COSMO-02: September 20th, 2002

KALUZA-KLEIN DARK MATTER

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Outline:

1. Introduction/Motivation
2. Relic Density
3. Detection
4. Outlook

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* [hep-ph/0206071] and [hep-ph/0209xxx].

Introduction: Dark Matter

- Most of the Universe is Dark
- CMB anisotropy and Hubble parameter measurements point to a flat universe with 30% dark matter and 4% baryonic
- (Consistent with clusters and BBN)
- Turner, astro-ph/0106035:

$$\begin{aligned} \Omega_M &= 0.33 \pm 0.035 \\ h &= 0.69 \pm 0.04 \end{aligned}$$

so:

$$\Omega_M h^2 = 0.16 \pm 0.04$$

- Structure formation prefers a non-relativistic WIMP

Introduction: Extra Dimensions

- Many exciting XD models have extra compact space dimensions:
  - Hierarchies from volume suppressions
  - Electro-weak Symmetry Breaking
  - Supersymmetry Breaking
  - GUT Breaking
  - Six Dimensions:
    - Proton Stability from remnant spacetime symmetry
    - Number of Fermion generations from Anomaly Cancellation
- New motivation : Dark Matter!

Universal Extra Dimensions

- A particularly interesting case phenomenologically has all fields propagating in the extra dimensions
  [Dienes, Dudas, Gherghetta; Appelquist, Cheng, Dobrescu]
- With no brane to explicitly break translational invariance, a Kaluza-Klein parity survives at low energies: -1^n
- KK-parity requires odd KK modes to couple in pairs
  - The lightest first-level KK mode is stable
  - First level KK modes must be pair-produced
- Electroweak precision measurements and direct searches require $M_{KK} \gtrsim 400$ GeV
- Note that for 5d or 6d this implies a high Planck scale
- The phenomenology depends crucially on the LKP

Boundary Terms

- In order to have chiral fermions in 4d, we need orbifold boundary conditions
- Radiative corrections will induce terms in the Lagrangian which live on the boundaries
  [Georgi, Grant, Hailu]
- These terms are $\log$ divergent in the effective theory: no prediction for their sizes
  [Cheng, Matchev, Schmaltz]
- If these terms are large, the usual KK mode mass spectrum can be significantly distorted
  [Carena, TT, Wagner]
- However, KK parity is still respected provided the terms living on both boundaries are identical
- The radiative corrections *are* symmetric

Identity of the LKP

- To have a good WIMP, we need the LKP to be non-baryonic and electrically neutral

- If we imagine the boundary terms are zero at the cut-off scale, they will be induced at loop size:

$$\delta M \quad \sim \quad M \frac{\alpha}{4\pi} \log\left(\frac{\Lambda}{M}\right)$$

- Since $\alpha_1 \ll \alpha_2 \ll \alpha_3$, we can imagine that the smallest corrections are to the U(1) gauge boson

$$\begin{pmatrix} \frac{1}{R^2} + \frac{1}{4} g_1^2 v^2 + \delta M_1^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{1}{R^2} + \frac{1}{4} g_2^2 v^2 + \delta M_2^2 \end{pmatrix}$$

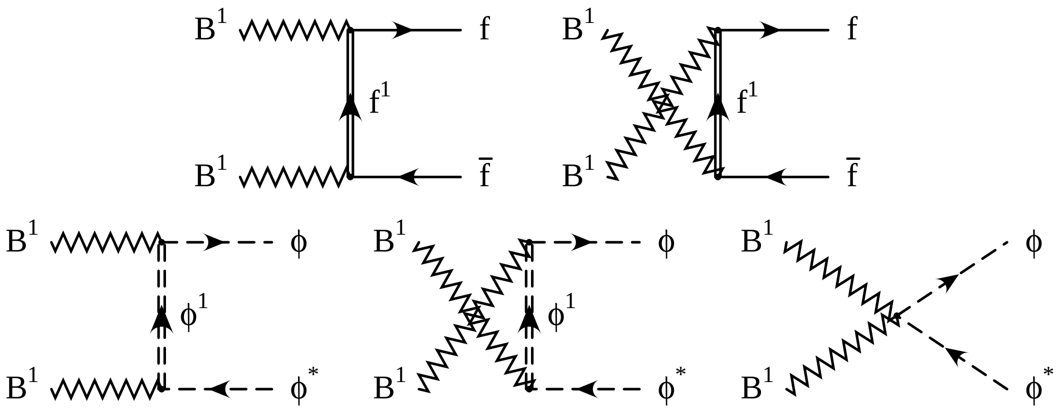
- Since $\delta M \sim 1/R \gg v$, we can reasonably expect the LKP to be purely a KK mode of the U(1) gauge boson: $B_\mu^{(1)}$

- Following this line of reasoning, we can expect the NLKP to be the right-handed electron: $e_R^{(1)}$

Annihilation Rates

- To estimate the relic density, we assume our LKP was in thermal equilibrium in the early universe, and apply the Boltzmann equation to determine its freeze-out temperature: $x_f \equiv m/T_f$

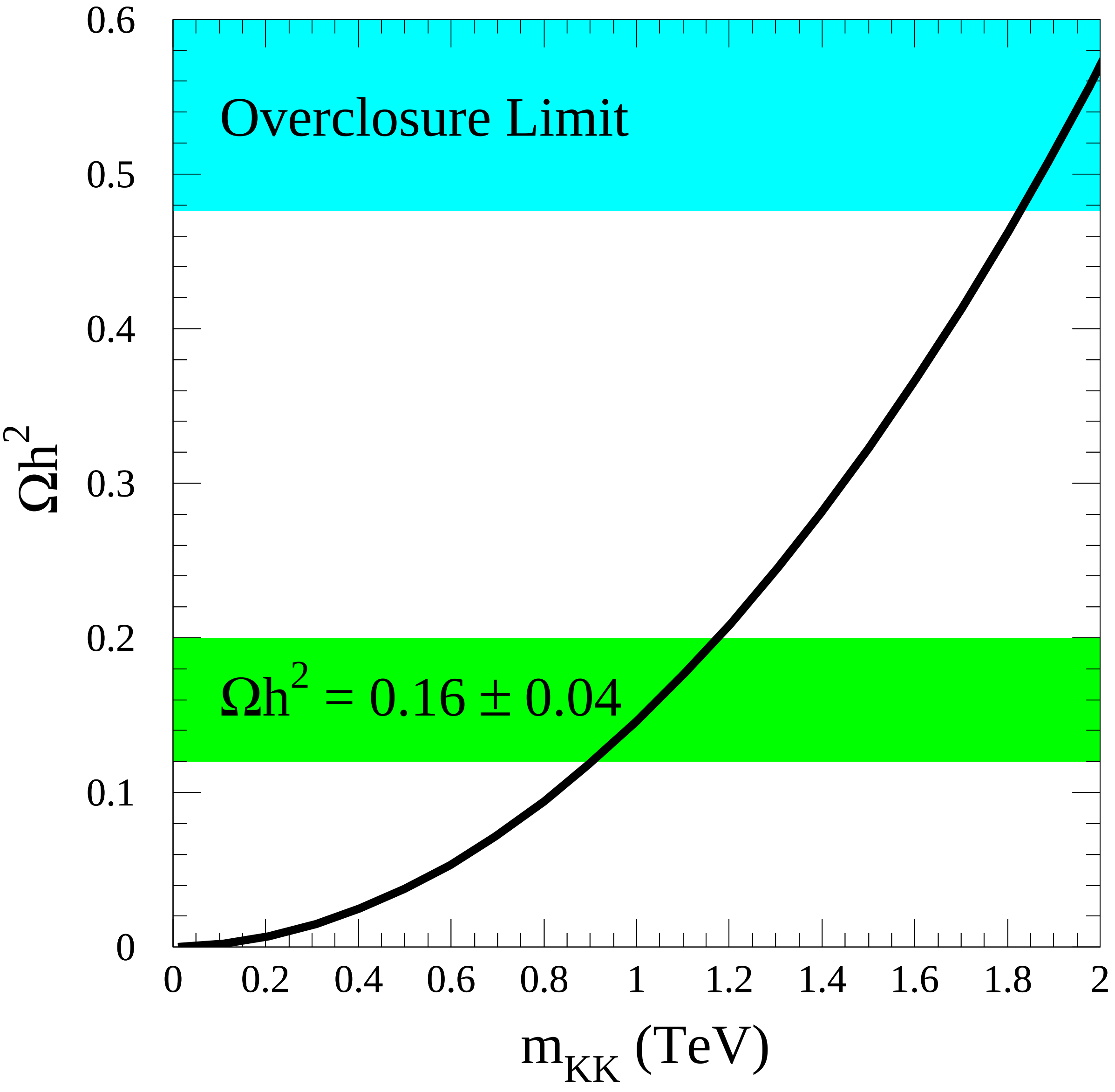
- We compute the mutual annihilation cross sections of the LKP into zero modes:



$$\Omega h^2 \simeq \frac{10^9 x_f}{M_{Pl}\sqrt{g_*}} \frac{1}{a + 3b/x_f}$$

$$\langle \sigma v \rangle \simeq a + bv^2 = a + 6b/x$$

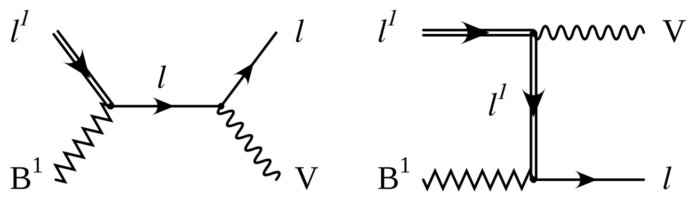
Relic Density



- Relic density favors the mass range 850 - 1200 GeV

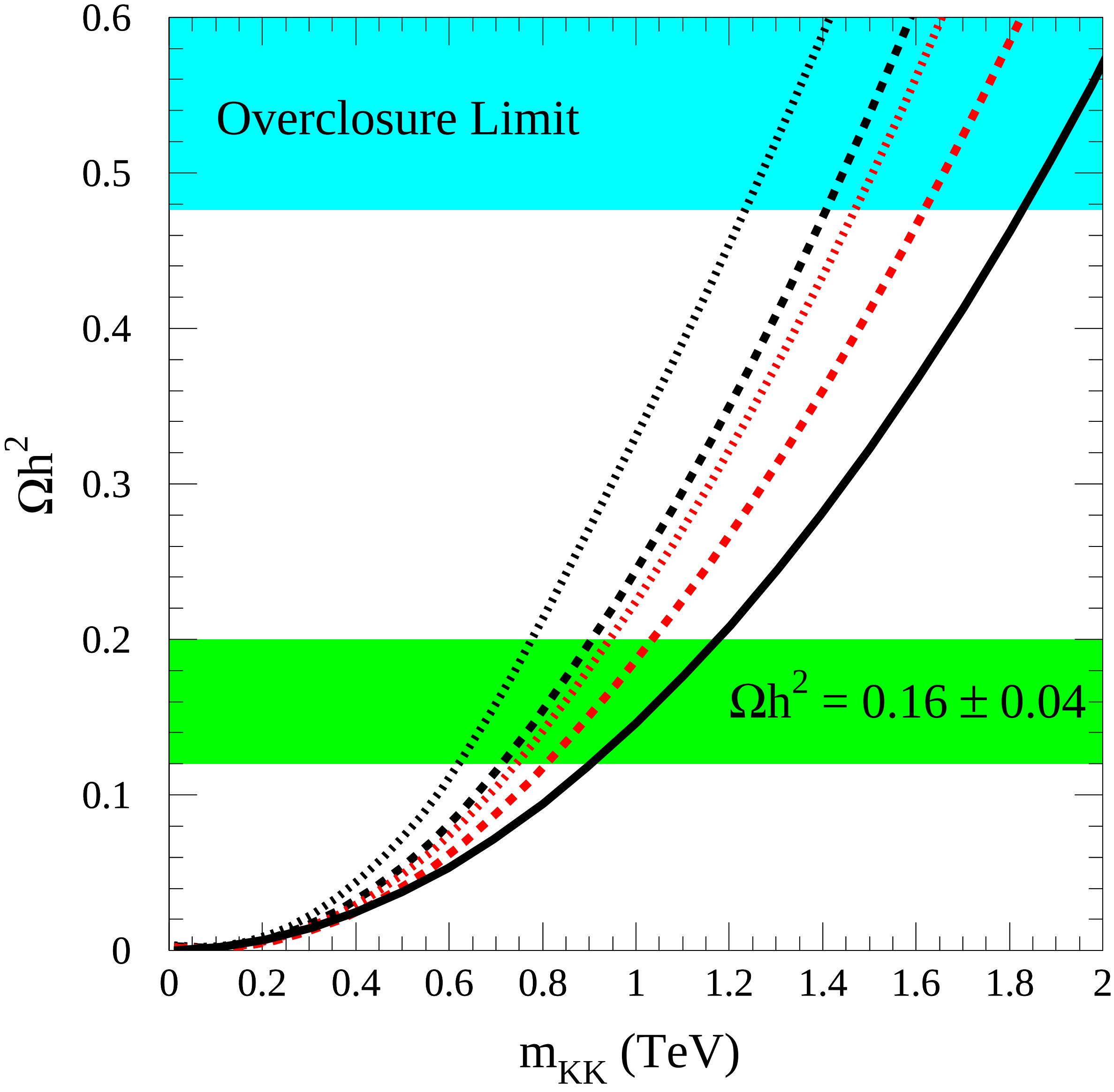
Coannihilation with $e_R^{(1)}$

- If the mass of the $e_R^{(1)}$ is close to $B^{(1)}$, it may substantially affect the relic density



- The $e_R^{(1)}$ pairs annihilate roughly as efficiently as pairs of $B^{(1)}$, but mutual annihilation smaller
- The freeze-out temperature is roughly unchanged
- If the mass splitting is small: some $e_R^{(1)}$ left over at freeze-out: eventually decay to $B^{(1)}$ and $e^{(0)}$
- The resulting relic density is increased
- Unlike the usual SUSY case, in which NLSP's keep the neutralinos in equilibrium longer, resulting in a smaller relic density

Coannihilation with $e_R^{(1)}$



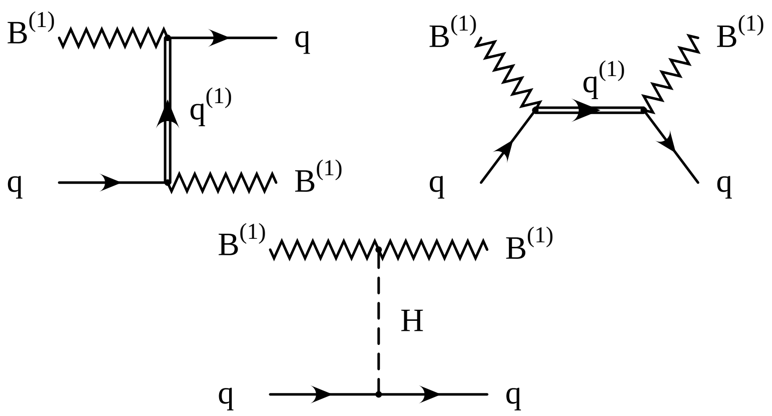
- $\Delta \equiv (m_{e_R^{(1)}} - m_{B^{(1)}})/m_{B^{(1)}} = 1\%, 5\%$
- dashed lines: 1 flavor; dotted lines: 3 flavors

Detection

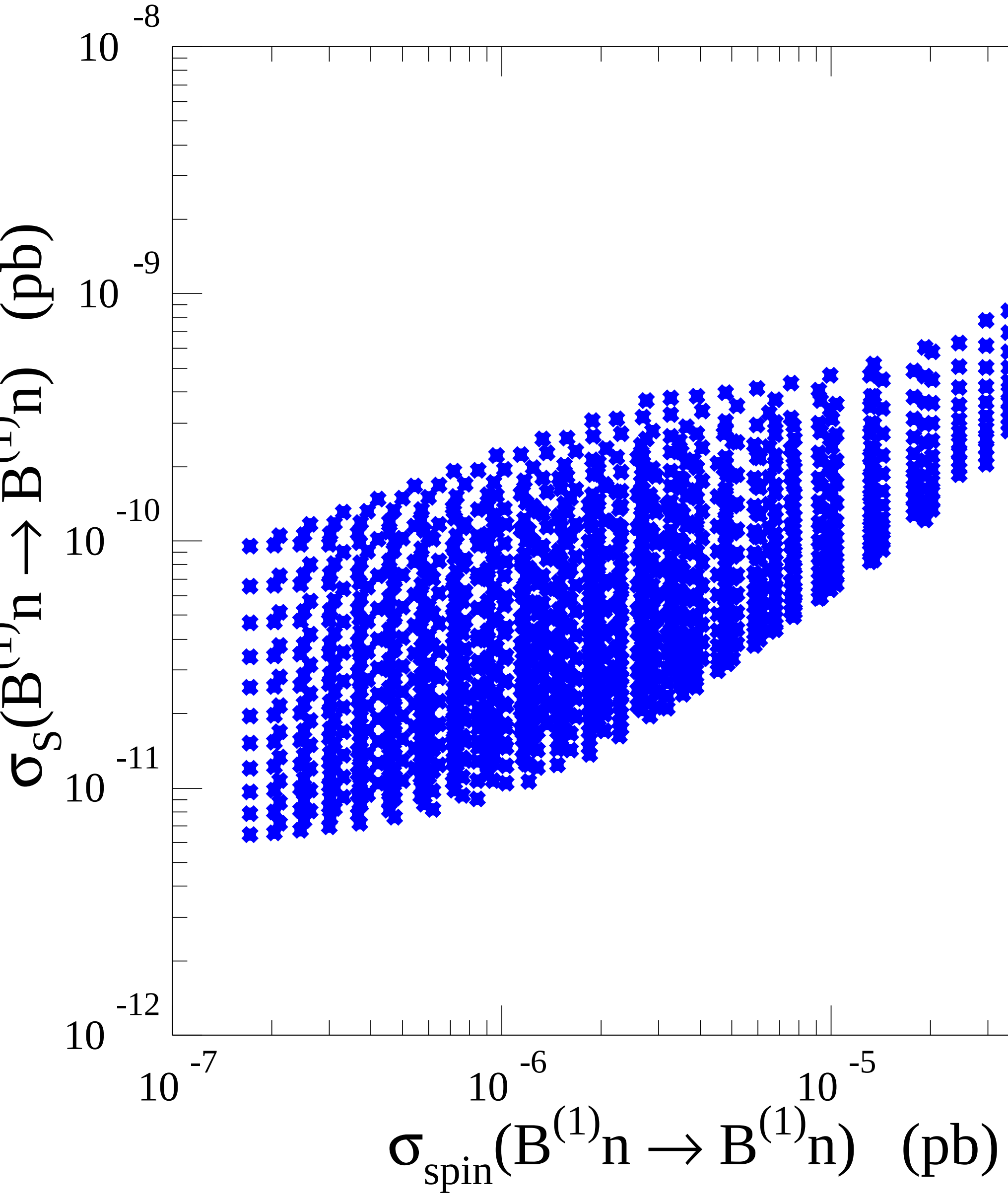
- Indirect Detection
  - LKPs accumulate in gravitational wells and annihilate into energetic particles
  - Future ν, e^+, and γ detectors have sensitivity to lower range of LKP mass

    [Kribs, Hooper; Cheng, Feng, Matchev]
- Direct Detection
  - LKP scattering from a heavy nucleus

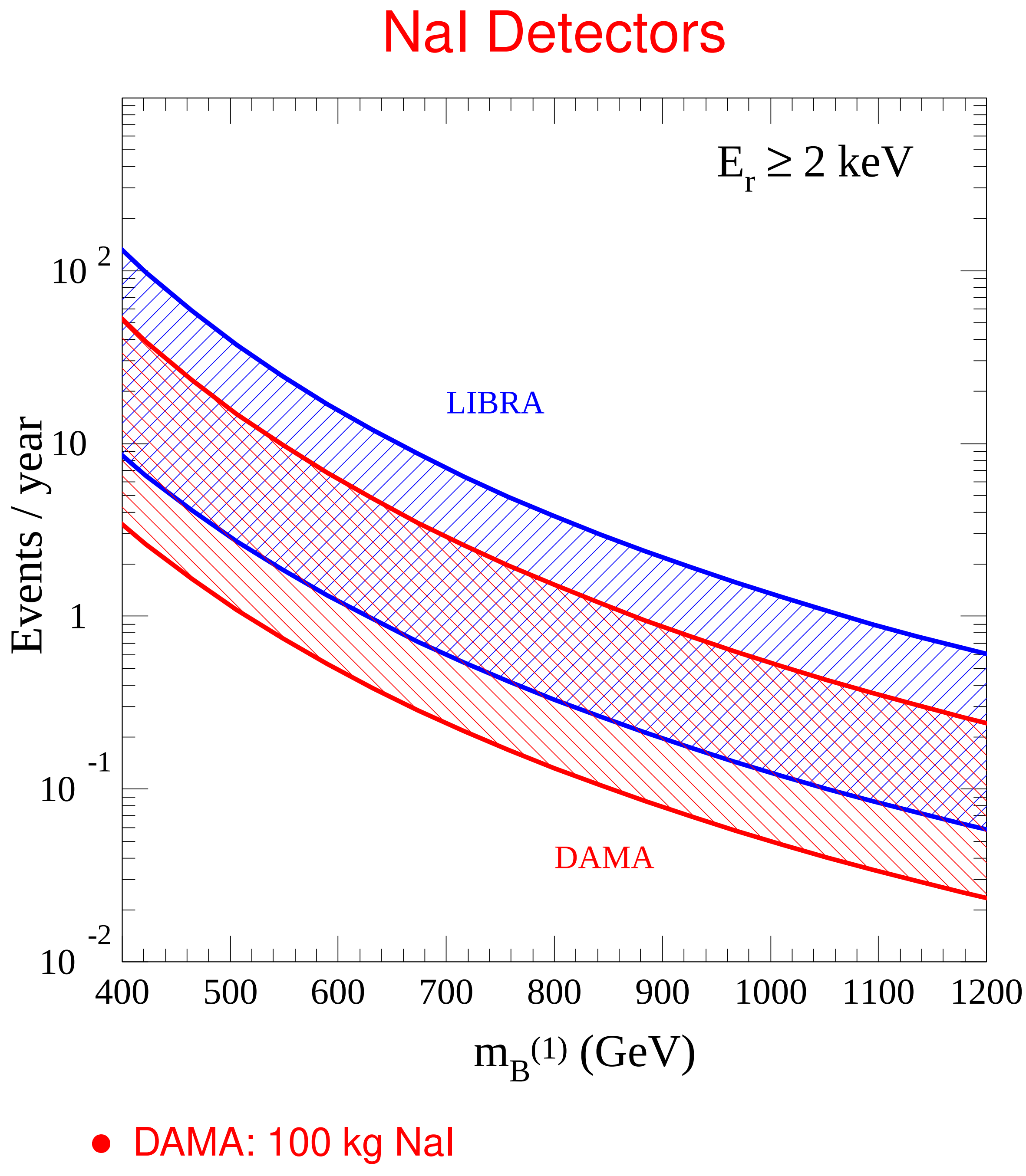
    [Servant, TT; Cheng, Feng, Matchev]

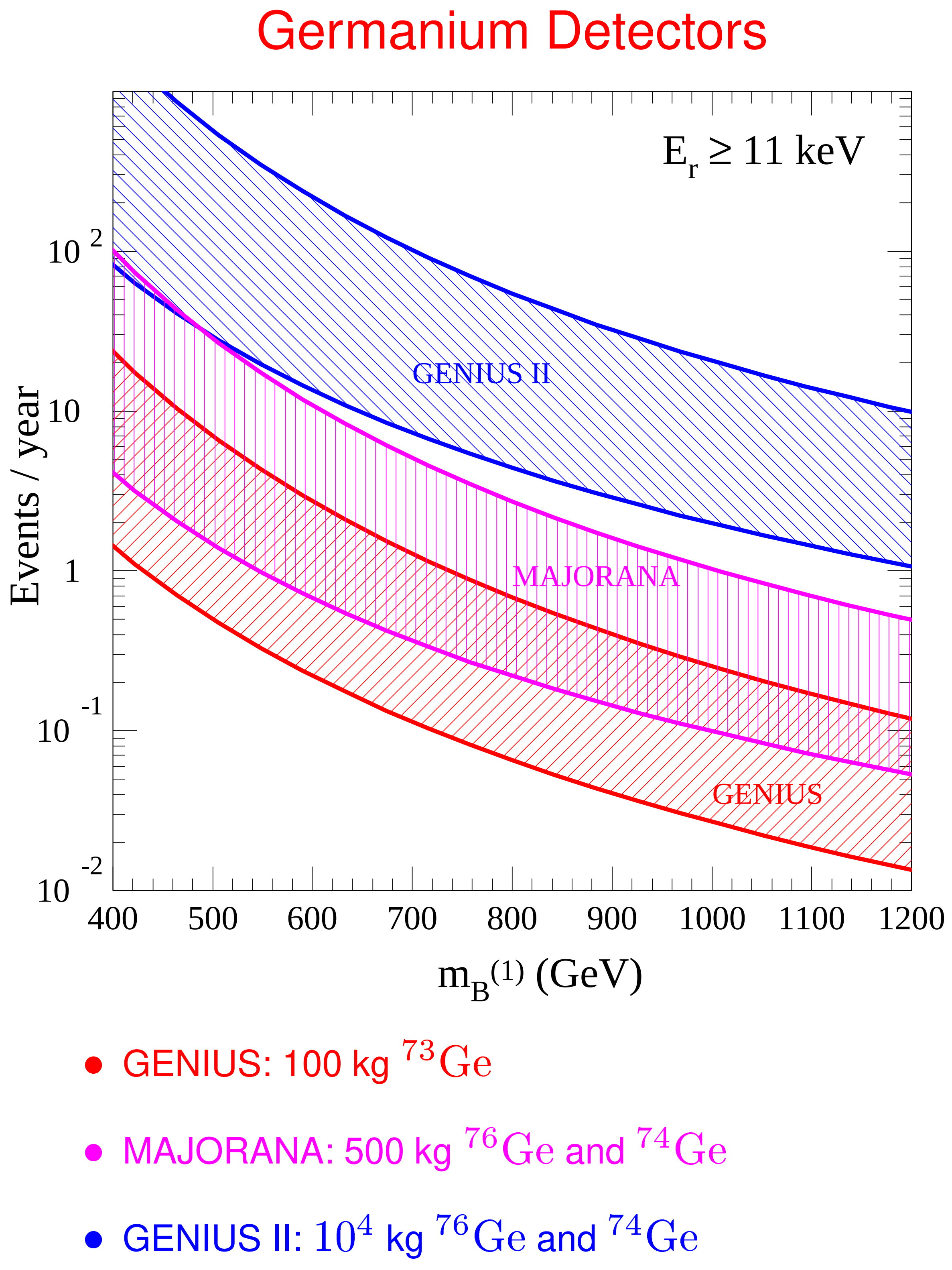


Nucleon Cross Sections

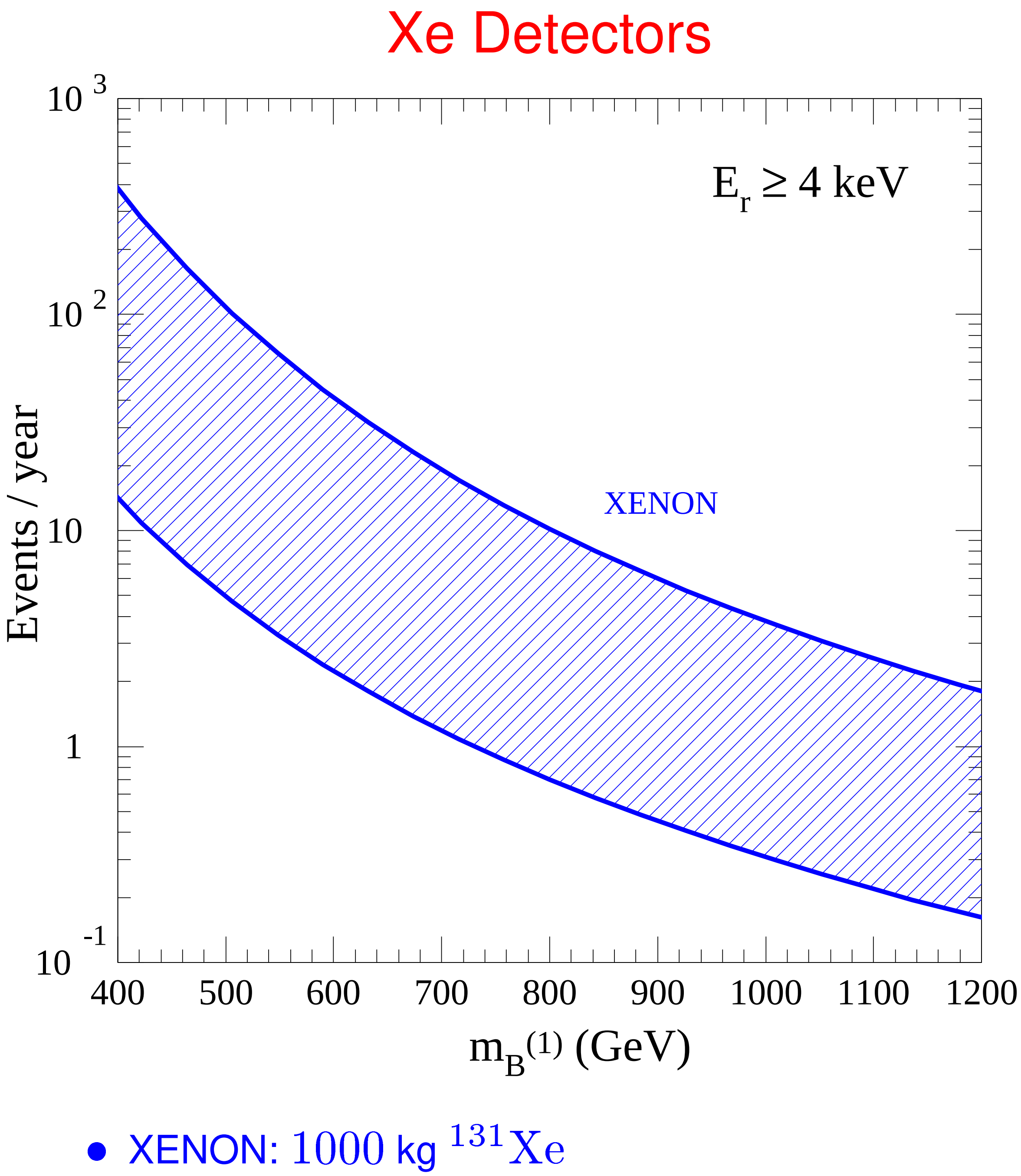


- 600 GeV $\leq m_{B^{(1)}} \leq$ 1.2 TeV
- 115 GeV $\leq m_h \leq$ 200 GeV
- $5\% \leq \Delta_q \leq 15\%$


NaI Detectors
E_r ≥ 2 keV
LIBRA
DAMA
Events / year
10^2
10
1
10^-1
10^-2
400
500
600
700
800
900
1000
1100
1200
m_B(1) (GeV)
DAMA: 100 kg NaI
LIBRA: 250 kg NaI



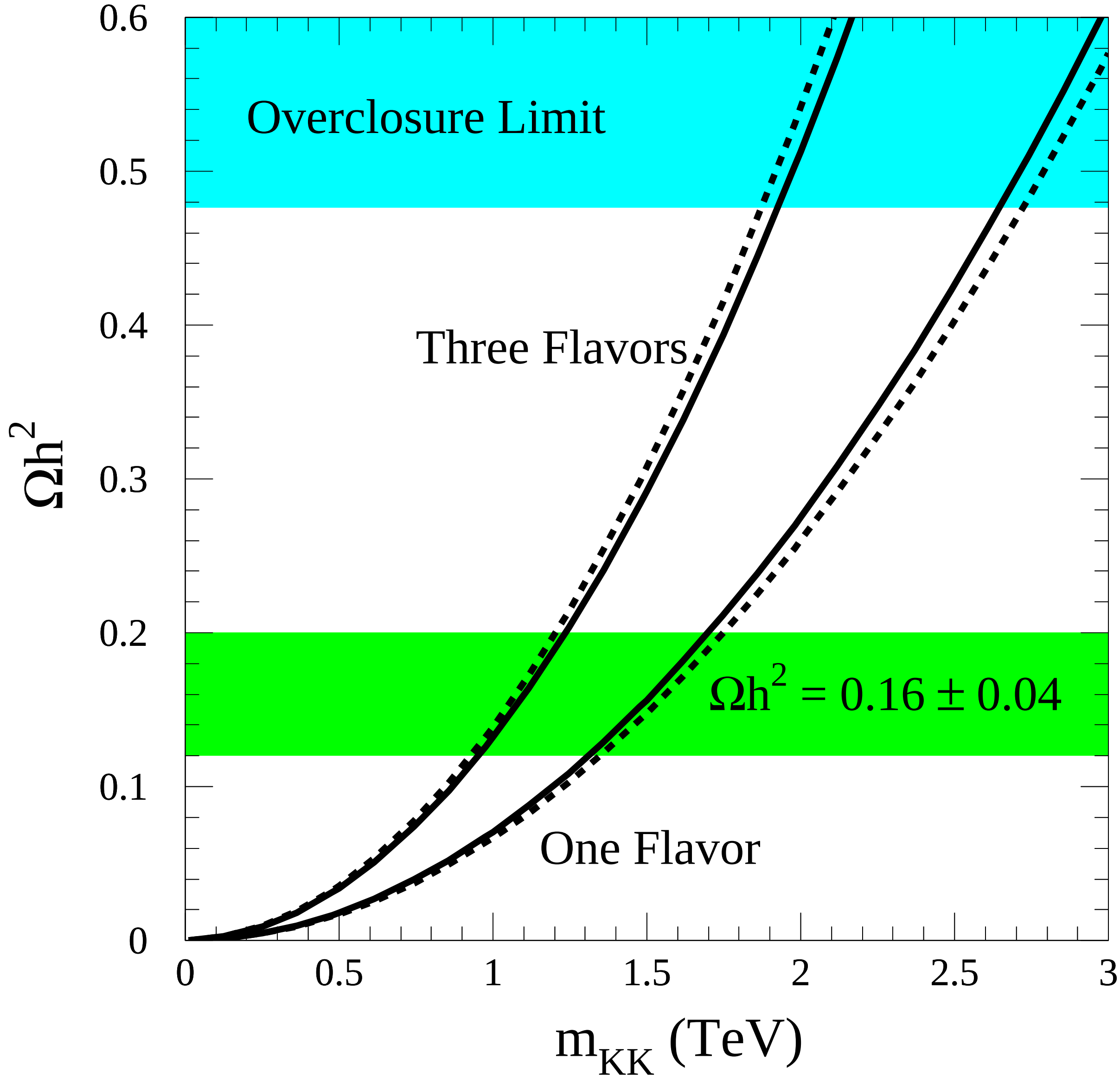
Germanium Detectors
$E_r \geq 11$ keV
GENIUS II
MAJORANA
GENIUS
Events / year
$m_{B^{(1)}}$ (GeV)
● GENIUS: 100 kg ^{73}Ge
● MAJORANA: 500 kg ^{76}Ge and ^{74}Ge
● GENIUS II: 10^4 kg ^{76}Ge and ^{74}Ge


Xe Detectors
$E_r \geq 4$ keV
XENON
Events / year
$m_{B^{(1)}}$ (GeV)
● XENON: 1000 kg ^{131}Xe

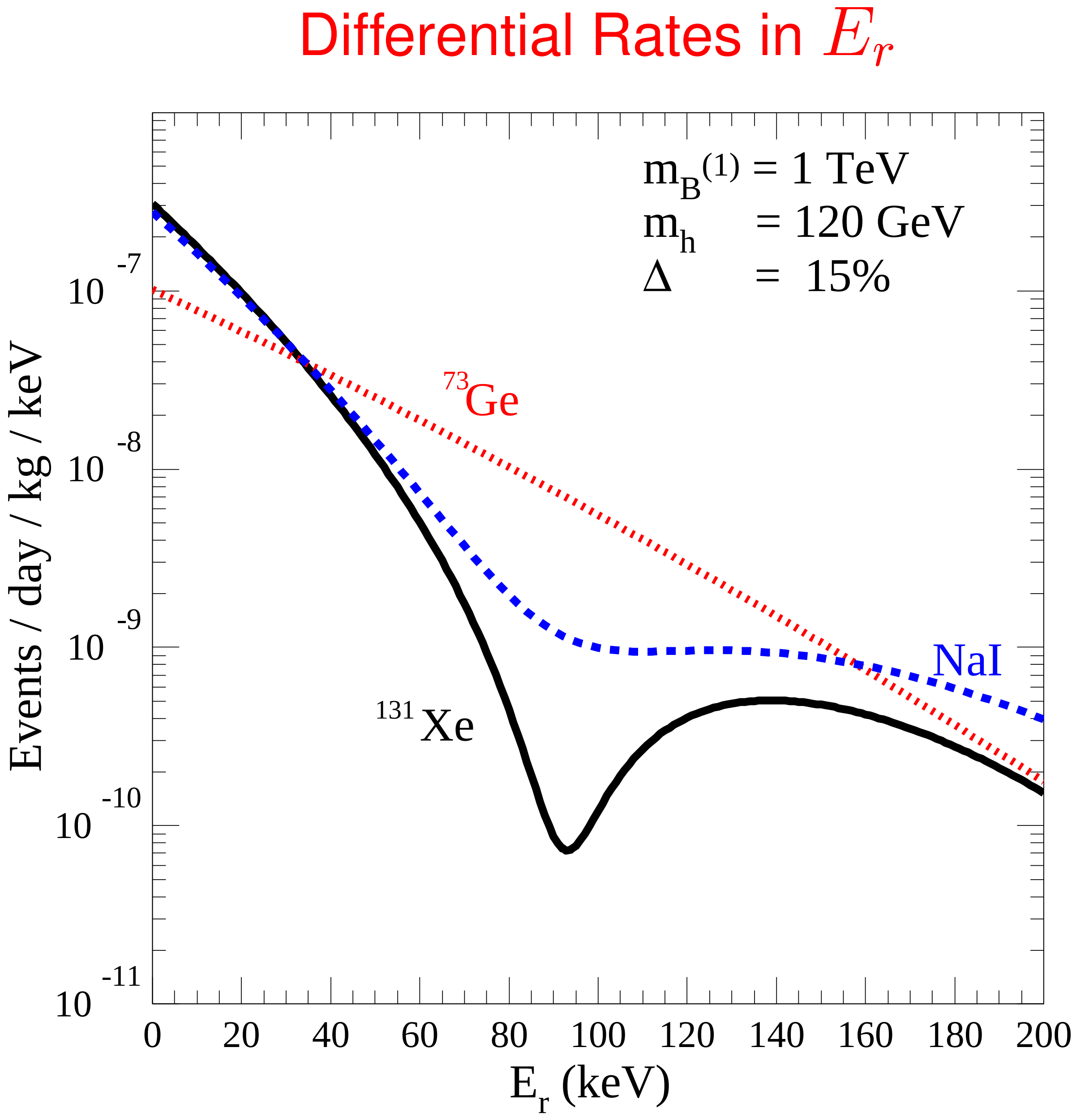
Outlook

- Extra dimensional theories can have a KK parity which raises the possibility of KK dark matter
- We have examined the relic densities expected in these theories, when the LKP is $B^{(1)}$
- Including coannihilation, KK masses between 600 - 1200 GeV are favored to account for DM
- This is the range which will be probed at colliders such as the LHC!
- Heavy WIMPs are a challenge for direct detection, with nuclear effects important
- Multiple events per year require high mass detectors with heavy target nuclei
- Neutrino LKP? Higgs LKP? More dimensions???

Neutrino LKP



- Larger masses favored with respect to $B^{(1)}$
- Dashed lines: coannihilation with $e_L^{(1)}$


Differential Rates in E_r
$m_{B^{(1)}}$ = 1 TeV
m_h = 120 GeV
Δ = 15%
^{73}Ge
NaI
^{131}Xe
Events / day / kg / keV
E_r (keV)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0
20
40
60
80
100
120
140
160
180
200