Astrophysical implications of a visible dark matter sector from a custodially warped GUT

Can we find a well motivated DM model with no dark sector and with more robust CR signals?

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Outline

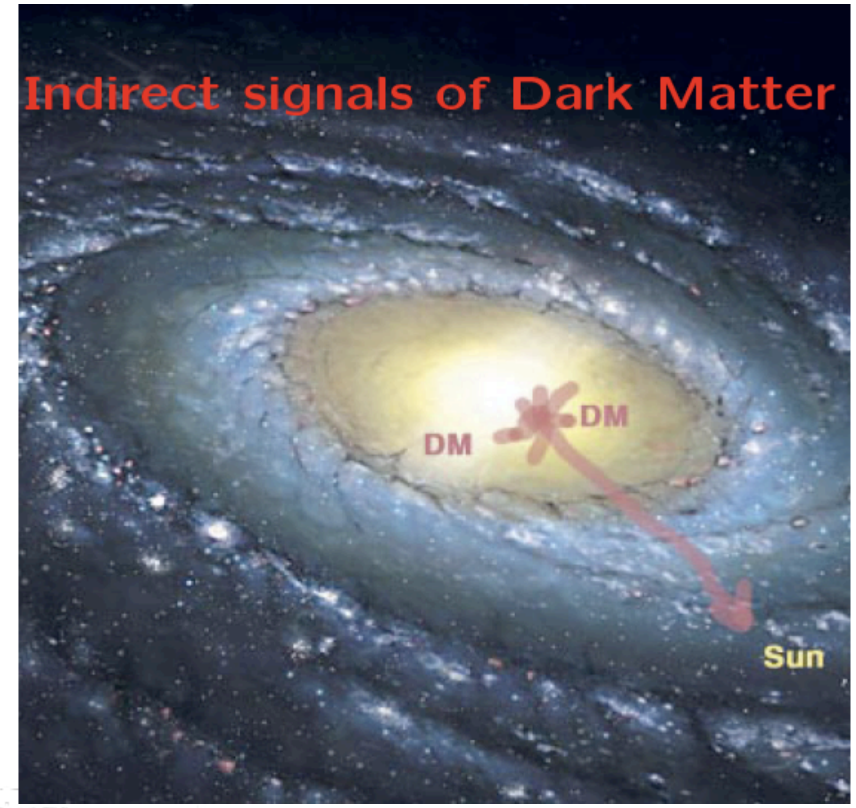
- Intro: the model aspect: RS- address hierarchy, nice flavor; GUT => Proton stability (gauged B) => Stable DM.

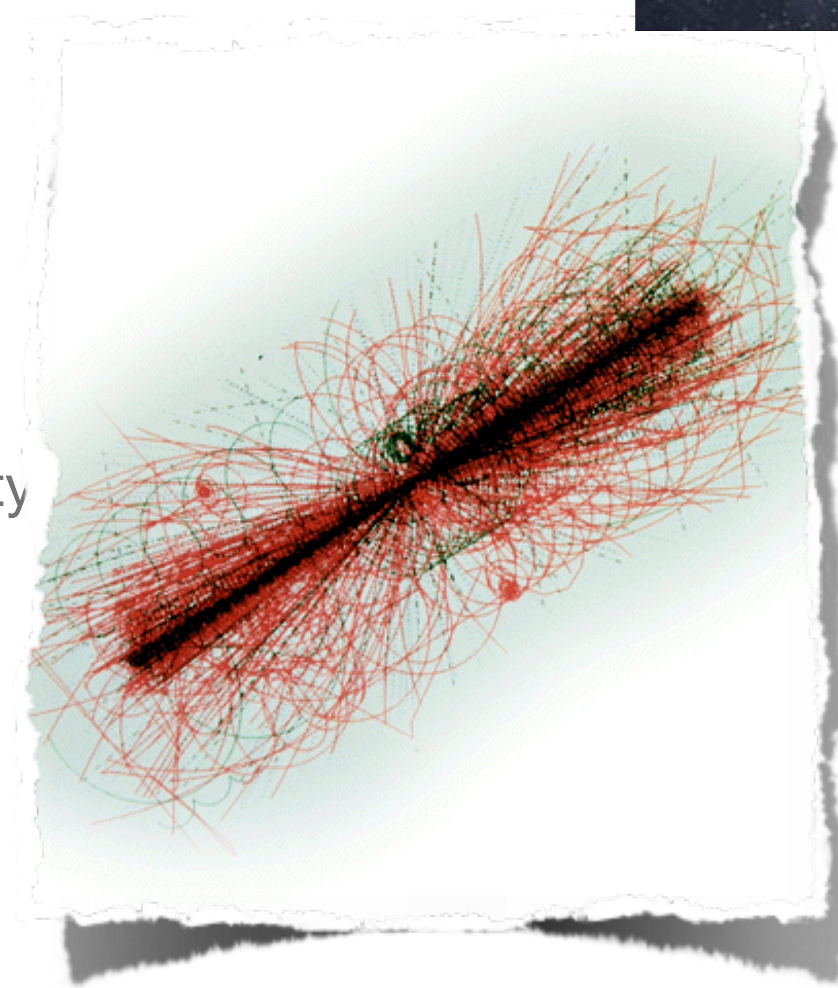
- Need to embed custodial $Z\bar{b}b$ symmetry into GUT

- Light Radion (~100 GeV) => Sommerfeld Enhancement (no dark sector)

- Signature of the model
  1) Signals in GCR
  (also constraints from Relic Density & Direct Detection)
  2) Signals @ LHC

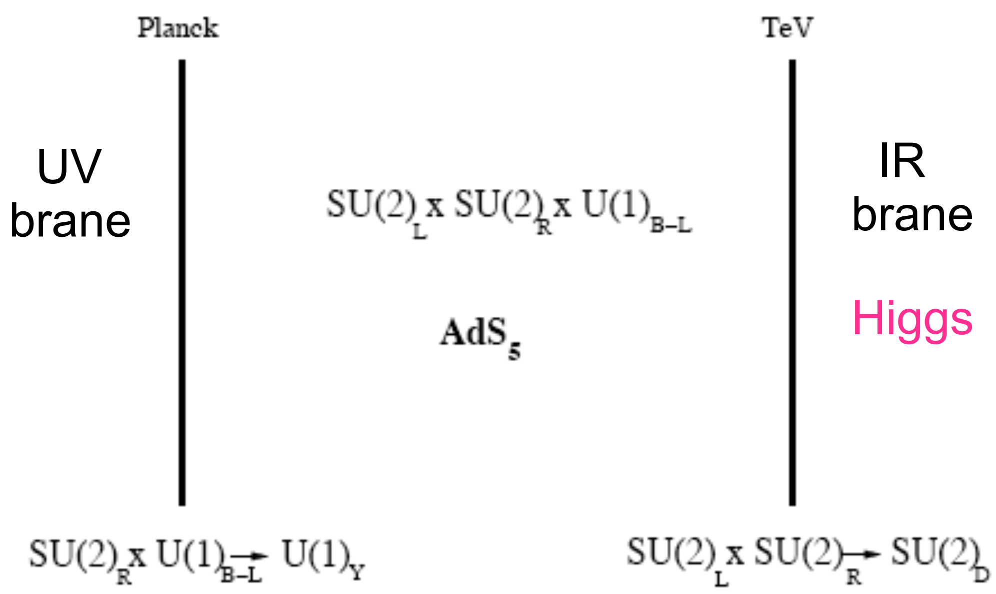
- Summary





Intro: realistic RS scenario with SM in the bulk

- Realistic EWSB model with fermions and gauge bosons in the bulk, incorporating custodial SU(2) symmetry   Agashe, Delgado, May and Sundrum

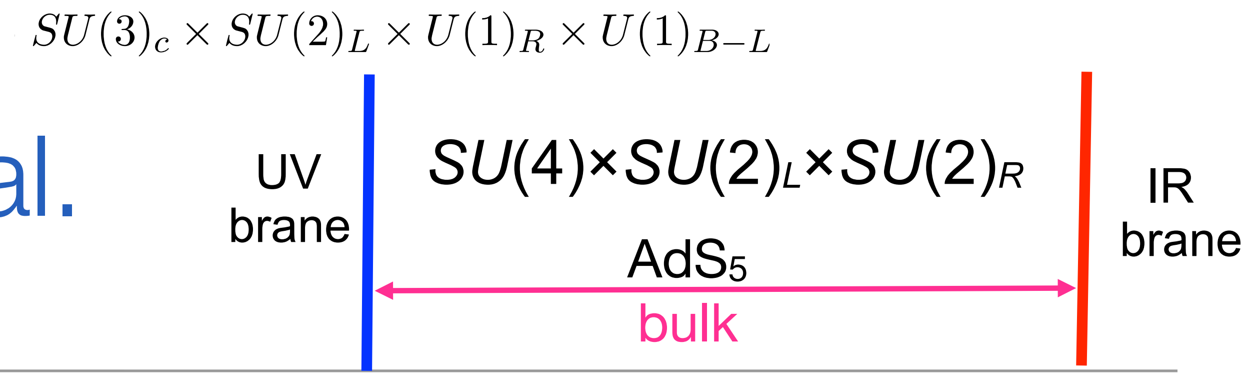


- Needs $U(1)_B$ symmetry gauged in the bulk to suppress proton decay, which need to be broken at the UV brane (For RSGUT, broken to Z_3 => DM)   Agashe and Servant

- AShift in $Zb\bar{b}$ is larger than that allowed by EWPT for KK scale lower than 5 TeV: custodial symmetry to protect a shift in $Zb\bar{b}$ is needed   Agashe, Contino, Da Rold and Pomarol

    - Not clear how to unify it

Pati-Salam+custodial.



Warm up; canonical representation (no custodial)

breaking pattern: $SU(4)_c \times SU(2)_R \to SU(3)_c \times U(1)_Y$ (on the UV)

$$Y = T_{3R} - \sqrt{2/3}X \qquad X = \mathrm{diag}\sqrt{3/8}\,(-1/3, -1/3, -1/3, 1) \qquad \mathrm{Tr}X^2 = 1/2.$$

X are the charges under the non-QCD U(1) generator present in SU(4)

The combination of T_{3R} and X which is orthogonal to hypercharge will be denoted by Z'.

	$SU(4)_c \sim SU(3)_C \times U(1)_X$	$SU(2)_L$	$SU(2)_R$
LH	$\mathbf{4} \sim \mathbf{3}_{-\frac{1}{3}} + \mathbf{1}_1$	$\mathbf{2}$	$\mathbf{1}$
RH	$\mathbf{4} \sim \mathbf{3}_{-\frac{1}{3}} + \mathbf{1}_1$	$\mathbf{1}$	$\mathbf{2}$
H	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$

Agashe and Servant

$SU(2)_L$ doublet fermions: $T^3_R = 0$ and $T^3_L = \pm 1/2$; RH fermions: $T^3_R = \pm 1/2$ and $T^3_L = 0$

simplest full unification model

$$SO(10) \supset SU(4) \times SU(2)_L \times SU(2)_R$$

$$Y = T_{3R} - \sqrt{\frac{2}{3}} X$$

the hypercharge normalization is the same as that of SU(5) -> maintain at least SM level of coupling unification when fully unified into SO(10)

	$SU(4)_c \sim SU(3)_C \times U(1)_X$	$SU(2)_L$	$SU(2)_R$
t_R, ν'	$\mathbf{15} \sim \mathbf{3}_{\frac{-4}{3}}, \mathbf{1}_0 \ldots$	$\mathbf{1}$	$\mathbf{1}$
$(t,b)_L$	$\mathbf{15} \sim \mathbf{3}_{\frac{-4}{3}}, \ldots$	$\mathbf{2}$	$\mathbf{2}$
τ_R	$\mathbf{4} \sim \mathbf{1}_1, \ldots$	$\mathbf{1}$	$\mathbf{2}$
$(\nu,\tau)_L$	$\mathbf{4} \sim \mathbf{1}_1, \ldots$	$\mathbf{2}$	$\mathbf{1}$
b_R	$\mathbf{15} \sim \mathbf{3}_{\frac{-4}{3}}, \ldots$	$\mathbf{1}$	$\mathbf{3}$
H	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$

DM has vanishing coupling to Z’

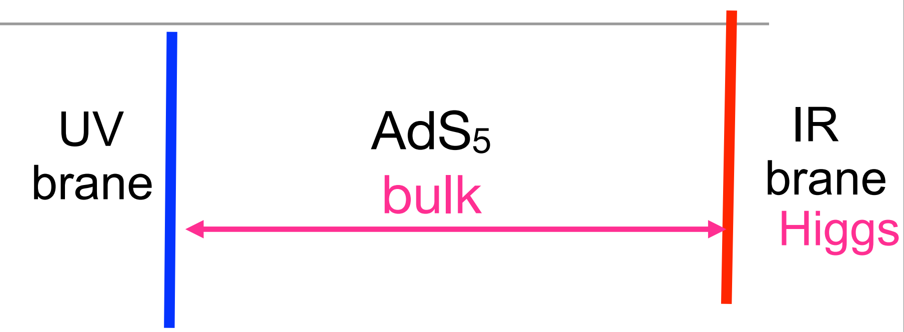
Protection for Z to τ_R pair is also possible

Particle contents relevant for DM (in-)direct detection

SM	t_R, $(t,b)_L$, τ_R, μ_R, W, Z, h

Non-SM	Comments (quantum numbers)
ν'	DM: exotic RH ν (SM singlet) with $B = 1/3$
ϕ	radion (scalar with Higgs-like coupling to SM)
Z'	extra/non-SM $U(1)$ in GUT
X_s	leptoquark GUT gauge boson

Light Radion and Sommerfeld Enhancement

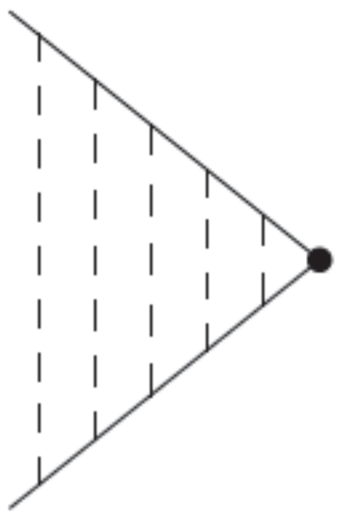


- Radion mode - fluctuation in the distance of two branes
    - Radius must be stabilized (Symmetry of AdS space needs to be broken)
        - Radion interaction to the matter field is proportional to 5D energy momentum tensor

$$\boxed{\frac{r}{\Lambda_r} m_f \bar{f} f}$$

Light Radion and Sommerfeld Enhancement

- Naively, a pseudo-scalar with a goldstone like derivative coupling to matter cannot be a light force carrier:
    - it leads to spin-dependent potential, which vanishes when averaged over angles ⇒ no long range interaction with s-wave ⇒ no SE
- Radion is an exception, since it's a pseudo-scalar from spontaneous symmetry breaking of space-time symmetry



$$\left[\frac{d^2}{dx^2} + \frac{e^{-\epsilon_\phi x}}{x} + \epsilon_v^2\right]\chi(x) = 0\ , \quad \epsilon_v = \frac{v}{\alpha}\ , \quad \epsilon_\phi = \frac{m_\phi}{\alpha M}\ , \quad \alpha = \frac{\lambda^2}{4\pi}$$

$$\lambda = \frac{M_{DM}}{\Lambda_r} = O(1) \qquad SE = \left|\frac{\frac{d\chi}{dx}(x \to 0)}{\epsilon_v}\right|^2$$

Light Radion and Sommerfeld Enhancement

Based on AdS/CFT correspondence, this nice feature of the radion as a mediator of SE is dual to light dilaton exchange in 4D CFT (see Rattazzi's tlak)

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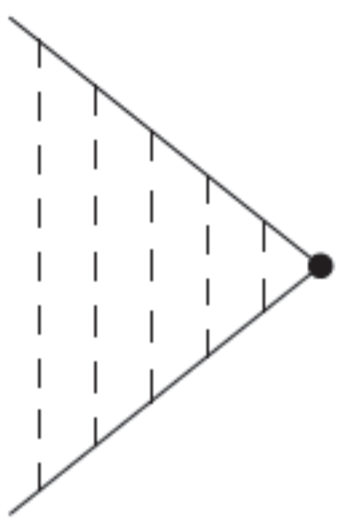

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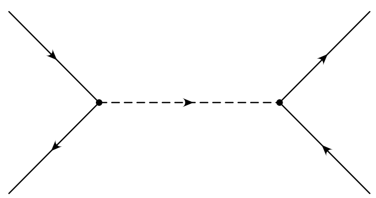
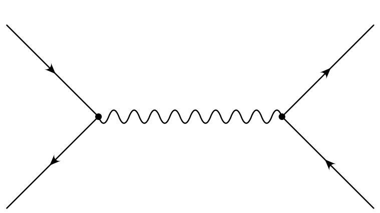
Light Radion, SE and Direct Detection

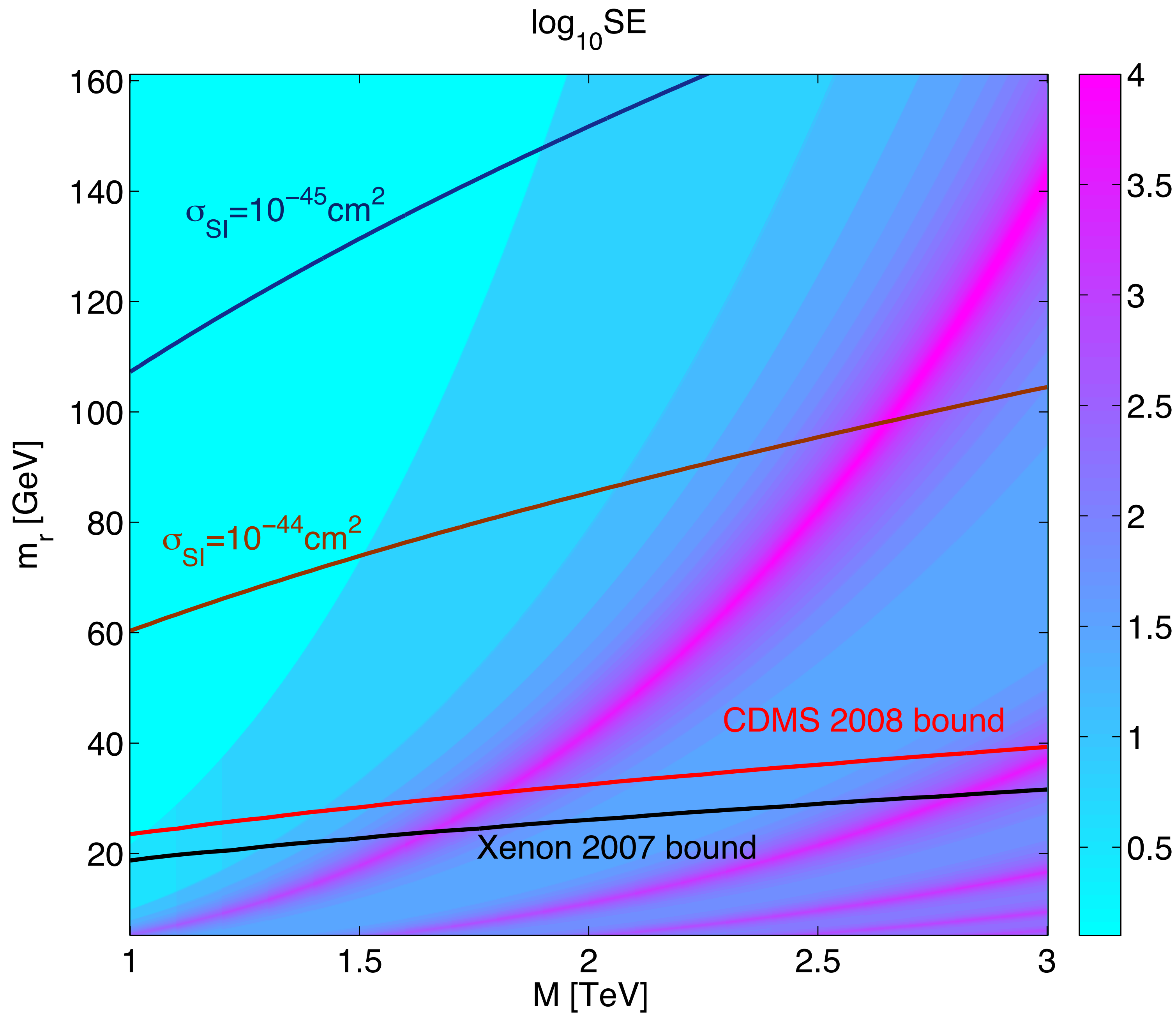
- For small radion mass (below 50 GeV), direct detection is dominated by t-channel radion exchange



$$\boxed{\sigma\left(\nu' N \to \nu' N\right) \propto \frac{M_{\nu'}^2 m_N^4}{\Lambda_r^4 m_r^4}.}$$

- (For very heavy radion, Z-mediated through mixing of Z'-Z becomes more important, if DM-nu' coupling is non-vanishing)

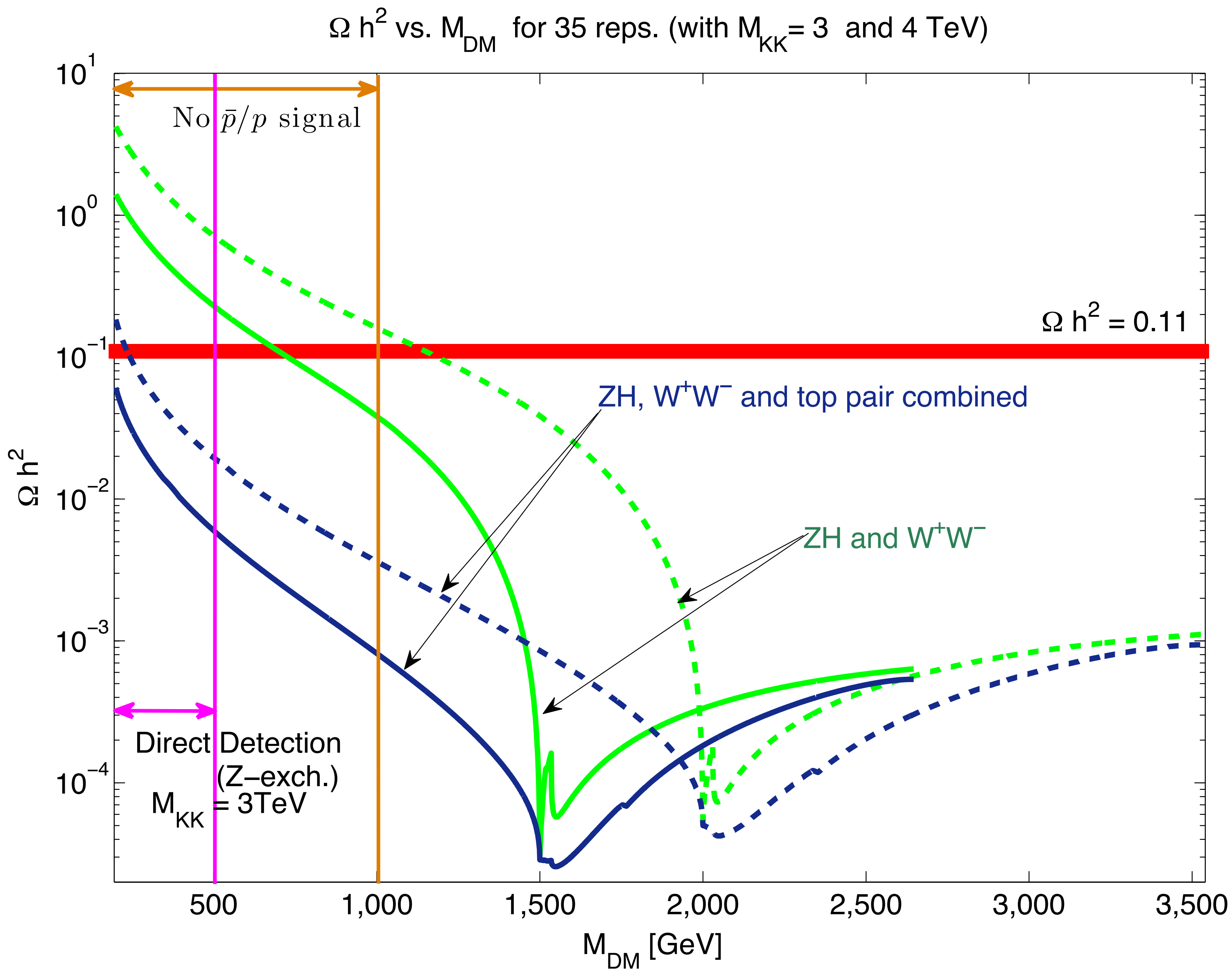




evts in DD experiment ~ n x sigma ~ sigma / M

Relic density constraint- case for non-vanishing DM-Z′ coupling (sizable leptonic BR)

- DM abundance is correlated with the DM-Z′ coupling size, in particular whether $T_{3R}^{V'}$ vanishes or not



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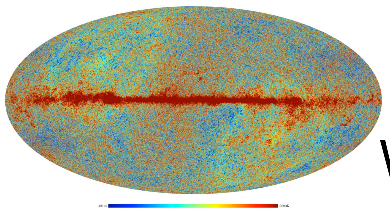
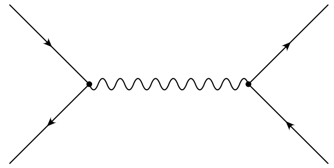
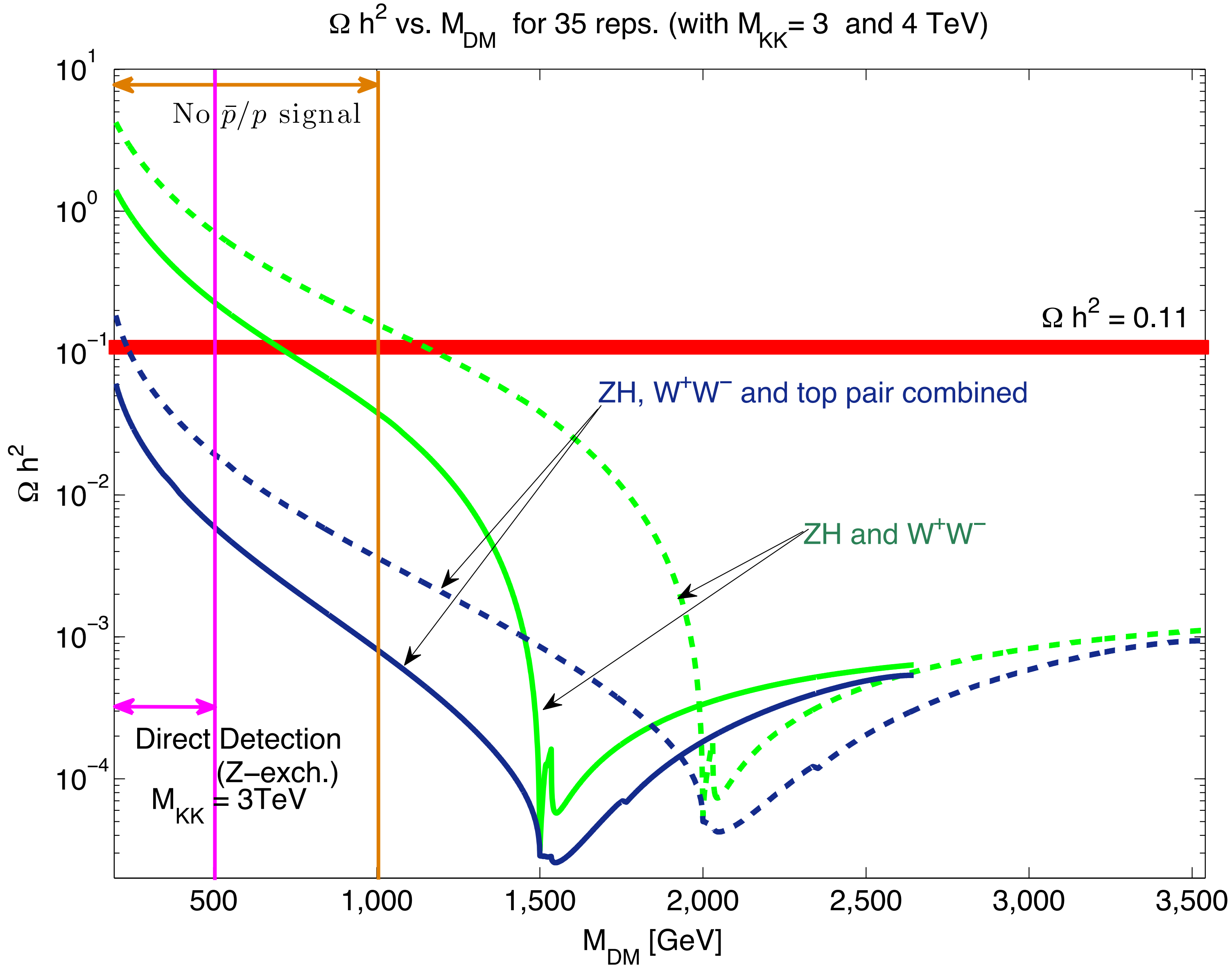


Implies velocity-weighted annihilation cross section at cosmological era

$$\langle \sigma v \rangle \sim \text{few } 10^{-26}\ \text{cm}^3\,\text{s}^{-1}$$





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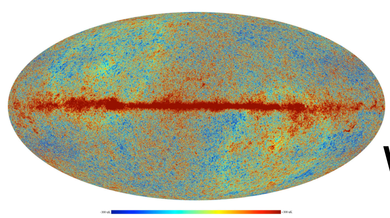

WMAP

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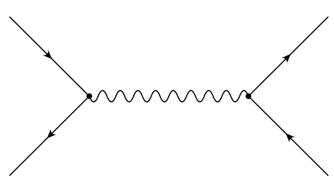

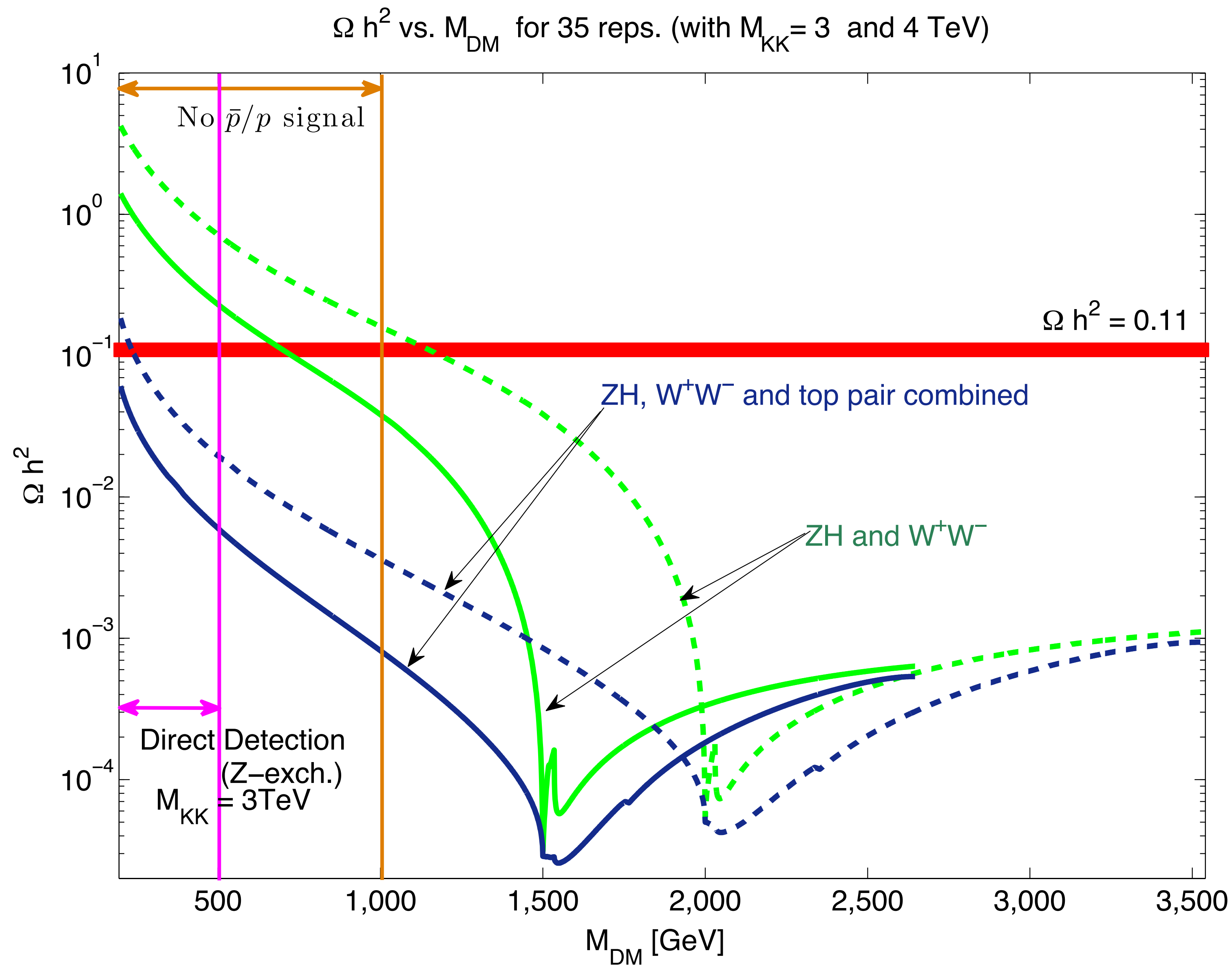

resulting relic abundance is too low unless the DM mass is ultra light (tension with direct detection experiments)

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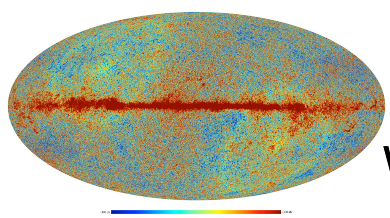

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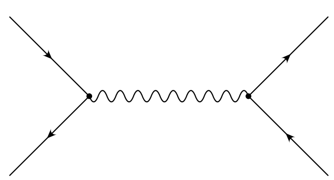
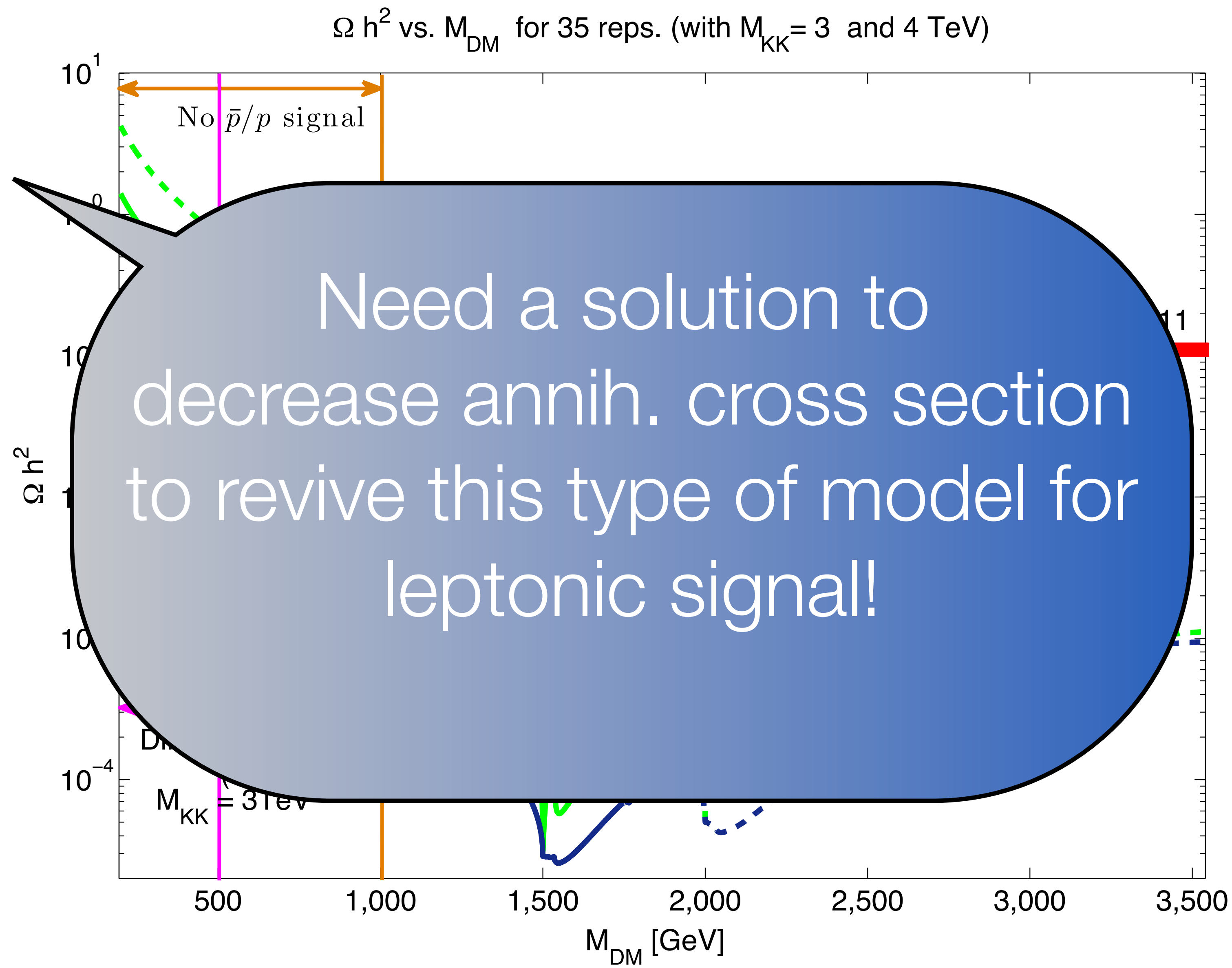




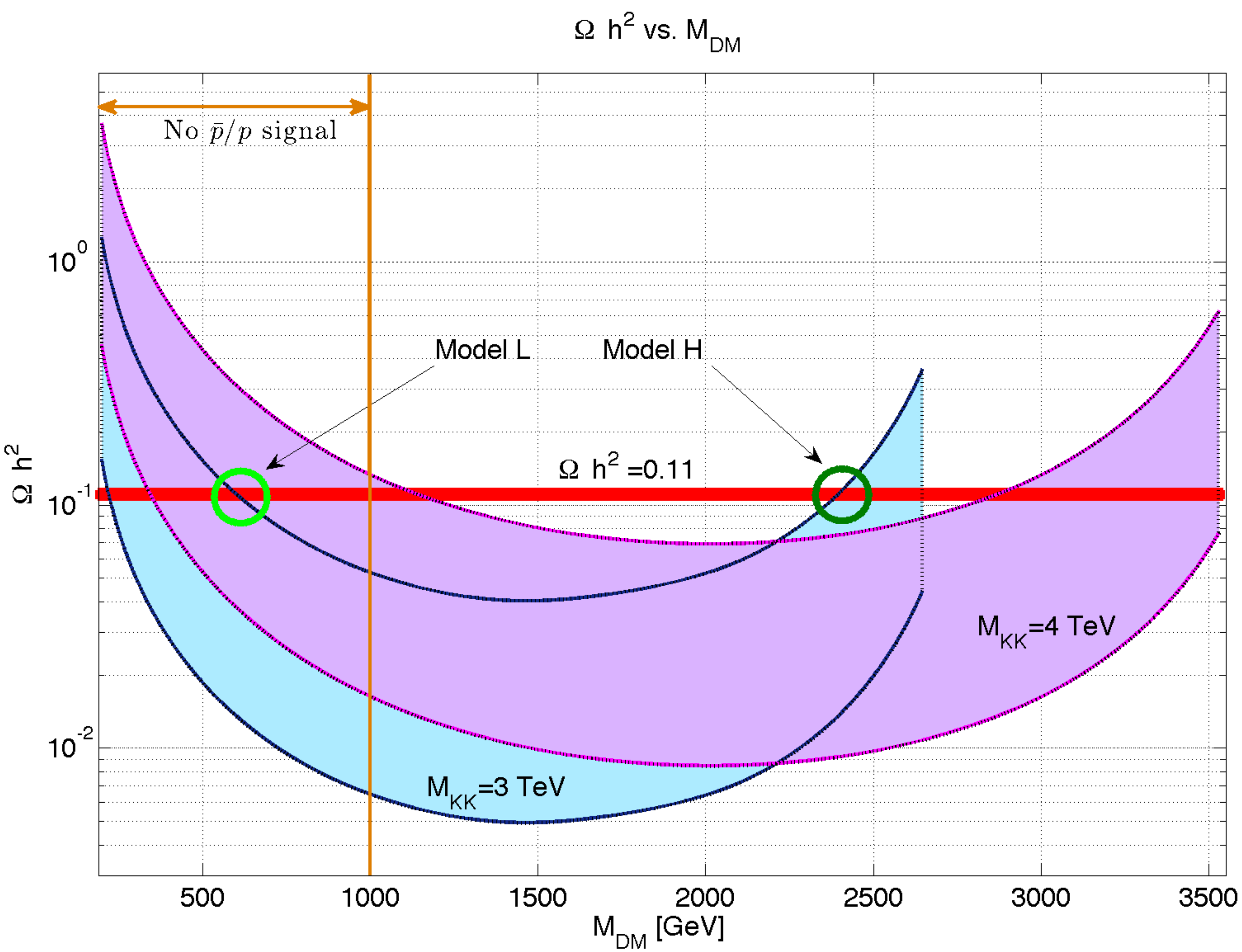
Need a solution to decrease annih. cross section to revive this type of model for leptonic signal!

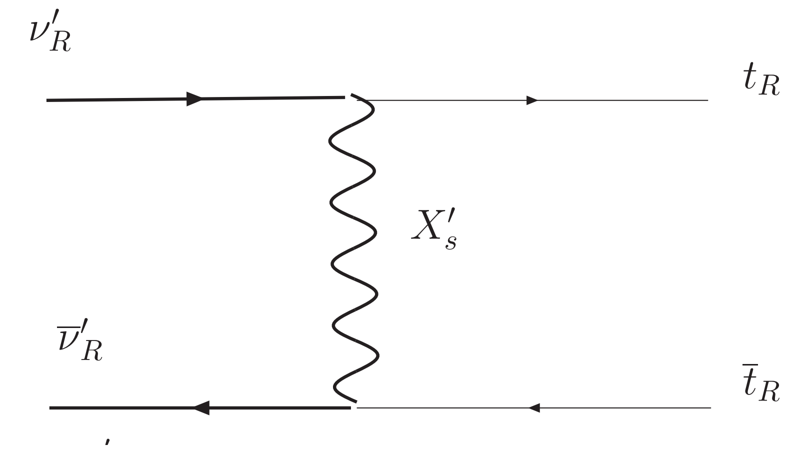
resulting relic abundance is too low unless the DM mass is ultra light (tension with direct detection experiments)

Relic density constraint- case for vanishing DM-Z′ coupling (no leptonic BR)

$0.35 < g_{LR} < 1$

- The most dominant annihilation channel is via t-channel X_s exchange channel into final state heavy quarks, say $t_R \bar{t}_R$





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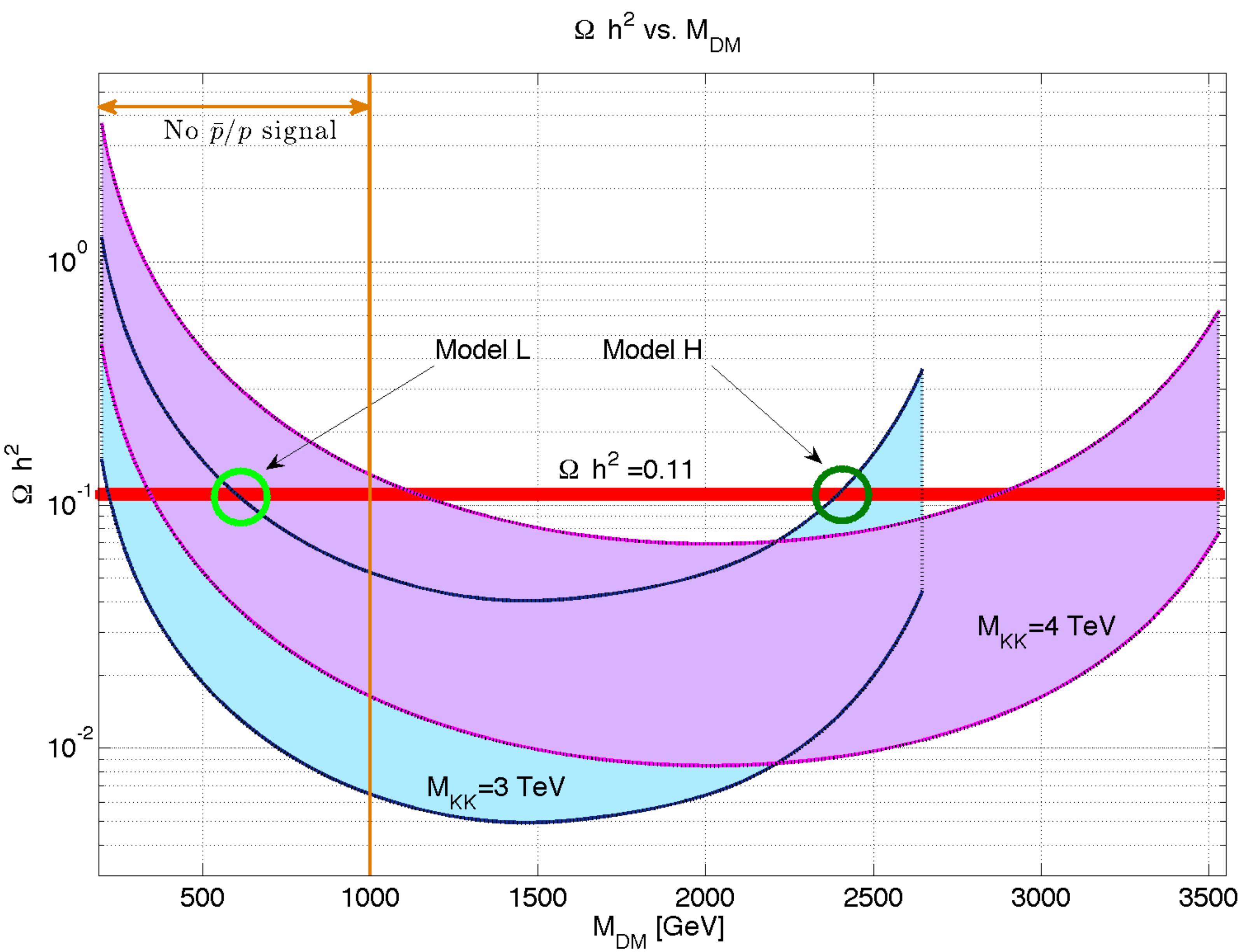
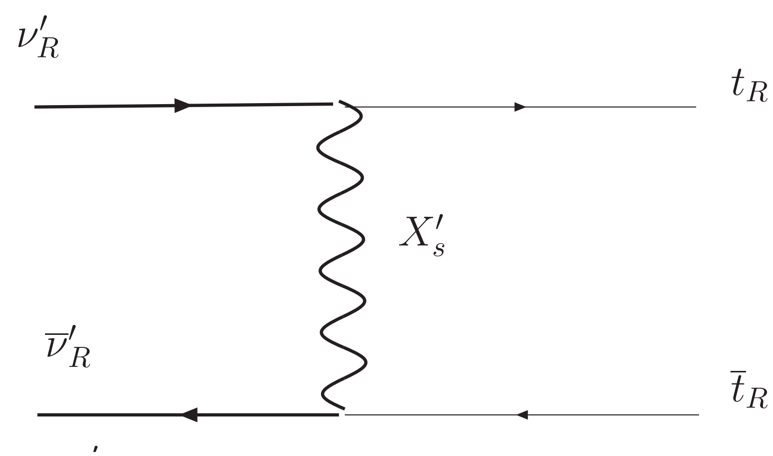




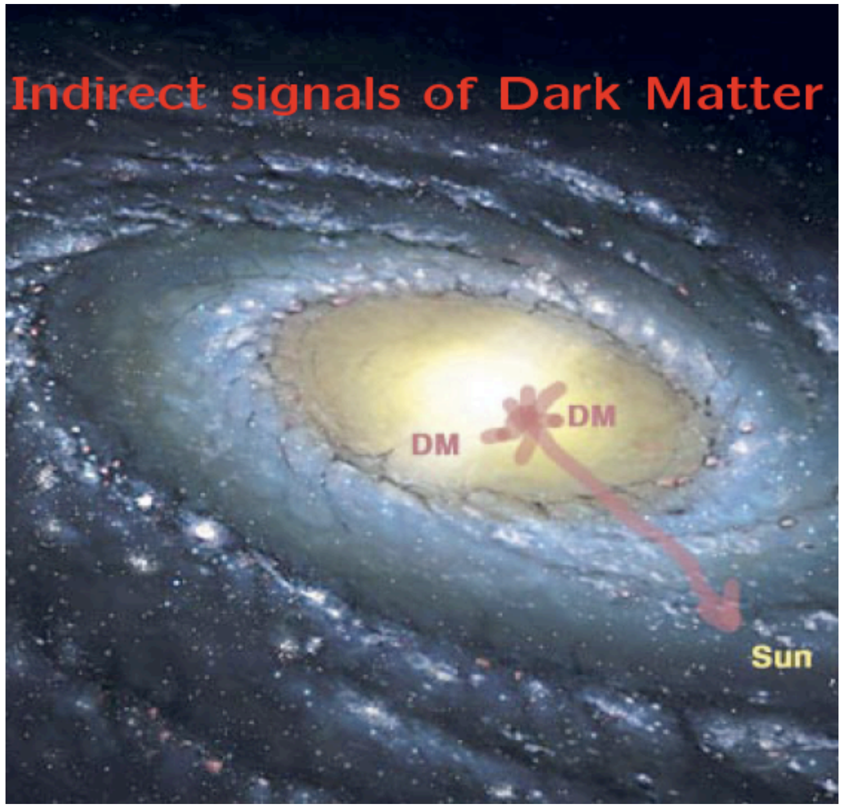
•Sizable region of the parameter space with

-correct DM abundance

-and consistent with bounds from direct detection experiments

Signals in Galactic CRs

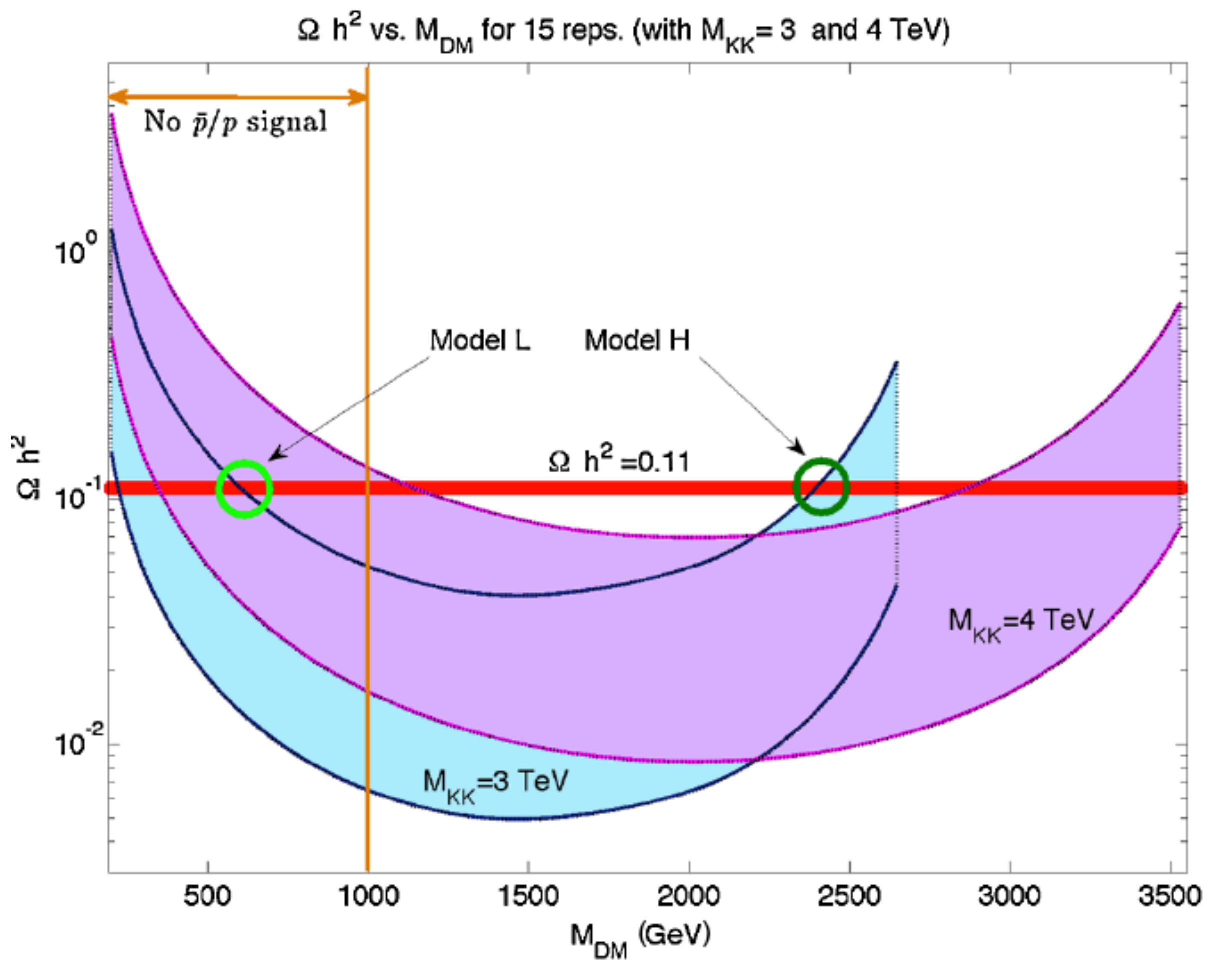
- Local antimatter injection rates
- Robust signals
- Antiproton signals
- Constraints from photons and neutrino



Benchmark model points

Model L: M = 600 GeV, m_r > 40 GeV
In principle one can obtained a sizable SE while decreasing Λ_r, however, in this case we find tension with direct detection bounds.

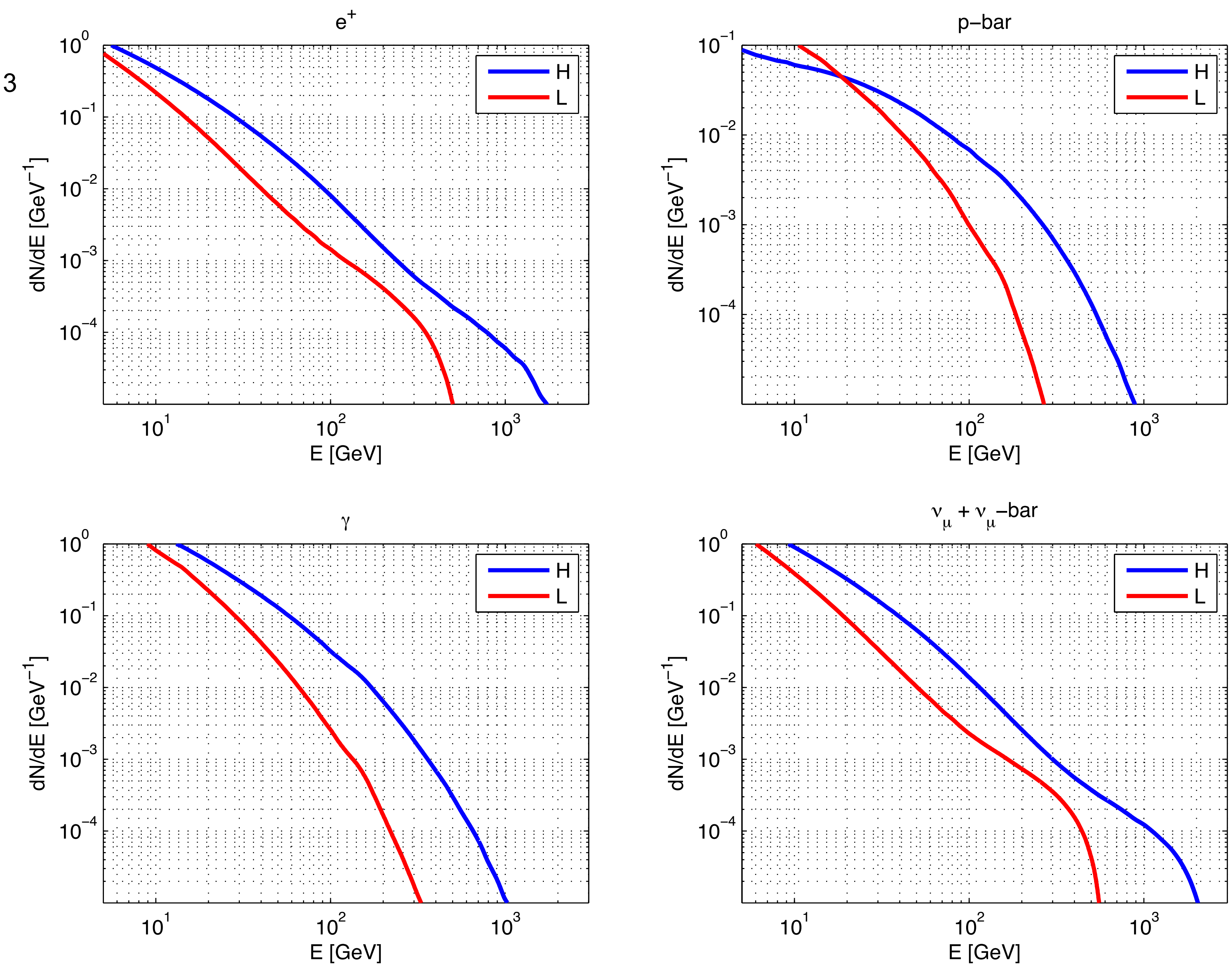
Model H: M = 2400 GeV, m_r = O(100) GeV
In this case theres a wide range of radion masses and corresponding Λ_r which yield a sizable SE and consistent with direct experiment.



Local antimatter injection rates

$$\frac{dN_\alpha}{d\epsilon}$$

3



Decayed final state annihilation spectra: These spectra, together with the DM mass and Sommerfeld enhancement factor serve as the particle physics input required for the calculation of indirect detection signals

2 Robust astro signals

Katz, Blum & Waxman

Can we make astrophysicists jump from their seats?

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i) Katz, Blum, Waxman: No tension with model independent estimates (no need for primary source)
ii) our model doesn't have much to say about it

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pbar/p: the other way to go (slightly model dep)

- high energy antiprotons above a few of GeV suffer only small energy losses as they travel through the Galaxy
- the secondary anti-proton flux up to E ~ 200 GeV can be computed in a model independent manner, based on the existing CR nuclei data

Katz, Blum & Waxman

  - need to introduce only one free parameter to the calculation;
    - namely an energy independent effective volume factor encoding the ratio between the different spatial extensions of the DM and the spallation sources.

$$\frac{n_{\bar{p},DM}(\epsilon,\vec{r}_{sol})}{n_{\bar{p},sec}(\epsilon,\vec{r}_{sol})} = f_V \frac{Q_{\bar{p},DM}(\epsilon,\vec{r}_{sol})}{Q_{\bar{p},sec}(\epsilon,\vec{r}_{sol})}$$

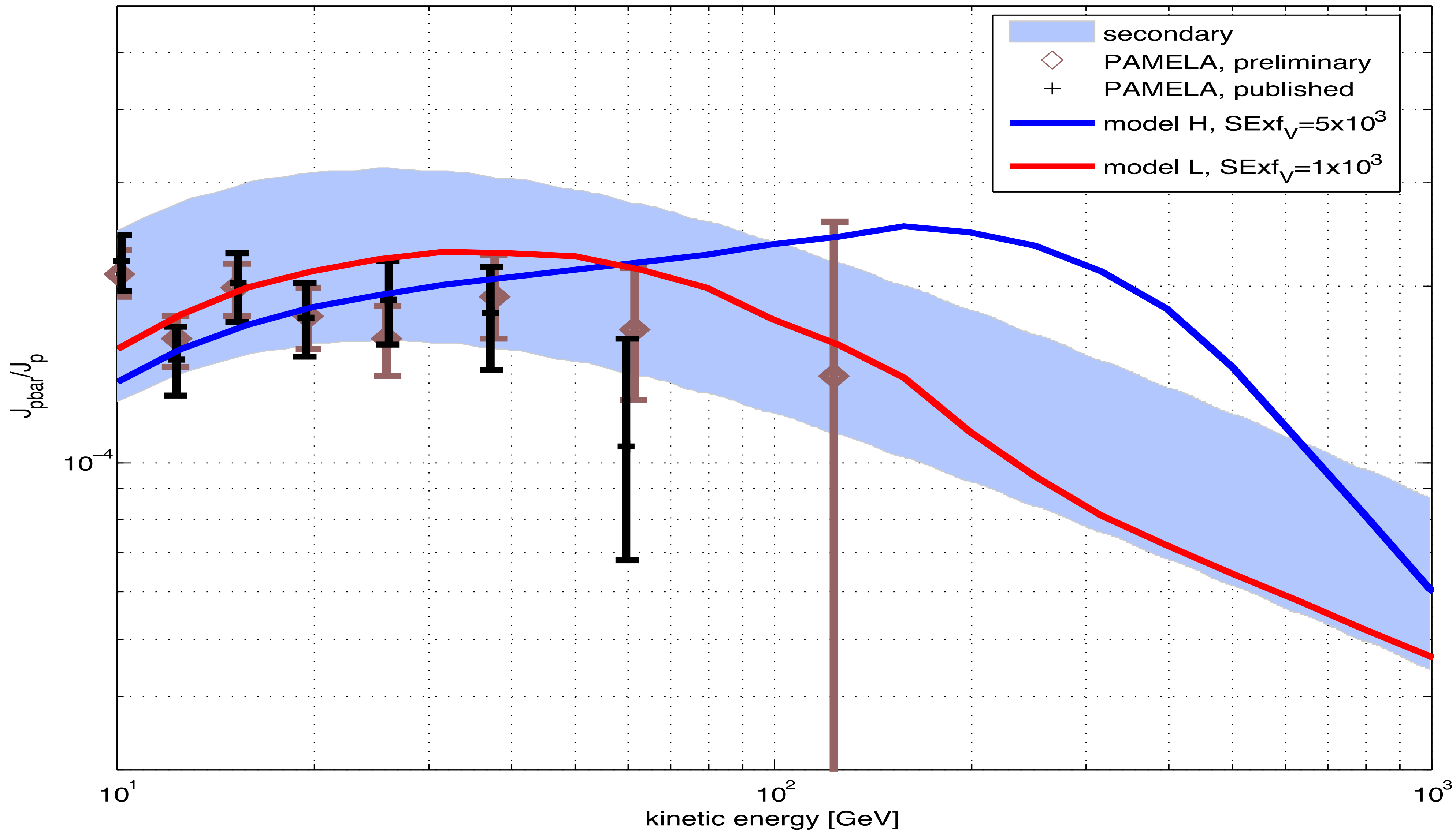
Antiproton signals in GCRs

secondary anti-proton to the primary proton flux ratio:constrained by the B/C data

$$\frac{J_{\bar{p}}(\epsilon,\vec{r}_{sol})}{J_p(\epsilon,\vec{r}_{sol})} = \left(\frac{J_{\bar{p}}(\epsilon,\vec{r}_{sol})}{J_p(\epsilon,\vec{r}_{sol})}\right)_{sec} \times \left[1 + f_V \frac{Q_{\bar{p},DM}(\epsilon,\vec{r}_{sol})}{Q_{\bar{p},sec}(\epsilon,\vec{r}_{sol})}\right]$$

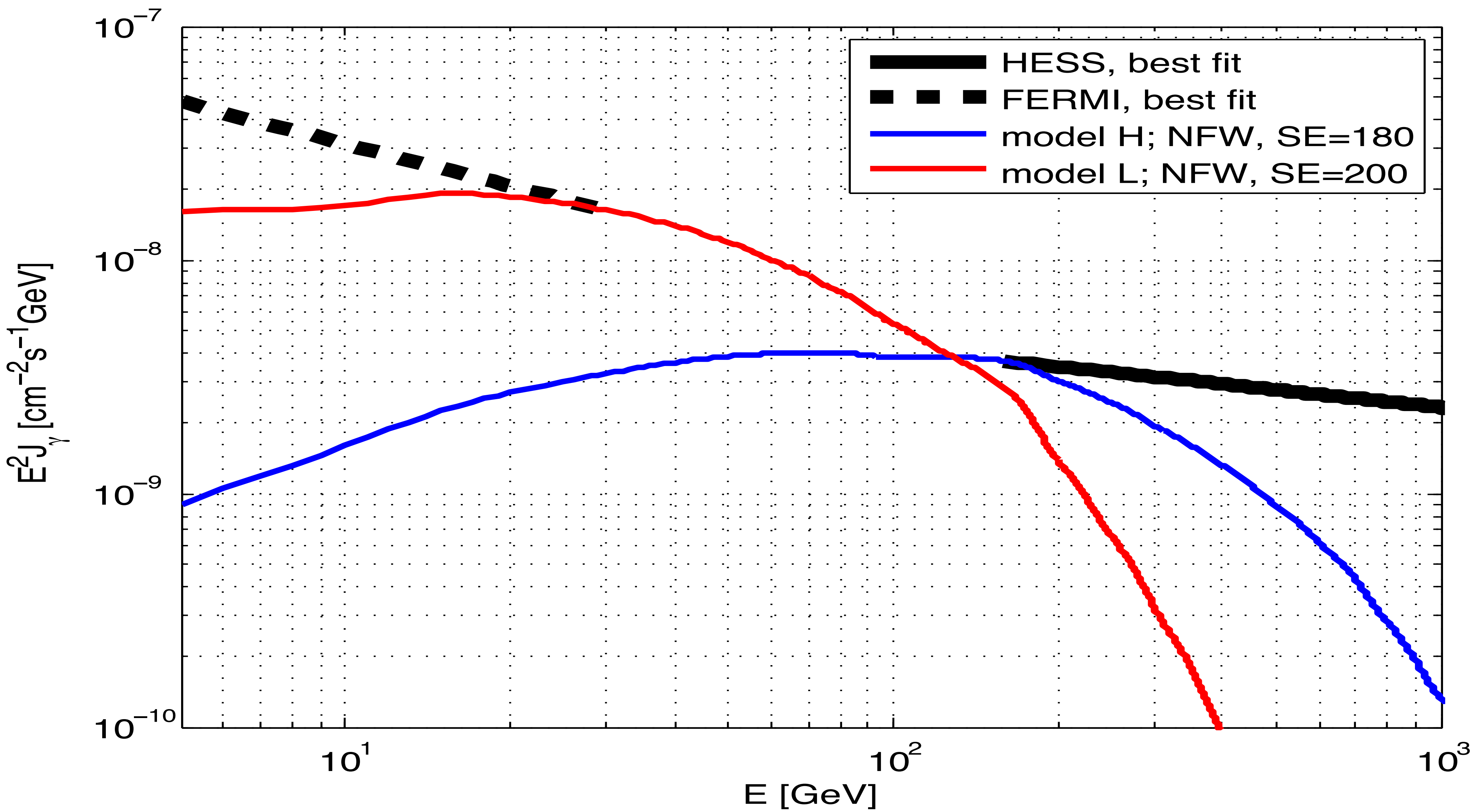
volume factor

local secondary injection rate



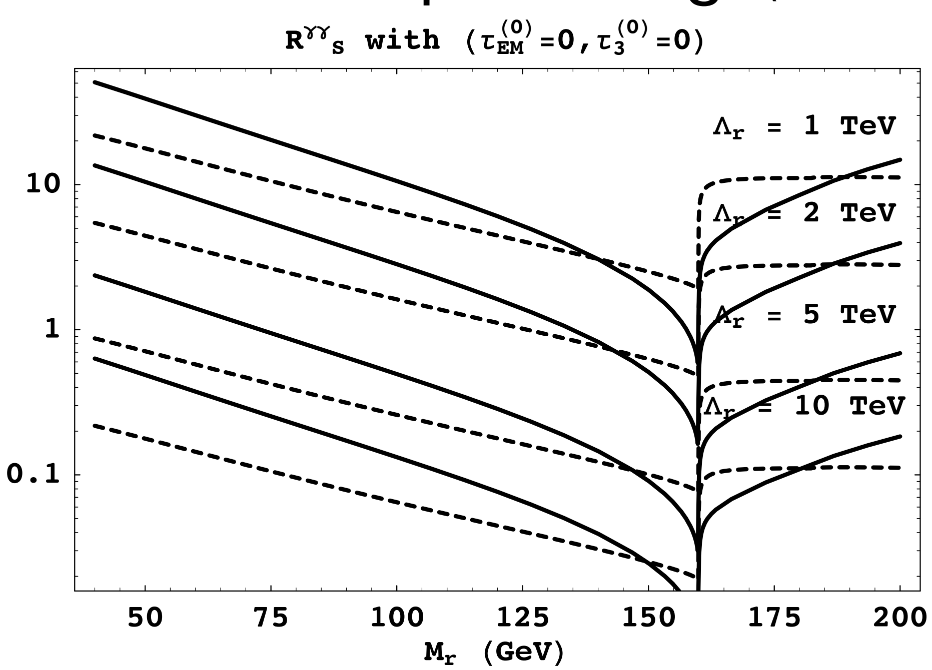
Gamma ray constraints from FERMI and HESS

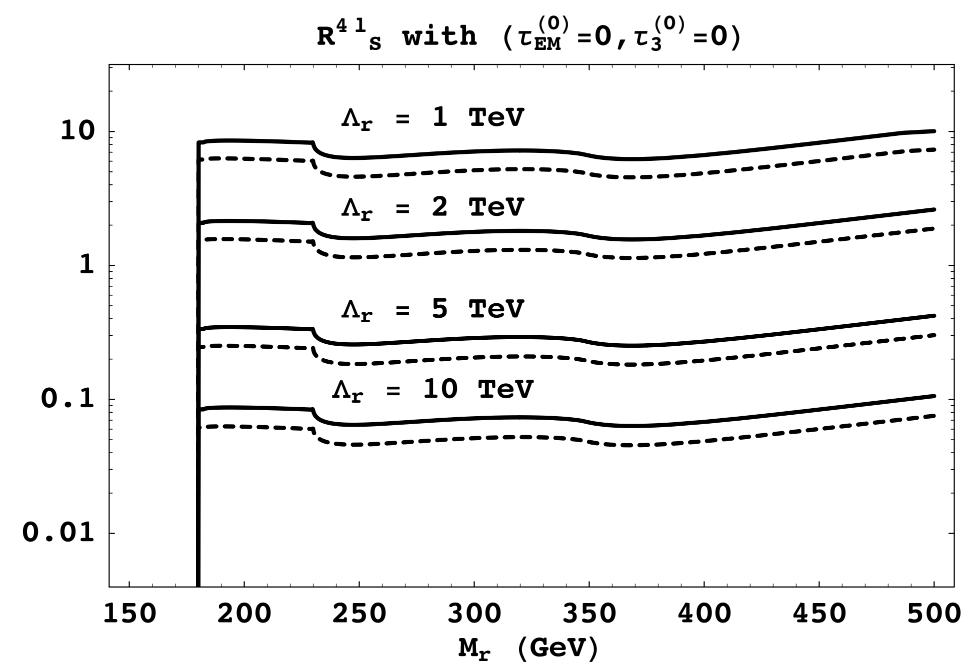
- evaluated with an NFW DM halo profile and the maximal Sommerfeld factor allowed by the GC data



Can we test it?
2) LHC Signals

- Light radion O(100) GeV will be interesting particle to look for. (depending on it's mass): specially if mr~O(100) GeV: gg → r → γγ & gg → r → ZZ → 4l channels promising (Csaki, Hubisz, SJL)



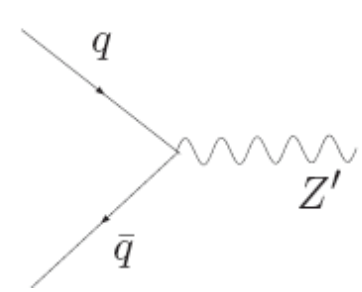


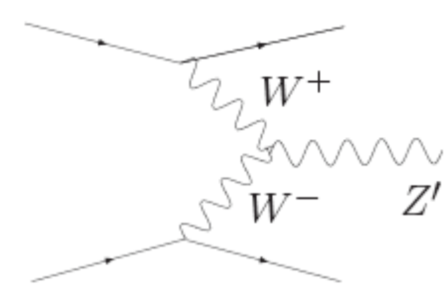
$$R_S^{\gamma\gamma} \equiv \frac{S(r)}{S(h_{SM})}$$

- Difficult to produce DM, or GUT gauge bosons @ LHC

  - ~3 TeV Z' decaying into boosted τ_R pair

custodial protection -> composite tau -> high pT tau





Summary

- The recent/future experimental searches for anti-matter in cosmic rays up to energies of roughly a TeV motivates studies of particle physics models of dark matter (DM) where DM annihilation dynamics could yield observed signal.
- RS GUT with order of 100 GeV radion can result in a sizable Sommerfeld enhancement of the annihilation cross-section.
- With a possible large boost, we can have an interesting anti-proton signal in the future.
- Custodial symmetry for $Z \to b\bar{b}$ is required in order to ameliorate little hierarchy problem, and we show how to incorporate it
- For LHC, radion will be an interesting signature. Highly boosted tau's (and positron signal in GCR) might be possible, but need to overcome constraints for WMAP (relic abundance)

Backups

RS GUT and Dark Matter

Agashe, Servant

- However, KK mode of X, Y gauge bosons are localized in IR (TeV) brane

  if leptons and quarks are unified in the same mutiplet, KK modes will mediate proton decay with only Yukawa suppression

- Split multiplets for proton stability (GUT breaking on boundary: Hall, Nomura): quark and lepton zero-modes from different multiplets

  break the GUT group down to the SM by boundary conditions

$$\bar{5}_q = \begin{pmatrix} q^{(0)} \\ l'^{\,(n\neq 0)} \end{pmatrix} \quad \text{X,Y} \qquad\qquad \bar{5}_l = \begin{pmatrix} q'^{\,(n\neq 0)} \\ l^{(0)} \end{pmatrix} \quad \text{X,Y}$$

- Need to $U(1)_B$; assign multiplets by baryon-number of zero-mode => break it on the UV brane

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Not enough protection since brane-localized mass terms can mix the (KK) leptons from the “quark” multiplet (i.e., which contains a quark zero-mode) with the zero-mode lepton from the other (lepton) multiplet

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$$\bar{5}_q = \begin{pmatrix} q^{(0)} \\ l'^{\,(n\neq 0)} \end{pmatrix}_{B=\frac{1}{3}} \quad \text{X,Y} \qquad\qquad \bar{5}_l = \begin{pmatrix} q'^{\,(n\neq 0)} \\ l^{(0)} \end{pmatrix}_{B=0} \quad \text{X,Y}$$

Not enough protection since brane-localized mass terms can mix the (KK) leptons from the "quark" multiplet (i.e., which contains a quark zero-mode) with the zero-mode lepton from the other (lepton) multiplet

- Need to $U(1)_B$; assign multiplets by baryon-number of zero-mode => break it on the UV brane

RS GUT and Dark Matter

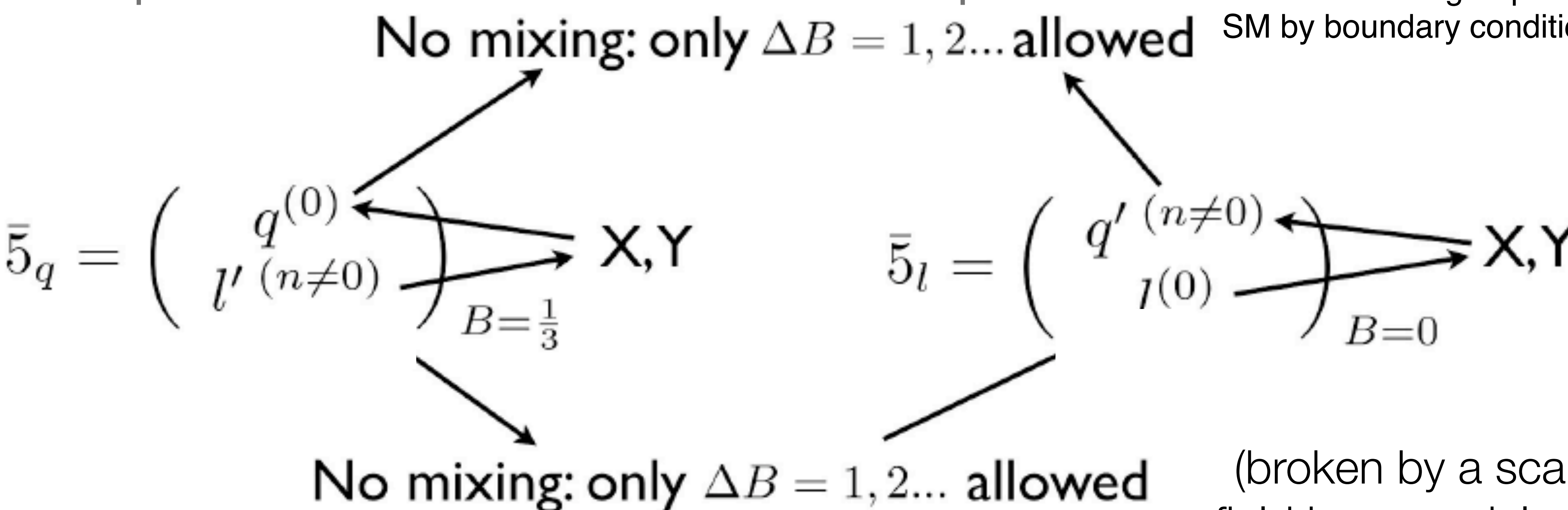
Agashe, Servant

- However, KK mode of X, Y gauge bosons are localized in IR (TeV) brane

  if leptons and quarks are unified in the same mutiplet, KK modes will mediate proton decay with only Yukawa suppression

- Split multiplets for proton stability (GUT breaking on boundary: Hall, Nomura): quark and lepton zero-modes from different multiplets

break the GUT group down to the SM by boundary conditions



(broken by a scalar field in a special way)

Not enough protection since brane-localized mass terms can mix the (KK) leptons from the “quark” multiplet (i.e., which contains a quark zero-mode) with the zero-mode lepton from the other (lepton) multiplet

- Need to $U(1)_B$; assign multiplets by baryon-number of zero-mode => break it on the UV brane

DM candidate: ν' - Lightest Z_3 charged Particle

Agashe, Servant

- Extra particles (including X, Y gauge bosons) in the GUT model are charged under the following Z_3 symmetry:

$$\boxed{\Phi \quad \to \quad e^{2\pi i \left(\frac{\alpha - \bar{\alpha}}{3} - B\right)} \Phi}$$

α, $\bar{\alpha}$ are the number of color, anti-color indices on Φ)

=> the lightest Z_3 charged particle (dubbed "LZP") is stable

- DM candidate: ν'_R is the SM singlet GUT partner of t_R (i.e., with quantum numbers of a RH neutrino), but with (exotic) baryon number of 1/3.

- ν'_R : KK fermion with (-,+) boundary condition => its mass depending on bulk mass (c) parameter for GUT multiplet which dictates the profile of t_R

$$m_{\rm DM}(c) \approx \begin{cases} 0.65\,(c+1)\,M_{\rm KK} & \text{if } c > -0.25 \\ 0.83\,\sqrt{c+\frac{1}{2}}\,M_{\rm KK} & \text{if } -0.25 > c > -0.5 \\ 0.83\,\sqrt{c^2-\frac{1}{4}}\,M_{\rm KK}\exp\left[k\pi R\left(c+\frac{1}{2}\right)\right] & \text{if } c < -0.5 \end{cases}$$

=> the more closely t_R is localized toward IR brane, the lighter the mass of ν'_R

DM candidate: ν′ - Lightest Z_3 charged Particle

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=> the lightest Z_3 charged particle (dubbed “LZP”) is stable

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- ν'_R : KK fermion with … ending on bulk mass (c) parameter f … of t_R

DM emergence is a spin-off of proton stability

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=> the more closely t_R is localized toward IR brane, the lighter the mass of ν'_R

Pati-Salam Custodial GUT model

- Shift in $Z b\bar{b}$ is larger than that allowed by EWPT for KK scale lower than 5 TeV.
- A custodial symmetry to protect such a shift in $Z b\bar{b}$ was proposed which requires non-canonical EW quantum numbers. Agashe, Contino, Da Rold and Pomarol

$$\frac{g}{\cos\theta_W}\left[Q_L^3 - Q\sin^2\theta_W\right] Z^\mu \bar{\psi}\gamma_\mu\psi$$

$SU(4)_C \times SU(2)_L \times SU(2)_R$

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Before EWSB we have $Q^3_L = T^3_L$, but this is not guaranteed anymore after EWSB.

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$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R, = \mathrm{O}(4) \to \mathrm{O}(3) = \mathrm{SU}(2)_V \otimes P_{LR}$$

- The idea is to preserve subgroups of the custodial symmetry $SU(2)_V \otimes P_{LR}$ that can protect Q^3_L: $\mathrm{U}(1)_L \otimes \mathrm{U}(1)_R \otimes P_{LR} \to \mathrm{U}(1)_V \otimes P_{LR}$

$$T_L = T_R\ , \qquad T^3_R = T^3_L$$

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$$T_L = T_R\ , \qquad T_R^3 = T_L^3$$

or discrete symmetry $|T_L, T_R; T_L^3, T_R^3\rangle \to |T_L, T_R; -T_L^3, -T_R^3\rangle$

$$T_L^3 = T_R^3 = 0$$

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We need to construct a custodial model based on unification

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We need to construct a custodial model based on unification

- Such a symmetry can also be extended to protect the shift in Z coupling to τ_R => allow τ_R to be localized closer to the TeV brane

=> larger couplings of KK gauge boson to τ_R => relevant for the GCRs signal.

Now embedding cust' into Pati-Salam

- $T_{3R} = -1/2$ for $(t,b)_L$ and thus $T_{3R} = 0,\ -1$ for t_R and b_R to obtain the top, bottom masses

	$SU(4)_c \sim SU(3)_C \times U(1)_X$	$SU(2)_L$	$SU(2)_R$
$t_R,\ \nu'$	$\mathbf{4} \sim \mathbf{3}_{\frac{-1}{3}},\ \mathbf{1}_1 \ldots$	$\mathbf{1}$	$\mathbf{5}$
$(t,b)_L$	$\mathbf{4} \sim \mathbf{3}_{\frac{-1}{3}}, \ldots$	$\mathbf{2}$	$\mathbf{4}$
τ_R	$\mathbf{1} \sim \mathbf{1}_0$	$\mathbf{1}$	$\mathbf{3}$
$(\nu,\tau)_L$	$\mathbf{1} \sim \mathbf{1}_0$	$\mathbf{2}$	$\mathbf{2}$
b_R	$\mathbf{4} \sim \mathbf{3}_{\frac{-1}{3}}, \ldots$	$\mathbf{1}$	$\mathbf{5}$
H	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$

Table 7: Simplest model with custodial representation for b_L, but not for RH charged leptons: the subscripts denote the $\sqrt{8/3}\ X$ charge.

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$(t,b)_L$	$\mathbf{4} \sim \mathbf{3}_{\frac{-1}{3}},\ldots$	$\mathbf{2}$	$\mathbf{4}$
τ_R	$\mathbf{1} \sim \mathbf{1}_0$	$\mathbf{1}$	$\mathbf{3}$
$(\nu,\tau)_L$	$\mathbf{1} \sim \mathbf{1}_0$	$\mathbf{2}$	$\mathbf{2}$
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Table 7: Simplest model with custodial representation for b_L, but not for RH charged leptons: the subscripts denote the $\sqrt{8/3}\,X$ charge.

$$Y = T_{3R} - \sqrt{\frac{32}{3}}X \qquad X = \mathrm{diag}\sqrt{3/8}\,(-1/3,-1/3,-1/3,1) \qquad \mathrm{Tr}X^2 = 1/2.$$

$$(t_R,\nu') : \quad diag(2,1,0,-1,-2) \oplus -4 \times \frac{1}{2} diag(-\frac{1}{3},-\frac{1}{3},-\frac{1}{3},1)$$

$$(t,b)_L : \quad \frac{1}{2} diag(3,1,-1,-3) \oplus -4 \times \frac{1}{2} diag(-\frac{1}{3},-\frac{1}{3},-\frac{1}{3},1)$$

$$(\tau)_R : \quad diag(1,0,-1) \oplus 0$$

not protected by cust'

More interesting rep' where coupling of Z to τ_R pair is also protected!

$$Y = T_{3R} + \sqrt{1/6}X \qquad X = \mathrm{diag}\sqrt{3/8}\,(-1/3,-1/3,-1/3,1)$$

	$SU(4)_c \sim SU(3)_C \times U(1)_X$	$SU(2)_L$	$SU(2)_R$
$t_R,\ \nu'$	$\mathbf{35} \sim \mathbf{3}_{\frac{8}{3}},\ \mathbf{1}_4 \ldots$	$\mathbf{1}$	$\mathbf{3}$
$(t,b)_L$	$\mathbf{35} \sim \mathbf{3}_{\frac{8}{3}}, \ldots$	$\mathbf{2}$	$\mathbf{2}$
τ_R	$\overline{\mathbf{35}} \sim \mathbf{1}_{-4}, \ldots$	$\mathbf{1}$	$\mathbf{1}$
$(\nu,\tau)_L$	$\overline{\mathbf{35}} \sim \mathbf{1}_{-4}, \ldots$	$\mathbf{2}$	$\mathbf{2}$
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	$SU(4)_c \sim SU(3)_C \times U(1)_X$	$SU(2)_L$	$SU(2)_R$
$t_R,\ \nu'$	$\mathbf{10} \sim \mathbf{3}_{\frac{2}{3}},\ \mathbf{1}_2 \ldots$	$\mathbf{1}$	$\mathbf{5}$
$(t,b)_L$	$\mathbf{10} \sim \mathbf{3}_{\frac{2}{3}}, \ldots$	$\mathbf{2}$	$\mathbf{4}$
τ_R	$\overline{\mathbf{4}} \sim \mathbf{1}_{-1}, \ldots$	$\mathbf{1}$	$\mathbf{1}$
$(\nu,\tau)_L$	$\overline{\mathbf{4}} \sim \mathbf{1}_{-1}, \ldots$	$\mathbf{2}$	$\mathbf{2}$
b_R	$\mathbf{10} \sim \mathbf{3}_{\frac{2}{3}}, \ldots$	$\mathbf{1}$	$\mathbf{5}$
H	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$

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b_R	$\mathbf{10} \sim \mathbf{3}_{\frac{2}{3}}, \ldots$	**1**	**5**
H	**1**	**2**	**2**

Pati-Salam+custodial

Branching rules for $SU_4 \supset SU_3 \times U_1$

$(100) = 4 = 1(1) + 3(-1/3)$ (establishes normalization of U_1 generator)

$(010) = 6 = 3(2/3) + \bar{3}(-2/3)$

$(200) = 10 = 1(2) + 3(2/3) + 6(-2/3)$

$(101) = 15 = 1(0) + 3(-4/3) + \bar{3}(4/3) + 8(0)$

$(011) = 20 = 3(-1/3) + \bar{3}(-5/3) + \bar{6}(-1/3) + 8(1)$

$(020) = 20' = \bar{6}(-4/3) + 6(4/3) + 8(0)$

$(003) = 20'' = 1(-3) + \bar{3}(-5/3) + \bar{6}(-1/3) + \overline{10}(1)$

$(400) = 35 = 1(4) + 3(8/3) + 6(4/3) + 10(0) + 15'(-4/3)$

$(201) = 36 = 1(1) + 3(-1/3) + \bar{3}(7/3) + 6(-5/3) + 8(1) + 15(-1/3)$

$(210) = 45 = 3(8/3) + \bar{3}(4/3) + 6(4/3) + 6(4/3) + 8(0) + 10(0) + 15(-4/3)$

$(030) = 50 = 10(2) + \overline{10}(-2) + 15(2/3) + \overline{15}(-2/3)$

$(500) = 56 = 1(5) + 3(11/3) + 6(7/3) + 10(1) + 15'(-1/3) + \overline{21}(-5/3)$

$(120) = 60 = \bar{6}(-1/3) + 6(7/3) + 8(1) + 10(1) + 15(-1/3) + \overline{15}(-5/3)$

$(111) = 64 = 3(2/3) + \bar{3}(-2/3) + \bar{6}(2/3) + 6(-2/3) + 8(2) + 8(-2) + 15(2/3) + \overline{15}(-2/3)$

R. SLANSKY

Unification

$t_R,\ \nu'$

$(t, b)_L$

$SO_{10} \supset SU_2 \times SU_2 \times SU_4$

$10 = (2, 2, 1) + (1, 1, 6)$

$16 = (2, 1, 4) + (1, 2, \bar{4})$

$45 = (3, 1, 1) + (1, 3, 1) + (1, 1, 15) + (2, 2, 6)$

$54 = (1, 1, 1) + (3, 3, 1) + (1, 1, 20') + (2, 2, 6)$

$120 = (2, 2, 1) + (1, 1, 10) + (1, 1, \overline{10}) + (3, 1, 6) + (1, 3, 6) + (2, 2, 15)$

$126 = (1, 1, 6) + (3, 1, \overline{10}) + (1, 3, 10) + (2, 2, 15)$

$144 = (2, 1, 4) + (1, 2, \bar{4}) + (3, 2, \bar{4}) + (2, 3, 4) + (2, 1, 20) + (1, 2, \overline{20})$

$210 = (1, 1, 1) + (1, 1, 15) + (2, 2, 6) + (3, 1, 15) + (1, 3, 15) + (2, 2, 10) + (2, 2, \overline{10})$

$210' = (2, 2, 1) + (1, 1, 6) + (4, 4, 1) + (3, 3, 6) + (2, 2, 20') + (1, 1, 50)$

$320 = (2, 2, 1) + (1, 1, 6) + (4, 2, 1) + (2, 4, 1) + (3, 1, 6) + (1, 3, 6) + (2, 2, 15) + (3, 3, 6) + (1, 1, 64) + (2, 2, 20')$

$560 = (2, 1, 4) + (1, 2, \bar{4}) + (4, 1, 4) + (1, 4, \bar{4}) + (2, 3, 4) + (3, 2, \bar{4}) + (2, 1, 20) + (1, 2, \overline{20}) + (2, 1, 36) + (1, 2, \overline{36}) + (2, 3, 20) + ($

Couplings for model with/without leptonic channel

Coupling	Value (in units of $g_{LR}\sqrt{k\pi R}$)	Comments
$\overline{\nu'_R}\gamma_\mu Z'^{\,\mu}\nu'_R$	$-a_{\nu'_R}\cos^{-1}\theta'$	$a_{\nu'_R}\sim 1$
$\overline{\hat{\nu'}_R}\gamma_\mu Z'^{\,\mu}\hat{\nu'}_R$	$-a_{\hat{\nu'}_R}\cos^{-1}\theta'$	$a_{\hat{\nu'}_R}\sim\left(\frac{m_{\nu'}}{M_{\rm KK}}\right)^2$
$\overline{t_R}\gamma_\mu Z'^{\,\mu}t_R$	$-\frac{2}{3}a_{t_R}\cos^{-1}\theta'\sin^2\theta'$	$a_{t_R}\lesssim 1$
$\overline{(t,b)_L}\gamma_\mu Z'^{\,\mu}(t,b)_L$	$a_{(t,b)_L}\cos^{-1}\theta'\left(-\frac{1}{2}-\frac{1}{6}\sin^2\theta'\right)$	$a_{(t,b)_L}\lesssim 1$ such that $\sqrt{a_{t_R}\,a_{(t,b)_L}}\sim\frac{1}{Y_{KK}}\sim\frac{1}{7}$
$\overline{(\nu,\tau)_L}\gamma_\mu Z'^{\,\mu}(\nu,\tau)_L$	$a_{(\nu,\tau)_L}\cos^{-1}\theta'\left(\frac{1}{2}+\frac{1}{2}\sin^2\theta'\right)$	$a_{(\nu,\tau)_L}\lesssim\frac{1}{10}$
$\overline{\tau_R}\gamma_\mu Z'^{\,\mu}\tau_R$	$a_{\tau_R}\cos^{-1}\theta'\sin^2\theta'$	$a_{\tau_R}\lesssim 1$
$\overline{\mu_R}\gamma_\mu Z'^{\,\mu}\mu_R$	$a_{\mu_R}\cos^{-1}\theta'\sin^2\theta'$	$a_{\mu_R}\lesssim 1$
$\overline{b_R}\gamma_\mu Z'^{\,\mu}b_R$	$a_{b_R}\cos^{-1}\theta'\left(-1+\frac{1}{3}\sin^2\theta'\right)$	$a_{b_R}\lesssim\frac{1}{10}$
$Z_{long.}Z'_\mu h$	$a_{Z'H}\frac{\cos\theta'}{2}\left(p^\mu_{Z_{long.}}-p^\mu_h\right)$	$a_{Z'H}\sim 1$
$W^+_{long.}Z'_\mu W^-_{long.}$	$a_{Z'H}\frac{\cos\theta'}{2}\left(p^\mu_{W^+_{long.}}-p^\mu_{W^-_{long.}}\right)$	$a_{Z'H}\sim 1$
$\overline{\nu'_R}\hat{\nu'}_R\phi$ (radion)	$\frac{m_{\nu'_R}}{\Lambda_r}$ (no $g_{LR}\sqrt{k\pi R}$)	$\Lambda_r\equiv\sqrt{6}M_{Pl.}e^{-k\pi R}$

A model with Non-vanishing DM Z' =>large leptonic BR for DM annihilation

Coupling		Comments
$\overline{\nu'_R}\gamma_\mu X^\mu_s t_R$	$\sqrt{k\pi R}\,\frac{g_4}{\sqrt{2}}a_{t_R\nu'_R}$	$a_{t_R\nu'_R}\sim\sqrt{a_{t_R}}$
$\overline{\nu'_R}\hat{\nu'}_R\phi$	$\frac{m_{\nu'_R}}{\Lambda_r}$	same as in Tab. 5

A model with vanishing DM Z': no leptonic BR for DM annihilation

Indirect detection: signature in GCRs

- CR injection rate density

$$\boxed{Q_{\alpha,DM}(E,\vec{r}) = \frac{1}{4}n^2(\vec{r})\frac{d\sigma v(DMDM \to \alpha)}{dE}}$$

$$\epsilon = \frac{E}{GeV}, \quad M_1 = \frac{M}{TeV}, \quad \overline{\sigma v} = \frac{<\sigma v>_{\rm tot}}{6 \cdot 10^{-26}\ cm^3 s^{-1}}, \quad n_o(\vec{r}) = \frac{n(\vec{r})}{n(\vec{r}_{sol})} \qquad n(\vec{r}_{sol}) = 0.3cm^{-3}\mathrm{GeV}/M$$

$$\Rightarrow \quad \boxed{Q_{\alpha,DM}(\epsilon,\vec{r}) = 1.3 \cdot 10^{-33}\ n_o^2(\vec{r})\frac{\overline{\sigma v}}{M_1^2}\frac{dN_\alpha}{d\epsilon} \quad cm^{-3}s^{-1}GeV^{-1}}$$

$\frac{dN_\alpha}{d\epsilon}$ Particle Physics input: Energy dependent BR into stable final state α

differential number of stable final state particles of specie α per annihilation event