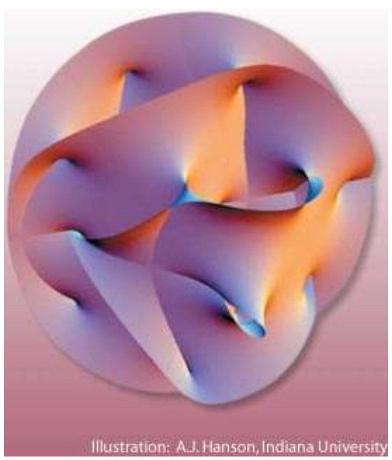
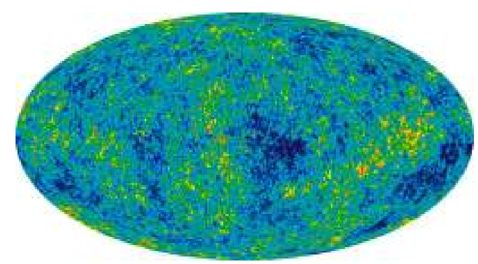
Task D: String Theory and Theoretical Cosmology

THE UNIVERSITY of WISCONSIN MADISON



Daniel J. H. Chung
Akikazu Hashimoto
Gary Shiu



PIs & Task Merger

- Faculty: Daniel Chung – theoretical cosmology
  Akikazu Hashimoto – string theory
  Gary Shiu – string theory/cosmology
- Reasons for merging tasks D + J → new D
  - Albrecht Klemm → C4 position at Bonn
  - Daniel Chung's OJI award ended in 09
  - Natural synergy and balance
- Other notable changes
  - Shiu's NSF CAREER award ended in 09
  - Shiu promoted to full professor
  - Chung and Hashimoto promoted to associate professor
- Task's role: interfaces with activities in collider physics, phenomenology, and mathematics.
- Plan: Continue to support 2 postdocs

Postdocs

Name	Years	Notes
Calin Lazariou	2003-2004	→ Faculty appointment at University of Dublin, Ireland
Fernando Marchesano	2003-2005	→ Munich → CERN → Faculty appointment at IFT, Madrid
Ian Ellwood	2004-2007	→ University of Kentucky → UCSF
Minxin Huang	2004-2007	→ CERN → IPMU
Ghazal Geshnizjani	2004-2007	→ Perimeter Institute
Thomas Grimm	2005-2007	→ Bonn → Faculty appointment at LMU, Munich
H.Y. Chen	2007-Present	Cambridge, UK → Appointed till 2011
Bjorn Garbrecht	2007-2009	→ Faculty appointment at RWTH Aachen University, Germany
Jinn-Ouk Gong	2007-2008	→ University of Leiden, Netherlands → CERN
Peter Ouyang	2007-Present	→ Purdue University
Diego Trancanelli	2010-	Santa Barbara → Arriving Fall 2010
Jiajun Xu	2010-	Cornell → Arriving Fall 2010

Postdocs visiting long term with their own funding:
Niayesh Afshordi (1/3 of the time during 2004 - 2007)
Thomas Van Riet (Fulbright Fellow) (1/08 - 5/08)
Yoske Sumitomo (Nishina Foundation Fellow) (3/09 - 11/09)

• Students

Name	PhD	advisor	Notes
Chiantese	05	Klemm	→finance industry
Thomas	05	Hashimoto	→Shell Oil
Maiden	06	Shiu	→finance industry
Romano	07	Chung	→Kyoto
Underwood	08	Shiu	→McGill (IPP and Lorne Trottier Fellowships)
Haque		Hashimoto	PhD expected 11
Kiewe		Shiu	PhD expected 14
Long		Chung	PhD expected 11/12
McGuirk		Shiu	PhD expected 11/12
Yoo		Chung	PhD expected 13
Zhou		Chung	PhD expected 11/12

• Conferences organization
  - "Great Lakes Strings" in April 2008
  - "COSMO08" in August 2008
  - "International String Phenomenology Conference" in May 2011

Order of Presentation

- Chung – theoretical cosmology
- Hashimoto – formal aspects of string theory
- Shiu – string phenomenology/cosmology

Theoretical Cosmology

[PI: Daniel J. H. Chung]

Theme:
Novel observables connecting high energy theory and cosmology.

Cosmology Observables ⟷ **High Energy Theory Observables**

Research interests during the past and next 3 years

- Electroweak scale phase transition
- Inflationary cosmology
- Dark sector (dark matter + dark energy)

Daniel Chung's Publications Since 2007

- D. J. H. Chung and A. J. Long, "Electroweak Phase Transition in the munuSSM," Phys. Rev. D **81**, 123531 (2010), arXiv:1004.0942.
- D. J. H. Chung and P. Zhou, "Gravity Waves as a Probe of Hubble Expansion Rate During An Electroweak Scale Phase Transition," Phys. Rev. D **82**, 024027 (2010), arXiv:1003.2462.
- D. J. H. Chung, B. Garbrecht, M. J. Ramsey-Musolf and S. Tulin, "Supergauge interactions and electroweak baryogenesis," JHEP **0912**, 067 (2009), 0908.2187.
- D. J. H. Chung, B. Garbrecht, M. J. Ramsey-Musolf and S. Tulin, "Lepton-mediated electroweak baryogenesis," Phys. Rev. D **81**, 063506 (2010), arXiv:0905.4509.
- D. J. H. Chung, B. Garbrecht, M. J. Ramsey-Musolf and S. Tulin, "Yukawa Interactions and Supersymmetric Electroweak Baryogenesis," Phys. Rev. Lett. **102**, 061301 (2009), arXiv:0808.1144.
- D. J. H. Chung, B. Garbrecht and S. Tulin, "The Effect of the Sparticle Mass Spectrum on the Conversion of B-L to B," JCAP **0903**, 008 (2009), arXiv:0807.2283.
- R. Bean, D. J. H. Chung and G. Geshnizjani, "Reconstructing a general inflationary action," Phys. Rev. D **78**, 023517 (2008), arXiv:0801.0742.
- D. J. H. Chung, L. L. Everett, K. Kong and K. T. Matchev, "Connecting LHC, ILC, and Quintessence," JHEP **0710**, 016 (2007), 0706.2375.
- D. J. H. Chung, L. L. Everett and K. T. Matchev, "Inflationary Cosmology Connecting Dark Energy and Dark Matter," Phys. Rev. D **76**, 103530 (2007), 0704.3285.
- N. Afshordi, D. J. H. Chung, M. Doran and G. Geshnizjani, "Cuscuton Cosmology: Dark Energy meets Modified Gravity," Phys. Rev. D **75**, 123509 (2007), astro-ph/0702002.
- E. Komatsu *et al.*, "Non-Gaussianity as a Probe of the Physics of the Primordial Universe and the Astrophysics of the Low Redshift Universe," arXiv:0902.4759.
- D. Baumann *et al.* [CMBPol Study Team Collaboration], "CMBPol Mission Concept Study: Probing Inflation with CMB Polarization," AIP Conf. Proc. **1141**, 10 (2009).

Chung's Other Activities Since 2007

- 16 conference talks, 5 seminars, 1 summer school
- White paper contributions: 0902.4759 (non-Gaussianity), 0811.3919 (CMBPol)
- Coorganizing activities
    - Cosmo 08 (Madison, WI)
    - Workshop on DM, LHC, and Cosmology 2009 (Seoul, S. Korea)

Postdoc Work

Garbrecht 6/07-8/09

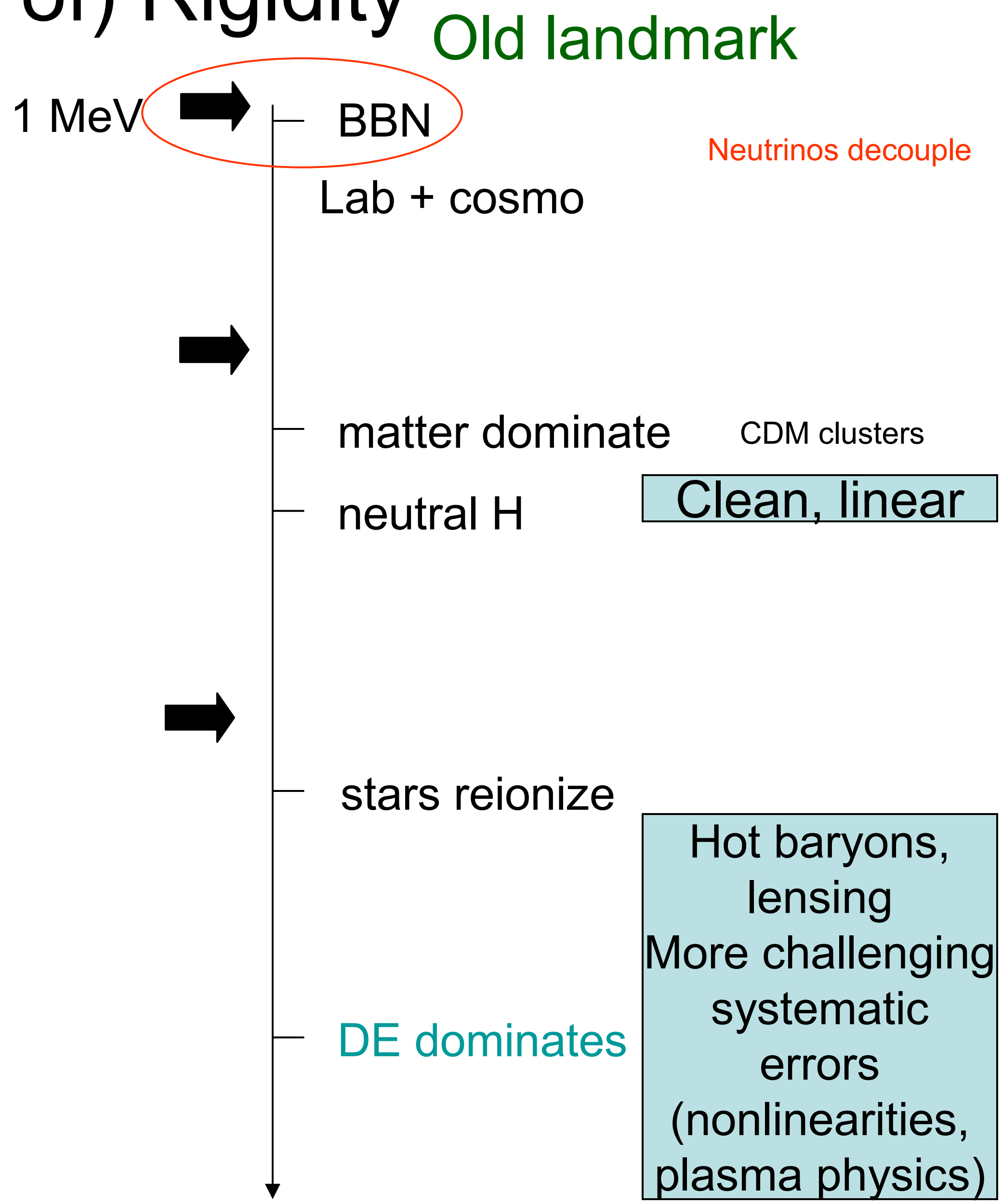
- R. A. Battye, B. Garbrecht, A. Moss and H. Stoica, "Constraints on Brane Inflation and Cosmic Strings," JCAP **0801**, 020 (2008) [arXiv:0710.1541 [astro-ph]].
- R. A. Battye, B. Garbrecht and A. Pilaftsis, "Textures and Semi-Local Strings in SUSY Hybrid Inflation," JCAP **0809**, 020 (2008) [arXiv:0807.1729 [hep-ph]].
- B. Garbrecht and T. Konstandin, "Separation of Equilibration Time-Scales in the Gradient Expansion," Phys. Rev. D **79**, 085003 (2009) [arXiv:0810.4016 [hep-ph]].

Gong 6/07-8/09

- J. O. Gong and S. C. Park, "Minimal extra dimensional cosmology from hidden sector gauge theory," arXiv:0801.0333 [hep-ph].
- J. O. Gong and S. C. Park, "Minimal extra dimensional cosmology from hidden sector gauge theory," arXiv:0801.0333 [hep-ph].
- J. O. Gong and M. Sasaki, "Curvature perturbation spectrum from false vacuum inflation," JCAP **0901**, 001 (2009) [arXiv:0804.4488 [astro-ph]].
- R. K. Jain, P. Chingangbam, J. O. Gong, L. Sriramkumar and T. Souradeep, "Double inflation and the low CMB multipoles," JCAP **0901**, 009 (2009) [arXiv:0809.3915 [astro-ph]].

1) Electroweak Scale Phase Transition

(Lack of) Rigidity



(Lack of) Rigidity

- inflaton (“solves” flatness + horizon + relic; generates density perturbations)
- (re)heats (couples to SM)

Moduli oscillate

gravitino

Leptogenesis

Anticipated new landmark

LHC

- EWPT
- Baryon chemical potential freeze in
- WIMP freeze out

Lab + cosmo

- QCD PT
- axion oscillate

Old landmark

1 MeV

- BBN

Neutrinos decouple

Lab + cosmo

- matter dominate

CDM clusters

- neutral H

Clean, linear

- stars reionize
- DE dominates

Hot baryons, lensing
More challenging systematic errors (nonlinearities, plasma physics)

Implications?

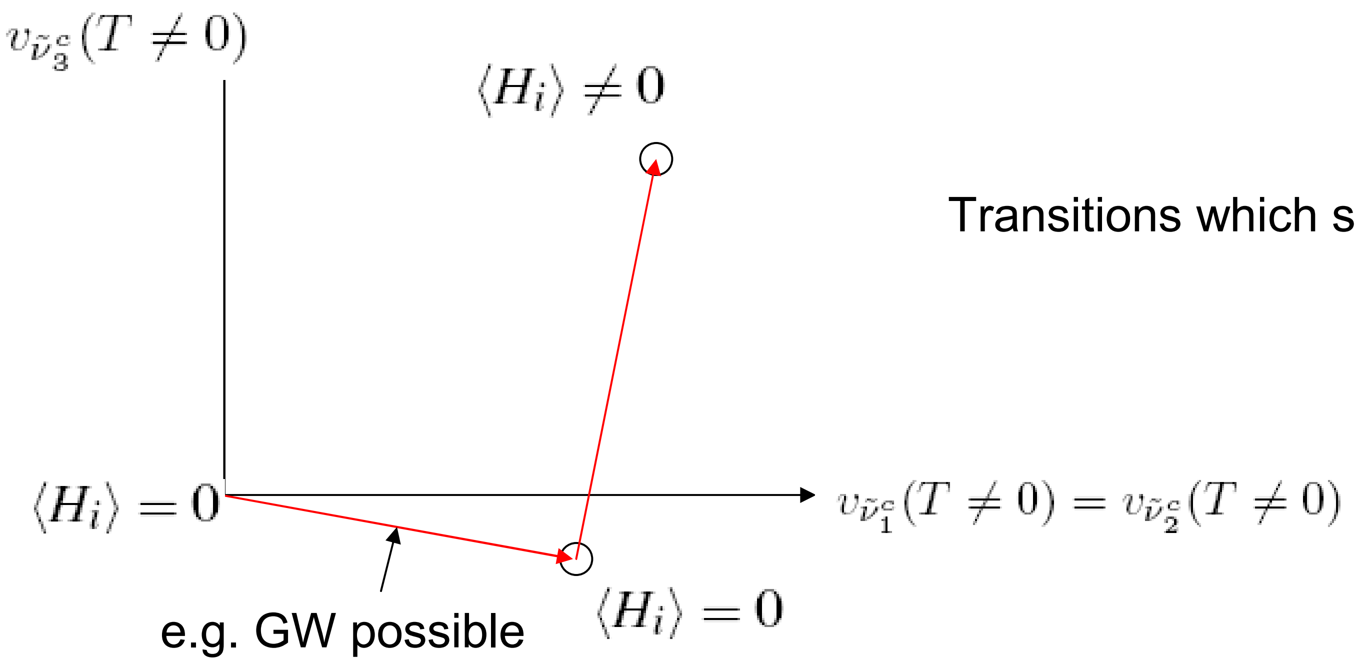
- Electroweak Baryogenesis: Bubble/plasma dynamics
  - Good: Overconstraint possible
  - Bad: 1 number, mild tuning of parameters
- Leptogenesis: B-L to B conversion
  - Good: Connection to a lot of “natural” UV physics
  - Bad: Overconstraint unlikely
- Gravity Waves: Bubble stirs up fluid
  - Good: Overconstraint possible
  - Bad: Measurability is uncertain
- DM: Freeze out physics can be affected
  - Good: Overconstraint possible
  - Bad: narrow parametric window
- CC: IR contribution
  - Good: Overconstraint possible
  - Bad: narrow parametric window, and
    dependence on multiple discoveries
- Source of density inhomogeneity perturbations on small scale
  - Good: Overconstraint possible in principle
  - Bad: Any signal is likely to be completely erased due to phase space mixing

Recent Contributions

- Electroweak Baryogenesis
  - 1004.0942 – Techniques for finding 1st order PT region with multiple singlets
  - 0908.2187 – Numerically studied supergauge equilibration; identified kinematic bottle necks
  - 0905.4509 – MSSM parametric region in leptons carry the CP asymmetry was explored; split diffusion
  - 0808.1144 – Corrected common mistake of neglecting b-Yukawa; decouples 1st 2 generations
- Leptogenesis: B-L to B conversion
  - 0807.2283 – Computed conversion factor dependence on the sparticle mass spectral dependence
- Gravity Waves: Bubble stirs up fluid
  - 1003.2462 – Robust transformation law of the grav wave spectrum with H; probe of energy density
- DM: Freeze out physics can be affected
- CC: IR contribution
- Source of density inhomogeneity perturbations on small scale

Example of a Transition Different from NMSSM in $\mu\nu\mathrm{SSM}$

[1004.0942]



Transitions which shuts off B-violation.

How can one find this parametric point approximately analytically?

1) With $\langle H_i \rangle = 0$ look in a parametric region where there is a discrete symmetry G

→ Whenever singlets obtain VEVs (trivially achieved by soft masses), the coset space will form a rep. of G

2) Radiative corrections lift degeneracy: look for a deeper min.
3) Look along the deeper min direction and tune $\frac{E_{\mathrm{eff}}}{\lambda_{\mathrm{eff}}\phi(0)} \approx \frac{1}{2}$ where

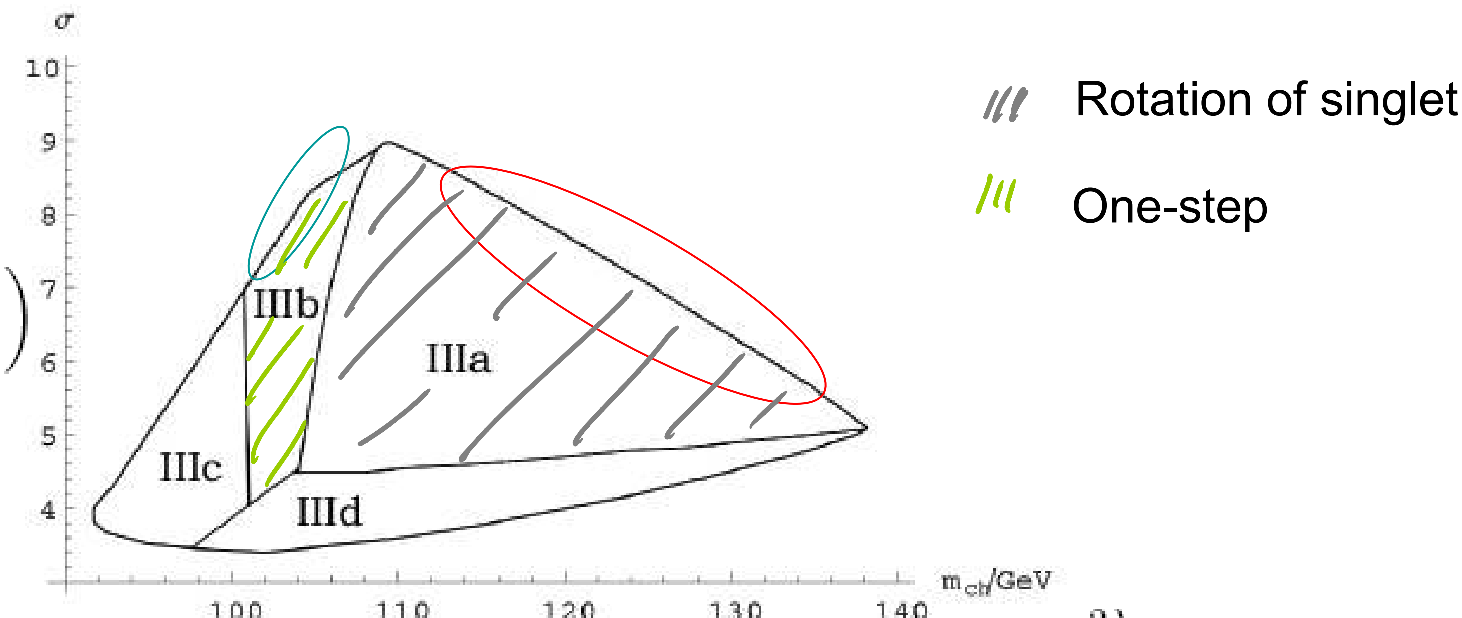
$$V(\phi, T) \approx \left[-\frac{M^2}{2} + c_1 T^2\right]\phi^2 - E_{\mathrm{eff}}\phi^3 + \frac{\lambda_{\mathrm{eff}}}{4}\phi^4$$

(more below)

½ marks the point when $\dfrac{v(T_c)}{T_c} \longrightarrow \infty$, with $T_c \to 0$

$$a_\lambda H_1 \cdot H_2 \tilde{\nu}_i^c \in \mathcal{L}_s \qquad\qquad -\lambda H_1 \cdot H_2 \nu_i^c + \frac{1}{3}\kappa \left(\nu_i^c\right)^3 \in W$$

$$\sigma = 2\left(\frac{a_\lambda}{m_{\rm ch}\lambda} + \frac{\kappa}{3\lambda}\right)$$



$$m_{\rm ch} = 3\lambda v_{\tilde{\nu}^c}$$

↑

$$m^2_{\tilde{\nu}^c}$$

[1004.0942 w/ Andrew Long]

Interesting: tuning has a group theoretic origin applicable to what we may find at LHC and beyond

[0808.1144]

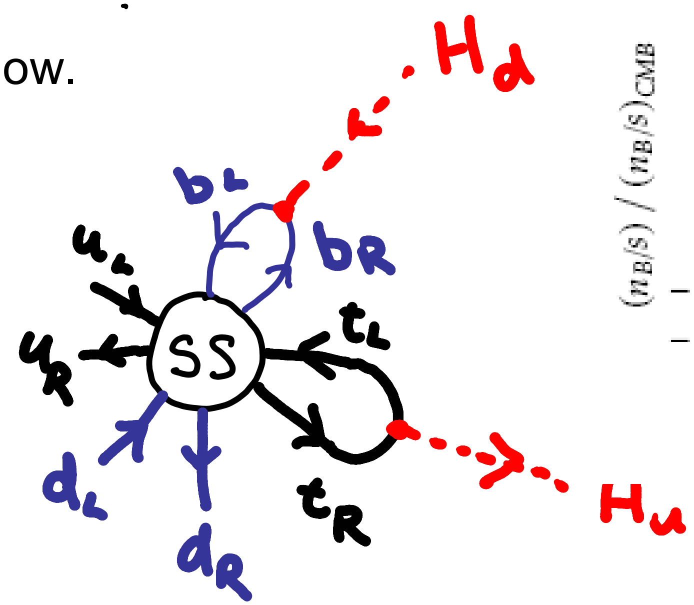
Prior to 2008, b-yukawa coupling was neglected in MSSM bgenesis.

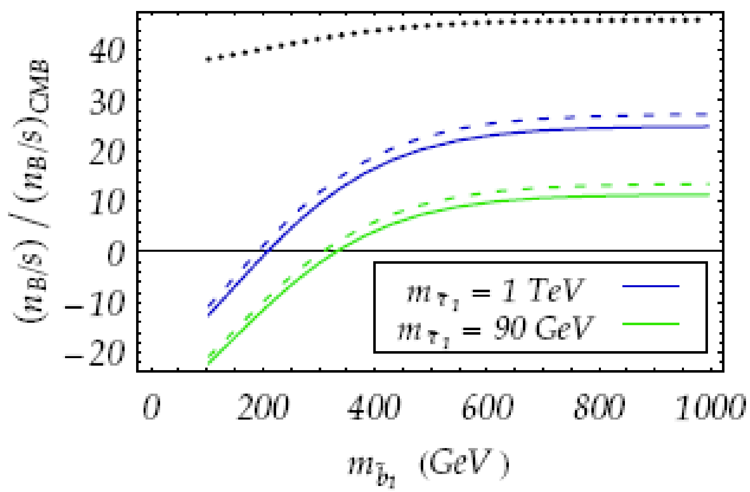
Not comparing Γ_t to Γ_b

$$\tau_{\rm diff} \equiv \bar{D}/v_w^2 \sim 100 \text{ GeV}^{-1} \gg \frac{1}{\Gamma_X}$$ → equilibrium

First 2 generations decouple if $\tan\beta \gtrsim 5$!

No net anomaly inflow.





Near Future

- Group theoretic techniques for identifying 1st order PT (w/ Long)
    - Condition for origin playing a special role
    - Custodial symmetry and representation of coset space

- B-L to B conversion for non-first order transitions (i.e. resolve the difference between Harvey-Turner and Shaposhnikov-Laine + compute sparticle mass spectrum dependence)

$$\langle Y_p(t)\rangle \equiv \mathrm{Tr}[\rho(t_0) Y\left(\{\psi(t)\}\right)] - \langle v(t)| Y\left(\{\psi(t)\}\right)|v(t)\rangle$$

- Incorporate non-equilibrium effects into Weinberg-Nanopoulos theorem on global charge generation.

    Best outcome: novel low scale leptogenesis model

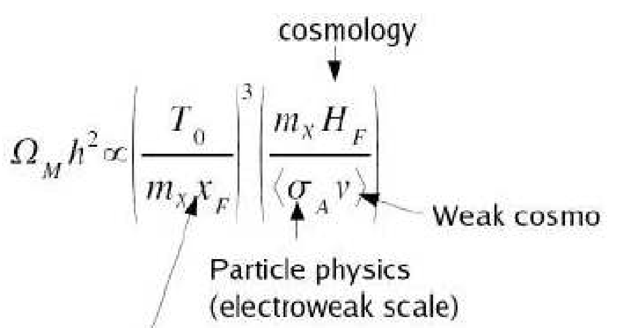
2) Probes of the Dark Sector

Dark Energy Connection w/ Collider Physics

0706.2375 – use WIMPs during freeze out as a probe of dark energy.

e.g. quintessence w/ kinetic dominated boundary conds.

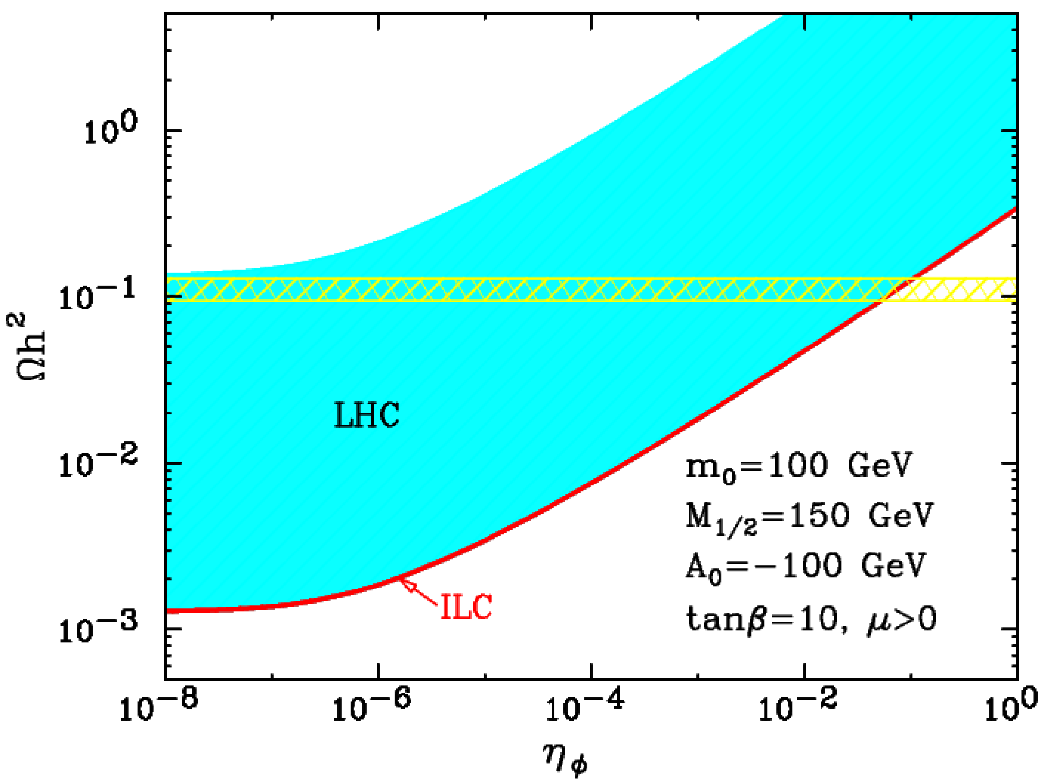
Good testbed for understanding the rigidity of cosmology and advocating more precise measurement of DM properties.



$\frac{T_F}{m_\chi}$ ~1/20 with log dependence on $H_F, \langle \sigma_A v \rangle, m_\chi$

Dark matter abundance is boosted:

$$\eta_\phi \equiv \rho_\phi / \rho_\gamma |_{T=1\,\mathrm{MeV}}$$



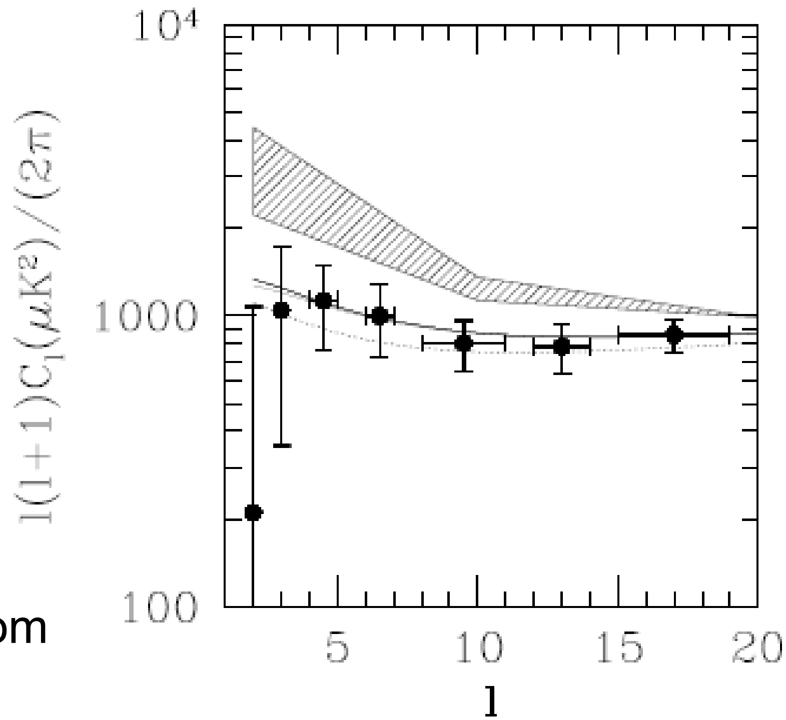
Cuscuton Cosmology

astro-ph/0702002

$$S = -\frac{M_p^2}{2}\int d^4x\sqrt{g}R + \int d^4x\sqrt{g}\left[\mu^2\sqrt{|\partial_\mu\psi\partial^\mu\psi|} - U(\psi)\right] + S_{DM}$$

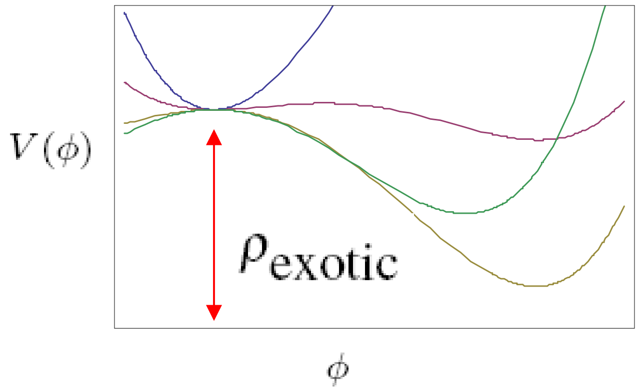
$$U(\psi) = U_0\exp\left[-\frac{\mu^2 r_c}{M_p^2}\psi\right]$$

Same H as self-acc DGP, but no ghosts nor ISW problems.



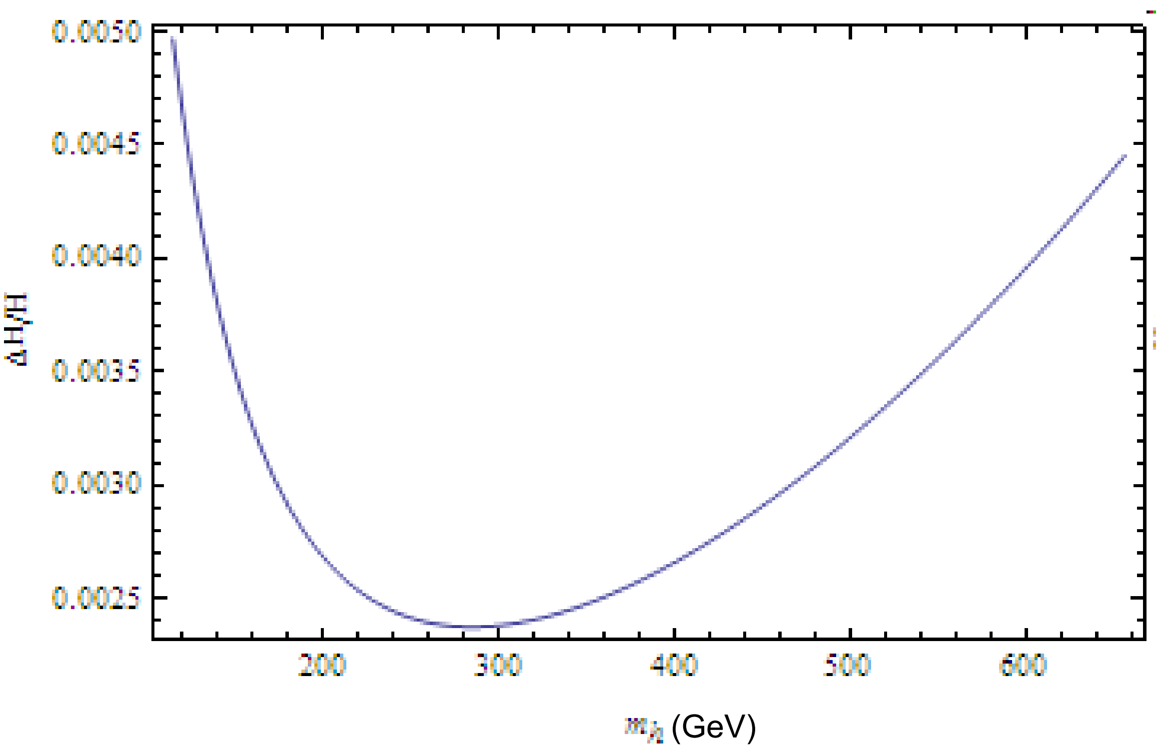
1) Class of novel models
2) Challenges model dependent wisdom

Near Future



SM:

(w/ Long)

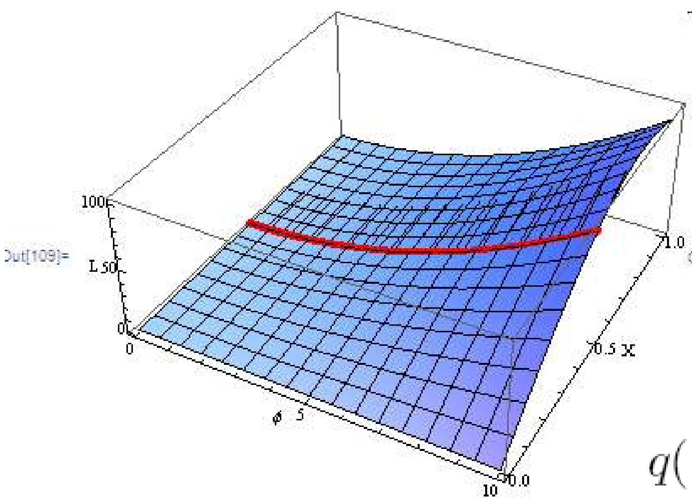


Inflationary Cosmology

- 0801.0742 – What is the most generic single field action consistent with large non-Gaussianities (not of local type)?

  e.g.

  observable → $\{\epsilon(N_e), c_s(N_e)\}$



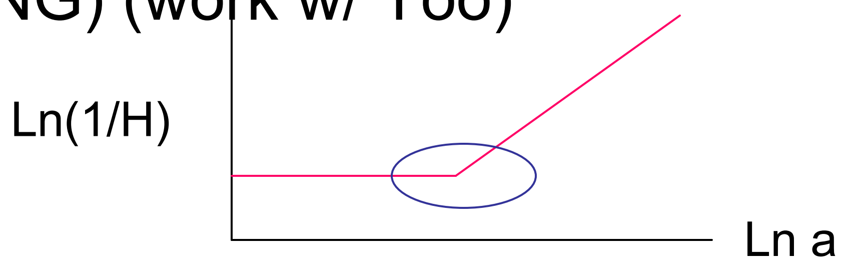
$$
\begin{aligned}
\mathcal{L}(\phi, X) &= q(\phi, X) + \mathcal{L}^{obs}(\phi, \frac{M_p^4}{2}) - q(\phi, \frac{M_p^4}{2}) \\
&+ \left[\partial_X \mathcal{L}^{obs}(\phi, \frac{M_p^4}{2}) - \partial_X q(\phi, \frac{M_p^4}{2})\right](X - \frac{M_p^4}{2}) \\
&+ \frac{1}{2}\left[\partial_X^2 \mathcal{L}^{obs}(\phi, \frac{M_p^4}{2}) - \partial_X^2 q(\phi, \frac{M_p^4}{2})\right](X - \frac{M_p^4}{2})^2
\end{aligned}
$$

$q(\phi, X)$ is arbitrary!

- More conventional Hamilton-Jacobi formalism also given
- 0704.3285 – B-mode measurement in the near future can “model independently” rule out kination domination

Near Future

Isocurvature from particle production can create local non-Gaussianities (NG) (work w/ Yoo)



$$\delta\rho_X \sim m^2 X^2$$

$$\langle \delta\rho_X \delta\rho_X \rangle \sim m^4 \langle XX \rangle^2$$

$$\langle \delta\rho_\phi \delta\rho_\phi \rangle \sim (V')^2 \langle \delta\phi \delta\phi \rangle$$

Fermionic particle production, isocurvature, and NG (work w/ Zhou)

Investigating the possibility and the phenomenology of inflationary models where the confining scale of a strongly interacting sector is at the horizon scale.

Formal aspects of string theory

Publications since 2007

- A. Hashimoto and P. Ouyang, "Probing the non-SUSY vacua of field theories in 2+1 dimensions"
- A. Hashimoto, S. Hirano, and P. Ouyang. "Branes and fluxes in special holonomy manifolds and cascading field theories," `arXiv:1004.0903`
- O. Aharony, A. Hashimoto, S. Hirano, and P. Ouyang. "D-brane Charges in Gravitational Duals of 2+1 Dimensional Gauge Theories and Duality Cascades." *JHEP* **01** (2010) 072 `arXiv:0906.2390`
- S. S. Haque and A. Hashimoto, " Mass-spin relation for quark anti-quark bound states in non-commutative Yang-Mills theory," *Nucl. Phys.* **B829** (2010) 555-572. `arXiv:0903.4841`
- A. Hashimoto, P. Ouyang, "Supergravity dual of Chern-Simons Yang-Mills theory with $\mathcal{N} = 6, 8$ superconformal IR fixed point," *JHEP* **10** (2008) 057 `arXiv:0807.1500`
- S. S. Haque and A. Hashimoto, "Microscopic Formulation of Puff Field Theory," *JHEP* **05** (2008) 040, `arXiv:0801.4354`.
- D. Dhokarh, S. S. Haque and A. Hashimoto, "Melvin Twists of global $AdS_5 \times S_5$ and their Non-Commutative Field Theory Dual," *JHEP* **08** (2008) 084, `arXiv:0801.3812`.
- A. Hashimoto, "A Note on Spontaneously Broken Lorentz Invariance," *JHEP* **08** (2008) 040, `arXiv:0801.3266`.
- "Non-commutativity and Open Strings Dynamics in Melvin Universes," Danny Dhokrah, Akikazu Hashimoto, and Sheikh Shajidul Haque, *JHEP* **08** (2007) 027, `arXiv:0704.1124`
- "Aspects of Puff Field Theory," Ori J. Ganor, Akikazu Hashimoto, Sharon Jue, Bom Soo Kim, and Anthony Ndirango, *JHEP* **08** (2007) 035, `hep-th/0702030`.

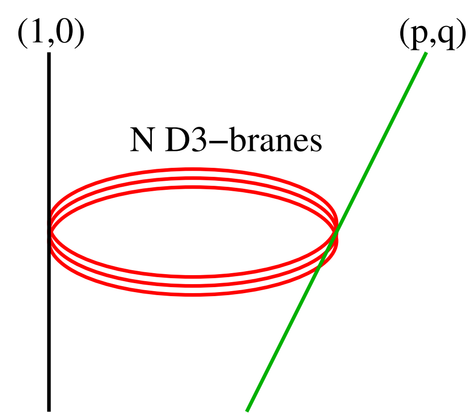
- "Supergravity solution of intersecting branes and AdS/CFT with flavor," Sergey A. Cherkis and Akikazu Hashimoto, *JHEP* **11** (2002) 036, `hep-th/0210105`

Bagger Lambert/ABJM Theories

- Superconformal Field theory in 2+1 dimensions with $\mathcal{N} = 6, 8$ SUSY

  "the first nontrivial example (above two dimensions) since the construction of $\mathcal{N} = 4$ super Yang-Mills theory over 30 years ago. Thus, we expect that this theory will play a role in the future development of string theory and M-theory..." John Schwarz

- $U(N)_k \times U(N + l)_{-k}$ Chern-Simons theory with 2 bifundamental matter
- $AdS_4 \times S^7/Z_k$ with l units of discrete torsion
- $\#$ DOF scales as $N^{3/2}$
- HW construction ($p = 1,\ q = k$)
- Condition for SUSY $\boxed{N > \frac{l(l-k)}{2k}}$



Main Theme

• How does one describe the dynamics of this field theory in the regime where SUSY is broken

• How does the breaking of SUSY manifest itself in the gravity dual

• Are there other interesting features near the boundary of SUSY

In other words, we are investigating the *phase structure* of a class of 2+1 field theories which is interesting to begin with

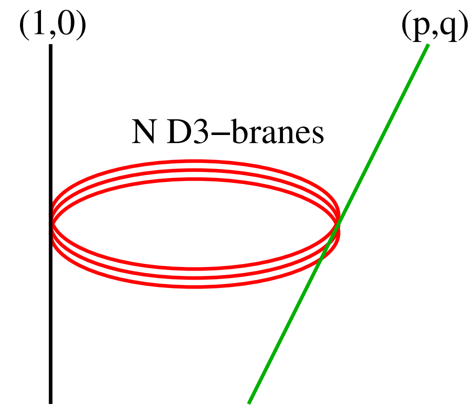
• Novel, related to M2, condensed matter, landscape, ...

Closer examination revealed additional connection to subtle *quantum issues* in M and string theories e.g. topology and flux quantizations, Freed-Witten anomalies, special holonomy manifolds, duality cascades, ...

• Any concrete realization of *dynamical supersymmetry breaking* is interesting

• Our strategy: to study this and related systems in detail. Extend the list of familiar examples to enhance intuition. Check subtle consistencies from multiple points of view → learned a lot

A little background



- In hep-th/0210105, with S. Cherkis, AH studied SUGRA dual of closely related system with $p = 0$ or $q = 0$

- This is a periodic version of Hanany-Witten construction, originally designed to make *Intriligator-Seiberg Mirror Symmetry* manifest by *embedding* to string theory

- Our focus was in taking $\alpha' \to 0$ decoupling limit

- Constructing explicit gravity dual for Yang-Mills theories in 2+1 with matter in the fundamental (few of its kind which is UV complete)

- Make Intriligator-Seiberg Mirror Symmetry manifest *via holography*

- Thought briefly about general (p, q). Knew about the interesting $3/16$ SUSY

- Missed the enhanced $6/16$ and $8/16$ SUSY in the deep IR

Holographic dual preliminary

- T-dual along the S^1: LWY geometry

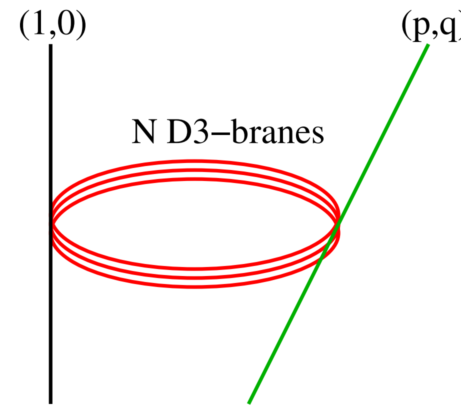
- $8d$, hyper-Kähler, asymptotically $R^3 \times S^1 \times R^3 \times S^1$

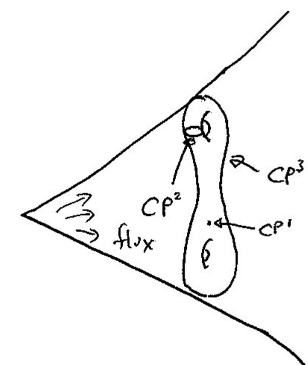
- Moduli-space of monopoles and dyons

- Metric with $sp(2)$ holonomy.

- Asymptote to R^8 near core (like Taub-NUT $\rightarrow R^4$)

- Reduce on one S^1 and make the other S^1 infinite in size to decouple $3+1 \rightarrow 2+1$





- Fixed r is CP^3 which has CP^2 and CP^1 as homology cycles

- Orbifold Z_k, and add integer D2 and fractional D2 (D4 wrapped on CP^1) and compute back reactions

- D2, D4, and D6 $\leftrightarrow F_6 = *\tilde{F}_4$, $\tilde{F}_4$, and F_2 though CP^3, CP^2, and CP^1

• A BPS ansatz with self-dual 4-form field strength and some warp factor on the LWY geometry is not difficult to construct

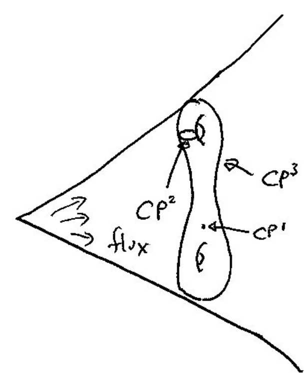
• A self-dual 4-form is conjectured to exist on LWY from expectation based on existence of bound states of magnetic monopoles and relation to S-duality

• Surprisingly, explicit expression for this 4-form is not known

• But enough is known about the 4-form to draw conclusions about the charges (and there are other examples where the 4-form is under better control)

• First puzzle: when computing

$$\int_{CP^2} \tilde{F}_4, \qquad \int_{CP^3} *\tilde{F}_4,$$



at some fixed r, the answer *depends* on r. Gauss' law?

• Modified Bianchi identity:

$$d\tilde{F}_4 + H \wedge F_2 = 0 \Rightarrow \int_{CP^2} \tilde{F}_4 + B \wedge F_2 \equiv \text{Page Charge}$$

Three different notion of charges

(Marolf hep-th/0006117)

	Localized	Gauge-Invariant	Quantized	Conserved
Brane Charge	Yes	Yes		
Maxwell Charge		Yes		Yes
Page Charge	Yes		Yes	Yes

$$\int_{CP^2} \tilde{F}_4 + B \wedge F_2 \equiv \text{Page Charge}$$

$$\int_{CP^2} \tilde{F}_4 \bigg|_{r=\infty} \equiv \text{Maxwell Charge}$$

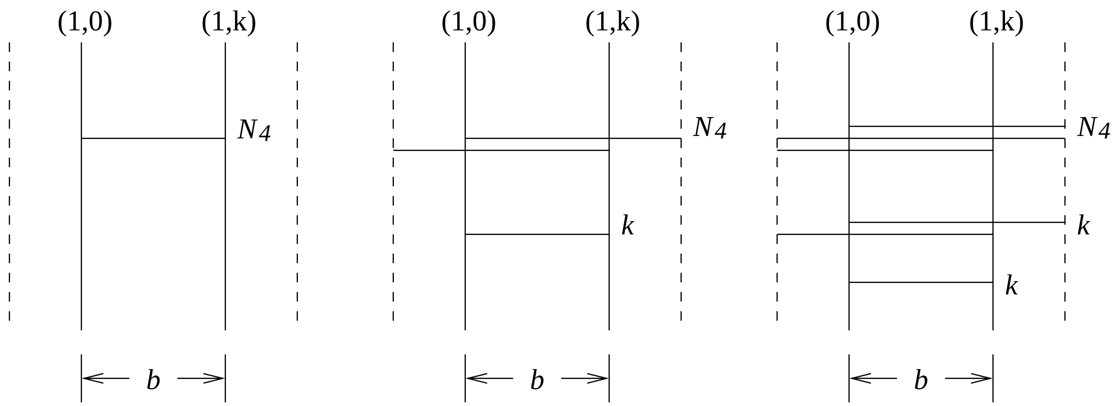
$$\int_{CP^2} \tilde{F}_4 \bigg|_{r=0} \equiv \text{Brane Charge}$$

- Page charge are integer quantized but not invariant under *large gauge transformation* $\int_{CP^1} B \to \int_{CP^1} B + 1$
- Maxwell charges are gauge invariant but not integer valued and runs with r

• The pattern of transformation of charges under large gauge transformation

$$N \to N + l$$
$$l \to l + k$$

matches expectation from HW brane creation effect



• Gauge ambiguity $\leftrightarrow$ Seiberg Duality

• Running of Maxwell charges is just like in Cascading Klebanov-Strassler

• Here, brane creation is an additional ingredient. Also, the cascade terminates in the UV.

$$
\begin{aligned}
Q_2^{Maxwell} &= N_2 + \left(N_4 - \frac{k}{2}\right) b_\infty + \frac{k}{2} b_\infty^2, \\
Q_4^{Maxwell} &= \left(N_4 - \frac{k}{2}\right) + k b_\infty
\end{aligned}
$$

• This is invariant under large gauge transformation, and interpretable as D2 and D4 charges induced by the WZ term $C \wedge e^B$ of the D-brane action

• The $\frac{k}{2}$ is the manifestation of CP^2 not being a spin manifold, requiring half integral shifts in the flux (Freed-Witten anomaly)

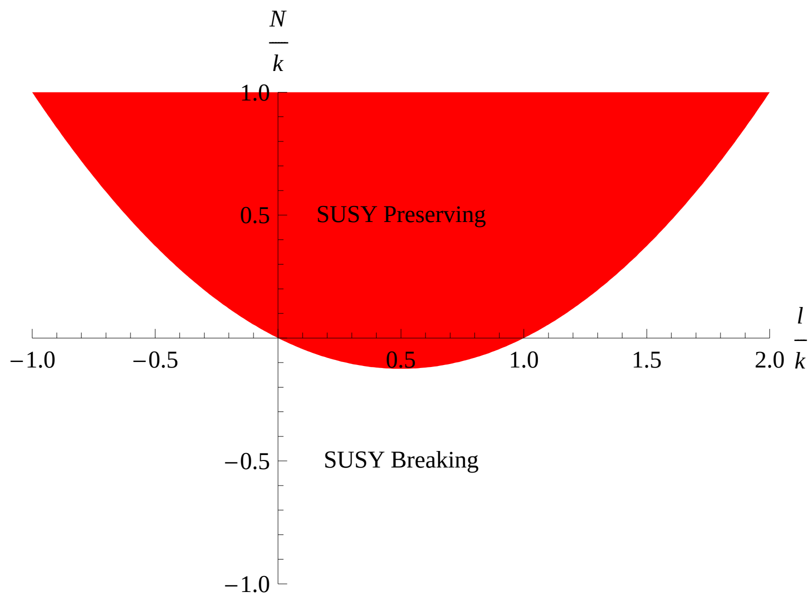
• On the other hand,

$$
\begin{aligned}
Q_2^{brane} &= N_2 - \frac{N_4(N_4 - k)}{2k} \\
Q_4^{brane} &= 0
\end{aligned}
$$

• Q_2^{brane} is the radius of AdS_4 and is related to its entropy. $Q_2^{brane} = 0$ is the threshold of SUSY. Analogous to $k > N/2$ for $\mathcal{N} = 1$ $U(N)_k$ CS theory (Witten)

SUSY and SUSY breaking

As a function of N and l, one can visualize the region where SUSY is unbroken as a parabola



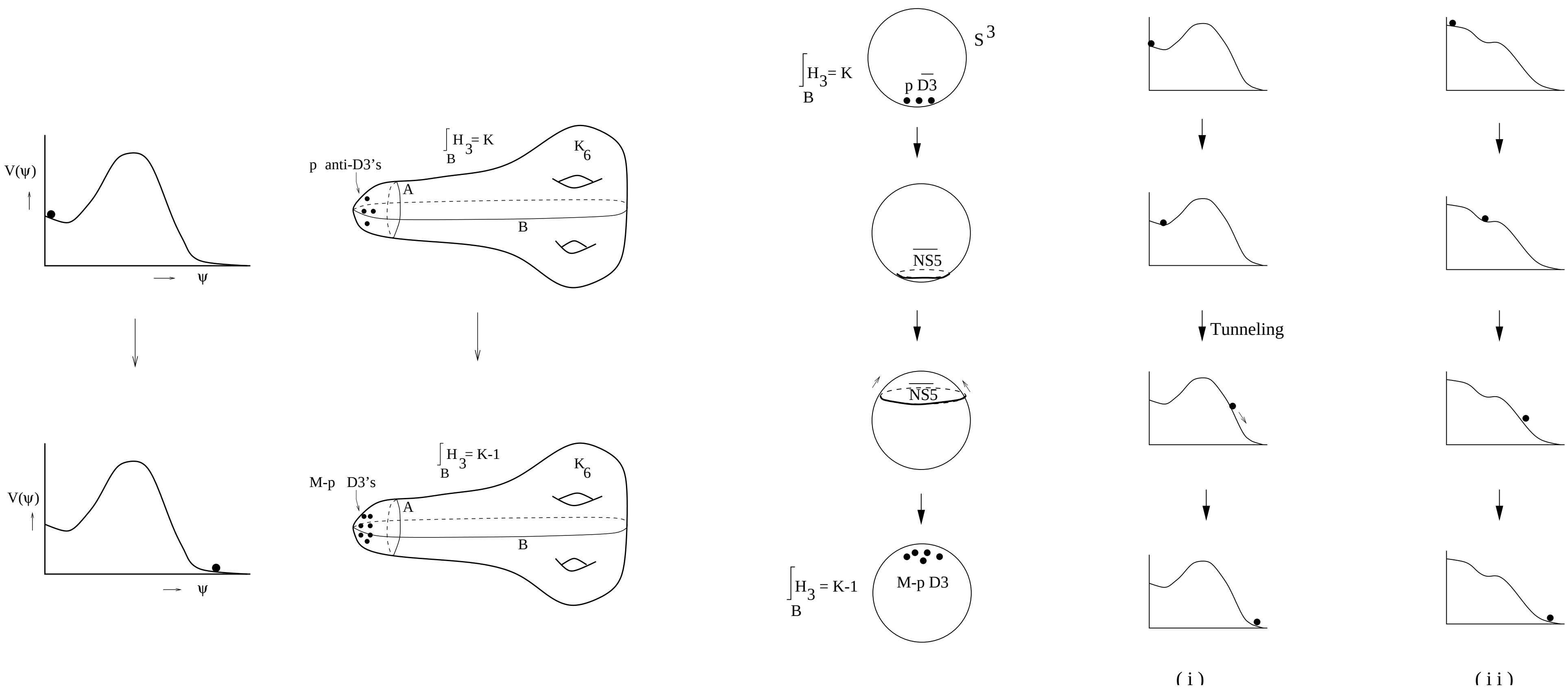
The edge of the parabola is the threshold of SUSY breaking. Going inside the parabola corresponds to adding a D2-brane. Going outside corresponds to starting at the threshold solution and adding an *anti D2-brane*.

- Expect CS-YM-Matter system to develop a mass-gap
- Expect IR deformation of the gravity dual

- Need reliable and tractable non-BPS ansatz (very hard)

- Similar SUSY condition exits in a related system where IR has finite size S^4. (e.g. B_8 of CGLP, and Stenzel geometry)

- Small number of SUSY breaking anti D2 can be treated as a probe, just as was the case for similar setup in Klebanov-Strassler system (Kachru, Pearson, Verlinde)



Impact of this work

Recently, Drukker, Marino, and Putrov (arXiv:1007.3837) carried out a computation of the partition function of $U(N)_k \times U(N+l)_{-k}$ using the $localization\ technique$ originally developed by Kapustin, Willett and Yaakov.

DMP demonstated very impressively that the free energy scaled as

$$\#^{3/2}$$

for the first time, from first principles in field theory.

What is especially noteworthy about the conclusion of DMP is that they find explicit dependence of $\#$ and l, which they find to be of the form

$$\# = N - \frac{l(l-k)}{2k}$$

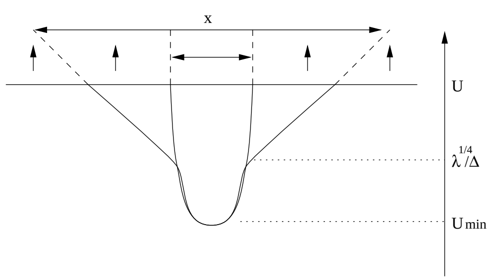
thereby reproducing $exactly$ the expression for Q_2^{brane} ...

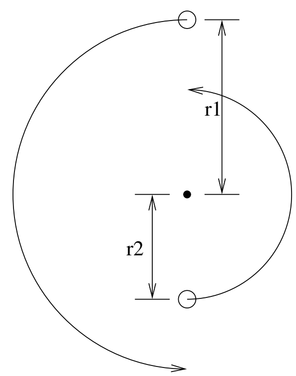
There are some subtle errors in flux quantization reported in the literature. ...

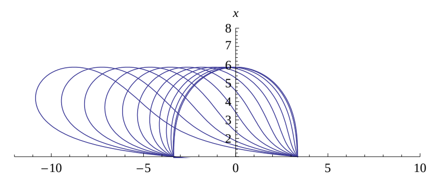
Positronium Bound State In Non-Commutative Geometry

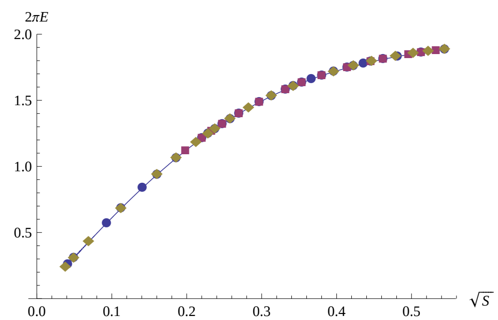
Shajid Haque and AH, arXiv:0903.4841

- $q\bar{q}$ potential $V(r)$ in non-commutative geometry is a subtle concept
- $E(J)$ for spinning $q\bar{q}$ bound state is a probe of $V(r)$
- Numerically computed $E(S)$ using holographic technique





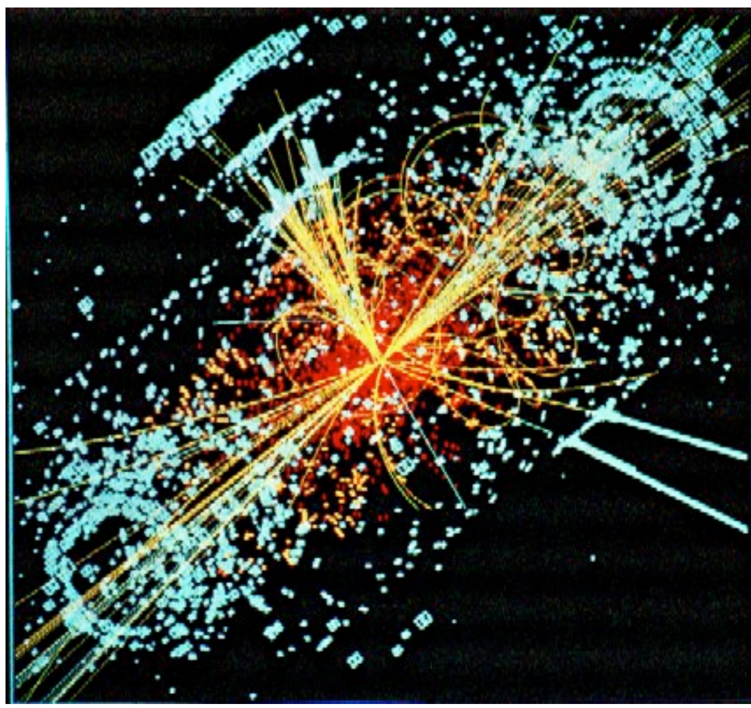
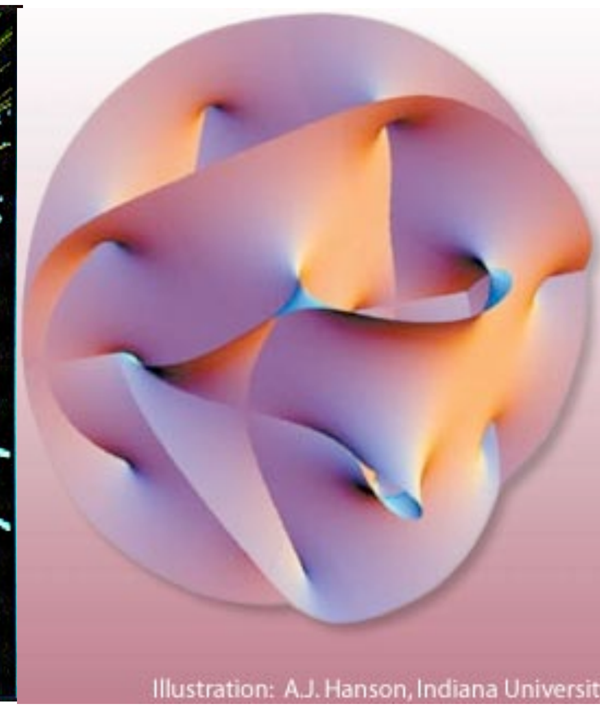


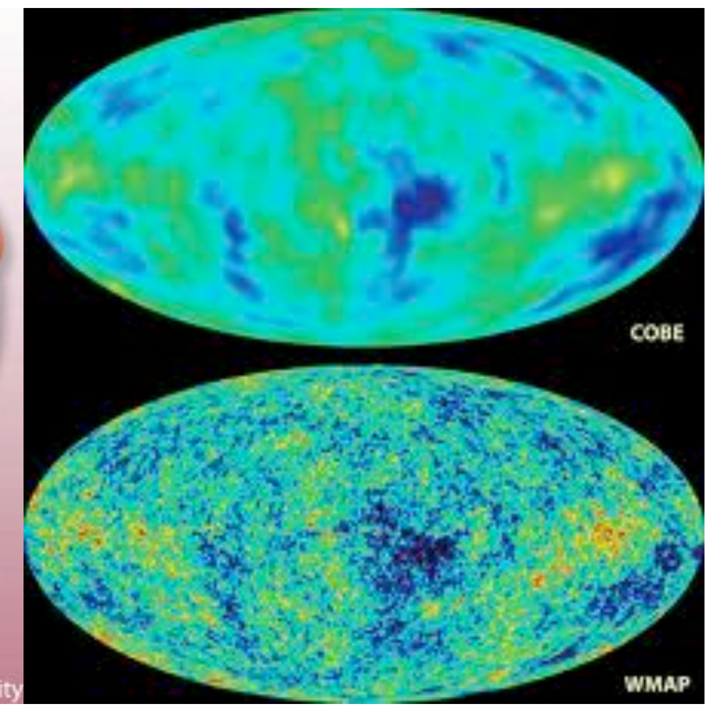


- Point was to specify momentum, rather than position of the quarks
- Finally, closure in how one might probe local data such as $q\bar{q}$ potential in non-commutative geometry.[1]

[1] $\langle O(x)O(y)\rangle$ correlator was addressed by GHI in 2000

String Phenomenology & String Cosmology



Gary Shiu

Task D: String Theory & Theoretical Cosmology

Goals of Research Program

- Focus on the synergistic interface between string theory, particle physics and cosmology.
- String theory provides a promising framework because:
  - Some key issues in particle physics beyond the Standard Model (BSM) and in cosmology *require* a UV completion.
  - Fruitful in motivating new phenomenological scenarios (SUSY, brane world, large/warped extra dimensions, DBI inflation,...).
  - Offers new powerful tools to study QFTs.
- Explore the implications/predictions of string theory to particle physics & cosmology; help elucidate microphysics of string theory.

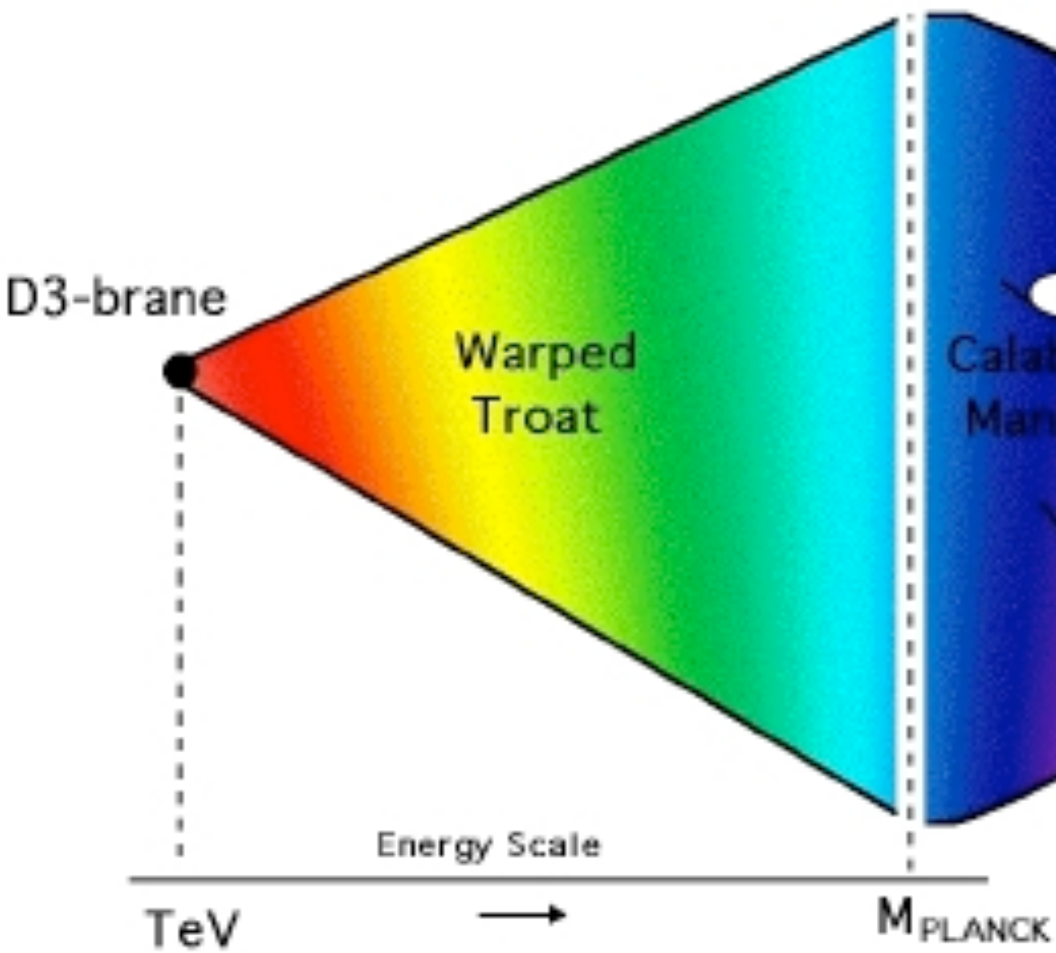
Gary Shiu's Publications since 8/2007

1. Z. Dong, T. Han, M.x. Huang and **G. Shiu**, ``Top Quarks as a Window to String Resonances," arXiv:1004.5441 [hep-ph].
2. P. McGuirk, **G. Shiu** and Y. Sumitomo,``Holographic gauge mediation via strongly coupled messengers," Phys. Rev. D **81**, 026005 (2010) [arXiv:0911.0019 [hep-th]].
3. P. McGuirk, **G. Shiu** and Y. Sumitomo,``Non-supersymmetric infrared perturbations to the warped deformed conifold," arXiv:0910.4581 [hep-th].
4. U.H. Danielsson, S.S. Haque, **G. Shiu** and T. Van Riet,``Towards Classical de Sitter Solutions in String Theory,' JHEP **0909**, 114 (2009) [arXiv:0907.2041 [hep-th]].
5. H.Y. Chen, Y. Nakayama and **G. Shiu**,``On D3-brane Dynamics at Strong Warping," Int. J. Mod. Phys. A **25**, 2493 (2010) [arXiv:0905.4463 [hep-th]].
6. X. Chen, B. Hu, M.x. Huang, **G. Shiu** and Y. Wang,``Large Primordial Trispectra in General Single Field Inflation," JCAP **0908**, 008 (2009) [arXiv:0905.3494 [astro-ph.CO]].
7. H.Y. Chen, L.Y. Hung and **G. Shiu**,``Inflation on an Open Racetrack," JHEP **0903**, 083 (2009) [arXiv:0901.0267 [hep-th]].
8. F. Marchesano, P. McGuirk and **G. Shiu**,``Open String Wavefunctions in Warped Compactifications," JHEP **0904**, 095 (2009) [arXiv:0812.2247 [hep-th]].
9. S.S. Haque, **G. Shiu**, B. Underwood and T. Van Riet,``Minimal simple de Sitter solutions," Phys. Rev. D **79**, 086005 (2009) [arXiv:0810.5328 [hep-th]].
10. H. Y. Chen, P. Ouyang and **G. Shiu**,``On Supersymmetric D7-branes in the Warped Deformed Conifold," JHEP **1001**, 028 (2010) [arXiv:0807.2428 [hep-th]].
11. H.Y. Chen, J.O. Gong and **G. Shiu**,``Systematics of multi-field effects at the end of warped brane inflation," JHEP **0809**, 011 (2008) [arXiv:0807.1927 [hep-th]].
12. **G. Shiu**, G. Torroba, B. Underwood and M.R. Douglas,``Dynamics of Warped Flux Compactifications," JHEP **0806**, 024 (2008) [arXiv:0803.3068 [hep-th]].
13. **G. Shiu**, B. Underwood, K.M. Zurek and D.G.E. Walker, ``Probing the Geometry of Warped String Compactifications at the LHC," Phys. Rev. Lett. **100**, 031601 (2008).
14. P. McGuirk, **G. Shiu** and K.M. Zurek,``Phenomenology of Infrared Smooth Warped Extra Dimensions," JHEP **0803**, 012 (2008) [arXiv:0712.2264 [hep-ph]].
15. M.x. Huang, **G. Shiu** and B. Underwood,``Multifield DBI Inflation and Non-Gaussianities," Phys. Rev. D **77**, 023511 (2008) [arXiv:0709.3299 [hep-th]].
16. S. Sarangi, **G. Shiu** and B. Shlaer,``Rapid Tunneling and Percolation in the Landscape," Int. J. Mod. Phys. A **24**, 741 (2009)[arXiv:0708.4375 [hep-th]].

Independent work by students & postdocs since 8/2007

1. H.Y. Chen, J.O. Gong, K. Koyama and G. Tasinato, ``Towards multi-field D-brane inflation in warped throat," arXiv:1007.2068 [hep-th].
2. H.Y. Chen and K. Petunin, ``Notes on Wall Crossing and Instanton in Compactified Gauge Theory with Matter," arXiv: 1006.5957 [hep-th].
3. H.Y. Chen, N. Dorey and K. Petunin, ``Wall Crossing and Instantons in Compactified Gauge Theory, " JHEP **1006**, 024 (2010) [arXiv:1004.0703 [hep-th]].
4. H.Y. Chen, K. Hashimoto and S. Matsuura, ``Towards a Holographic Model of Color-Flavor Locking Phase," JHEP **1002**, 104 (2010) [arXiv:0909.1296 [hep-th]].
5. L.L. Everett, I.W. Kim, P. Ouyang and K.M. Zurek, ``Moduli Stabilization and Supersymmetry Breaking in Deflected Mirage Mediation," JHEP **0808**, 102 (2008) [arXiv:0806.2330 [hep-ph]].
6. L.L. Everett, I.W. Kim, P. Ouyang and K.M. Zurek, ``Deflected Mirage Mediation: A Framework for Generalized Supersymmetry Breaking," Phys. Rev. Lett. **101**, 101803 (2008) [arXiv:0804.0592 [hep-ph]].
7. B. Underwood, ``Brane Inflation is Attractive," Phys. Rev. D **78**, 023509 (2008) [arXiv:0802.2117 [hep-th]].
8. H.Y. Chen and D.H. Correa, ``Comments on the Boundary Scattering Phase," JHEP **0802**, 028 (2008) [arXiv:0712.1361 [hep-th]].

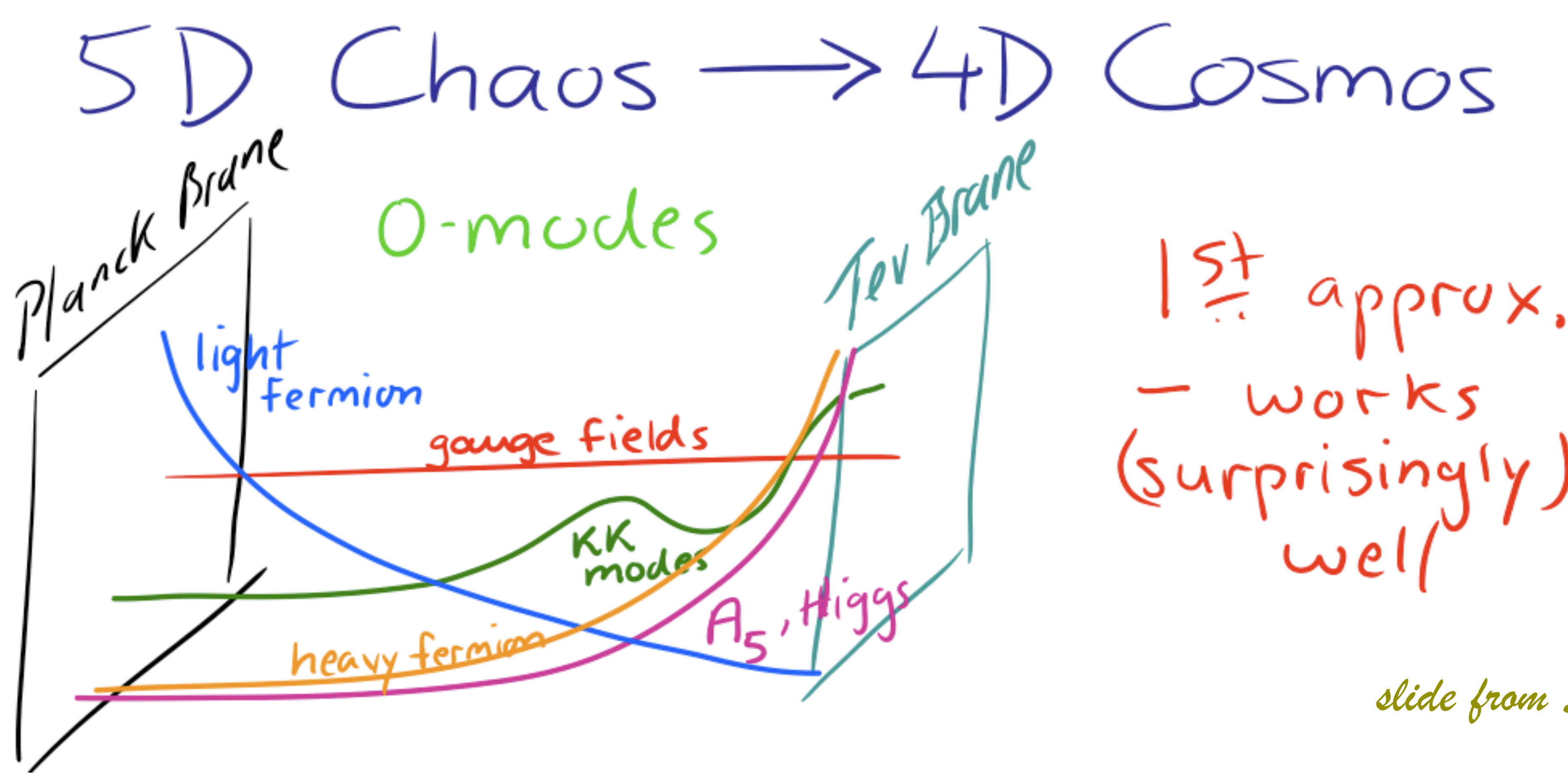
Warped Compactification



- Electroweak & Yukawa hierarchies *(Ref. [8,14])*
- LHC signatures & particle physics constraints *(Ref. [13,14])*
- Metastable SUSY Breaking *(Ref. [2,3])*
- Holographic dual of strongly coupled BSM scenarios *(Ref. [2,3])*
- String Inflation Models *(Ref. [10,11])*
- CMB and other cosmological signatures & constraints *(Ref. [6,15, 16])*
- Subtle issues in warped EFT *(Ref. [5,8,12])*

Warped Extra Dimensions

There have been substantial efforts in building *phenomenological* models of warped extra dimensions.

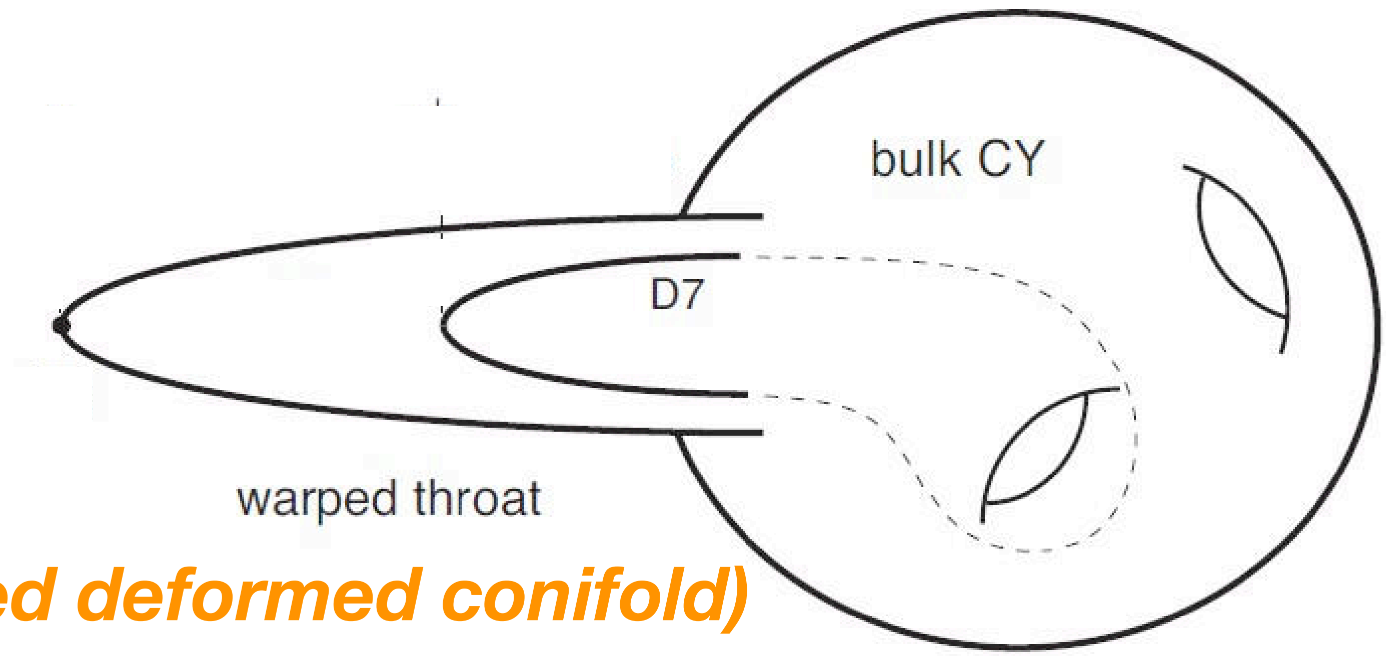


slide from Sundrum

Question: Are there new features when embedded in string theory?

Warped String Backgrounds

Strongly warped regions (or warped throats) can be generated in the presence of *background fluxes.*



(e.g., warped deformed conifold)

D7-branes wrap

$$S_4 \subset X_6$$

Type IIB warped background:

$$ds_{10}^2 = \Delta^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + \Delta^{1/2}e^\Phi \hat{g}_{mn}dy^m dy^n$$

Consistency requires:

$$F_5 = (1 + *_{10})F_5^{\text{int}} \qquad F_5^{\text{int}} = \hat{*}_6 d\left(\Delta e^\Phi\right)$$

Open Strings in Warped Backgrounds

Marchesano, McGuirk, GS

- Starting from the "κ-symmetric" fermionic D-brane action:

$$S_{\rm D7}^{\rm fer} = \tau_{\rm D7} \int d^8\xi \, e^{-\Phi} \sqrt{|\det\left(P[G]+\mathcal{F}\right)|}\, \bar{\Theta} P_-^{\rm D7} \left(\Gamma^\alpha \mathcal{D}_\alpha - \frac{1}{2}\mathcal{O}\right)\Theta$$

(and its bosonic counterpart), we found:

Gaugino/Modulino: $\theta(x^\mu, x^a) = \Delta^{3/8}\lambda(x^\mu)\otimes\eta(x^a)$ "IR peaked"

Wilsonlino: $\theta(x^\mu, x^a) = \Delta^{-1/8}\lambda(x^\mu)\otimes\eta(x^a)$ "UV peaked"

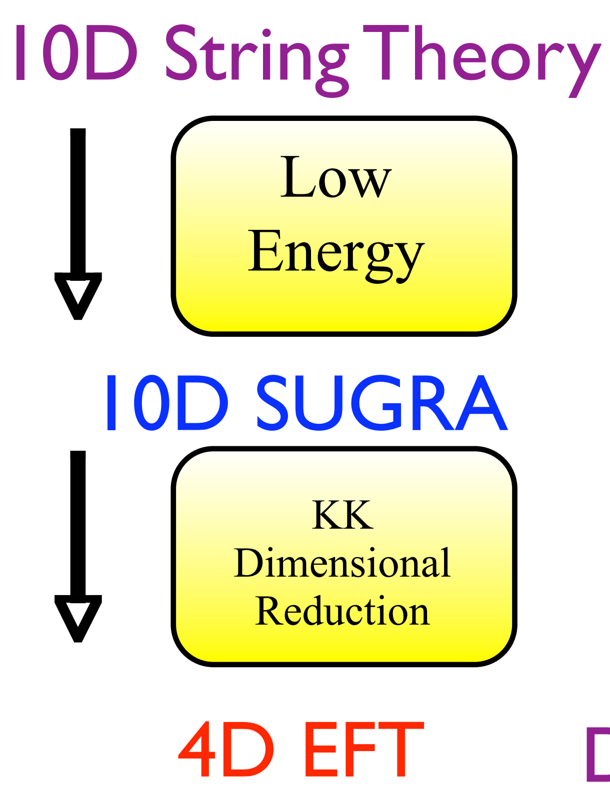
while light *bosonic* modes have a *flat profile*. Much richer **flavor hierarchies** in the presence of other *bulk & worldvolume fluxes*.

- Results are readily applicable to RS-like model building from string theory, holographic gauge mediation (later), and warped EFT.

Warped Effective Action

[GS, Torroba, Underwood, Douglas];
[Marchesano, McGuirk, GS]; [Chen, Nakayama, GS]

- **Flux compactification:** stabilized moduli and exponential hierarchy; starting point for many string theory based BSM scenarios & inflationary models. Need to determine **4D EFT** precisely.
- However, dim. reduction at strong warping is extremely subtle, e.g.:



- General KK ansatz (compensators)
- Backreaction of moduli on warp factor
- 10D Gauge redundancies/constraints
- Mixing/sourcing of KK modes with moduli

Difficult to extract, e.g., Kahler potential in warped EFT!

Warped Effective Action

- The Kahler potential was previously assumed to take this form:

$$K = -\log\left(\int e^{-4A}\Omega\wedge\overline{\Omega}\right) - 3\log\left(-i(\rho-\overline{\rho})\right) - \log(-i(\tau-\overline{\tau}))$$ DeWolfe, Giddings

but the moduli space metric is not diff. invariant: $\delta\tilde{g}_{mn} \to \delta\tilde{g}_{mn} + \nabla_{(m}\zeta_{n)}$

$$\mathrm{K} = -\log\left(\int e^{-4A}\Omega\wedge\overline{\Omega}\right) \Rightarrow G_{\alpha\overline{\beta}} = -\frac{1}{V_W}\int e^{-4A}\chi_\alpha\wedge\chi_{\overline{\beta}}$$

thus $\chi \to \chi + d\alpha \Rightarrow G_{\alpha\overline{\beta}} \neq G_{\alpha,\overline{\beta}}$

- Ansatz for fluctuations:

$$ds^2 = e^{2A}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A}(\tilde{g}_{mn} + \delta\tilde{g}_{mn})dy^m dy^n$$

does not solve 10D eoms!

Warped Effective Action

GS, Torroba, Underwood, Doulgas

- A more general metric ansatz is needed:

$$
\begin{aligned}
ds^2 &= e^{2A(y,u)}\tilde{g}_{\mu\nu}(x)dx^\mu dx^\nu + g_{ij}(y,u)dy^i dy^j \\
&+ 2e^{2A(y,u)}(\partial_\mu\partial_\nu u^I(x)K_I(y)dx^\mu dx^\nu + \partial_\mu u^I(x)B_{iI}(y)dx^\mu dy^i)
\end{aligned}
$$

metric compensators

and analogously, flux compensators are introduced.

- Compensators restore gauge invariance:

$$
G_{IJ}(u) = \frac{1}{4V_W}\int d^6y\sqrt{\tilde{g}_6}\; e^{-4A}\tilde{g}^{ik}\tilde{g}^{jl}\delta_I\tilde{g}_{ij}\delta_J\tilde{g}_{kl}
$$

while imposing the Hamiltonian constraints:

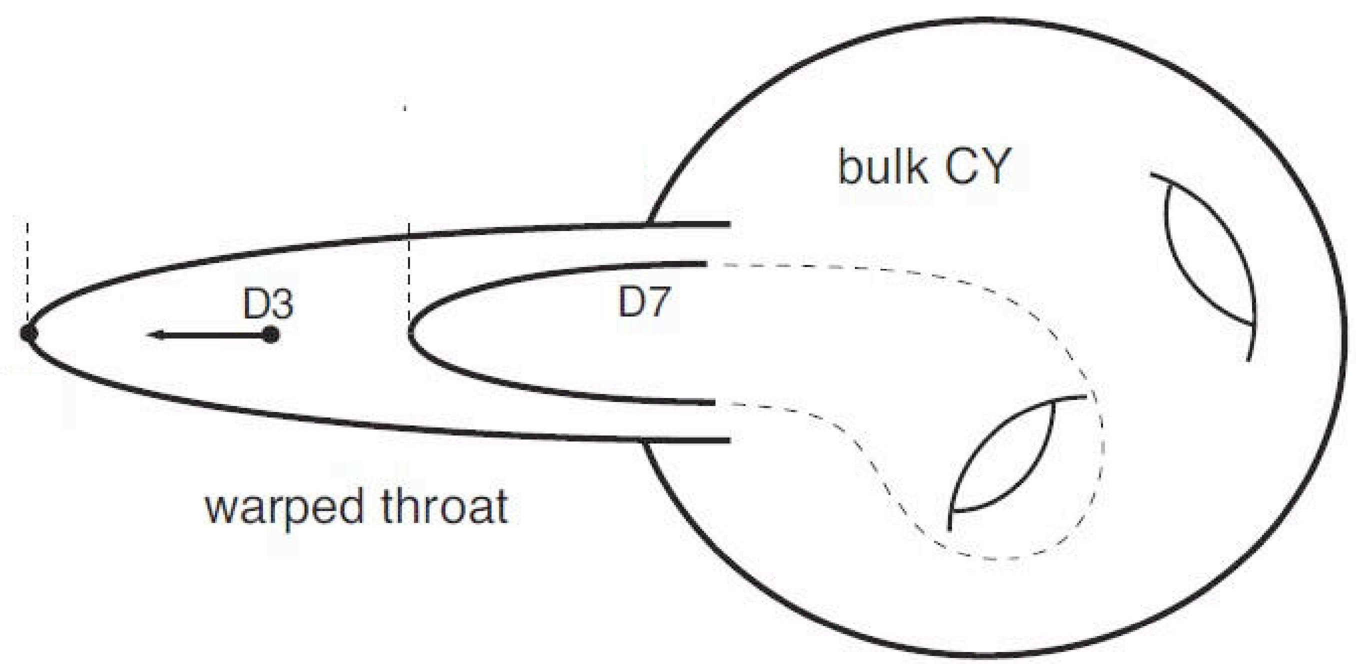
$$
\tilde{g}^{ik}\tilde{\nabla}_i\big(\delta_I\tilde{g}_{kj} - \frac{1}{2}\tilde{g}_{kj}\,\delta_I\tilde{g}\big) - 4\tilde{g}^{ik}\,\partial_i A\,\delta_I\tilde{g}_{kj} = 0
$$

Warped Effective Action

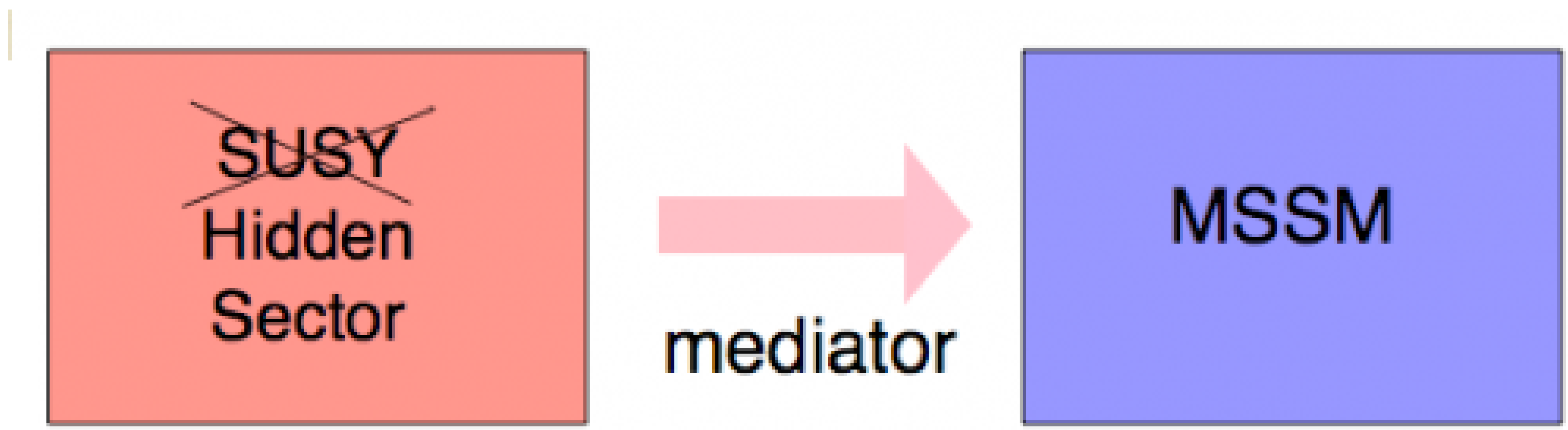
- Generalized to include open string fluctuations ([Marchesano,McGuirk, GS];[Chen,Nakayama,GS]), e.g., including D3-position modulus:

$$K = -3\log\left(-i(\rho - \bar{\rho}) - \gamma k(Y, \overline{Y}) + 2\frac{V_W^0}{V_{CY}}\right), \quad \gamma = \frac{T_3 \kappa_4^2}{3}$$

- Applications to D-brane inflation, as well as particle physics scenarios with D3-branes in a strongly warped geometry:



SUSY Breaking & Mediation

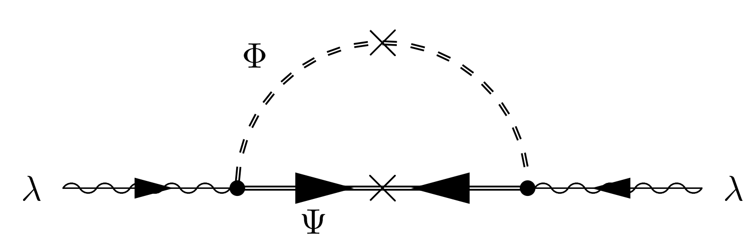


- An important recent insight about SUSY breaking is that the SUSY breaking vacuum can be **metastable** (Intriligator, Seiberg, Shih).

- Strong coupling dynamics is often involved in ~~SUSY~~ (e.g. DSB), but for models where the messengers are ***weakly coupled***, perturbative techniques are sufficient for analyzing the SUSY breaking effects on the visible sector:

★ Gravity Mediation (Planck suppressed operators ⇒weakly coupled)

★ Minimal Gauge Mediation

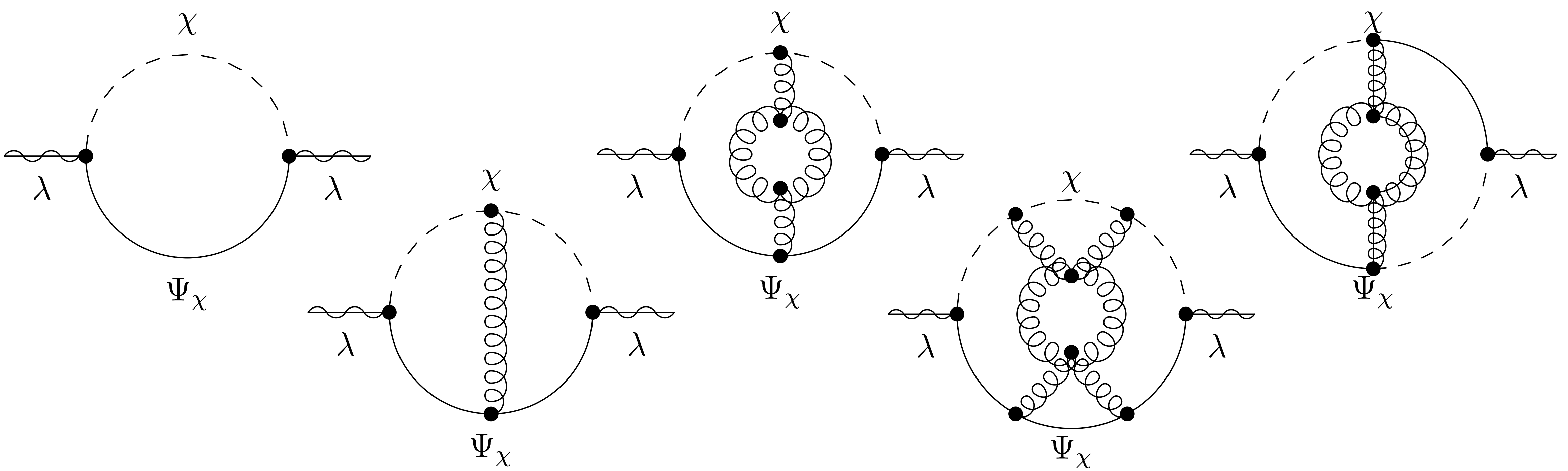


$$m_{\lambda_r} \sim \alpha_r \frac{F}{M}$$
$$r = 1, 2, 3$$

General Gauge Mediation

- If one defines gauge mediation more generally (Meade, Seiberg, Shih) as one that gives vanishing soft terms as $g_{vis} \to 0$, one expects *many models* with strongly coupled messengers. Perturbative techniques are not applicable.

- In such scenarios, visible sector soft terms can receive large corrections at all orders of hidden sector loops.



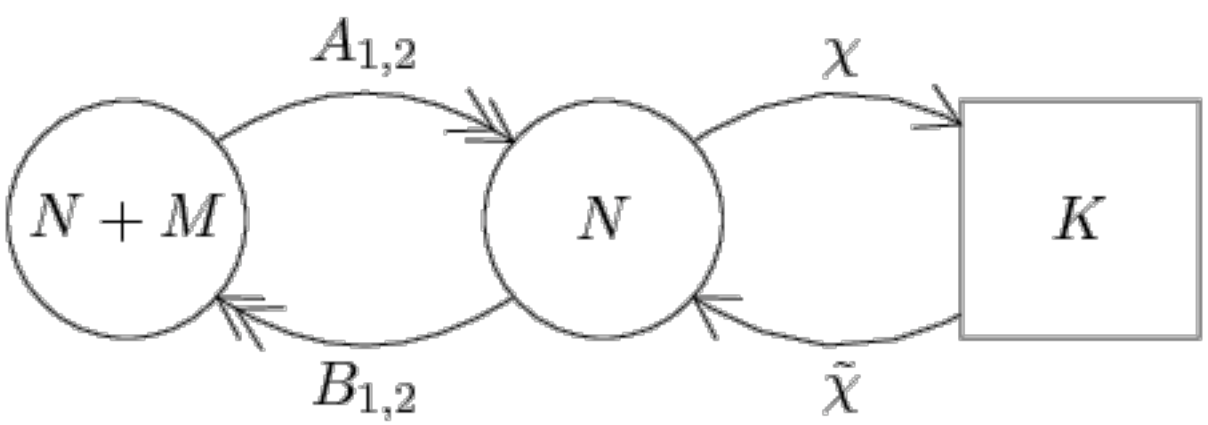
- Modern tools to study strong coupling physics: Seiberg duality, Holography, ..

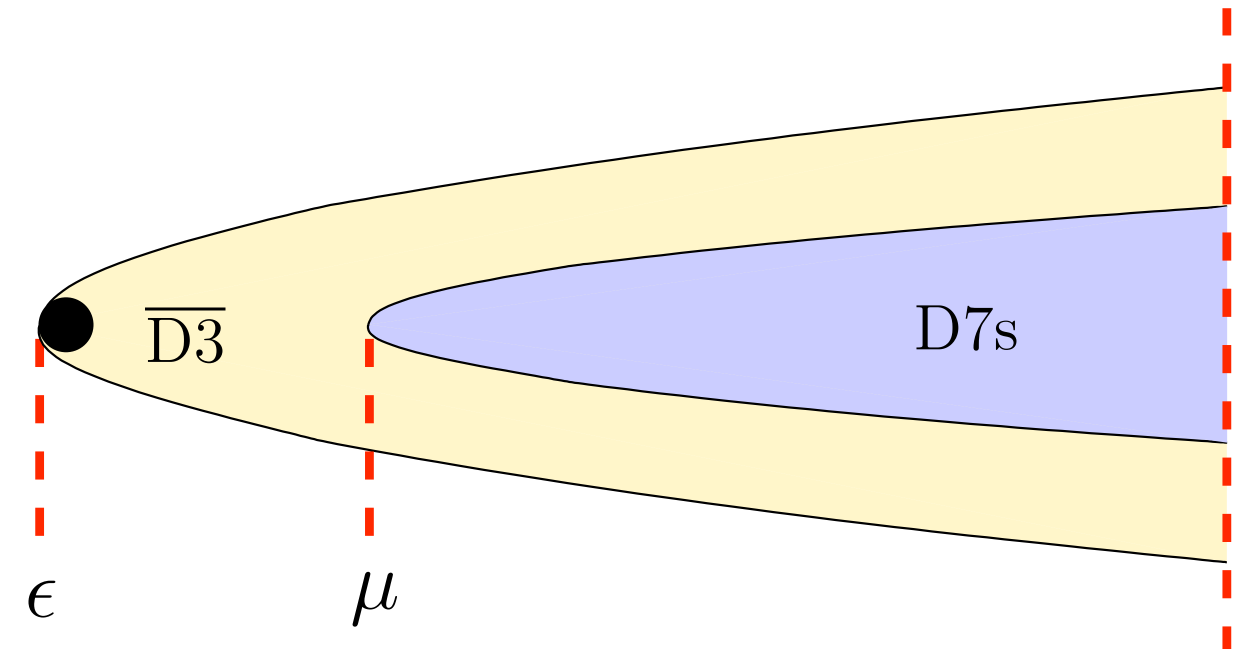
Holographic Gauge Mediation

[McGuirk, GS, Sumitomo]

SU(N+M) × SU(N) × SU(K)

hidden sector — visible sector





Gauge Side	Gravity Side
Metastable SUSY breaking state in a confining hidden sector gauge theory	$\overline{\text{D3}}$-brane in the warped deformed conifold
Introduce a flavor group ⊃ visible sector, and the associated messenger "quarks"	Introduce D7-branes
Calculate soft terms by summing **all hidden sector loop** contributions.	Calculate soft terms by analyzing **classically** how D7-fields react to a ~~SUSY~~ background.

Holographic Gauge Mediation

McGuirk, GS, Sumitomo,
arXiv:0910.4581 [hep-th], 0911.0019 [hep-th]

- Constructed the backreacted solution of an $\overline{\text{D3}}$-brane in the warped deformed conifold (warp factor, dilaton, fluxes perturbed, angular geometry squashed).

- Skipping details, we (i) analyzed the pullback of the SUSY breaking background on the D7-brane, (ii) dimensionally reduced the 7-brane gauge theory to 4D using the warped gaugino wavefunction obtained by [Marchesano, McGuirk, GS], and (iii) expressed the gravity computation results in terms of gauge theory quantities, and found:

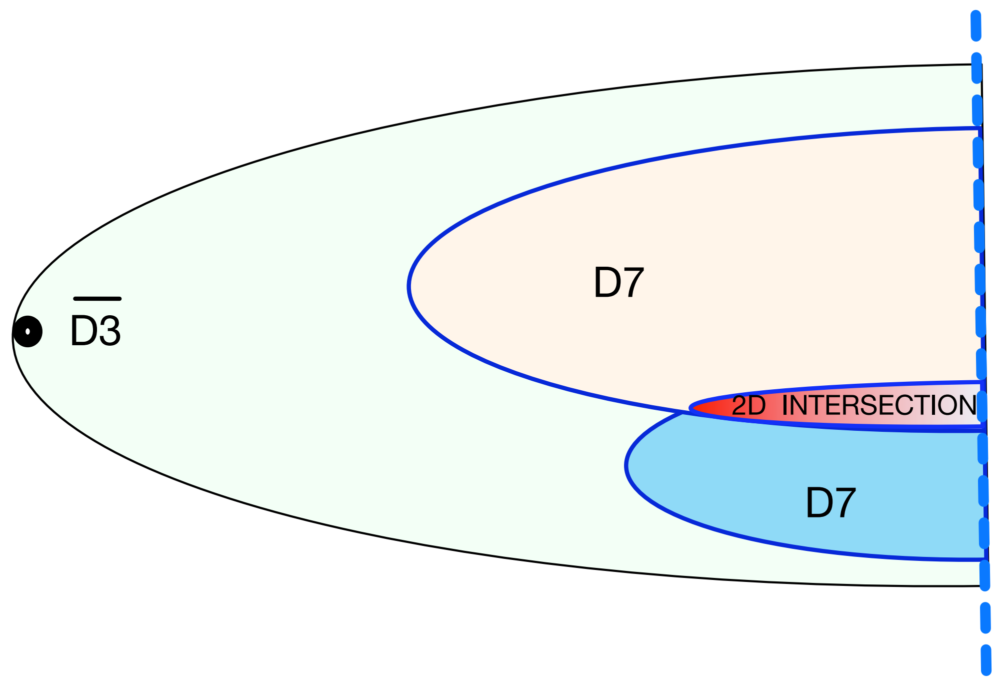
$$\delta m_{1/2} \sim g_{\text{vis}}^2 \frac{F^2}{m_\chi^3} \left(\left(\frac{m_\chi}{\Lambda_\varepsilon} \right)^{3/2} - 1 \right)^{3/2}$$

(c.f. minimal gauge mediation)

where the "effective" F-term $F = \sqrt{\lambda}\, \Lambda_{\mathcal{S}}^2$ $\quad \Lambda_{\mathcal{S}} \sim \mathcal{S}^{1/4} \Lambda_\varepsilon$ $\quad \mathcal{S} \sim \dfrac{P T_{D3}}{(g_s M \alpha')^2}$

Chiral Matter

- The chiral sector of the Standard Model and their superpartners (sfermions) are localized at D7-branes intersections:



UV intersection ↔ “elementary”

IR intersection ↔ “composite”

- If the 7-branes intersect in the UV, sfermion masses follow from gaugino mediation [Kaplan, Kribs, Schmaltz; Chacko, Luty, Nelson, Ponton]

$$m^2 \sim \alpha_{SM}\ m_\lambda^2\ \log(LM_Z)$$

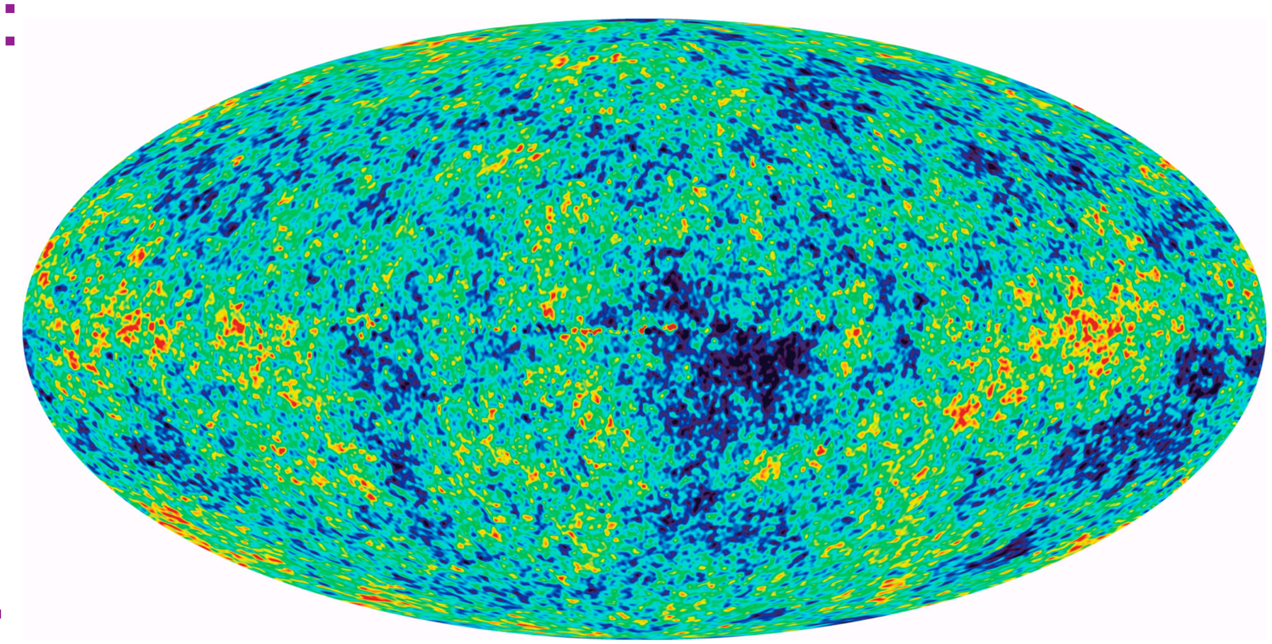
L=AdS radius

- More generally, the visible sector could be realized holographically on intersecting D7-branes with world-volume flux (composites).

Marchesano, McGuirk, GS, in progress

String Theory & Inflation

- **Inflation:** successful effective theory solving the flatness & horizon problems. Its generic predictions:

  ✤ nearly scale invariant
  ✤ Gaussian

  density perturbation spectrum in excellent agreement with data.

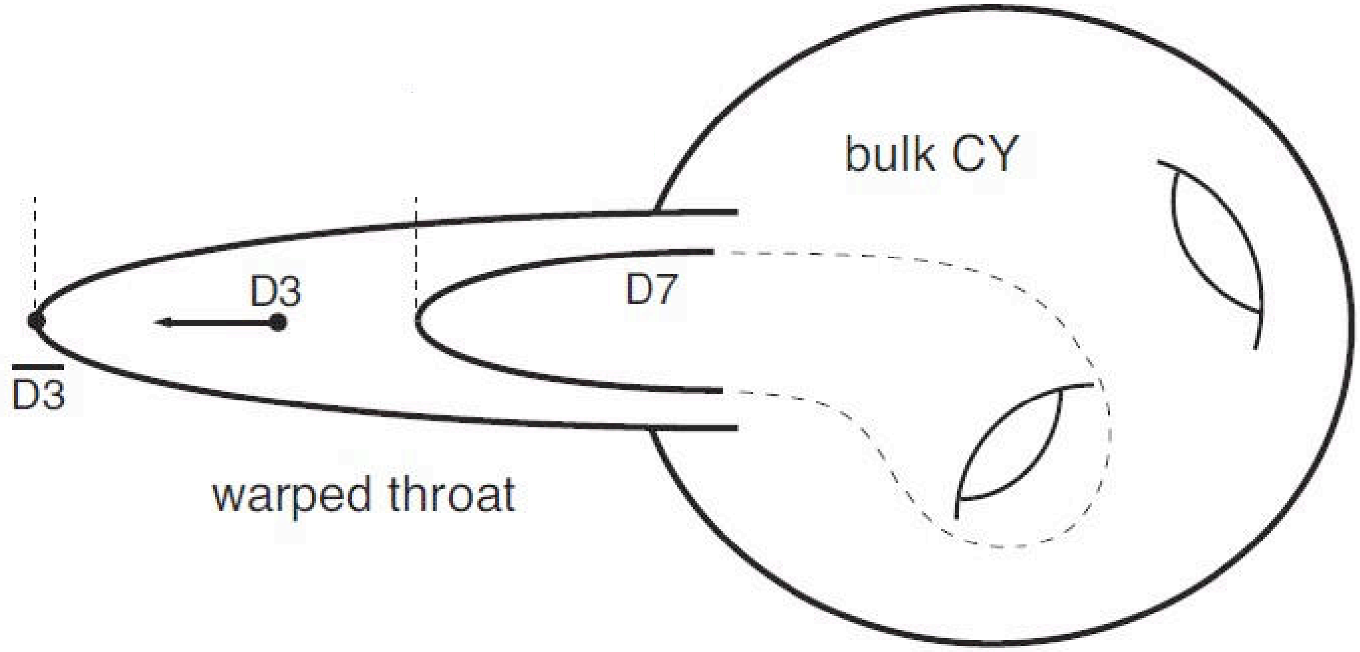
- However, the success/predictions of inflation are highly UV sensitive:

$$\Delta V \equiv \mathcal{O}_6 = V_0 \frac{\phi^2}{M_P^2} \Longrightarrow \Delta\eta \sim 1 \qquad \eta \equiv M_P^2 \frac{V''}{V}$$

all kinds of corrections (g_s, α’, warping, non-perturbative,...) to the EFT can significantly alter the physics.

D-brane Inflation

- **Idea:** Find a controllable setup where a modulus does not have a potential at leading order, & systematically include corrections.



$$W = A_0 f(z)^{1/n} e^{-a\rho}$$

$$K = -3\log(-i(\rho - \overline{\rho}) - \gamma k(Y, \overline{Y}))$$

- Integrating out other moduli (with m≤ m_{KK} << M_P), we should ask:
  - Multi-field effects?
  - What moduli-stabilizing D7-branes can be introduced?

D-brane Inflation

- To be concrete, we considered the warped deformed conifold:

$$\sum_i z_i^2 = w_1 w_2 - w_3 w_4 = \epsilon^2$$

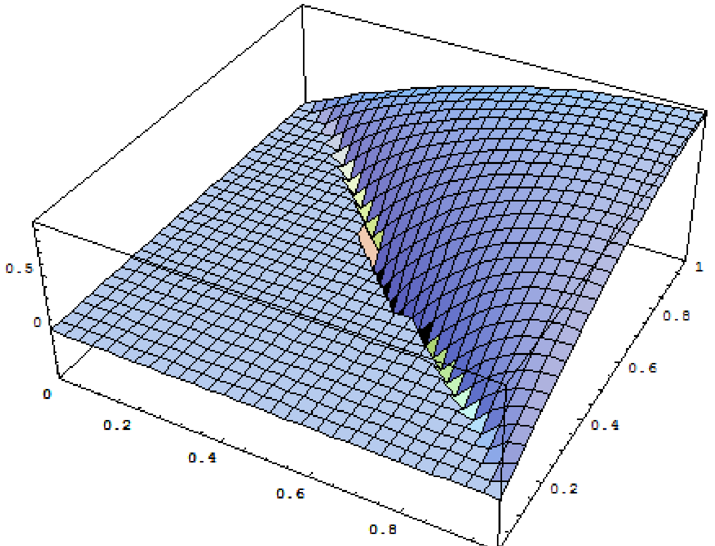
- Not all holomorphic functions f(z) = 0 define a *stable 7-brane*: [Chen, Ouyang, GS]

  ✓ Kuperstein embedding: $z_i = \mu$ is SUSY

  – Ouyang embedding: $w_i = \mu$ breaks SUSY unless a *specific* worldvolume flux is turned on (which we solved numerically).

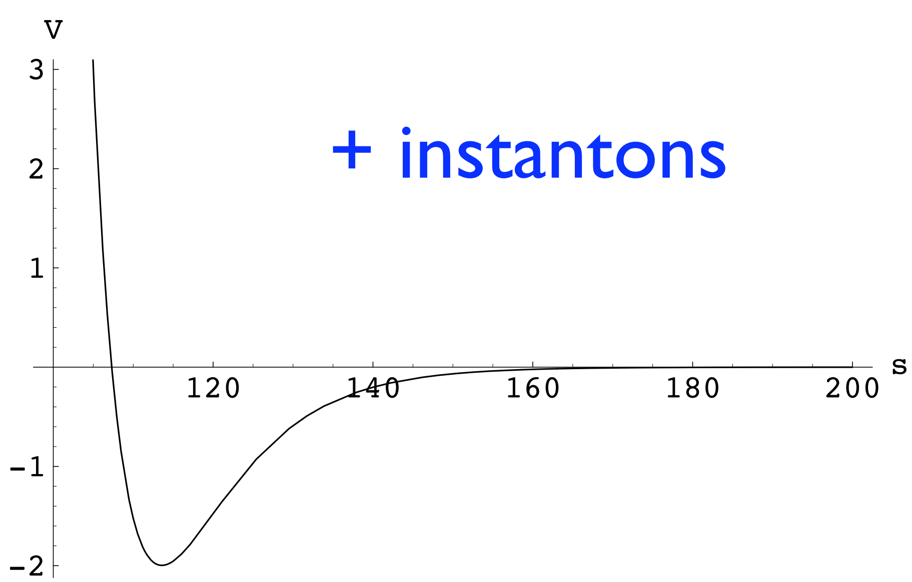
- Angular motion of D3-branes (under some conditions) can lead to interesting non-Gaussian CMB signatures.

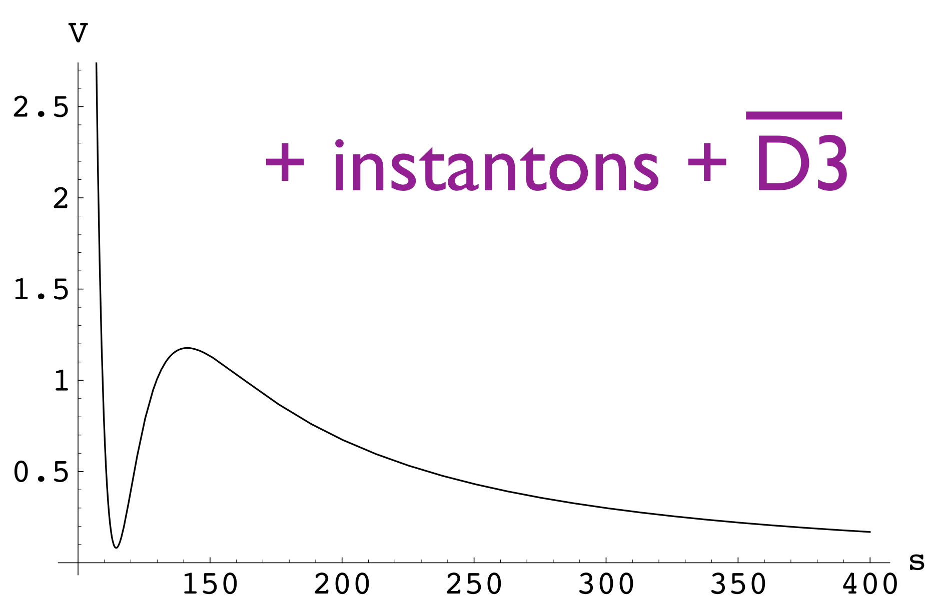
  [Huang,GS,Underwood]; [Chen,Gong,GS]



Constructing de Sitter Solutions

- Observational cosmology suggests an accelerating universe.
- There exist no-go theorems for obtaining de Sitter vacua (e.g., Maldacena, Nunez); can be evaded with orientifold planes (e.g., KKLT).
- Non-perturbative instanton effects are used to stabilize moduli, and anti-branes are introduced to uplift vacuum energy.





- Can one construct de Sitter vacua in string theory without invoking non-perturbative effects and anti-branes? [Haque, GS, Underwood, Van Riet]

Constructing de Sitter Solutions

- Consider the two universal moduli (ρ,τ):

$$\mathrm{d}s_{10}^2 = \tau^{-2}\mathrm{d}s_4^2 + \rho\,\mathrm{d}s_6^2\,, \qquad \tau \equiv \rho^{3/2}\mathrm{e}^{-\phi}\,,$$ (10D string frame)

- Various contributions to 4D potential scale with (ρ,τ) as:

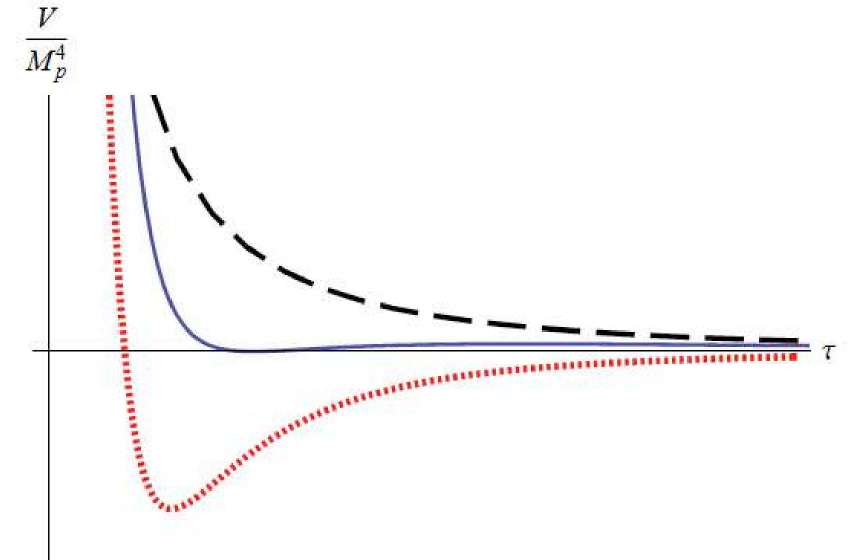
$$V_R = U_R\rho^{-1}\tau^{-2}\,, \qquad V_H = U_H\rho^{-3}\tau^{-2}\,, \quad V_q^{RR} = U_q\tau^{-4}\rho^{3-q} \qquad V_{Dp/Op} = T_p Vol(\Sigma)\tau^{-3}\rho^{\frac{p-6}{2}}$$

- For Ricci flat internal space (e.g., Calabi-Yau), V_R=0 ⇒ no-go!

Hertzberg, Kachru, Taylor, Tegmark

- Type IIA minimal ingredients to evade no-go: negative internal curvature, and a non-zero Romans mass. [Haque. GS. Underwood. Van Riet]

(c.f. Silverstein)



Constructing de Sitter Solutions

[Danielsson, Haque, GS, Van Riet]

- Manifolds with SU(3) structure:

$$\mathrm{d}J = -\frac{3i}{2} W_1 \Omega_R \,,$$
$$\mathrm{d}\Omega = W_1 J \wedge J + W_2 \wedge J \,,$$

- Ansatz for fluxes which only involve "universal forms":

$$F_2 = \mathrm{e}^{-3\phi/4} f_1 J + i \mathrm{e}^{-3\phi/4} f_2 W_2 \,,$$
$$H = \mathrm{e}^{\phi/2} h \Omega_R \,, \qquad F_0 = \mathrm{e}^{-5\phi/4} m$$
$$F_4 = \mathrm{e}^{-\phi/4} g_1 \epsilon_4 + \mathrm{e}^{-\phi/4} g_2 J \wedge J \,.$$

- This enables us to solve the flux eoms & Bianchi id. by selecting f_i, g_i, & h; and the Einstein equations can be checked:

$$\mathcal{R}_{mn} = -\frac{3i}{4} (\Omega_R)_n{}^{ps} \partial_{[p} (W_2)_{sm]} - \frac{1}{4} W_1 (W_2)_{mr} J_n{}^r - \frac{1}{2} (W_2)_{mq} (W_2)_n{}^q + \frac{5}{4} g_{mn} |W_1|^2 \,.$$

- Orientifold plane: $\mathrm{d}F_2 = mH + \mu \Omega_R$ "smeared"

- There exist a parameter window of W_1 and W_2 where dS is possible!

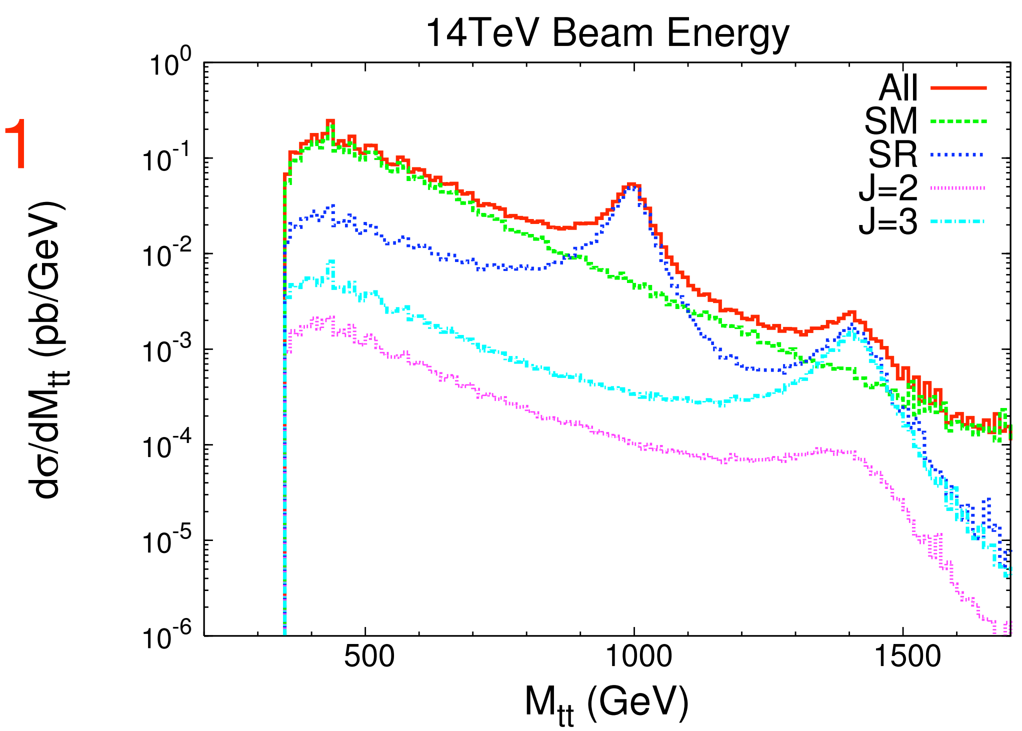
- Finding explicit geometries, unsmearing the O-planes [in progress]

Other Projects in Brief

- "Top quarks as a window to string resonances" Z. Dong, T. Han, M. Huang, GS, arXiv:1004.5441

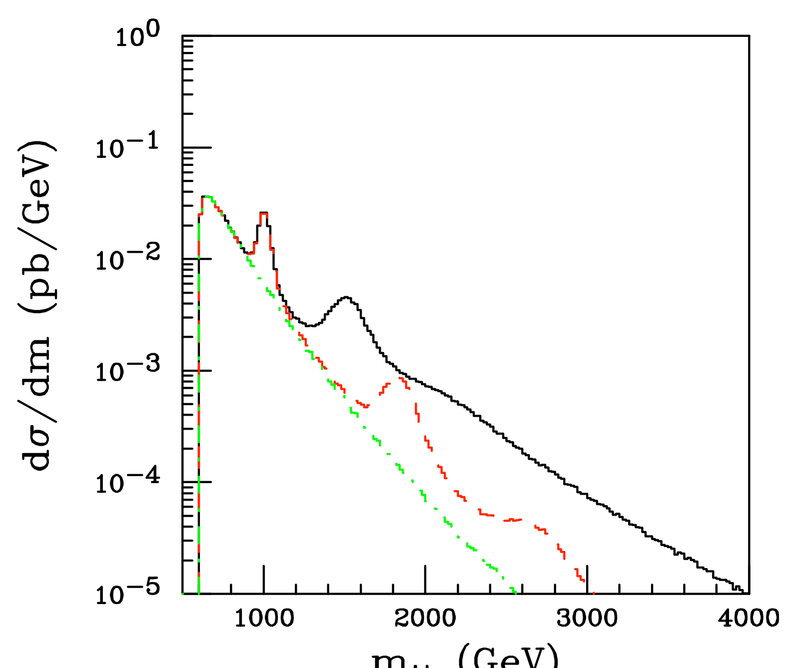
  To leading g_s order, $gg \to t\bar{t}$ is model-independent (extra dims, SUSY, brane configurations, etc)

  - ❖ Soft UV Regge behavior
  - ❖ Unusual angular distributions
  - ❖ Mass ratios between resonances



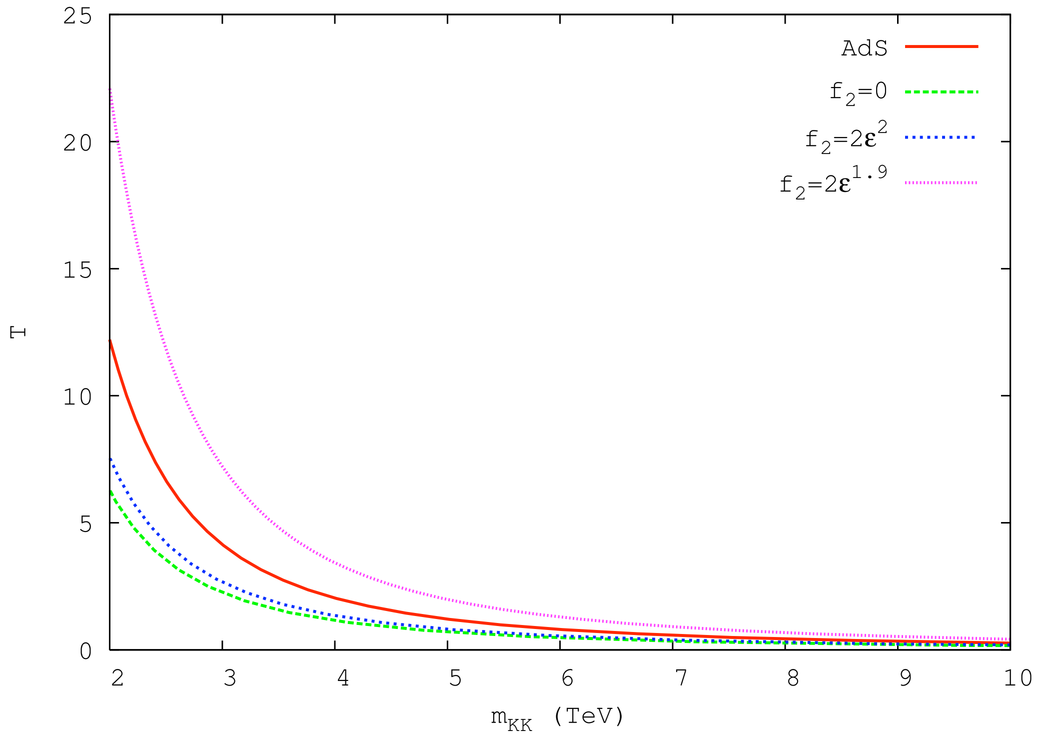
- "Probing the geometry of warped string compactifications at the LHC", GS, B. Underwood, K. Zurek, D. Walker, PRL 2008.

  - ❖ Small changes in warped geometry lead to drastic changes in the masses of KK modes and their couplings to the Standard Model.



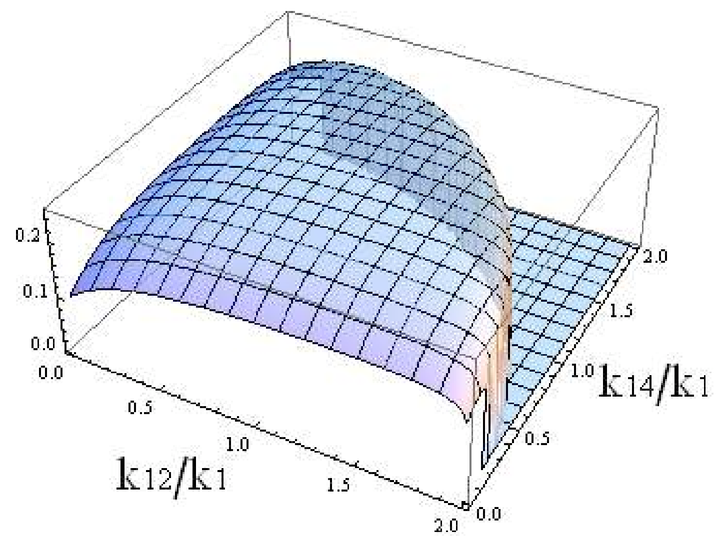
Other Projects in Brief

- "Phenomenology of infrared smooth warped extra dimensions", P. McGuirk, GS, K. Zurek, JHEP 2008.
  - ❖ Effects of infrared modifications of warped geometries on KK masses & couplings, and precision electroweak parameters S and T.



- "Large primordial trispectra in general single field inflation", X. Chen, B. Hu, M. Huang, GS, Y. Wang, JCAP 2009.
  - ❖ Large scalar 4-point functions (trispectra) in general single field inflation, where:

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[M_{\rm Pl}^2 R + 2P(X,\phi)\right]$$



Summary & Future Directions

- Many exciting and important questions lie at the interface of string theory, particle physics, and cosmology.
- String theory provides not only a UV complete framework, but also a tool to address issues in BSM physics & cosmology.
- Explore new string model building possibilities (embedding the Standard Model in compactifications with fluxes and/or generalized geometries; realizing concrete inflationary/de Sitter solutions in string theory).
- Derive the effective action of string compactifications (with intersecting branes, including warping, non-perturbative, compactness corrections, ...).
- Develop tool to study BSM scenarios difficult using conventional approaches (e.g., using holography in models with strong coupling).

Other activities since 8/2007

- 16 invited conference talks, 9 international school lecture Series, 5 public lectures, 4 colloquia, 12 seminars.
- Organizer of:
  - Great Lake Strings Conference, Madison, May 2008
  - Cosmo 08 International Conference, Madison, August 2008
  - String Vacuum Project Meeting, KITP, Santa Barbara, May 2010
  - Tenth International String Phenomenology Conference, Madison, 2011
- International Advisory Committee: Annual String Phenomenology Conference (since 2004); Cosmology since Einstein Symposium, 2011.