Splitting KK spectrum and phenomenology

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based on
SCP, J. Shu, [arXiv: 0901.0720]
Chen, Nojiri,SCP, J. Shu, Takeuchi, [arXiv:0903.1971]

"If particle physicists were in Florence learning Italian, the model builders would know how to ask for lodging and acquire the vocabulary that would be essential to finding their way around, but they might talk funny and never fully comprehend the Inferno. String theorist, on the other hand, might aspire to grasp the subtleties of Italian literature- but run the risk of starving to death before learning how to ask for dinner! "

From Lisa Randall [Warped passages]

Obvious solution

- Model builders (for better understanding of what they are actually doing) should talk to string theorists.
- String theorists also should talk to model builders (for nice dinner).

Extra dimension

- String theory told us that we need to have supersymmetry and extra dimensions for string theory being consistent
- If M_{susy}=O(1) TeV, we can address “hierarchy problem”. (need a mechanism of TeV susy breaking. Theory is technically natural even $M_G \gg M_{susy}$)
- If M_{kk}=O(1) TeV, as in e.g. RS, we can also address “hierarchy problem” with extra dimension. (Need stabilization mechanism.)

- SUSY+R-parity, theory is less constrained by low energy data. LSP is a good DM candidate.

- Extra dimension + KK-parity, LKP is a good DM candidate.

- Notorious problems in 4D often have simple solutions in (4+n)D. Doublet-Triplet problem of GUT, hierarchical Yukawa couplings, big hierarchy problem, SUSY breaking etc..

- No reason why we should stay in D=4! We can enjoy higher dimension (as string theory needs it).

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My topics

- A brief review of "Universal" extra dimension (UED). (+PAMELA, ATIC/PPB-BETS)
- Split KK spectrum#1: Double Kink mass for fermion
- Split KK spectrum#2: Brane localized kinetic term
- Summary

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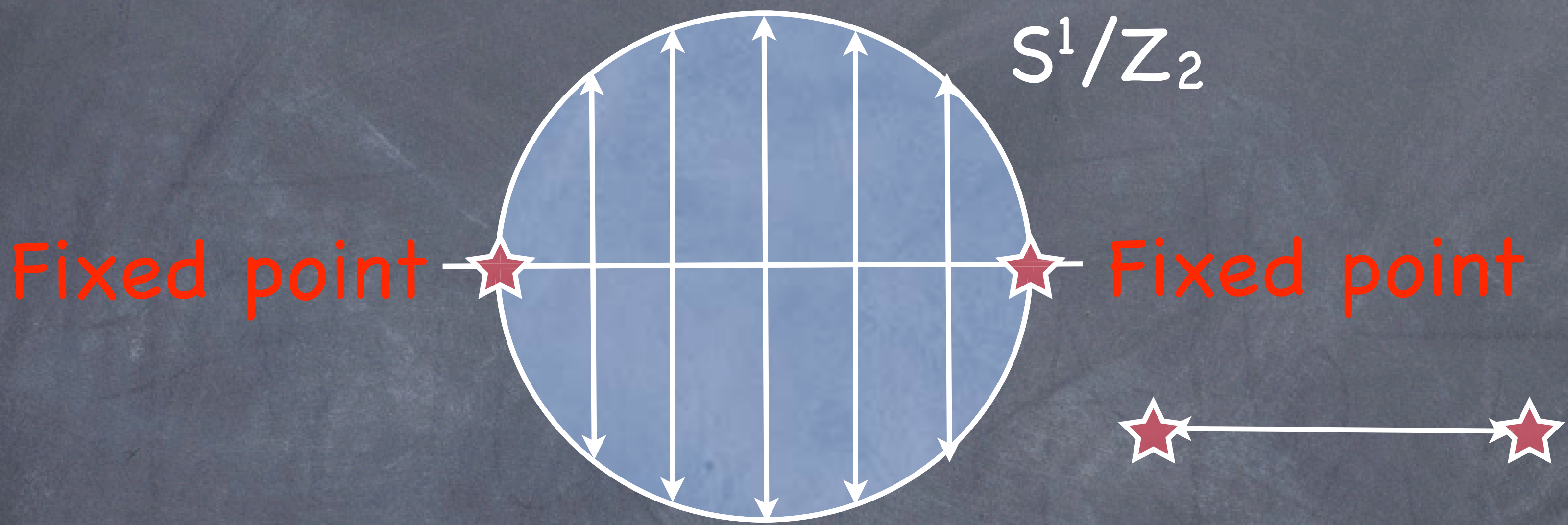
Universal Extra Dimension (UED)

- The most naive way of extending the SM into higher dimension.
- All the SM particles are promoted to 5D fields propagating in a flat extra dimension.
- The extra dimension is chosen to be the orbifold S^1/Z_2. 4D effective theory is chiral (=the SM + KK states).

S^1/Z_2 orbifold



- Z_2: y->-y, Two fixed points (y=0, pi R)
- $A_{mu}(x,-y)=A_{mu}(x,y)$, $A_5(x,-y)=-A_5(x,y)$
- Minimal spinor in 5D = Dirac spinor. Fermion spectrum is doubled (each SM fermion is promoted to 5D Dirac spinor which has L and R component).

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The UED action :

All fields are in 5D

The UED bulk action on $S^1/\mathbb{Z}_2$ is

$$S_{UED,bulk} = S_g + S_H + S_f \tag{1}$$

with

$$S_g = \int d^5x \left(-\frac{1}{4\hat{g}_3^2} G^A_{MN} G^{AMN} - \frac{1}{4\hat{g}_2^2} W^I_{MN} W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{MN} \right) \tag{2}$$

$$S_H = \int d^5x \left((D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda} (H^\dagger H)^2 \right) \tag{3}$$

$$S_f = \int d^5x \left(i\bar{f}\gamma^M D_M f + \left(\hat{\lambda}_E \bar{L} E H + \hat{\lambda}_U \bar{Q} U \tilde{H} + \hat{\lambda}_D \bar{Q} D H + \text{h.c.} \right) \right) \tag{4}$$

G=SU(3)XSU(2)XU(1)

f=(Q,U,D,L,E)

$$\gamma^M = (\gamma^\mu, i\gamma^5)$$

$$f = f_L + f_R$$

Neumann BCs are imposed on:

$$H, G_\mu^A, W_\mu^a, B_\mu, Q_L, L_L, U_R, D_R, E_R$$

Dirichlet BCs are imposed on:

$$G_5^A, W_5^a, B_5, Q_R, L_R, U_L, D_L, E_L$$

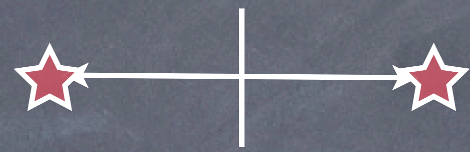
*The resultant zero mode spectrum is the same as the SM.

*KK mode basis :

$$\{f^{(n)}\} \sim \{ \sin(ny/\pi R), \cos(ny/\pi R)\}$$

$$m_n^2 \simeq n^2/R^2$$

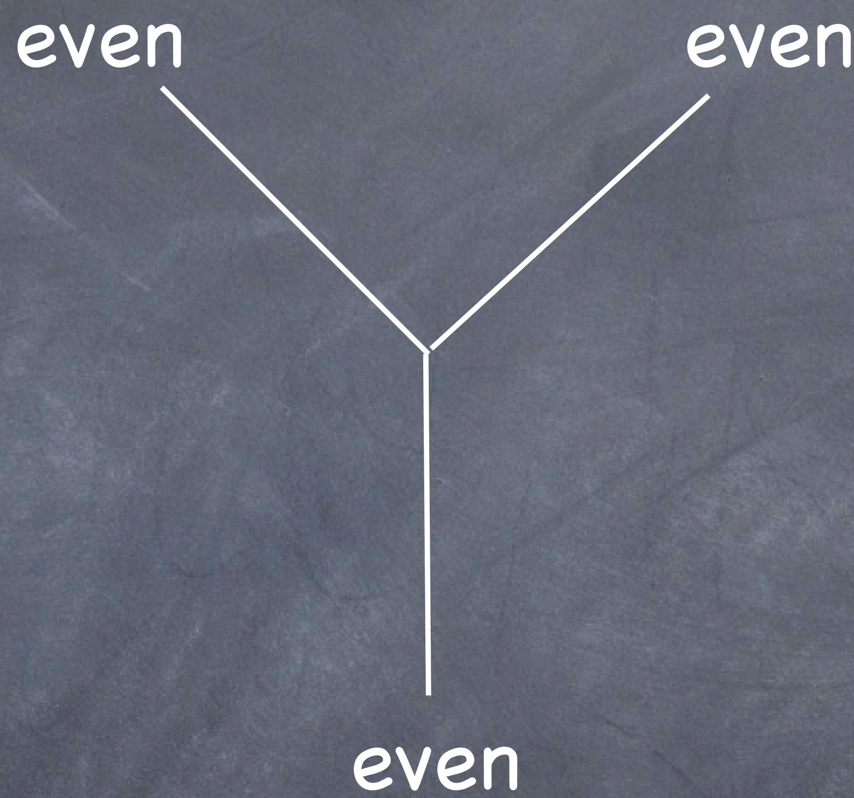
KK-parity



- The reflection symmetry about the mid point of extra dimension is respected: KK-parity conservation (An accidental symmetry)

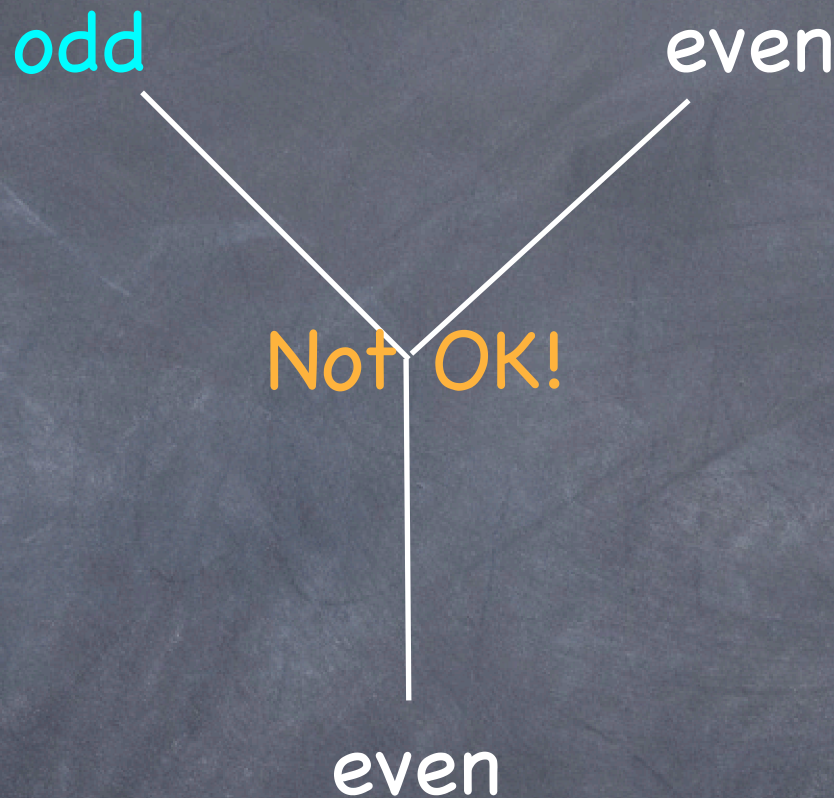
- Remnant symmetry of KK-number conservation (=momentum conservation along 5th direction=translational invariance which is broken by fixed points)

SM-SM-SM
vertex is OK



SM particles
=zero modes (KK even)

SM-SM-DM vertex is NOT allowed!



LKP(lightest 1^{st} KK particle) is stable

Never produced singly

Less constrained (1/R>300 GeV)

KK photon is LKP

$$\delta(m^2_{B^{(n)}}) = \frac{g'^2}{16\pi^2 R^2}\left(\frac{-39}{2}\frac{\zeta(3)}{\pi^2} - \frac{n^2}{3}\ln \Lambda R\right)$$

$$\delta(m^2_{W^{(n)}}) = \frac{g^2}{16\pi^2 R^2}\left(\frac{-5}{2}\frac{\zeta(3)}{\pi^2} + 15n^2 \ln \Lambda R\right)$$

$$\delta(m^2_{g^{(n)}}) = \frac{g_3^2}{16\pi^2 R^2}\left(\frac{-3}{2}\frac{\zeta(3)}{\pi^2} + 23n^2 \ln \Lambda R\right)$$

$$\delta(m_{Q^{(n)}}) = \frac{n}{16\pi^2 R}\left(6g_3^2 + \frac{27}{8}g^2 + \frac{1}{8}g'^2\right)\ln \Lambda R$$

$$\delta(m_{u^{(n)}}) = \frac{n}{16\pi^2 R}\left(6g_3^2 + 2g'^2\right)\ln \Lambda R$$

$$\delta(m_{d^{(n)}}) = \frac{n}{16\pi^2 R}\left(6g_3^2 + \frac{1}{2}g'^2\right)\ln \Lambda R$$

$$\delta(m_{L^{(n)}}) = \frac{n}{16\pi^2 R}\left(\frac{27}{8}g^2 + \frac{9}{8}g'^2\right)\ln \Lambda R$$

$$\delta(m_{e^{(n)}}) = \frac{n}{16\pi^2 R}\frac{9}{2}g'^2 \ln \Lambda R\,.$$

RG-running from "cutoff scale" to 1/R scale:

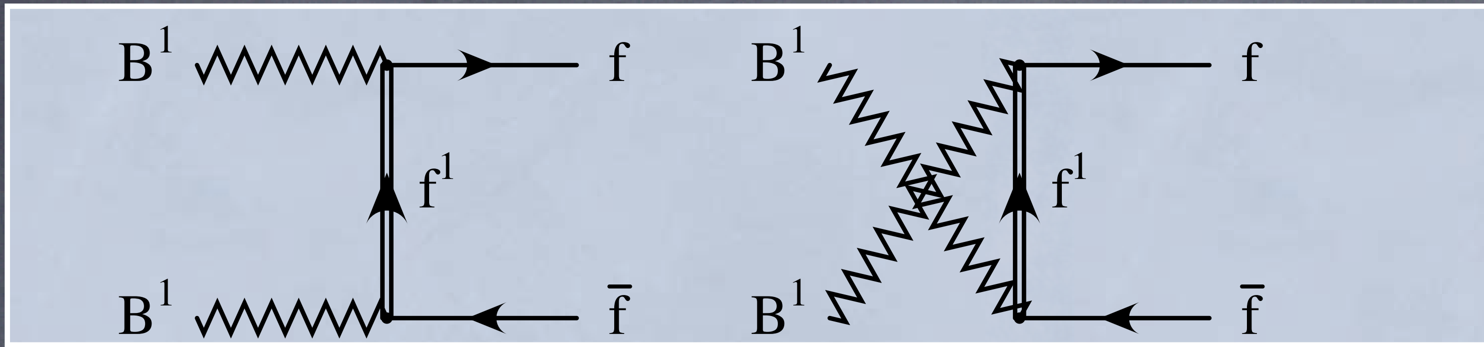
1. KK photon -0.2%
2. KK gluon +30%
3. KK quarks +14%
4. KK leptons +1%

==> aligned by U(1)y

WIMP

Cheng et.al.

Relic Density



+coannihilation with leptons,quarks

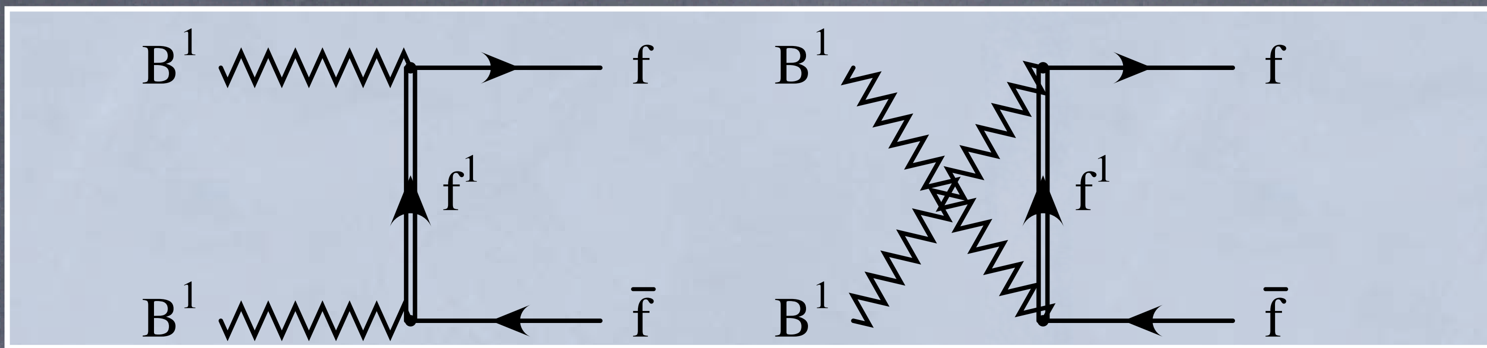
$$\langle \sigma v \rangle_{B_1 B_1 \to f \bar{f}} \simeq \frac{2 g_1^4 C_f}{9 \pi m_{B_1}^2} \frac{1}{(1 + r_f^2)^2}$$

$$\Omega \simeq \frac{10^{-26} \mathrm{cm}^3 s^{-1}}{\langle \sigma v \rangle} = 0.23$$

$$m_{B_1} \simeq 600 - 700 \mathrm{GeV}$$

*Taking coannihilation into account.

(slightly) leptophilic

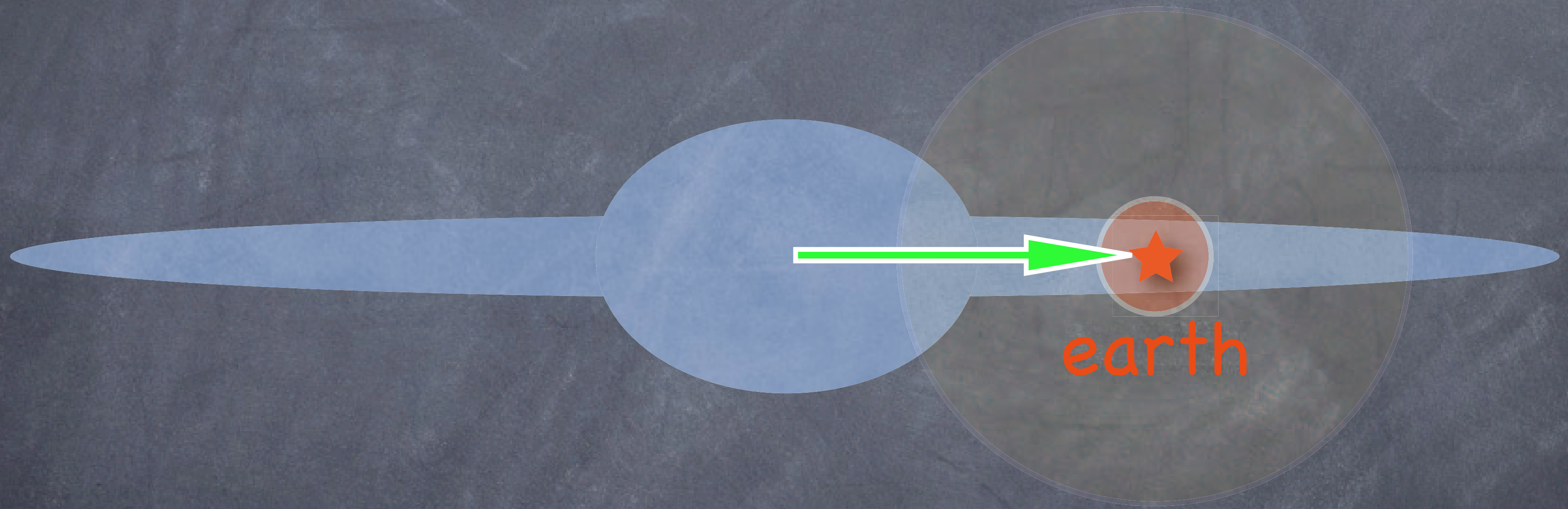


$$\boxed{l_R : q_R = 1^4 : 3 \times (2/3)^4 = 1 : 16/27}$$

$$\sigma_{B_1 B_1 \to f\bar{f}} \sim N_c Y_f^4$$

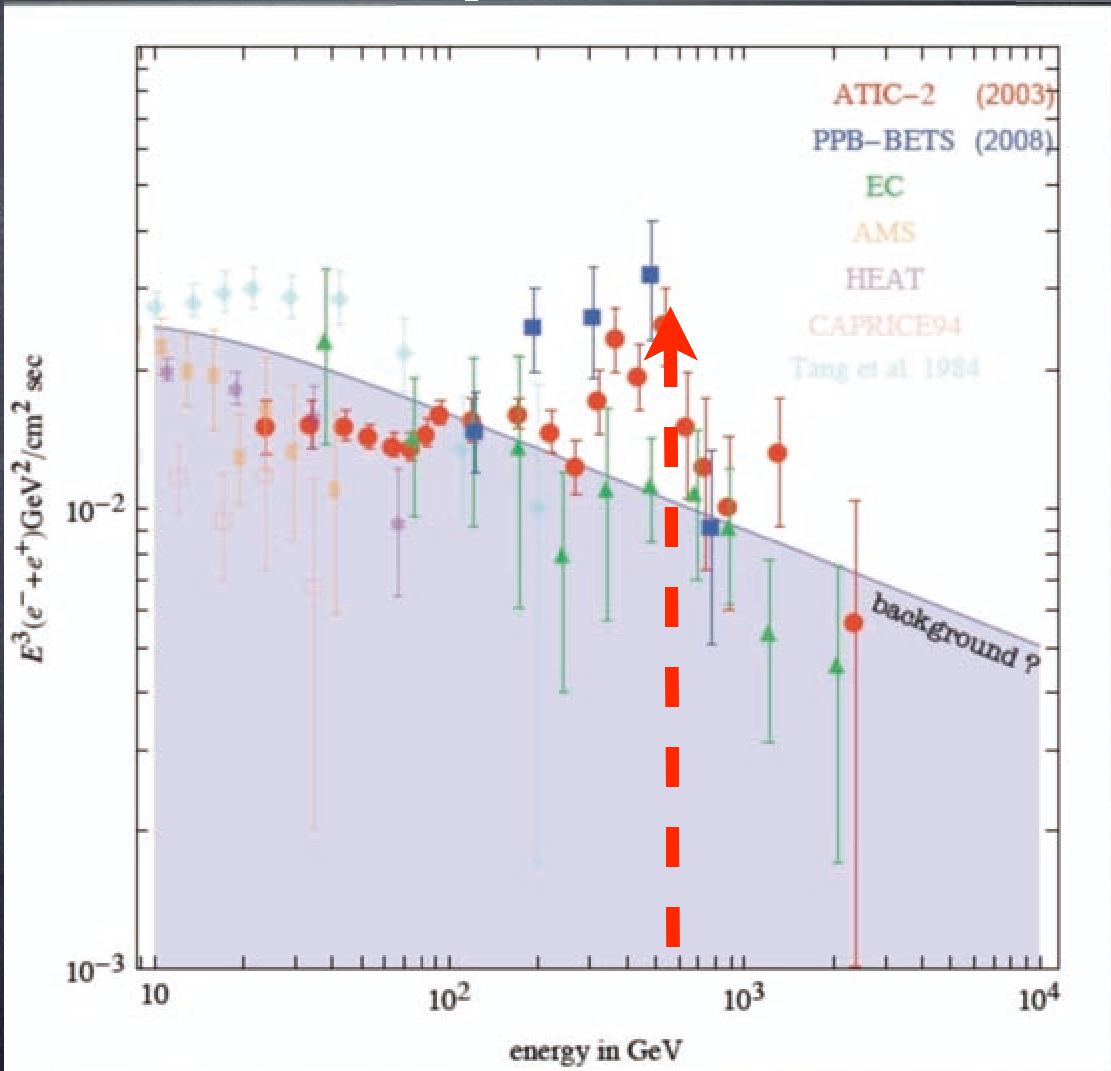
B1+B1->e+,gamma,p-..

In our galaxy



- Positron mostly from “local” source
- Photon goes straight (mostly from the center)
- Antiproton diffuses longer

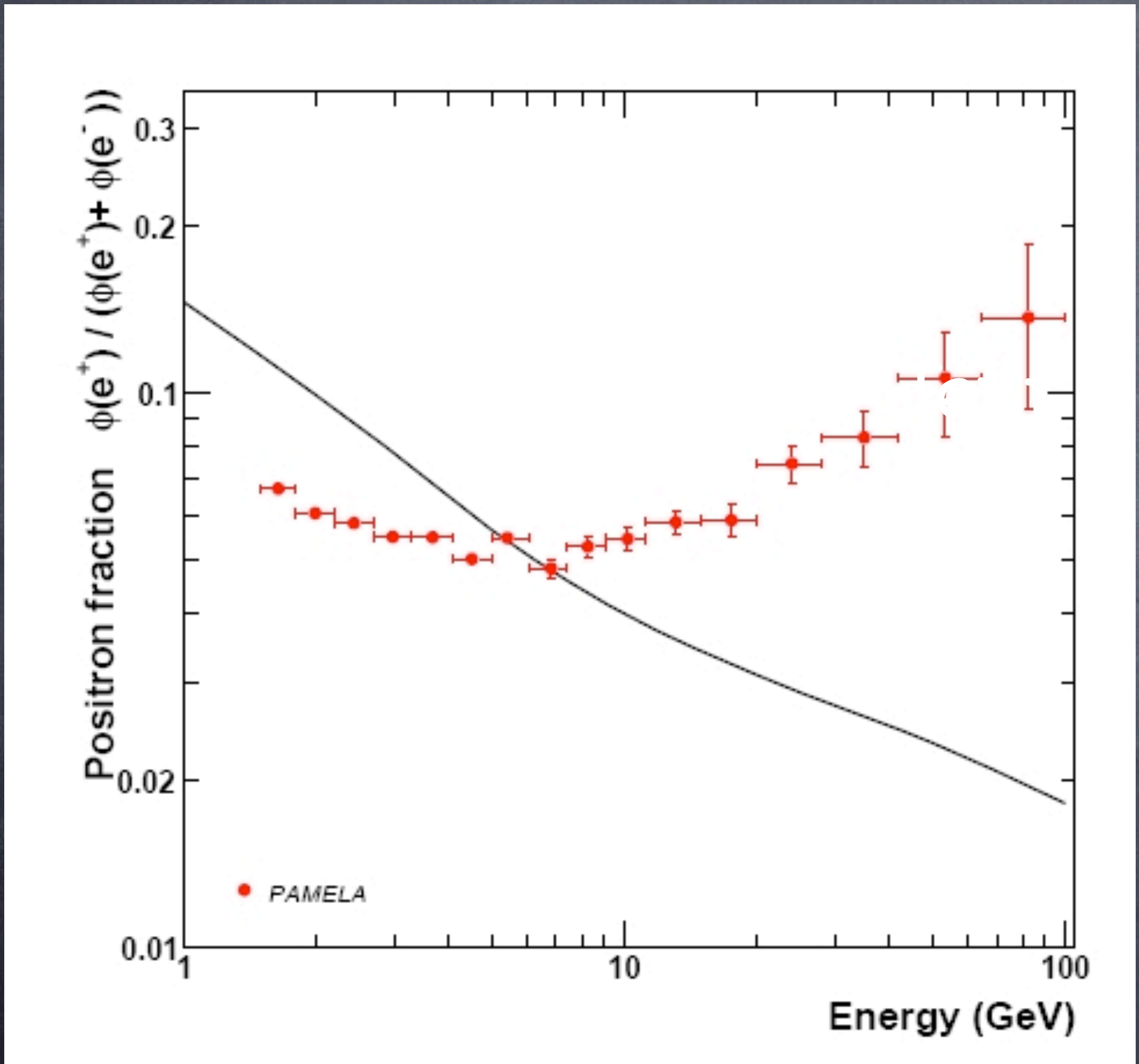
ATIC,PPB-BETS found "peak" at 650 GeV



The peak position of (e-e+) coincide the UED prediction!

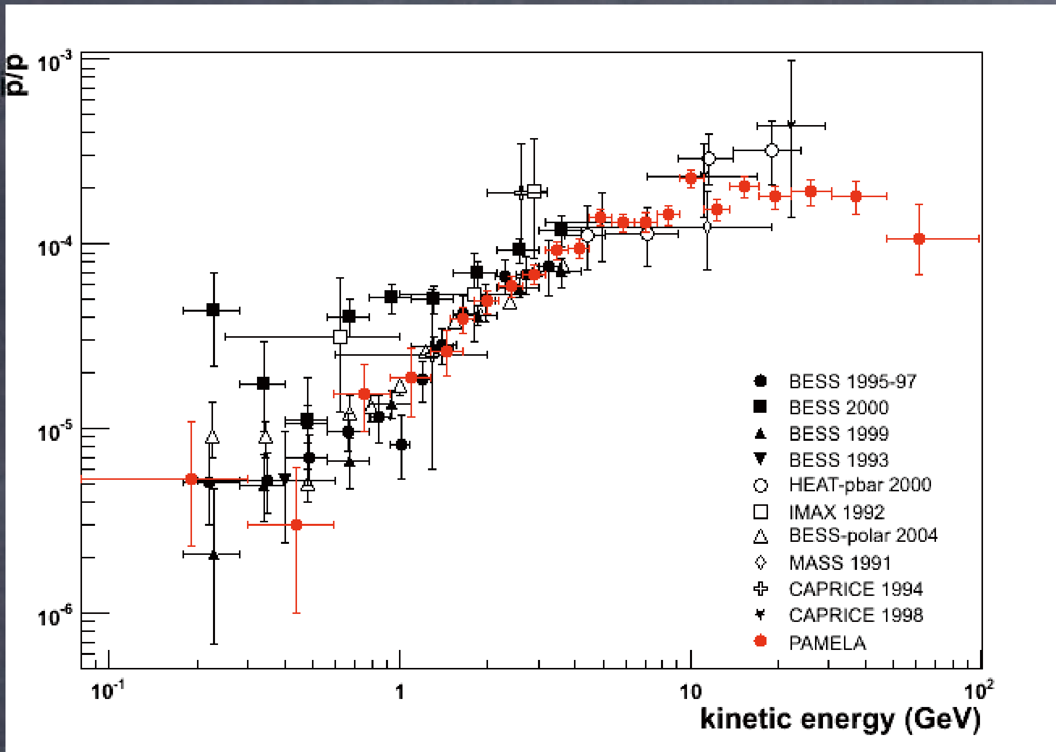
Chang et.al.
Nature Vol.456 362(2008)[ATIC]
Torii et.al.
0809.0760[PPB-BETS]

PAMELA anomaly



The low energy "tail" can be a solution to PAMELA anomaly

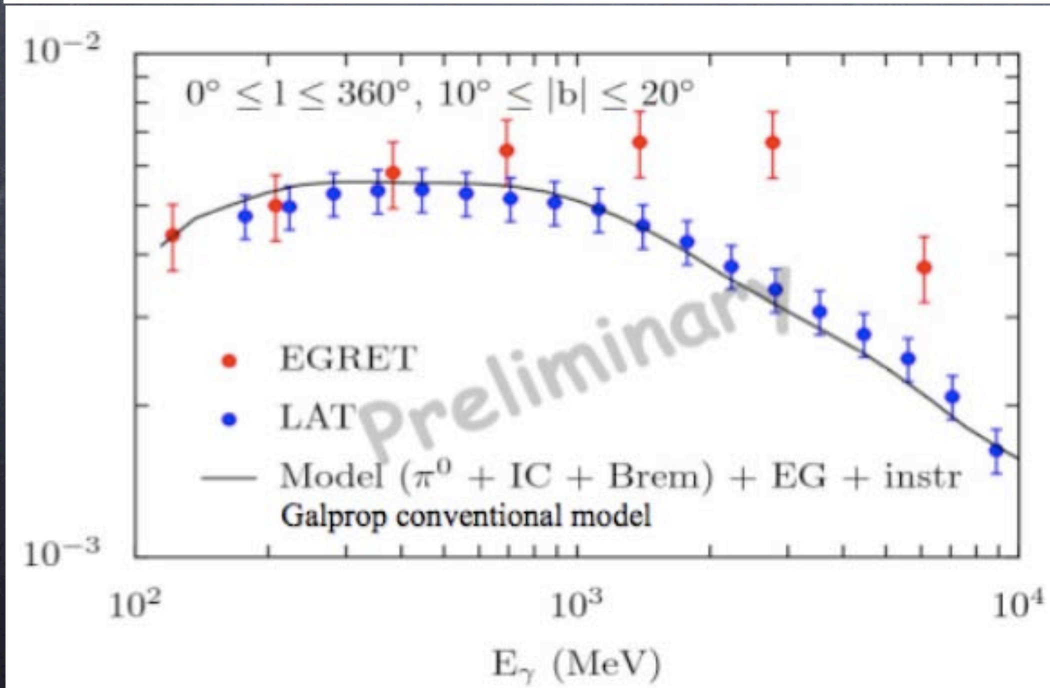
O. Adriani et.al.
arXiv:0810.4995v1
[astro-ph]



However!

No excess in anti-proton

PAMELA, PRL(2009)



No excess in gamma-ray from Halo

Fermi, preliminary

==> ‘Hint’ for extension

How shall we go?

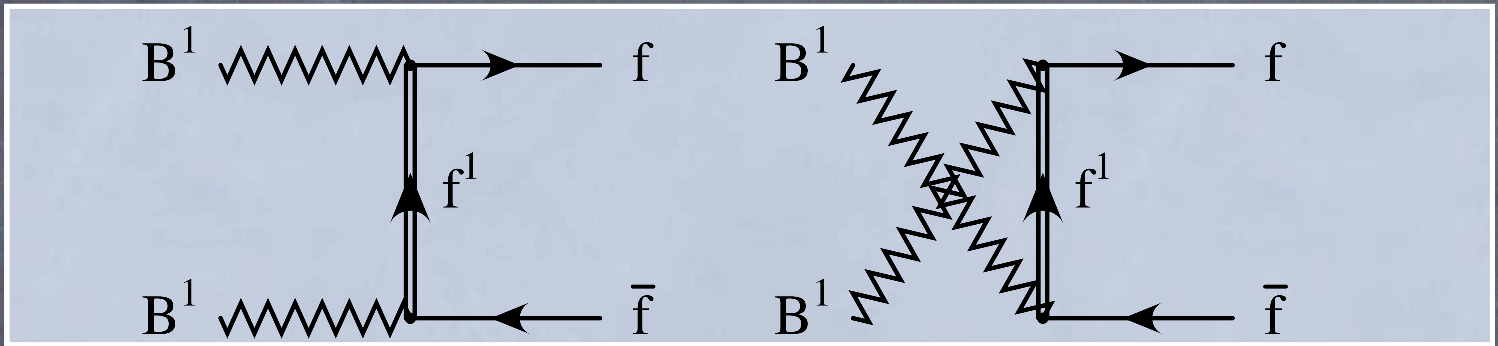
*The excesses in PAMELA, ATIC electronic fluxes can be understood by the LKP pair annihilation.

*No excess in hadronic channels (i.e. Hadrophobic or leptophilic)

*No excess in gamma-ray (->related to hadronic BR since (pion->2gamma) is a significant source)

==> hadronic BR need to be suppressed!

split-spectrum helps



$$\langle \sigma v \rangle_{B_1 B_1 \to f \bar{f}} \simeq \frac{2 g_1^4 C_f}{9 \pi m_{B_1}^2} \frac{1}{(1 + r_f^2)^2}$$

$$r_f = \frac{m_f}{m_{B_1}}$$

Making quarks heavier,

hadronic BF is naturally suppressed!

UED with split spectrum
=split UED

SCP, J.Shu 0901.0720

Chen, Nojiri, SCP, Shu, Takeuchi 0903.1971

In minimal UED:

KK mass =1/R (+RGE<O(10)%)

In split-UED:

KK mass = f(1/R, m_5, a) (+RGE)

*m_5:Bulk mass parameter

*a:Brane localized kinetic term (BLKT)

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Dirac mass term for fermion is allowed

- In 5D the minimal spinor representation is Dirac. So all the SM fermions are promoted to Dirac fields in 5D.
- Dirac mass term is generically allowed by gauge symmetry and Lorentz symmetry.
- According to the orbifold Z_2 symmetry, the mass term should be 'odd'.

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Z_2: y->-y

$$\Psi(x,y) \to \Psi(x,-y) = \pm\gamma_5\Psi(x,y)$$

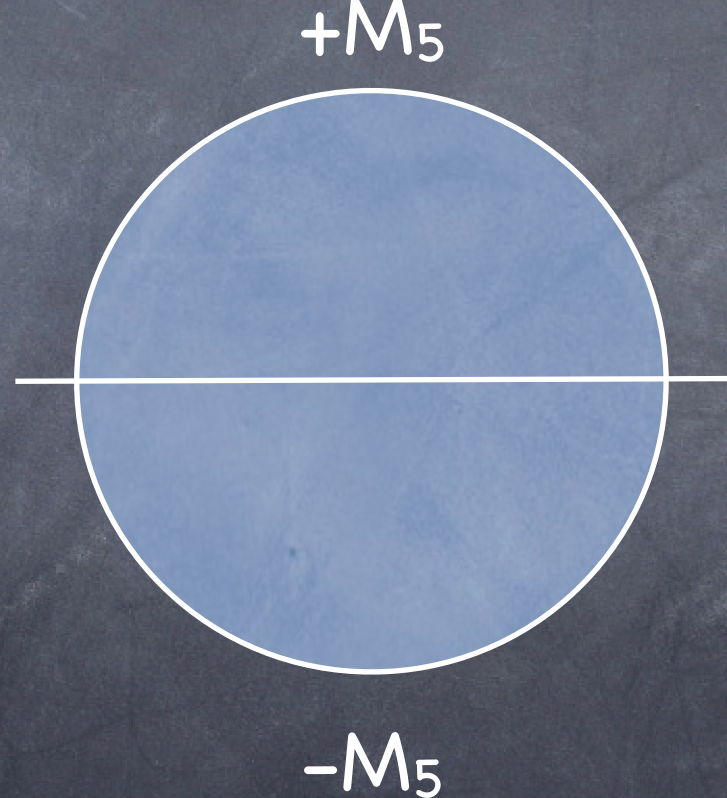
$$\bar{\Psi}\Psi \to -\bar{\Psi}\Psi$$

Thus, Dirac mass term should be "odd" under Z_2 parity

$$M_5(y)\bar{\Psi}\Psi$$

$$M_5(y) \to M_5(-y) = -M_5(y)$$

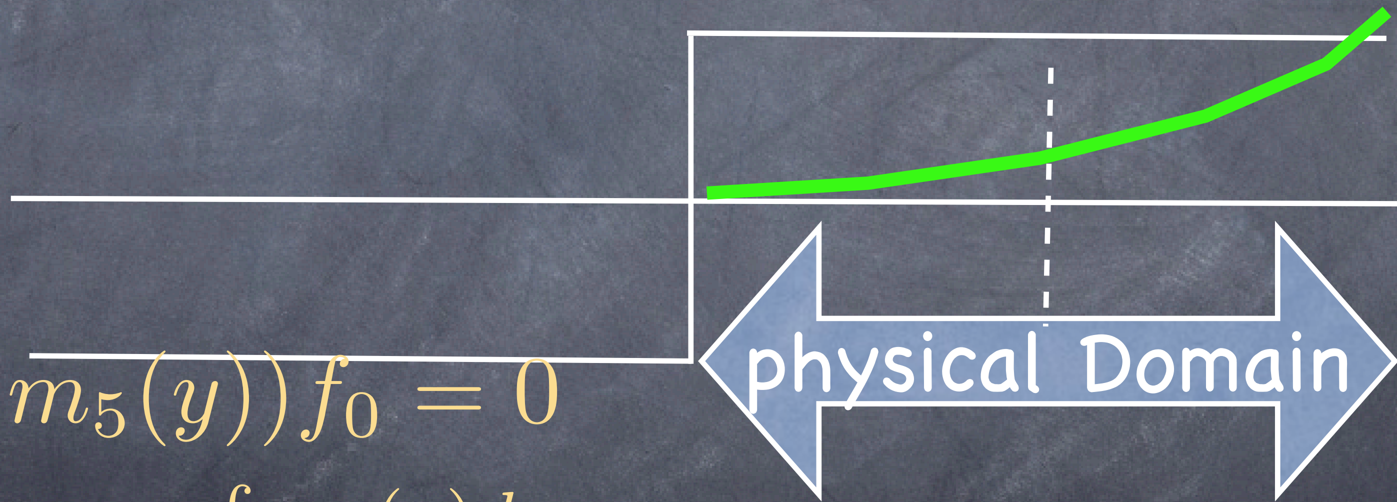
A naive choice: A kink mass



Kink-Mass Breaks KK parity

$$S = \int d^5 \bar{\Psi} i \Gamma_M D^M \Psi - \lambda \Phi(y) \bar{\Psi}\Psi$$

$$m_n^2 = \mu^2 + k_n^2$$



$$(\partial_5 - m_5(y)) f_0 = 0$$

$$f_0 \sim e^{\int m_5(y) dy}$$

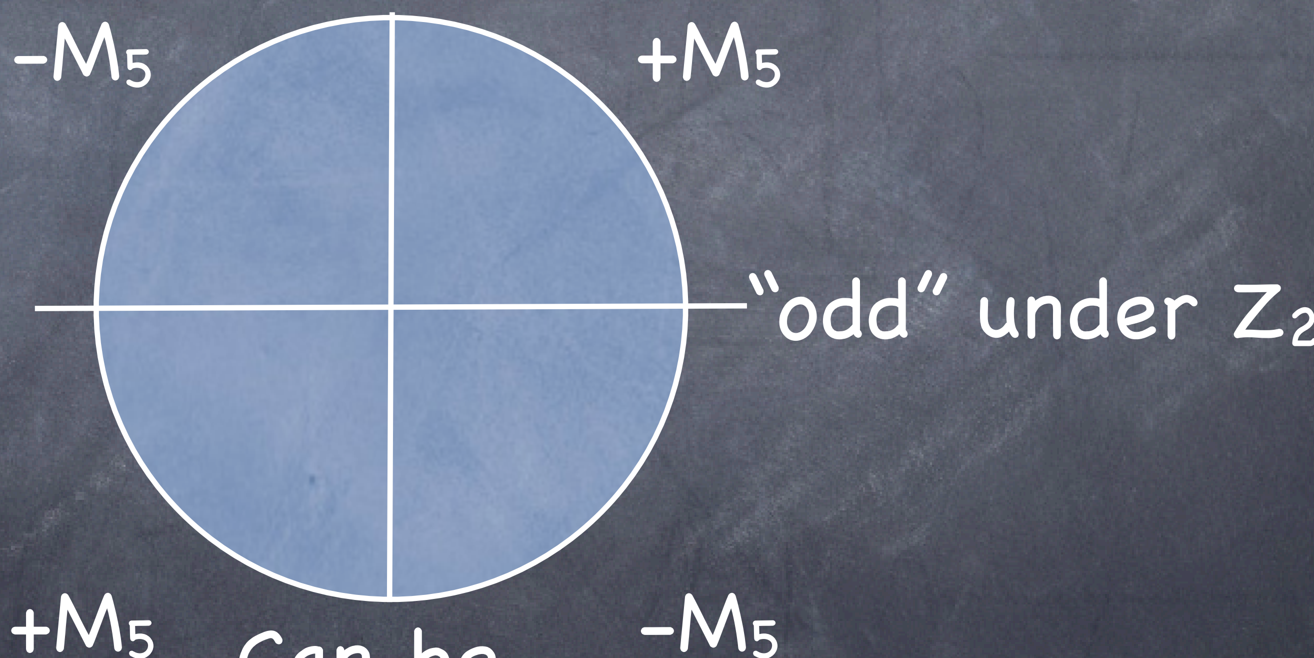
Zero mode wave function

$$f(y) \sim e^{\mu y}$$

KK-parity is not respected.

Double kink mass

SCP, Shu(2009)

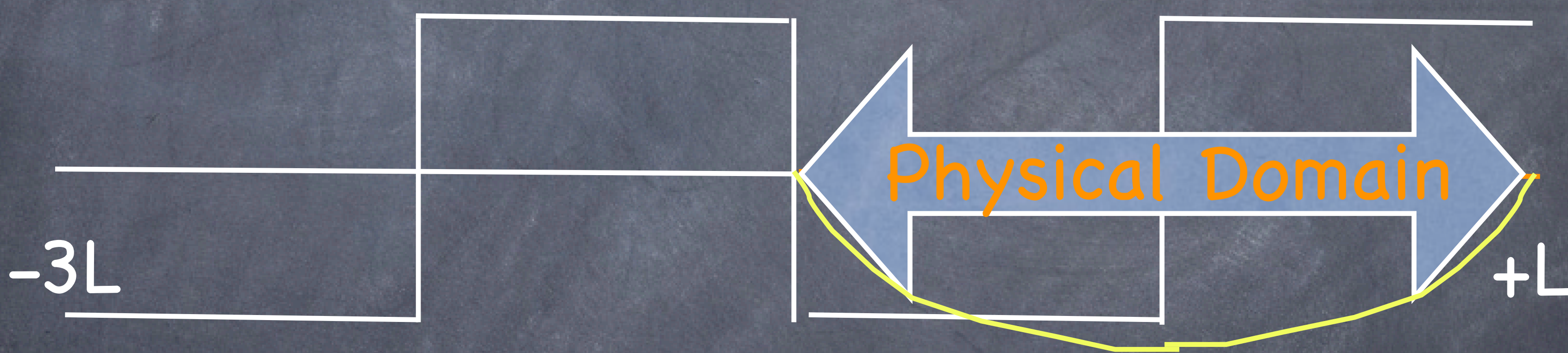


Can be embedded in $S^1/Z_2 X Z_2'$

Double kink-mass

$$m_n^2 = \mu^2 + k_n^2$$

$$S = \int d^5 \bar{\Psi} i \Gamma_M D^M \Psi - \lambda \Phi(y) \bar{\Psi} \Psi$$



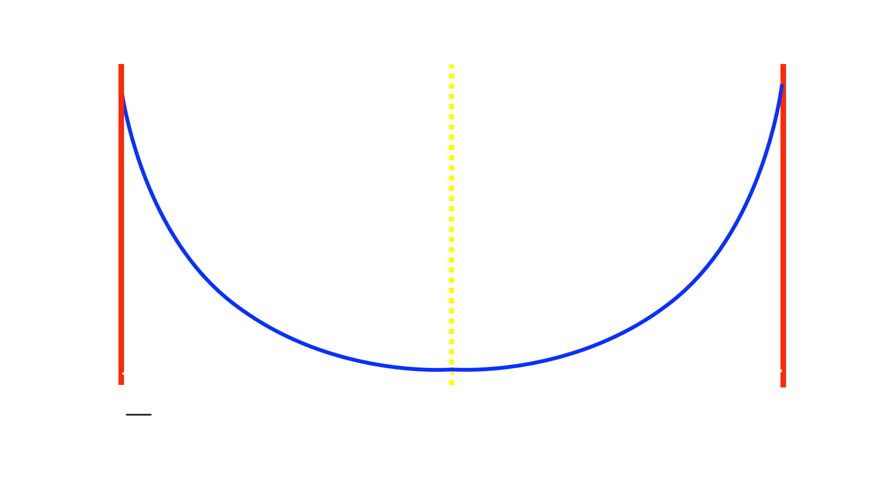
Zero-mode profile

$$\begin{aligned} f(y) &= e^{\int_{-L}^{y} m(y) dy} \\ &= e^{-m(y-L)} (y < 0) \\ &= e^{m(y+L)} (y > 0) \end{aligned}$$

KK-parity respected (good!)

An example of Split-UED

- Double Kink-mass for quarks introduced (1 new parameter)
- Quarks are quasi-localized on boundaries (split-wave function)
- KK parity respected
- KK quarks are heavier by 5D mass term (split-spectrum)



$$m_n^2 = \mu^2 + k_n^2$$

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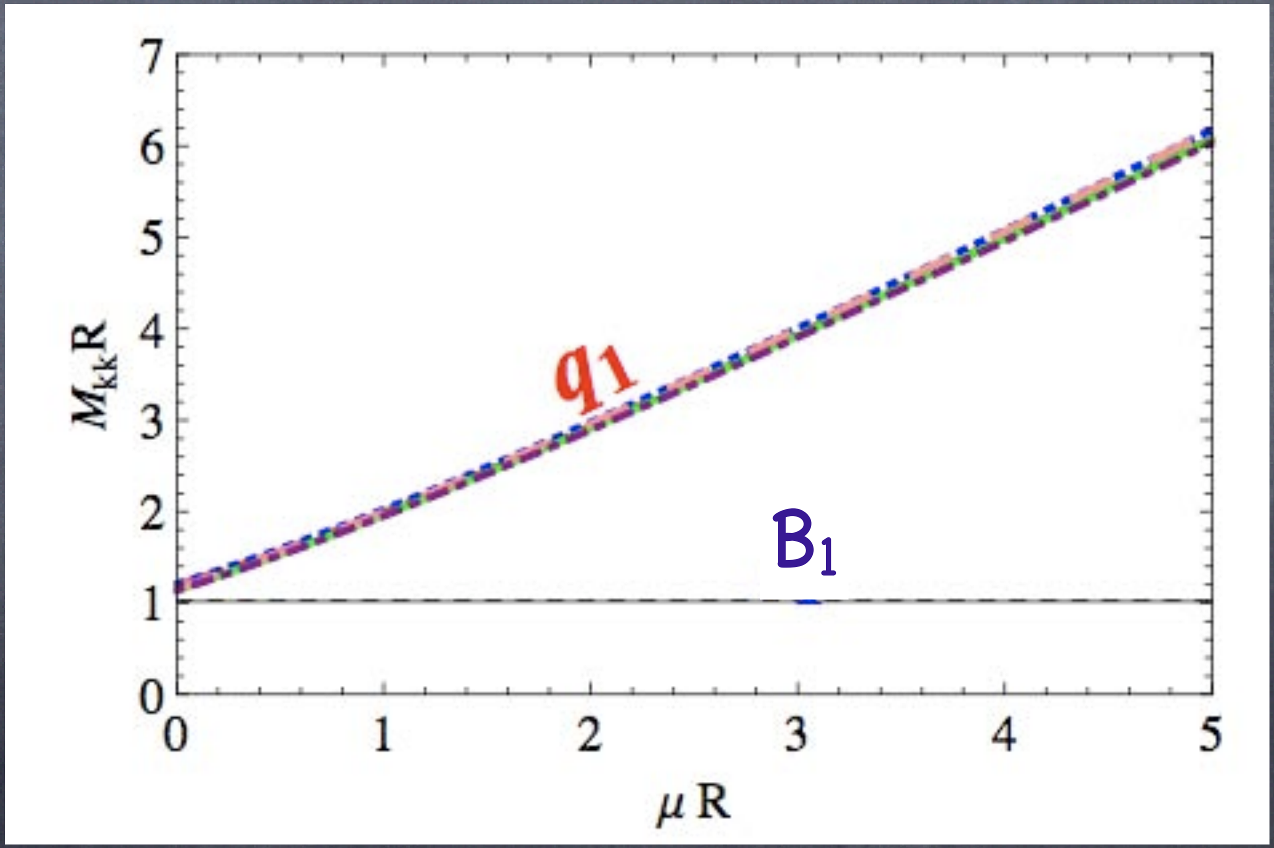
Mass spectrum in SUED

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



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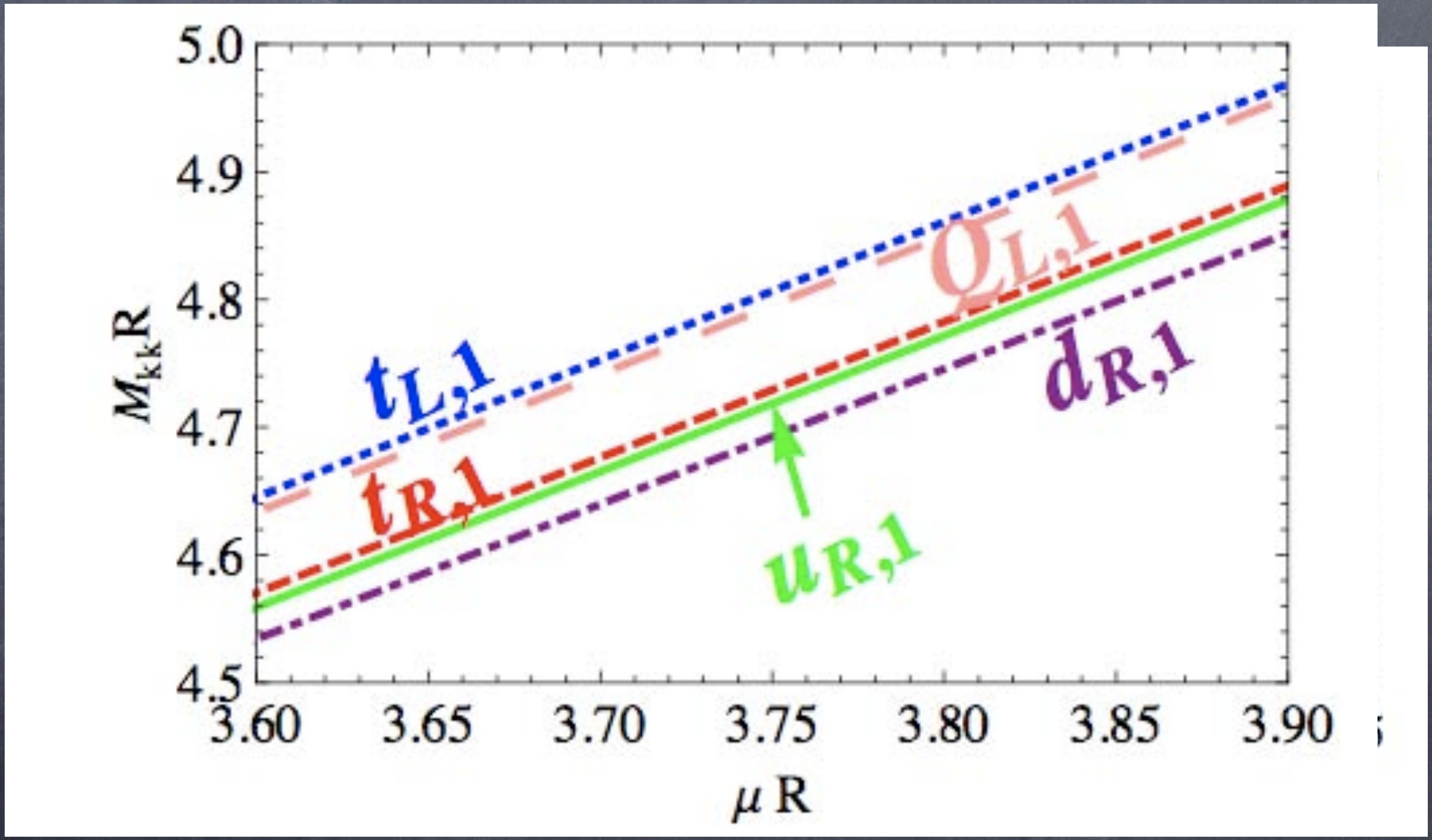
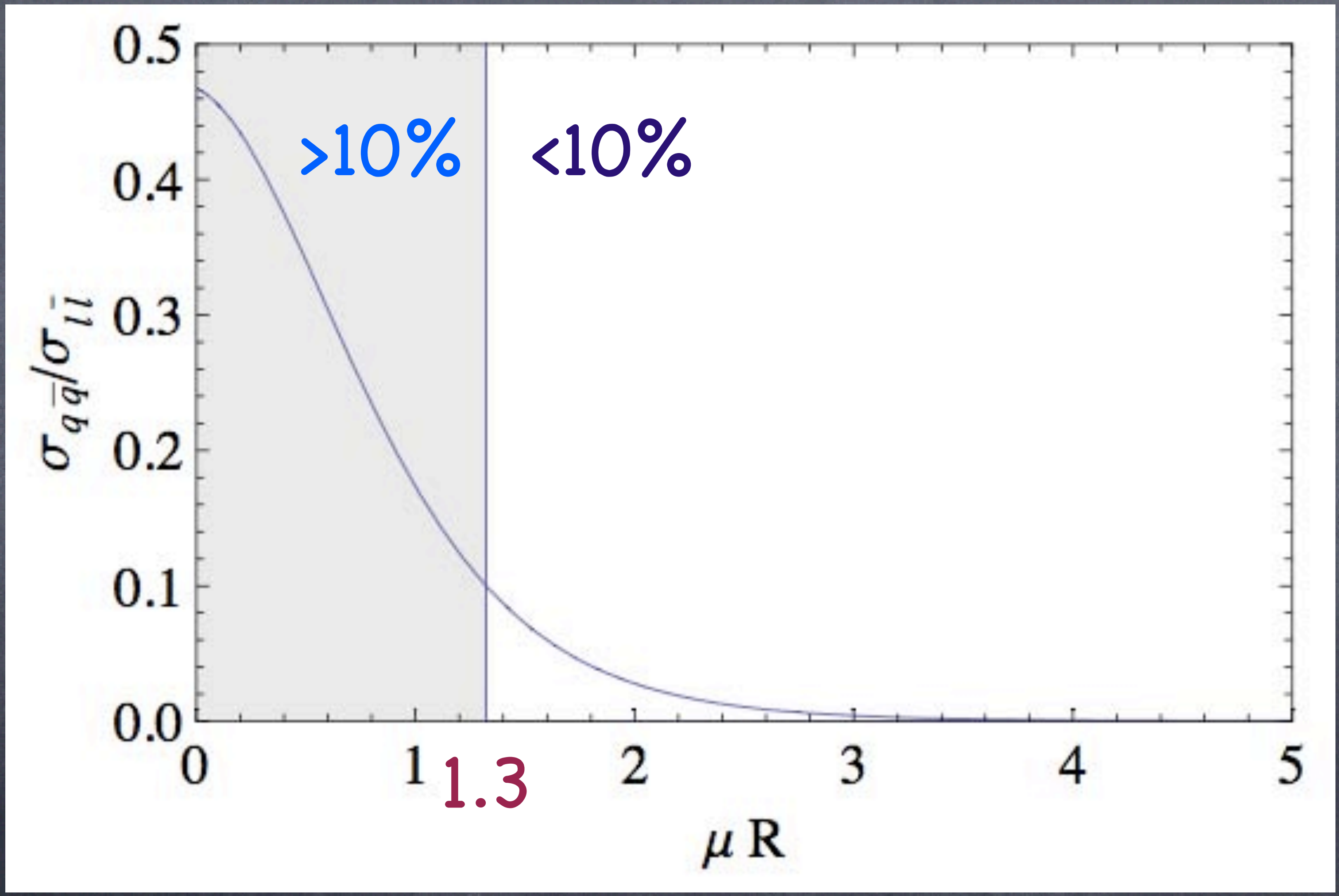


Branching Fraction

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



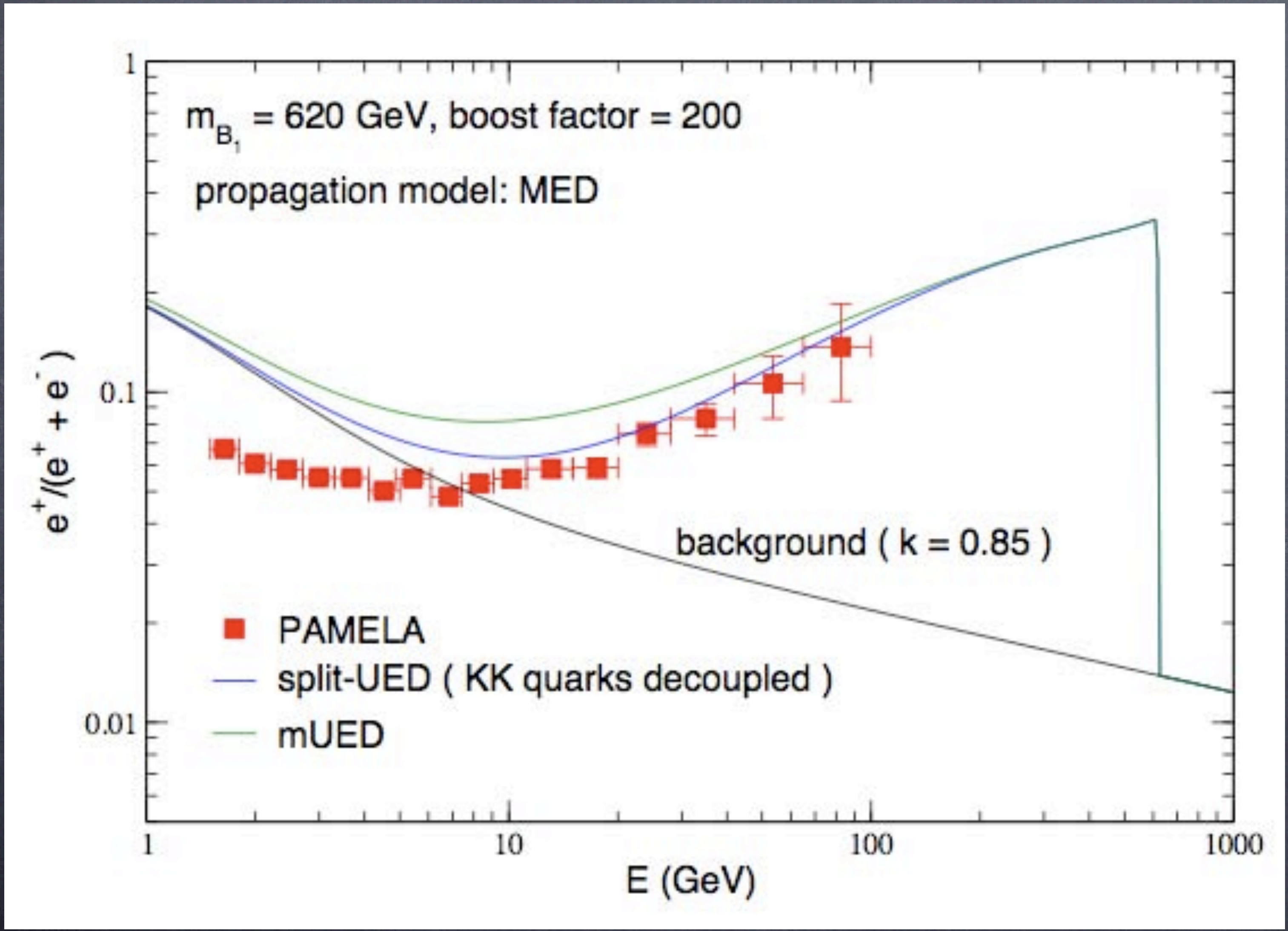
Branching Fraction

Chen, Nojiri, SCP, Shu, Takeuchi(2009)

μ (GeV)	0	200	400	600	800	1000
M_{q_1} (GeV)	713	863	1026	1198	1378	1566
BR($B_1 B_1 \to q\bar{q}$)	29.4%	26.4%	20.6%	14.3%	8.9%	5.2%
BR($B_1 B_1 \to l\bar{l}$)	64.3%	67.1%	72.3%	78.2%	83.0%	86.5%
BR($B_1 B_1 \to \nu\bar{\nu}$)	3.8%	3.9%	4.3%	4.6 %	4.9%	5.1%
BR($B_1 B_1 \to \phi\phi^*$)	2.3%	2.4%	2.6%	2.8%	3.0%	3.1%

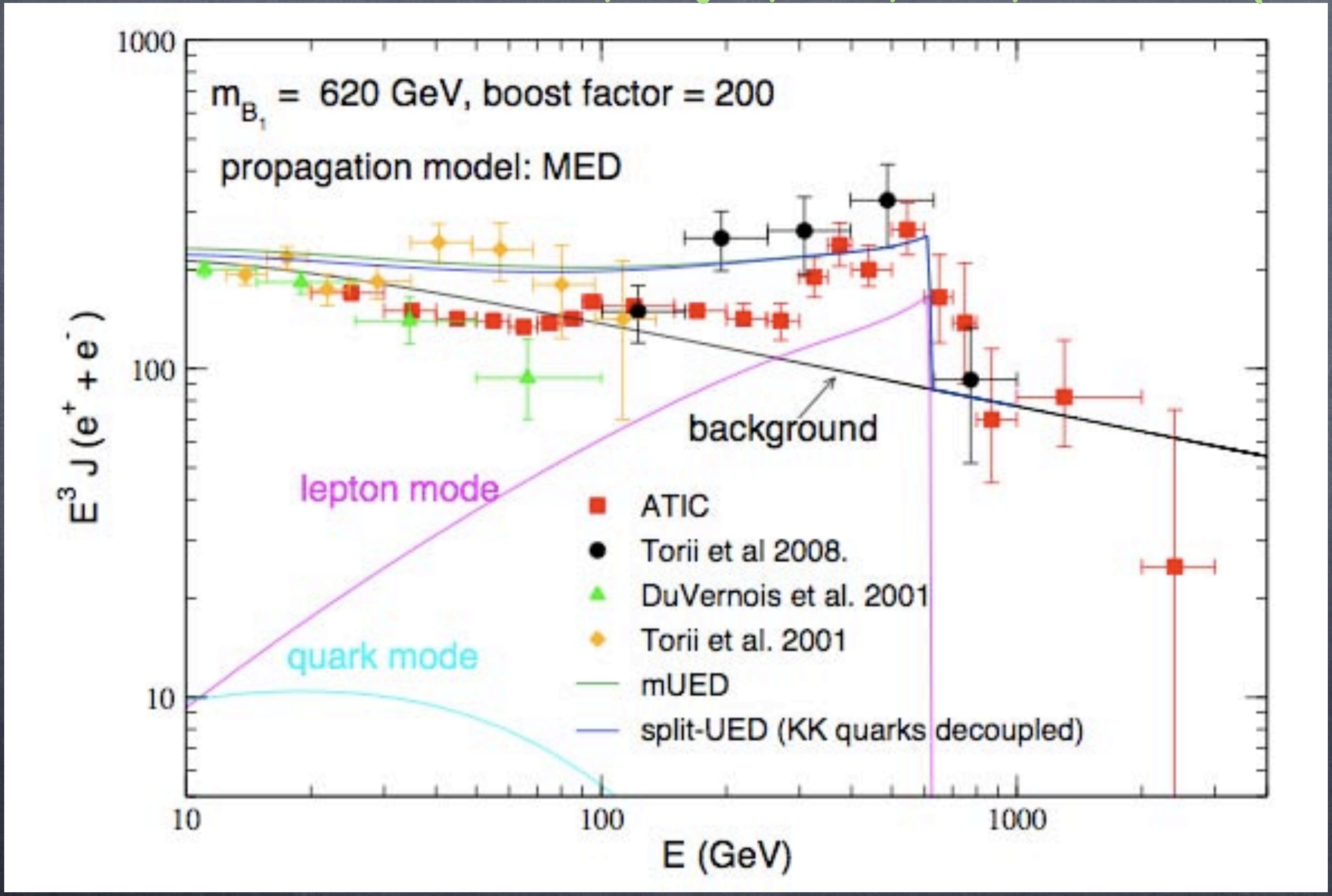
Fitting PAMELA

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



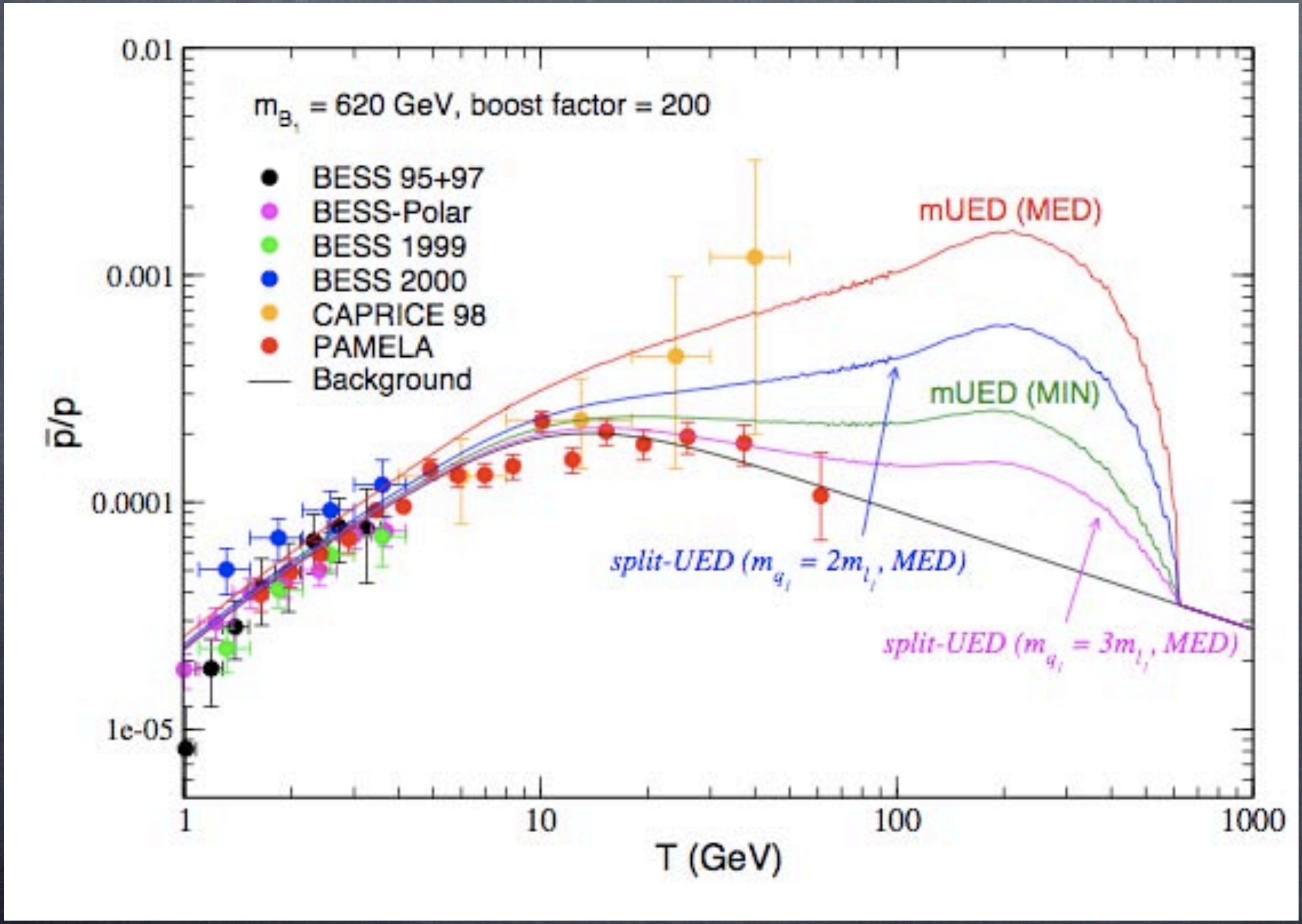
Fitting ATIC/PPB-BETS

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



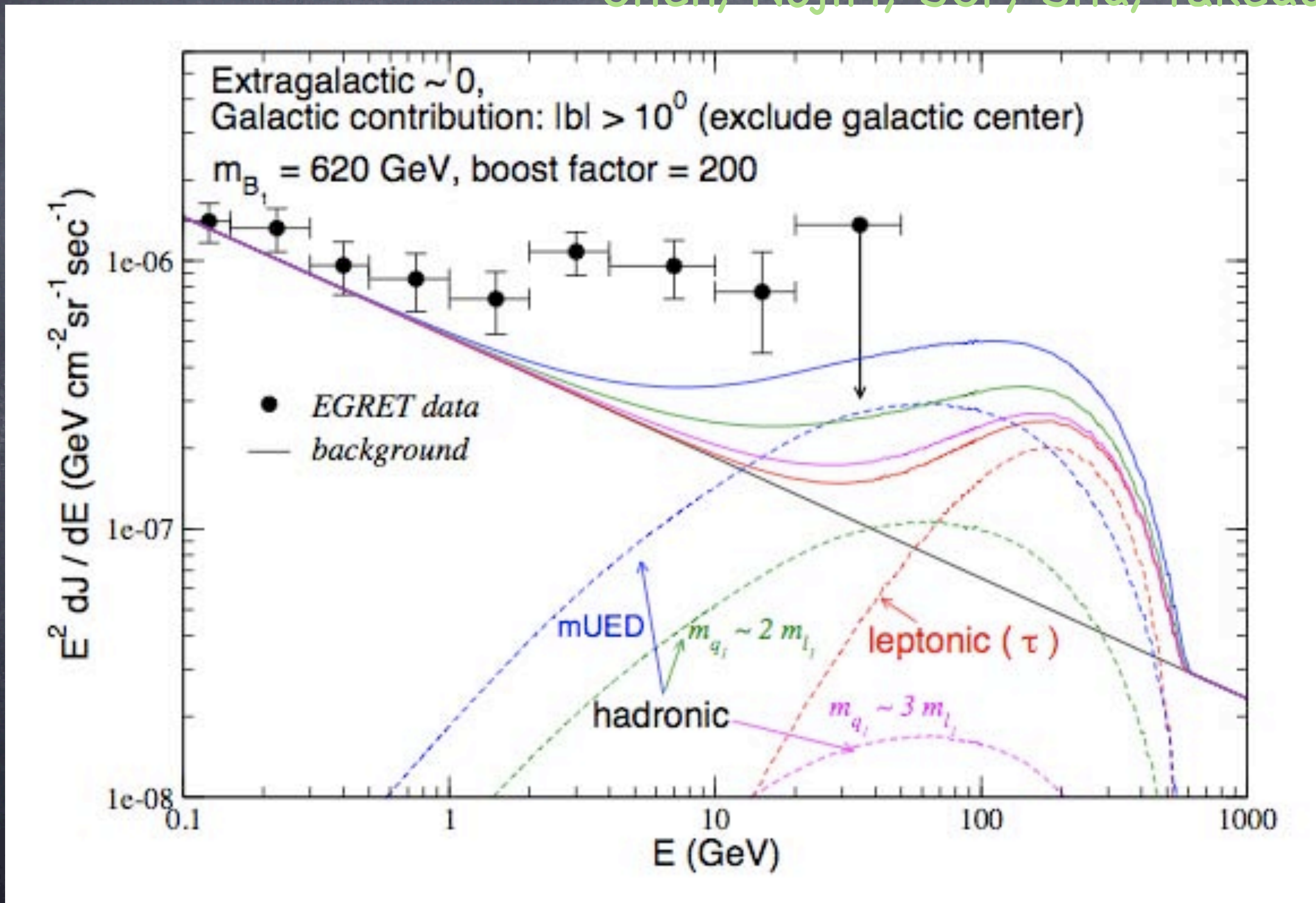
No Anti-proton excess

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



No gamma-excess in E<20 GeV

Chen, Nojiri, SCP, Shu, Takeuchi(2009)



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Brane Localized Kinetic term (BLKT)

- UED is an effective theory below a cut-off scale.
- NDA suggests:

$$\Lambda R \sim \frac{24\pi^3 R}{g_5^2} \sim \frac{24\pi^2}{g_4^2} \sim 100(?)$$

- One may include all terms at least Dim4 operators. BLKT can be included for consistency.

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The Action

Carena, Tait, Wagner(2002)

$$
\begin{aligned}
S &= \int d^5x\{-\frac{1}{4g_5^2}F^{MN}F_{MN} \\
&- \delta(x_5)\frac{r_a}{4g^2}F^{\mu\nu}F_{\mu\nu} - \delta(x_5-\pi R)\frac{r_b}{4g^2}F^{\mu\nu}F_{\mu\nu}\}
\end{aligned}
$$

For KK-parity conservation, we take

$$r_a = r_b = a$$

$a = g_5^2/g^2$

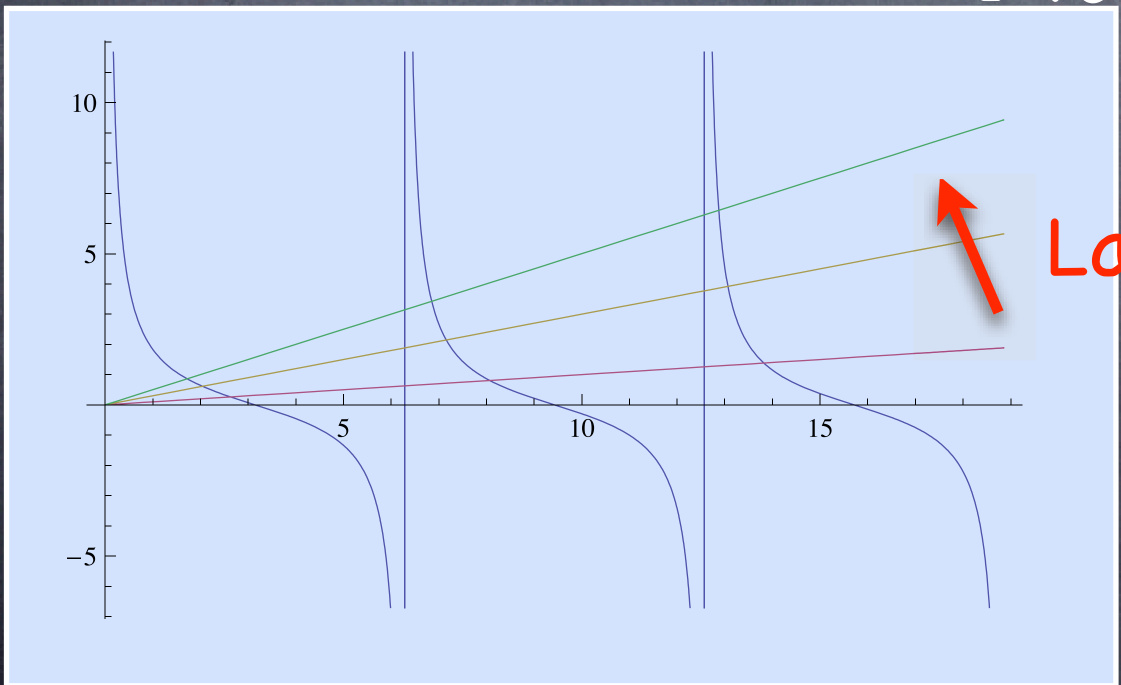
: dimension=length=1/energy

KK spectrum

Carena, Tait, Wagner(2002)
Flacke, Menon,Phalen(2009)

$$\frac{am_n}{2} = \frac{\cos(m_n\pi R) \pm 1}{\sin(m_n\pi R)}, \quad (m_0 = 0, m_n > 0)$$

+1 for odd KK modes
-1 for even KK modes

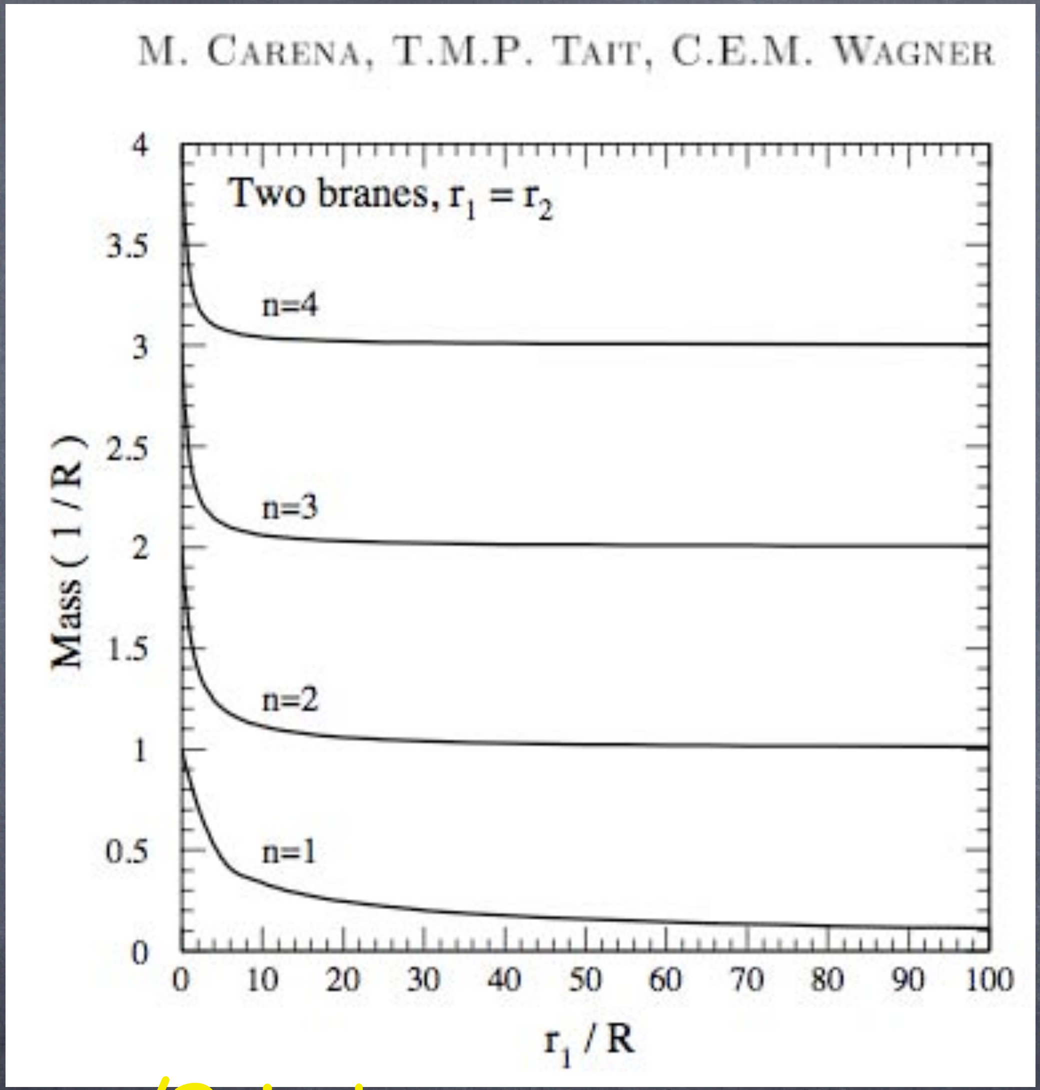


When a>>R,

$$m_1^2 \simeq \frac{4}{\pi a R}$$

mass Gap is ~1/R

KK spectrum with BLKT



As a/R is larger,
KK mass is smaller
(goes arbitrarily small!)

$$m_1^2 \simeq \frac{4}{\pi a R}$$

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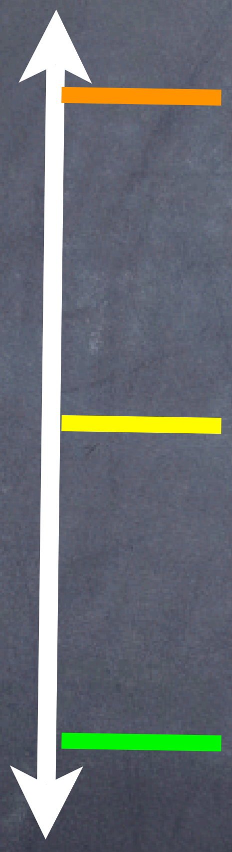
Taking (Bulk Mass+BLKT), we can get the split-spectrum



$$m_{q_1} = \sqrt{m_5^2 + k_n^2}$$

Large M_5==> Heavy fermions

(assuming BLKT for fermion is small)

1/R

$$m_{B_1} \simeq \frac{2}{\sqrt{\pi a R}}$$

0

Large a==> Light gauge bosons

Interesting examples

(1)M_{B1}=600 GeV, M_{q1}=1300 GeV
==>fits PAMELA, ATIC/PPB-BETS,Fermi gamma-ray (with BF=200)
(2)M_{B1}=200GeV, M_{q1}>M_{l1}=1.2 TeV, 1/R=1TeV
==>fits PAMELA (with BF<<100)
(but cannot fit ATIC/PPB-BETS, Fermi??)

More dramatic examples

(1) M_{B1}=500 GeV, 1/R>10 TeV

==> Only light DM particle at the LHC

(2) Mg1=800 GeV, 1/R>1000 TeV

==>Long lived KK gluon

Extreme case: Remnant of Decoupled Extra dimension

M_{B1}=1 TeV, 1/R=M_{GUT}, a/R=M_{GUT}/TeV

(NB) NDA suggests:

Carena, Tait, Wagner (2002)

$$\frac{a}{R} \sim \frac{6\pi}{\Lambda R},$$
$$\Lambda R \sim \frac{24\pi^3 R}{g_5^2} \sim \frac{24\pi^2}{g_4^2},$$

Thus $\frac{a}{R} \sim \frac{g_4^2}{4\pi} \sim 1$

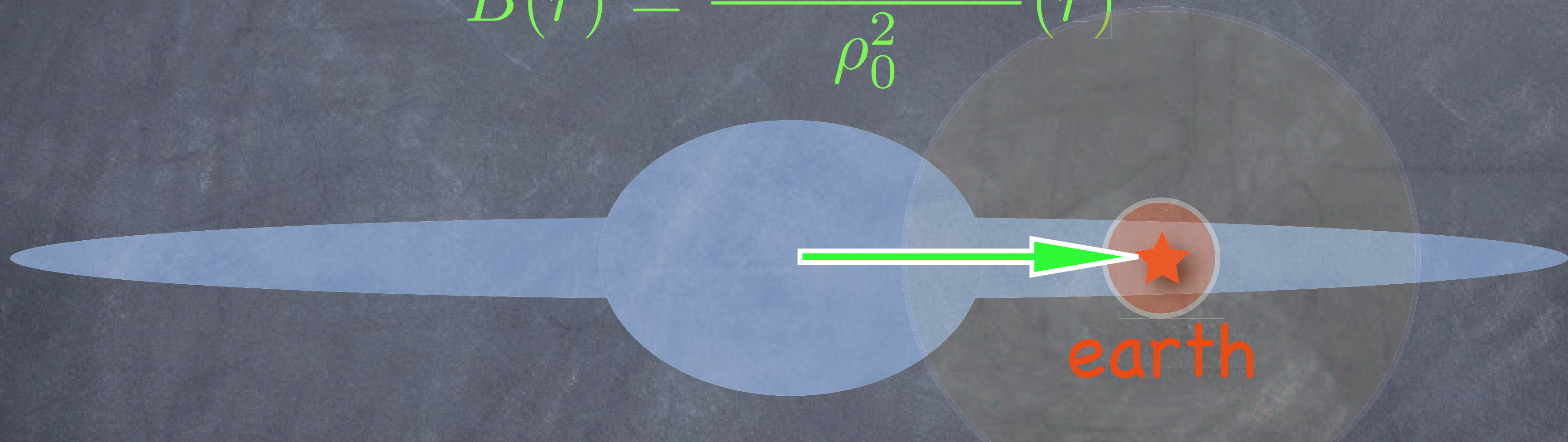
This extreme case is unnatural (but allowed anyway.)

Summary

- UED with KK-parity is an interesting model of dark matter.
- KK spectrum is controlled by (1/R, m5, a) keeping KK-parity intact.
- PAMELA, ATC/PPB-BETS might be solved by KK dark matter with split-spectrum. We can enjoy the rich phenomenology.

Local Boost factor

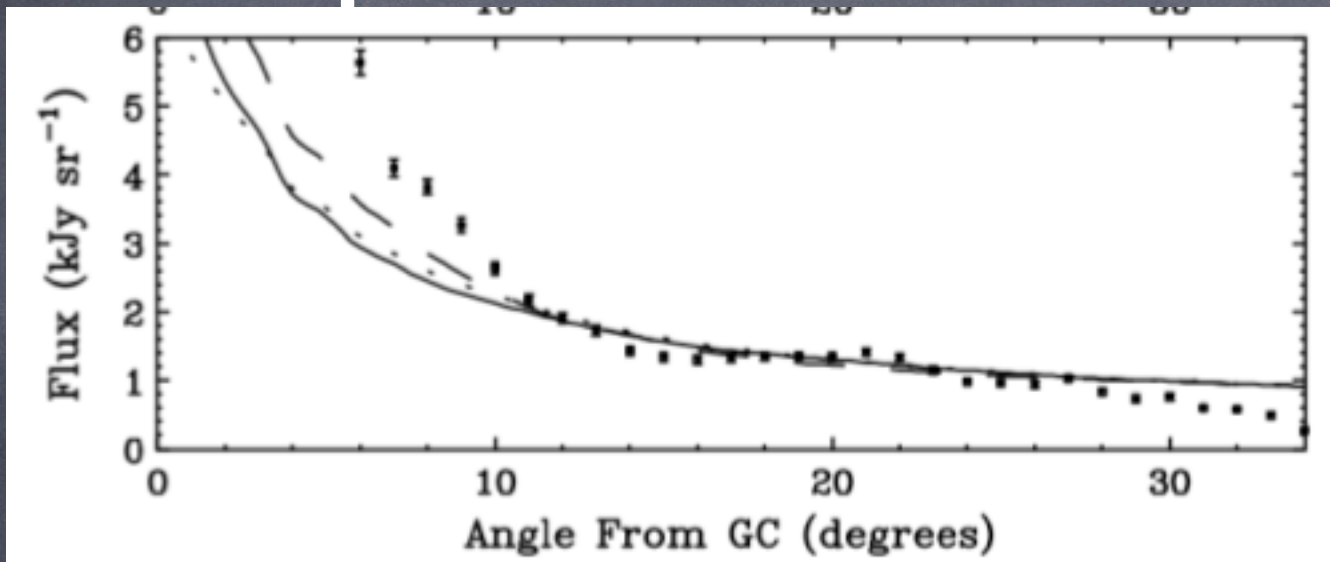
$$B(\vec{r}) = \frac{(\rho_0 + \delta\rho)^2}{\rho_0^2}(\vec{r})$$

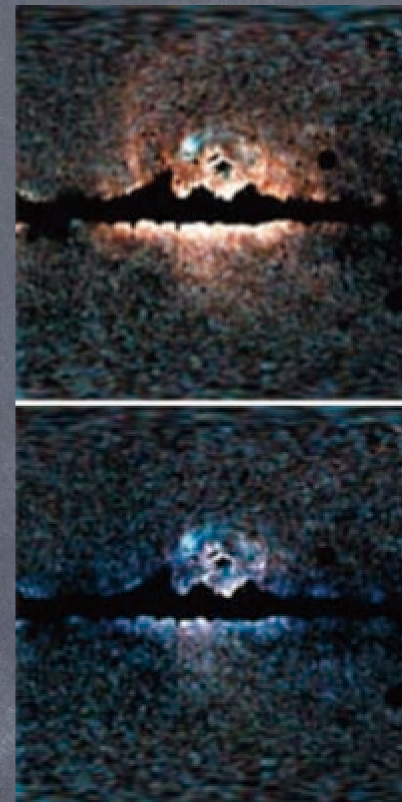


$B_{center} < B_{earth} < B_{far}$

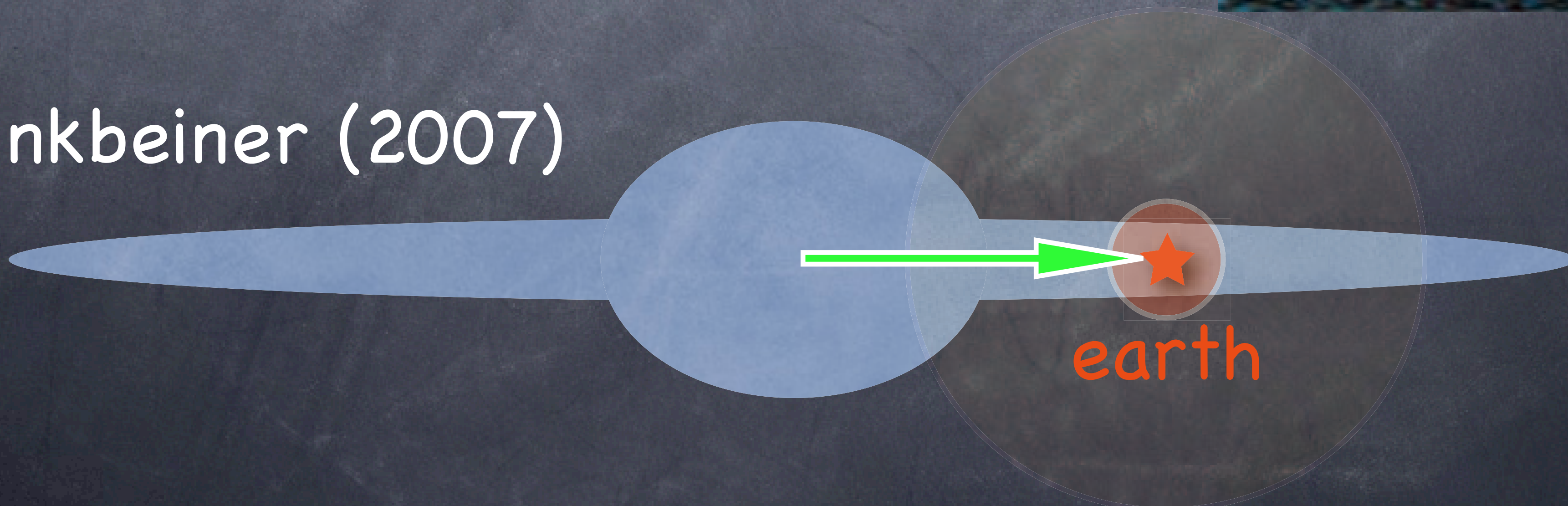
- Positron mostly from "local" source
- Antiproton diffuses longer
- Photon goes straight (mostly from the center)
- B(photon) < B(p-) < B(e+)

WMAP Haze: photon from GC



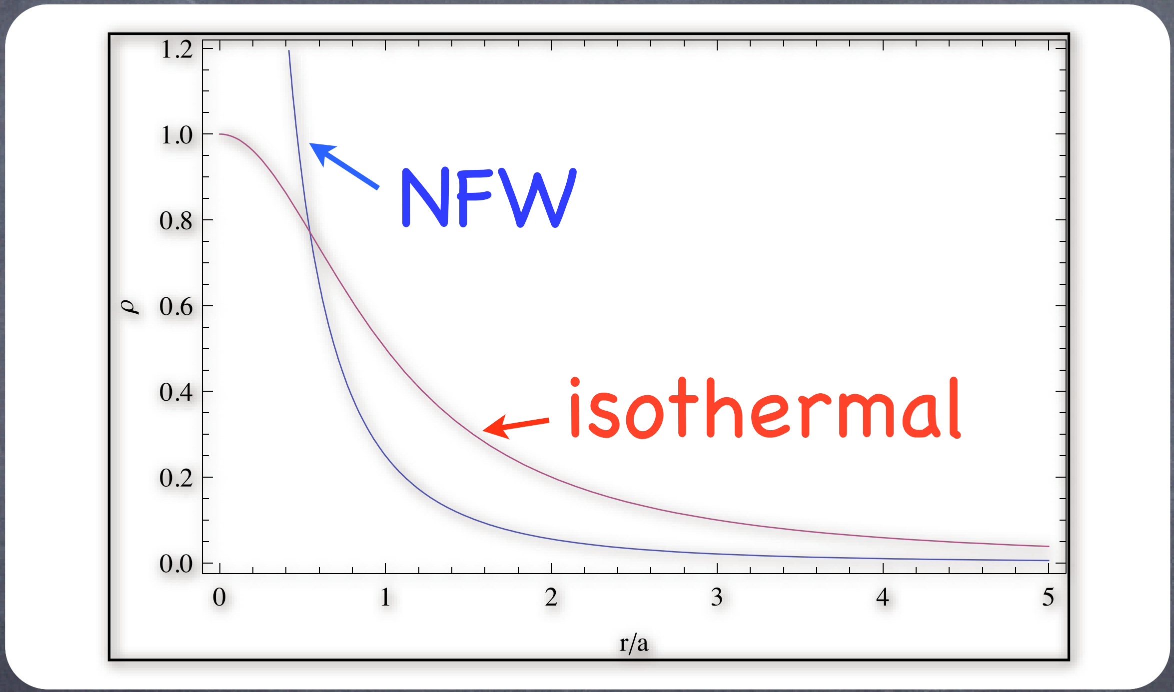


Finkbeiner (2007)



Halo profile

$$\rho(r) = \frac{\rho_0}{(r/a)^\gamma [1 + (r/a)^\alpha]^{(\beta-\gamma)/\alpha}}$$



Profile	alpha	beta	gamma
NFW	1	3	1
Isothermal	2	2	0

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