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# Indirect Dark Matter Searches

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Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time
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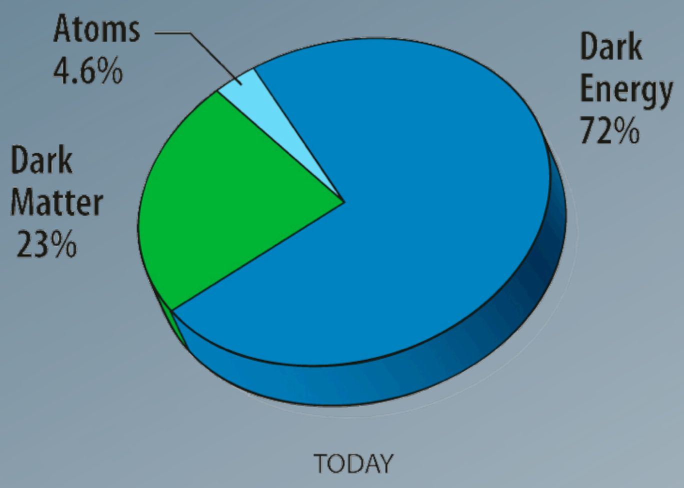
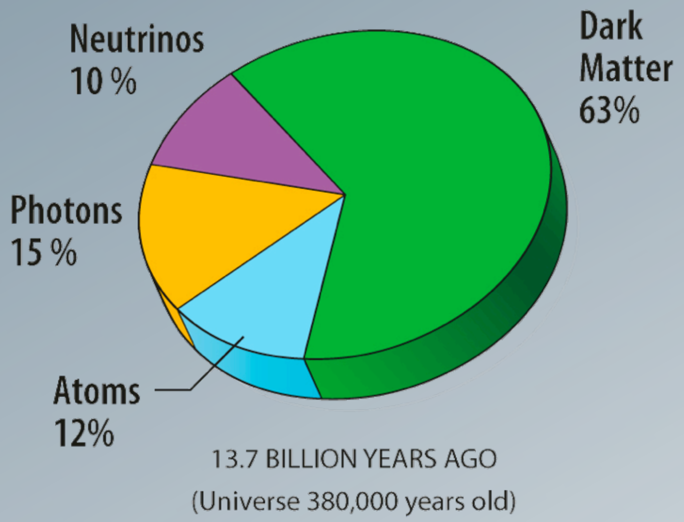
# Dark matter





credit: WMAP

- *Existence* by now essentially impossible to challenge!
  - $\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - (collisionless) (bullet cluster)

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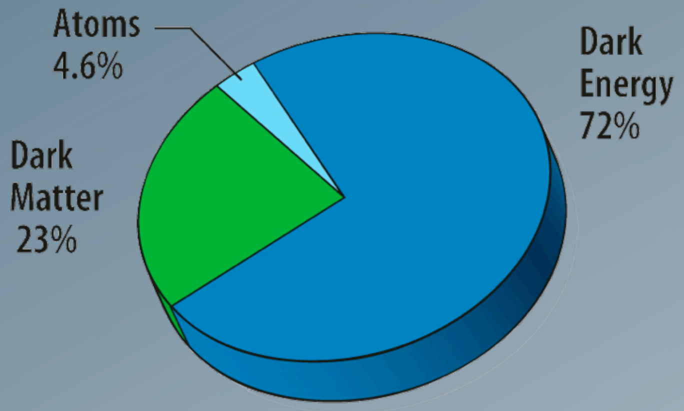
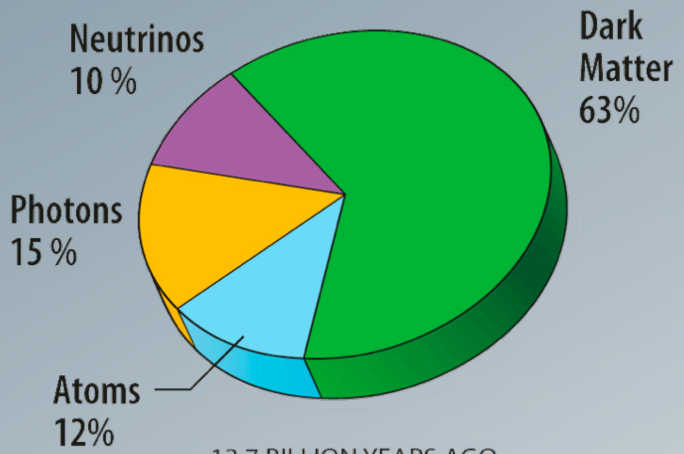


TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

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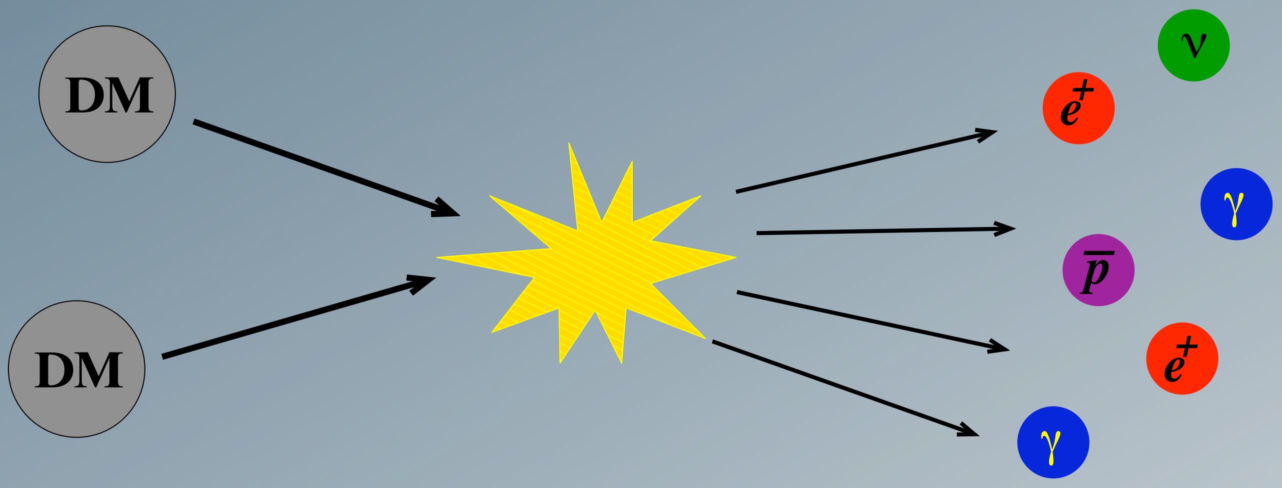
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - (collisionless) (bullet cluster)
- *WIMPS* are particularly good candidates:
  - ✓ well-motivated from particle physics [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production “automatically” leads to the right relic abundance

# Indirect DM searches



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds

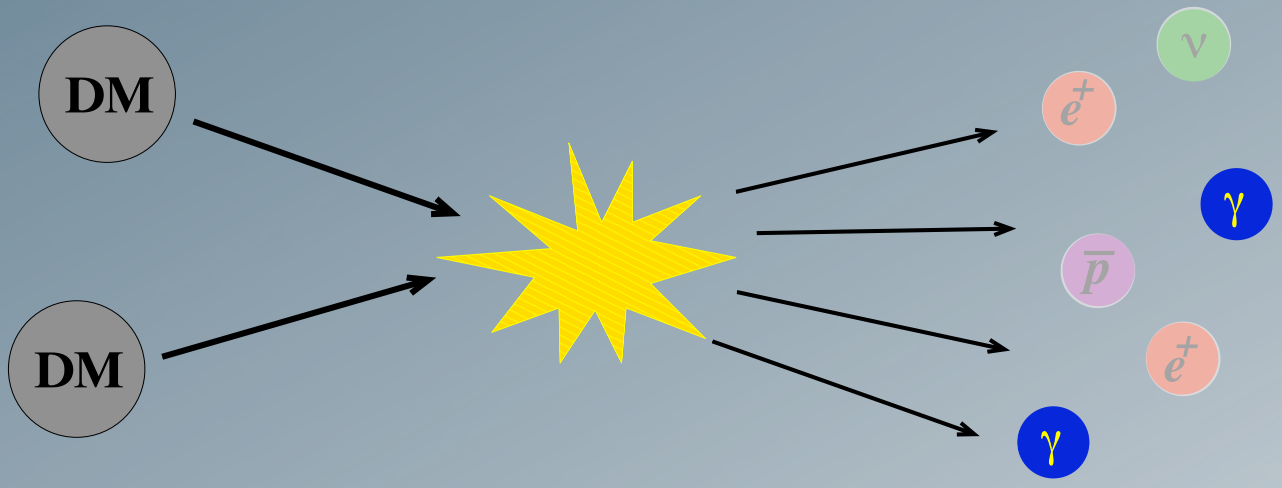
- The challenge: i) absolute rates

  $\rightsquigarrow$ regions of high DM density

  ii) discrimination against other sources

  $\rightsquigarrow$ low background; clear signatures

# Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

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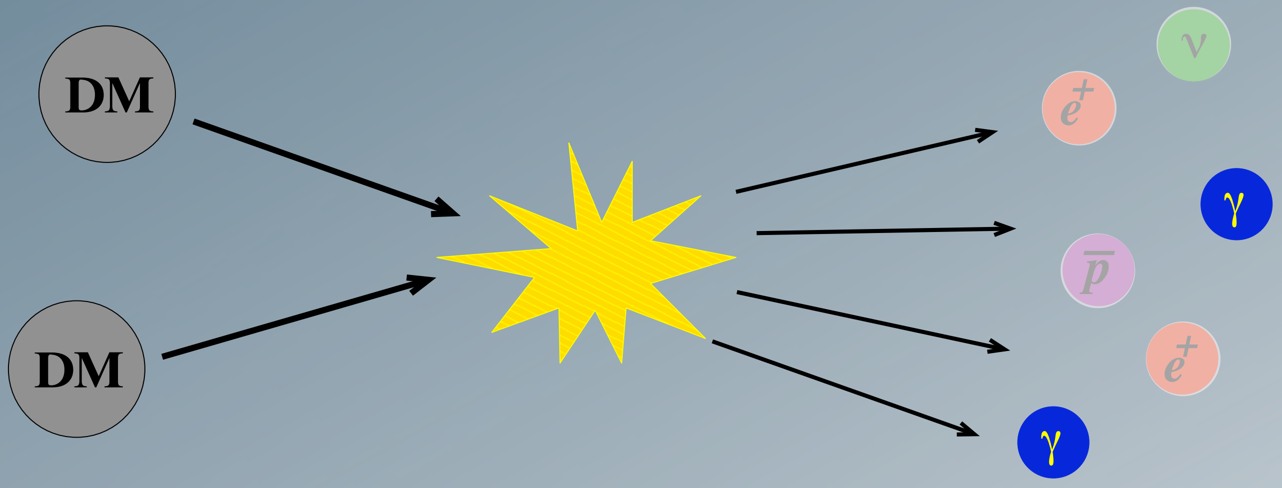

Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for ⇦ maybe most important!

# Gamma-ray flux

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

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

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$\langle\sigma v\rangle_{\rm ann}$ : total annihilation cross section

$m_\chi$ : WIMP mass $(50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV})$

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for point-like sources:

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⇓ high accuracy spectral information

⇓ large uncertainty in normalization

# Halo profiles

## ΛCDM *N*-body simulations

$$\rho_{\mathrm{NFW}} = \frac{c}{r(a+r)^2}$$

$$\rho_{\mathrm{Einasto}}(r) = \rho_s\, e^{-\frac{2}{a}\left[\left(\frac{r}{a}\right)^{\alpha}-1\right]}$$

$$(\alpha \approx 0.17)$$

$\rightsquigarrow$ rather stable result

## Fits to rotation curves?

$$\rho_{\mathrm{Burkert}} = \frac{c}{(r+a)(a^2+r^2)}$$

$$\rho_{\mathrm{iso}} = \frac{c}{(a^2+r^2)}$$

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- Situation a bit unclear; effect of baryons?
  (But could also lead to a steepening of the profile!)
- Difference in annihilation flux several orders of magnitude for the galactic center
- Situation much better for e.g. dwarf galaxies

# Substructure

- *N*-body simulations: Halo contains a lot of substructure!
- Indirect detection effectively involves some averaging:

$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1+{\rm BF})\langle \rho_\chi \rangle^2$$

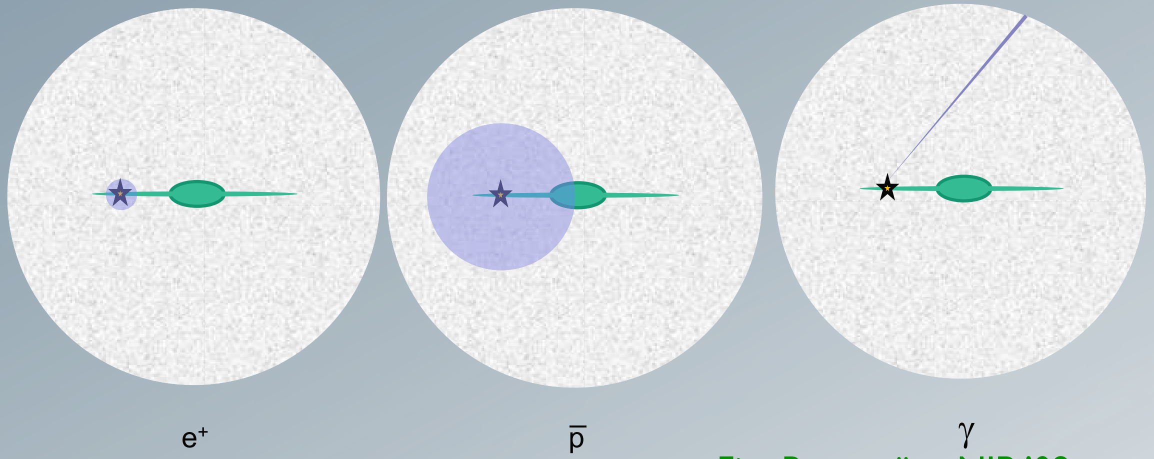


Fig.: Bergström, NJP '09

- "Boost factor"
  - each decade in M$_{\rm subhalo}$ contributes about the same

e.g. Diemand, Kuhlen & Madau, ApJ '07

⇨ *important to include realistic value for* $M_{\rm cut}$ *!*

*NB: not* $M_{\rm cut} \simeq 10^{-6} M_\odot$*, but model-dependent* $10^{-11} M_\odot \leq M_{\rm cut} \leq 10^{-3} M_\odot$ *!!!*

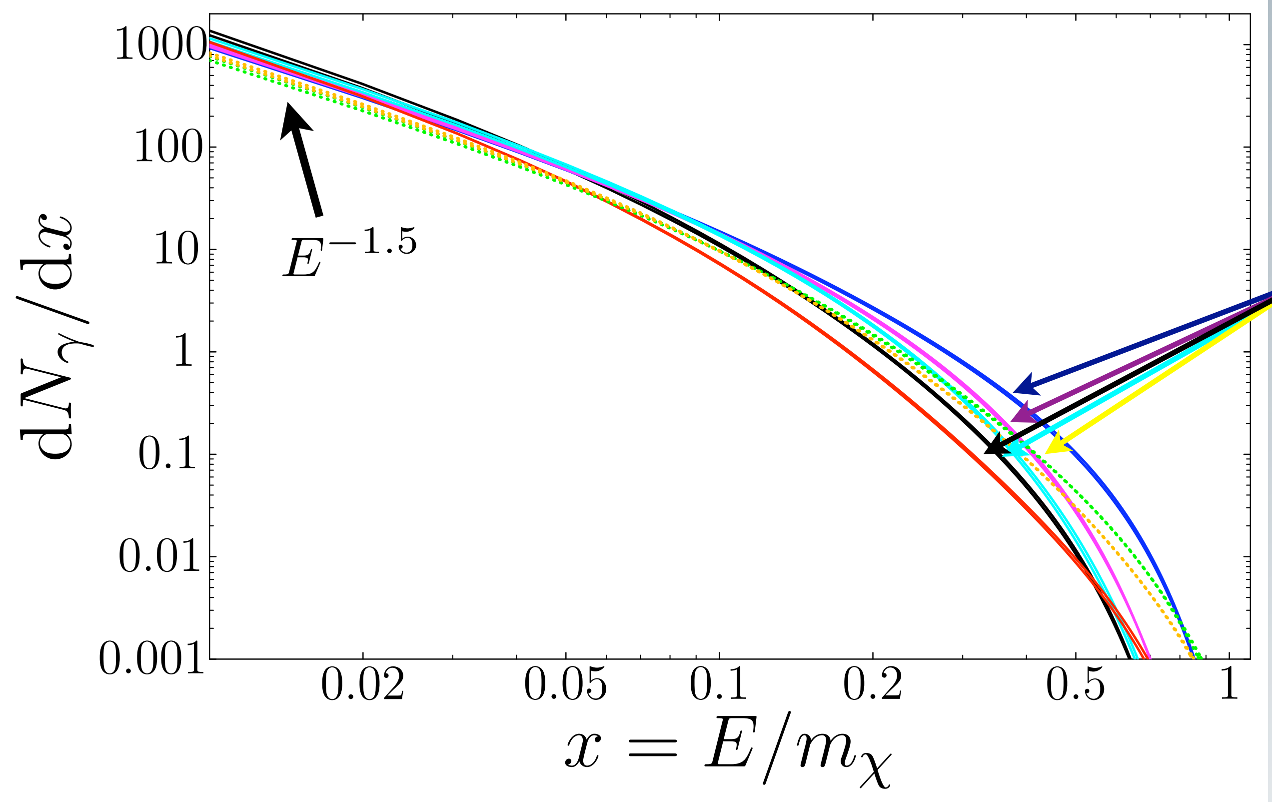
TB. NJP '09

  - depends on uncertain form of microhalo profile ($c_{\rm v}$ ...) and $dN/dM$ (large extrapolations necessary!)

# DM annihilation spectra

# DM annihilation spectra

- Secondary photons from fragmentation
  - mainly from $\pi^0 \to \gamma\gamma$
  - result in a rather featureless, model-independent spectrum



**various (gauge boson and quark) final states**

Bertone et al., astro-ph/0612387

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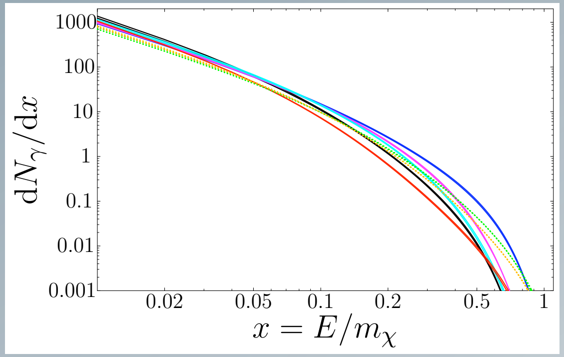

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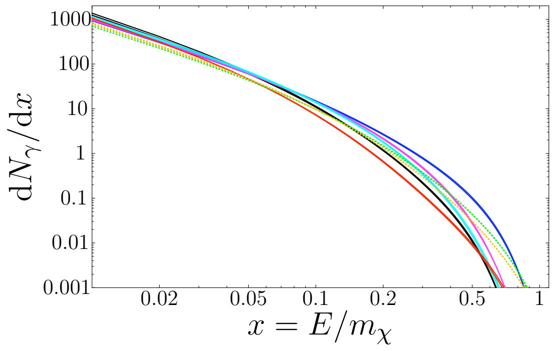
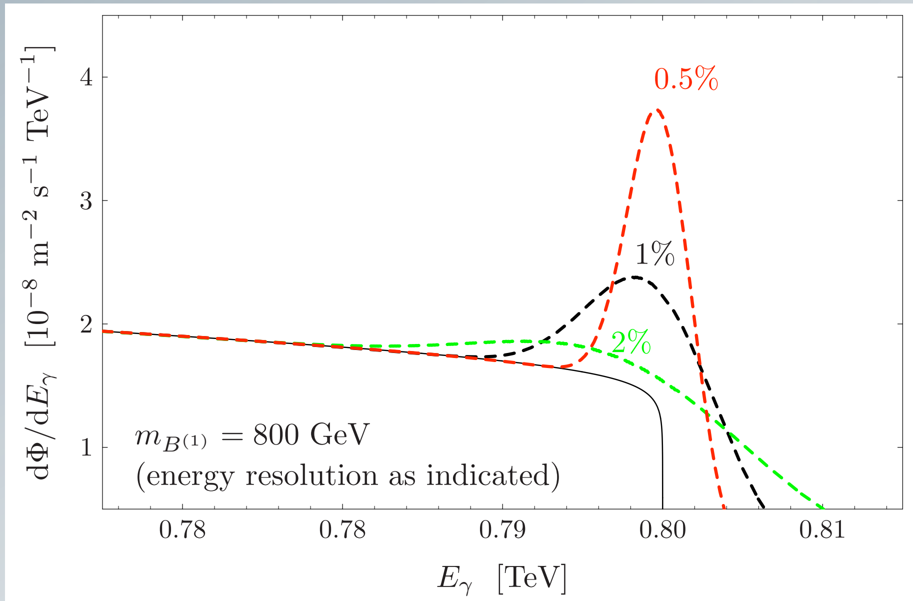


- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

Bergström, Ullio & Buckley, ApJ '98

  - necessarily loop suppressed: $\mathcal{O}(\alpha^2)$
  - smoking-gun signature



Bergström, TB, Eriksson & Gustafsson, JCAP '05

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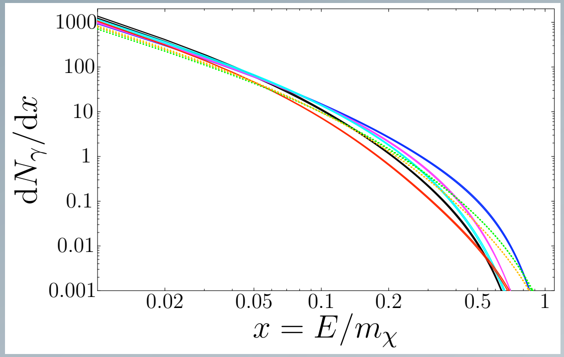

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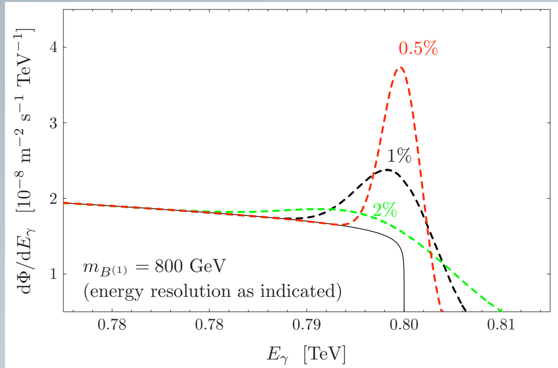

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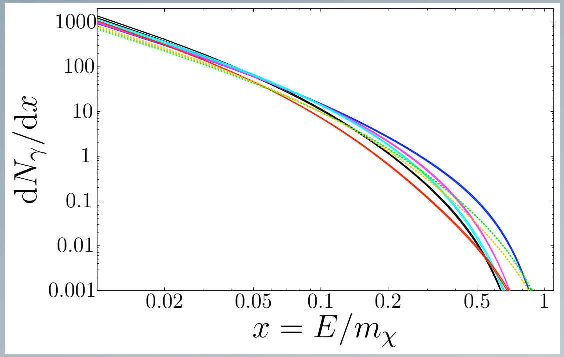

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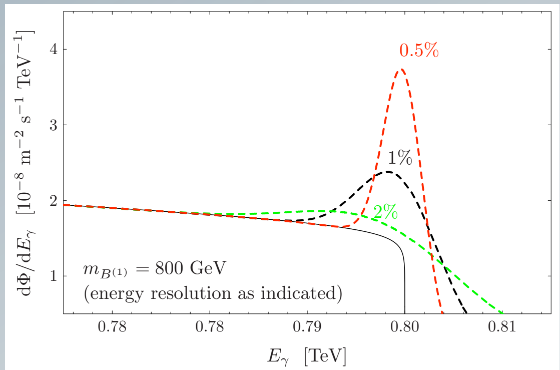
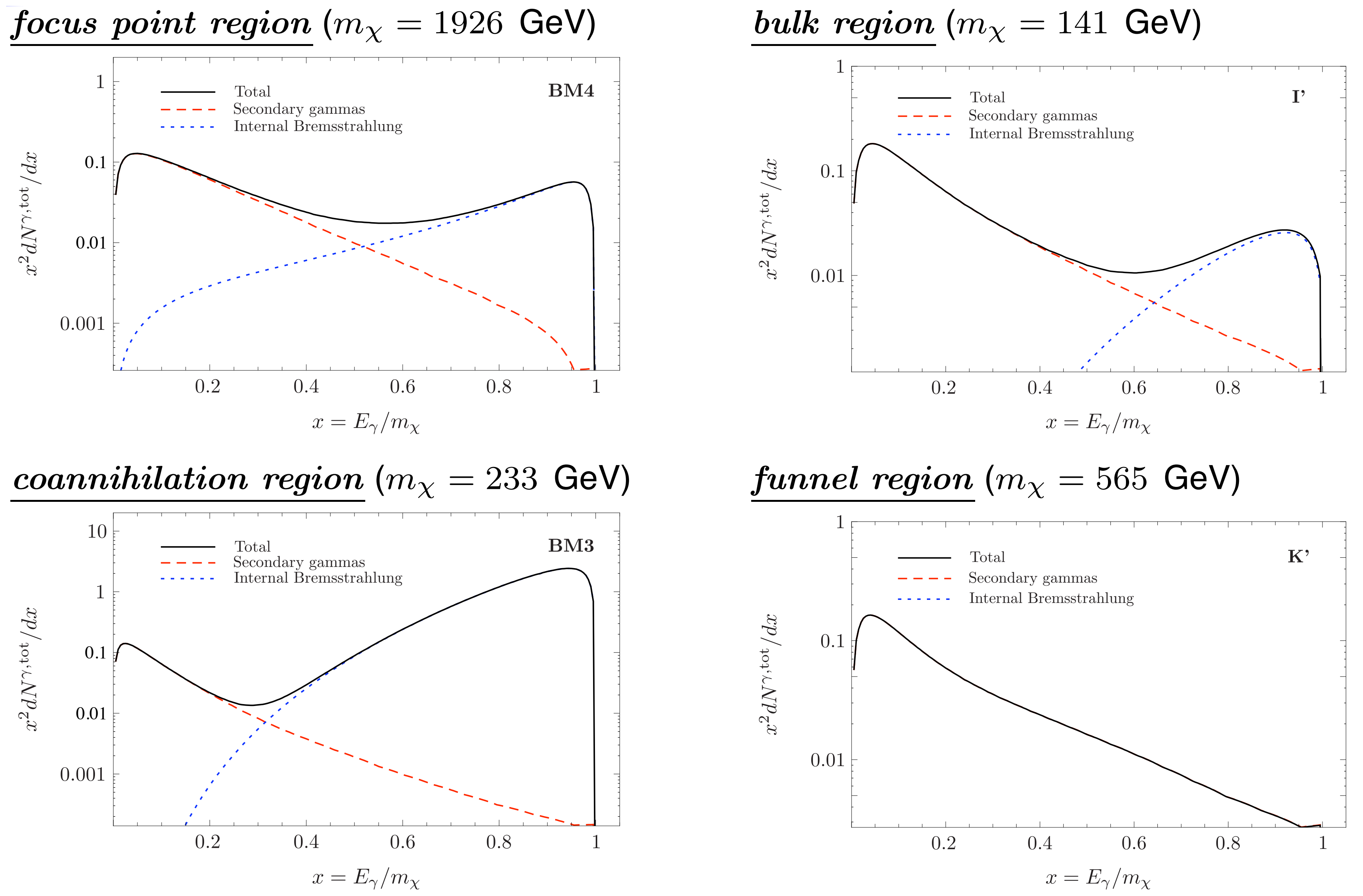


- Internal bremsstrahlung (IB)
  - whenever charged final states are present: $\mathcal{O}(\alpha)$
  - characteristic signature (details model-dependent!)
  - generically dominates at high $E_\gamma$

Birkedal, Matchev, Perelstein & Spray, hep-ph/0507194
TB, Bergström & Edsjö, JHEP '08

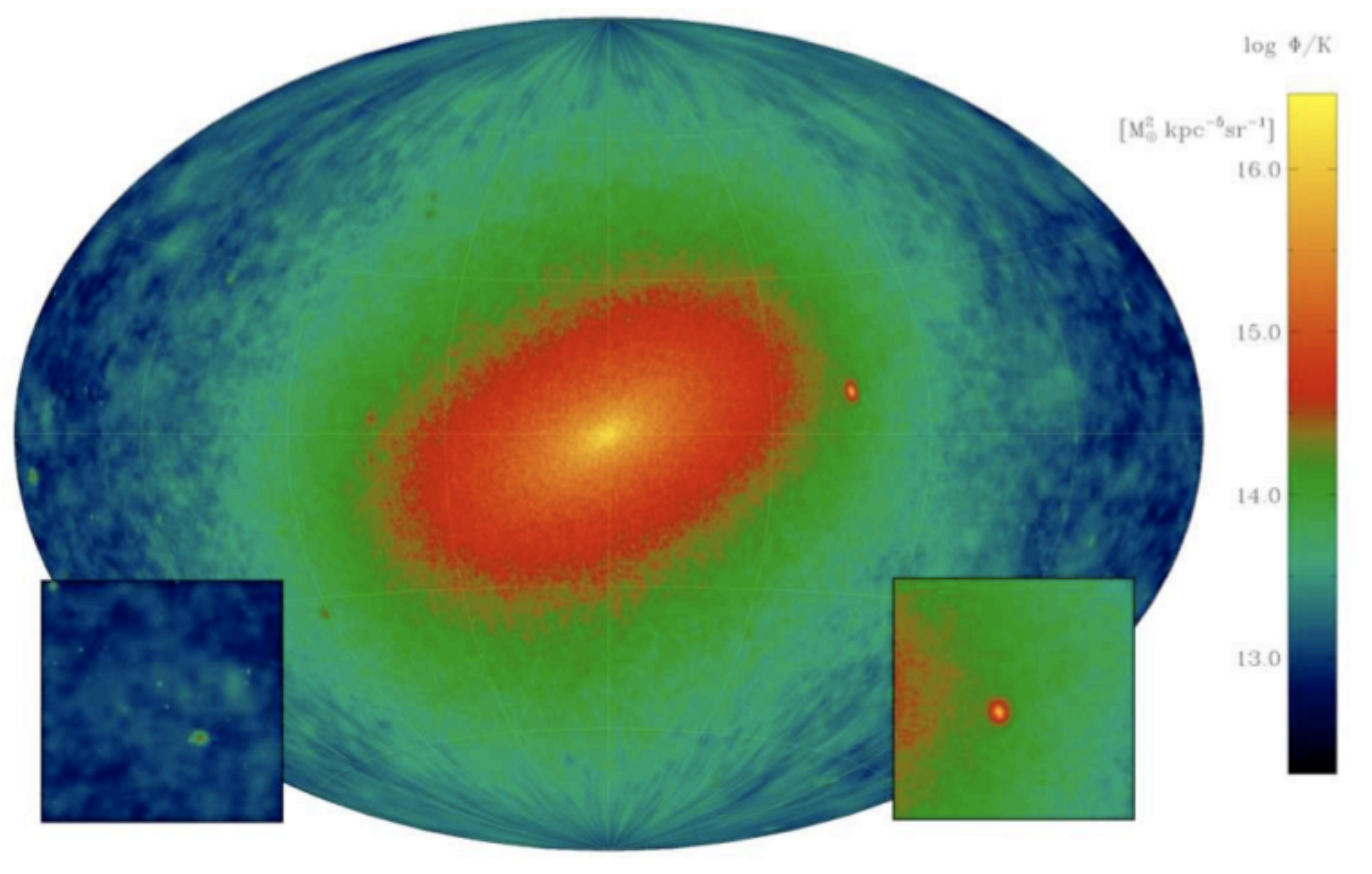
# mSUGRA spectra



(benchmarks taken from TB, Edsjö & Bergström, JHEP '08 and Battaglia et al., EPJC '03)

# Observational targets

Diemand, Kuhlen & Madau, ApJ ’07



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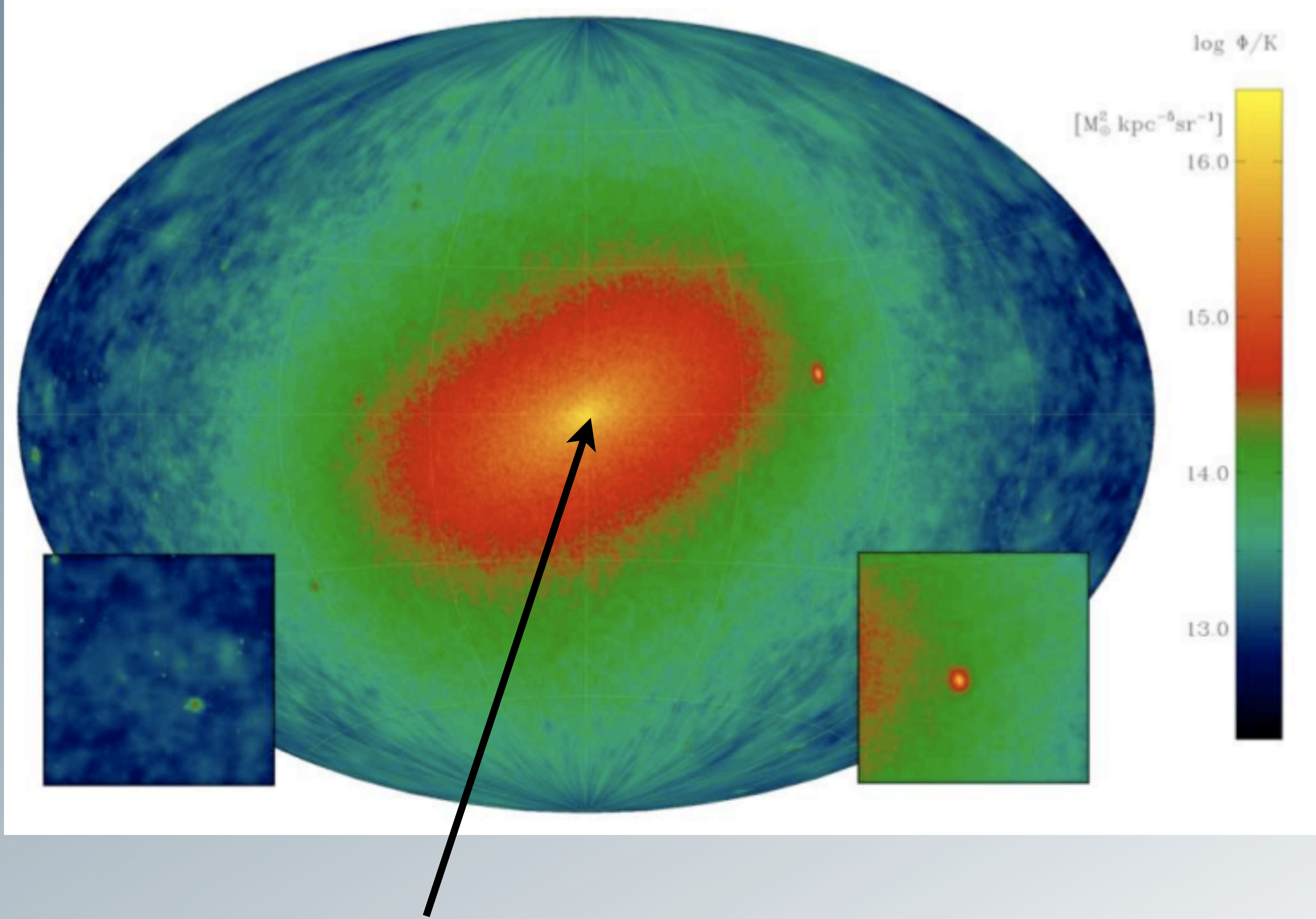

Galactic center

- brightest DM source in sky
- large background contributions

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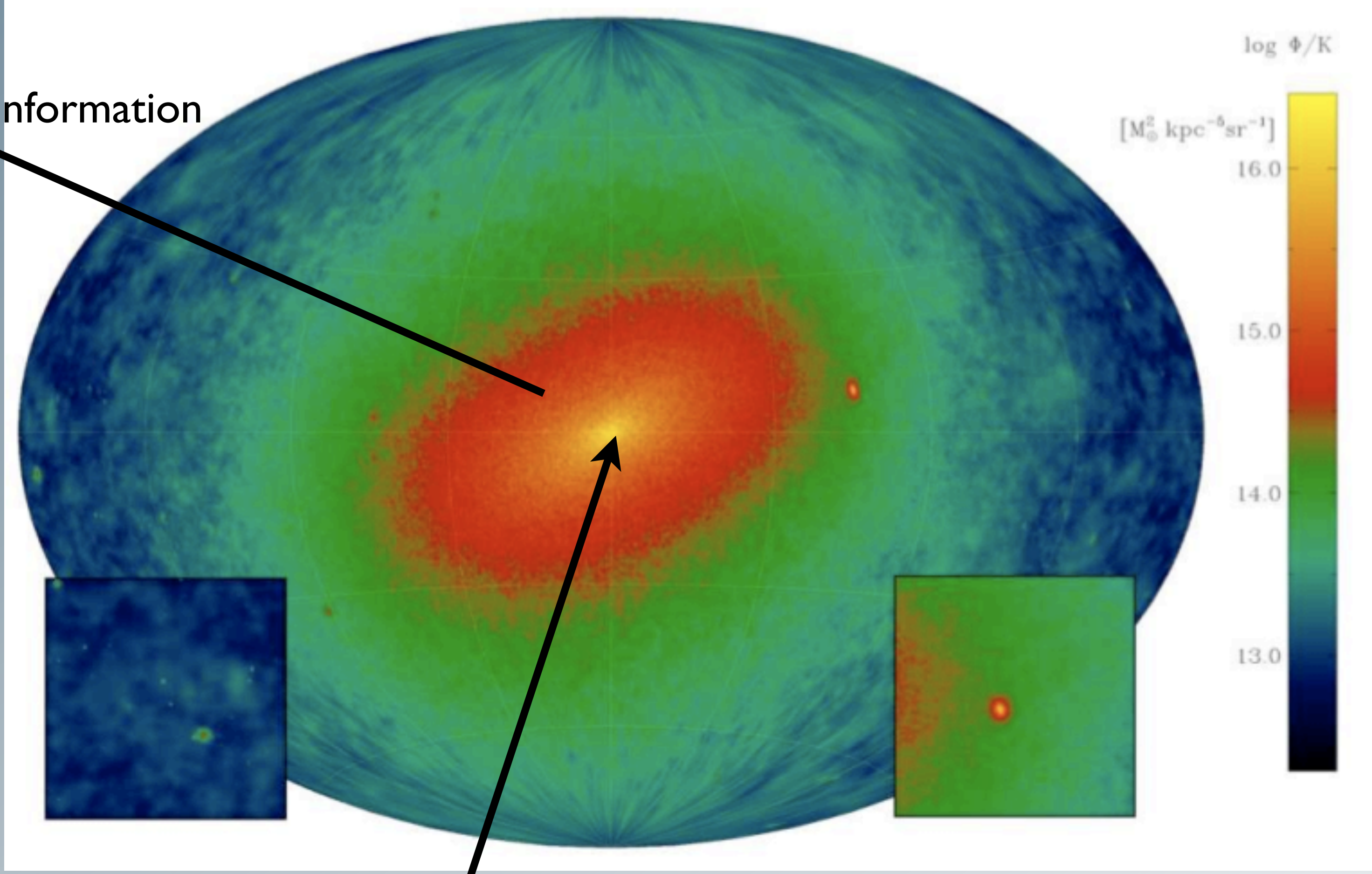
## Galactic halo

- good statistics, angular information
- galactic backgrounds?



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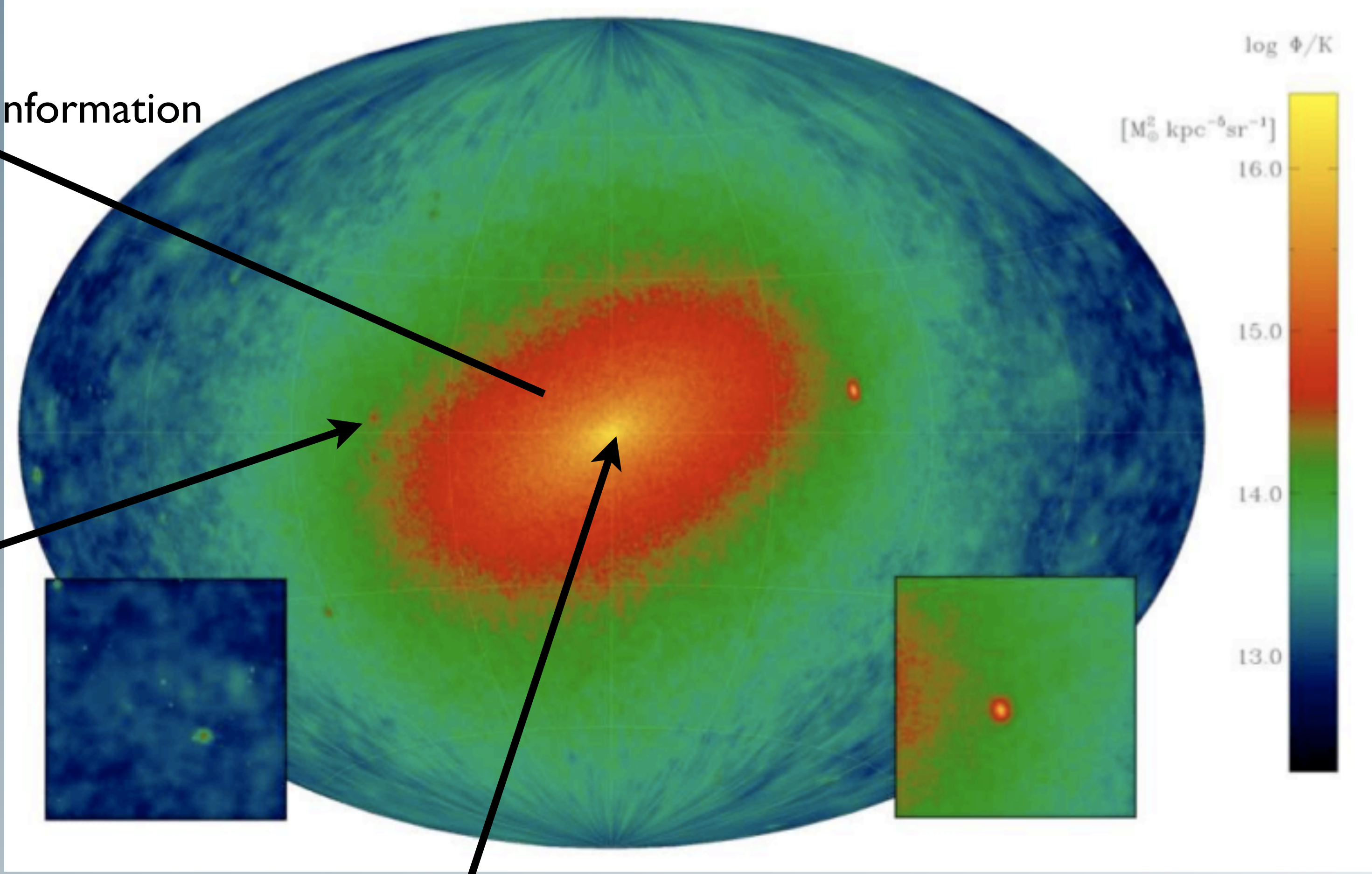

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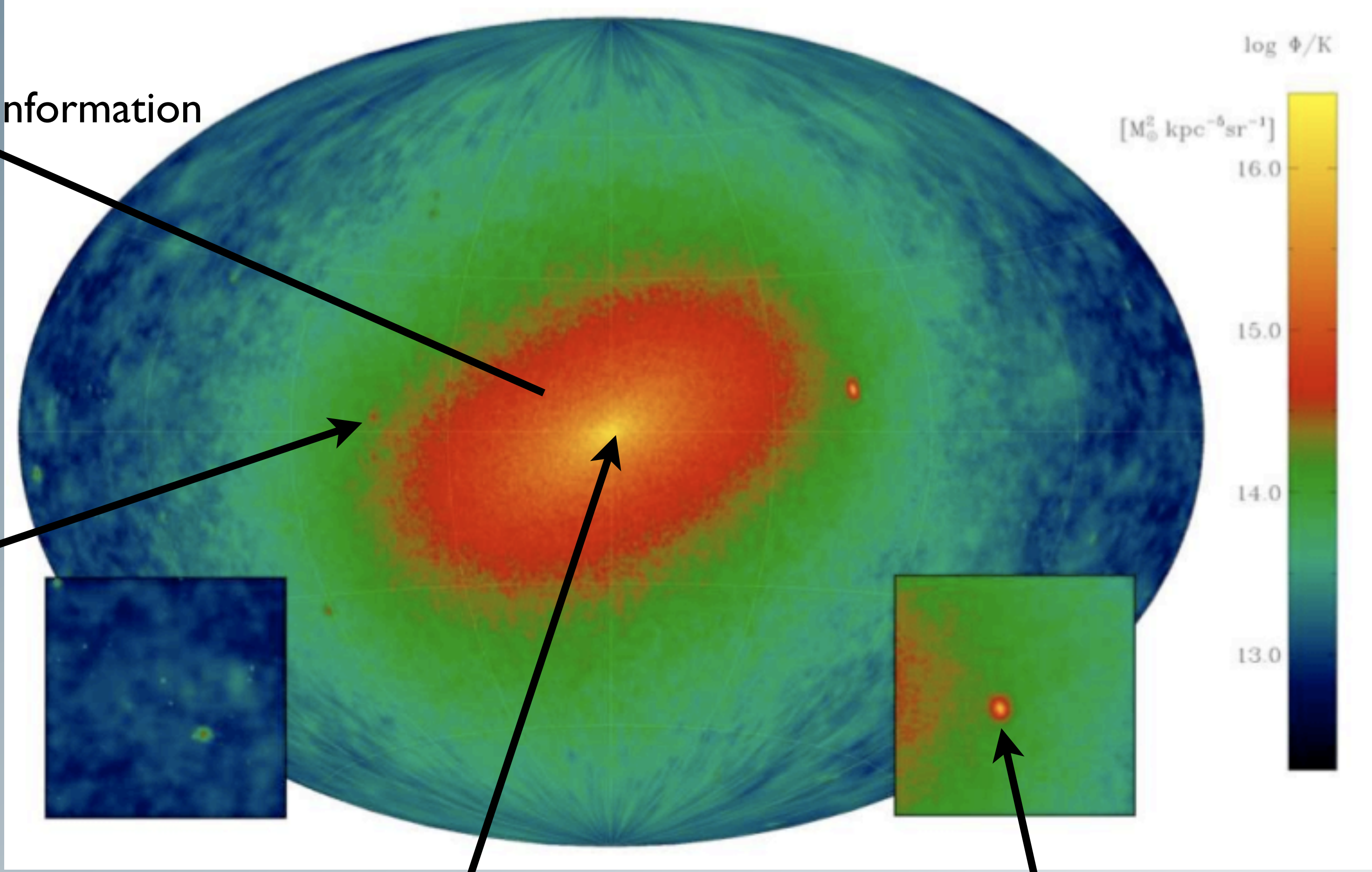

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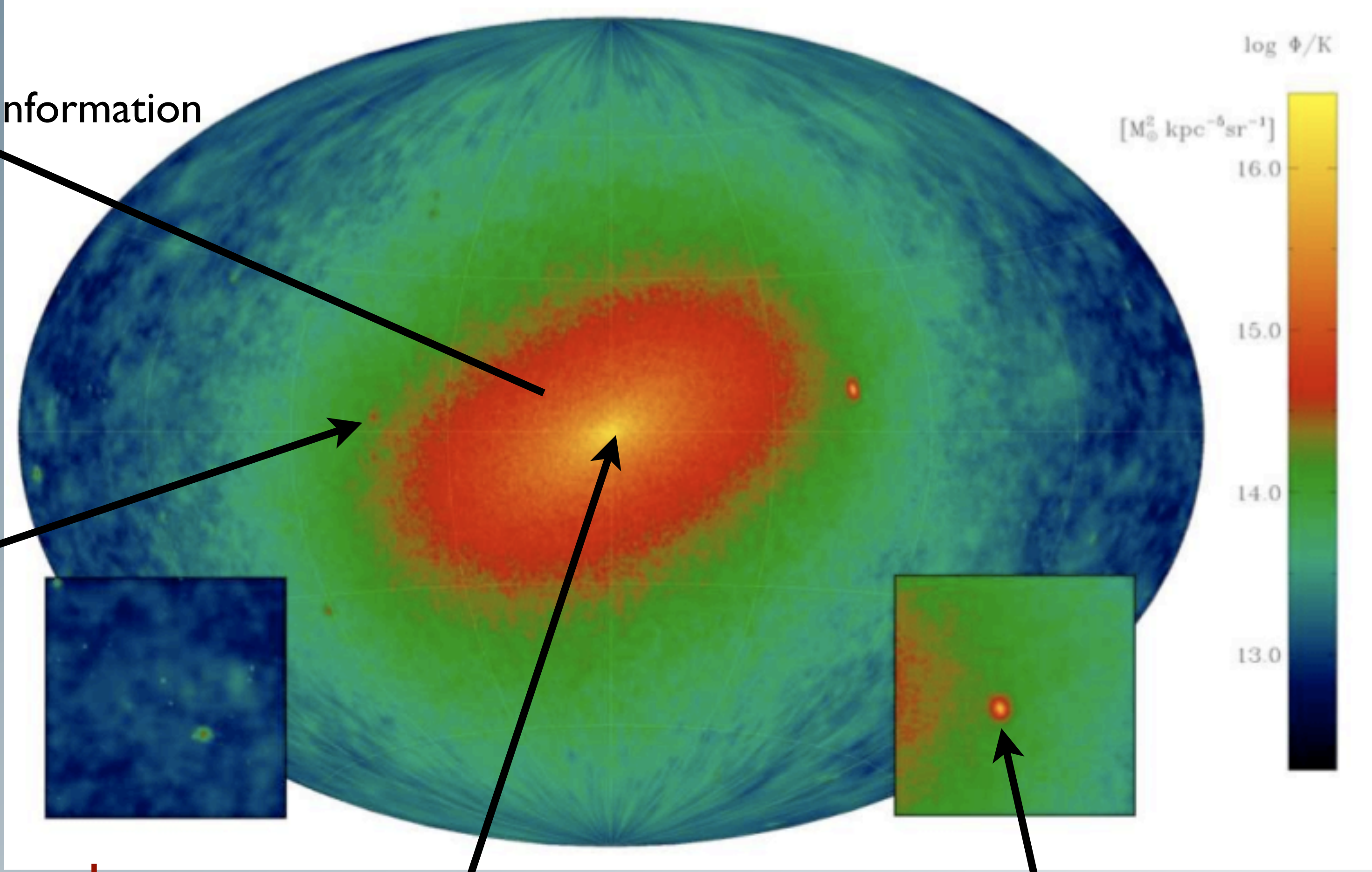

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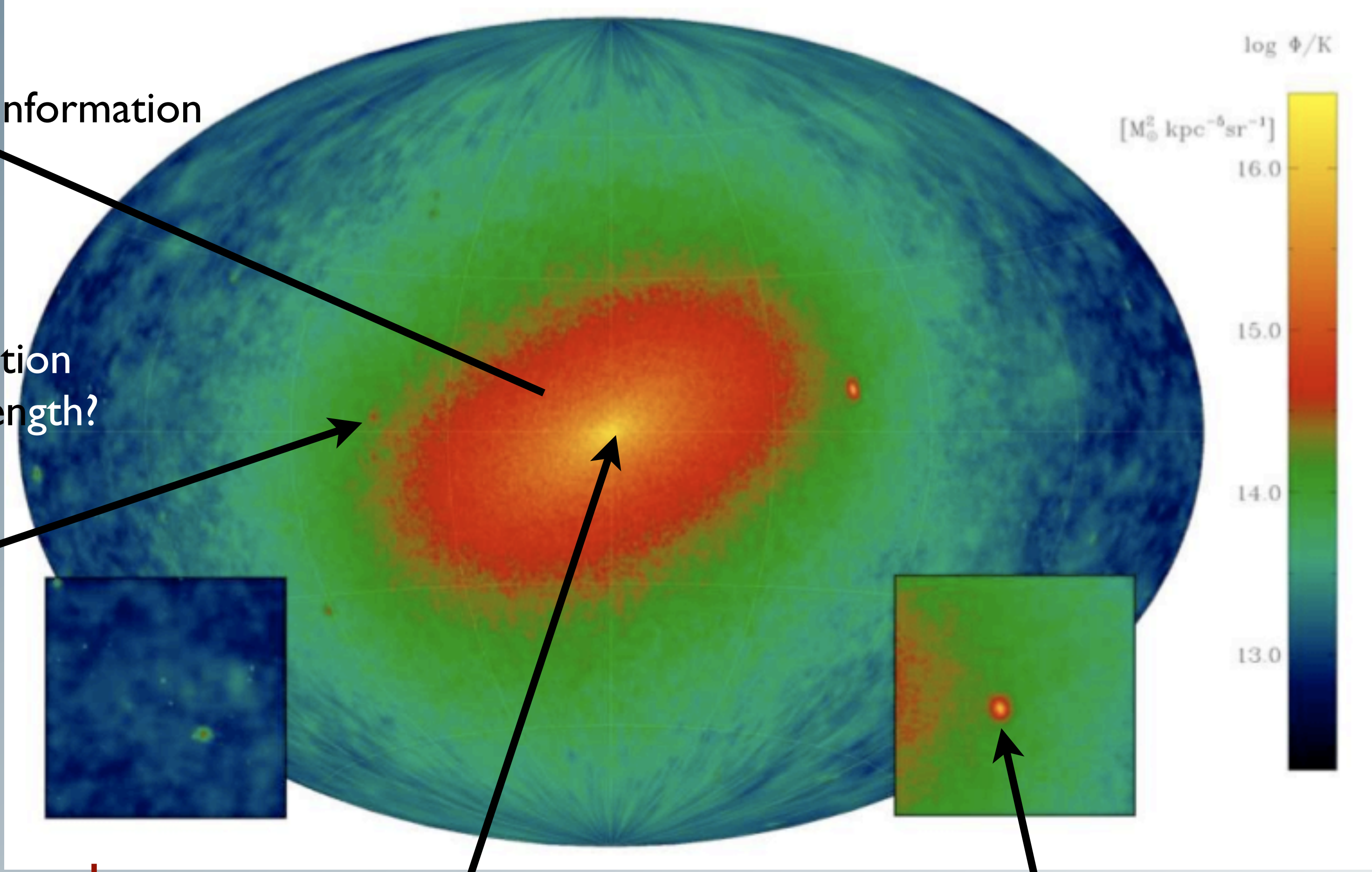

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## Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?

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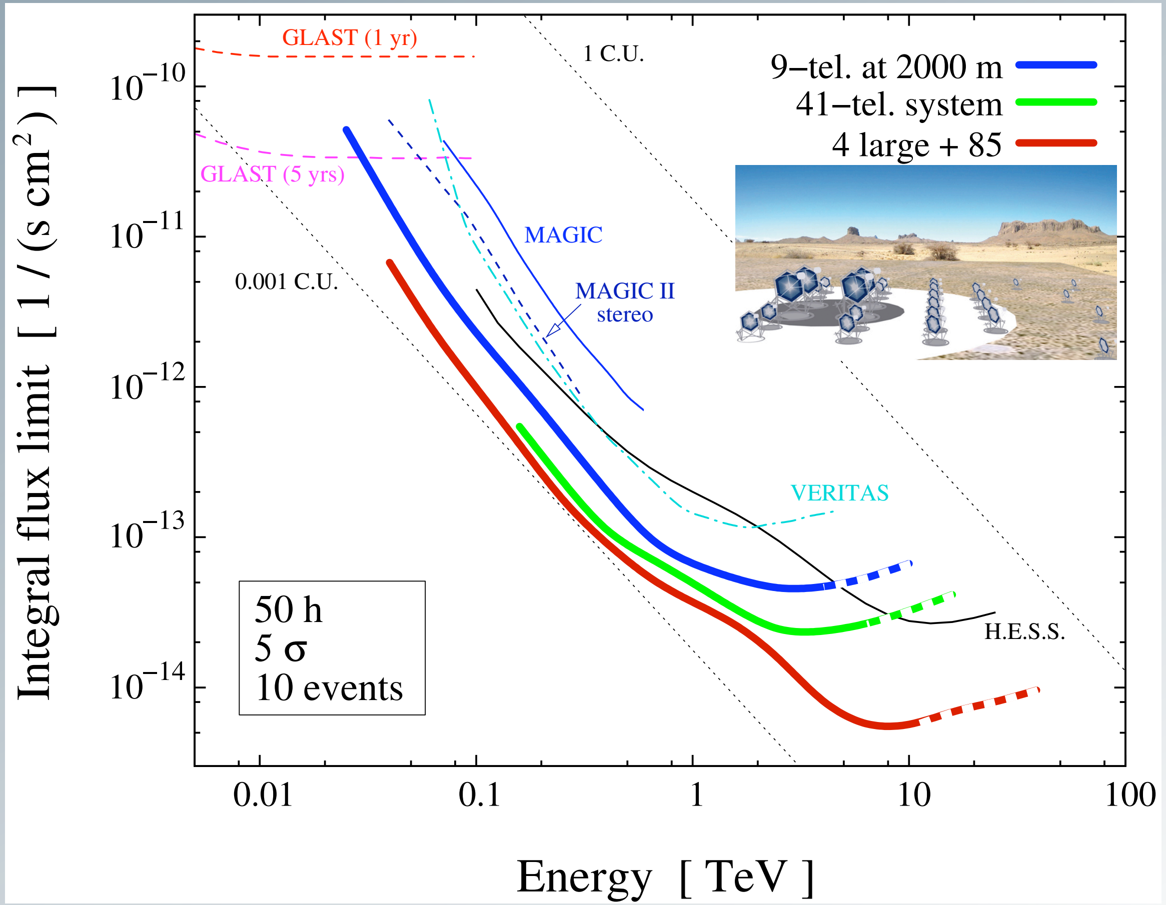
# Telescopes & Sensitivities

## Ground-based

- large eff. Area (~km$^2$)
- small field of view
- lower threshold $\gtrsim$ 40 GeV



Bernlöhr et al., '07

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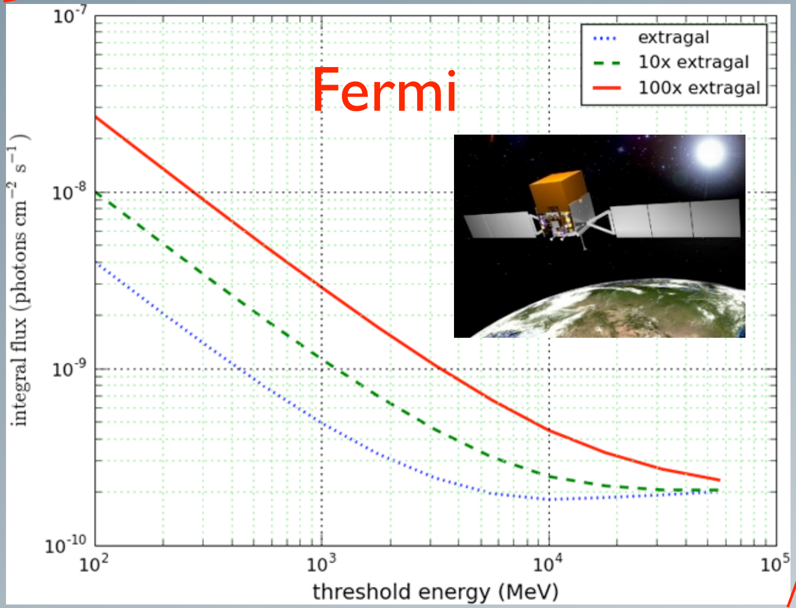
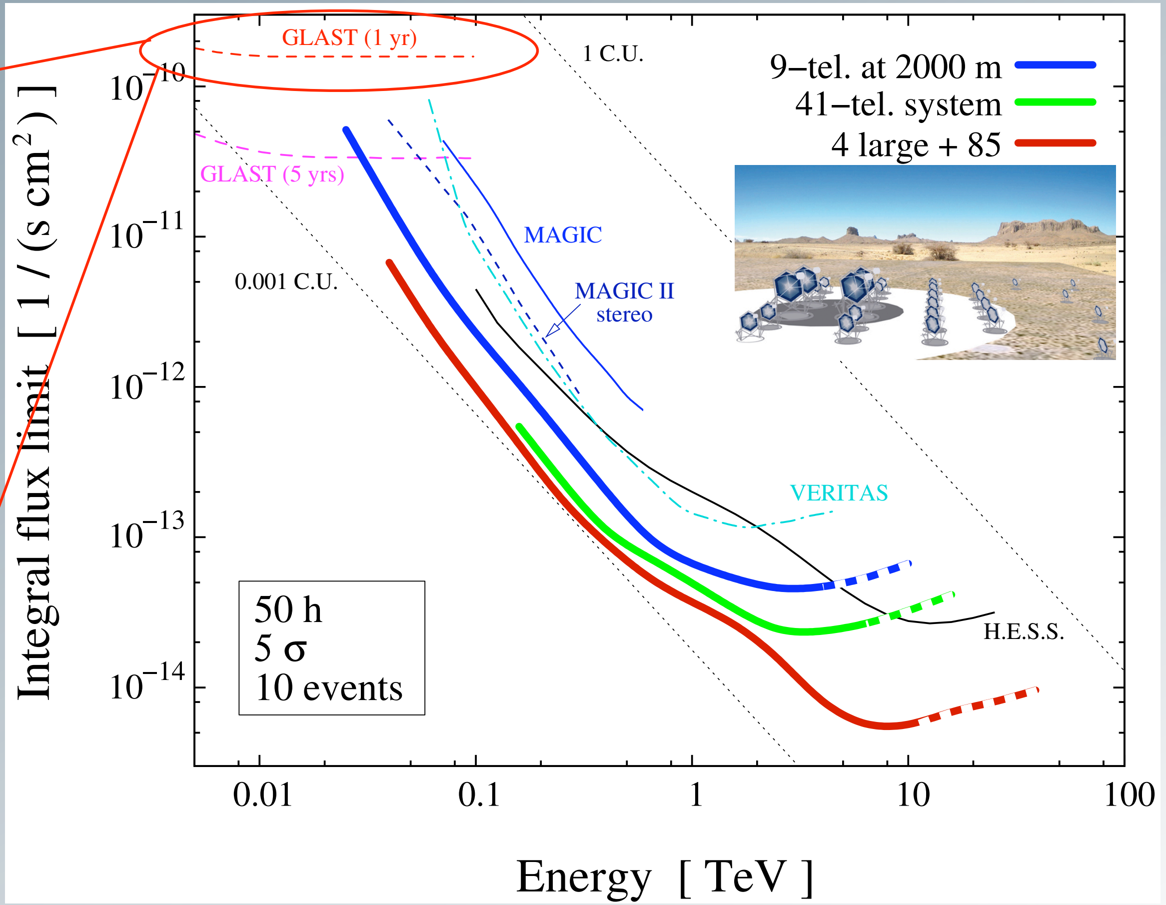


(from the LAT webpage)



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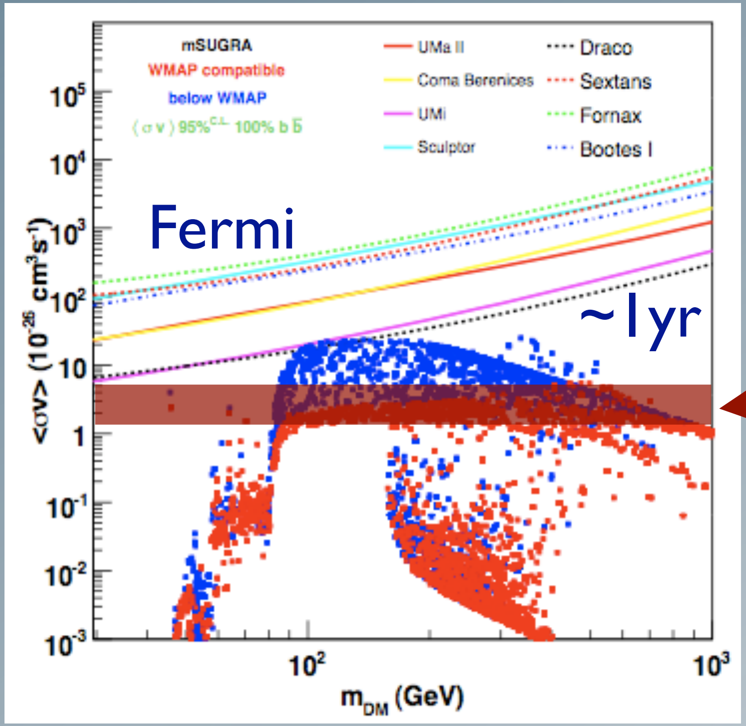
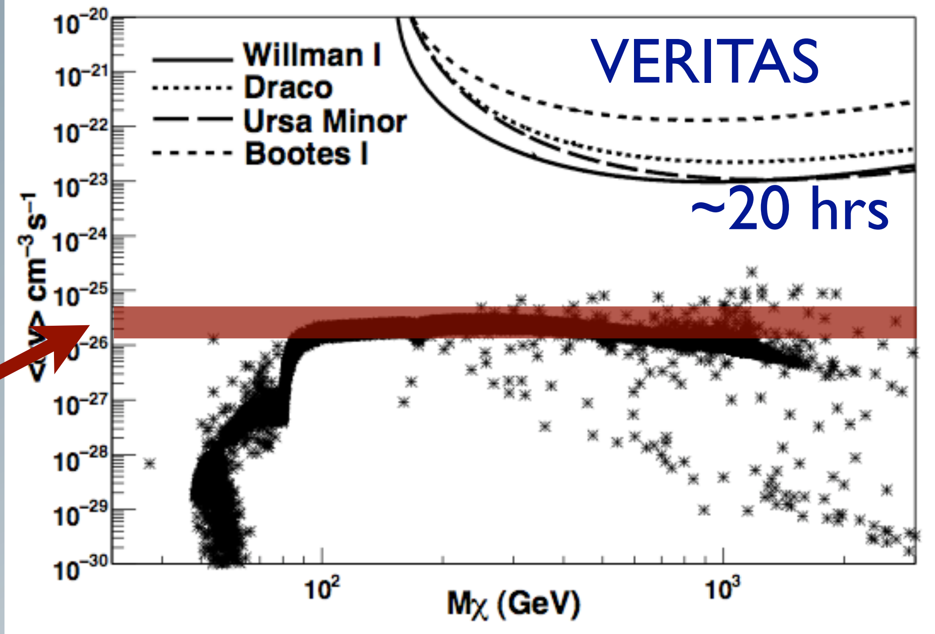
# Observational status: dwarfs

- Greatly improved recent limits from Dwarf galaxies:



Abdo *et al*, 1001.4531

standard thermal value



Acciari *et al*, 1006.5955

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- Limits will improve further by stacking (and exposure)

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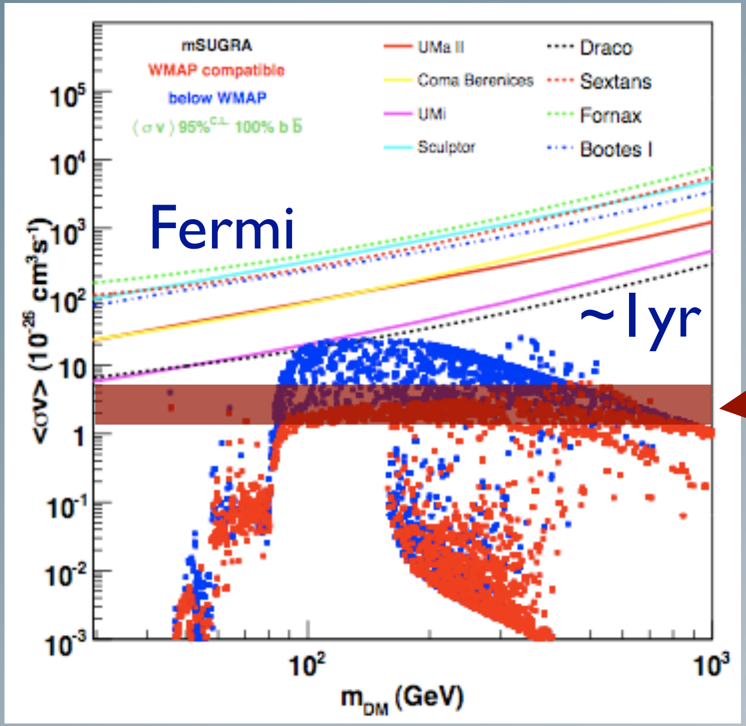

Fermi

~1yr

Abdo *et al*, 1001.4531

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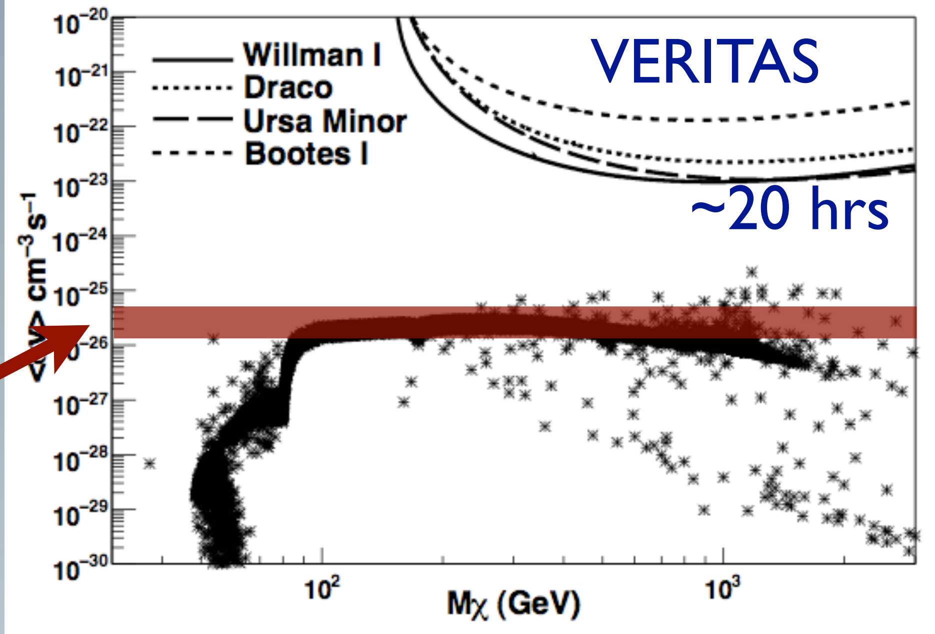

VERITAS

~20 hrs

Acciari *et al*, 1006.5955

see also talk by J. Aleksic

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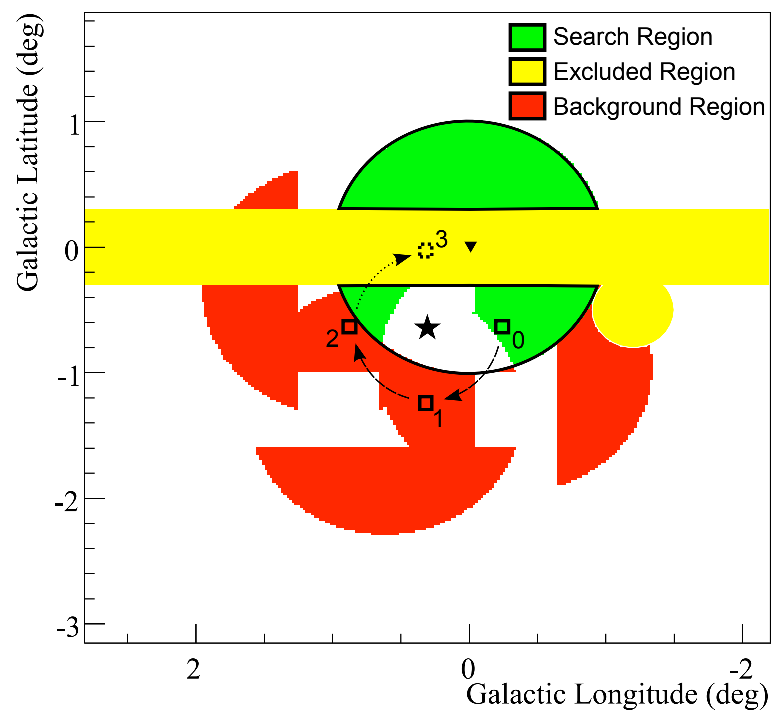
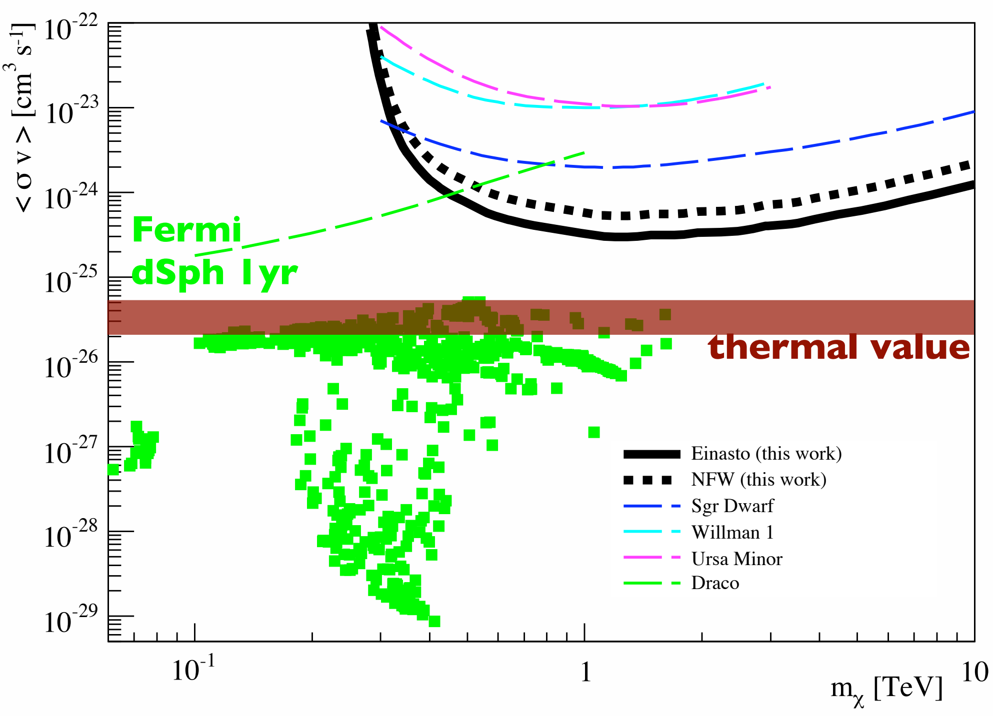
# Galactic center

- Recent strong limits from HESS by using a clever background subtraction method: Abramowski *et al*, 1103.3266





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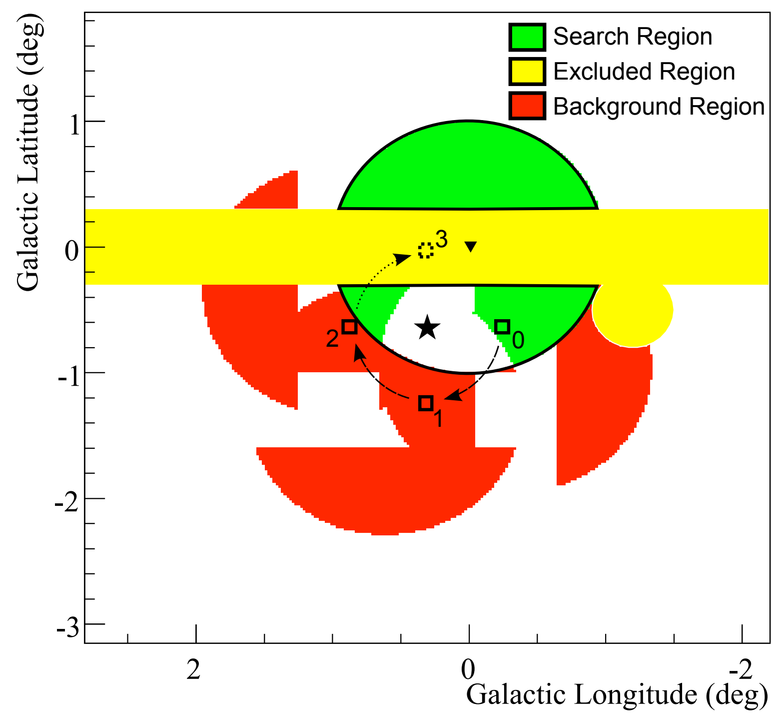

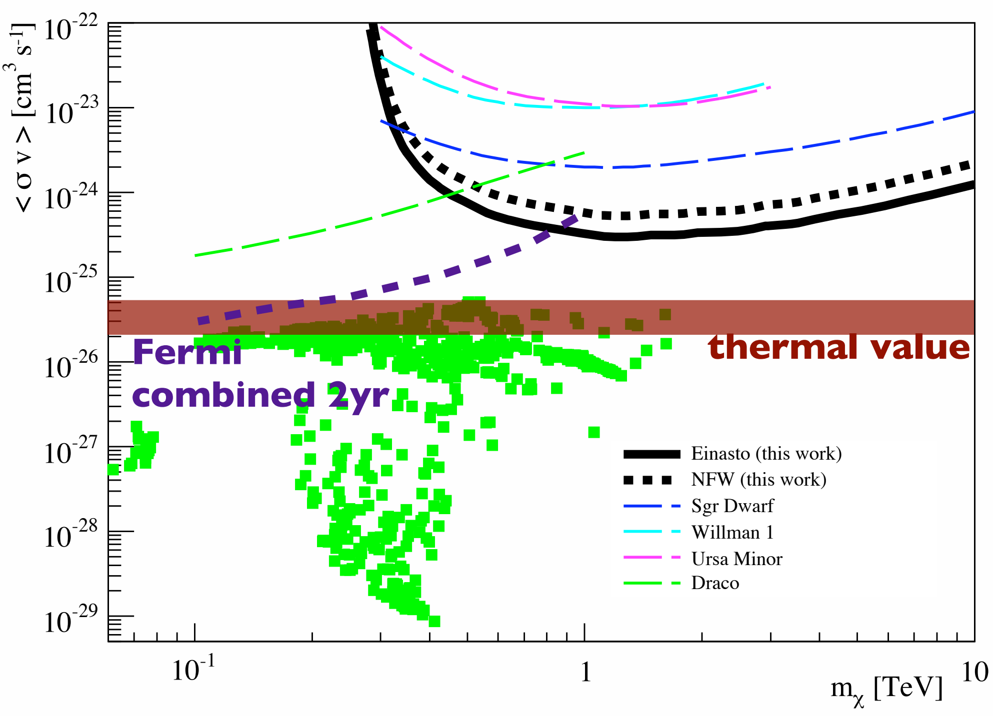

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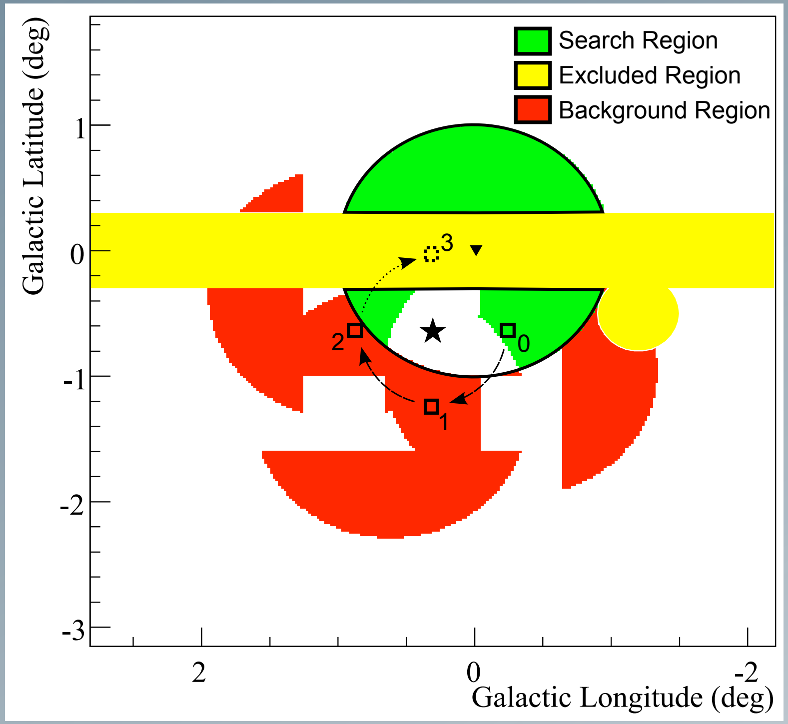
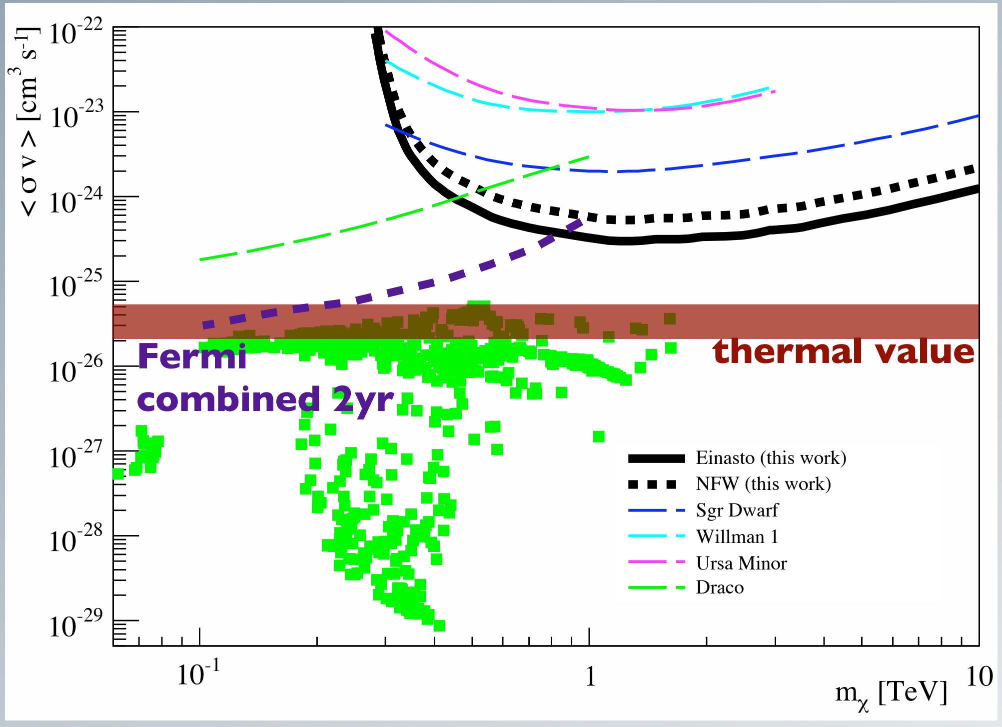
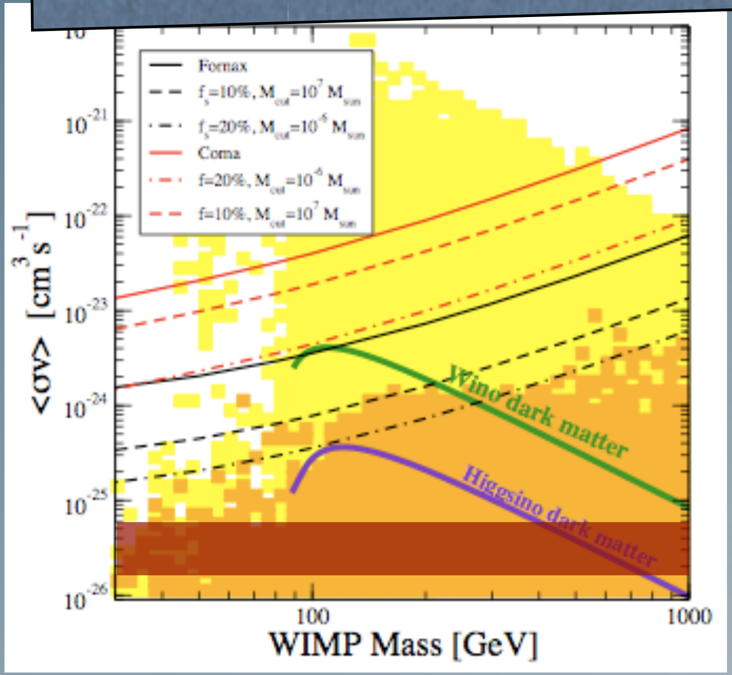




⇨ Indirect searches start to be very competitive!

# Galaxy clusters & diff. BG



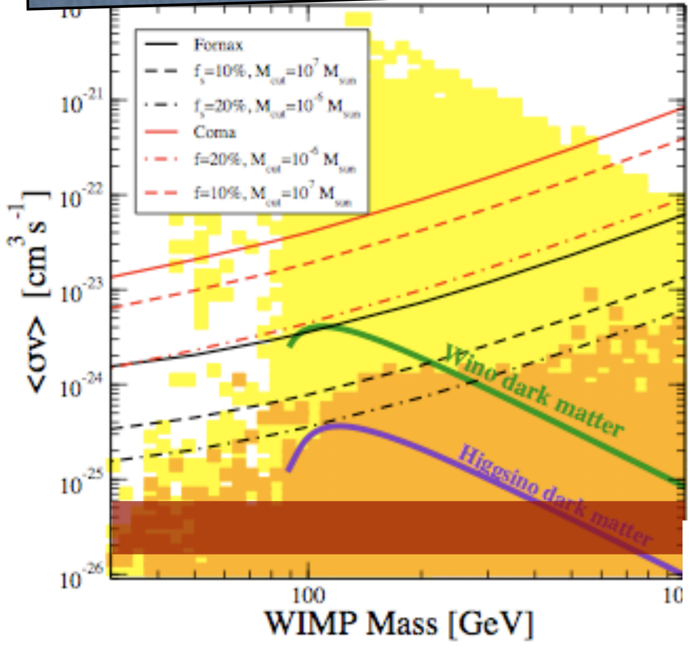
Almost as constraining:

galaxy clusters

(NB: much better discovery potential!)

Ackermann *et al*, 1001.4531 [Fermi-LAT collaboration]

# Galaxy clusters & diff. BG



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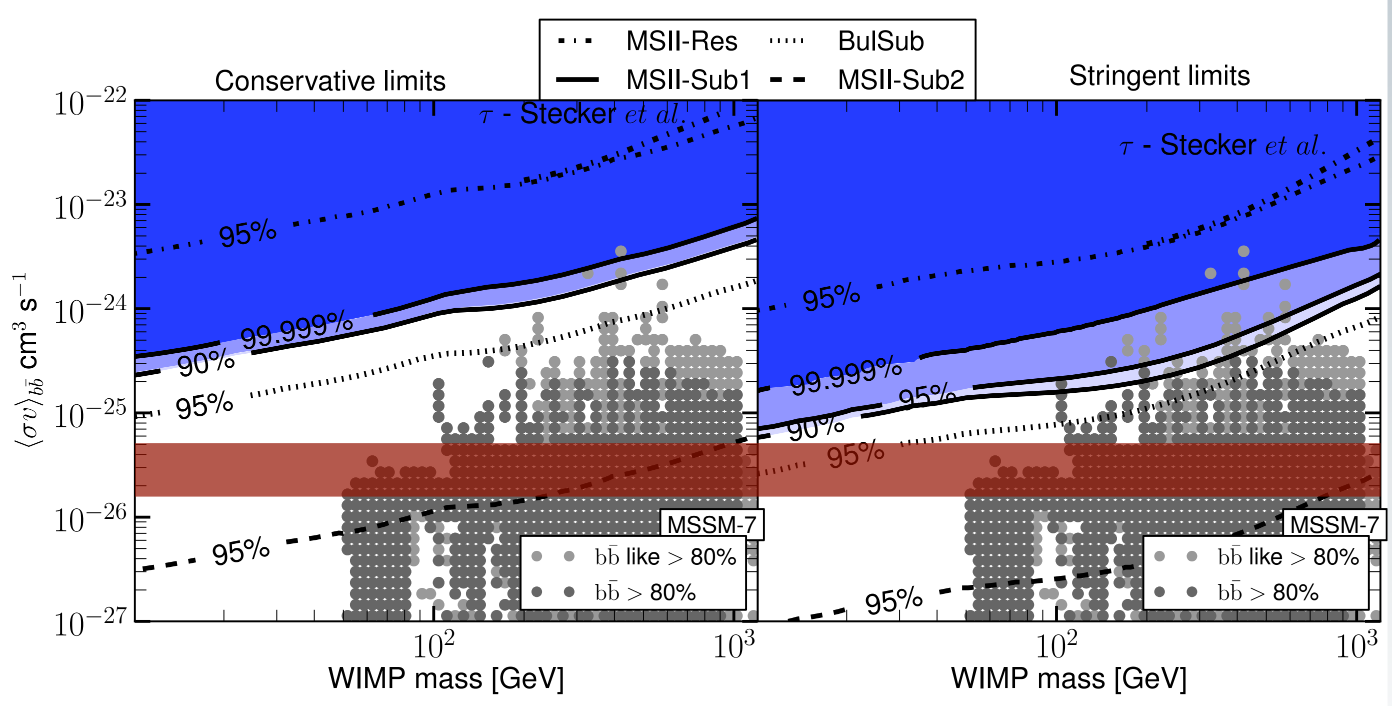
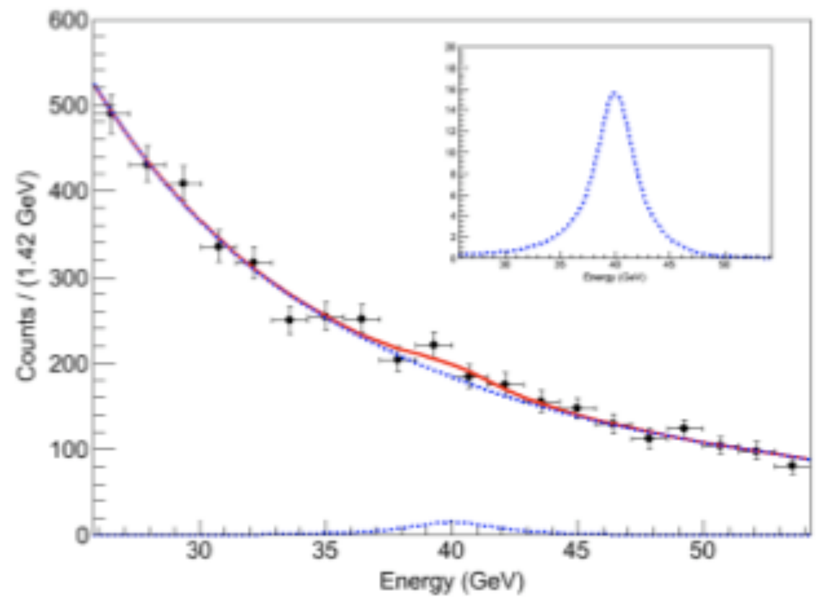
Constraints from the diffuse gamma-ray background depend strongly on subhalo model

Abdo *et al*, 1001.4531 [Fermi-LAT collaboration]

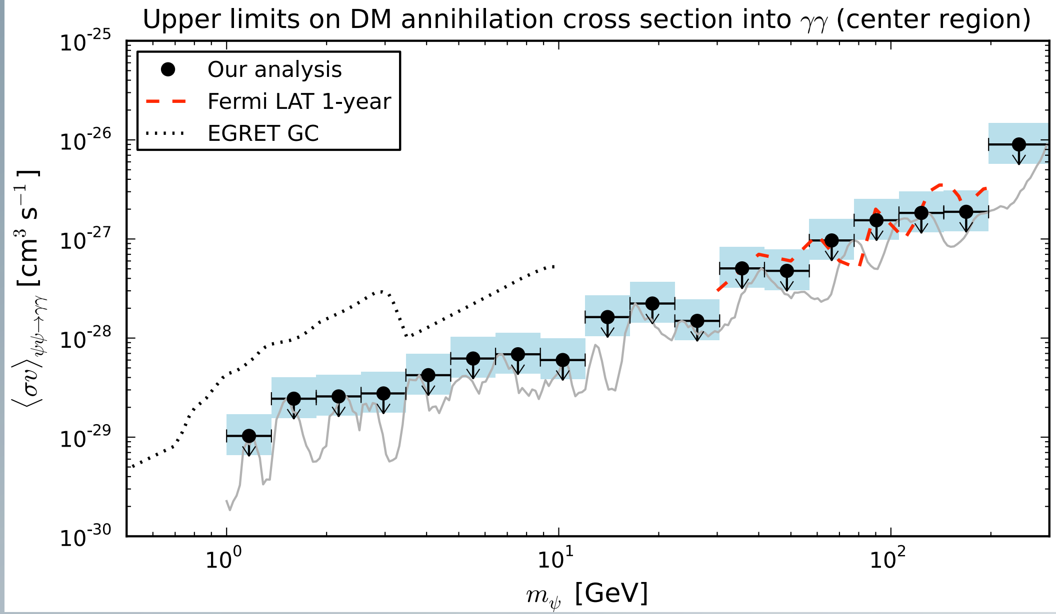


# Search for spectral features

- Fermi all-sky search for line signals:



Abdo *et al*, 1001.4836



Vertongen & Weniger, JCAP 2011

(NB: natural expectation $\langle\sigma v\rangle_{\gamma\gamma} \sim \alpha_{\rm em}^2 \langle\sigma v\rangle_{\rm therm} \simeq 10^{-30}{\rm cm}^3{\rm s}^{-1}$ )

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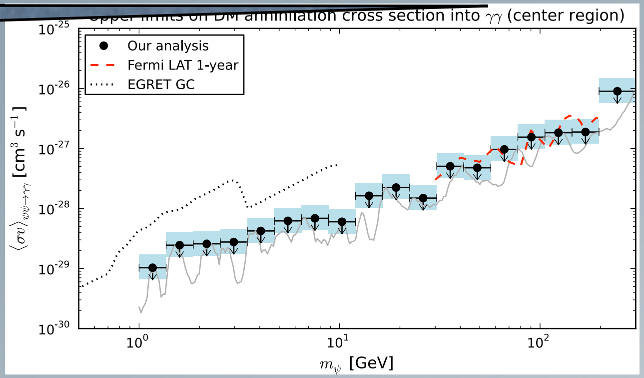

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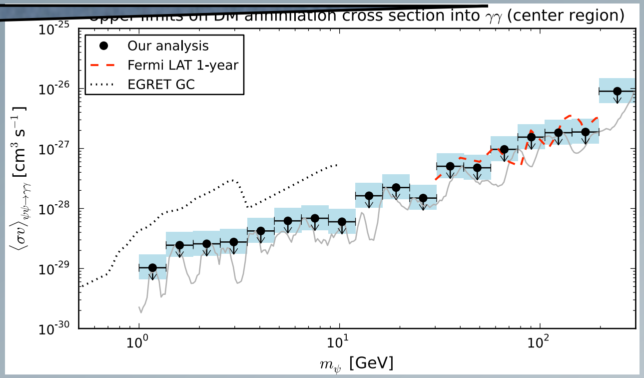
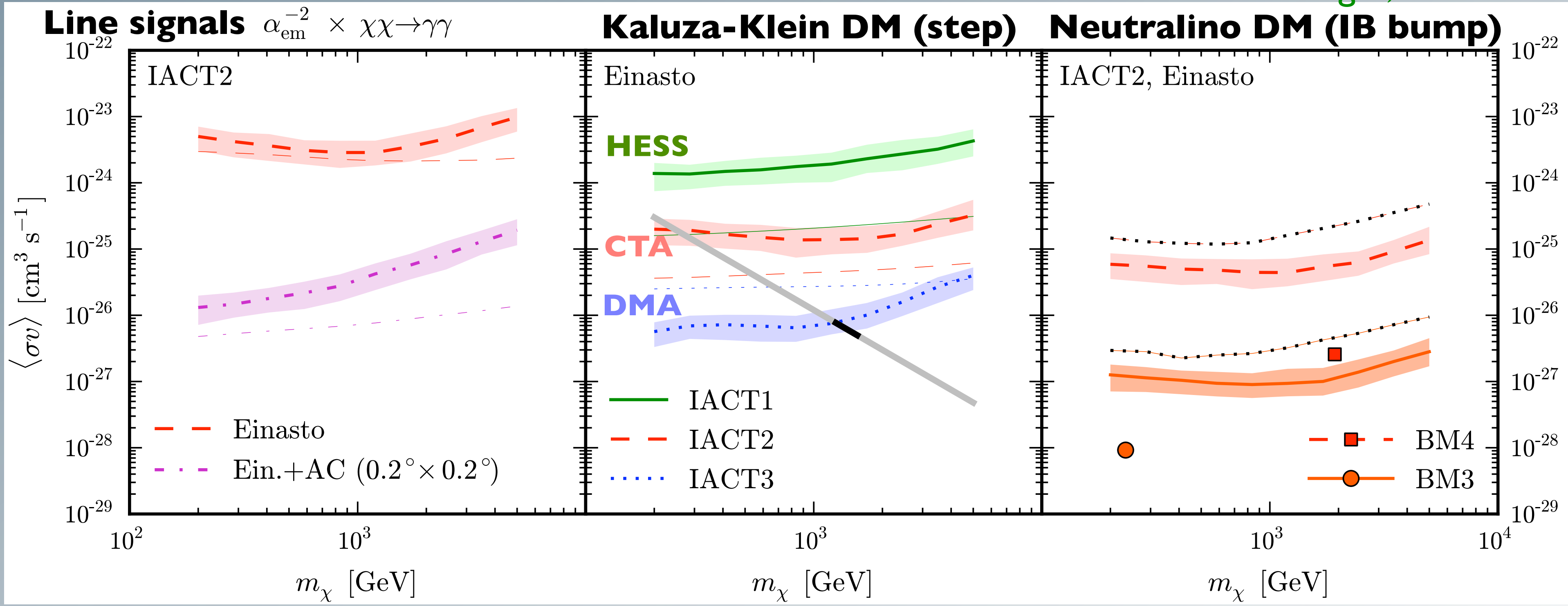


- Searching for sharp steps or IB "bumps" may well be more promising:

TB, Calore, Vertongen & Weniger, 1106.1874



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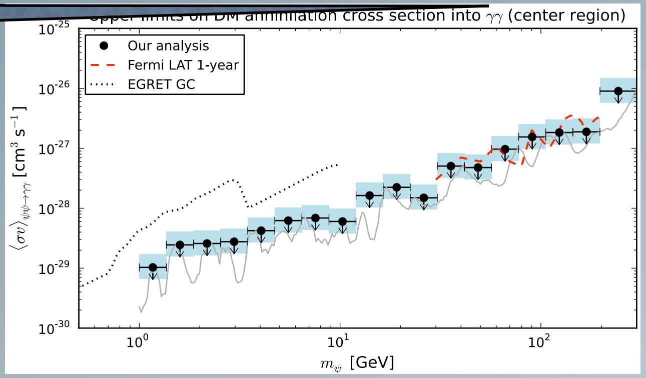

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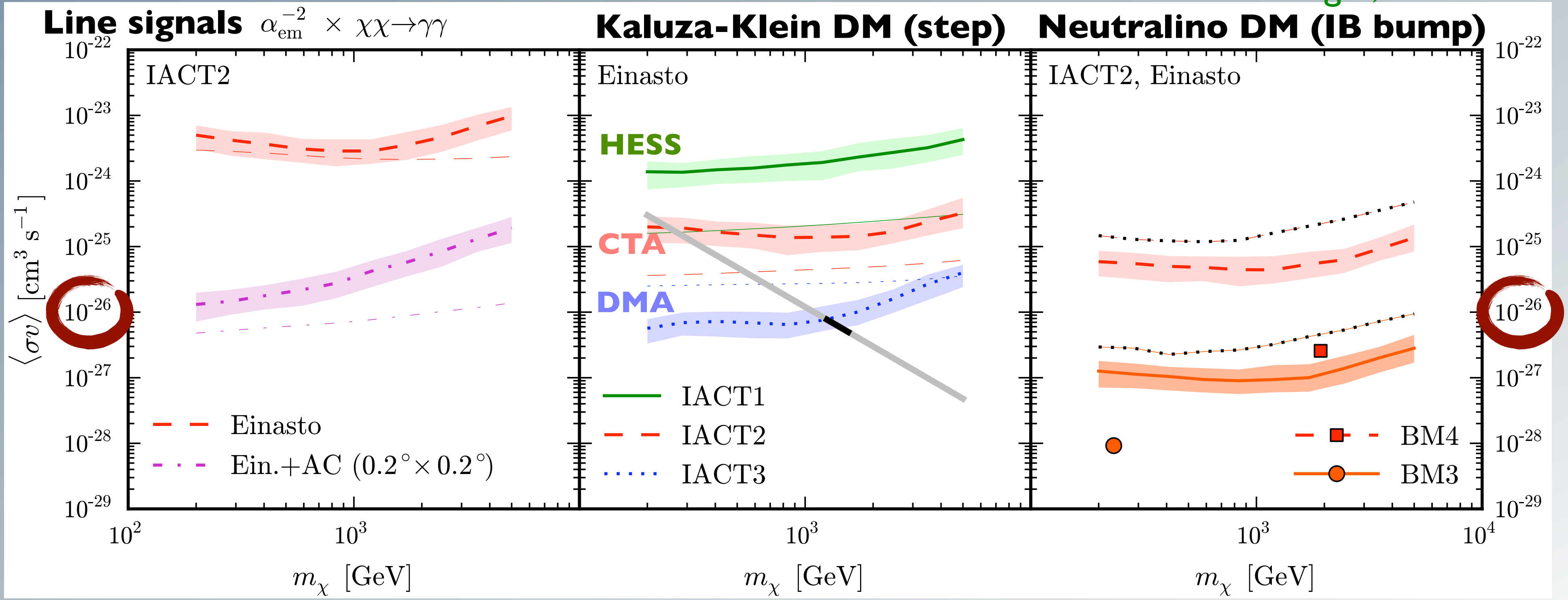

**Line signals** $\alpha_{\rm em}^{-2} \times \chi\chi\to\gamma\gamma$

**Kaluza-Klein DM (step)**

**Neutralino DM (IB bump)**

⇨ *Natural cross sections well within reach!*

# Indirect DM searches

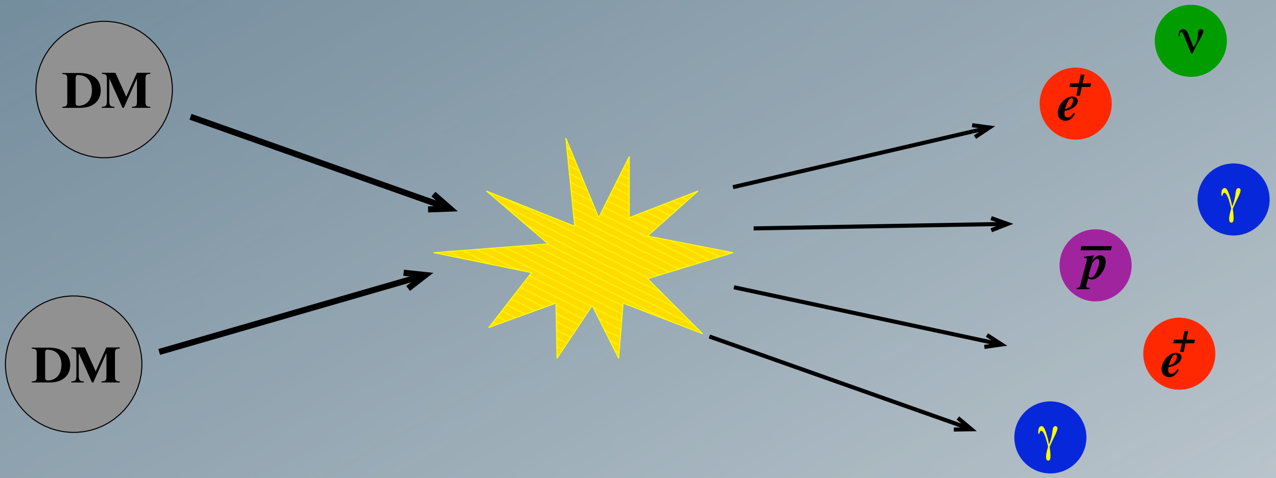
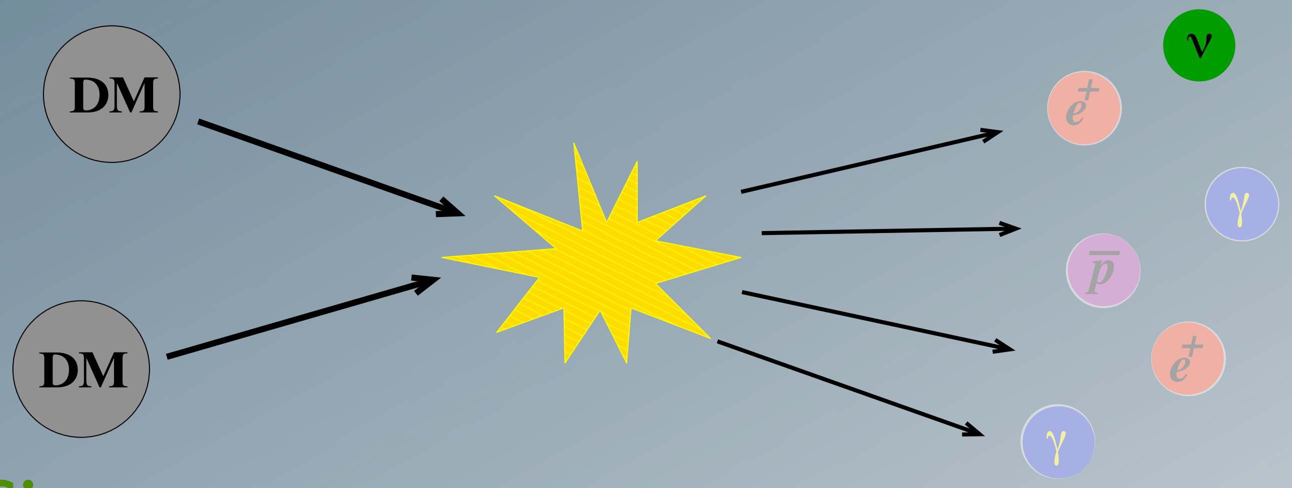


Fig. from J.Edsjö

# Indirect DM searches



## Neutrinos:

- Unperturbed propagation like for photons
- But signal significance (for the same target) usually considerably worse
- New feature: signals from the center of sun or earth!

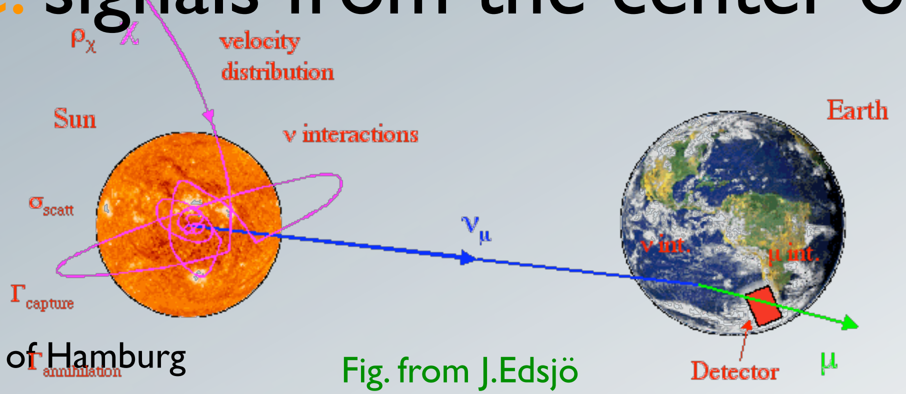


Fig. from J.Edsjö

# Neutrino signals

$$\dot{N} = C - \underbrace{C_A N^2}_{2\Gamma_A} - C_E N$$

capture rate

evaporation rate

⇒ **Annihilation rate:**

$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\sqrt{C_A C}}$$

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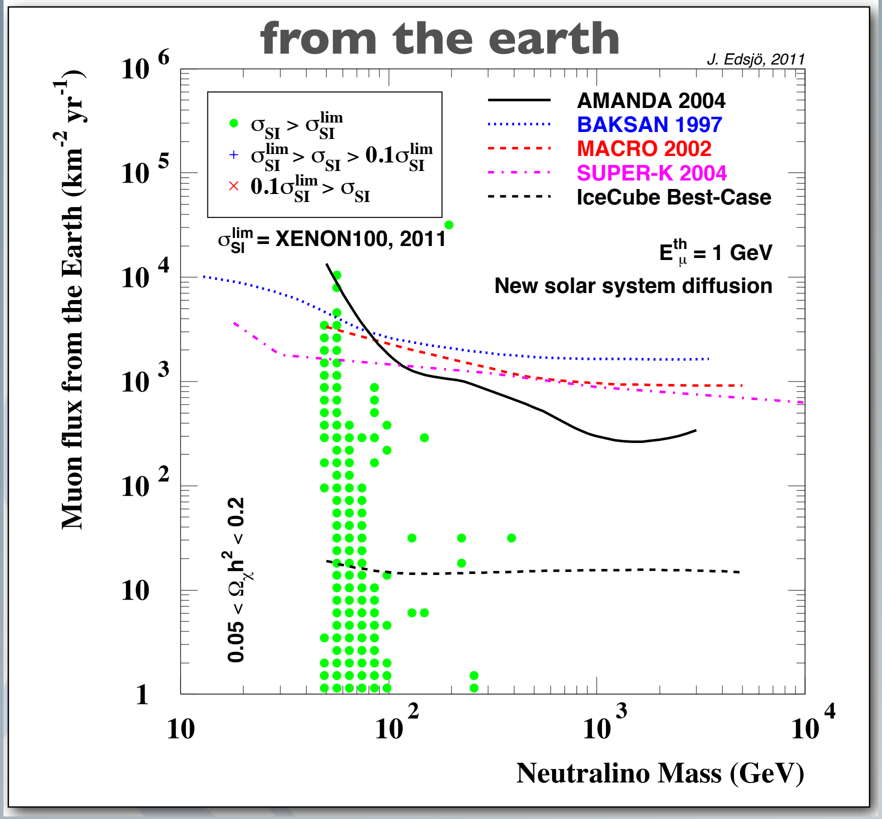

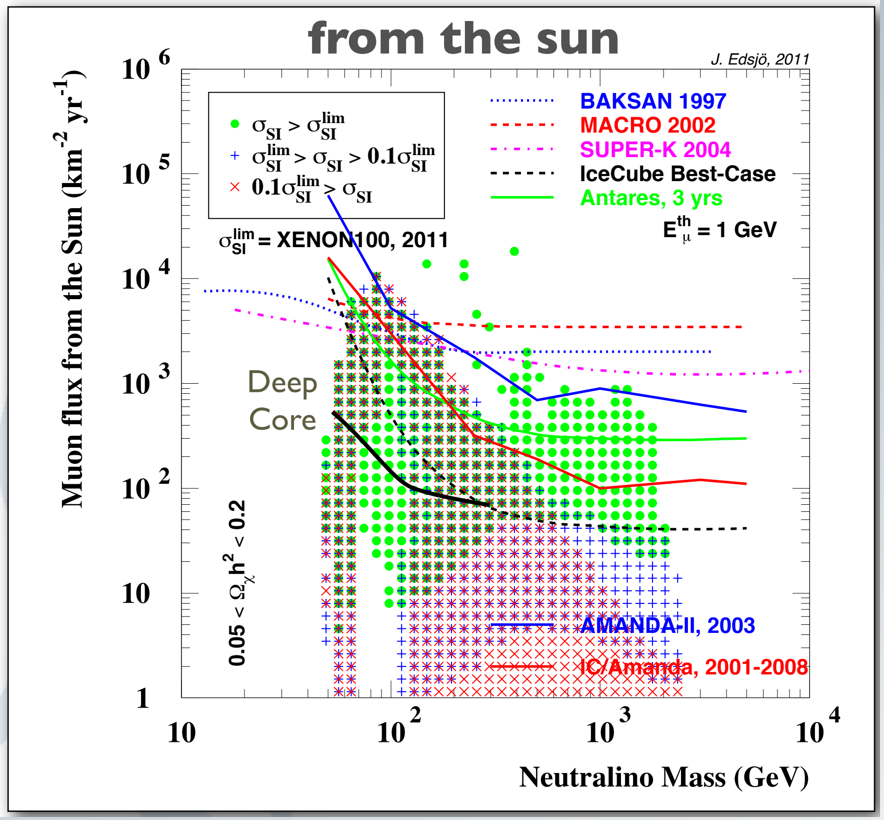

→ more in talks from
G. Lambard & F. Lee

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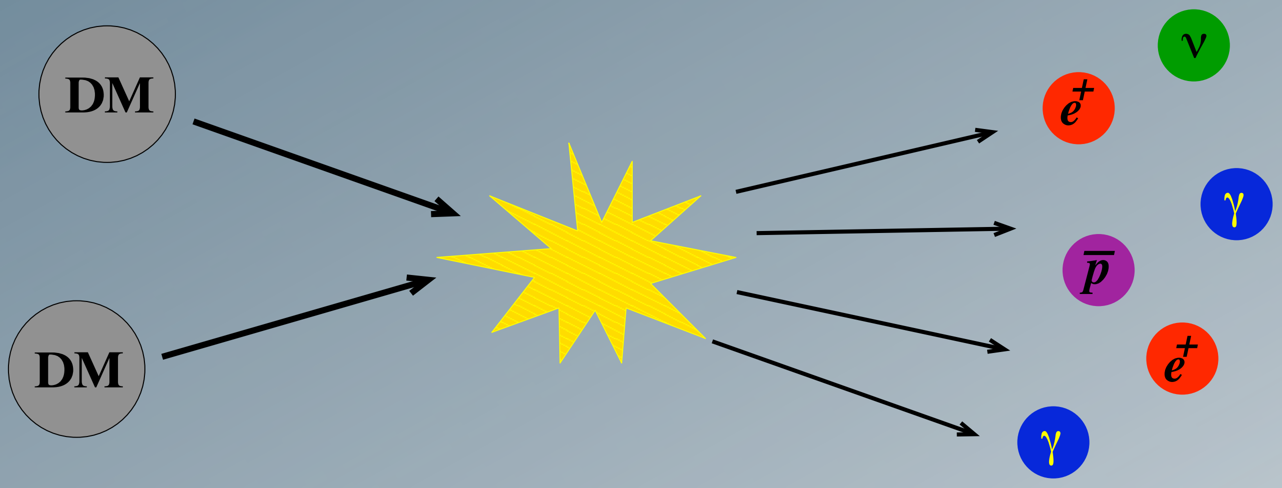

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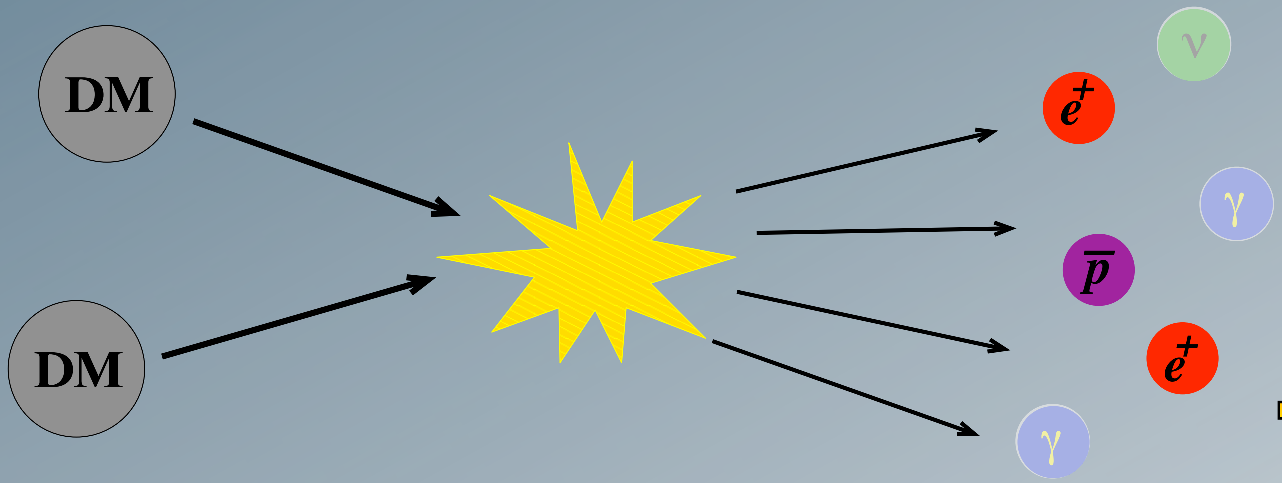

⇨ talks by
O. Adriani &
B. Bertucci

## Charged cosmic rays:

- GCRs are confined by galactic magnetic fields
- After propagation, no directional information is left
- Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter

  ⇨ focus on antimatter (low backgrounds!)

# Propagation

- Little known about Galactic magnetic field distribution
- Random distribution of field inhomogeneities
  $\rightsquigarrow$ propagation well described by diffusion equation

$$\boxed{\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p}b_{\mathrm{loss}}\psi - \frac{\partial}{\partial p}K\frac{\partial}{\partial p}\psi = q_{\mathrm{source}}}$$

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Sources
(primary &
secondary)

# Analytical vs. numerical

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- Numerically
  - ⊕ 3D possible
  - ⊕ any magnetic field model
  - ⊕ realistic gas distribution, full energy losses
  - ⊖ computations time-consuming
  - ⊖ "black box"

e.g.

Strong, Moskalenko, …

DRAGON

Evoli, Gaggero, Grasso & Maccione

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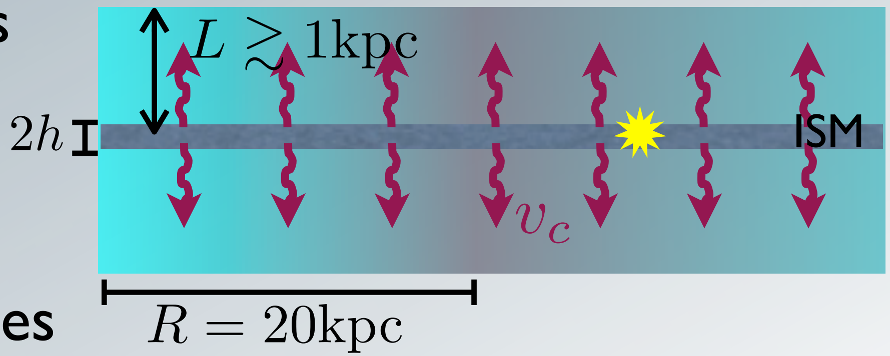
DRAGON
Evoli, Gaggero, Grasso & Maccione

- (Semi-)analytically
  - ⊕ Physical insight from analytic solutions
  - ⊕ fast computations allow to sample full parameter space
  - ⊖ only 2D possible
  - ⊖ simplified gas distribution, energy losses

e.g. Donato, Maurin, Salati, Taillet, ...

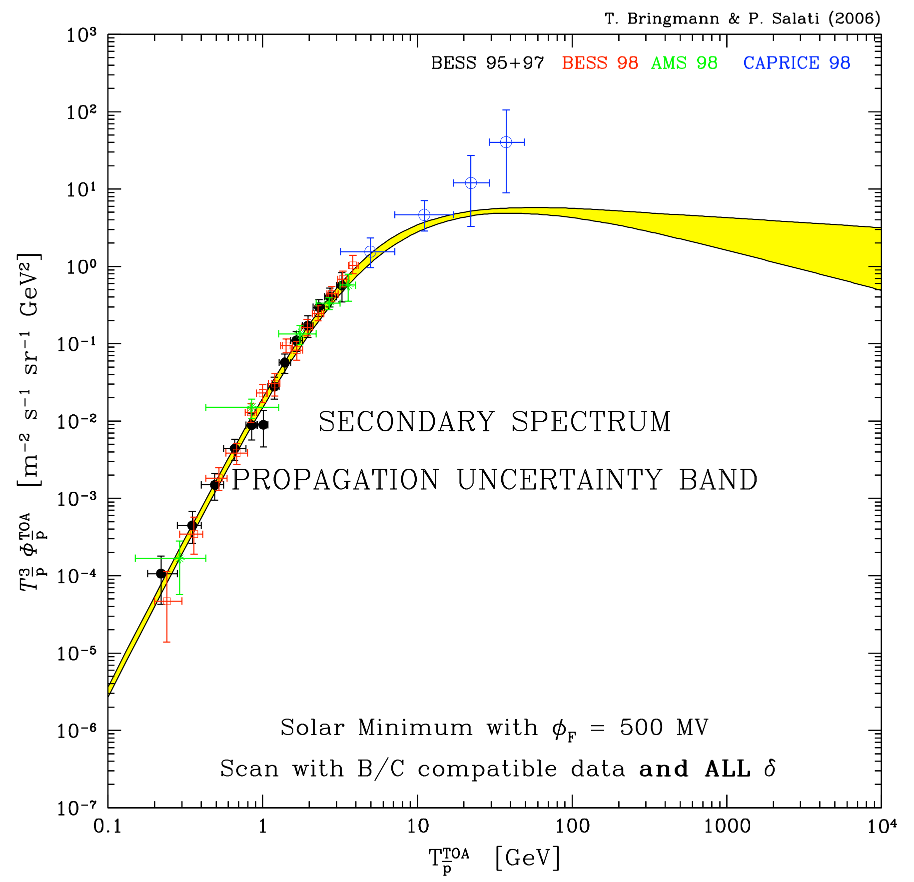


# E.g. secondary antiprotons

- Propagation parameters $(K_0, \delta, L, v_a, v_c)$ of two-zone diffusion model strongly constrained by B/C

Maurin, Donato, Taillet & Salati, ApJ '01

- This can be used to predict fluxes for other species:



TB & Salati, PRD '07

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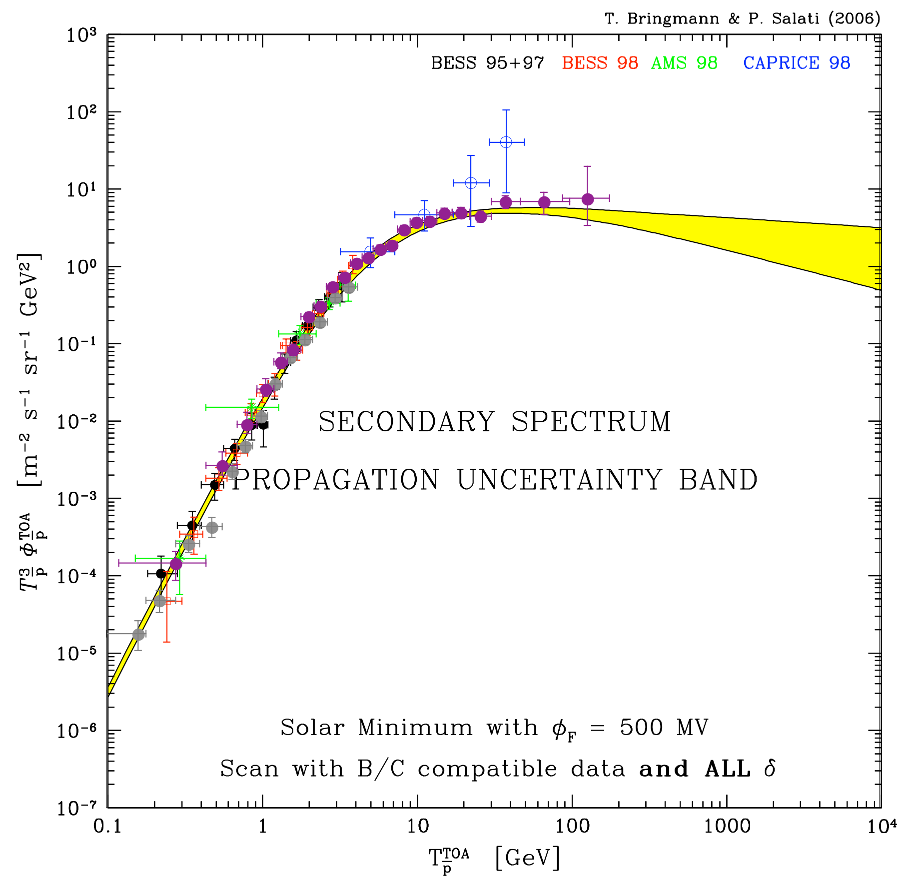

TB & Salati, PRD '07

excellent agreement with new data:

BESSpolar 2004

Abe *et al.*, PRL '08

PAMELA 2008

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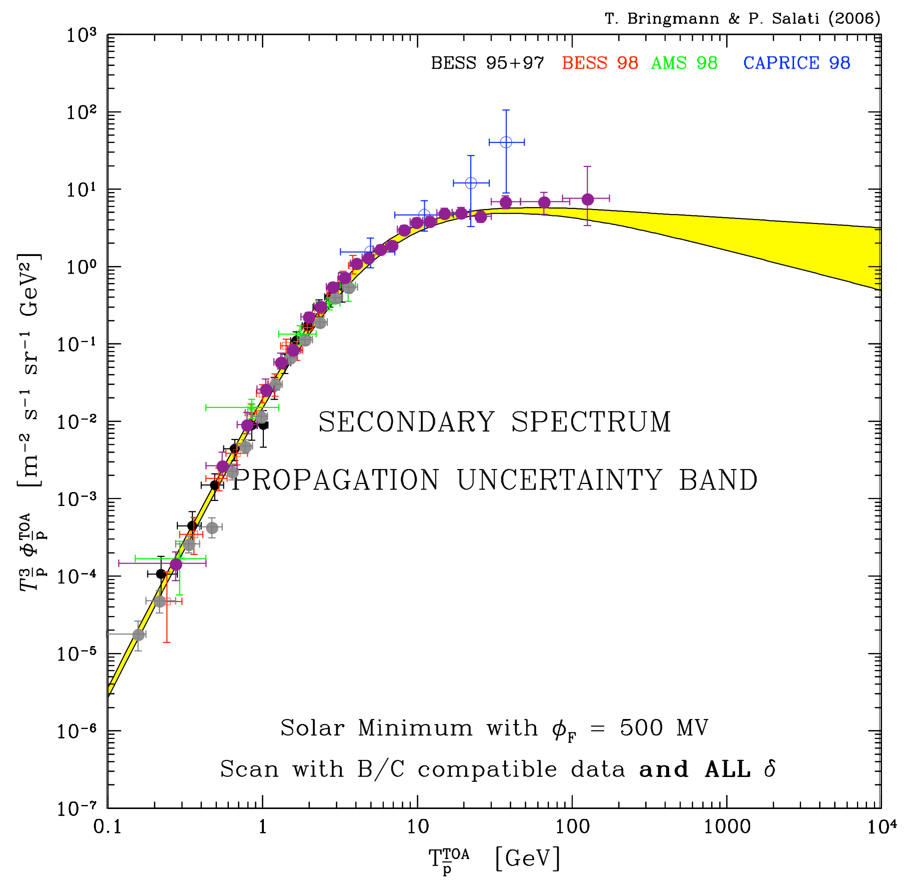

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➩ very nice test for underlying diffusion model!

# Antiprotons

- Rather straightforward to handle:
  - no significant astrophysical sources
  - for $E_{\bar{p}} \gtrsim 10\,\mathrm{GeV}$ completely diffusion dominated
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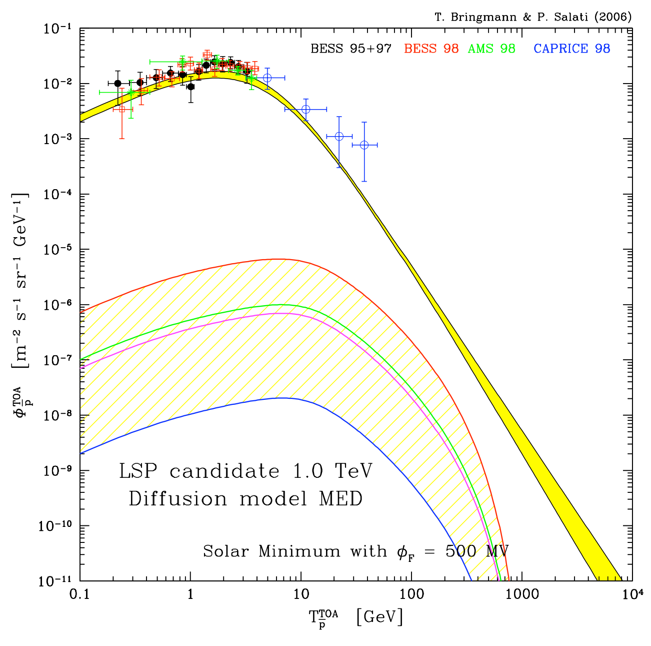

TB & Salati, PRD '09

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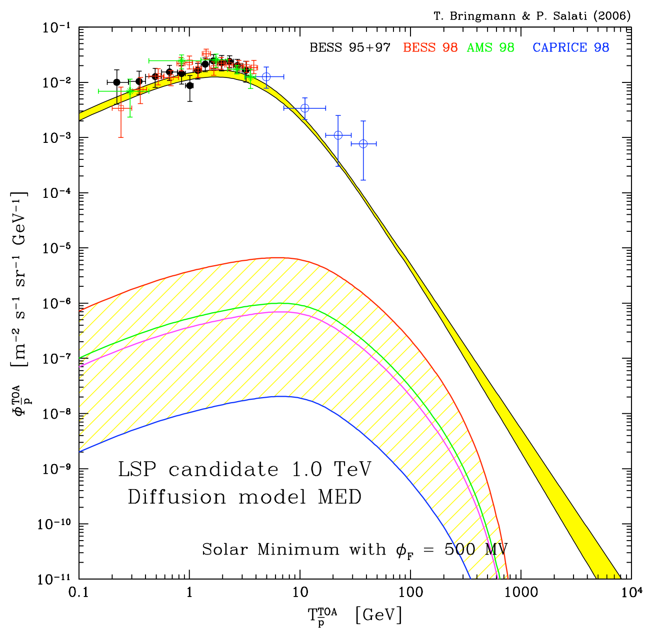

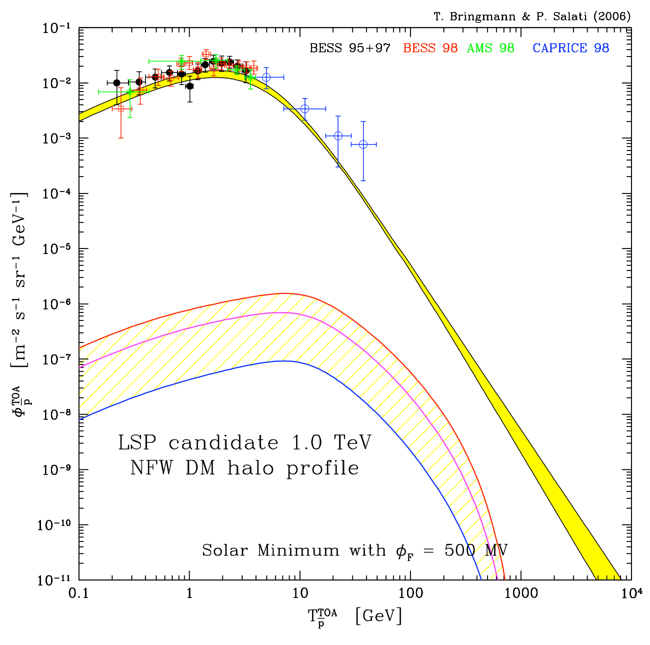

TB & Salati, PRD '09

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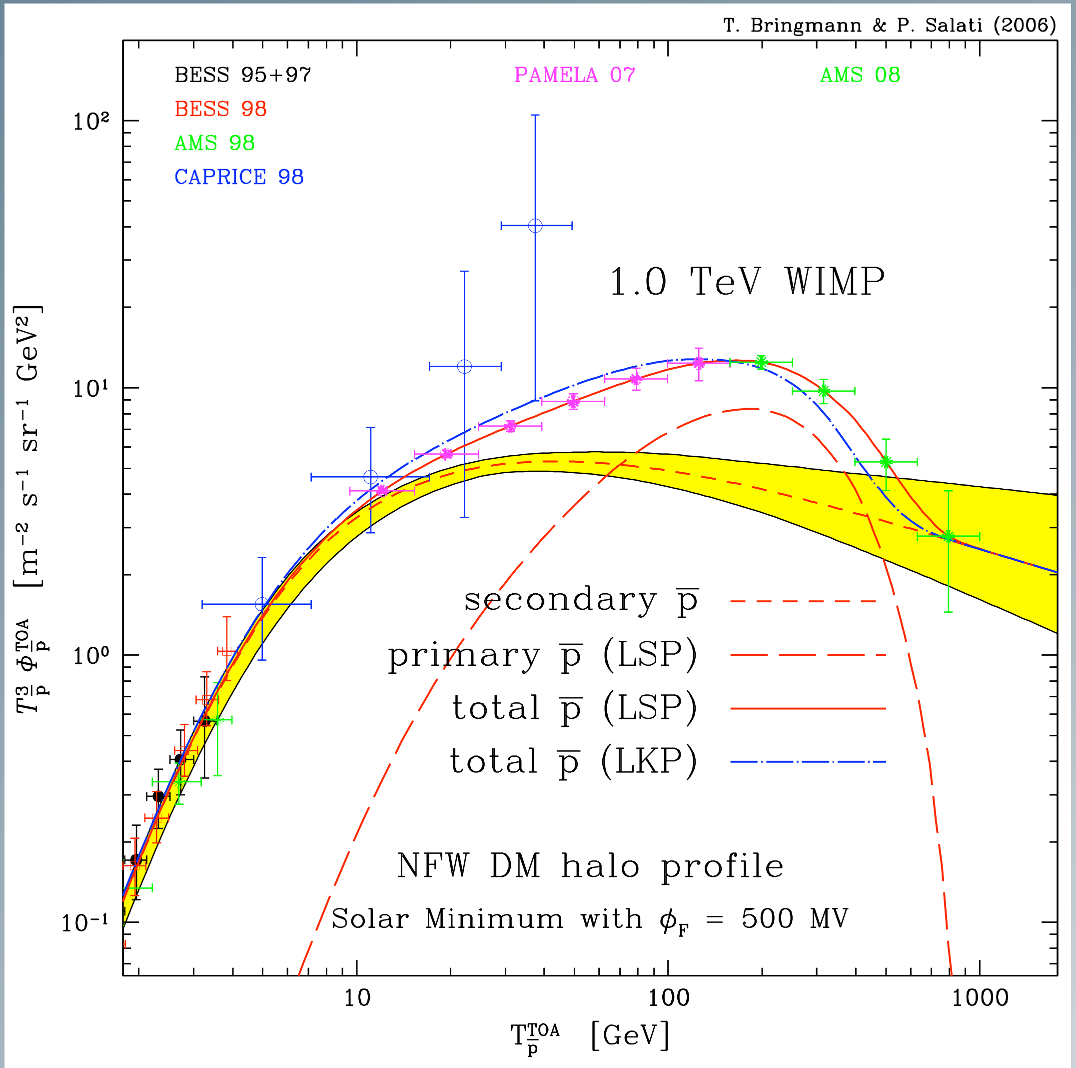

TB & Salati, PRD '09

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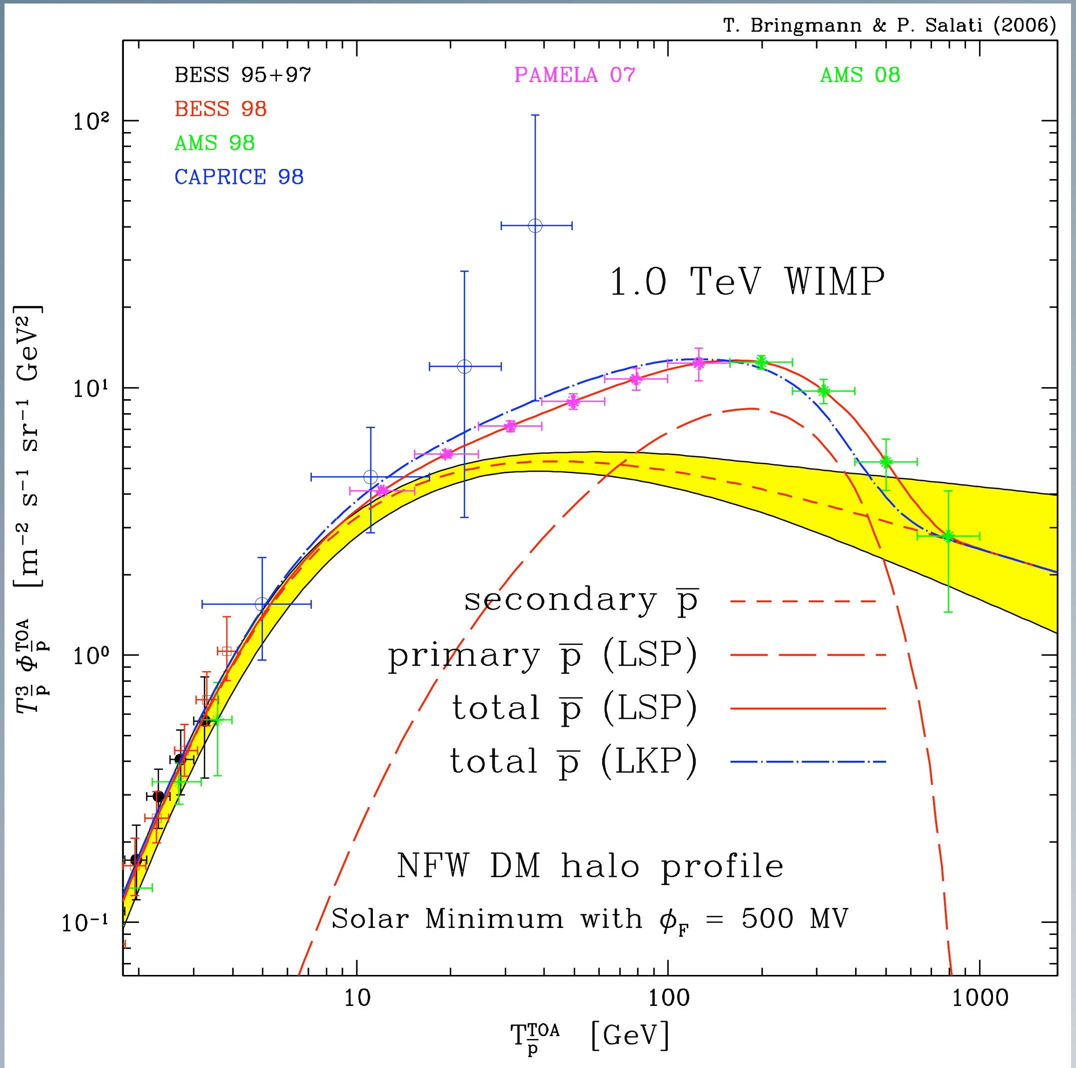


TB & Salati, PRD '09

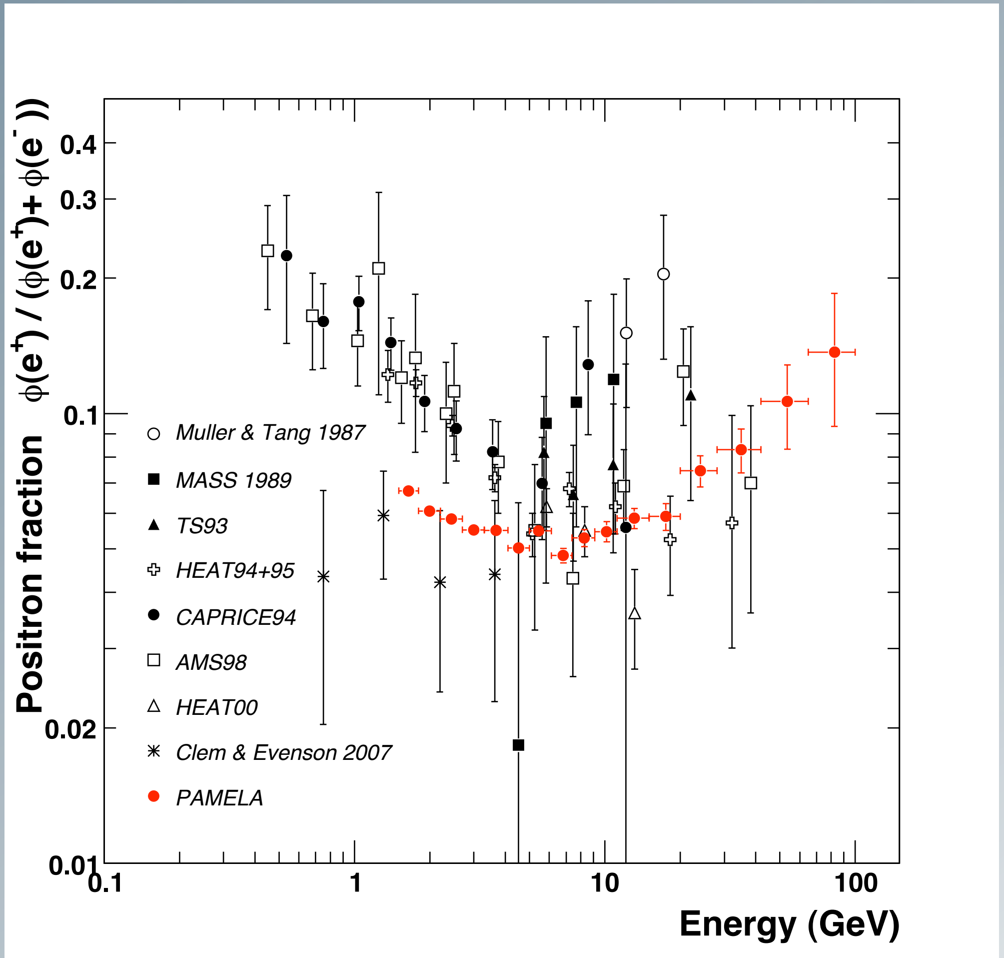
⊖ Cannot be used to discriminate between DM candidates…

⊕ …but are quite efficient in settings constraints!

- light SUSY DM
  Bottino *et al.*, PRD '98+05
- non-standard DM profile proposed by deBoer
  Bergström *et al.*, JCAP '06
- DM explanations for the PAMELA $e^+/e^-$ excess
  Donato *et al.*, PRL '09
- "Evidence" for DM seen in Fermi data towards the GC
  TB, 0911.1124
- …

# Positrons

Excess in cosmic ray positron data has triggered great excitement:



Adriani *et al.*, Nature '09

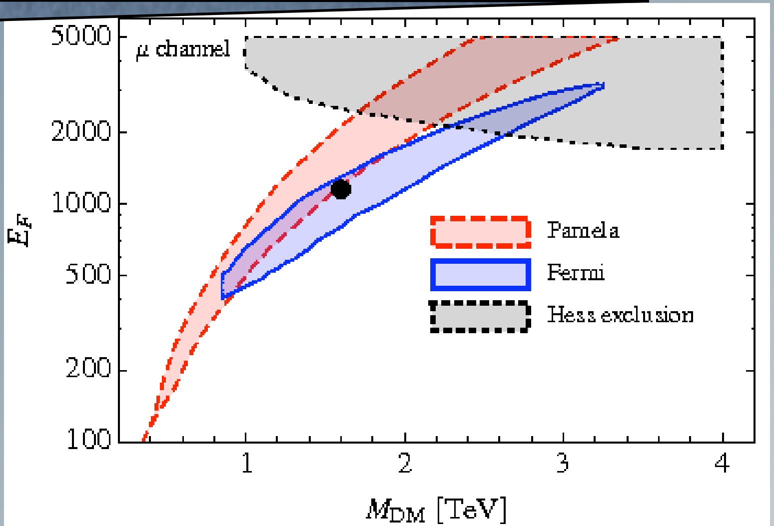
(> 500 citations since 10/08!)

⇨ Are we seeing a DM signal ???

# DM explanations

- Model-independent analysis:
  - strong constraints on hadronic modes from $\bar{p}$ data
  - $\chi\chi \rightarrow e^+e^-$ or $\mu^+\mu^-$ favoured
  - large boost factors generic – $\mathcal{O}(10^3)$

➩ highly non-conventional DM!



Bergström, Edsjö & Zaharijas, PRL '09

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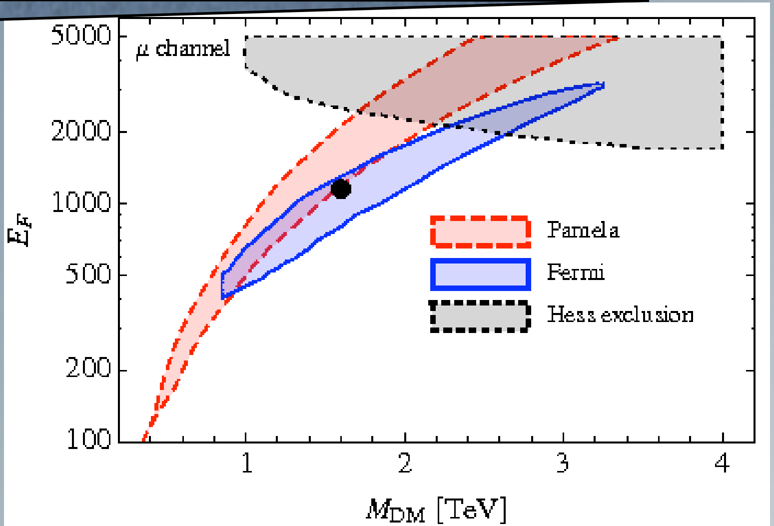

Bergström, Edsjö & Zaharijas, PRL '09

- Propagation uncertainties *not* the main problem:
  - secondaries ~2-4, primaries ~5 (cf. $\bar{p}\ldots$) Delahaye *et al.*, PRD '08, A&A '09
  - for $e^\pm$, energy loss is dominant ➡ must be locally produced (~ kpc)
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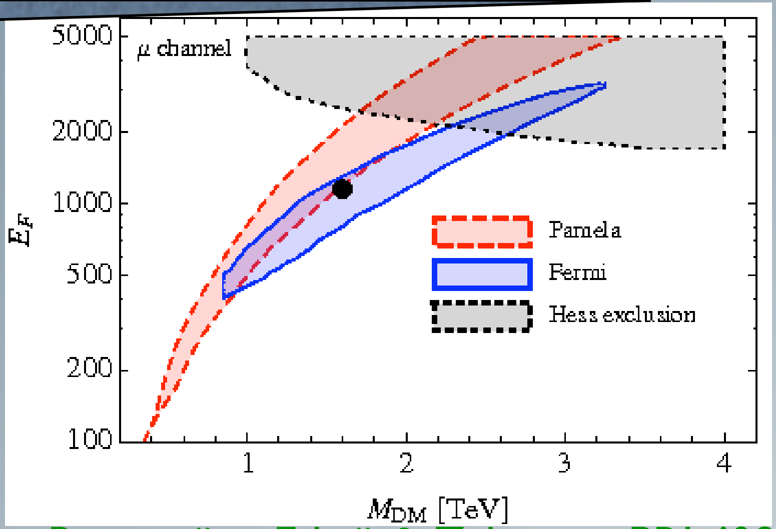

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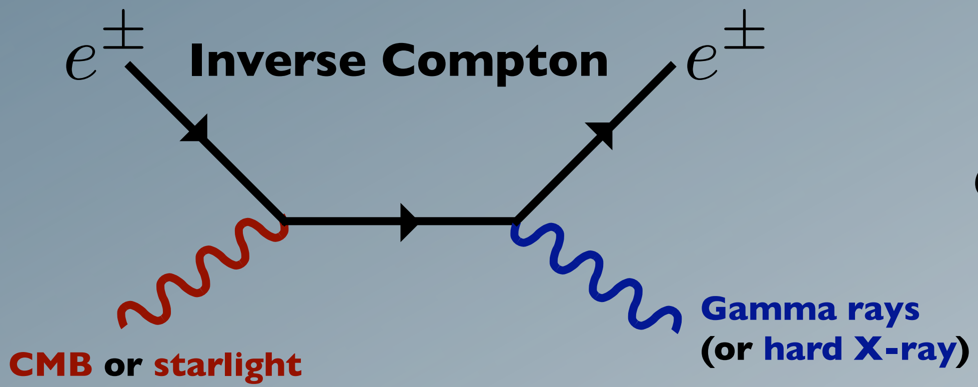
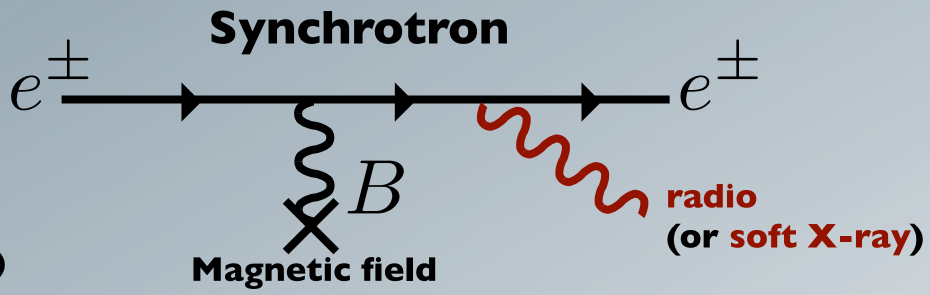
- ***but***: many good astrophysical candidates for primary sources in the cosmic neighbourhood:
  - pulsars Grasso *et al.*, ApP ’09 Yüksel *et al.*, PRL ’09 Profumo, 0812.4457
  - old SNRs Blasi, PRL ’09 Blasi & Serpico, PRL ’09
  - and further proposals...

# Multi-wavelength approaches

- In principle, high-energy positrons (and electrons!) from DM annihilations could induce further signals:





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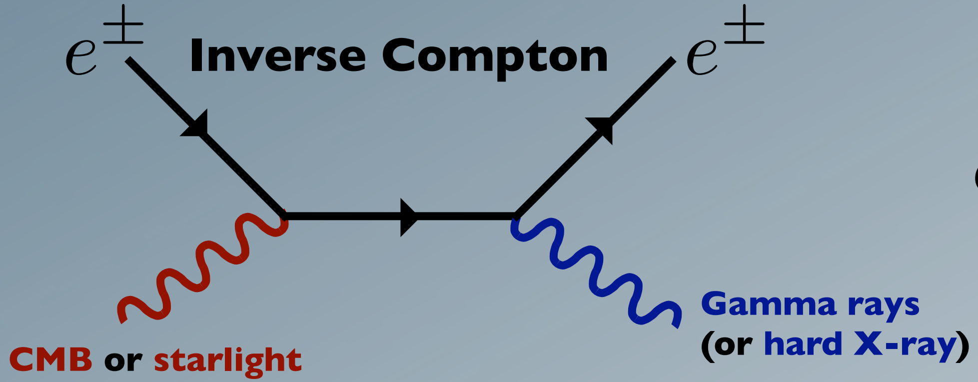
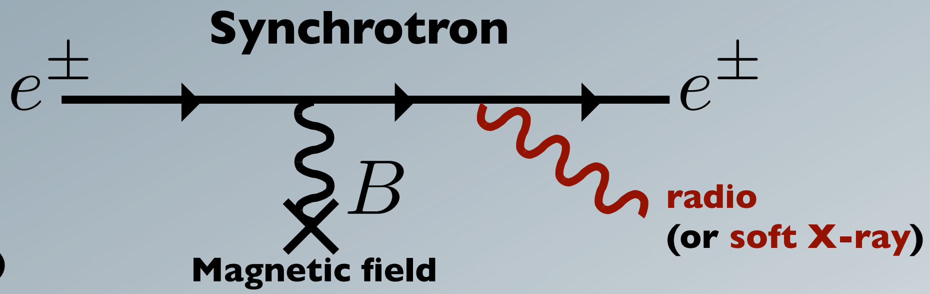
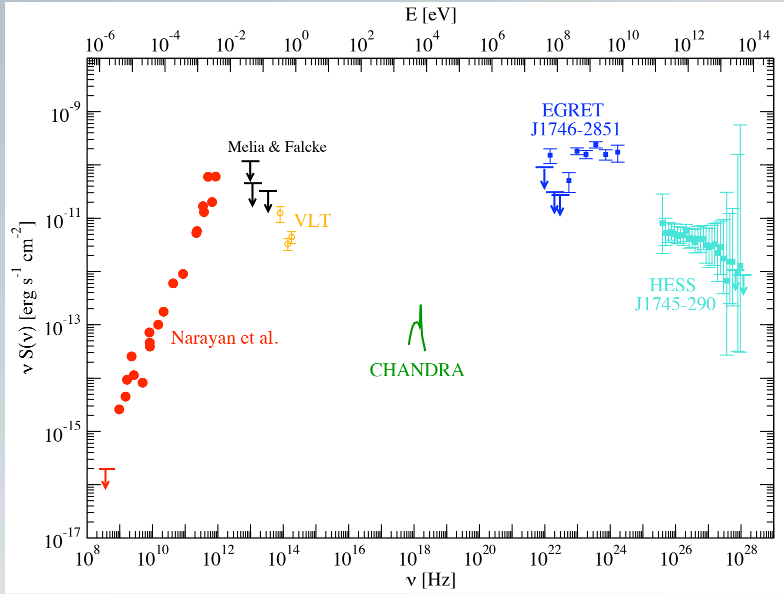




- E.g. the Galactic Center:

Regis & Ullio, PRD ’08



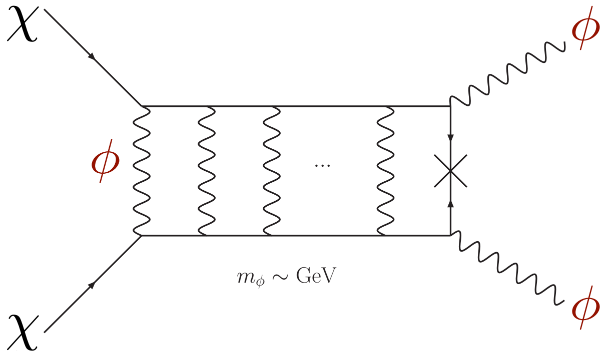
Gamma rays not necessarily most constraining!

➡ see also talk by M. Regis

# "A theory of dark matter"

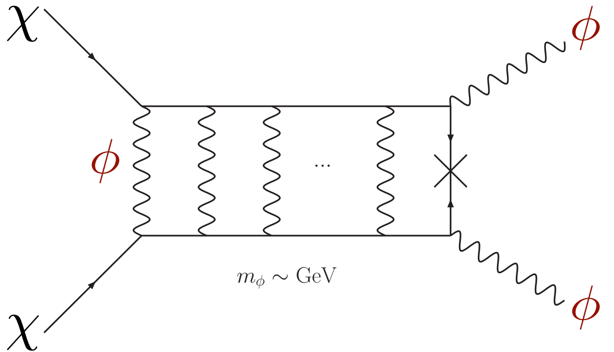
Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD '09

- ***idea***: introduce new force in dark sector, with $m_\phi \lesssim 1\,\mathrm{GeV}$
  - large annihilation rates (Sommerfeld enhancement)
  - later decay: $\phi \rightarrow e^+e^-$ or $\mu^+\mu^-$ (kinematics!)



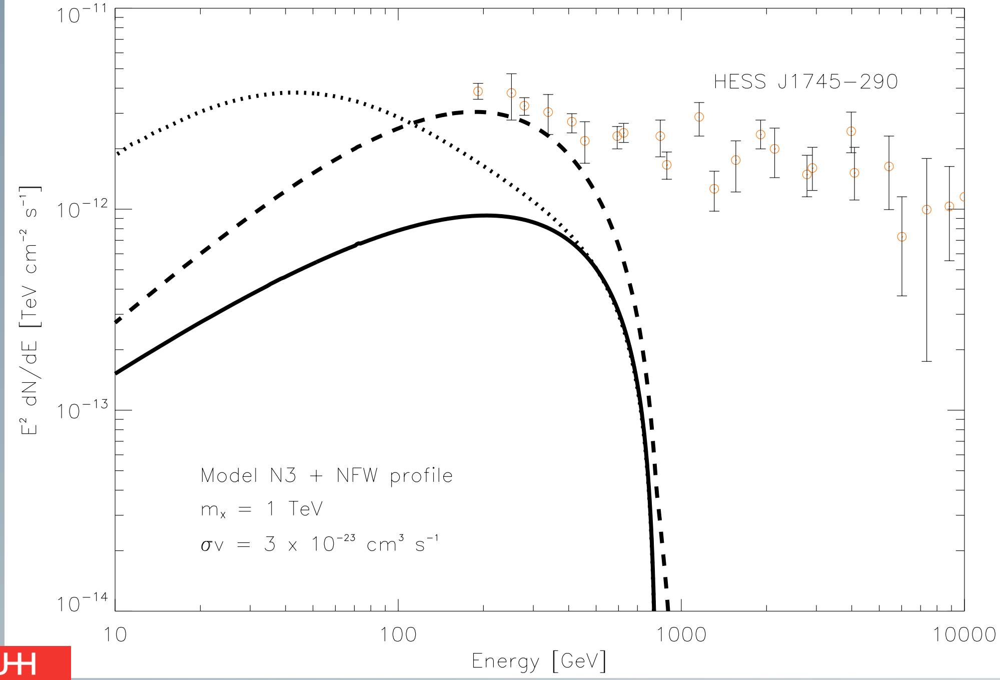
# “A theory of dark matter”

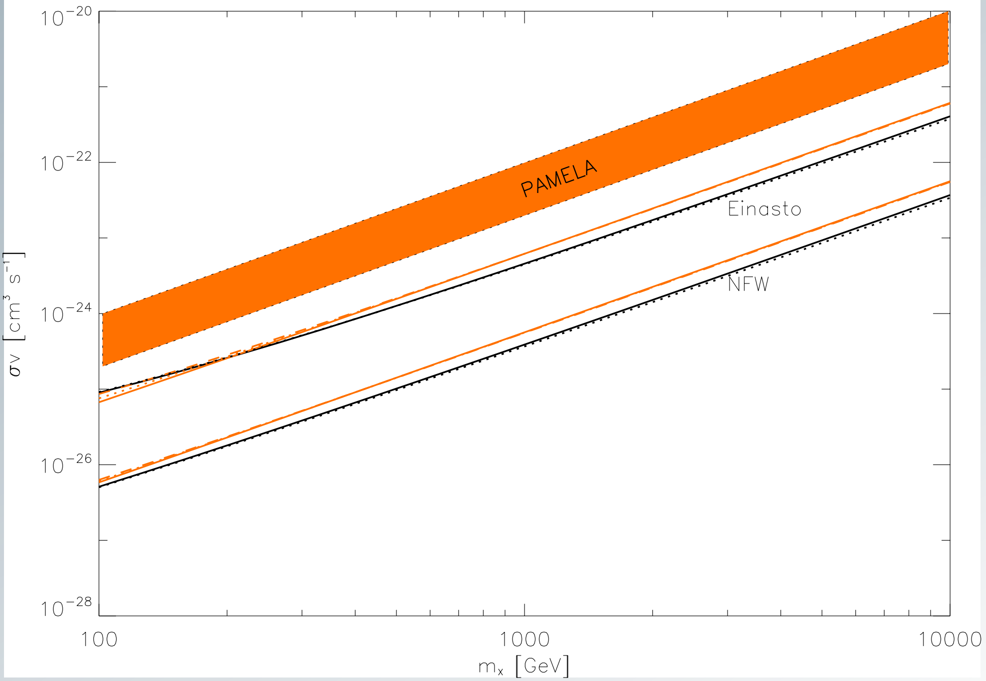
Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD ’09



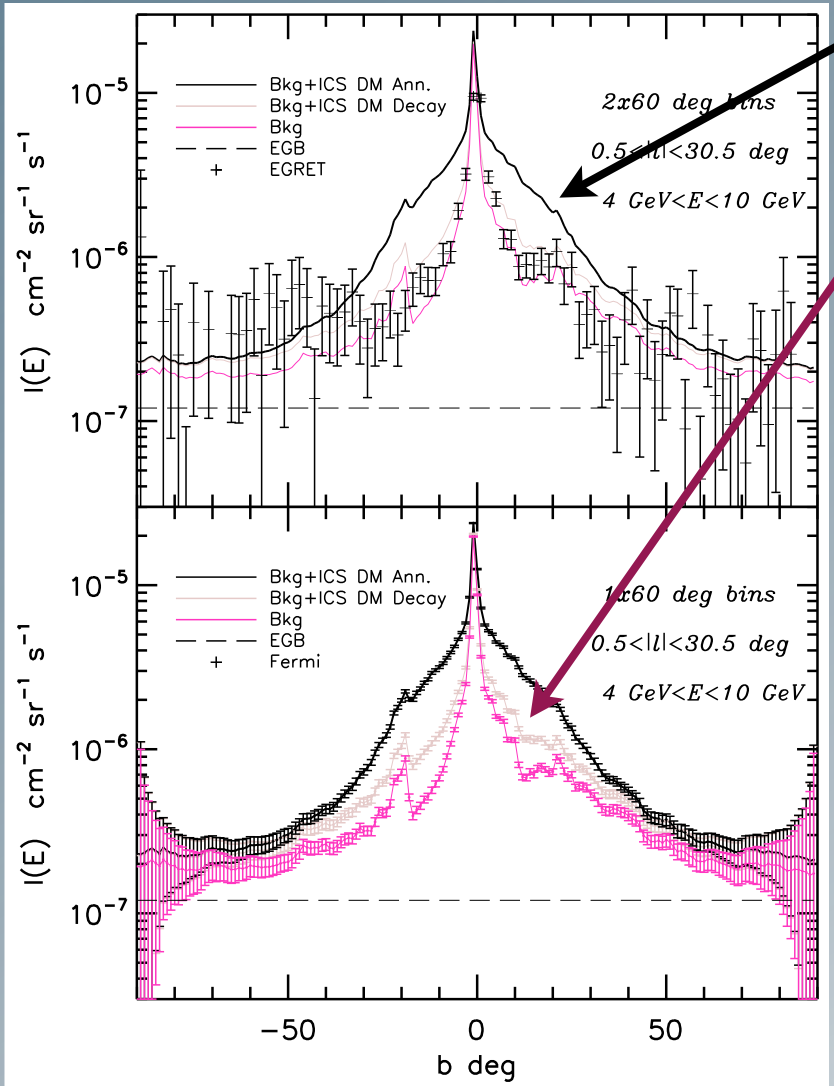
- ***idea***: introduce new force in dark sector, with $m_\phi \lesssim 1\,\mathrm{GeV}$
  - large annihilation rates (Sommerfeld enhancement)
  - later decay: $\phi \to e^+e^-$ or $\mu^+\mu^-$ (kinematics!)
- ***but***: strong constraints from $\gamma$ (IB) and radio (synchroton)!

Bertone, Bergström, TB, Edsjö & Taoso, PRD ’09





# Diffuse $\gamma$-ray constraints



Borriello, Cuoco & Miele, PRL '09

- Already EGRET data in some tension with annihilating WIMP explanation of PAMELA
- Prediction for Fermi:
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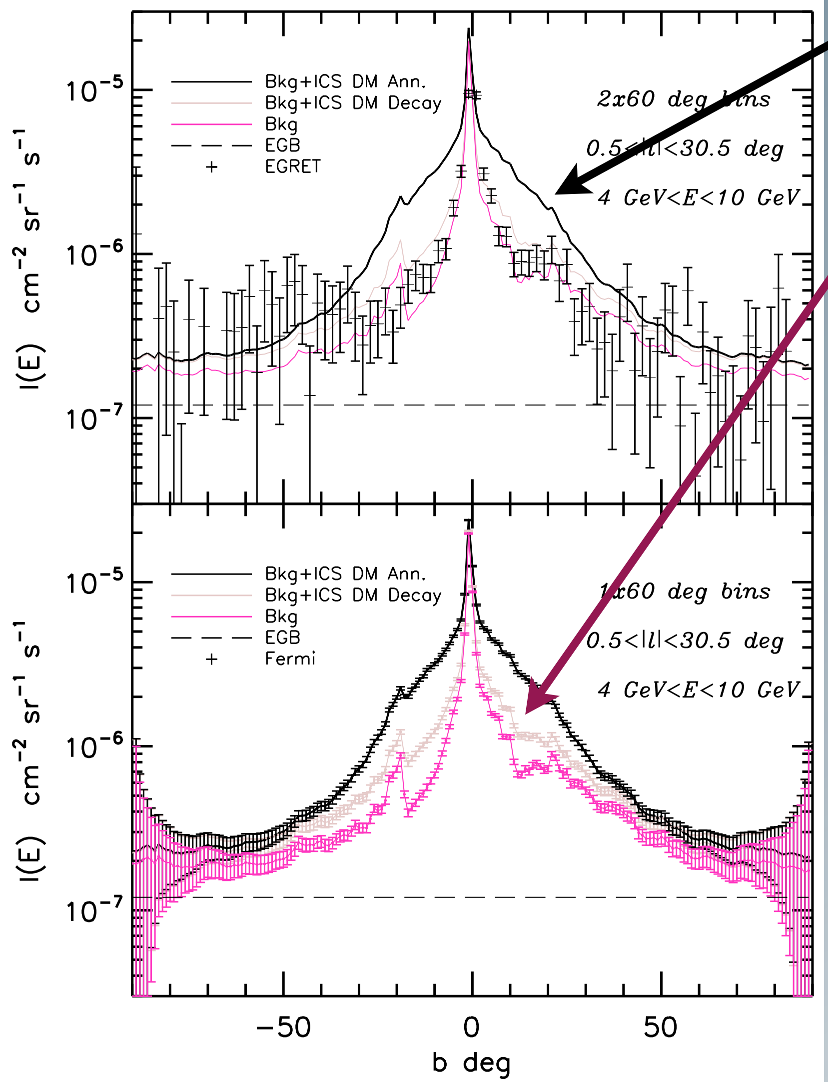
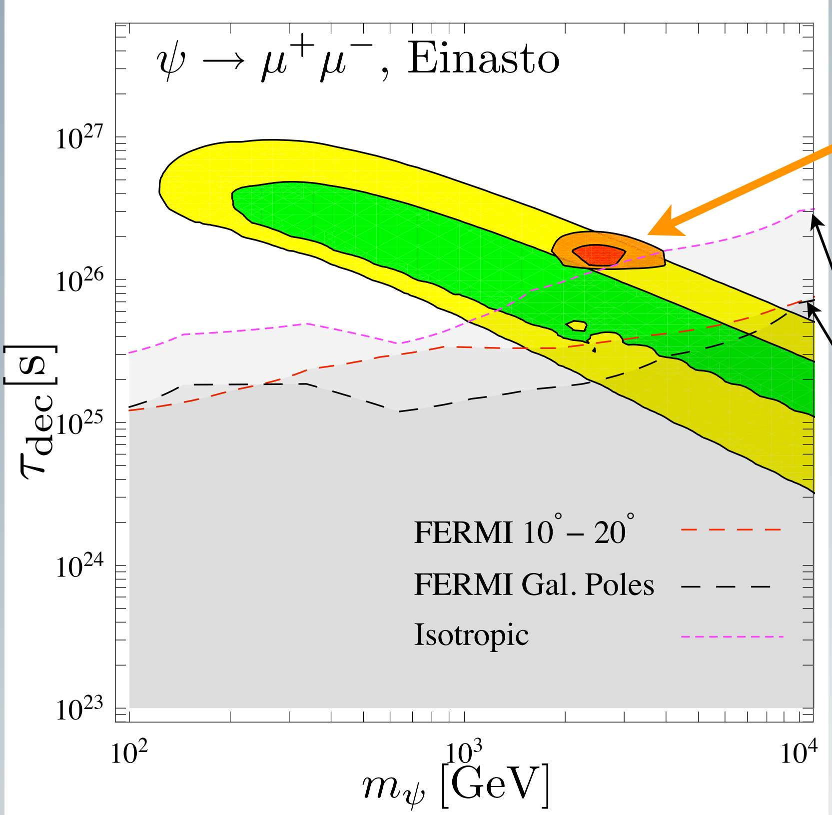


Borriello, Cuoco & Miele, PRL '09



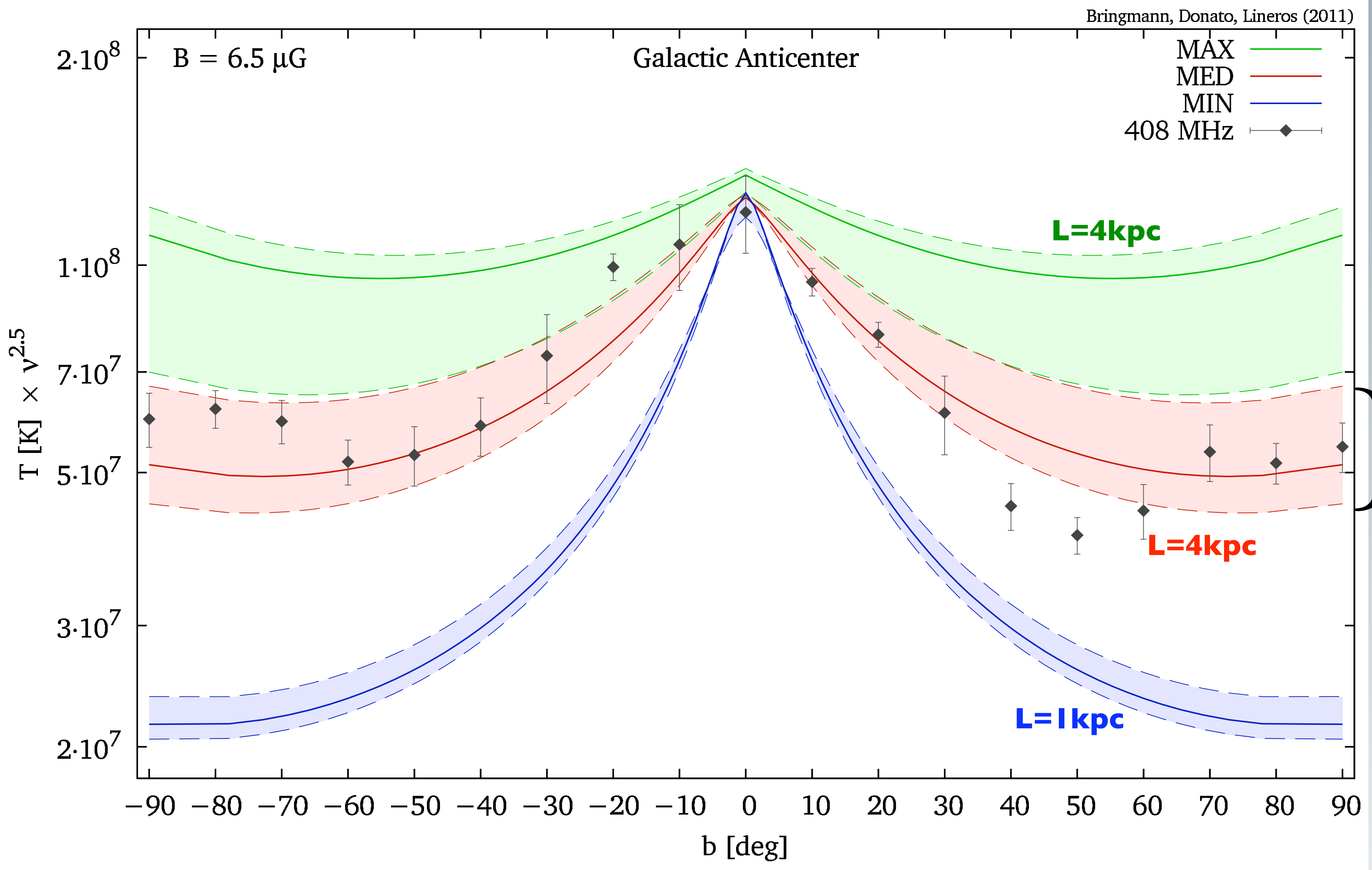
PAMELA
+Fermi
+Hess

After 1yr
Fermi

Cirelli, Panci & Serpico, 0912.0663

# Radio constraints on halo size

TB, Donato & Lineros, 1106.4821



range allowed by B/C

➡ Important for $\bar{p}$ constraints (in particular light DM – cf. direct searches!)

# The Dark Matter Array

- How far can we, eventually, get with indirect searches? Let's do a Gedankenexperiment...

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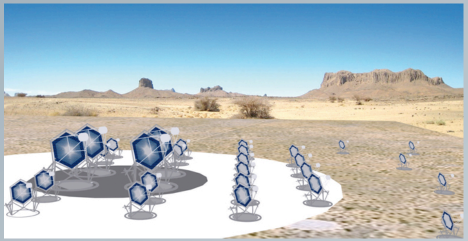

- Focus on a CTA-like design
  ➪ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$
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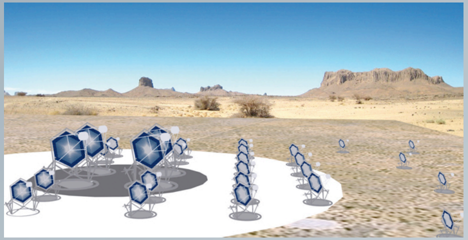

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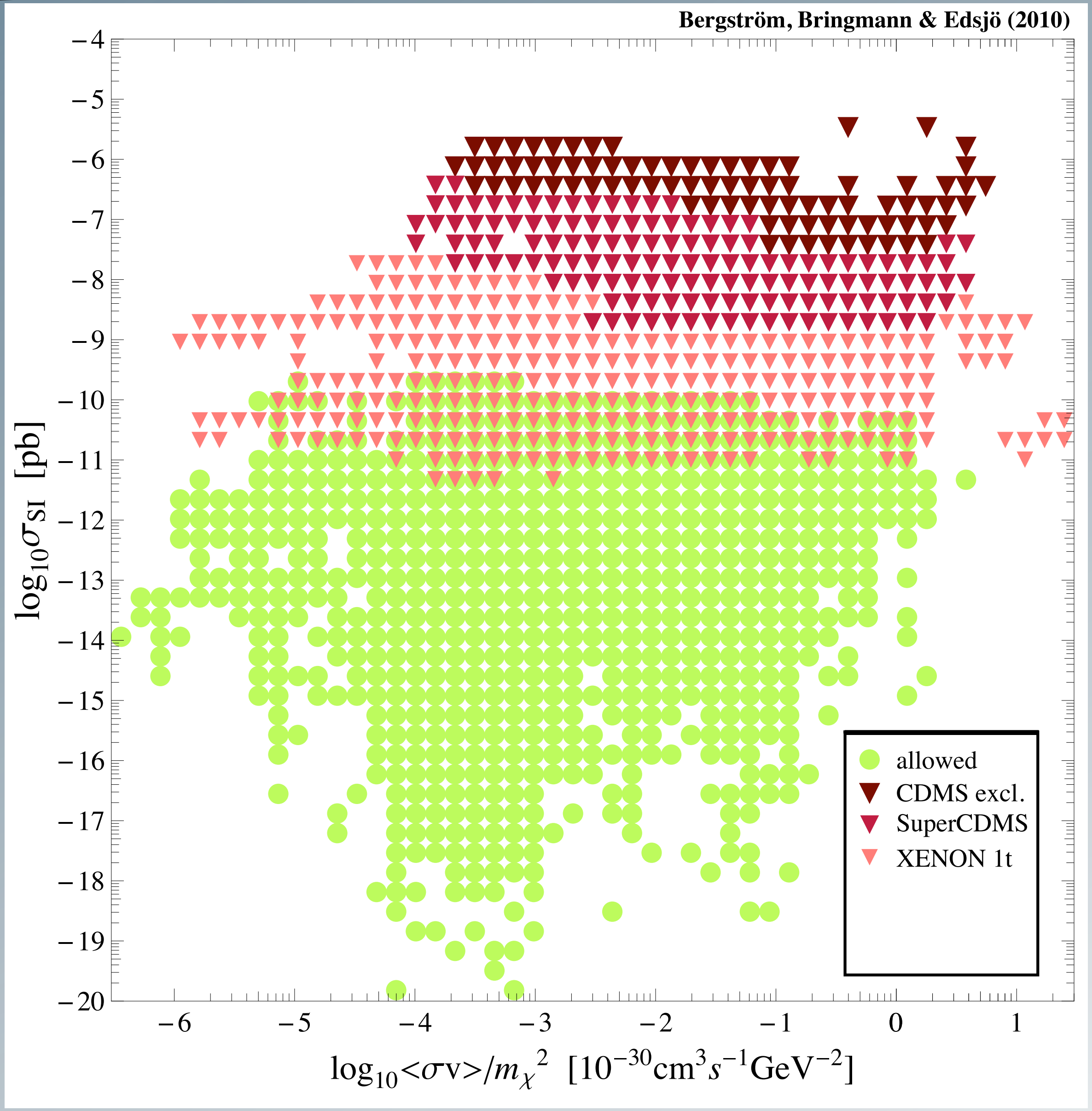
***Main idea. Details to be worked out...***

# Direct vs. indirect detection

MSSM+mSUGRA scan:
~$10^6$ models, $3\sigma$ WMAP,
all collider bounds OK



Bergström, TB & Edsjö, PRD '11

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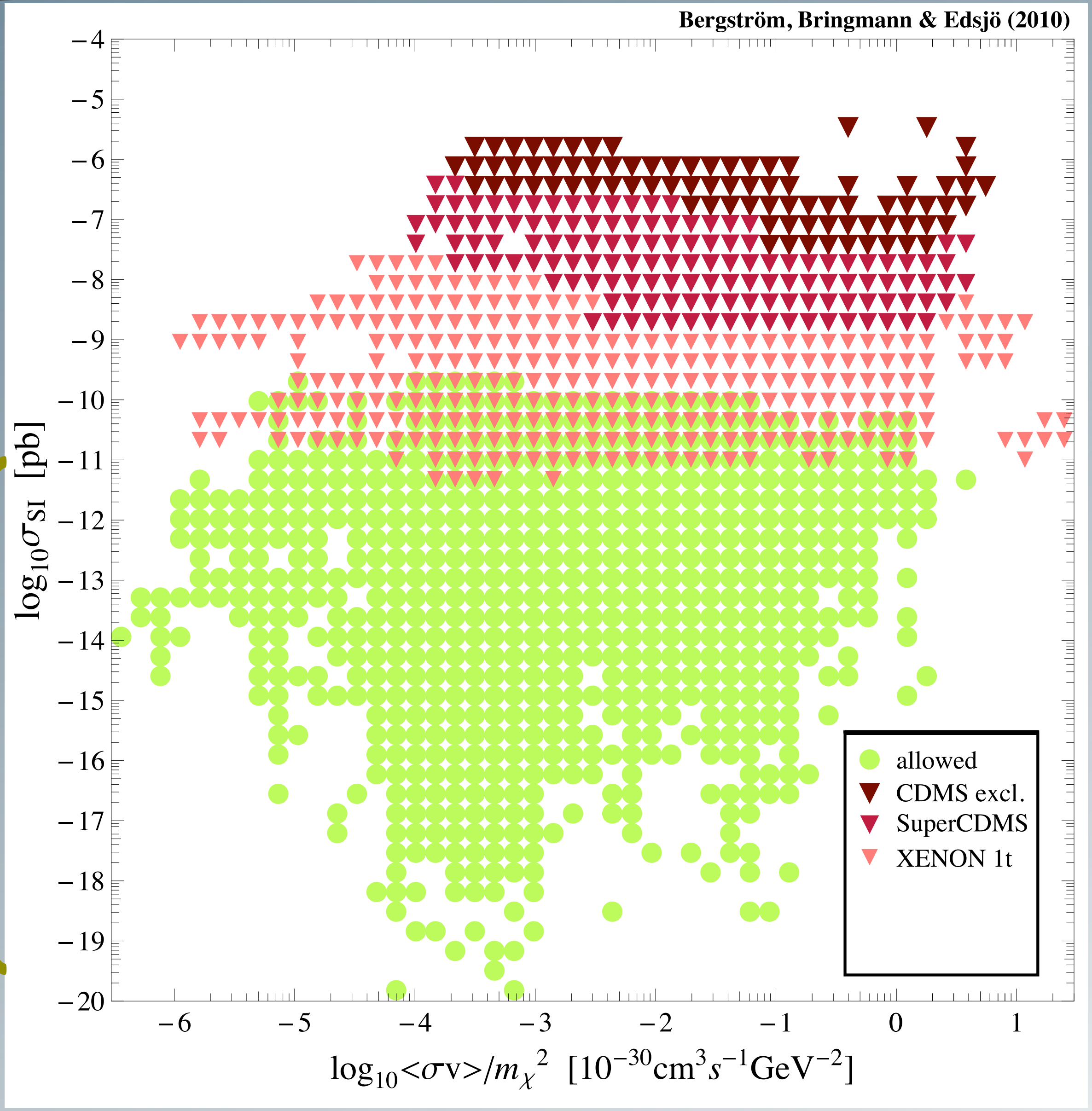

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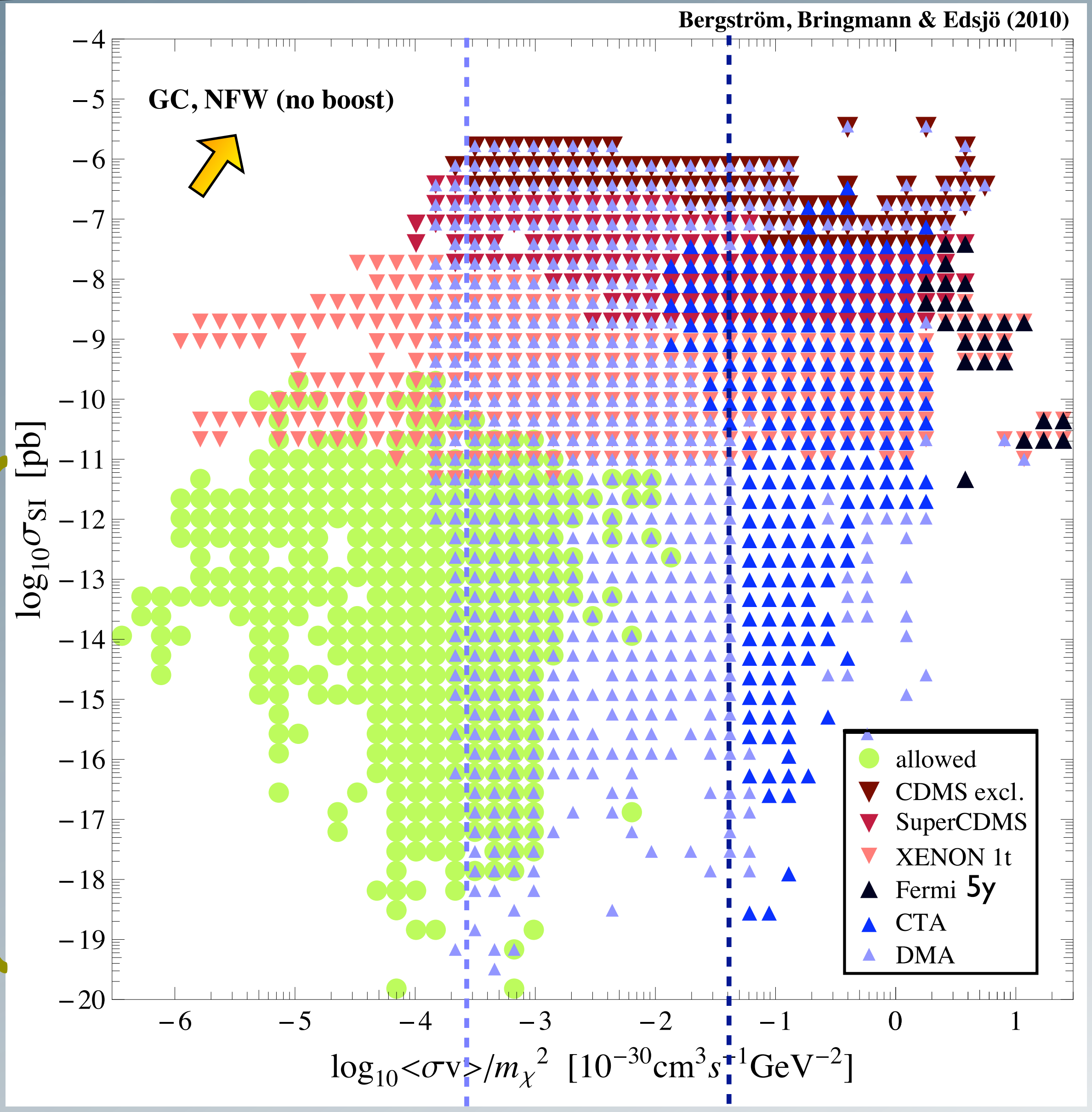

**CTA/DMA:**
assume Fermi background model, power-law extrapolation for
$E > 100\,\mathrm{GeV}$

Demand
$S > 5\sqrt{S+B}$
in “best” bin

Bergström, TB & Edsjö, PRD ’11

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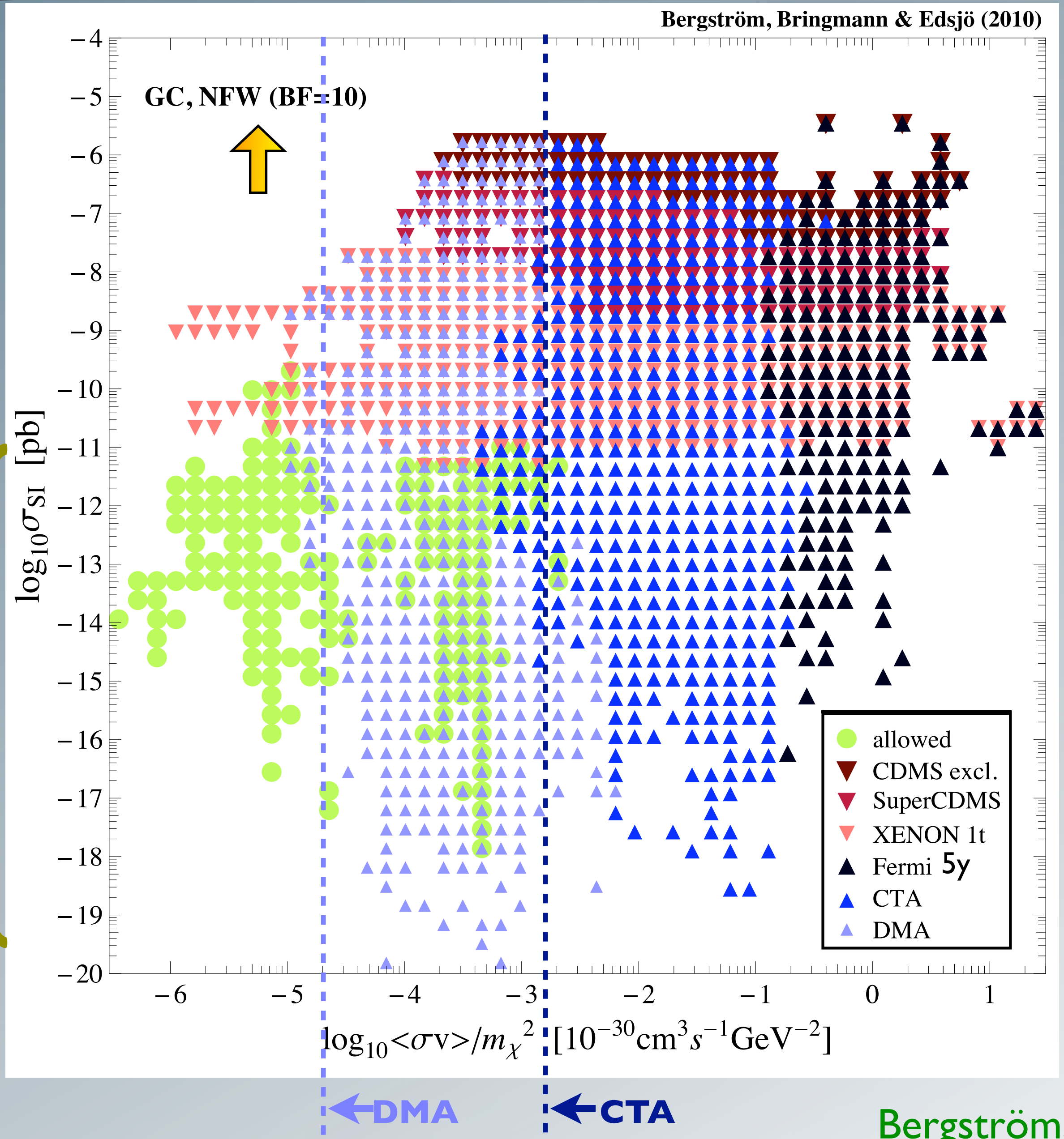

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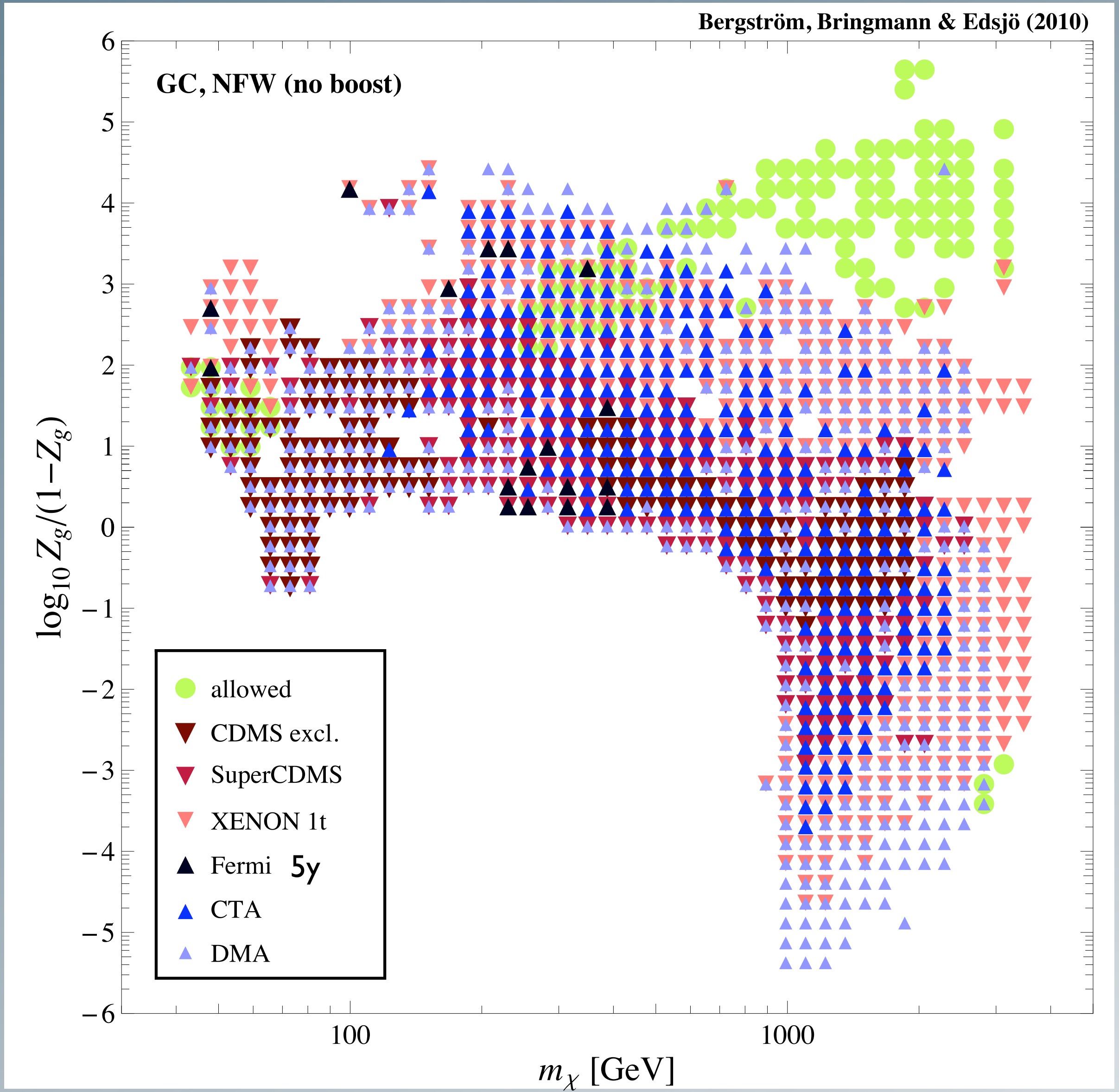

Bergström, TB & Edsjö, PRD ’11

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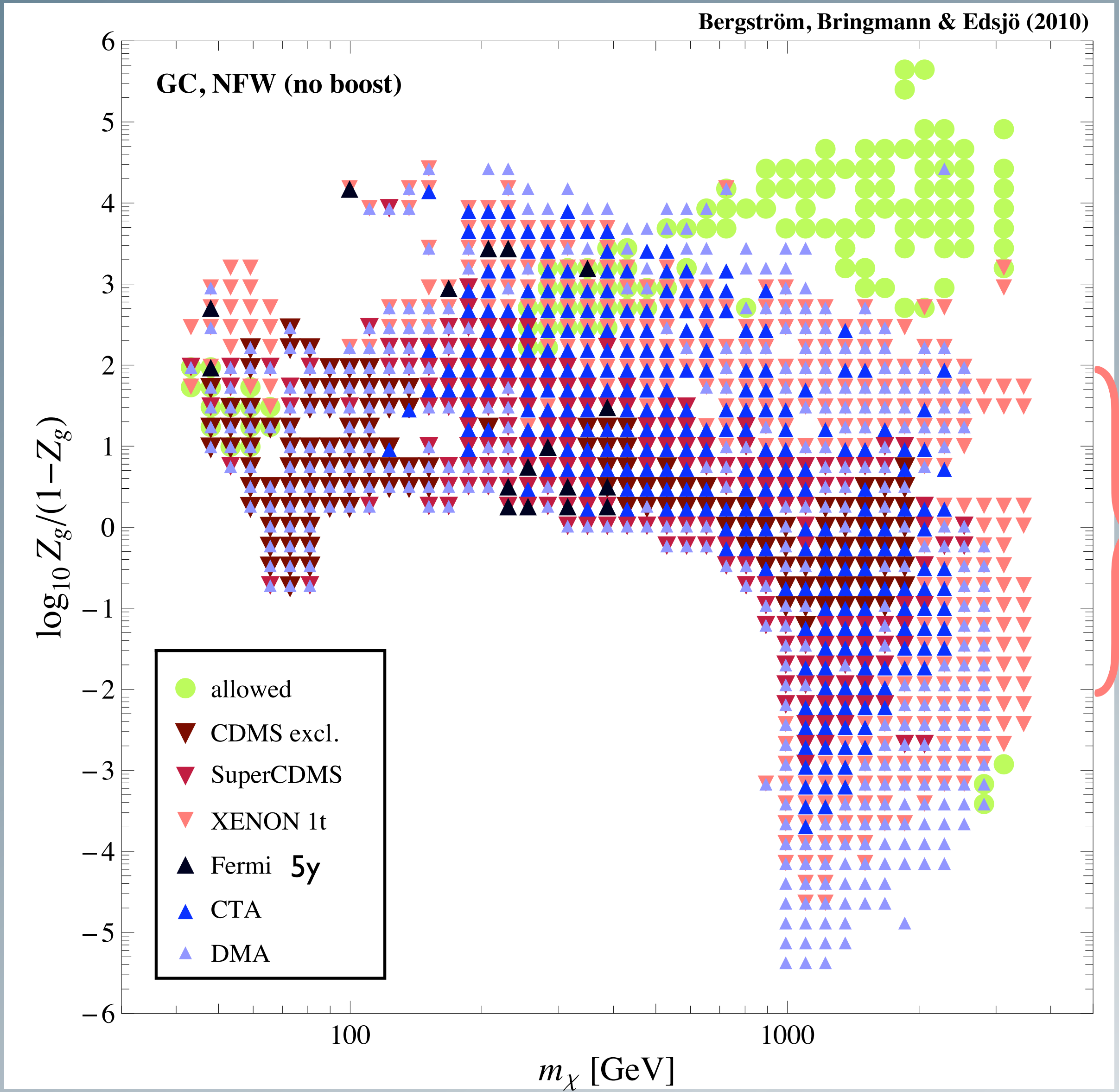

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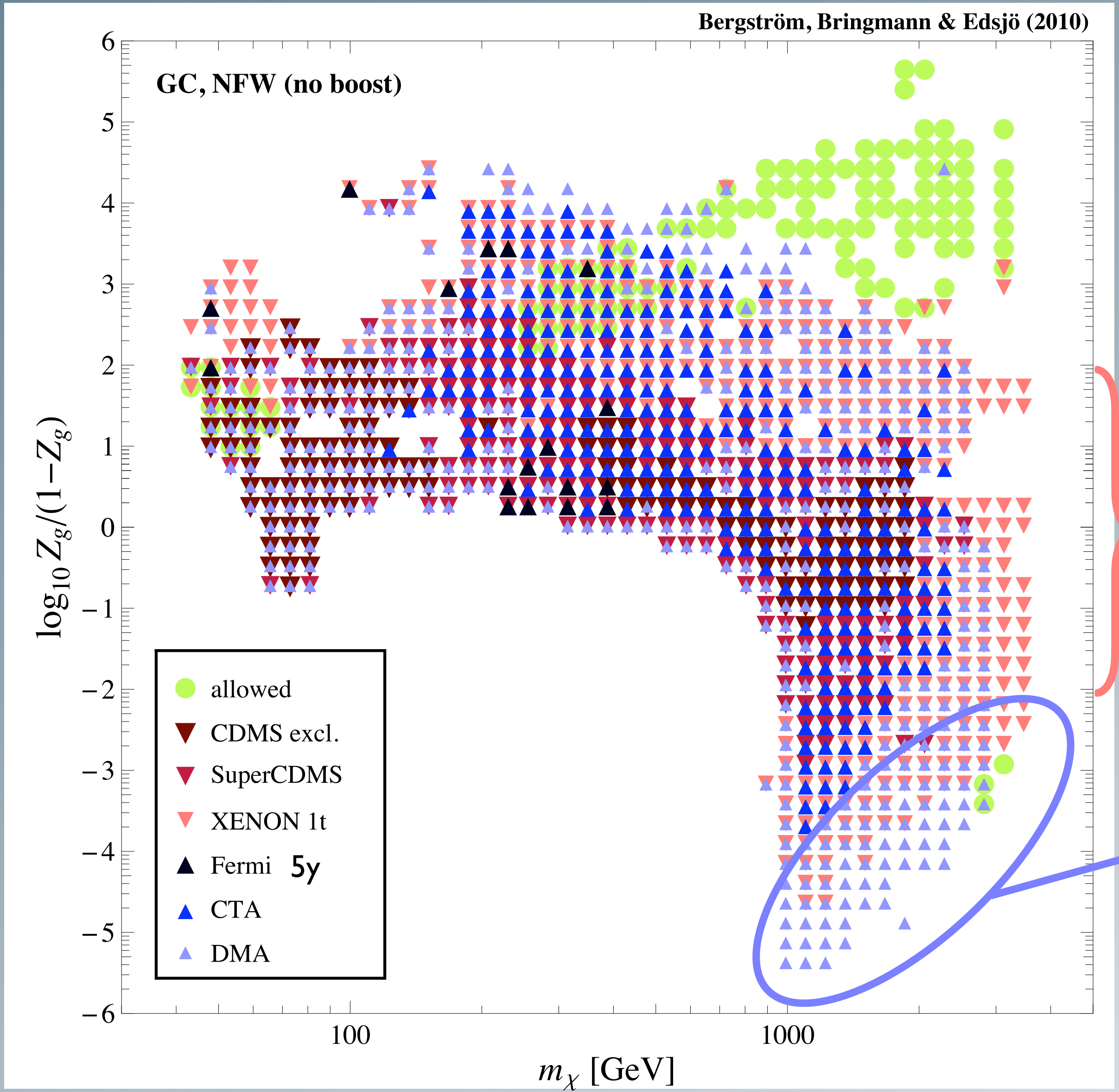

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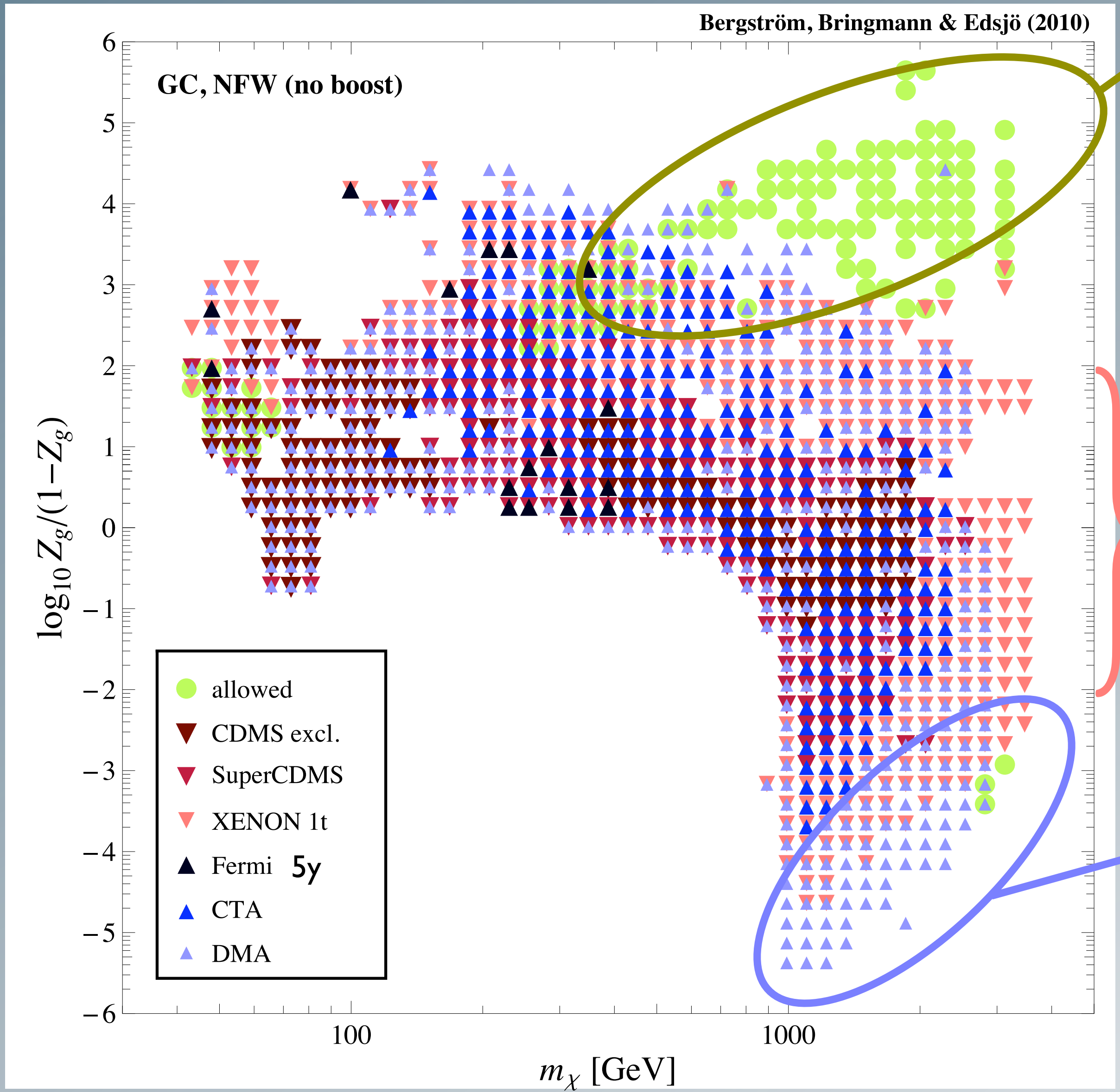

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NB! Sommerfeld effects not yet included...

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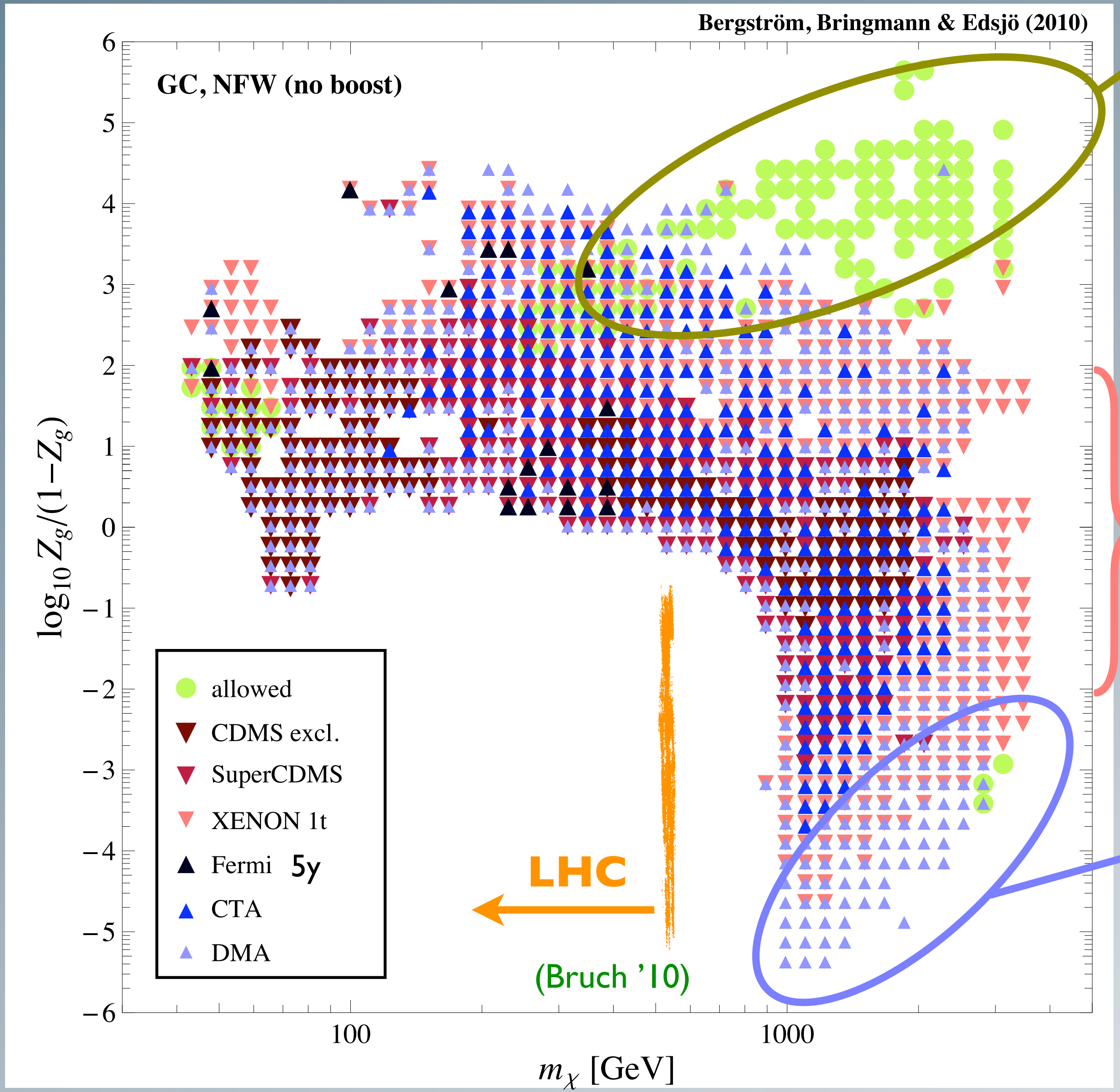

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*Thank you for your attention!*

# Backup slides

# The WIMP "miracle"

- The number density of Weakly Interacting Massive Particles in the early universe:

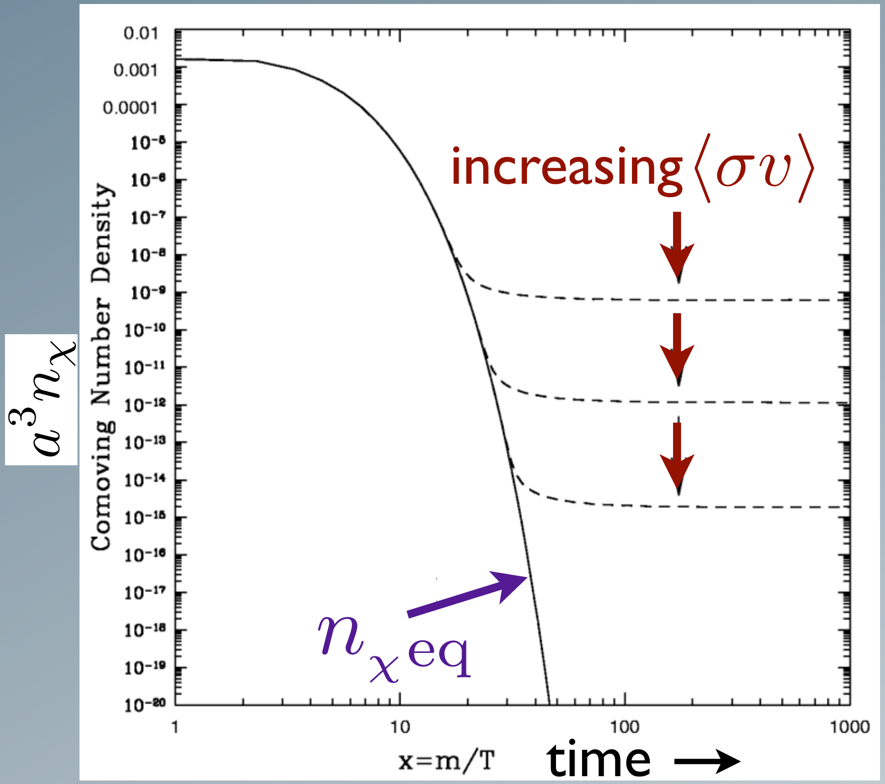

Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\mathrm{eq}}^2\right)}$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ **(thermal average)**

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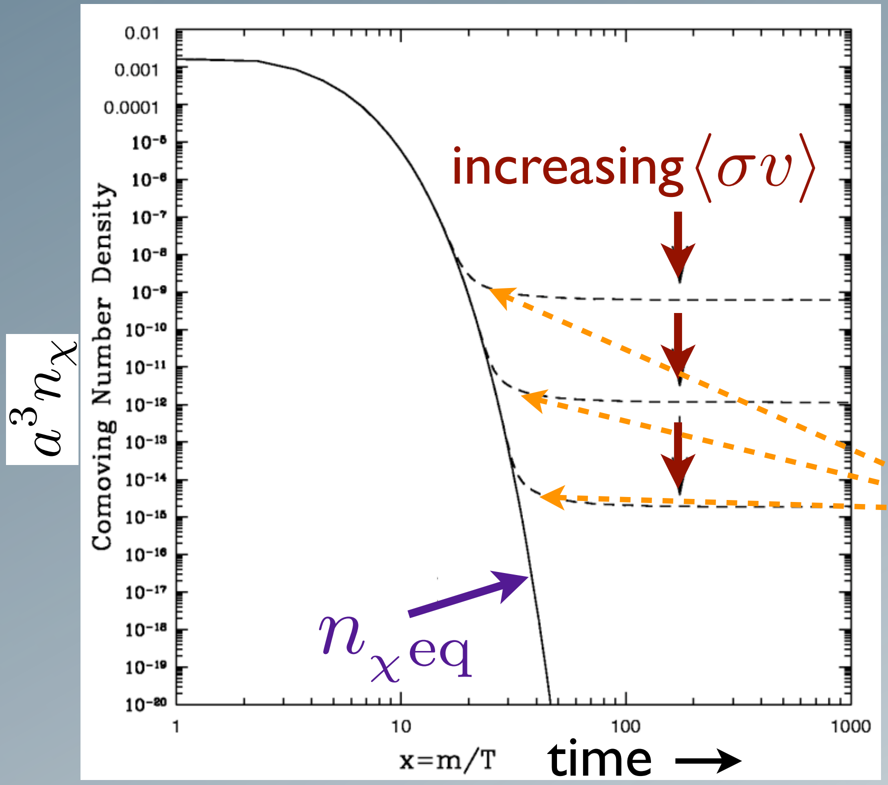

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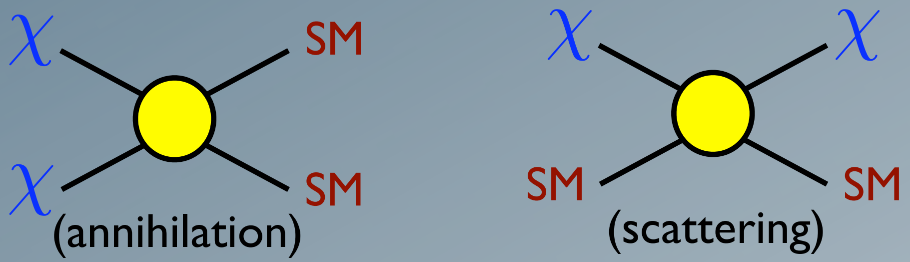
“Freeze-out” when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

for weak-scale interactions!

- Relic density (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

# Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



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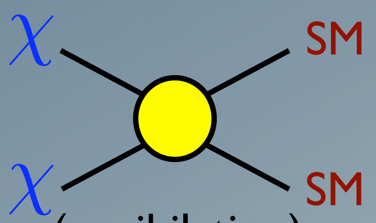
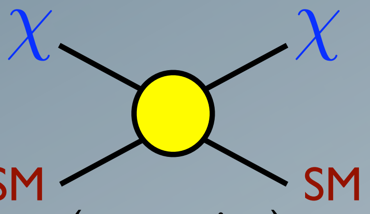


(annihilation)



(scattering)

⇩

$$\boxed{T_{\rm cd} \sim m_\chi/25}$$

chemical decoupling

⇩

$$\Omega_\chi$$

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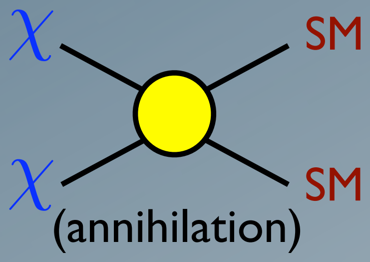

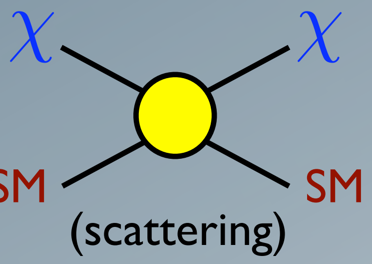

⇩

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chemical decoupling

⇩

$$\Omega_\chi$$

⇩

$\boxed{T_{\rm kd} \sim m_\chi/(10^2..10^5)}$

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⇩

$$M_{\rm cut}$$

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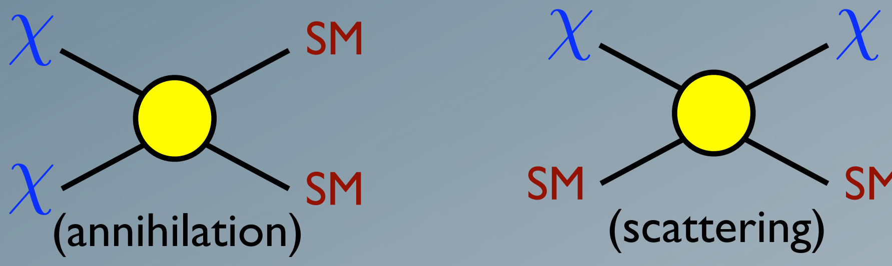

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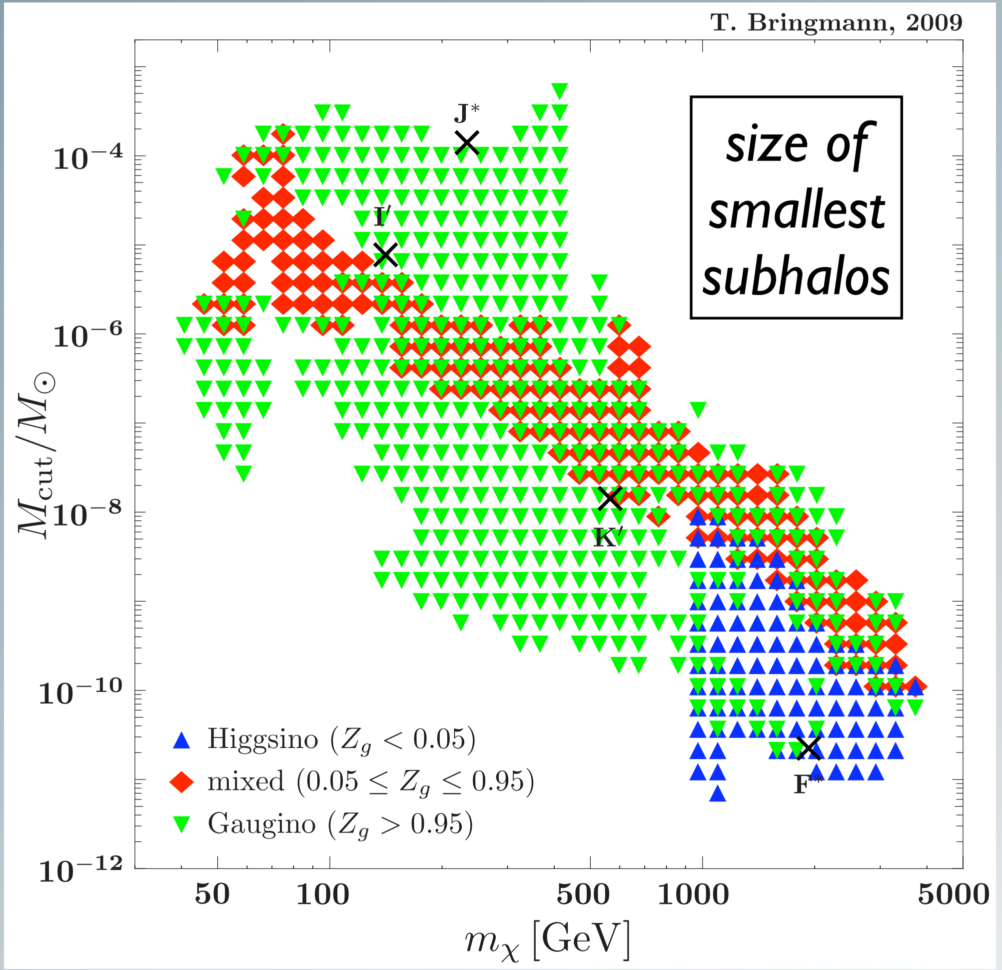
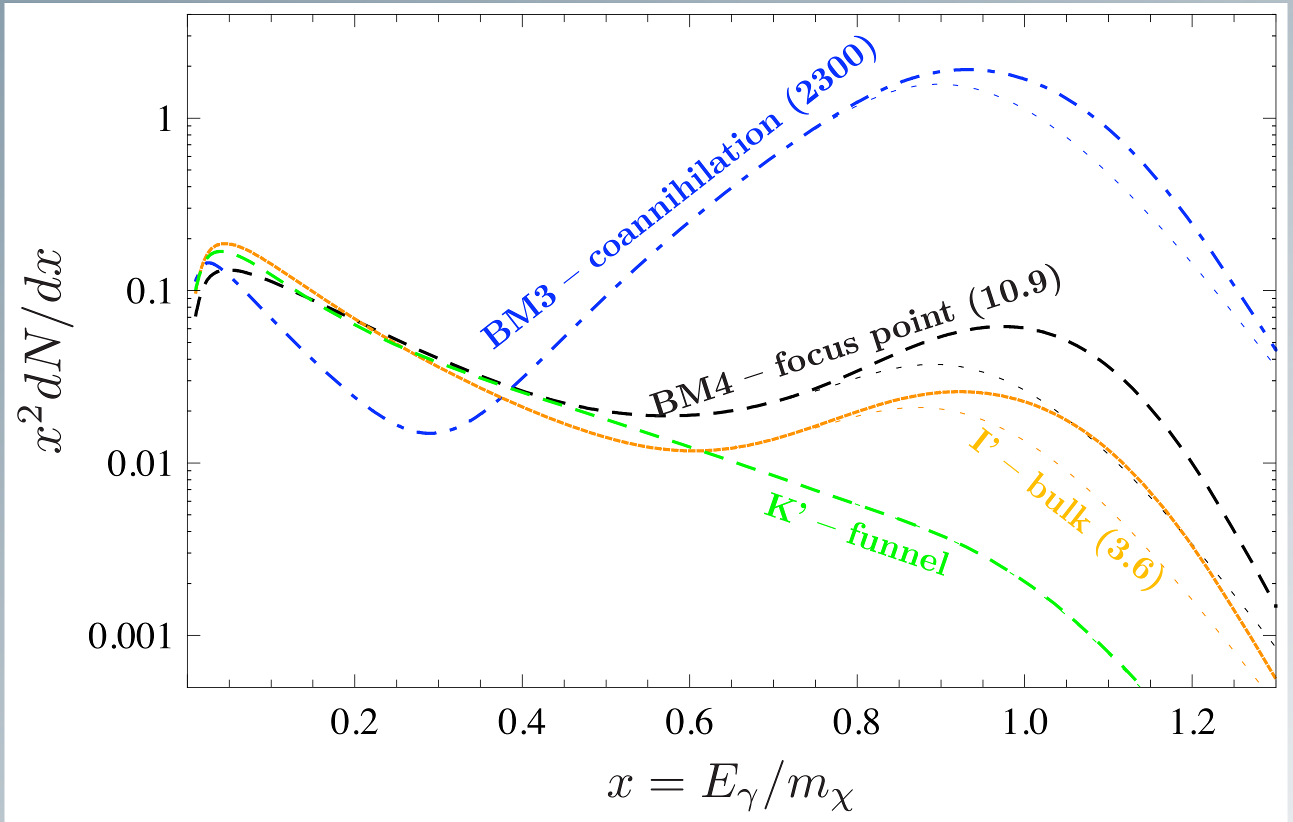


TB, NJP '09

- *no "typical" $M_{\rm cut} \sim 10^{-6} M_\odot$, but model-dependent*
- *a window into the particle-physics nature of dark matter!*

# Comparing DM spectra

- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: mSUGRA benchmarks (assume energy resolution of 10%)



TB, PoS '08

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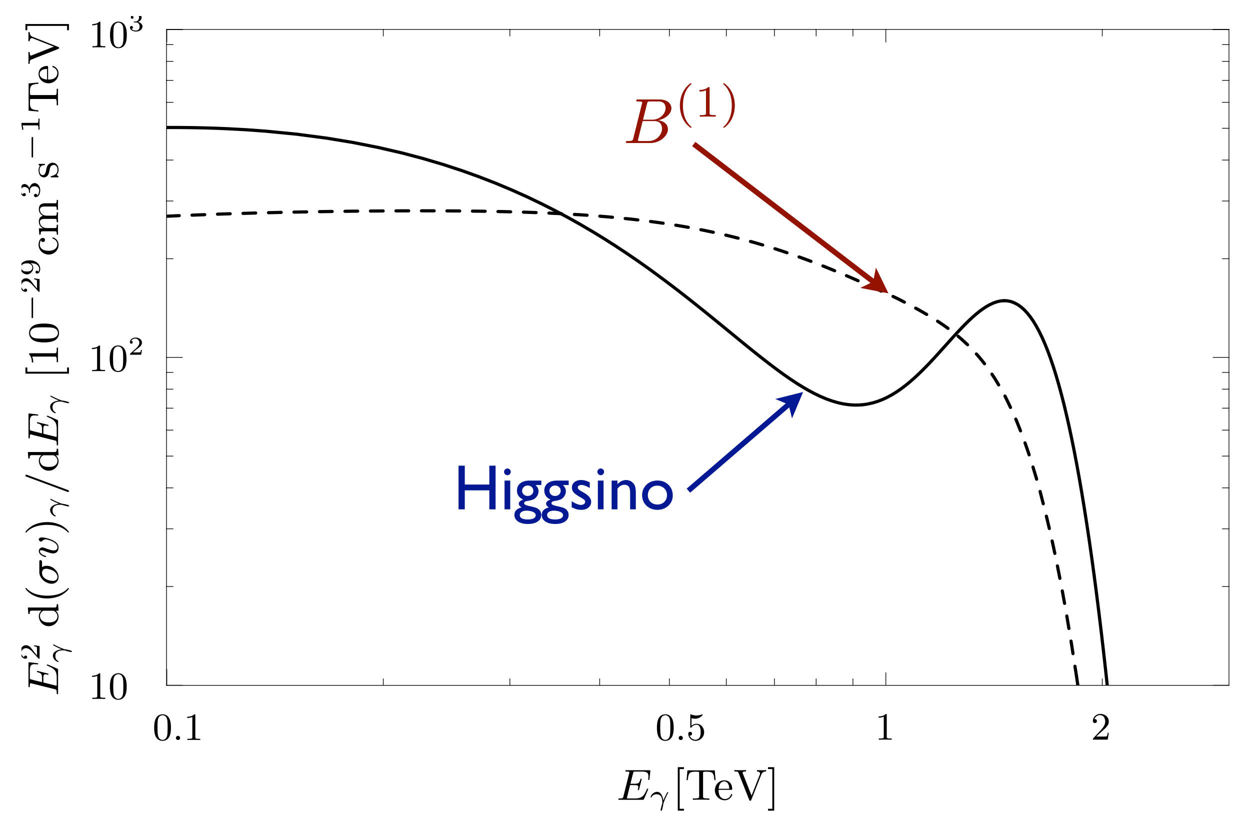
  - Example: Higgsino vs KK-DM (about same mass; assume $\Delta E = 15\%$)



Bergström *et al.*, ’06

# IB: total flux enhancement

- IB contributions important at high energies
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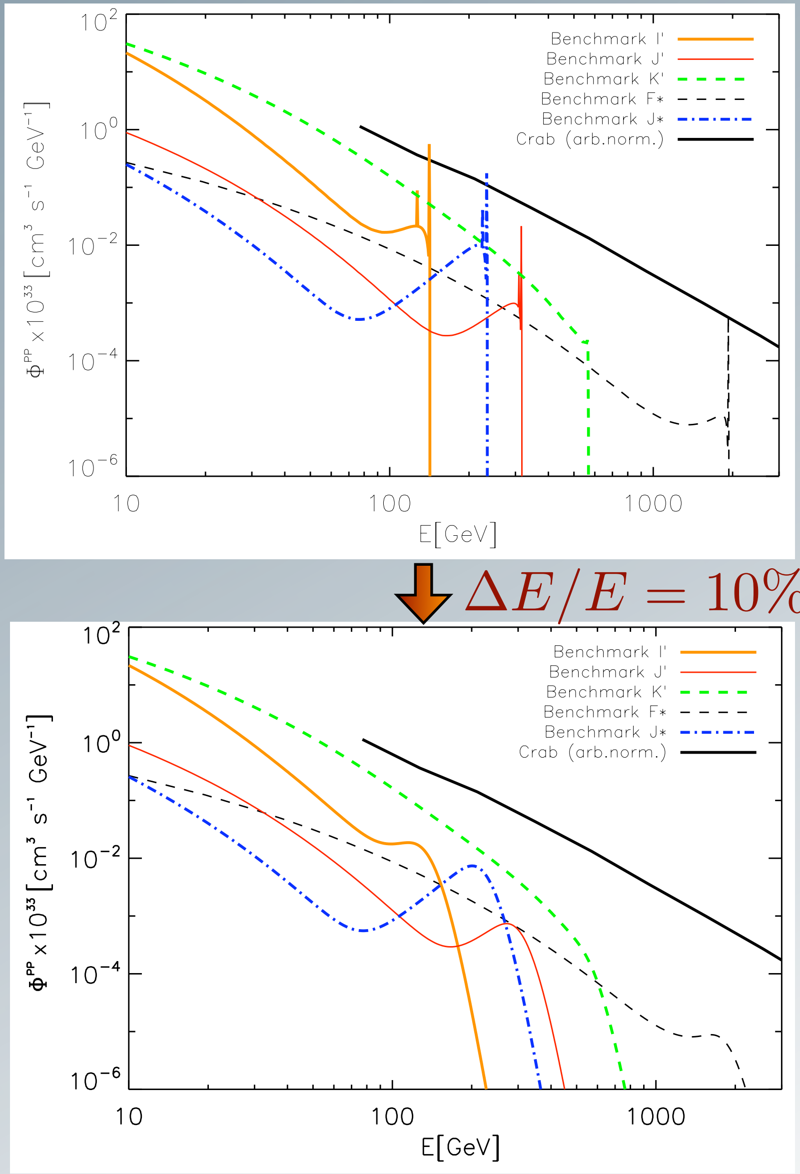
    TB, Doro & Fornasa, JCAP '09
    Cannoni et al., PRD '10
  - CTA could see a DM signal from Willman 1 for a large class of models (less optimistic prospects for Draco)



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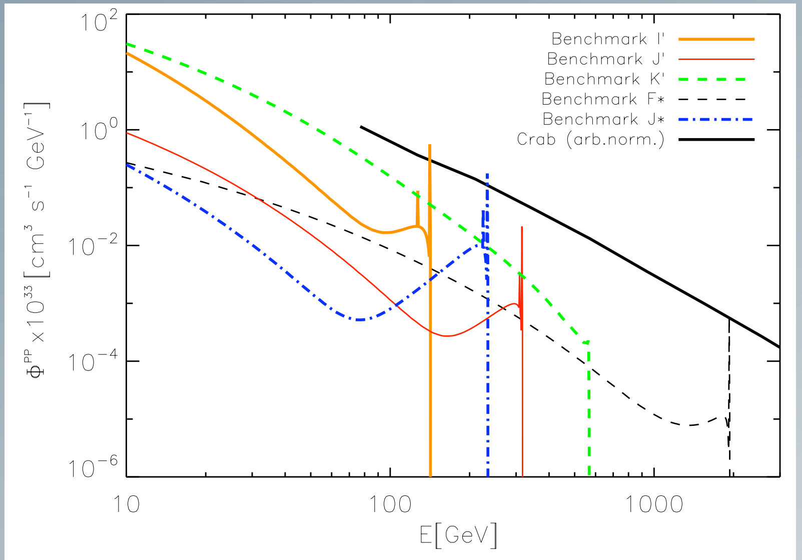
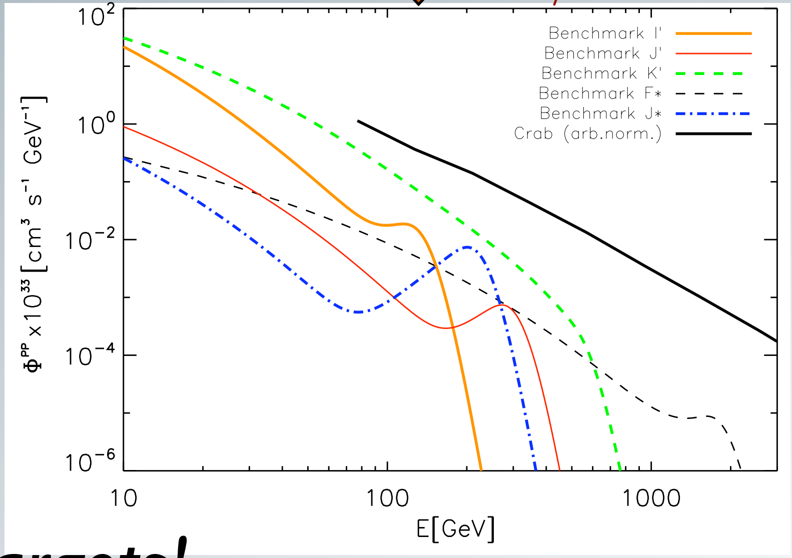


$\Delta E/E = 10\%$



TB, Doro & Fornasa, JCAP '09

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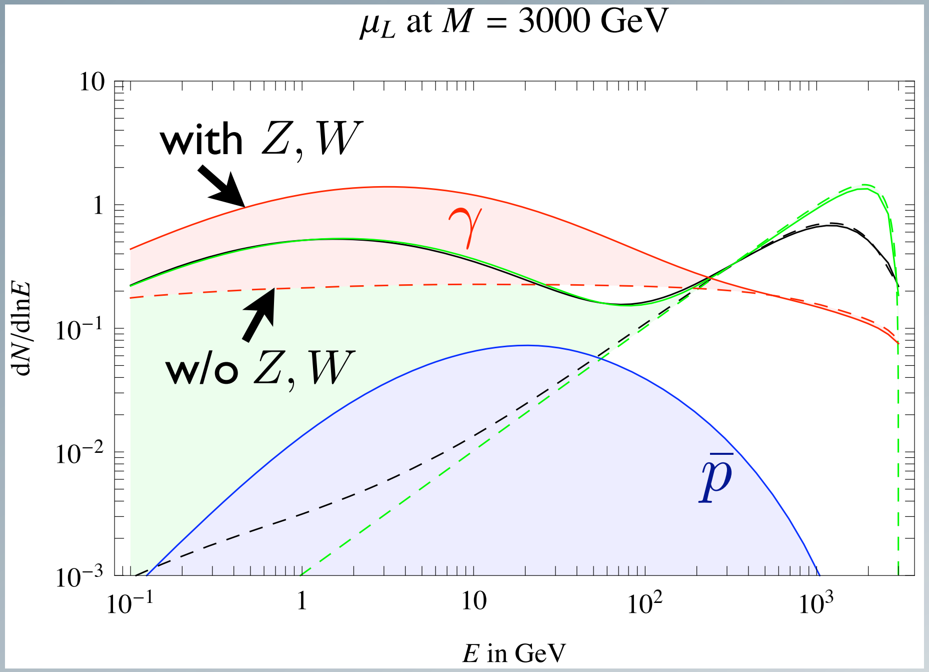
➡ *important to include also for other targets!*

# Electroweak corrections

- FSR of $Z$ and $W^{\pm}$:
  - can open new channels like $\bar{p}$ ($\rightsquigarrow$ leptophilic models!)
  - sizable changes in spectrum for large $m_\chi$ (mostly at small $E_\gamma$)

Bell, Dent, Jacques & Weiler, PRD '08
Kachelriess, Serpico & Solberg, PRD '09
Ciafaloni & Urbano, PRD '10



Ciafaloni *et al.*, 1009.0224

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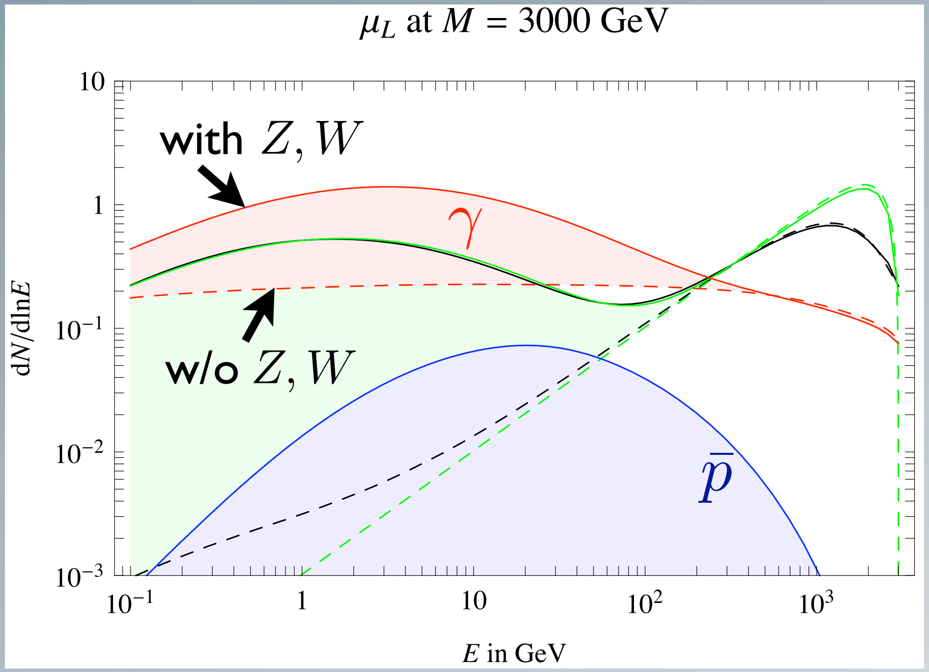
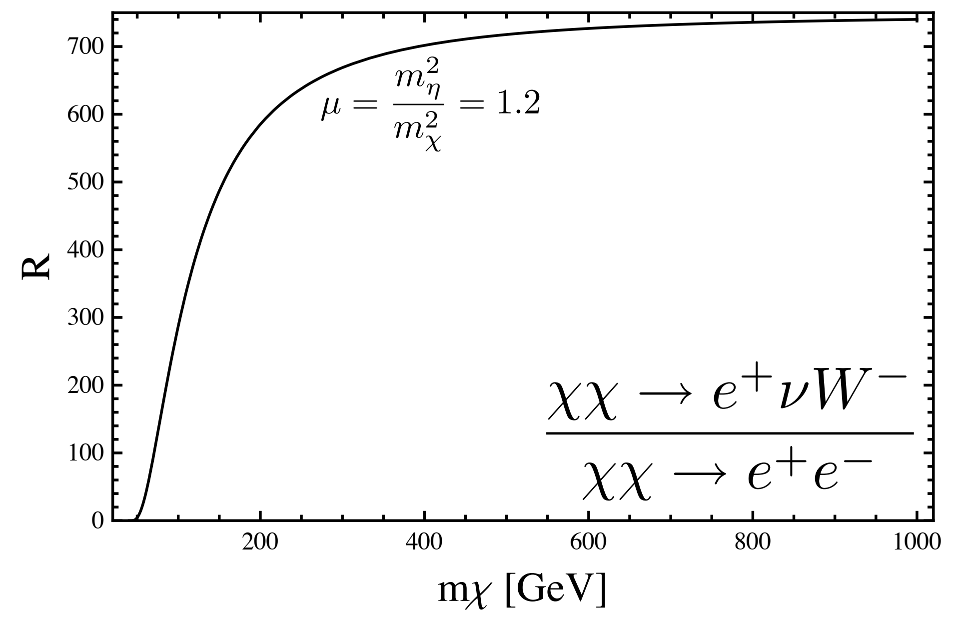


Ciafaloni *et al.*, 1009.0224

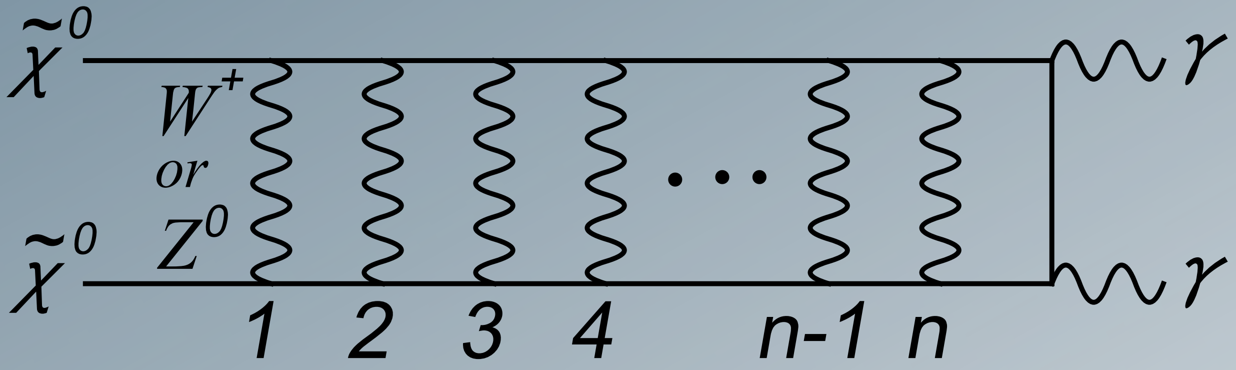


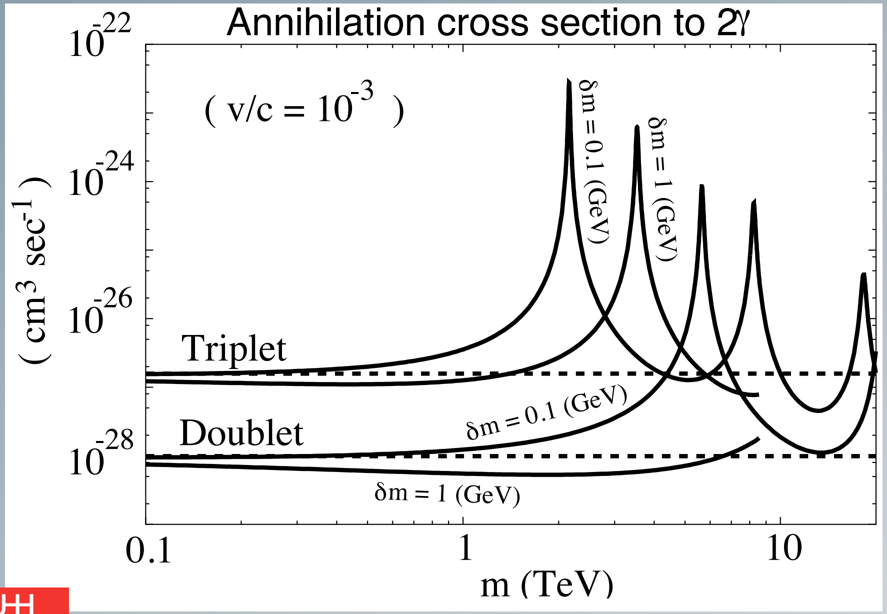
- VIB lifts helicity or $v^2$ suppression (just like for photons, but numerically larger effect!)

Ciafaloni *et al.*, 1104.2996
Bell *et al.*, 1104.3823

# Sommerfeld enhancement

Relevance of non-perturbative effects for DM annihilations pointed out long before PAMELA:



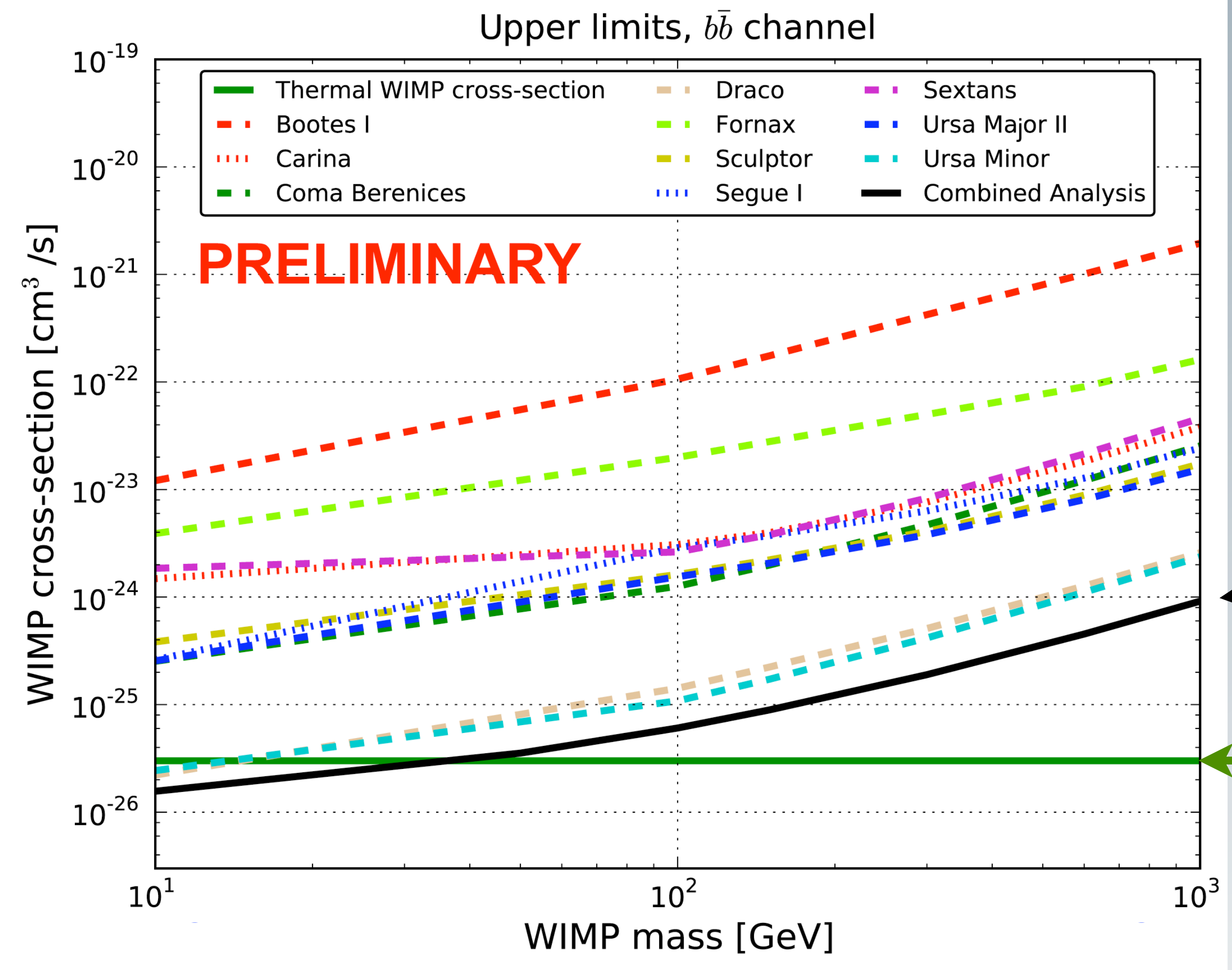


→ *considerable enhancement of annihilation rates possible!*

Hisano, Matsumoto, Nojiri, Saito, … ’03 - ’06

# Dwarf stacking

- Combined analysis for dwarf galaxies, fully including uncertainty in J-factor:



**all dwarfs**

$3 \cdot 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$

Fermi-LAT, Fermi symposium 2011

# SUSY DM and PAMELA

- Neutralino annihilation helicity suppressed:

$$\langle \sigma v \rangle \propto \frac{m_\ell^2}{m_\chi^2}$$

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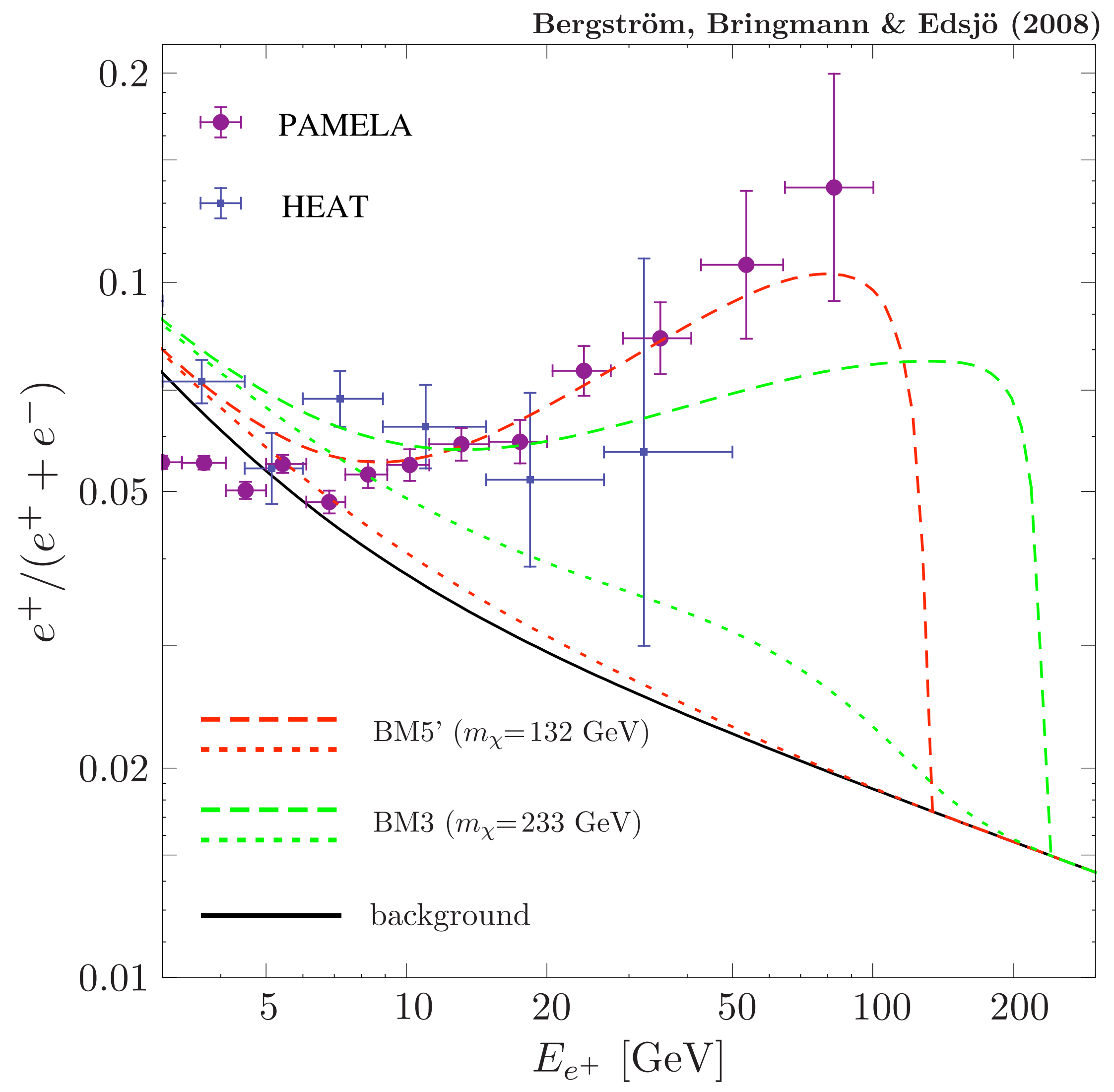

Bergström, TB & Edsjö, PRD '08

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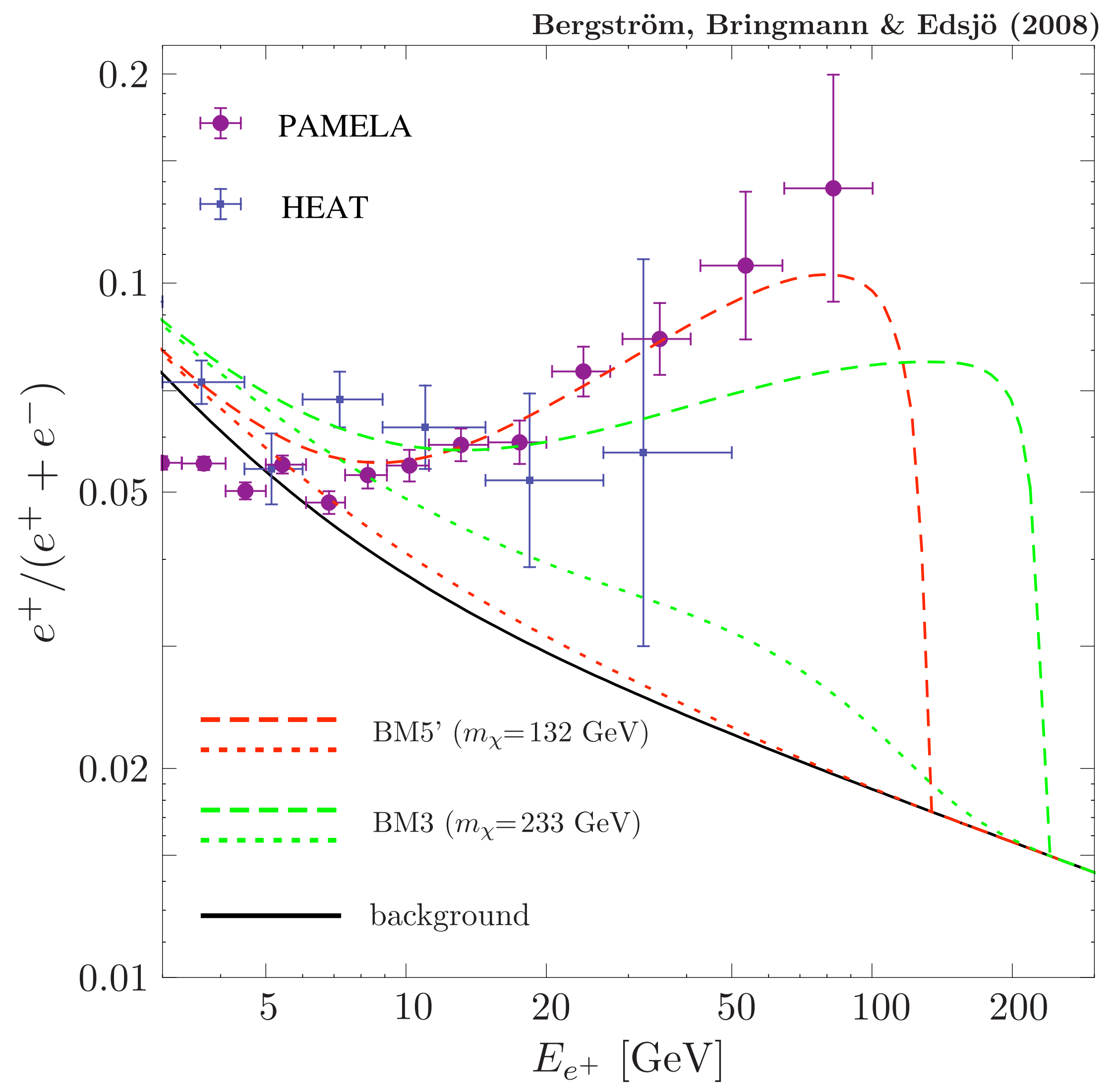
- ***but***: enormous boost factors needed w.r.t. thermal cross section...



Bergström, TB & Edsjö, PRD '08