New Ideas for Particle Dark Matter from Physics Beyond the Standard Model

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Dark Matter

- We live in interesting times...
- Tevatron/LHC capable of discovering BSM physics, but...
- So far, dark matter is our best evidence for new physics.
  - We know how much there is ($\Omega_{DM} = 0.23 \pm 0.04$).
  - We don't know what it is: a new equation or a new particle.
- WIMPs are motivated by both particle physics and astrophysics.
  - Predicted in many particle theories BSM.
  - Give the right order of magnitude Ω_{DM}.
  - Since they must have been able to annihilate in the Early Universe, they should also produce observable signals in direct and indirect dark matter detection experiments.
- Is this simply a coincidence?

Quick terminology guide

- WIMP: Weakly Interacting Massive Particle
- GIMP: Gravitationally Interacting Massive Particle

New Hacker's Dictionary:

- WIMP: [acronym: 'Windows, Icons, Menus, Pointer']
A graphical-user-interface environment, esp. as described by a hacker who prefers command-line interfaces for their superior flexibility and extensibility. However, it is also used without negative connotations; one must pay attention to voice tone and other signals to interpret correctly.

- GIMP: an acronym for GNU Image Manipulation Program – a freely distributed piece of software suitable for such tasks as photo retouching, image composition and image authoring.

Outline

- Fermionic supersymmetry (SUSY)
- New ideas about particle dark matter candidates in fermionic supersymmetry
  - Minimal SUGRA: focus point SUSY WIMPs.
  - SUSY GIMPs.
- Bosonic supersymmetry (BS, UED)
- New ideas about particle dark matter candidates from extra dimensions
  - UED: Kaluza-Klein dark matter WIMPs.
  - Kaluza-Klein GIMPs.

Fermionic supersymmetry

- Fermionic supersymmetry is an extra dimension theory with new anticommuting coordinates θ_α:

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

- If ψ^α are the SM fermions, ϕ are their superpartners (sfermions) with
  - spins differing by 1/2
  - identical couplings
  - unknown masses
- Discovering new particles with those properties IS discovering supersymmetry
- R-parity conservation $\Longrightarrow$ stable LSP.
- Neutral LSP (neutralinos) $\Longrightarrow$ SUSY WIMPs.

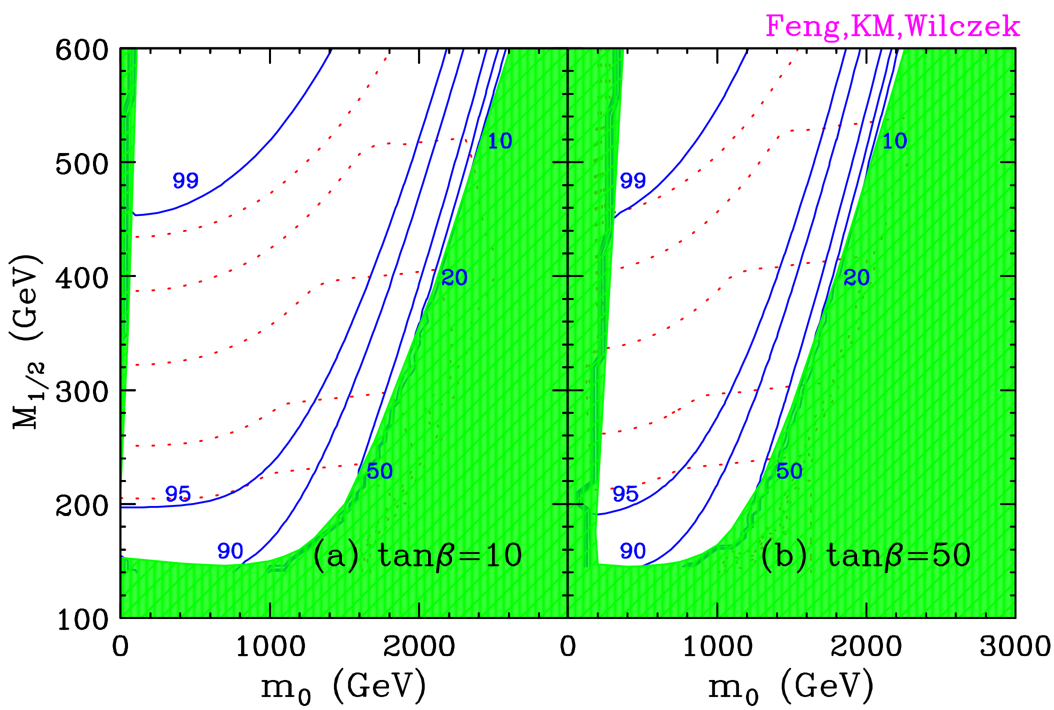
Gaugino fraction of SUSY WIMPs

- The lightest neutralino $\tilde{\chi}_1^0$ is a mixture of $\tilde{b}^0$, $\tilde{w}^0$, $\tilde{h}_u^0$, $\tilde{h}_d^0$:

$$\tilde{\chi}_1^0 = a_1\,\tilde{b}^0 + a_2\,\tilde{w}^0 + a_3\,\tilde{h}_u^0 + a_4\,\tilde{h}_d^0$$

- Gaugino fraction R_χ of the LSP:

$$R_\chi \equiv |a_1|^2 + |a_2|^2.$$

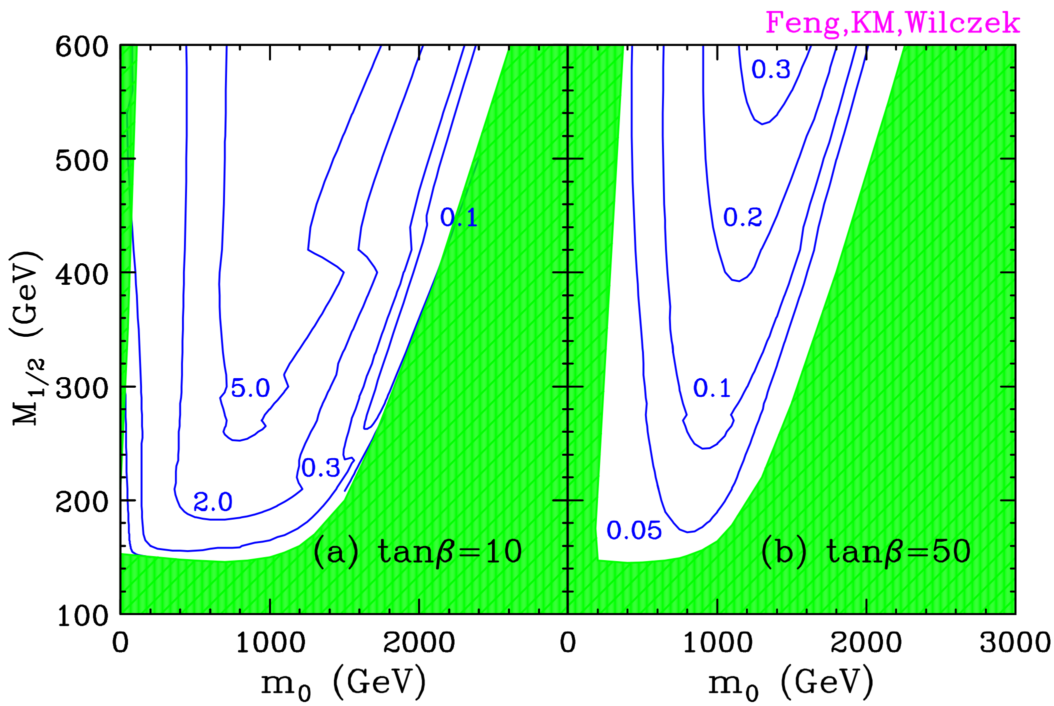


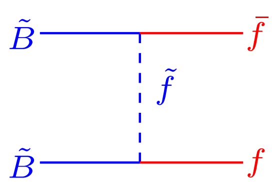
- Focus point region: $m_0 \gtrsim 1$ TeV.
- The focus point region exhibits a mixed LSP.

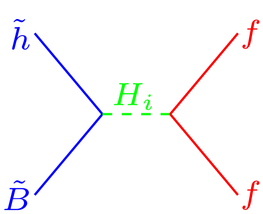
Focus point dark matter WIMPs

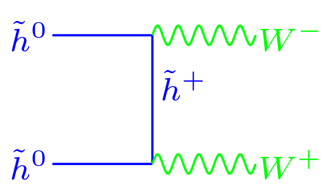
- Mixed LSP allows $\chi\chi \to W^+W^-$, $\chi\chi \to ZZ$, $\chi\chi \to H^0 \to f\bar{f}$.

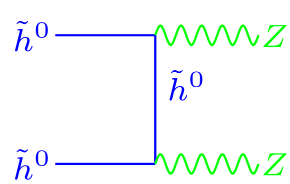
$\Omega_\chi h^2$ decreases again in the FP region!







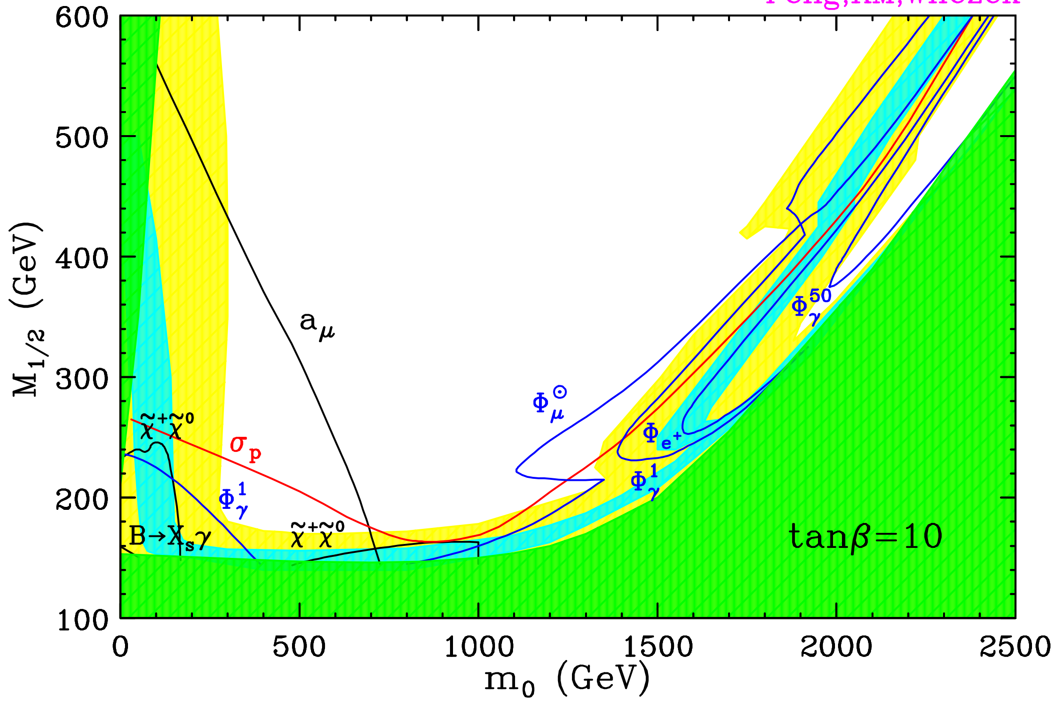




SUSY WIMP detection

- Combination of "all" pre-LHC experiments
  - Direct SUSY searches: Tevatron
  - Indirect SUSY searches: E827, B-factories
  - Direct WIMP searches: CDMS, CRESST, GENIUS
  - Indirect WIMP searches: Amanda, AMS, GLAST

Feng,KM,Wilczek



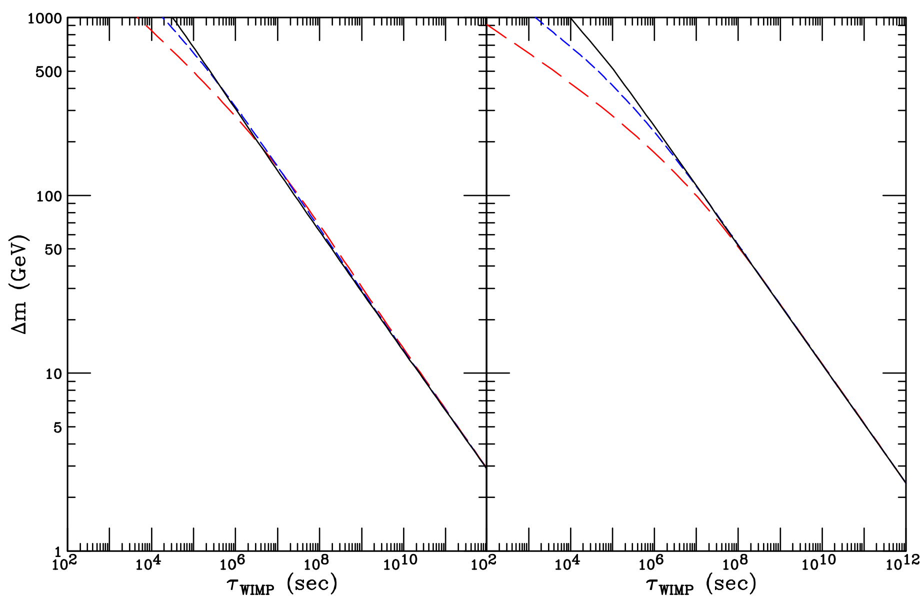
- Many possible DM signals before 2007-08.
- Particle physics and astrophysics probes are highly complementary.

SUSY GIMPs

- What about gravitino LSP (i.e. GIMP)? Certainly possible.
- Ω_{CDM} is determined by the NLSP annihilation rate.
- Later on, the NLSP decays, e.g. $\tilde{B} \to \tilde{G}\gamma$ and the GIMP automatically inherits the correct relic density

Feng,Rajaraman,Takayama hep-ph/0302215

SUSY UED

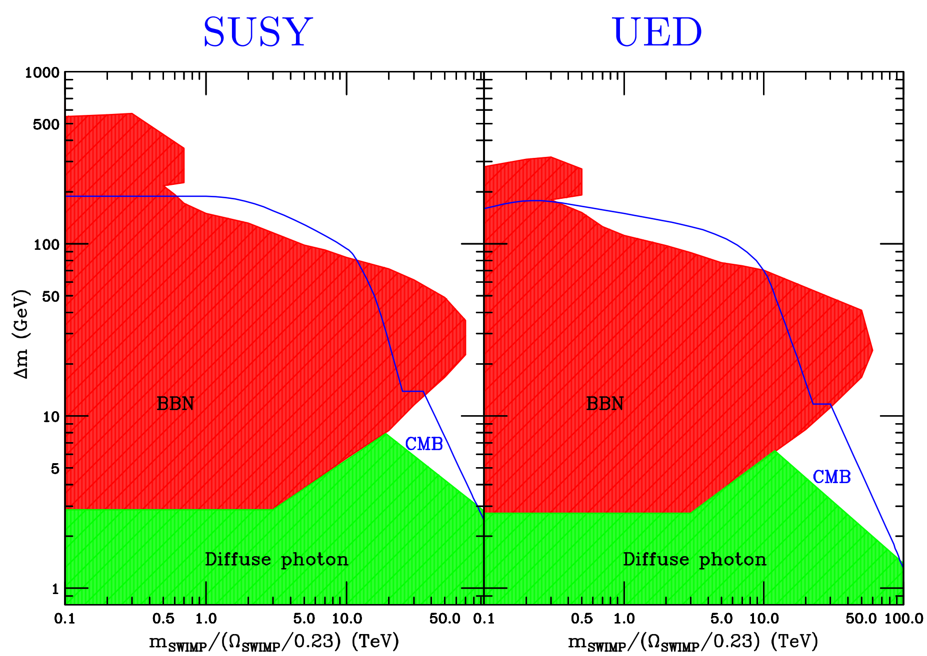


- Formerly ruled out "charged LSP" is now OK, e.g. $\tilde{\tau} \to \tilde{G}\tau$.
- Does this all make any sense?

SUSY GIMP constraints

- Summary of SUSY GIMP constraints from $\tilde{B} \to \tilde{G}\gamma$:

  Feng,Rajaraman,Takayama hep-ph/0302215



- Big Bang Nucleosynthesis
- Cosmic Microwave Background
- Diffuse photon flux

Bosonic supersymmetry

Appelquist, Cheng, Dobrescu, hep-ph/0012100

- Universal Extra Dimensions is an extra dimension theory with new bosonic coordinates y (spanning a circle of radius R):

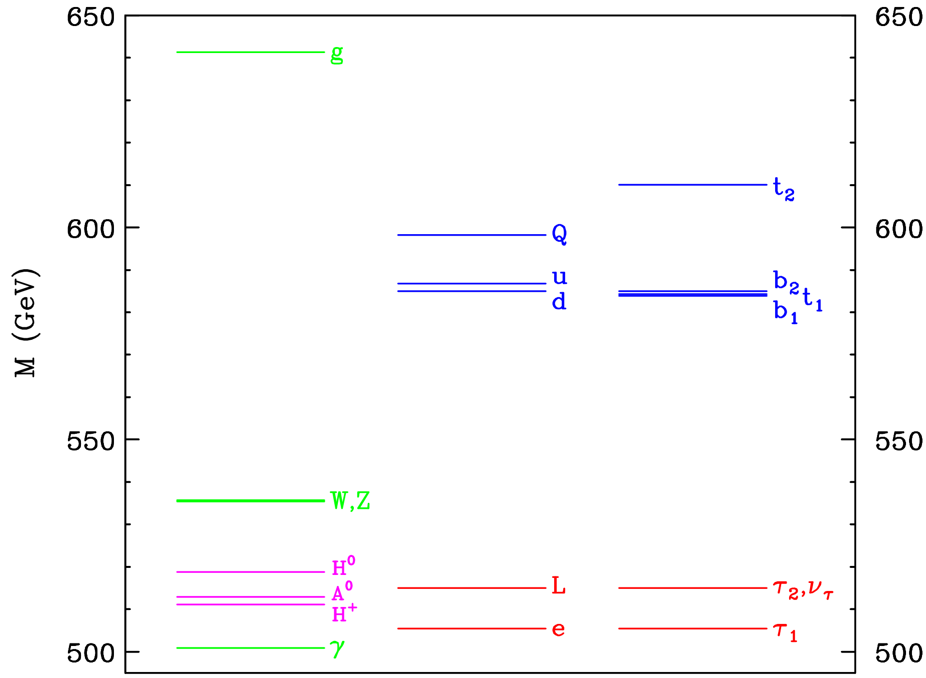
$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \phi^n(x^\mu)\cos(ny/R) + \chi^n(x^\mu)\sin(ny/R)$$

- If ϕ is a SM field, ϕ^n and χ^n are KK partners with
  - identical spins
  - identical couplings
  - unknown masses of order n/R
- Discovering new particles with those properties IS discovering extra dimensions
- Conservation of KK-parity $(-1)^{KK} \Longrightarrow$ stable LKP.
- Neutral LKP $(B^1_\mu) \Longrightarrow$ Kaluza-Klein WIMP.

Bosonic supersymmetry spectrum

- Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this:

Cheng, KM, Schmaltz, hep-ph/0204342

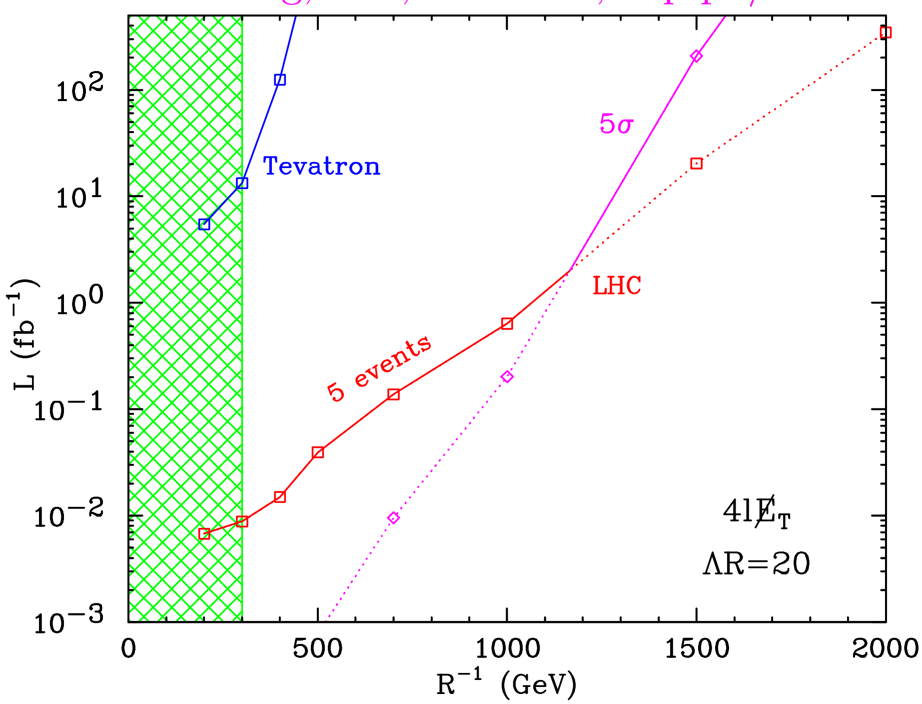


- Mimics (fermionic) supersymmetry!
- Seems difficult to discover at the LHC, but...
- $W_1^{\pm}$, Z_1 have pure leptonic branchings!
- $\sin^2\theta_W^1 \approx 0 \Longrightarrow \gamma^1 \approx B^1$, similar to $\tilde{B}$ in SUSY.

Bosonic supersymmetry discovery reach at the Tevatron and LHC

- Discovery reach in the $Q_1 Q_1 \to 4\ell \not{E}_T$ channel.

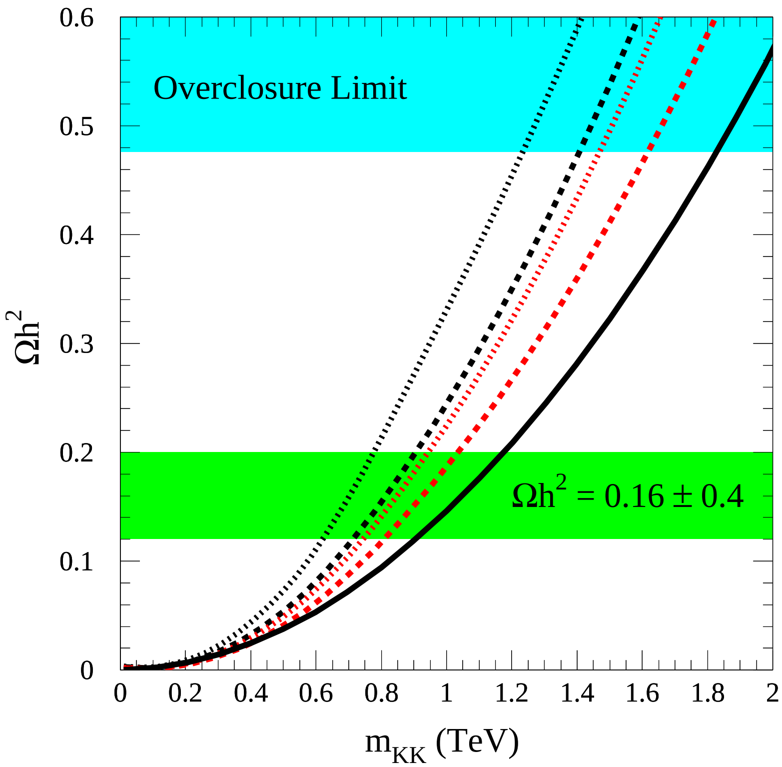
Cheng, KM, Schmaltz, hep-ph/0205314



- Typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (LHC can't measure it)

Kaluza-Klein dark matter

- Relic density: G.Servant, T.Tait, hep-ph/0206071



- Unlike supersymmetry: no helicity suppression

$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P\sqrt{g_*}}\frac{x_F}{a+3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

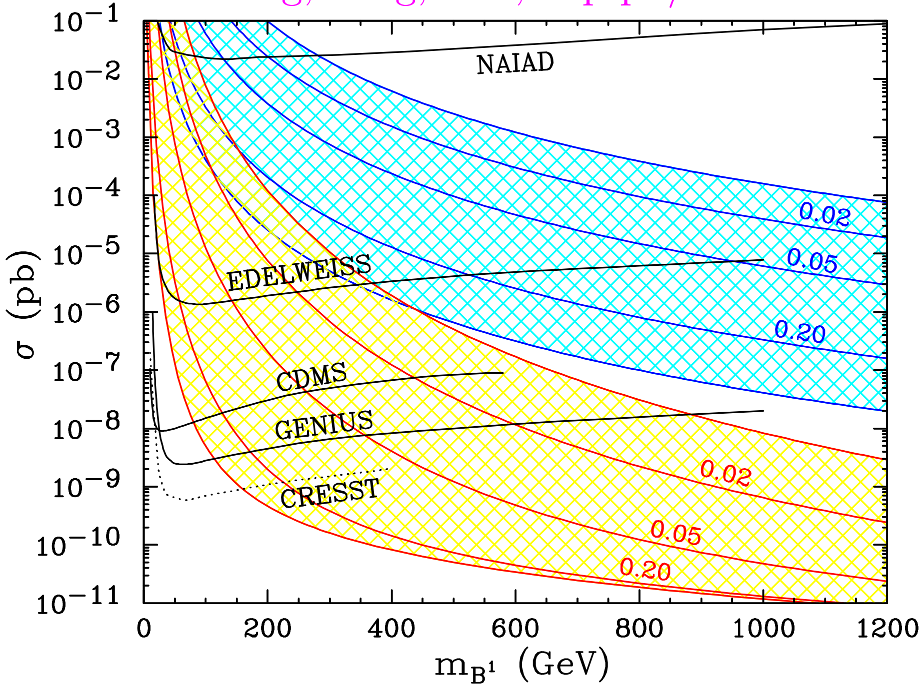
$$a = \frac{\alpha_1^2}{M_{KK}^2}\frac{380\pi}{81}; \qquad b = -\frac{\alpha_1^2}{M_{KK}^2}\frac{95\pi}{162}.$$

- Unlike supersymmetry: coannihilation lowers the bound

KK WIMP Direct Detection

- As usual, spin-dependent and spin-independent cross-sections.

Cheng, Feng, KM, hep-ph/0207125



- The signals are enhanced near the s-channel resonance:

$\sigma \sim (m_{q^1} - m_{B^1})^{-2}$. Unnatural in SUSY, guaranteed here.

Cheng, Feng, KM, hep-ph/0207125
Servant, Tait, hep-ph/0209262
Majumdar, hep-ph/0209277

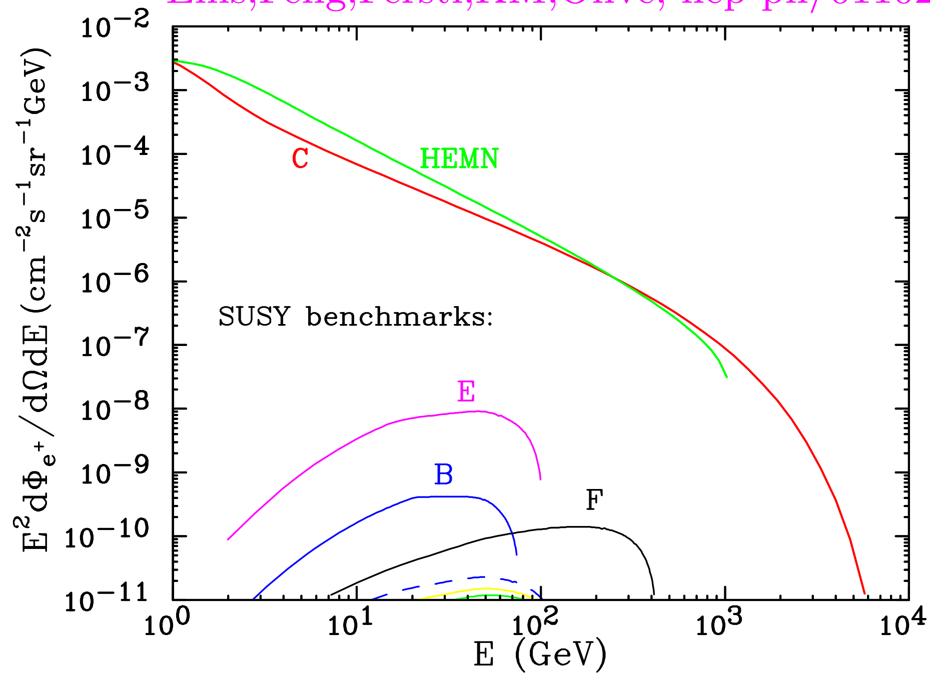
- Constructive interference: lower bound!

KK WIMP Indirect Detection: Positrons

- The shape and normalization of the background are uncertain:

Moskalenko, Strong, astro-ph/9905283

Ellis,Feng,Ferstl,KM,Olive, hep-ph/0110225



- Unless you see a bump, it is difficult to tell...
- It is easier to see a bump at high E_{e^+}.
- AMS-II will be able to measure high-p_T positrons!

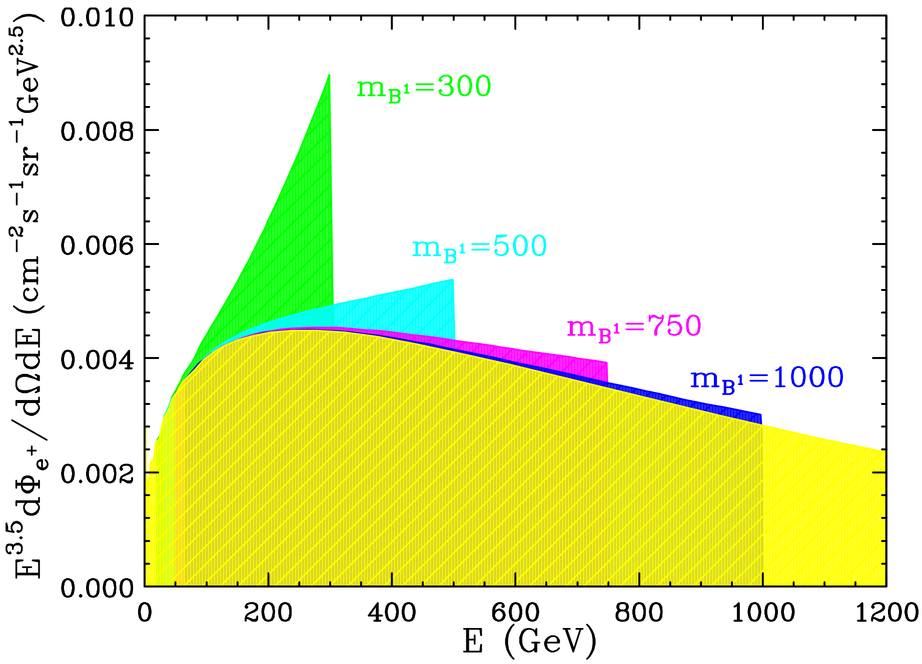
KK WIMP Indirect Detection: Positrons

- Annihilation into fermion pairs is not helicity suppressed.

$$B(B^1 B^1 \to e^+ e^-) = 20\%$$

- There is a bump! The positrons are monoenergetic at birth. Some smearing from propagation through the galaxy.

Cheng, Feng, KM, hep-ph/0207125



- A smoking gun signal!

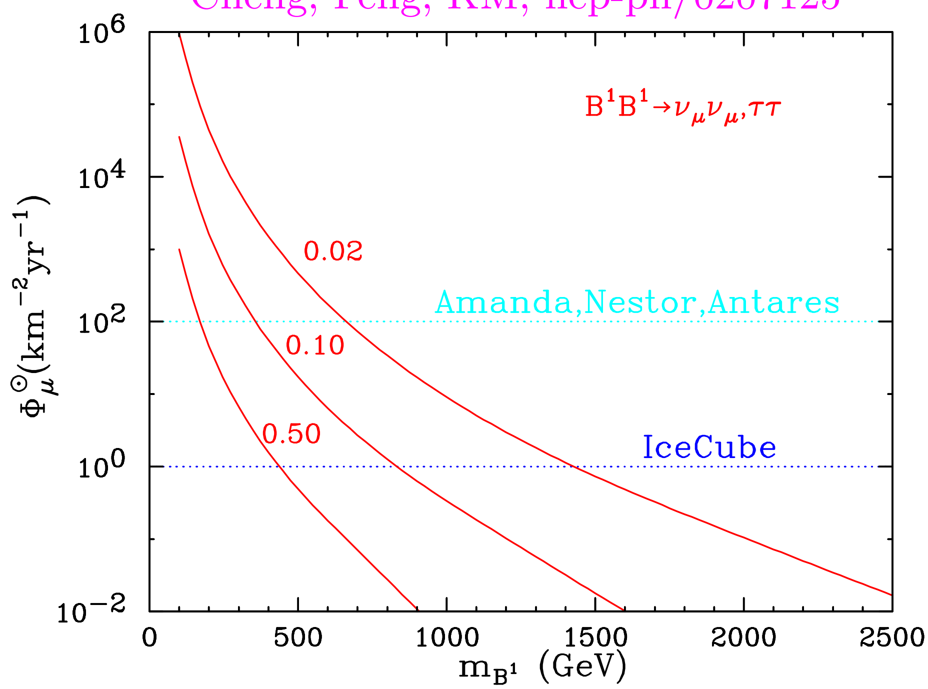
KK WIMP Indirect Detection: Neutrinos

- Several channels: $\nu_\mu \bar{\nu}_\mu$, $\mu^+\mu^-$, $\tau^+\tau^-$, $t\bar{t}$, $b\bar{b}$, $c\bar{c}$, hh...

$$B(B^1 B^1 \to \nu_\mu \bar{\nu}_\mu) = 1.2\%$$
$$B(B^1 B^1 \to \ell^+ \ell^-) = 20\% \text{ per generation!}$$

- Discovery reach of neutrino telescopes

Cheng, Feng, KM, hep-ph/0207125



- Conservative estimate:
  - neglecting neutrinos from hadronic final states
  - neglecting $\tau - \mu$ neutrino oscillations

Hooper,Kribs, hep-ph/0208261

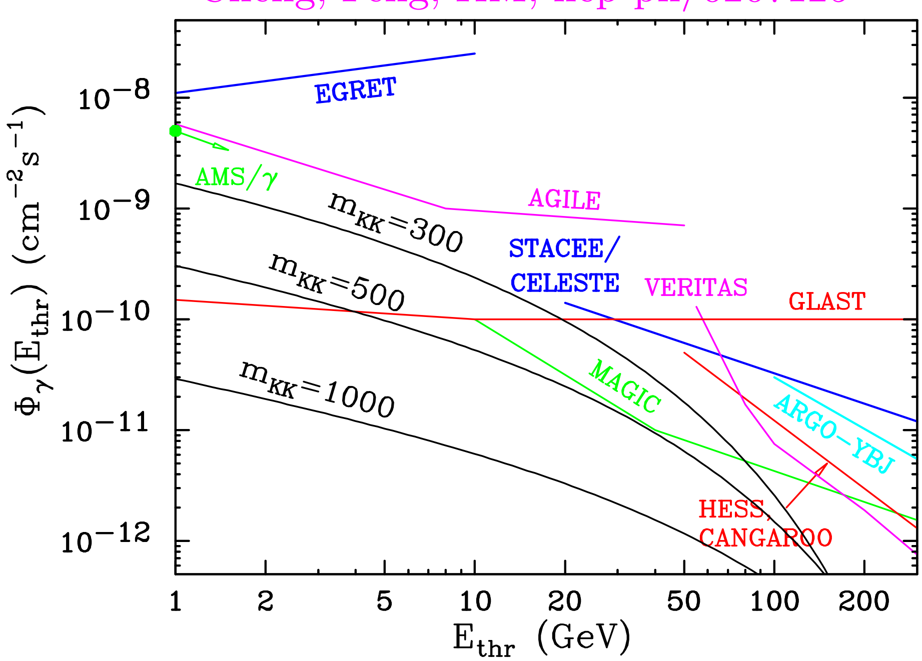
Bertone, Servant, Sigl, hep-ph/0211342

KK WIMP Indirect Detection: Photons

- Hard photons from dark matter annihilation in the galactic center.

$$\Phi_\gamma(E_{th}) = 5.6 \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\, \bar{J}(\Delta\Omega)\, \Delta\Omega$$
$$\times \left[\frac{1\ \mathrm{TeV}}{m_{B^1}}\right]^2 \sum_q \frac{\langle \sigma_{qq} v\rangle}{\mathrm{pb}} \int_{E_{th}}^{m_{B^1}} dE \frac{dN_\gamma^q}{dE}\ .$$

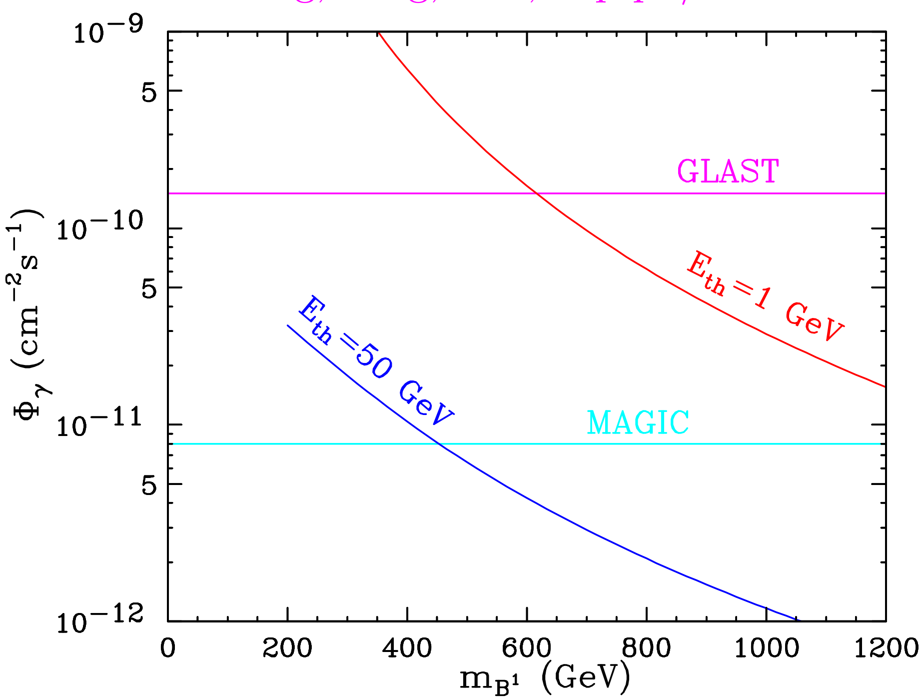
Cheng, Feng, KM, hep-ph/0207125



KK WIMP Indirect Detection: Photons

- Reach of two representative experiments: low and high threshold.

Cheng, Feng, KM, hep-ph/0207125



- The signals may be further enhanced by halo clumpiness.
- Astrophysical uncertainty from halo modelling ($\bar{J}$).

KK GIMPs

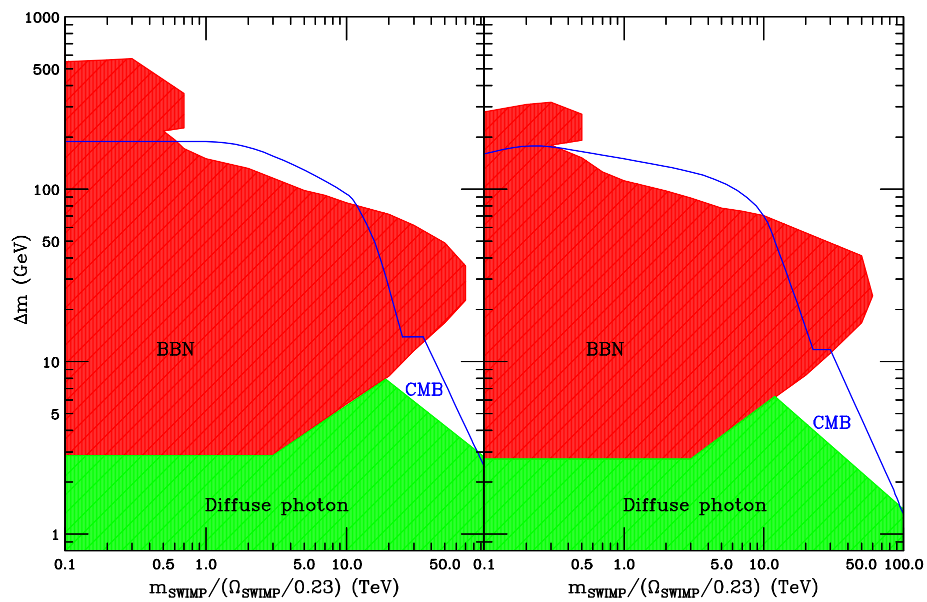
- What about a graviton LKP? Certainly possible.

$$B^1 \to G^1\gamma,\ G^1 Z,\ G^1 q\bar{q},\ G^1\ell^+\ell^-, \ldots$$

- Summary of KK GIMP constraints (right):
  - Big Bang Nucleosynthesis
  - Cosmic Microwave Background
  - Diffuse photon flux

Feng,Rajaraman,Takayama hep-ph/0302215

SUSY UED



- KK GIMPs are a disaster for dark matter detection experiments...

The Message

- End of the era of the tyrrany of the Bino WIMP.
- Recent new ideas in particle physics lead to novel opportunities for dark matter candidates.
- Dark matter detection experiments should be prepared for surprises, avoid theory bias.
- Extra dimensions also yield natural dark matter candidates, with calculable rates for detection.
- SUSY or KK GIMPs yield no signals, but may be detected indirectly through the decay products of the NLSP (NLKP).
- Astroparticle physics experiments provide important guidelines for particle theorists.