Dark Matter Annihilation Signal in Gamma Rays

– the importance of radiative corrections

Torsten Bringmann, Stockholm University

based on:

- TB, Bergström & Edsjö, JHEP **0801** (2008) 049 [0710.3169 [hep-ph]]
- Bergström, TB, Eriksson & Gustafsson, PRL **95** (2005) 241301 [hep-ph/0507229]

Outline

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Myth 1 ***"Usually, radiative corrections to leading order results can safely be neglected in DM physics"***

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Myth 2 *"All DM annihilation spectra look more or less the same"*

Evidence for dark matter (1)

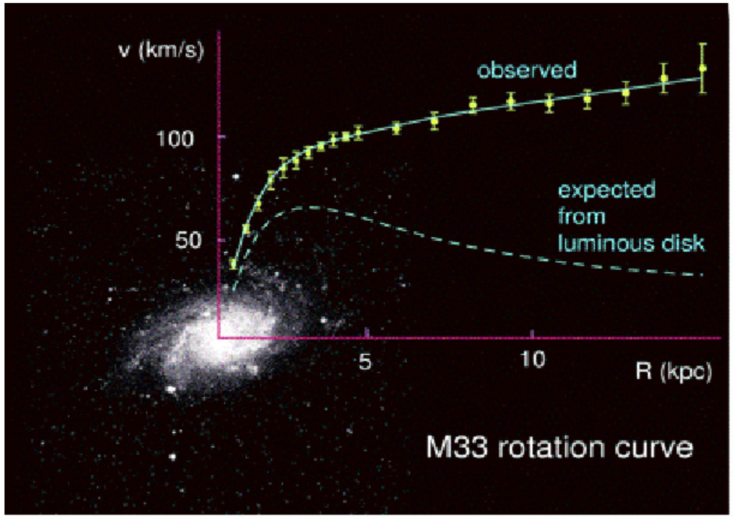


Fig.: Bergström '00

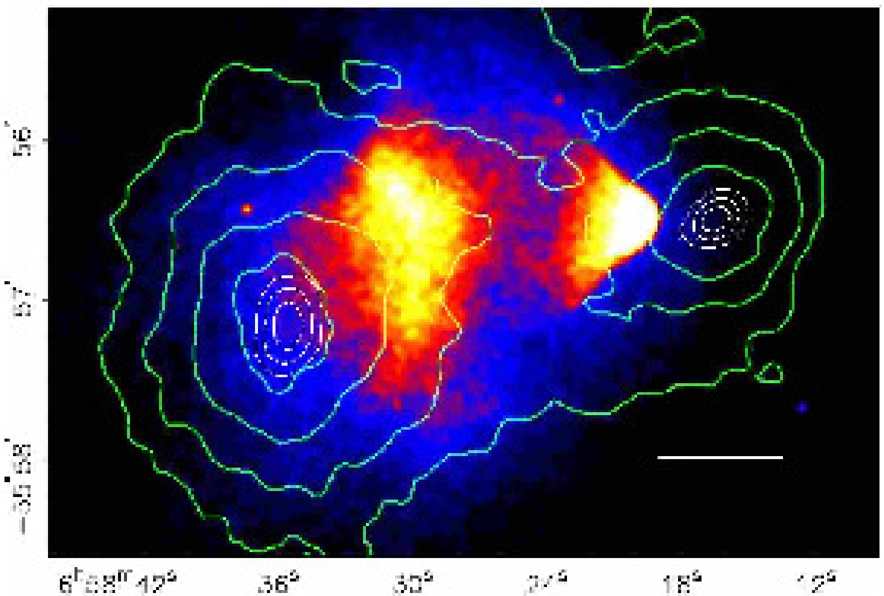
For a long time the most convincing evidence:
galactic rotation curves

(but historically the first evidence: velocity dispersion of galaxies in the COMA cluster)

Zwicky '33

Direct evidence for DM from the "Bullet" cluster: gravitational potential clearly displaced from the plasma (the main baryonic component)

Clowe et al, '06



Evidence for dark matter (2)

Gravitational lensing can even be used to map the large-scale distribution of the dark matter:

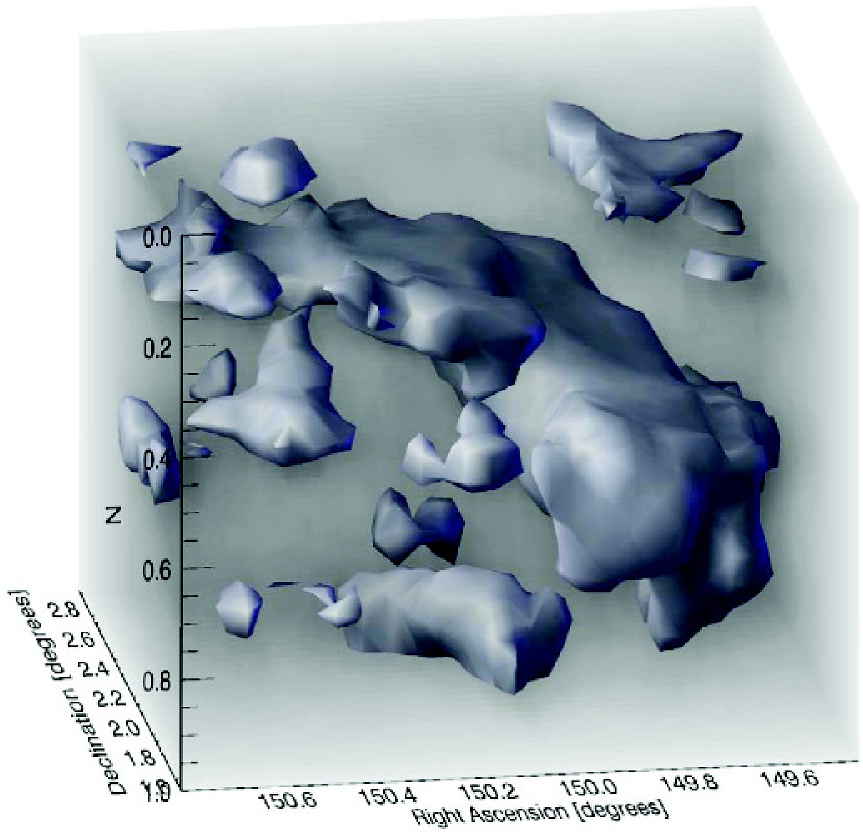
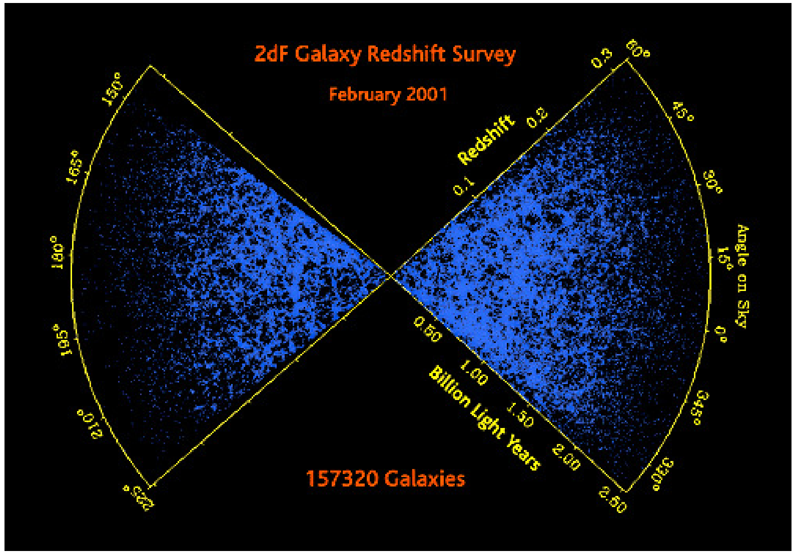


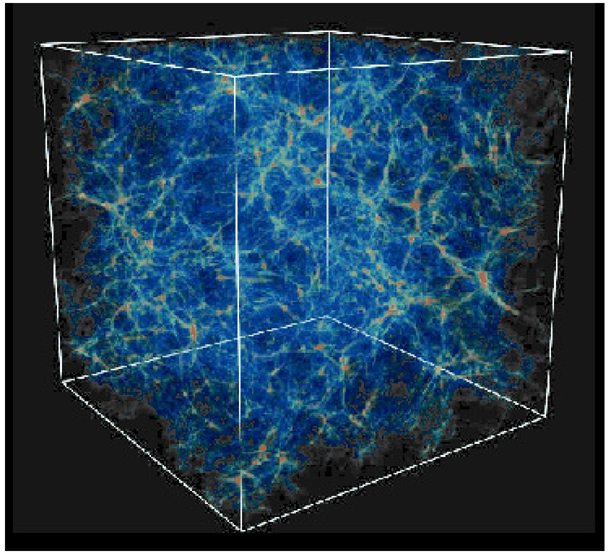
Figure 5 | 3D reconstruction of the dark matter distribution. The three axes correspond to Right Ascension, Declination, and redshift: with distance from the Earth increasing towards the bottom. The redshift scale is highly compressed, and the survey volume is really an elongated cone. An isodensity contour has been drawn at a level of $1.6\times10^{12}\,M_{\odot}$ within a circle of radius 700 *kpc* and Δz=0.05. This was chosen arbitrarily to highlight the filamentary structure. The faint background shows the full distribution, with the level of the grey scale corresponding to the local density. Additional views are provided in supplementary Fig. 7.

An intersecting network of filaments is found, consistent with the predictions from gravitationally induced structure formation.

Massey et al, Nature ’07

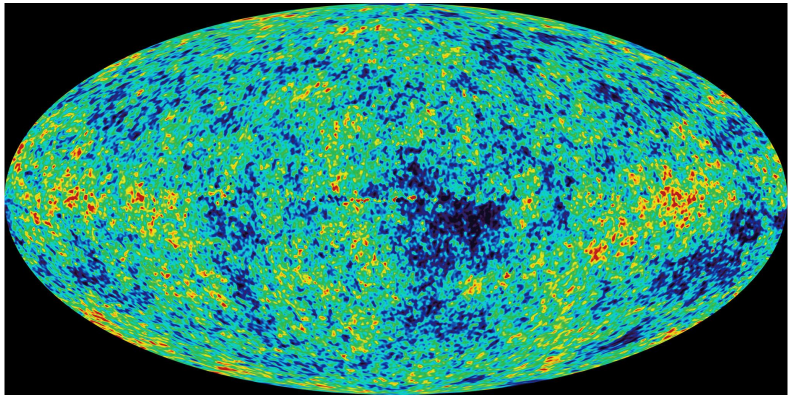
Evidence for dark matter (3)

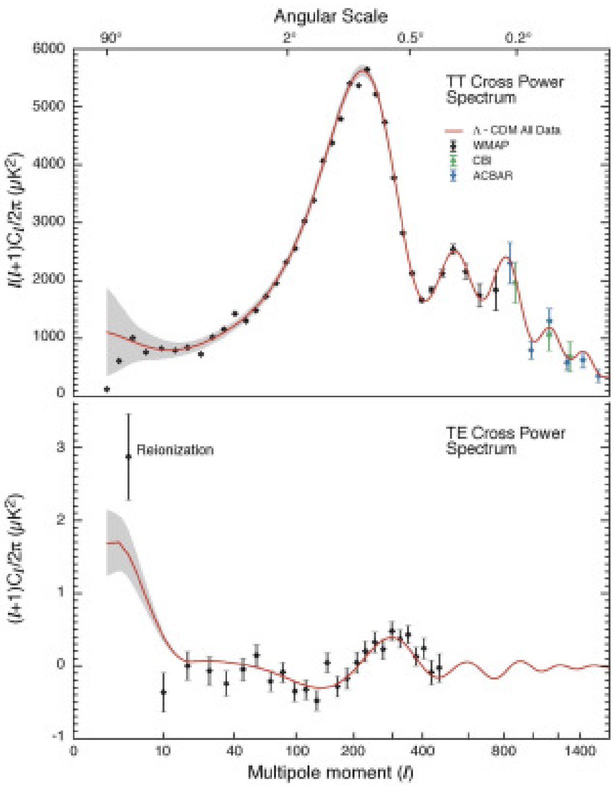




In order to reconcile the matter distribution observed in large scale structure surveys with that of N-body simulations, the universe has to be dominated by a dissipation-less and cold (free-streaming effects are negligible) matter component.

Evidence for dark matter (4)





On even larger scales, the cosmic microwave background provides further evidence that the total matter content is dominated by a non-baryonic component.

Furthermore, the inferred *baryonic* matter component is consistent with the predictions from big bang nucleosynthesis.

Dark Matter

By now, we definitely know it's there!

- $\Omega_{CDM} = 0.233 \pm 0.013$ (update after WMAP5)
- electrically neutral (dark)
  and dissipationless (structure formation)
- non-baryonic (CMB, BBN)
- cold, i.e. negligible free-streaming effects (LSS)
- collisionless ("Bullet" cluster, ...)

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... but what is it???

WIMPs

W eakly ***I*** interacting ***M*** assive ***P*** articles are particularly well-motivated DM candidates as they

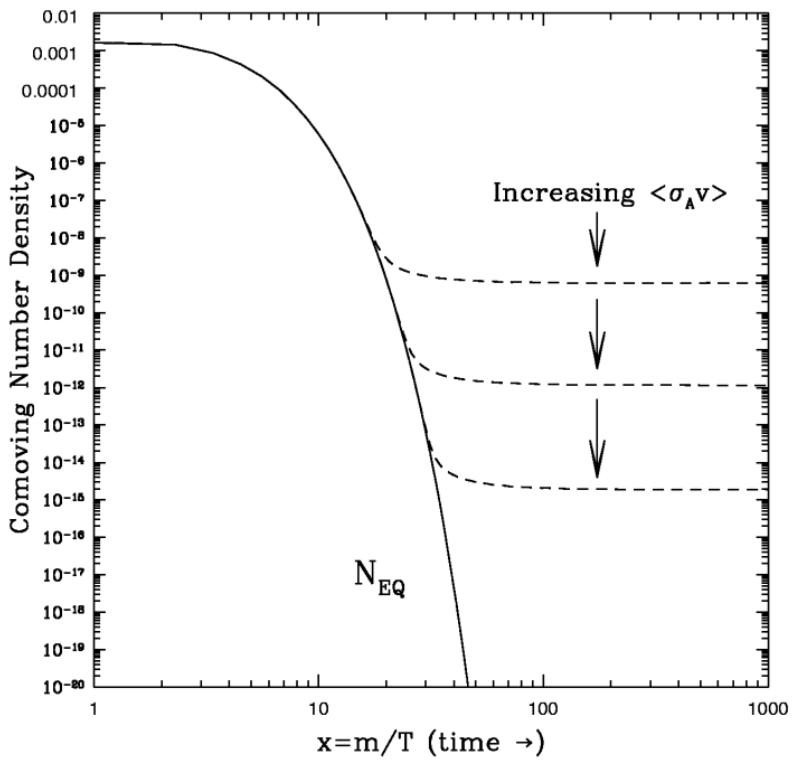
- naturally give the right relic density
  (through thermal production in the early universe)
- appear in all kinds of extensions to the SM
  (introduced for independent reasons, connected to new physics that is expected at the TeV scale)

The WIMP "miracle"

In the early universe, the WIMP number density n is determined by the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\rm eq}^2 \right)$$

Once the interaction rate falls behind the expansion rate of the universe, WIMPs decouple from the thermal bath. Today, their relic density is then given by:



Jungman, Kamionkowski & Griest, PR '96

$$\Omega_{\rm WIMP} h^2 \sim \frac{3\cdot 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma v \rangle} = \mathcal{O}(0.1)$$ [for interaction strengths of the weak type]

WIMP candidates

A viable WIMP dark matter candidate is thus obtained in any SM extension that

- contains a new, stable particle
- which couples to SM particles, but has zero electric and color charge
- and is not too strongly coupled to the Z boson
  (constraint from direct DM searches).

$\rightarrow$ The required mass scale is then simply obtained by solving the Boltzmann equation.

Popular examples (nice for LHC!): SUSY, extra-dimensional scenarios, Little-Higgs models,...

DM searches

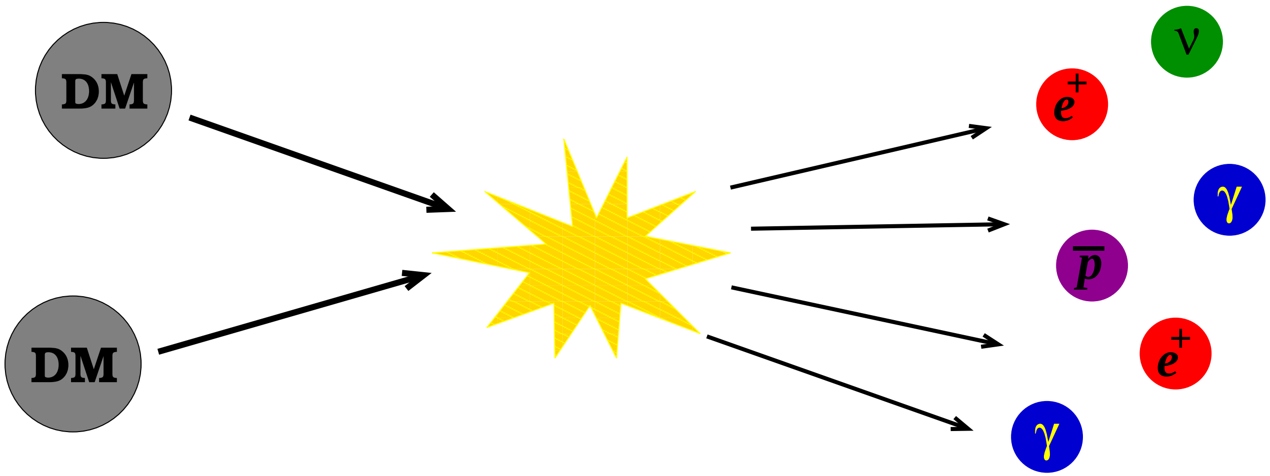
Possible ways to unveil the DM nature:

- Accelerator searches
  $\rightsquigarrow$ usually missing energy as a signal, but also the spectrum of other new particles provides valuable information
- Direct searches
  $\rightsquigarrow$ measure the recoil of DM particles impinging on the nuclei of terestrial detectors
- Indirect searches
  $\rightsquigarrow$ look for DM annihilation products in the galactic halo

All these approaches are complementary!

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
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- Clear spectral signatures to look for

γ rays from DM annihilations

The expected gamma-ray flux $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$ from a source with DM density ρ is given by

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

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$\langle\sigma v\rangle_{\mathrm{ann}}$	:	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

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

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$\Delta\psi$	:	angular resolution of detector
D	:	Distance to *point-like* source

DM annihilation spectra

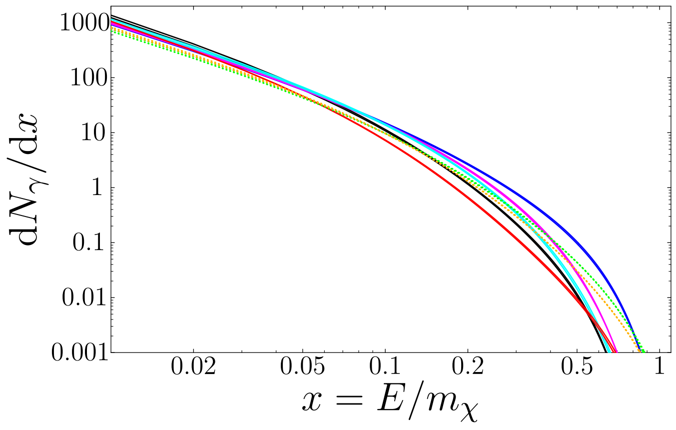
($\rightsquigarrow$ ***entirely determined by the underlying microphysics!***)

3 types of contributions:

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

Secondary photons

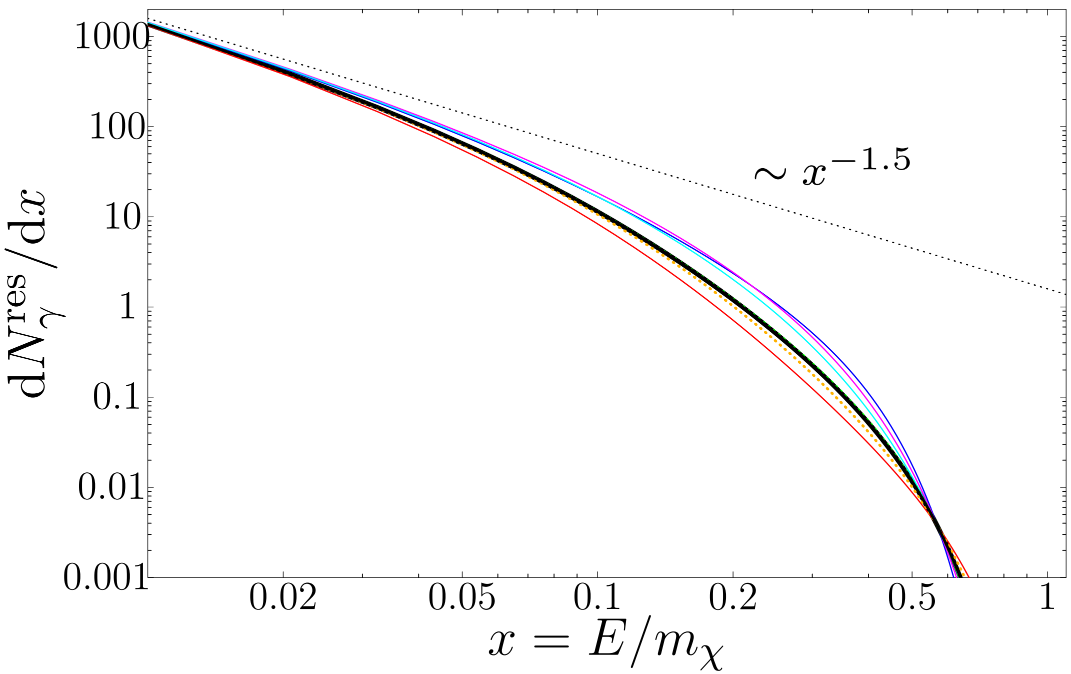
Quark and gauge boson fragmentation give essentially degenerate photon spectra: (Figs. from Bertone et al., astro-ph/0612387)



rescale

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

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_χ up to 50%
    (unless exact branching ratios are known independently)

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Direct annihilation into photons

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

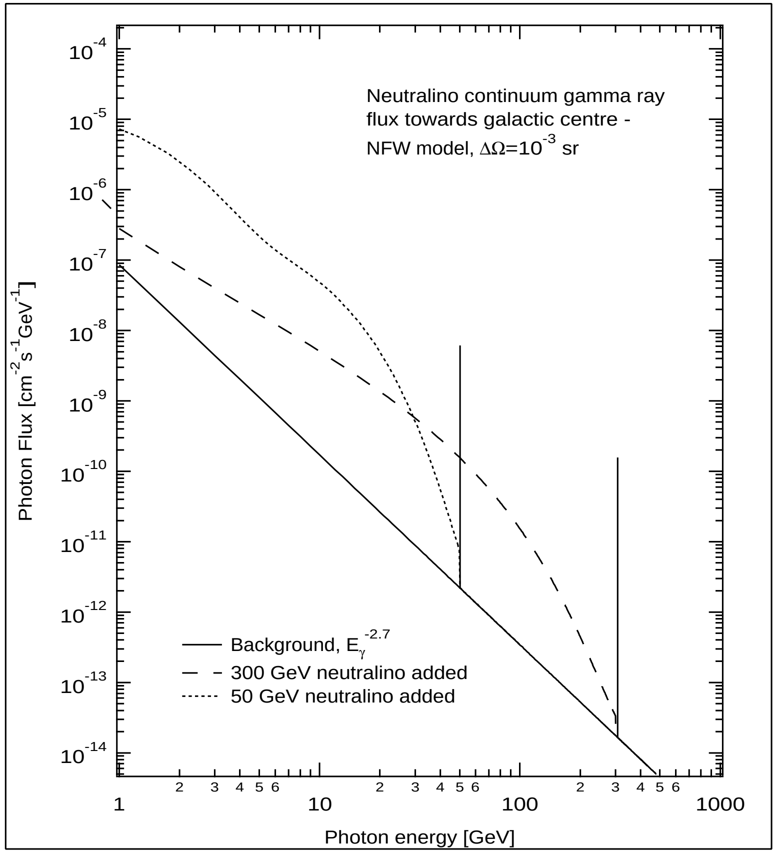


Fig. from Bergström, Ullio & Buckley '97

particularly prominent examples include:

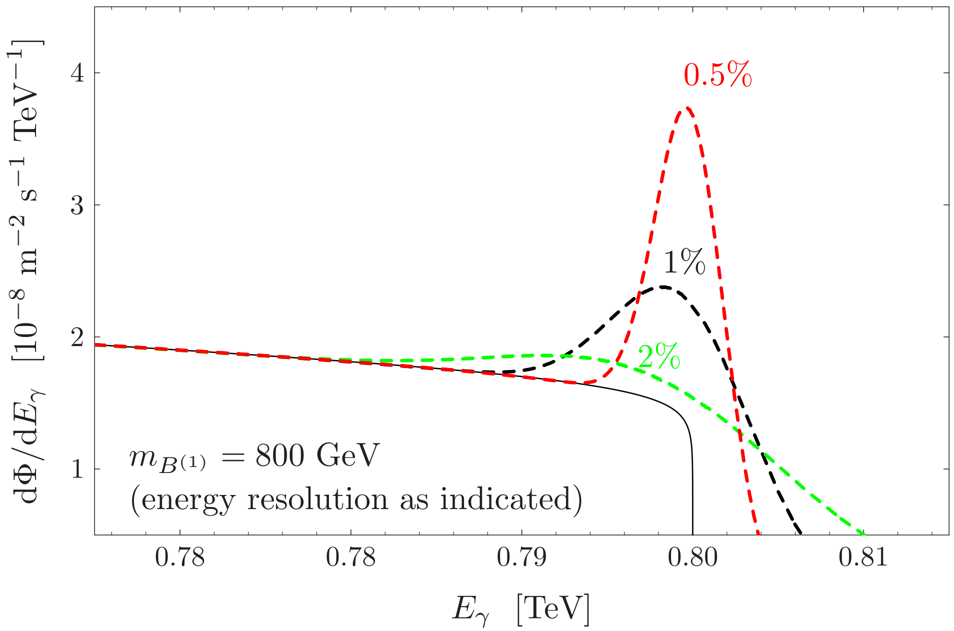
- almost pure Higgsinos or Winos
  e.g. Hisano et al. '05
- Inert Higgs dark matter
  Gustafsson et al. '07

Line signals (2)

<u>but</u>:
the signal is necessarily loop-suppressed, i.e. $\mathcal{O}\left(\alpha^2\right)$

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

e.g. the LKP in UED:



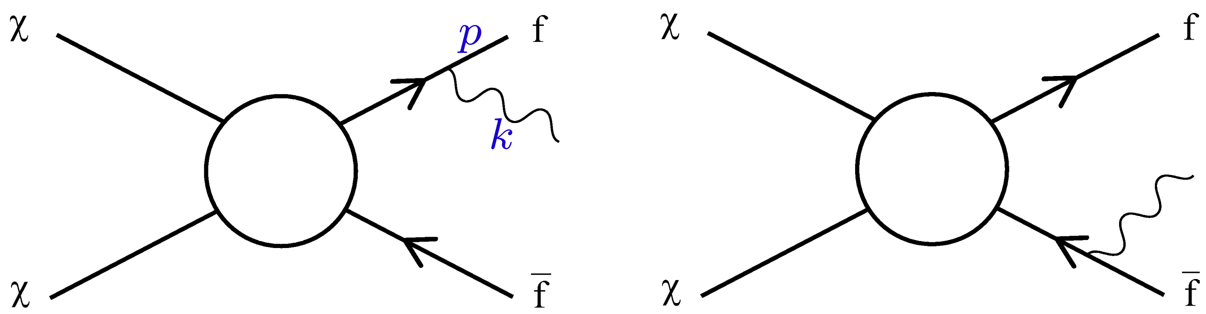
Bergström, TB, Eriksson & Gustafsson '04

Internal bremsstrahlung

- Whenever DM annihilates into charged final states f, this is ***automatically***, at $\mathcal{O}\left(\alpha\right)$, 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 $\to$ 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 $f\bar{f}\gamma$

  $\to$ these contributions are 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
$\rightarrow$ 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)

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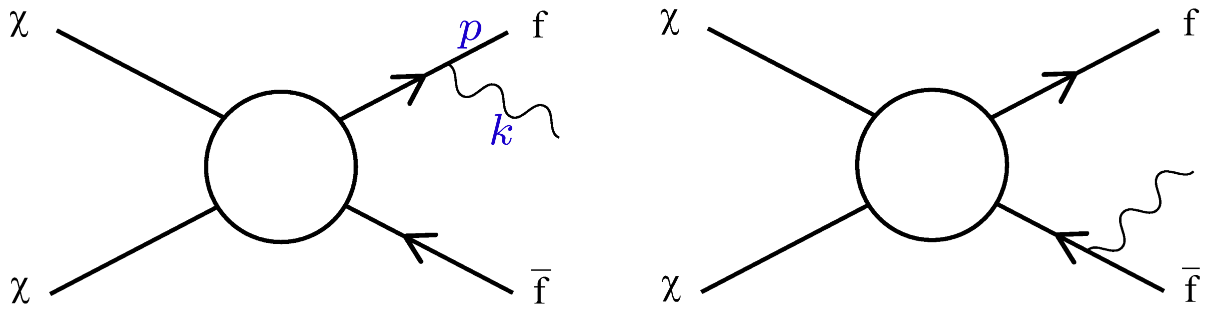

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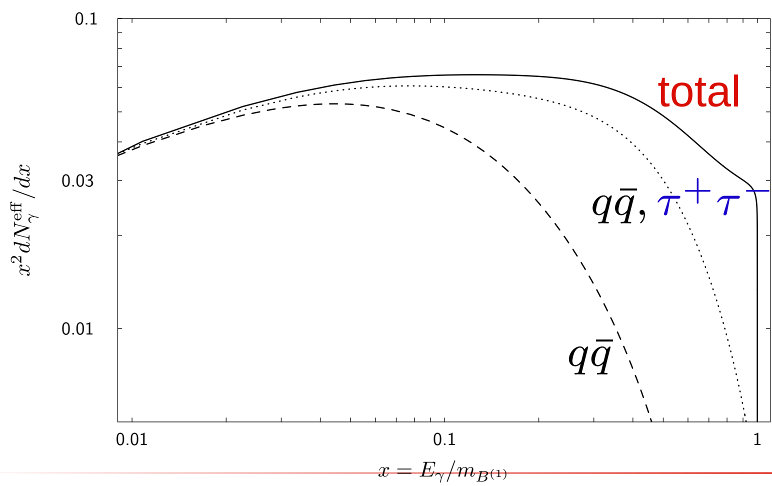
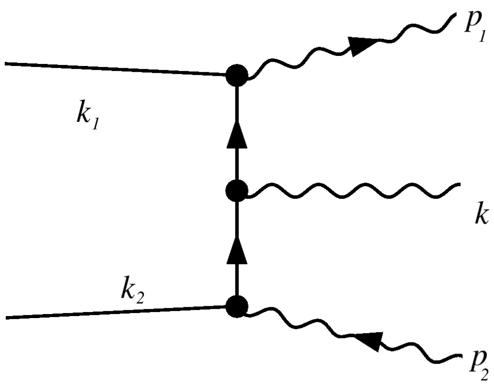
- Example: LKP in UED
  - $m_{B^{(1)}} \sim 1\,\mathrm{TeV}$
  - high branching ratio into leptons ($\sim 60\,\%$)

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:



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

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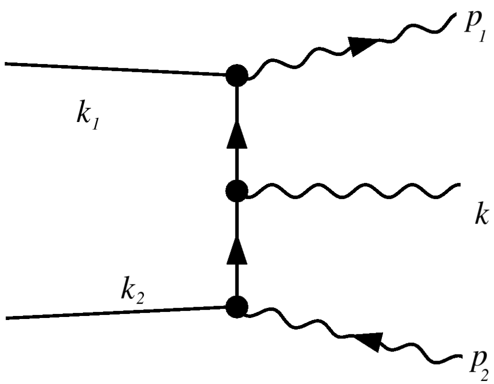

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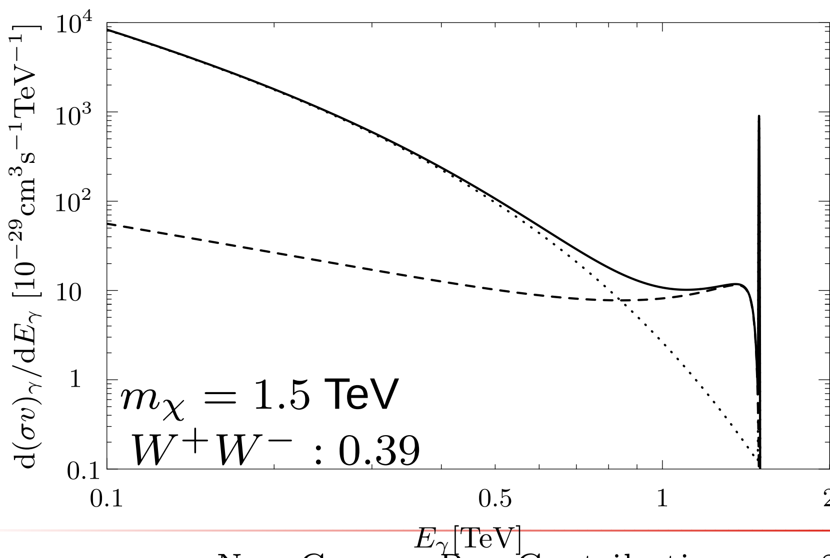
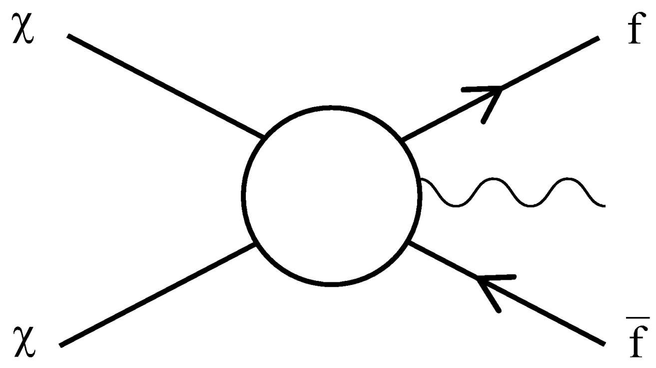
- Example: Higgsino
  - TeV mass
  - high b.r. to W^+W^-

Bergström et al., PRL '05b

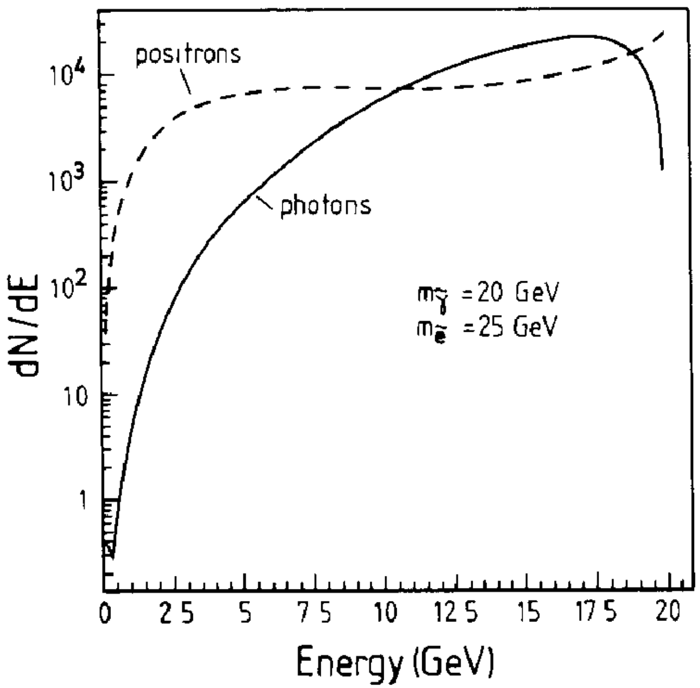


Charged virtual particles (2)



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! $\rightarrow$ mSUGRA...



IB and SUSY

TB, Bergström & Edsjö, JHEP ’08

- identify all relevant final states for neutralino annihilation:
  - $q\bar{q}\gamma$, $\ell^+\ell^-\gamma$, $W^+W^-\gamma$, $W^\pm H^\mp\gamma$, $H^+H^-\gamma$

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  - use general, unspecified couplings at this step
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    - the amplitude (insert an $P_{{}^1S_0}$ projector)
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DarkSUSY $\longleftarrow$ ***NEW beta version by the end of next week!***

scanning SUSY

TB, Bergström & Edsjö, JHEP ’08

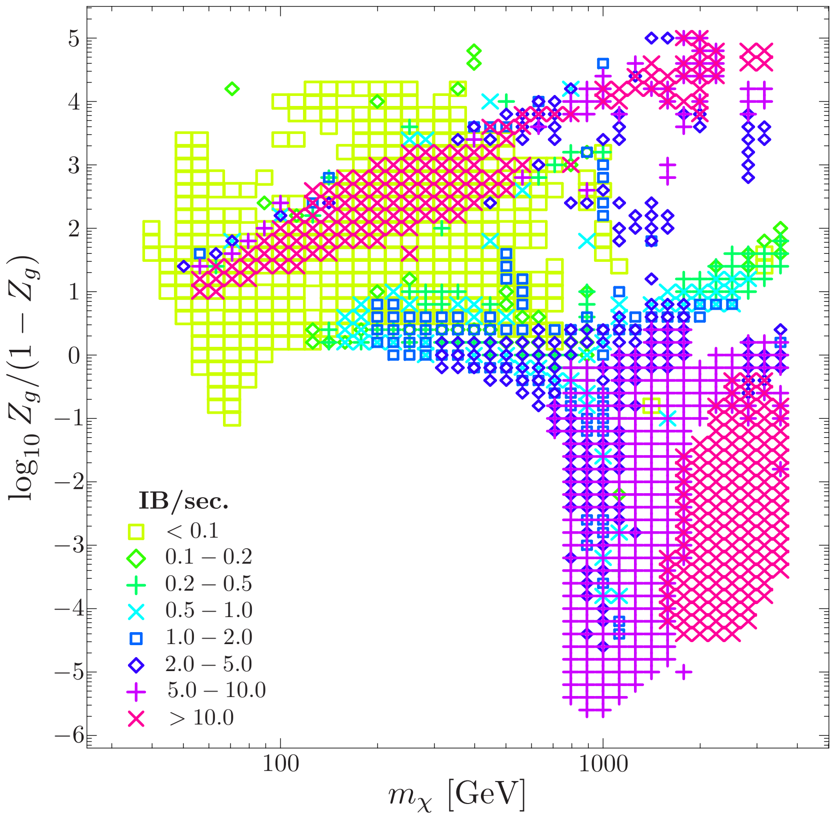
- calculate IB from all possible final states of neutralino annihilations
- scan mSUGRA and the MSSM

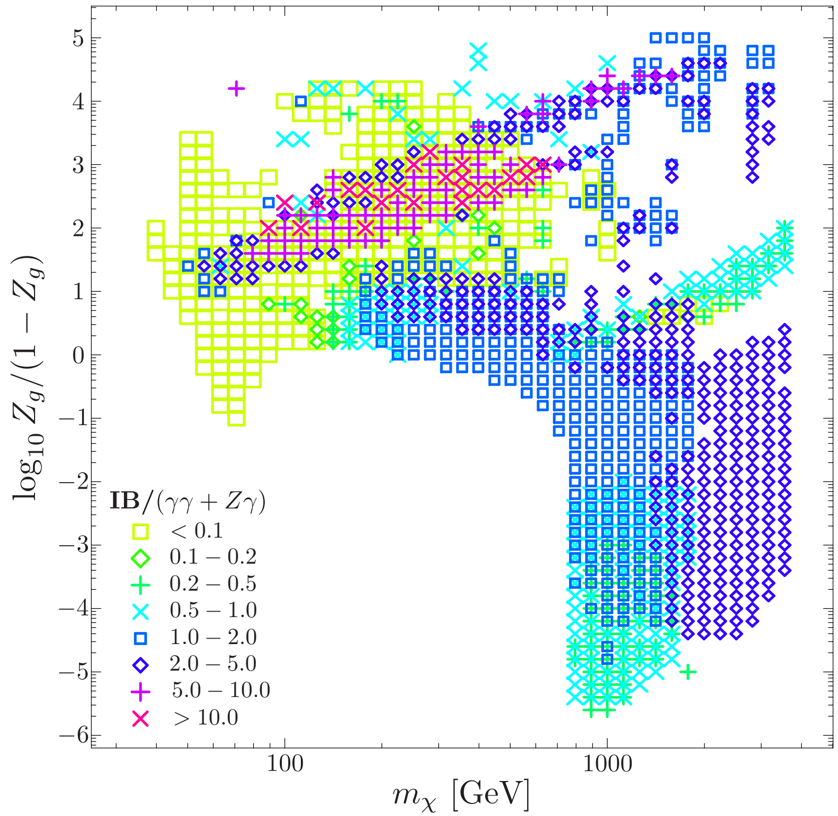
  include $\sim 10^6$ models with $\Omega_\chi h^2$ as determined by WMAP, all accelerator constraints OK

“Gaugino”

“mixed”

“Higgsino”

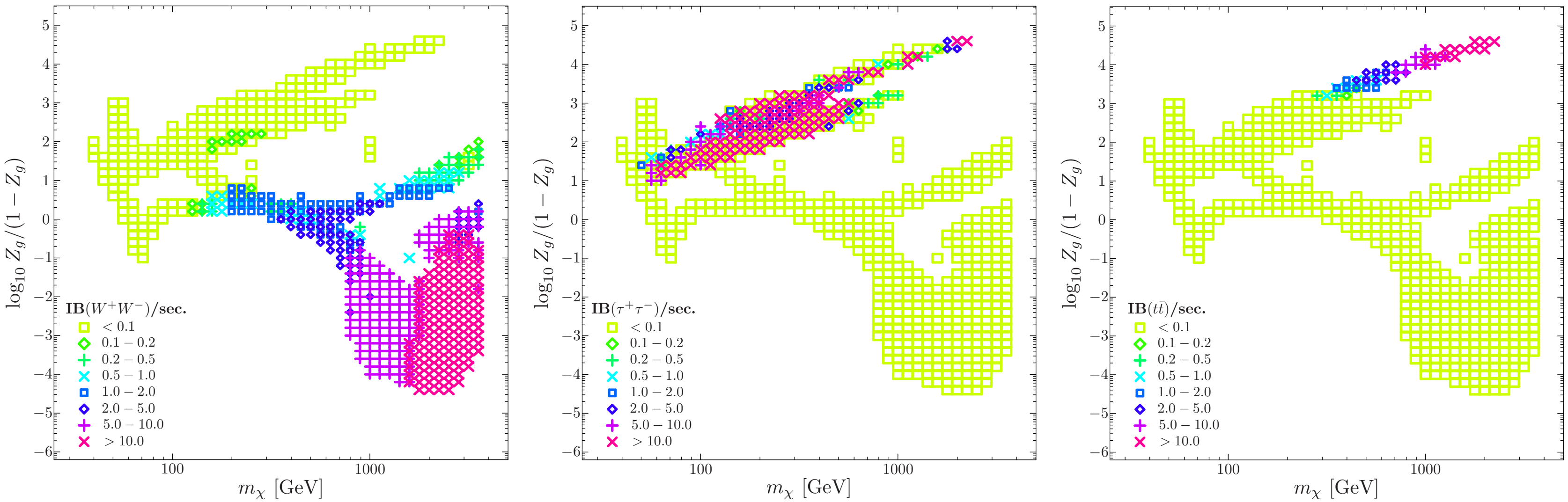




IB by components

TB, Bergström & Edsjö, JHEP '08

mSUGRA



$\rightsquigarrow$ ***IB important in phenomenologically particularly relevant coannihilation and focus point regions!***

- similar regions for all $\ell^+\ell^-$
- other channels always $< 10\%$ of total secondary flux

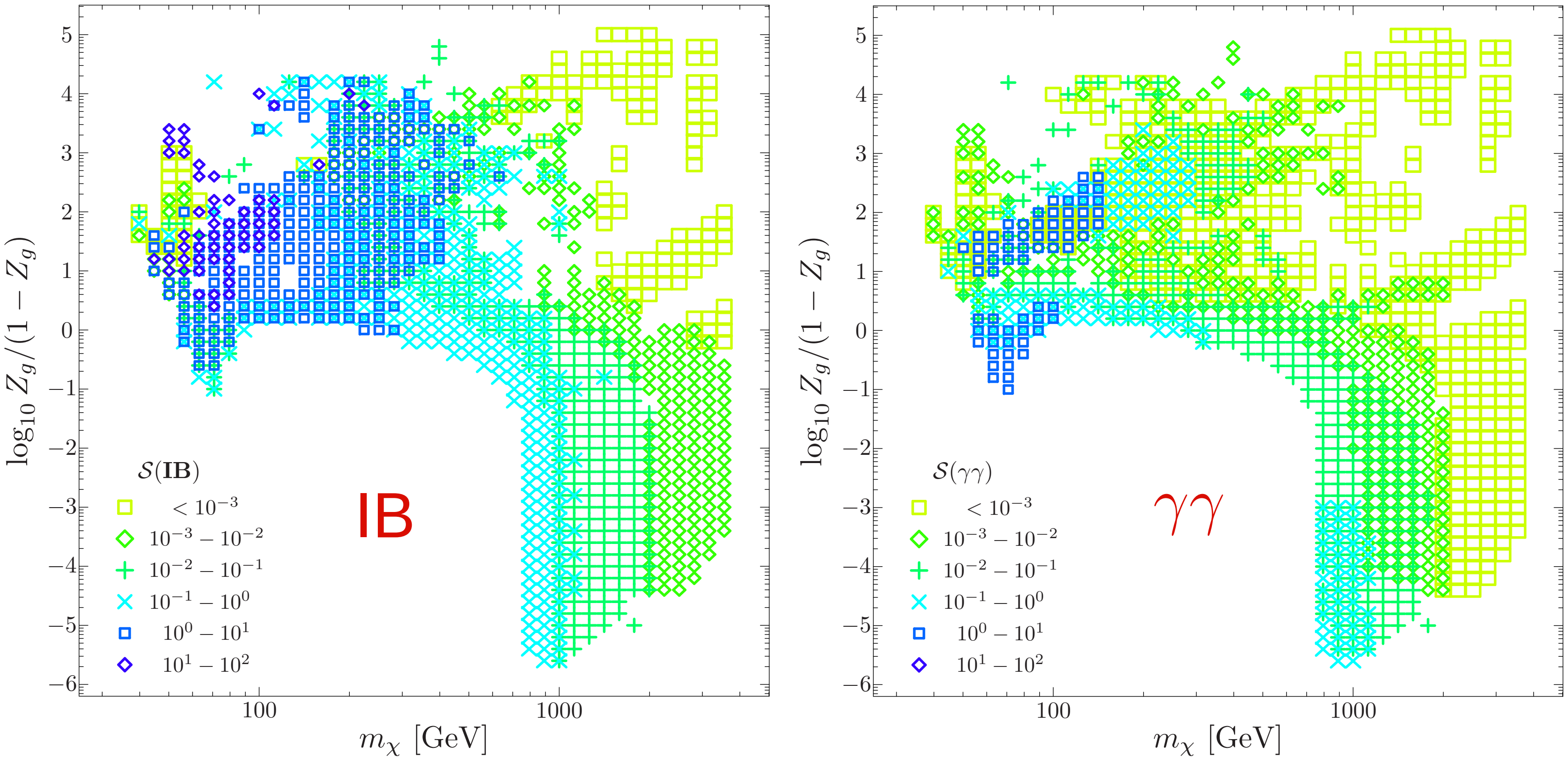
MSSM

- W^+W^- and $t\bar{t}$ roughly as in mSUGRA
- $W^\pm H^\mp$ contributes up to 100% for $m_\chi \gtrsim 1$ TeV
- $u\bar{u}$ contributes up to 200% for heavy Binos

Total IB fluxes

TB, Bergström & Edsjö, JHEP '08

$$\mathcal{S} \equiv N_\gamma \frac{\langle \sigma v \rangle}{10^{-29}\mathrm{cm}^3\mathrm{s}} \left(\frac{m_\chi}{100\mathrm{GeV}}\right)^{-2} \propto \text{signal at earth}$$



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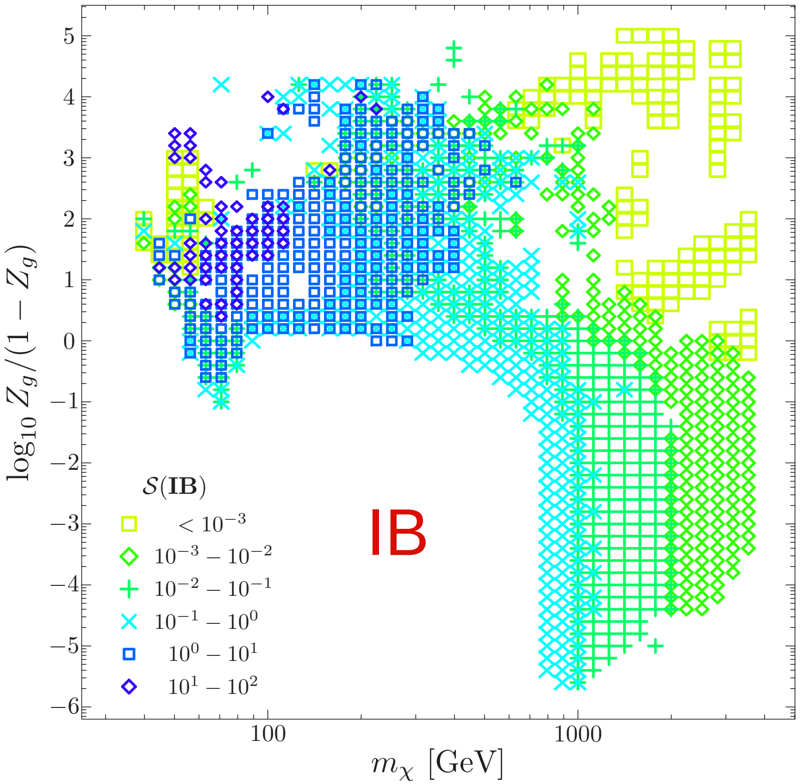
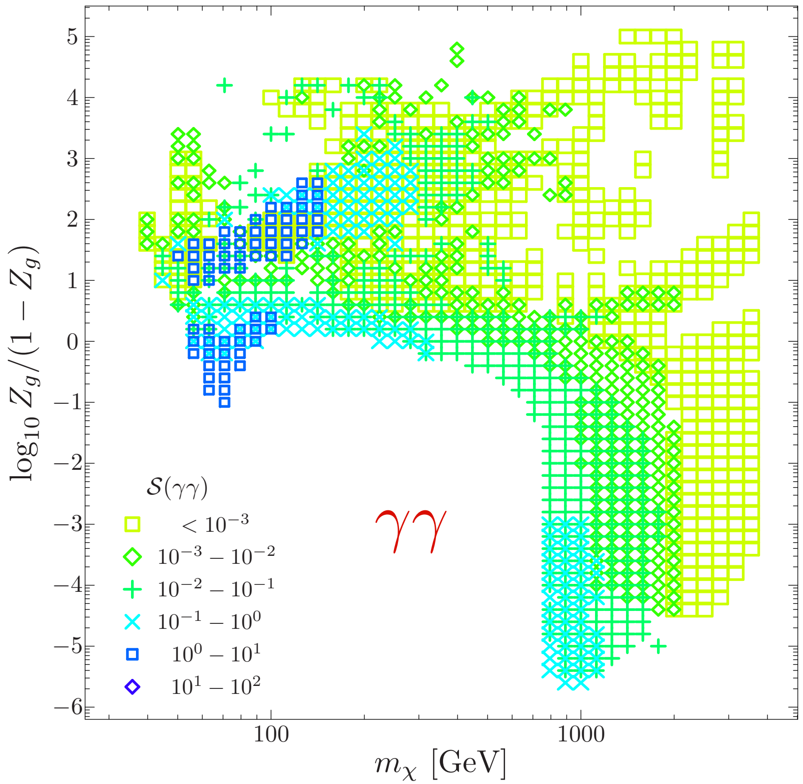




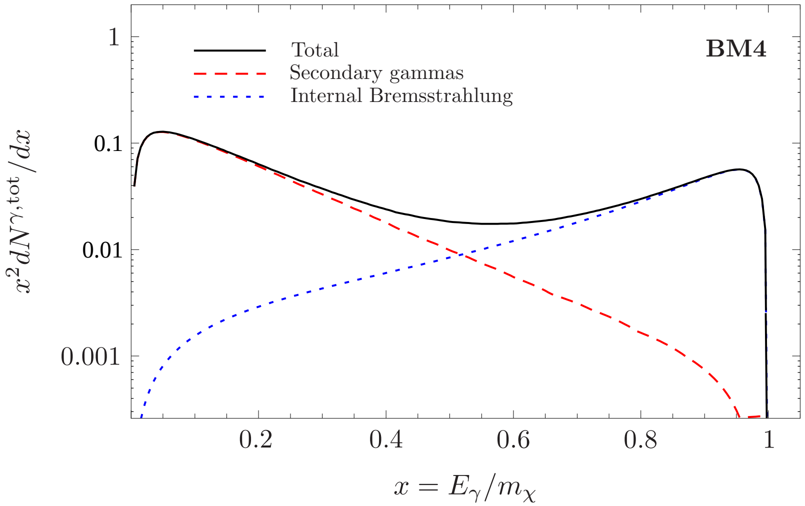
for comparison: Moore or cNFW for gc $\rightsquigarrow$ HESS would need (50h, 5σ)

- $\mathcal{S} \gtrsim 10^{-2}$ if $m_\chi \sim 1$ TeV
- $\mathcal{S} \gtrsim 1$ if $m_\chi \sim 100$ GeV

mSUGRA spectra

TB, Bergström & Edsjö, JHEP '08

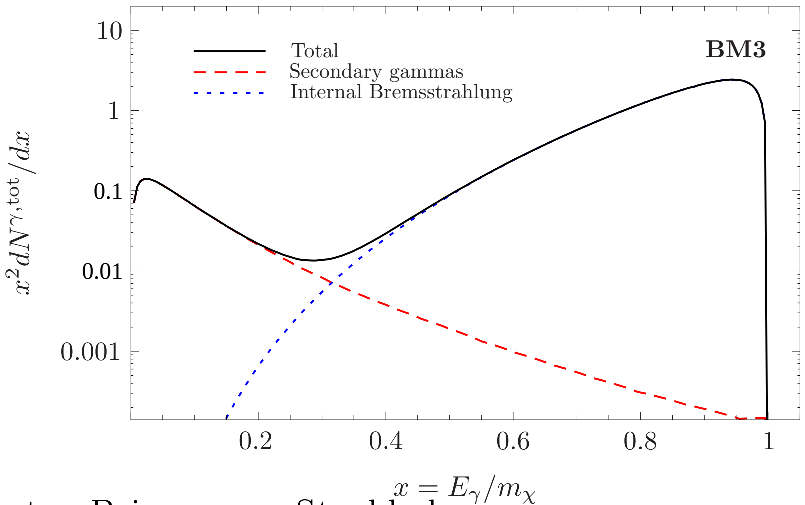
$\rightsquigarrow$ largest IB contributions expected in focus point and $\tilde{\tau}$-coannihilation regions:



focus point region

m_0	$m_{1/2}$	$\tan\beta$	A_0	sgn	m_χ	$\frac{Z_g}{1-Z_g}$
$3\cdot 10^4$	10^4	32	$6\cdot 10^3$	+1	1926	10^{-4}

IB/sec. $= 10.8$
IB/lines $= 2.1$



coannihilation region

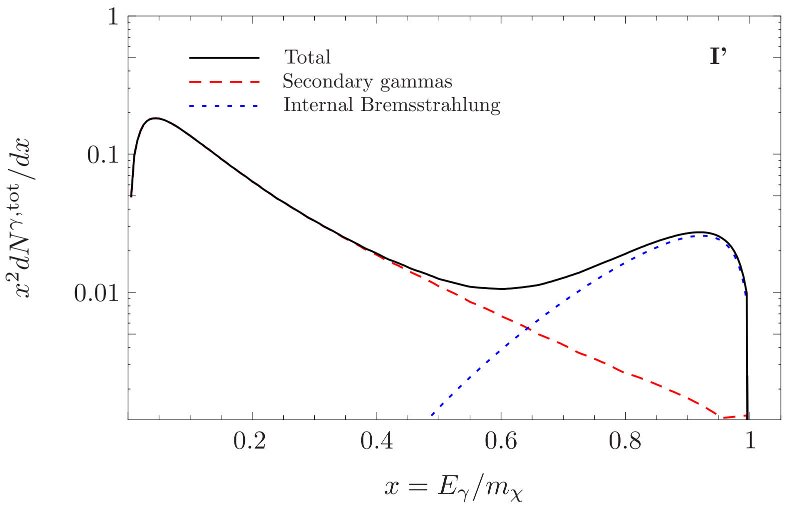
m_0	$m_{1/2}$	$\tan\beta$	A_0	sgn	m_χ	$\frac{Z_g}{1-Z_g}$
101	576	3.9	28.3	+1	233	220

IB/sec. $= 2.3\cdot 10^3$
IB/lines $= 5.0$

mSUGRA spectra (2)

What about other relevant mSUGRA regions?

$\rightsquigarrow$ take benchmarks from Battaglia et al., hep-ph/0306219:

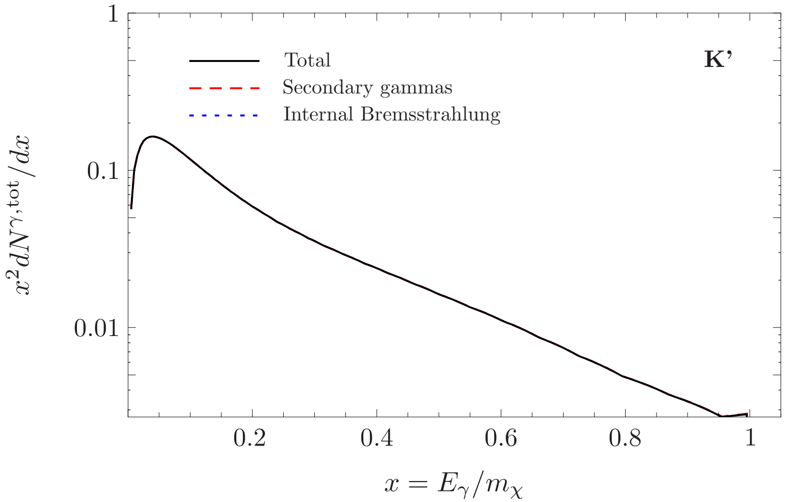


bulk region

m_0	$m_{1/2}$	$\tan\beta$	A_0	sgn	m_χ	$\frac{Z_g}{1-Z_g}$
181	350	35	0	+1	141	72

IB/sec. $= 3.7$

IB/lines $= 3.6$



funnel region

m_0	$m_{1/2}$	$\tan\beta$	A_0	sgn	m_χ	$\frac{Z_g}{1-Z_g}$
1001	1300	51	0	-1	565	703

s-channel diagrams completely dominate

$\rightsquigarrow$ "no" IB contributions

(apart from FSR, already included in PYTHIA)

Comparing IB spectra

- all spectra share a pronounced cutoff...
- ... 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)

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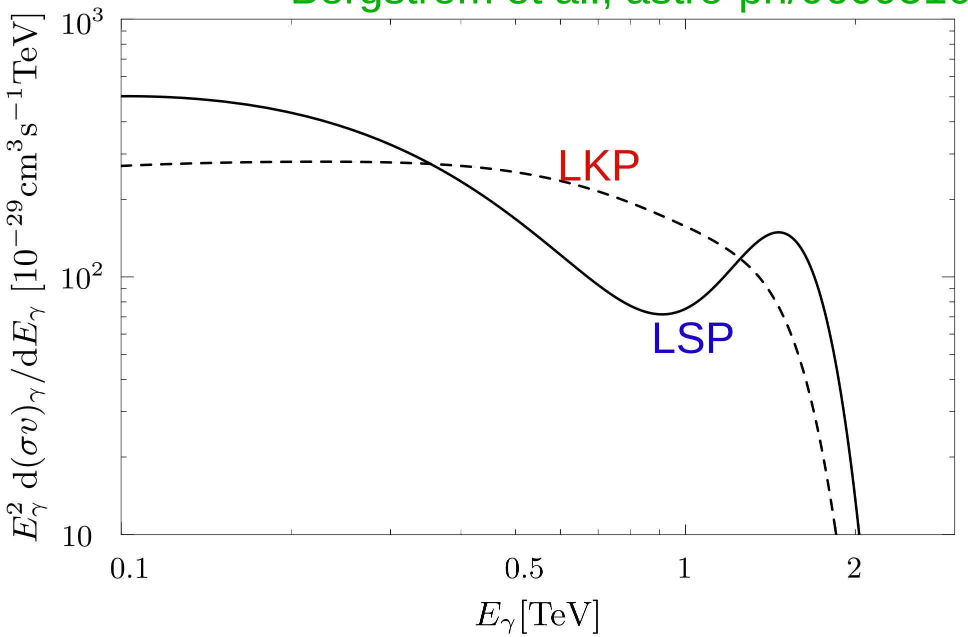
  (see, e.g., the spectra shown before)

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

    (assume same mass and energy resolution of 15 %)

Bergström et al., astro-ph/0609510



Summary

Internal bremsstrahlung

- 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 a pronounced cutoff
- can even be used to distinguish between different DM candidates

Summary

Internal bremsstrahlung

- 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
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- can even be used to distinguish between different DM candidates

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

outlook

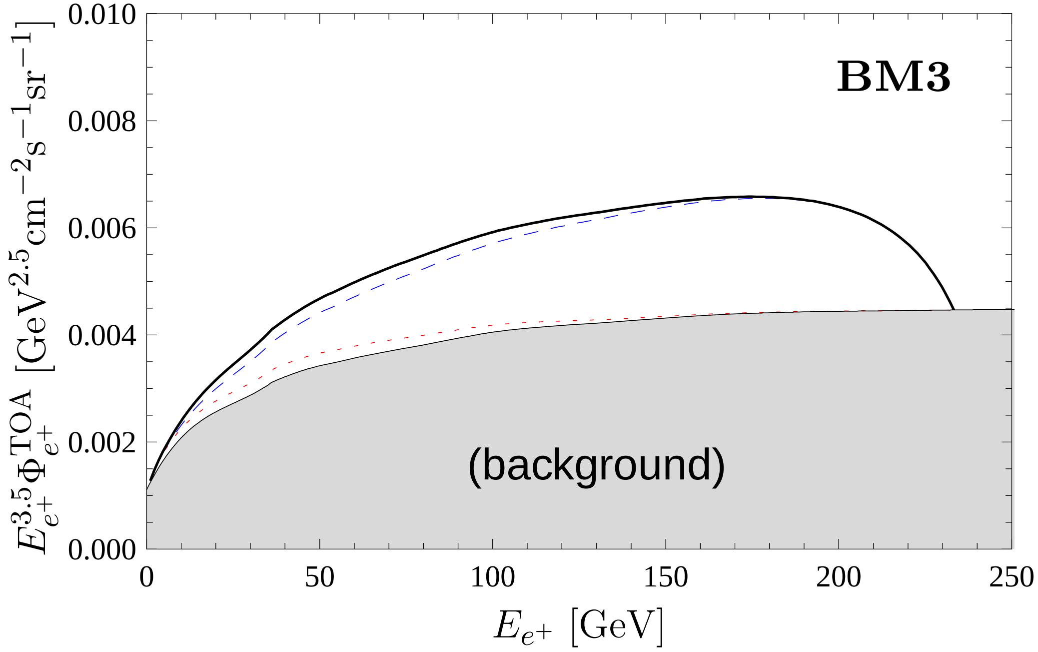
What about positrons from neutralino annihilations?

$\rightsquigarrow$ enormous enhancements for $e^+e^-\gamma$ final states possible:

Bergström, TB, Edsjö, in prep.

flux at TOA, after propagation:

- No radiative corrections
- Adding only $e^+e^-\gamma$ channel
- Including radiative corrections to all channels



***but*:** large boost factors still necessary...

(5×10^3 in the above figure)

outlook (2)

Further, obvious next steps include (in descending priority):

- re-analyze prospects for classical targets like
  - the galactic center
  - dwarf galaxies
  - DM clumps or IMBHs
  - extragalactic gamma rays
- complementarity with colliders
- effect on relic density Ω_{CDM}?
- other channels than positrons
- ...