Dark Matter in a twisted bottle!

Giacomo Cacciapaglia

IPN Lyon (France)

With: A.Arbey, A.Deandrea, B.Kubik, J.Llodra-Perez, L.Panizzi

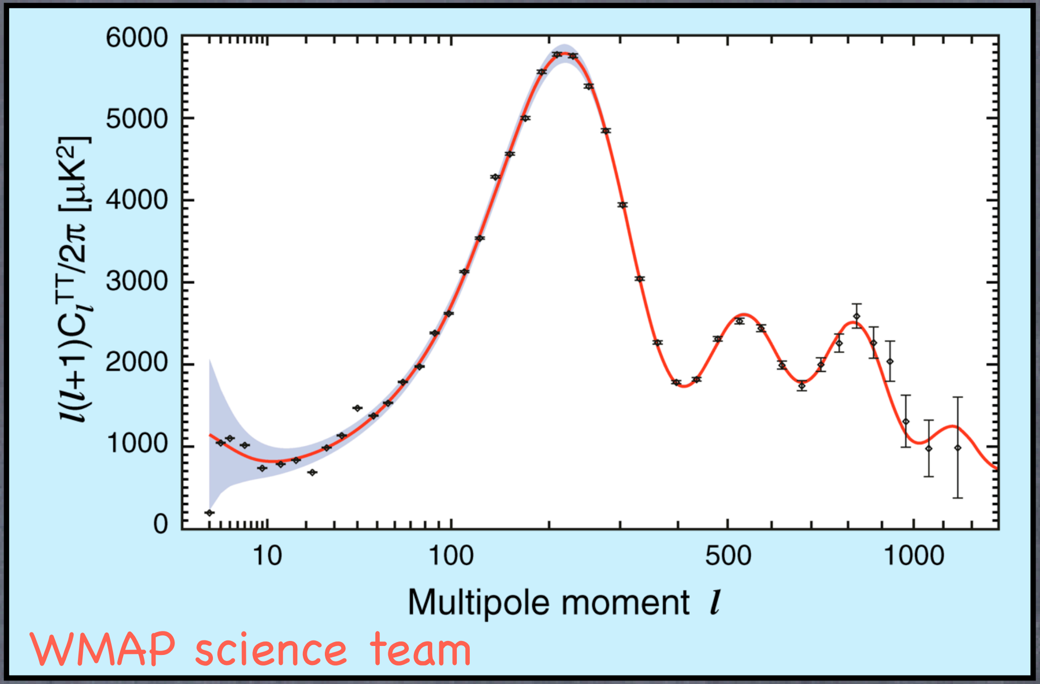
SMU, Dallas

03-18-2013

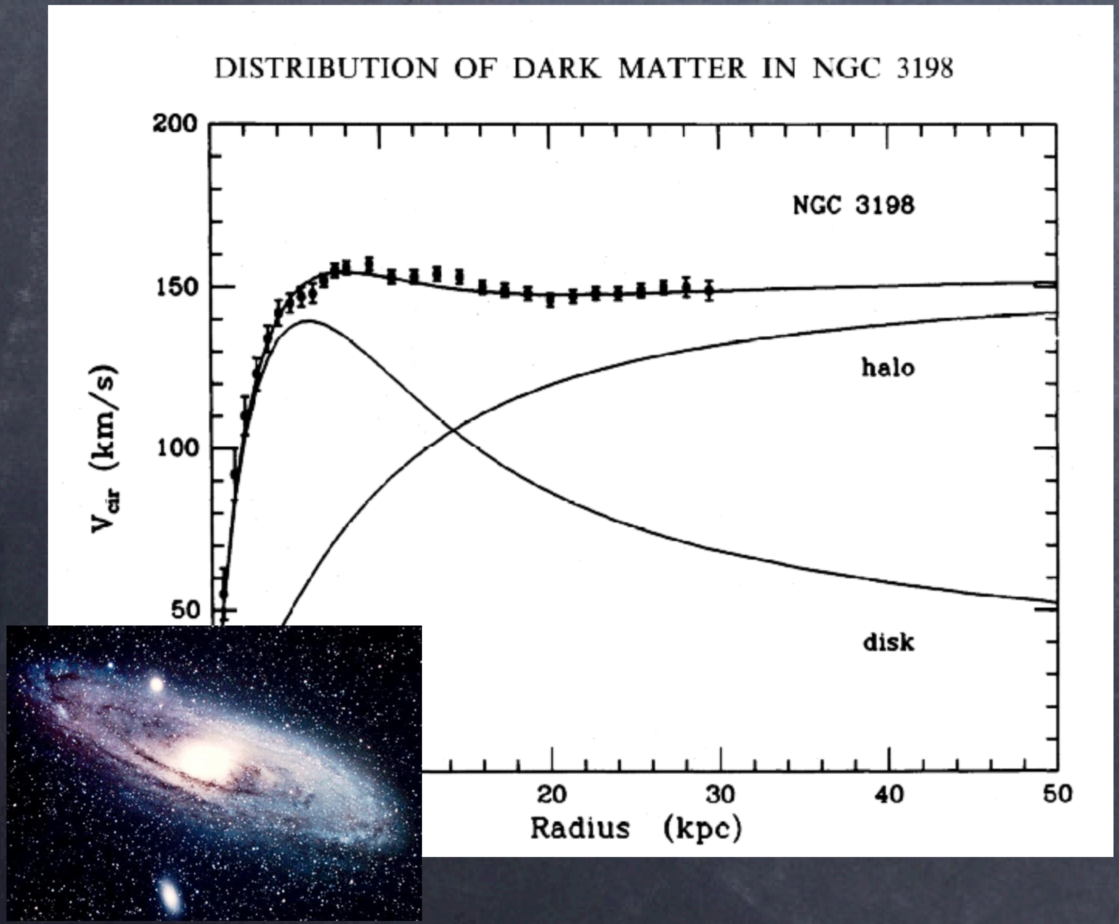
Why do we need Dark Matter?

Observations both in Astrophysics
and Cosmology suggest
the presence of "Dark" Matter,
not explained in the Standard Model!

Cosmic Microwave Background:



Astrophysical measurements:

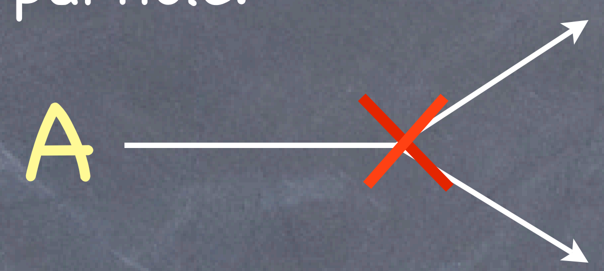


- The Universe contains 4.6% of baryons, and 23.3% of unknown matter.
- The flat rotation curves of spiral galaxies can be explained by the presence of extra non-luminous matter.

WIMP paradigm

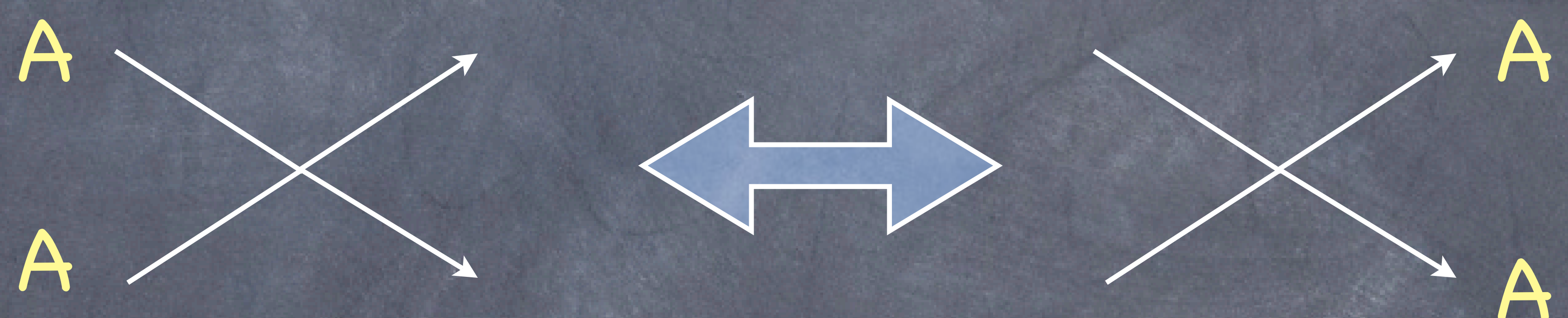
Extra dimensions?

- A stable neutral particle:

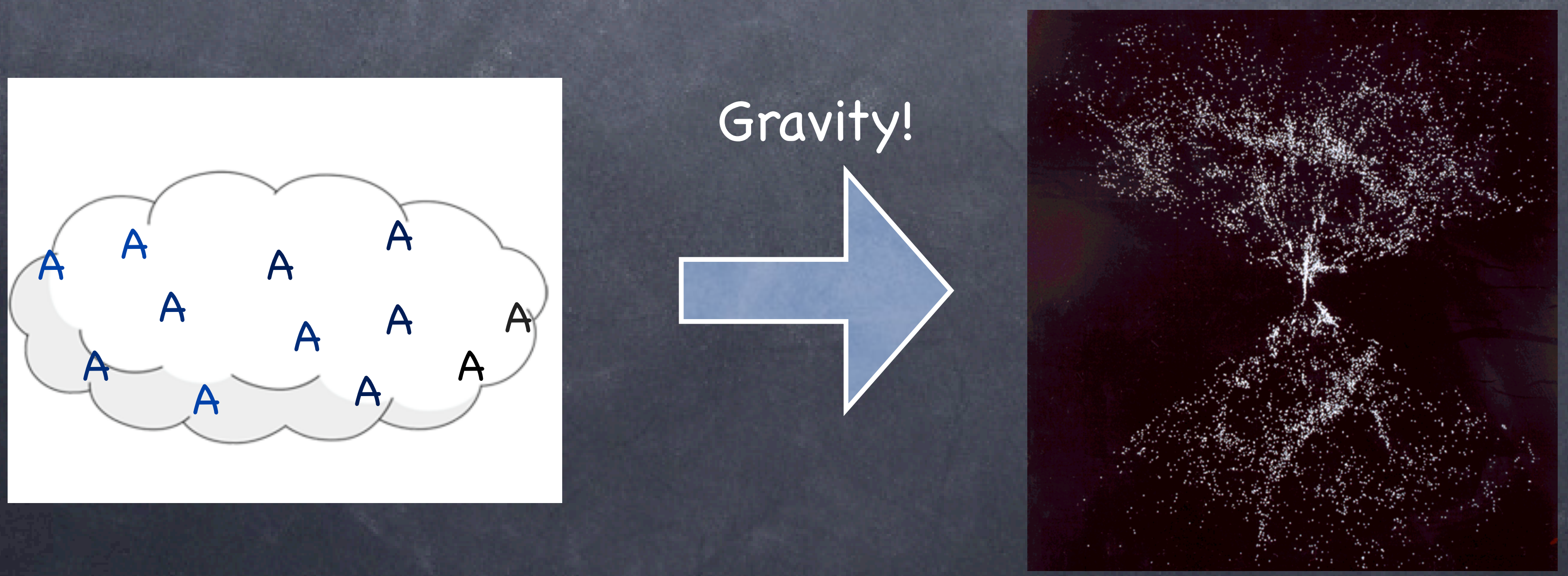


Forbidden by symmetry!

- Thermally produced in the early universe:



- Left as a “relic” when the annihilations become ineffective!



CfA survey

A closer look to Extra Dimensions

Action for a massless scalar in D-dimensions

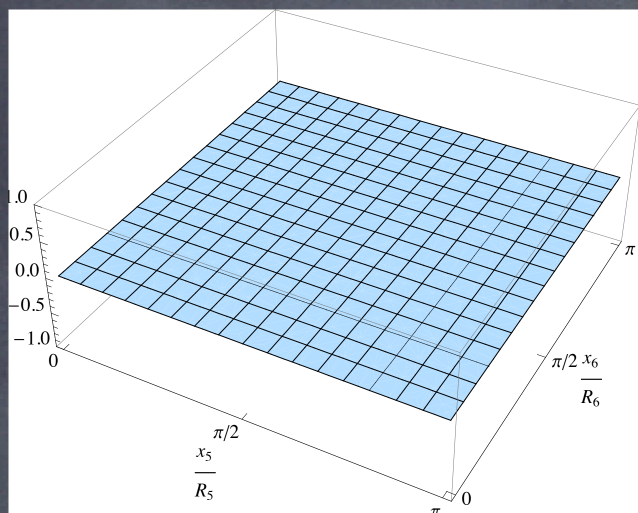
$$S = \int d^D x \left\{ \partial_\mu \phi^\dagger \partial^\mu \phi - \sum_{j=5}^{D-4} \partial_j \phi^\dagger \partial_j \phi \right\}$$

Expansion in 4-dim fields on compact extra space:

$$\phi(x_\mu, x_j) = \int \frac{d^4 p}{(2\pi)^4} e^{i p_\mu x^\mu} \sum_{\vec{k}} \varphi_{\vec{k}}(p_\mu) f_{\vec{k}}(x_j)$$

- D-dim fields correspond to tower of massive 4-dim fields
-

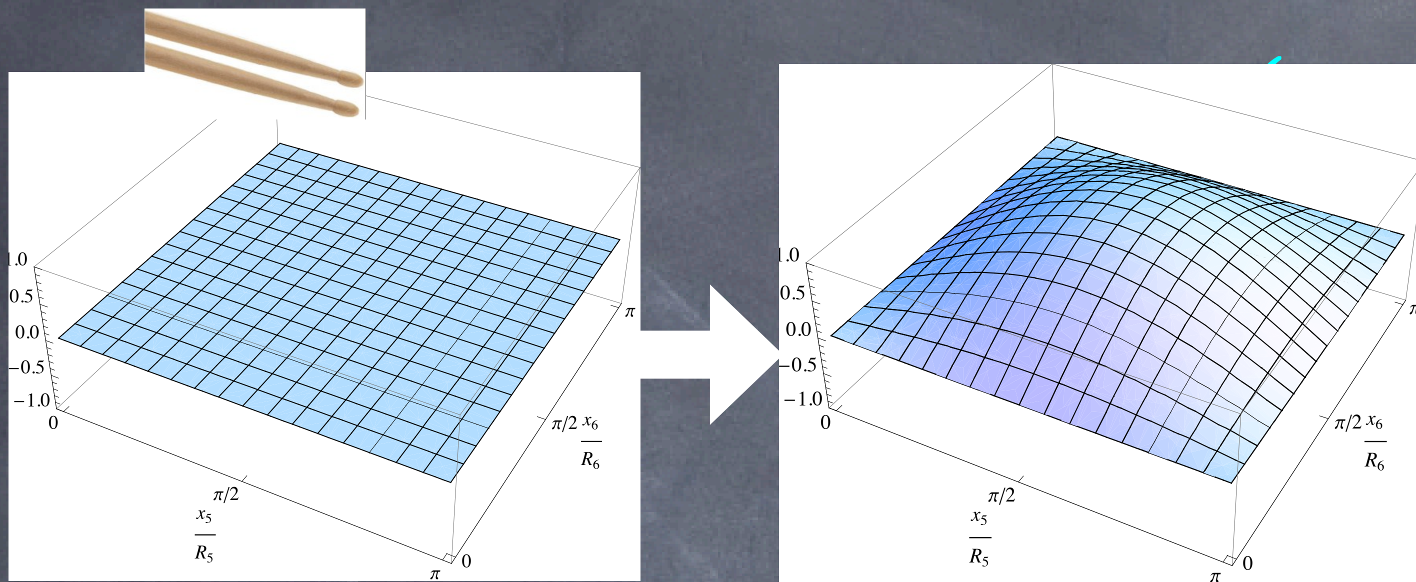
A closer look to Extra Dimensions



The extra space is
like a vibrating membrane,
a drum!

- D-dim fields correspond to tower of massive 4-dim fields

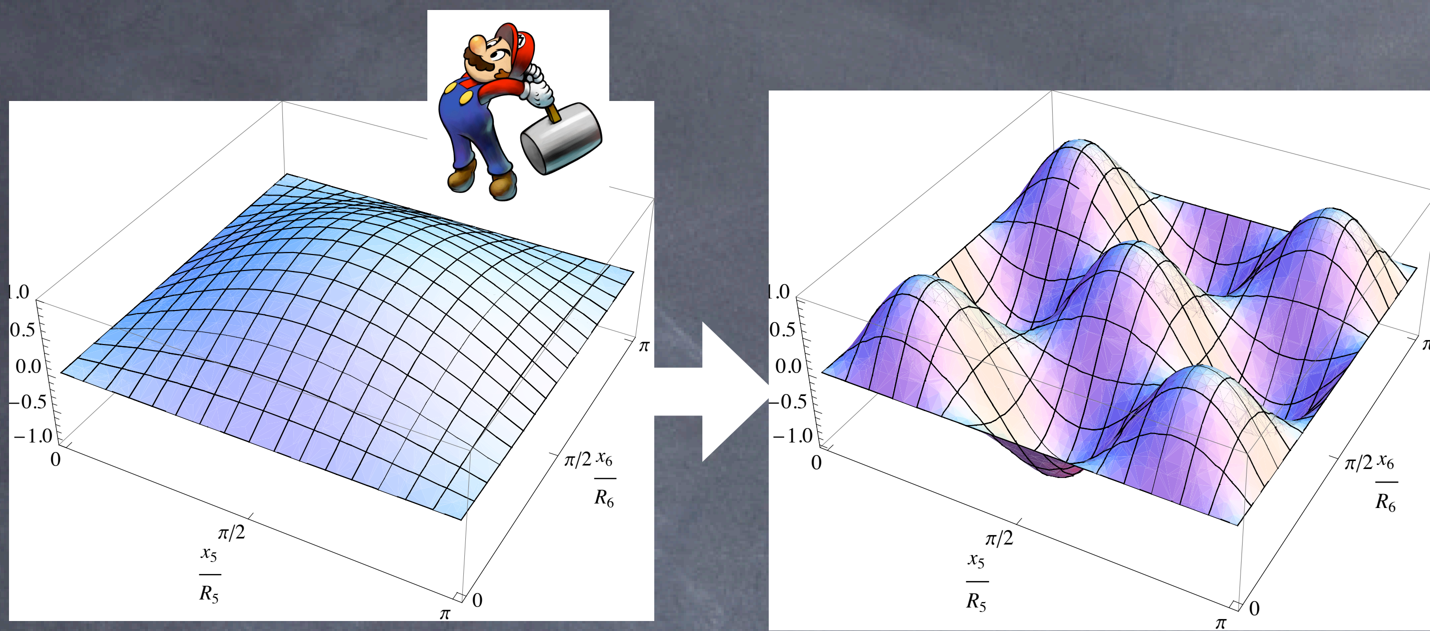
A closer look to Extra Dimensions



Transferring energy can excite a vibration.

- D-dim fields correspond to tower of massive 4-dim fields
- k's are like frequencies of vibrating membrane!
-

A closer look to Extra Dimensions

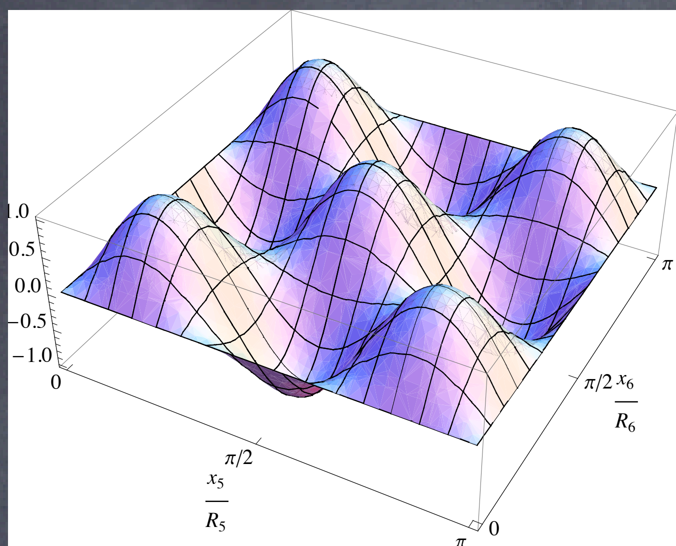


Increasing energy:
more massive mode!
$E = mc^2$!

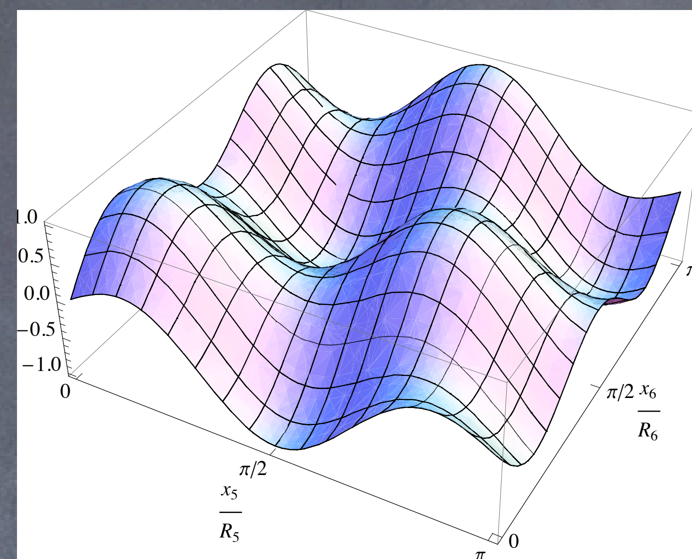
- D-dim fields correspond to tower of massive 4-dim fields
- k's are like frequencies of vibrating membrane!
- Masses and interactions determined by the wave functions $f_{\vec{k}}(x_i)$!

A closer look to Extra Dimensions

RPP



Chi2



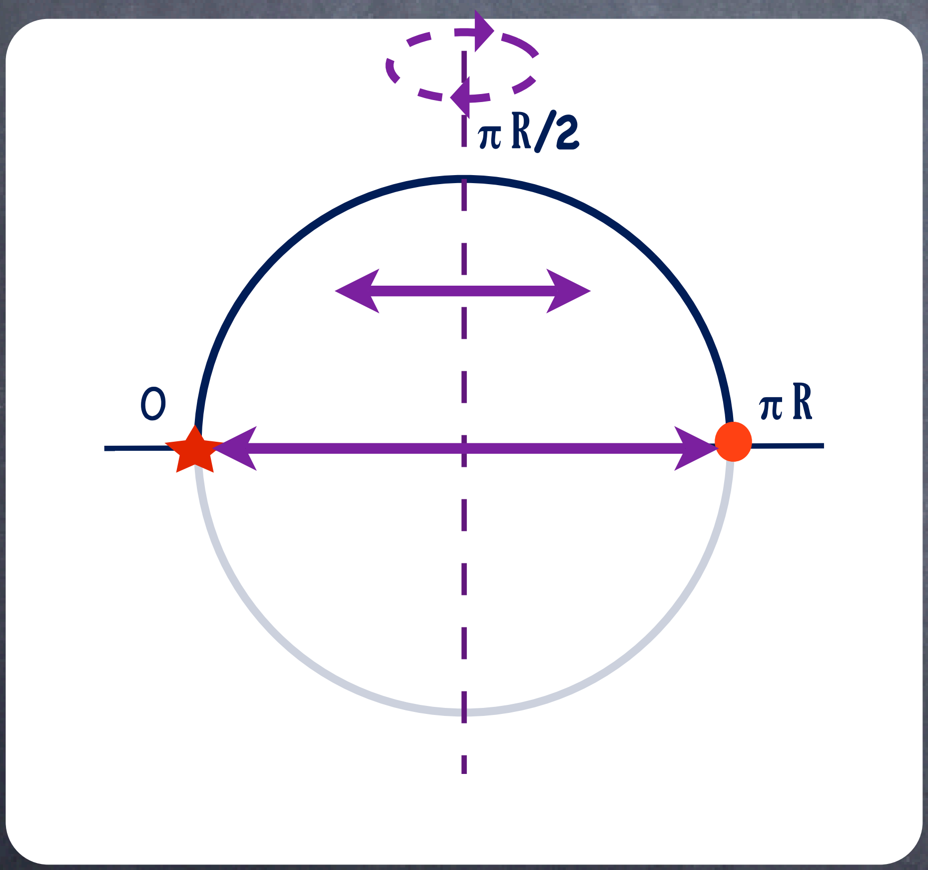
Symmetries
= geometry of
the membrane!

- D-dim fields correspond to tower of massive 4-dim fields
- k's are like frequencies of vibrating membrane!
- Masses and interactions determined by the wave functions $f_{\vec{k}}(x_i)$!
- Symmetries of the compact space = global symmetries of 4-dim fields: transformation properties of the wave functions!
- Can such symmetry stabilise the Dark Matter?

Stability of the Dark Matter “requires” a symmetry!

Can it arise ``naturally” from extra dimensions?

- Symmetries of the compact space ARE parities for the Kaluza-Klein modes!
- The physics is in the wave functions: for instance



Orbifold $S^1/\mathcal{Z}_2$

$$x_5 \to \pi R - x_5$$

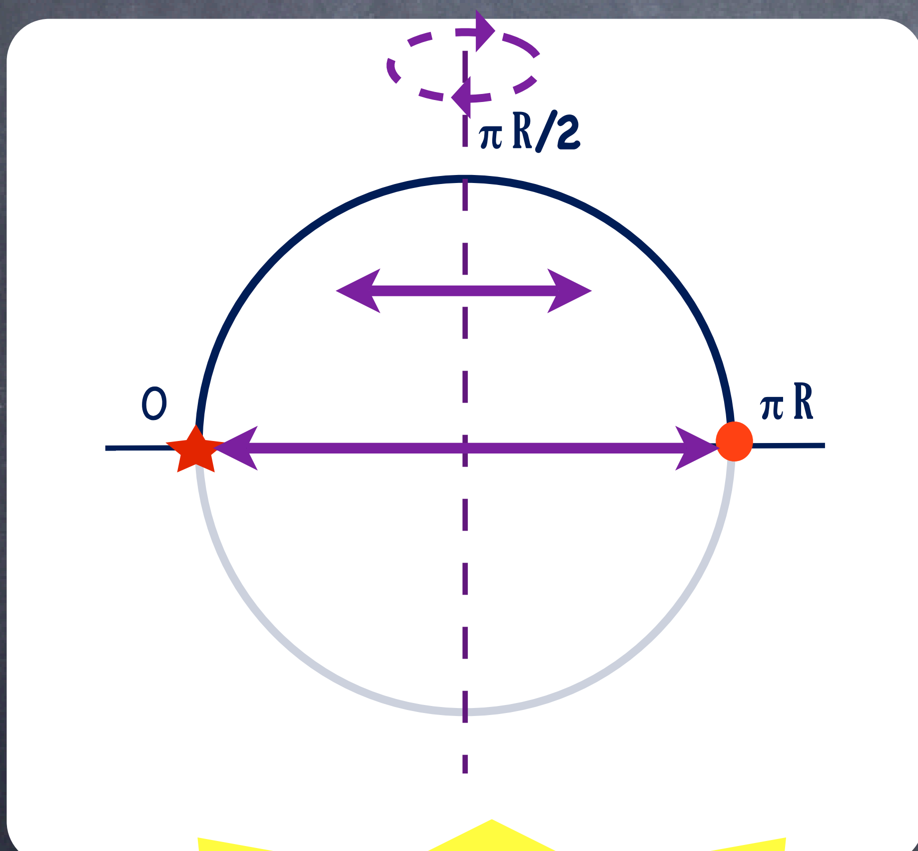
$$\cos\left(k\frac{x_5}{R}\right) \to (-1)^k \cos\left(k\frac{x_5}{R}\right).$$

However, fixed points (in red)
are NOT invariant!

Stability of the Dark Matter "requires" a symmetry!

Can it arise ``naturally" from extra dimensions?

- Symmetries of the compact space ARE parities for the Kaluza-Klein modes!
- The physics is in the wave functions: for instance



Orbifold $S^1/\mathcal{Z}_2$

$$x_5 \to \pi R - x_5$$

$$\cos\left(k\frac{x_5}{R}\right) \to (-1)^k \cos\left(k\frac{x_5}{R}\right).$$

However, fixed points (in red) are NOT invariant!

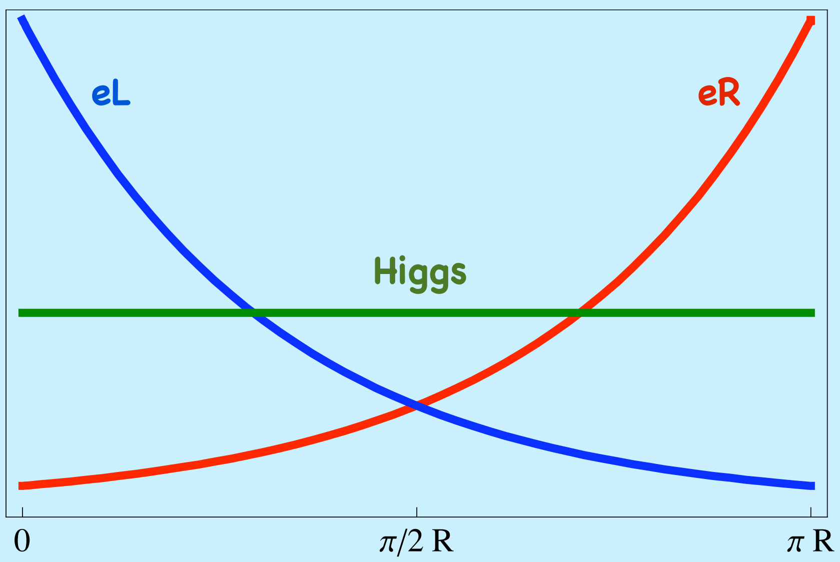
KK-parity is ad-hoc symmetry!

Stability of the Dark Matter "requires" a symmetry!

Can it arise ``naturally" from extra dimensions?

des!

In Gauge-Higgs Unification models, or models of flavour, fermion localisation is essential!



Bulk fermion masses break the KK parity!

Already pointed out by
Barbieri, Contino, Creminelli, Rattazzi, Scrucca
hep-th/0203039

KK-parity is ad-hoc symmetry!

KK-parity absent in interesting models!

Do orbifolds exist without fixed points and with chiral fermions?

G.C., A.Deandrea, J.Llodra-Perez 0907.4993

- There is none in 5D...
- In 6D there are 17 orbifolds (characterised by the discrete symmetry groups of the flat plane)...
- only ONE has chirality and no fixed points/lines! Unique candidate!

Requiring an exact parity
and chirality is rather restrictive!

The “flat” real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$

G.C., A.Deandrea, J.Llodra-Perez 0907.4993

$$r : \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases} \qquad g : \begin{cases} x_5 \sim x_5 + \pi R_5 \\ x_6 \sim -x_6 + \pi R_6 \end{cases}$$

Translations defined as:

$$\begin{aligned} t_5 &= g^2 \\ t_6 &= (gr)^2 \end{aligned}$$

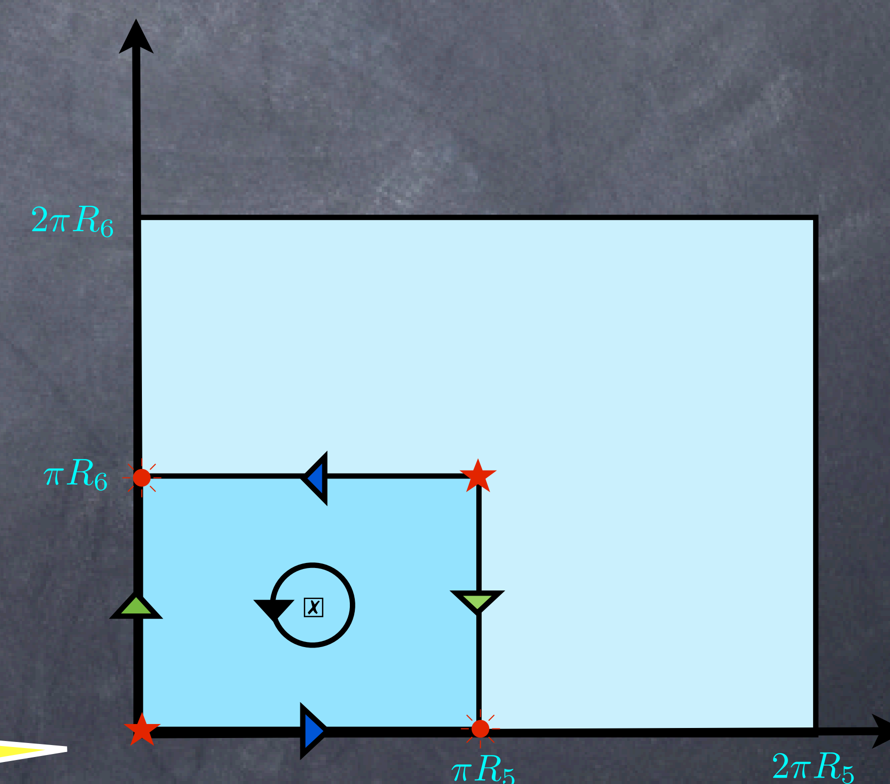
Two singular points:

$$(0, \pi) \sim (\pi, 0)$$

$$(0, 0) \sim (\pi, \pi)$$

KK parity is an exact symmetry of the space!

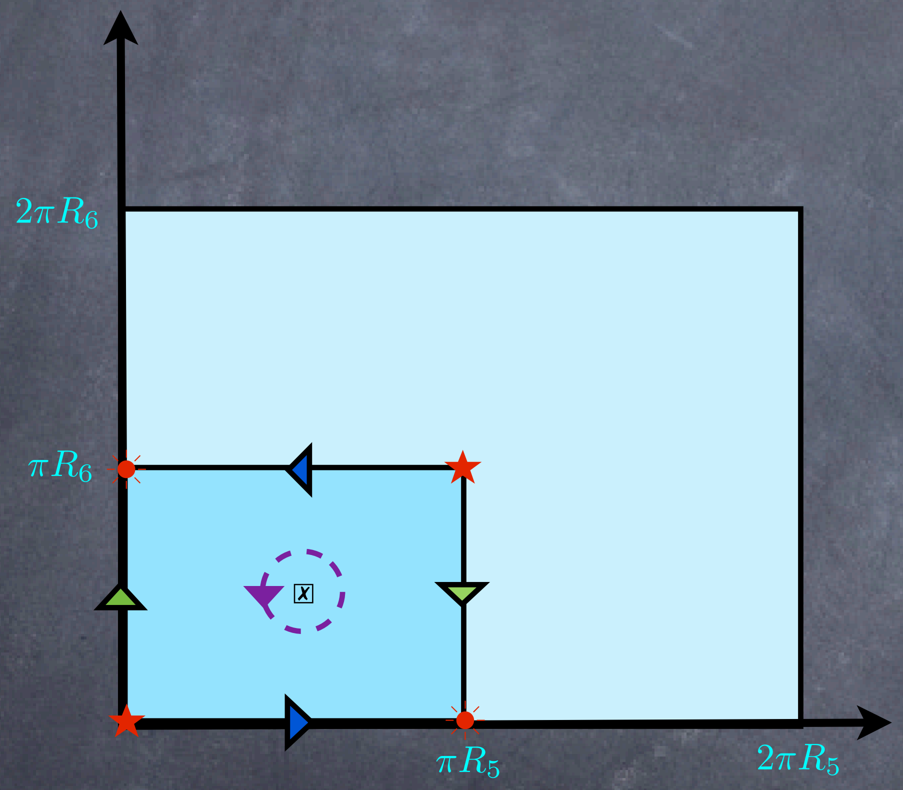
Spectrum and interactions determined by these symmetries!



The "flat" real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$

G.C., B.Kubik 1209.6556



Fundamental domain invariant under:

$$r' : \begin{cases} x_5 \to -x_5 + \pi R_5 \\ x_6 \to -x_6 + \pi R_6 \end{cases}$$

Can be redefined as a translation,
which commutes with orbifold symmetries:

$$p_{KK} = r' * r : \begin{cases} x_5 \to x_5 + \pi R_5 \\ x_6 \to x_6 + \pi R_6 \end{cases}$$

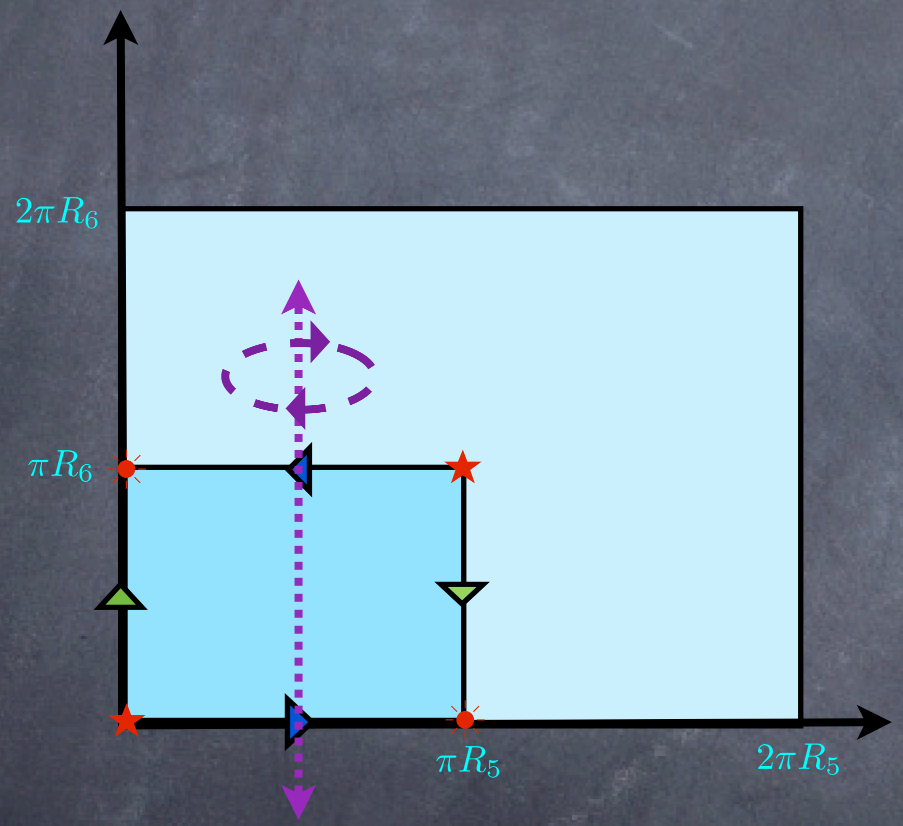
$$\text{Modes } (k, l) : \ p_{KK} = (-1)^{k+l}$$

This is an exact symmetry!

The "flat" real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$

G.C., B.Kubik 1209.6556



Fundamental domain invariant under:

$$m_4 \ : \begin{cases} x_5 \to -x_5 + \pi R_5 \\ x_6 \to x_6 \end{cases}$$

Can be redefined as a translation,
which commutes with orbifold symmetries:

$$m_4 * g * r \ : \begin{cases} x_5 \to x_5 \\ x_6 \to x_6 + \pi R_6 \end{cases}$$

$$\text{Modes } (k,l) : \ p'_{KK} = (-1)^l$$

This symmetry is respected by bulk interactions!

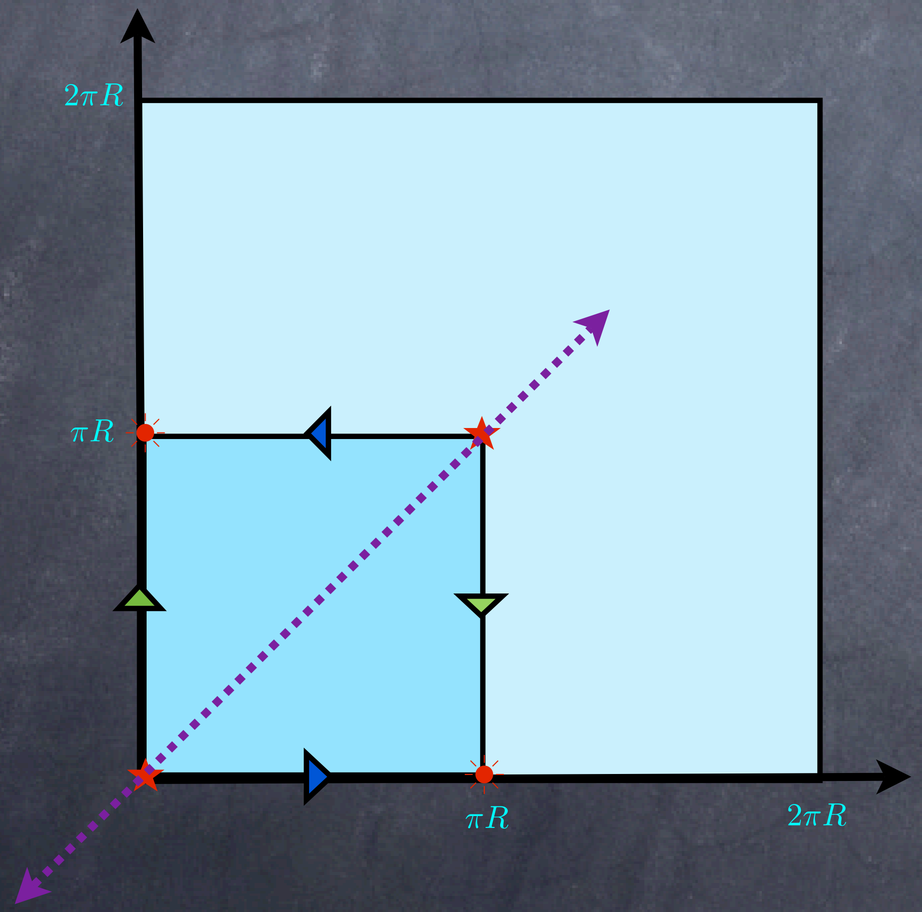
Violated by localised interactions!

The "flat" real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$

G.C., B.Kubik 1209.6556

Case of symmetric radii:



Fundamental domain invariant under:

$$m_d : \begin{cases} x_5 \to x_6 \\ x_6 \to x_5 \end{cases}$$

However, it is not a good symmetry, because it does NOT commute with the glide:

$$m_d * g * m_d = g * r : \begin{cases} x_5 \to -x_5 + \pi R_5 \\ x_6 \to x_6 + \pi R_6 \end{cases}$$

It does not respect orbifold projections:
e.g., a (-+) field mapped into a (--) field!

Spectrum of the SM

$p_{KK} = (-1)^{k+l}$	+	−	+	+	−
	(0,0) m = 0	(1,0) & (0,1) m = 1	(1,1) m = 1.41	(2,0) & (0,2) m = 2	(2,1) & (1,2) m = 2.24
Gauge bosons G, A, Z, W	✓		✓	✓	✓
Gauge scalars G, A, Z, W		✓	✓		✓
Higgs boson(s)	✓		✓	✓	✓
Fermions	✓	✓	✓ (x2)	✓	✓ (x2)

DM candidate here!

Spectrum of the SM

	+	-	+	+	-
$p_{KK} = (-1)^{k+l}$	(0,0) m = 0	(1,0) & (0,1) m = 1	(1,1) m = 1.41	(2,0) & (0,2) m = 2	(2,1) & (1,2) m = 2.24
Gauge bosons G, A, Z, W	✓		✓	✓	✓
Gauge scalars G, A, Z, W		✓	✓		✓
Higgs boson(s)	✓		✓	✓	✓
Fermions	✓	✓	✓ (x2)	✓	✓ (x2)

One-loop corrections are crucial to determine spectrum and decays!

G.C., A.Deandrea, J.Llodra-Perez 1104.3800

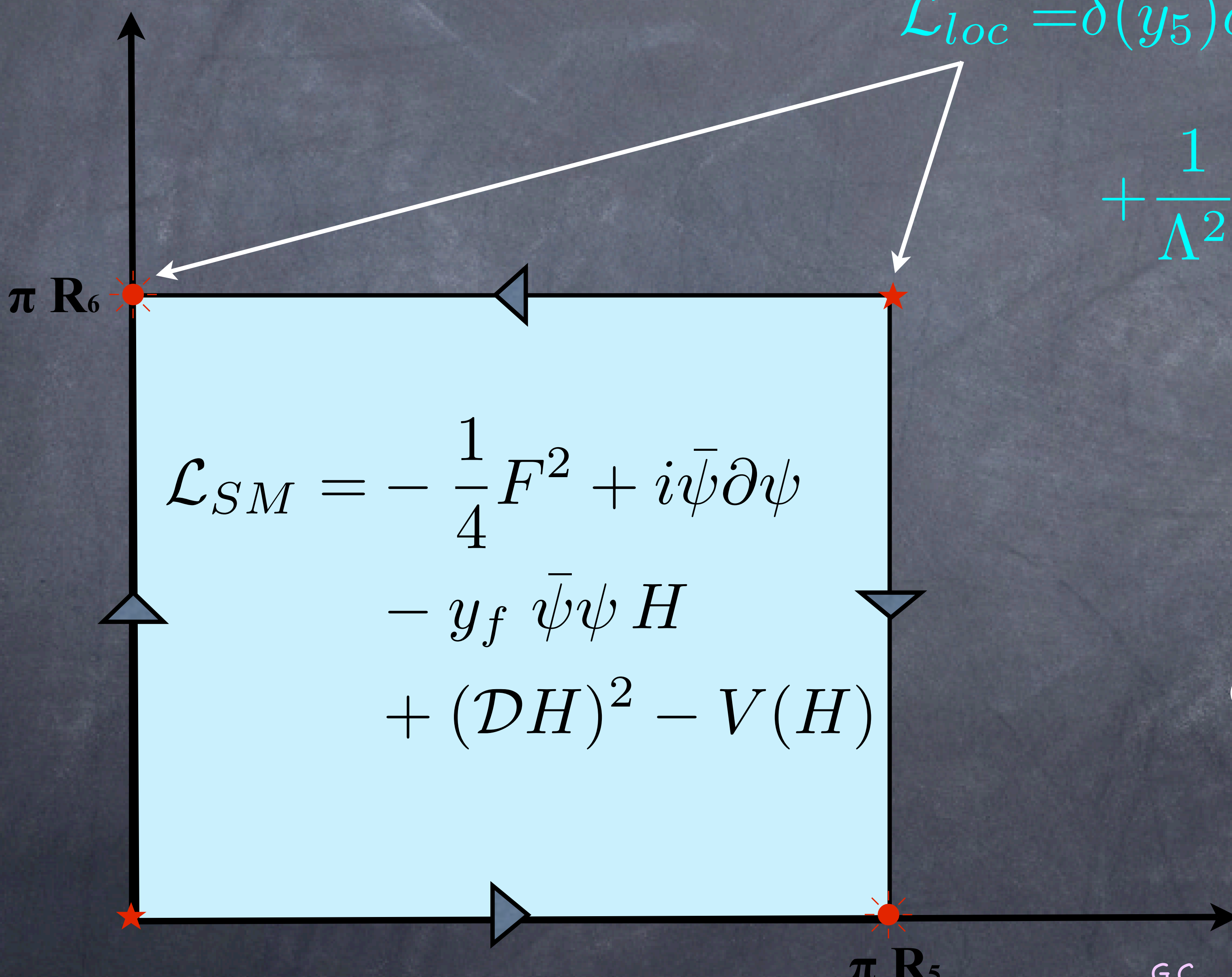
G.C., B.Kubik 1209.6556

Spectrum of the SM

Localised: KK number violating!

Bulk: KK number conserving!

$$\mathcal{L}_{loc} = \delta(y_5)\delta(y_6)\left\{ -m_{loc}^2 H^2 + \frac{1}{\Lambda^2}\left(-\frac{1}{4}F^2 + \dots \right) \right\}$$



$$\mathcal{L}_{SM} = -\frac{1}{4}F^2 + i\bar{\psi}\partial\psi - y_f\,\bar{\psi}\psi\,H + (\mathcal{D}H)^2 - V(H)$$

Higher order operators!

Counter-terms for 1-loop log divergences!

G.C., A.Deandrea, J.Llodra-Perez 1104.3800

Spectrum of the SM

We focus on two different limits:

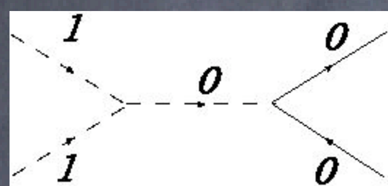
- asymmetric radii R4 > R5
- only (1,0) and (2,0) modes relevant

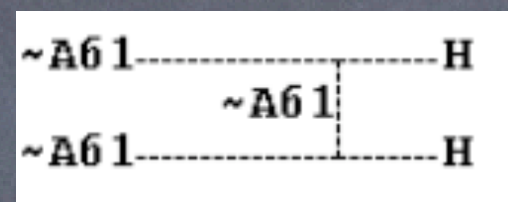
- symmetric radii R4 = R5
- (1,0) and (0,1) exactly degenerate (up to higher order ops)
- only state (2,0) + (0,2) relevant: mass splitting nearly doubled, couplings to SM pair
- (2,0) - (0,2) decouples (up to higher order operators)

WMAP bounds!

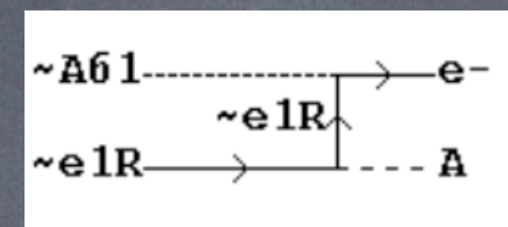
A.Arbey, G.C., A.Deandrea, B.Kubik 1210.0384

There are several equally relevant contributions:



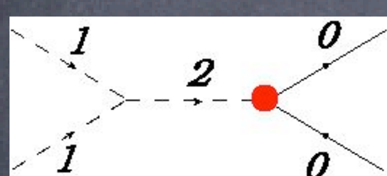


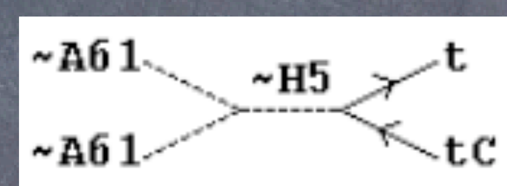
Annihilation



Co-annihilation

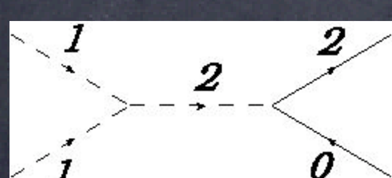
(small mass splitting)

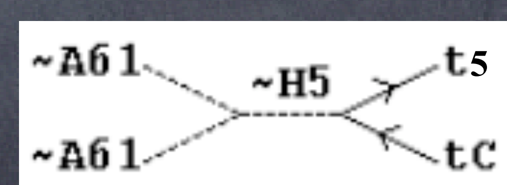




Resonant annihilation

(s-channel level 2 states!)





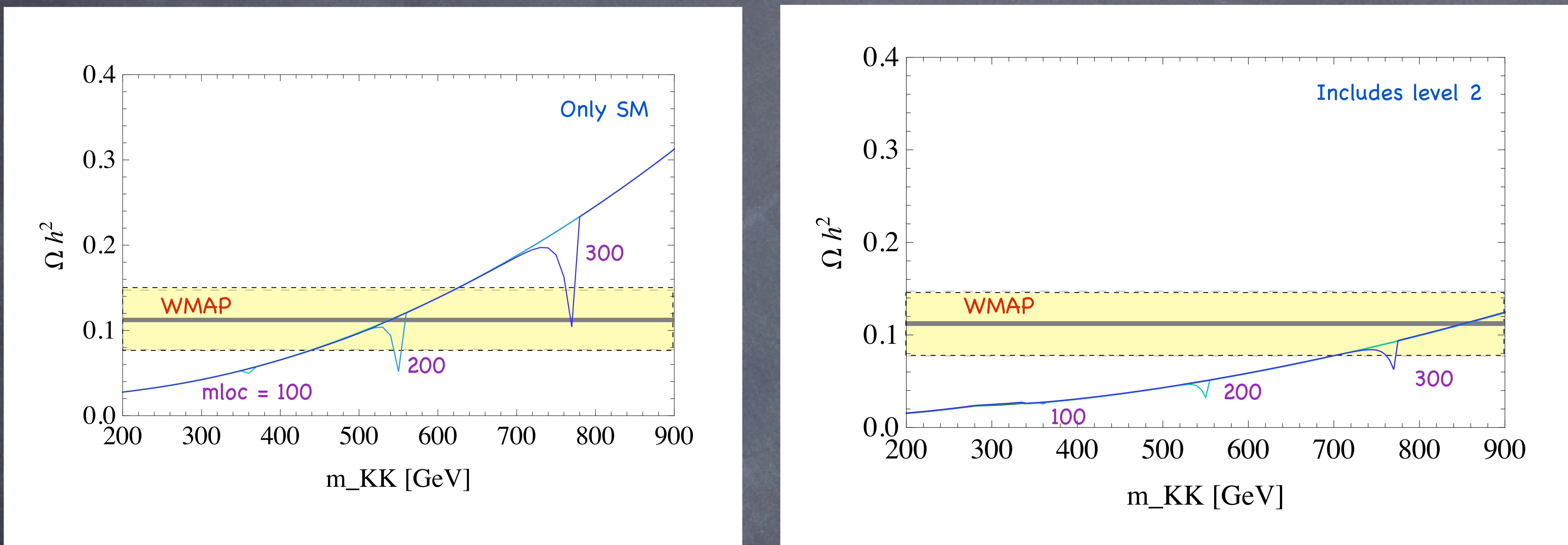
G.Belanger, M.Kakizaki, A.Phukov 1012.2577

Level 2 annihilation

(level 2 decaying into SM pair!)

WMAP bounds: tier (2) effect

Numerical results from MICROMEGAS

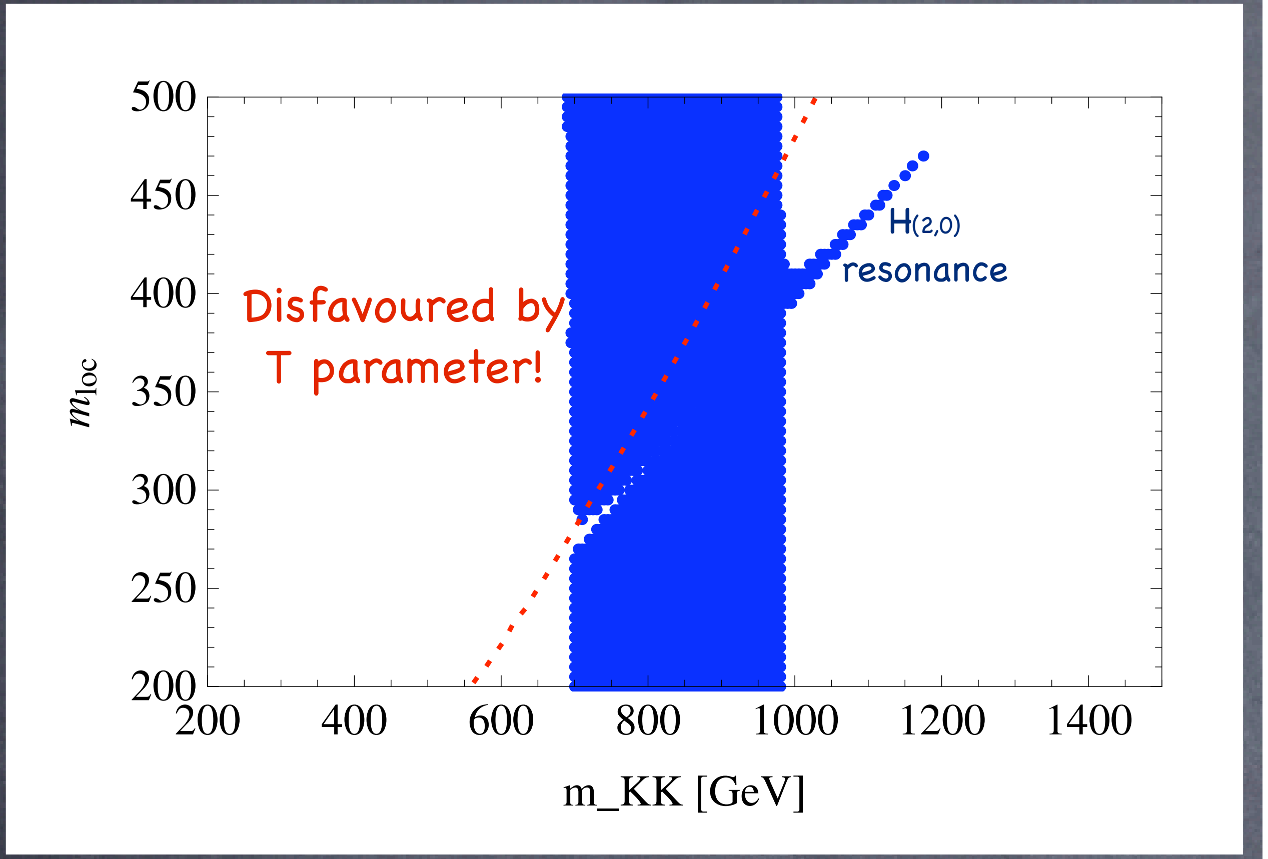


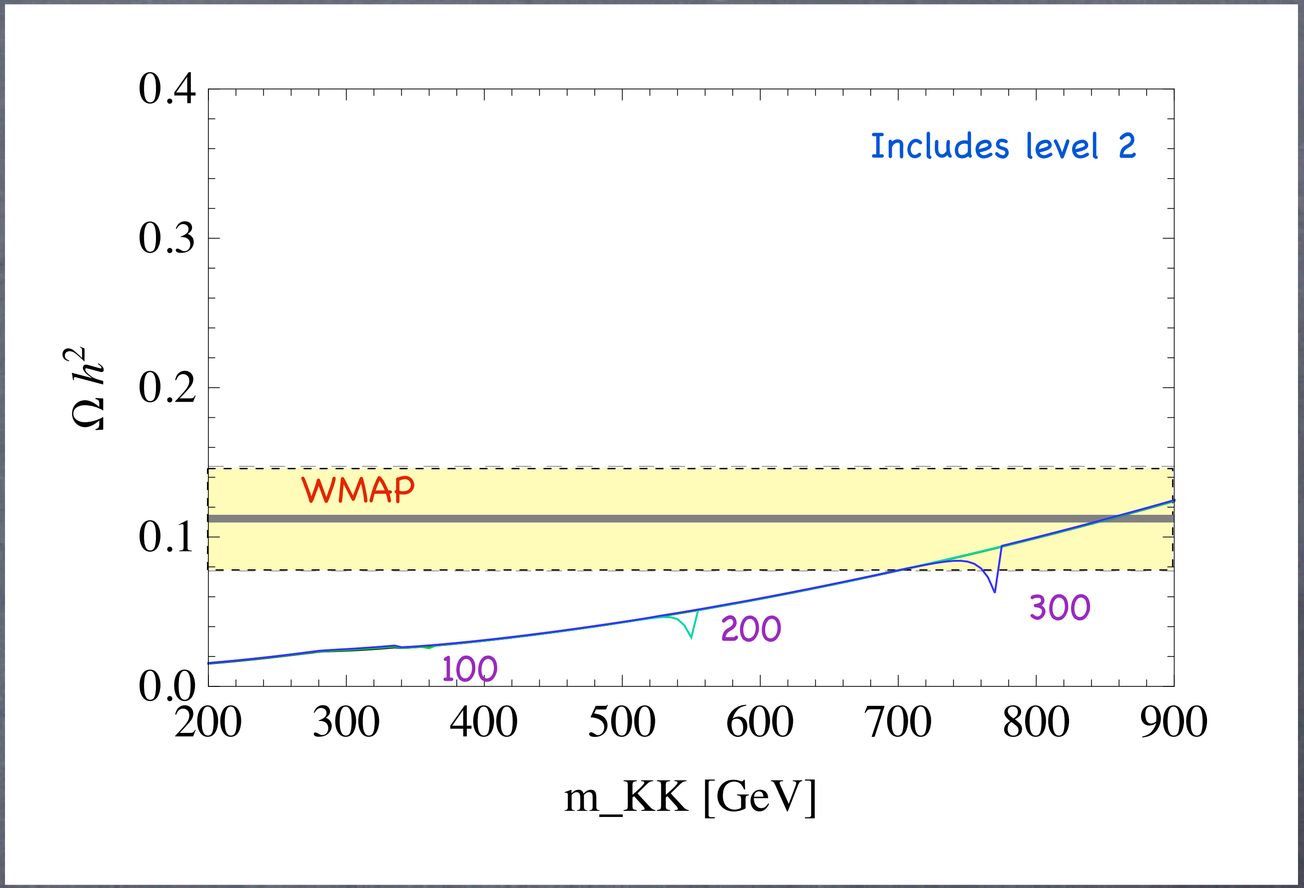
$R_5 > R_6$

- Annihilation into level-2 ⇒ increased cross-sections ⇒ higher mKK
- mloc controls $H_{(2,0)}$ resonance!
- $H_{(2,0)}$ opens resonant funnel!

WMAP bounds: $H_{(2)}$ resonance

Numerical results from MICROMEGAS





$R_5 > R_6$

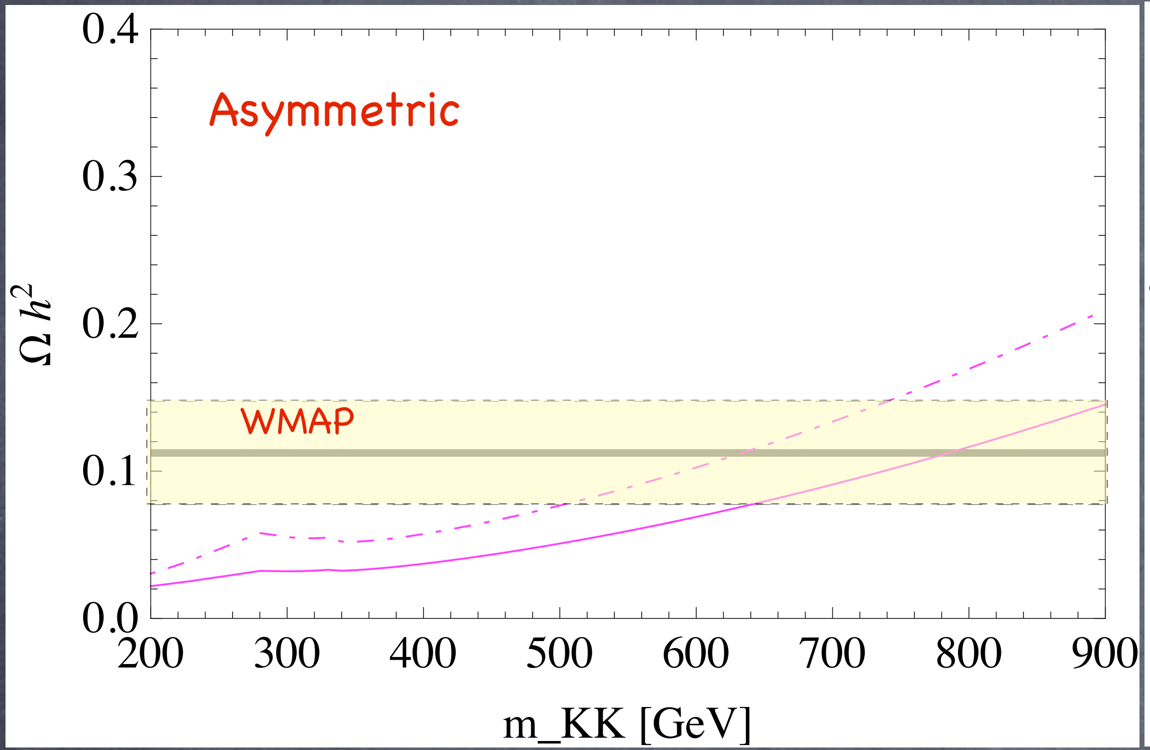
- Annihilation into level-2 ⇒ increased cross-sections ⇒ higher mKK
- mloc controls $H_{(2,0)}$ resonance!
- $H_{(2,0)}$ opens resonant funnel up to 1200!

WMAP preferred range:

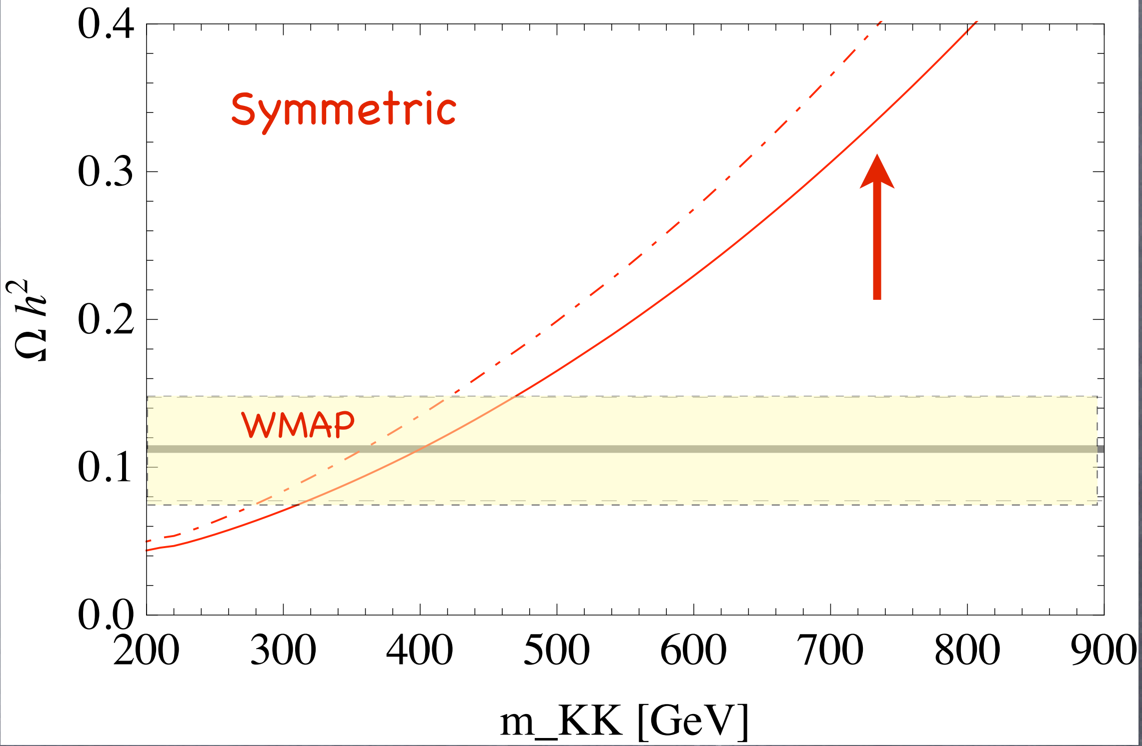
700 < mKK < 1000

WMAP bounds: $R_5 > R_6$ vs. $R_5 = R_6$

Numerical results from MICROMEGAS



$R_5 > R_6$

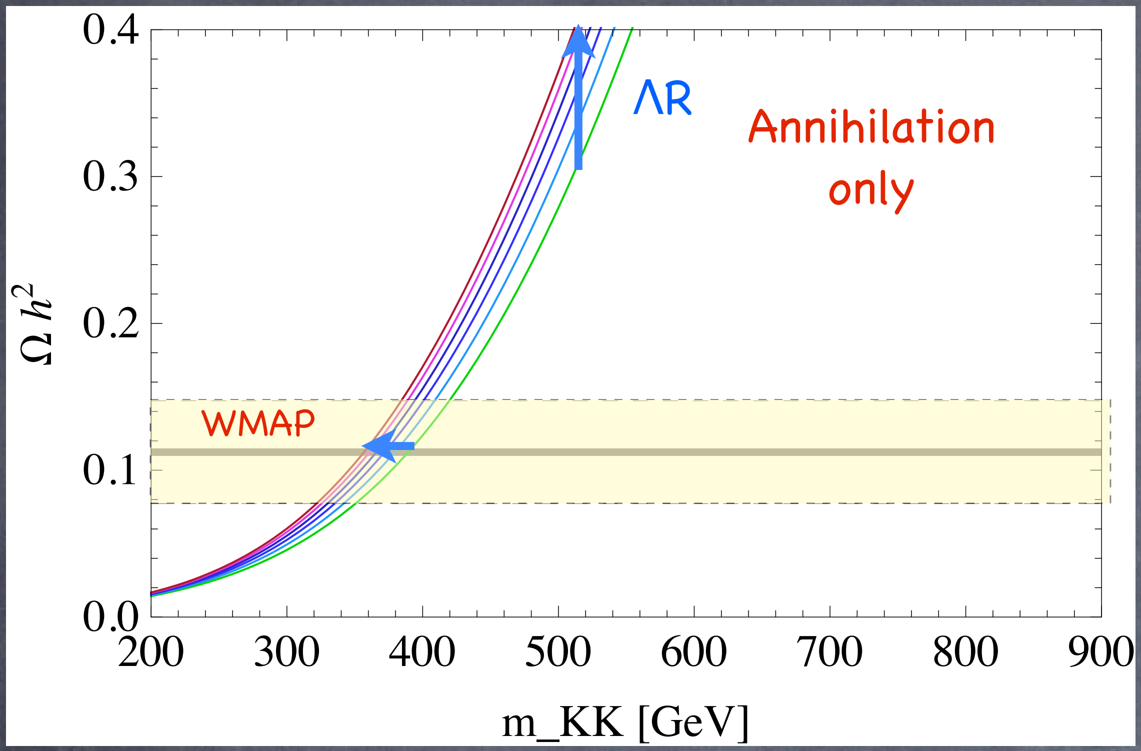


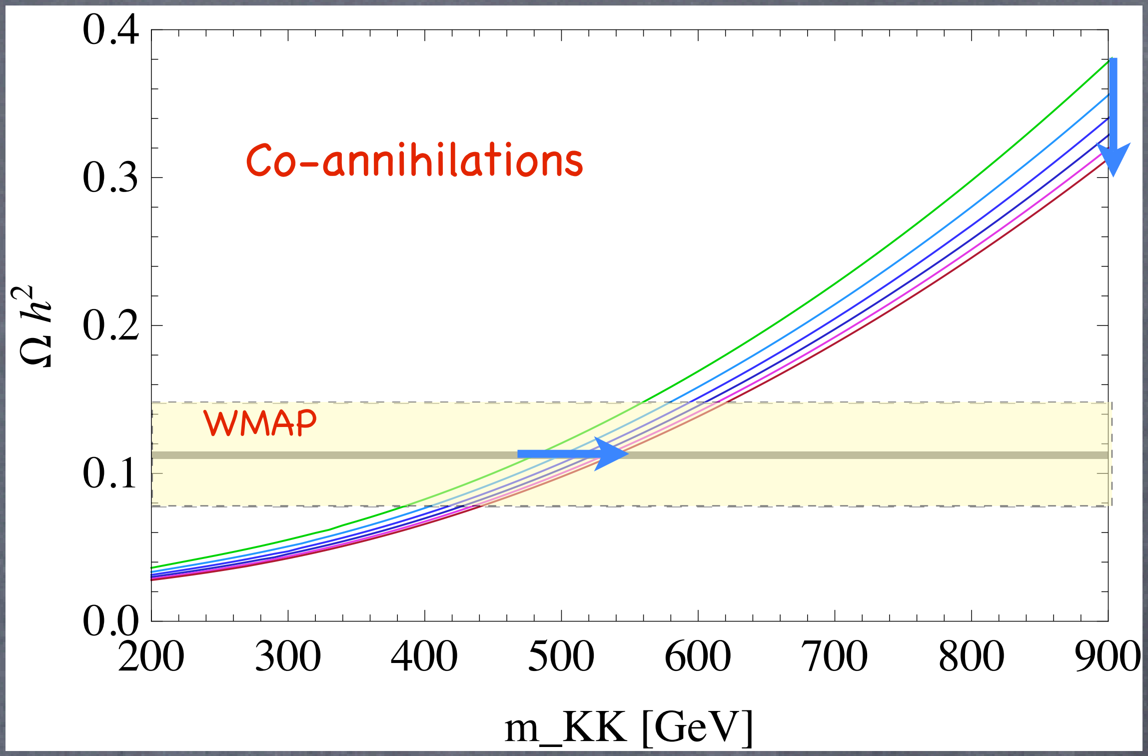
$R_5 = R_6$

- In the symmetric case, we have typically smaller mKK
- The reason is that two tiers contribute to the relic abundance!

WMAP bounds: cut-off dependence

Numerical results from MICROMEGAS





$R_5 > R_6$

- In the annihilation case, larger mass splitting suppressed cross sections (t-channel exchange of massive states)

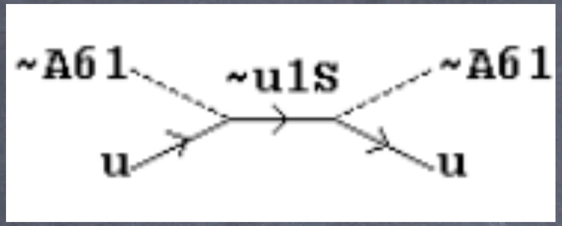
  ➜ mKK decreases

- For co-annihilation, larger mass splitting implies the other states contribute less, thus less degrees of freedom available!

  ➜ mKK increases

Direct detection bounds

Numerical results from MICROMEGAS

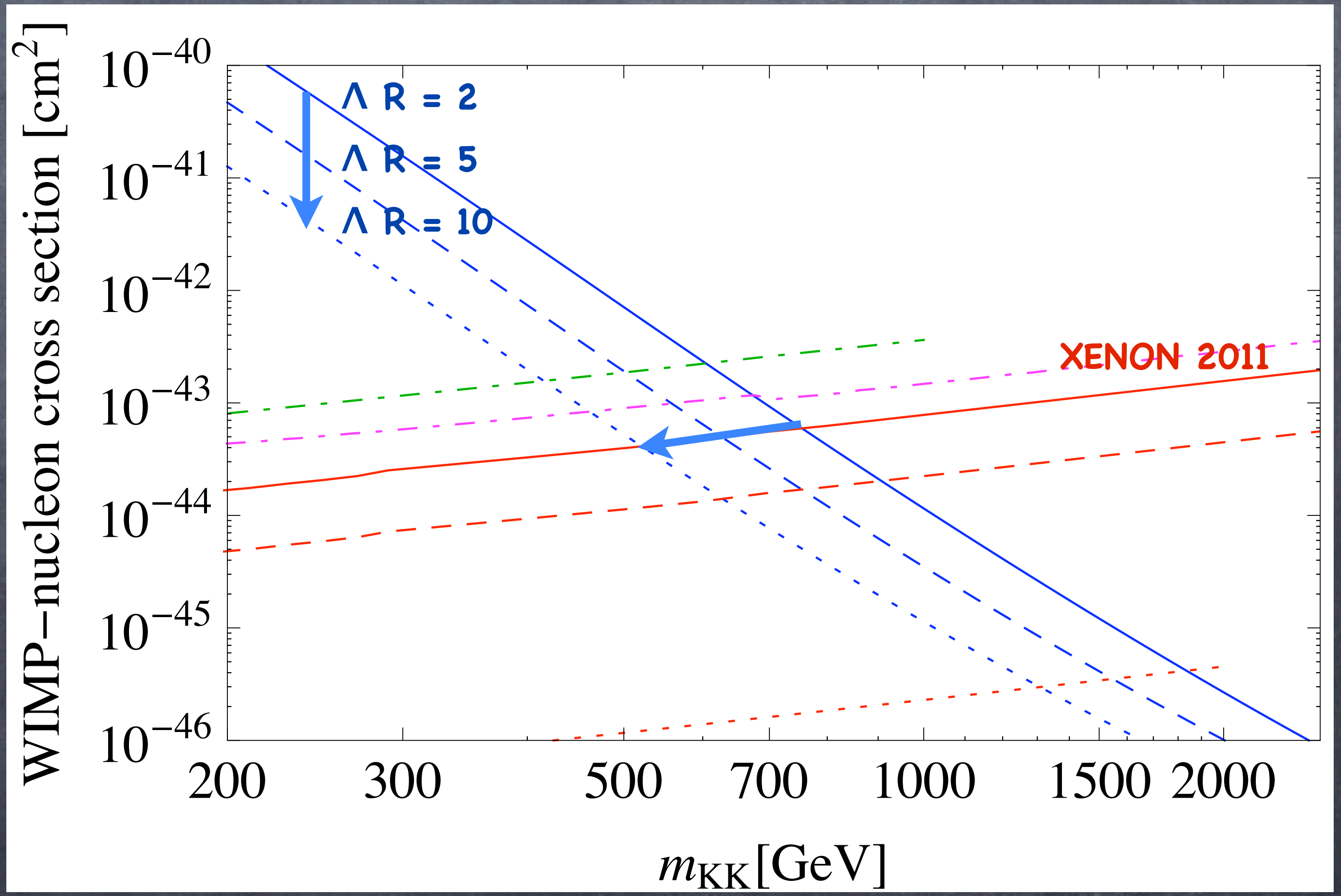


Relevant processes:
crucial the loop corrections
to level-1 masses!

- The Spin-Independent cross section is enhanced by the small splittings!

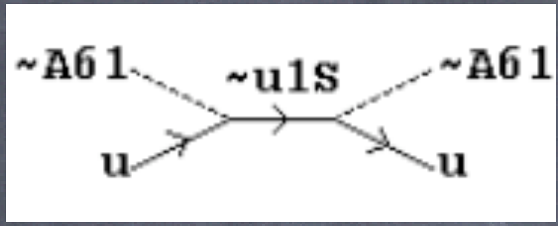
Bound sensitive to
cut-off Λ
via log-div. loops!

Independent on
radii config.



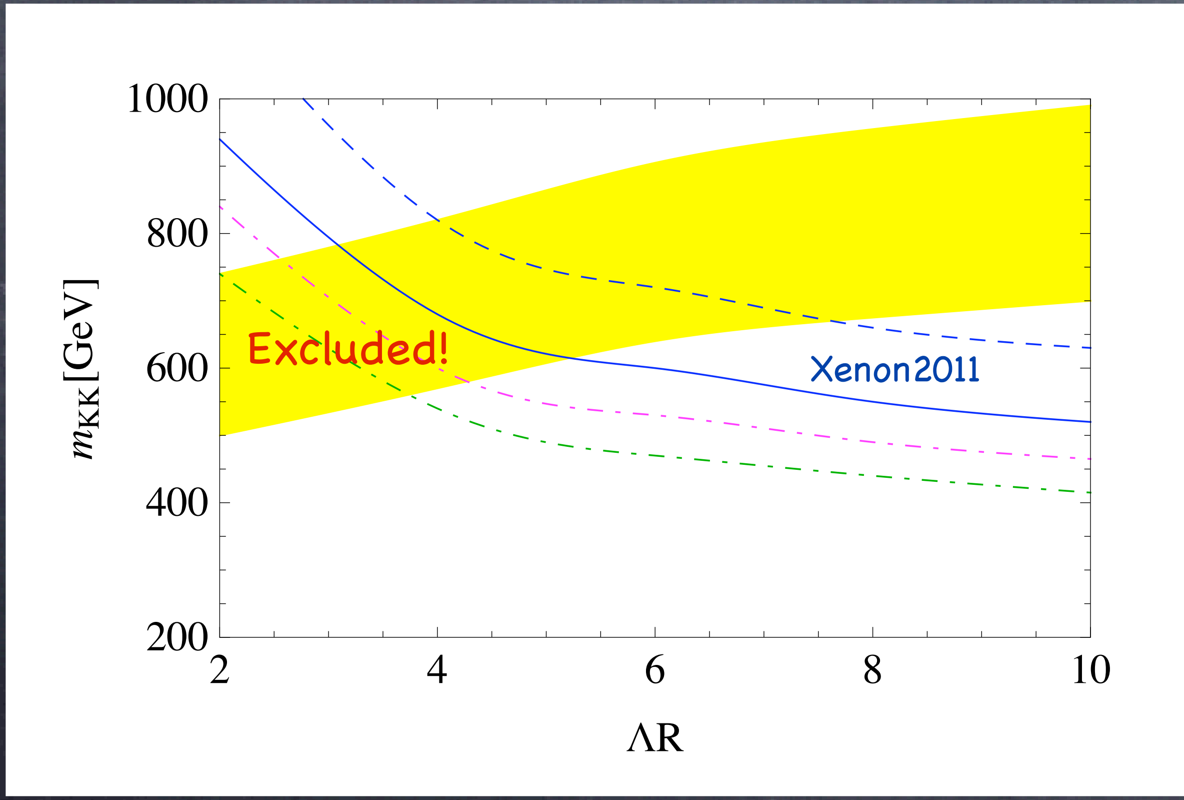
Direct detection bounds

Numerical results from MICROMEGAS

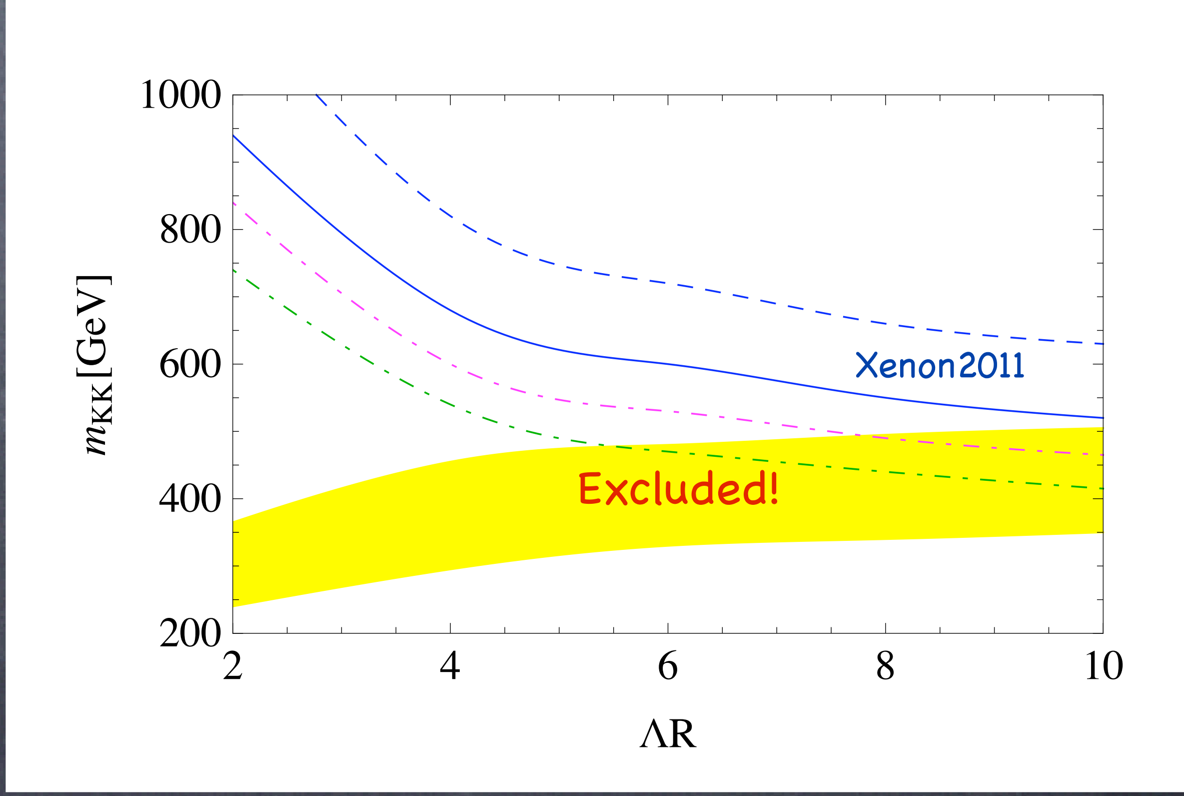


Relevant processes:
crucial the loop corrections
to level-1 masses!

- The Spin-Independent cross section is enhanced by the small splittings!



$R_5 > R_6$



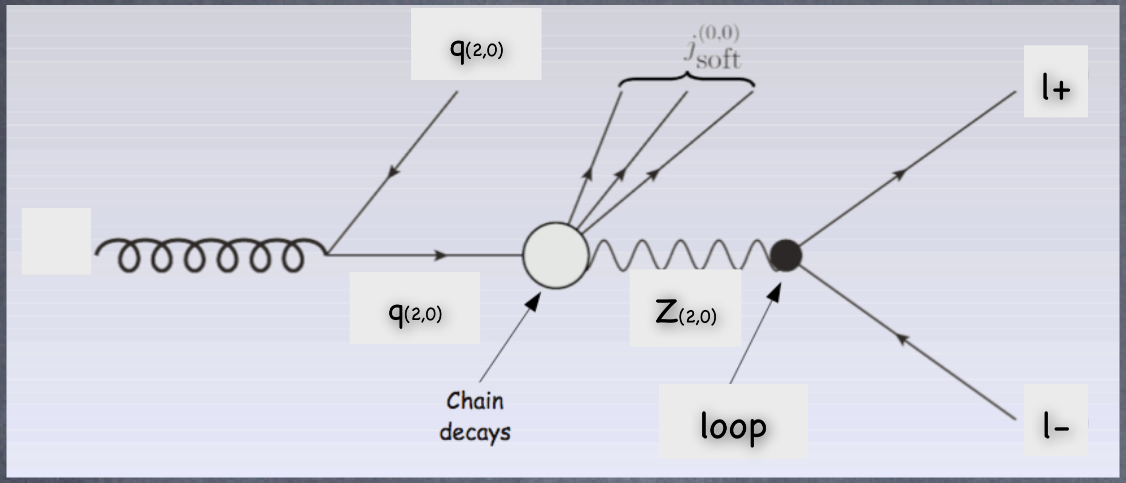
$R_5 = R_6$

LHC signatures without MET:

tiers (2,0) and (0,2)

G.C., B.Kubik 1209.6556

- Cleanest channels are di-lepton (Z′) and single lepton + MET (W′):

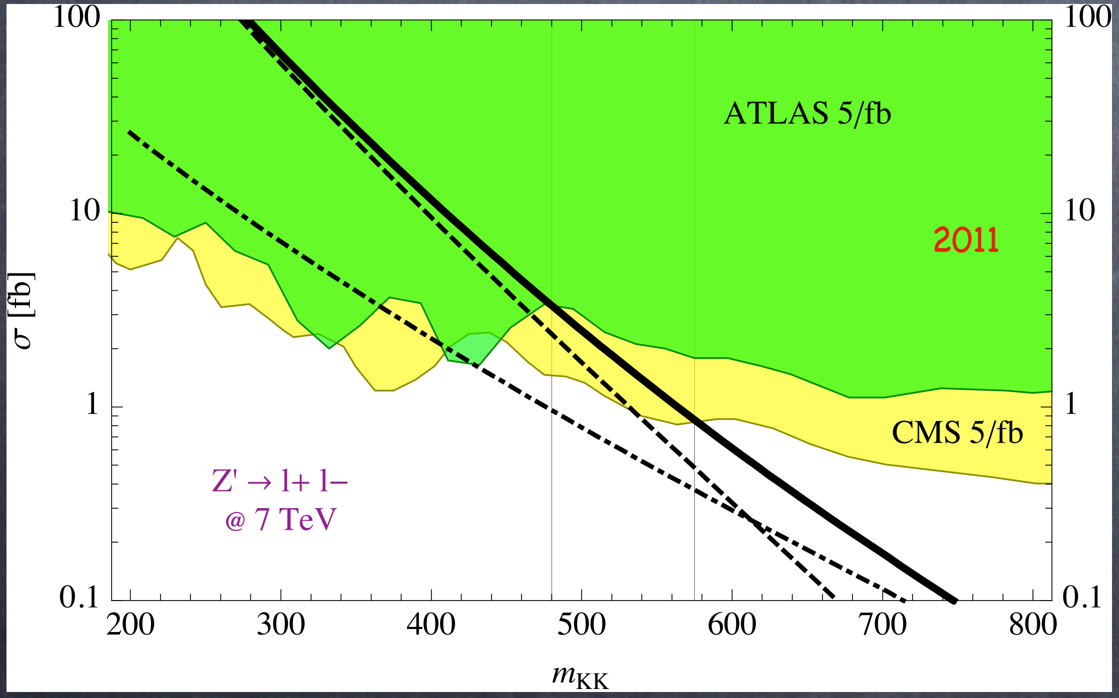


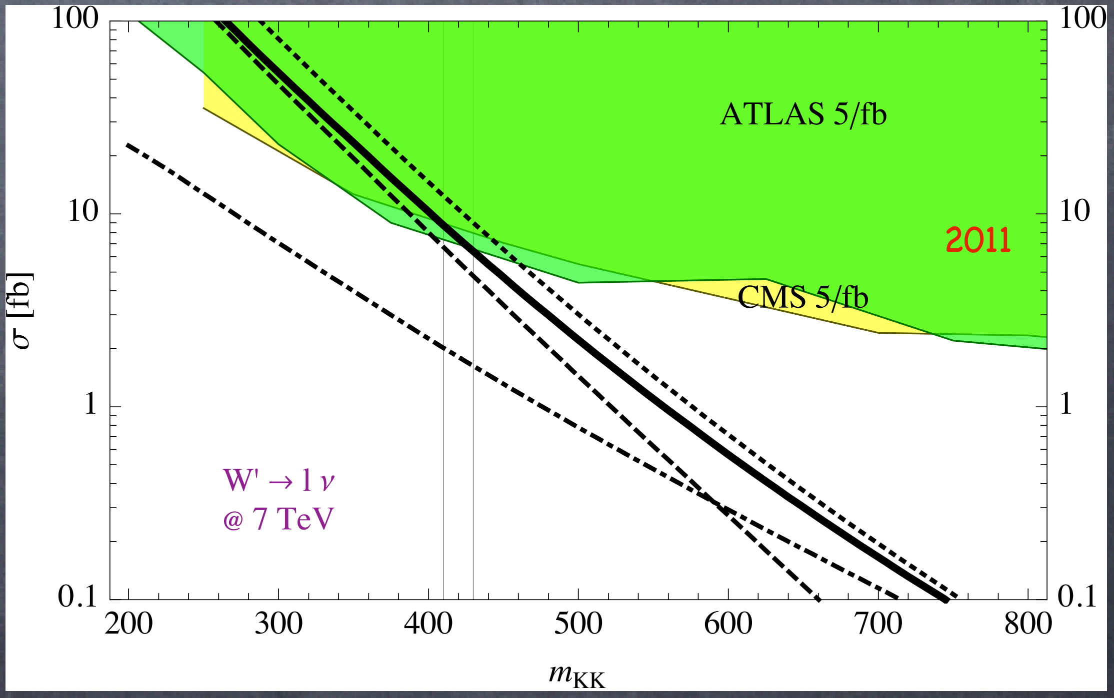
$Z_{(2,0)}$, $A_{(2,0)}$ -> l l

BR: 0.2% !!

$W_{(2,0)}$ -> l ν

2011 Data only!





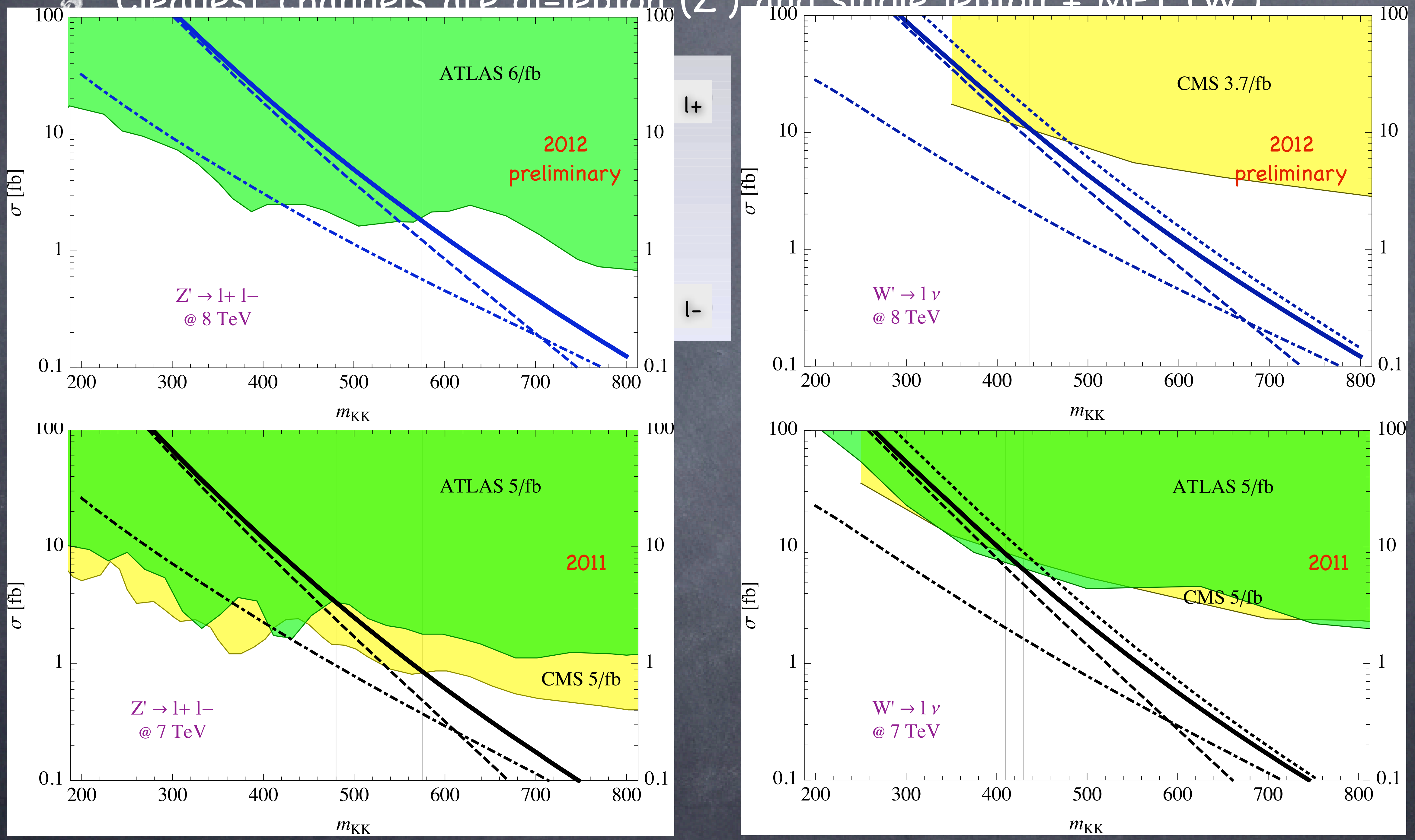
$R_5 > R_6$

LHC signatures without MET:

tiers (2,0) and (0,2)

G.C., B.Kubik 1209.6556

- Cleanest channels are di-lepton (Z') and single lepton + MET (W'):

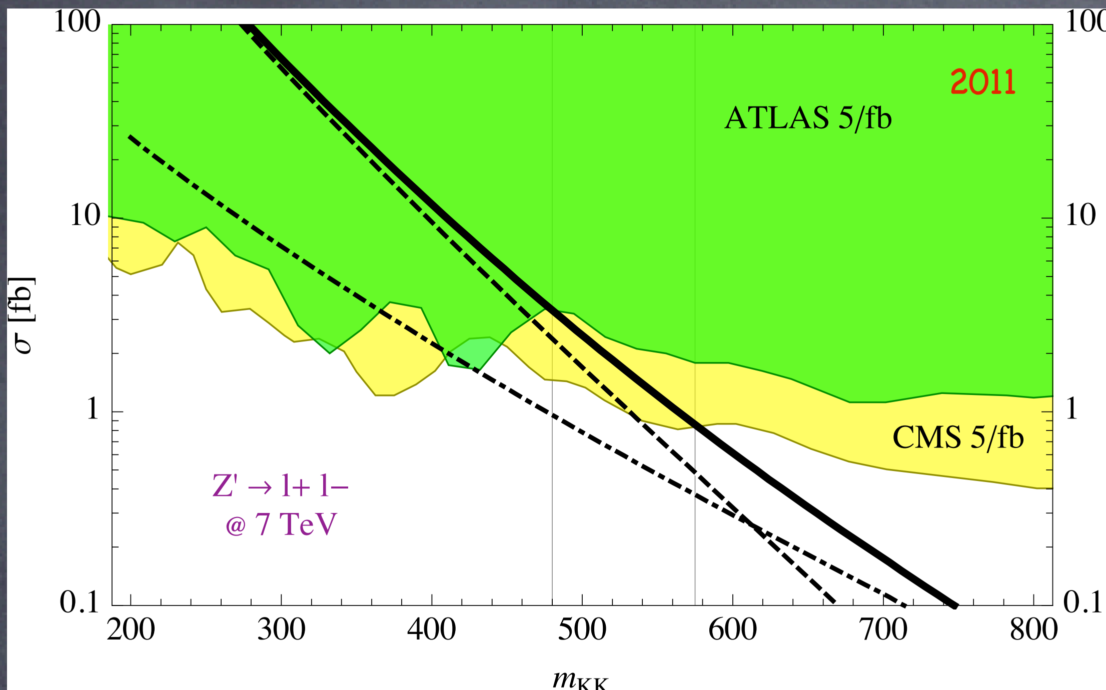


$R_5 > R_6$

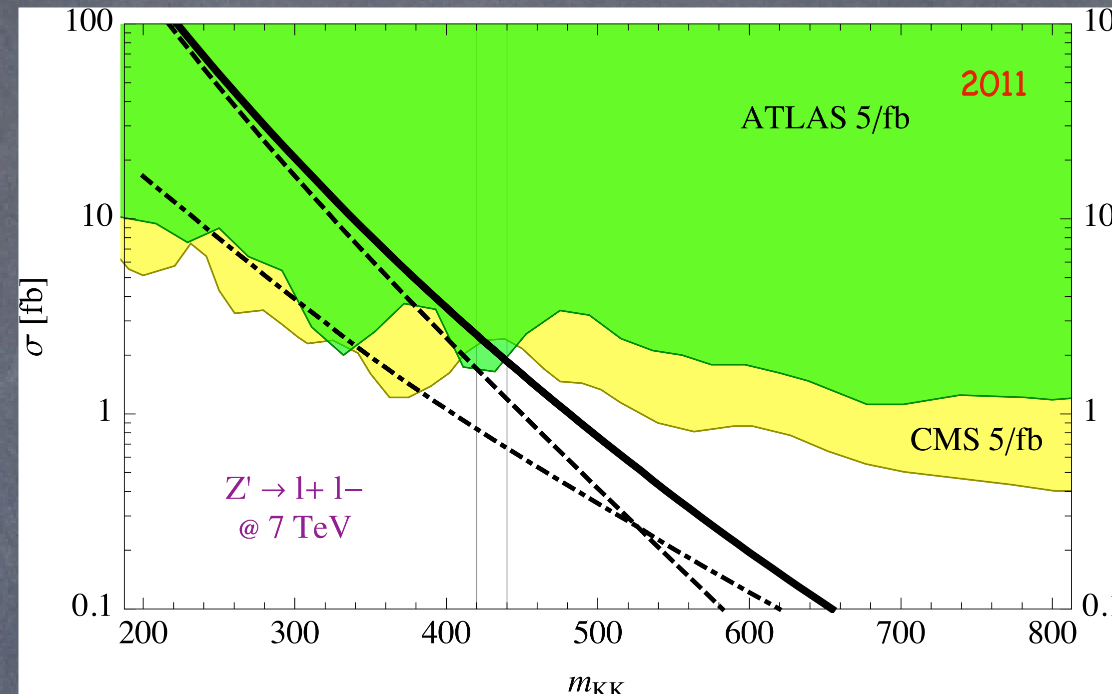
LHC signatures without MET:

tiers (2,0) and (0,2)

G.C., B.Kubik 1209.6556



$R_5 > R_6$



$R_5 = R_6$

- smaller production due to higher masses (for same mKK)
- larger splitting in tier (2) opens up decay modes into pair of (1) modes: e.g. $q_{(2)} \to q_{(1)}\ G_{(1)}$
- suppressed branching into SM pairs!

Other LHC bounds

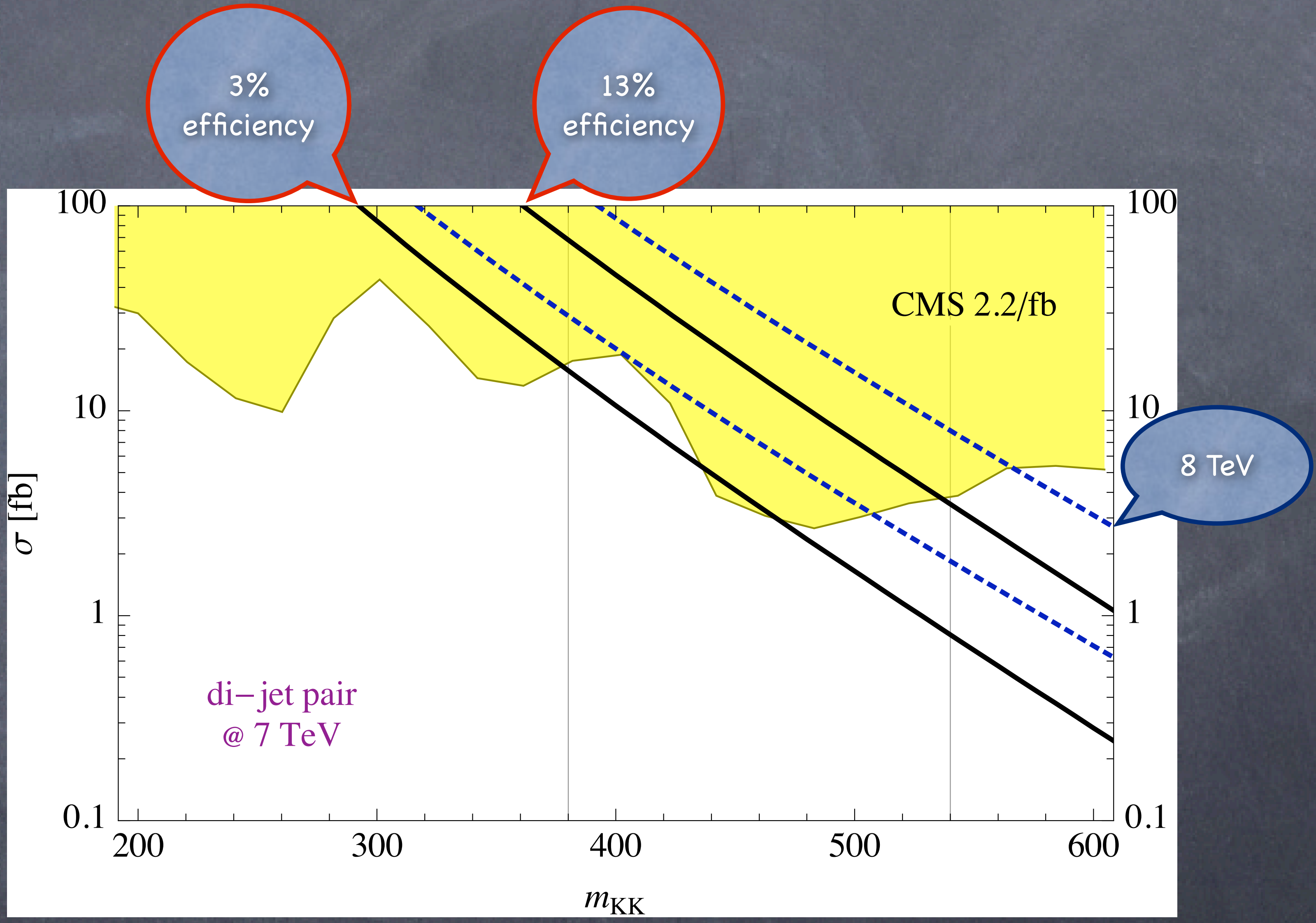
G.C., B.Kubik 1209.6556

Pair of di-jet resonances

Events with 4 high-pT jets.

Reconstruct two invariant masses with similar value.

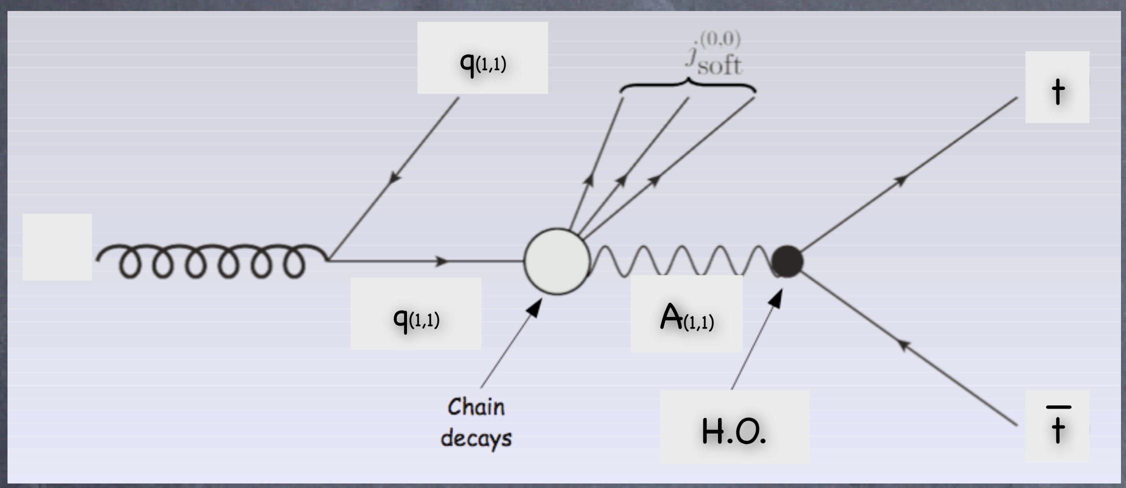
Other kinematic cuts to obtain smooth QCD background.



$R_5 > R_6$

Other LHC bounds

4-top final state: search in same-sign dileptons



G.C., R.Chierici, A.Deandrea, L.Panizzi, S.Perries, S.Tosi
1107.4616

Tier (1,1) cannot decay at loop level into SM, nor into a pair of (1,0) + (0,1)!

Chain decay into lightest state A(1,1)

A(1,1) can decay into t tbar!

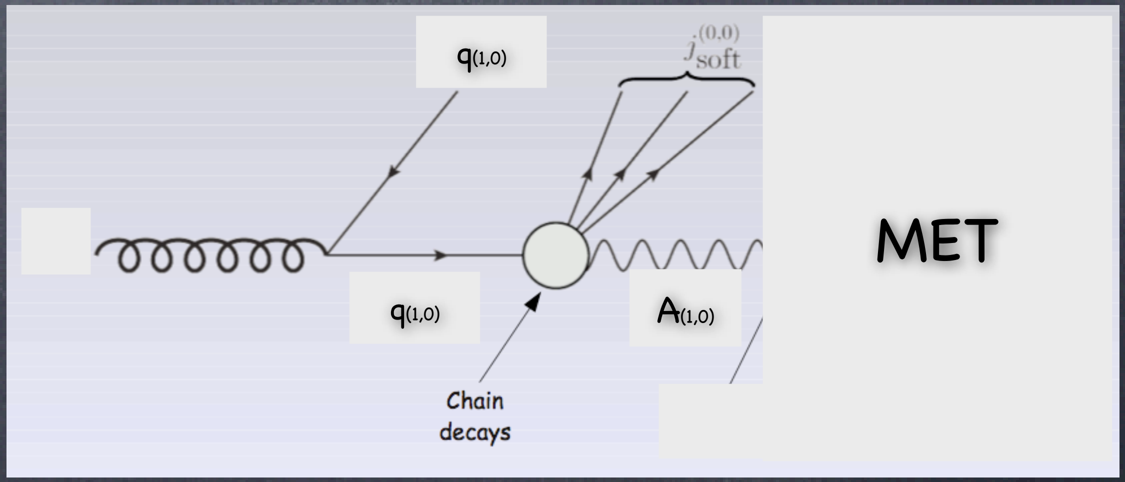
HUGE production cross sections: all KK states contribute to it!

ATLAS search under evaluation!

MET signatures from (1,0) and (0,1):

lighter, but relying on ISR!

G.C., A.Deandrea, J.Ellis, L.Panizzi, J.Marrouche 1302.4750



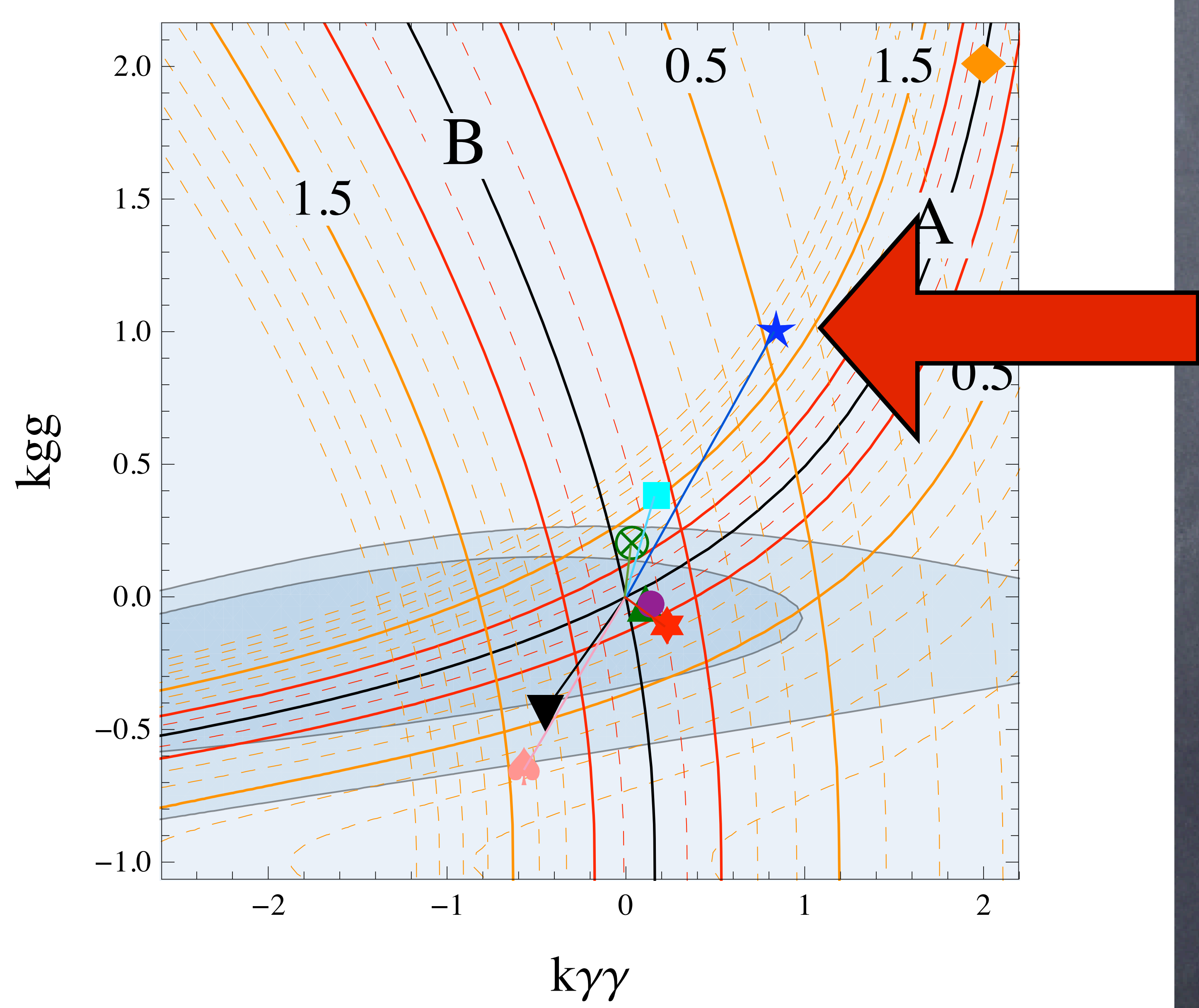
LHC: the Higgs discovery!

G.C., A.Deandrea, J.Llodra-Perez 0901.0927
G.C., A.Deandrea, G.Drieu La Rochelle, J.B.Flament 1210.8120

- The KK resonances of W and top contribute to H→gg and H →γγ loops!

CMS data (HCP12)

- H →γγ
- H →ZZ



mKK = 600 GeV

k_{gg}, $k_{\gamma\gamma} \approx 1/mKK^2$

Conclusions and outlook

- Exact KK parity is a very selective requirement on XDs: RPP in 6D flat!
- SM on the RPP: rich pheno, very nice interplay of LHC, WMAP and Direct Detection experiments!
- Case $R_5 = R_6$ excluded by Direct Detection + WMAP.
- Case $R_5 > R_6$ preferred range $700 < mKK < 1000$ GeV.
- LHC bounds @ $mKK > 600$ GeV level (leptonic Z' and W')
- Others: signatures with MET (+ jets) from (1,0) and (1,2); 4 tops from (1,1); etc.

For the levels (1,0) and (0,1):

$$m = m_{KK} + \delta m$$