Neutralino annihilation to mono-energetic gamma rays

Haim Goldberg
Northeastern University, Boston

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- **D-branes, dijet signals at the LHC and all that**
- **Strings, broken R-symmetry, and efficient s-wave annihilation of neutralinos**
- **Copious branching to monoenergetic gamma rays**
- **. . . and prospects for near term discovery**

L. Anchordoqui, HG, D. Hooper, D. Marfatia, T. Taylor, Phys. Lett. B683 (2010) 321 (arXiv:0912.0517 [hep-ph])

TeV scale strings

- Large extra spatial dimensions and D-brane constructs allow

$\longrightarrow$ low string scale compatible with weak 4-D gravity – in toroidal compactification

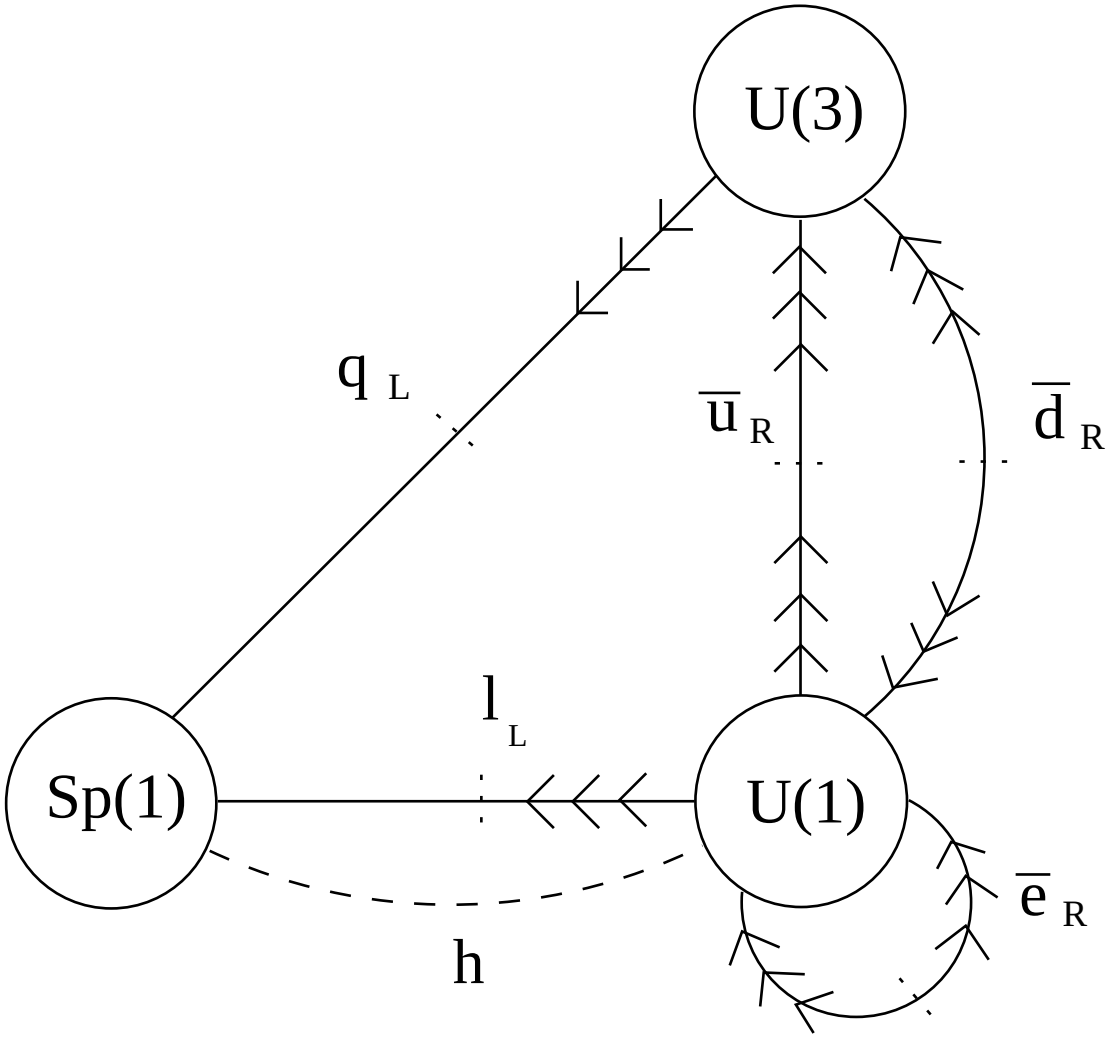
$$M_{\rm Pl}^2 \sim M_s^2 \ (M_s R)^n$$

$\longrightarrow$ Regge recurrences in TeV region

- Open strings can terminate on stack of N identical D branes

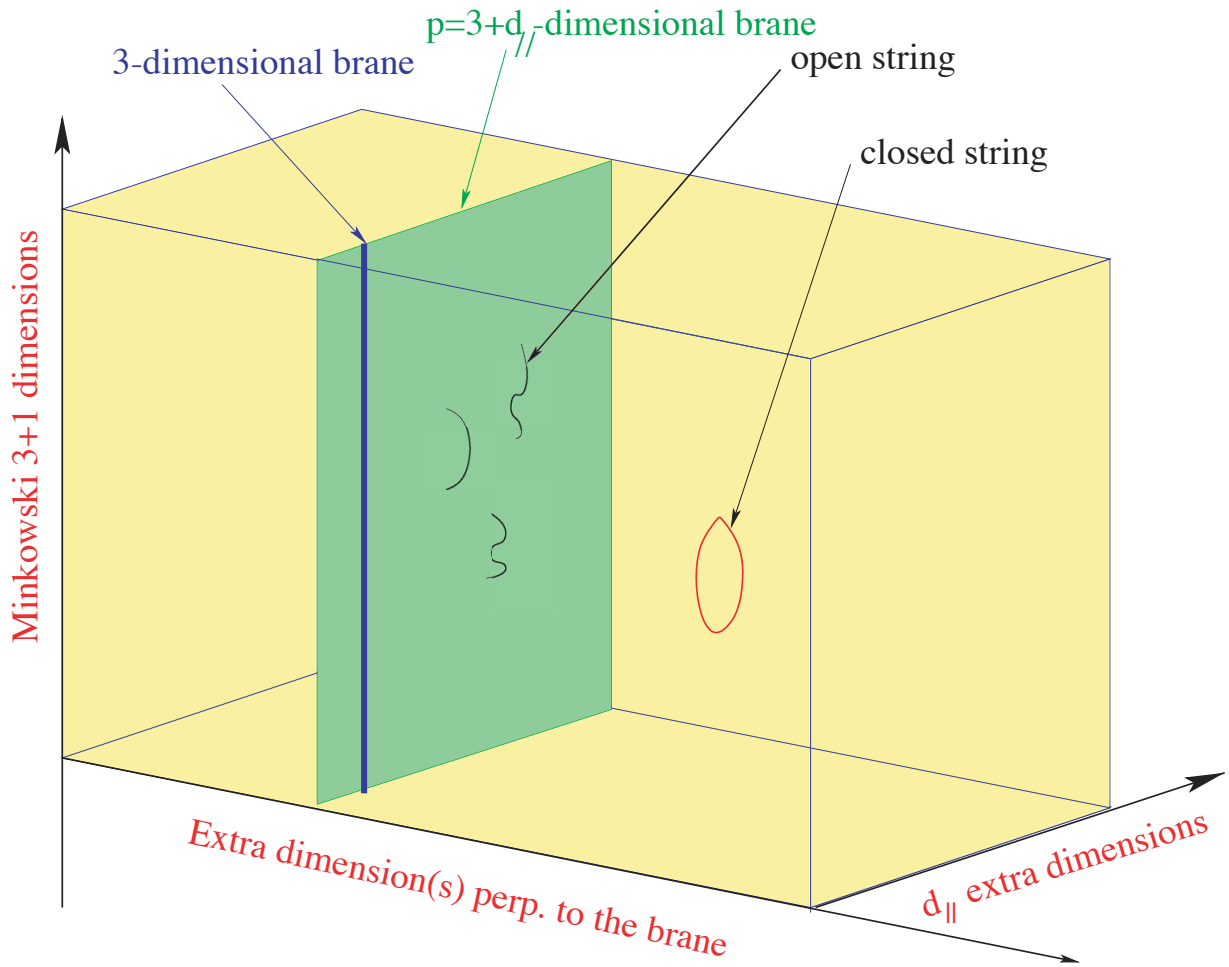
$\longrightarrow$ $U(N)$ gauge group for each stack. Matter fields in bifundamental representations

Quivers



Berenstein, Pinansky, [hep-th/0610104]; Antoniadis, Kiritsis, Tomaras, [hep-ph/0004214]

Parallel and perpendicular extra dimensions



Antoniadis [hep-th/0710.4267]

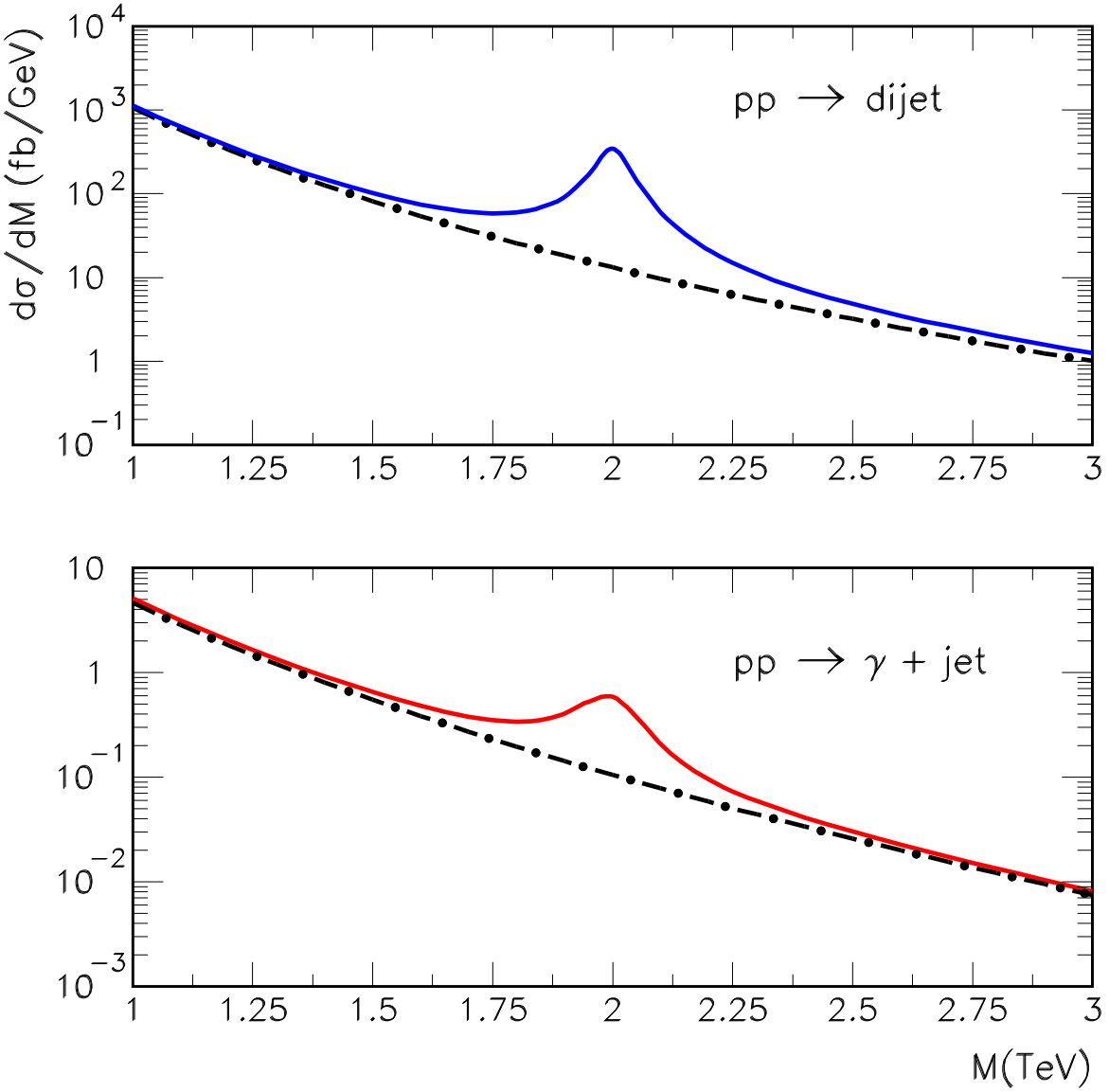
Model independence on the color brane

- Consider scattering on the U(3) brane, involving quarks and gluons
- Gluons live only on a single stack of color branes, don't see other branes
- Momentum in all the $p-3$ extra parallel dimensions conserved, so **4-point functions** $gg \longrightarrow gg,\ q\bar{q} \longrightarrow gg,\ qg \longrightarrow qg$ do not excite KK or winding modes – **only Regge recurrences independent of compactification.**
- Not so for $qq \longrightarrow qq$ – these live on intersecting branes, and parallel momentum not conserved – **KK/winding modes involved.**

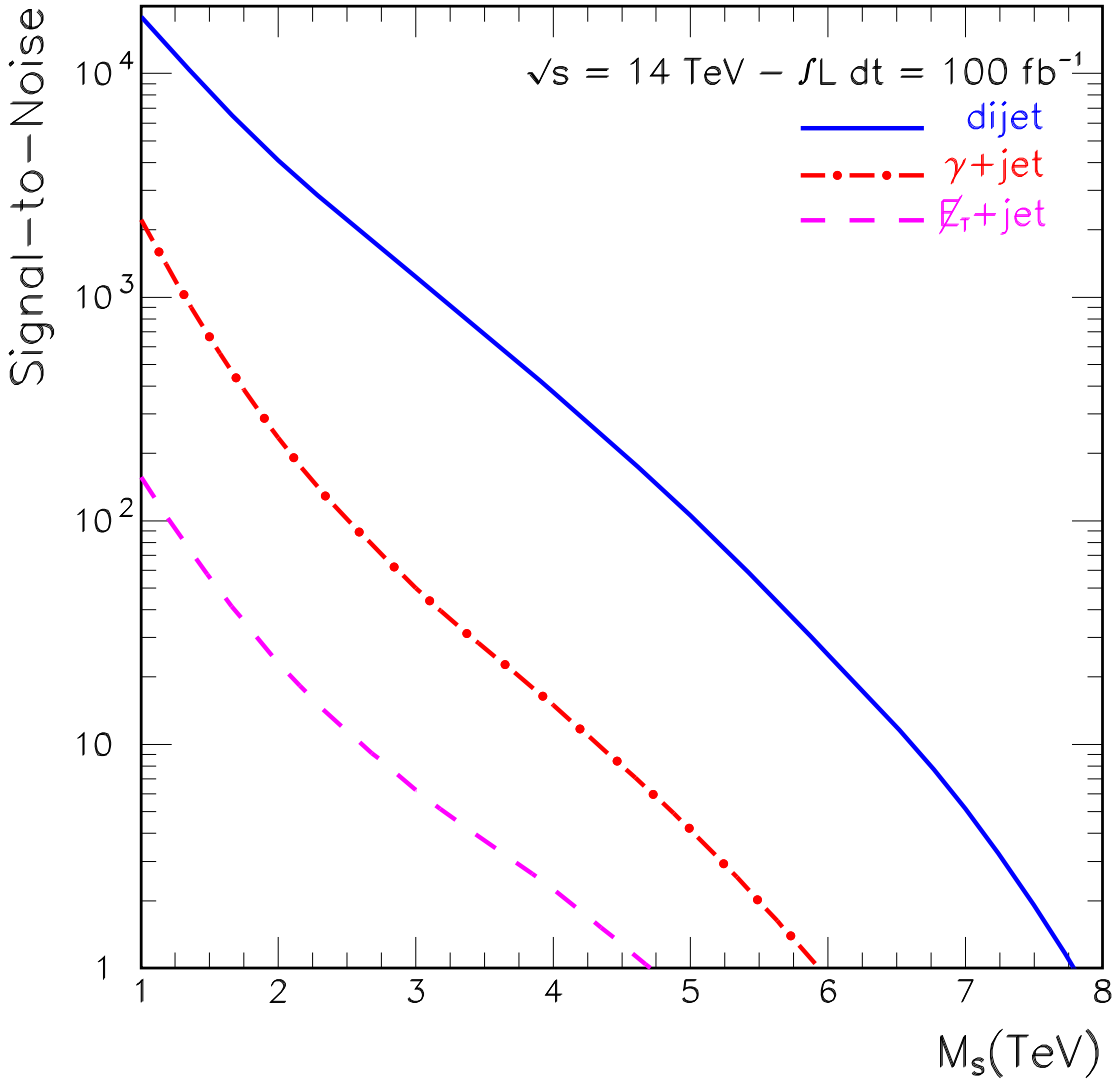
Bumps, etc at LHC

L. Anchordoqui, HG, D. Lust, S. Nawata, S. Stieberger, T. Taylor, Phys.Rev.Lett.101:241803,2008; Nucl.Phys.B821:181-196,2009.

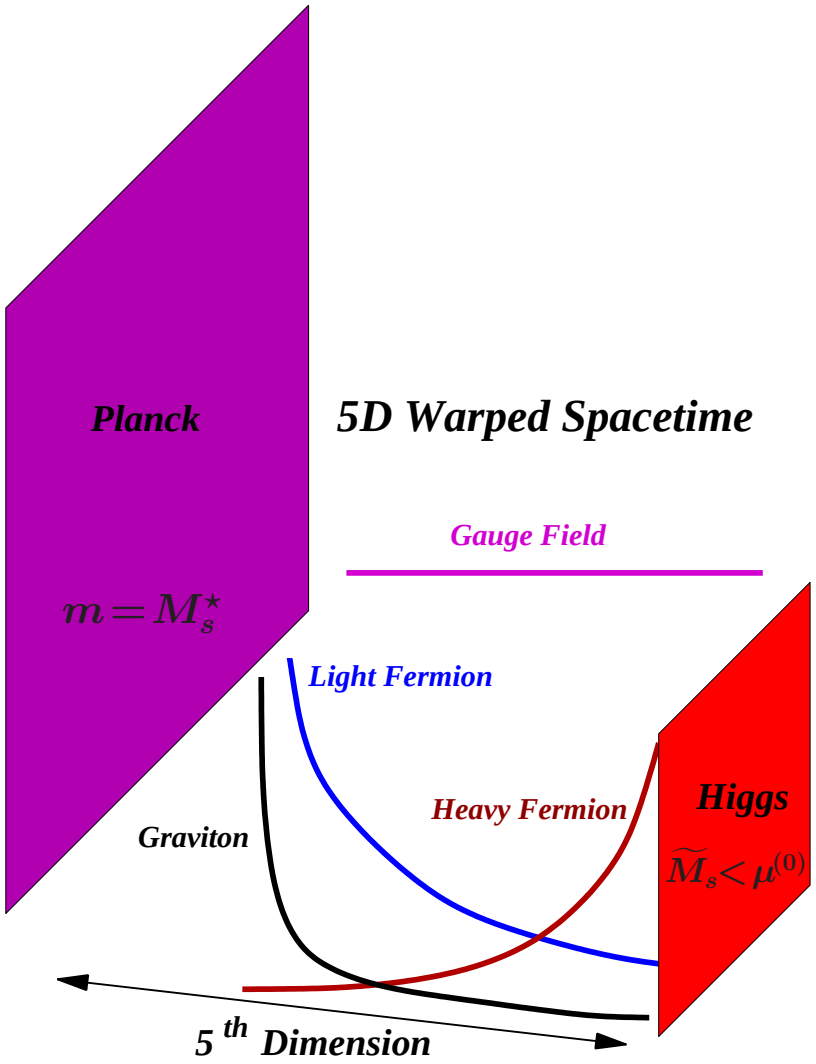
Dijets and direct photons



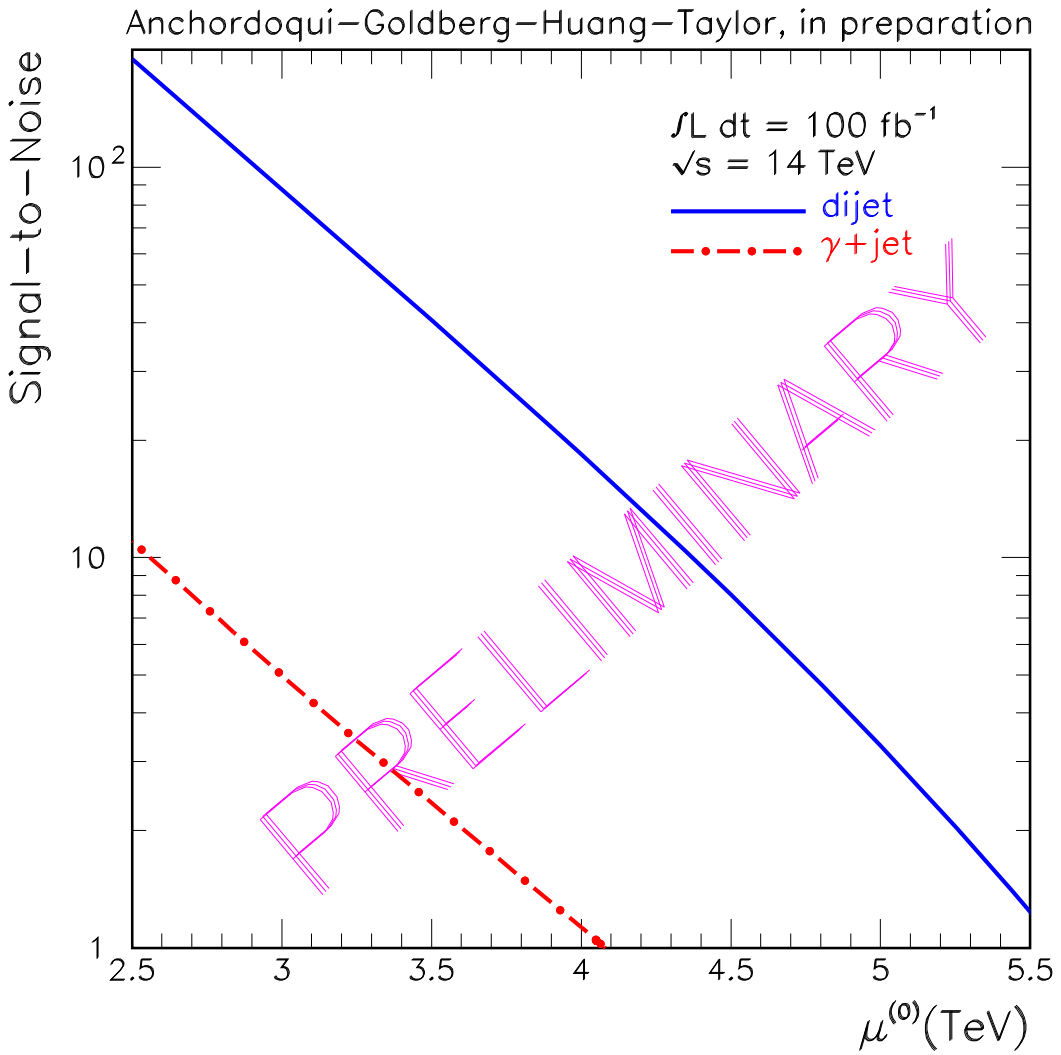
5σ discovery reach at LHC



Randall-Sundrum geometry



5σ discovery reach at LHC–Randall-Sundrum



Dark matter detection

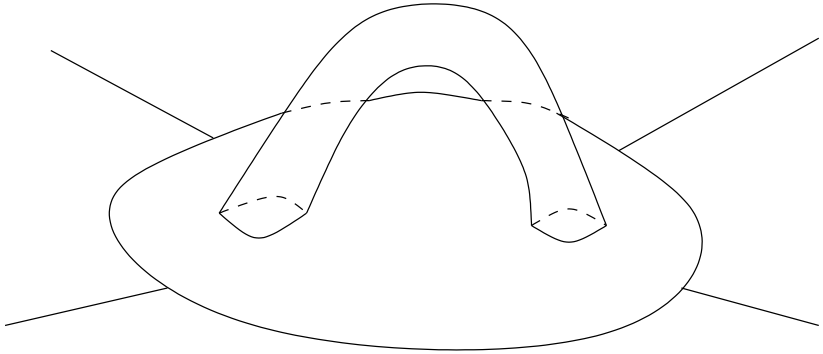
- Neutralino LSP's (χ^0's) are prime candidates for dark matter HG, Phys. Rev. Lett. 50, 1419 (1983)
- Annihilation hindered because of p-wave barrier
- Direct Detection in CDMS, XENON, etc.
- Indirect Detection: excess of γ-rays, $e^{\pm}$, ν's from dense astrophysical environments
- ID via monoenergeticγ rays from $\chi^0\chi^0 \to \gamma\gamma,\ \gamma Z$ are loop induced in the MSSM, and for the bino are small (BR $\sim$ 0.1%)

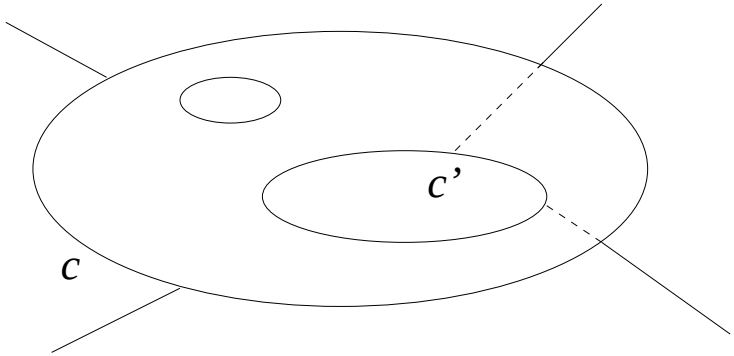
  L. Bergstrom, P. Ullio, Nucl. Phys. B504, 27(1997); Phys. Rev. D57, 1962 (1998); Z. Bern, P. Gondolo, M. Perelstein, Phys. Lett. B411 86, 1997

New string-based s-wave annihilation to gauge bosons

- s-wave annihilation demands that the χ^0's have same helicity
- Since $\chi^0\chi^0$ is the A term of a chiral superpotential WW, and the two gauge bosons $(\sim F^2)$ are in the F term of the same or a different WW, there is a violation of R-symmetry by two units $|\Delta r| = 2$.
- R-charge deficit related to Euler characteristic $\chi = 2 - 2g - h$ of the string world sheet via $-2\chi \geq |\Delta r|,\ \chi \leq 0$.
- Therefore require $\chi = -1 \rightarrow g = 1, h = 1$ or $g = 0, h = 3$

The topologies





I. Antoniadis, K. S. Narain, T. R. Taylor, Nucl Phys B729, 235(2005)

Stacks, boundaries and effective interactions

- **Effective lagrangian calculable from topology of compactified dimensions if gaugino and gauge boson vertices are attached to two different boundaries.**

- **Additional non-topological contributions if emitted gauge bosons are in same stack as gauginos, and vertices are attached to same boundary**

$$\mathcal{L}_{\rm eff} = 3\, g_s^3 N\, M_s^{-3}\, \widetilde{F}^{(0,3)}\, (\mathrm{Tr}\, WW)\, (\mathrm{Tr}\, WW)|_{\theta\theta} + h.c.$$

$$= \frac{3}{8}\, g_s^3 N\, M_s^{-3}\, \widetilde{F}^{(0,3)}\, (\mathrm{Tr}\, \lambda\lambda)\, (\mathrm{Tr}\, FF) + h.c. \quad .$$

$N = 6 =$ **no of stacks traced out in empty boundary.**

Constraint from relic abundance

- **To generate measured relic density $\Omega_{\rm CDM}h^2 = 0.113 \pm 0.003$ requires annihilation rate**

$$\begin{aligned} \langle \sigma v \rangle_{\rm eff} &= \sigma v|_{WW} + \sigma v|_{gg} + \sigma v|_{BB} \\ &\simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s} \end{aligned}$$

- **For each gluon or W pair**

$$\begin{aligned} \sigma v|_{W^i W^i} &= \sigma v|_{g^i g^i} \\ &= \frac{c}{4\pi} \left(3 g_s^3 N \widetilde{F}^{(0,3)} \right)^2 \left(\frac{\hbar}{M_s \, c} \right)^2 \left(\frac{M_\chi}{M_s} \right)^4 \end{aligned}$$

Constraint (cont'd)

- To take account of non-topological contributions to $\chi\chi \to BB$ define

$$\zeta = \frac{\mathcal{M}(BB)}{\mathcal{M}(W^3W^3)}$$

- Relic constraint is

$$(1 + 0.083(\zeta^2 - 1)) \left(\frac{\widetilde{F}^{(0,3)}}{2.8}\right)^2 \left(\frac{g_s}{0.2}\right)^6 \left(\frac{\rho}{0.5}\right)^4 \left(\frac{2\ \mathrm{TeV}}{M_s}\right)^2 \simeq 1\,.$$

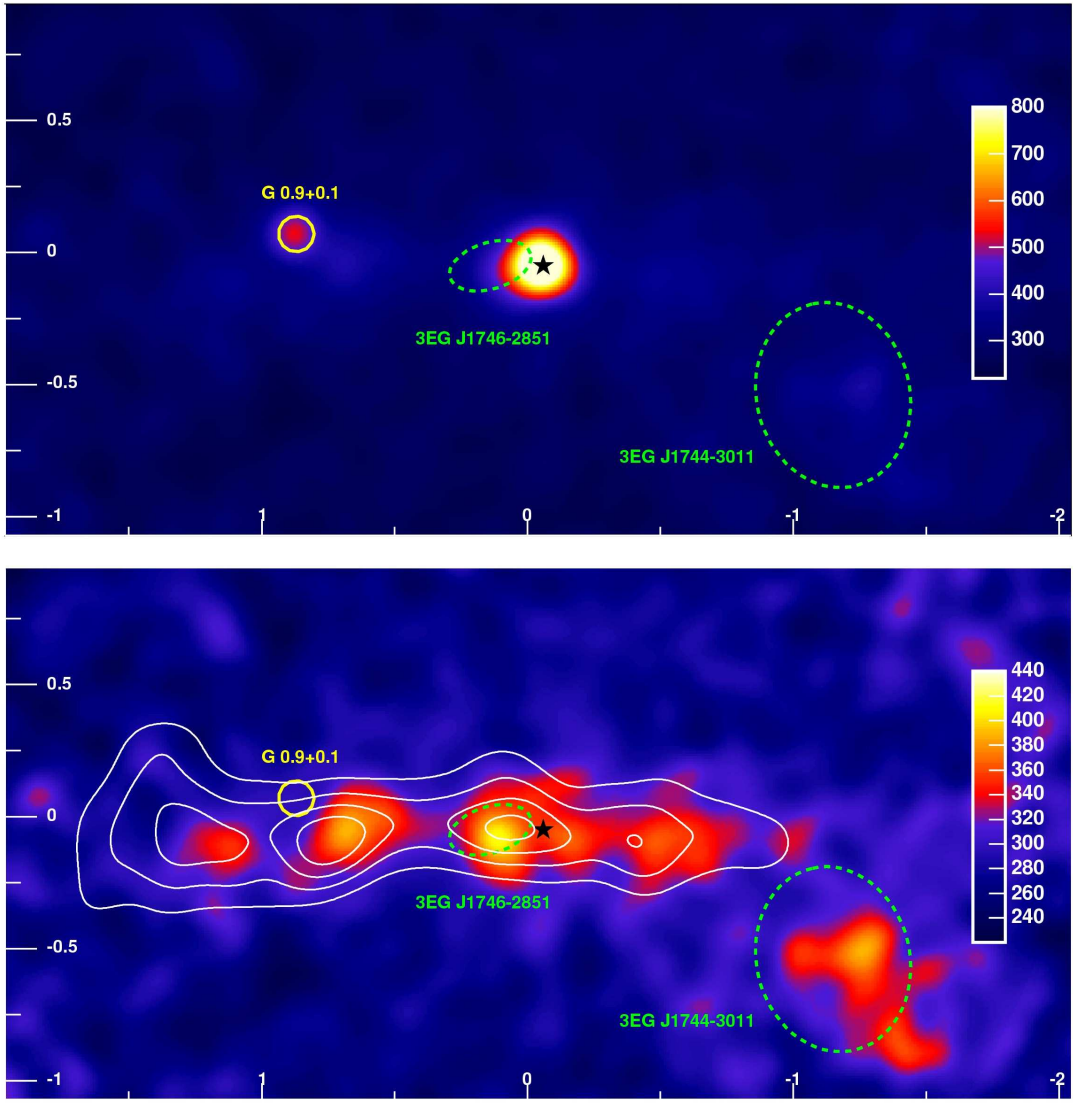
The Smoking Gun

- **Rewrite cross sections in terms of $\gamma,\ Z,\ W^{\pm},\ g$**

$$
\begin{aligned}
\sigma v|_{\gamma\gamma} &= \sigma v|_{W^3W^3}\left(\sin^2\theta_W + \zeta\cos^2\theta_W\right)^2 , \\
\sigma v|_{ZZ} &= \sigma v|_{W^3W^3}\left(\cos^2\theta_W + \zeta\sin^2\theta_W\right)^2 , \\
\sigma v|_{\gamma Z} &= \sigma v|_{W^3W^3}\ 2\cos^2\theta_W\sin^2\theta_W\ (1-\zeta)^2 , \\
\sigma v|_{W^+W^-} &= 2\,\sigma v|_{W^3W^3} , \\
\sigma v|_{gg} &= 8\,\sigma v|_{W^3W^3}
\end{aligned}
$$

- **For $\zeta \simeq 1$ obtain nearly 10% branching into $\gamma\gamma$ – a large number of gamma rays with energy $\sim M_\chi$.**

H.E.S.S. and Galactic Center

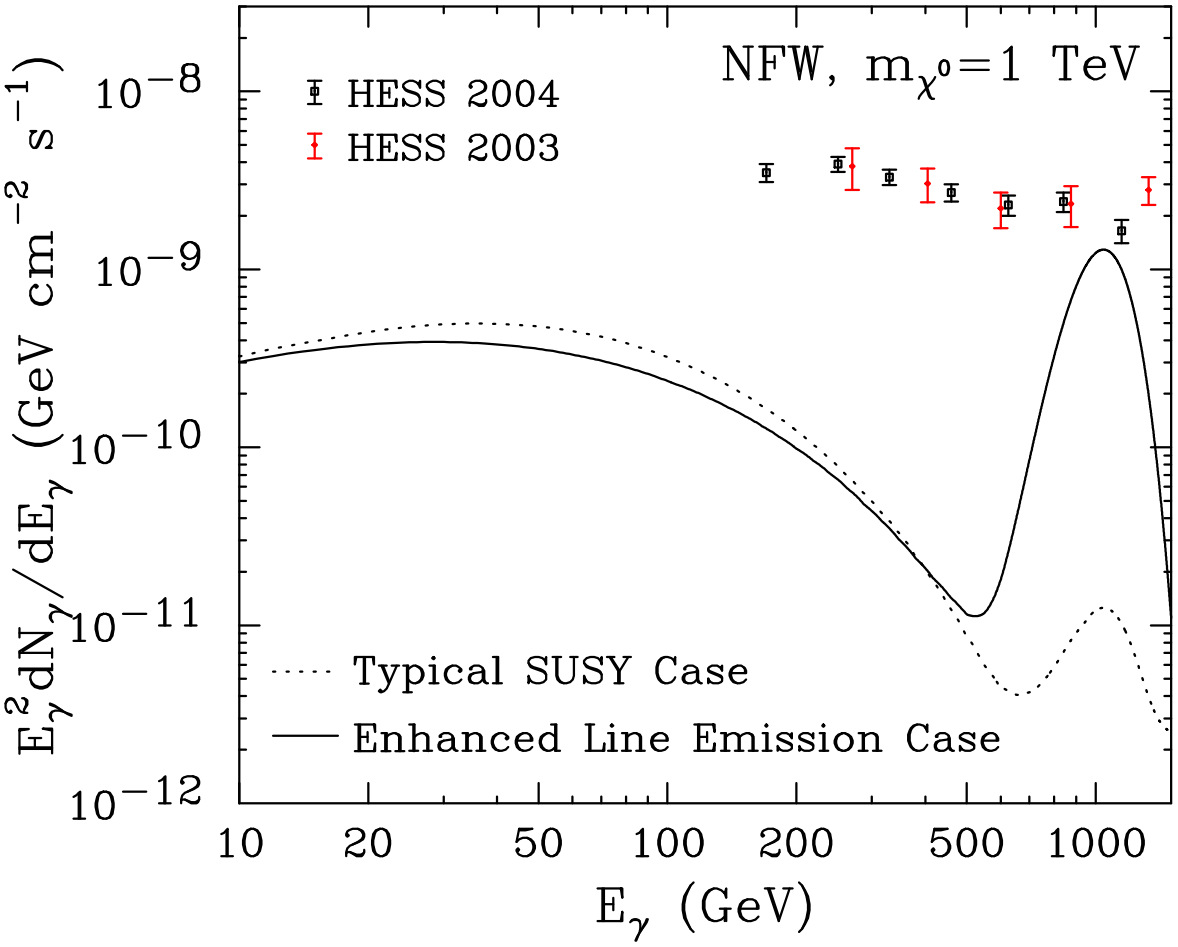


Gamma ray flux from annihilation in GC

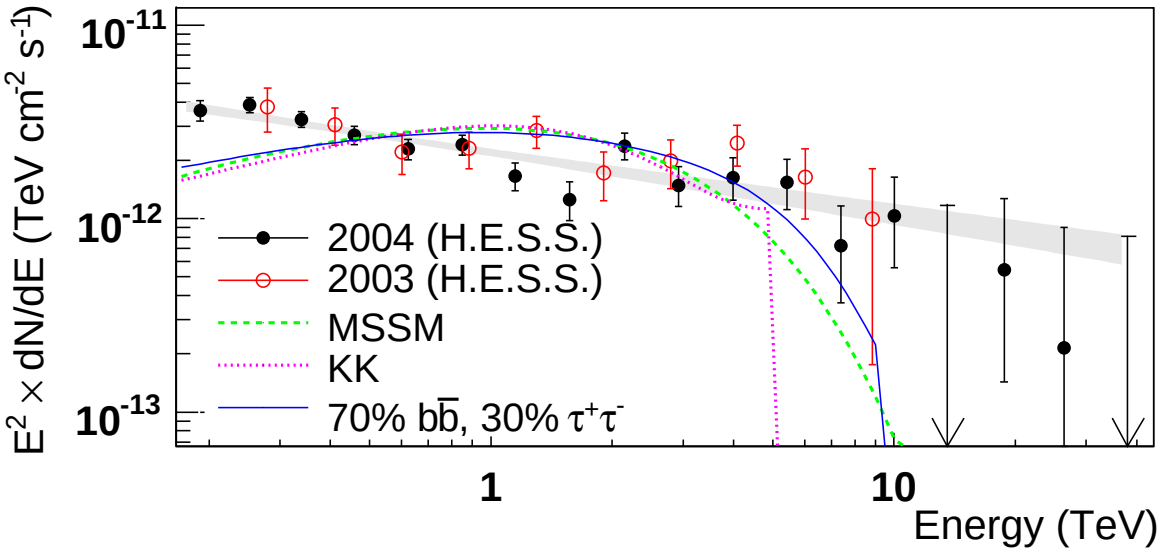
- **Typical branching ratio into monoenergetic gamma rays 1-2 orders of magnitude larger than from 1 loop SUSY**

- $$\Phi_\gamma(E_\gamma, \psi) \simeq \frac{\sigma v|_i}{8\pi} \left.\frac{dN_\gamma}{dE_\gamma}\right|_i \int_{\rm l.o.s.} n^2_{\chi^0}(r)\; dl(\psi)\; d\psi\,,$$

Spectrum


NFW, m_{χ^0}=1 TeV
HESS 2004
HESS 2003
Typical SUSY Case
Enhanced Line Emission Case
$E_\gamma^2 dN_\gamma/dE_\gamma$ (GeV cm^{-2} s^{-1})
E_γ (GeV)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10
20
50
100
200
500
1000

Hint?


10^{-11}
10^{-12}
10^{-13}
$E^2 \times dN/dE$ (TeV cm^{-2} s^{-1})
2004 (H.E.S.S.)
2003 (H.E.S.S.)
MSSM
KK
70% $b\bar{b}$, 30% $\tau^+\tau^-$
1
10
Energy (TeV)

Summary

- Within the context of D-brane TeV-scale string compactifications, we constructed a model that generates a supersymmetric R-symmetry violating effective Lagrangian which allows for the s-wave annihilation of neutralinos (once gauginos acquire mass through an unspecified mechanism).
- The model allows for a neutralino relic abundance consistent with the measured dark matter density.
- The branching fractions to monochromatic gamma rays is orders of magnitude larger than in the MSSM.
- A very bright and distinctive gamma-ray line that

may lie within the reach of current or next-generation gamma-ray telescopes is predicted.

- **A flux near the limit presently imposed by the H.E.S.S. data would strongly support a near purely topological origin for the R-symmetry violating effective Lagrangian.**