Indirect detection of Dark Matter WIMPs: a multiwavelength perspective

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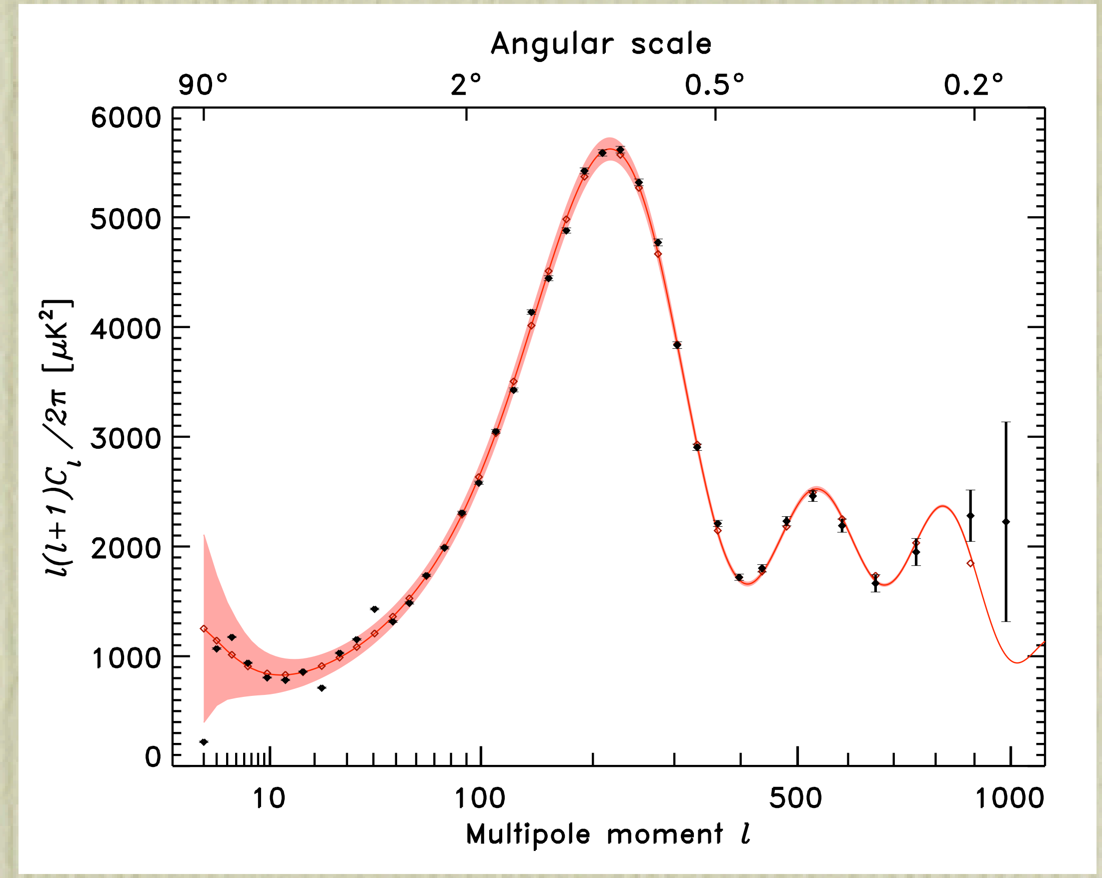
DM in the era of precision cosmology:

The Standard Model of Cosmology as a minimal recipe (a given set of constituents for the Universe and GR as the theory of gravitation) to be tested against a rich sample of (large scale) observables:
CMB temperature fluctuations, galaxy distributions, lensing shears, peculiar velocities, the gas distribution in the intergalactic medium, SNIa as standard candles, ...

All point to a single “concordance” model:

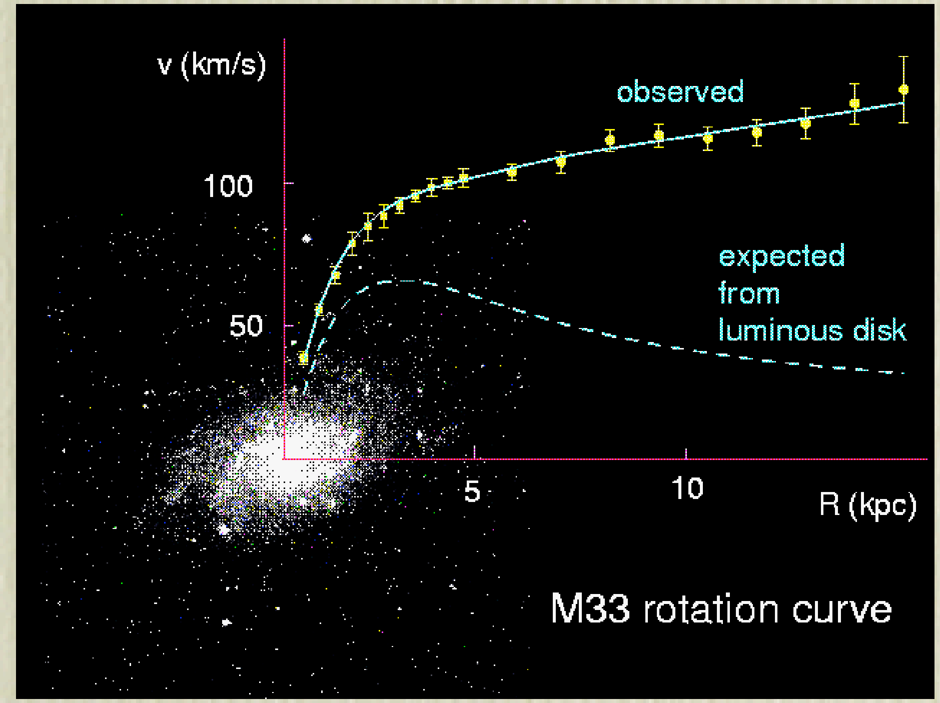
$$\Omega_{Tot} \sim 1 \qquad \underbrace{\Omega_M \sim 0.24}_{\Omega_{DM} \sim 0.20 \qquad \Omega_b \sim 0.04} \qquad \Omega_{DE} \sim 0.76 \qquad \ldots$$

Overwhelming evidence for DM as building block of all structures in the Universe:



from the largest scales (3-yr WMAP, 2006)

down to galactic dynamics (adapted from Bergström, 2000)



Cosmological and astrophysical observations point to a description of dark matter as a optically-dark (i.e. dissipation-less) and collision-less fluid, with negligible free-streaming effects.

Recipes with large violations of one of these properties, such as **Baryonic DM and Hot DM**, **are excluded**, while **Non-baryonic Cold DM is the preferred paradigm**.

Standard picture: Gaussian adiabatic primordial density perturbations, with nearly scale-invariant spectrum, shared by the CDM term (meaning a term for which only gravity matters), in a Universe in which a Λ term dominates at recent times.

DM: the particle physicist's perspective

An upper limit on the interaction strength, while other crucial info (e.g., the mass scale) are missing or poorly constrained. Further hints may come from the DM production scheme; the most beaten paths have been:

i) DM as a ***thermal relic product*** (or in connection to thermally produced species);

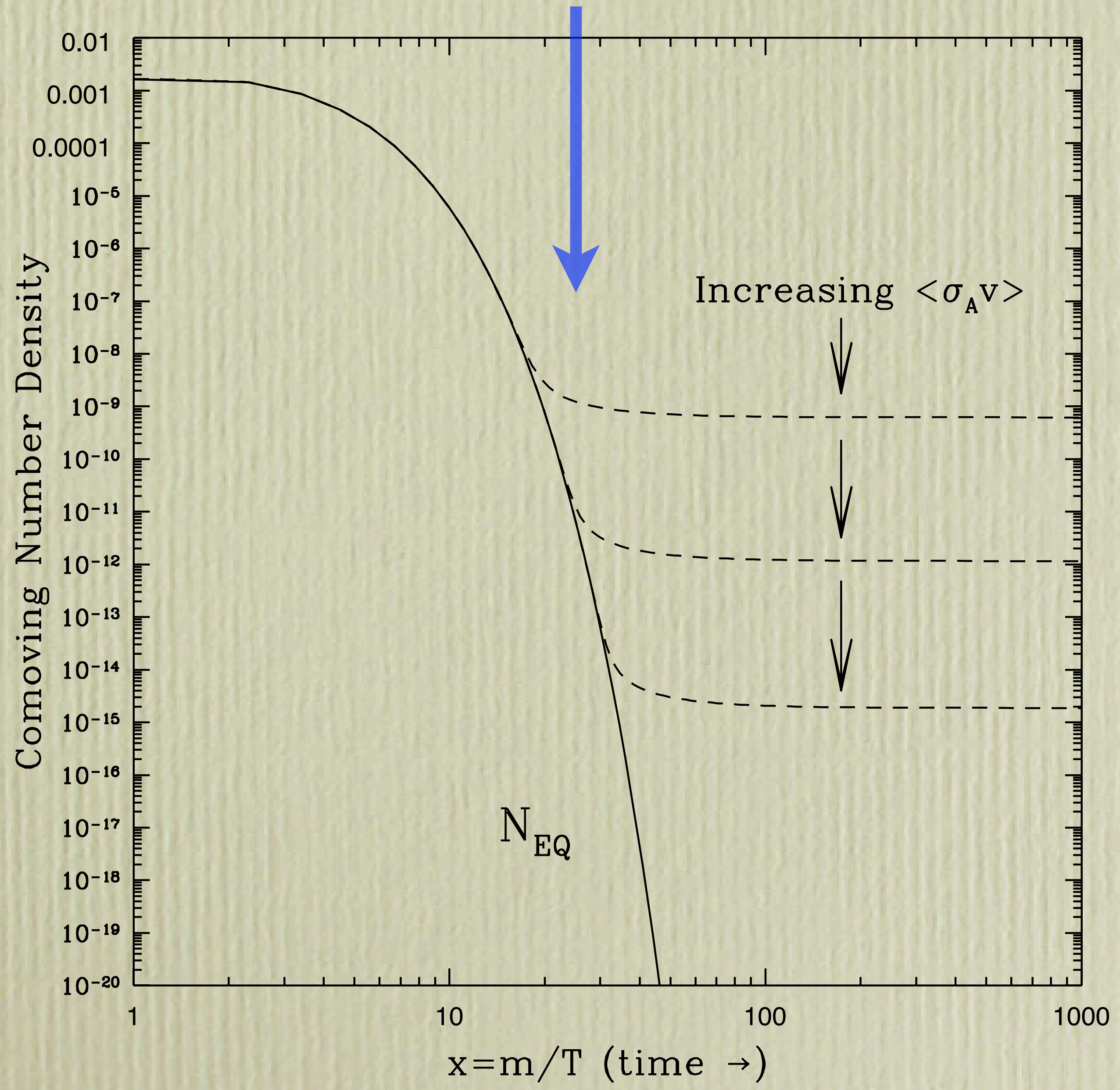
ii) DM as a ***condensate***, maybe at a phase transition; this usually leads to very light scalar fields;

iii) DM ***generated at large T***, most often at the end of (soon after, soon before) inflation; candidates in this scheme are usually supermassive.

CDM particles as thermal relics

Freeze-out:

$H \sim \Gamma$



Jungman, Kamionkowski & Griest, 1996

Non-relativistic at freeze-out, relic density set by the pair annihilation rate into lighter SM particles:

$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

↓

WIMP

WIMP DM candidates

The recipe for WIMP DM looks simple. Just introduce an extension to the SM with:

i) a new stable massive particle;
ii) coupled to SM particles, but with zero electric and color charge;
ii b) not too strongly coupled to the Z° boson
(otherwise is already excluded by direct searches).

Solve the Boltzmann eq. and find the mass scale of your stable Lightest: SUSY Particle, Kaluza-Klein or Braneworld state, Extra-Fermion, Little Higgs state, etc.

Likely, not far from M_W, maybe together with additional particles carrying QCD color: LHC would love this setup!

Neutralino LSP as DM

In the MSSM there are four such states, with mass matrix:

$$\mathcal{M}_{\tilde{\chi}^0_{1,2,3,4}} = \begin{pmatrix} M_1 & 0 & -\frac{g' v_1}{\sqrt{2}} & +\frac{g' v_2}{\sqrt{2}} \\ 0 & M_2 & +\frac{g v_1}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} \\ -\frac{g' v_1}{\sqrt{2}} & +\frac{g v_1}{\sqrt{2}} & 0 & -\mu \\ +\frac{g' v_2}{\sqrt{2}} & -\frac{g v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix}$$

and lightest mass eigenstate (most often the LSP):

$$\tilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}^0_1 + N_{14}\tilde{H}^0_2$$

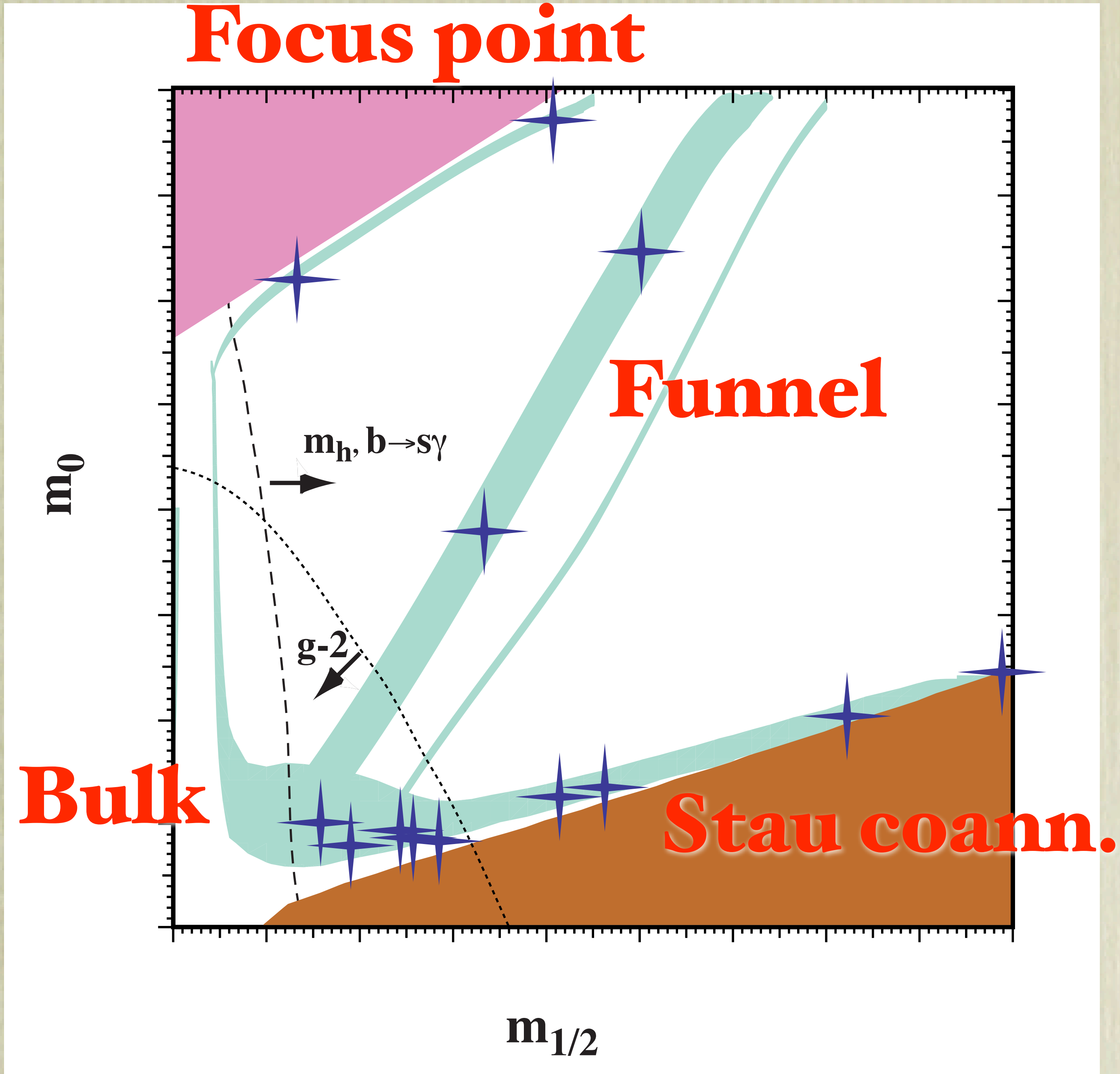
A very broad framework, which gets focussed on narrow slices in the parameter space once more specific LSP DM frameworks are introduced.

Unavoidable strategy: focus on a given scenario and discuss its phenomenology

Example: CSSM

Thin slices in the parameter space selected by the relic density constraint.

Minimal scheme, but general enough to illustrate the point.



Scalar mass

Gaugino mass

Battaglia et al. 2001

The focus point regime is analogous to **SPLIT SUSY**

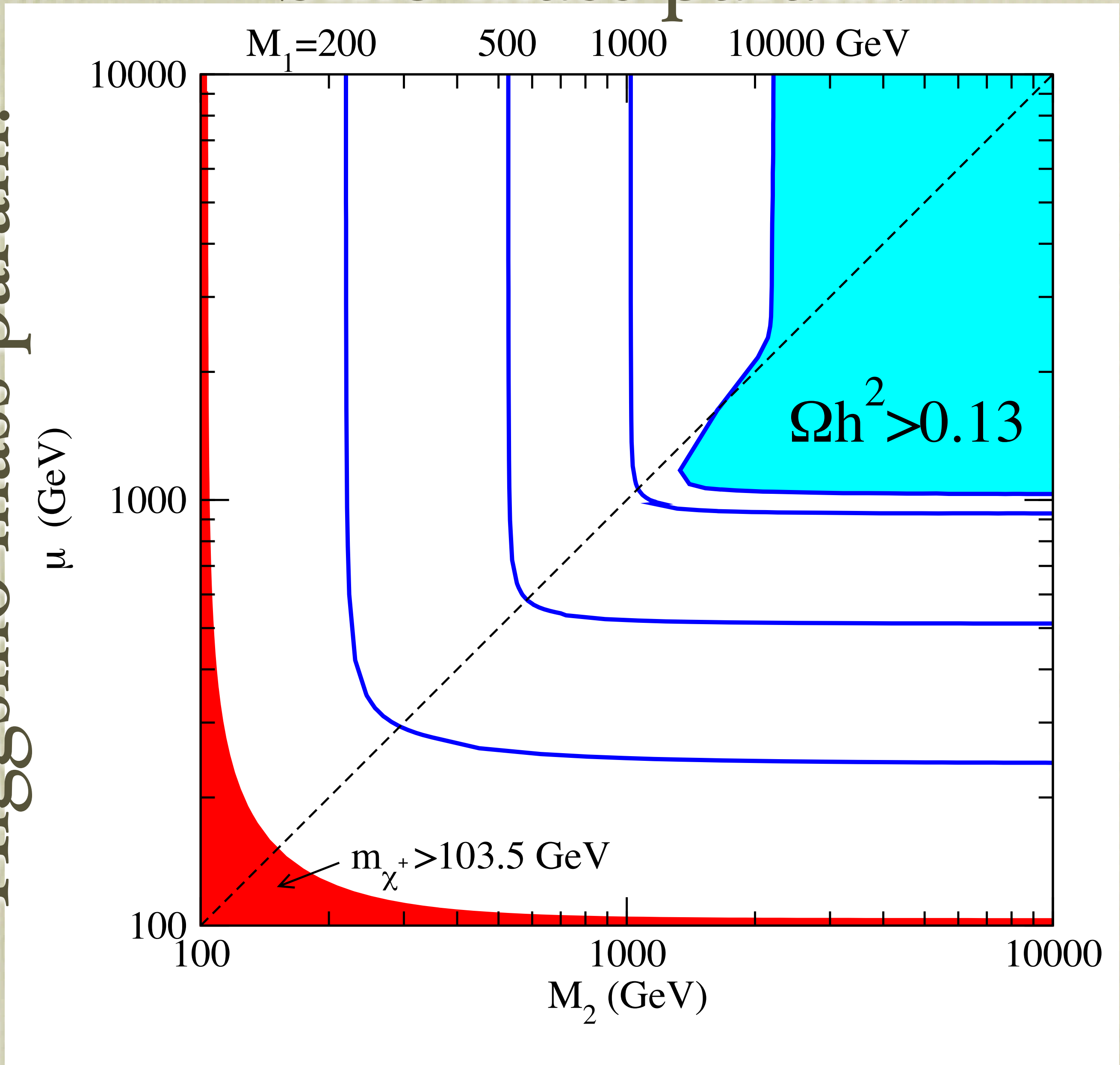
Arkani-Hamed & Dimopoulos, 2004;
Giudice & Romanino, 2004

Scalars decoupled at a high scale; DM constraints prevent gauginos and/or higgsinos from being very heavy as well

Masiero, Profumo & P.U., 2004

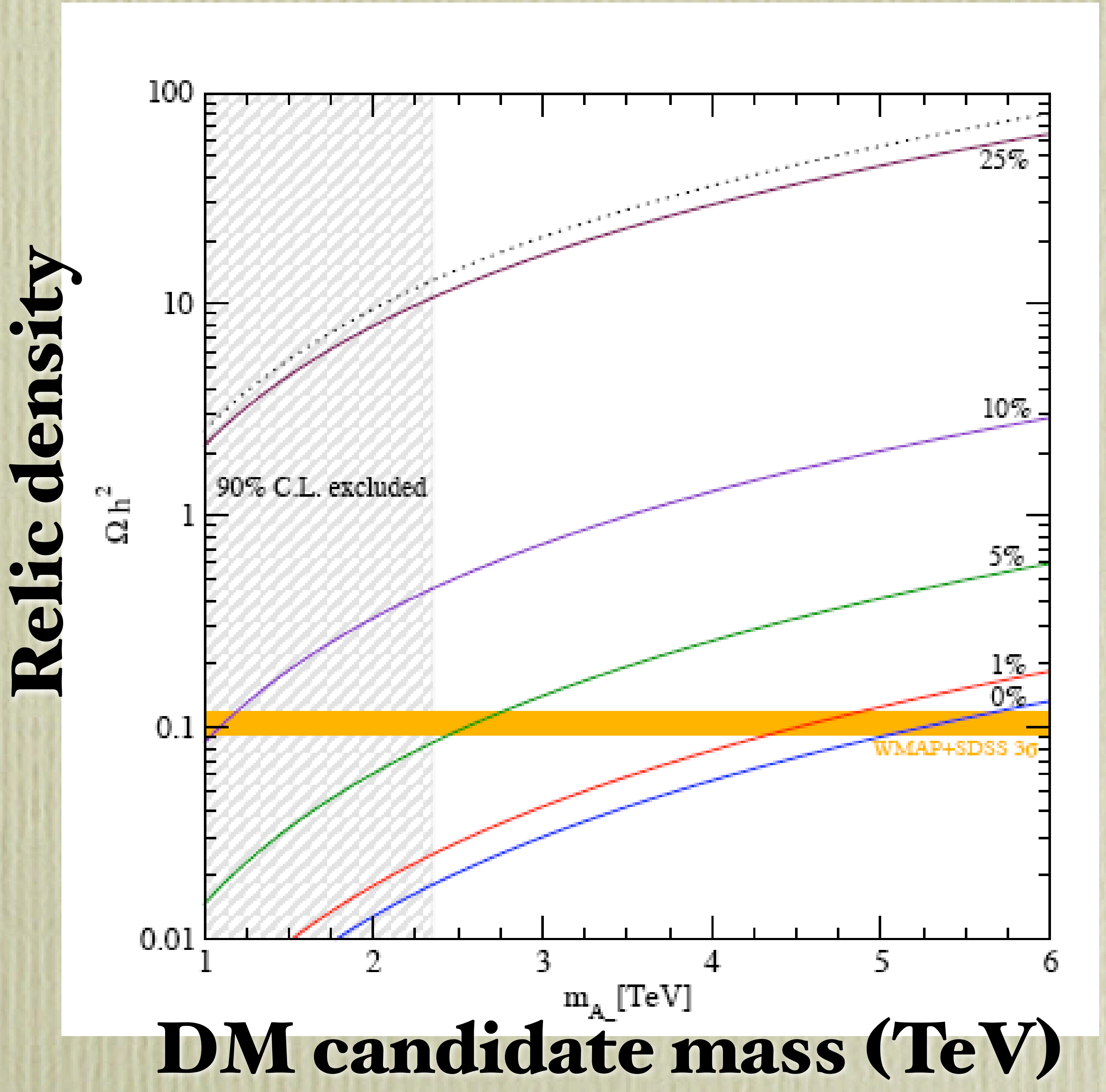
bino mass param.

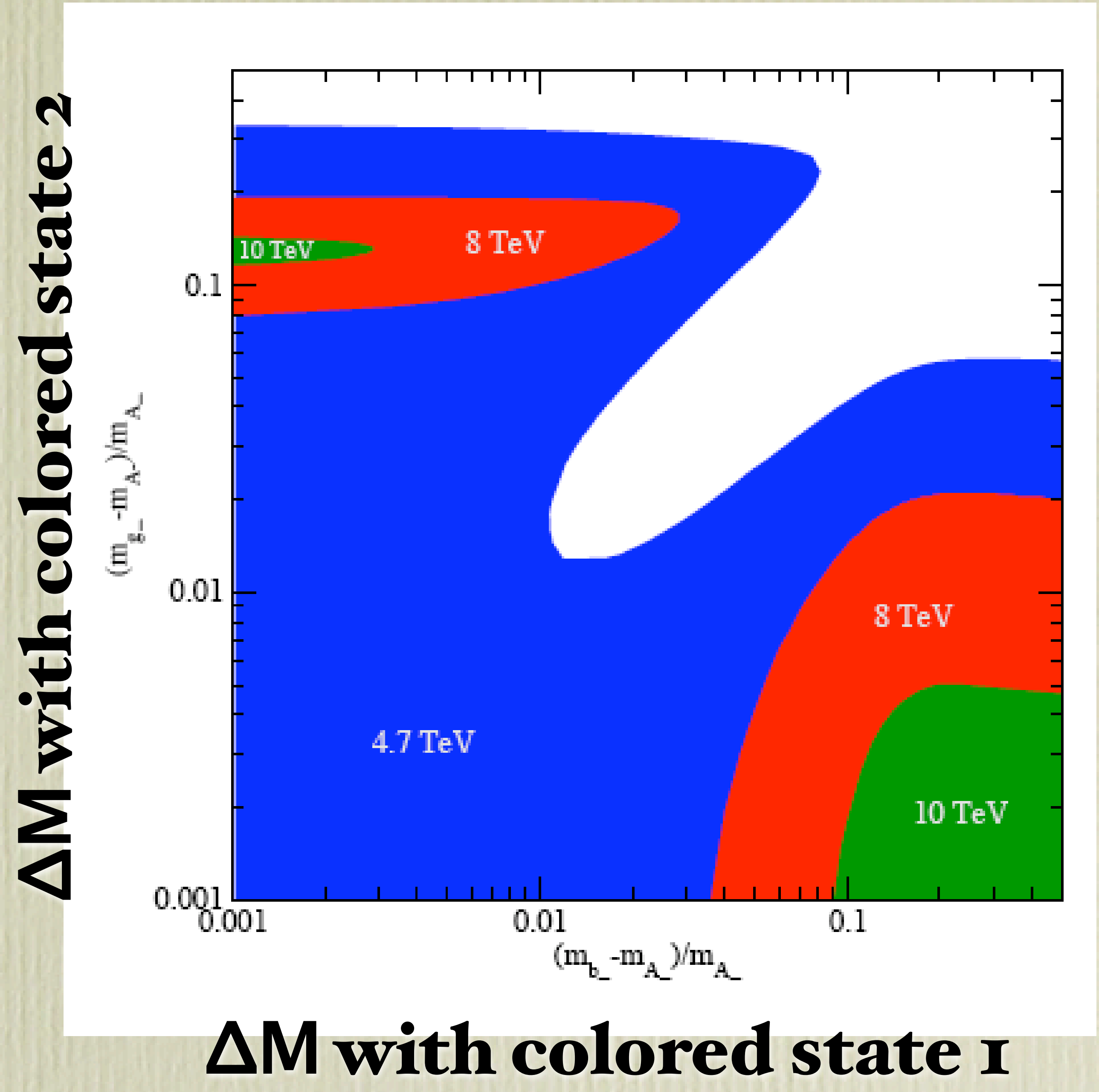
Higgsino mass param.



wino mass param.

An extreme case: **LKP in 5D theory with gauge-Higgs unification**

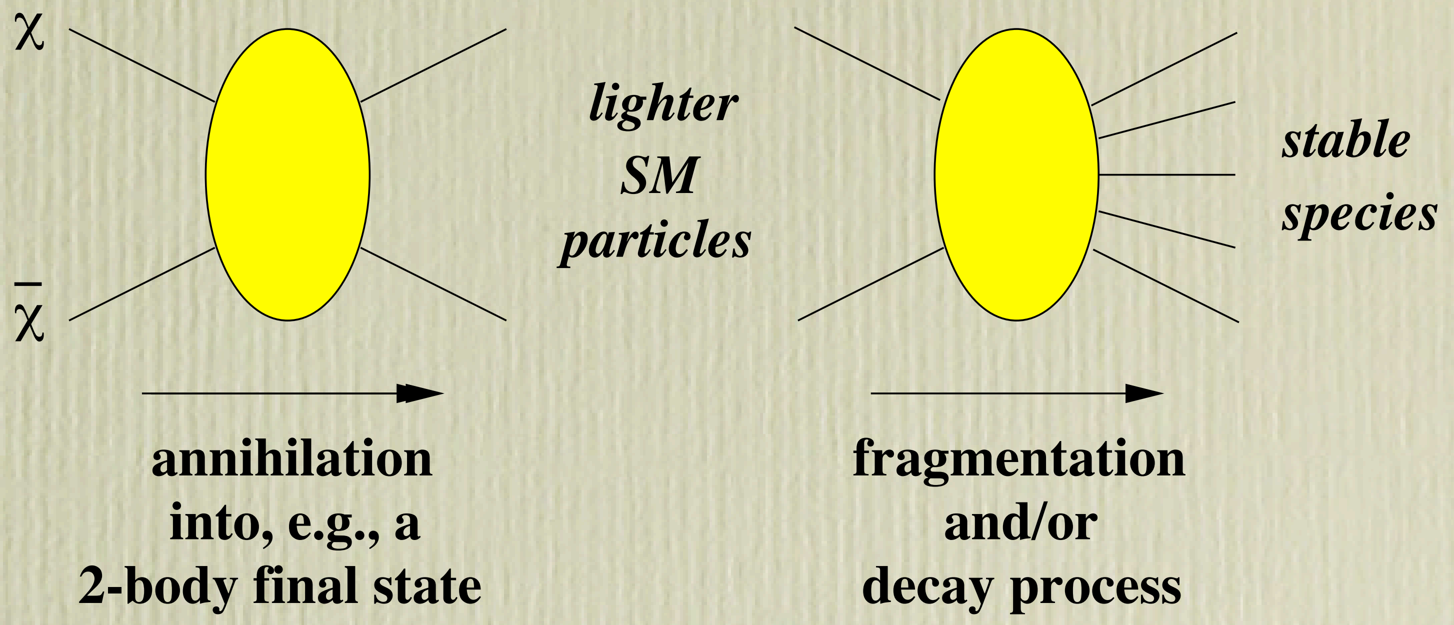




Coannihilations with strongly-interacting states may shift the DM scale in the multi-TeV range,
Regis, Serone & P.U. 2007.

A chance for indirect detection of DM WIMPs stems from the WIMP paradigm itself:

Pair annihilation rate in today's halos (i.e. at T=0) not too far from the one at freeze-out



χ

$\bar{\chi}$

lighter SM particles

stable species

annihilation into, e.g., a 2-body final state

fragmentation and/or decay process

The induced fluxes are small: identify the channels with low or well-understood backgrounds.

Most analyses have focussed on **gamma-ray** emission, mainly from the DM halo of our own Galaxy, and the WIMP induced contribution to local antimatter fluxes, namely **antiprotons**, **positrons** and **antideuterons**.

Far from guaranteed that these strategies may pay off:

Searches with gamma-ray telescopes

The next-generation of space-based telescopes is almost ready for launch:

GLAST

launch on

february 5, 2008

GLAST @ SLAC

12/16 Towers in the GRID on 7/10/05

+ Agile (in orbit and working), AMS (...)

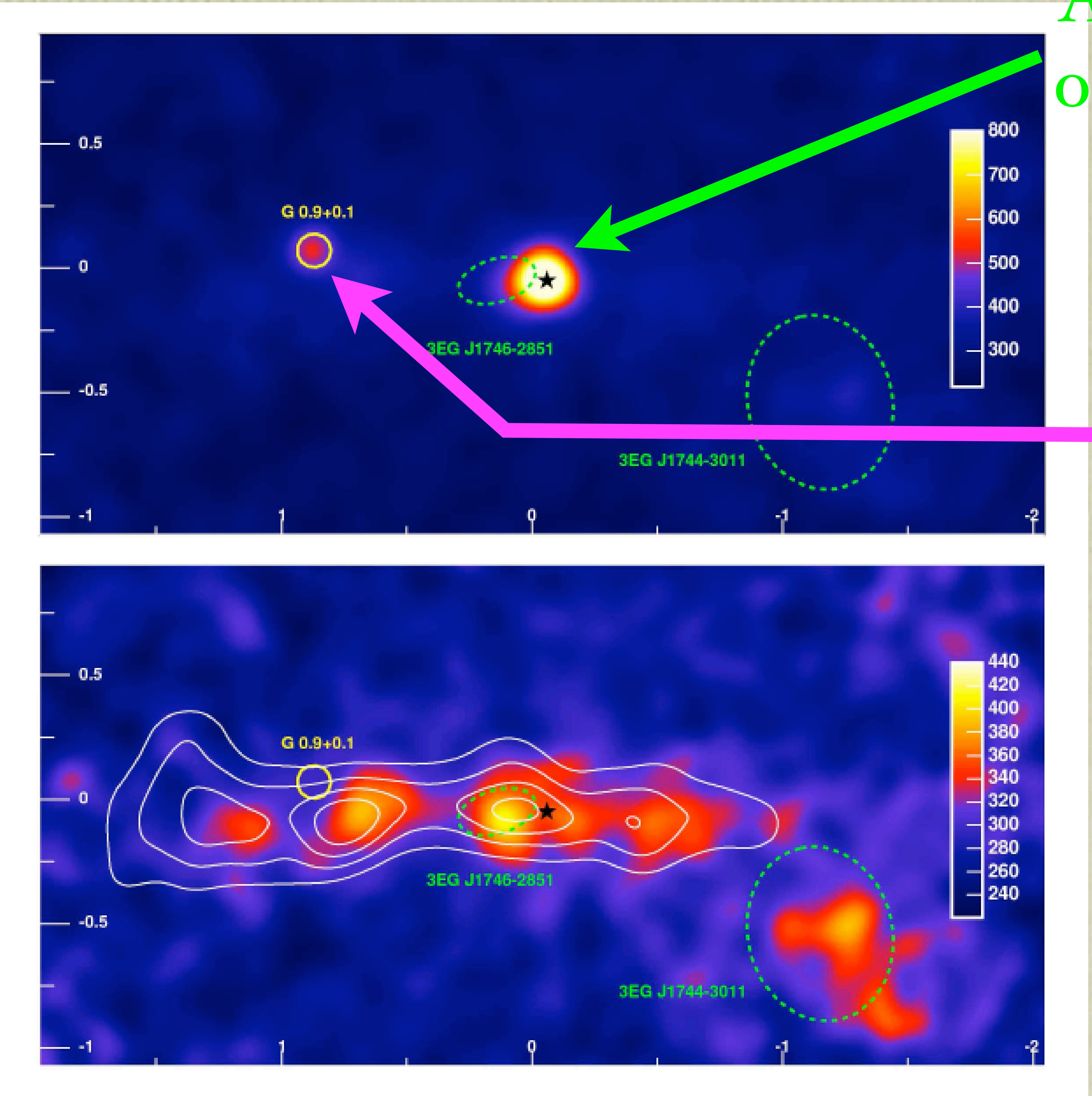
The new era of gamma-ray astronomy with ground-based telescopes has already produced spectacular results:

HESS telescope in Namibia, fully operative since 2003

+ Magic, Stacee, Veritas, ...

Tens of new TeV sources reported in the latest years, compared to the 12 sources known up to 2003

First VHE map of the Galactic Center by HESS:

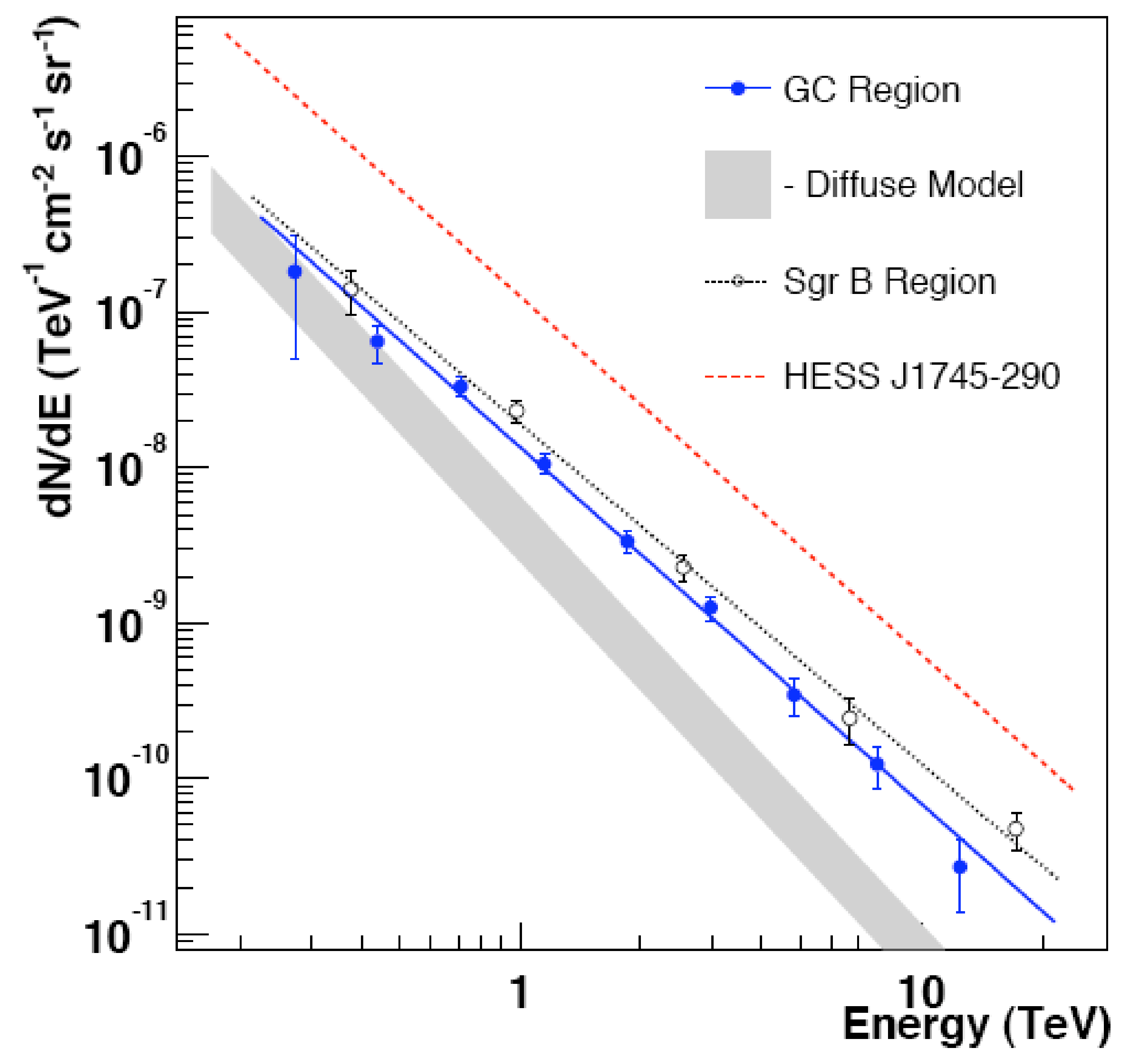


A source at the position of the central BH, Sgr A*

A new plerion discovered

+ diffuse emission from the GC region

Spectral features of central source/excess:



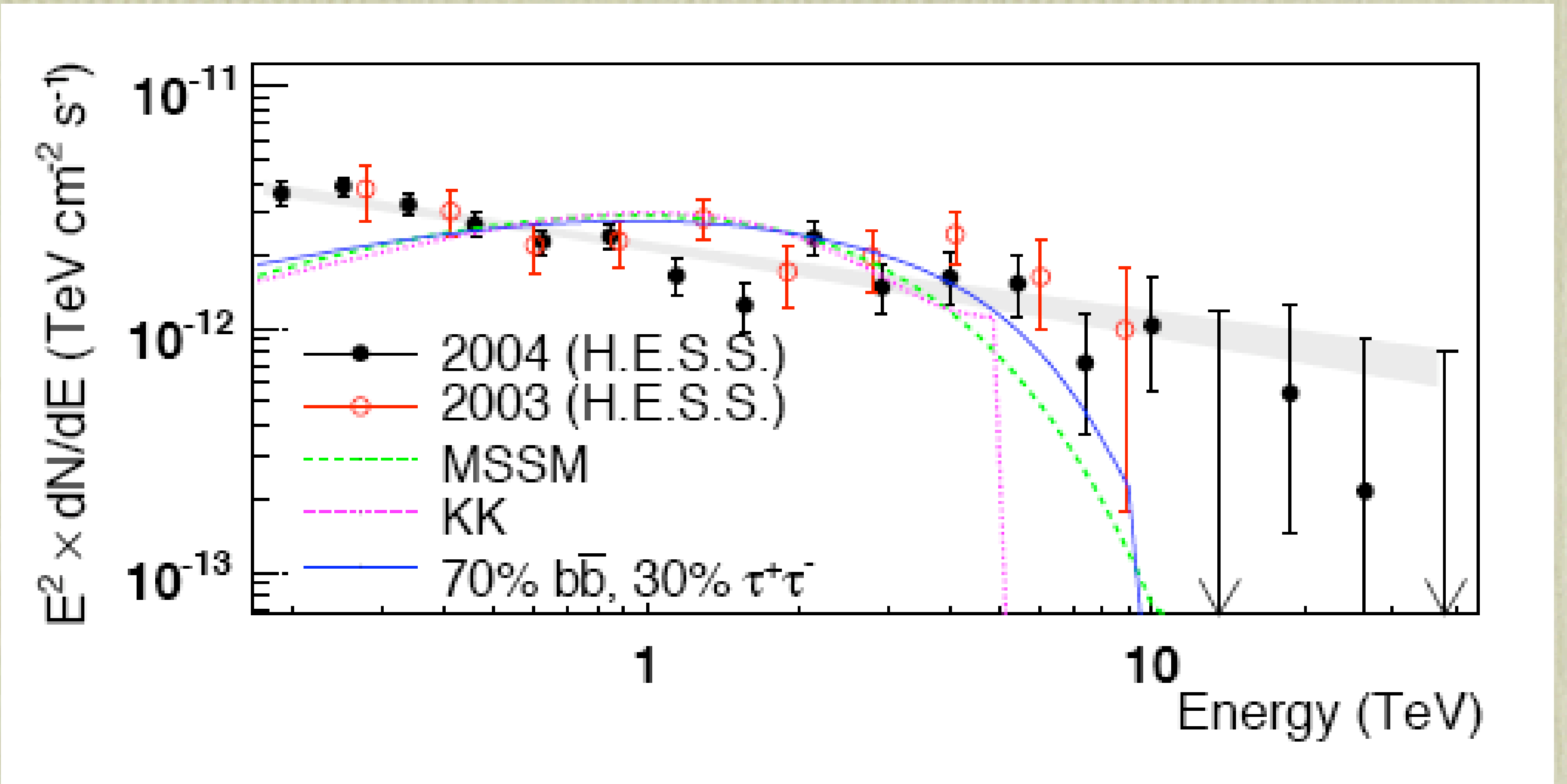
Aharonian et al, 2006

Single power law (Γ ~ 2.2) from

~150 GeV to ~30 TeV

Tentatively:
the central source is a SN remnant and the diffuse emission from in the central region is due to protons injected in the explosion

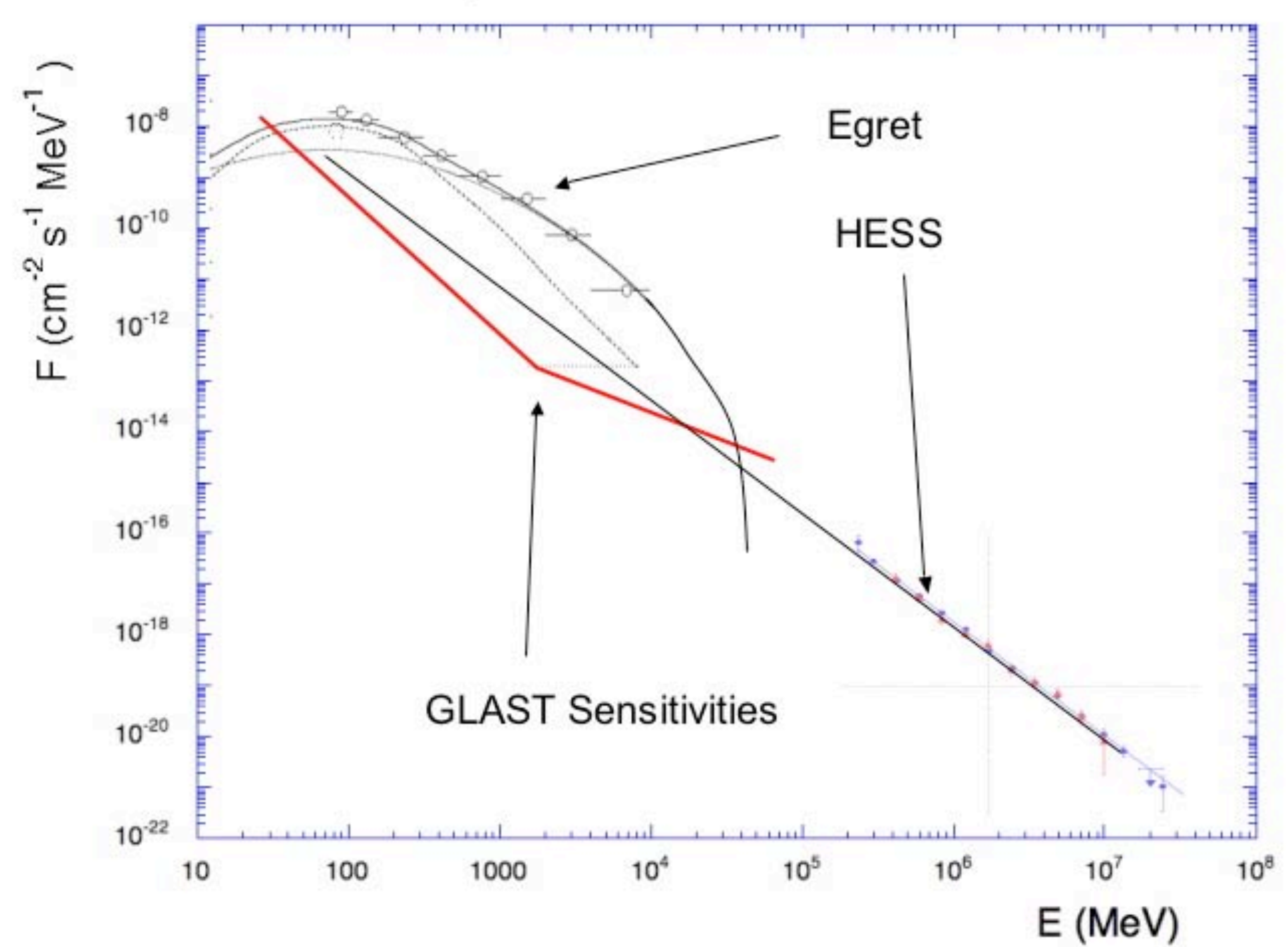
The GC may not be any longer the best bet for indirect dark matter detection!



Aharonian et al., 2007

it is ***very hard*** to support the hypothesis that the central source detected by HESS & MAGIC is due to WIMP annihilations: a standard astrophysical source, i.e. large background for an eventual WIMP component!

it might still be that a DM component could be singled out, e.g. the EGRET GC source (?):



a DM source can fit the EGRET data; GLAST would detect its spectral and angular signatures and identify without ambiguity such DM source!

Morselli 2005; analysis in Cesarini, Fucito, Lionetto, Morselli & P.U., 2004

Collective effects of subhalos in the Milky Way

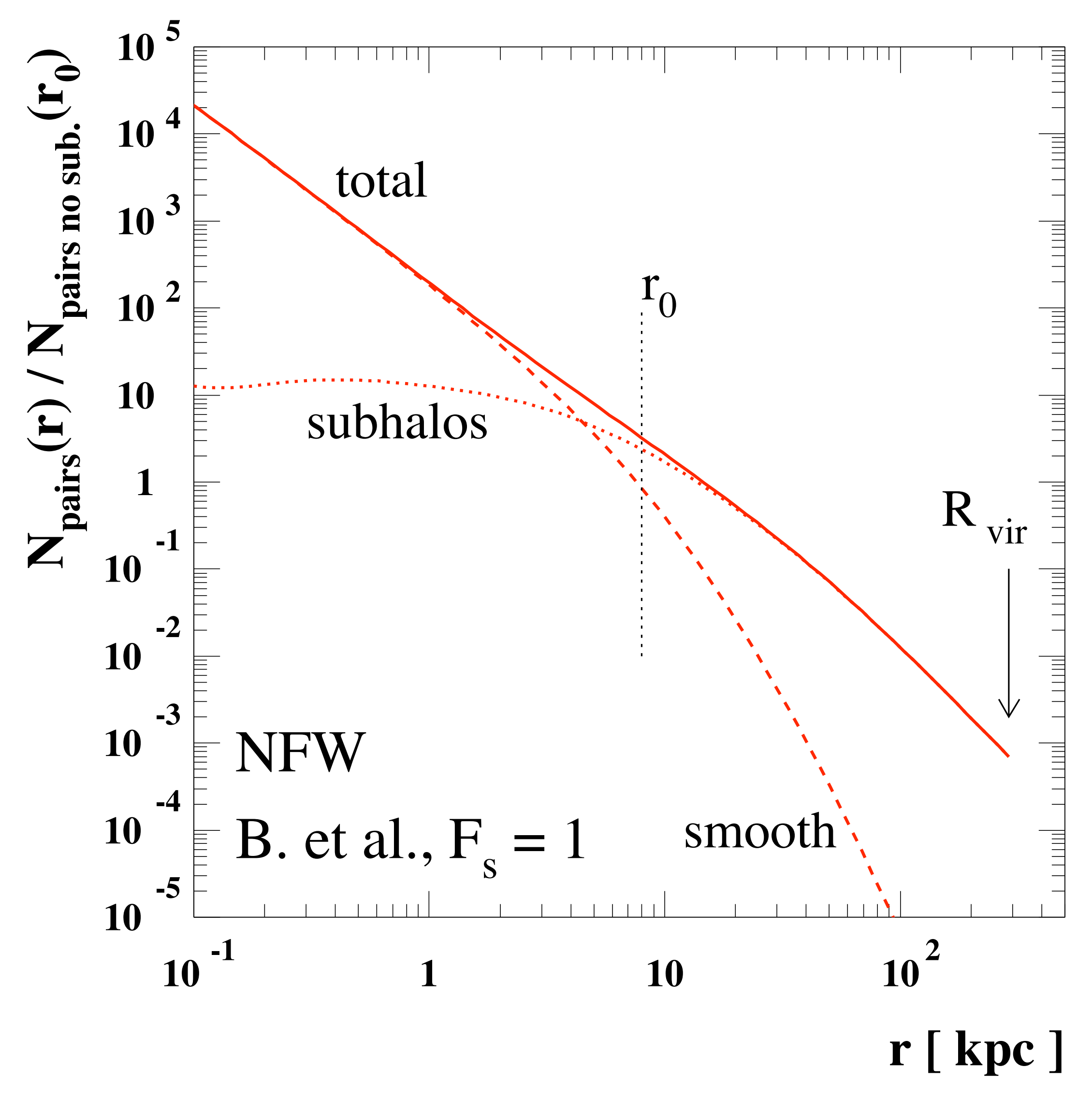
... or the desperate need of "BOOST FACTORS" to claim DM explanations for "excesses" in the measured γ-flux, positron flux, ...

Hard task to make predictions, since one needs a realistic modeling, among others, of:

- the initial subhalo mass function, including its spatial dependence within the hosting halo;
- the dynamical evolution of the subhalo population (mainly dynamical friction effects);
- the tidal disruption of subhalos, including the effect of baryonic components in the Galaxy.

A problem which has recently received some attention in relation to DM detection (e.g.: Taylor & Babul, 2004; Berezinsky et al., 2005; Diemand et al., 2006 & 2007; Salati et al., 2006; Lavalle et al., 2007).

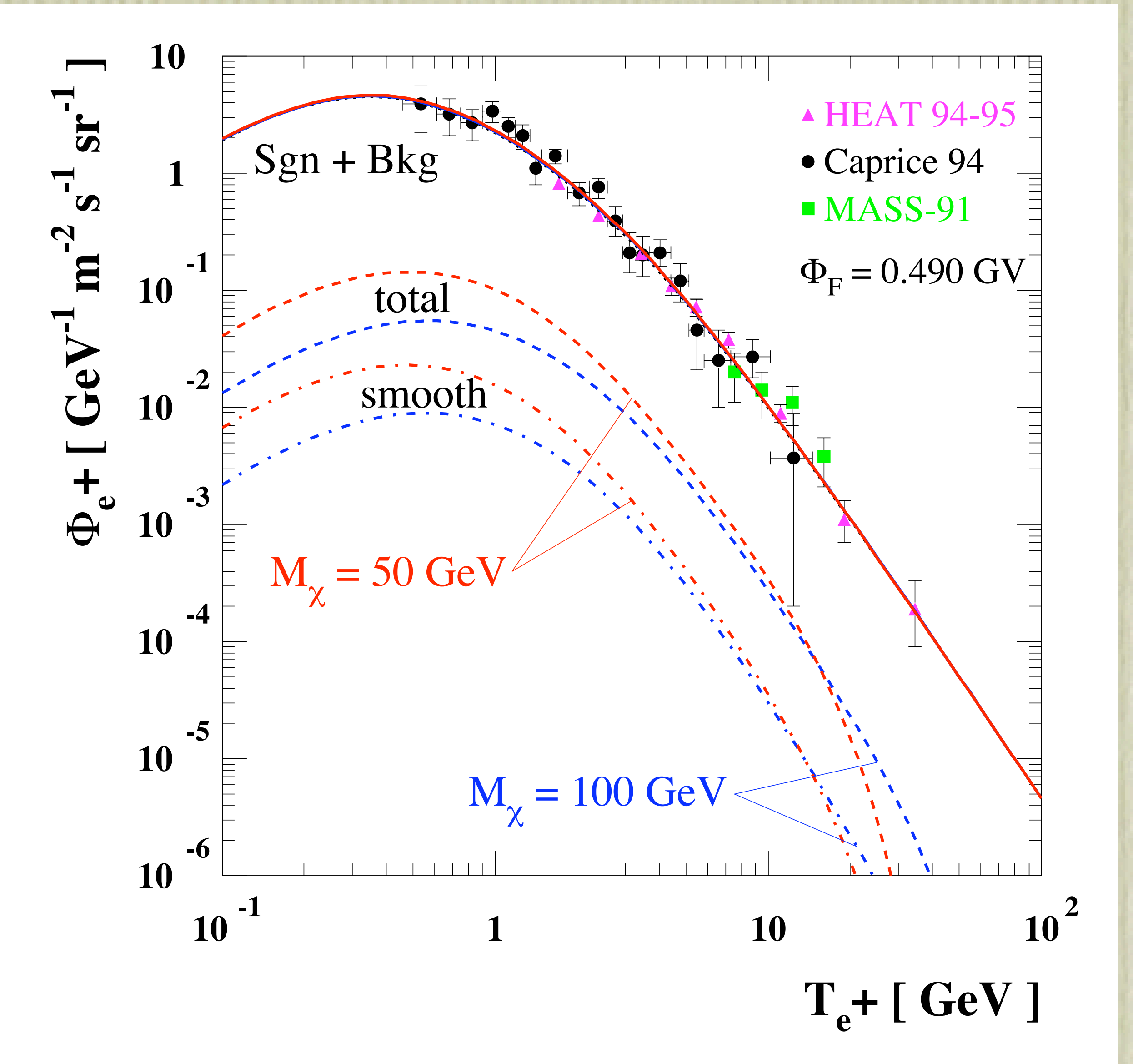
A further attempt to to extrapolate a consistent picture out of the latest N-body simulation results:



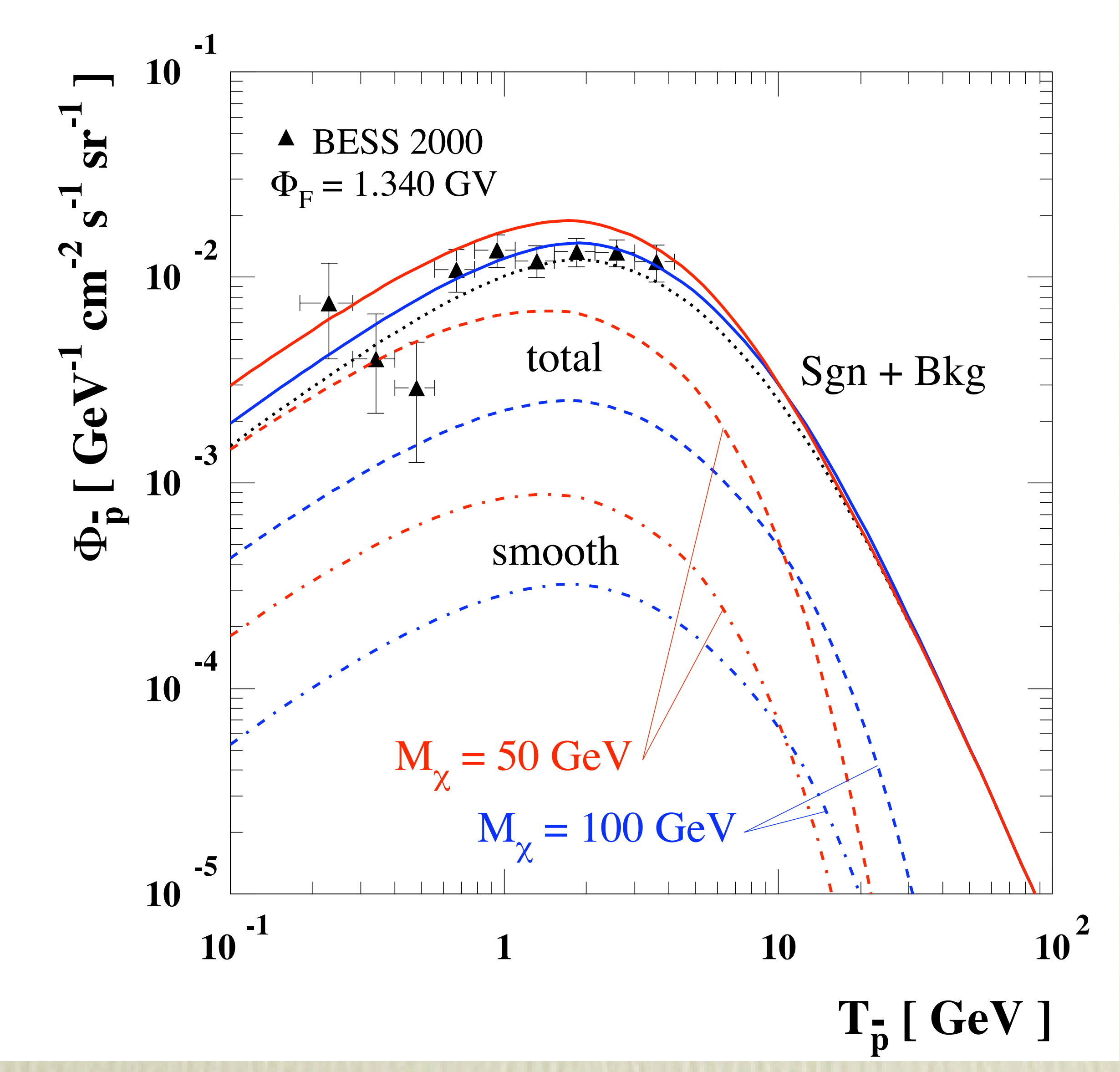
Bisesi & P.U., 2007 to appear.

Hard to produce a positron excess without overproducing antiprotons

positrons



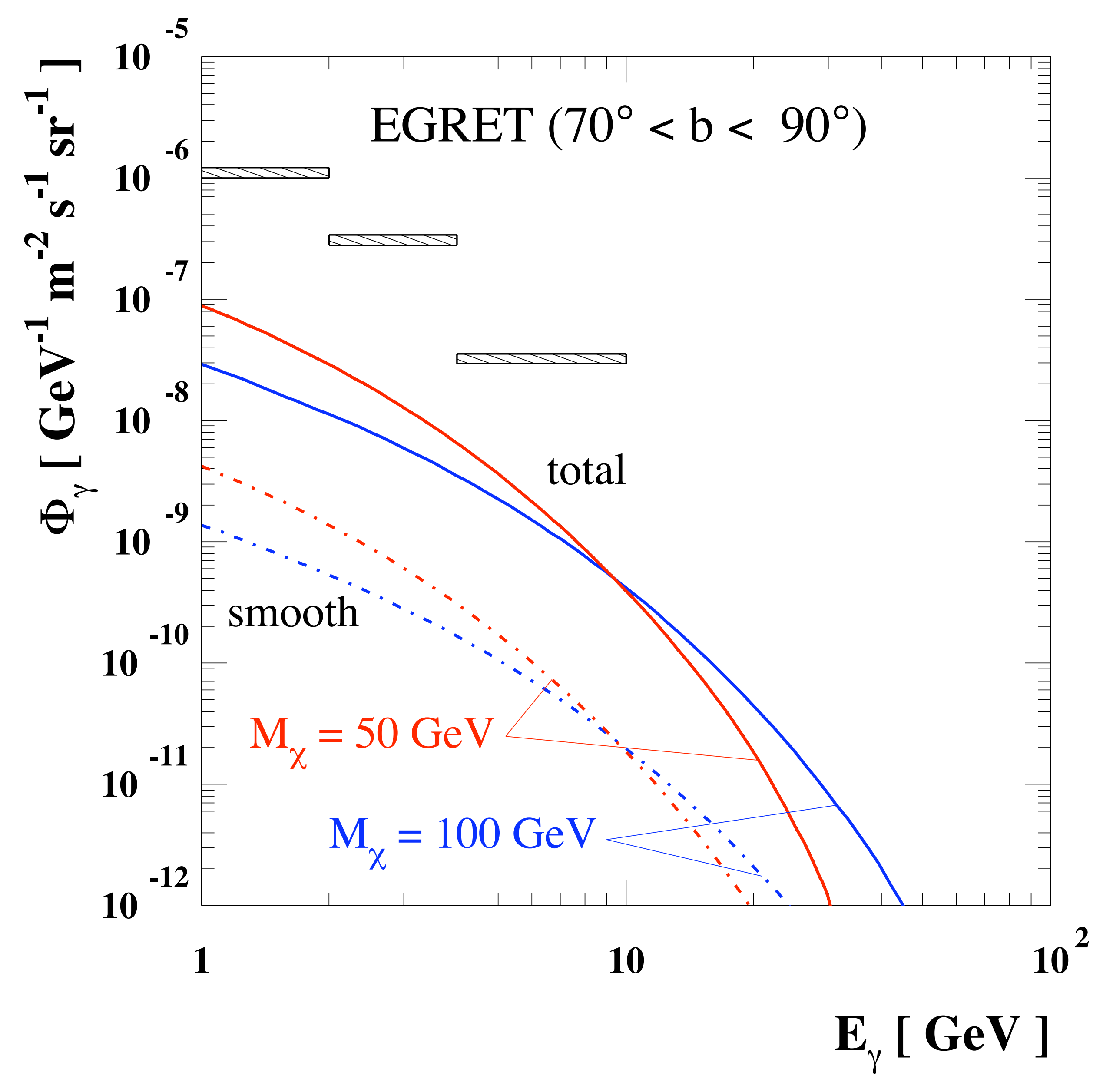
antiprotons



propagation with GALPROP, under standard assumptions

The largest enhancement is for γ-rays (high latitude)

possibly a target
for GLAST,
assuming that
the diffuse galactic
background
component can be
reliably subtracted
out



What about other “smoking-gun” signals?

On the market:

- Gamma-ray lines
- Antideuterons
- Detection of a full set of same spectra unidentified gamma-ray sources
- ...

(Apologies for list of relevant reference not fitting on this slide...)

Multifrequency study of external (as opposed to loca) dark matter dominated objects proposed here

Multiwavelength detection strategy:

Derive self-consistent predictions for prompt annihilation yields:

gamma-rays (neutrinos)

and for terms from the interaction/back-reaction of electrons and positrons on background radiation/fields:

Synchrotron Inverse Compton Bremsstralung

+ SZ effect

Multicomponent spectra extending from the radio band up to the gamma-ray band.

The multiwavelength perspective has been applied to the GC: see, e.g., Aloisio, Blasi & Olinto, 2004; Bergstrom, Fairbairn & Pieri, 2006; however the GC is crowded spot!

We propose multifrequency DM detection in galaxy clusters and dwarf galaxies

Colafrancesco, Profumo & P.U., 2006 & 2007

Case 1: Why galaxy clusters?

- point to a regime where DM dominates;
- ideal setup to test the ΛCDM hierarchical clustering picture;
- low background expected;
- there are cases (such as for the Coma cluster) with extended data sample to use as guideline.

WIMP source functions in clusters:

$$Q_i(r,E) = \langle \sigma v \rangle_0 \sum_f \frac{dN_i^f}{dE}(E) B_f \mathcal{N}_{\rm pairs}(r)$$

total rate

energy spectra

branching ratios

density of WIMP pairs

with:

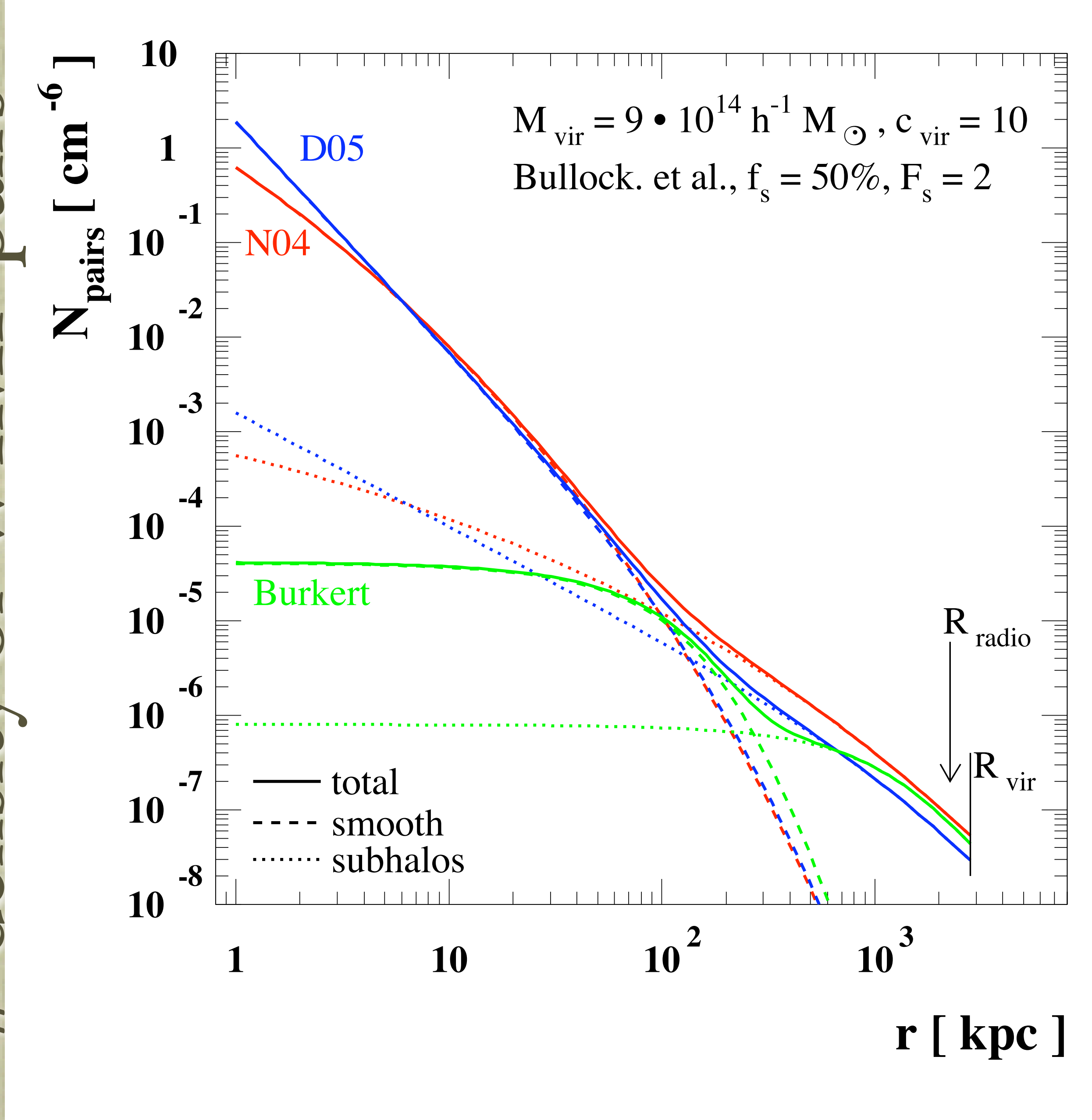
$$\mathcal{N}_{\rm pairs}(r) = \frac{\bar{\rho}^2}{2\,M_\chi^2}\left[\frac{\left(\rho' g(r/a) - f_s\,\tilde{\rho}_s\,g(r/a')\right)^2}{\bar{\rho}^2} + f_s \Delta^2 \frac{\tilde{\rho}_s\,g(r/a')}{\bar{\rho}}\right]$$

smooth halo component

mean overdensity in clumps

clumps radial distribution

Focus on **COMA cluster**, fitting all dynamical constraints:



density of WIMP pairs

radial coordinate in Coma

Navarro et al. 2004 (N04):

$$g_{N04}(x) = \exp[-2/\alpha(x^{\alpha} - 1)]$$

with $\alpha \simeq 0.17$

Diemand et al. 2005 (D05):

$$g_{D05}(x) = \frac{1}{x^{\gamma}(1+x)^{3-\gamma}}$$

with $\gamma \simeq 1.2$

Burkert 1995:

$$g_B(x) = \frac{1}{(1+x)\,(1+x^2)}$$

We need to convert from electron/positron sources to equilibrium populations after propagation; we implement a diffusion equation:

$$\frac{\partial}{\partial t}\frac{dn_e}{dE} = \nabla\left[D(E,\boldsymbol{x})\nabla\frac{dn_e}{dE}\right] + \frac{\partial}{\partial E}\left[b(E,\boldsymbol{x})\frac{dn_e}{dE}\right] + Q_e(E,\boldsymbol{x})$$

I) in the stationary limit and assuming spherical symmetry

II) with diffusion coefficient: $D(E) = D_0\frac{d_B^{2/3}}{B_\mu^{1/3}}\left(\frac{E}{1\ \mathrm{GeV}}\right)^{1/3}$

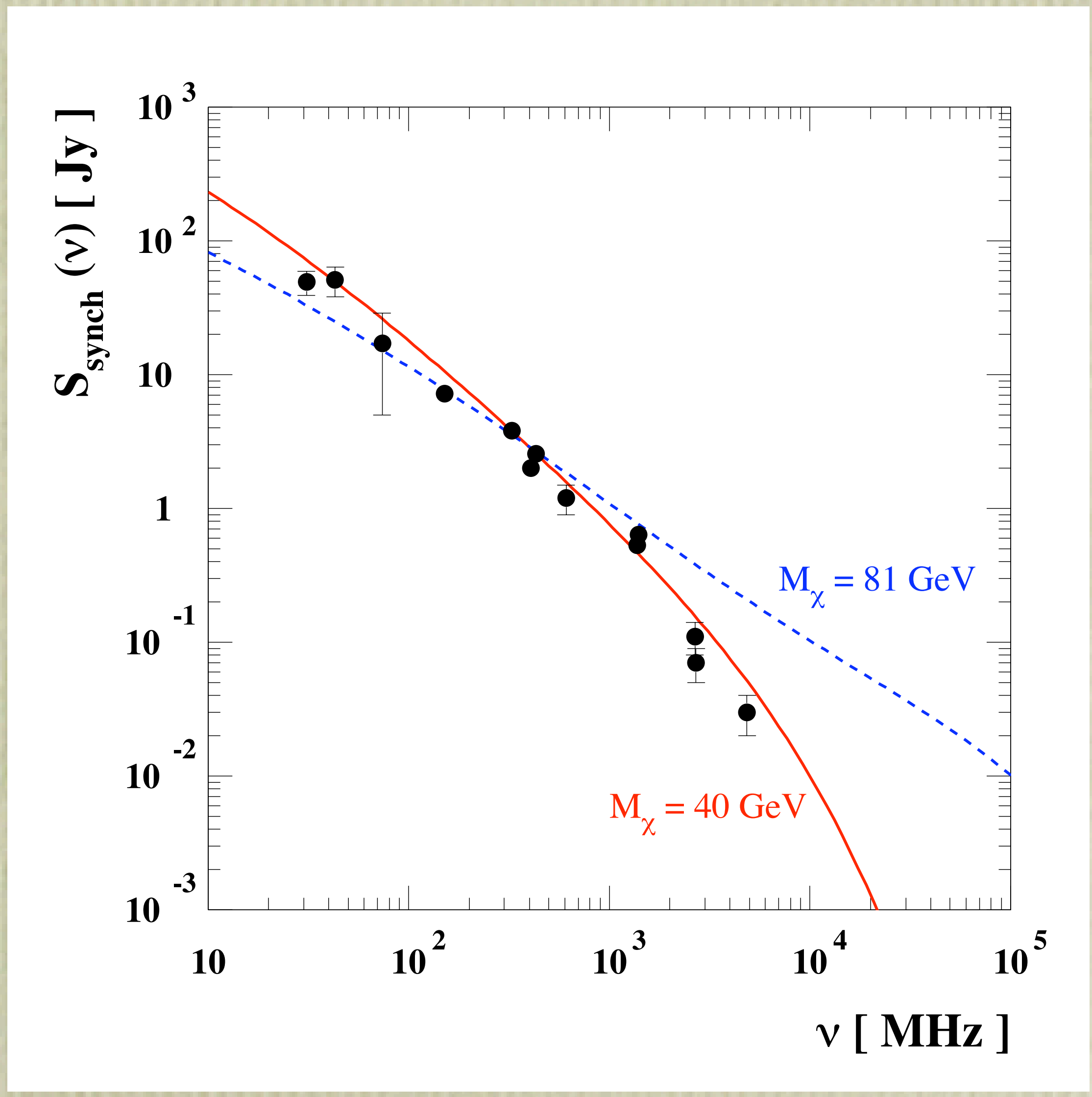
III) including all kind of energy loss terms:

$$b(E) \;=\; b_{IC}(E) + b_{syn}(E) + b_{Coul}(E) + b_{brem}(E)$$

(reacceleration/convection neglected)

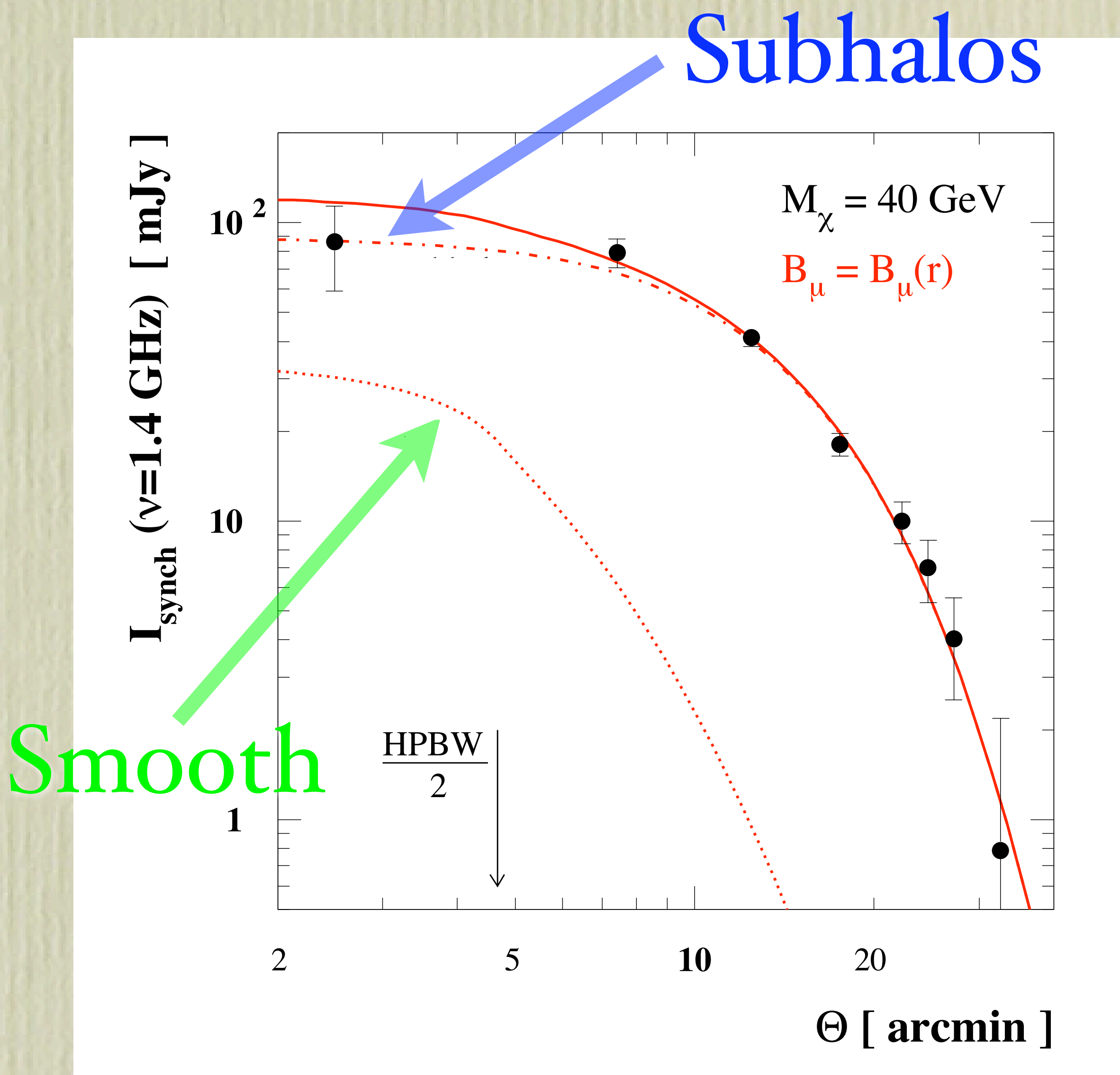
Add in a particle physics model and we are ready for making predictions; for Coma a DM component can fit:

the energy spectrum of the radio halo



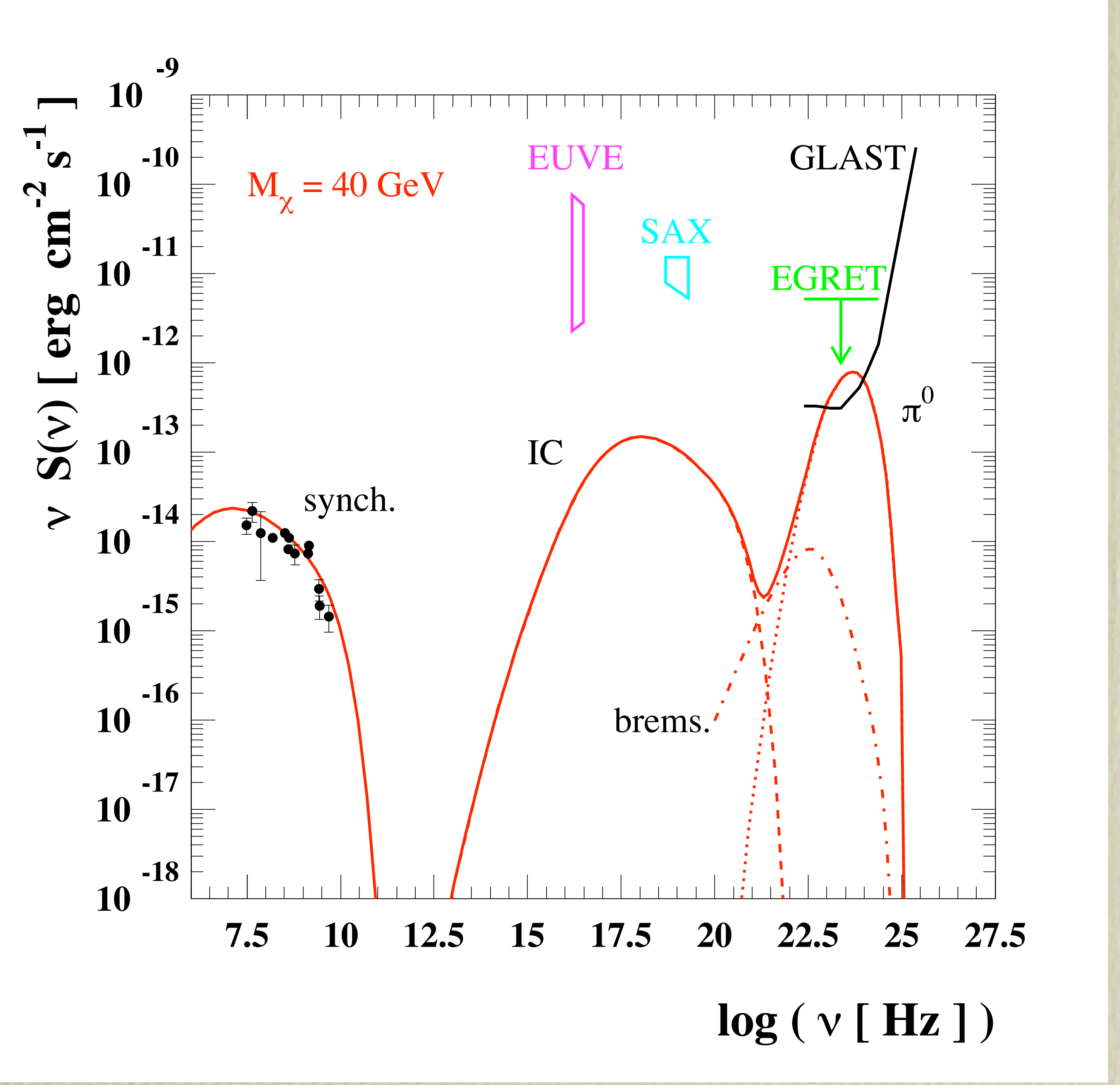
given WIMP mass and annihilation rate

... and its angular surface brightness



radial dependence of B from Faraday RM fits

and in these given setups we predict also:

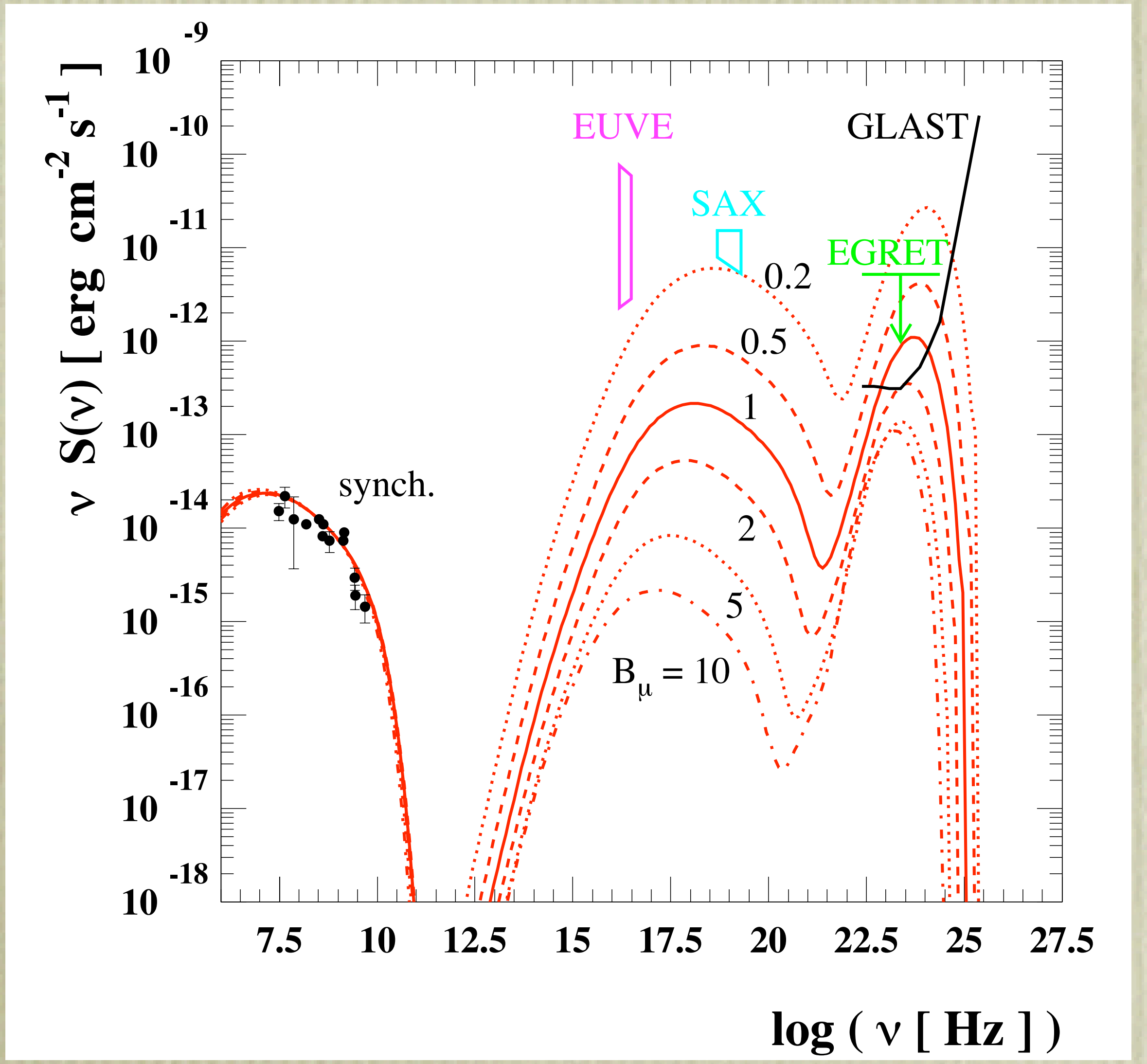


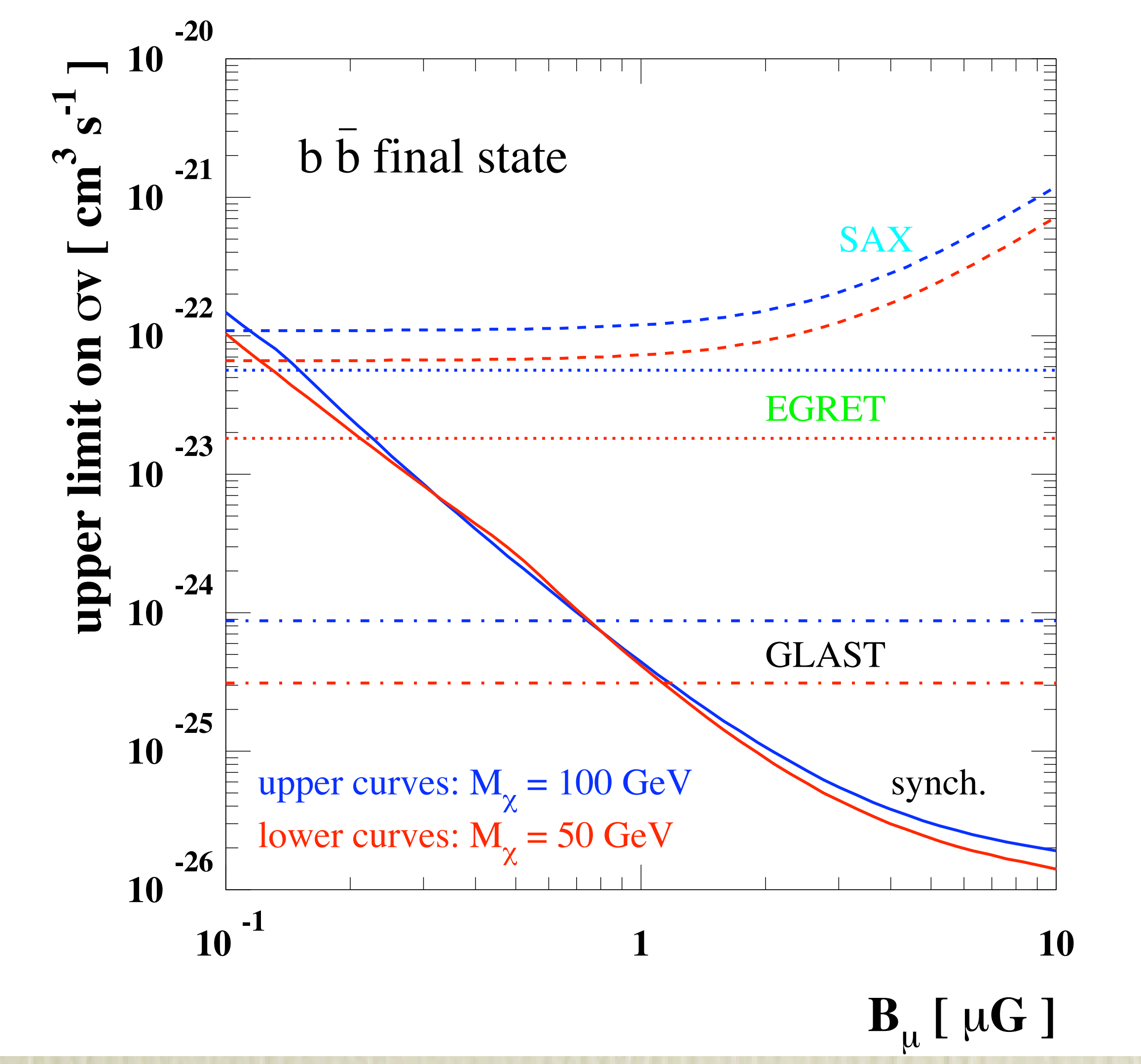
an associated gamma-ray flux within the sensitivity of GLAST

The role of the magnetic field in the game is a major one:

Take a few sample value for B and adjust mass and σv to fit the radio halo

Upper limit on σv for two sample values of the mass, varying B:





What about tracing WIMP annihilations through the Sunyaev-Zel'dovich Effect?

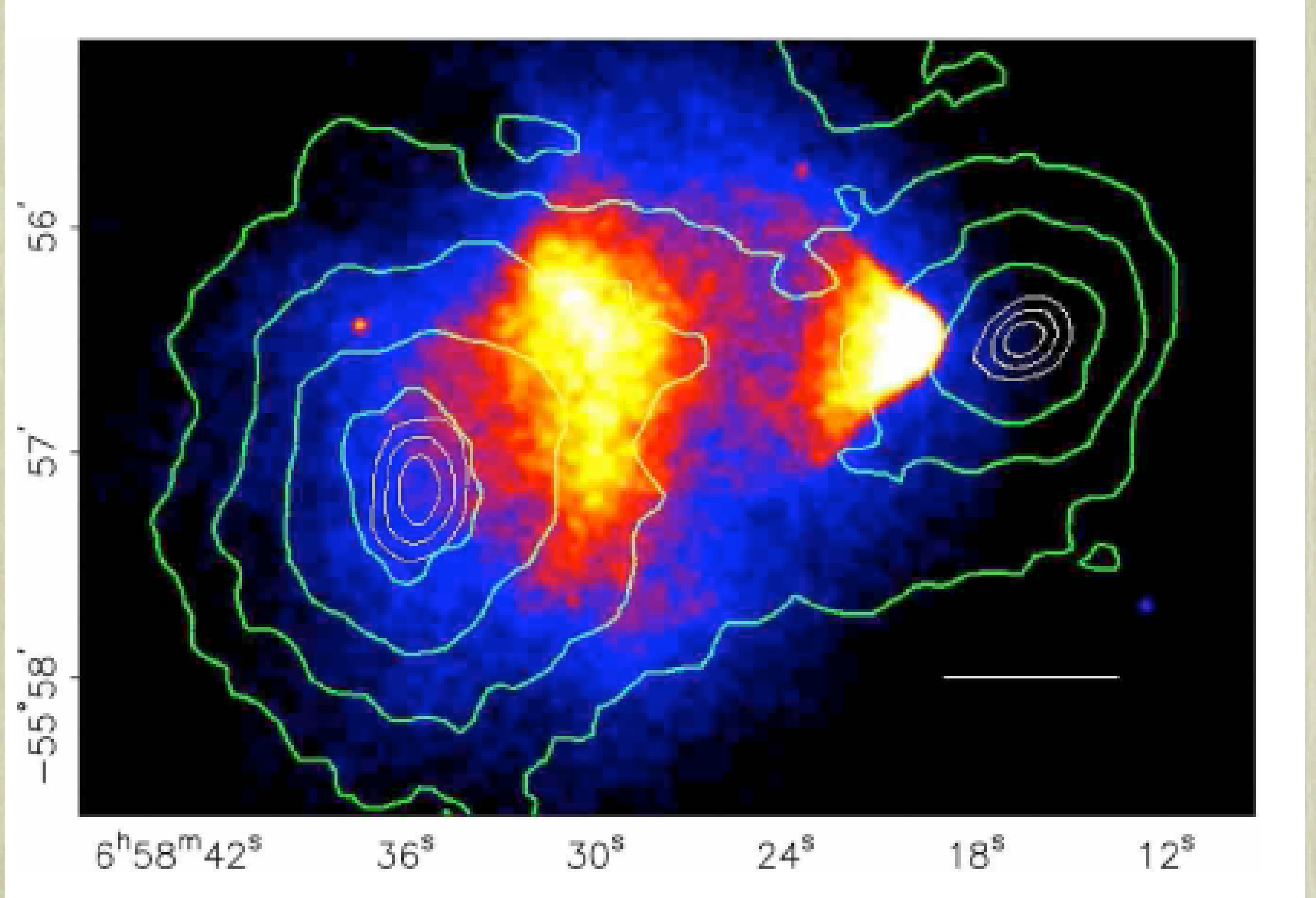
Colafrancesco, 2004

SZ: Compton scattering of CMB photons on the electron/positron populations in clusters. Net effect: low energy photons are "kicked up" to higher energy, hence there is a low frequency decrement and high frequency increment in the CMB spectrum.

In general, a large SZ effect is expected (and detected) in connection to the thermal gas in clusters, it may be hard to fight against this "background" in standard system.

What about systems having gone through a recent merging, with thermal components being displaced from the DM potential wells?

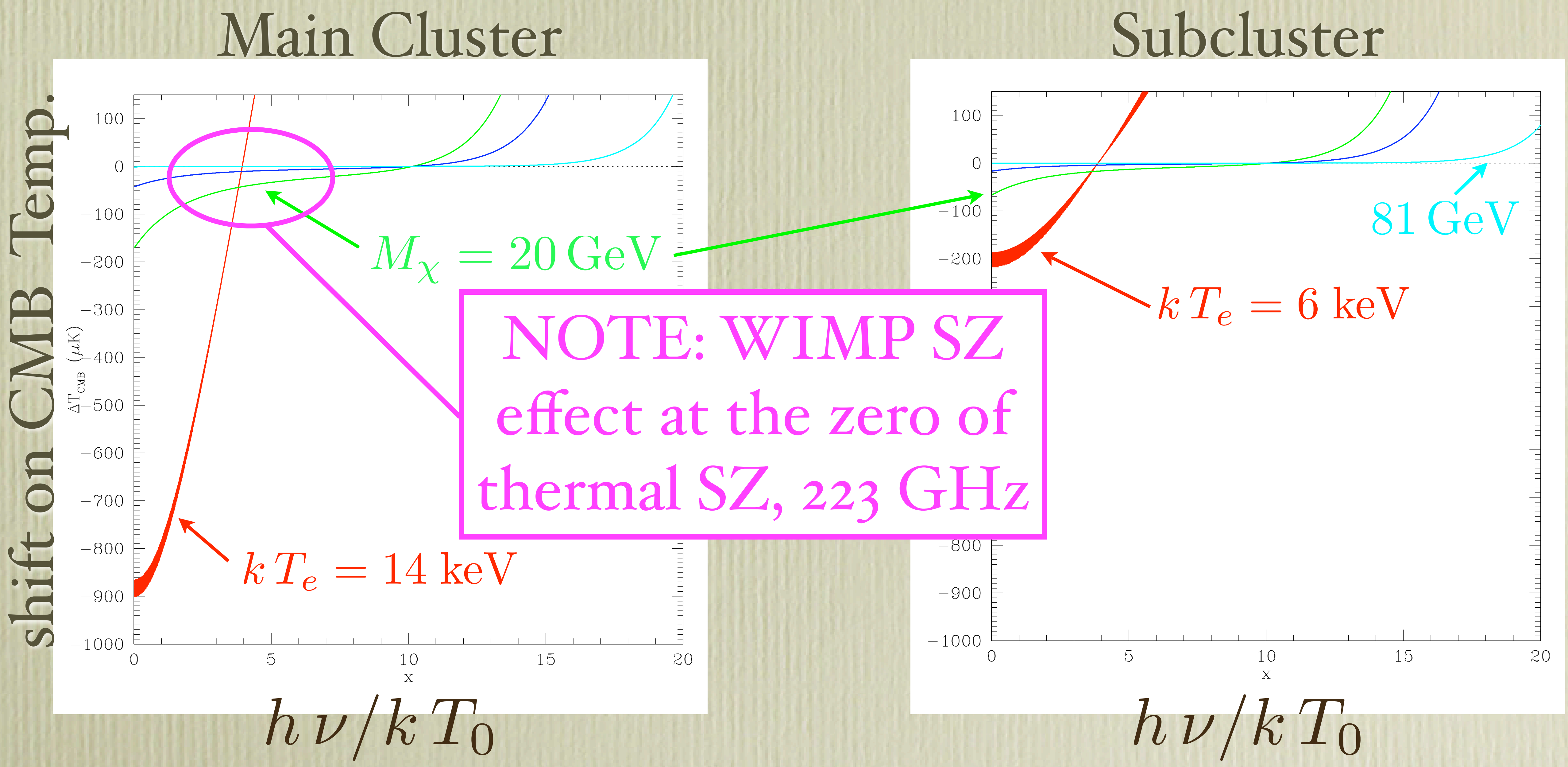
Colafrancesco, de Bernardis, Masi, Polenta & P.U., 2007 a remarkable example of this kind: 1E0657-558, the **"Bullet cluster"** at z=0.296



Lensing map of the cluster superimposed on Chandra X-ray image, Clowe et al. 2006

A supersonic cluster merger occurring nearly in the plane of the sky, with clean evidence for the separation of the collisionless DM from the collisional hot gas.

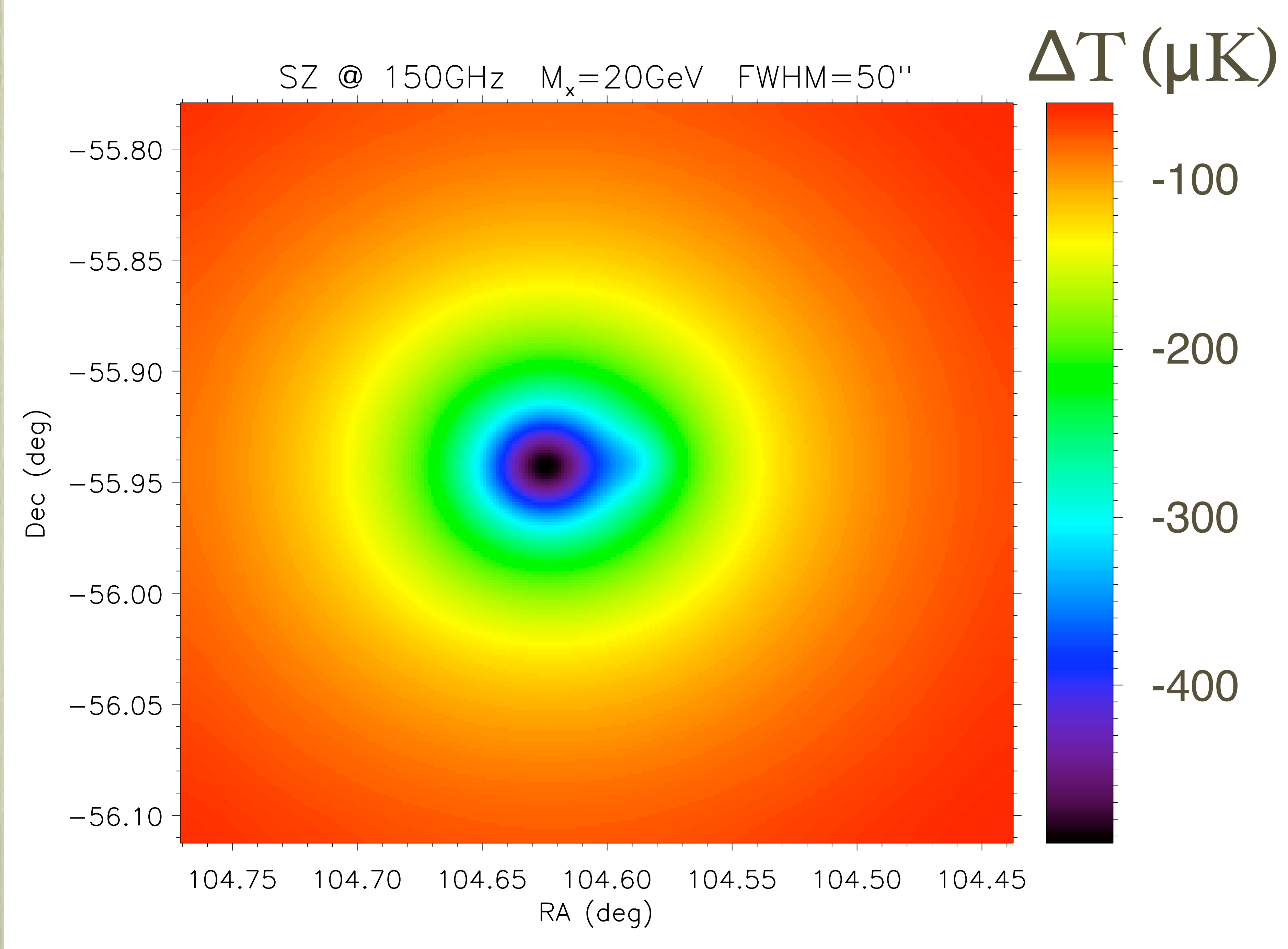
SZ effect in the simplified picture with two spherical DM halos (NFW profile) plus two isothermal gas components of given temperature (shock front neglected):



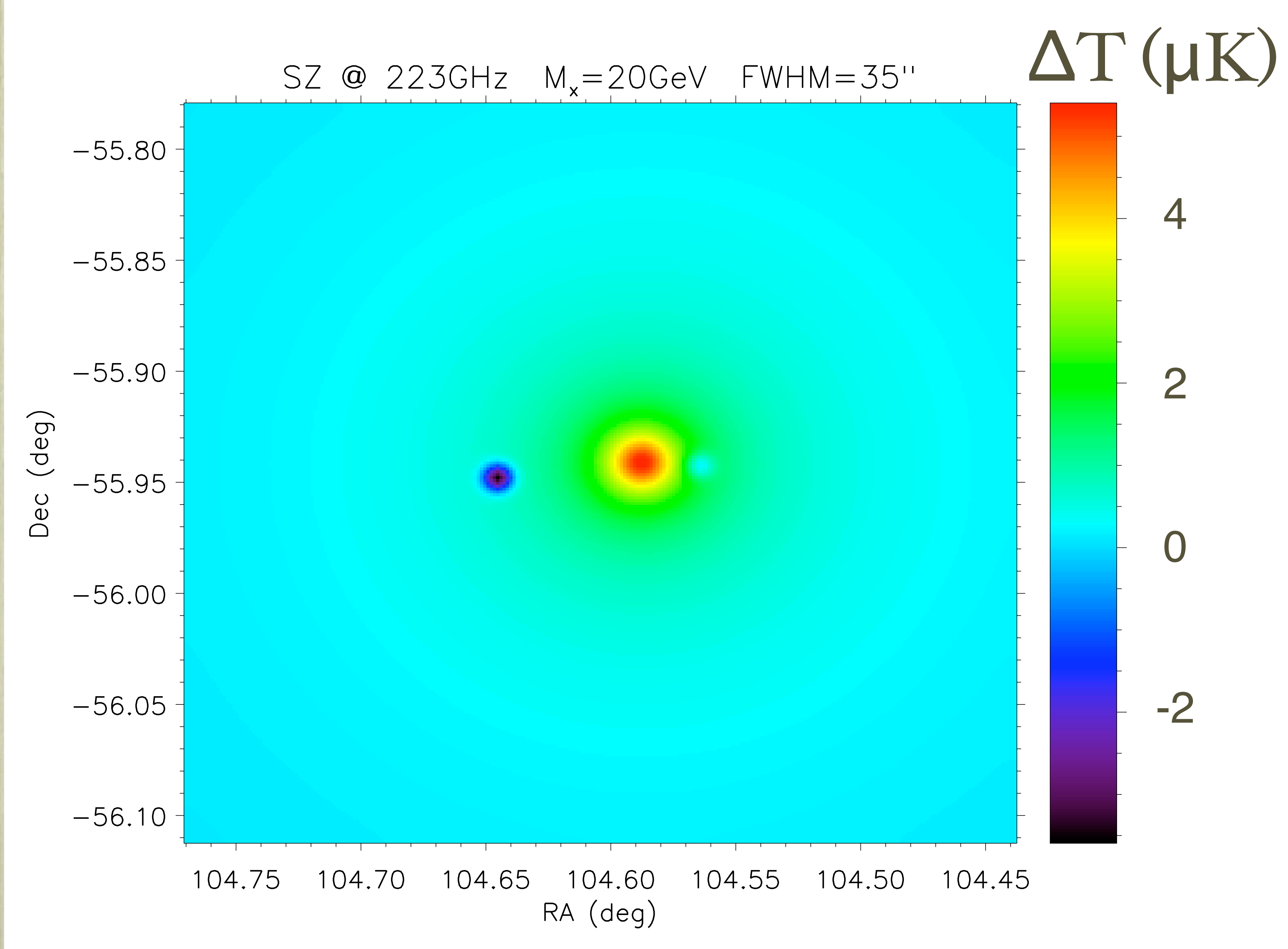
NOTE: WIMP SZ effect at the zero of thermal SZ, 223 GHz

Colafrancesco, de Bernardis, Masi, Polenta & P.U., 2007

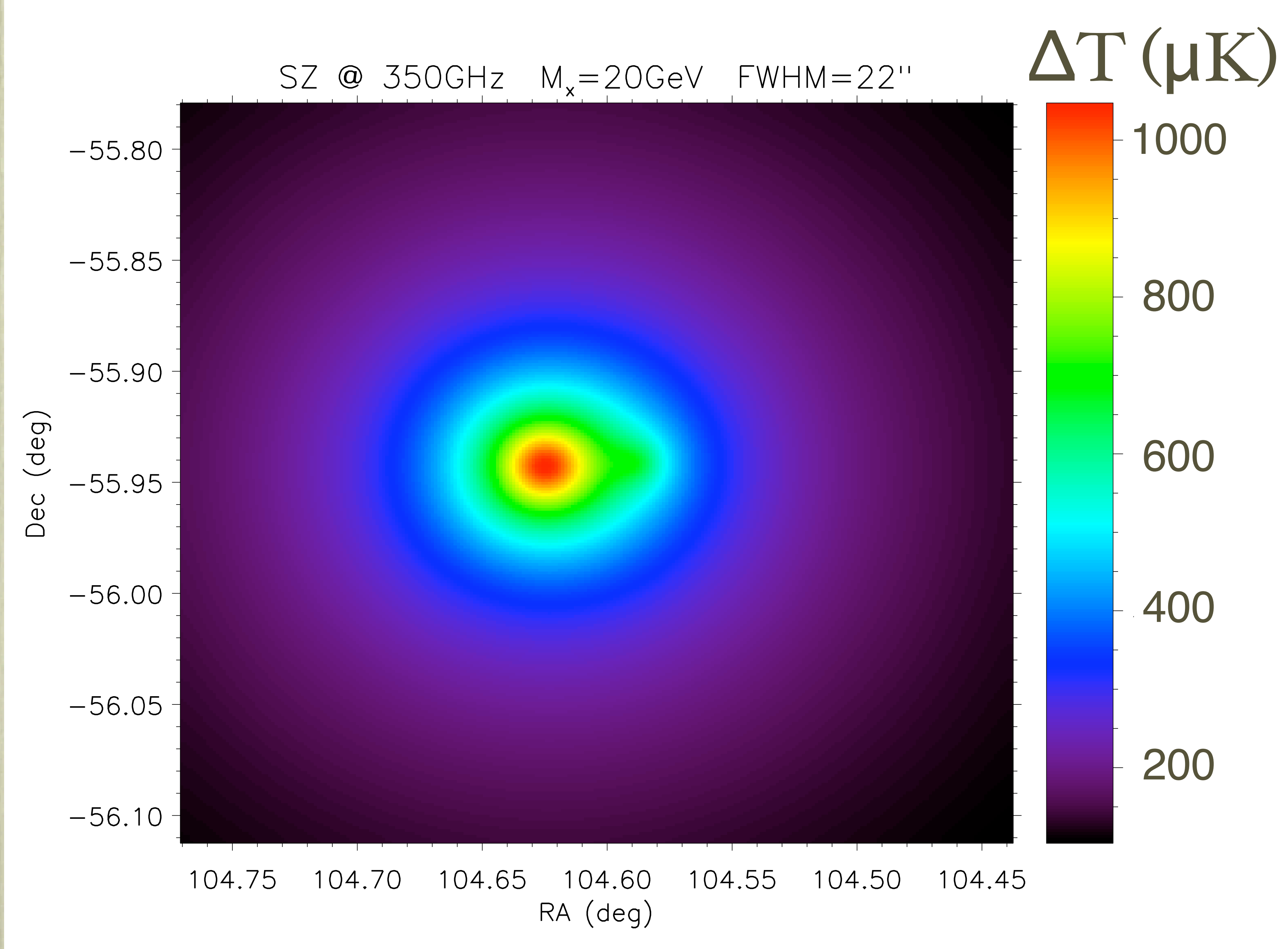
SZ map at 150 GHz:



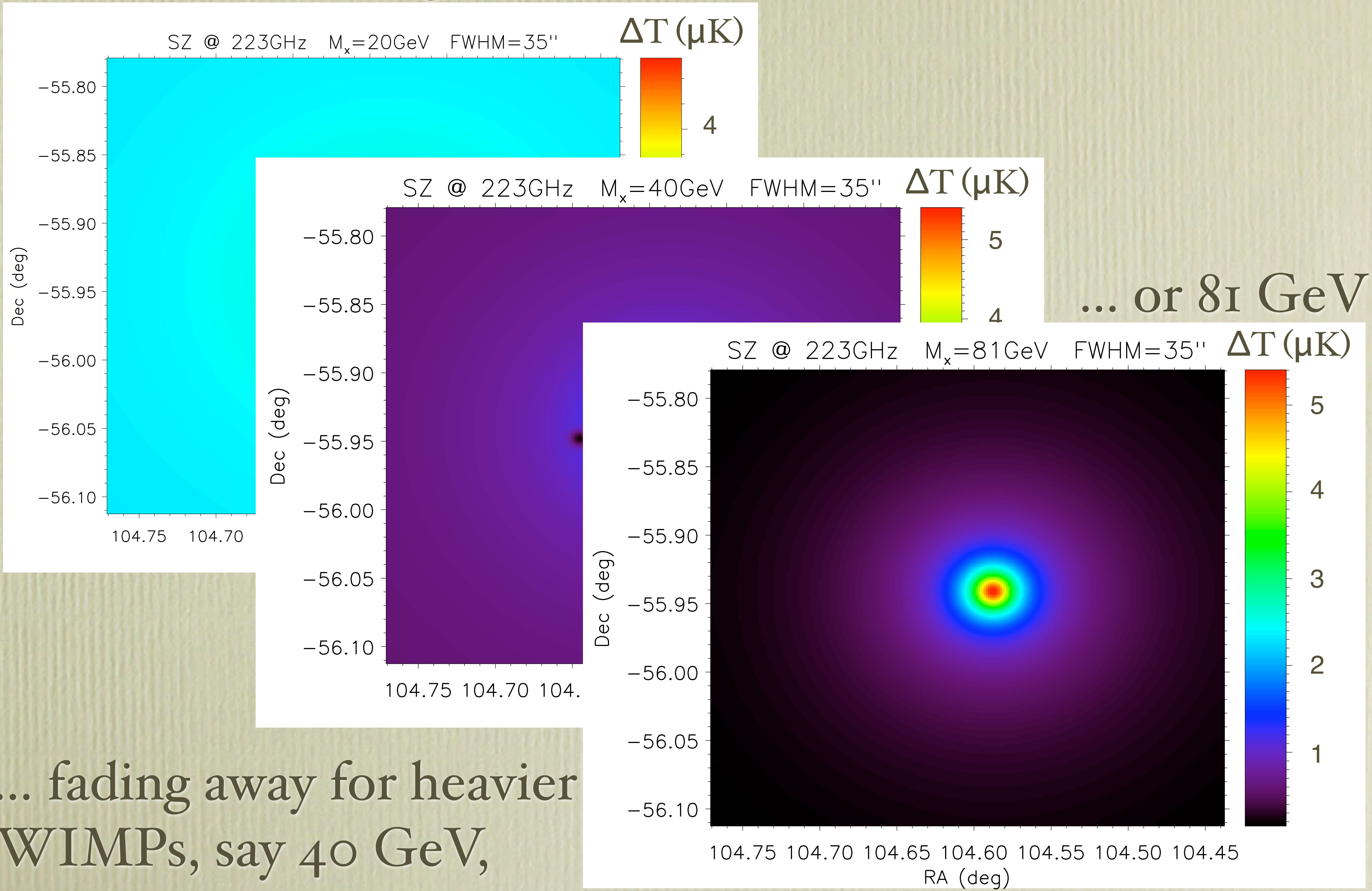
SZ map at 233 GHz:



SZ map at 350 GHz:



A light WIMP, say 20 GeV, gives a detectable (though small) effect:



... fading away for heavier WIMPs, say 40 GeV,

... or 81 GeV

In case of light WIMP DM, we propose this as a (tough) target for OLIMPO, maybe for the South Pole Telescope, the Atacama Cosmology Telescope, APEX, ...

To achieve detection a number of issues needs to be addressed: *contamination, bias and/or noise*, from CMB anisotropies, emission of galaxies and AGNS along the line of sight, temperature distributions in the hot gas, kinematic SZ, atmospheric noise ...

... not to mention uncertainties in the estimate for the signal. *Still, this is possibly a unique probe of the nature of DM, deserving further investigations.*

The Bullet cluster is too far away for a detection with GLAST, while the radio flux could be marginally detectable with LOFAR. Are there any such systems at lower z and thus suitable for a multifrequency study?

Coming back to the multifrequency DM detection approach, we had mentioned a second case of interest:

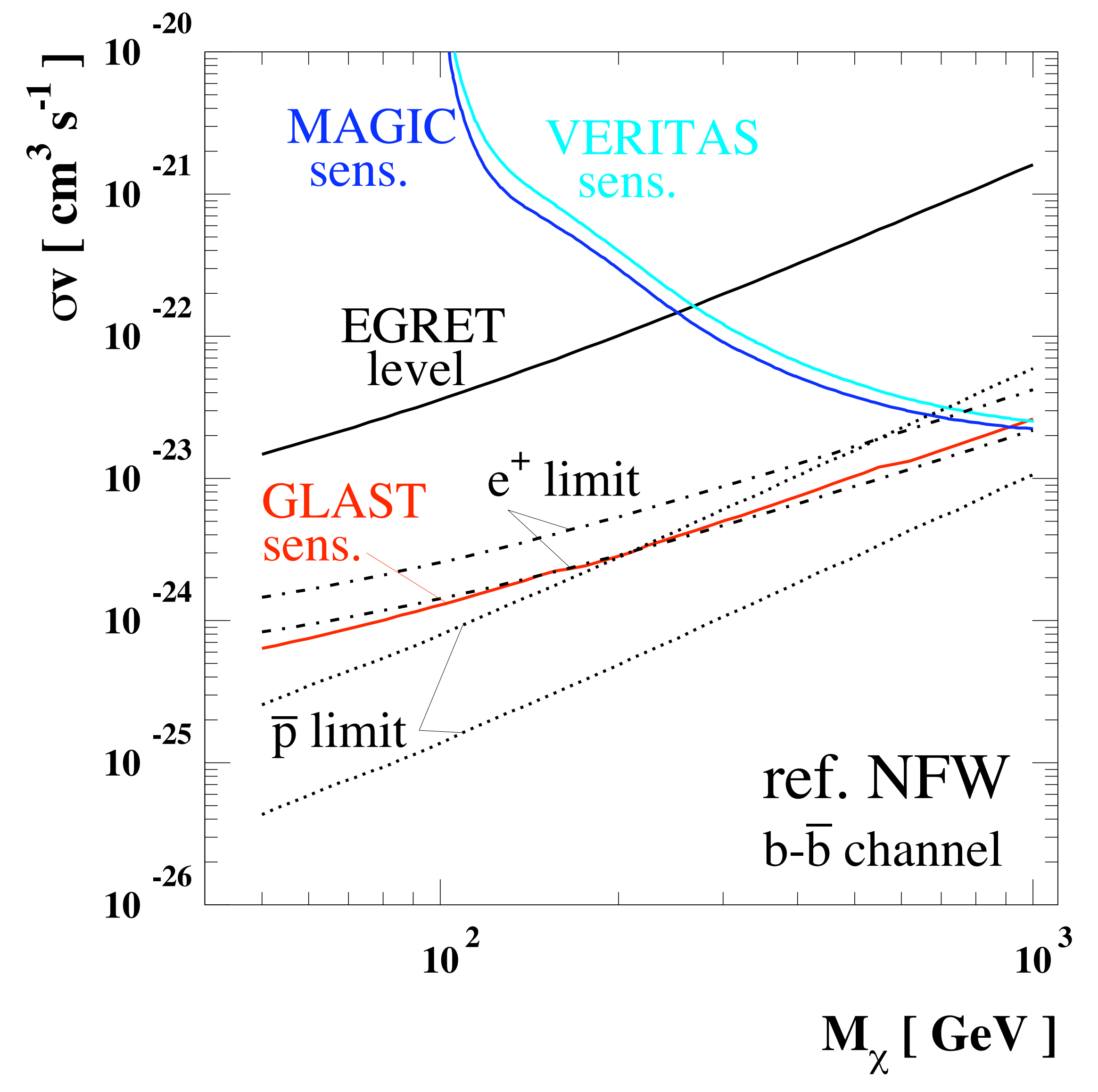
Case 11: Why dwarf galaxies?

- they are the among the most DM-dominated systems (M/L ~ 250) and a few are nearby (4 within 100 kpc)
- no competing astrophysical (background) source?
- ideal targets for multi-wavelength studies
- rich datasets will be available soon

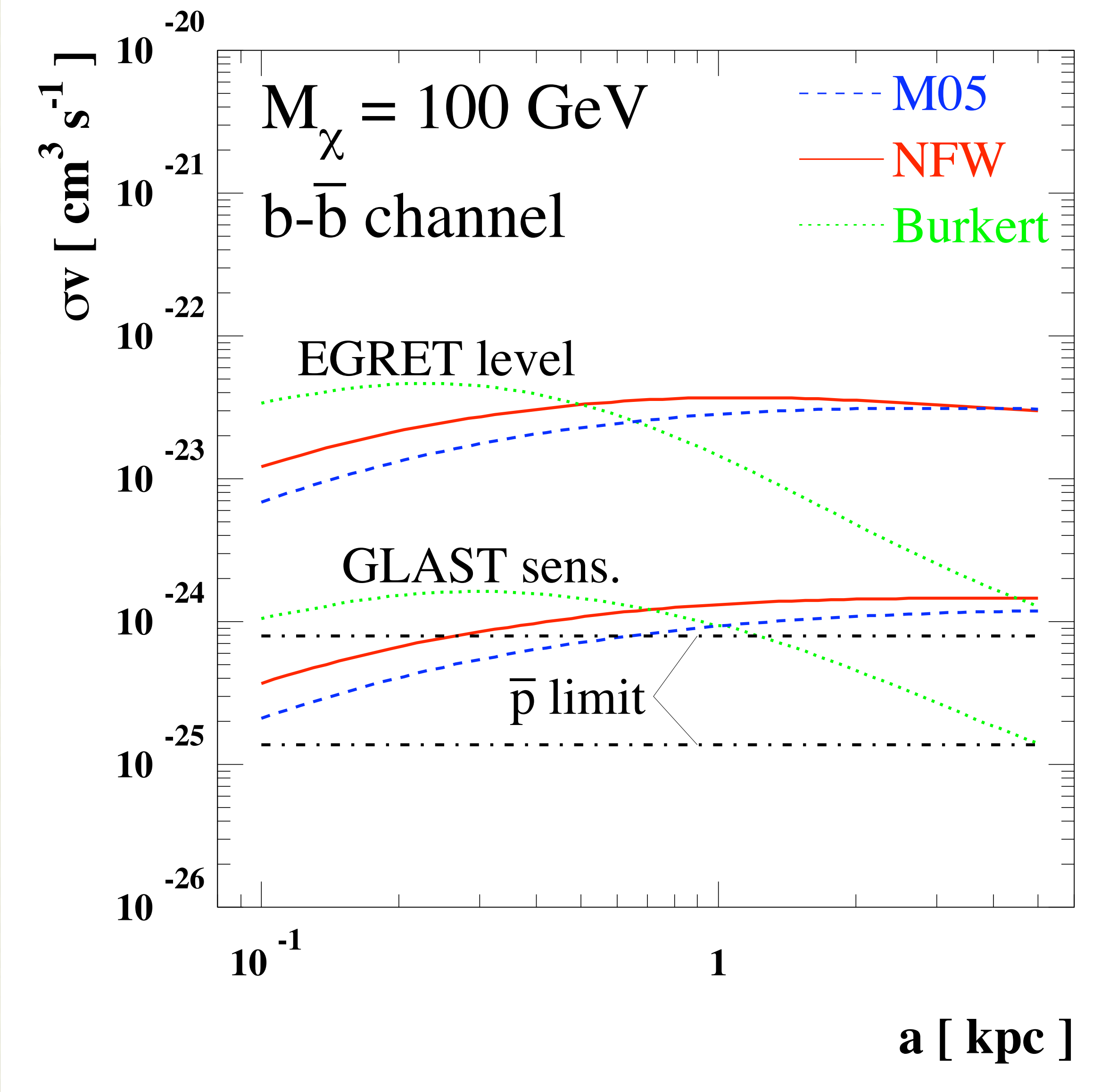
For gamma-ray studies of dwarf galaxies, see, e.g.: Baltz et al., 2000; Tyler, 2002; Evans, Ferrer & Sarkar, 2004; Bergstrom & Hooper, 2005; Profumo & Kamionkowski 2006

Focus on **Draco**, the closest (80 kpc) dwarf not severely affected by tides (at least in its central part)!

Strategy: select a halo model, fit free parameters, find γ-flux for a given WIMP setup

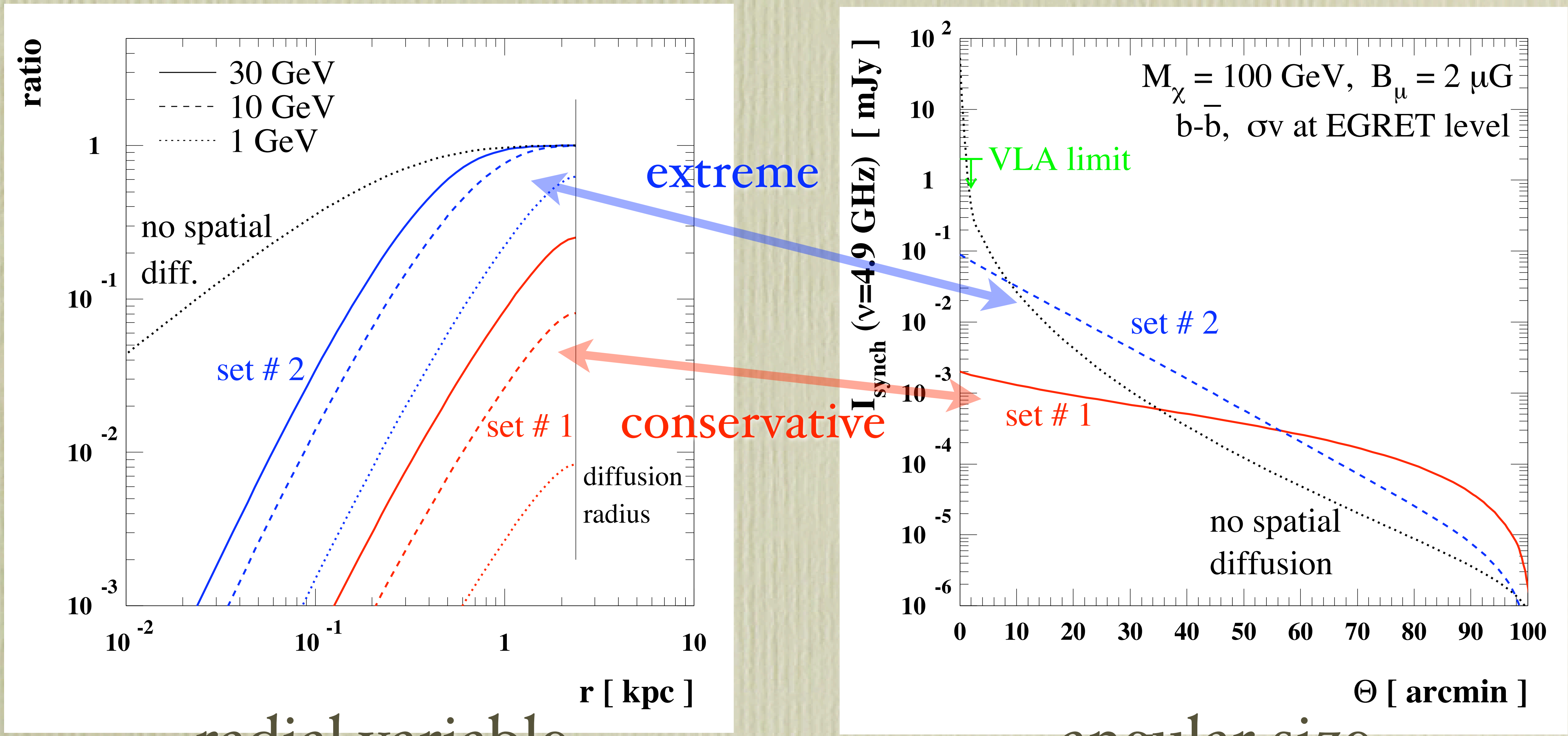


WIMP mass



Profile scale factor

A multi-wavelength target? Likely a magnetic field structure is associated to Draco, so that a e^{-}/ e^{+} population from WIMP annihilations builds up, but (contrary to Coma) in regime of spatial diffusion:



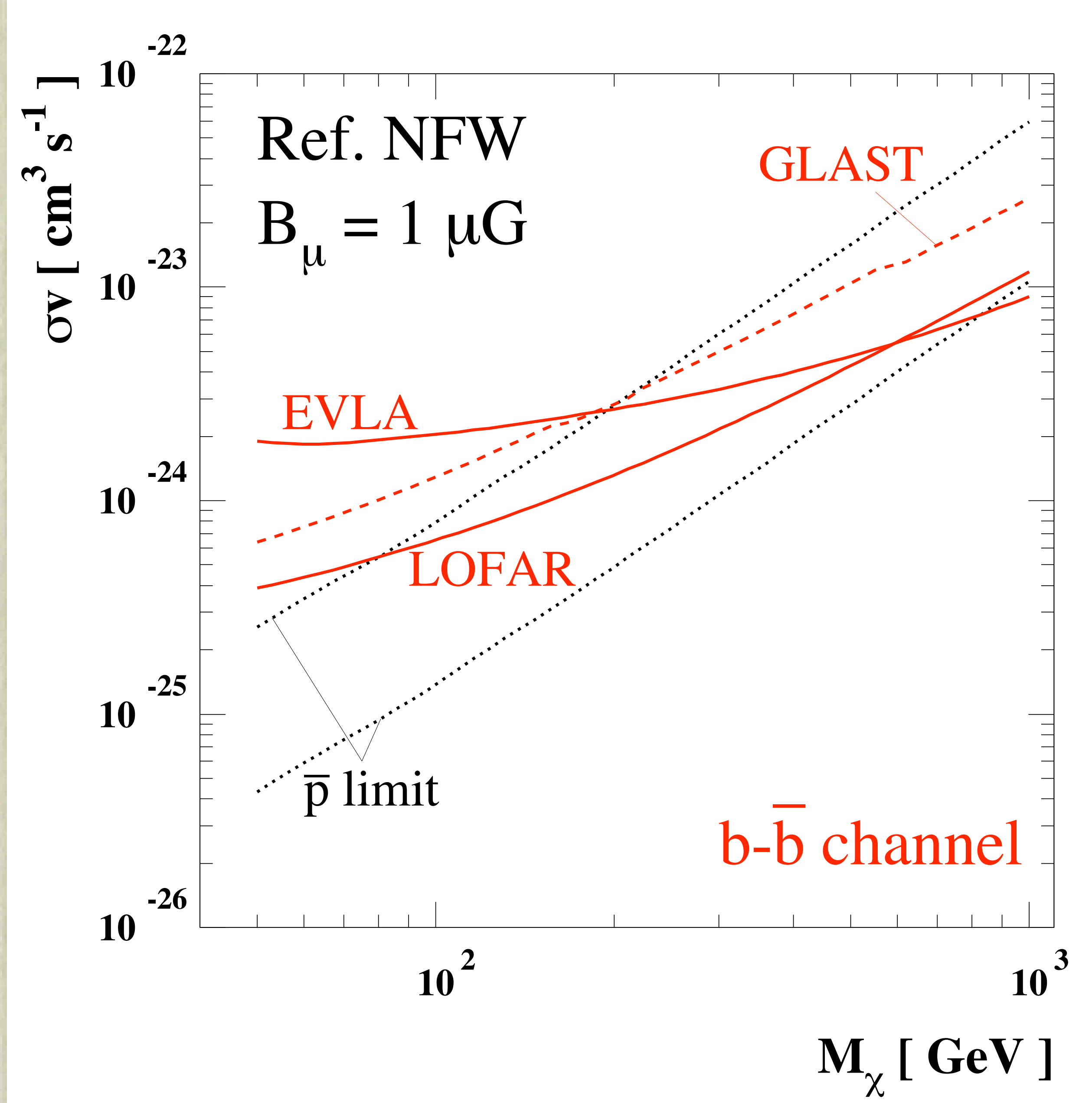
radial variable

angular size

N.B.: Point-like γ-ray source ⇔ extended radio source

No extended radio survey of Draco has been performed so far, we provide a motivation here:

In case of a γ-ray flux at a level detectable by GLAST, a synchrotron component should be at a level detectable for next generation radio telescopes



Conclusions

Multifrequency observations of external dark matter dominated halos may lead to the discovery of WIMP dark matter.

The SZ effect is an important complementary probe of the nature of dark matter.