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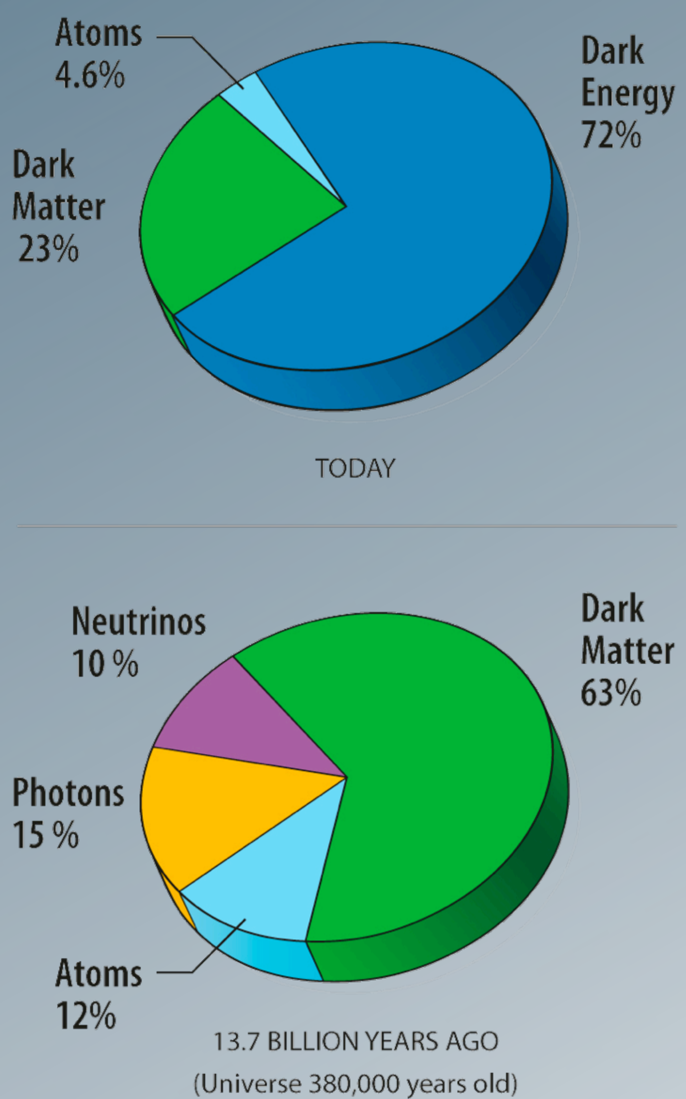
Indirect Dark Matter Searches

Torsten Bringmann, University of Hamburg

Outlook

- Introduction
- Messengers for indirect DM searches
  - Gamma rays
  - Antimatter
  - ...
- Multiwavelength/-messenger approach
- How far can we get?
- Direct vs. indirect searches
- Summary

Dark matter



credit: WMAP

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

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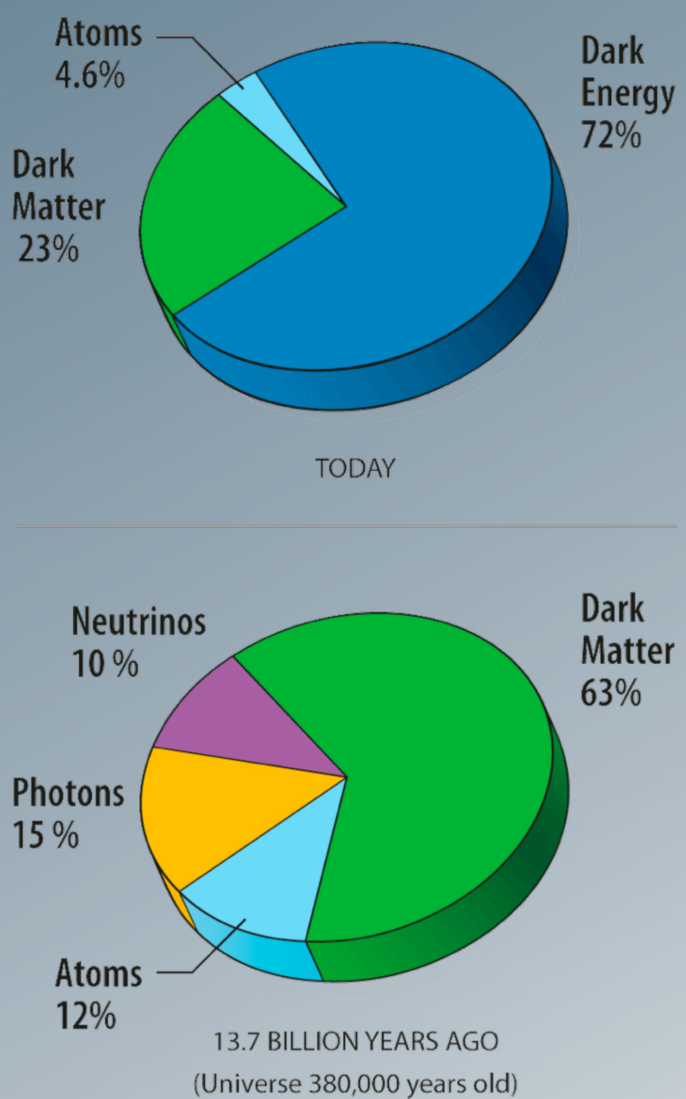

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- *WIMPS* are particularly good candidates:
  - ✓ well-motivated from particle physics [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production “automatically” leads to the right relic abundance

The WIMP "miracle"

- The number density of **W**eakly **I**nteracting **M**assive **P**articles in the early universe:

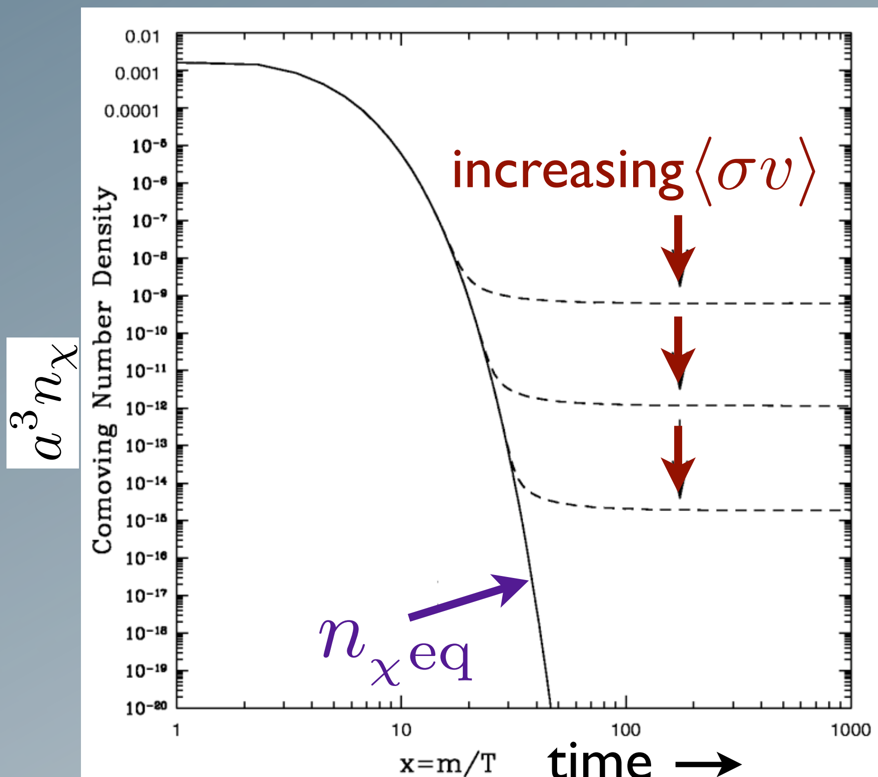


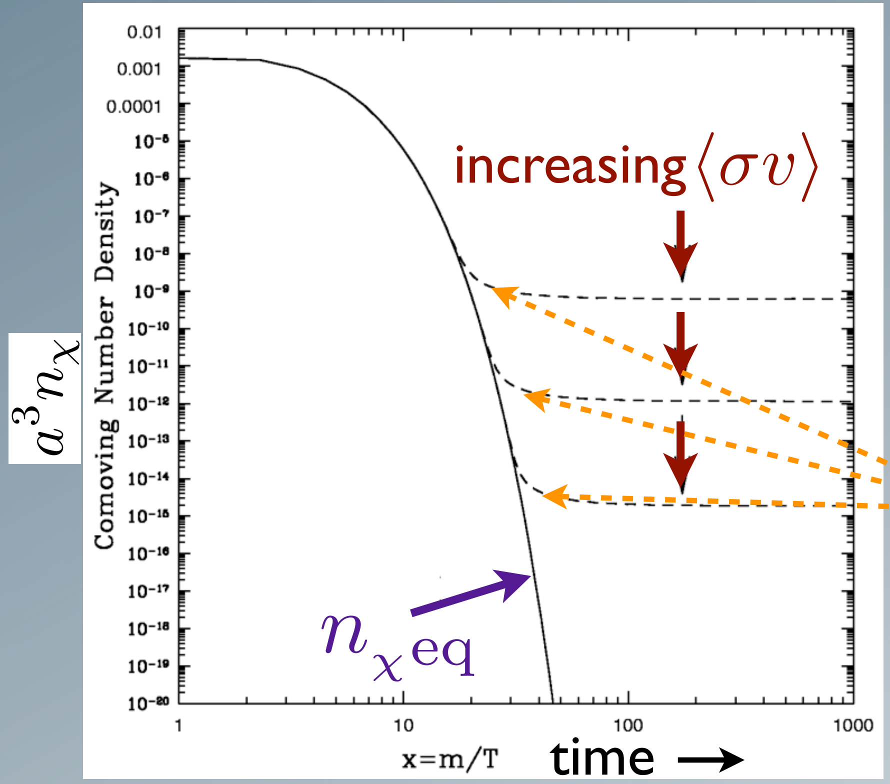
Fig.: Jungman, Kamionkowski & Griest, PR'96

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

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

The WIMP "miracle"

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



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

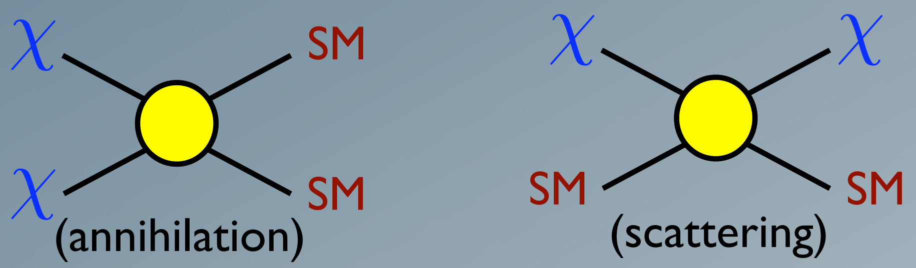
"Freeze-out" when annihilation rate falls behind expansion rate ($\rightarrow a^3 n_\chi \sim \mathrm{const.}$)

for weak-scale interactions!

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

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



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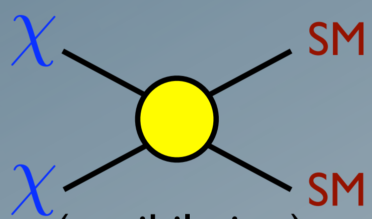
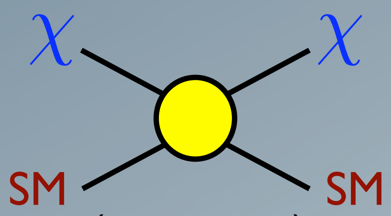


(annihilation)



(scattering)

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

chemical decoupling

$$\Omega_\chi$$

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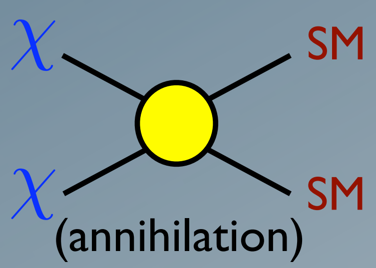

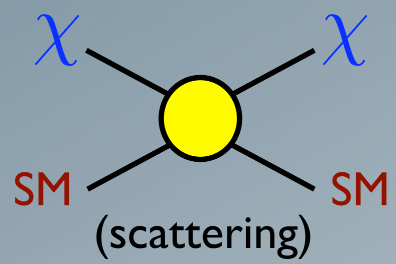

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chemical decoupling

$$\Omega_\chi$$

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

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$$M_{\rm cut}$$

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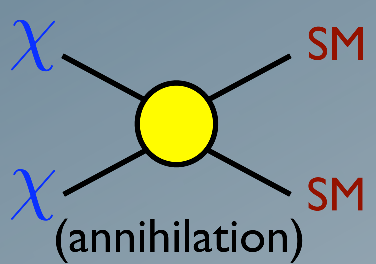

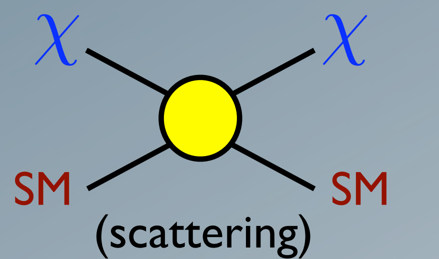

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Ω_χ

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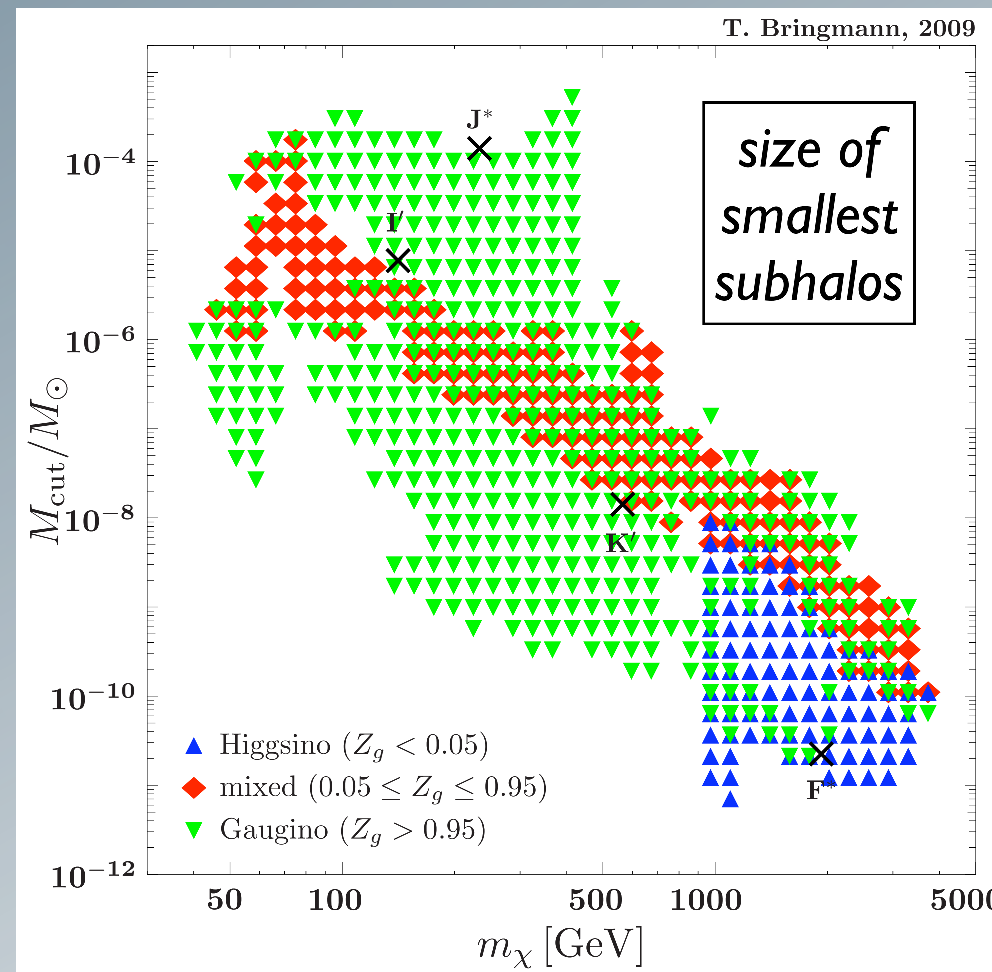
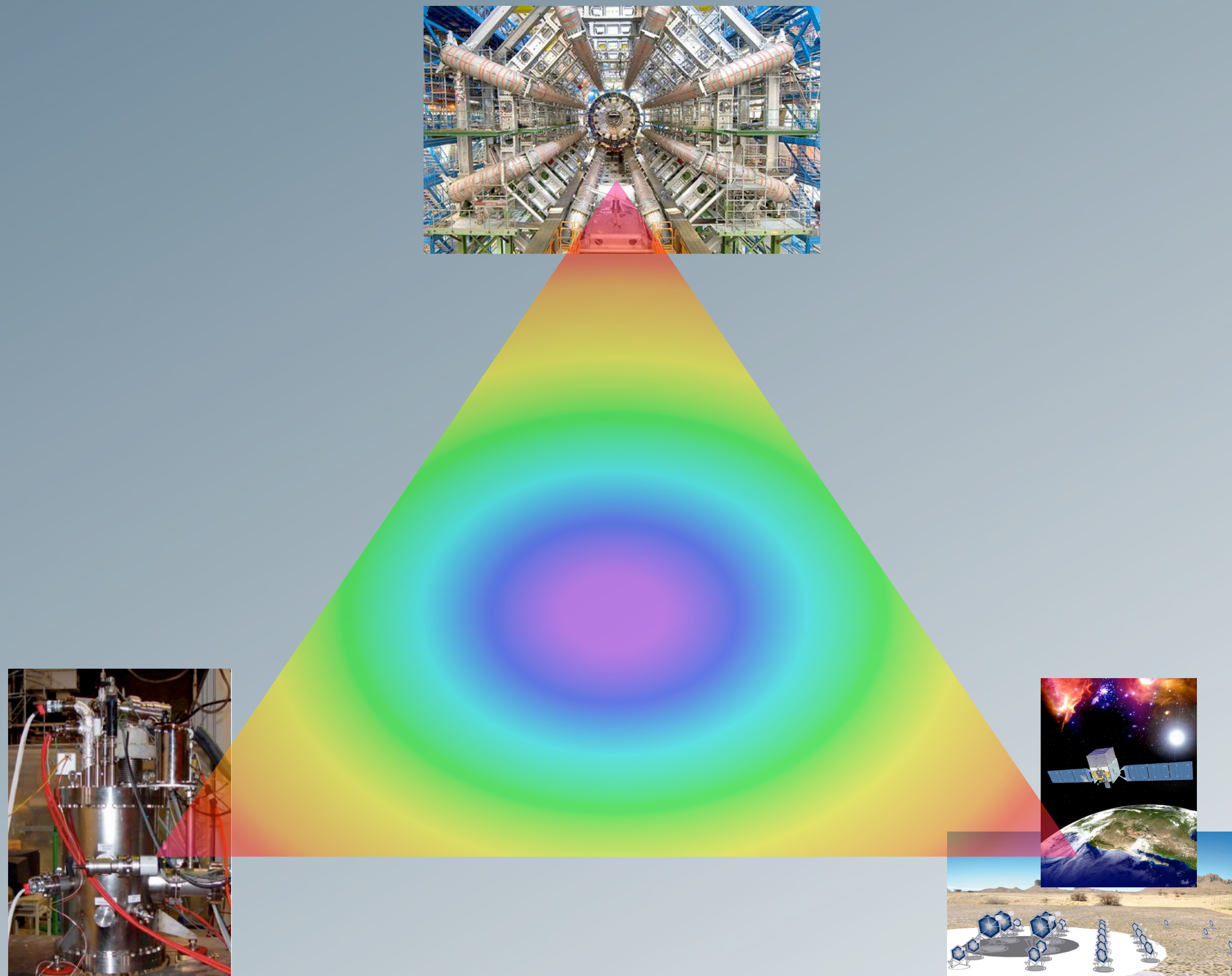
$M_{\rm cut}$



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!*

Strategies for DM searches



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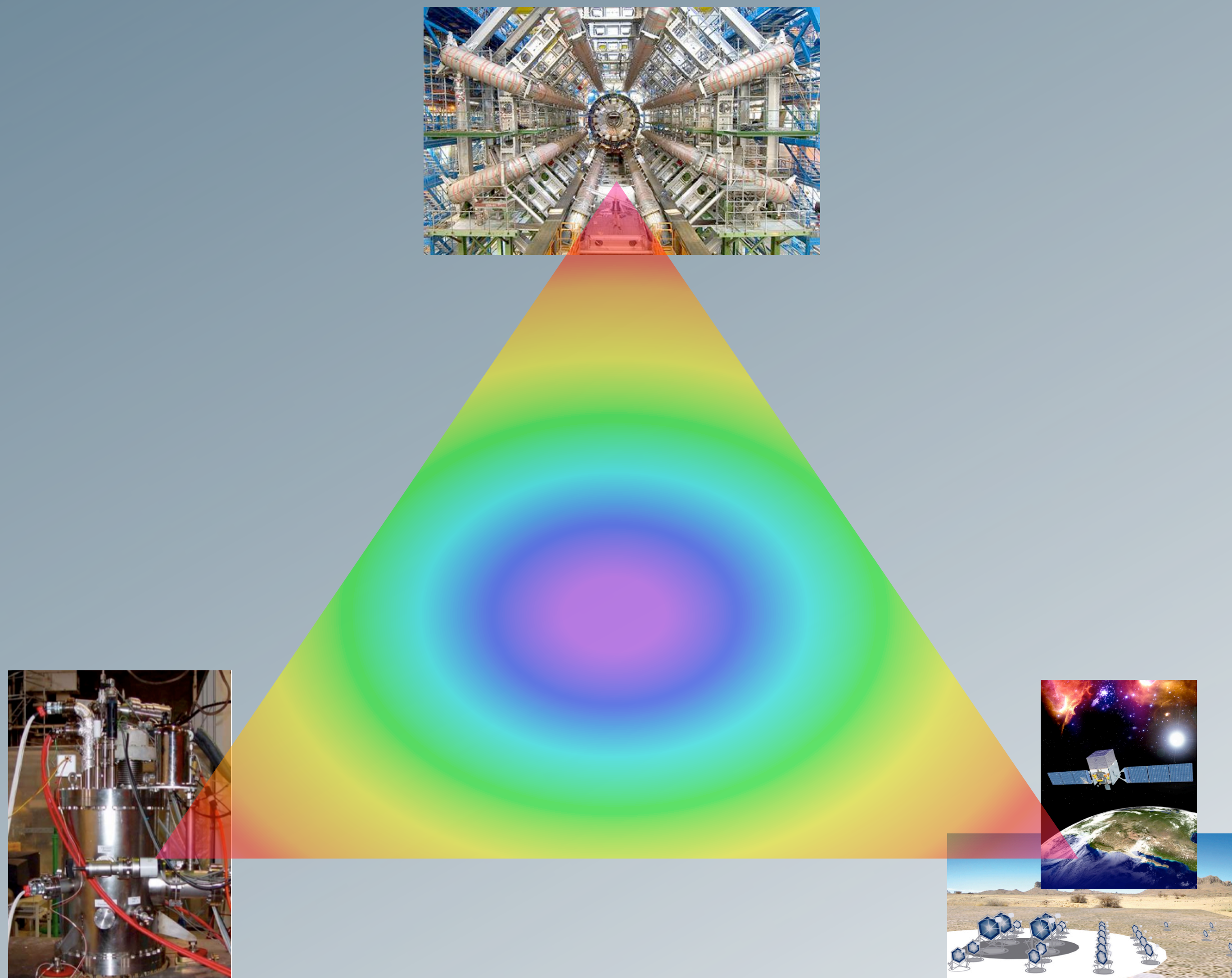
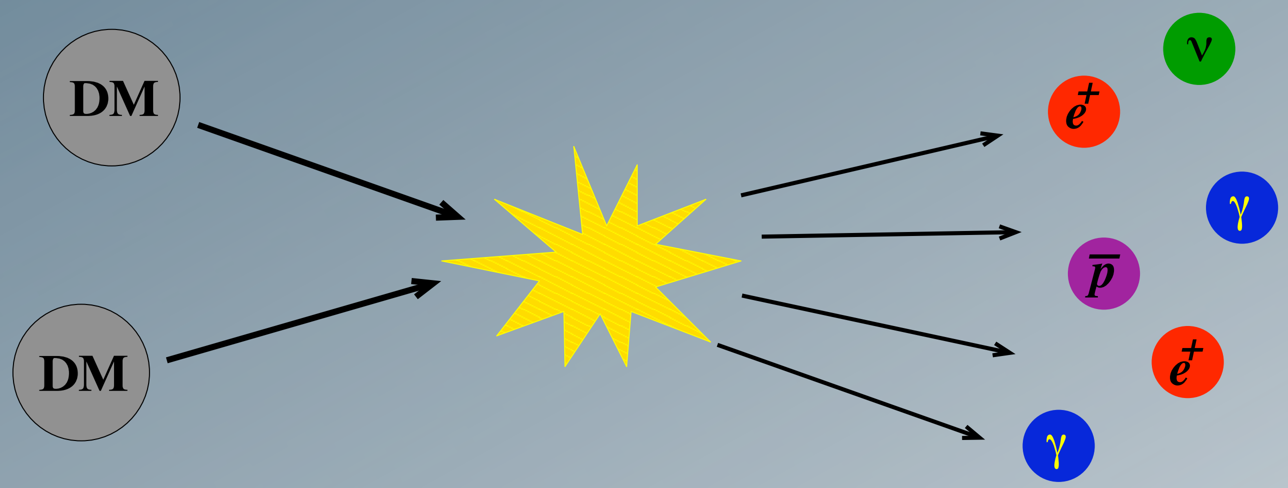


➩ *all complementary!*

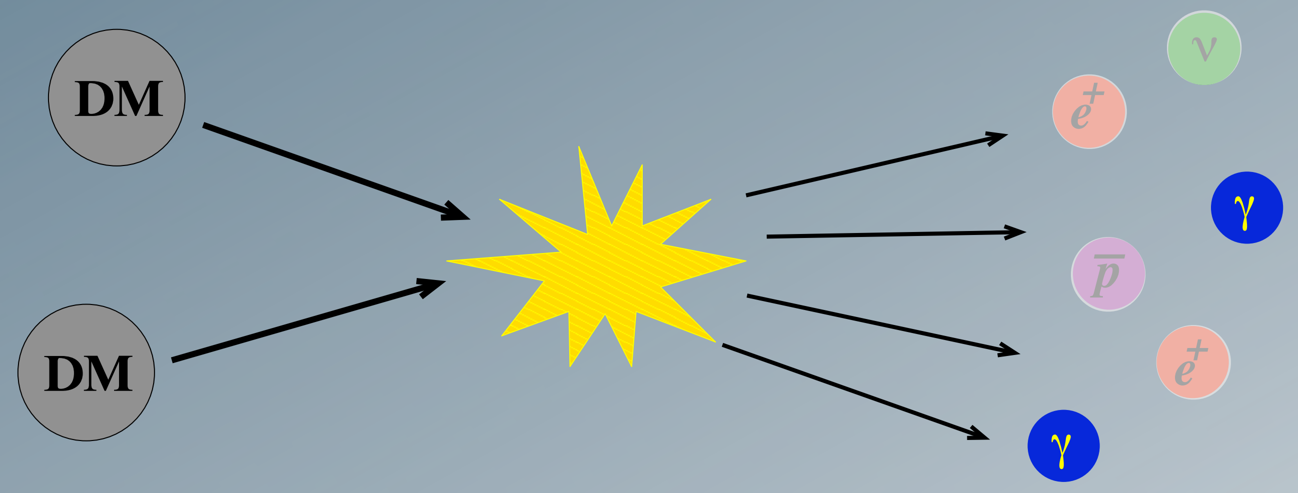
Indirect DM searches



- 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



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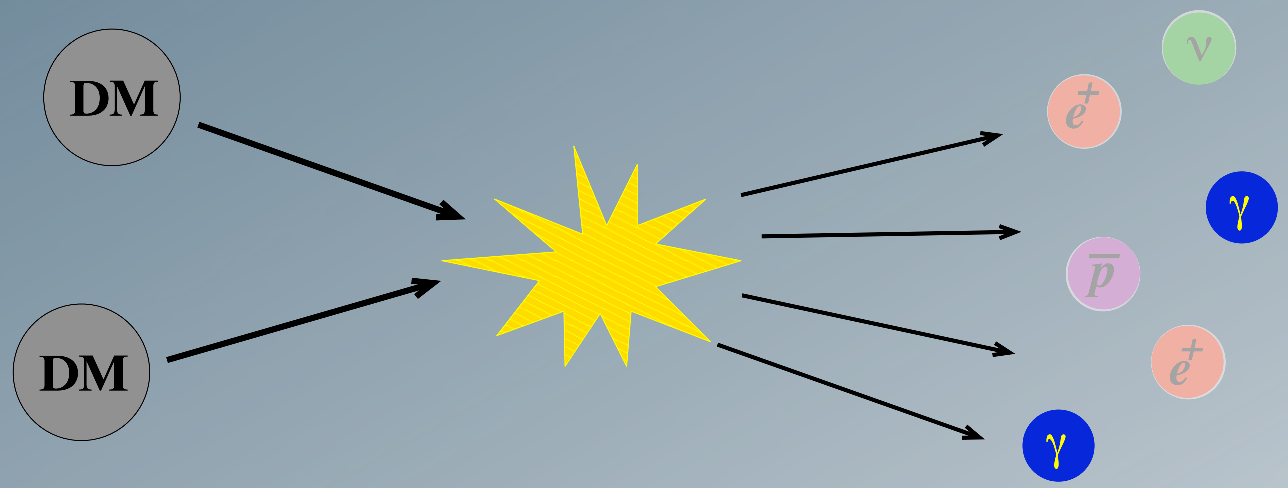

Gamma rays:

- 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

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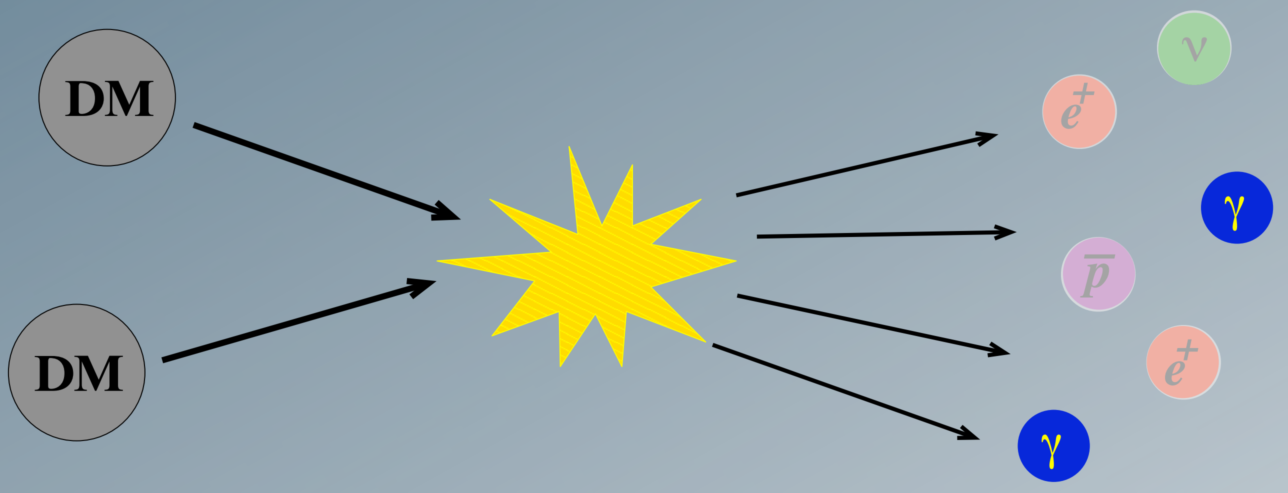

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- Clear spectral signatures to look for ⇦ maybe most important!

Gamma-ray flux

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

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

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particle physics

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

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

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particle physics | astrophysics

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→ large uncertainty in normalization

Halo profiles

<u>ΛCDM *N*-body simulations</u>

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

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

$(\alpha \approx 0.17)$

$\rightsquigarrow$ rather stable result

<u>Fits to rotation curves?</u>

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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

$\Rightarrow$ see talks by C. Frenk & A. Zentner

Substructure

- *N*-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!
- Indirect detection effectively involves some averaging:

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

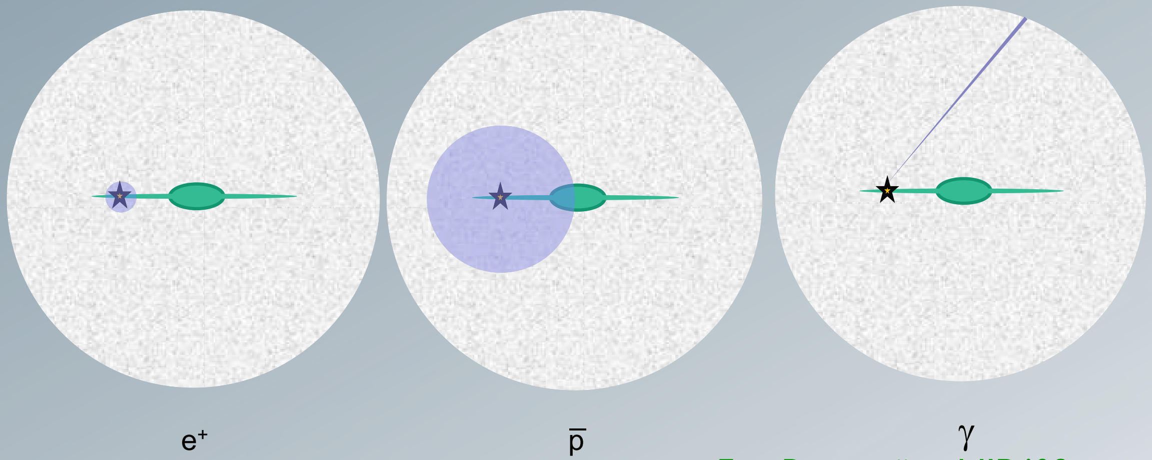

Fig.: Bergström, NJP '09

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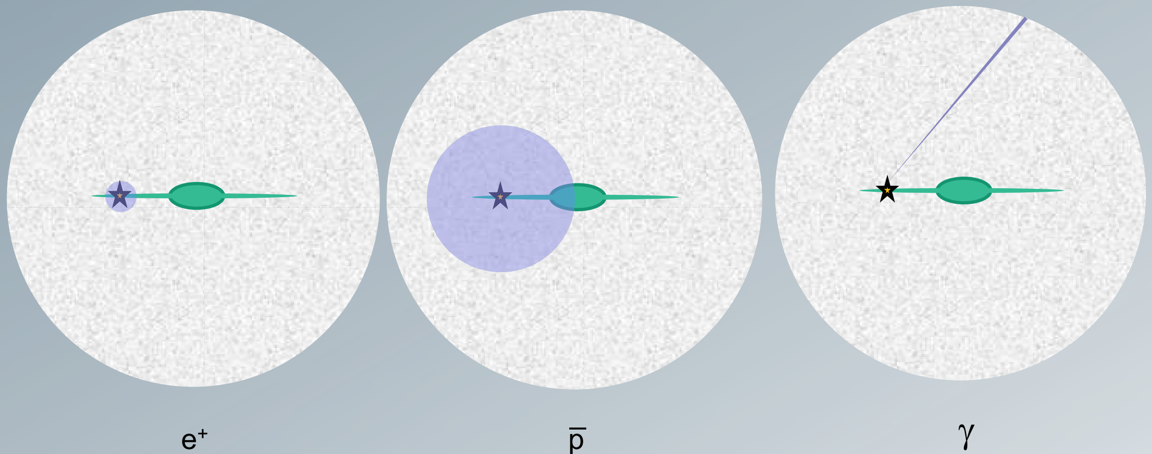


Fig.: Bergström, NJP '09

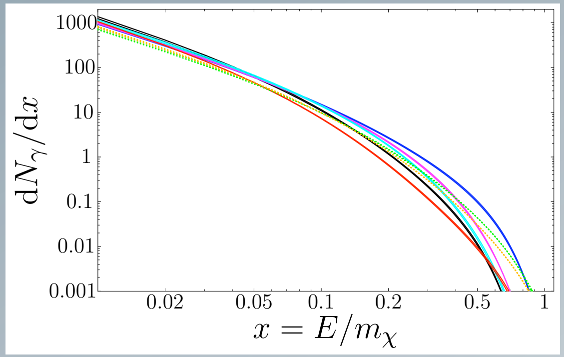
- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes about the same

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

    ⇒ *important to include realistic value for* $M_{\rm cut}$ *!*
  - depends on uncertain form of microhalo profile ($c_{\rm v}$ ...) and dN/dM (large extrapolations necessary!)

DM annihilation spectra

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



Bertone et al., astro-ph/0612387

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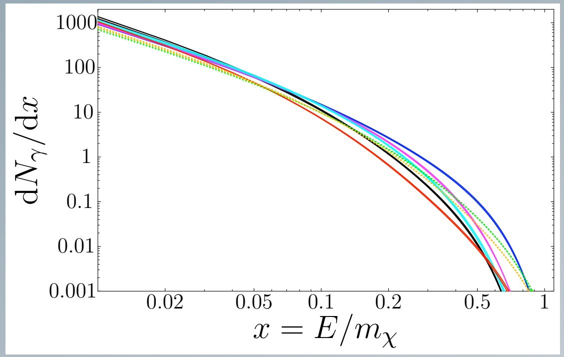

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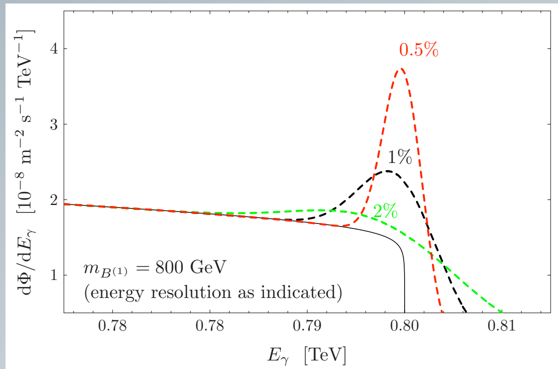
- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

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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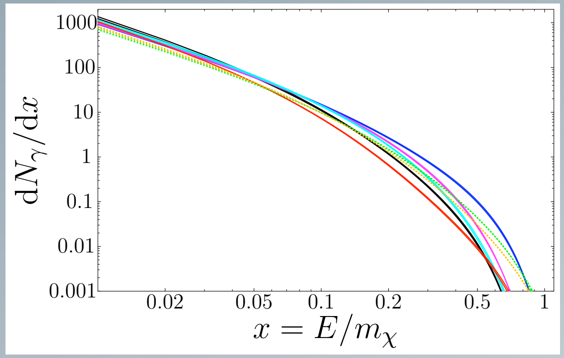

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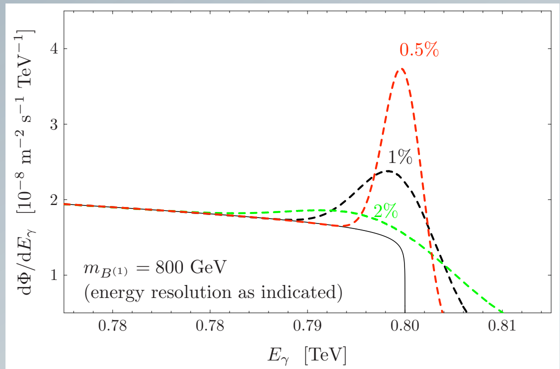

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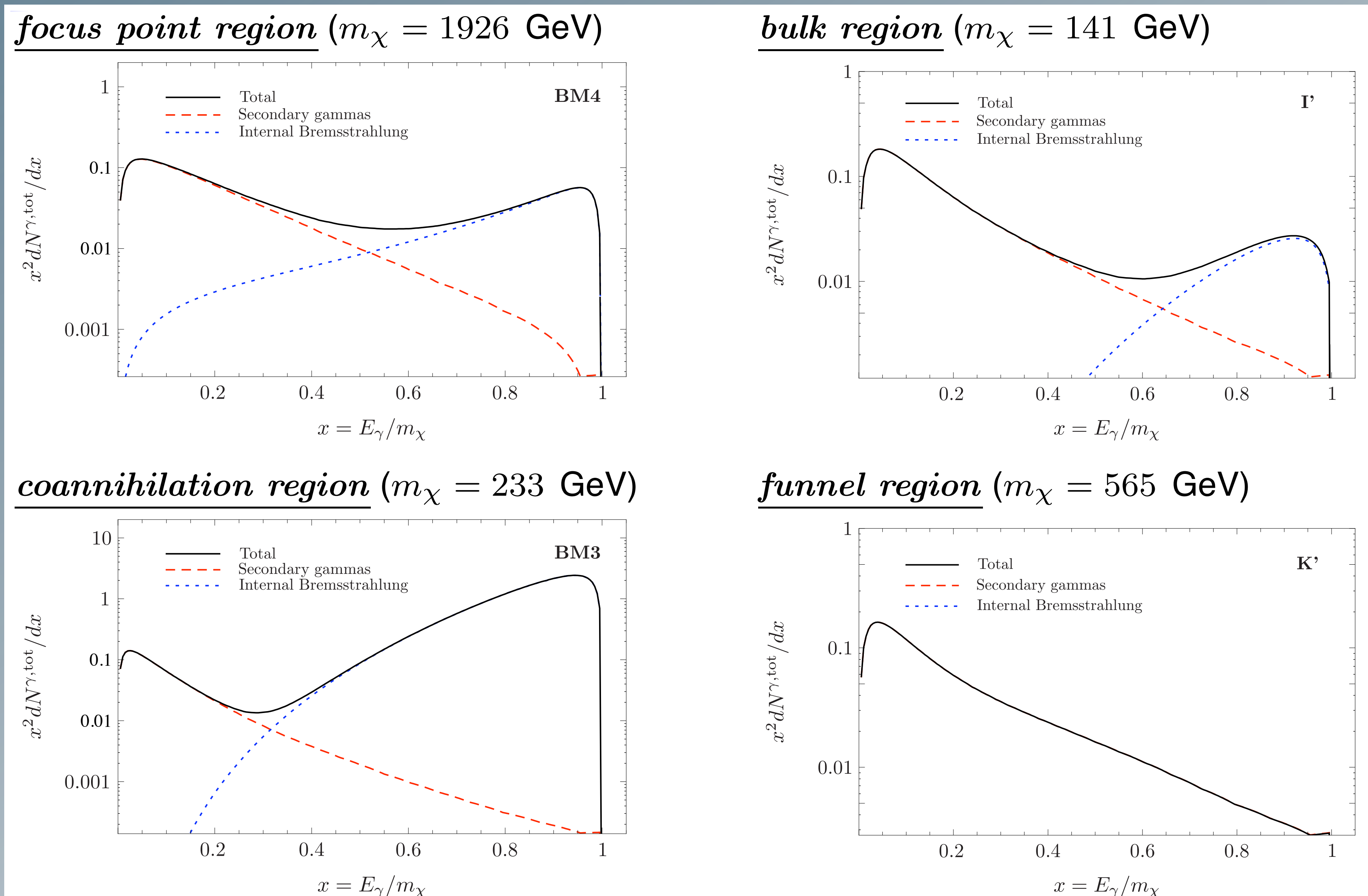
- Internal bremsstrahlung (IB)
  - whenever charged final states are present: $\mathcal{O}(\alpha)$
  - characteristic signature (details model-dependent!)
  - usually dominant at high energies

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

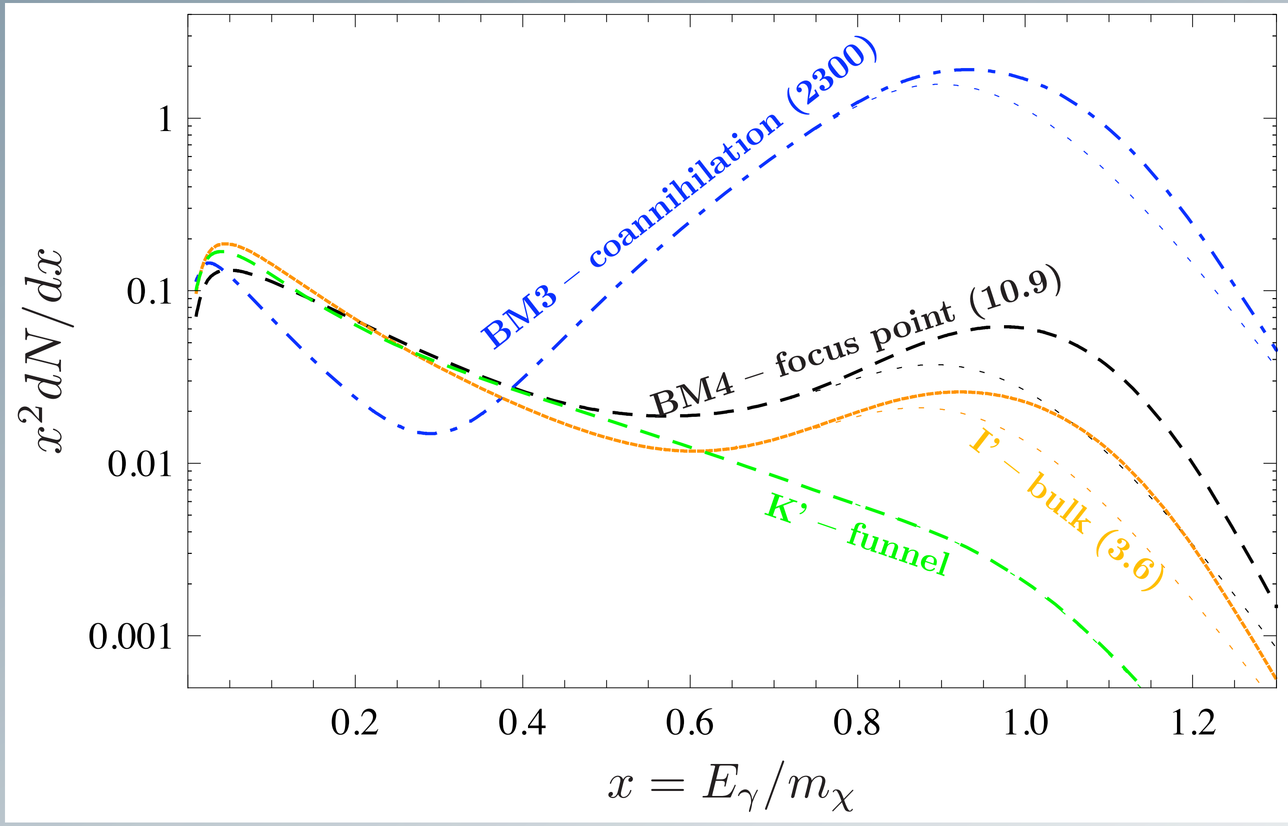
mSUGRA spectra



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

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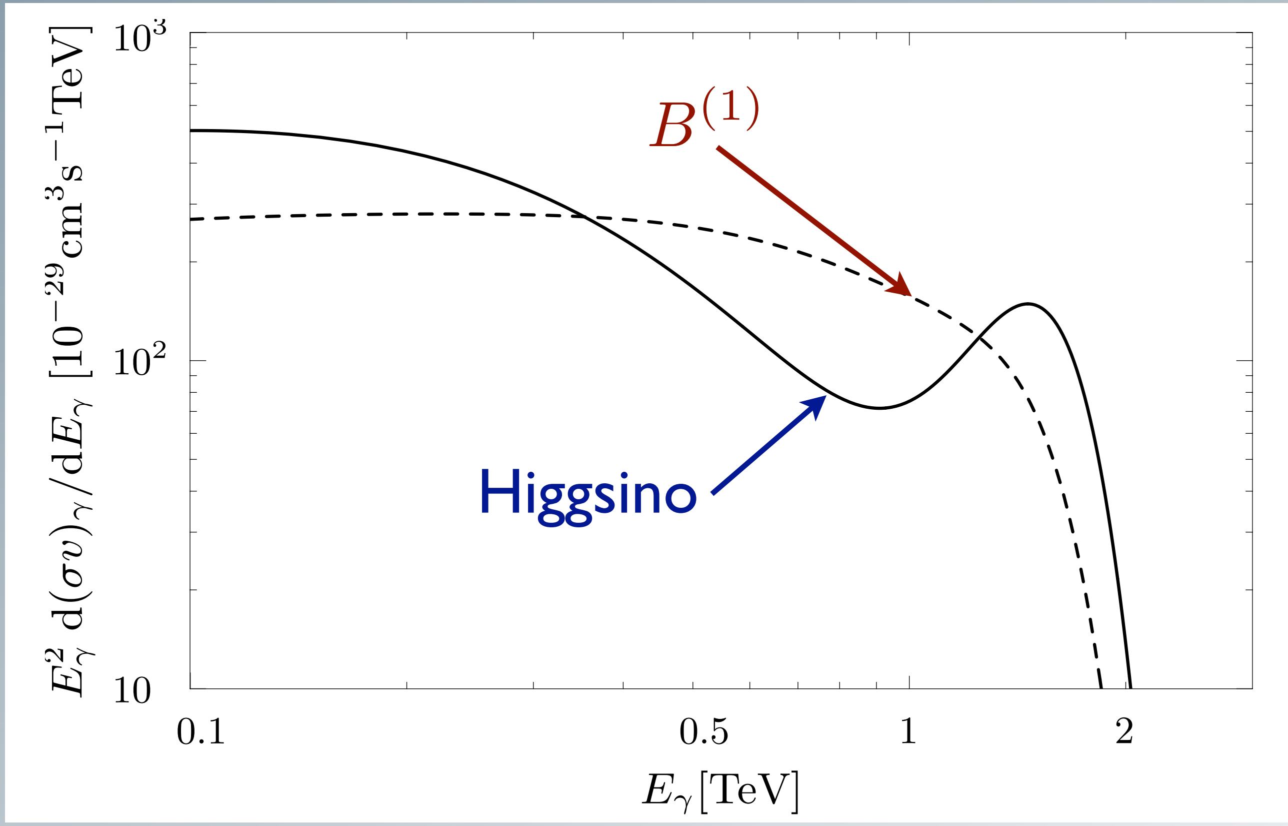
  - Example: Higgsino vs KK-DM (about same mass; assume $\Delta E = 15\%$)



Bergström *et al.*, '06

IB: total flux enhancement

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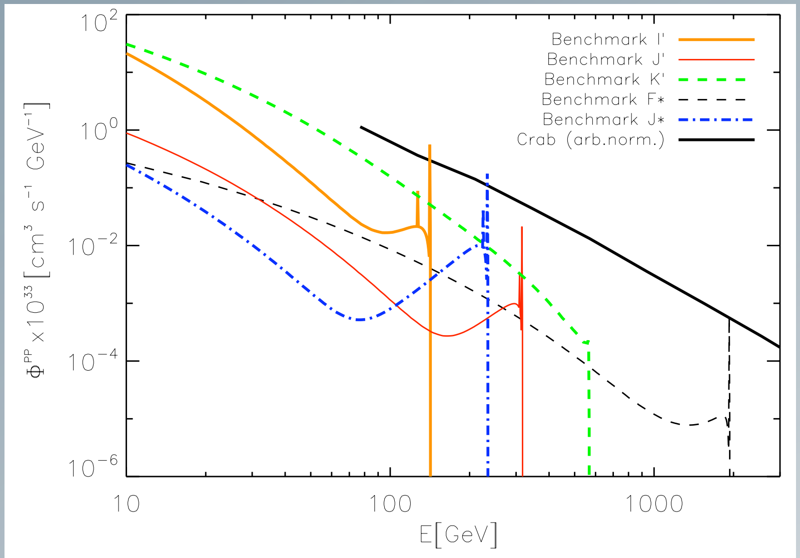
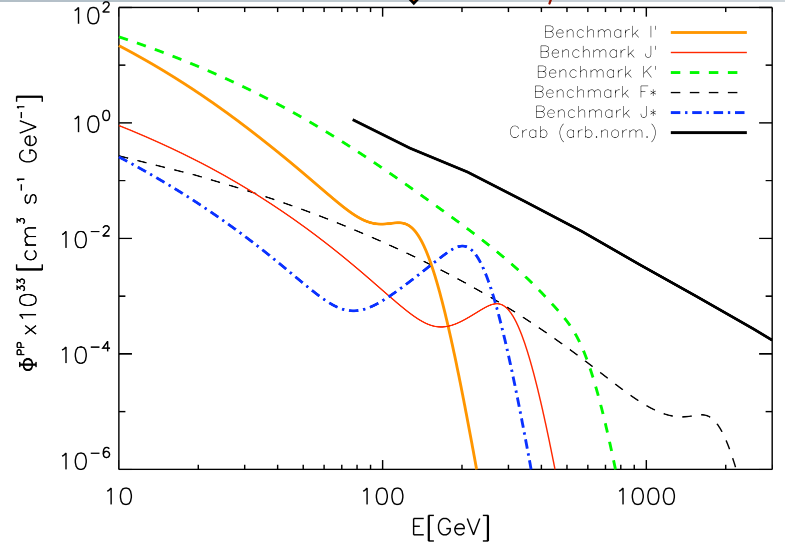


$\Delta E/E = 10\%$



TB, Doro & Fornasa, JCAP '09

- Example: Dwarf galaxies
  - IB boosts effective sensitivity by a factor of up to ~10
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    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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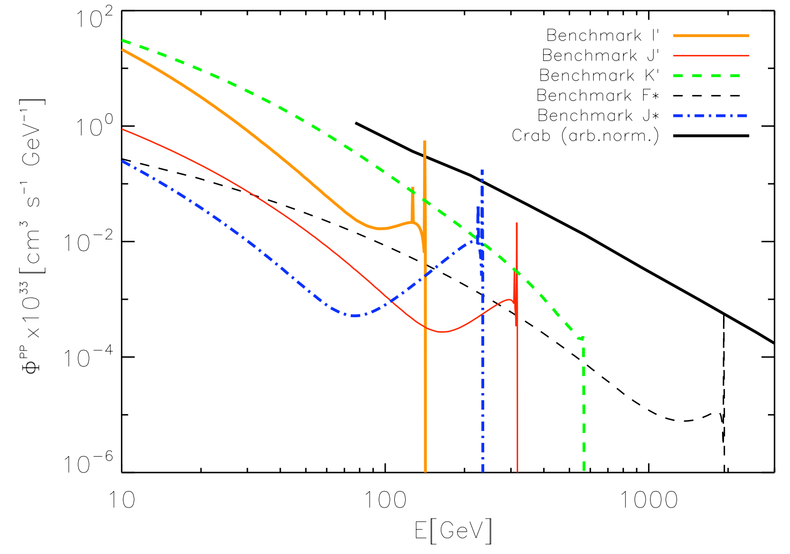

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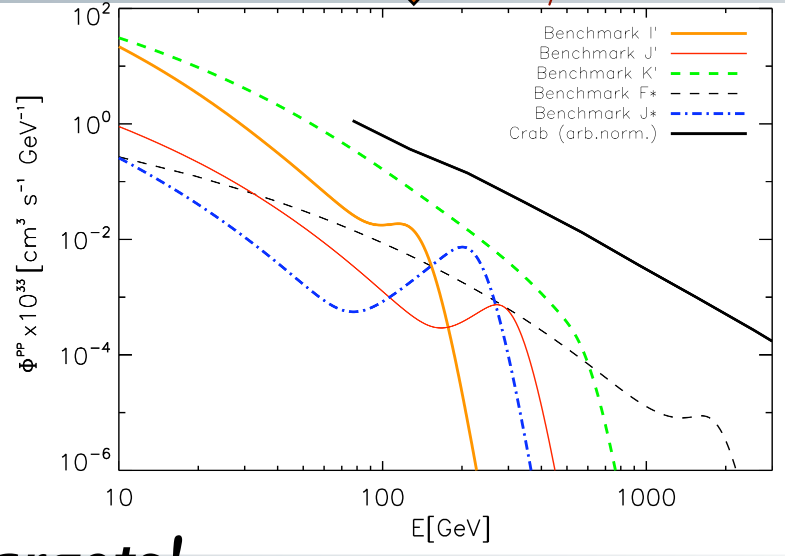
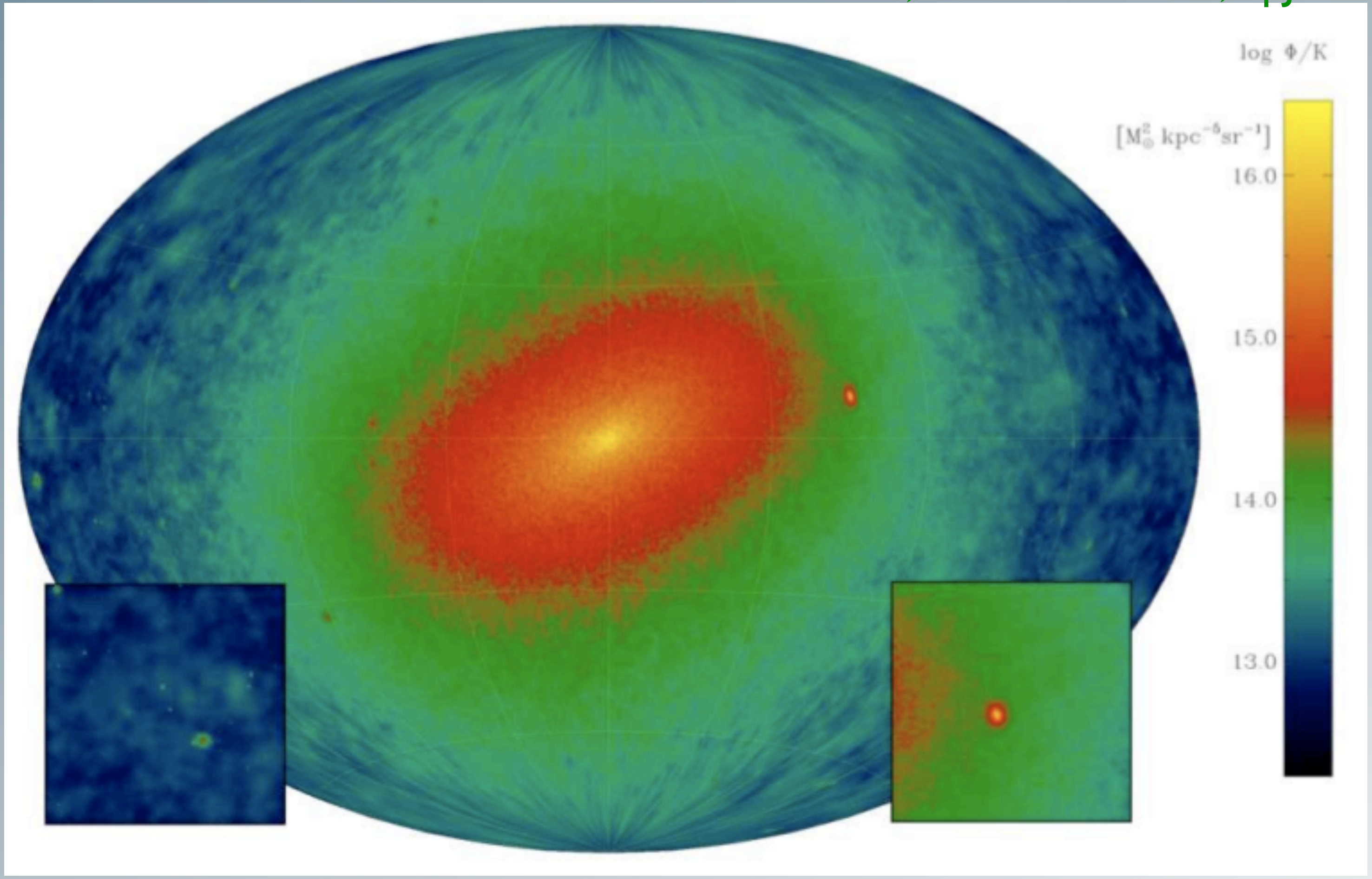


TB, Doro & Fornasa, JCAP '09

➜ *important to include also for other targets!*

Where to look

Diemand, Kuhlen & Madau, ApJ '07



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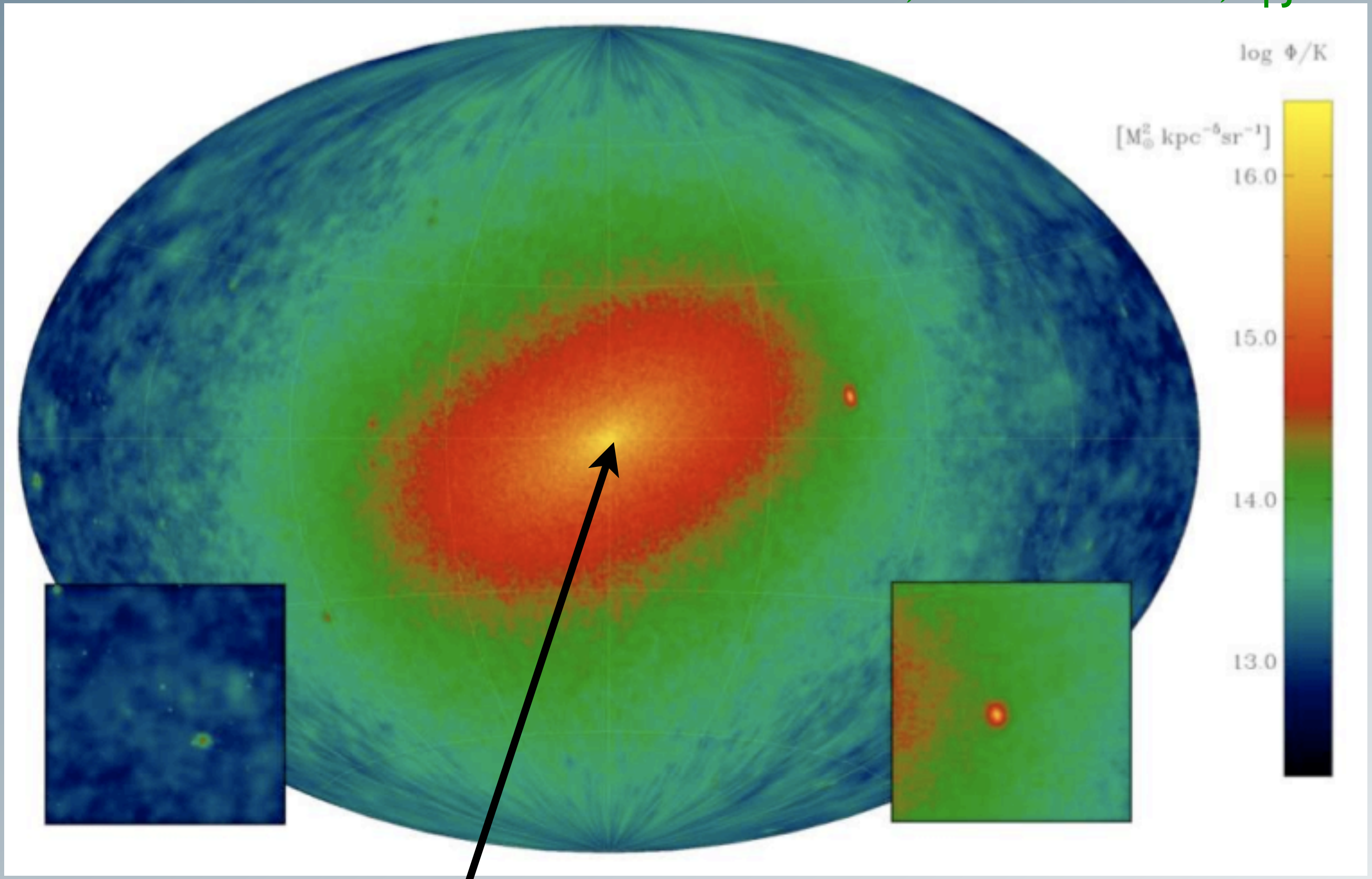

Galactic center

- brightest DM source in sky
- large background contributions

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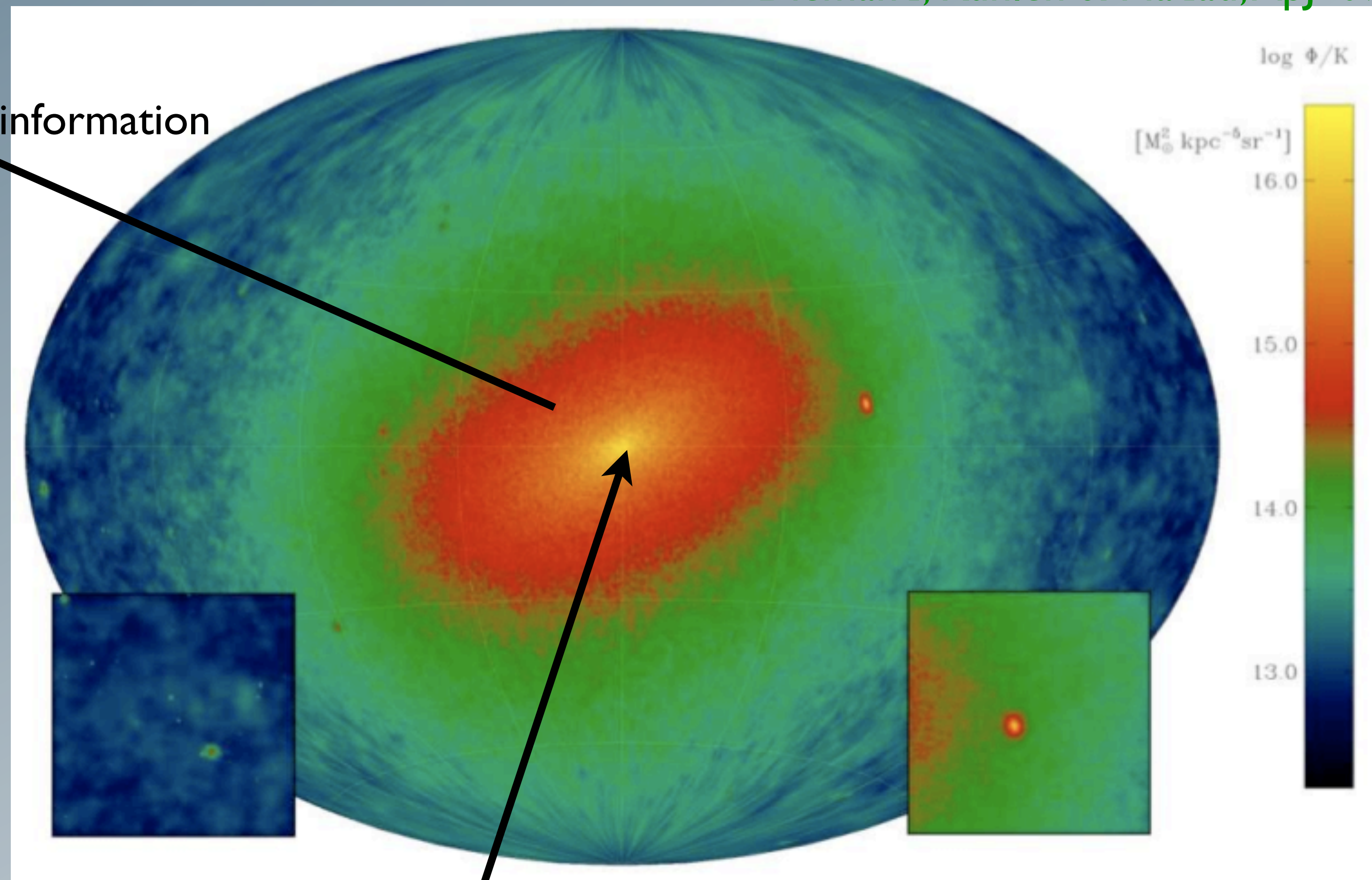

Galactic halo

- good statistics, angular information
- galactic backgrounds?

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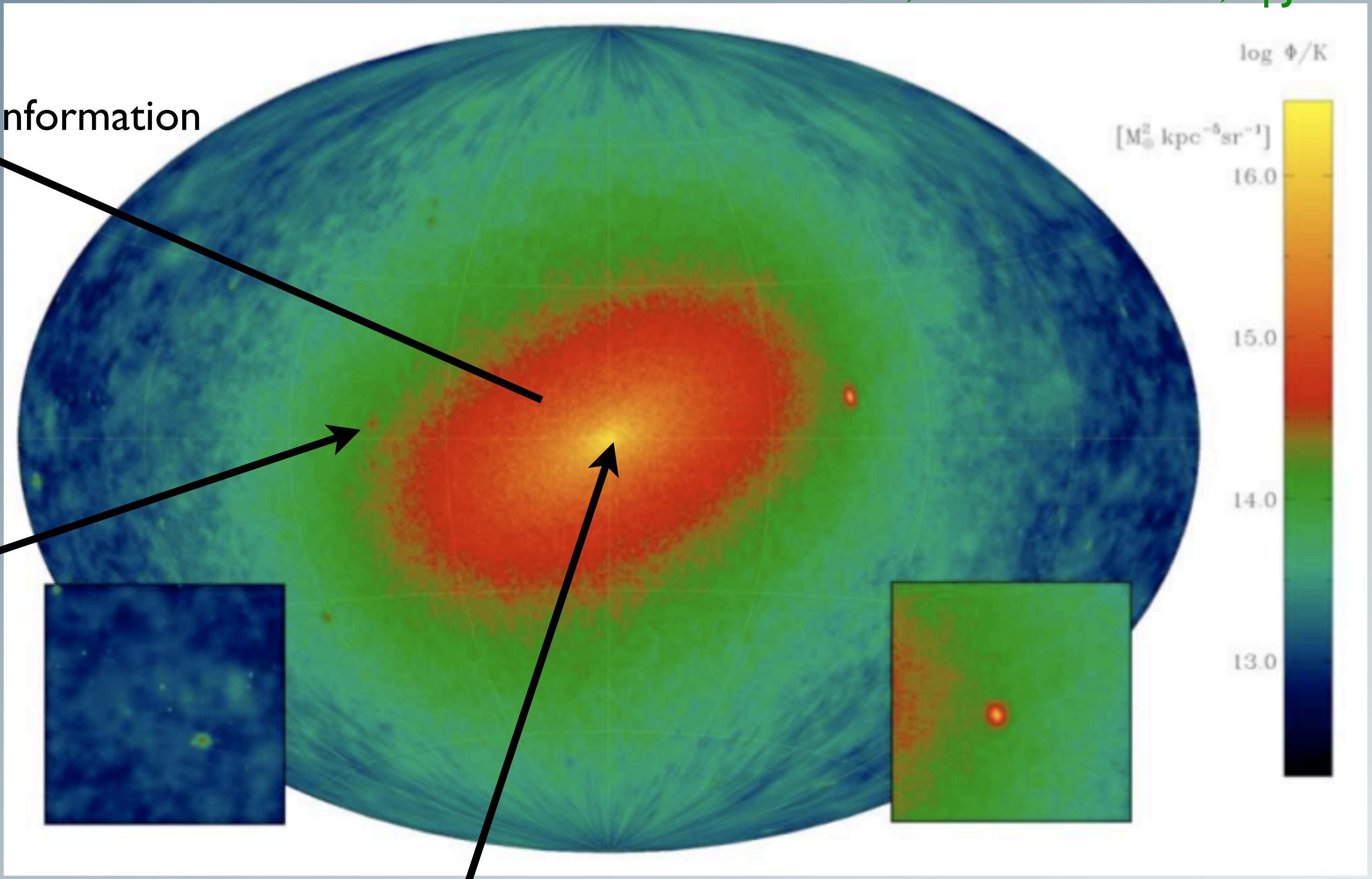

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- good statistics, angular information
- galactic backgrounds?

Dwarf Galaxies

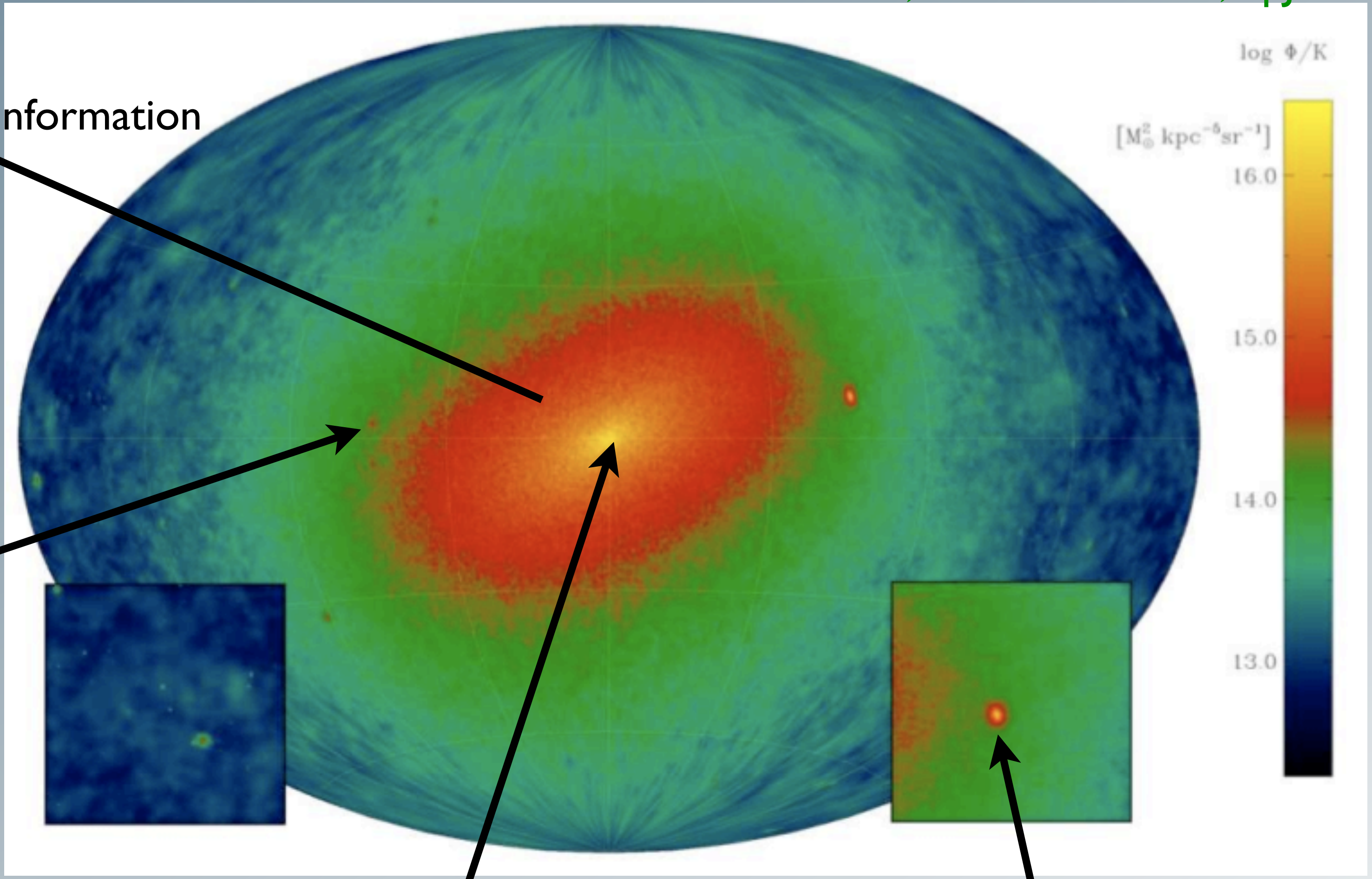
- DM dominated, M/L~1000
- fluxes soon in reach!

Galactic center

- brightest DM source in sky
- large background contributions

Where to look

Diemand, Kuhlen & Madau, ApJ '07



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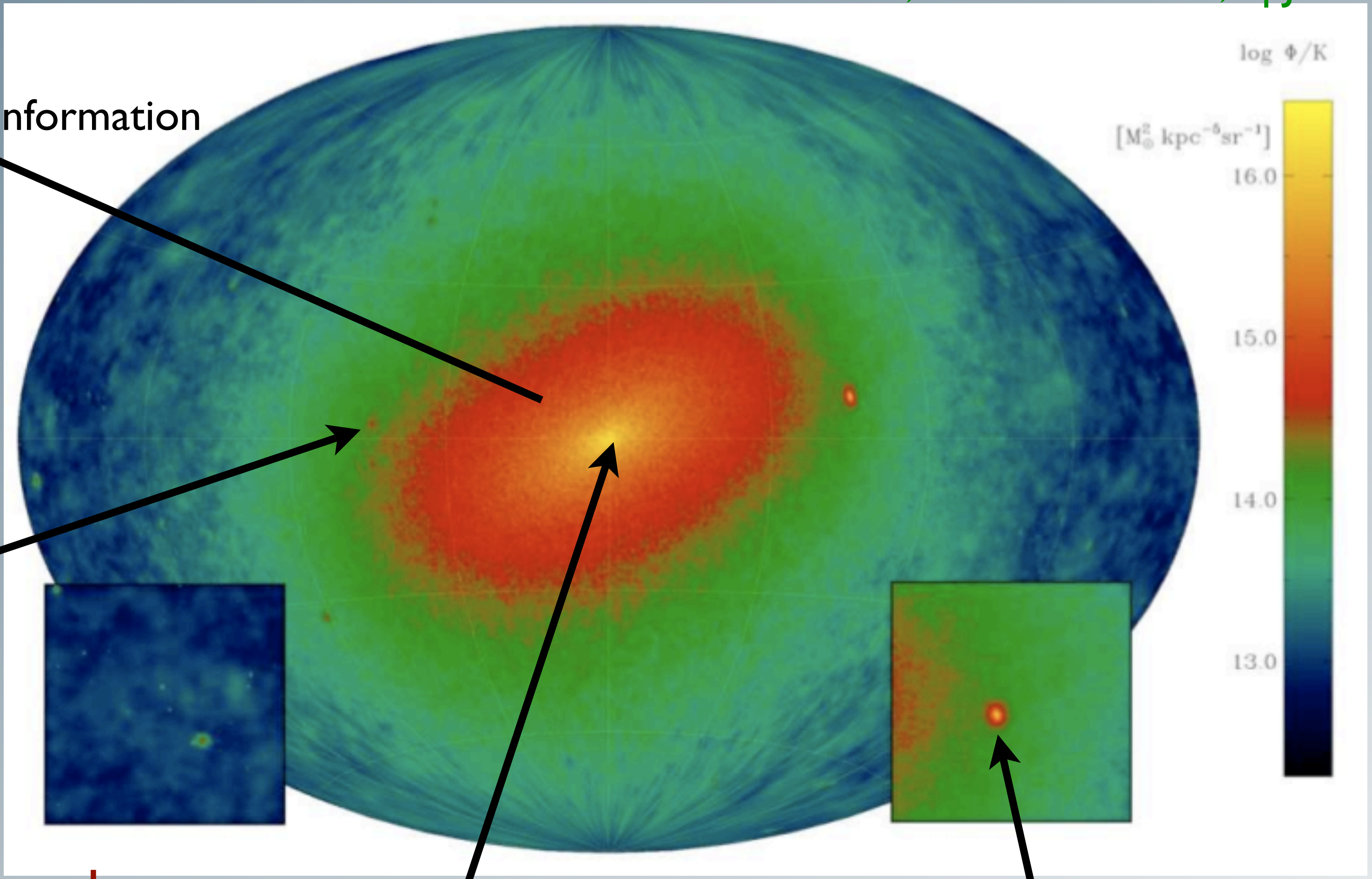

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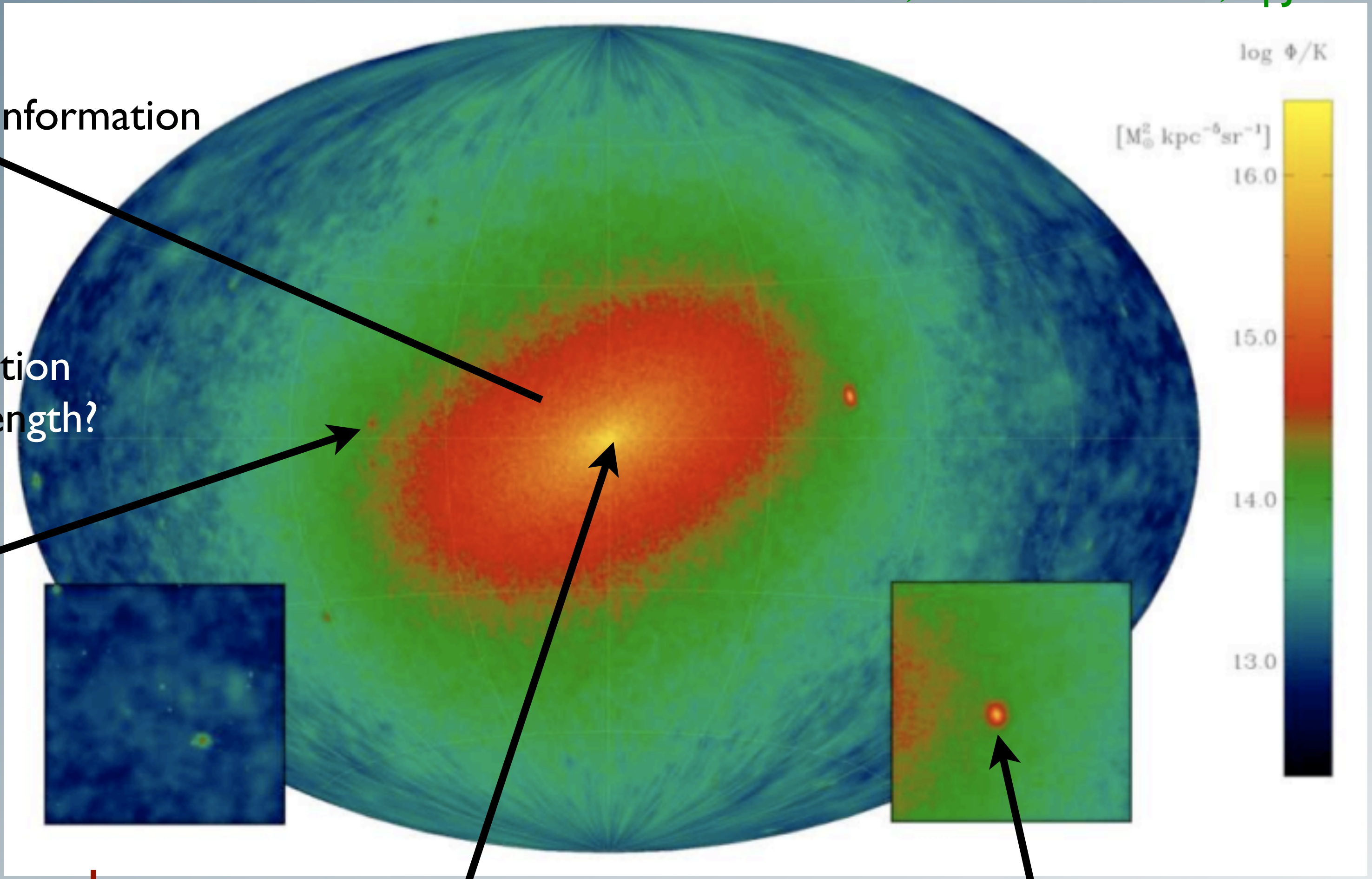

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Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?

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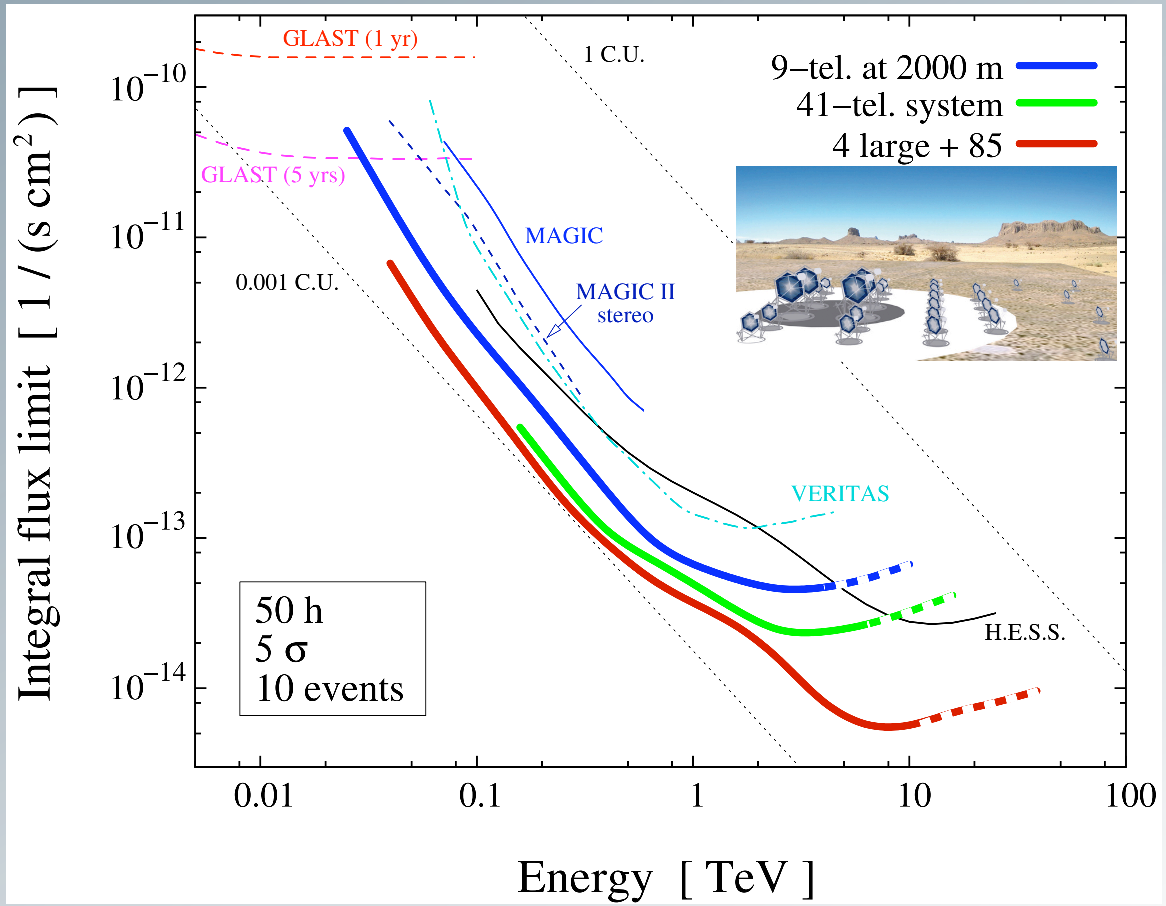
- large eff. Area (~km^2)
- small field of view
- lower threshold $\gtrsim$ 40 GeV



Bernlöhr et al., '07

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- upper bound on resolvable E_γ

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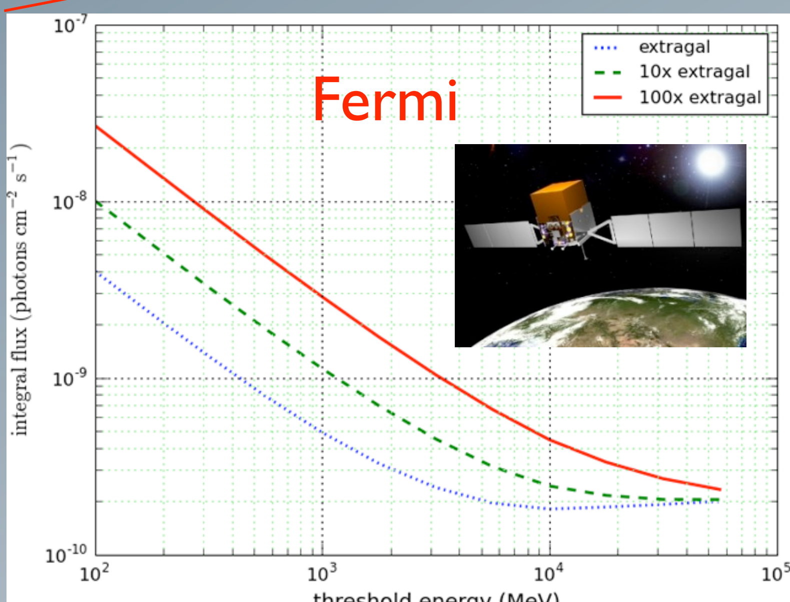
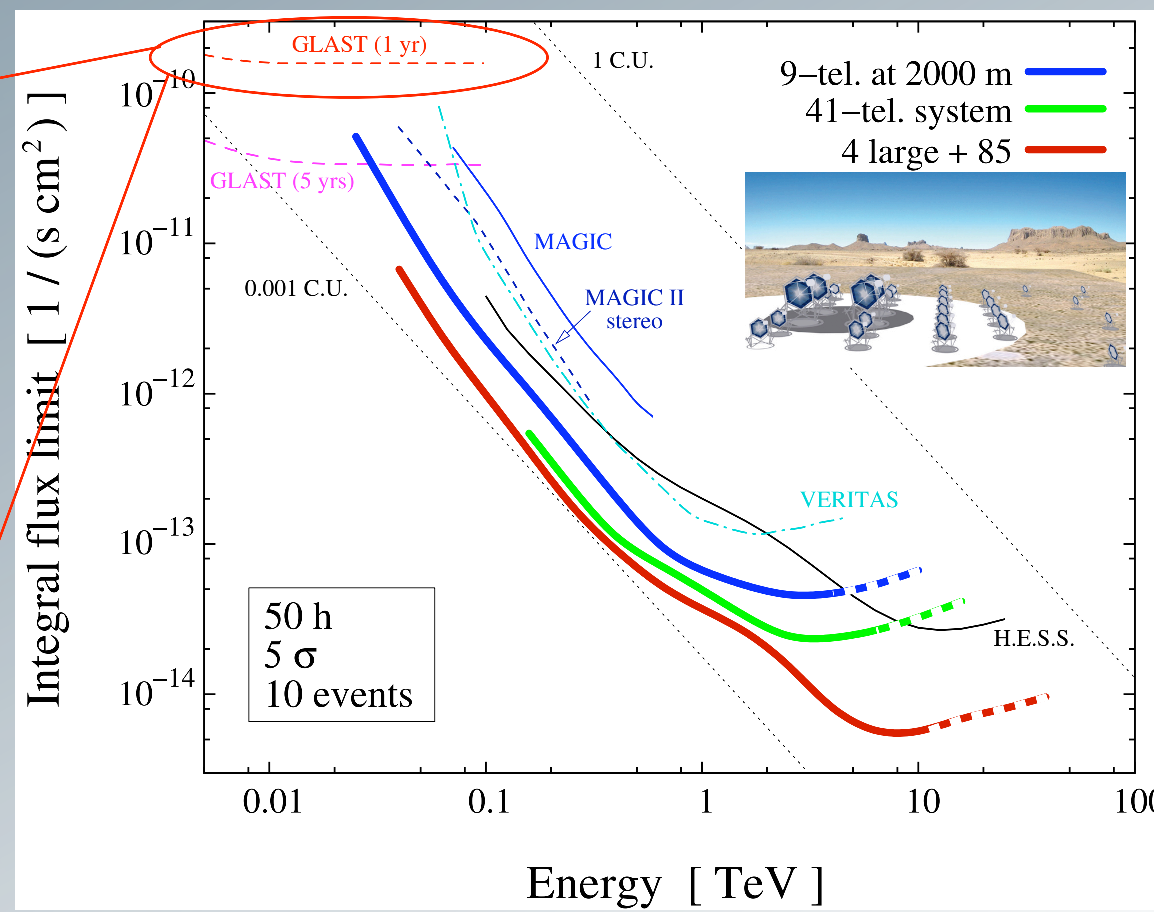


(from the LAT webpage)



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- … but indirect searches start to be very competitive!

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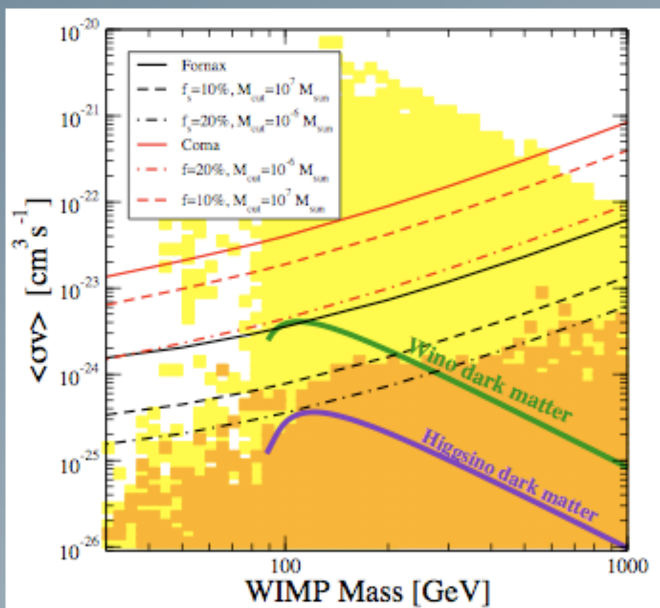

Fermi - Clusters, 1002.2239

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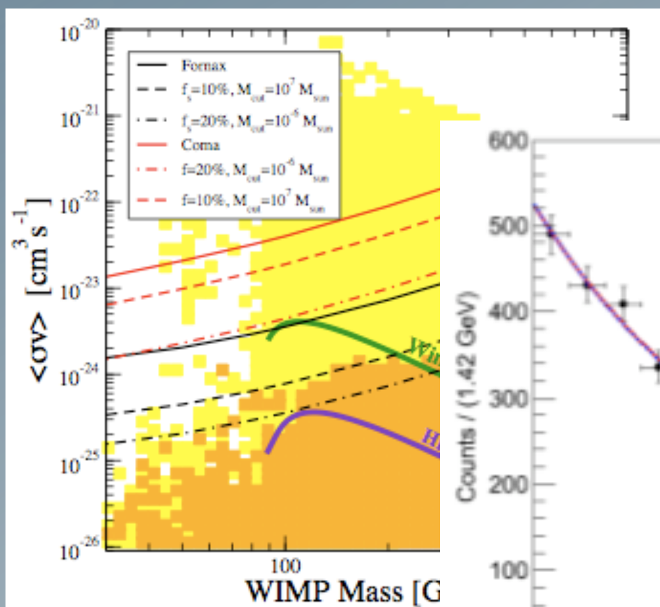

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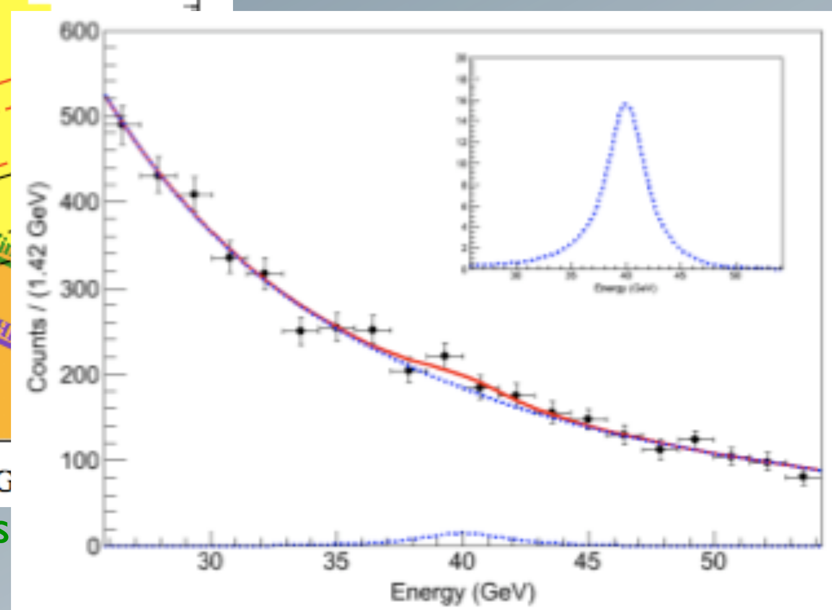

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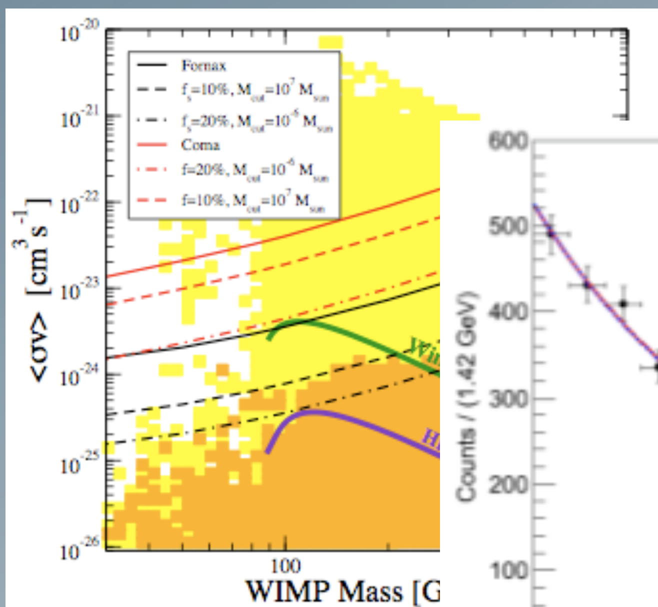

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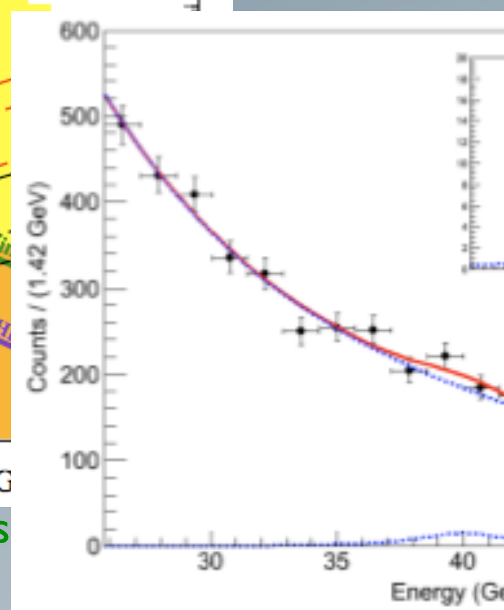

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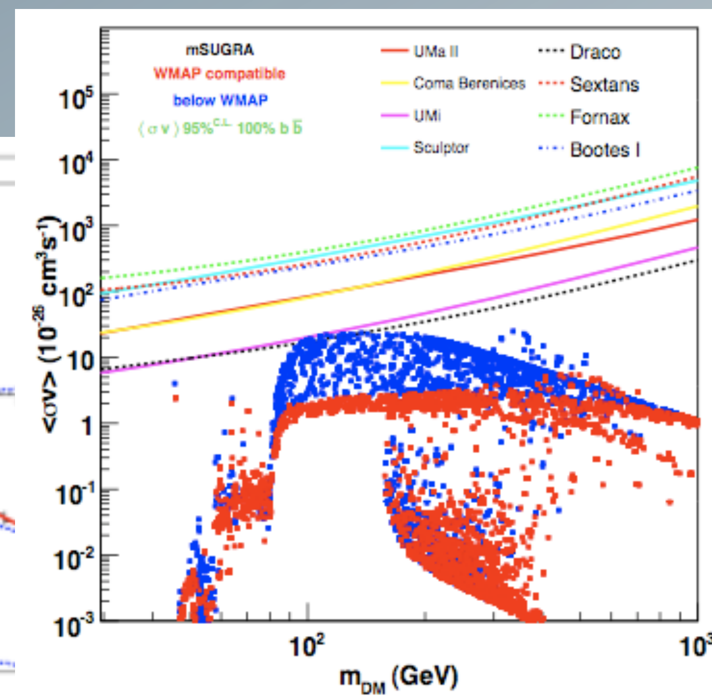

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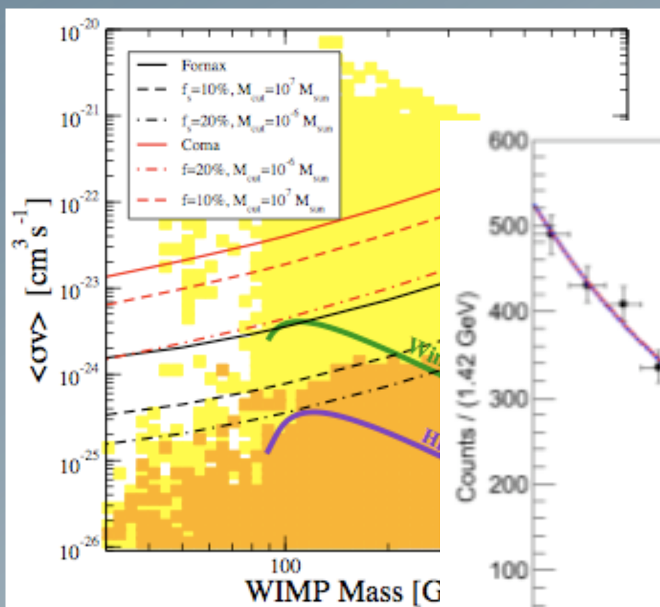

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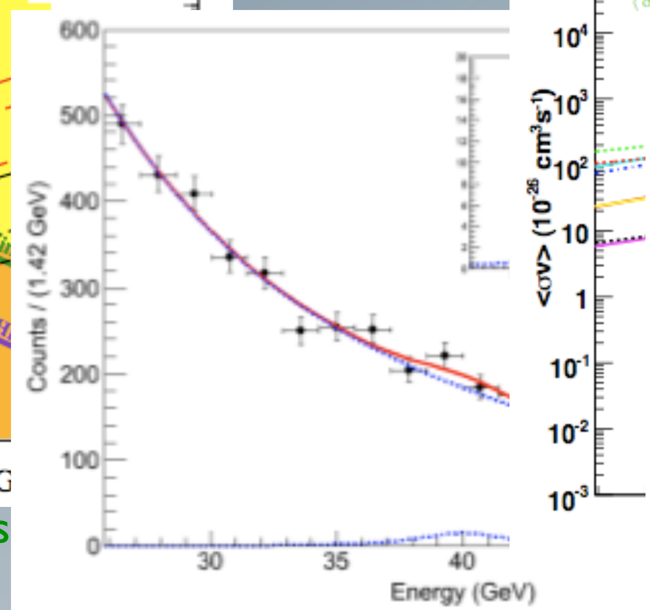

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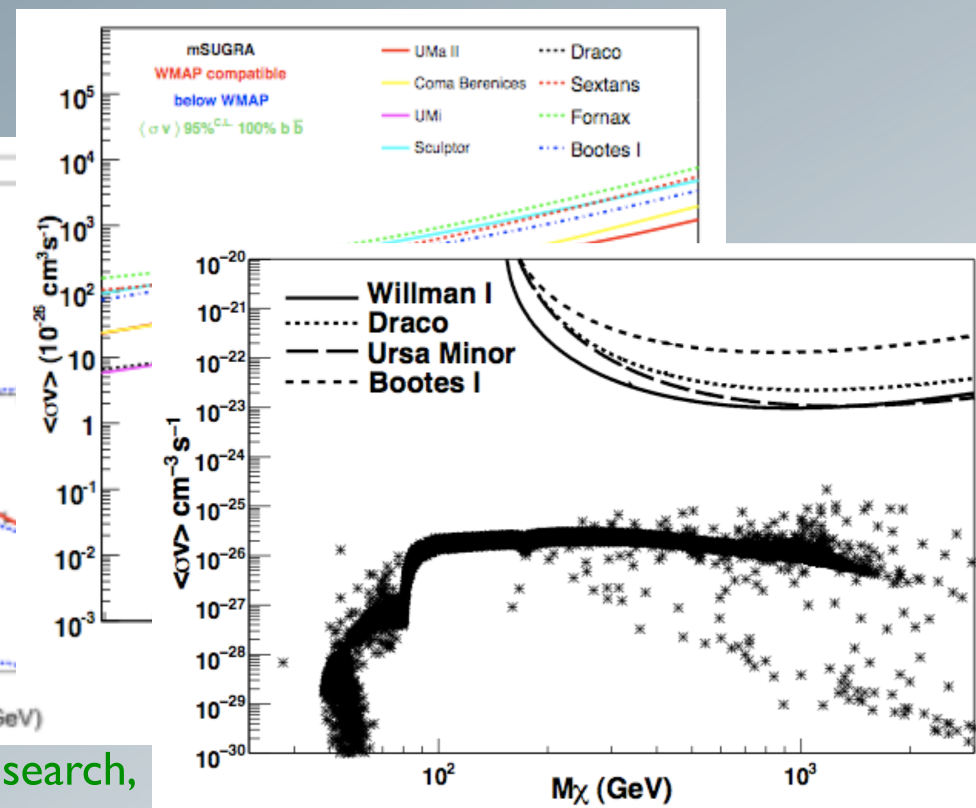

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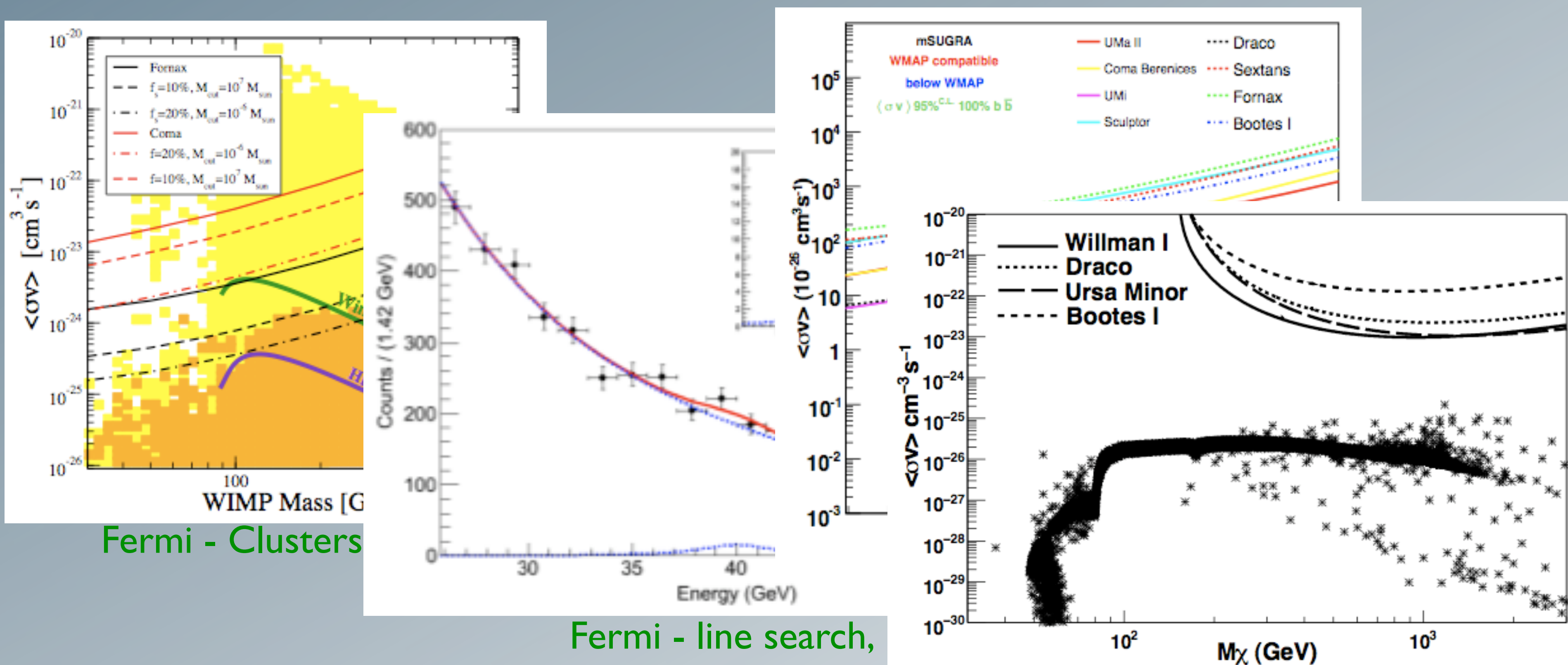

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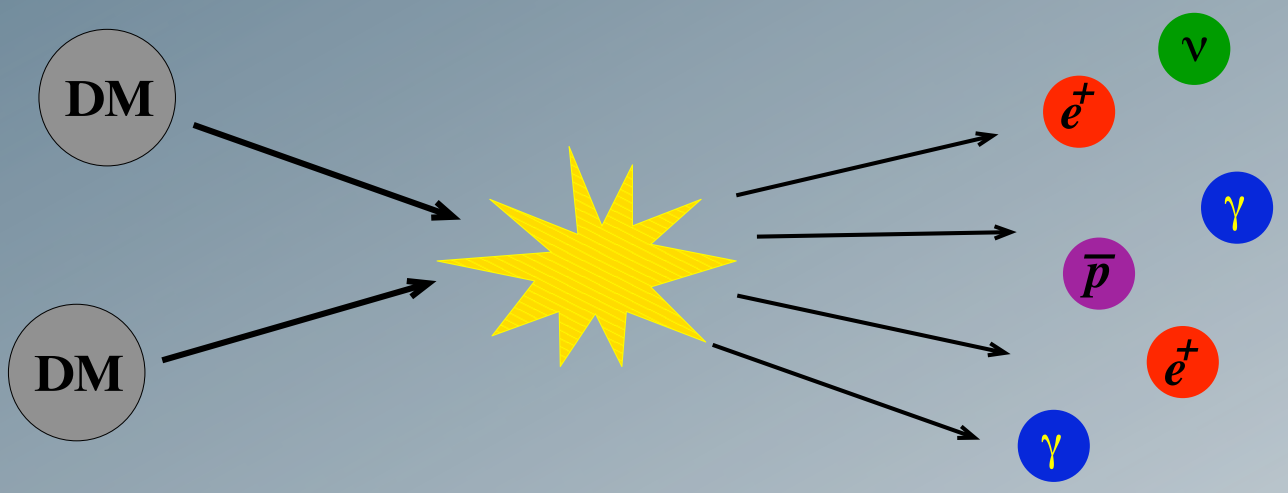
➩ For more details, see talks by:

S.Murgia, B. Cañadas (Fermi), M.Vivier (VERITAS), ...

Indirect DM searches



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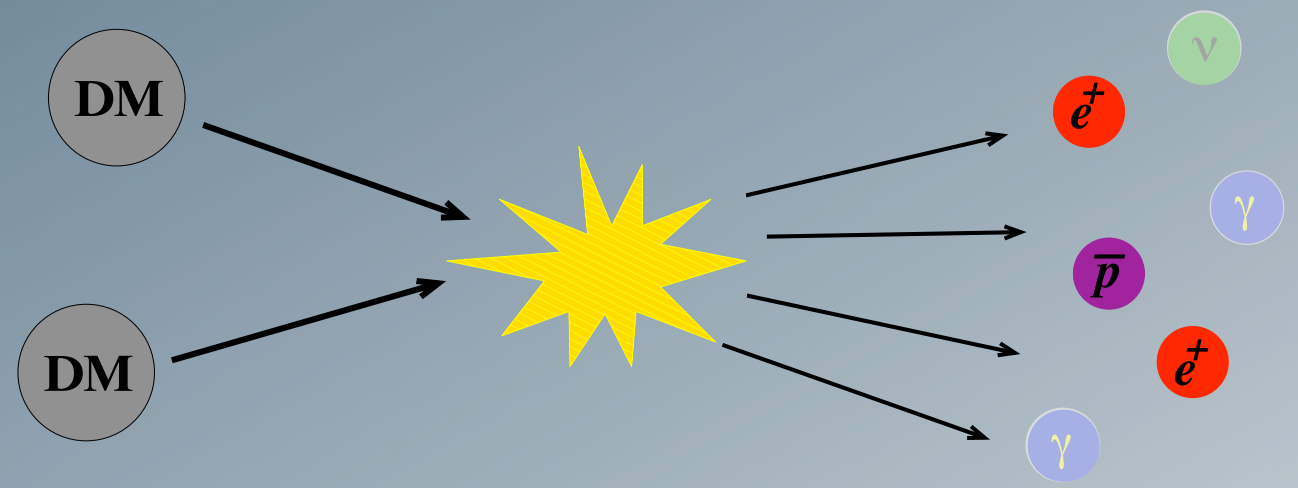

Charged cosmic rays:

- 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

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

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Sources (primary & secondary)

Analytical vs. numerical

How to solve the diffusion equation?

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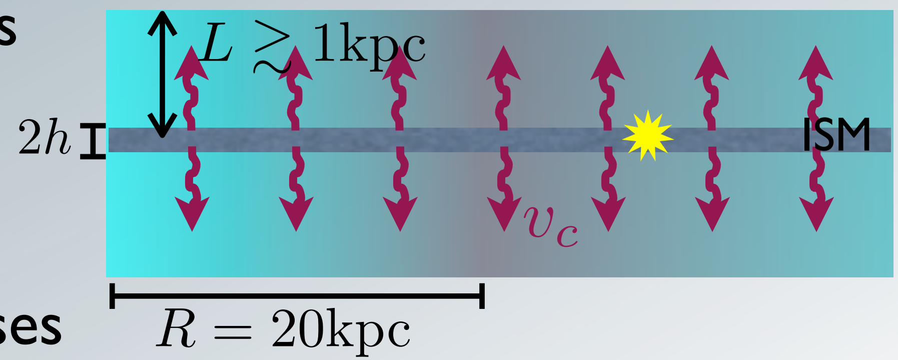
- (Semi-)analytically
  - ⊕ Physical insight from analytic solutions
  - ⊕ fast computations allow to sample full parameter space
  - ⊖ only 2D possible
  - ⊖ simplified gas distribution, energy losses

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

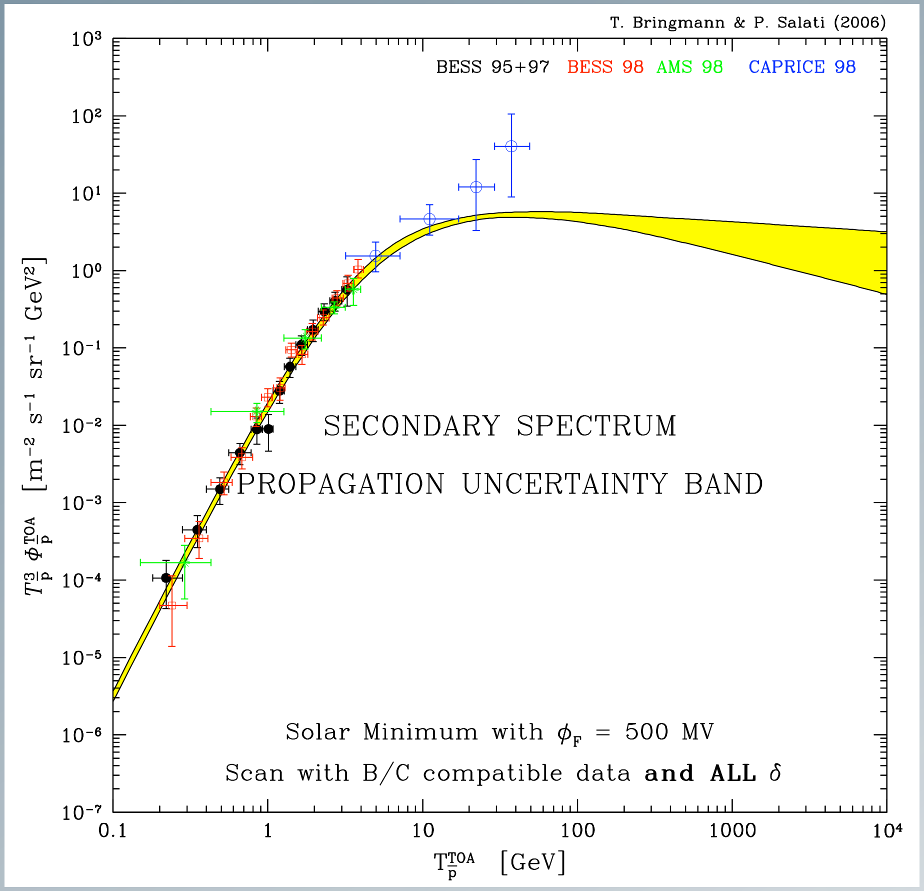


E.g. secondary antiprotons

- 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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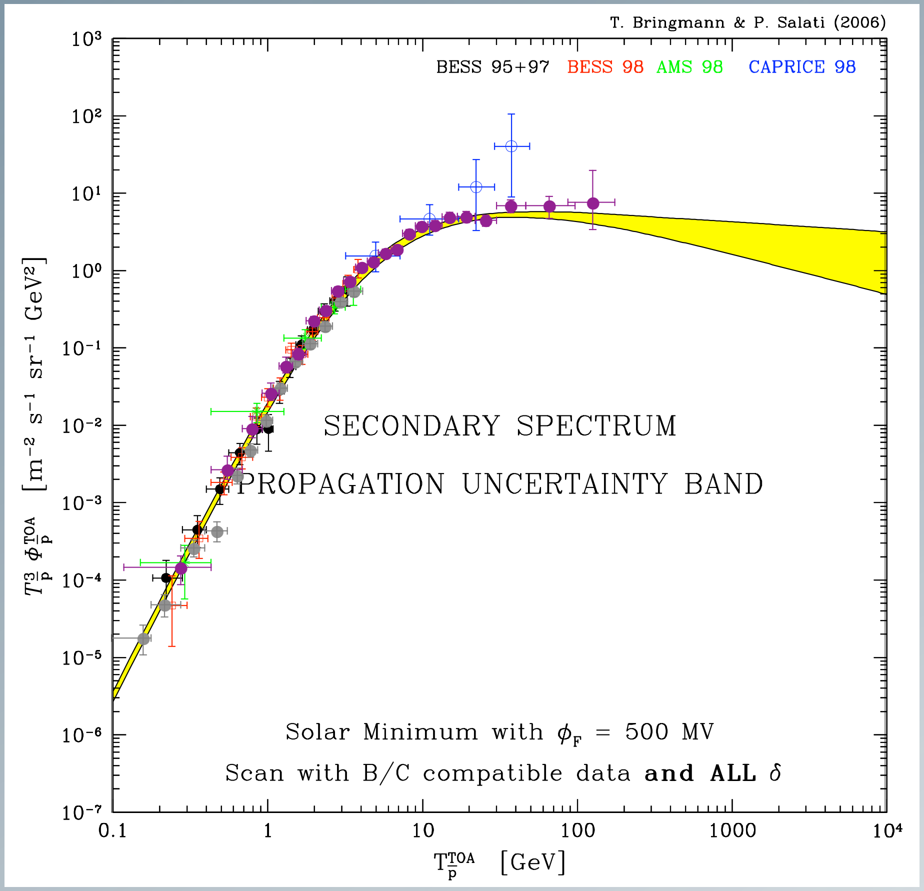

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excellent agreement with new data:

BESSpolar 2004
Abe *et al.*, PRL '08

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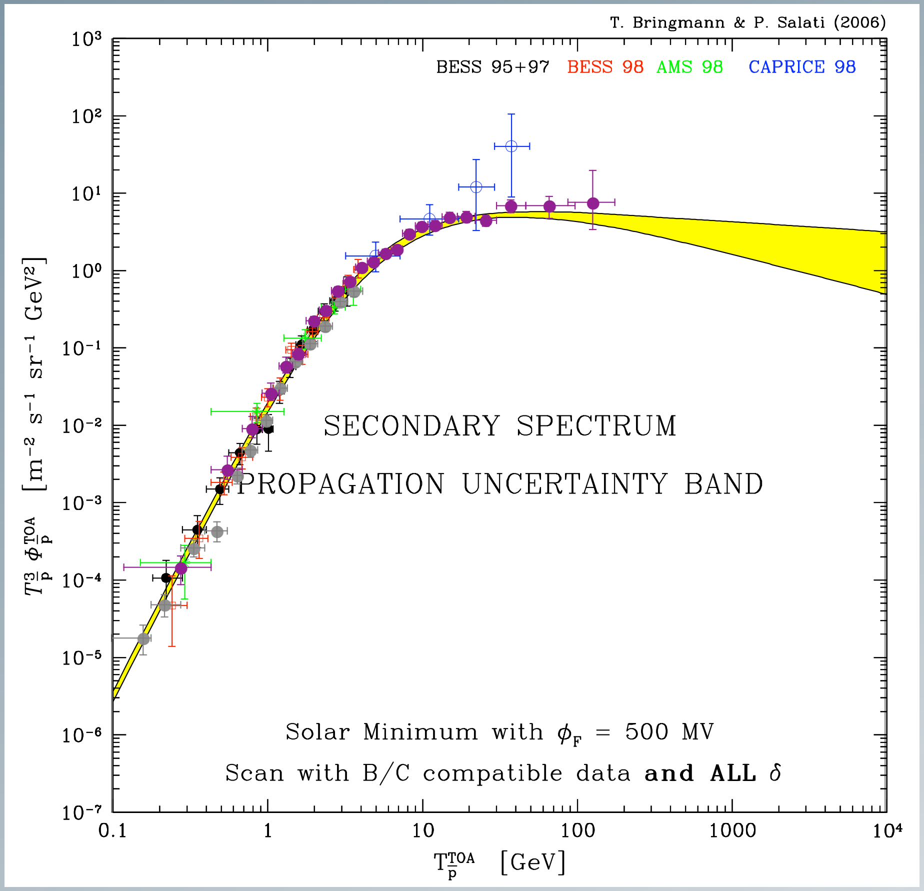

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➡ very nice test for underlying diffusion model!

Antiprotons

- Rather straightforward to handle:
  - no significant astrophysical sources
  - for $E_{\bar{p}} \gtrsim 10\,\mathrm{GeV}$ completely diffusion dominated
- Uncertainties in $\bar{p}$ flux from DM annihilation much larger than for secondaries!

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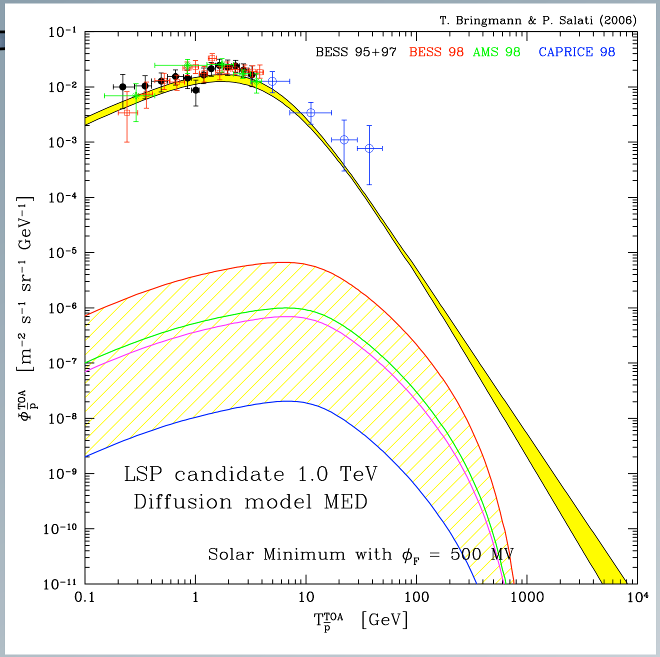

TB & Salati, PRD '09

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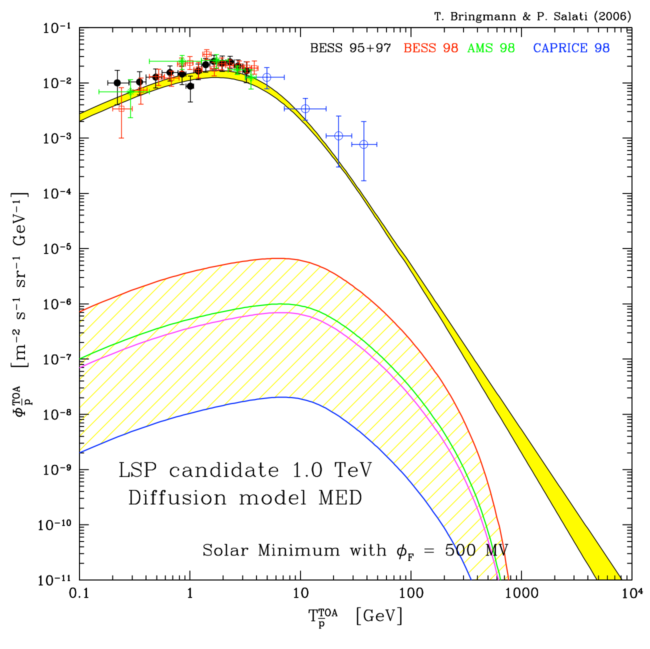
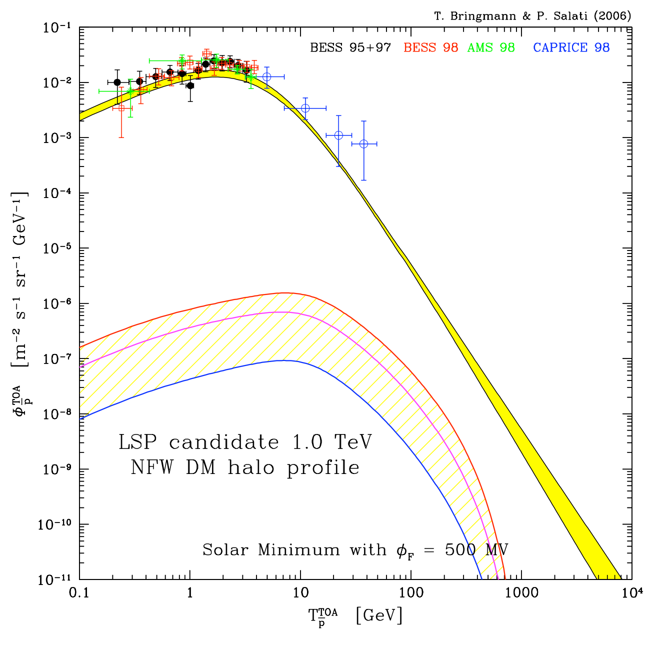
  - up to ~40 from range of propagation parameters compatible with B/C





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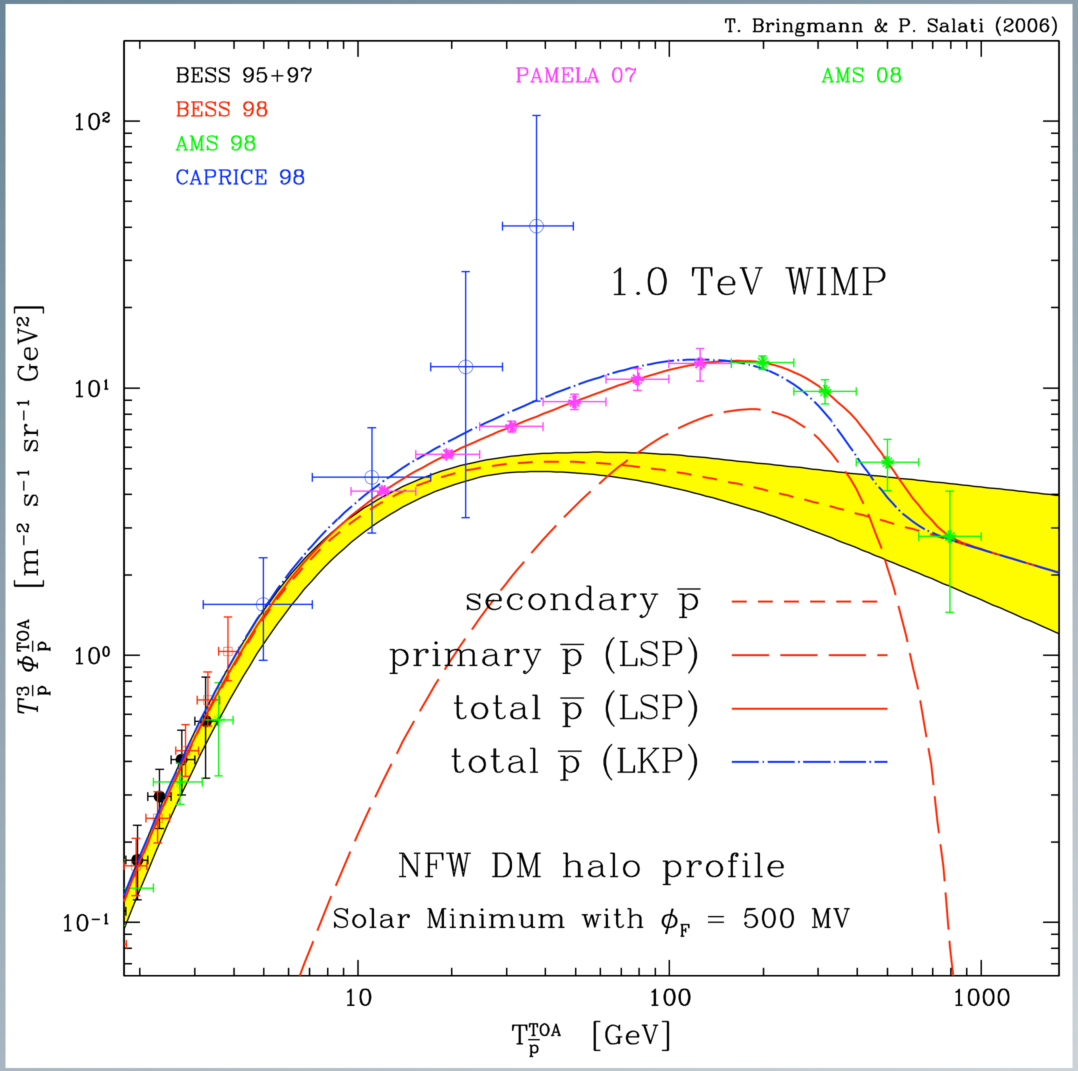

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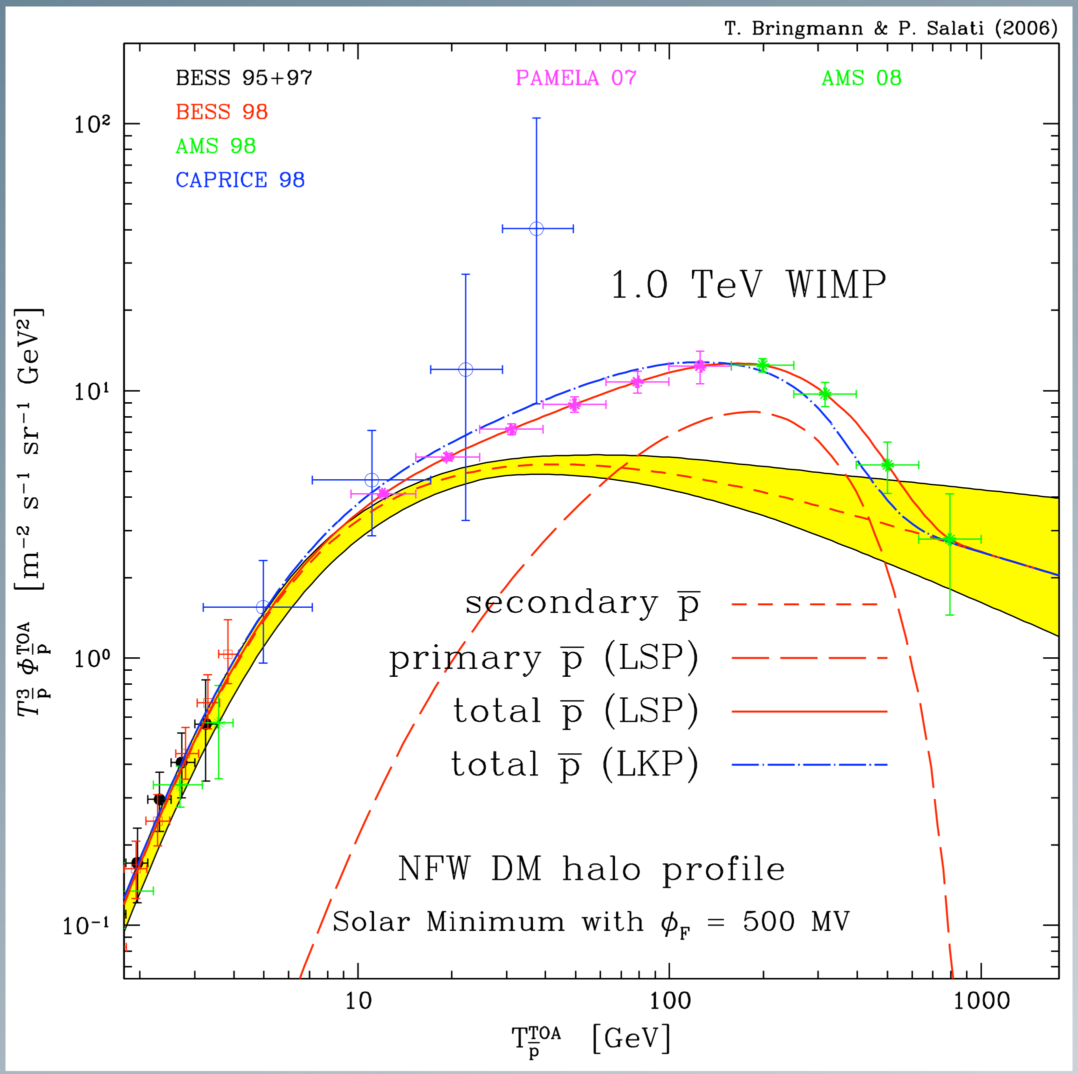
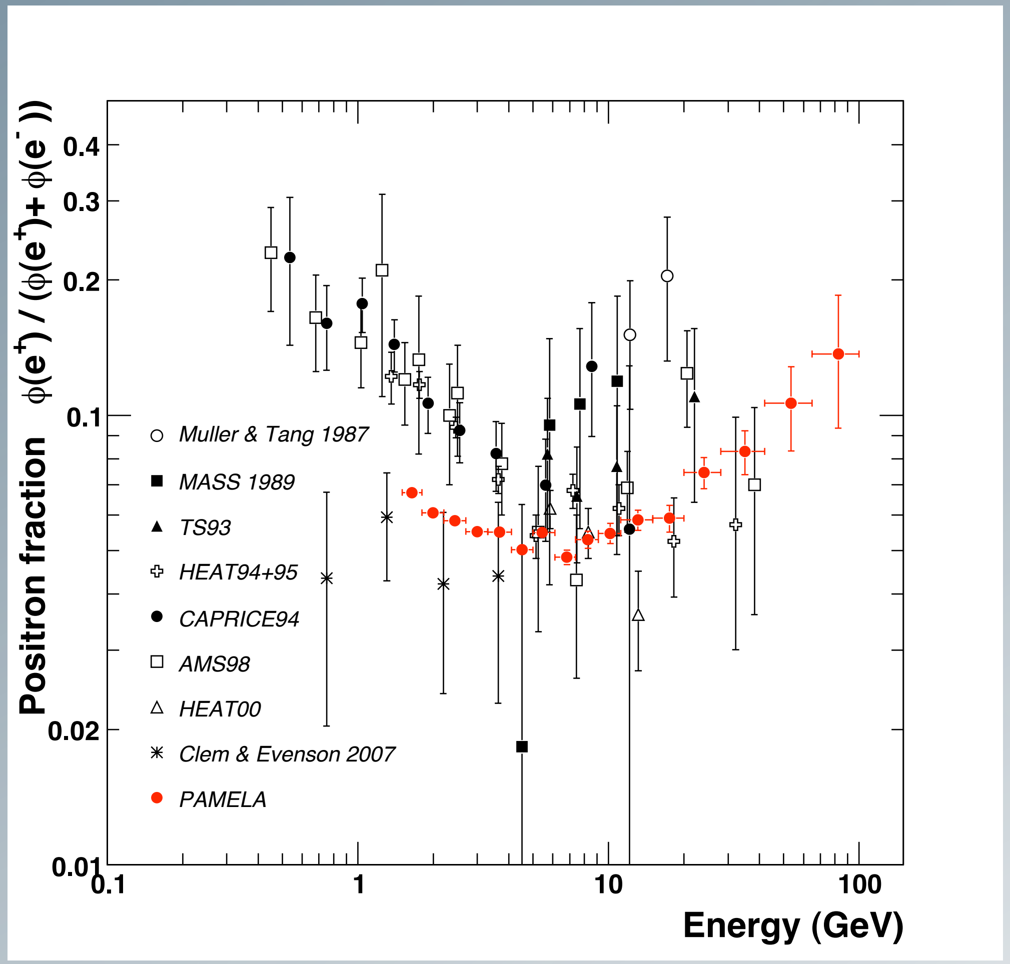


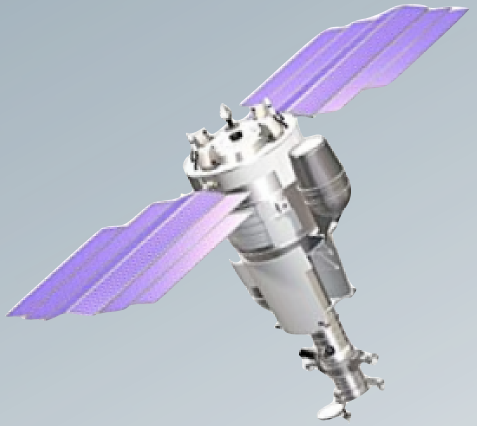
TB & Salati, PRD '09

- 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 ???

SUSY DM and PAMELA

- Neutralino annihilation helicity suppressed:

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

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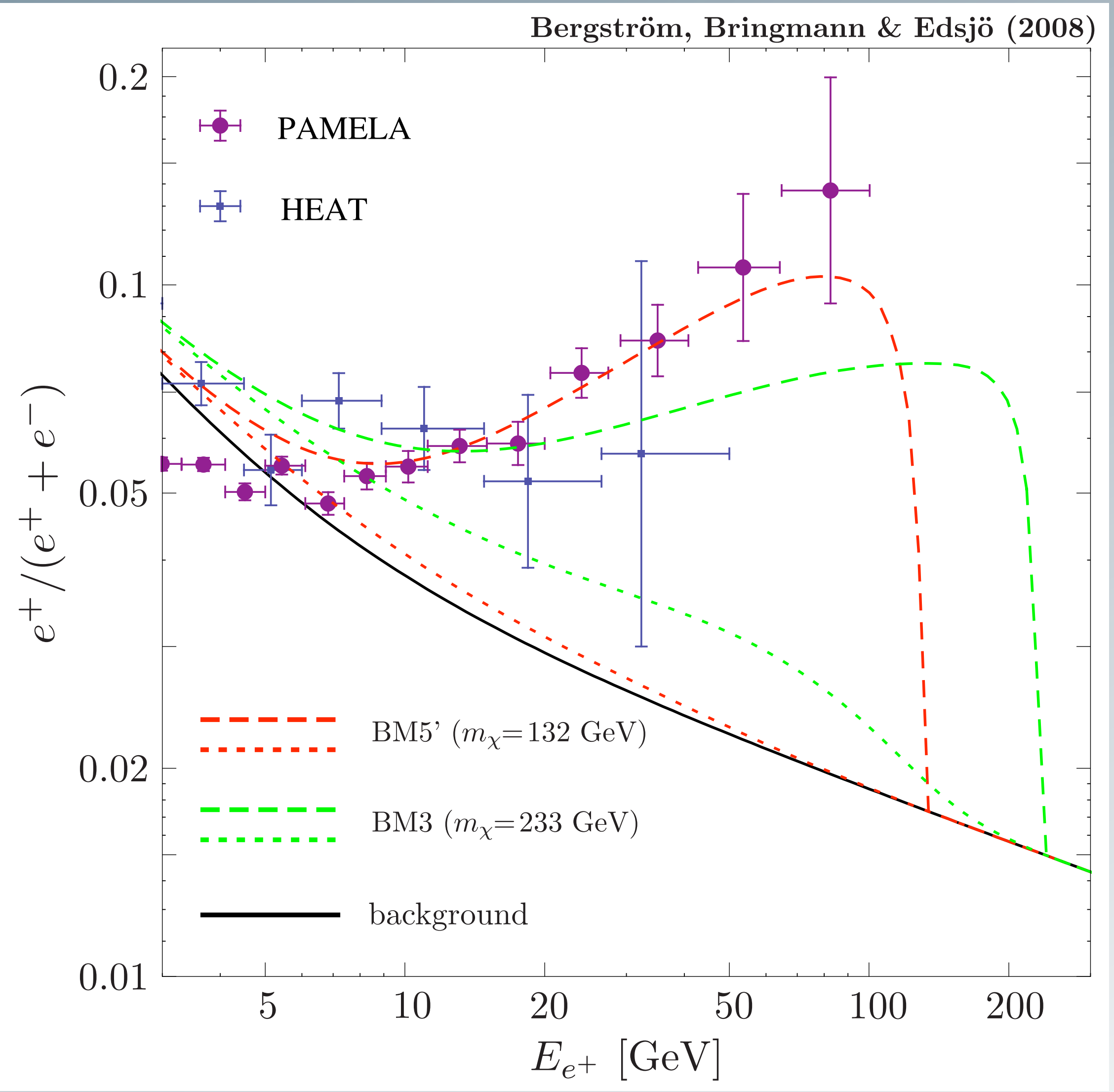
  - ⇨ first attempt to connect PAMELA to DM



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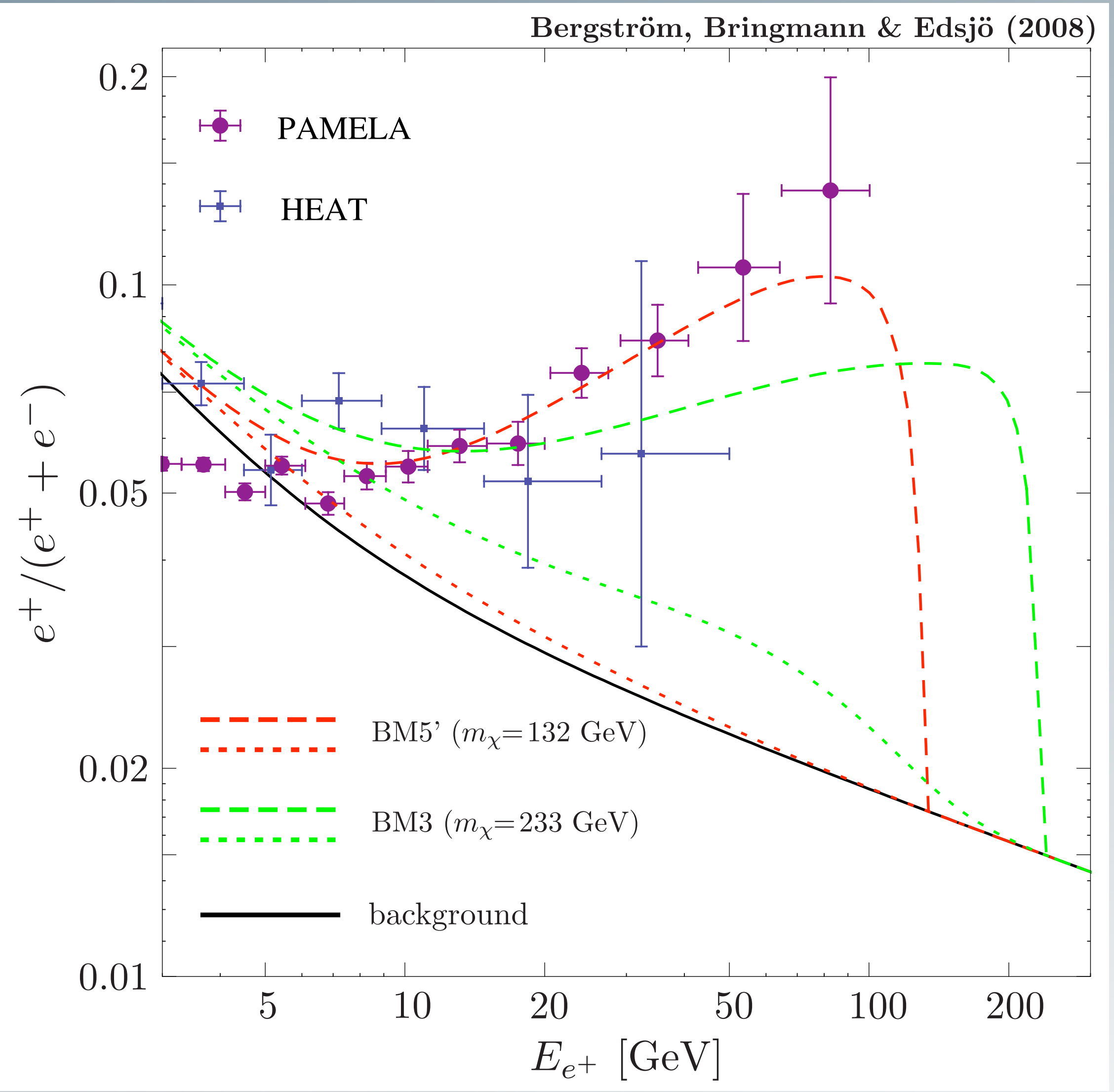
- ***but***: enormous boost factors needed w.r.t. thermal cross section...



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Other DM explanations

- By now, a *large* number of further DM-related attempts to explain the PAMELA data has appeared on the market
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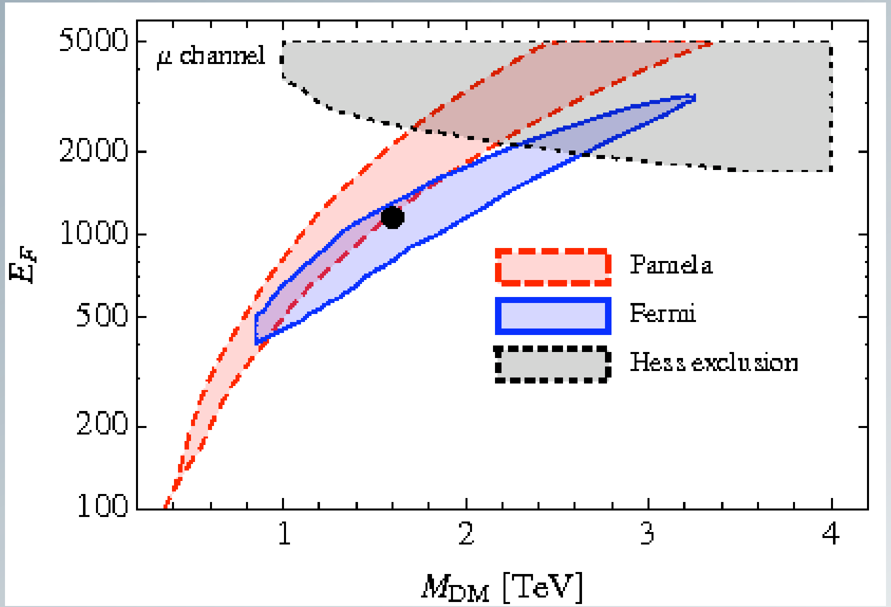

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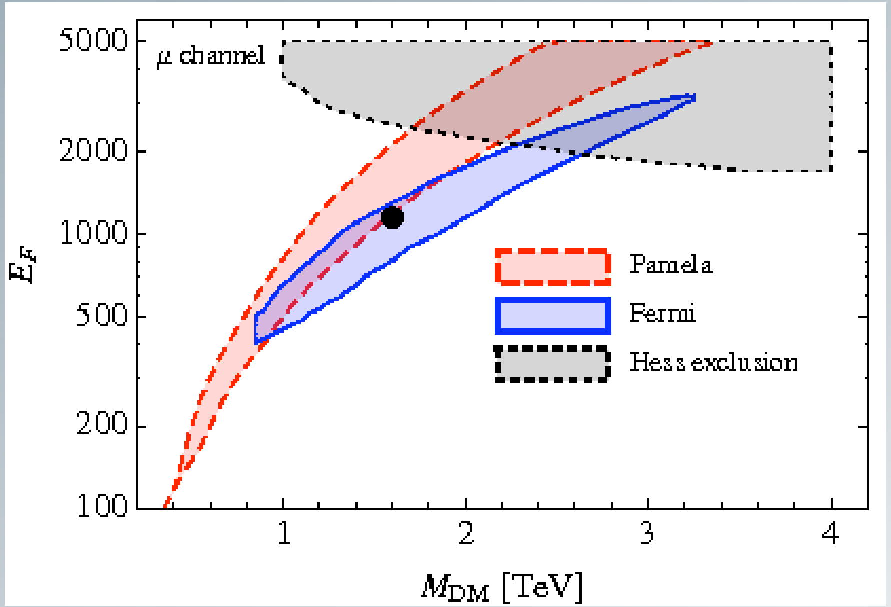

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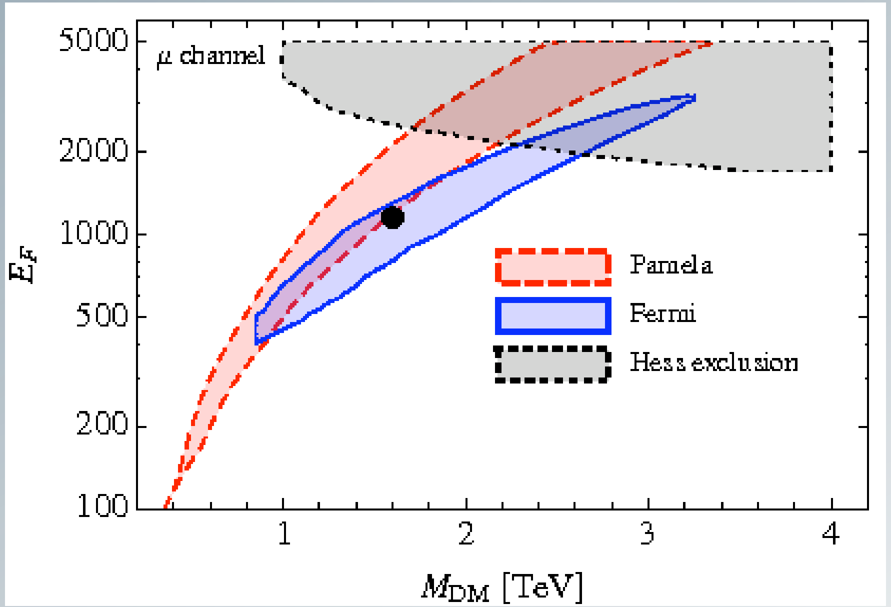

Bergström, Edsjö & Zaharijas, PRL '09

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- Besides: DM by far not the only explanation...

Astrophysical sources

- Propagation uncertainties *not* the main problem:
  - secondaries ~ 2-4 Delahaye *et al.*, A&A '09
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- ***but***: many good astrophysical candidates for primary sources in the cosmic neighbourhood!
  - pulsars Grasso et al., ApP '09; Yüksel, Kistler & Stanev, PRL '09; Profumo, 0812.4457; Malyshev, Cholis & Gelfand, PRD '09
  - old supernova remnants Blasi, PRL '09; Blasi & Serpico, PRL '09
  - GRB Ioka, 0812.4851
  - Large arm/interarm difference in SN rate Shaviv, Nakir & Piran, PRL '09
  - effect of SNR on near dense cloud Fujita, Kohri, Yamazaki & Ioka, PRD '09

Astrophysical sources

- Propagation uncertainties *not* the main problem:
  - secondaries ~ 2-4   Delahaye *et al.*, A&A '09
  - primaries ~ 5   Delahaye *et al.*, PRD '08
  - i.e. *much* better than for primary antiprotons: for $e^{\pm}$, energy loss is dominant ⇨ must be locally produced (~ kpc)
  - very difficult to explain PAMELA data without primary component

- ***but***: many good astrophysical candidates for primary sources in the cosmic neighbourhood!
  - pulsars   Grasso et al., ApP '09; Yüksel, Kistler & Stanev, PRL '09; Profumo, 0812.4457; Malyshev, Cholis & Gelfand, PRD '09
  - old supernova remnants   Blasi, PRL '09; Blasi & Serpico, PRL '09
  - GRB   Ioka, 0812.4851
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⇨ see talk by S. Sarkar

Multi-messenger approaches

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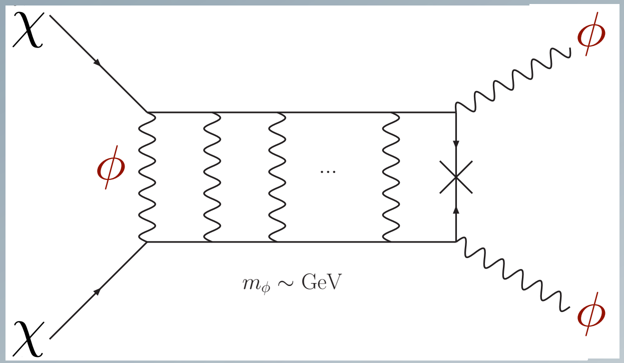
- In order to disentangle these possibilities (astro-physical vs. DM), cleaner spectral signatures are needed
  ⇨ wait for upcoming higher statistics experiments ???
- More promising – and probably anyway needed – is the combination of different detection channels!

"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!)



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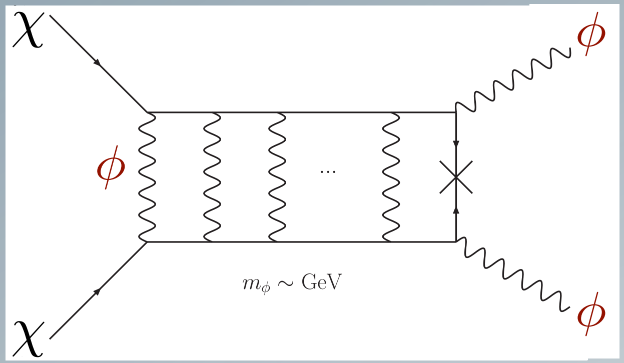
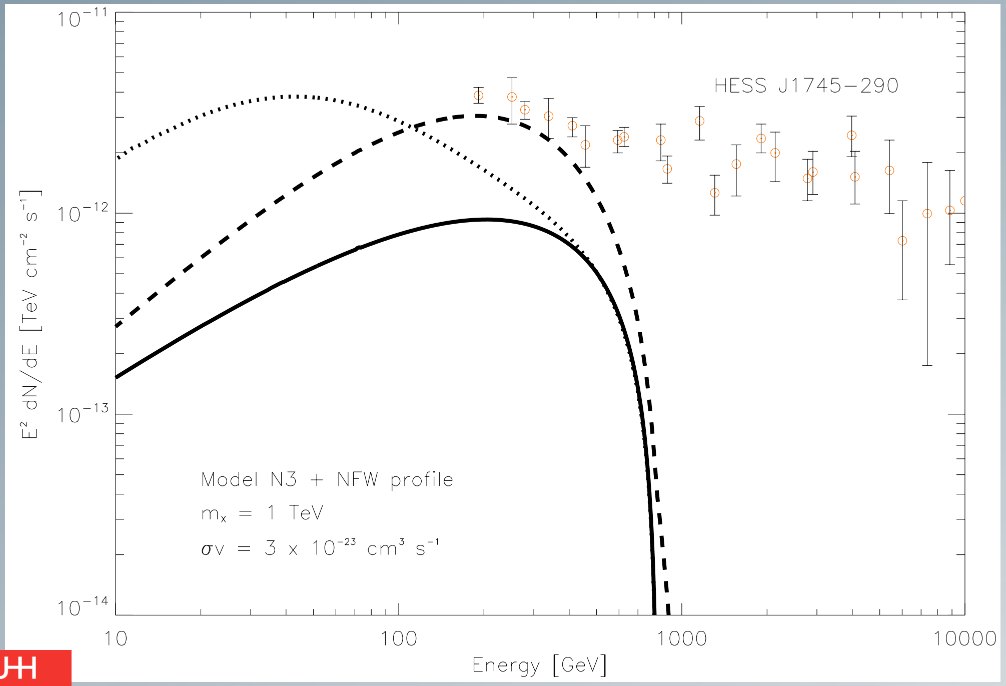
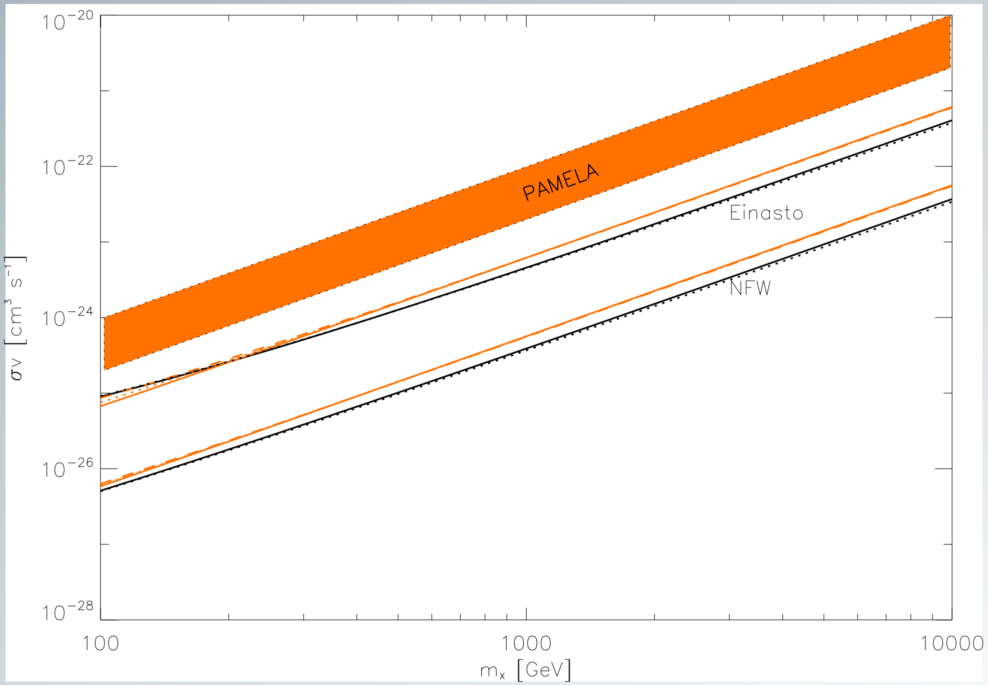


- ***but***: strong constraints from γ (IB) and radio (synchroton)!

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

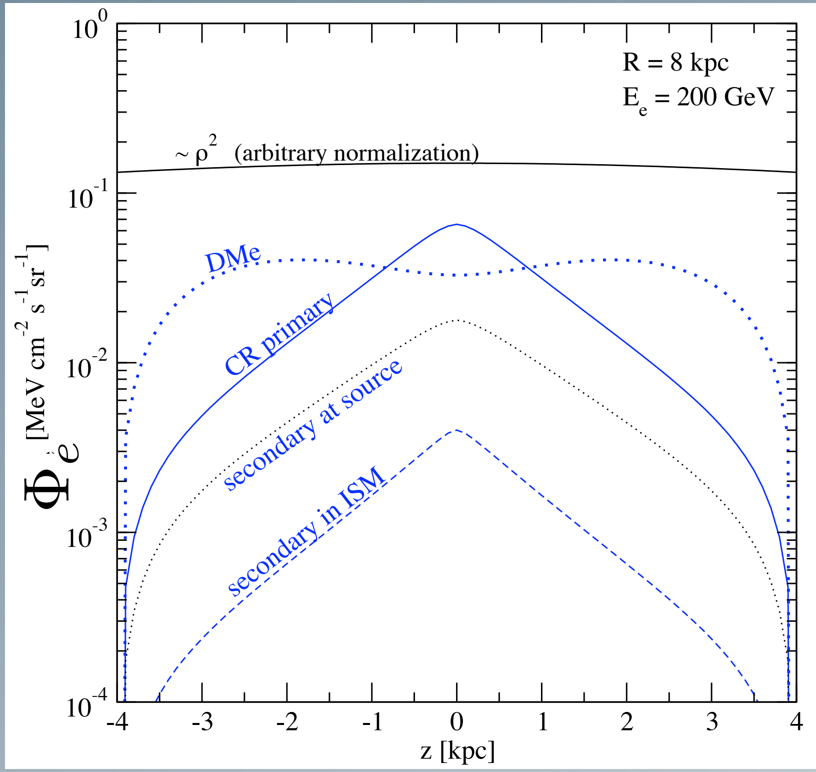




Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

Regis & Ullio, PRD '09



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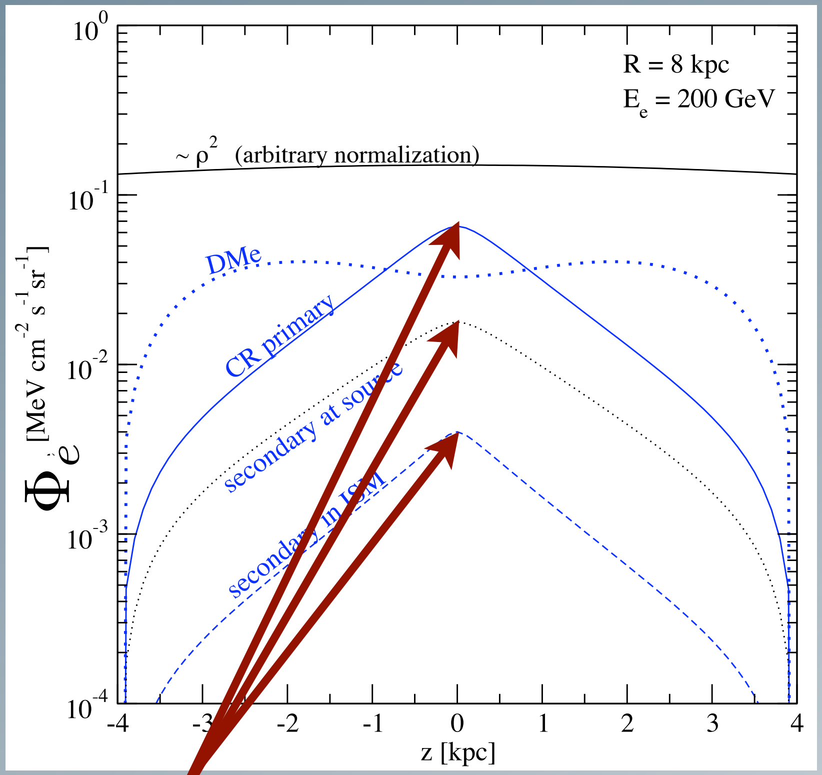

Primary/secondary astrophysical source localized at z=0

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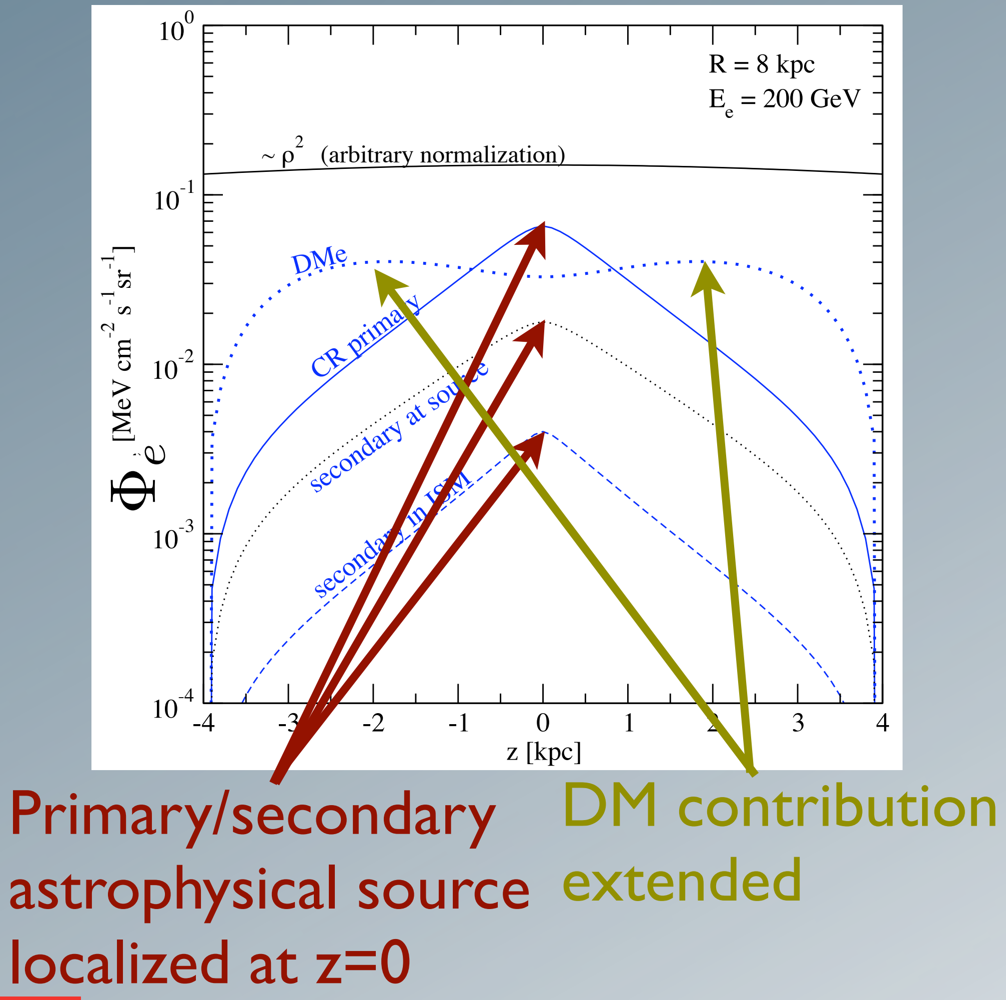

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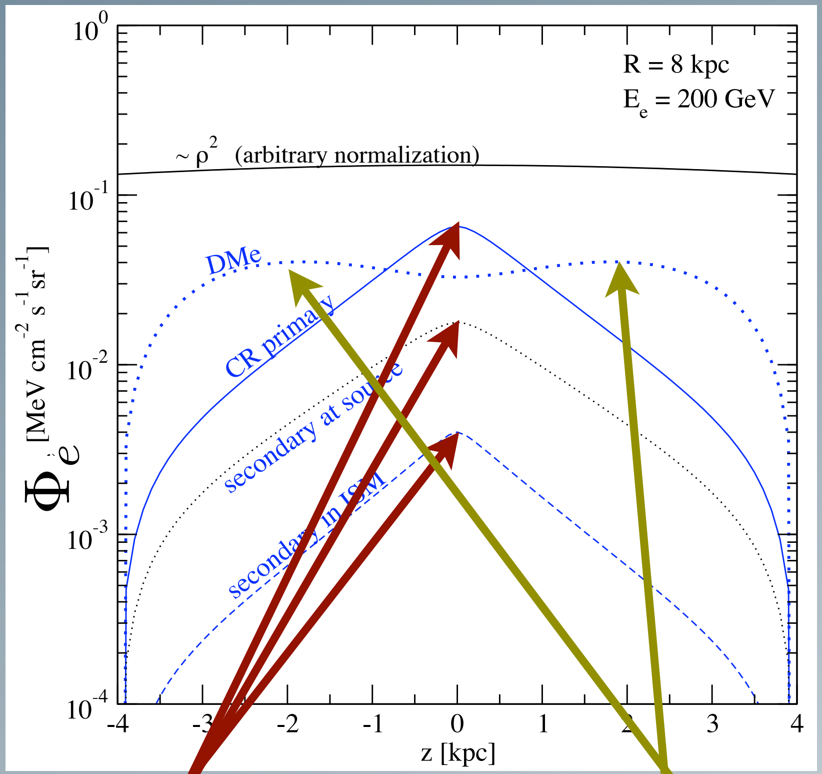

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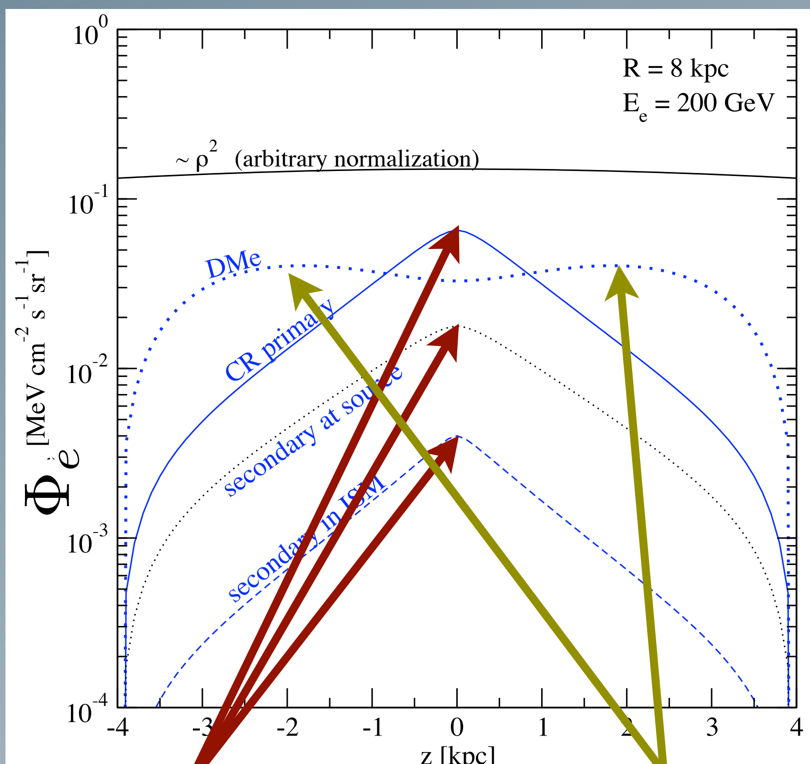

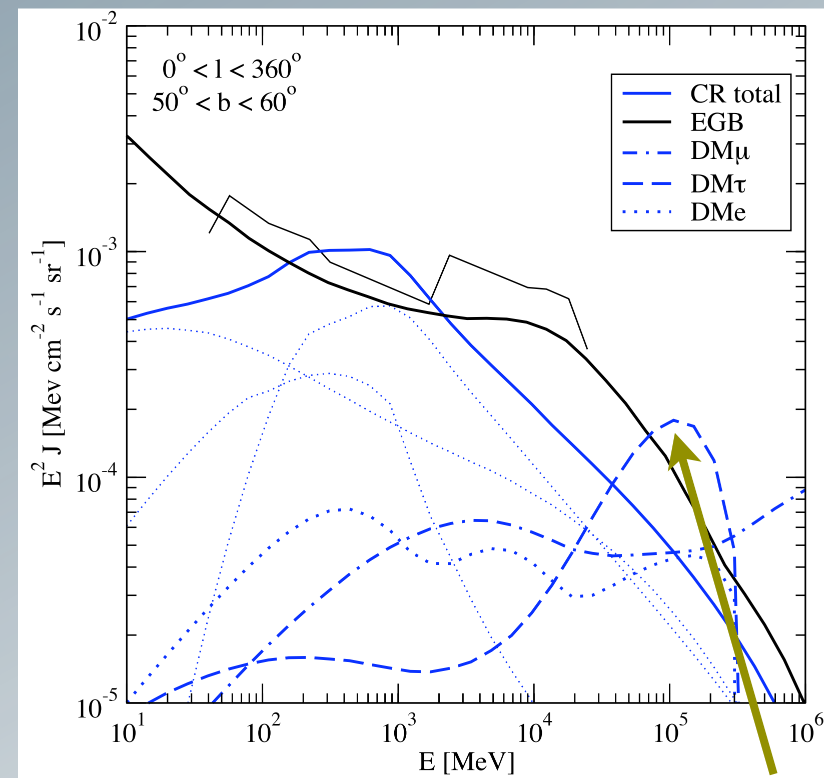

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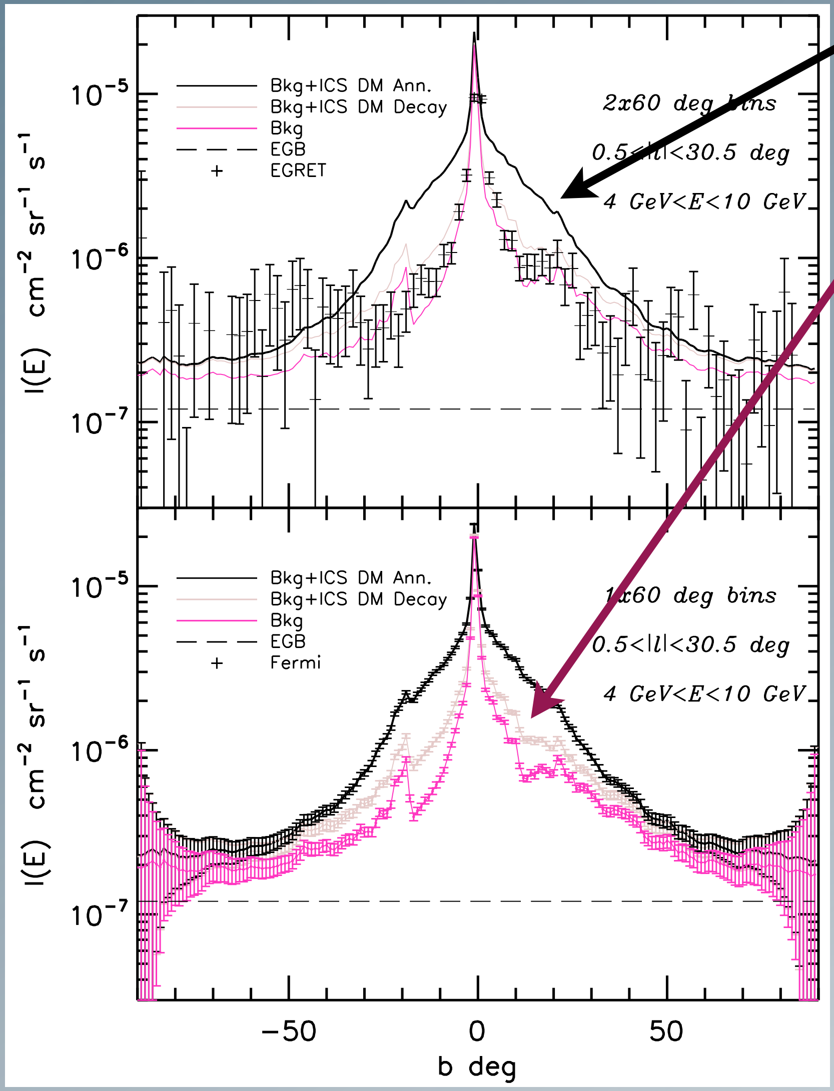
IC+FSR emission from DM component could be seen against diffuse background

Diffuse γ-ray constraints



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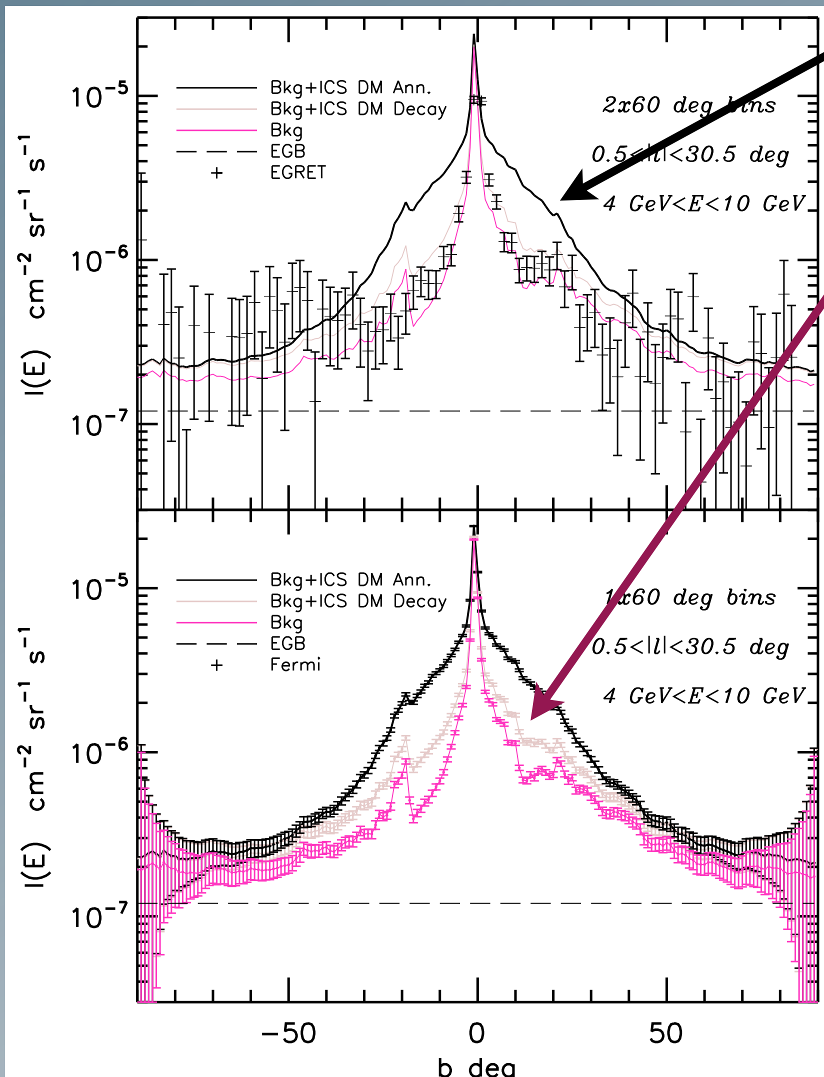

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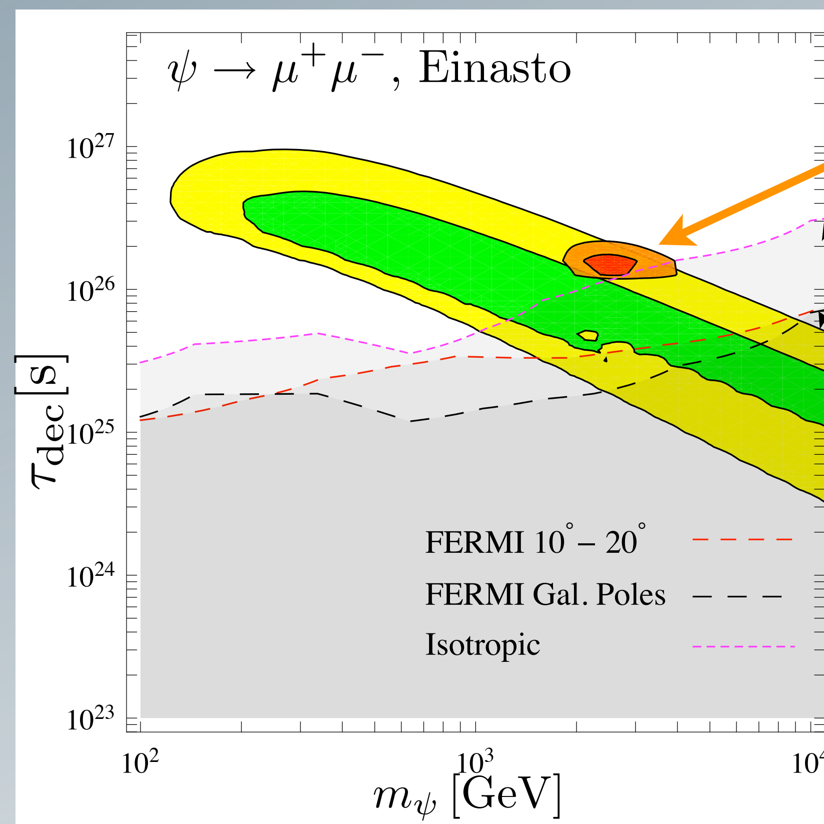
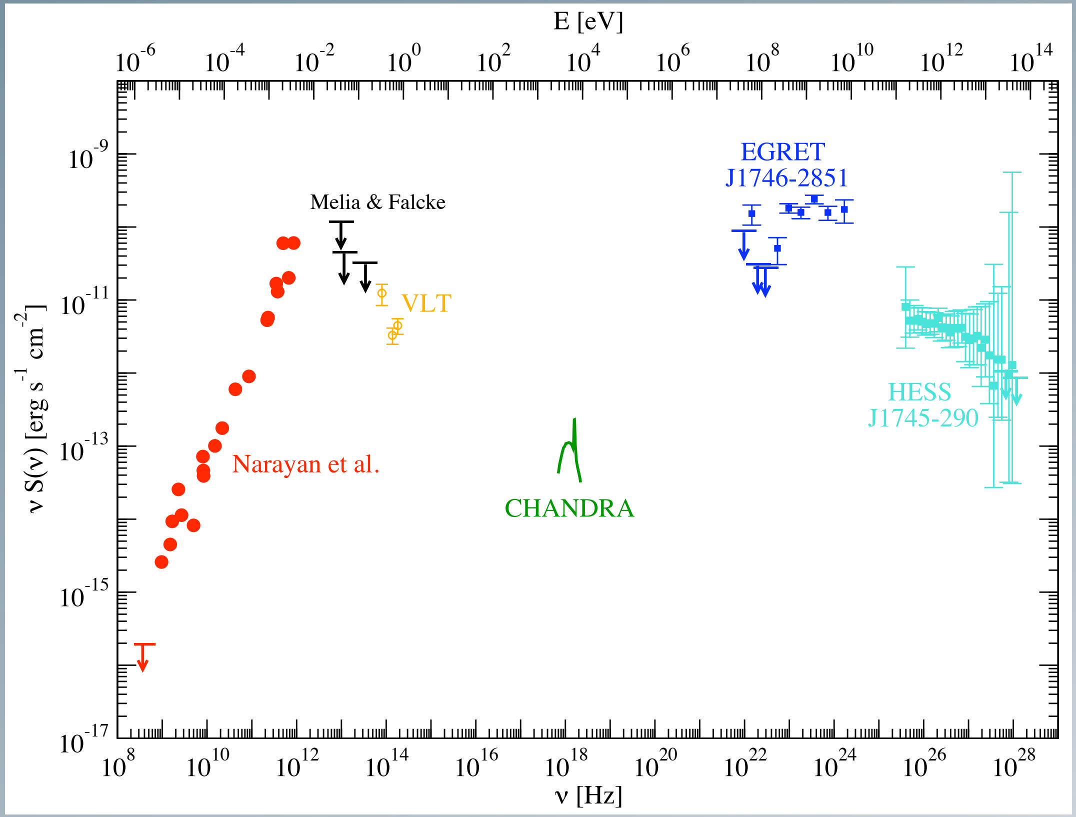


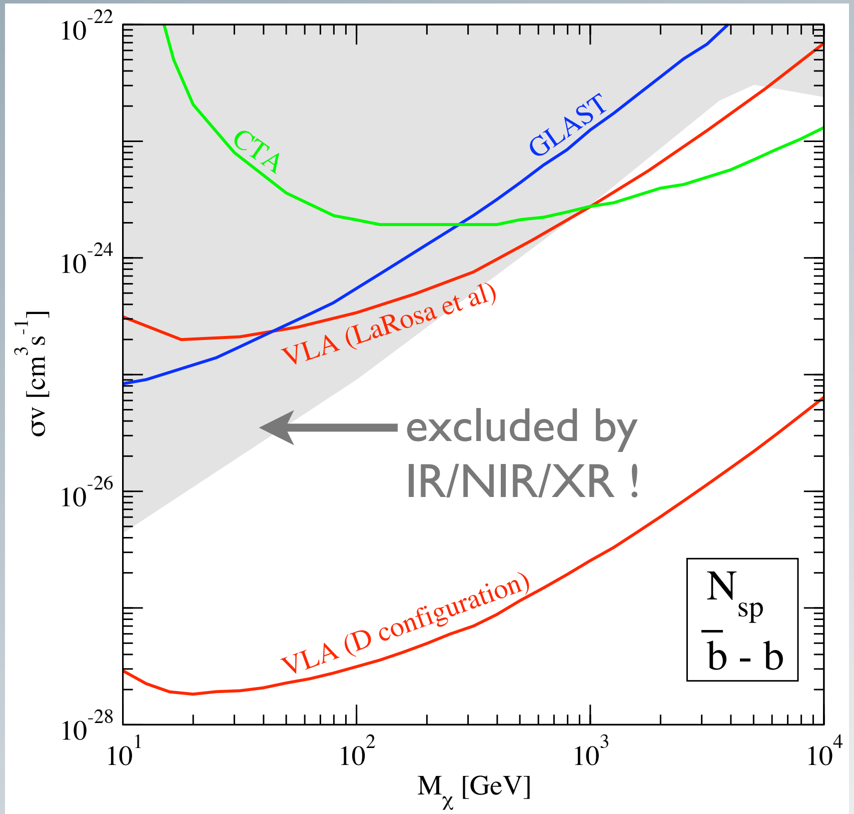
Cirelli, Panci & Serpico, 0912.0663

Multi-Wavelength

- E.g. the Galactic Center: An interesting target for multi-wavelength searches!

Regis & Ullio, PRD '08





⇨ Gamma rays not necessarily most constraining!

How far can we go?

- Impressive improvements of direct detection limits in recent years!
- Potential of indirect searches not yet fully capitalized:
  - small eff. areas (Fermi)
  - relatively short observation times (HESS, VERITAS, MAGIC, …)
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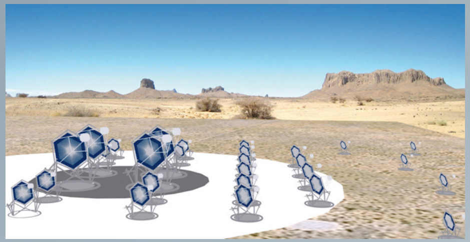
  $\rightsquigarrow$ access to observation time will continue to be an issue
- What could a dedicated future dark matter indirect detection experiment achieve?

➩ *Let's think BIG…!*

The Dark Matter Array

- Focus on a CTA-like design with a large array of Cherenkov Telescopes



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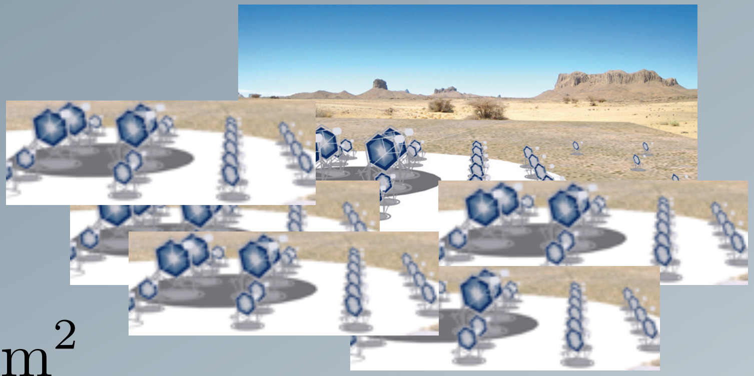

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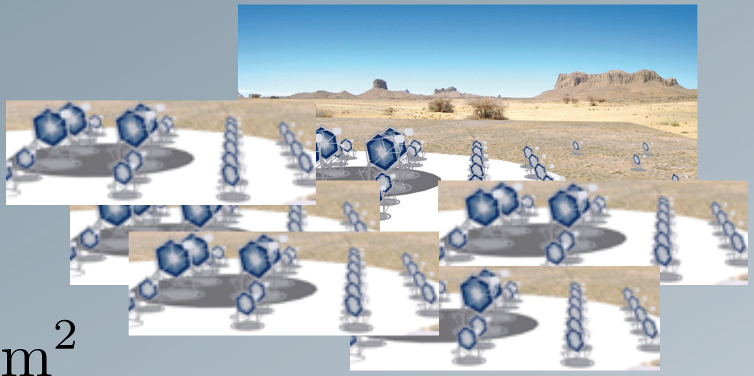

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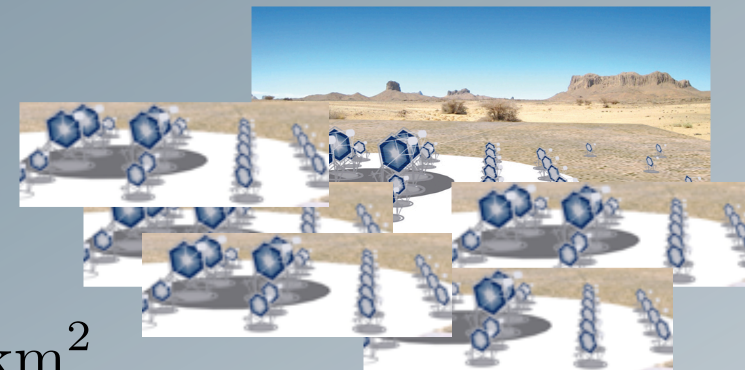

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5@5 – a 5 GeV energy threshold array of imaging atmospheric Cherenkov telescopes at 5 km altitude

F.A. Aharonian [a,*], A.K. Konopelko [a], H.J. Völk [a], H. Quintana [b]

"5@5"

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We discuss the concept and the performance of a powerful future ground-based astronomical instrument, 5@5 – a **5** GeV energy threshold stereoscopic array of several large imaging atmospheric Cherenkov telescopes (IACTs) installed **at** a very high mountain elevation of about **5** km a.s.l. – for the study of the γ-ray sky at energies from approximately 5 to 100 GeV, where the capabilities of both the current space-based and ground-based γ-ray projects are quite limited.

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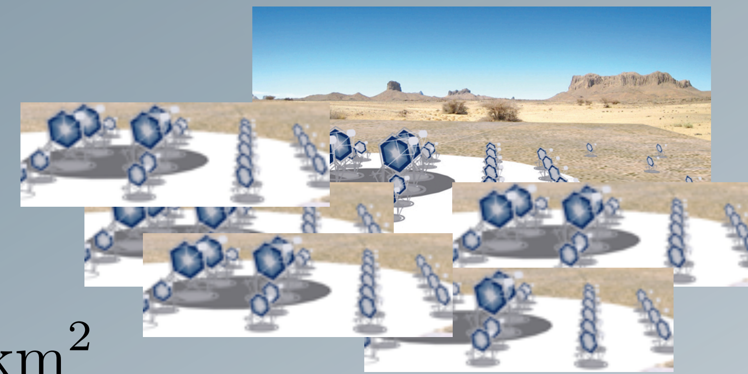

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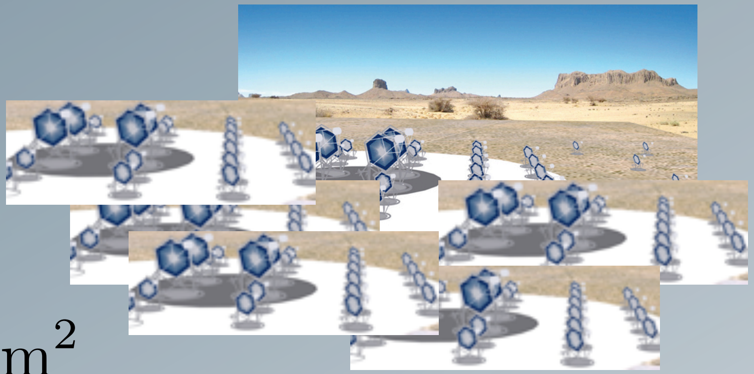

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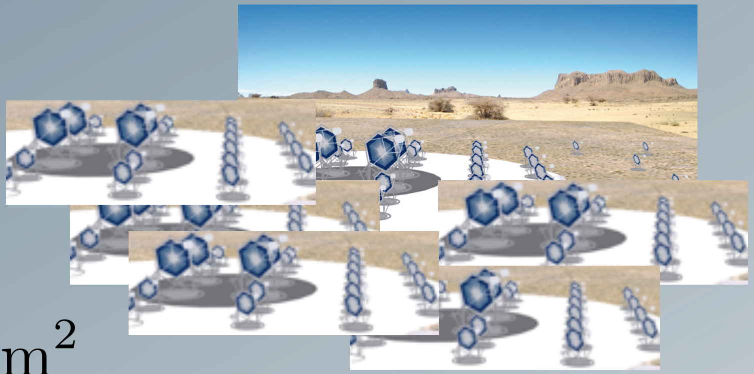

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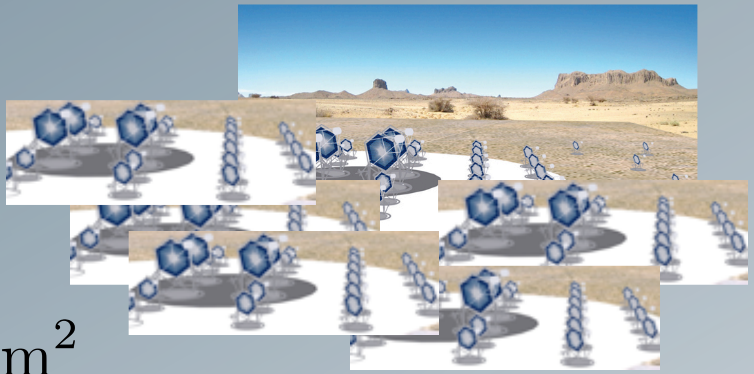

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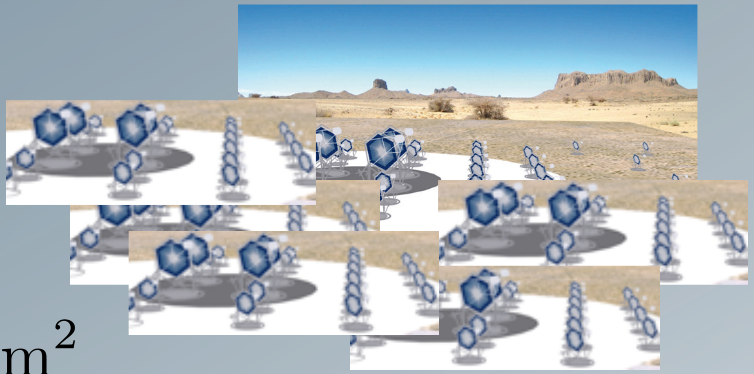

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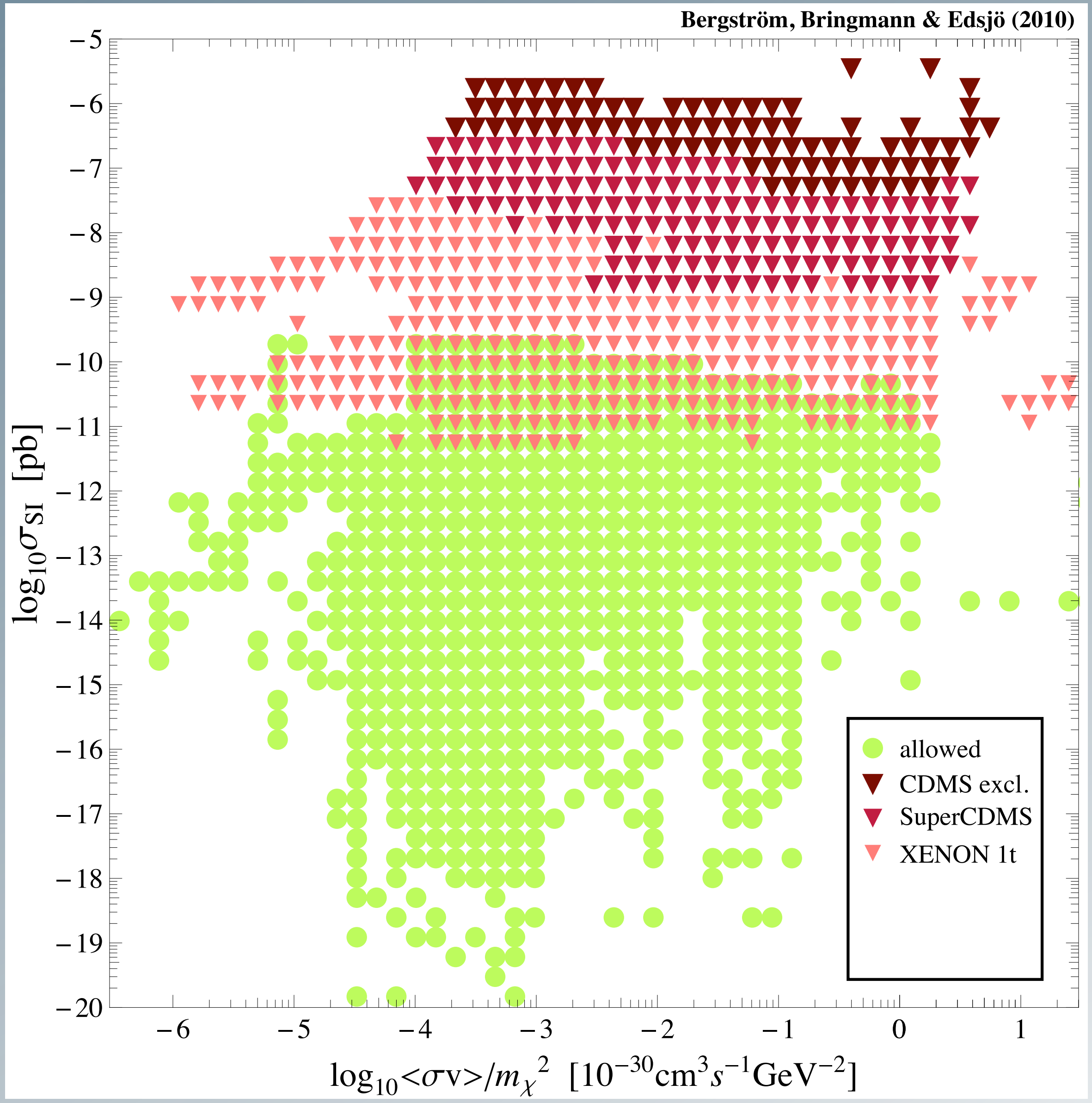
Maybe…
But should be investigated further!

Direct vs. indirect detection

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



preliminary!

(Bergström, TB & Edsjö, in prep.)

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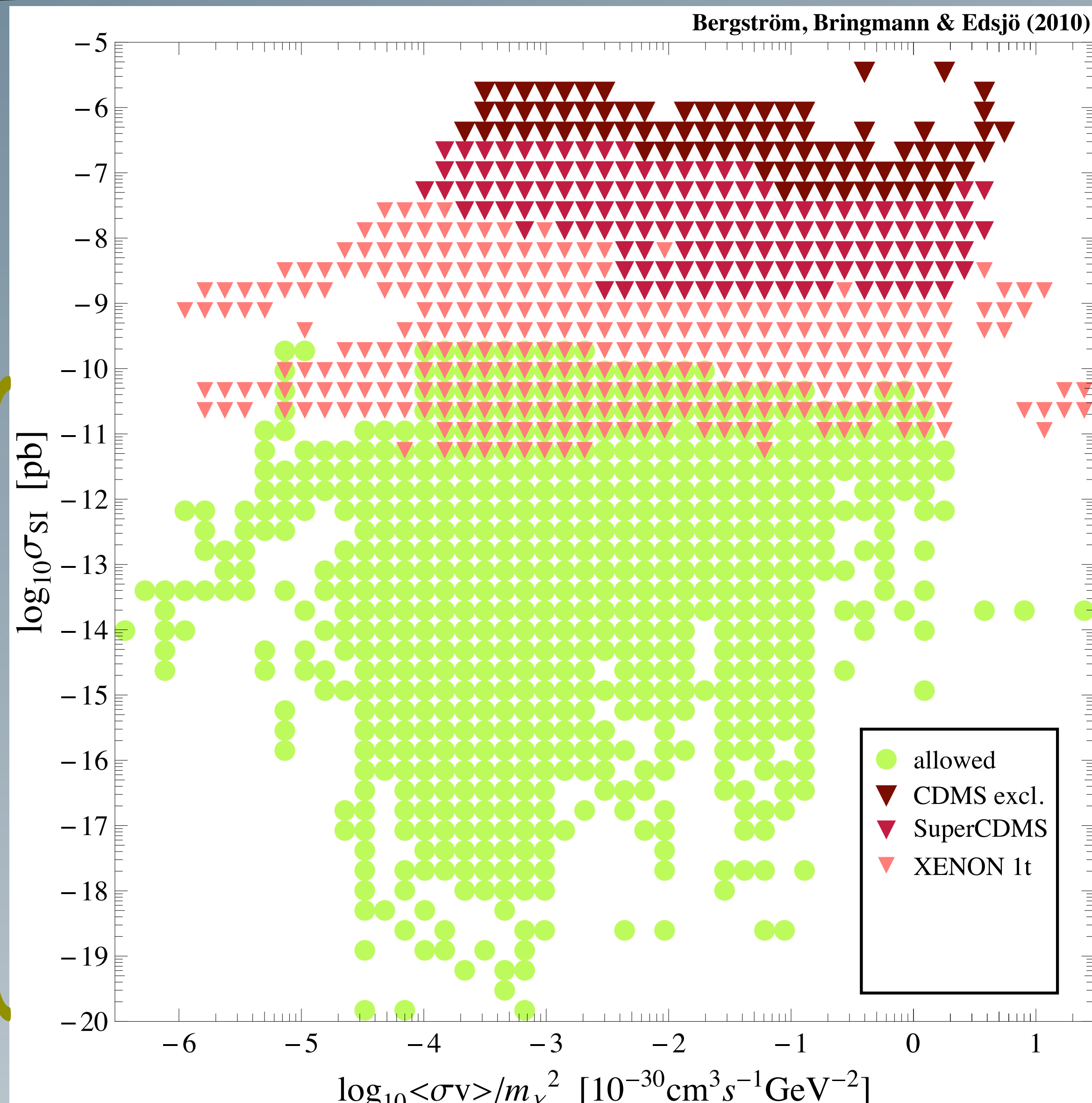

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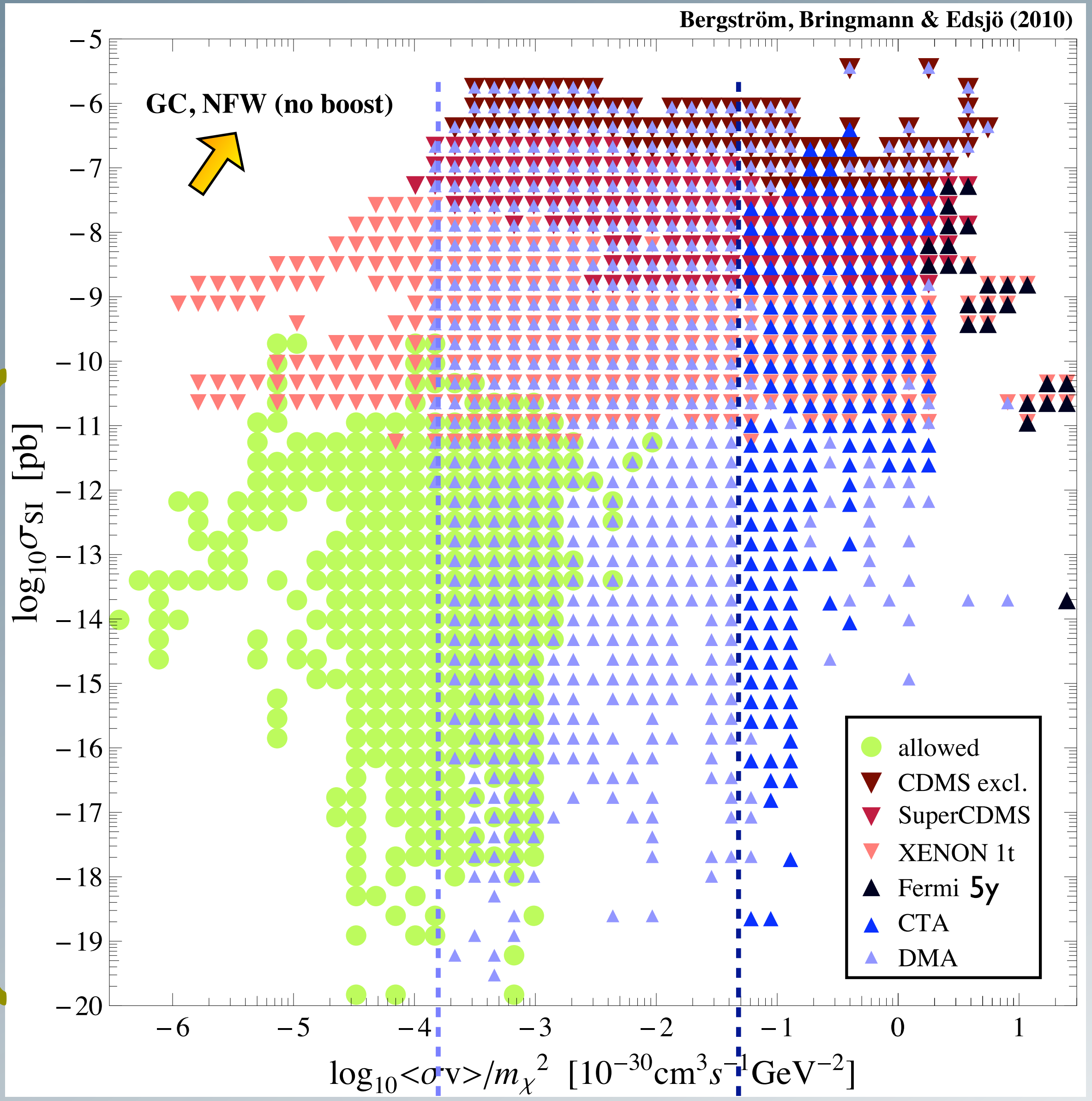

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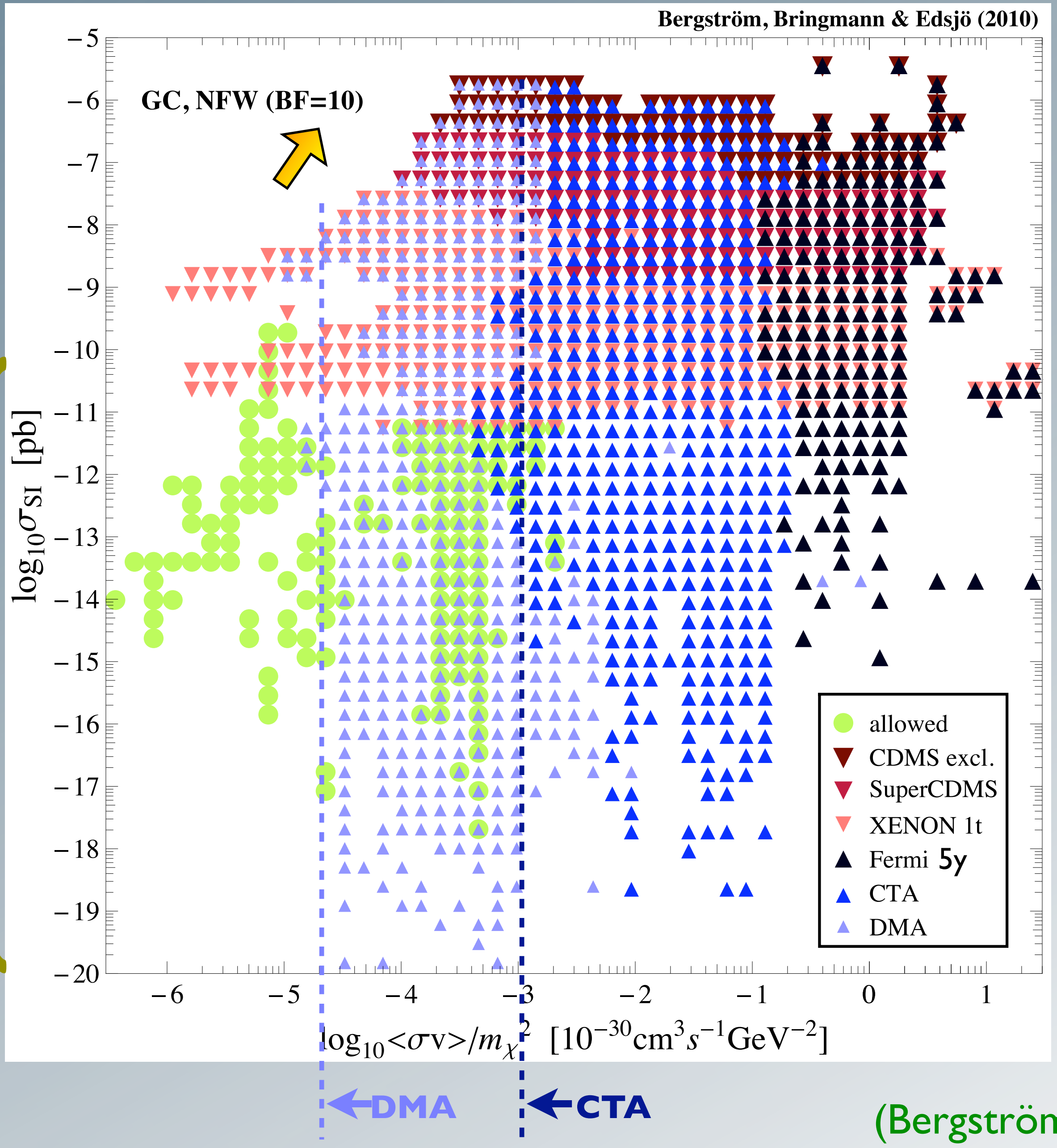

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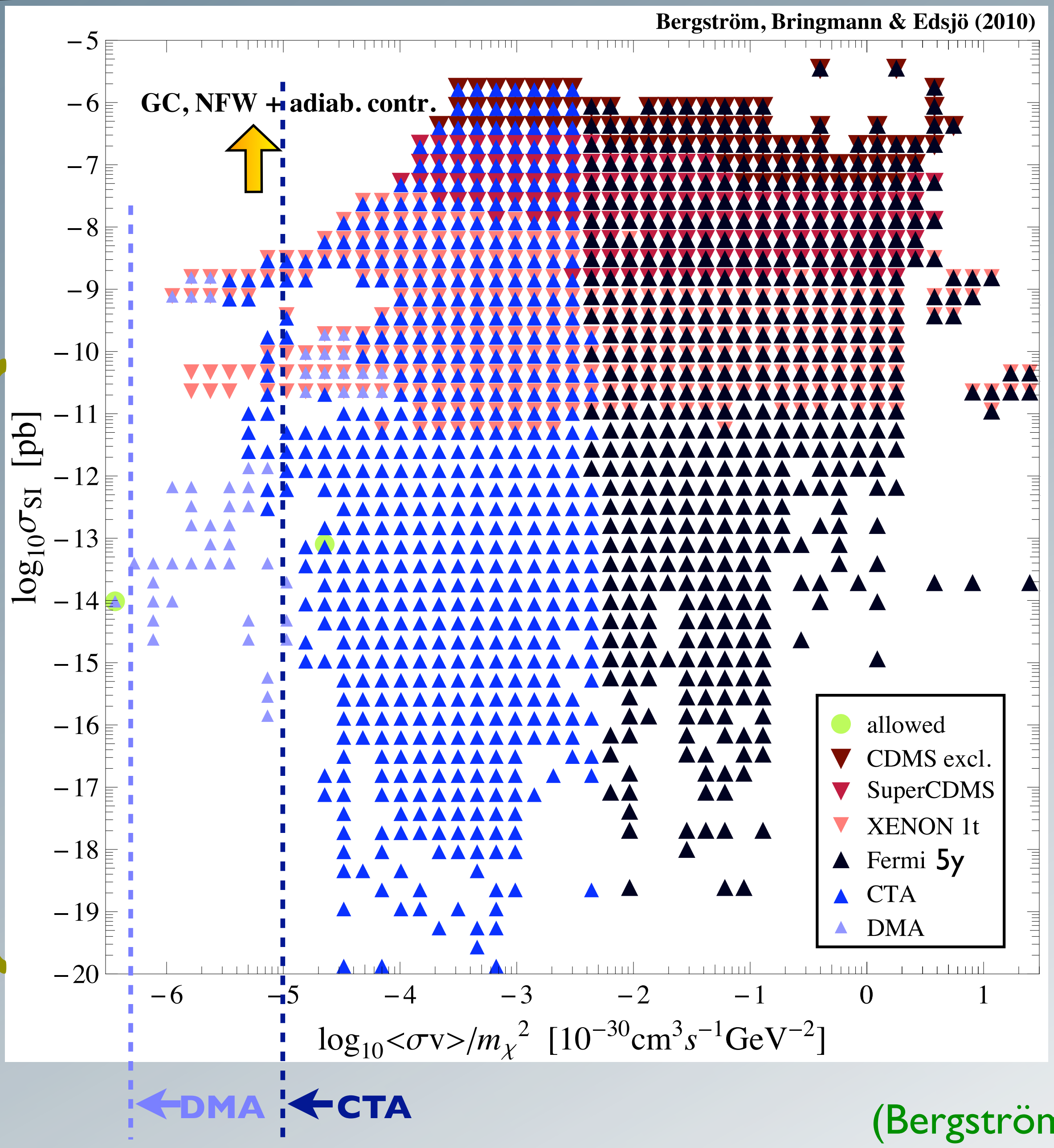

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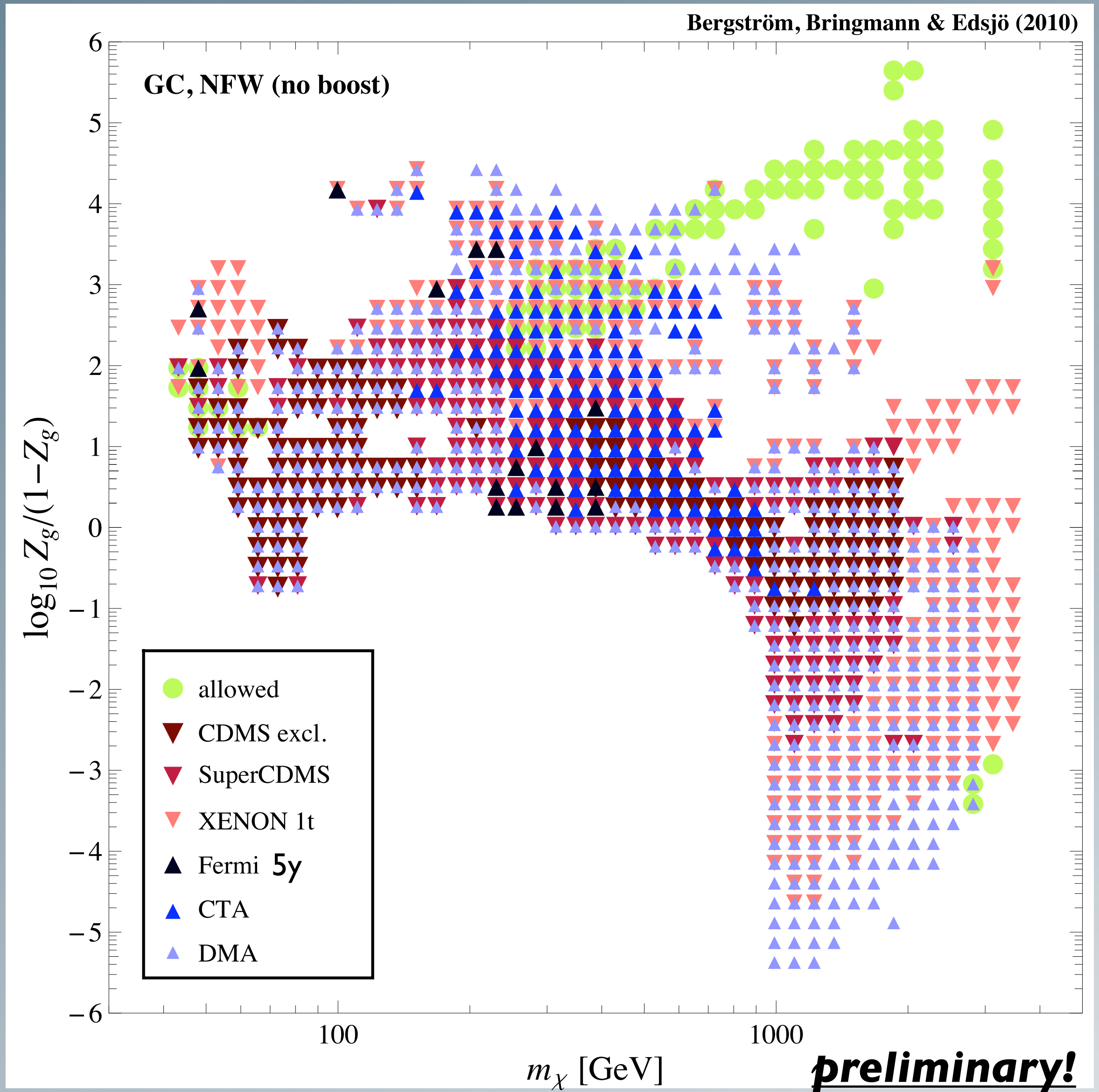

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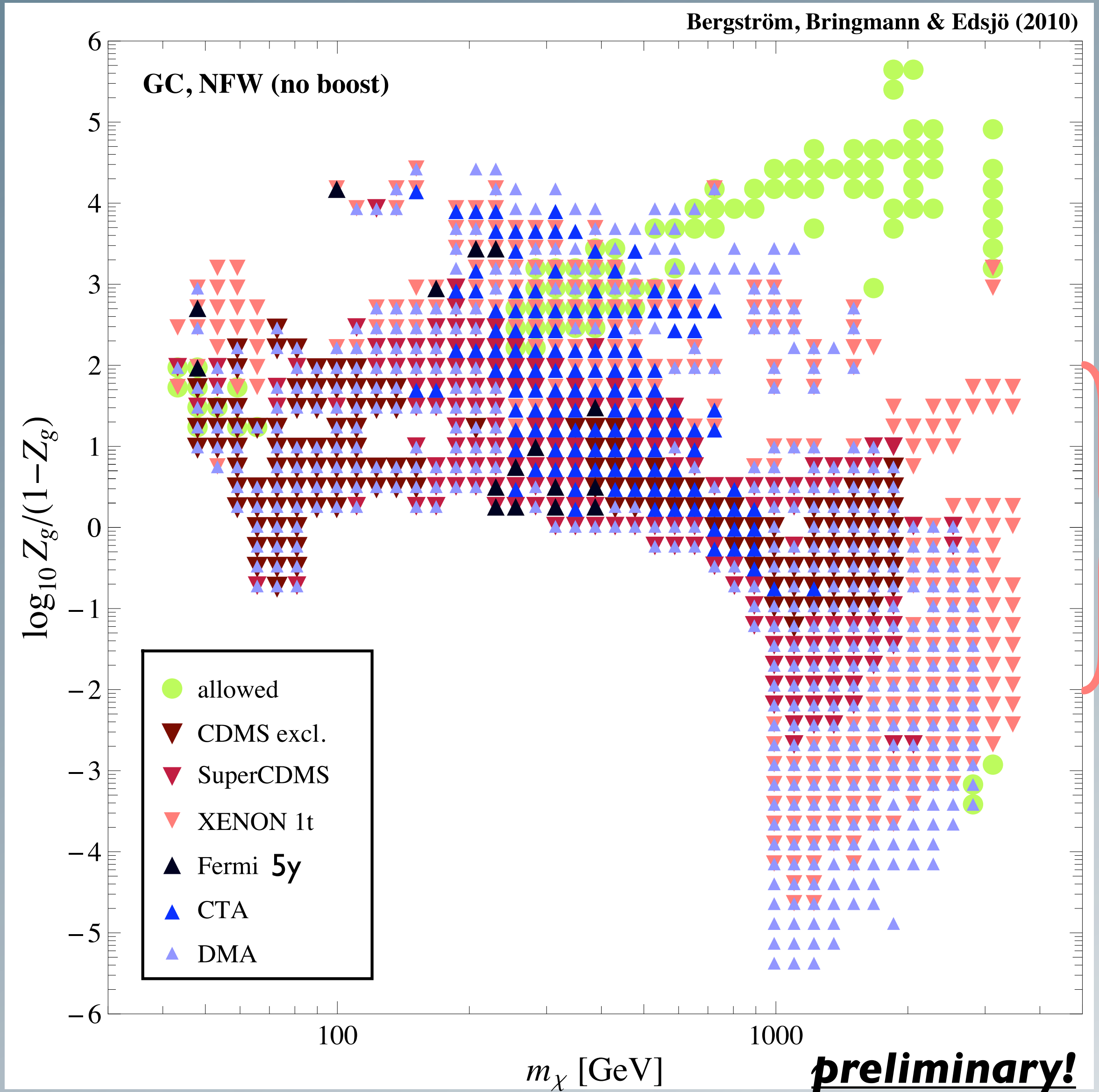

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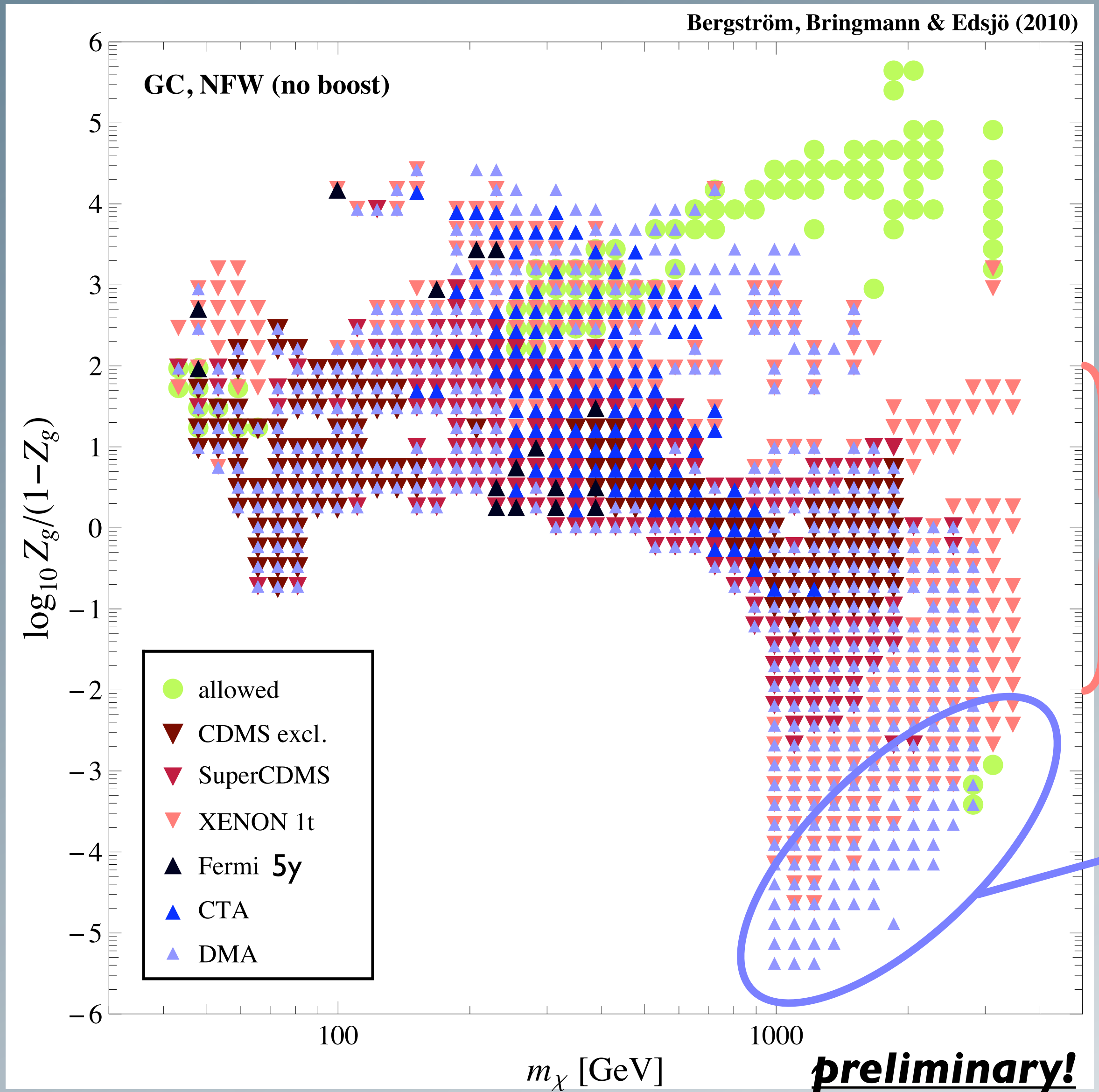

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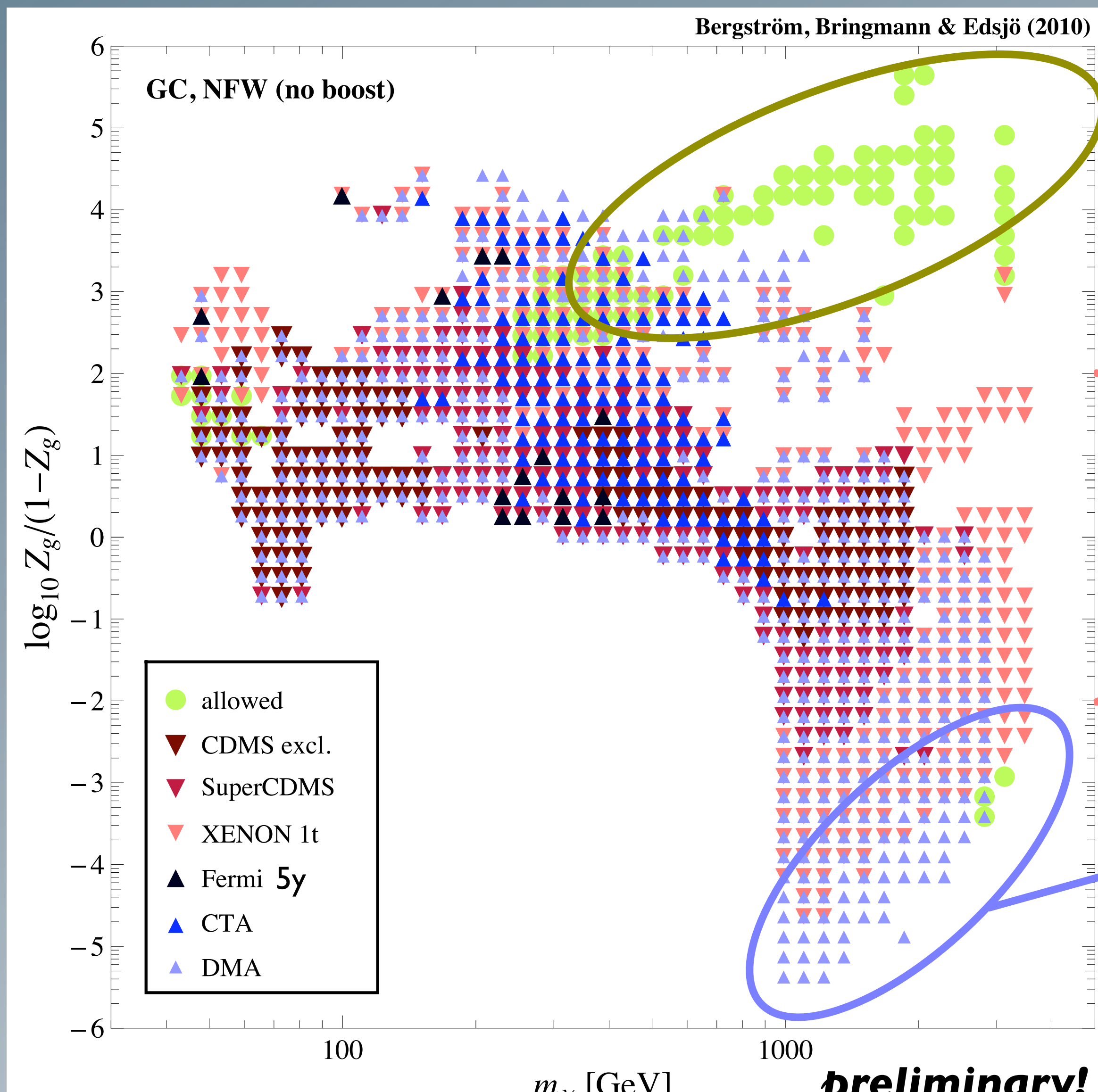

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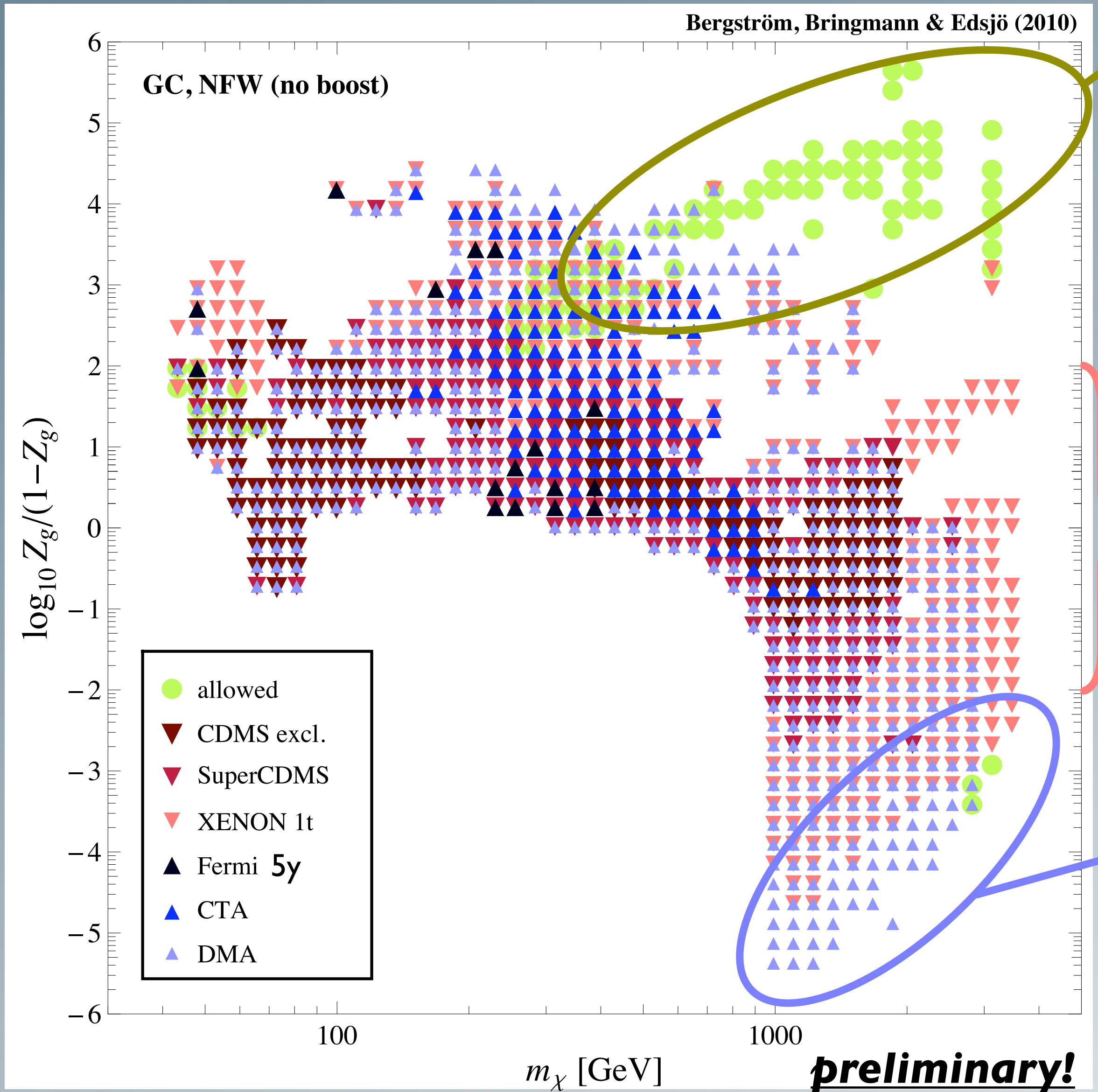

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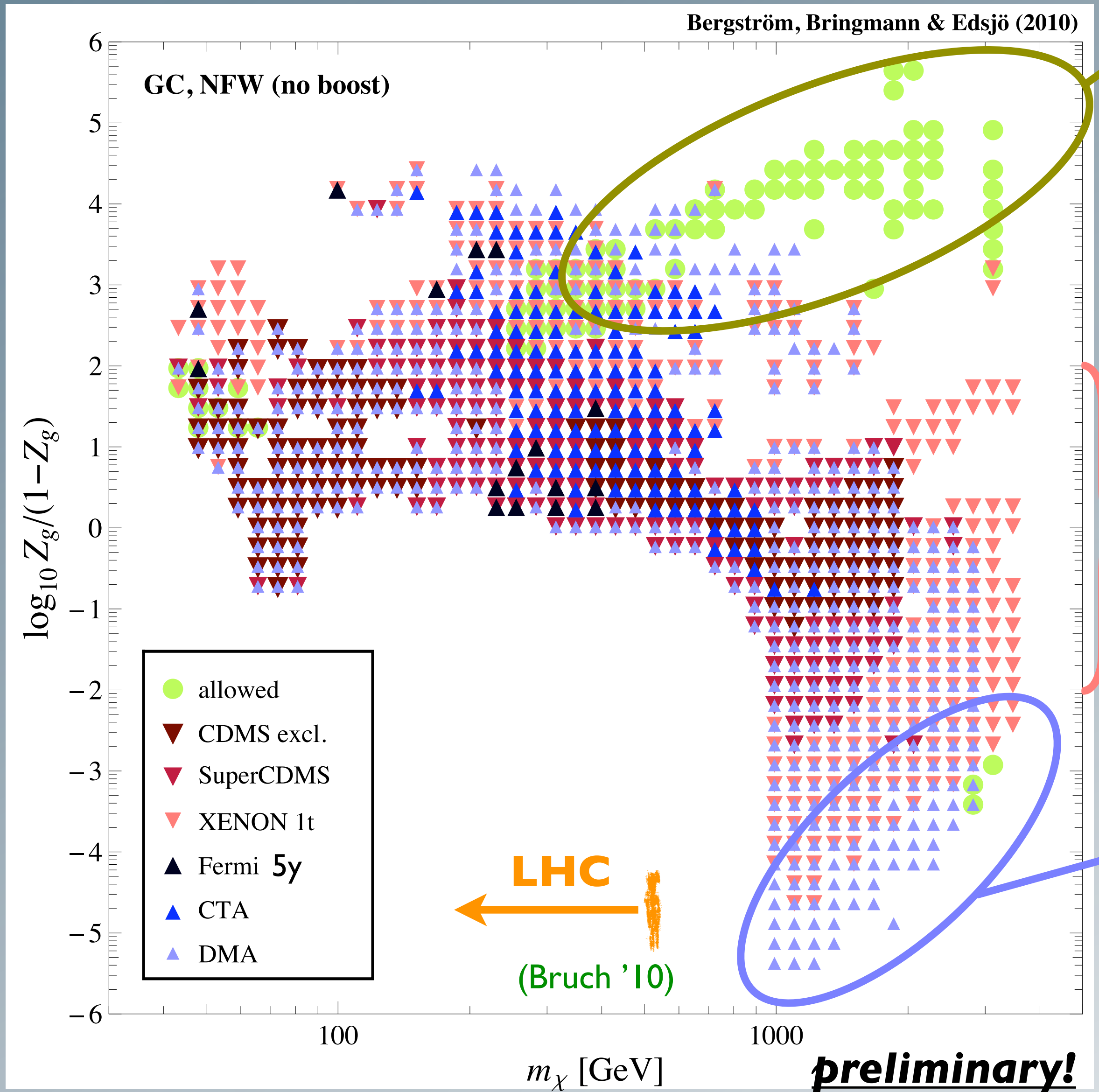

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- Direct detection experiments, and the LHC, will also (continue to) close in on the nature of DM
  - make use of complementarity of the different approaches - **synergy!**
- A dedicated DM experiment like the "Dark Matter Array" could
  - fully exploit the potential of indirect searches (especially when combined with multiwavelength/-messenger techniques)
  - cover a large part of the parameter space that neither direct nor accelerator searches could hope to reach!