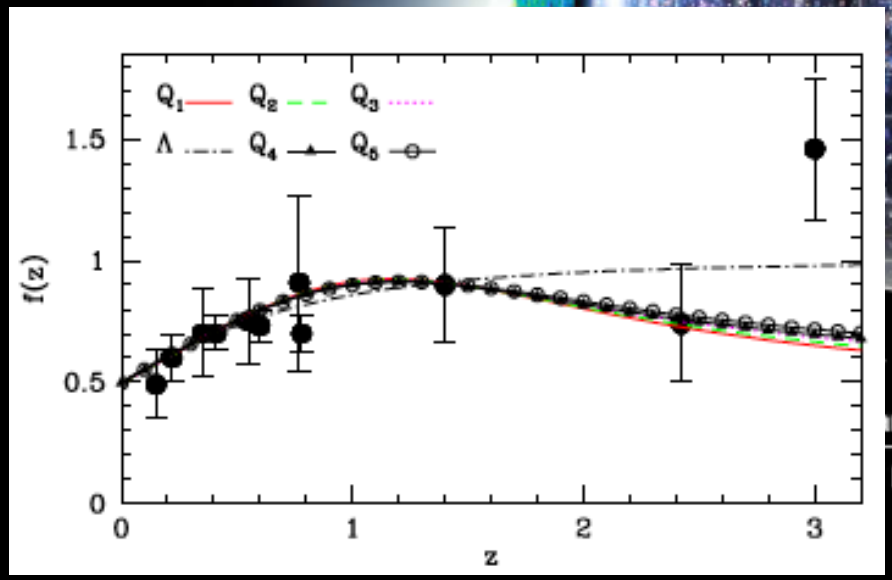
$$V(\phi) \sim 2Q^2\, e^{2\Phi} + \text{string loops}$$

$$Q^2 = \frac{(\vec{U}_J^2)^2}{t^2 + t_P^2} \ll 1$$

Sufficiently small (time-dependent) dilaton mass terms $O(Q^2\,\Phi^2)$ for sufficiently low brane-world bounce velocities
no dilaton decays to SM particles, except massless ones, photons, during dilaton dominance period.


Dilaton Domi-nance
DM Decouples Radiation era
Matter Domi-nance
Dark Energy Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years
Time





Matter Domi-nance

COSMOLOGY TESTS CONSISTENT WITH CURRENT DATA

GROWTH OF GALAXIES CAN DIFFERENTIATE DILATON COSMOLOGIES FROM STANDARD ΛCDM

Basilakos, NEM, Mitsou, Plionis 1107.3532, AP (2012)

Time

Equations of Motion, under the assumption of Dilaton dominance, ignore non-critical (non-equilibrium) terms

$$\ddot{\phi} + 3\,H\,\dot{\phi} + V^{'}(\phi) \;=\; 0\,,$$

$$3\,H^2 \;=\; \frac{\dot{\phi}^2}{2} + V(\phi)\,,$$

$$2\,\dot{H} \;=\; -\,(\,\varrho_\phi + p_\phi\,) \;=\; -\,\dot{\phi}^2\,.$$

$$\frac{d\rho}{dt} + 3\hat{H}(\,\rho + p) - \frac{\dot{\phi}}{\sqrt{2}}\,(\rho - 3p) = 0$$

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$$\frac{dn}{dt} + 3\frac{\dot{a}}{a}n = \Gamma(t)n + \int \frac{d^3p}{E}C[f] \quad , \quad \Gamma(t) \equiv \dot{\Phi} + \frac{1}{2}\eta\left(e^{-\Phi}g^{\mu\nu}\tilde{\beta}^{\rm Grav}_{\mu\nu} + 2e^{\Phi}\tilde{\beta}^{\Phi}\right), \; \eta = -1$$

$$2\,\dot{H} \;=\; -\,(\,\varrho_\phi + p_\phi\,) \;=\; -\,\dot{\phi}^2\,.$$

$$\frac{d\rho}{dt} + 3\hat{H}(\,\rho + p) - \frac{\dot{\phi}}{\sqrt{2}}\,(\rho - 3p) = 0$$

Lahanas, NEM, Nanopoulos

BOLTZMANN EQUATION FOR THERMAL DM SPECIES AFFECTED

$$\frac{dn}{dt} + 3\frac{\dot{a}}{a}\,n = \Gamma(t)\,n + \int \frac{d^3\mathbf{p}}{E}\,C[f(\mathbf{p},t)]$$

$$\Gamma(t) = \dot{\Phi} + \text{non} - \text{critical terms}$$

$$\dot{\Phi} < 0$$

Boltzmann equation Modifications for Thermal Dark matter Relics, e.g. Neutralinos

Lahanas, NEM, Nanopoulos

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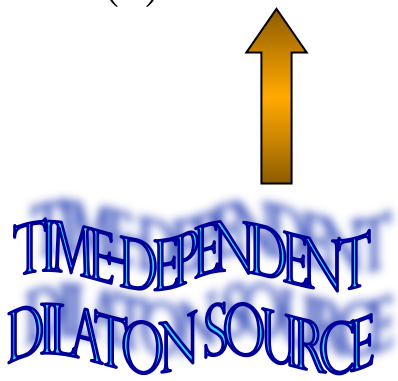

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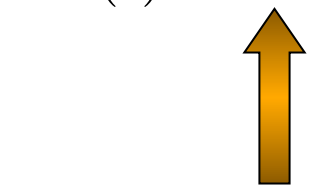

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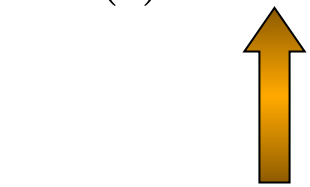

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Dilaton dominance in early Universe affects generically DM abundance

Lahanas

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(e.g. DM decoupling era)

$$\Phi \sim -\text{Ln}(a(t))$$

$$\dot{\Phi} \sim -H < 0$$

Dilaton dominance in early Universe affects generically DM abundance

Lahanas

Lahanas, NEM, Nanopoulos

Modified expression for relic abundance

$$\Omega_{\tilde{\chi}} h_0^2 \;=\; \left(\Omega_{\tilde{\chi}} h_0^2\right)_{no-source} \times \left(\frac{\tilde{g}_*}{g_*}\right)^{1/2} \exp\left(\int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{x} dx\right)$$

with $\left(\Omega_{\tilde{\chi}} h_0^2\right)_{no-source} = \frac{1.066 \times 10^9 \text{ GeV}^{-1}}{M_{Planck}\sqrt{g_*}\, J}$ $\qquad J \equiv \int_{x_0}^{x_f} \langle v\sigma \rangle \, dx.$

NB: Notice presence of non-critical/dilaton prefactor $R = \left(\frac{\tilde{g}_*}{g_*}\right)^{1/2} \exp\left(\int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{x} dx\right)$

O(10) Dilution for Dark matter (e.g. neutralinos)
Baryon Density unchanged

...OR MORE → CAN PUSH SUSY PARTNER MASSES OUT OF REACH OF LHC !

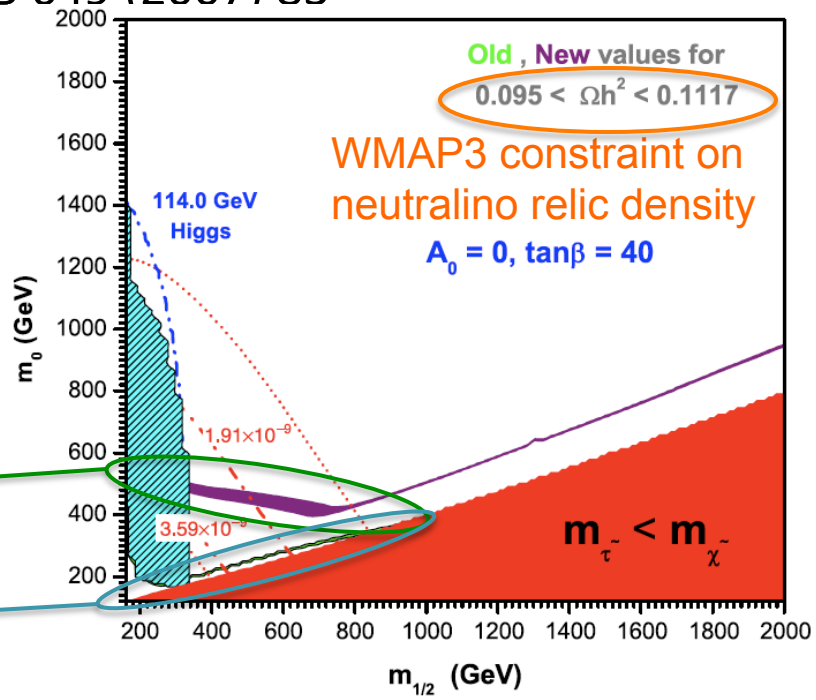
LHC signatures of Dilaton DM Dilution – More room for SUSY

Lahanas, NEM, Nanopoulos

- The presence of the time-dependent dilaton affects the relic density calculation, since it modifies the Boltzmann equation
- O(10) dilution for dark matter (neutralinos)

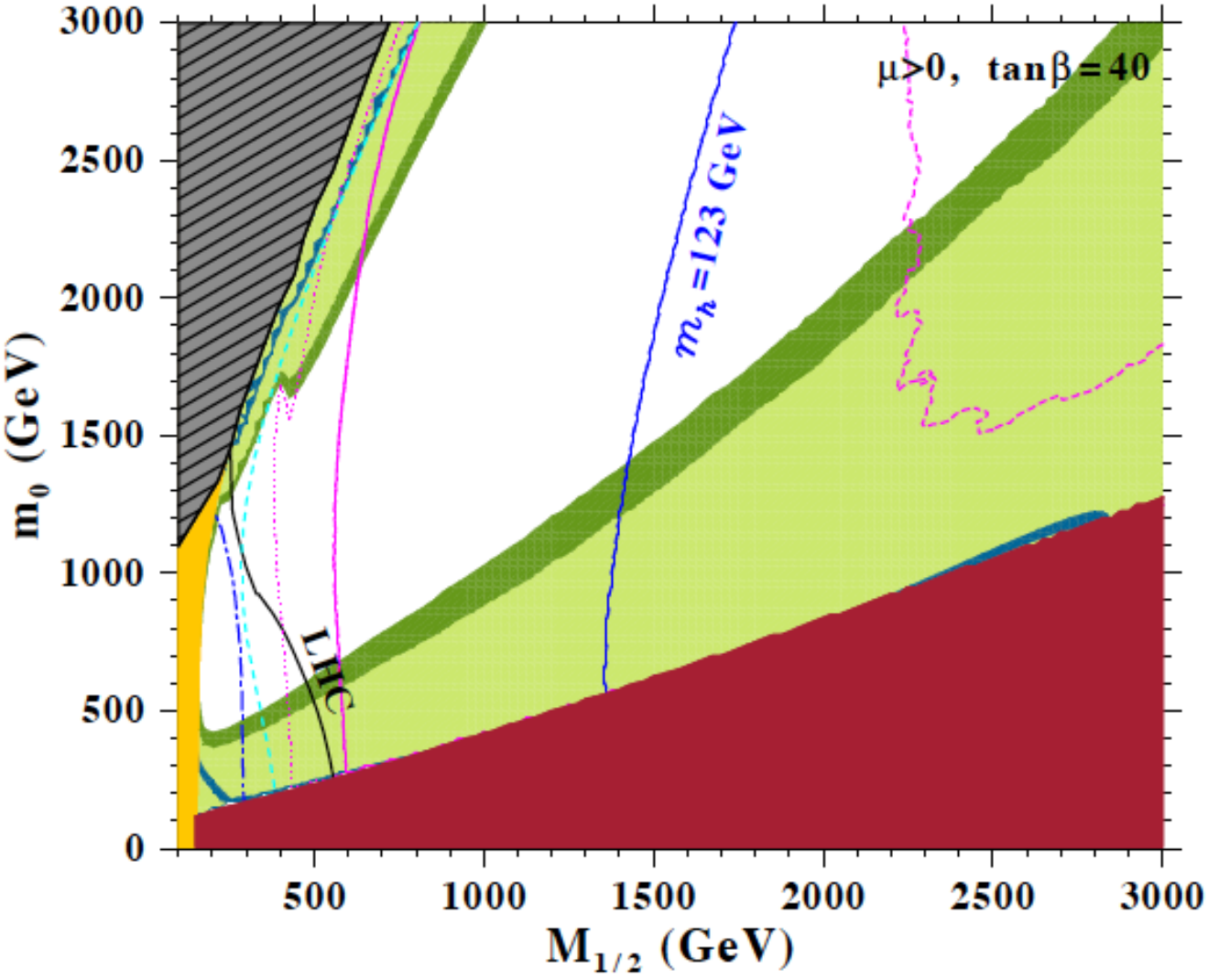
  ⇨ **more room for Supersymmetry at colliders …**

  – e.g. Lahanas, NM, Nanopoulos, PLB 649 (2007) 83
- LHC signatures also affected
  - Higgs + jets + MET
  - Z + jets + MET
  - 2τ + jets + MET
  - Dutta et al, PRD 79 (2009) 055002 [0808.1372 [hep-ph]]



SSC-allowed

ordinary cosmology-allowed



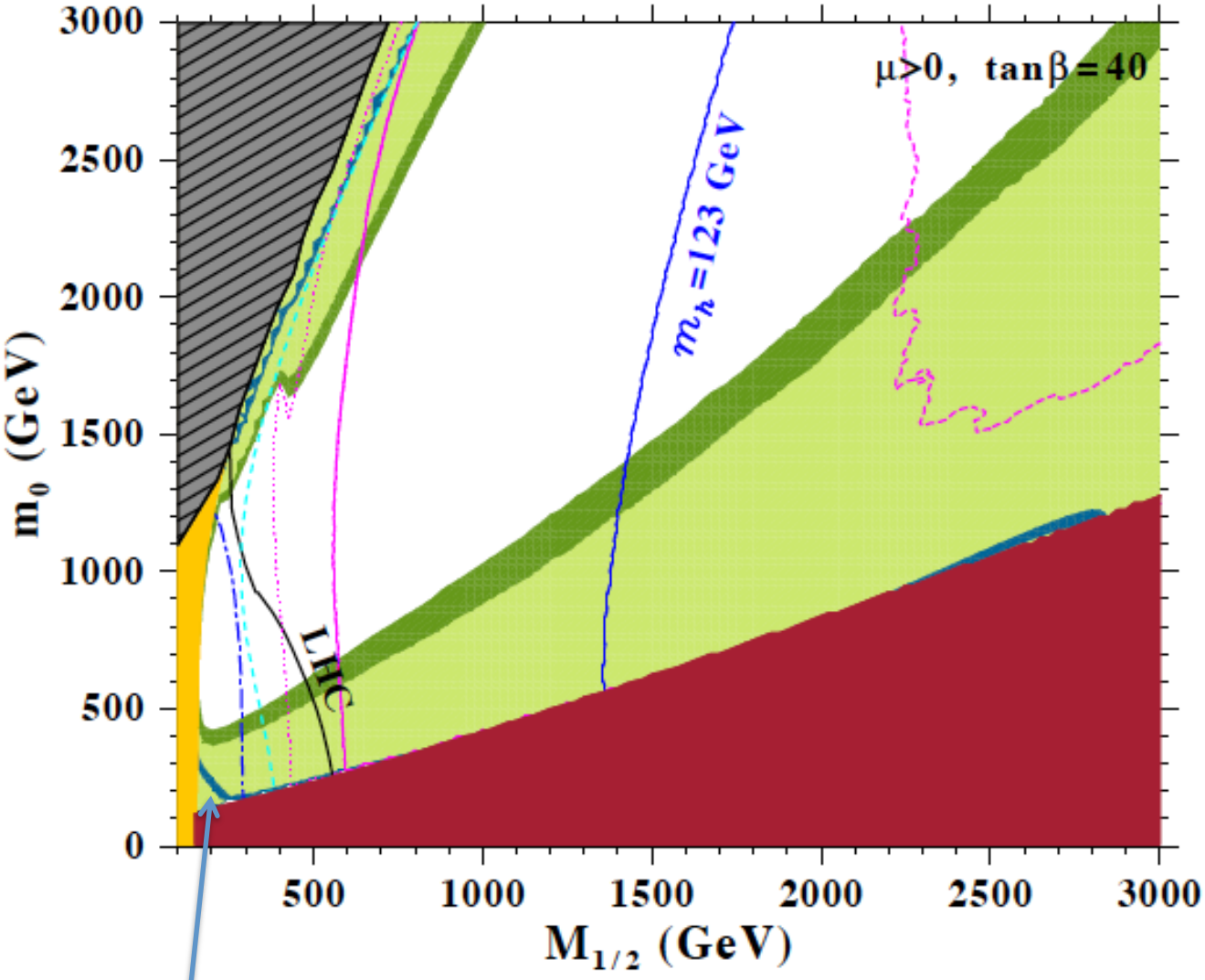
Post LHC 7TeV Run

Lahanas, Spanos 2012

WMAP7 DM bounds allowed

Neutralino lighter than WMAP7 bounds

PHENOMENOLOGICAL DILATON-DEFORMED MODELS



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Lahanas, Spanos 2012

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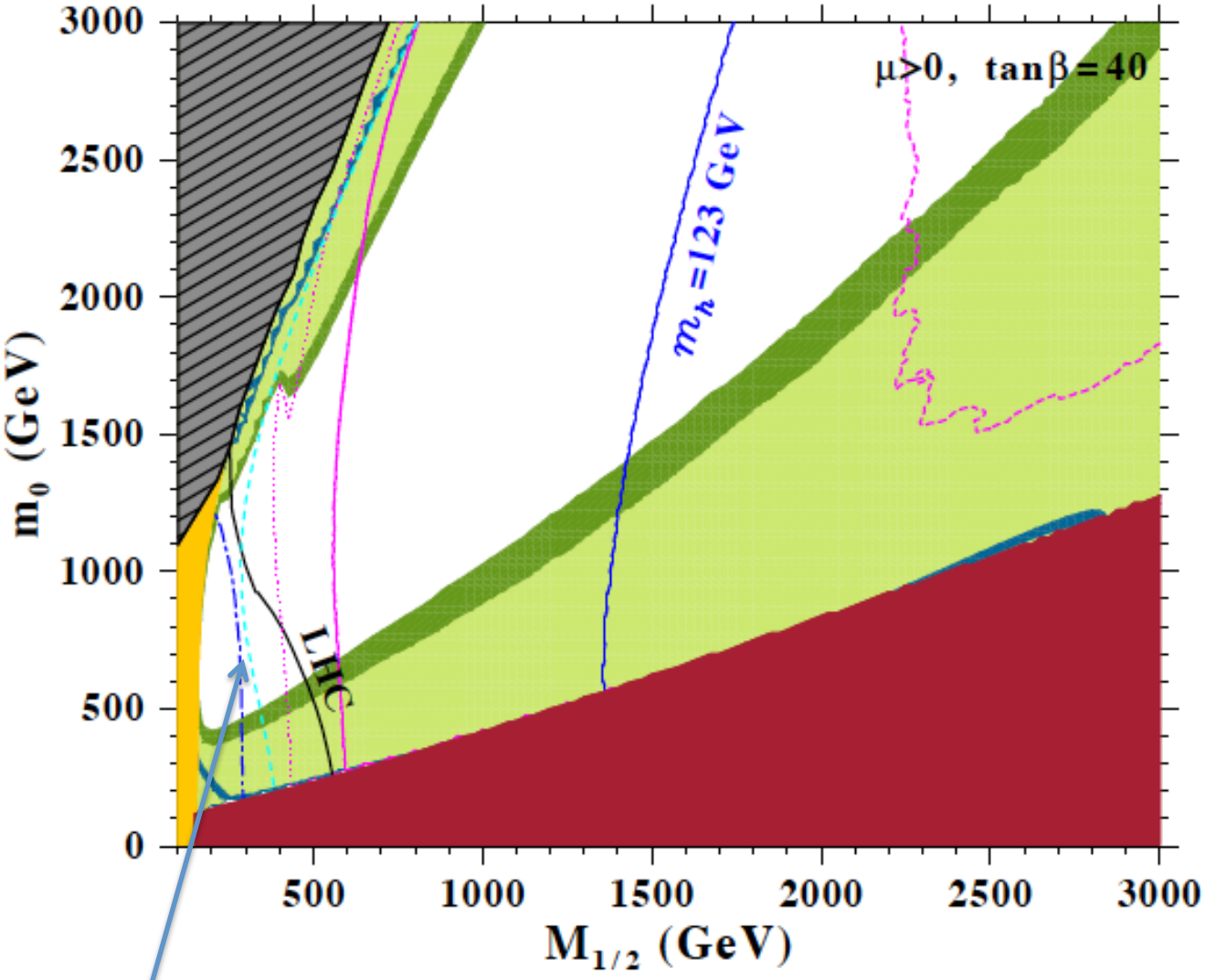
PHENOMENOLOGICAL DILATON-DEFORMED MODELS

NO-DILATON DEFORMATION WMAP7 ALLOWED



Post LHC 7TeV Run

Lahanas, Spanos 2012

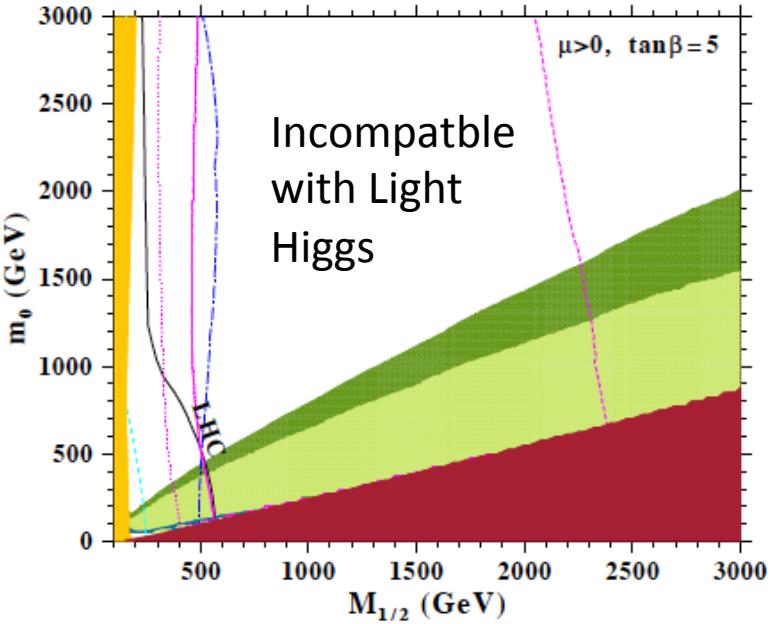
WMAP7 DM bounds allowed

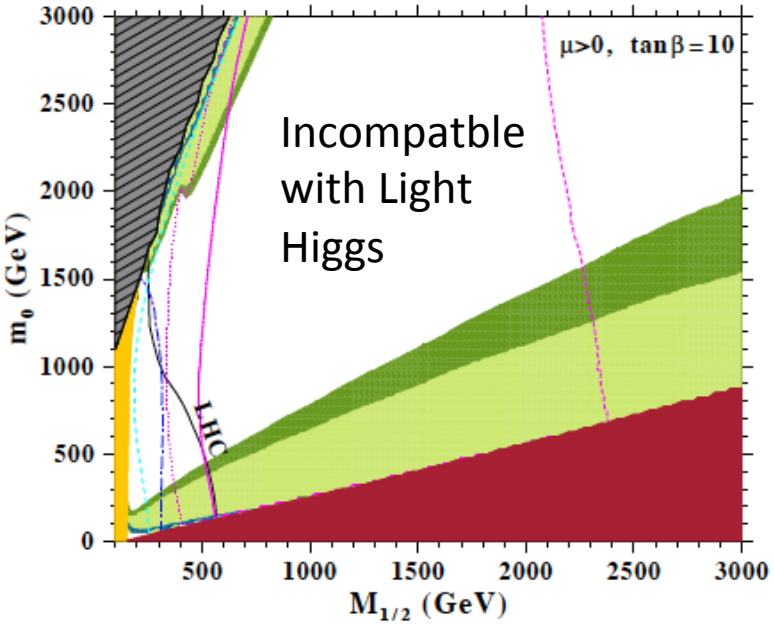
Neutralino lighter than WMAP7 bounds

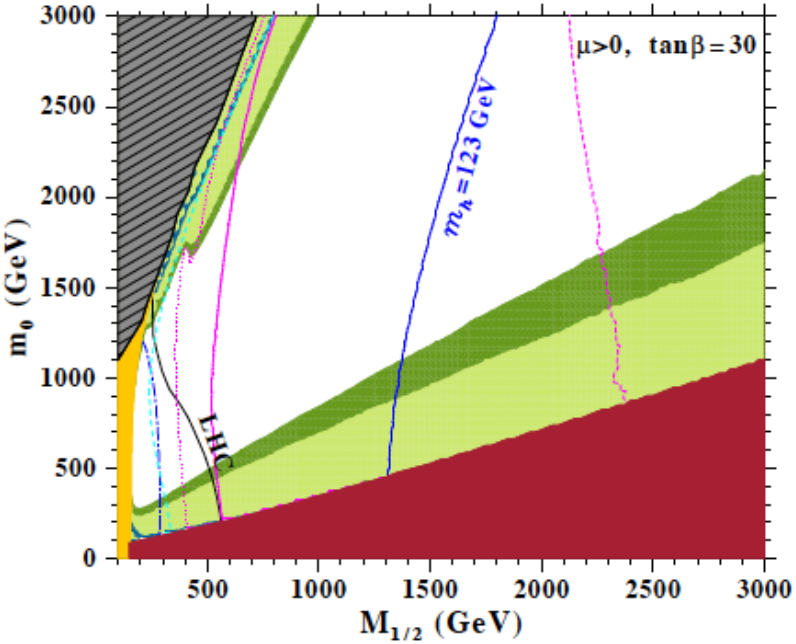
PHENOMENOLOGICAL DILATON-DEFORMED MODELS

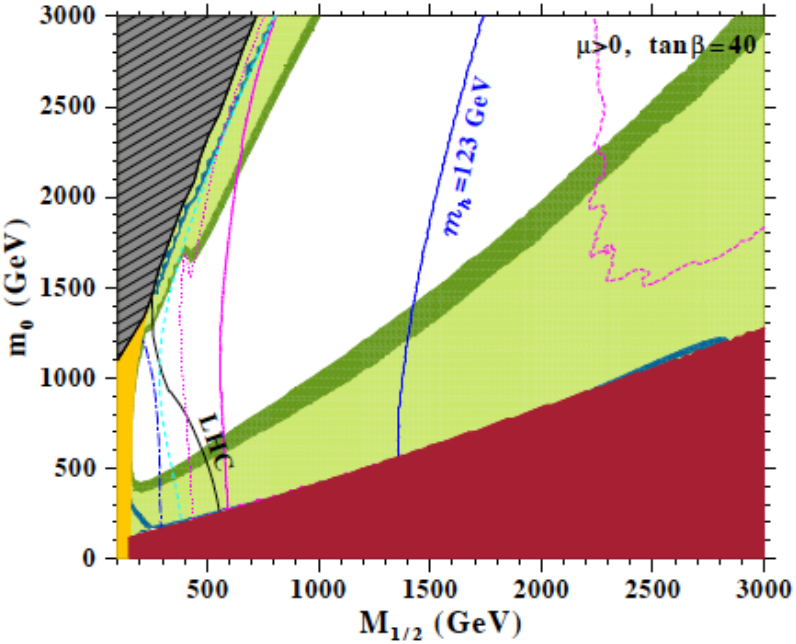
XENON 100 exclusion
(caution: re-analysis in presence of dilaton dominance should be made though)

Lahanas, Spanos 2012

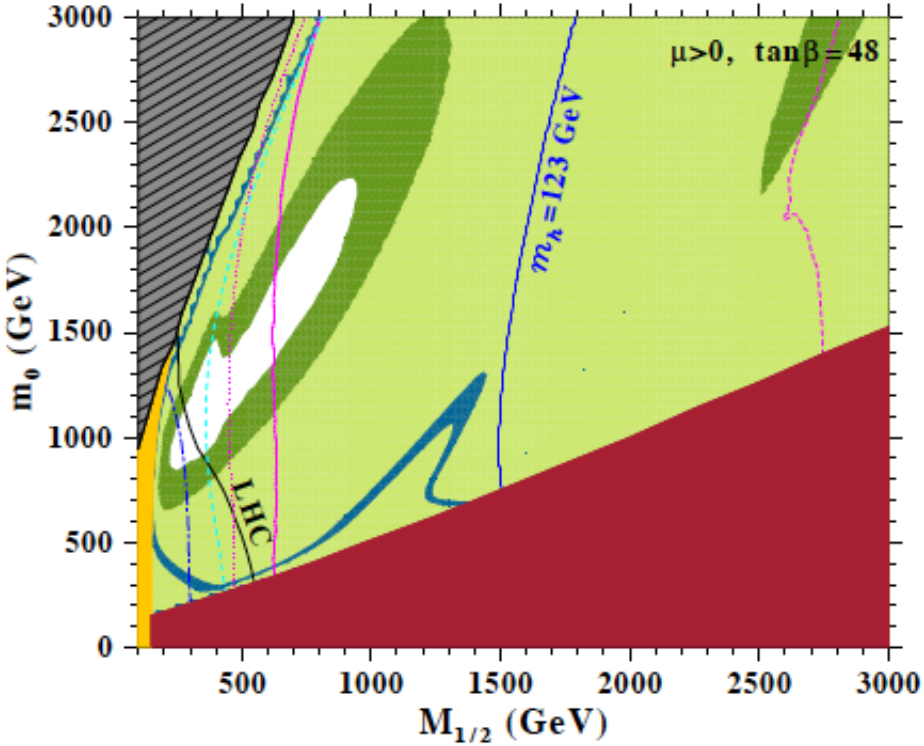


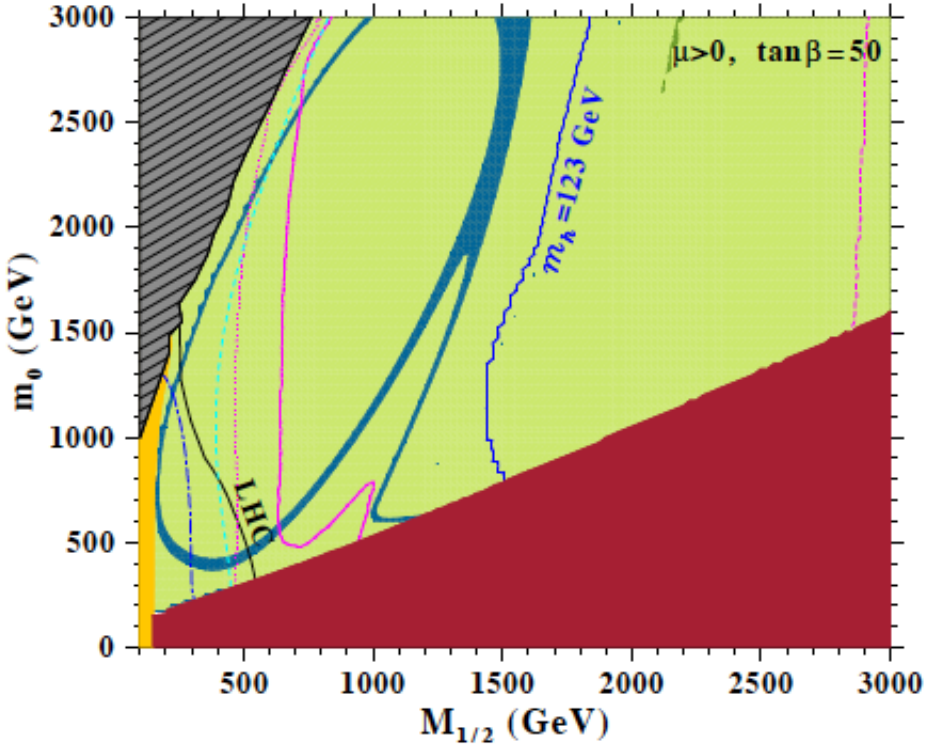






Lahanas, Spanos 2012

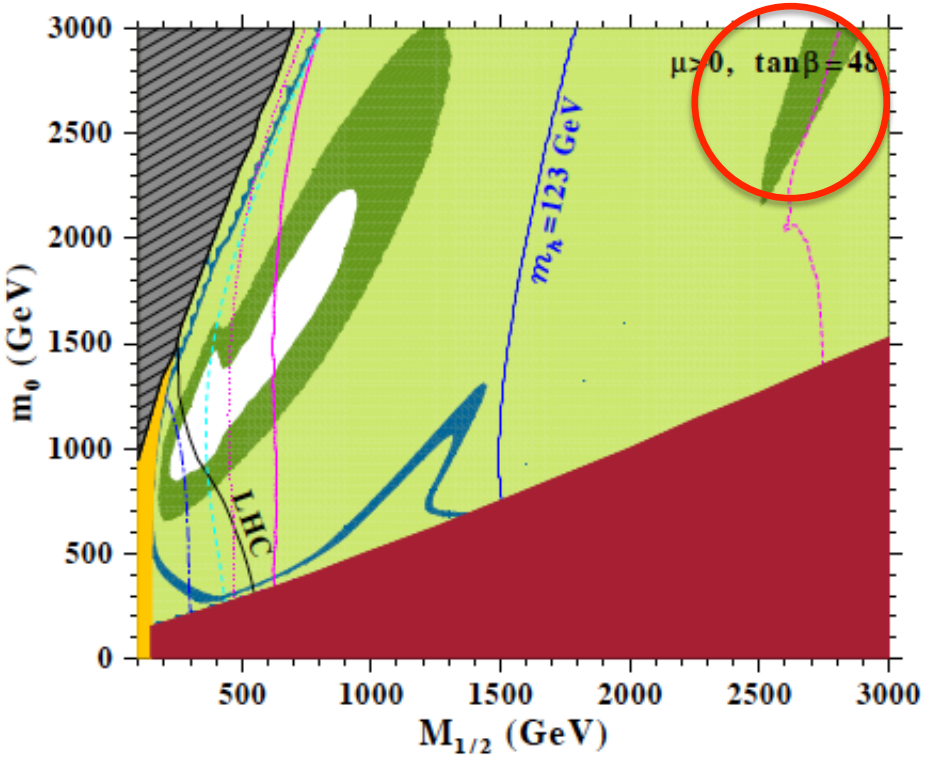


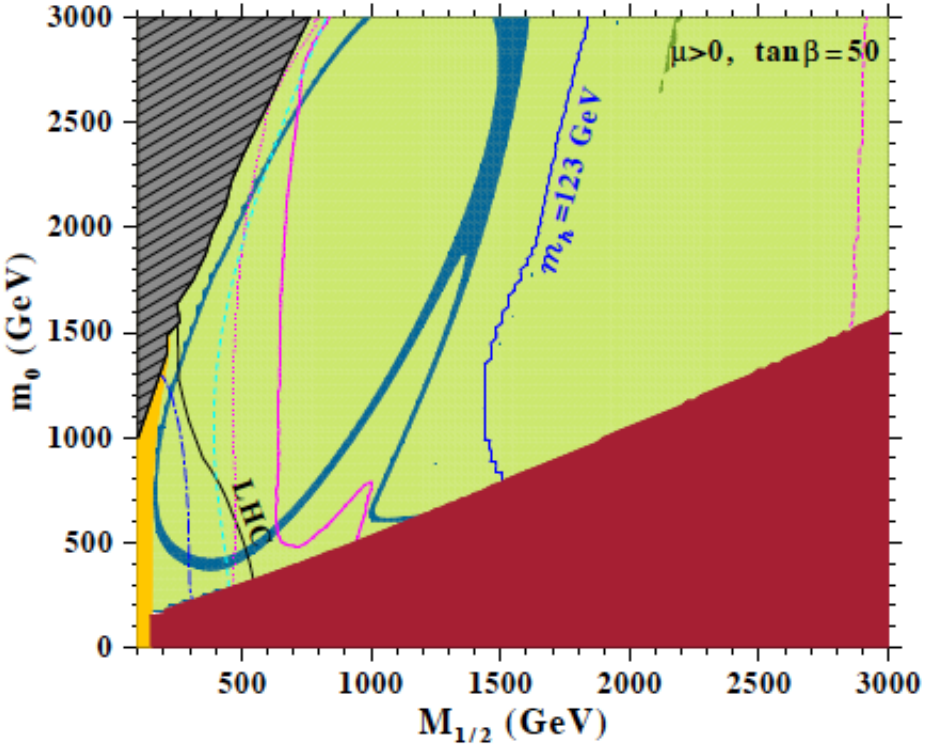


Conclusion:

Due to dilaton DM dilution, SUSY models, e.g. CMSSM, can become compatible with WMAP data and Higgs masses larger than 123 GeV, for tan β > 25 .

Lahanas, Spanos 2012





Conclusion:

Due to dilaton DM dilution, SUSY models, e.g. CMSSM, can become compatible with WMAP data and Higgs masses larger than 123 GeV, for tan β > 25 . There are *allowed* regions of SUSY *BEYOND LHC* reach, e.g. (m_0, $M_{1/2}$) = (2500, 2600) GeV, tanβ = 48

...Now something different

LORENTZ & CPT VIOLATION IN STRING UNIVERSE AND THE OBSERVED BARYON ASYMMETRY

Generic Concepts

- ***Leptogenesis***: physical ***out of thermal equilibrium*** processes in the (***expanding)*** Early Universe that produce an asymmetry between leptons & antileptons

- ***Baryogenesis***: The corresponding processes that produce an asymmetry between baryons and antibaryons

- ***Ultimate question: why is the Universe made only of matter?***

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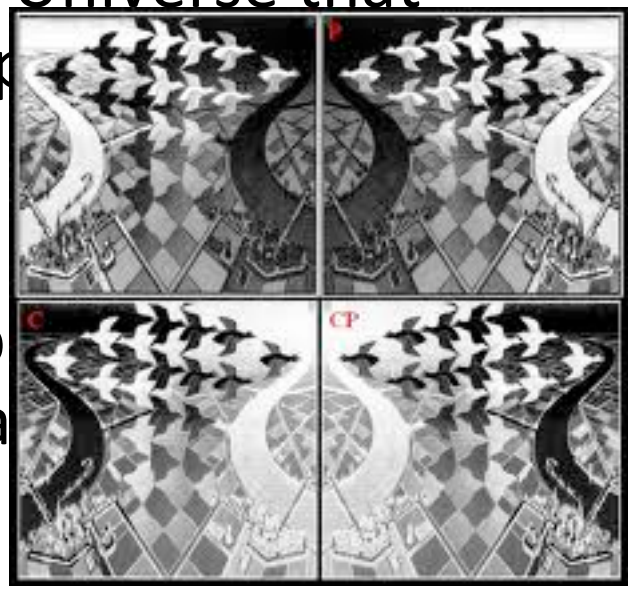
- ***Baryogenesis***: The corresponding p produce an asymmetry between ba antibaryons



escher

- ***Ultimate question: why is the Universe made only of matter?***

CP VIOLATION & BARYON ASYMMETRY

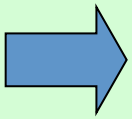
- Anomalous Violation of Baryon # (B), C & CP in SM
- Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$
- But Universe consists only of matter

Kuzmin, Rubakov, Shaposhnikov

$$\frac{n_B - \bar{n}_B}{n_B + \bar{n}_B} \sim \frac{n_B - \bar{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**



$n_B - \bar{n}_B$

but **CPV** in SM does **not** reproduce
the observed Baryon Asymmetry (assuming ***CPT***)

WHAT IF CPT IS VIOLATED IN THE EARLY UNIVERSE ?

GENERATE Baryon and/or Lepton ASYMMETRY without need for extra CPV sources, e.g. Heavy Sterile Neutrinos?

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell
revisited by:
Greenberg, Chaichian, Dolgov, Novikov…

WHAT IF CPT IS VIOLATED IN THE EARLY UNIVERSE ?

GENERATE Baryon and/or Lepton ASYMMETRY without need for extra CPV sources, e.g. Heavy Sterile Neutrinos?

CPT Invariance Theorem : X

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

CPT MAY be Vilolated if at least one of (i) – (iv) relaxed (e.g. in Early Universe geometries …)

$$\Delta n = n - \overline{n} = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\left(\frac{1}{1+e^{E_\nu/T}} - \frac{1}{1+e^{E_{\overline{\nu}}/T}}\right)$$

If CPTV @ freezeout:

$$E_\nu \neq E_{\overline{\nu}} \quad \Rightarrow \quad \Delta n \neq 0$$

WHAT IF CPT IS VIOLATED IN THE EARLY UNIVERSE ?

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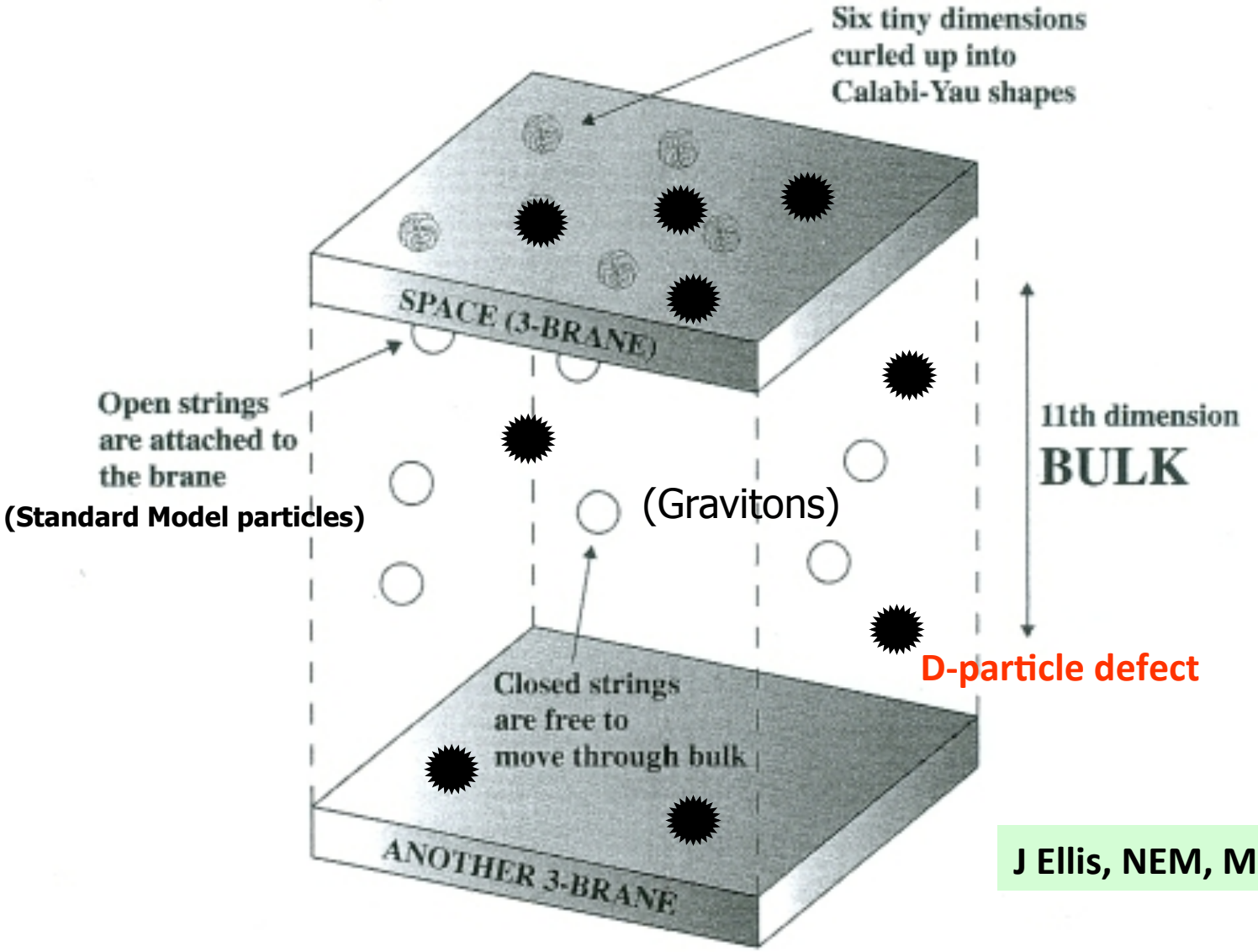
Lorentz Violating Backgrounds in Stringy Cosmologies?

ANTOHER VERSION of BRANE WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS :



J Ellis, NEM, M Westmuckett

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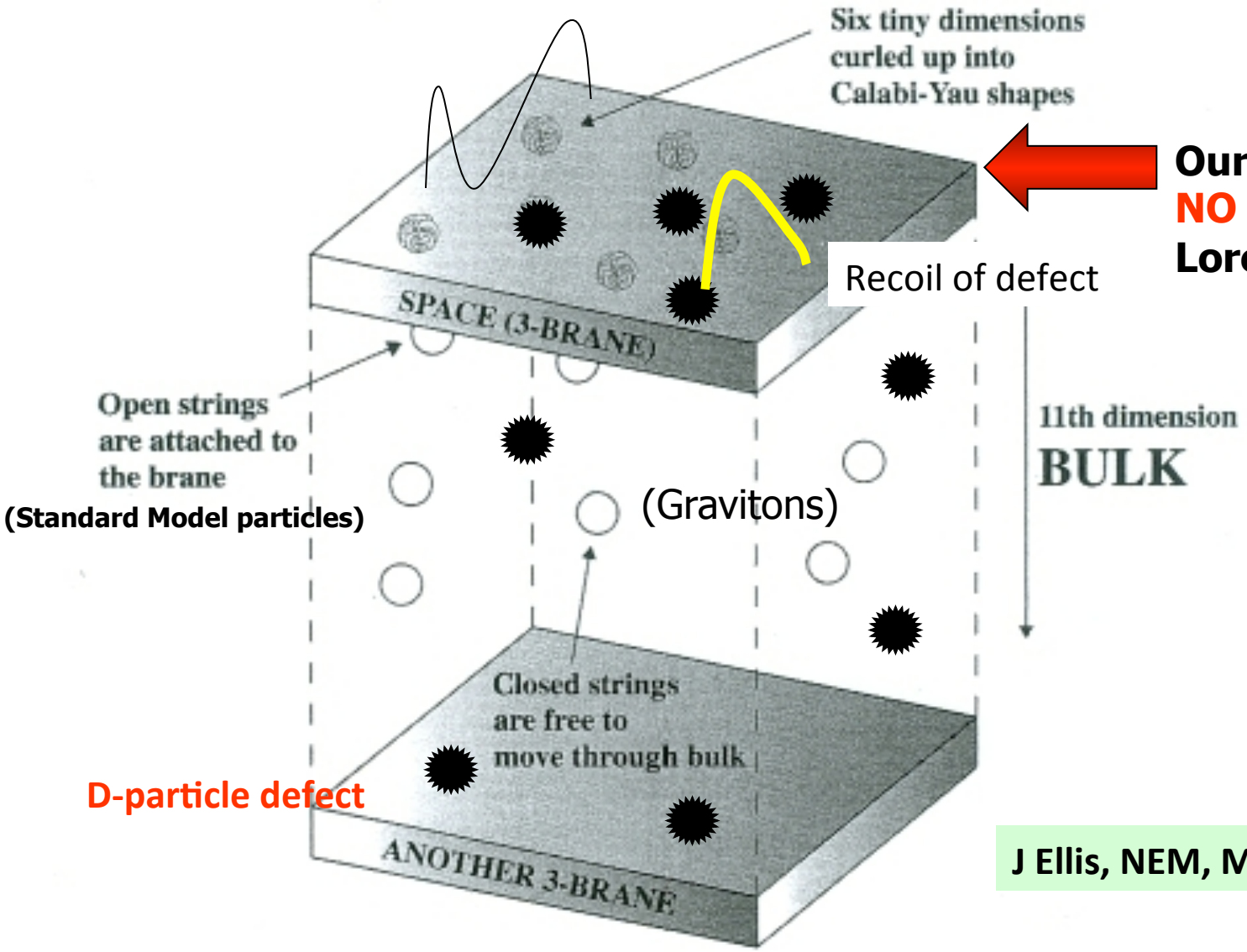
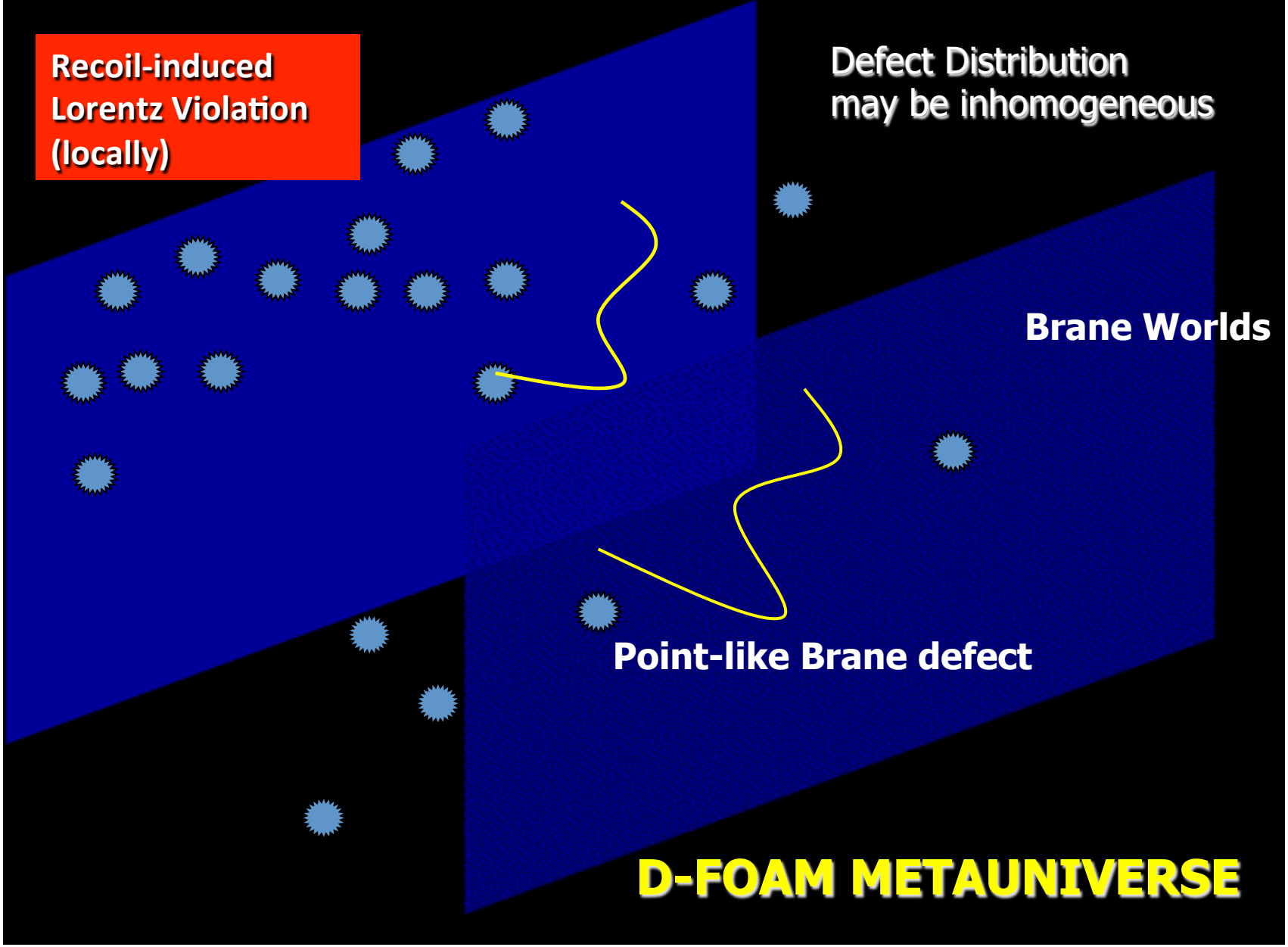


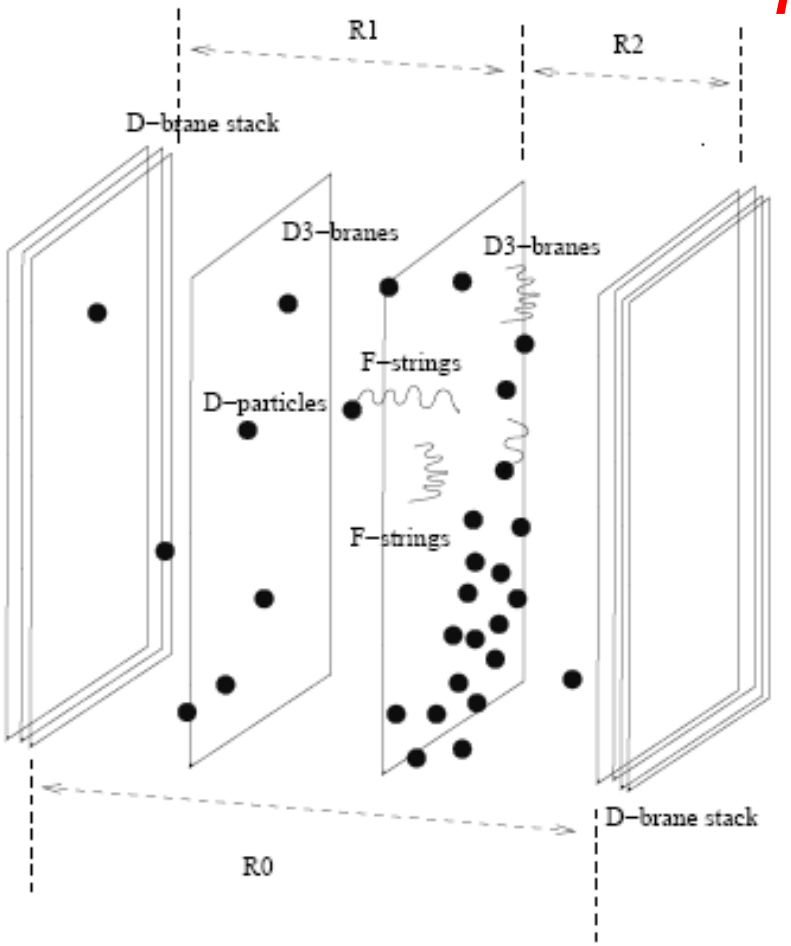
Our Universe
NO LONGER
Lorentz Invariant

J Ellis, NEM, M Westmuckett

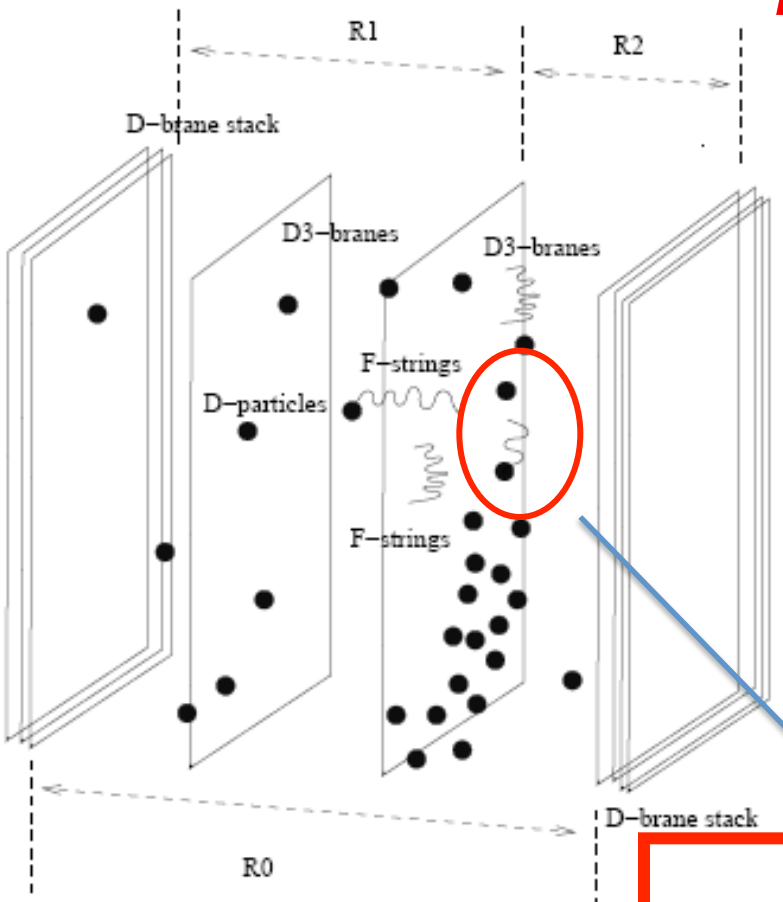


Colliding Brane world model of Space-Time with point-like space-time defects

Matter/D-foam Interactions

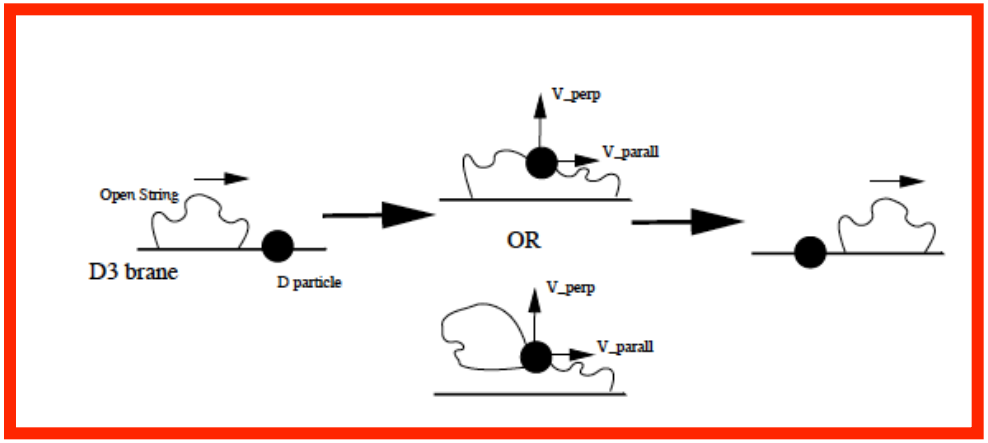


Matter/D-foam Interactions

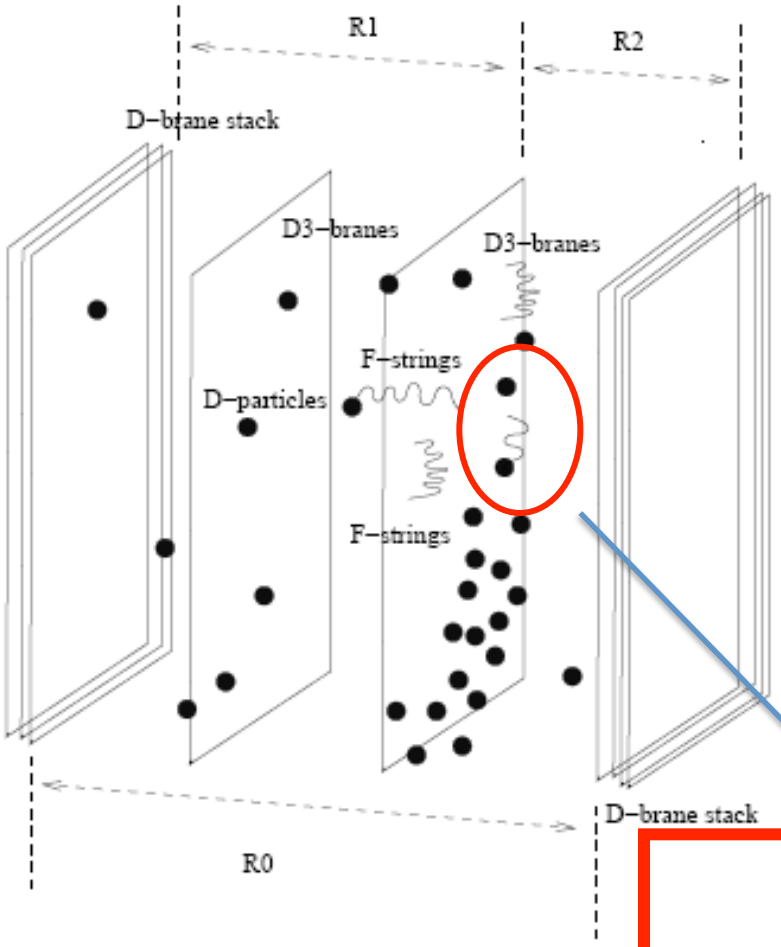


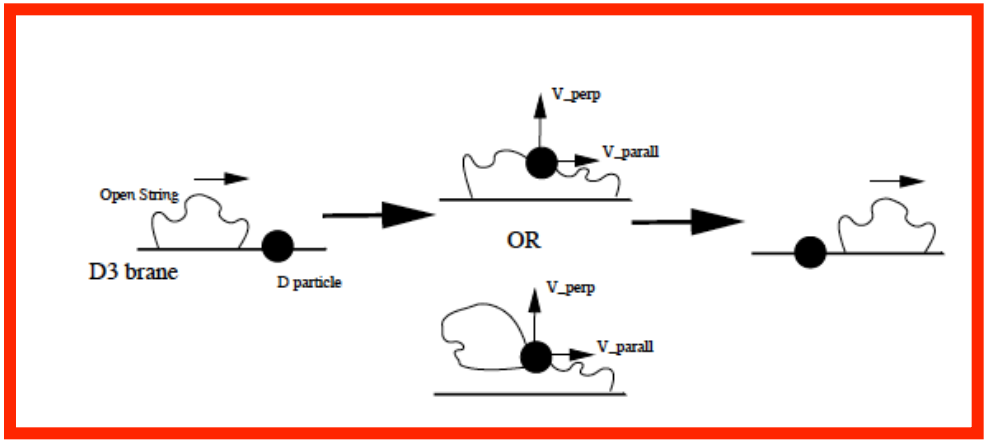
String ***Splitting*** & (``momentary'') **Capture** by the defects

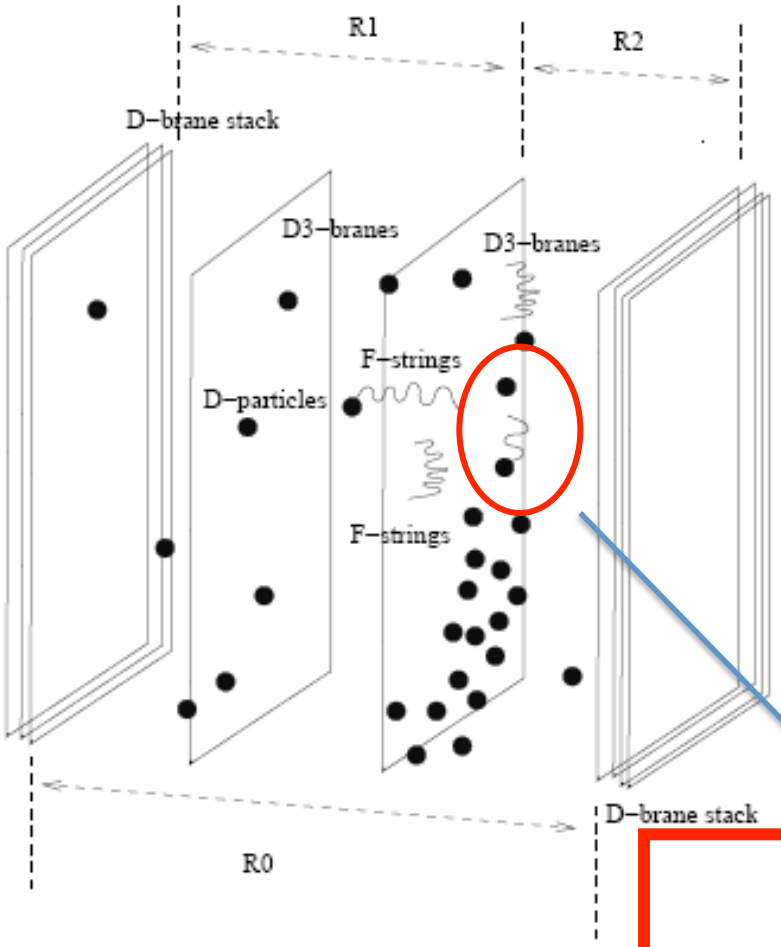
INTEMEDIATE STRING CREATION/EXCHANGE PURELY NON-LOCAL EFFECT



CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

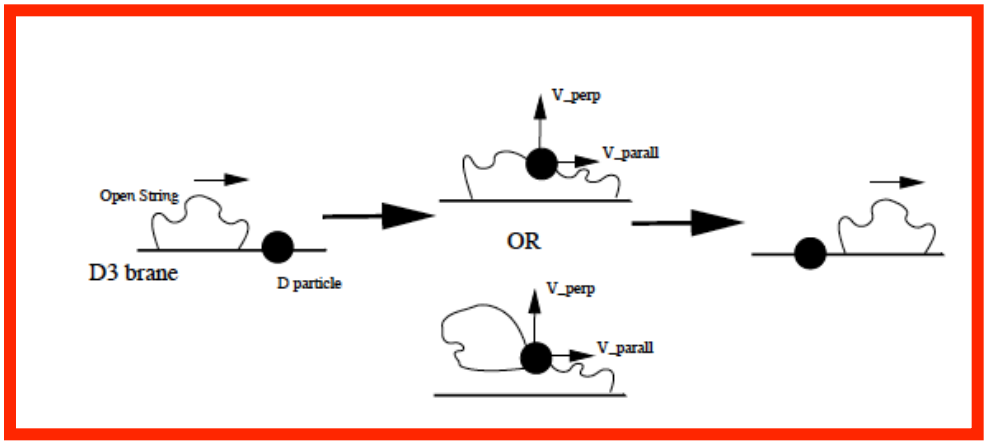




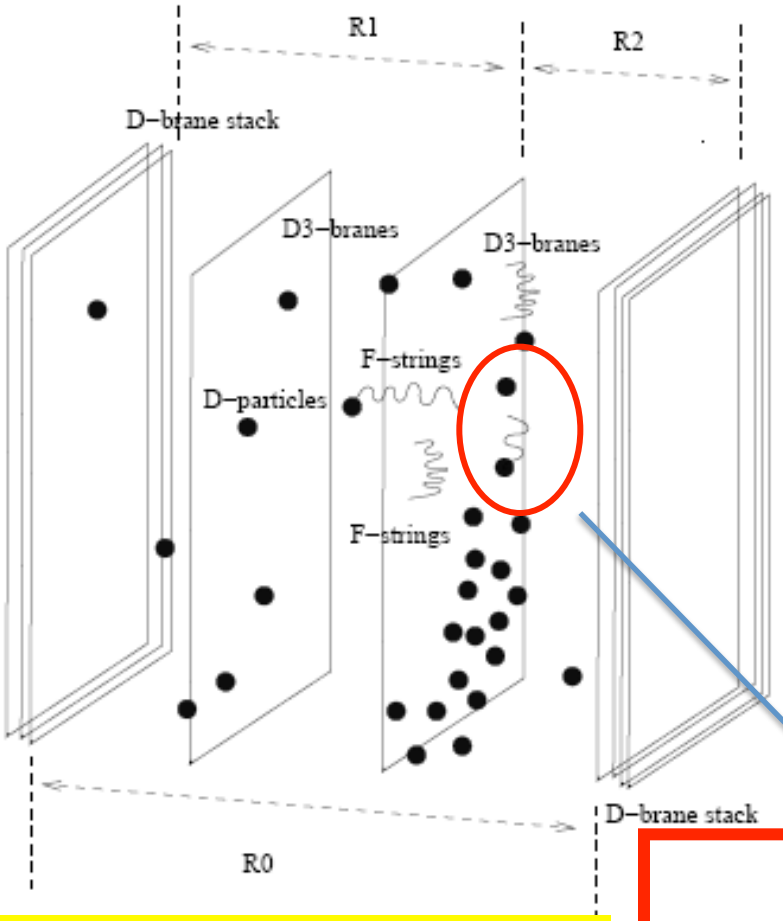


CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

ONLY ELECTRICALLY NEUTRAL EXCITATIONS (e.g. Photons, Neutrinos) INTERACT VIA CAPTURE DOMINANTLY WITH FOAM



ELLIS, NEM, SAKHAROV, NANOPOULOS



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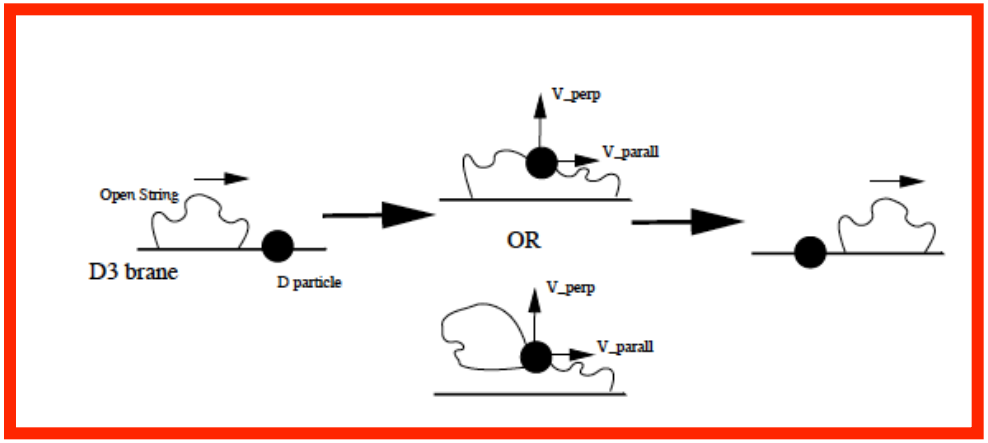
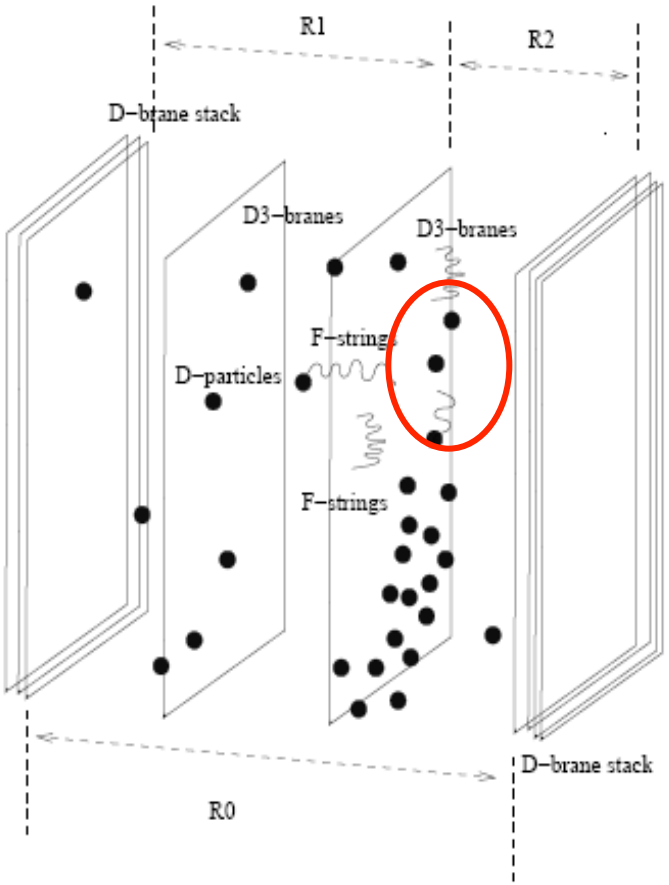


Time Delays due to Intermediate String Creation & Oscillations – ***Subluminal Vacuum Refractive Index***

J ELLIS, NEM, NANOPOULOS



***Local Lorentz Violation* due to direction of Defect recoil velocities**

***Induced metric* depends on momenta as well as coordinates (Finsler type) : e.g. u || X_1**

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{01} = g_s \frac{\Delta k_i}{M_s} \equiv u_1$$

Explicit local breaking of SO(3,1) down to SO(2,1) rotation and boosts in transverse directions

Space time Foam situations – Average over both populations of defects & quantum fluctuations

Isotropic & (in)homogeneous foam

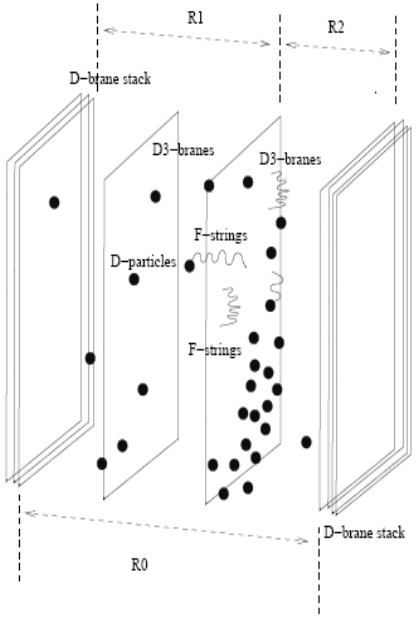
for a brane observer:

$$\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0$$

$$\frac{g_s^2}{M_s^2} \langle \Delta k_i \Delta k_j \rangle = \sigma^2 \delta_{ij}$$

Lorentz Invariance on Average

Violated in flcts



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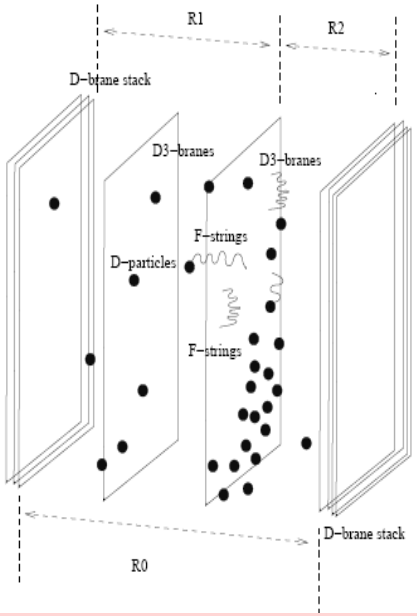

c.f. **Stochastic Foam, through coherent graviton states**

leading to light cone fluctuations

Ford (95)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
$$\langle h_{\mu\nu} \rangle = 0$$
$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

Modified Neutrino dispersion relations due to locally induced metric

$$p^\mu p^\nu g_{\mu\nu} = -m^2 \Rightarrow \qquad E = \vec{p}\cdot\vec{u} \pm \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2}$$

Interpret (Dirac) negative energies as corresponding to anti-particles

$$\ll E \gg = \ll \vec{p}\cdot\vec{u} \gg \pm \ll \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2} \gg$$

$$\ll E \gg \simeq \pm\sqrt{p^2+m^2}\left(1 + \frac{1}{2}\sigma^2\right), \qquad p \gg m$$

Momentum-Energy conservation during ν scattering with D-particles

$$\ll \vec{p}_1 + \vec{p}_2 \gg = \frac{M_s}{g_s} \ll \vec{u} \gg = 0$$

$$\ll E_1 \gg = \ll E_2 \gg + \frac{1}{2}\frac{M_s}{g_s} \ll u^2 \gg \qquad \Rightarrow$$

$$\ll E_2 \gg = \pm\sqrt{p^2+m^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

NEM, Sarkar, Tarantino

Phys.Rev. D84 (2011) 044050

D-foam Induced CPTV for Neutrinos

$$\ll E_\nu \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

$$\ll E_{\overline{\nu}} \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) + \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

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One can thus generate a Lepton asymmetry and, then through B-L conserving processes in the Early Universe a Baryon asymmetry.

D-foam Induced CPTV for Neutrinos

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$\pm B_0$

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± B_0

$$\Delta n = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\left[\frac{1}{1+\exp(E_\nu/T)} - \frac{1}{1+\exp(E_{\bar{\nu}}/T)}\right]$$

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star\, T^3\left(\frac{B_0}{T}\right)$$

BARYOGENESIS VIA LEPTOGENESIS

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3 \left(\frac{B_0}{T}\right)$$

@ T = T_d (decoupling Temp. of Lepton number (L) Violating processes) there is a ***constant ratio*** of net neutrino/antineutrino asymmetry (ΔL) to entropy density (~T^3)

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV

$\Delta L \sim 10^{-10}$, in agreement with observations (***Leptogenesis***)

Communicated to Baryon sector, and thus generates BAU either via a B-L conserving symmetry as in GUT models or via B - L conserving sphaleron processes → ***BARYOGENESIS***

BARYOGENESIS VIA LEPTOGENESIS

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for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV

$\Delta L \sim 10^{-10}$, in agreement with observations (***Leptogenesis***)

Communicated to Baryon sector, and thus generates BAU either via a B-L conserving symmetry as in GUT models or via B - L conserving sphaleron processes → ***BARYOGENESIS***

D-foam Induced CPTV for Neutrinos

$$\ll E_\nu \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

$$\ll E_{\overline{\nu}} \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) + \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

One can thus generate a Lepton asymmetry and through B+L conserving processes in the Early Universe a Baryon asymmetry.

The correct value (observed) for BAU is reproduced for

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implying that in these scenarios, for $\sigma^2 < 1$, one must have $M_s/g_s > 200$ TeV

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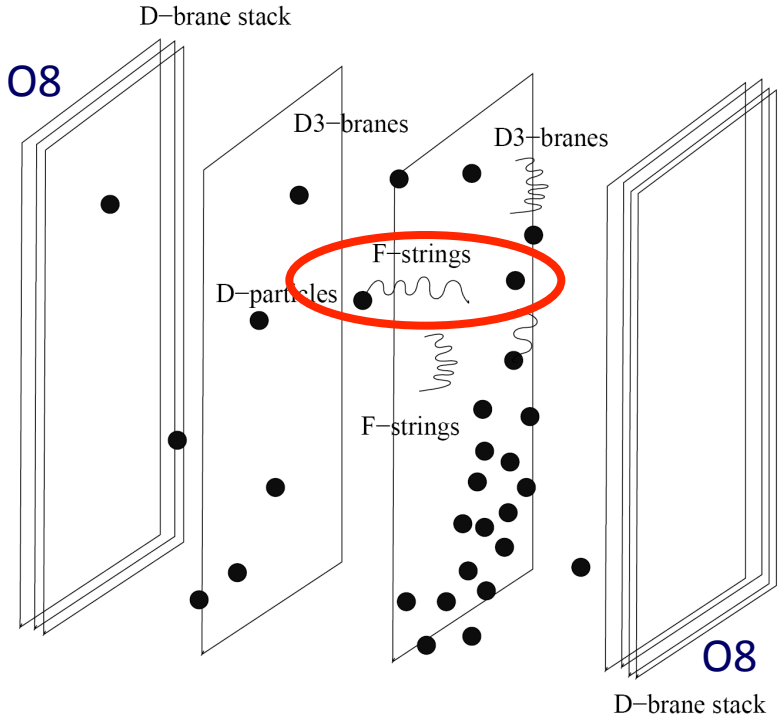
PHENOMENOLOGY OF EARLY UNIVERSE NEEDS TO BE CHECKED FOR COMPATIBILITY…. IN PROGRESS

D-foam & Cosmology

NEM, Mitsou, Sarkar, Vergou

Due to Bulk, populations of D-particles do not overclose the Universe – there are +, - contributions (depending on the relative distance) to brane vacuum energy from bulk D-particles, due to *stretched strings* between D-particles & the Brane Universe. They can *cancel out (average) D-mass* contributions on brane.



Negative Contributions from nearby bulk D-particles may also ***cancel out*** mass contributions of D-particles on the brane → **avoid** Universe **overclosure** → **no** significant **restriction** of D-foam populations… e.g. in eras for induced CPT Violation

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D-foam & DM Abundances

NEM, Mitsou, Sarkar, Vergou

The presence of D-foam induced momentum-dependent metric fluctuations due to interaction of neutral DM with the D-particle defects → modification of Boltzmann Eq.

BOTZMANN EQUATION FOR HEAVY SPECIES, m >> p

$$\frac{dn}{dt} + 3Hn = \Gamma(t)n + \frac{g}{(2\pi)^3}\int d^3\overline{k}\frac{C[f]}{\overline{k}_0}$$

$$\Gamma(t) = 2H\,a^4(t)m\left(\sigma_{01}^2 + \sigma_{02}^2 + \sigma_{03}^2\right)[9T + 2m]$$

$$\sum_i \sigma_{oi}^2 = \frac{g_s^2}{M_s^2}\sum_i \Delta_i^2$$

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Foam leads to vacuum
Particle production
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Foam dominance restricts available parameter space, e.g. for SUSY Dark Matter

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Significant effects only for low (TeV) String scales

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Weakly Interacting Dark Matter Phenomenology and Space-time Foam

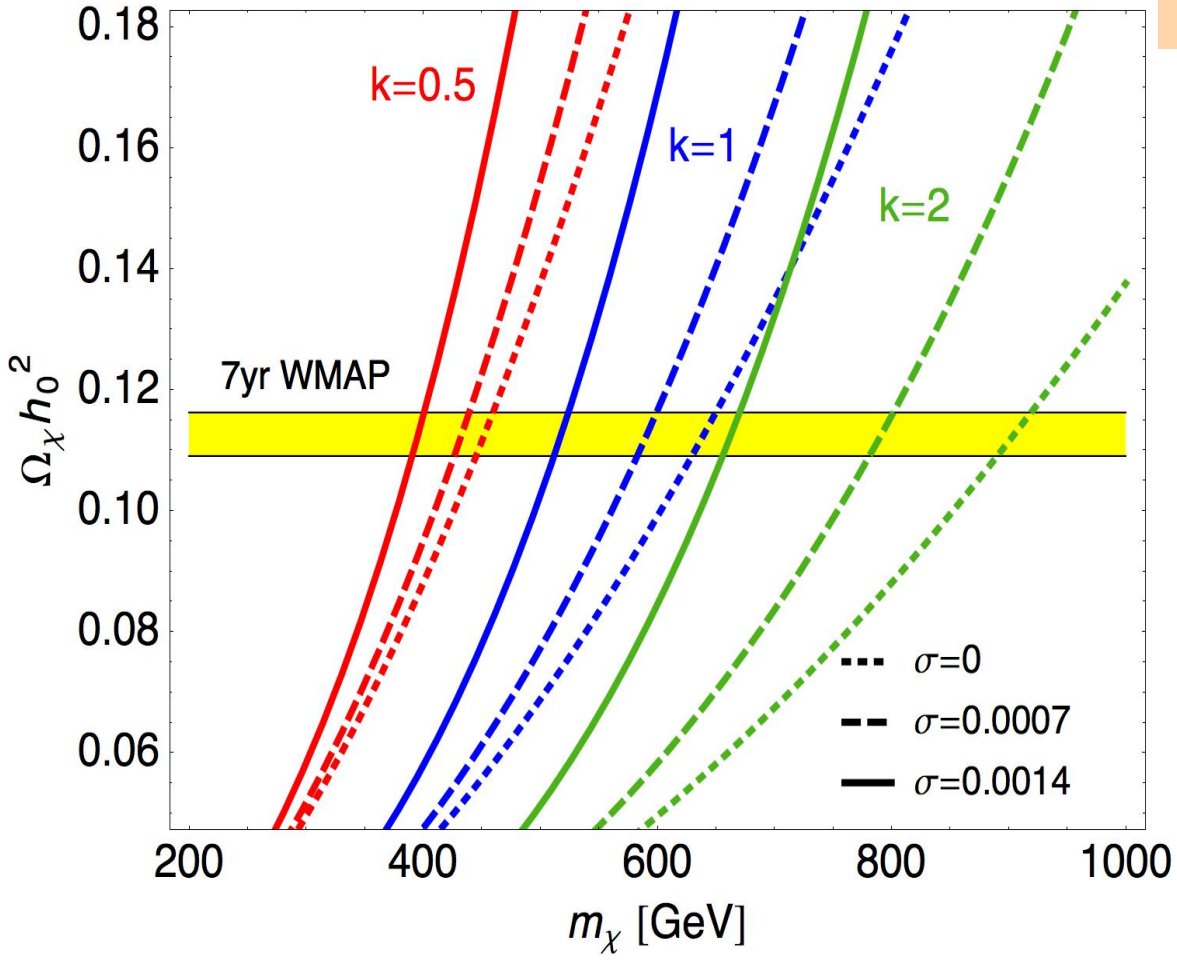
NM, Mitsou, Vergou, Sarkar 2010

IF D-FOAM DOMINANCE: INCREASE OF RELIC ABUNDANCE w.r.t. STANDARD COSMOLOGY

$$\frac{\Omega_\chi h_0^2}{(\Omega_\chi h_0^2)_{\text{no source}}} = 1 + \sigma^2\, m_\chi^2 \ ,$$

$$\sigma^2 \equiv 1.259\, \frac{g_s^2}{M_s^2} \sum_{i=1}^{3} \Delta_i^2 \ , \qquad (\Omega_\chi h_0^2)_{\text{no source}} = (2.6 \times 10^{-10}\ \text{GeV}^{-2}) \frac{16\pi^2 m_\chi^2}{k\, g_{\text{weak}}^4},$$

Weakly Interacting Dark Matter Phenomenology and Space-time Foam



NM, Mitsou, Vergou, Sarkar 2010

Foam fluctuations of order:

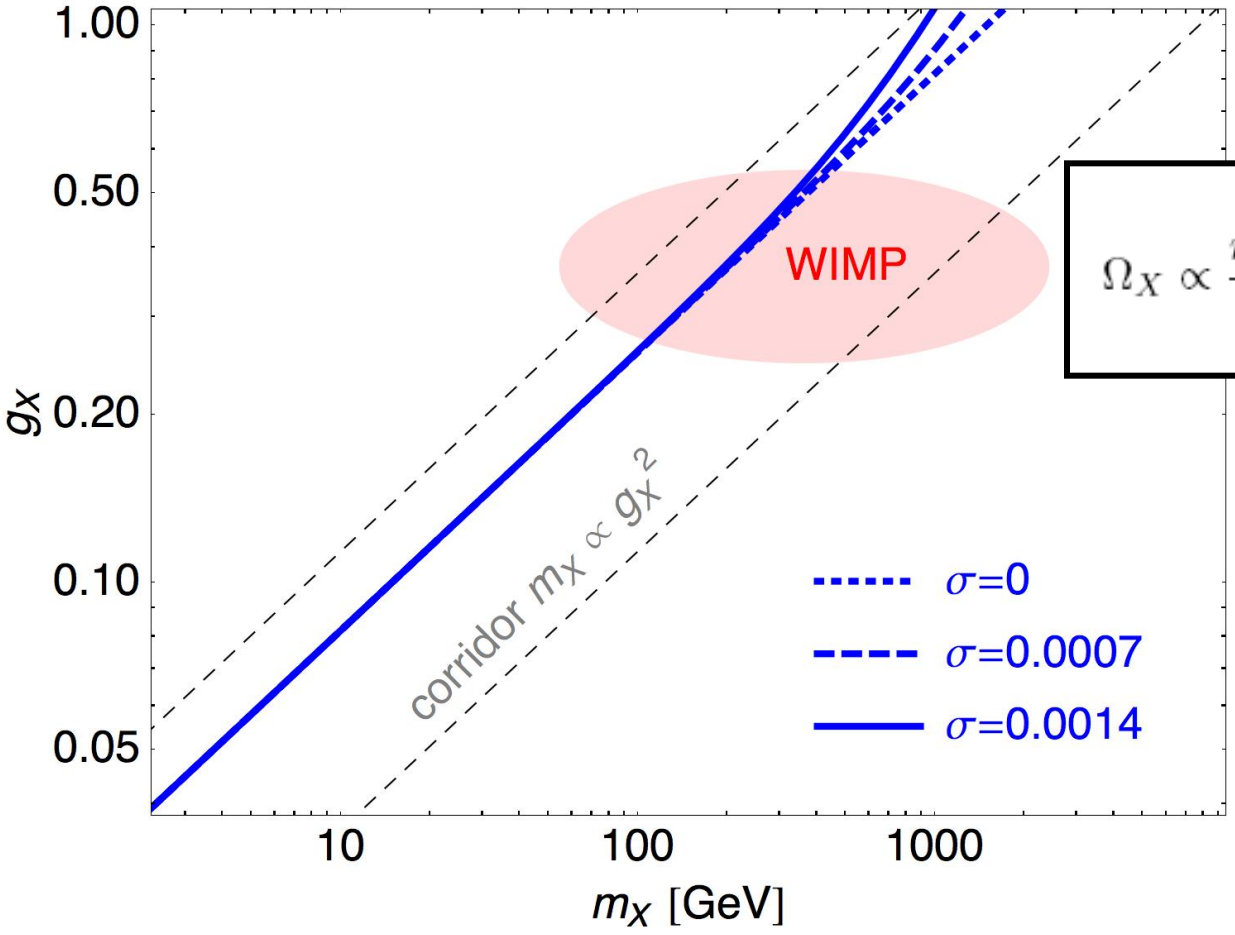
$$\sigma^2 = g_s^2 \frac{\Delta^2}{M_s^2}$$

Δ = O(1) dimensionless

Measurable effects For current or next Generation expts only if Low String scale O(1-10 TeV)

Cosmologically (WMAP_CMB) allowed regions for WIMP Dark Matter

Weakly Interacting Dark Matter Phenomenology and Space-time Foam



Exotic DM Wimp-like
(g_X, m_X)

$$\Omega_X \propto \frac{m_X^2}{g_X^4}\left[1+\left|\mathcal{O}\left(m_X^2\frac{g_s^2}{M_s^2}\sum_{i=1}^{3}\Delta_i^2\right)\right|\right]$$

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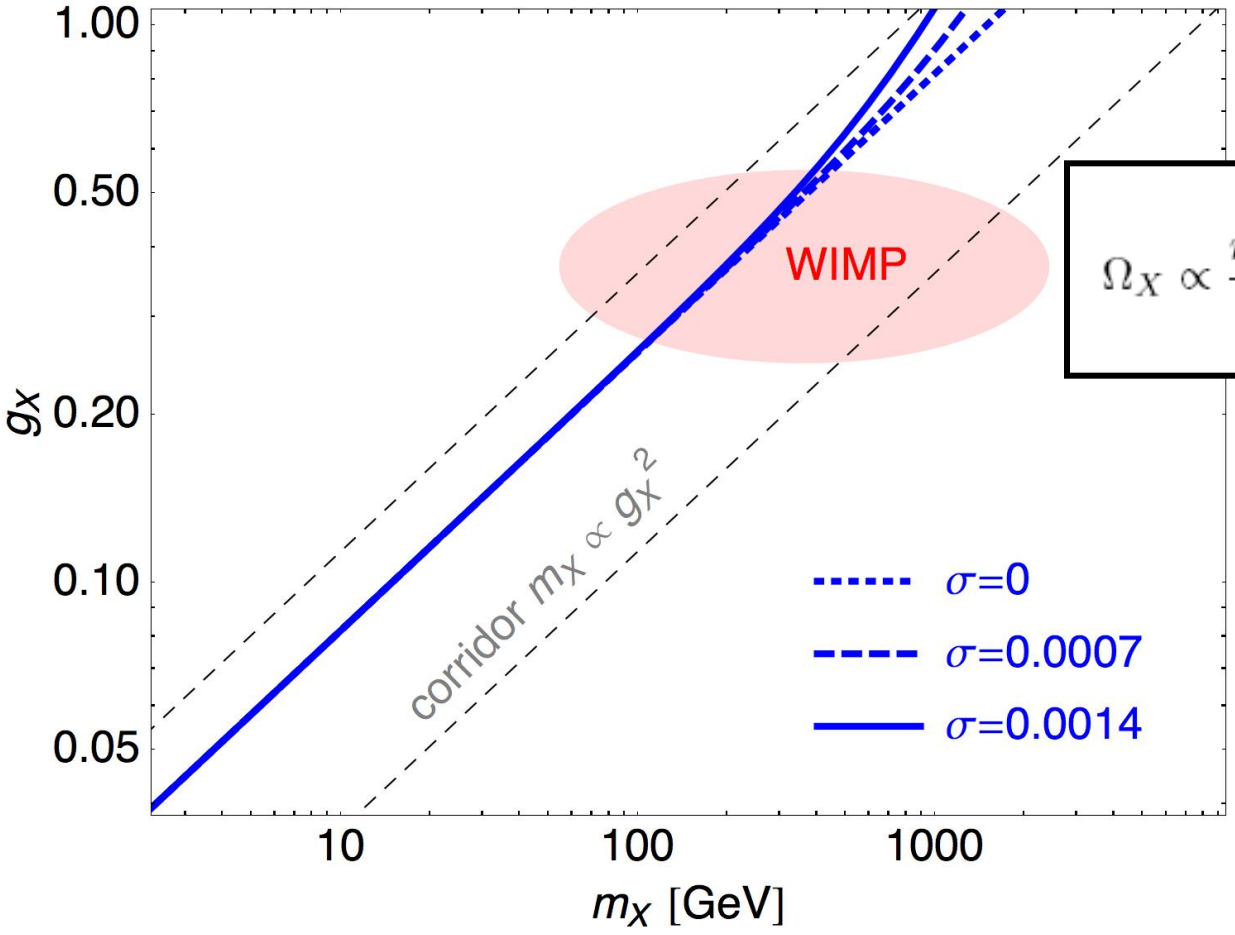

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Measurable effects For current or next Generation expts
Only if *Low* (TeV) String scale

Less DM parameter space available

Cosmologically (WMAP_CMB) allowed regions for dark Matter

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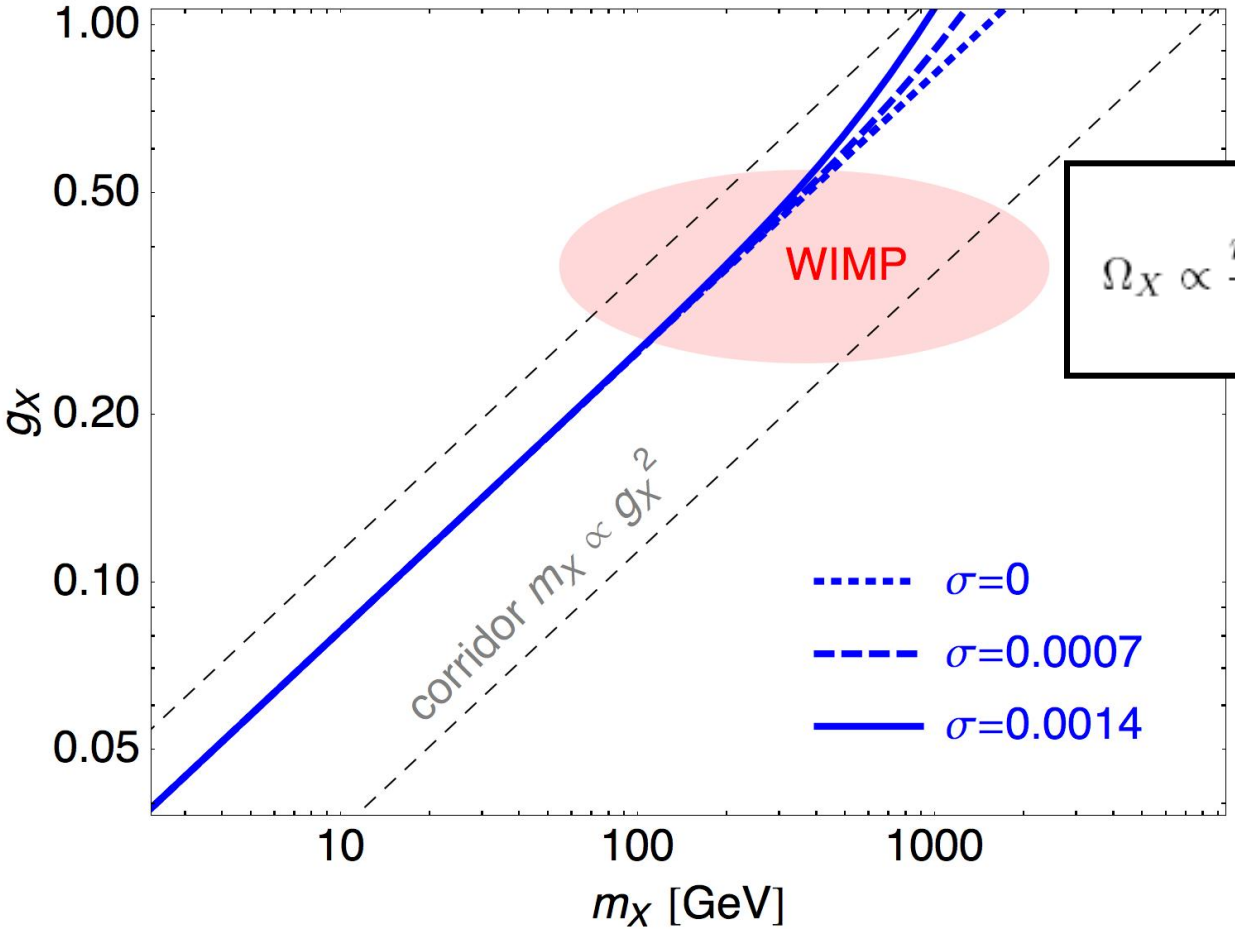

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BUT…
IF D-FOAM IS RELEVANT FOR BARYON ASYMMETRY

M_s/g_s > 200 TeV

…It does not lead to measurable effects @ LHC

Cosmologically (WMAP_CMB) allowed regions for dark Matter

CONCLUSIONS

- **No Evidence for DM as yet**

- We discussed **Colliding** or **Bouncing Brane** World Cosmologies that lead to **time-dependent dilaton fields** at early epochs – before Dark matter Decoupling.

- **Dilaton dominance** in such areas lead to **modification** of **DM abundances** → radical **effects** on Collider **searches** of **new Physics**

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- **More room for SUSY, heavier partners allowed → effects in LHC or pushing SUSY beyond the reach of LHC, allowing for Higgs masses > 125 GeV**

- **D-FOAM SCENARIOS ALSO CONSIDERED → LOCAL VIOLATION OF LORENTZ SYMMETRY (PRESERVATION ON AVERAGE OVER LARGE POPULATIONS OF D-EFECTS)**

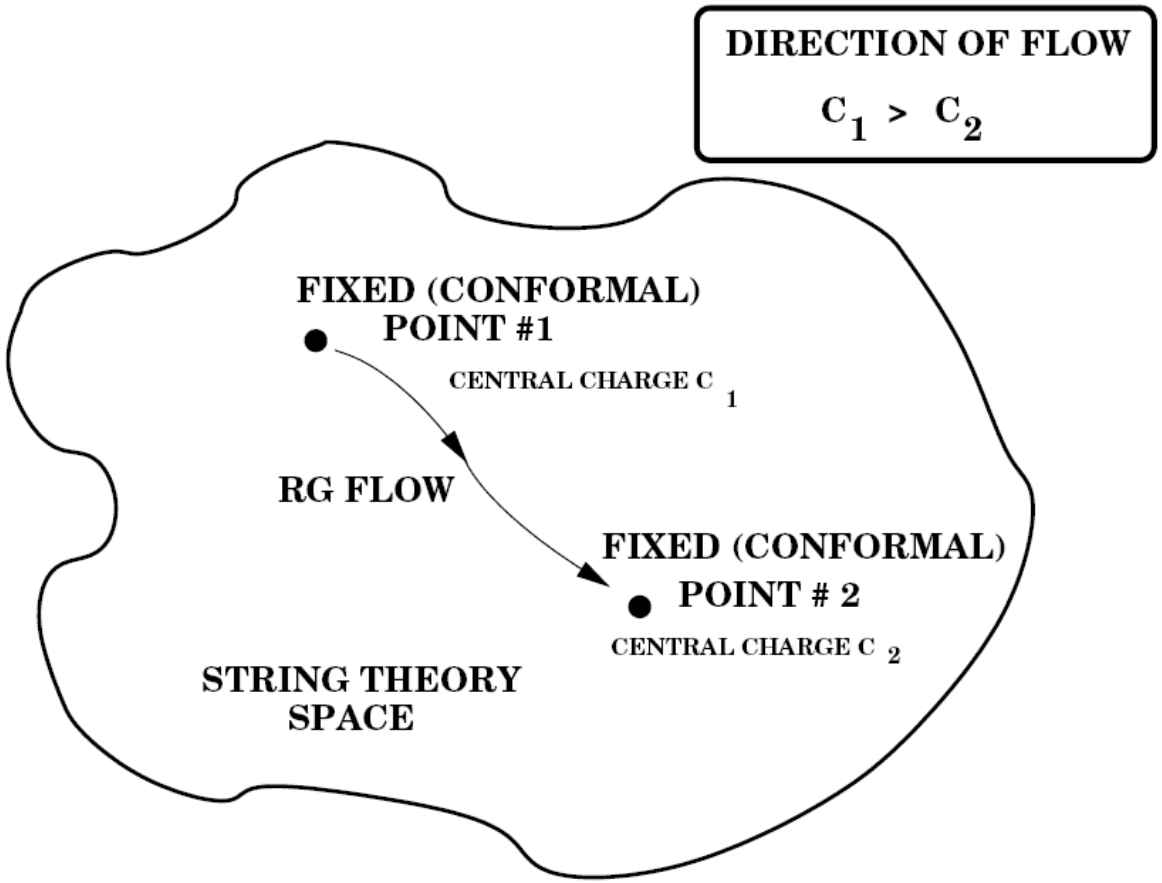
- **→ CPT VIOLATION**

- **→ LEPTOGENESIS → BARYON ASYMMETRY**
  (no need for extra CP Violation)


SPARES

A (non-critical) string theory time Arrow

Ellis, NEM Nanopoulos



Non-equilibrium Strings (non-critical), due to e.g. cosmically catastrophic events in Early Universe, for instance brane worlds collisions:

World-sheet conformal Invariance is disturbed

Central charge of world-Sheet theory ``runs'' To a minimal value

Zamolodchikov's C-theorem
An H-theorem for CFT

Change in degrees of Freedom (i.e. entropy)

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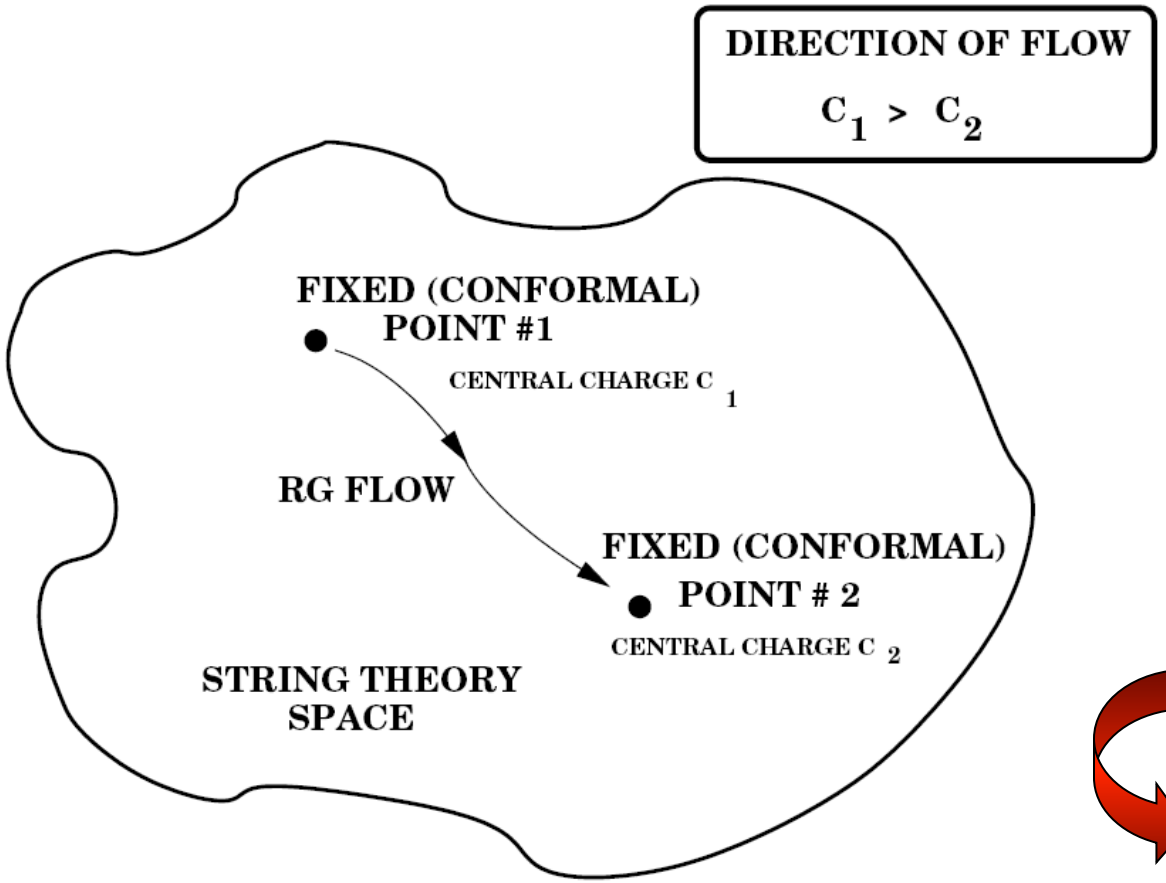

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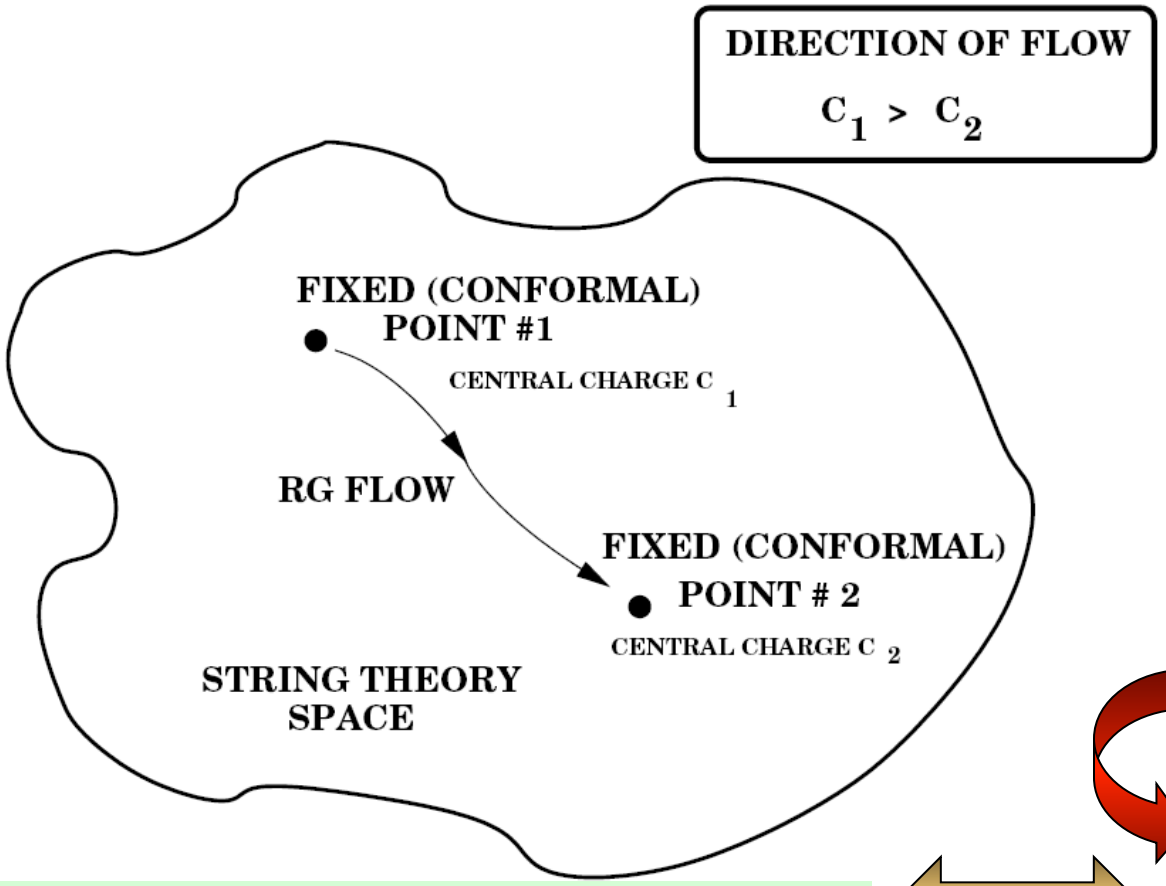

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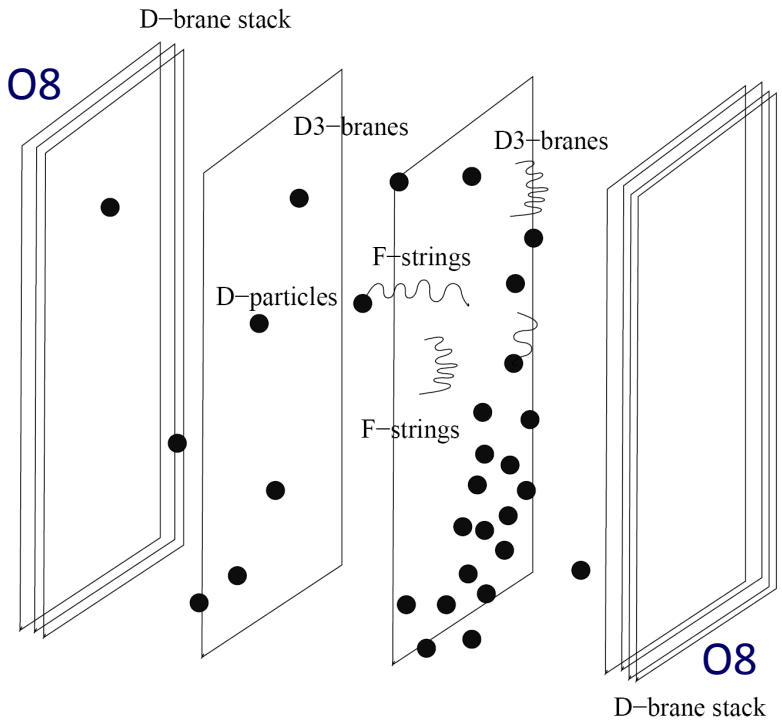
Time as Irreversible world-sheet Renormalization Group Flow – Time-dependent (non-stabilized) dilaton

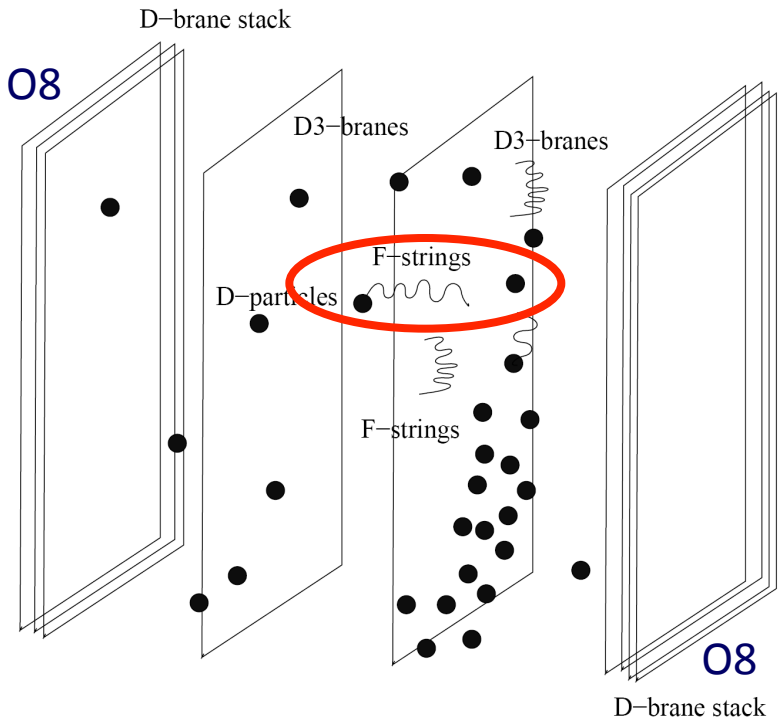
D-FOAM & THE DARK SECTOR



Ellis, NM, Westmuckett

Uses 8-Brane stacks to account For appropriate supersymemtries if no motion + Orientifold 8-Planes to compactify bulk 9th space dim.

Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only



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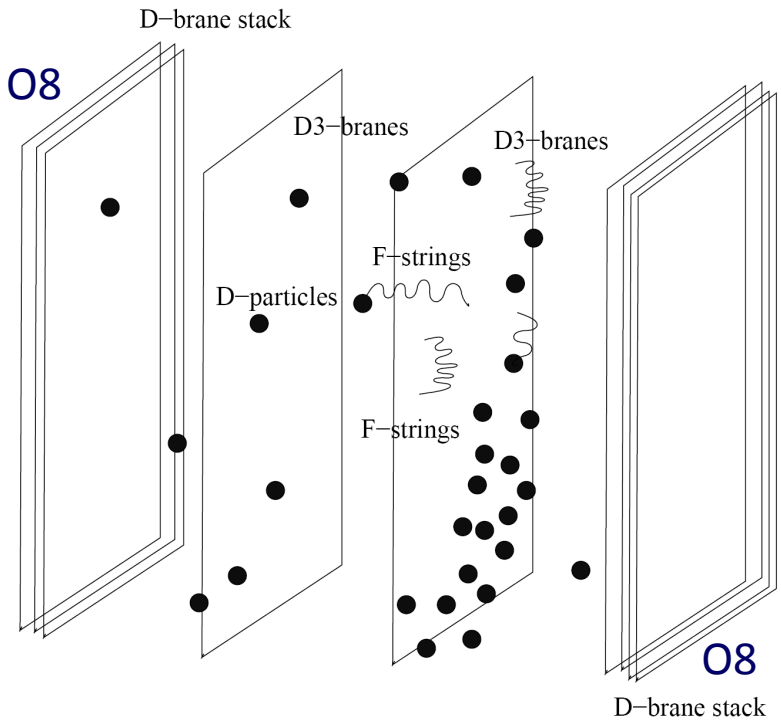

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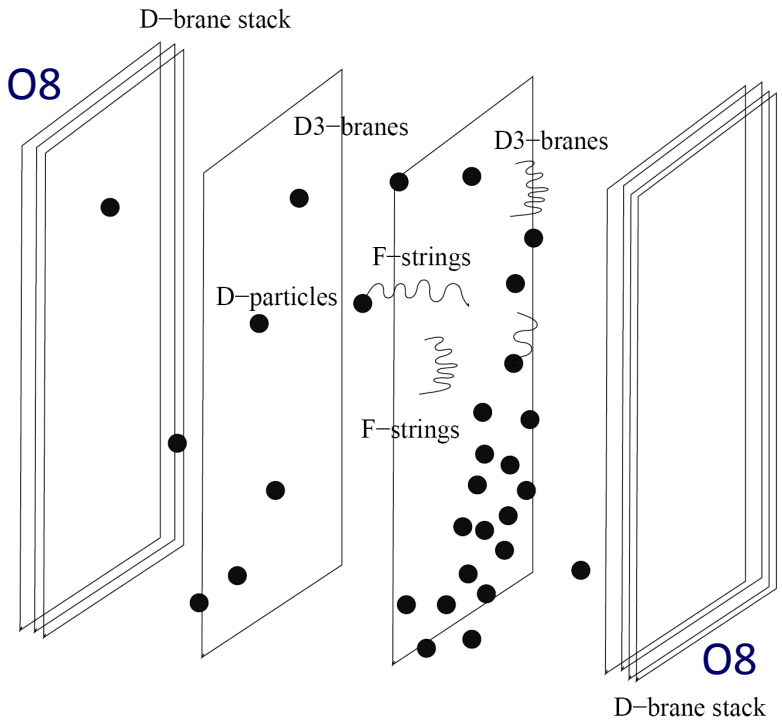
Velocity-independent terms cancelled by Orientifold O8 contributions



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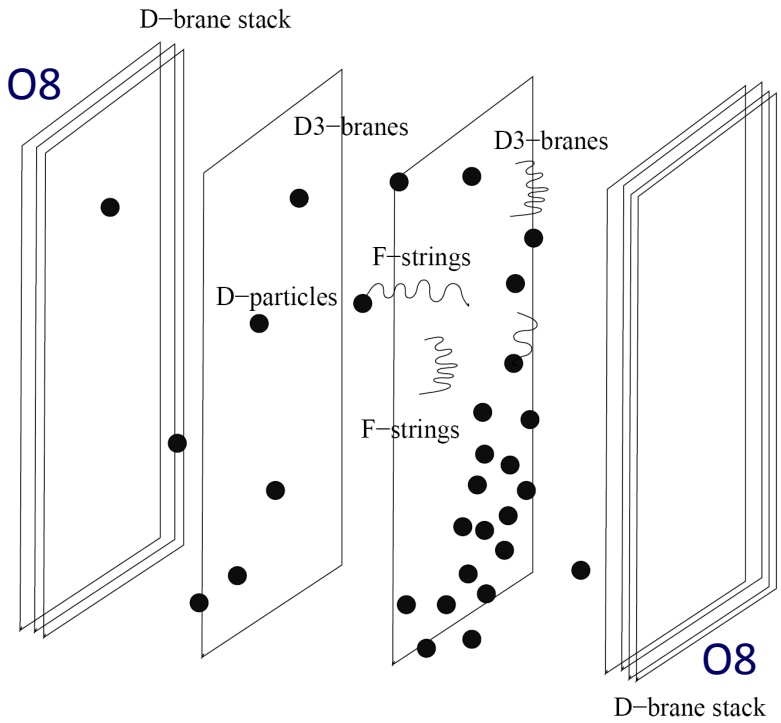

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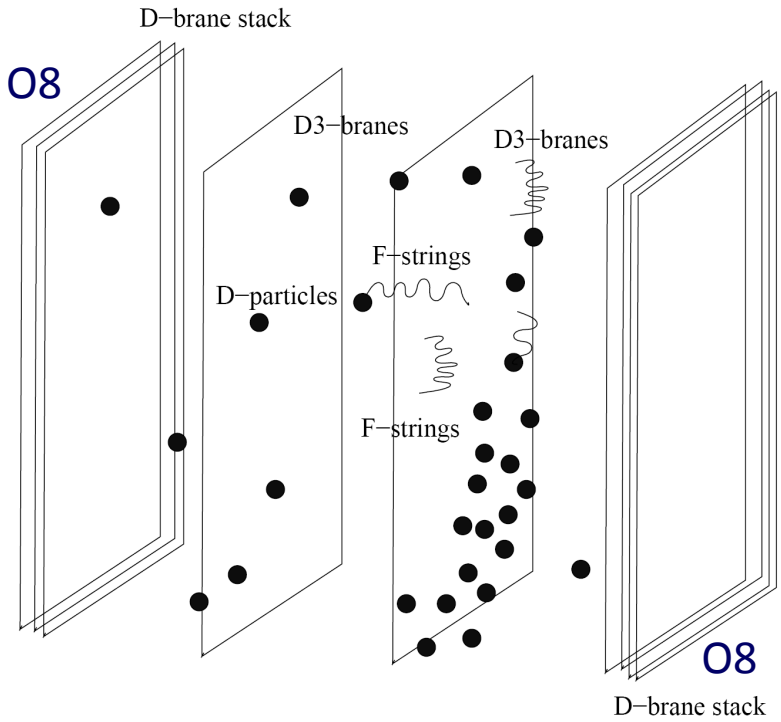
Sign of velocity-dependent terms in potential depends on D-particle/D-brane distance. May cancel out over long periods



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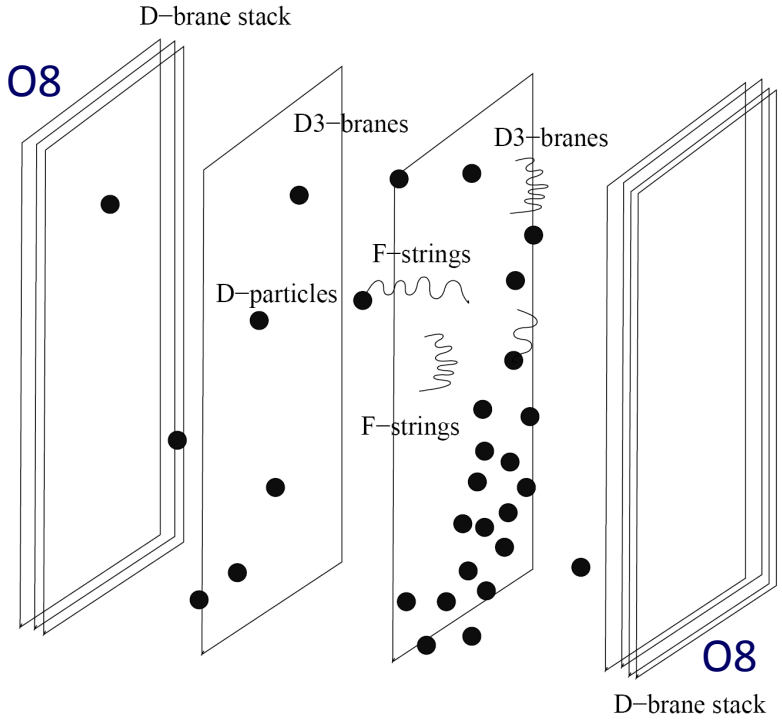

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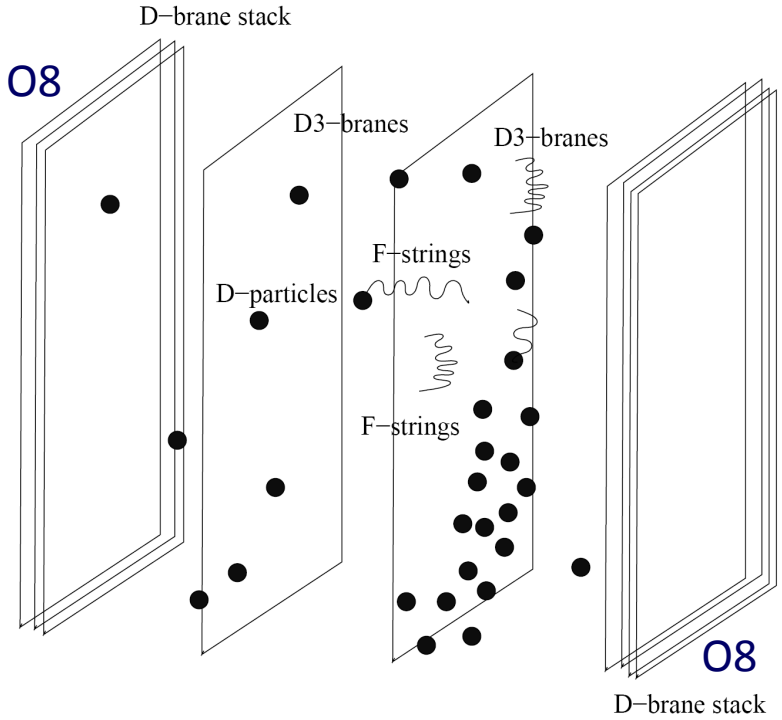

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