Indirect dark matter detection in light of high-resolution N-body simulations

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Main ref:
Lidia Pieri, JL, Gianfranco Bertone & Enzo Branchini arXiv:0908.0195

TeV Particle Astrophysics 2010, IAP-Paris

Outline

General motivation: thorough study of the impact of subhalos

• Dark matter distribution in a Milky-Way-like galaxy in light of recent N-body simulations:

Via Lactea II (Diemand et al) versus Aquarius (Springel et al)

• Implication for gamma-ray searches

• Implication for antimatter searches

• Conclusions & perspectives

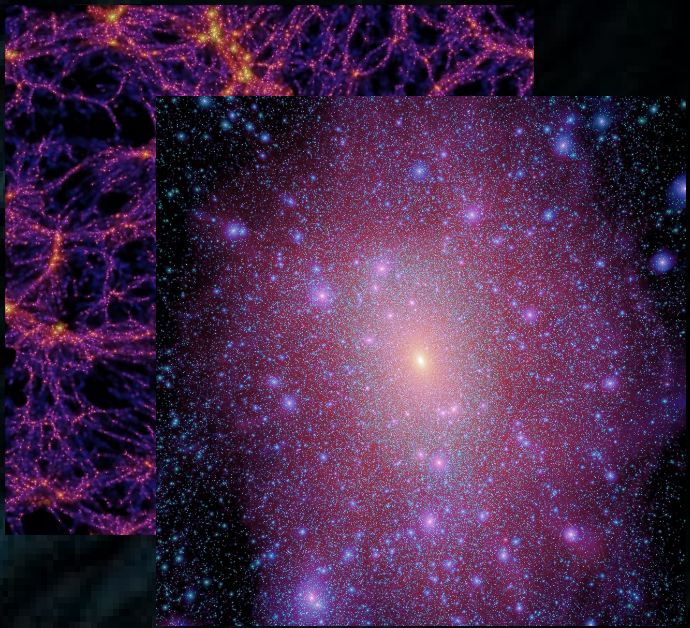
Via Lactea II versus Aquarius

Via Lactea II: Diemand et al (2008)
Aquarius: Springel et al (2008)

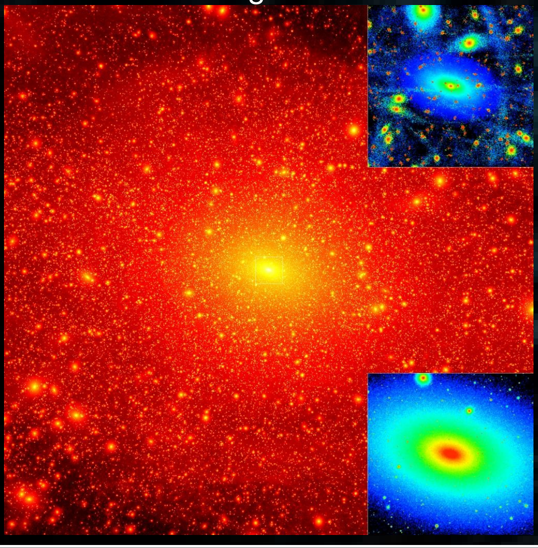
MW-like halos with ~ 1 billion particles of ~10^3 $M_\odot$
> 50,000-300,000 subhalos with masses > 10^6 -$10^{4.5}$ $M_\odot$

Slightly different cosmologies: WMAP3 vs WMAP5
(σ_8 = 0.74 vs 0.9)

http://www.mpa-garching.mpg.de/aquarius/



http://www.ucolick.org/~diemand/vl/index.html



Gamma-ray studies in:

Kuhlen et al (2008) – VL2
Springel et al (2008) – AQ

					Overall DM		Subhalos			
	$M_{\rm part}$ $[10^3 M_\odot]$	$N_{\rm part}$ $[10^8]$	M_{50} $[10^{12} M_\odot]$	R_{50} [kpc]	Density profile	$\rho_\odot$ [GeV/cm^3]	$M_{\rm sub}^{\rm res}$ $[10^4 M_\odot]$	$N_{\rm sub}^{\rm res}$ $[10^4]$	Mass slope	$f_{\rm sub}^{\rm res}$ [%]
VL2	4.1	4.7	1.9	402	NFW	0.42	$\sim 10^2$	5.3	2	10
AQ	1.7	14.7	2.52	433	Einasto	0.57	3.24	30	1.9	13.2

Limits of N-body simulations: the smallest scales of DM structures

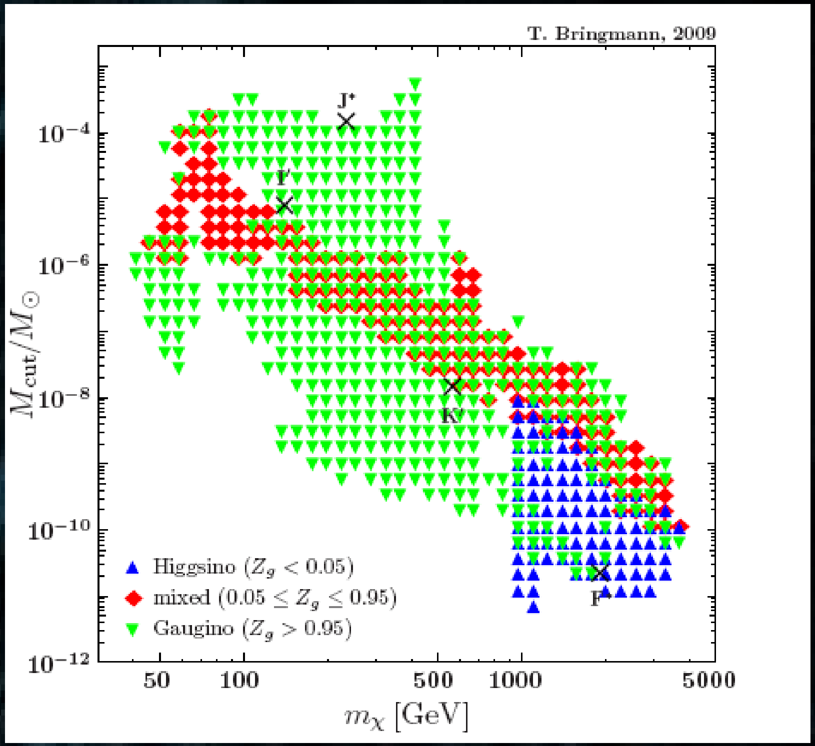
(see review by T. Bringmann (2009))

The free streaming scale depends on the time of kinetic (≠ chemical) decoupling of WIMPs from the primordial soup.

The weaker the collision rate, the earlier the gravitational collapse, the smaller the cut-off mass.

Subhalo mass down to 10^{-10}-10^{-6} $M_\odot$ (SUSY). The lighter the denser.

Tidal effects ? Large survival fraction (Berezinsky et al, 2008)



T. Bringmann arXiv:0903.0189

	$M_{\rm sub}^{\rm res}$ $[10^4 M_\odot]$	$N_{\rm sub}^{\rm res}$ $[10^4]$	Mass slope	$f_{\rm sub}^{\rm res}$ [%]
VL2	$\sim 10^2$	5.3	2	10
AQ	3.24	30	1.9	13.2

Extrapolation

down to 10^{-6} Msun

	$M_{\rm sub}^{\rm min}$ $[10^{-6} M_\odot]$	$N_{\rm sub}^{\rm tot}$ $[10^{15}]$	Mass slope	$f_{\rm sub}^{\rm tot}$ [%]
VL2	1	28	2	54.2
AQ	1	1.1	1.9	17.1

Adding subhalos: a self-consistent method (example for a spherical NFW host halo)

(i) Global fit to the N-body simulation (eg NFW)

$$\rho_{\rm MW}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm MW}(r) = M_{\rm MW}$$

(ii) Adding subhalos means splitting the global fit into a smooth + clumpy components

$$\text{Adding subhalos} \Rightarrow \rho_{\rm MW}(r) = \rho_{\rm sm}(r) + \rho_{\rm sub}(r)$$

$$\rho_{\rm sm}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm sm}(r) = (1 - f_{\rm sub})\, M_{\rm MW}$$

$$\rho_{\rm sub}(r) \text{ such that } 4\pi \int dr\, r^2 \rho_{\rm sub}(r) = f_{\rm sub}\, M_{\rm MW}$$

Warning !!!

$$\rho_{\rm sm}(r) \neq (1 - f_{\rm sub})\rho_{\rm MW}(r)$$

often assumed = in the past

(iii) Use N-body prescriptions: subhalo distribution cored in the center.

in Via Lactea, antibiased relation: subhalo distrib $\propto$ r $\times$ global smooth distrib

$$\rho_{\rm sm}(r) = \frac{\rho_{\rm MW}(r)}{(1 - r/r_b)} \propto \begin{cases} r^{-1} & \text{for } r \lesssim r_b \sim r_s \\ r^{-4} & \text{for } r \gtrsim r_b \sim r_s \end{cases}$$

$$\rho_{\rm sub}(r) = \frac{\rho_{\rm MW}(r)(r/r_b)}{(1 - r/r_b)} \propto \begin{cases} \text{cst} & \text{for } r \lesssim r_b \sim r_s \\ r^{-3} & \text{for } r \gtrsim r_b \sim r_s \end{cases}$$

Adding subhalos: a self-consistent method (example for a spherical NFW host halo)

(i) Global fit to the N

$\rho_{\rm MW}(r)$ such that 4π

(ii) Adding subhalos means splitting the glob
fit into a smooth + clumpy components

Adding subhalos $\Rightarrow \rho_{\rm MW}(r) = \rho_{\rm sm}(r) +$

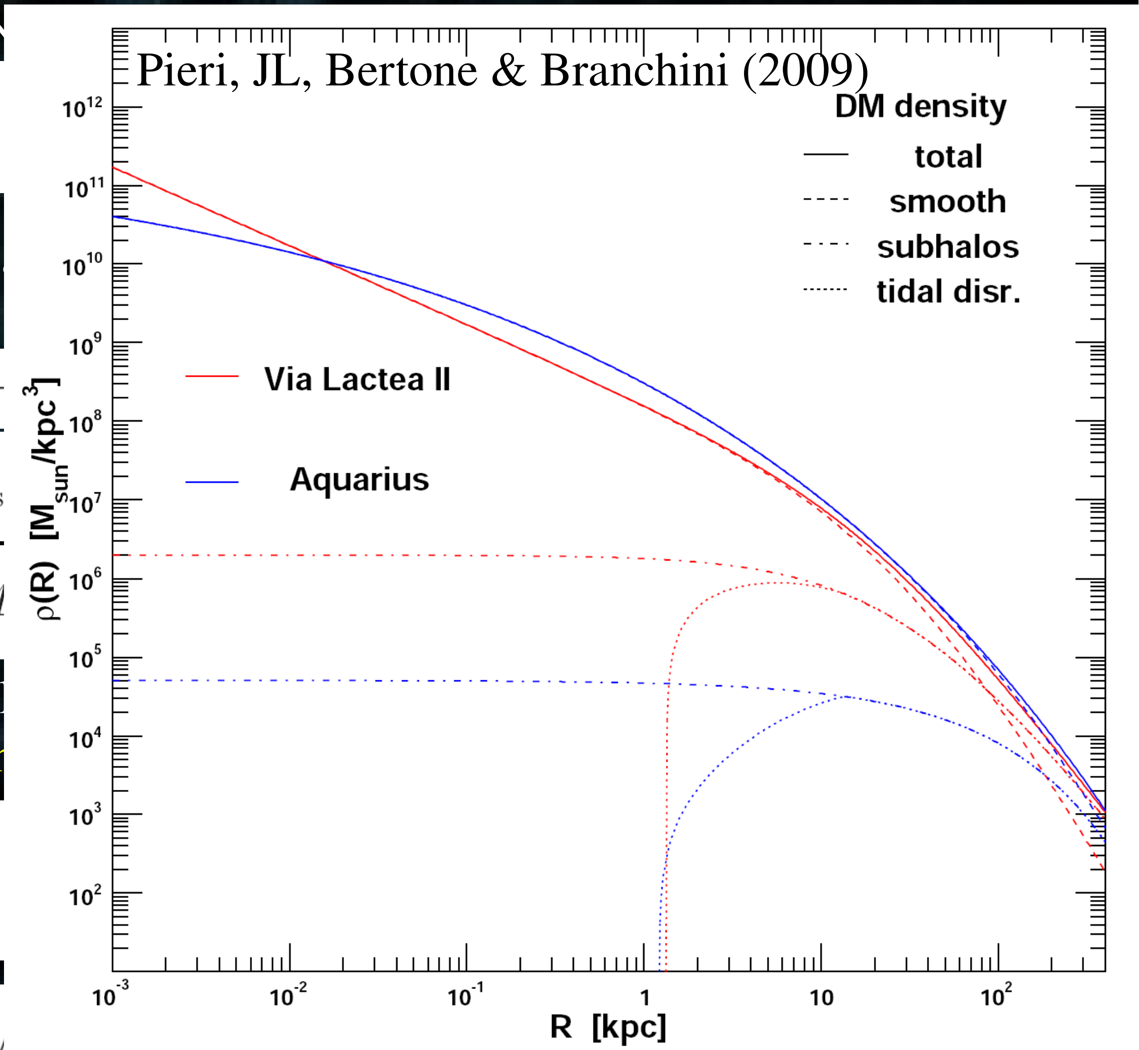
$\rho_{\rm sm}(r)$ such that $4\pi \int dr\, r^2 \rho_{\rm sm}(r) \quad = \quad (1 - f_{\rm s}$

$\rho_{\rm sub}(r)$ such that $4\pi \int dr\, r^2 \rho_{\rm sub}(r) \quad = \quad f_{\rm sub} M$

(iii) Use N-body prescriptions: subhal
in Via Lactea, antibiased relation

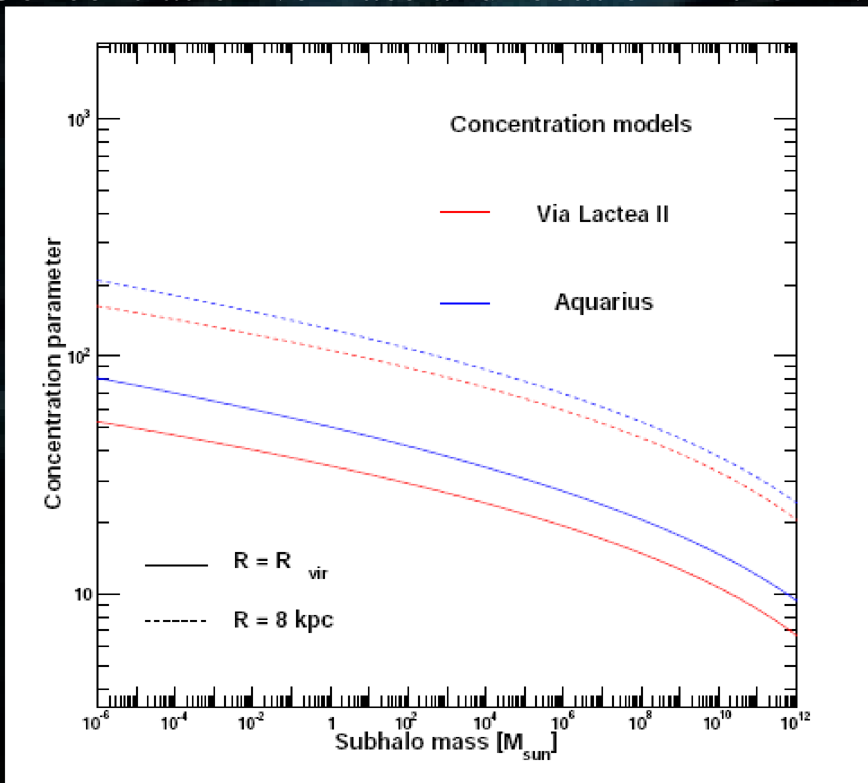
$$\rho_{\rm sm}(r) = \frac{\rho_{\rm MW}(r)}{(1 - r/r_b)}$$

$$\rho_{\rm sub}(r) = \frac{\rho_{\rm MW}(r)(r/}{(1 - r/r_b)} \propto \left\{ r^{-3} \quad \text{for } r \gtrsim r_b \sim r_s \right.$$

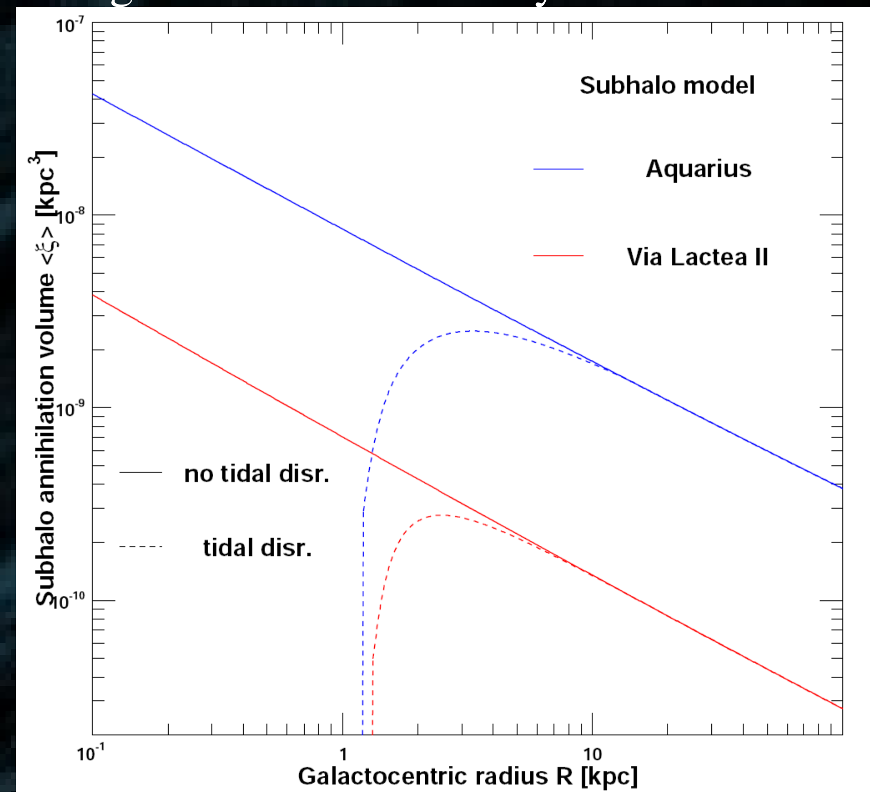


Subhalo properties
(extrapolated from simulations down to $10^{-6} M_\odot$)

Concentration vs mass and location in the MW



Averaged subhalo luminosity vs distance to GC



Profiles:
NFW for Via Lactea, Einasto for Aquarius

$$\rho_{\rm nfw}(r) = \rho_s \frac{(r/r_s)^{-1}}{(1+r/r_s)^2}$$
$$\rho_{\rm ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right\}$$

$$\frac{d\mathcal{P}}{dm} \propto m^{-\alpha}$$
$$\alpha_{\rm Aq} = 1.9$$
$$\alpha_{\rm VLII} = 2$$

Spatial dependence:
concentration + tidal disruption

$$\langle\xi\rangle(R) \equiv 4\pi \int dm \frac{d\mathcal{P}}{dm} \int dr\, r^2 \left(\frac{\rho(r,m,R)}{\rho_0}\right)^2$$

Gamma-rays: the diffuse components (DM only)

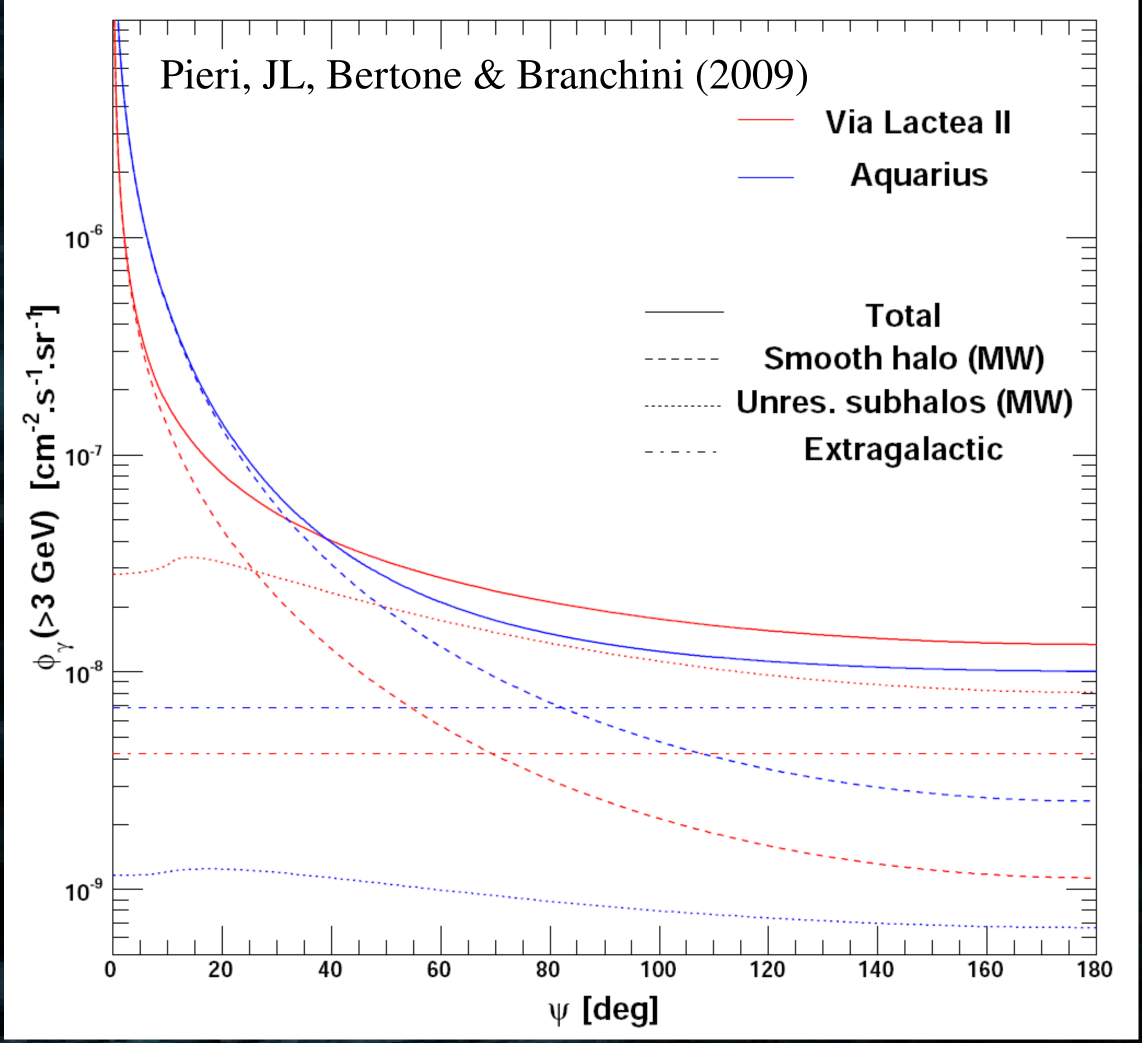
Gamma-ray flux above 3 GeV (resolution of 9')
(40 GeV WIMPs going to b-bbar)

3 different contributions:

- **The smooth Galactic DM halo** :
→ semi-analytical treatment
(e.g. Bergström et al, 1998)

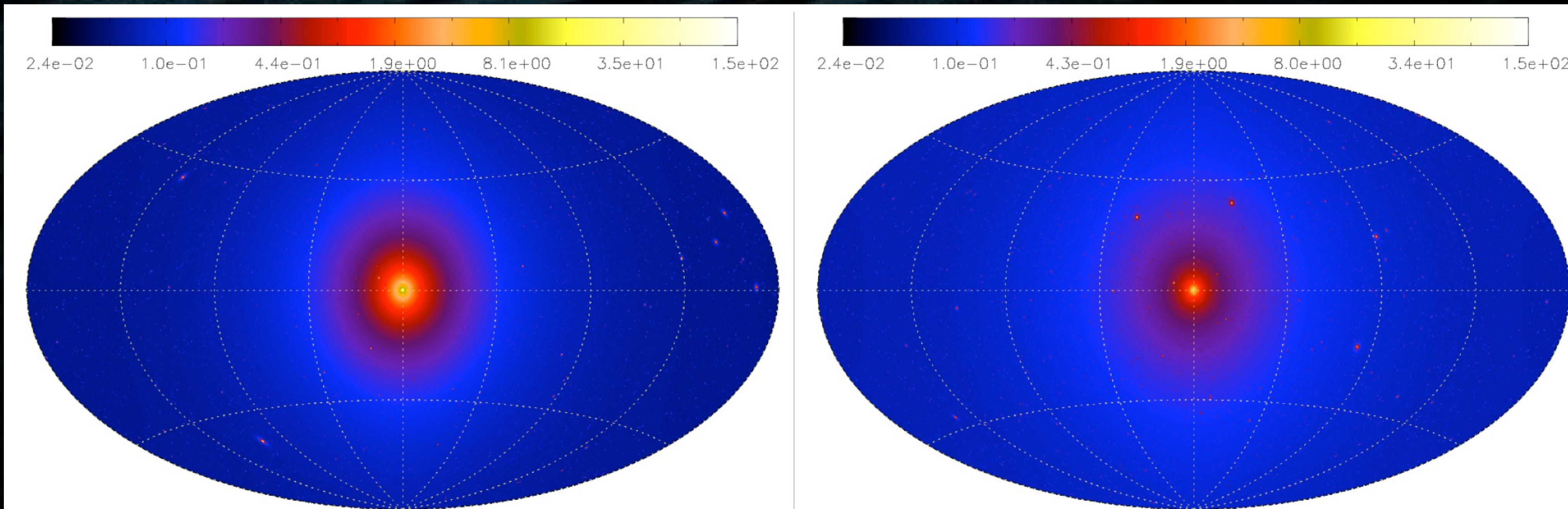
- **The Galactic subhalos**:
→ semi-analytical + MC techniques
(e.g. Bi, 2006; Pieri et al, 2008)

- **The extragalactic DM halos**:
→ semi-analytical
(e.g. Bergström et al, 2001; Ullio et al, 2002)



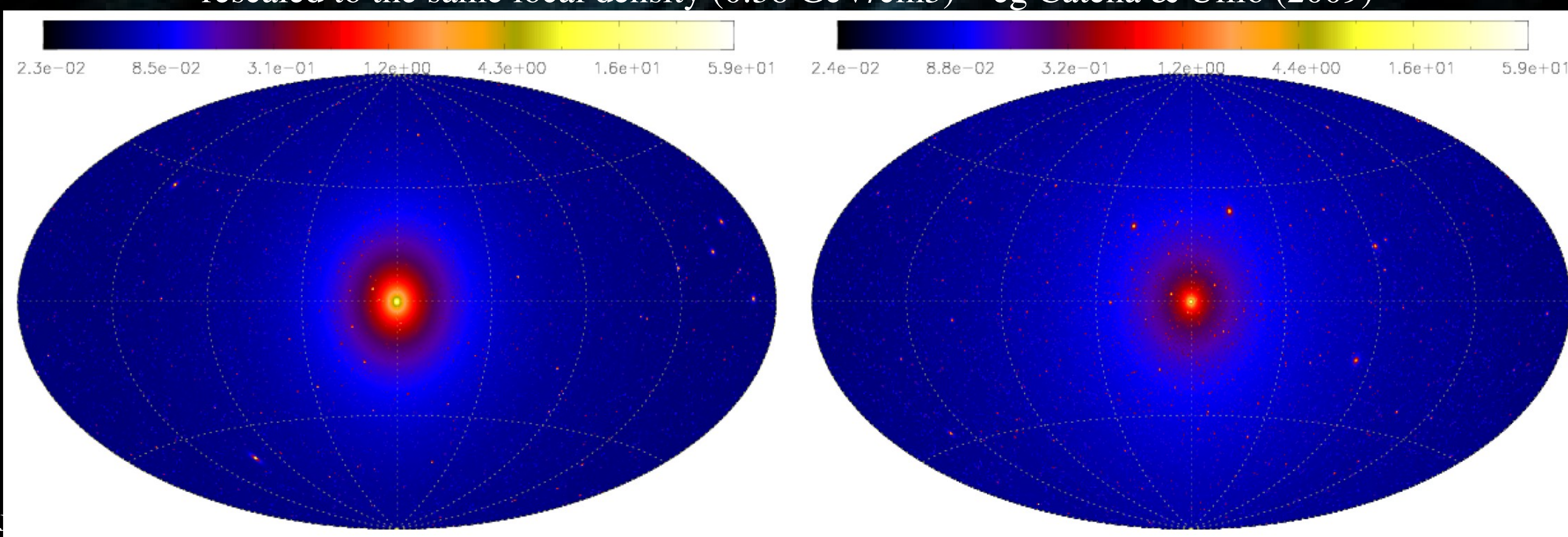
=> Large global subhalo effects for VL2
=> No global subhalo effects for Aquarius

Gamma-ray sky map (DM only)



Aquarius **Via Lactea II**

rescaled to the same local density (0.38 GeV/cm3) – eg Catena & Ullio (2009)

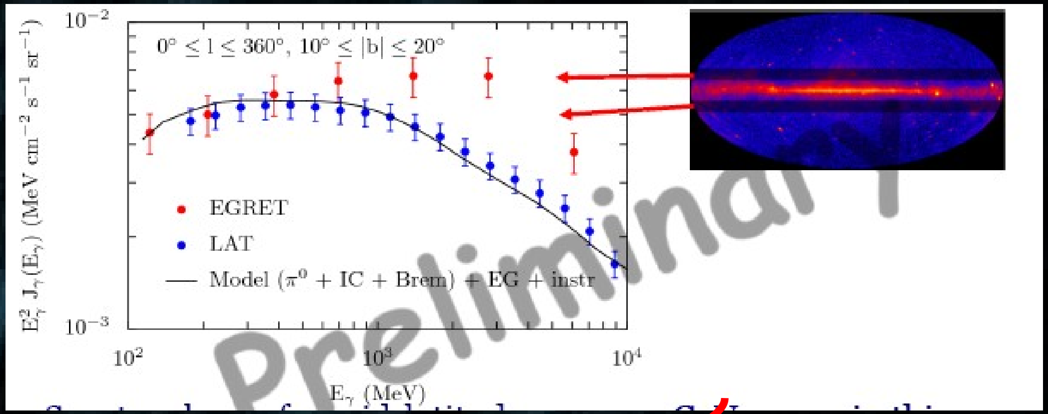


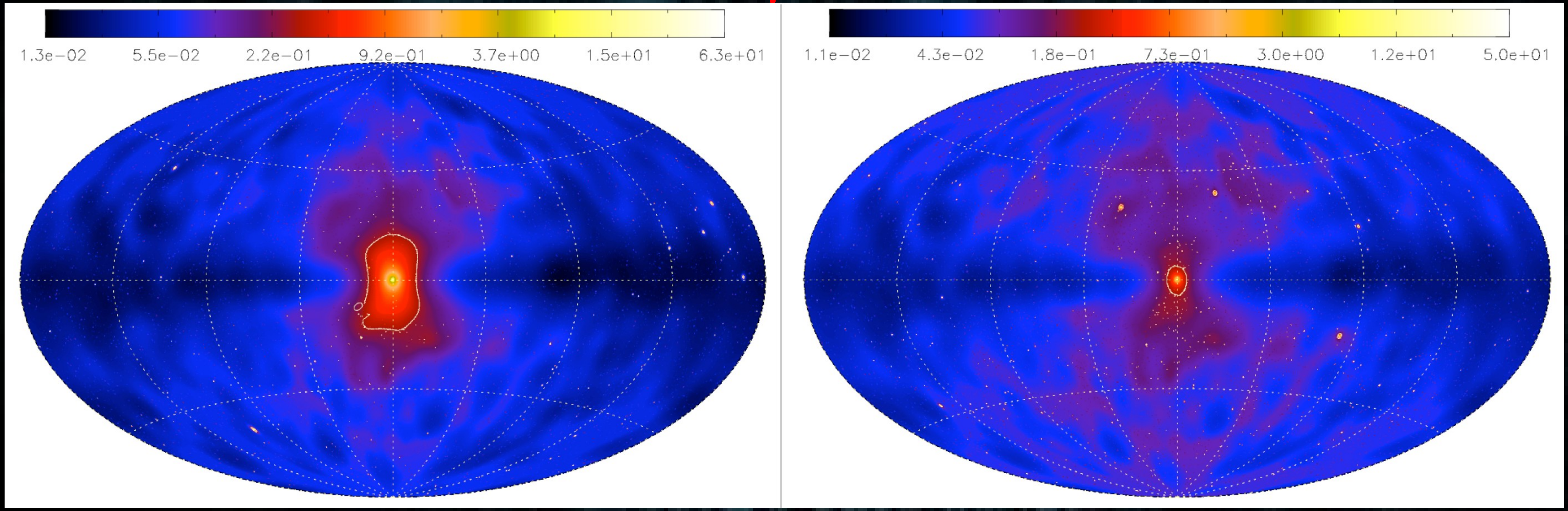
Sensitivity map for 5-year Fermi-LAT (wrt empirical astrophysical background)

Empirical diffuse emission model:
template maps from EGRET
(Cillis & Hartman 05)

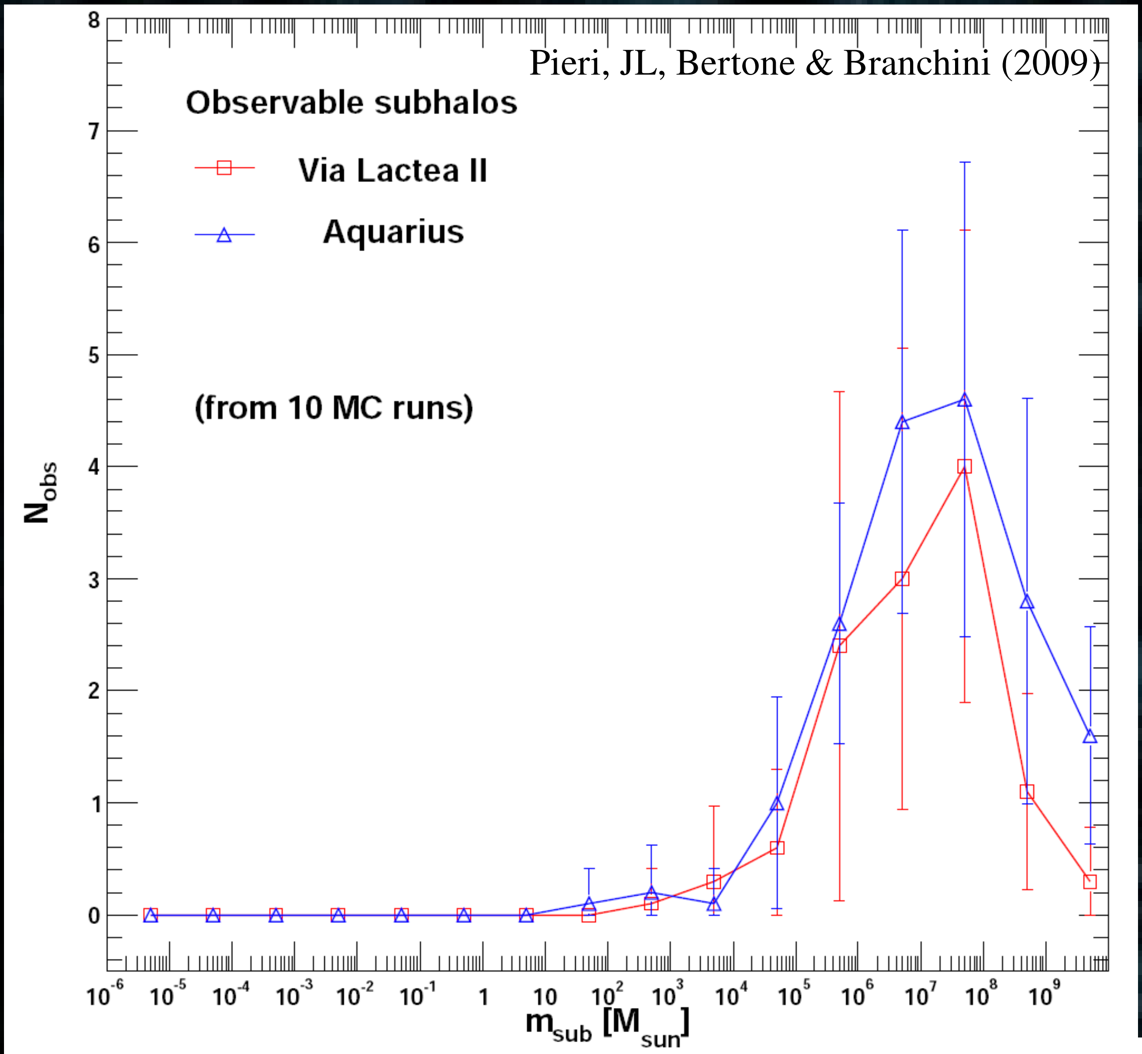
But EGRET is no longer a reference:
our Bg = EGRET – 50%

Johannesson (Moriond 2009) – Abdo et al (2009)





Sensitivity to individual subhalos



Galactic center:
astrophysical contributions not under control, notably cosmic ray electrons.

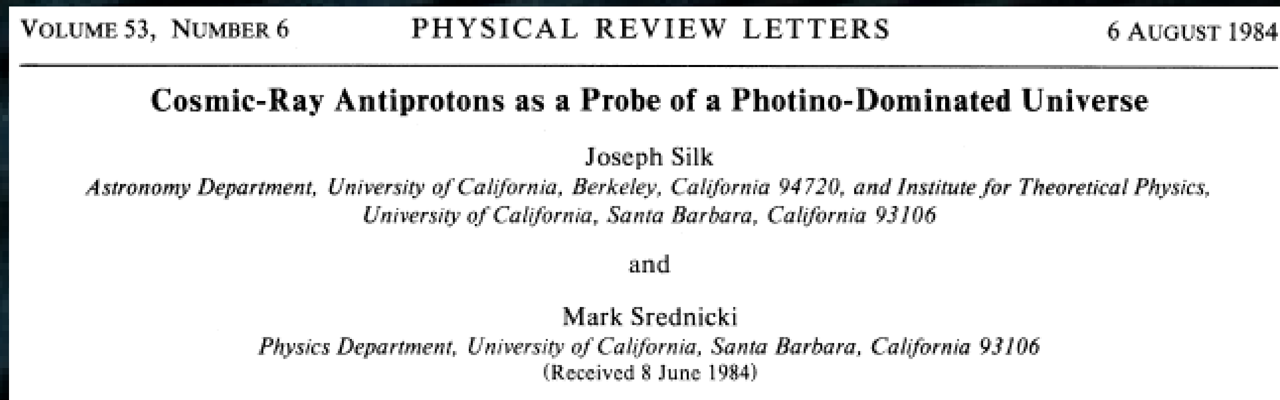
Subhalos:
clean signal if located at high latitude, no counterpart at lower energies ... but have to be very massive and nearby to be observable.

N <10 objects detectable with Fermi in 5 years.

Model A: 40 GeV WIMP going to b-bbar
Model B: 100 GeV WIMP going to WW

model	$VLII\ 3\ \sigma$	$VLII\ 5\ \sigma$	$Aq\ 3\ \sigma$	$Aq\ 5\ \sigma$
A	9.2 ± 2.6	4.1 ± 1.3	13.5 ± 2.5	7.3 ± 2.4
B	3.1 ± 1.1	1.4 ± 0.8	6.2 ± 2.1	2.9 ± 1.4

Complementarity with antimatter signal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Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

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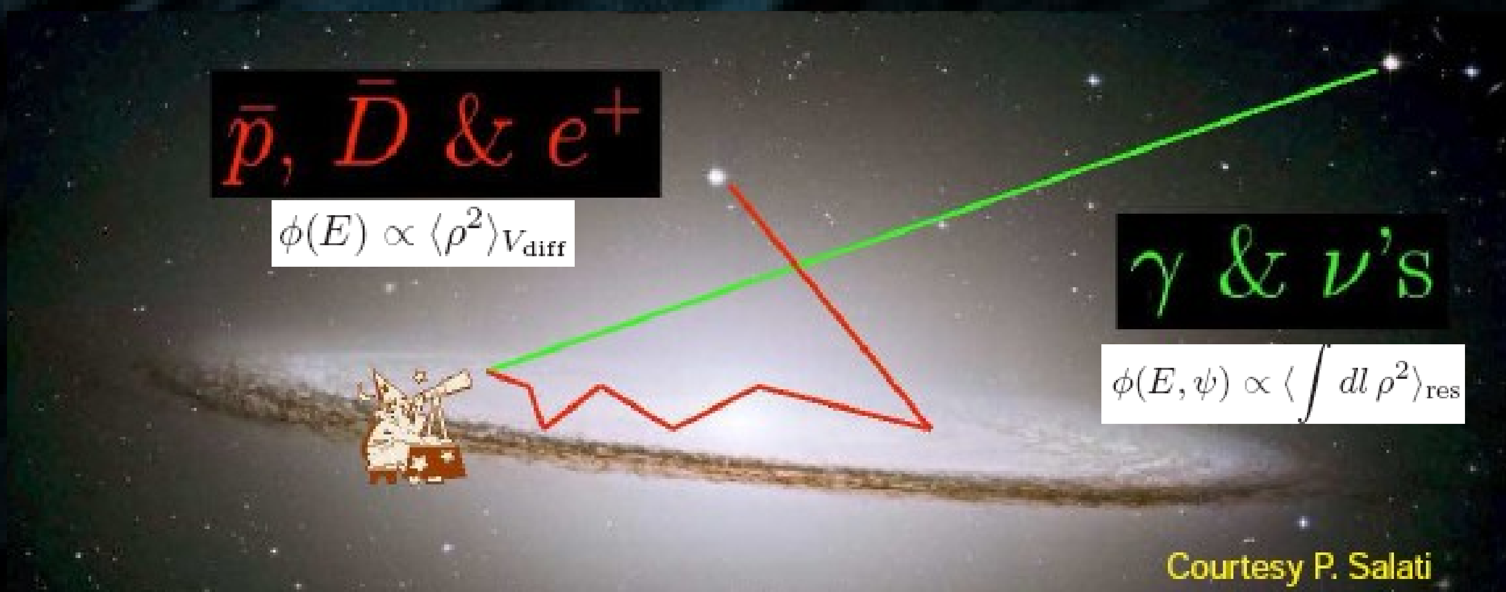
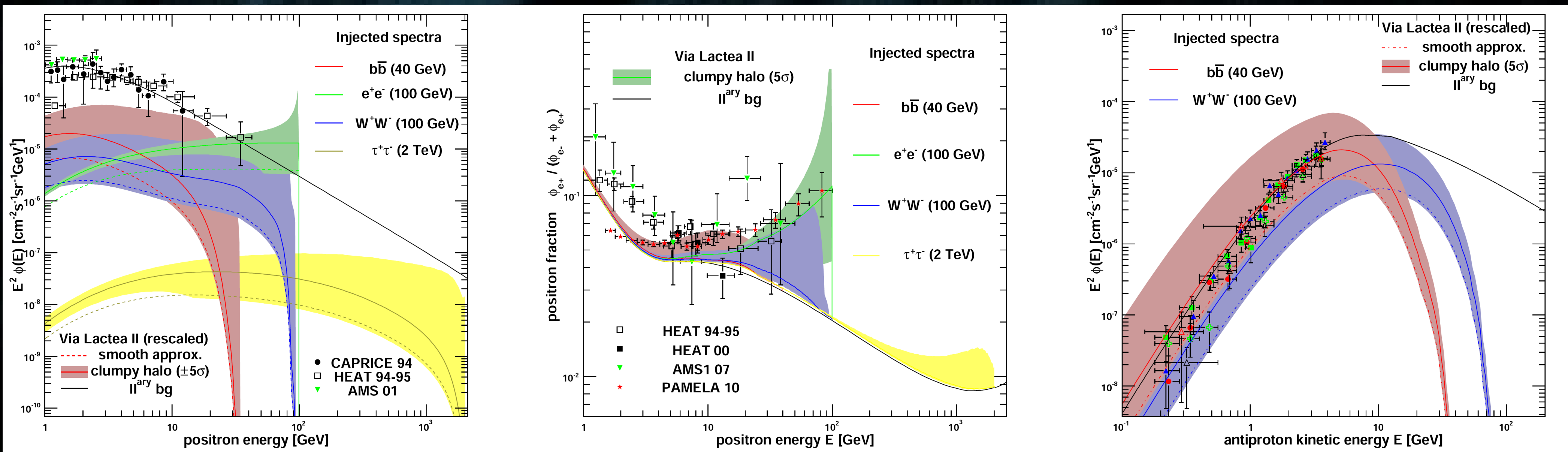


Main arguments:
- DM annihilation provides as many particles as antiparticles
- Antimatter cosmic rays are rare because secondary products
- DM-induced antimatter CRs may have specific spectral properties

But:
- We must control the backgrounds
- Antiprotons are secondaries, what about positrons ?
- Do the natural DM particle models provide clean signatures?

Dark Matter subhalos: energy-dependent boost factor < 5 (modulo variance)

Positron flux | Positron fraction | Antiproton flux



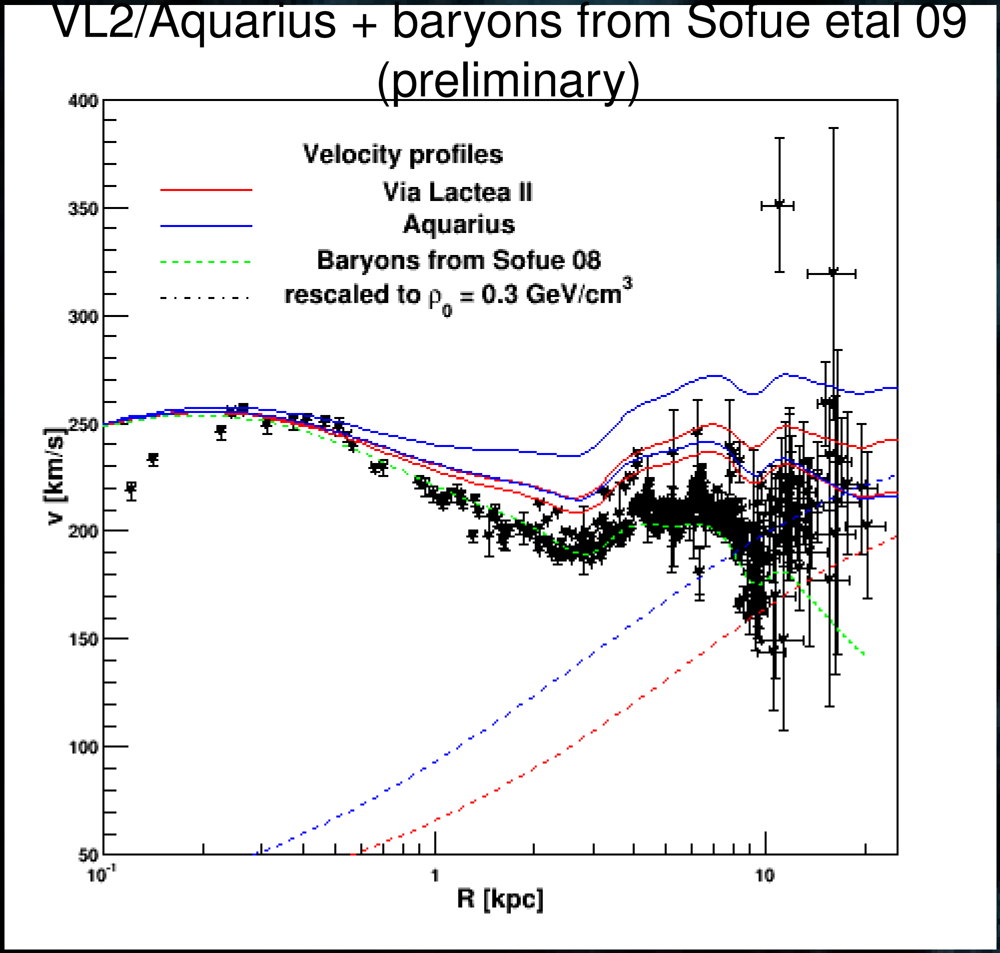
Pieri, JL, Bertone & Branchini (2009)
using results from Via Lactea II (Diemand et al) and Aquarius (Springel et al)
-- see early calculations in Lavalle et al (2007-2008) --

model	m_χ [GeV]	final state
A	40	bb
B	100	W^+W^-
C	100	e^+e^-
D	2000	$\tau^+\tau^-$

Important features:

- 40 GeV WIMP (b-bbar) excluded by antiproton constraints
- 100 GeV WIMP (WW) at the edge of tension with the antiproton data
- 100 GeV WIMP going t o e+e- can fit the PAMELA data; but pulsars not included => background must be known before any claim.

High-resolution is not the end of the story: what about baryons?



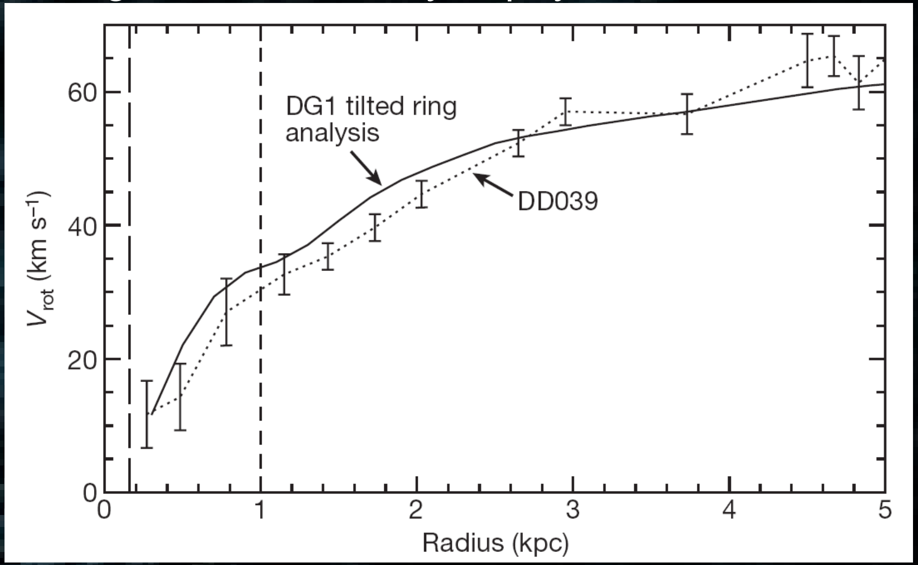
Kinematics data are available for the MW:
→ try to use them to improve predictions

Subhalos:
more efficient tidal stripping in the disk and the bulge, leading to a dark disk

Galactic center:
Adiabatic compression might increase the DM density, but competition with dynamical friction from SF feedback re-heating the gas.

=> Still large uncertainties

Governato et al 10:
CDM + high-resolution baryon physics can lead to cores



Conclusions & perspectives

• High-resolution N-body simulations, e.g. Via Lactea II (Diemand et al) and Aquarius (Springel et al), provide new insights to describe the subhalo phase-space.

• The prospect to observe subhalos with Fermi is weak: only a few objects are detectable in 5 years [astrophysical diffuse emission to be deeply refined – connection with cosmic rays].

• The antiproton signal provides interesting complementary constraints. The local positron background is not under control.

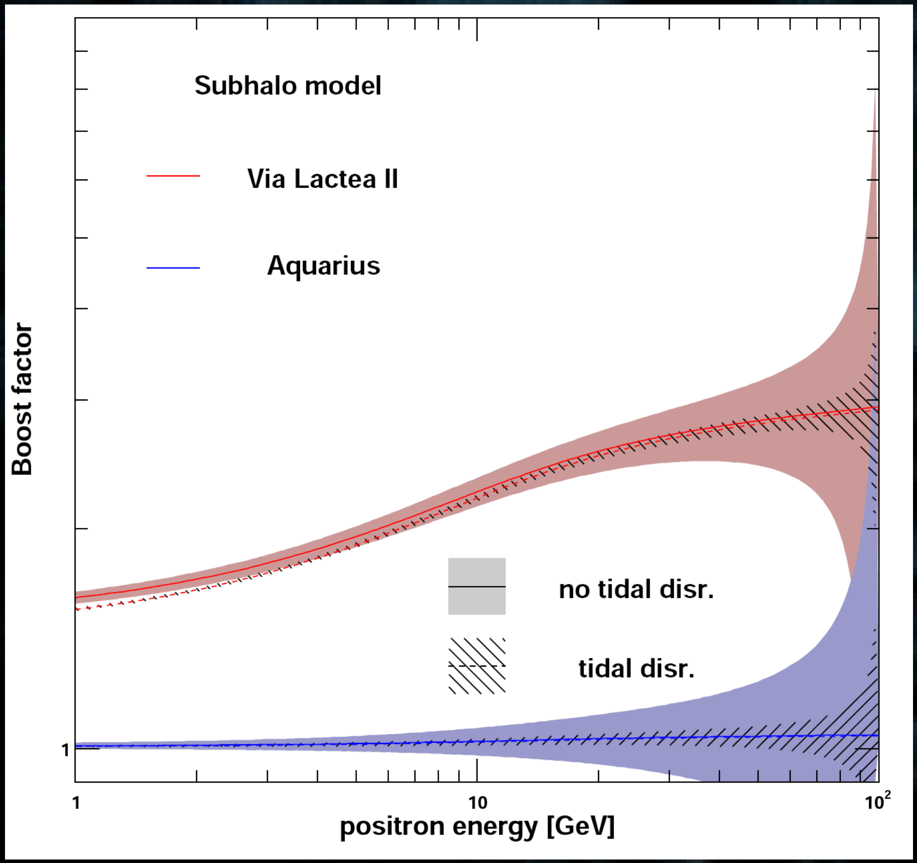
• **Caveats:** still large theoretical uncertainties due (i) to baryons and (ii) to our current understanding of the Galactic diffuse emission. Relevant to subhalos and the Galactic center. Many ongoing studies on that.

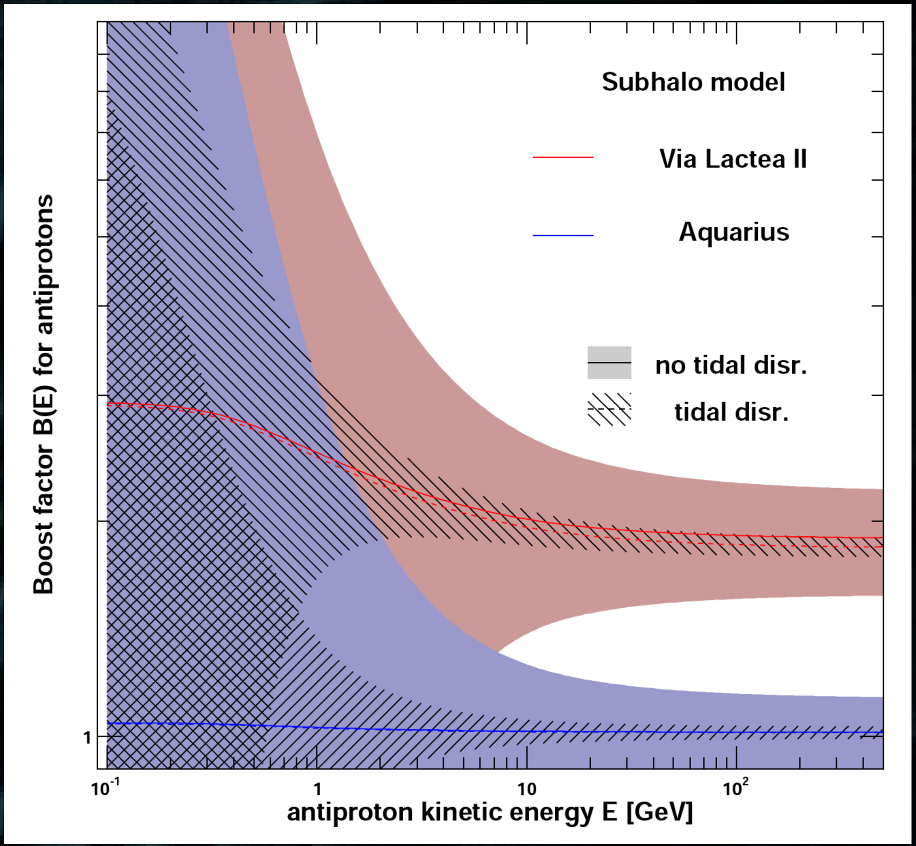
• Complementary methods mandatory. [LHC, direct detection, multi-messenger-wavelength-scale astrophysical signals]. Difficult, but maybe soon ...

Backup

Boost factors for positrons and antiprotons

Pieri, JL, Bertone & Branchini (2009)





See also Lavalle et al (2007,2008)