Impact of subhalos on dark matter searches

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Based on collabs. with: S. Blanchet, T. Bringmann, D. Maurin, P. Salati, R. Taillet, etc.

New Perspectives in Dark Matter

Lyon – 22-25 X 2013

Outline

Subhalos:
* from DM particle properties
* subhalo main features

Subhalo effects in direct DM searches

Subhalo effects in indirect DM searches:
* gamma-rays
* antimatter cosmic rays

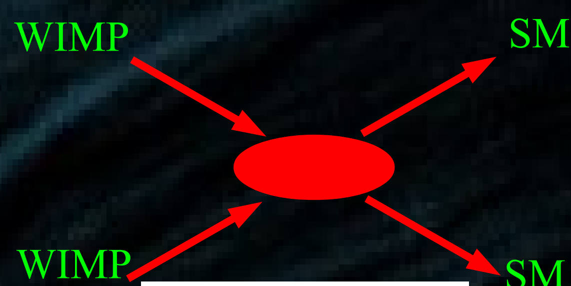
Other effects

Summary

From DM particle properties to subhalos

* $T > m$ and $\Gamma_{ann} > H$ (and $\Gamma_{scat} > H$):
Chemical equilibrium, $n/s = cst$
* $T < m$ and $\Gamma_{ann} > H$ (and $\Gamma_{scat} > H$):
Chemical equilibrium, $n/s \propto \exp(-m/T)$
(Boltzmann suppression)
* $T < m$ and $\Gamma_{ann} < H$ (and $\Gamma_{scat} > H$):
Chemical decoupling (freeze out)
* $T < m$ and $\Gamma_{scat} < H$:
Kinetic decoupling
=> free-streaming scale
=> minimal mass scale for structure formation
(modulo extra-damping from acoustic oscillations)

Annihilation
(→ chemical decoupling)



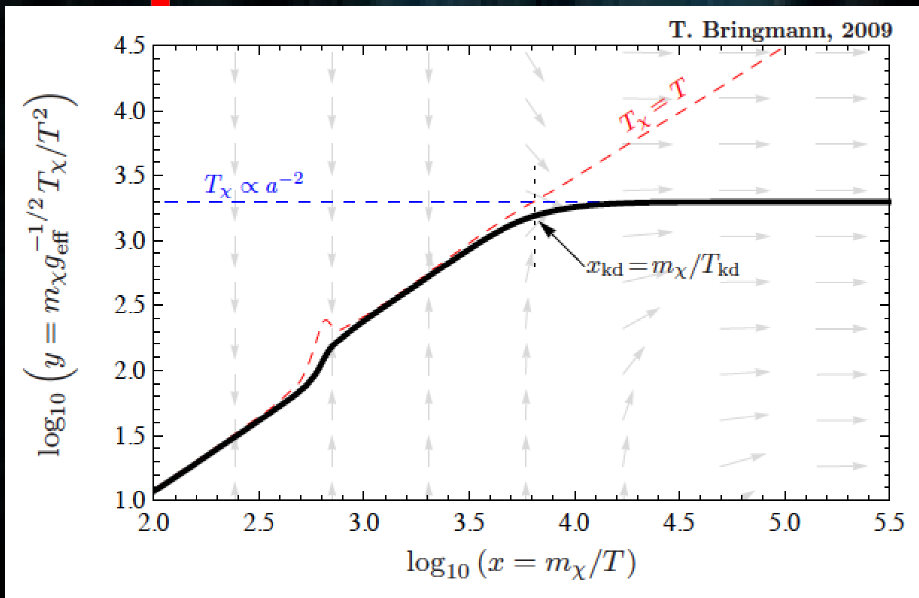
$$\Gamma_{ann} = \langle \sigma_{ann}\, v \rangle\, n_\chi$$

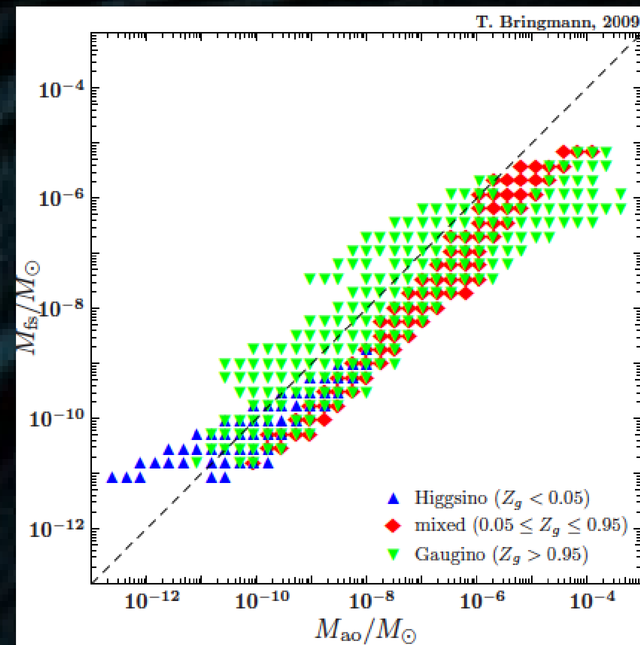
Scattering
(→ kinetic decoupling)

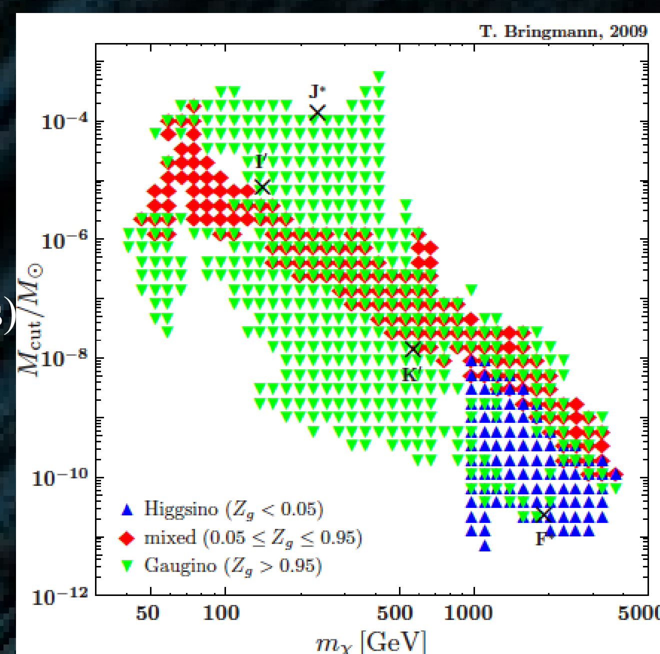
$$\Gamma_{scat} = \langle \sigma_{scat}\, v \rangle\, n_{plasma}$$

See e.g. Schmid++ 99, Boehm++ 00, Chen++ 01, Hofmann++ 01, Berezinsky++ 03, Green++ 04-05, Loeb++ 05.
For susy, see review in Bringmann 09.

From DM particle properties to subhalos







* T < m and Γ_{int} < H:

Kinetic decoupling

=> free-streaming scale

=> minimal mass scale for structure formation

(modulo extra-damping from acoustic oscillations)

$$l_{fs} = \frac{\pi}{k_{fs}} = \int_{t_{kd}}^{t_{eq}} dt' \, \frac{v_\chi(t')}{a(t')} \propto (T_\chi^{kd}/m_\chi)^{1/2} (a_{kd}/a_{eq}) \propto (m_\chi T_\chi^{kd})^{-1/2}$$

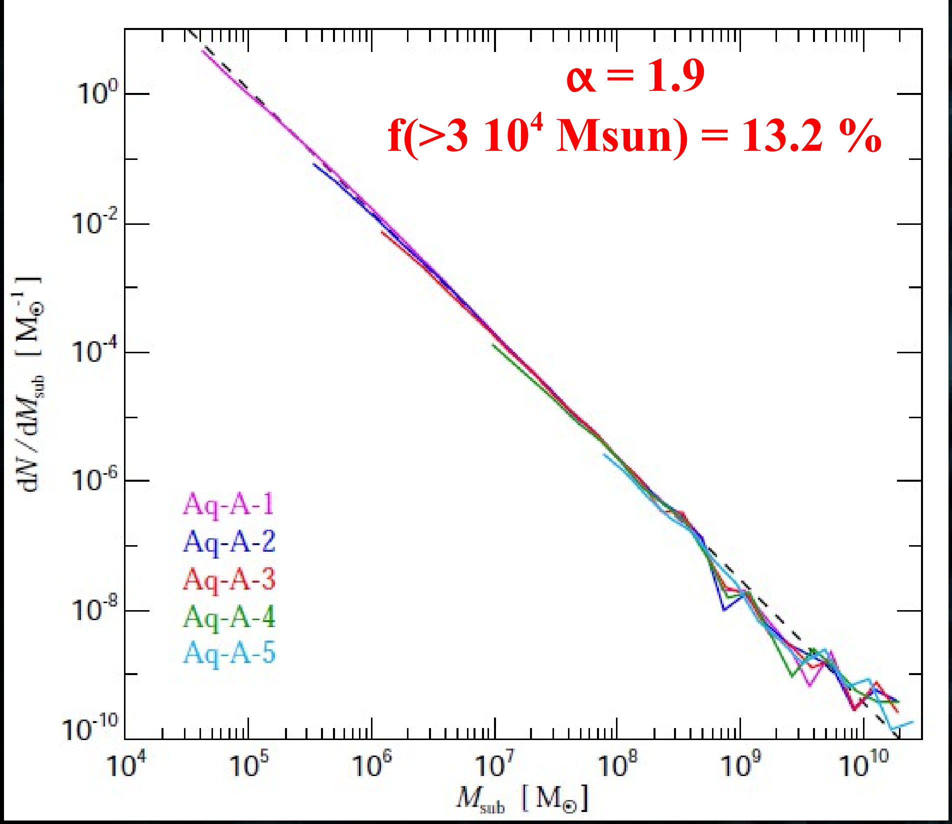
$$\frac{3}{2} T_\chi = \frac{\langle p_\chi^2 \rangle}{2\, m_\chi} = \frac{\int d^3p\, p^2\, f(p)}{2\, m_\chi \int d^3p\, f(p)} = \frac{\int d^3p\, p^2\, f(p)}{2\, m_\chi\, (2\pi)^3\, n_\chi}$$

$$\hat{L}\, f = E\, \partial_t f - H\, |\vec{p}|^2\, \partial_E f = \hat{C}[f]$$

$$\{\partial_t + 5\, H\}\, T_\chi = 2\, m_\chi\, c(T)\, \{T - T_\chi\}$$

Subhalo properties (1): the mass function

Subhalo mass function from Aquarius
(Springel et al, 2008)



Power law mass function

$$\frac{d\mathcal{P}_M(M)}{dM} = K_M \left[\frac{M}{M_\odot}\right]^{-\alpha}$$

$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M^2} \frac{\delta_c}{\sigma} \left|\frac{d\log\sigma}{d\log M}\right| \exp\left(-\frac{\delta_c^2}{2\sigma^2}\right)$$

Press & Schechter (1974): α = 2
Aquarius (Springel et al): α ~ 1.9
Via Lactea (Diemand et al): α ~ 1.9-2.0

NB: resolution limit => **assume scale invariance**

Calibrate subhalo mass content from simulations:

$$f_{\rm tot} = f_{\rm res} \times \frac{(M_{\rm max}^{2-\alpha} - M_{\rm min}^{2-\alpha})}{(M_{\rm max}^{2-\alpha} - M_{\rm res}^{2-\alpha})}$$

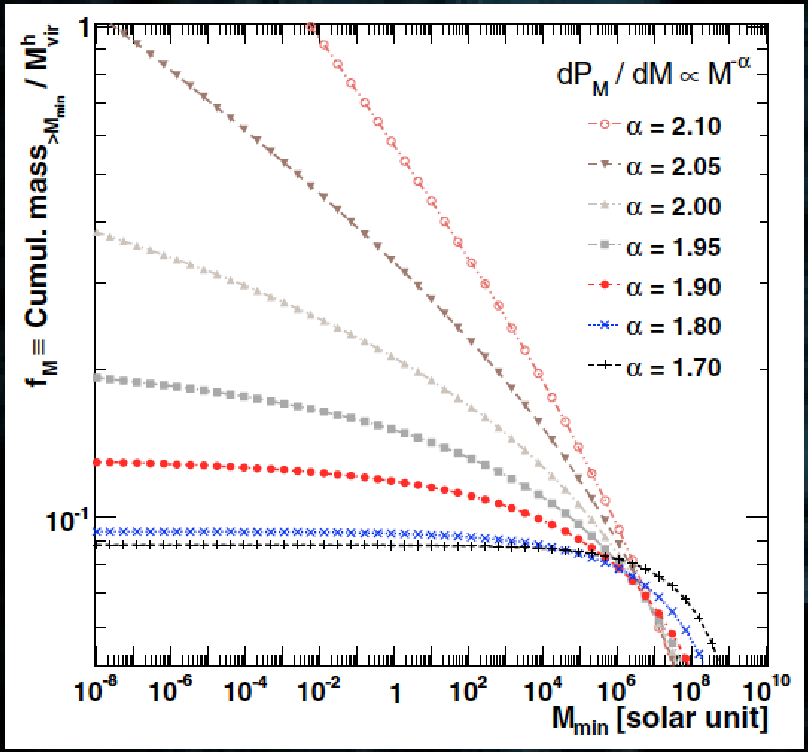
=> Get total number of subhalos:

$$N_{\rm tot} = \frac{f_{\rm tot} M_{MW}}{\langle M \rangle} \tilde{\propto} M_{\rm min}^{1-\alpha}$$

The subhalo mass content is determined by the minimal mass Mmin and the slope α, and is calibrated from the mass fraction resolved in N-body simulations => **> 10 OM extrapolation (...)**

Subhalo properties (1): the mass function

Subhalo mass fraction
(Lavalle++ 07)



Power law mass function

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Subhalo properties (2): internal shape

* Hard to predict from analytical studies (non-linear regime, hierarchical merging), but 2 exceptions:
    - central cores due to annihilation and/or Liouville theorem
    - smallest structures not affected by merging (e.g. Gurevich & Zybin 93)

=> Rely on fits from cosmological simulations => NFW and Einasto profiles (for objects without baryons/stars inside).

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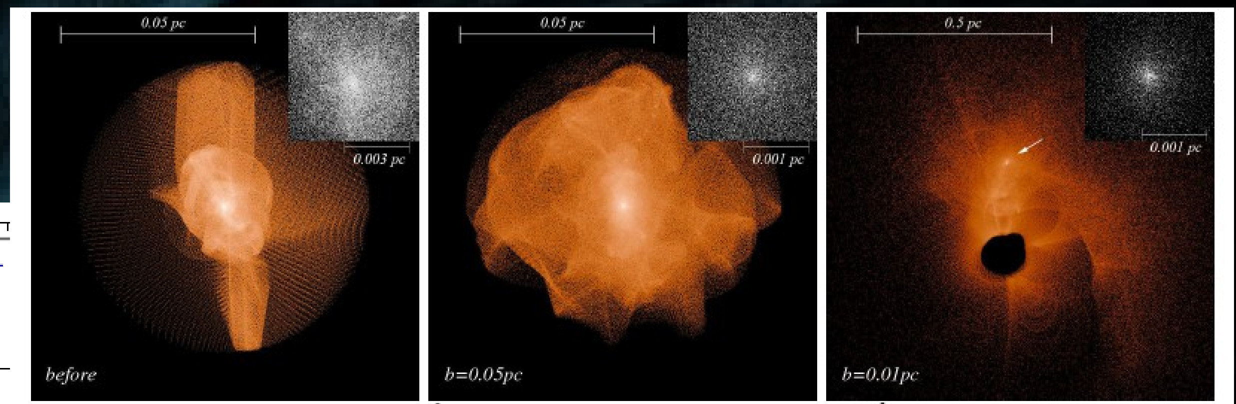
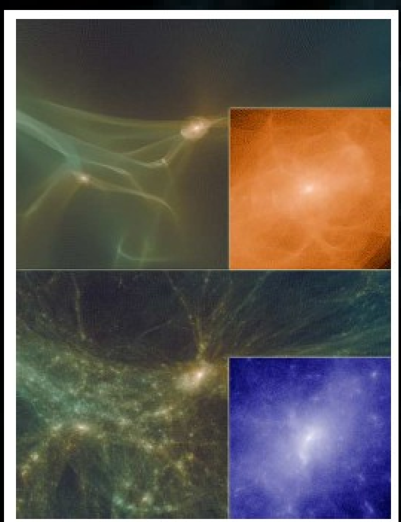
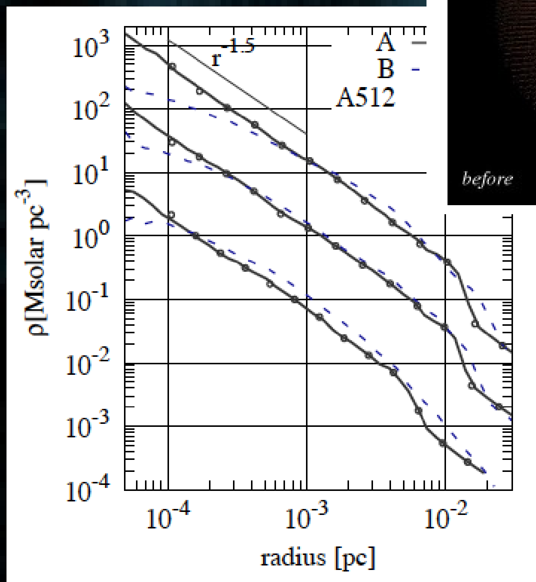
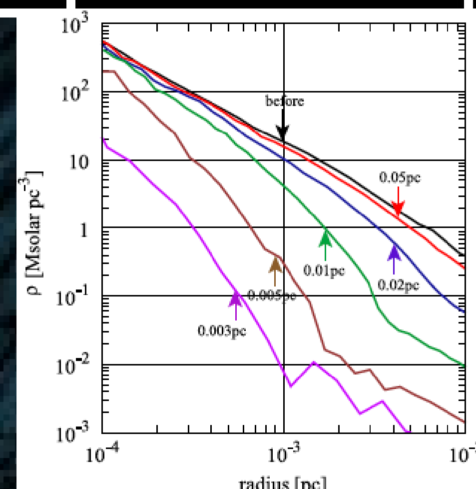


Ishiyama++ 12







Confirmed by Anderhalden++ 13 => smallest subhalos very cuspy

Subhalo properties (3): Concentration

Subhalo parameters:
1) set mass
2) calculate virial radius
3) choose density profile
4) concentration model → scale radius

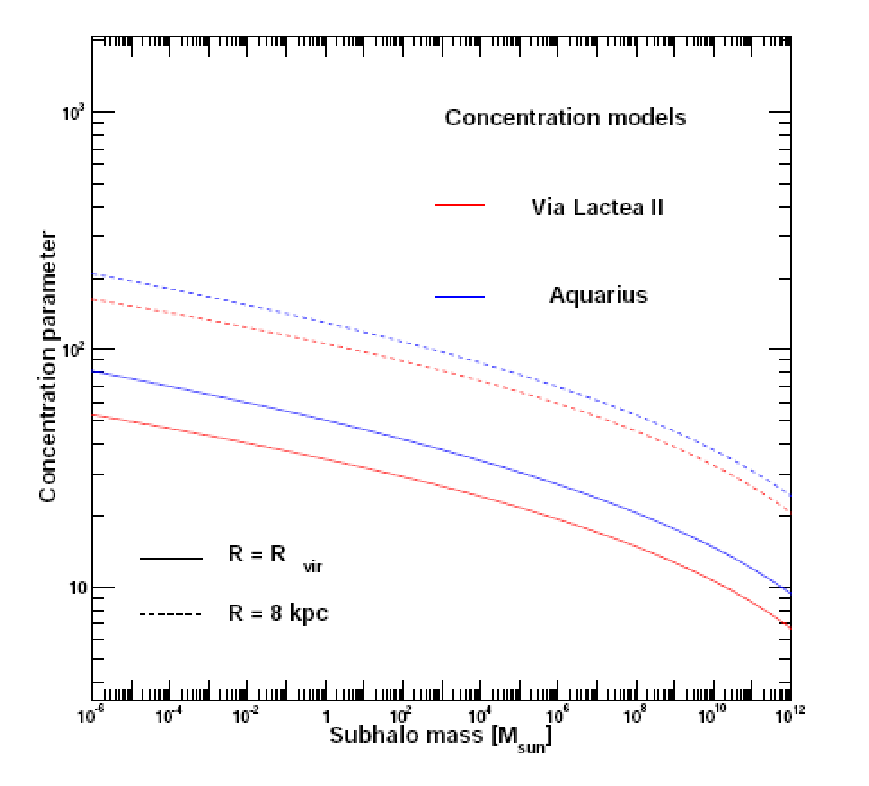
$$M_{\rm vir} = \frac{4\pi}{3}\,(\delta\,\rho_c)\,r_{\rm vir}^3$$

$$M_{200} = M_{\rm vir}(\delta = 200)$$

$$c_{200} = \frac{r_{200}}{r_{-2}}$$

Concentration vs mass and location in the MW

subhalo luminosity vs mass



Concentrations:

1) Impact of cosmological inputs.
2) Tidal effects: concentrations get larger when closer to the GC (demonstrated in VL2 and Aquarius).

Subhalo properties (4): spatial distribution

Trivial cases:

1) given from N-body analysis (still to check consistency)
2) subhalos track the host halo: dP/dV = rho(r)/M_{MW}

(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

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

Warning !!!

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

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

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

(iii) Use N-body prescriptions: subhalo distribution cored in the center.
in Via Lactea, **antibiased** relation: subhalo distrib ∝ r × global **smooth** distrib

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

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

Subhalo properties (4): spatial distribution

Trivial cases:
1) given from N-body analysis (still to check consistency)
2) subhalos track the host halo: dP/dV = rho(r)/M_{MW}

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

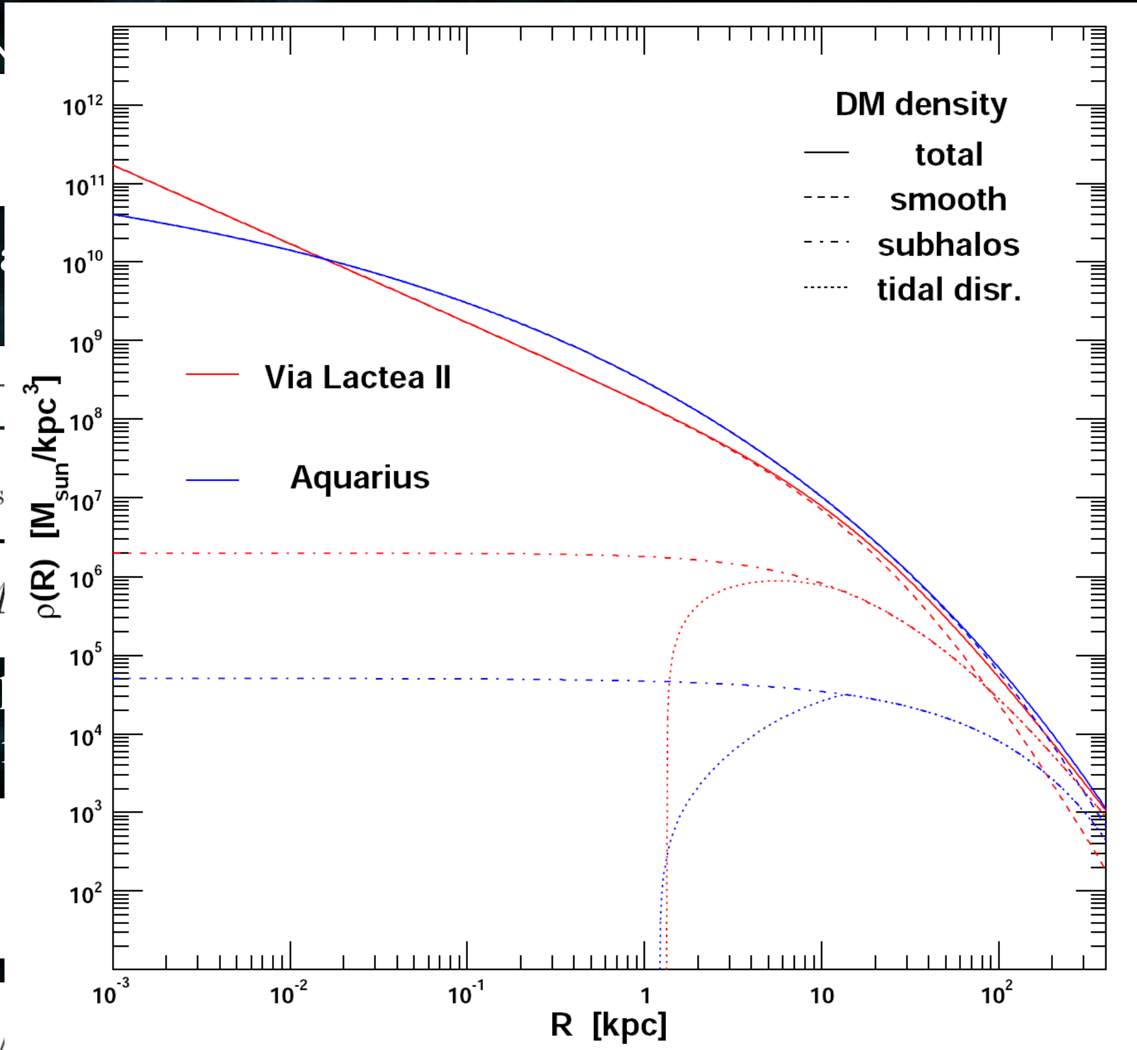
$\rho_{\rm sm}(r)$ such that $4\pi \int dr\, r^2 \rho_{\rm sm}(r) \;=\; (1 - f_s$

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

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

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

$\rho_{\rm sub}(r) = \dfrac{\rho_{\rm MW}(r)(r,}{(1 - r/r_b)} \propto \Big\{ r^{-3} \quad \text{for } r \gtrsim r_b \sim r_s$



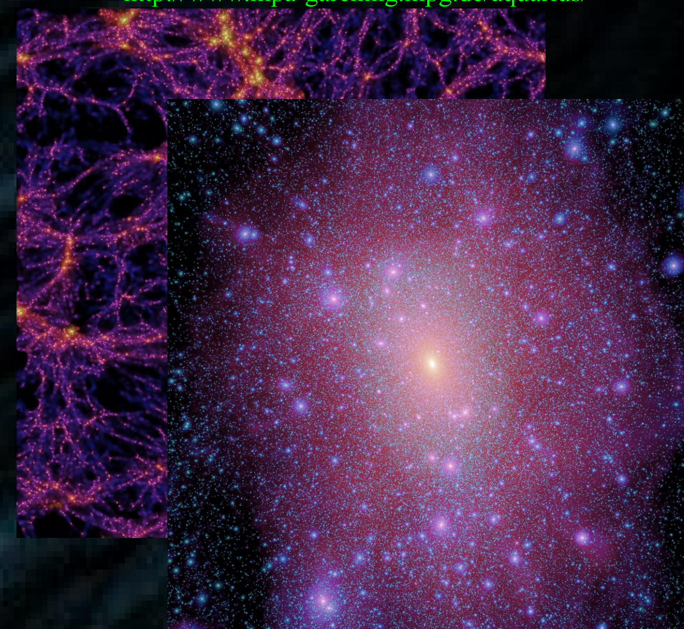
Use N-body info: Via Lactea II versus Aquarius

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

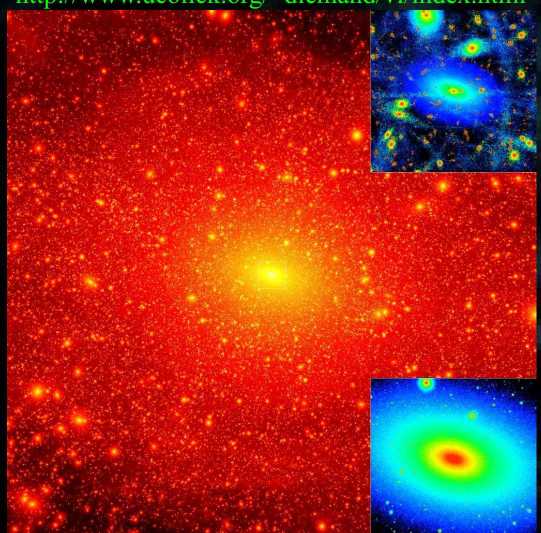
MW-like halos with ~ 1 billion particles of ~10^3 $M_\odot$
> 50,000-300,000 subhalos with masses > 10^6 -$10^{4.5}$ $M_\odot$

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]	$M^{\rm res}_{\rm sub}$ $[10^4 M_\odot]$	$N^{\rm res}_{\rm sub}$ $[10^4]$	Mass slope	$f^{\rm res}_{\rm sub}$ [%]
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

Subhalo impact on direct detection

e.g. Sikivie++ 92, Freese++ 01, Stiff++ 01

Encounters?

$$\Gamma_{\rm enc} = n_{\rm sub}^{\odot}\,\Sigma_{\rm enc}\int d^3v\,f_{\odot}(\vec{v})\,|\vec{v}_{\rm rel}| = n_{\rm sub}\,\Sigma_{\rm enc}\,v_{\odot}$$

$$\Sigma_{\rm enc} \approx \pi\,r_{\rm sub}^2 \approx 1.3\times 10^{-5}\,{\rm pc}^2\,(r_s/2\times 10^{-3}\,{\rm pc})^2$$

$$n_{\rm sub}^{\odot} \approx N_{\rm sub}\left\{\frac{\rho_{\odot}}{M_{\rm MW}}\right\} \approx 79\,{\rm pc}^{-3}\,(N_{\rm sub}/10^{16})\,\left\{\frac{(\rho_{\odot}/0.3\,{\rm GeV/cm}^2)}{(M_{\rm MW}/10^{12}M_{\odot})}\right\}$$

$$\Gamma_{\rm enc} \approx 0.2\,{\rm Myr}^{-1}$$

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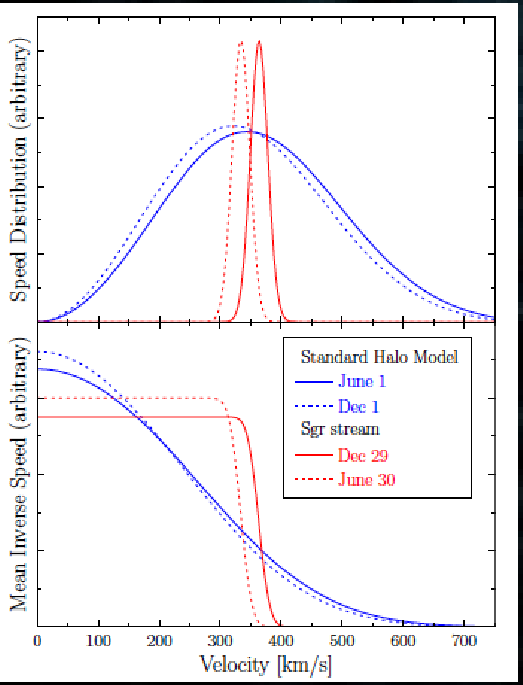
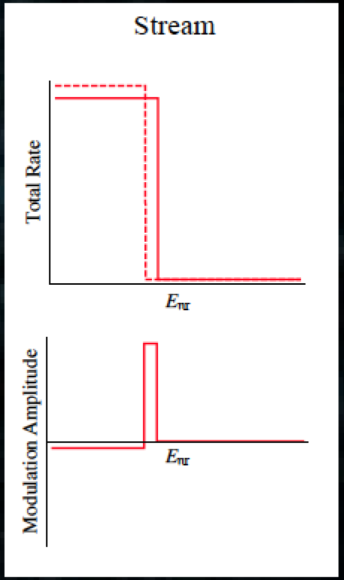
$$\Gamma_{\rm enc} \approx 0.2\,{\rm Myr}^{-1}$$

Freese++ 12



$$\frac{d\Gamma_{\chi-{\rm N}}}{dE_r}(E_r,t) = \frac{\sigma_{\chi-{\rm N}}\,\rho_{\odot}}{2\,m_{\chi}\,\mu_r^2}\,F^2(E_r)\int_{v>v_{\rm min}} d^3\vec{v}\,\frac{f(\vec{v},t)}{v}$$



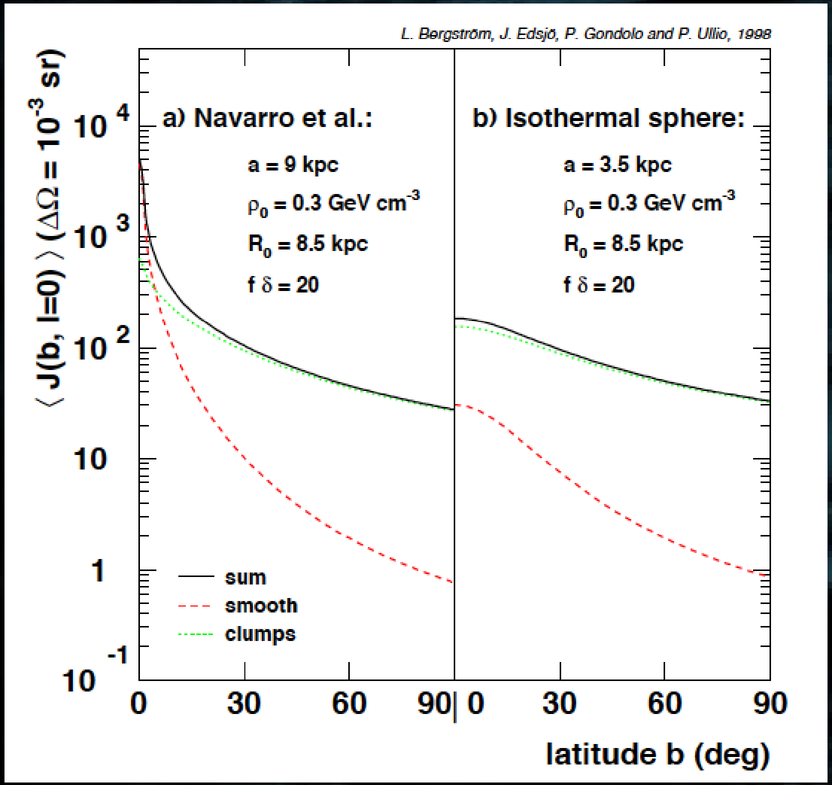
Subhalo impact on indirect detection
(much less uncertainties at the Galactic scale)

Original idea by Silk & Stebbins 93

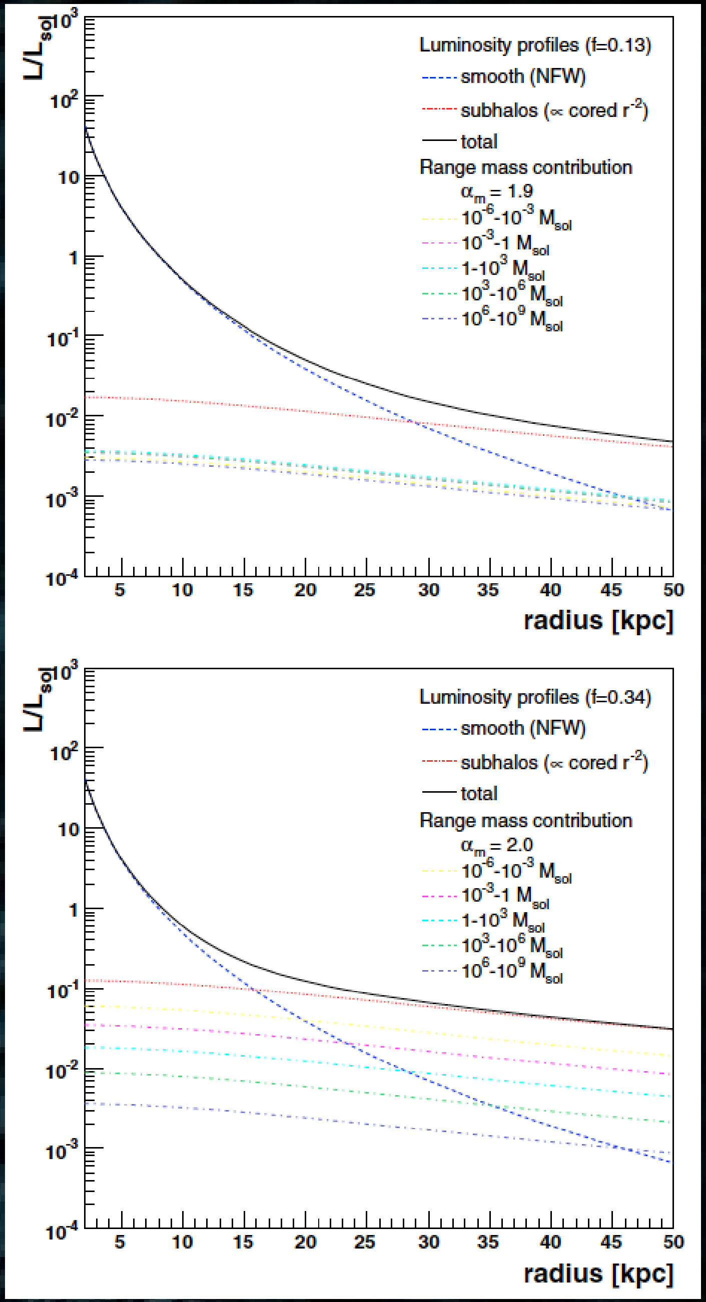
Global contribution to gamma-rays

$$\xi_{\rm NFW}(M) \,\tilde{\propto}\, M^{0.9} \Longrightarrow \langle \xi_{\rm NFW} \rangle \,\tilde{\propto}\, M_{\rm min}^{1.9-\alpha}$$

Bergström++ 98



JL++ 07



<u>Global picture:</u>

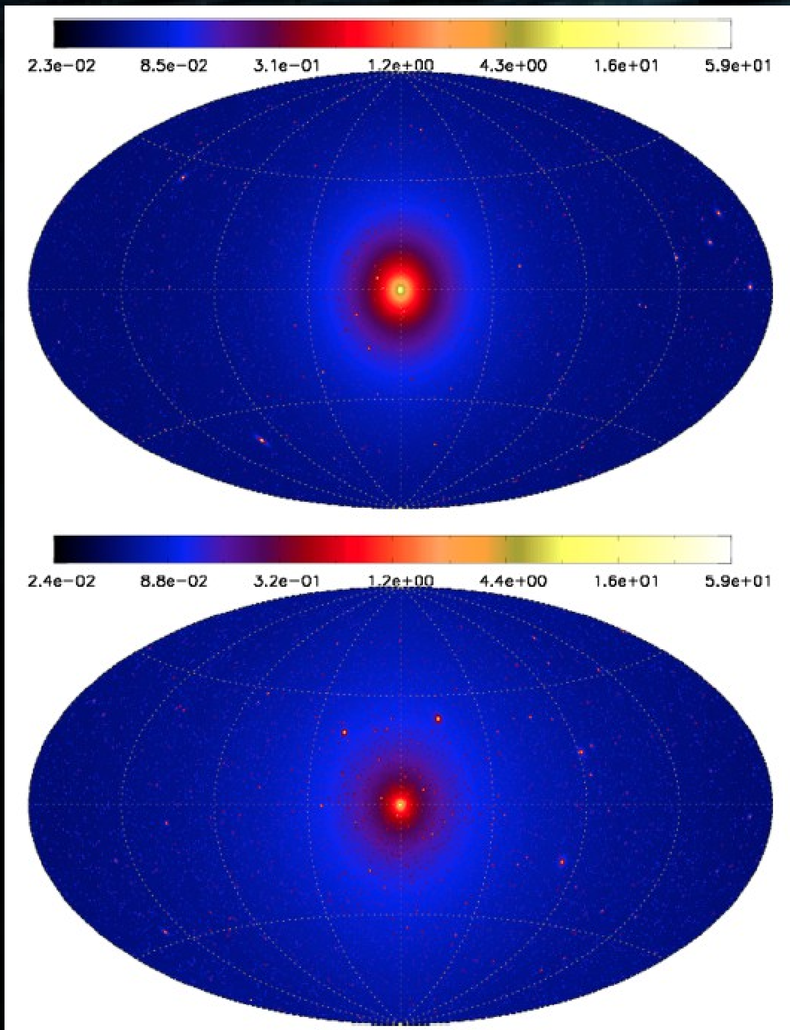
* Smooth DM annihilation rate scales like rho^2(r)
* Subhalo annihilation rate scales like dP(r)/dV ~ rho(r)

=> smooth dominates in central regions, subhalos dominate in the outskirts.

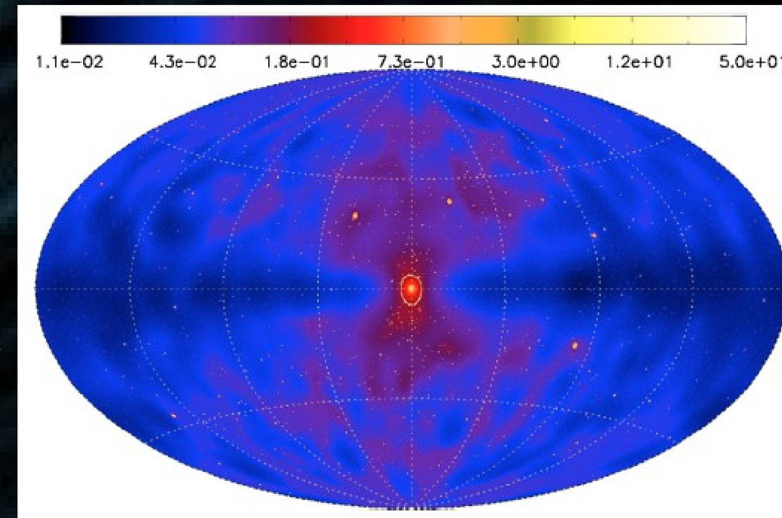
** Luminosity strongly affected by mass function
-1.9 slope => each mass decade contributes the same

Individual subhalos in gamma-rays

Pieri++ 11



Diffuse background model
(calibrated from data)

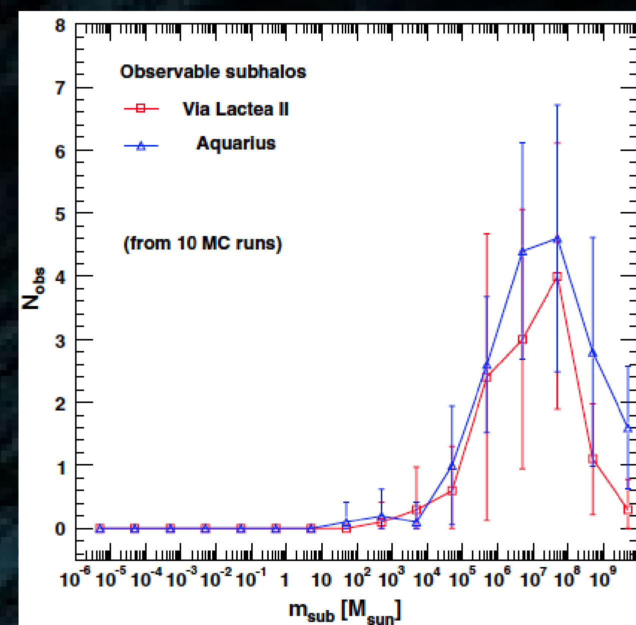


Analytical predictions possible, but background difficult to include
=> separate resolved/unresolved
=> MC simulations

Expected number of detection within 5 years of Fermi

Nobs ~ 10

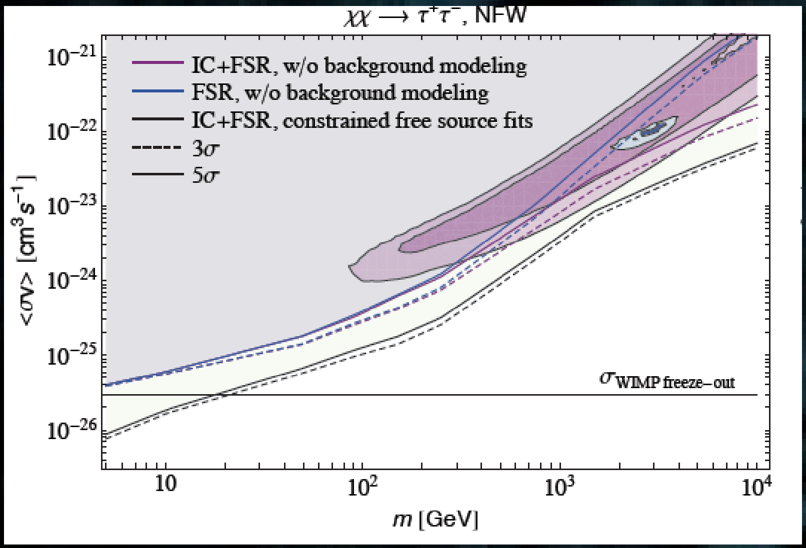
Compare with unidentified sources:
Nnid ~ 9
(from Belikov++ 11)
=> detailed spectral analysis required
=> can also be astro sources
=> line could help ...



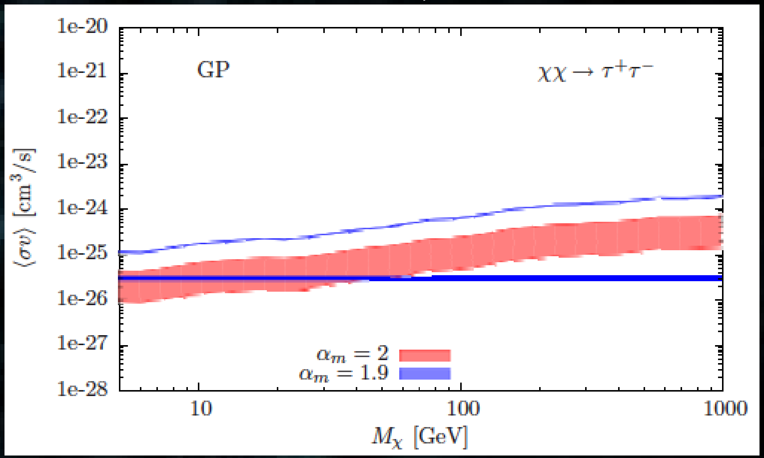
Want to play?
=> public code Clumpy by Combet++ 11

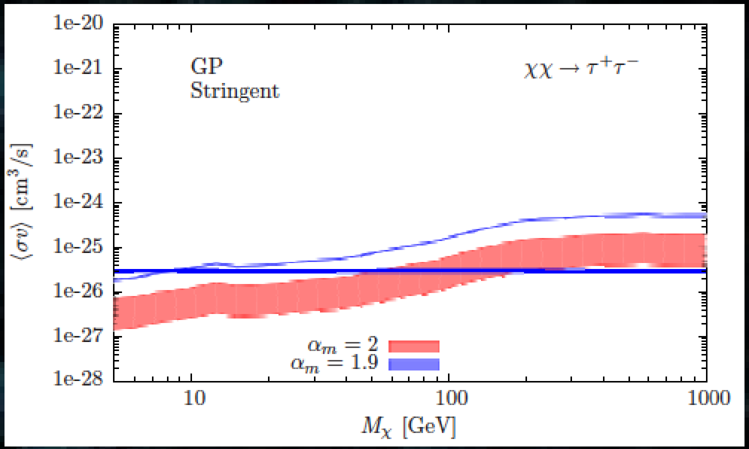
Constraints on/from WIMP annihilation?

Fermi Collab. 12
(e.g. Zaharijas++)



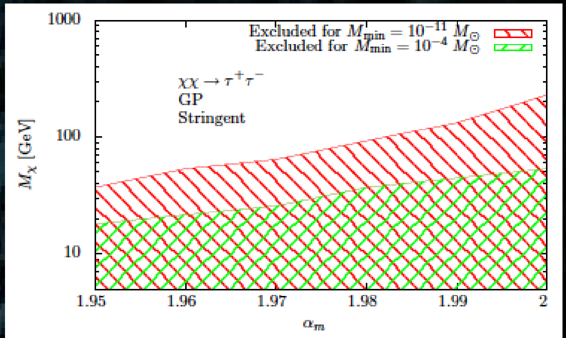
Blanchet, JL 12



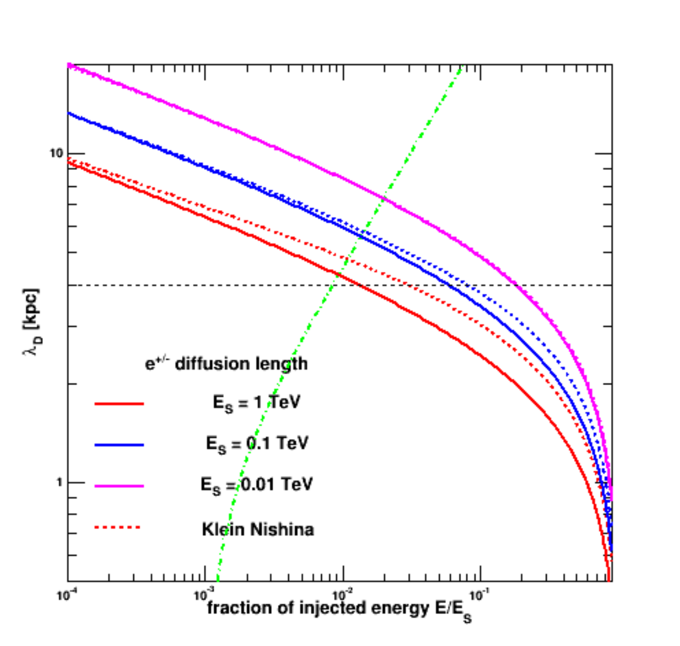


Simplistic analysis:
** compare Galactic pole emission to Fermi reconstruction of EGB
=> constraints similar to full Fermi analysis (no subhalos)
=> get stronger if EGB model assumed

=> room for improvement



Impact on antimatter production



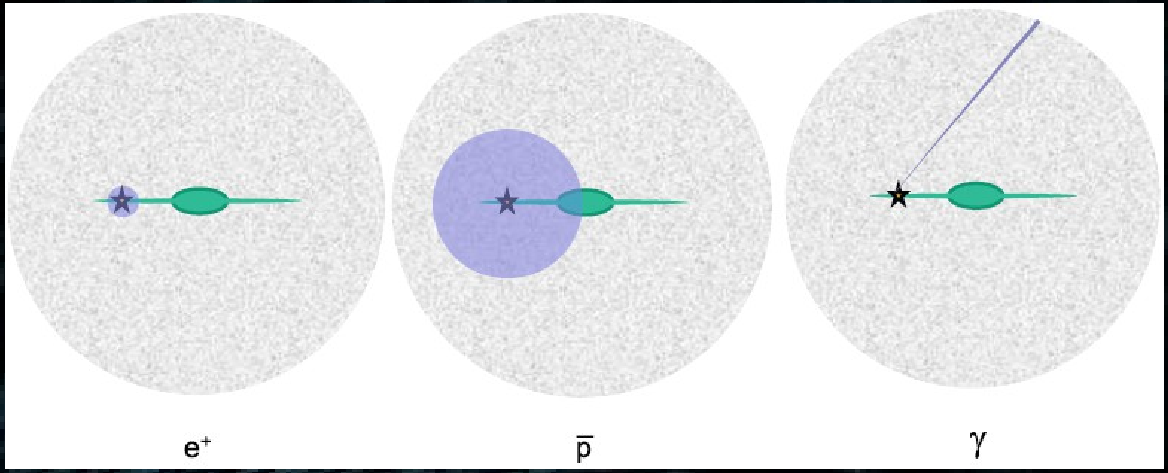
JL++ 08

2 types of messenger:
* "antinuclei": antiproton / antideuteron
* positrons
=> different propagation properties.

Antinuclei: spatial diffusion + spallation + convection
Positrons: spatial diffusion + energy losses

=> different propagation scales!
=> probe different parts of the MW
=> less sensitive to halo shape
NB: boundary effects when l>L or/and l>R

Bergström 09



Going into more details: a statistical approach (1)

General expression for the flux measured on Earth

$$\phi(E,\vec{x}_{\rm obs}) = \underbrace{\frac{\delta\,\langle\sigma v\rangle}{8\pi}\left[\frac{\rho_0}{m_\chi}\right]^2}_{\mathcal{S}} \int_{\rm (sub)halo} d^3\vec{x}_s \underbrace{\int dE_s\,\mathcal{G}(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s)\,\frac{dN(E_s)}{dE_s}}_{\tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_s)} \left[\frac{\rho(\vec{x}_s)}{\rho_0}\right]^2$$

The Green function encodes the propagation properties
=> trivial for gamma-rays

$$\int_{\rm (sub)halo} d^3\vec{x}_s \int dE_s\,G(E,\vec{x}_{\rm obs}\leftarrow E_s,\vec{x}_s) \overset{\gamma-\rm rays}{\longrightarrow} \int_{\rm l.o.s.} d\Omega_{\rm res}\,dl \int dE_s\,\delta(E-E_s)$$

Subhalos: point-like sources provided *G* does not vary too much over the object

$$\text{if } \lambda_{\rm prop} \gg r_s \Longrightarrow \int_{\rm sub} d^3\vec{x}_s\,\tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_s)\left[\frac{\rho_i(\vec{x}_s)}{\rho_0}\right]^2 \longrightarrow \tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_i)\,\underbrace{4\pi\int dr\,r^2\left[\frac{\rho_i(r)}{\rho_0}\right]^2}_{\xi_i}$$

$$\phi_i = \mathcal{S}\times\tilde{\mathcal{G}}(\vec{x}_{\rm obs}\leftarrow\vec{x}_i)\times\xi_i$$

$$\phi_{\rm tot} = \phi_{\rm sm} + \sum_{i\in\rm sub}\phi_i = \phi_{\rm sm} + N_{\rm tot}\langle\phi_{\rm sub}\rangle$$

$$\mathcal{B} = \frac{\phi_{\rm tot}}{\phi_{\rm smooth}} = \left\{\frac{\phi_{\rm sm}}{\phi_{\rm smooth}} \approx 1\right\} + N_{\rm tot}\frac{\langle\phi_{\rm sub}\rangle}{\phi_{\rm smooth}}$$

Going into more details: a statistical approach (2)

Define subhalo flux pdf

$$\langle \phi_{\rm sub} \rangle = \int d\phi \, \phi \, \frac{d\mathcal{P}_\phi(\phi)}{d\phi}$$

Flux pdf completely set by:

$$\frac{d\mathcal{P}_\phi(\phi)}{d\phi} \propto \underbrace{\frac{d\mathcal{P}_V(\vec{x})}{dV}}_{\text{spatial distrib.}} \times \underbrace{\frac{d\mathcal{P}_M(M,\vec{x})}{dM}}_{\text{mass distrib.}} \times \underbrace{\frac{d\mathcal{P}_c(c,M,\vec{x})}{dc}}_{\text{concentration distrib.}}$$

Then average subhalo flux entirely defined (as variance is)

$$\begin{aligned} \langle \phi_{\rm sub} \rangle &= \mathcal{S} \int d^3\vec{x}_s \, \tilde{\mathcal{G}}(\vec{x}_{\rm obs} \leftarrow \vec{x}_s) \, \frac{d\mathcal{P}_V(\vec{x}_s)}{dV} \int dM \, \frac{d\mathcal{P}_M(M,\vec{x}_s)}{dM} \int dc \, \frac{d\mathcal{P}_c(c,M,\vec{x})}{dc} \, \xi(\vec{x}_s, M, c) \\ &= \mathcal{S} \times \langle \tilde{\mathcal{G}} \, \langle \xi \rangle_{c,M} \rangle_V \approx \mathcal{S} \times \langle \tilde{\mathcal{G}} \rangle_V \times \langle \xi \rangle_{c,M} \end{aligned}$$

Recall: subhalo properties fully set by mass and concentration
(slight impact of location)

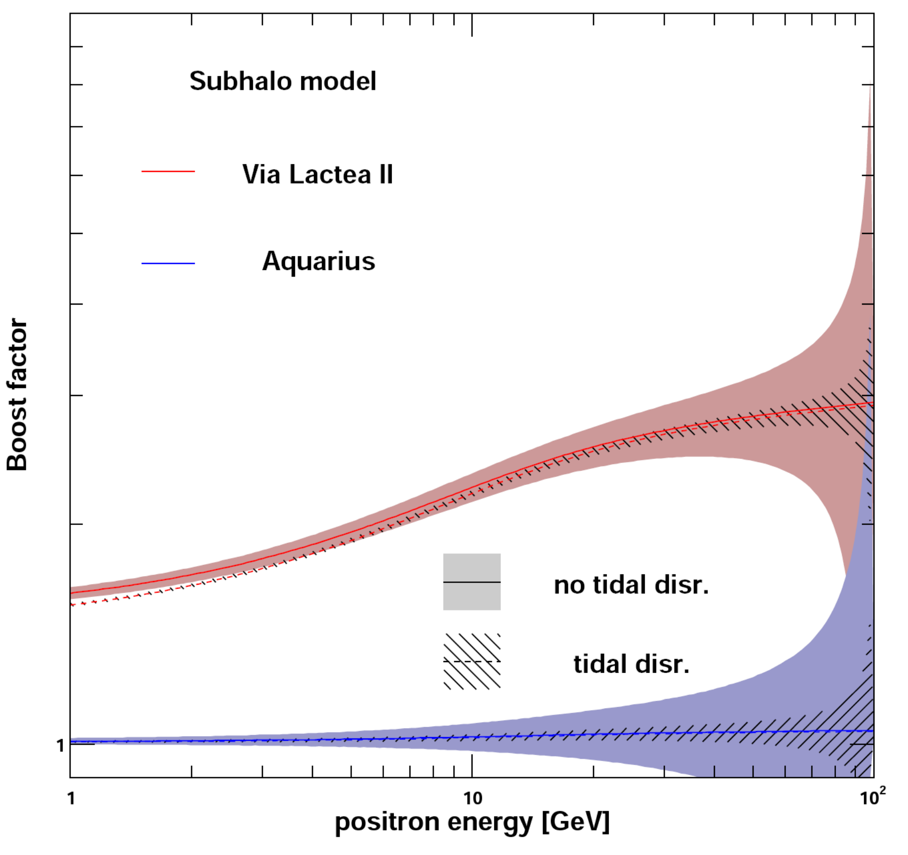
$$M_{\rm vir} = \frac{4\pi}{3} \, (\delta \, \rho_c) \, r_{\rm vir}^3$$

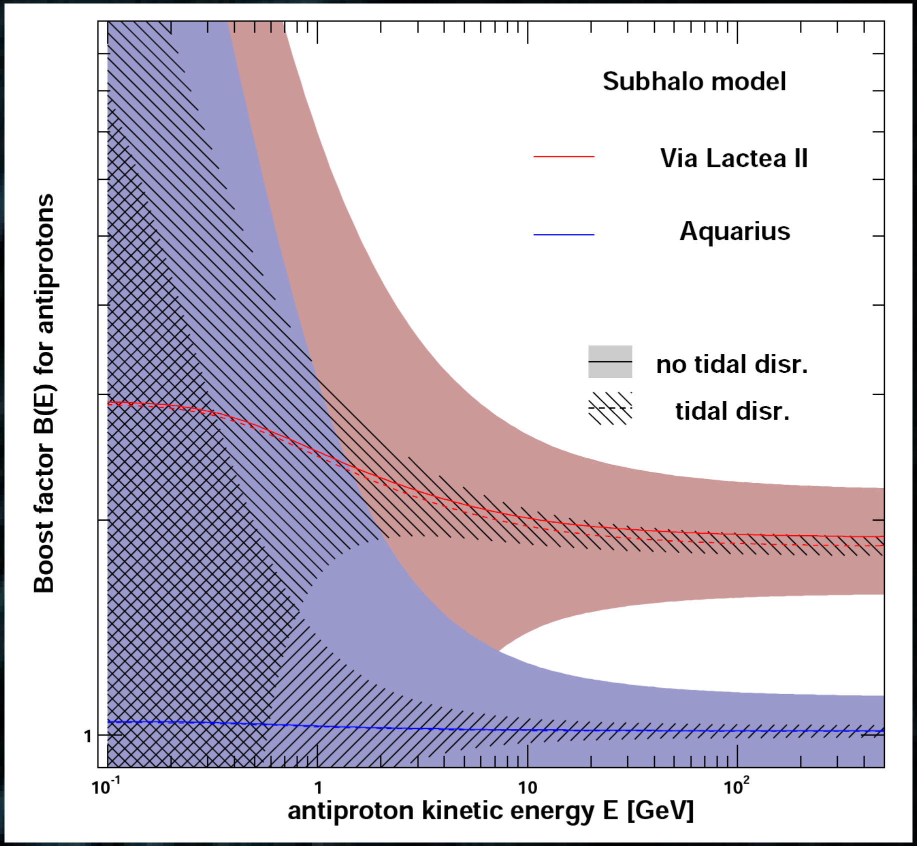
$$\begin{aligned} M_{200} &= M_{\rm vir}(\delta = 200) \\ M_{vir} &= M_{\rm vir}(\delta = \Delta(z) \, \Omega_m(z)) \end{aligned}$$

$$\begin{aligned} c_{200} &= \frac{r_{200}}{r_{-2}} \\ c_{\rm vir} &= \frac{r_{\rm vir}}{r_{-2}} \end{aligned}$$

Boost factors for positrons and antiprotons

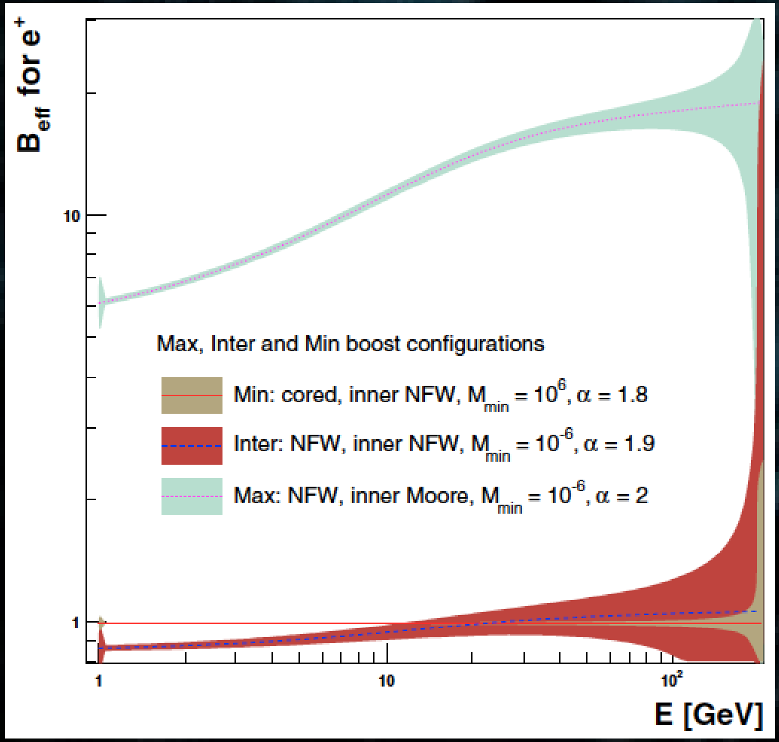
Pieri, JL, Bertone & Branchini (2009)

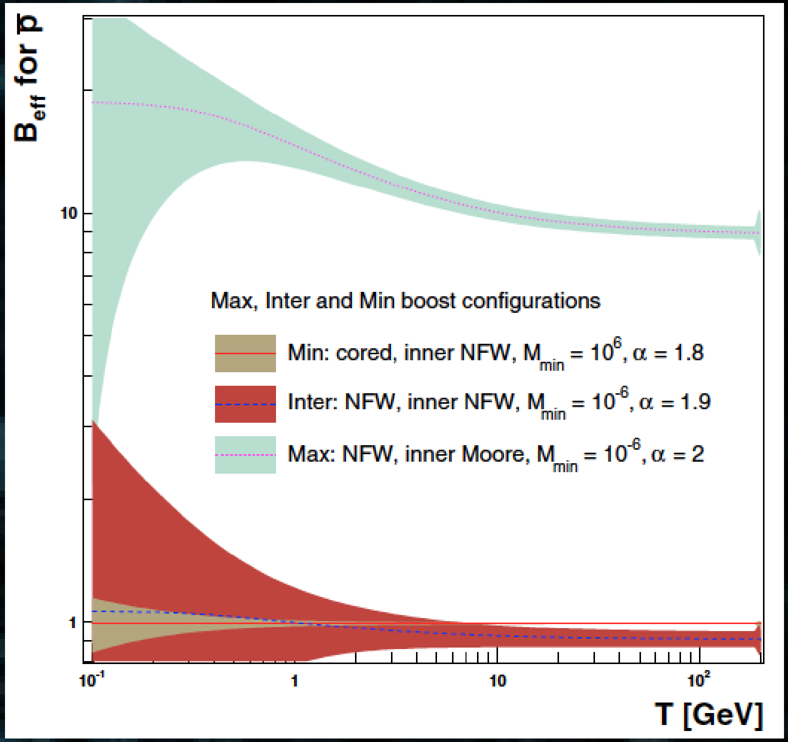




Boost factors for positrons and antiprotons

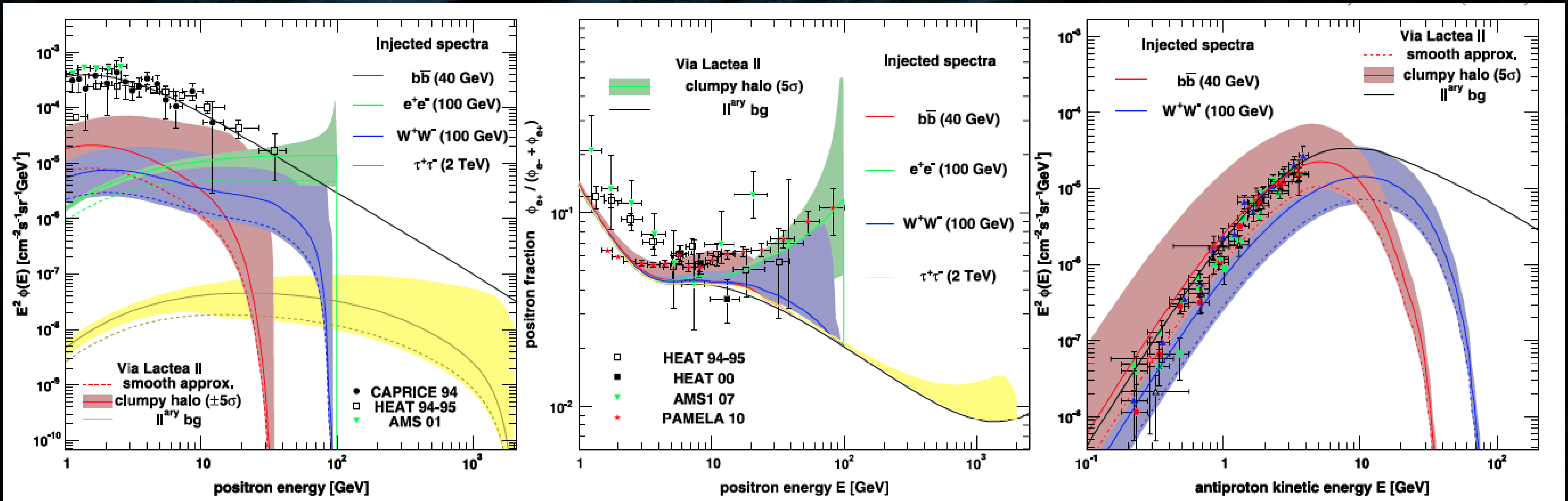
JL, Maurin++ 07 → the most extreme (and unrealistic) cases





Predictions for antimatter fluxes

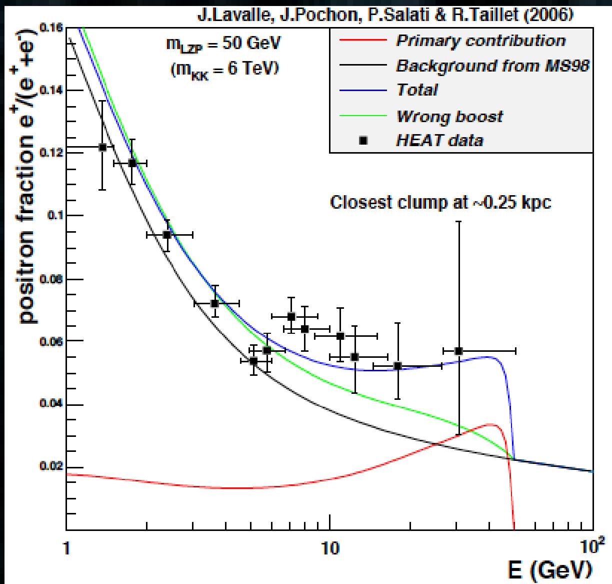
Pieri, JL, Bertone & Branchini (2009)



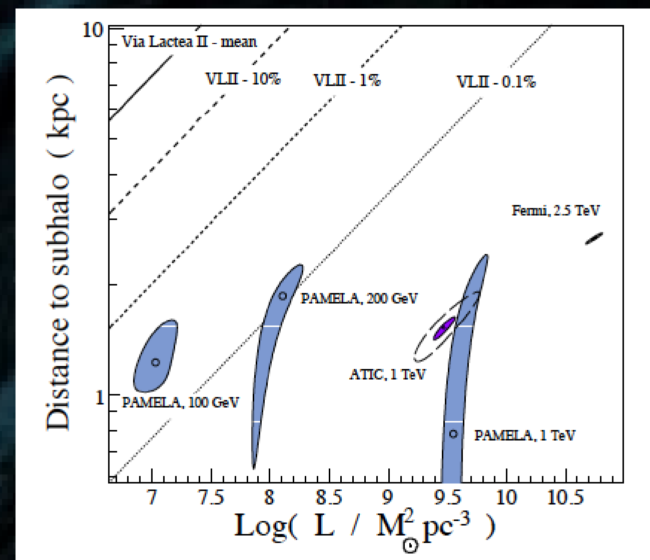
=> could marginally fit the PAMELA positron excess (100 GeV WIMP into e+e-)
=> no longer the case with AMS02 (up to 350 GeV)

=> antiprotons provide very strong constraints for hadrophilic models

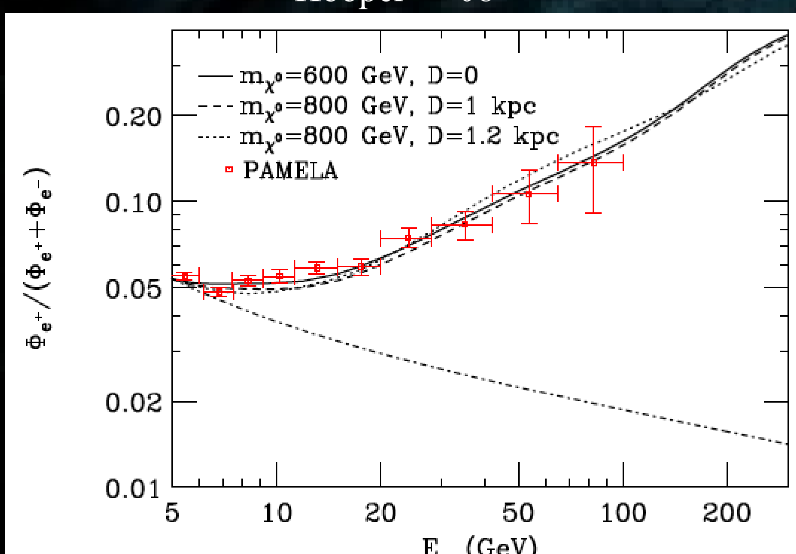
A single subhalo?



Brun++ 09

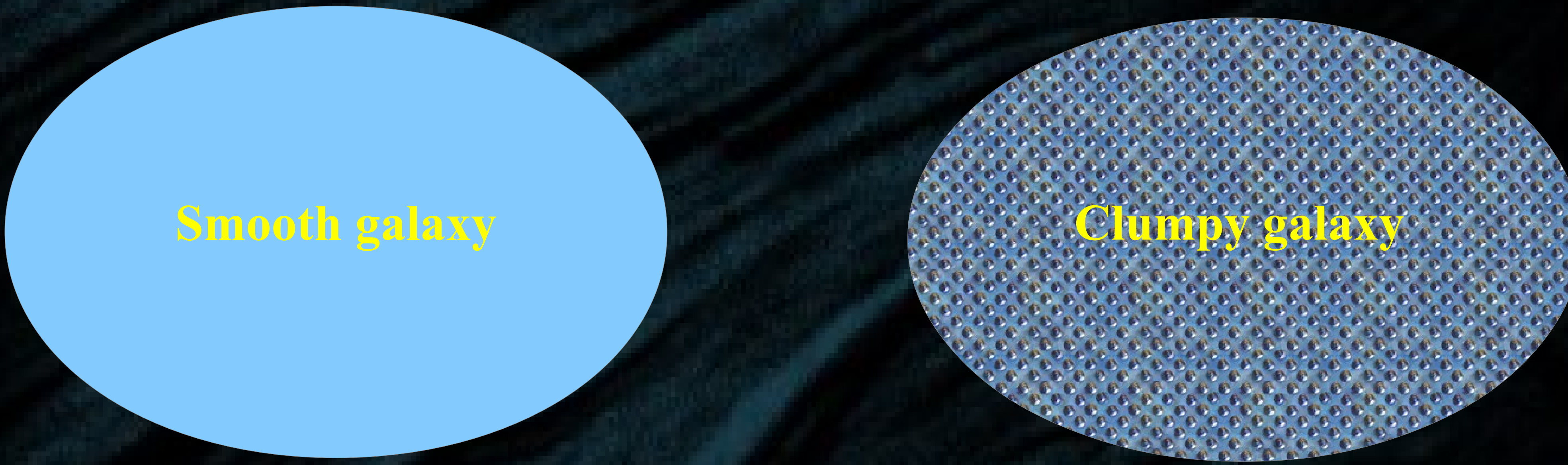


Hooper++ 08



=> Massive objects necessary (>10^7 Msun < 1 kpc)
=> Probability vanishingly small < 0.1 %
=> Primary astrophysical background?
=> Difficult to prove
=> Need a consistent multimessenger analysis

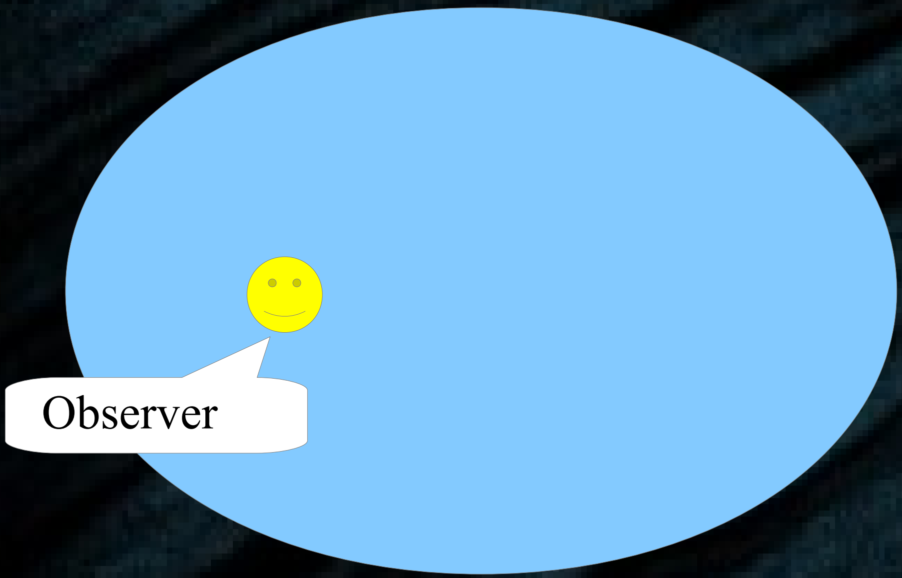
Summary picture for indirect detection

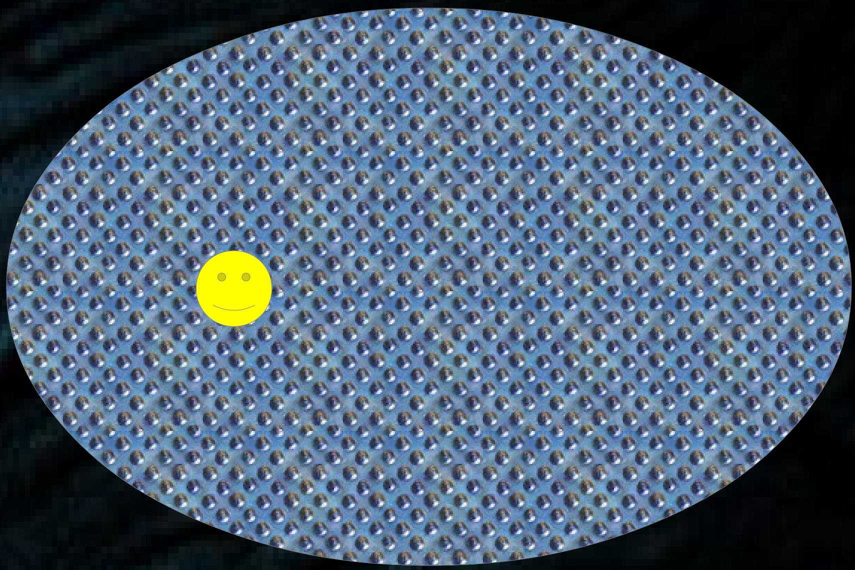


$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

The volume over which the average is performed depends on the cosmic messenger!

Summary picture for indirect detection





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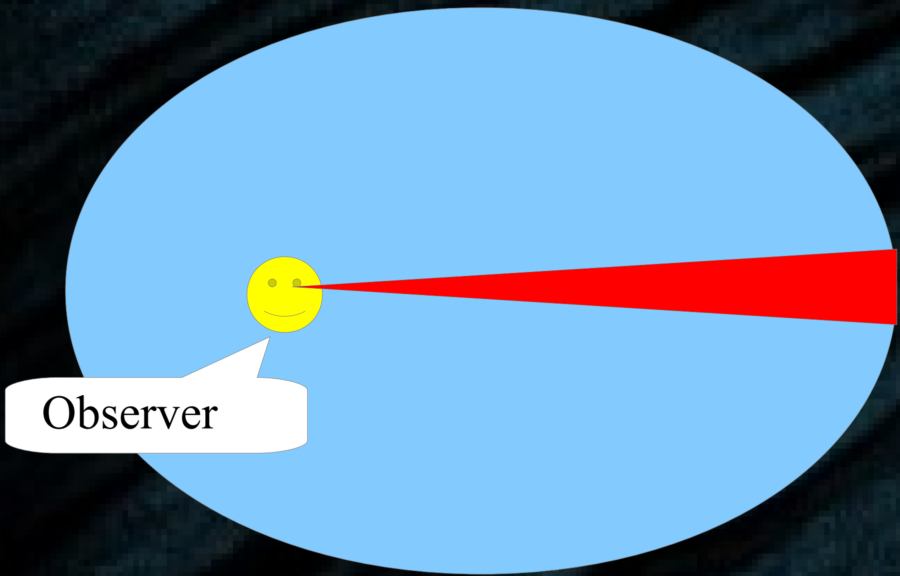
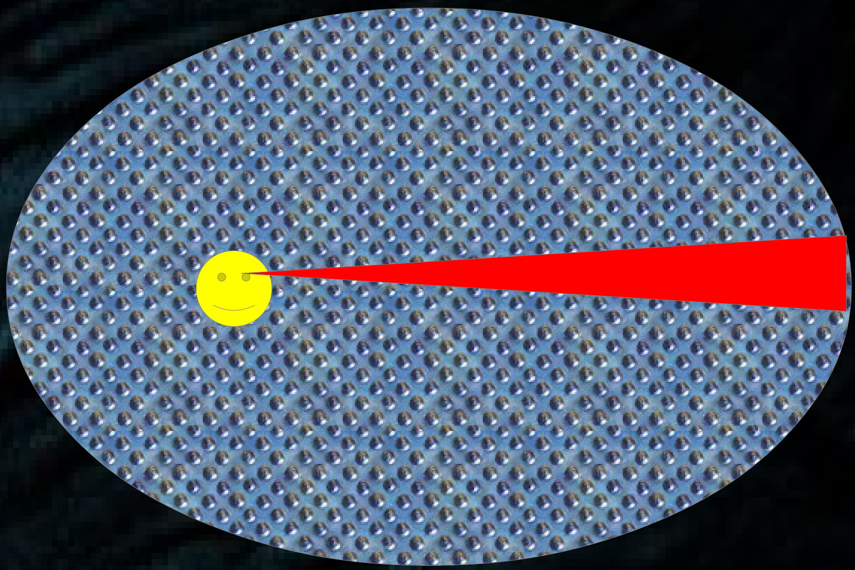
Summary picture for indirect detection





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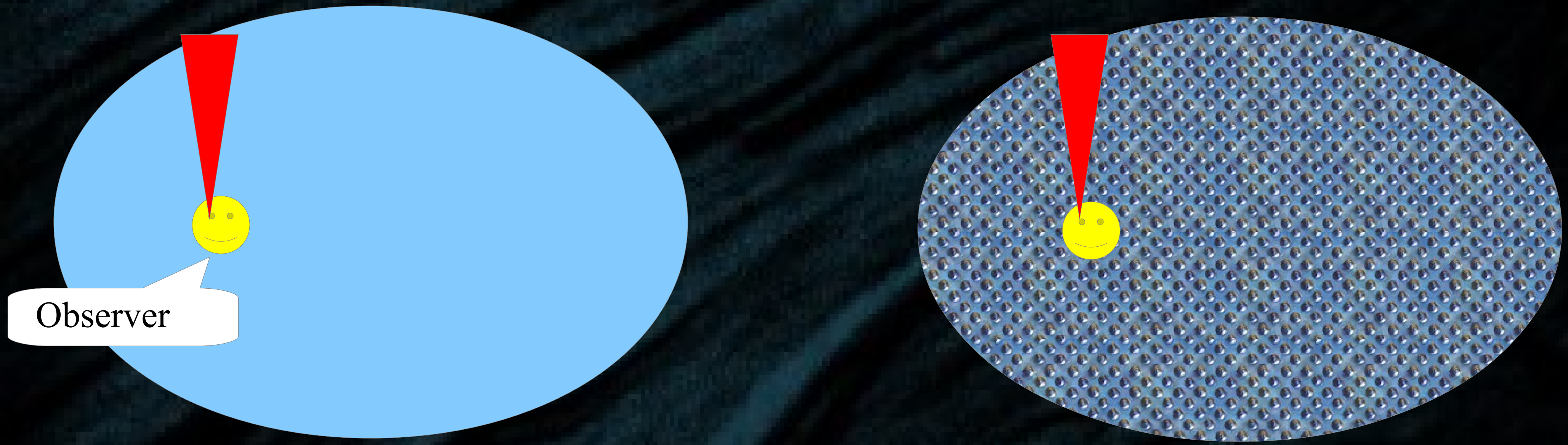
Summary picture for indirect detection



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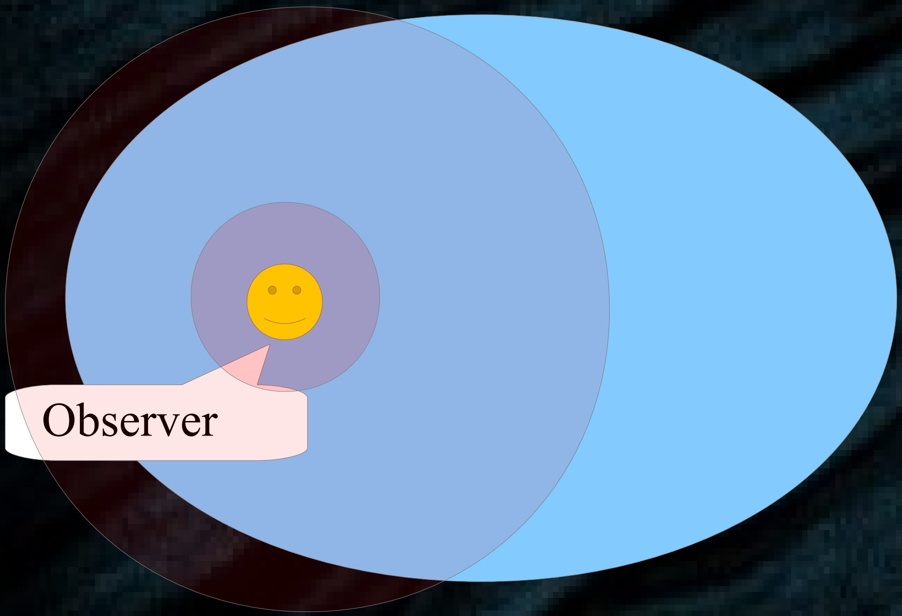
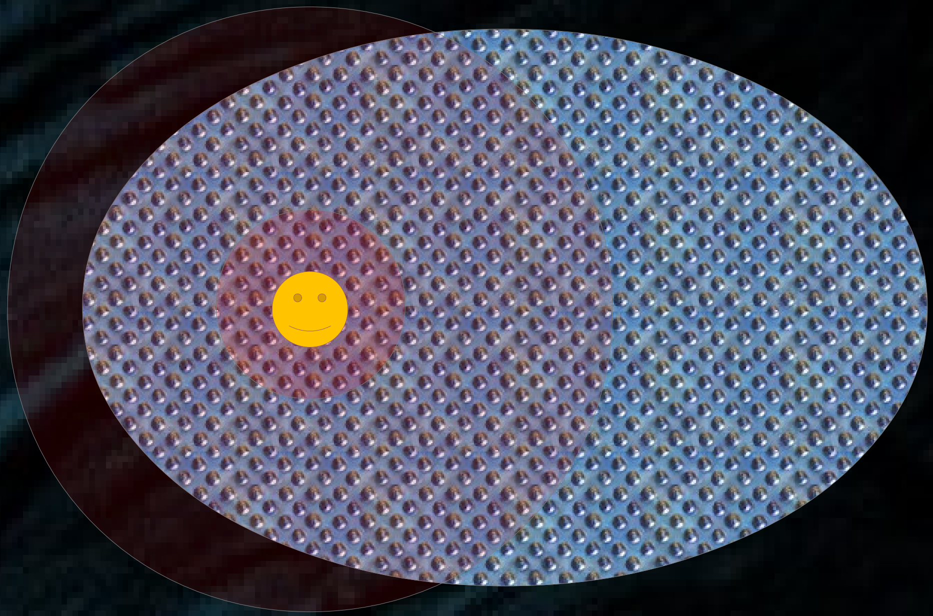
b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

Summary picture for indirect detection





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The volume over which the average is performed depends on the cosmic messenger!

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    a) To the Galactic center: the smooth halo is singular, clumps have no effect, **B ~ 1**

    b) To high latitudes/longitudes: the smooth halo contributes much less, **B>>1**

2) **Cosmic rays:** stochastic motion, define energy-dependent propagation scale.

    a) Large propagation scale: if enough to feel regions close to GC, then **B ~ 1**

    b) Small propagation scale: if we are sitting on a clump, then **B>>1**, otherwise **B moderate**

Other ways to detect subhalos?

Dynamical studies

DARK MATTER SUB-HALO COUNTS VIA STAR STREAM CROSSINGS

R. G. Carlberg[1]

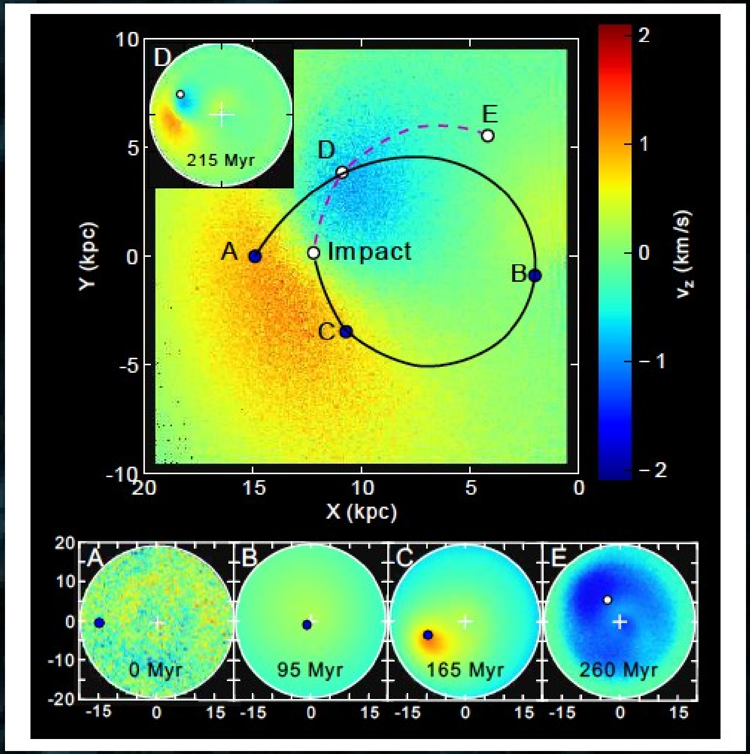
Draft version December 20, 2011

Carlberg++: subhalos induce gaps when they cross stellar streams (statistical measure => smallest of relevant objects dominate because of steep mass function)

Detecting Dark Matter Substructures around the Milky Way

Robert Feldmann,[1,**] and Douglas Spolyar[2,*]
[1]*Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[2]*Institut d'astrophysique de Paris, Paris, 75014, France*

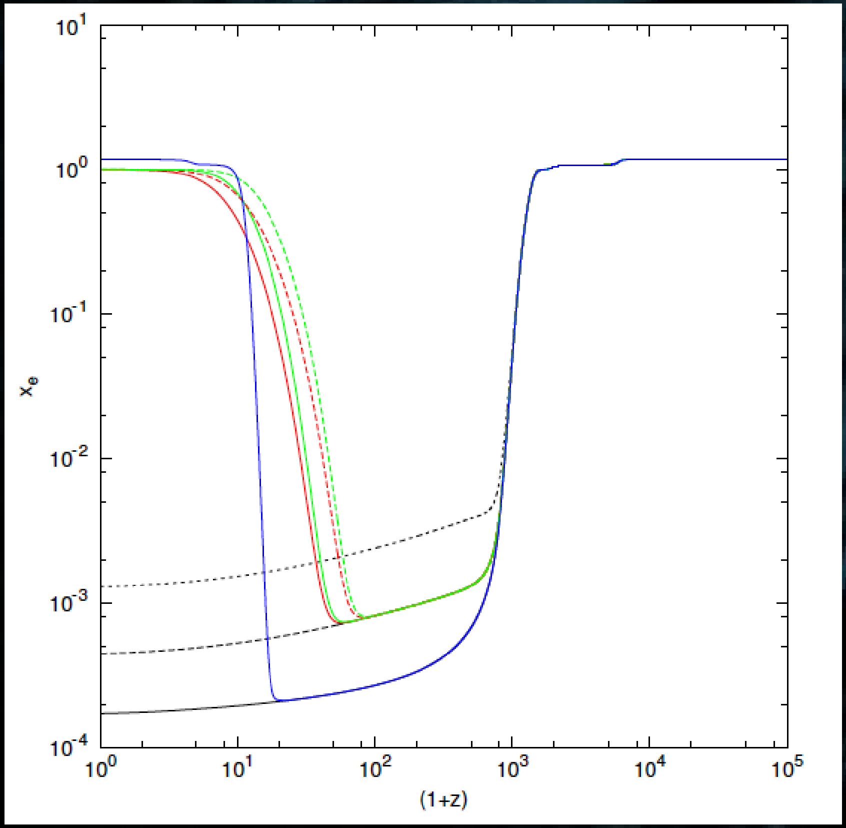
Subhalos pull stars when crossing the disk: could be observed with Gaia.

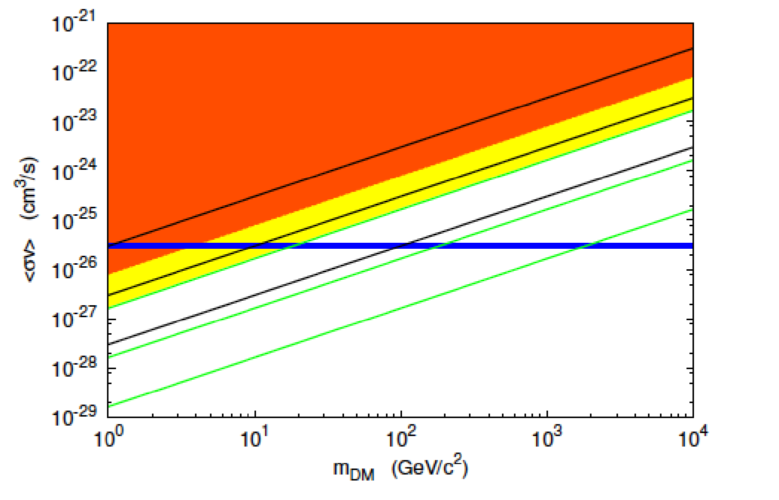


Limit: sensitive to big subhalos, > 10^6 Msun
(But see also Gonzales-Morales++ arXiv:1211.6745)

Reionization era

e.g. Giesen++ 12





Subhalo properties (Mmin, profile, concentration) affect reionization history
=>reionization may start earlier

=> Constraints on annihilation cross section.

Summary

* If DM made of WIMPs, subhalos must be around
* Cut-off mass depends on WIMP interaction properties
* Knowledge of internal properties needs to be improved (non-trivial environment dependence)

* Unambiguous detection via direct/indirect detection difficult (except for “known” massive subhalos, like satellite Dwarf Spheroidal Galaxies)

* Global effect => moderate boost factor (depends on messenger!)
* Leads to stronger constraints on WIMP annihilation (especially antiprotons)
**** Some room left for improvements

* Other impact on / constraints from cosmology (e.g. reionization, etc., not fully discussed).

* Some interesting ideas to detect them from kinematical studies (Gaia will help)