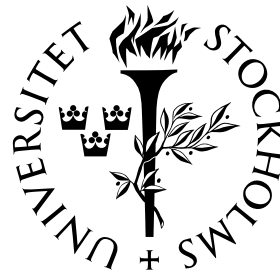


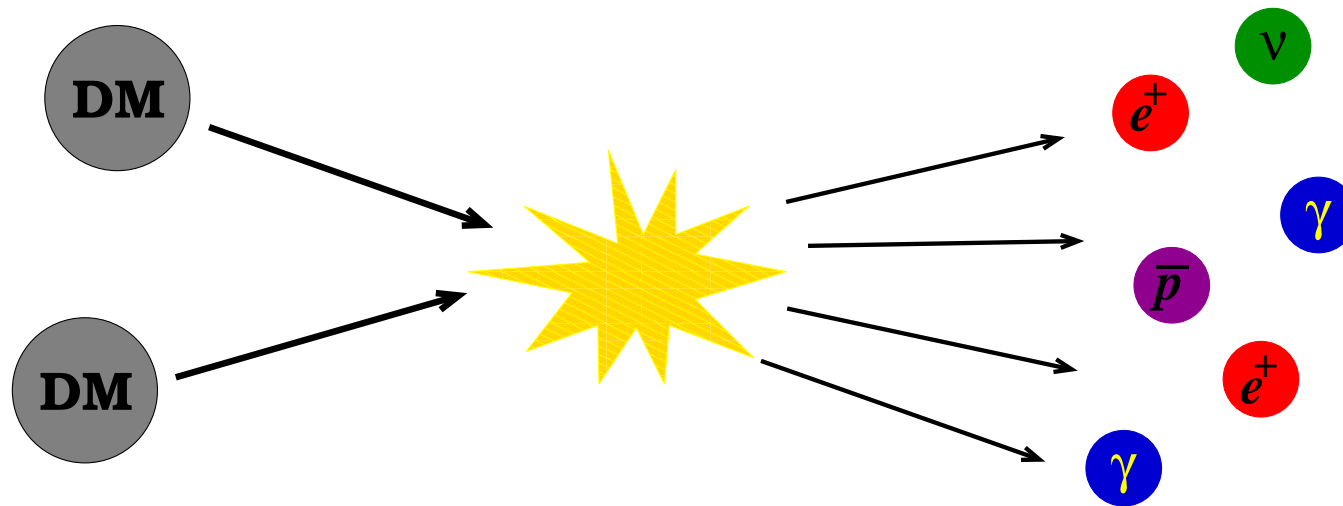
# Dark Matter Annihilation Signals

– the importance of radiative corrections

Torsten Bringmann, Stockholm University



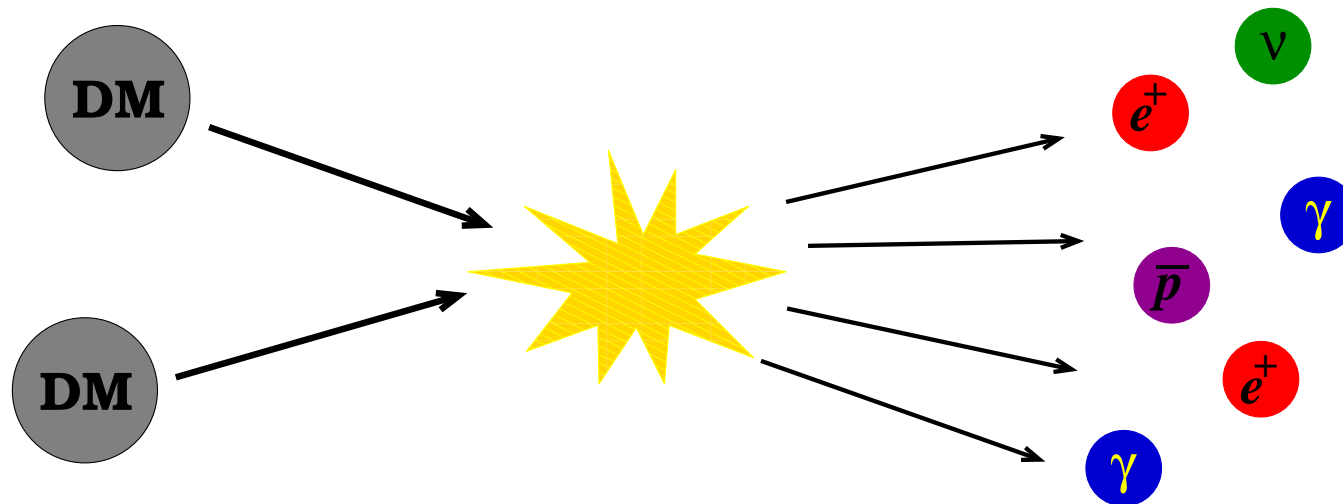
# Indirect DM detection



## Gamma rays:

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

# Indirect DM detection



## Gamma rays:

- Rather **high rates**
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- **Point** directly to the sources
- **No assumptions** about diffusive halo necessary
- **Clear spectral signatures** to look for



# DM annihilation spectra

( $\rightsquigarrow$  *entirely determined by the underlying microphysics!*)

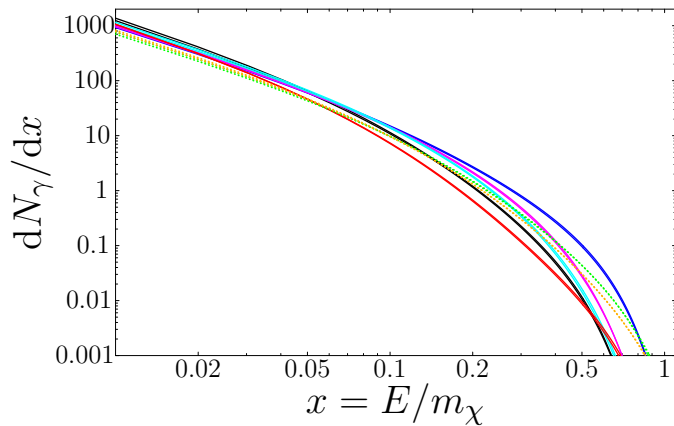
## 3 types of contributions:

- **Secondary photons** from fragmentation of decay products
  - mainly through  $\pi^0 \rightarrow \gamma\gamma$
  - result in a **rather featureless** spectrum
- **Line signals** from  $\chi\chi \rightarrow \gamma\gamma, Z\gamma, H\gamma$ 
  - necessarily loop-suppressed:  $\mathcal{O}(\alpha^2)$
  - “**smoking gun**” signature
- **Internal bremsstrahlung (IB)**
  - 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)

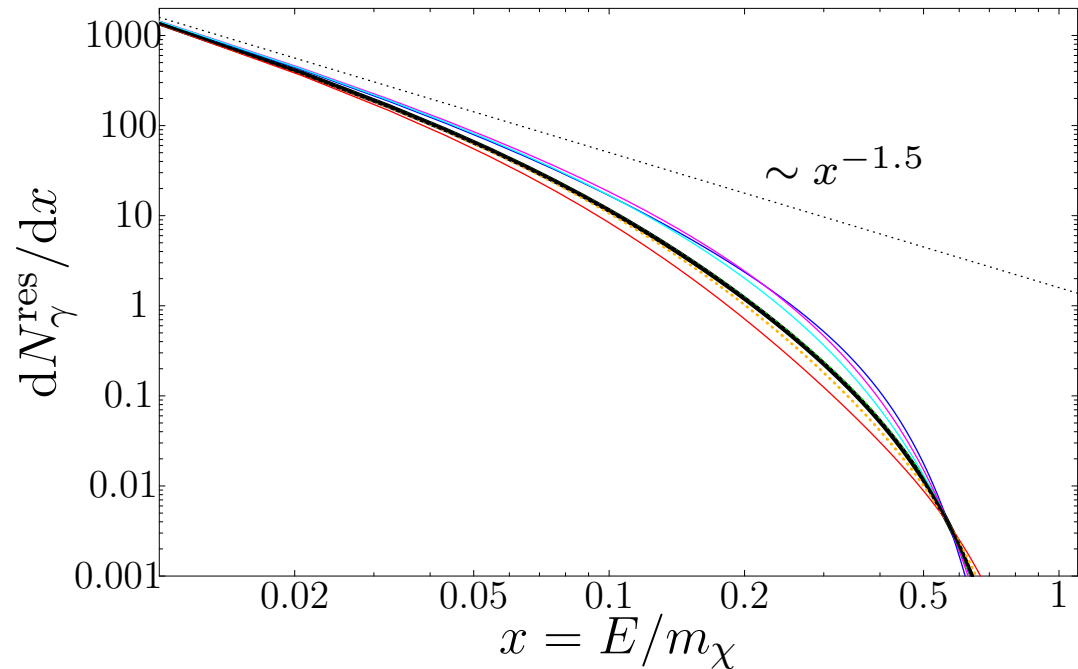


rescale



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

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





# Secondary photons (2)

---

Thus, if only these contributions are taken into account,

- “all DM annihilation spectra look the same”  
(only exception: a large branching ratio into  $\tau^+\tau^-$ )
- the kinematical **cutoff** at  $E_\gamma = m_\chi$  will **not** be **reconstructable** to a (very) high accuracy:
  - **observationally** challenging due to a considerable drop in the spectrum already at  $x \sim 0.5$ .
  - **theoretical** uncertainty in the inferred value of  $m_\chi$  up to 50%  
(unless exact branching ratios are known independently)



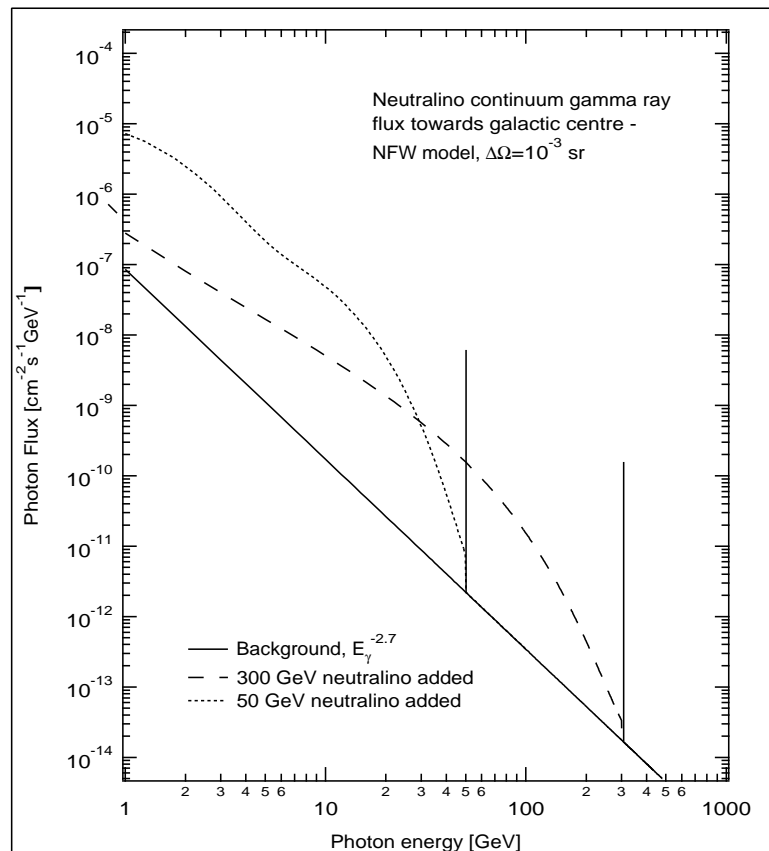
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# Direct annihilation into photons

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



particularly prominent  
**examples** include:

- almost pure **Higgsinos** or **Winos**  
e.g. Hisano et al. '05
- **Inert Higgs** dark matter  
Gustafsson et al. '07

Fig. from Bergström, Ullio & Buckley '97

# Line signals (2)

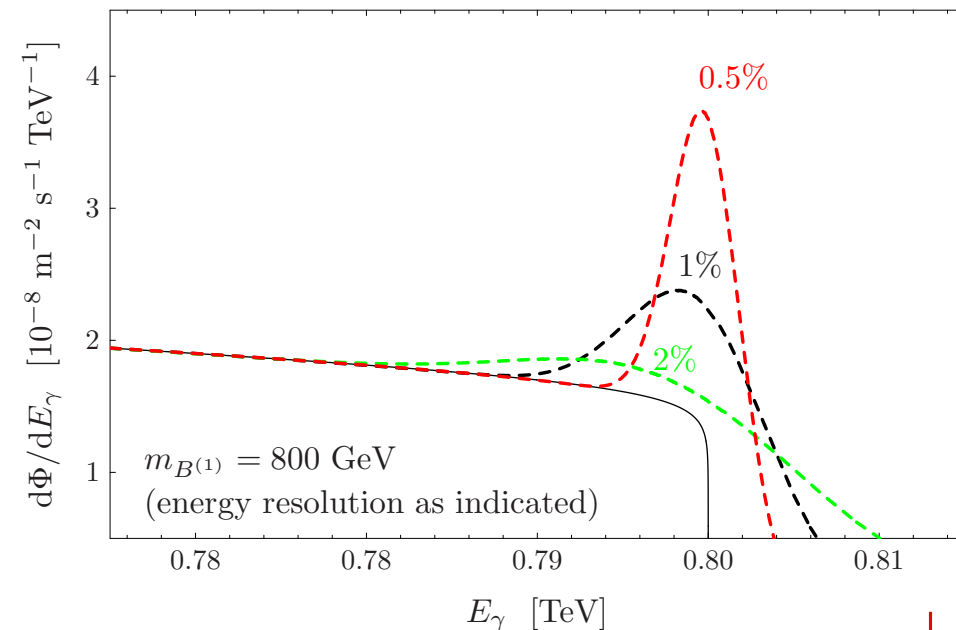
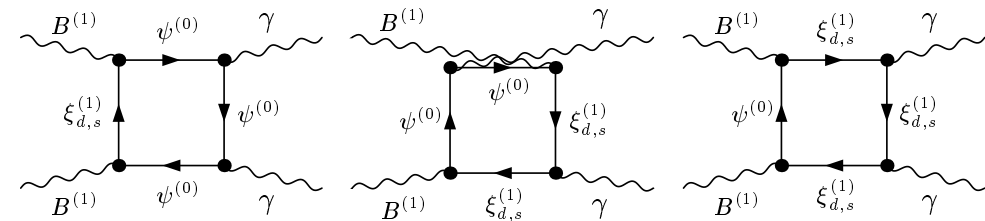
but:

the signal is necessarily **loop-suppressed**, i.e.  $\mathcal{O}(\alpha^2)$

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

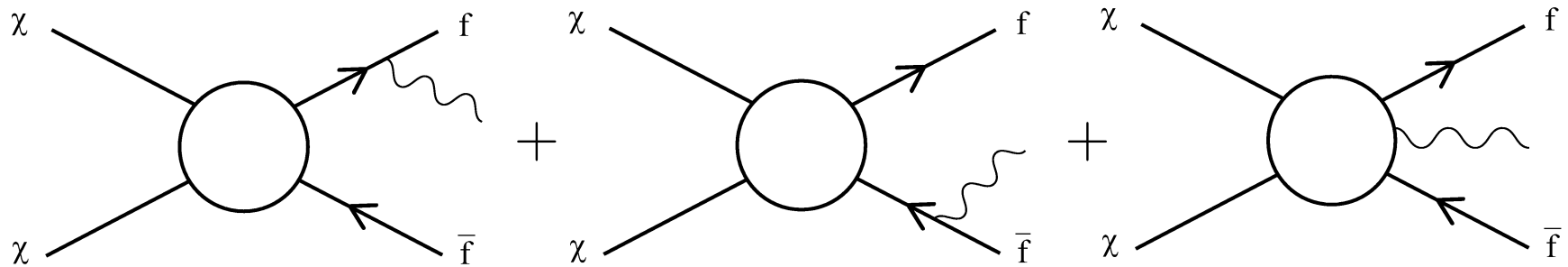
e.g. the **LKP** in UED:

Bergström, TB, Eriksson & Gustafsson '04



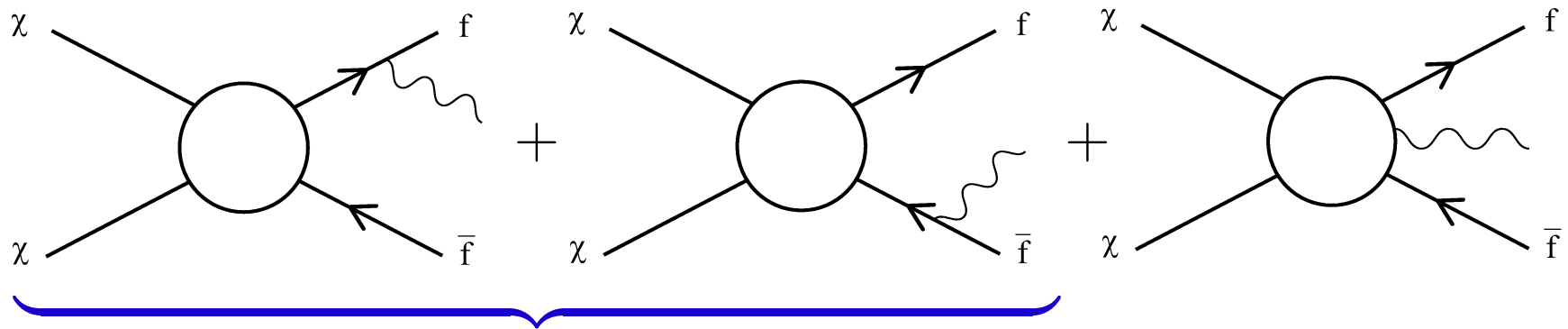
# Internal bremsstrahlung

Whenever DM annihilates into charged final states  $f$ , this is *automatically*, at  $\mathcal{O}(\alpha)$ , accompanied by  $\chi\chi \rightarrow f\bar{f}\gamma$ :



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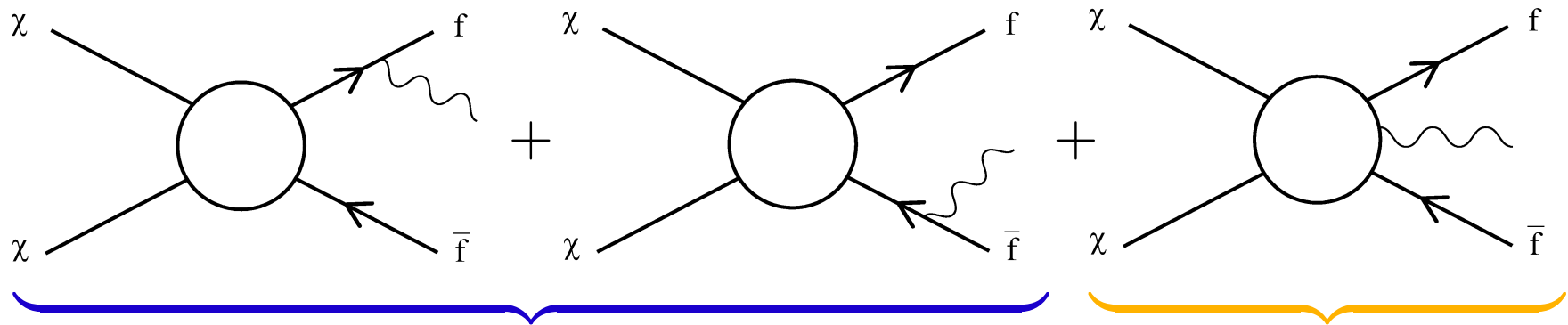


## Final state radiation

- “generically” dominant for  $m_f \ll m_\chi$
- model-independent spectrum

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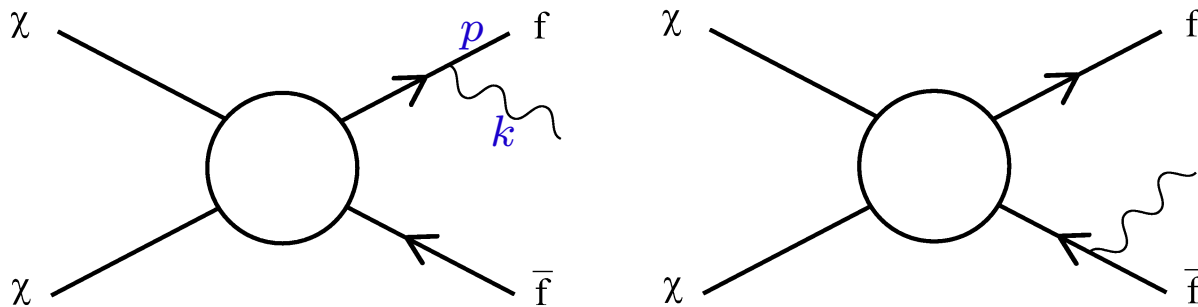
## Final state radiation

- “generically” dominant for  $m_f \ll m_\chi$
- model-independent spectrum

## “Virtual” IB

- dominant in two (important!) cases
- spectrum highly model-dependent

# Final state radiation



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

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

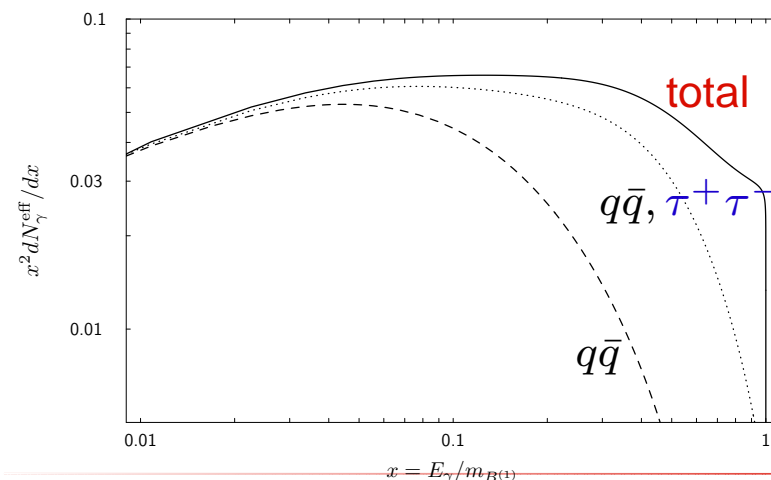
$$\frac{dN}{dx} \sim \sigma(\chi\chi \rightarrow f\bar{f}) \cdot \frac{\alpha Q^2}{\pi} \mathcal{F}(x) \log \frac{s}{m_f^2} (1-x)$$

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

## ● Example: **LKP** in UED

- $m_{B(1)} \sim 1 \text{ TeV}$
- high branching ratio into **leptons** ( $\sim 60\%$ )

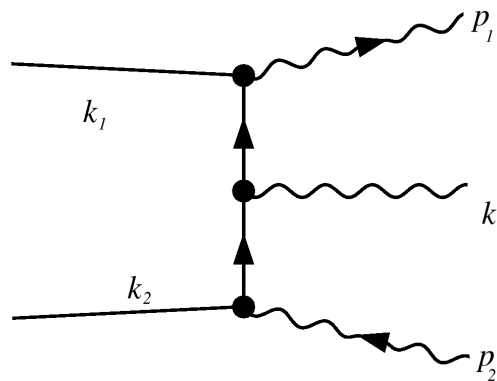
Bergström et al., PRL '05a



$x = E_\gamma/m_{B(1)}$

# Charged virtual particles (1)

“Light” charged **bosonic final states** receive an enhancement from ***t*-channel** diagrams if the internal particles are degenerate in mass with the DM particles:

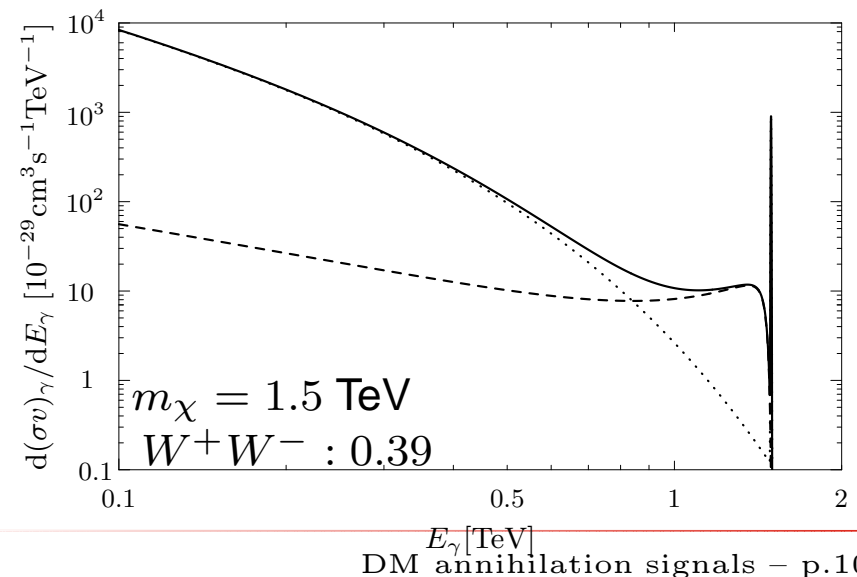


- $\mathcal{M} \propto \frac{1}{k_1 \cdot p_1} \frac{1}{k_2 \cdot p_2} \approx \frac{1}{m_\chi^2 E_1 E_2}$
- small  $E_1$  or  $E_2 \rightsquigarrow$  high  $E_\gamma$
- (Note that the contraction of *fermion* final legs leads to an additional  $E_f$  in the numerator)

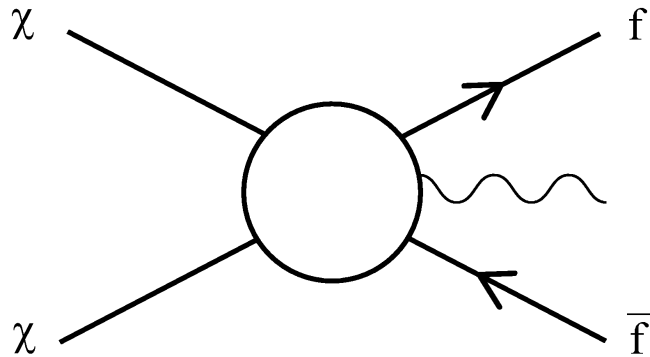
## • Example: Higgsino

- TeV mass
- high b.r. to  $W^+W^-$

Bergström et al., PRL '05b



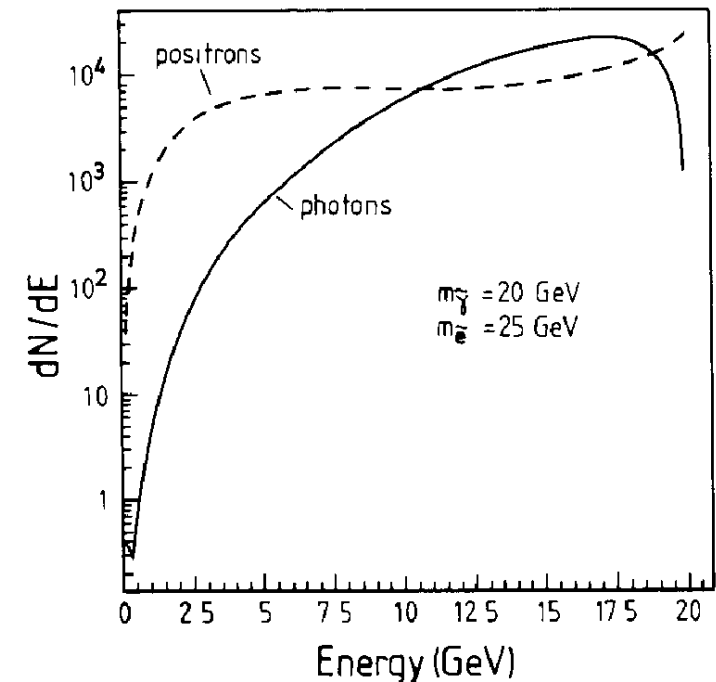
# Charged virtual particles (2)



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

## ● Example: **Leptons** in SUSY

- **helicity** suppression  $\propto \left(\frac{m_\ell}{m_\chi}\right)^2$
- 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! → **mSUGRA...**



# IB and SUSY

TB, Bergström & Edsjö, JHEP '08

- identify all relevant final states for neutralino annihilation:
  - $q\bar{q}\gamma, \ell^+\ell^-\gamma, W^+W^-\gamma, W^\pm H^\mp\gamma, H^+H^-\gamma$
- calculate amplitude, including **all** Feynman diagrams:
  - use general, unspecified couplings at this step
  - work in the  $v \rightarrow 0$  limit, which greatly simplifies
    - the amplitude (insert an  $P_{1S_0}$  projector)
    - the kinematics (now like the decay of a scalar)
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← **NEW release 5.0**  
(Gondolo, Edsjö, Bergström, Ullio,  
Schelke, Baltz, TB & Duda)

*...see talk by J. Edsjö!*

# Total IB fluxes

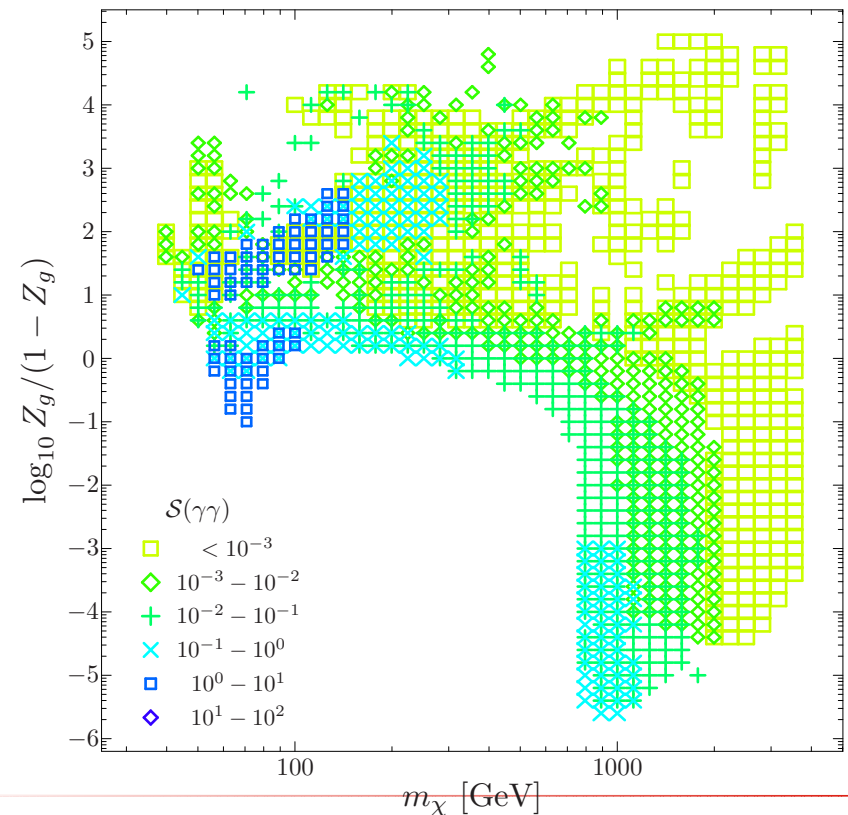
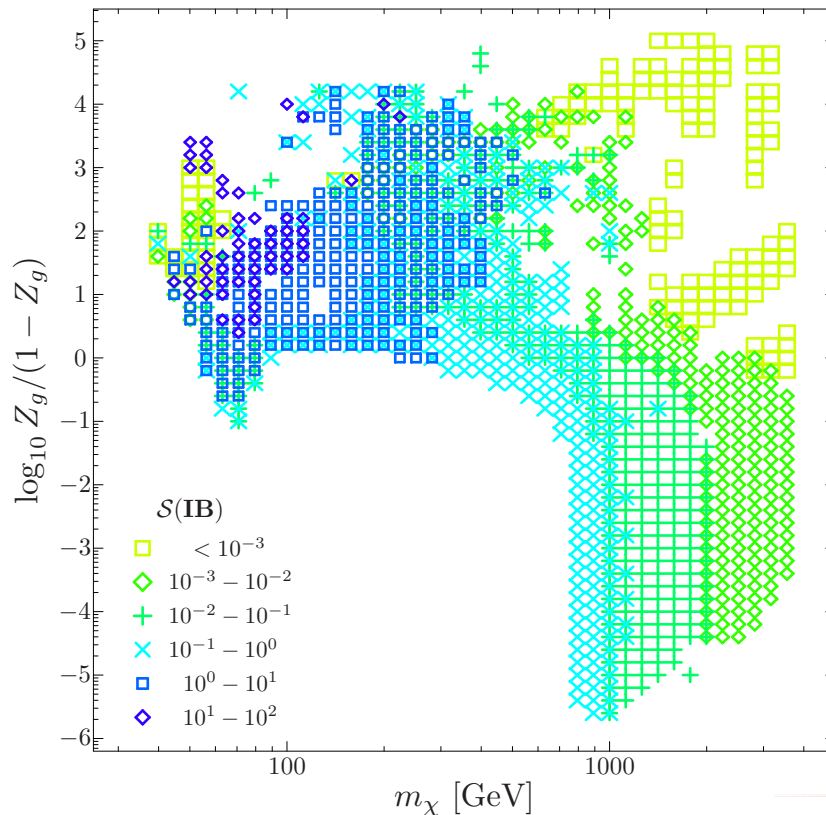
TB, Bergström & Edsjö, JHEP '08

- Perform a **scan** over mSUGRA and the MSSM  
include  $\sim 10^6$  models with  $\Omega_\chi h^2$  as determined by WMAP, all accelerator constraints OK
- $$\mathcal{S} \equiv N_\gamma (E_\gamma > 0.6 m_\chi) \frac{\langle \sigma v \rangle}{10^{-29} \text{cm}^3 \text{s}} \left( \frac{m_\chi}{100 \text{GeV}} \right)^{-2} \propto \text{signal at earth}$$
  
[HESS @ GC: need  $\mathcal{S} \gtrsim 10^{-2}$  ( $\mathcal{S} \gtrsim 1$ ) for  $m_\chi \sim 1 \text{ TeV}$  ( $m_\chi \sim 100 \text{ GeV}$ ) ]

“Gaugino”

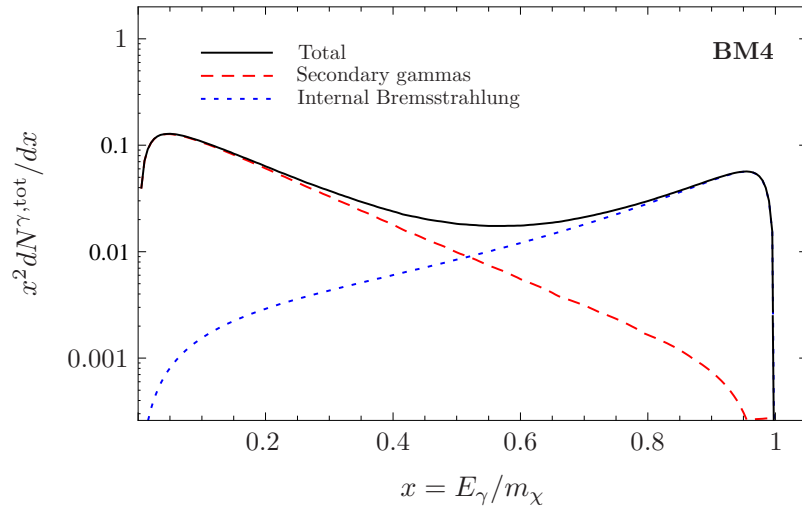
“mixed”

“Higgsino”

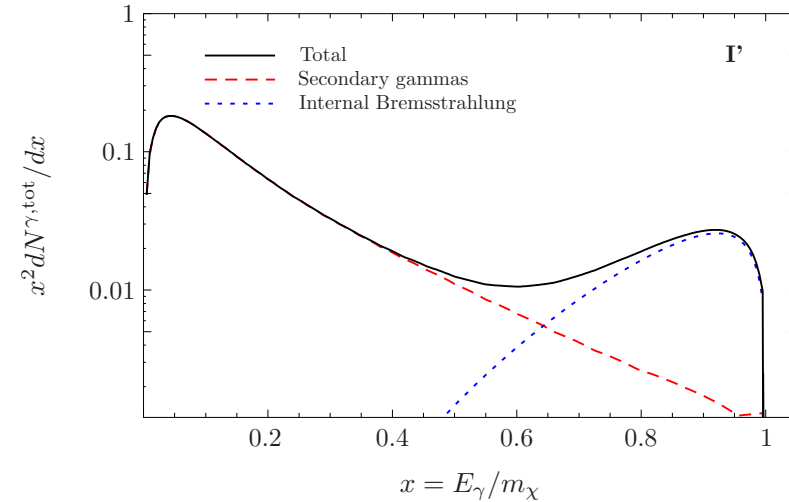


# mSUGRA spectra

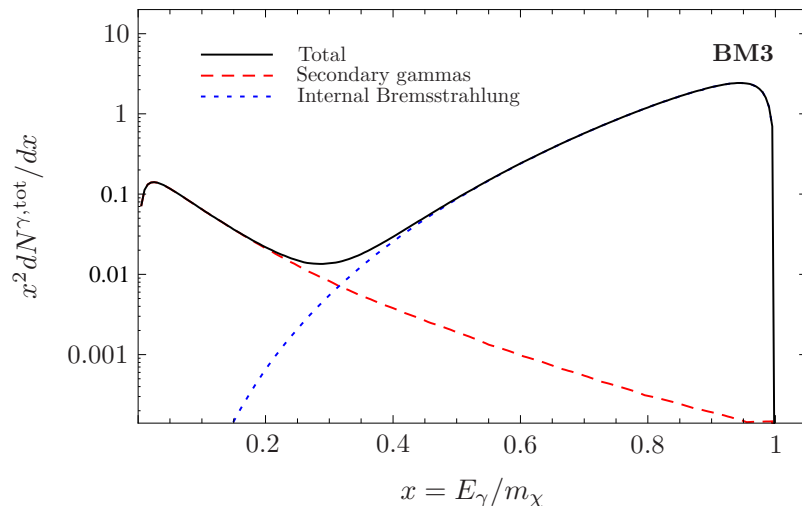
focus point region ( $m_\chi = 1926$  GeV)



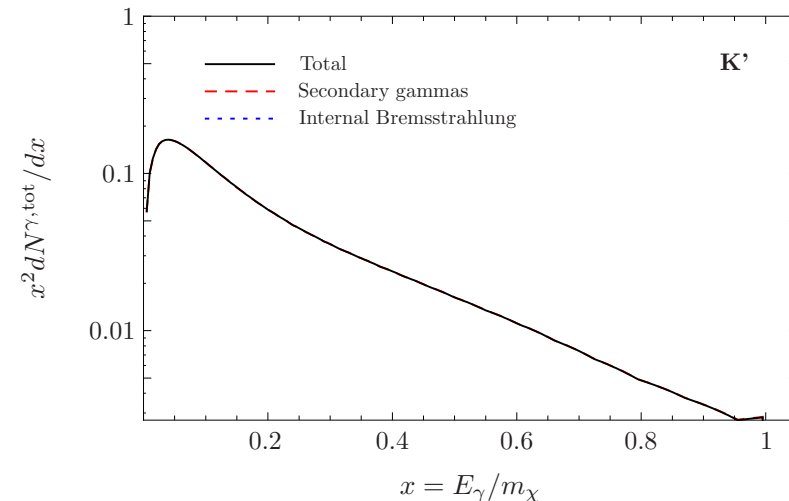
bulk region ( $m_\chi = 141$  GeV)



coannihilation region ( $m_\chi = 233$  GeV)



funnel region ( $m_\chi = 565$  GeV)



[benchmarks taken from TB, Bergström & Edsjö, '08 and Battaglia et al., '03]



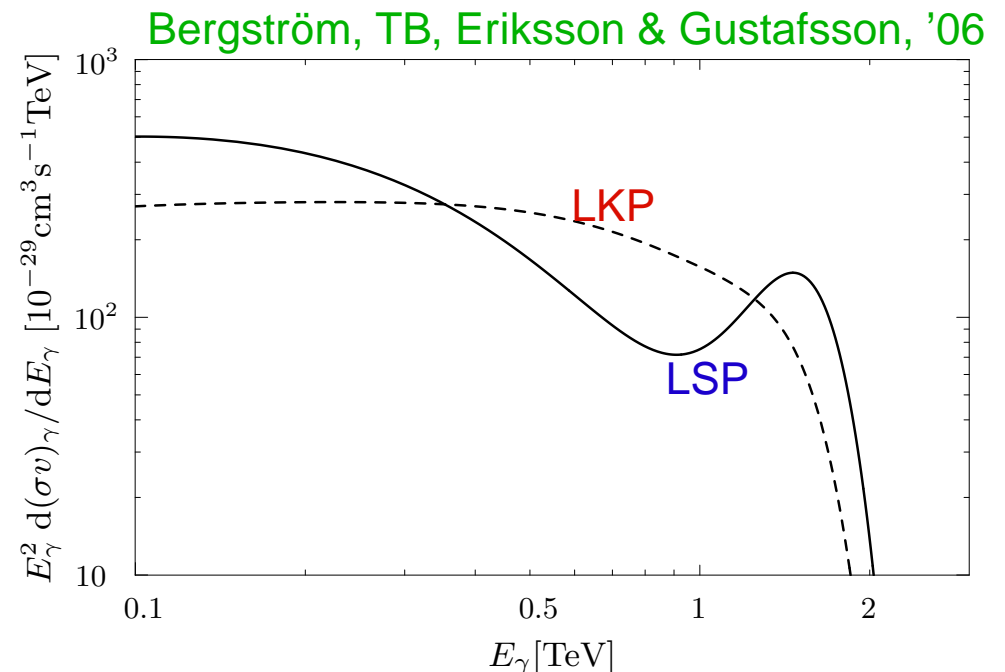
# Comparing IB spectra

- all spectra share a pronounced cutoff...  
( $\leadsto$  accurate determination of  $m_\chi$ )
- ... but also show further features at slightly lower energies
- In some cases, this could even be used to **distinguish** between different **DM candidates!**

(see, e.g., the spectra shown before)

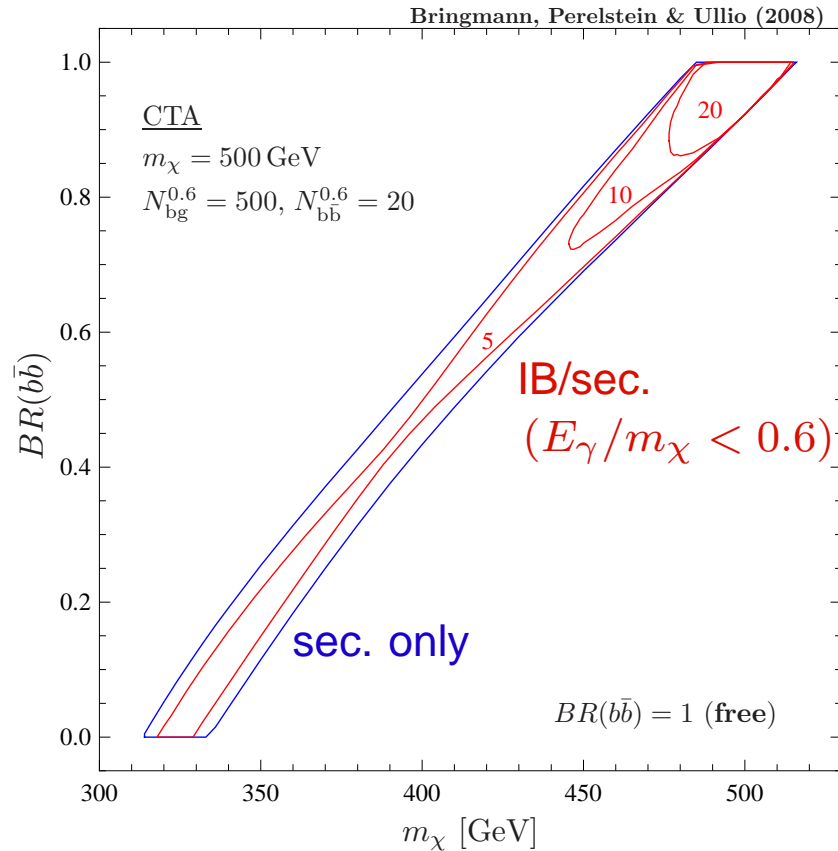
- further example:  
 **$B^{(1)}$**  vs. **Higgsino**

(assume same mass and  
energy resolution of 15 %)



# Model discrimination (2)

Better mass reconstruction  $\rightsquigarrow$  discriminate even secondary contributions!

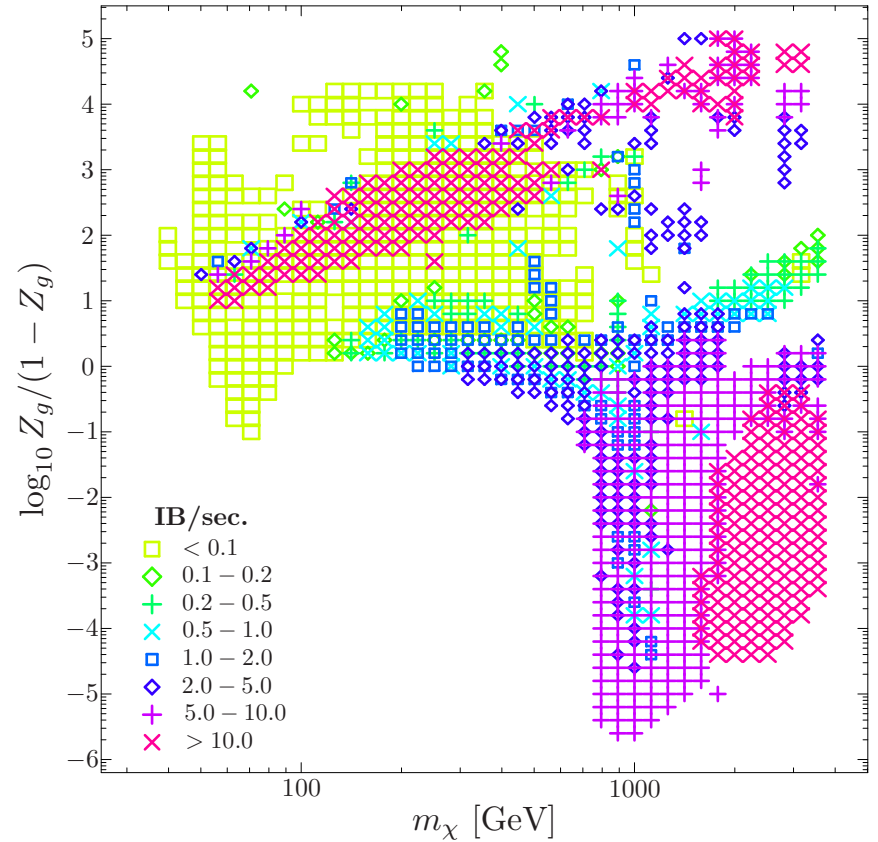
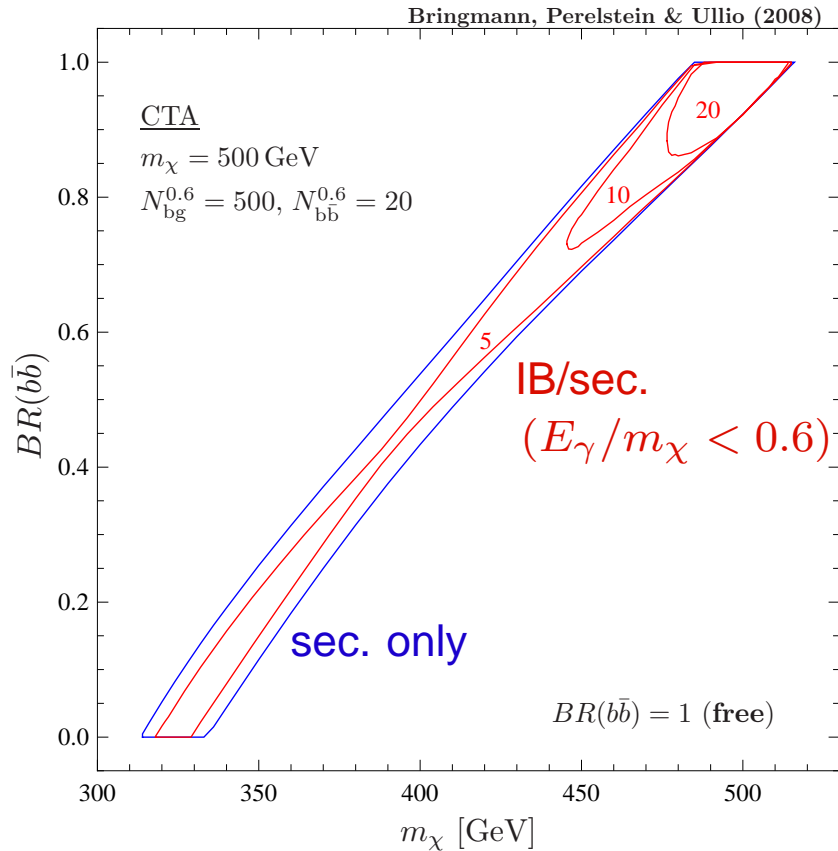


Given a signal detection, how well can CTA determine the annihilation channels (assuming  $BR(b\bar{b}) + BR(W^+W^-) = 1$ )?

TB, Perelstein & Ullio, in prep.

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For comparison: range of IB enhancements in SUSY

TB, Bergström & Edsjö, JHEP '08

TB, Perelstein & Ullio, in prep.

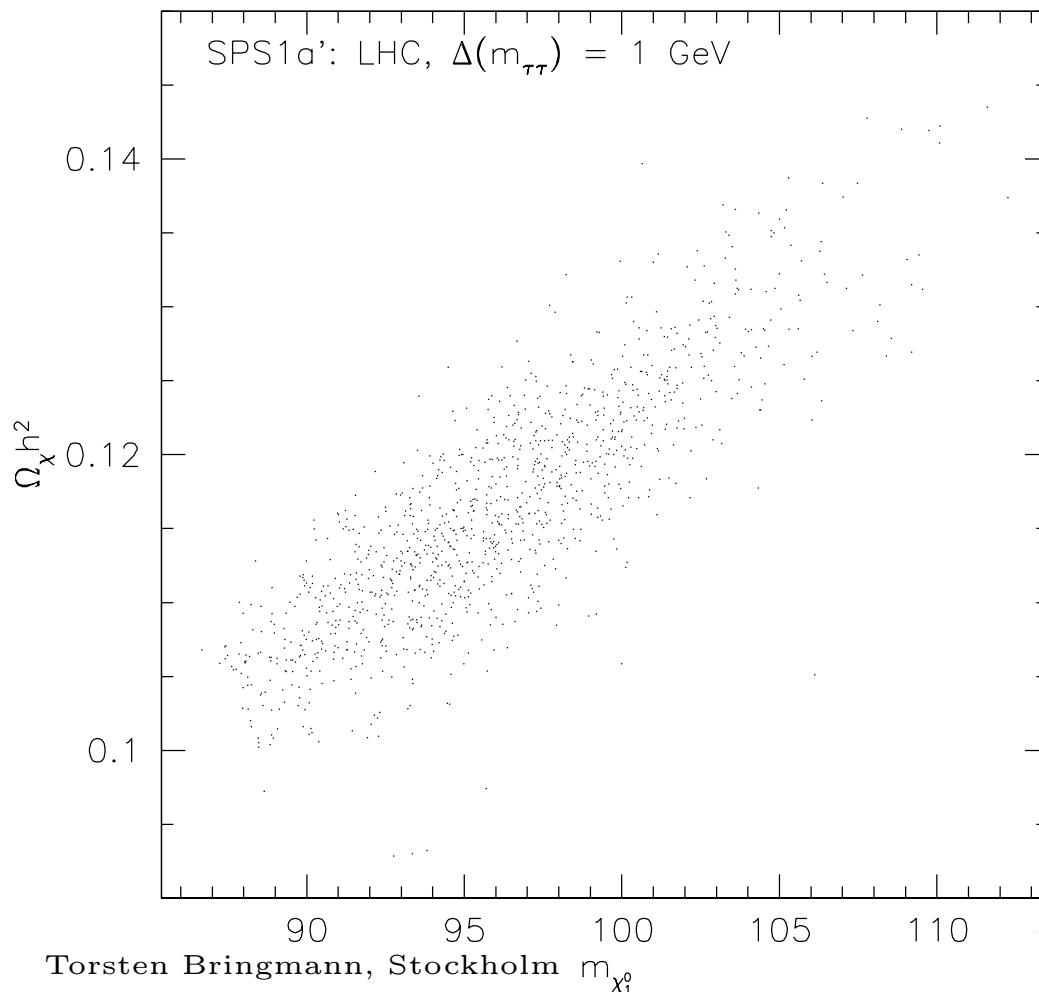


# Model discrimination (3)

Another example: consider a point in the **bulk region** and reconstruct model parameters from **LHC measurements**.

Baltz et al., '06

(NB! For other  $\Omega h^2$ -relevant regions,  $m_\chi$  is considerably less well determined!)

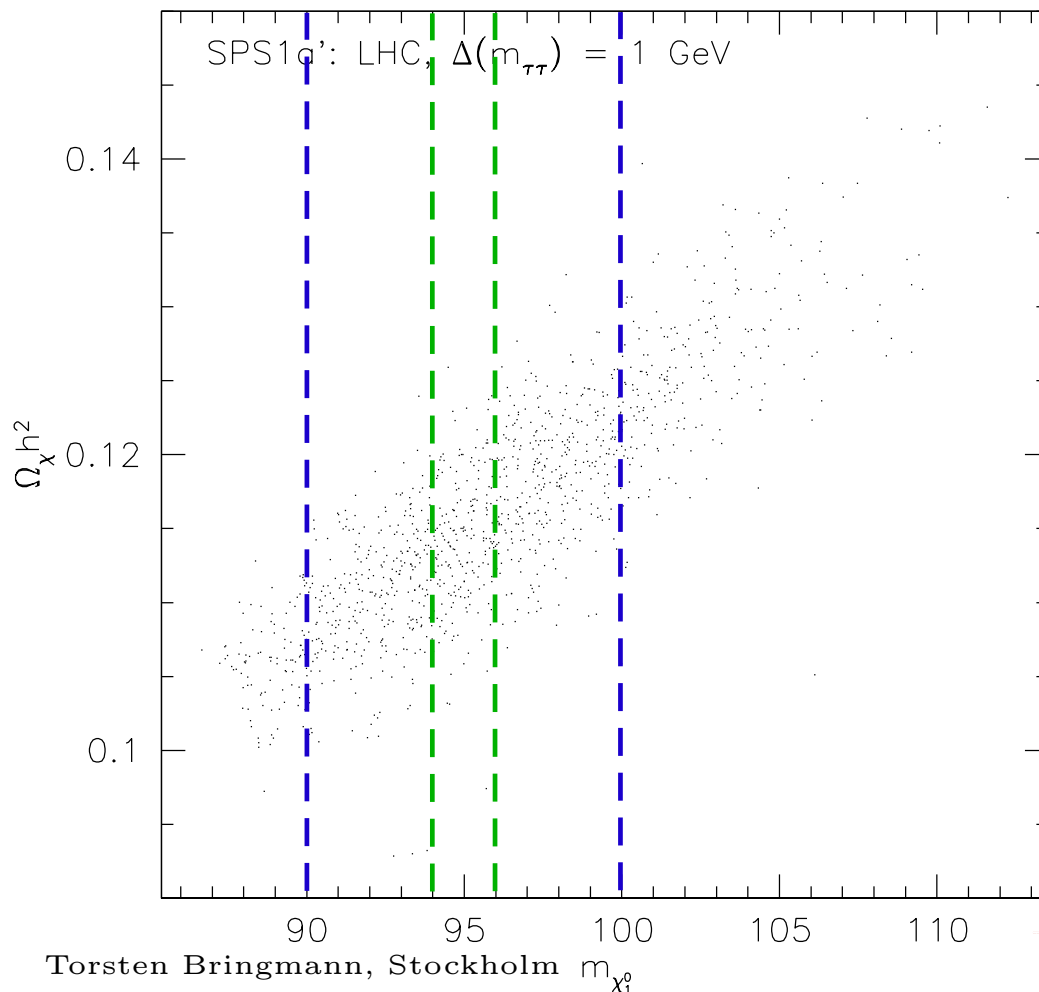


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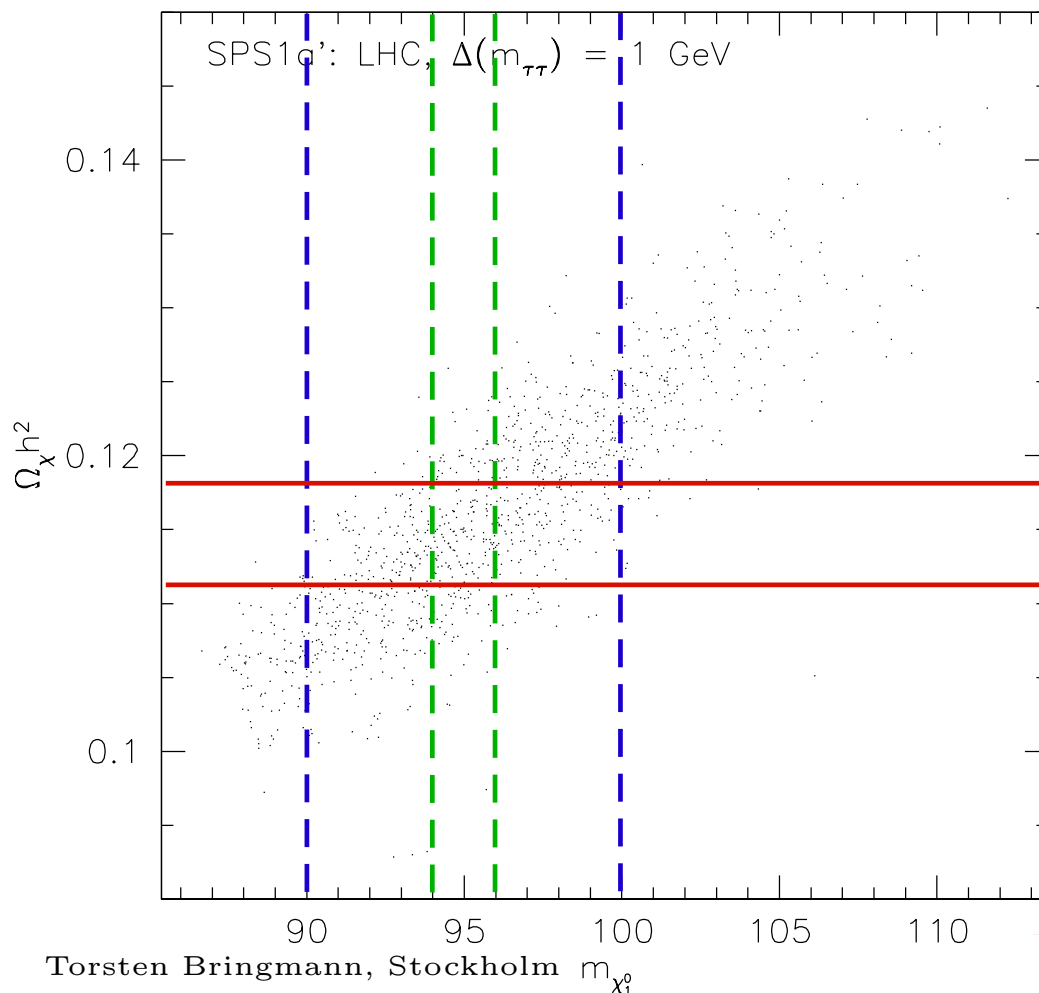
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- in this region, IB features lead to a very sharp cutoff  $\rightsquigarrow$  assume that a  **$\gamma$ -ray** detection determines the mass up to **5%** or **1%**
- add updated cosmological data after **WMAP5**  $\rightsquigarrow$  region of possible models shrinks considerably!



# Detectional prospects

- IB contributions important at **high energies**  
↪ this is where **Air Cherenov Telescopes** are **most sensitive!**
- Preliminary study for dSphs: (TB, Doro & Fornasa, in prep.)
  - Taking into account IB contributions **boosts** the effective sensitivity by a factor of **up to  $\sim 10$** .  
see also, e.g., talk by B. Adrian!
  - For reasonably optimistic astrophysical assumptions, **CTA** could see a DM signal from **Willman 1** (but not from, e.g., Draco) for a large class of models.
- Other “classical” sources?  
↪ *More detailed studies needed!*



# Positrons

---

- usually very **high boost factors** required
- What about  $e^+e^-\gamma$  channel?

Bergström, TB, Edsjö, in prep.

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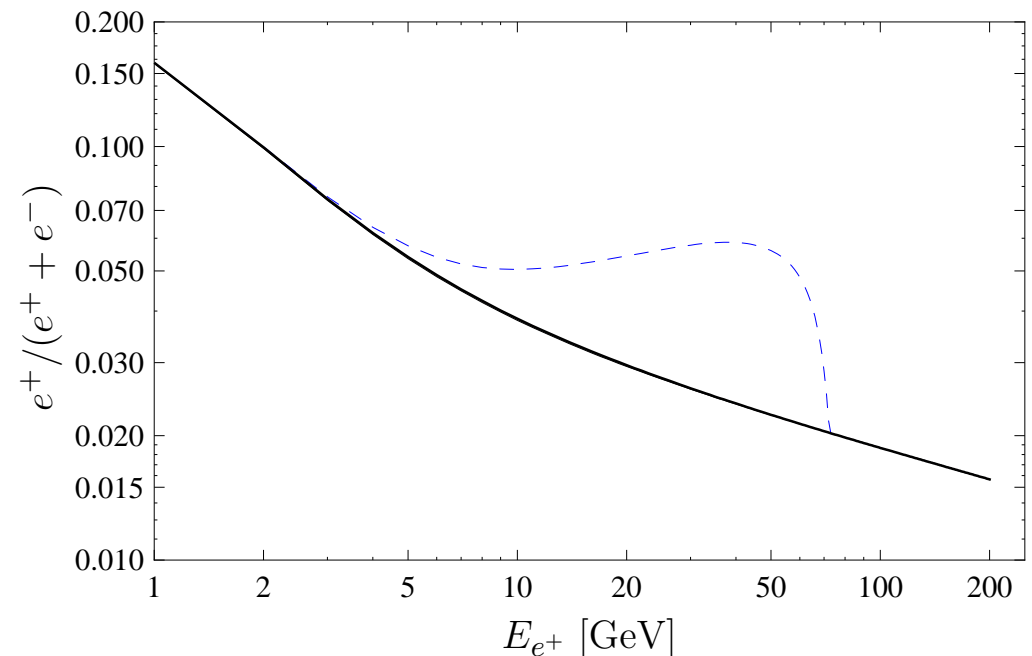
Bergström, TB, Edsjö, in prep.

example MSSM model:

(with  $m_\chi \sim 72$  GeV,  $m_{\tilde{e}} \sim 100$  GeV)

↪ flux at TOA, after propagation:

- background /  
no radiative corrections
- Including radiative corrections  
(main contribution:  $e^+e^-\gamma$ )



- much more **pronounced spectra** (cf. LKP)  
*but*: large boost factors still necessary...  
( $10^4$  in the above figure)



# Summary

---

## *Internal bremsstrahlung*

- in many situations completely **dominates** the spectrum for  $E_\gamma \gtrsim 0.6 m_\chi$  ( $\rightsquigarrow$  enhanced detectional prospects!)
- provides unique and **distinct spectral signatures** (note that DM annihilation spectra *not* model-independent!)
- allows a precise determination of the DM mass due to a **pronounced cutoff**
- can be used to infer important **DM properties** and thus to distinguish between different candidates



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  - allows a precise determination of the DM mass due to a **pronounced cutoff**
  - can be used to infer important **DM properties** and thus to distinguish between different candidates
- $\rightsquigarrow$  *should be regarded as at least equally important for the indirect detection of DM as, e.g., line signals!*