Gamma-ray spectra from dark matter annihilations

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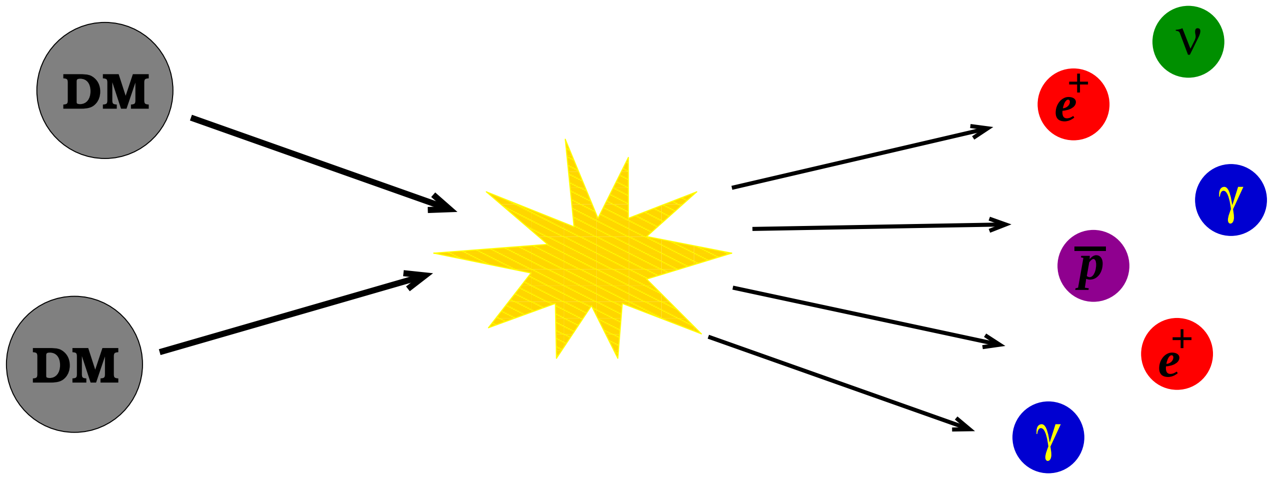
Indirect DM detection

The basic idea:



- Dark matter has to be (quasi-)stable against decay...
- ...but can usually pair-annihilate into SM particles.
- These annihilation products can then potentially be spotted in cosmic rays of various kinds.
- The challenge: a clear discrimination against background and astrophysical sources.

Why gamma rays ?

- Rather high rates
- Almost no attenuation when propagating through the halo
- Point directly to the sources
- No assumptions about diffusive halo necessary

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- Clear spectral signatures to look for

γ rays from DM annihilations

The expected gamma-ray flux $[\mathrm{GeV}^{-1}\mathrm{cm}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$ from a source with a high DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \underbrace{\frac{\langle\sigma v\rangle_{\mathrm{ann}}}{8\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}}_{\text{particle physics}} \cdot \underbrace{\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r})}_{\text{astrophysics}}$$

$$\simeq \left(D^2\Delta\psi\right)^{-1}\int d^3r\,\rho^2(\mathbf{r})$$

$\langle\sigma v\rangle_{\mathrm{ann}}$	:	total annihilation cross section
m_χ	:	DM particle mass (for WIMPs: $50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV}$)
B_f	:	Branching ratio into channel f
N_γ^f	:	Number of photons per annihilation
$\Delta\psi$	:	angular resolution of detector
D	:	Distance to *point-like* source

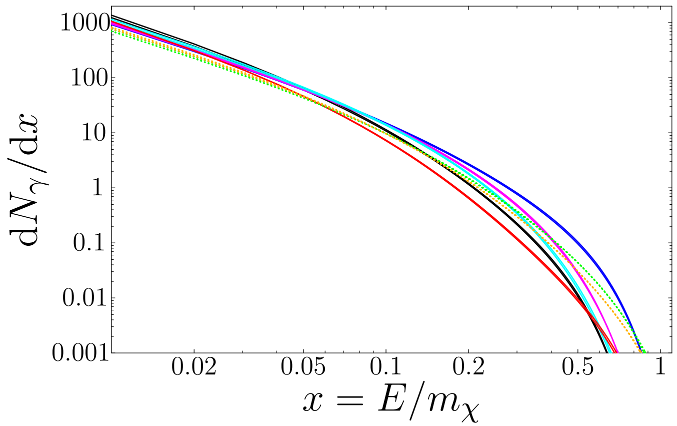
DM annihilation spectra

3 types of contributions:

- Secondary photons from fragmentation of decay products
  - mainly through $\pi^0 \to \gamma\gamma$
  - results in a rather featureless spectrum
- Line signals from $\chi\chi \to \gamma\gamma, Z\gamma, H\gamma$
  - necessarily loop-suppressed: $\mathcal{O}(\alpha^2)$
  - “smoking gun” signature
- Final state radiation (FSR)
  - appears whenever charged final states are present, $\mathcal{O}(\alpha)$
  - characteristic signature, usually dominant at high energies

Secondary photons

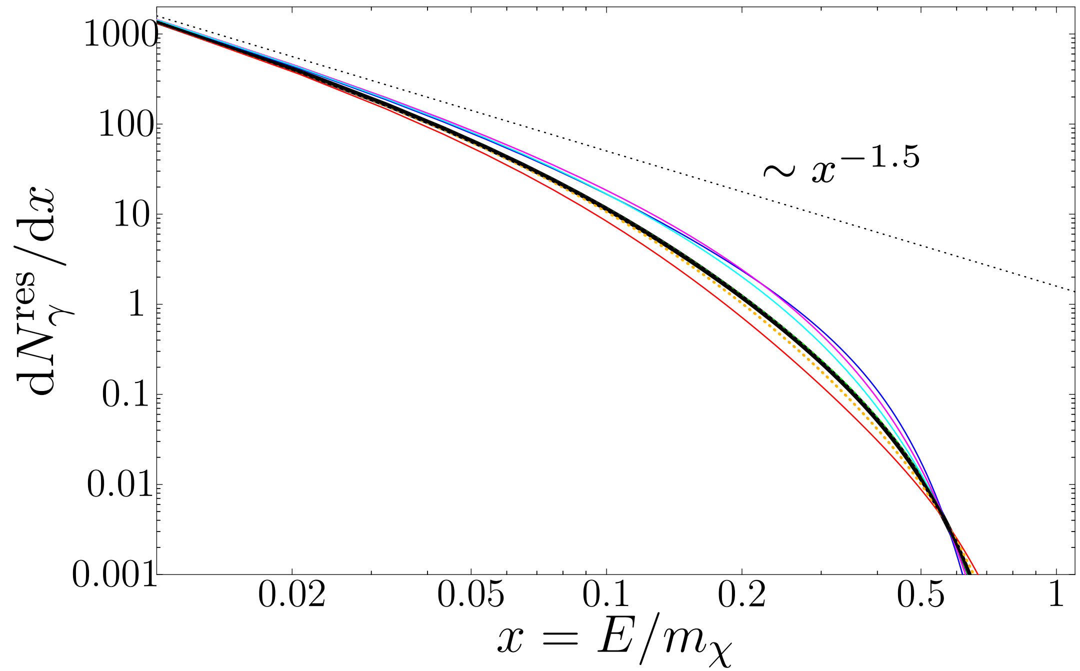
Quark and gauge boson fragmentation give essentially degenerate photon spectra: (Figs. from Bertone et al., astro-ph/0612387)



rescale $\longrightarrow$

$$\frac{dN_\gamma^{f,\,\mathrm{res}}}{dx}(x) \equiv A_f \frac{dN_\gamma^{\mathrm{f}}}{dx}(B_f x)$$

N.B.: $B_f \sim 1 - 1.5$



Direct annihilation into photons

The direct annihilation into photons ($\chi\chi \to \gamma\gamma, Z\gamma, H\gamma$) results in very sharp line signals (natural width $\sim 10^{-3}$ due to Doppler shift).

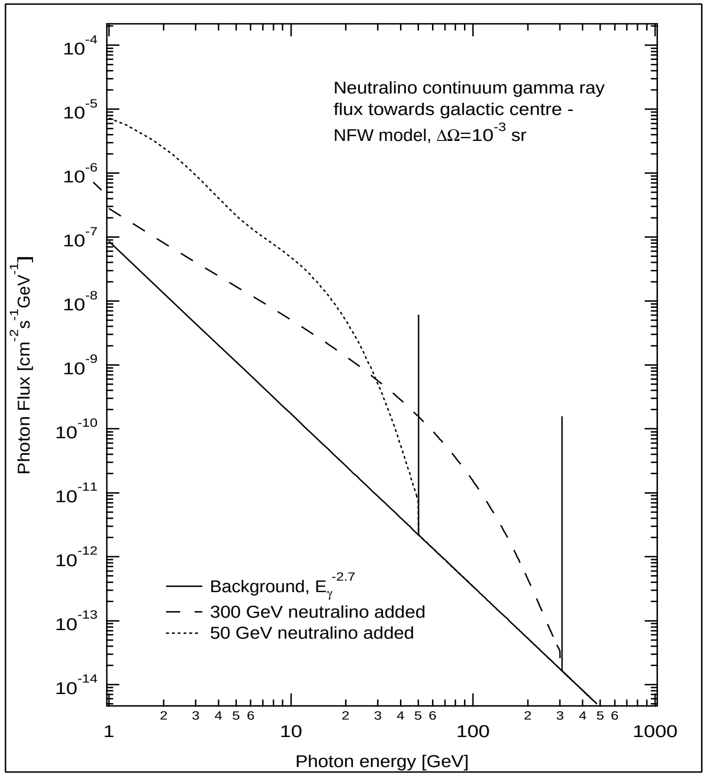


Fig. from Bergström, Ullio & Buckley '97

but:

energy resolution ($\gtrsim 10\%$) and sensitivity of current detectors in many cases not sufficient to discriminate the signal from the continuum part.

(A particularly prominant exception is, e.g., the case of almost pure Winos and Higgsinos, see Hisano et al. '05.)

Final state radiation

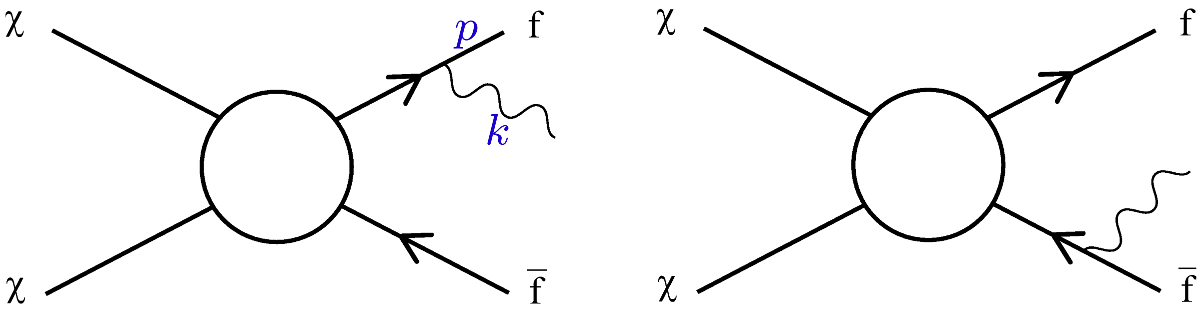
(internal bremsstrahlung)

- Whenever DM annihilates into charged final states f, this process is ***automatically*** accompanied by $\chi\chi \to f\bar{f}\gamma$.
- For $m_f \ll m_\chi$, the spectrum is usually dominated by photons emitted collinearly from the charged final states

  $\rightarrow$ spectrum rather model-independent.
- Under the following circumstances, however, photons radiated from charged virtual particles can dominate:
  - t-channel annihilation into bosonic f
  - a symmetry violated by $f\bar{f}$ but not by $f\bar{f}\gamma$

  $\rightarrow$ these contributions are highly model-dependent.

Collinear photons



propagator for f:

$$\propto \frac{1}{(k+p)^2 - m_f^2} = \frac{1}{2k\cdot p}$$

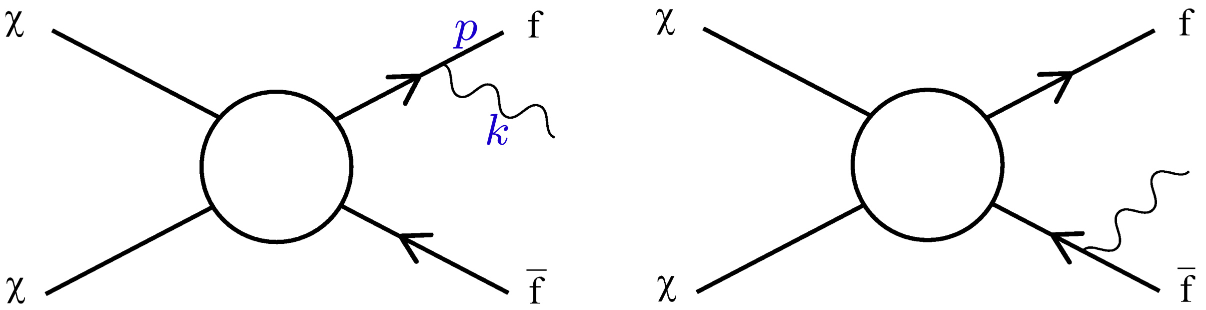
For collinear photons, the virtual f is almost on-shell

$\rightarrow$ Logarithmic enhancement of the cross section $(x \equiv E_\gamma / m_\chi)$:

$$\frac{dN}{dx} \sim \sigma(\chi\chi \rightarrow f\bar{f}) \cdot \frac{\alpha Q^2}{\pi} \mathcal{F}(x) \log \frac{s}{m_f^2}(1-x)$$

(see, e.g., Birkedal et al., hep-ph/0507194)

Collinear photons



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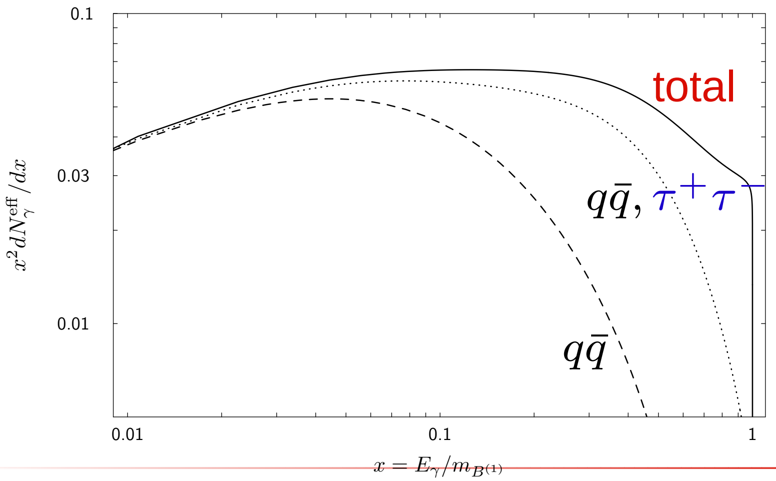
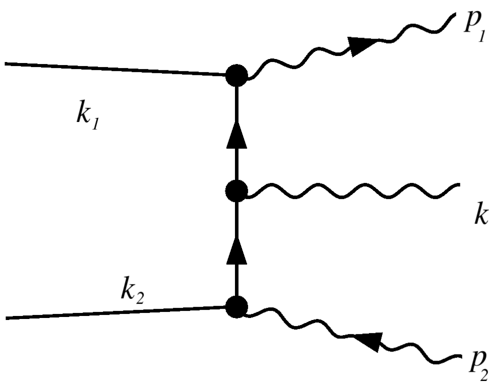
- Example: LKP in UED
  - $m_{B^{(1)}} \sim 1\,$TeV
  - high branching ratio into leptons ($\sim 60\,\%$)

Bergström et al., PRL '05a



Charged virtual particles (1)

"Light" charged bosonic final states get an enhancement from t-channel diagrams if the internal particles are degenerate in mass with the DM particles:



- $\mathcal{M} \propto \frac{1}{k_1 \cdot p_1} \frac{1}{k_2 \cdot p_2} \approx \frac{1}{m_\chi^2 E_1 E_2}$
- high $E_\gamma \rightsquigarrow$ small E_1 or E_2
- (Note that the contraction of *fermion* final legs leads to an additional E_f in the numerator)

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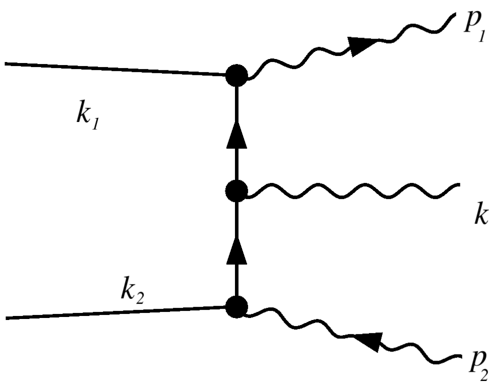

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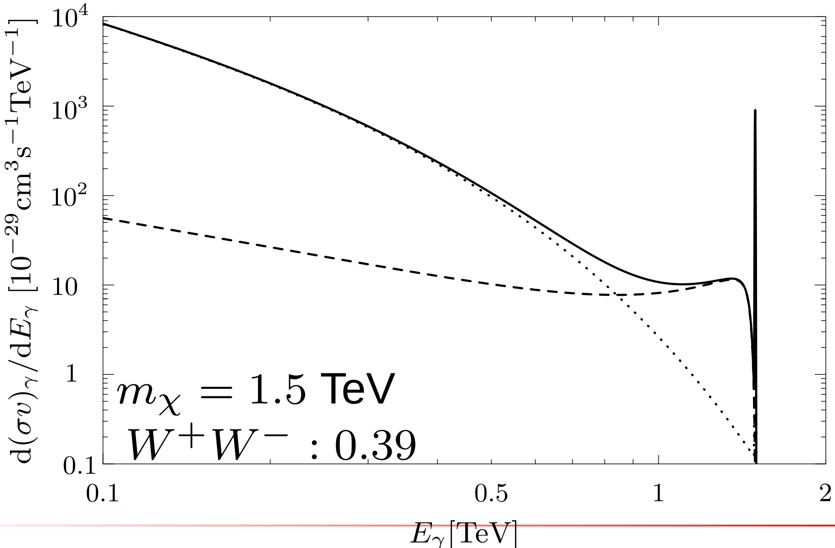
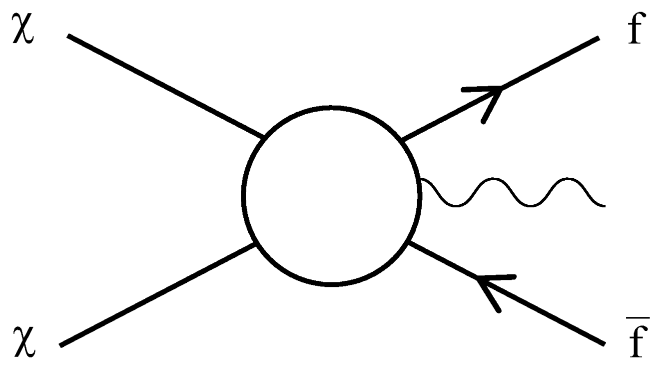
- Example: Higgsino
  - TeV mass
  - high W^+W^- b. r.

Bergström et al., PRL '05b

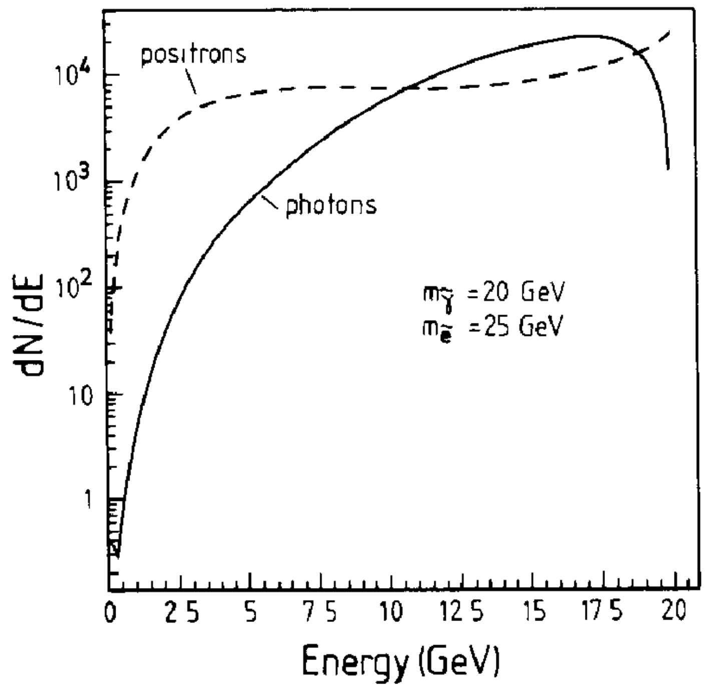


Charged virtual particles (2)



The 3-body final state may be allowed by a symmetry that is not satisfied fot the 2-body final state.

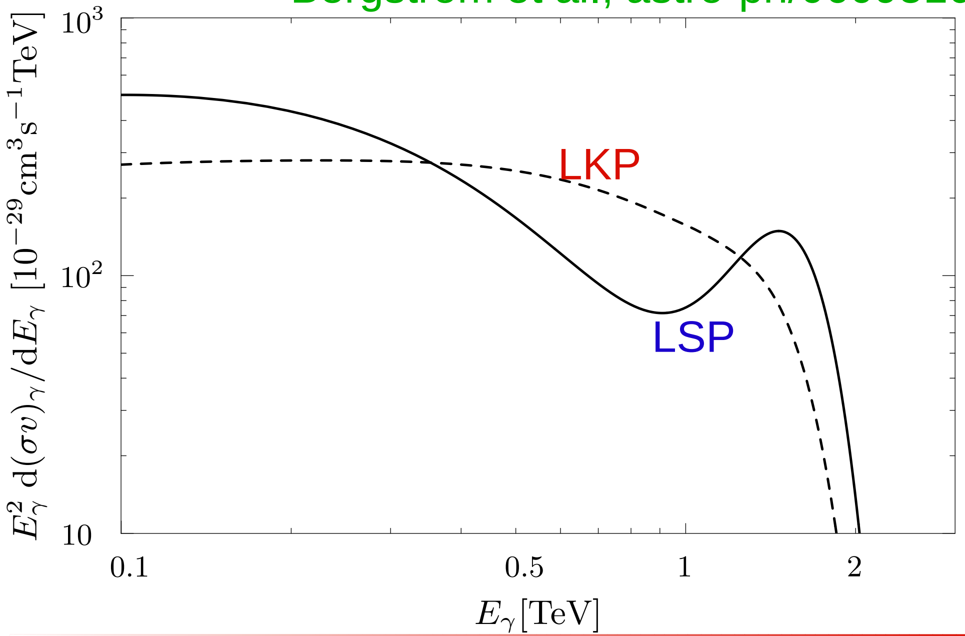
- Example: Leptons in SUSY
  - usually helicity suppressed
  - suppression no longer efficient for an additional photon in the final state, with $E_\gamma \sim m_\chi$
    Bergström, PLB '89
  - even greater enhancement when sleptons degenerate with neutralino! $\rightarrow$ mSUGRA...



FSR spectra

- provide a unique and distinct signature (not possible to mistake for astrophysical processes)
- the cutoff is more pronounced than for secondary photons $\rightsquigarrow$ DM mass can be determined to a higher accuracy
- Can even be used to distinguish between different DM candidates!
  - Example:
    $B^{(1)}$ vs. Higgsino
    (assume same mass and energy resolution of 15 %)

Bergström et al., astro-ph/0609510



FSR and SUSY

TB, Bergström & Edsjö, ’07 (in prep.)

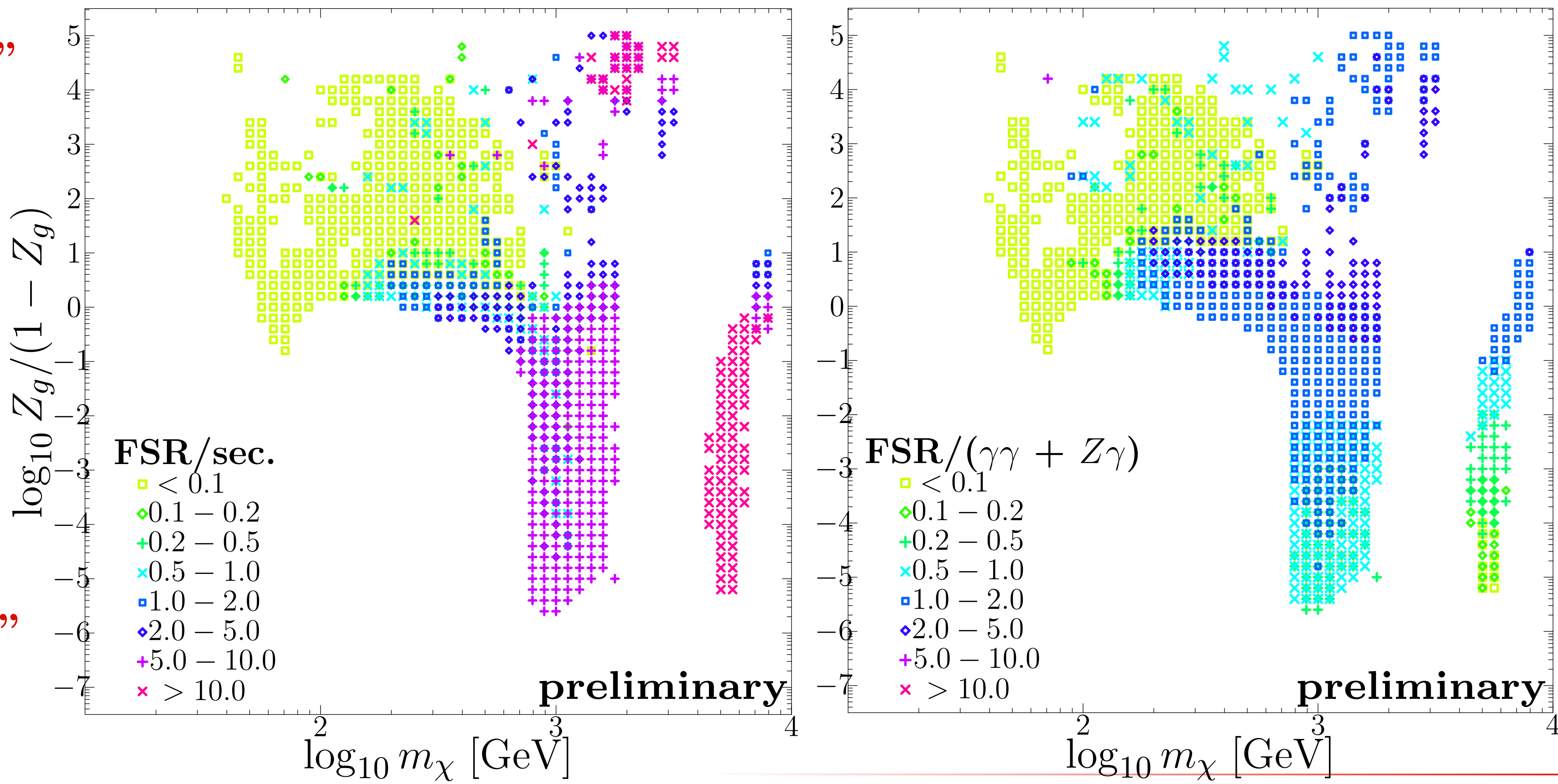
- include FSR from all possible final states in DarkSUSY
- Perform a scan over the whole MSSM

include $\sim 10^6$ models with $\Omega_\chi h^2$ as determined by WMAP

“Gaugino”

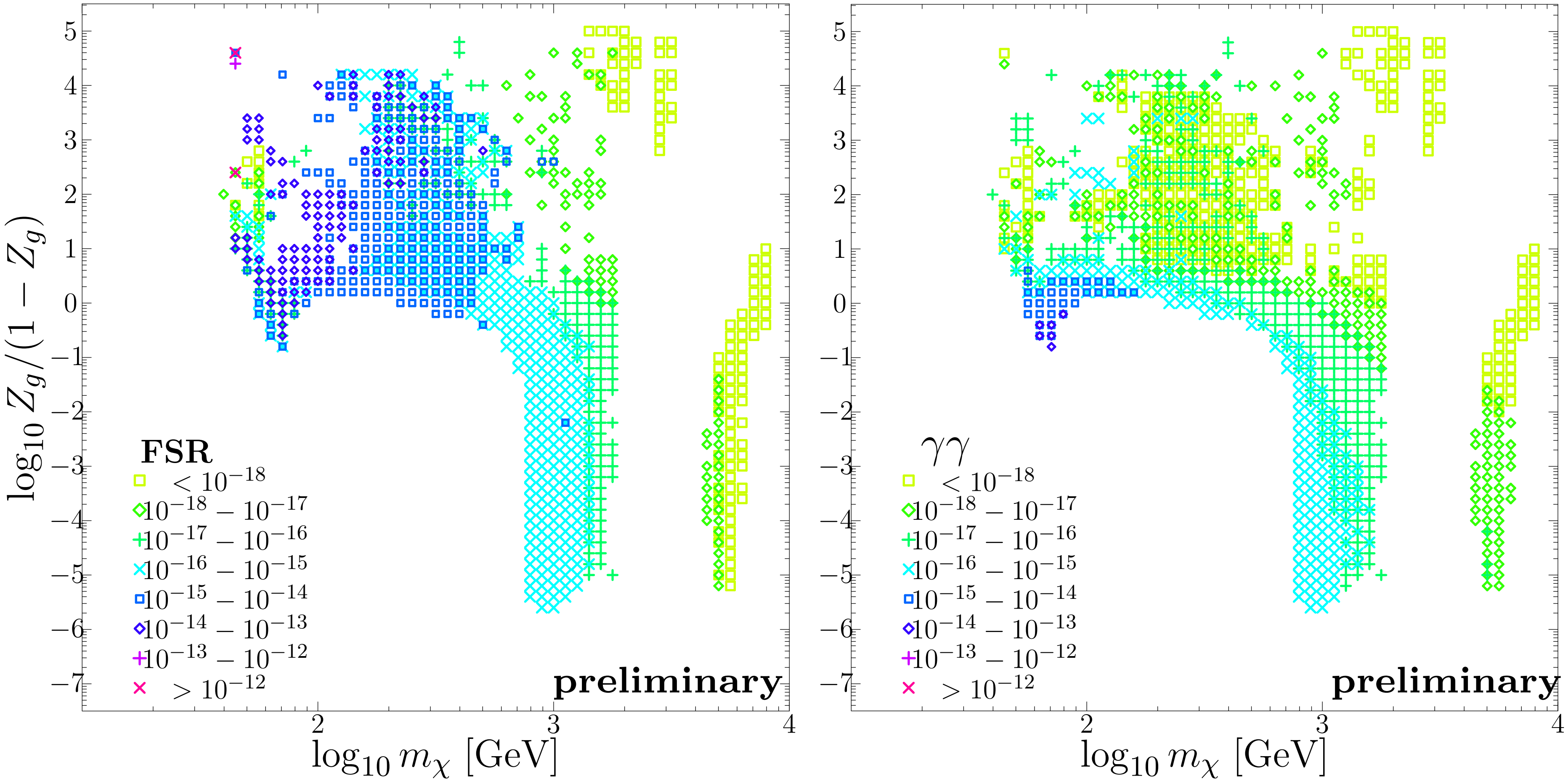
“mixed”

“Higgsino”



MSSM - total FSR fluxes

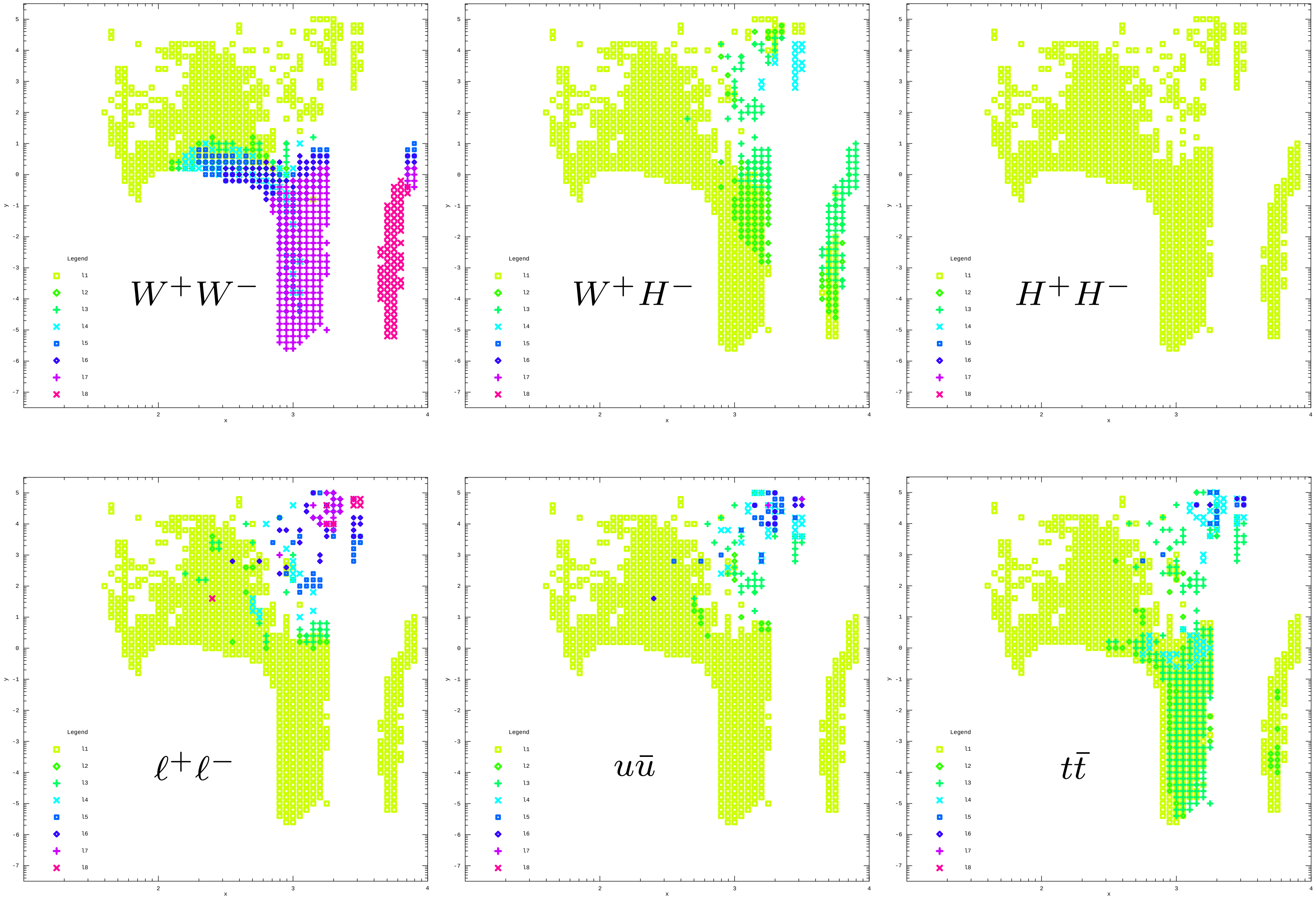
TB, Bergström & Edsjö, '07 (in prep.)



- All fluxes given in photons/(cm^{2}s)
- FSR: flux above $0.6\, m_\chi$

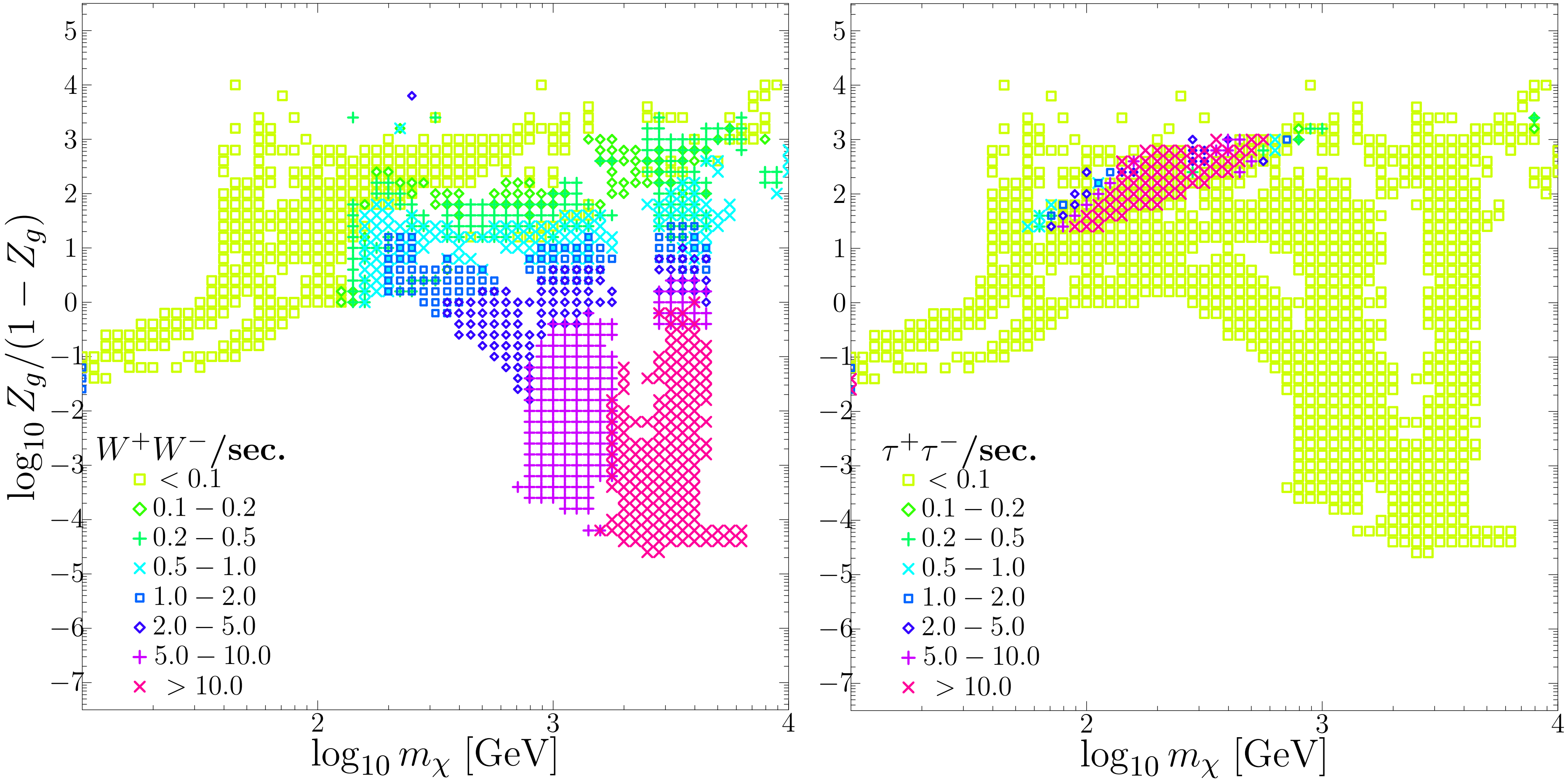
MSSM - FSR components

TB, Bergström & Edsjö, '07 (in prep.)



FSR in mSUGRA

TB, Bergström & Edsjö, '07 (in prep.)



$\rightsquigarrow$ Almost degenerate stops, typical in mSUGRA models, can give rise to enormous FSR contributions even for rather low neutralino masses!

Summary

Final state radiation

- in many situations completely dominates the spectrum for $E_\gamma \gtrsim 0.6 m_\chi$ (not only for heavy DM particles!)
- provides unique and distinct spectral signatures
- allows a precise determination of the DM mass due to the pronounced cutoff
- can even be used to distinguish between different DM candidates

$\leadsto$ ***should be regarded as at least equally important for the indirect detection of DM as line signals!***