Galactic Structure and Dark Matter Indirect Detection

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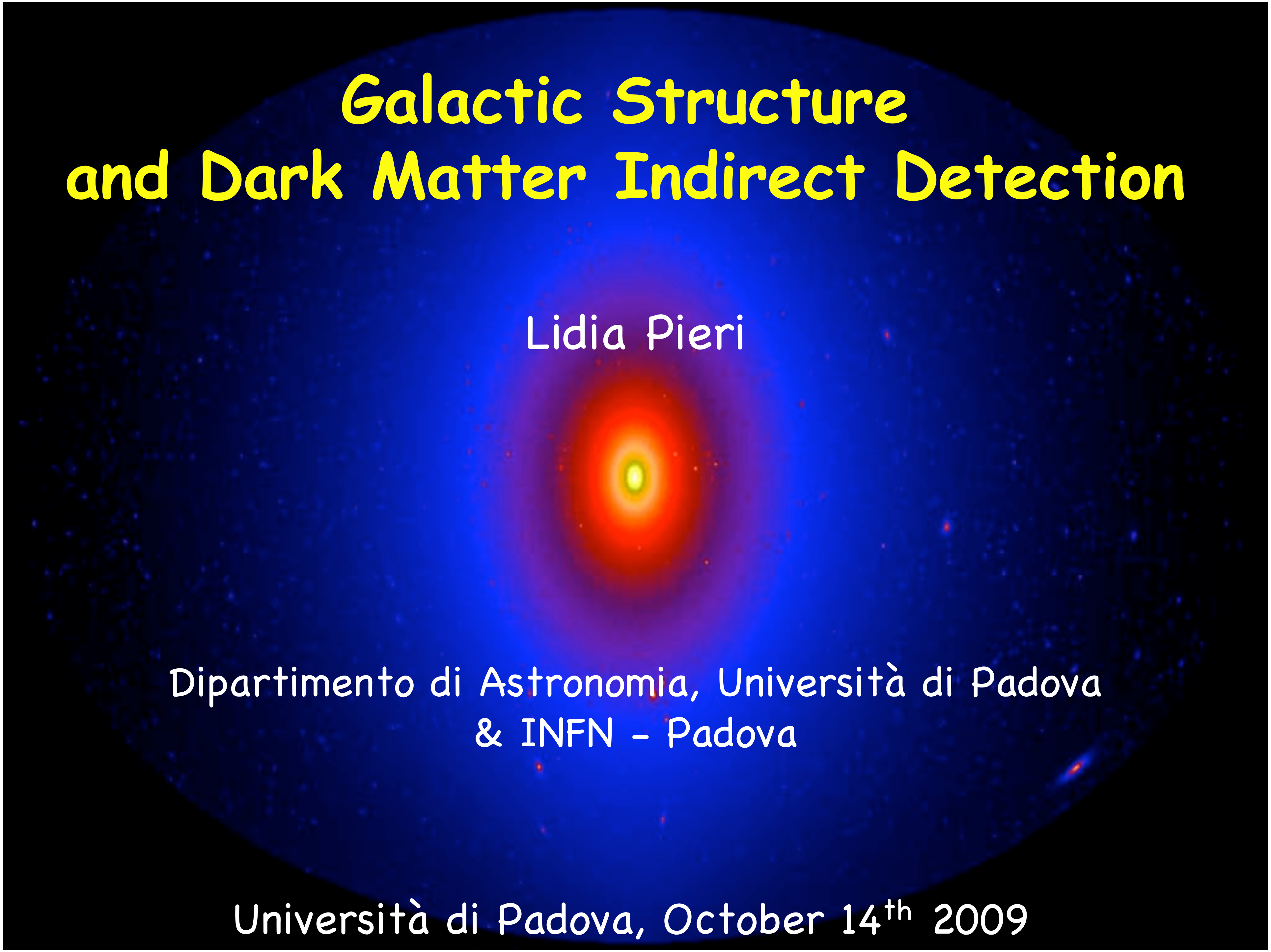

General outline

Indirect detection of dark matter:
Theoretical motivation

The role of substructures

Subhalo population of our galaxy:
-Prospects for detection in γ-rays
-Multi-wavelength analysis

Indirect detection of dark matter:
Theoretical motivation

Framework

The Standard Model of the Universe,
as derived from data on large scale
structures, distant supernovae, CMB, etc.

known particles unknown

$$\Omega_{tot} \equiv \frac{\rho_\gamma + \rho_\nu + \rho_b + \rho_{DM} + \rho_\Lambda}{\rho_c} \sim 1$$

value for a flat universe

predicts the existence of

- an unknown form of repulsive energy, or dark energy $\Omega_\Lambda \sim 0.73$
- and an *unknown type of non baryonic matter, or*

DARK MATTER $\Omega_{DM} \sim 0.23$

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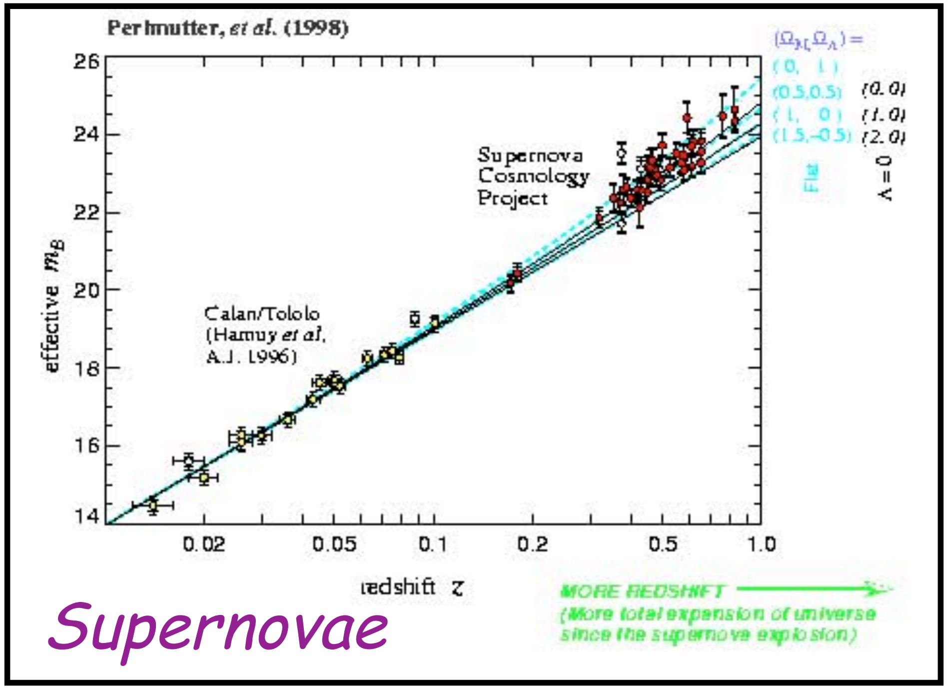
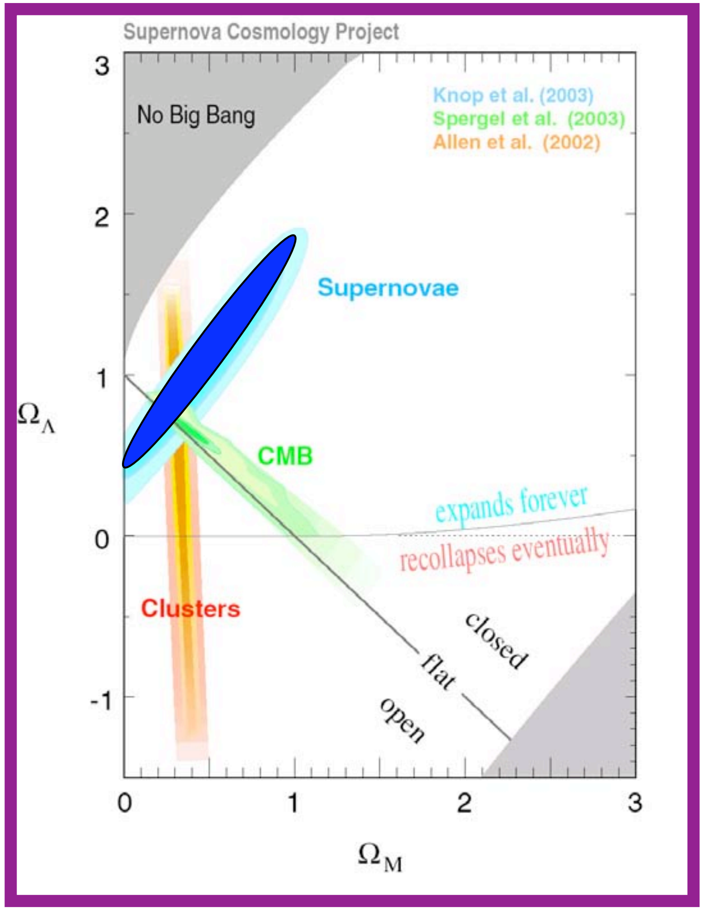
value for a flat universe

Ω_b ~ 0.005 (galaxies)
~ 0.04 (BBN)

$\Omega_\gamma \sim 10^{-5}$

$1.2 \cdot 10^{-3} < \Omega_\nu < 1.5 \cdot 10^{-2}$





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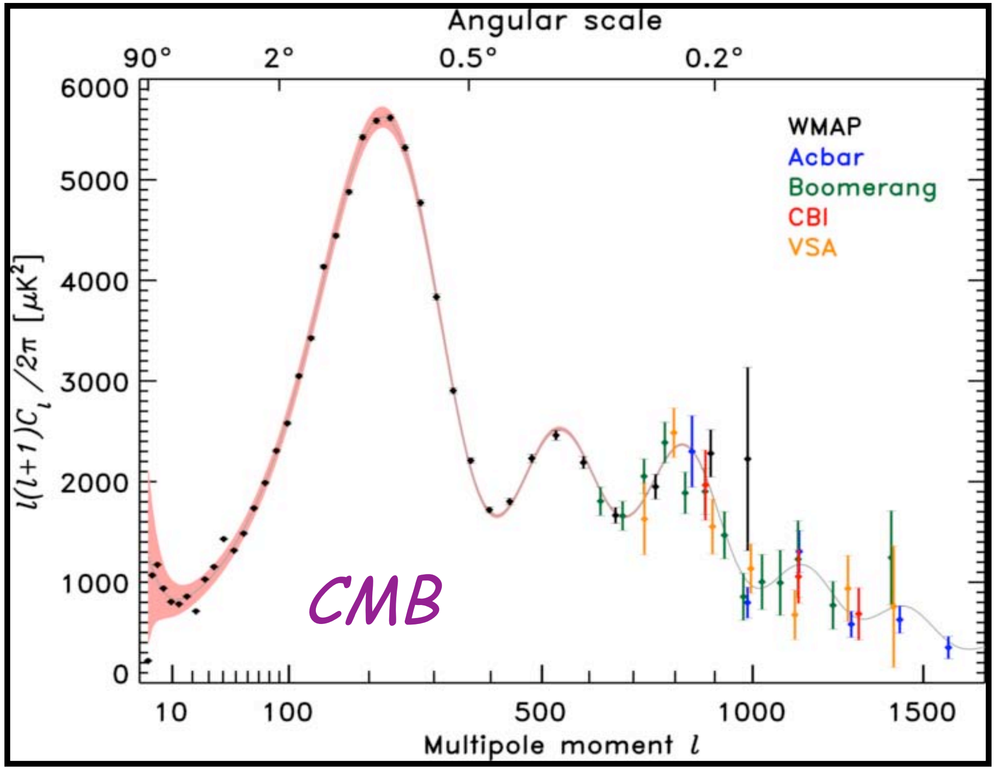
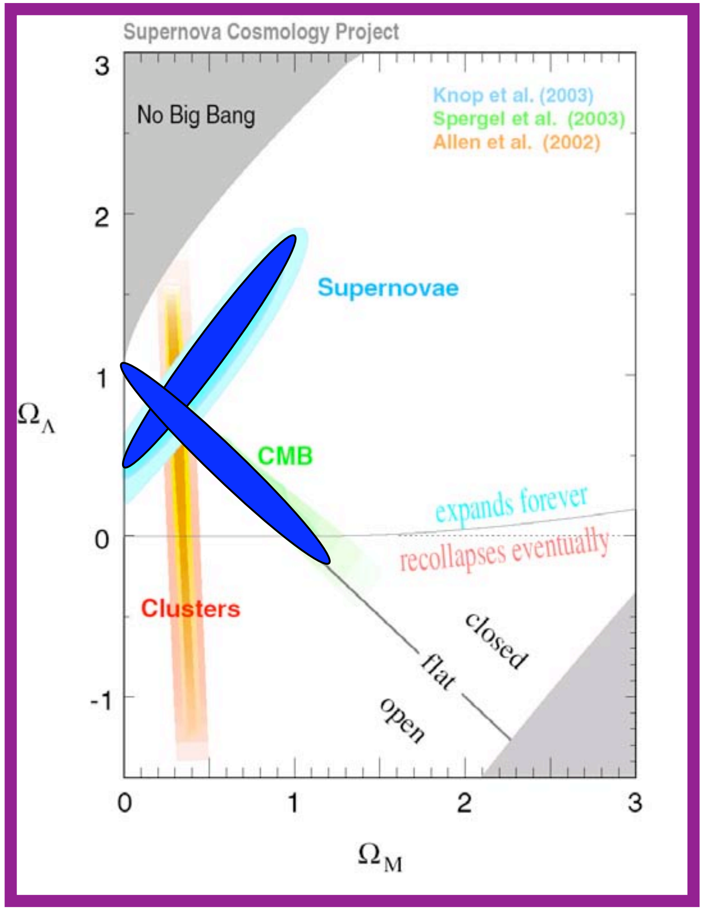




Framework
The Standard Model of the Universe

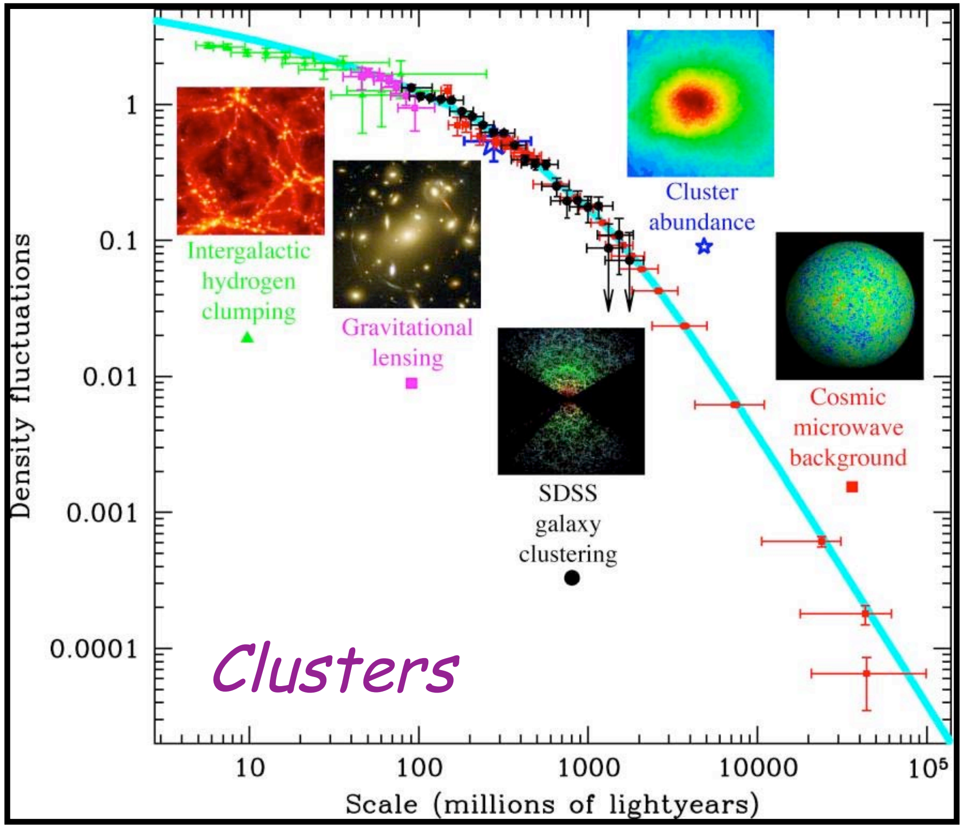
$$\Omega_{tot} \equiv \frac{\overbrace{\rho_\gamma + \rho_\nu + \rho_b}^{\text{known particles}} + \overbrace{\rho_{DM} + \rho_\Lambda}^{\text{unknown}}}{\rho_c} \sim 1$$

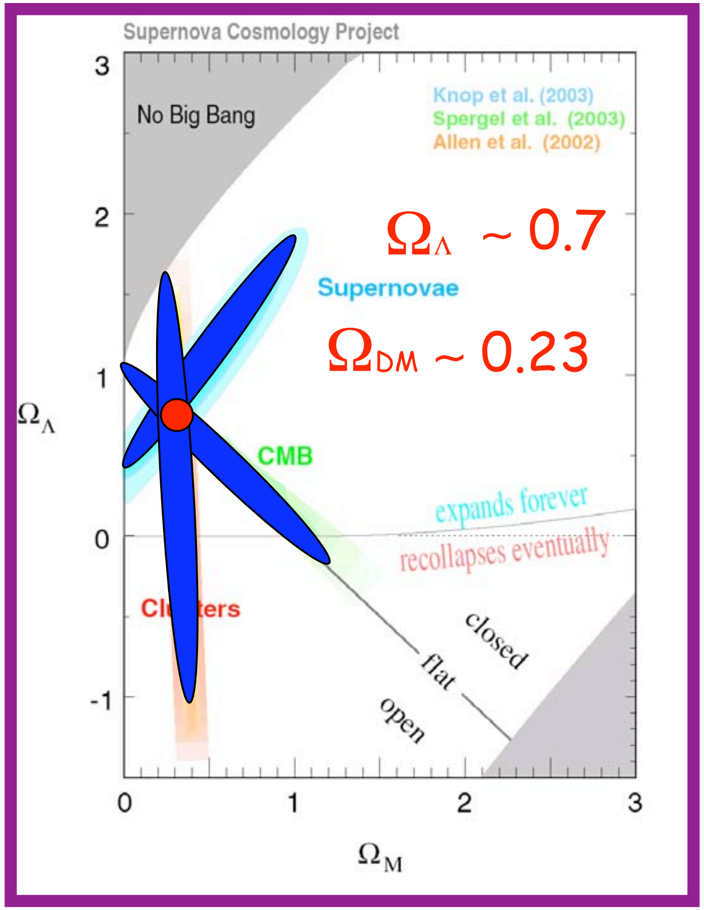
value for a flat universe

$$\Omega_b \quad \begin{matrix} \sim 0.005 \text{ (galaxies)} \\ \sim 0.04 \text{ (BBN)} \end{matrix}$$

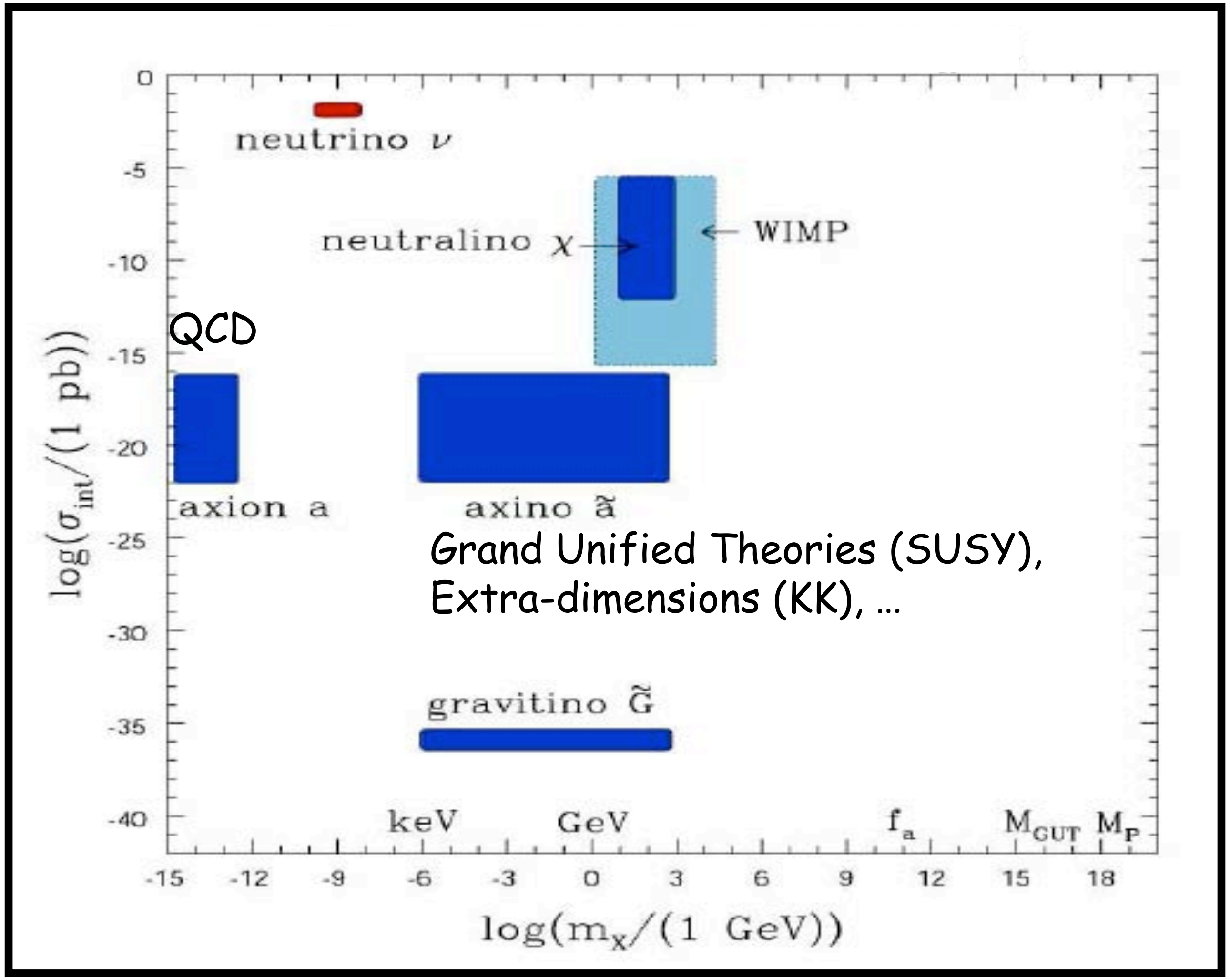
$$\Omega_\gamma \sim 10^{-5}$$

$$1.2 \cdot 10^{-3} < \Omega_\nu < 1.5 \cdot 10^{-2}$$





Dark because we haven't seen it (yet)
Matter because it interacts gravitationally building up the universe



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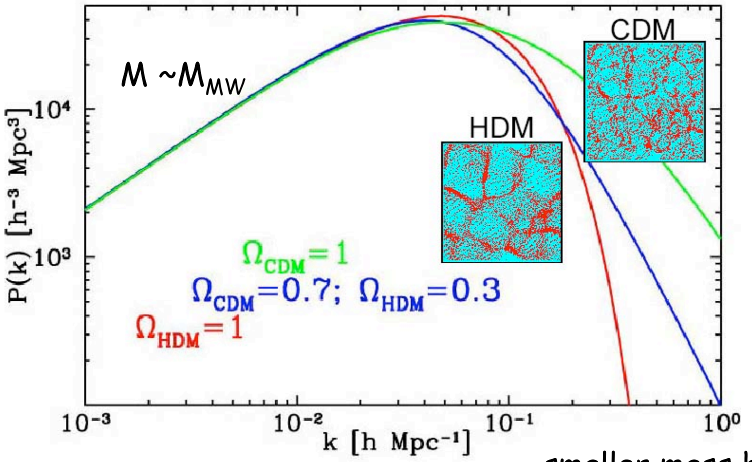
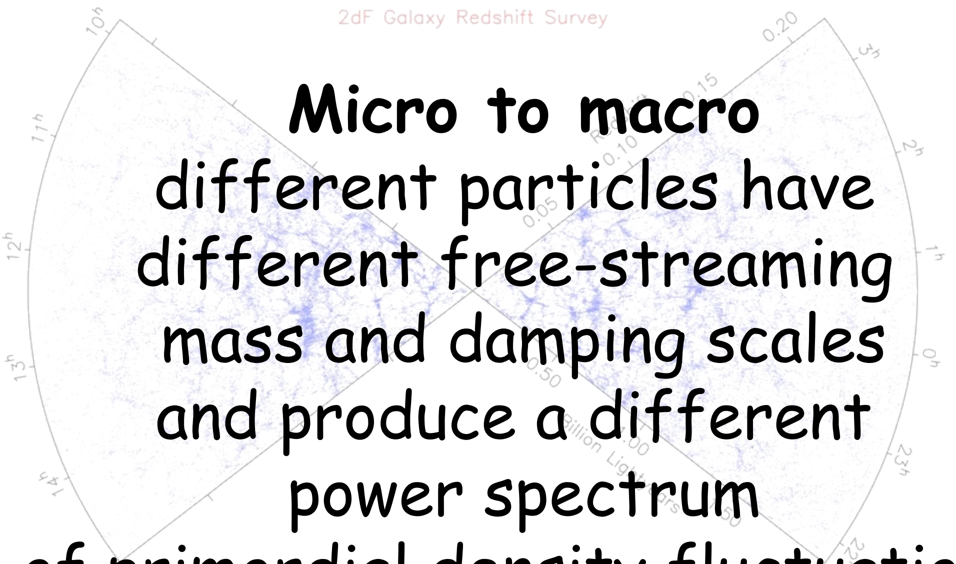


smaller mass halos



Micro to macro

different particles have different free-streaming mass and damping scales and produce a different power spectrum of primordial density fluctuations

Defining a DM halo

The damping of the power spectrum defines the scale (i.e. the mass) at which the primordial density fluctuation non-linearly collapses into a self-gravitating object, that is to say into **a DM halo**

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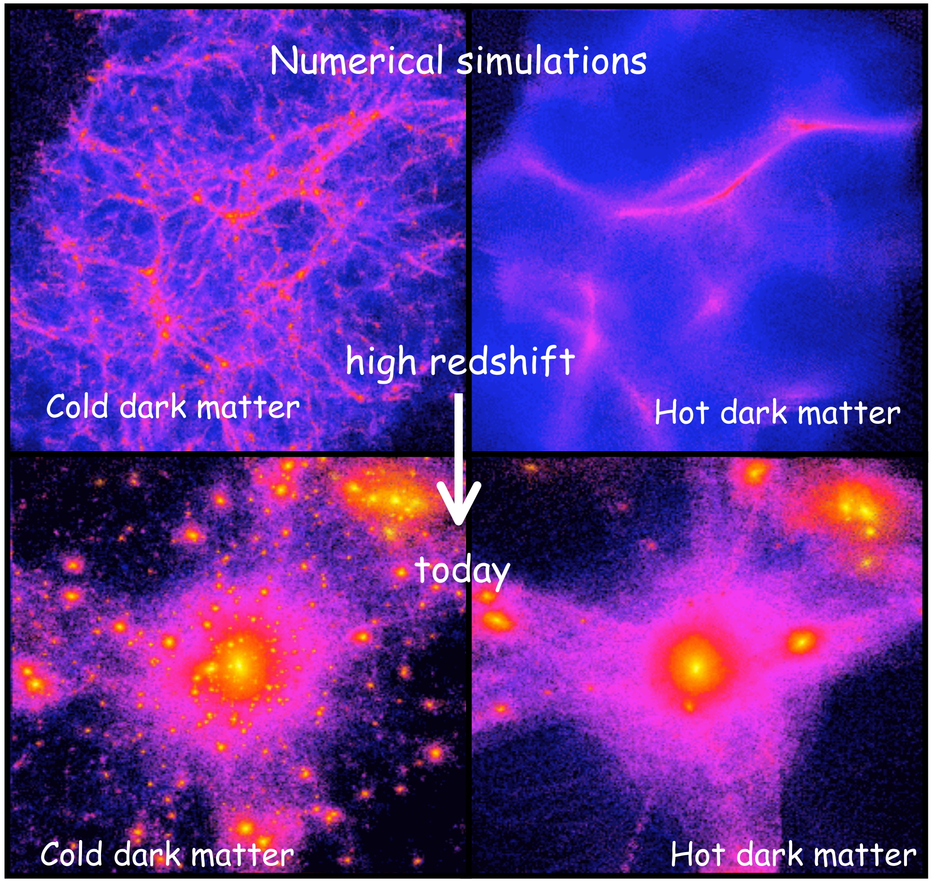
The evolution of DM halos

Primordial density fluctuations grow and collapse in gravitationally bound structures which eventually virialize.

The assembly hystory depends on the particle. CDM proceeds via hierarchical merging, HDM via fragmentation.

Baryons are captured in the dark matter potential well and form galaxies, clusters, etc.



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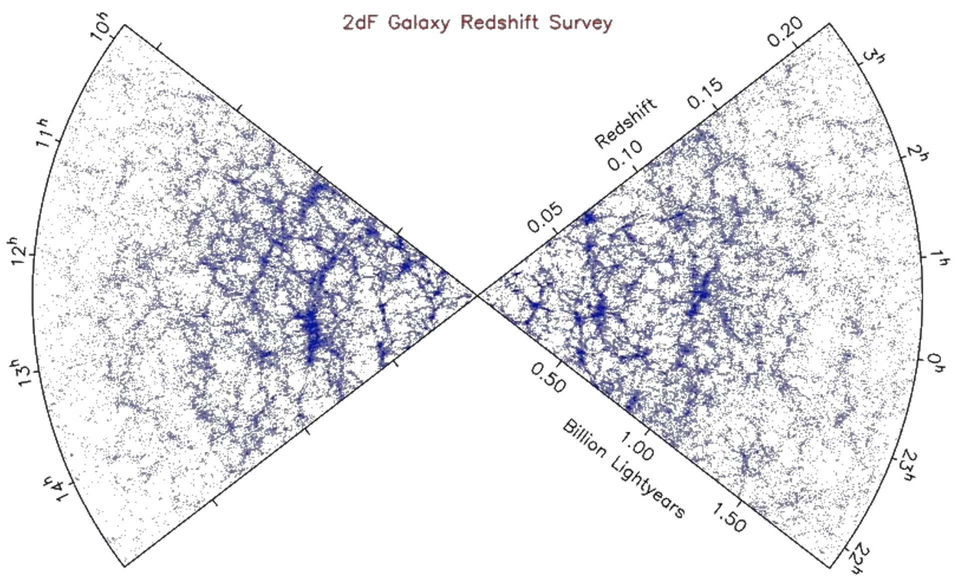
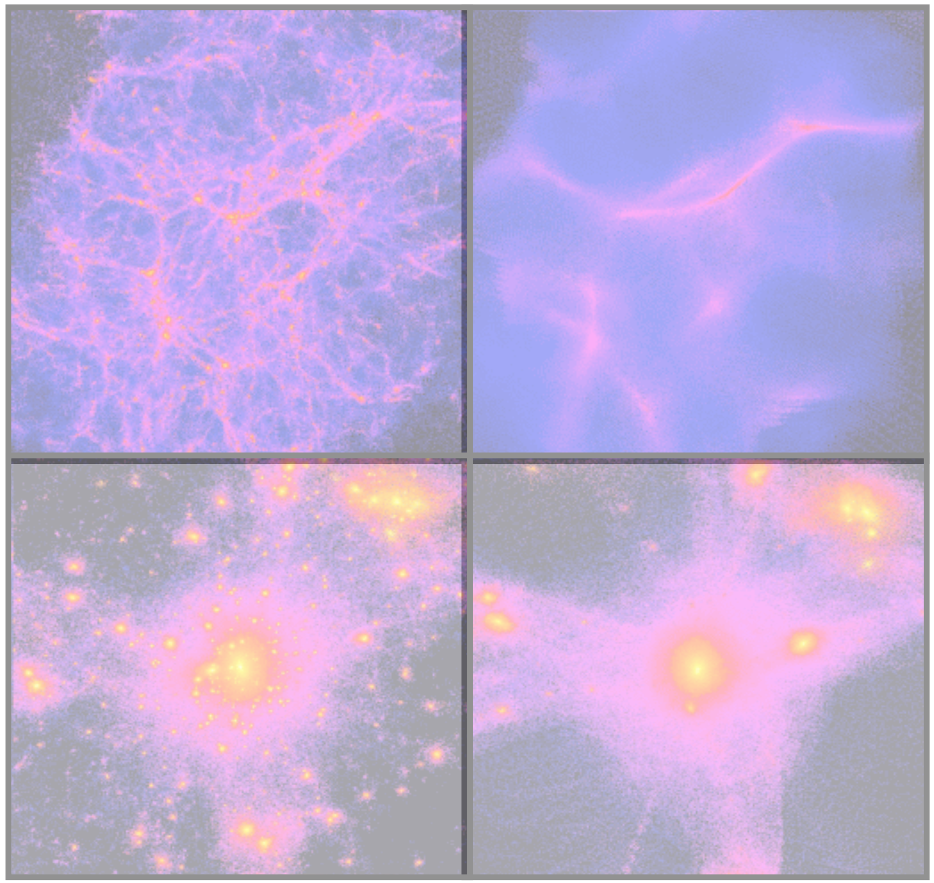
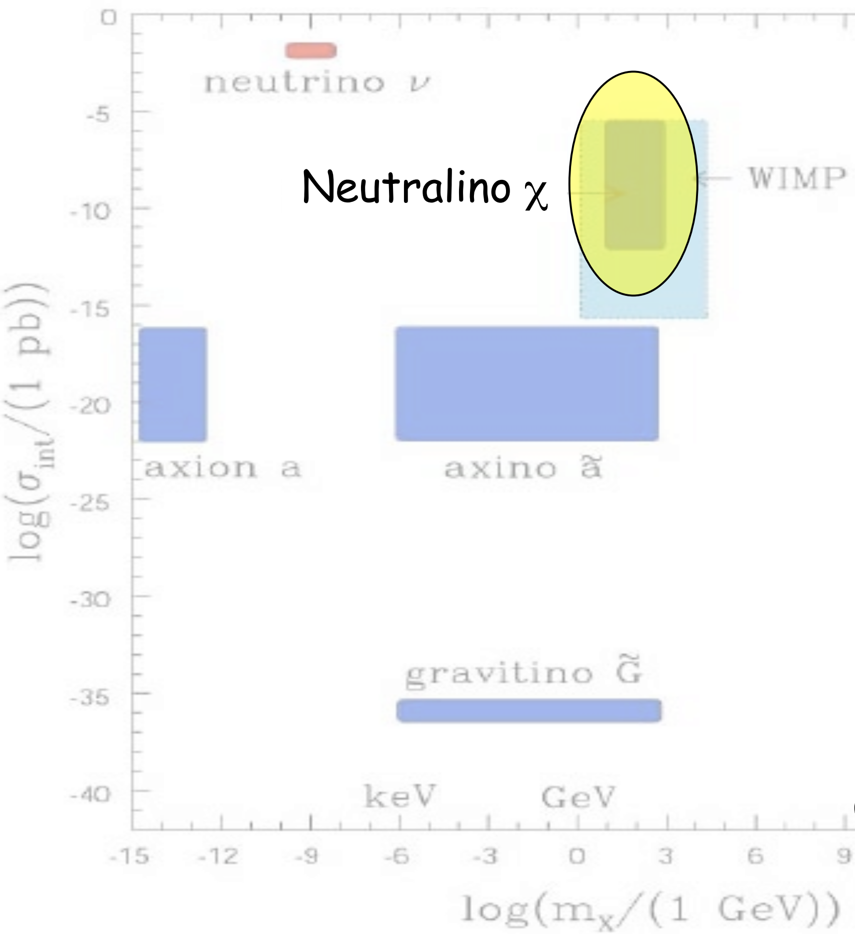
Comparison with the data
The observed large scale structure of the Universe compels the dark matter particle to be heavier than a few keV -> **CDM scenario**





Is the Neutralino the theoretical miracle?



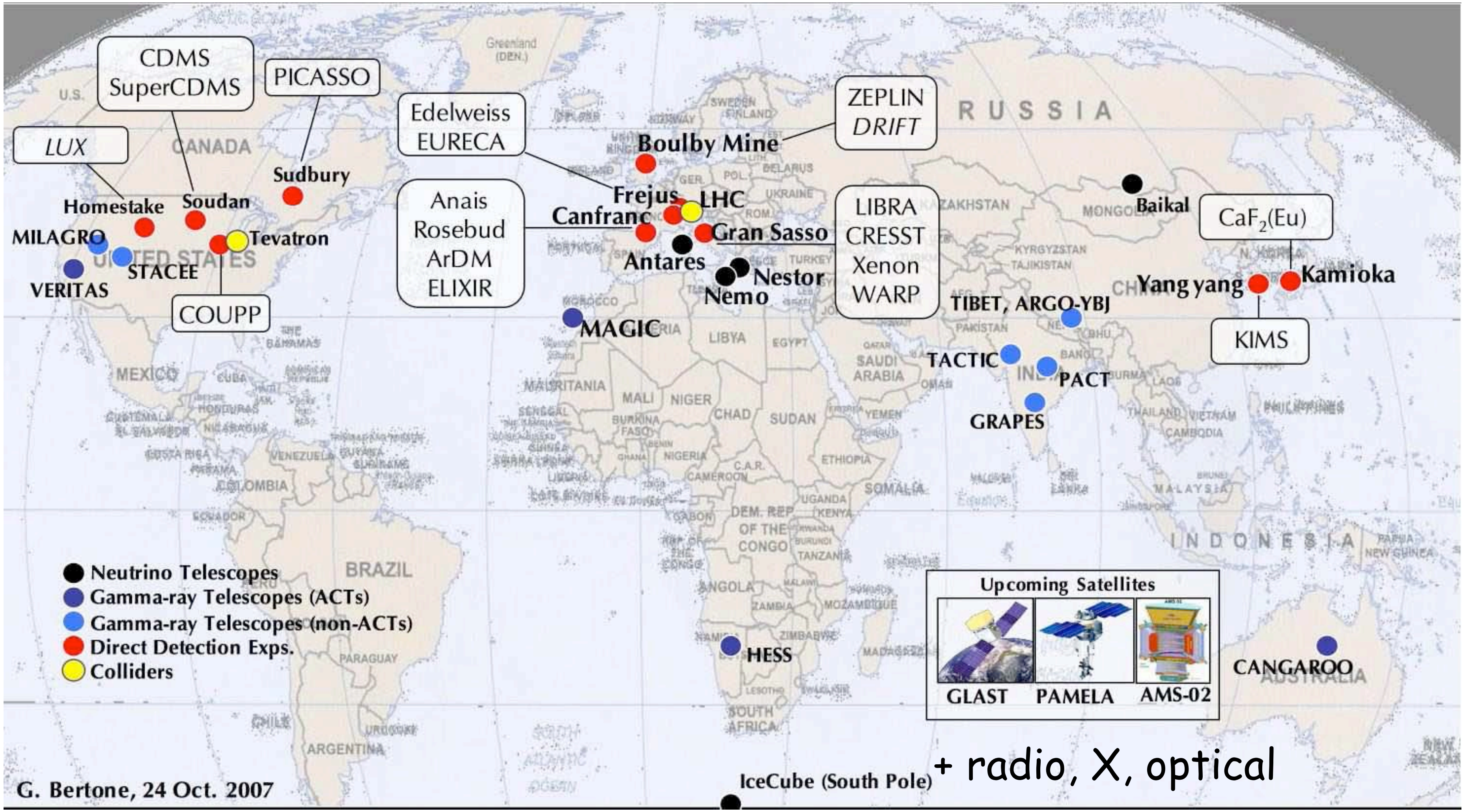
- ✓ useful (SUSY is welcomed)
- ✓ stable (R-parity)
- ✓ collisionless (weak interaction)
- ✓ gives the correct relic density (Boltzmann equation)
- ✓ is a CDM particle (decouples at T ~ M/20)

→ good for theorists

✓ it self-annihilates into SM particles of energies accessible by experiments

→ good for experimentalists

BIG EXPERIMENTAL EFFORTS

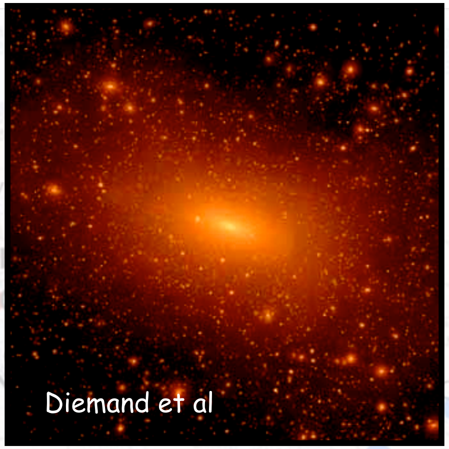


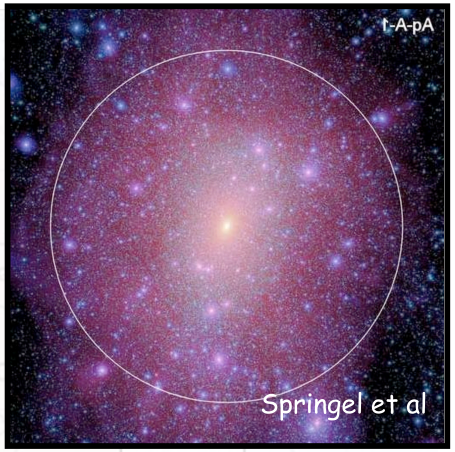
+ radio, X, optical

- accelerators Many possible patterns for final states (jets and missing energy) $m_\chi < 1\text{-}2$ TeV
- direct searches χ elastic diffusion on nuclei (nucleus recoil energy) 30 GeV $< m_\chi <$ 100-200 GeV
- indirect searches ($\chi\chi$ annihilation)
  - in close massive objects (Earth, Sun) $\rightarrow$ neutrinos
  - in the Galactic halo and other compact objects, $\rightarrow \gamma_s$, ν_s, antimatter

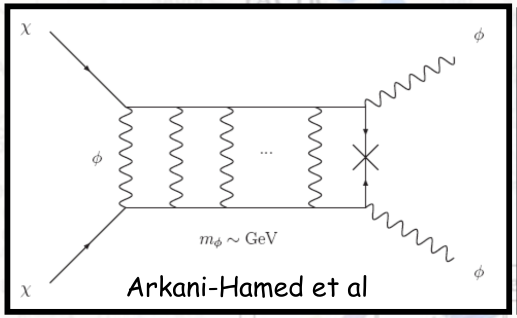
AND ACTIVE THEORETICAL MODELING

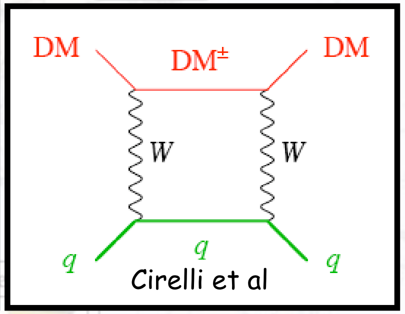
Numerical simulations of our galaxy

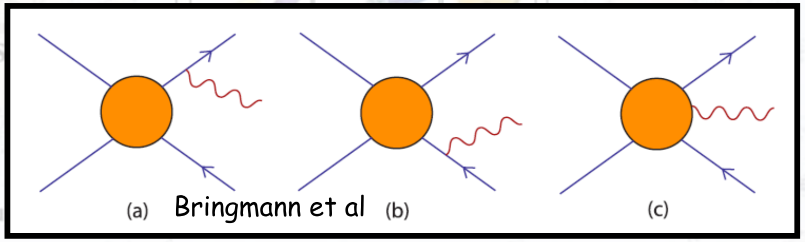




Particle physics modeling: new candidates explored, new effects added
(Sommerfeld enhancement of the annihilation cross-section, Internal bremmstrahlung, etc.)







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Indirect detection of dark matter:

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Subhalo population of our galaxy:
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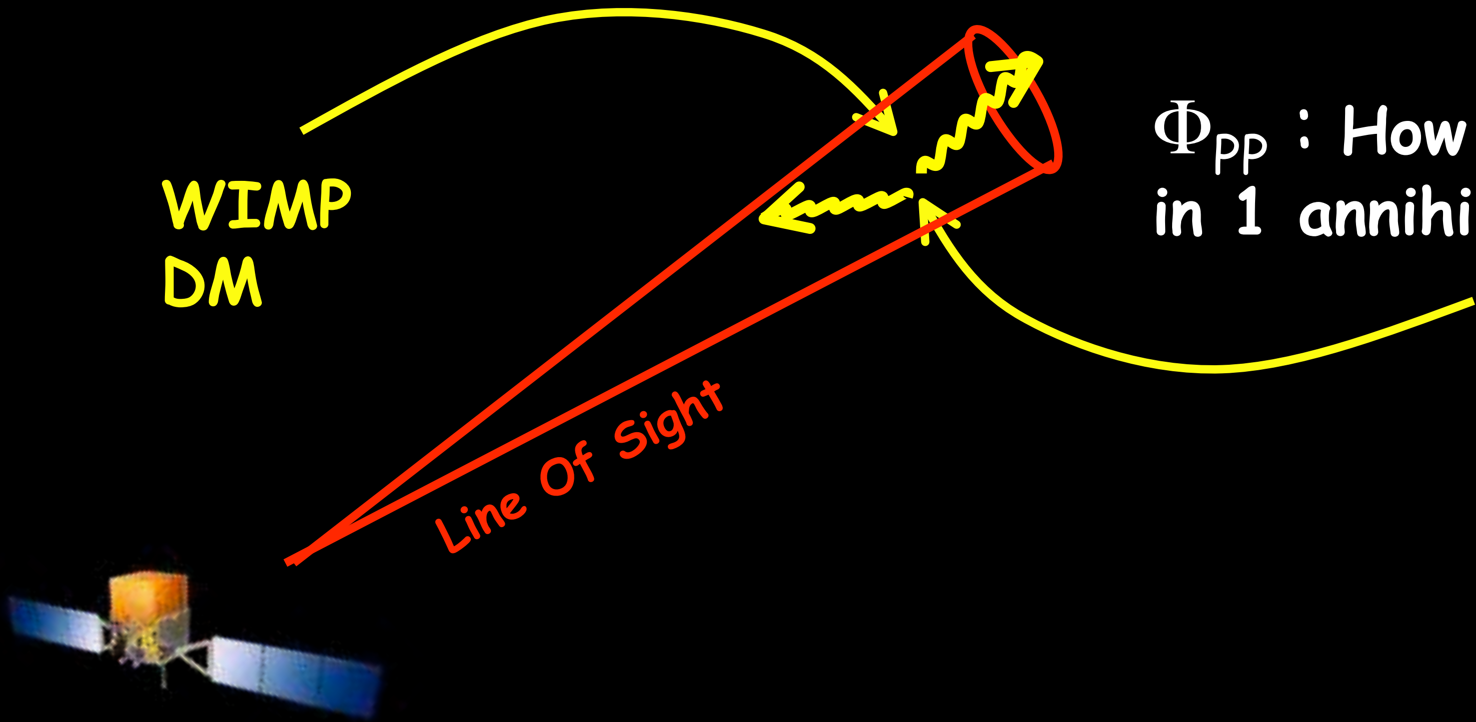
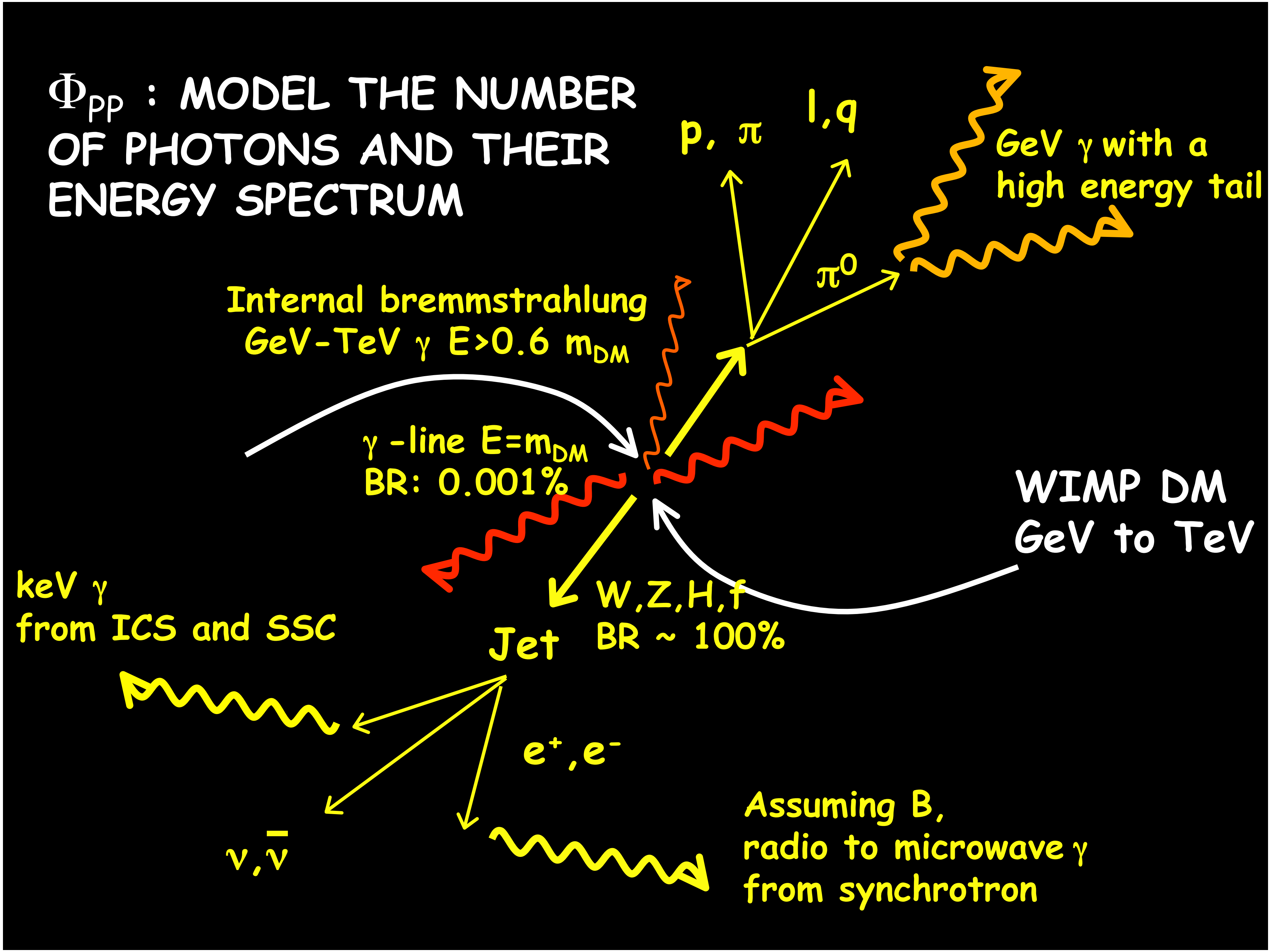
Indirect detection of γ-rays

$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$

$$\phi_{PP} = \frac{1}{4\pi}\,\frac{\sigma_{ann} v}{2 m_\chi^{\,2}} \int_{E_0}^{m_\chi} \sum_f \frac{dN_f^{\gamma}}{dE_\gamma} BR_f \, dE_\gamma$$

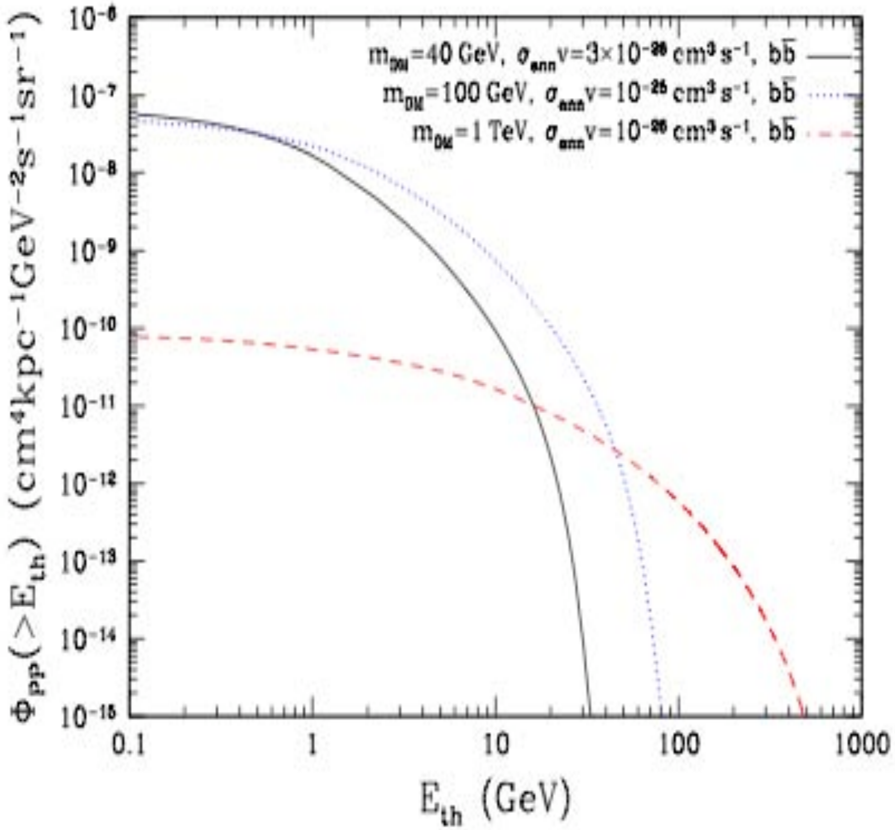


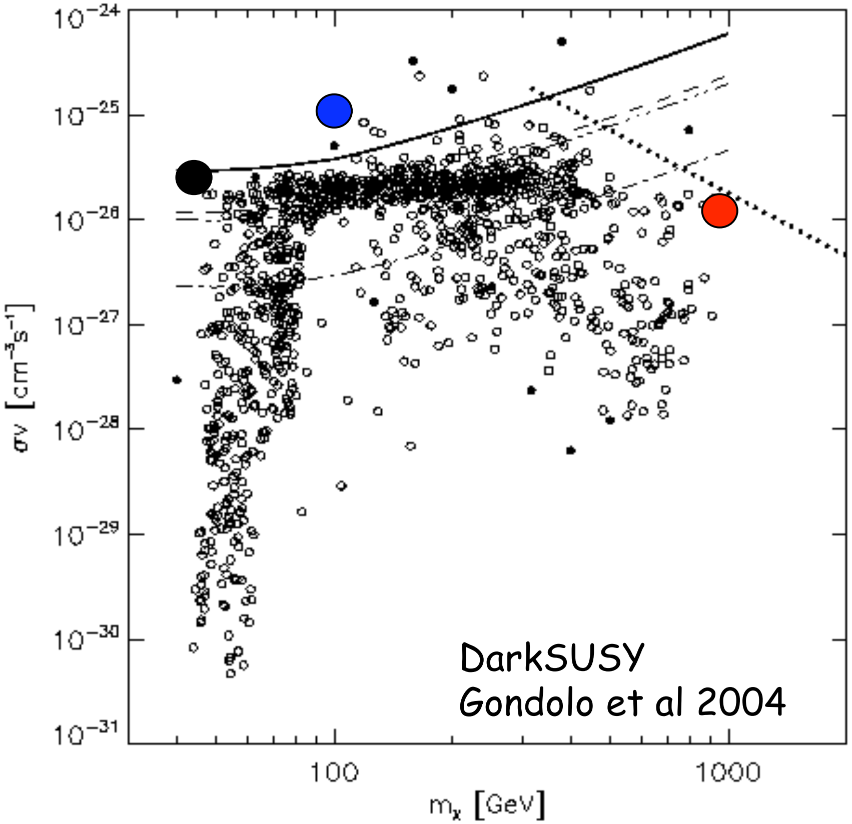
Φ_{PP} : How many γs in 1 annihilation


Φ$_{PP}$: MODEL THE NUMBER OF PHOTONS AND THEIR ENERGY SPECTRUM
p, π
l,q
GeV γ with a high energy tail
π^{0}
Internal bremmstrahlung
GeV-TeV γ E>0.6 m$_{DM}$
γ -line E=m$_{DM}$
BR: 0.001%
WIMP DM
GeV to TeV
keV γ
from ICS and SSC
W,Z,H,f
BR ~ 100%
Jet
e^{+},e^{-}
ν,$\bar{\nu}$
Assuming B,
radio to microwave γ
from synchrotron

Computing $\Phi_\gamma = \Phi_{particle\ physics} \times \Phi_{cosmology}$

$$\phi_{PP} = \frac{1}{4\pi} \frac{\sigma_{ann} v}{2 m_\chi^2} \int_{E_0}^{m_\chi} \sum_f \frac{dN_f^\gamma}{dE_\gamma} BR_f \, dE_\gamma$$





Pieri, Pizzella et al 2008 & Pieri, Bertone, Branchini 2008

Indirect detection of γ-rays

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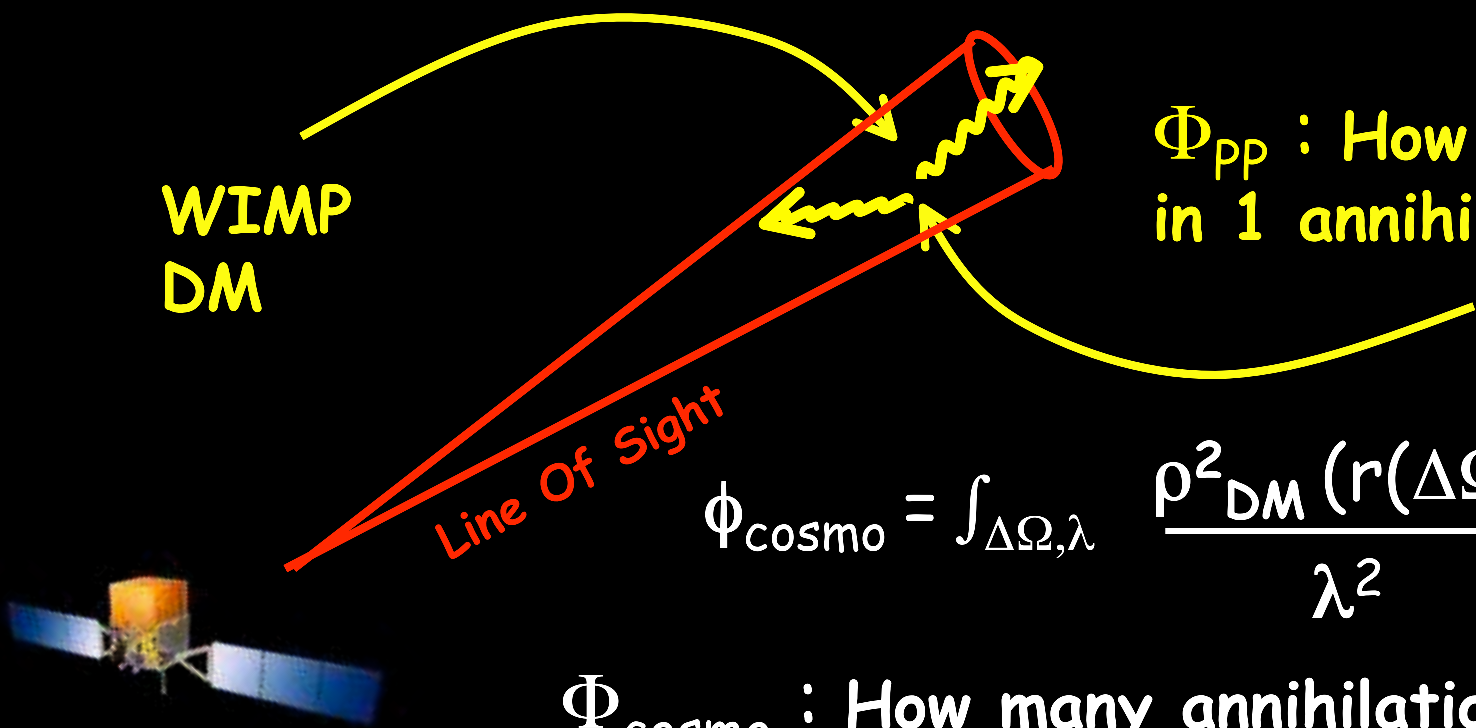


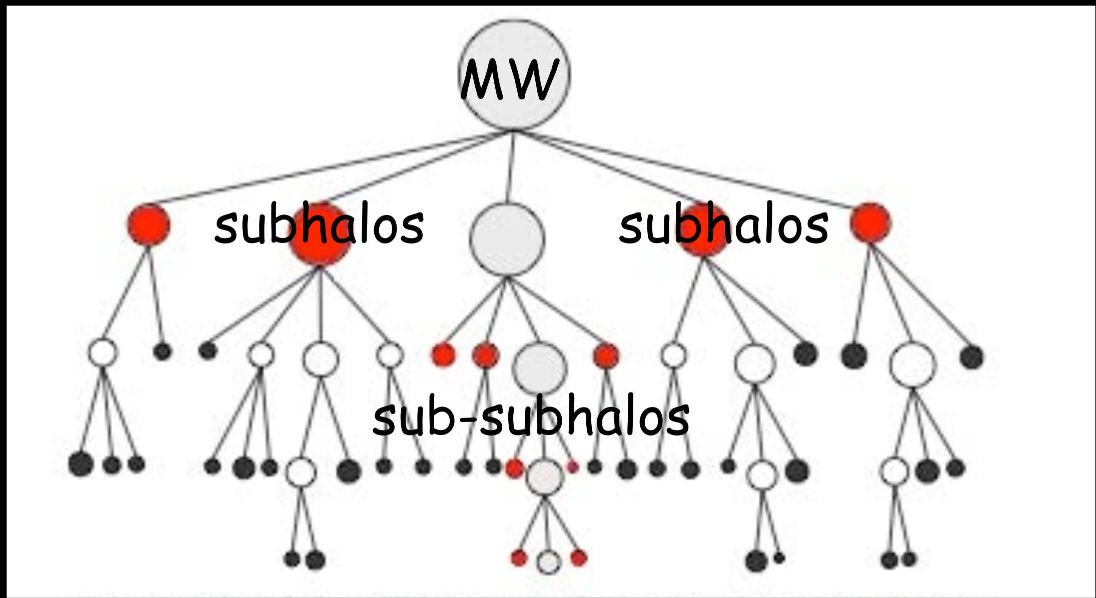
Φ_{PP} : How many γs in 1 annihilation

$$\phi_{cosmo} = \int_{\Delta\Omega,\lambda} \frac{\rho^2_{DM}(r(\Delta\Omega,\lambda))}{\lambda^2}\, d\lambda\, d\Omega$$

Φ_{cosmo} : How many annihilations ⇔ How many sources

Modeling the structure of dark matter halos

Halos form through a hierarchical process of successive mergers.
The halo of our Galaxy will be self-similarly composed by:
-a smoothly distributed component ($\rho^2_{DM(h)}$ single halo)
-a number of virialized substructures ($\rho^2_{DM(subh)}$ all halos)



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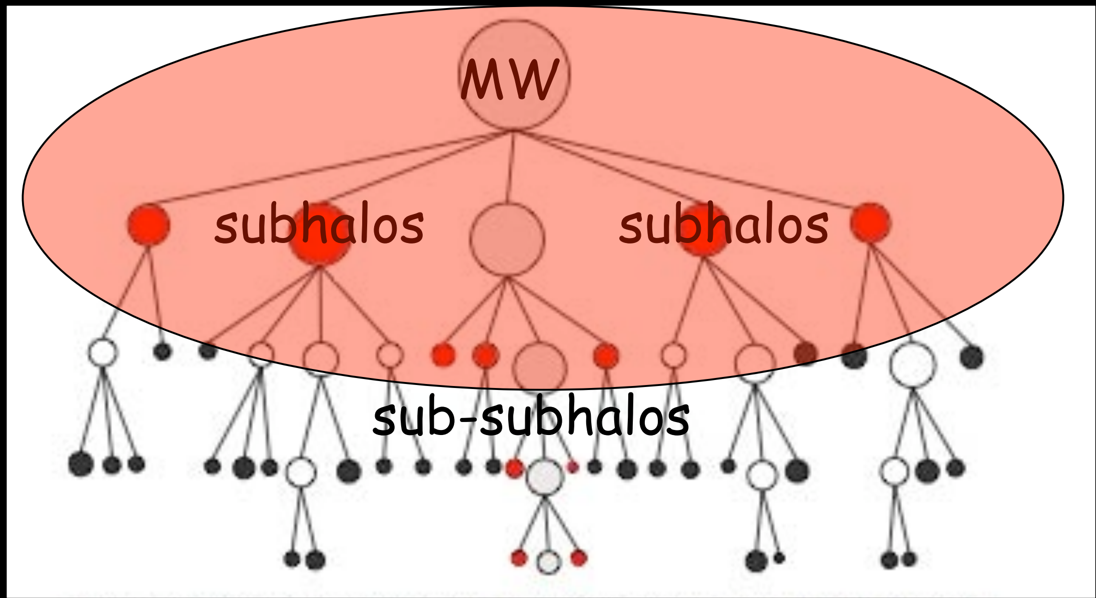

N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

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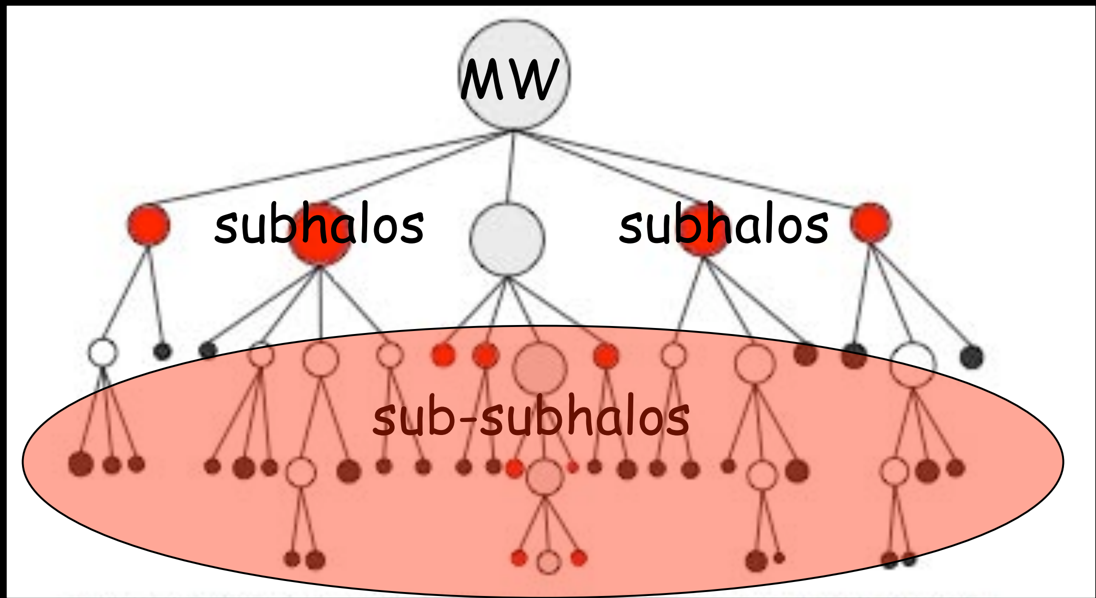
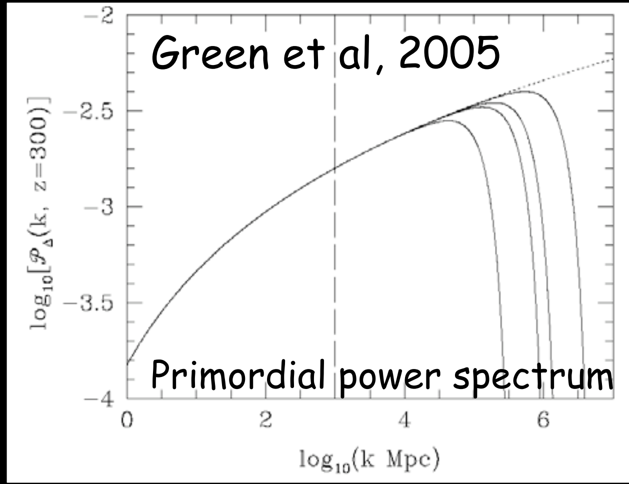


N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

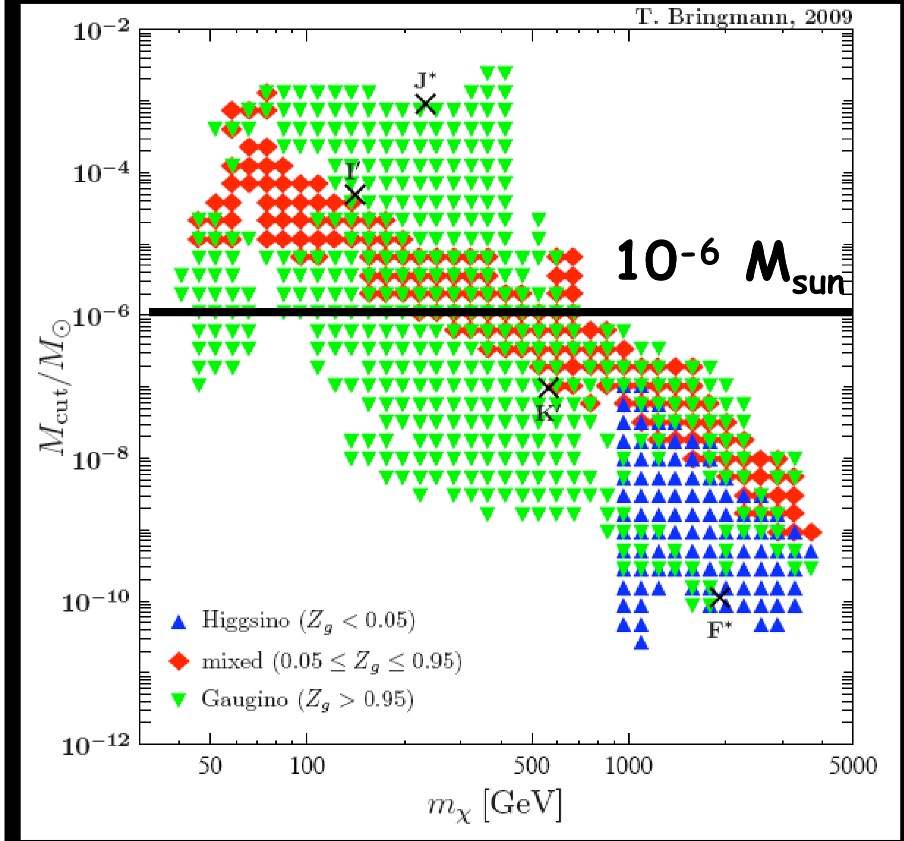
Microphysics and theory of structure formation sets the mass of the smallest halo because there is no enough cpu power to simulate small halos from collapse till today.

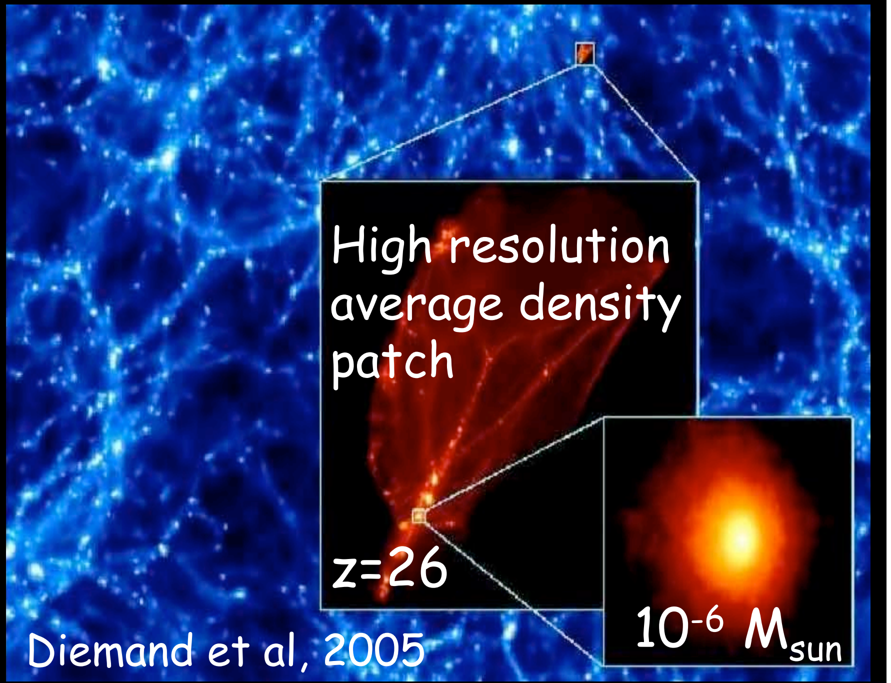
Modeling the structure of dark matter halos from theory of structure formation ($M < 10^5\ M_{sun}$)

Theory: Damping of the primordial power spectrum due to CDM free streaming or acoustic oscillations after kinetic decoupling

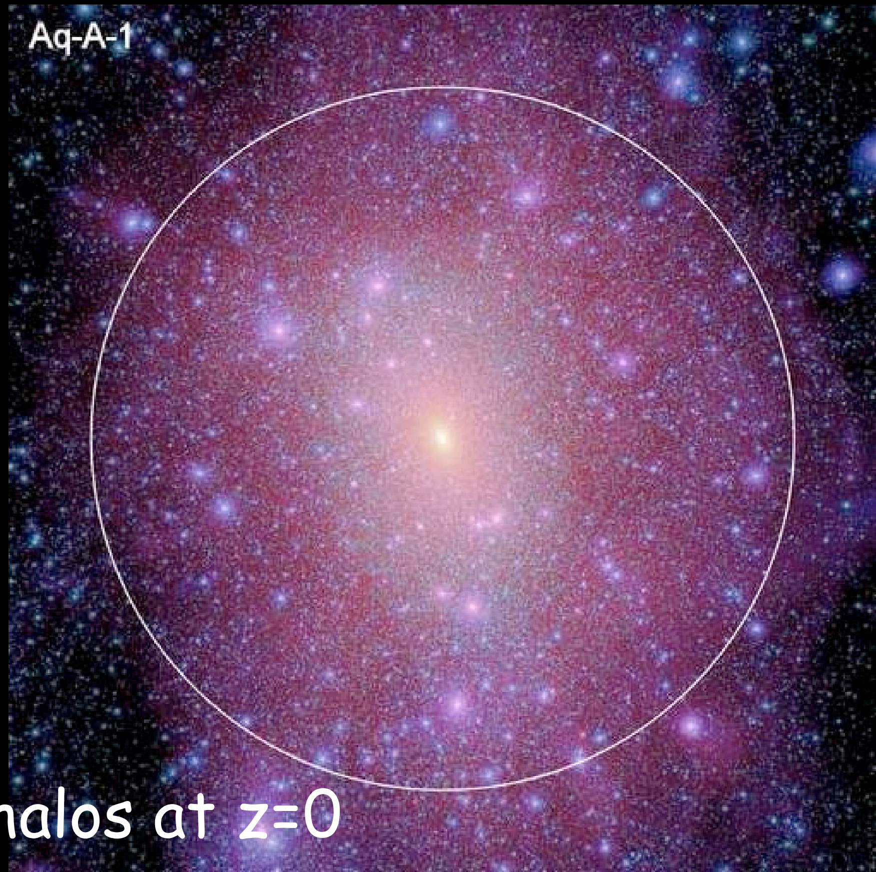


Typical M_{min} for a WIMP = $10^{-6}\ M_{sun}$





Modeling the structure of dark matter halos from N-body simulations ($M > 10^5\ M_{sun}$)



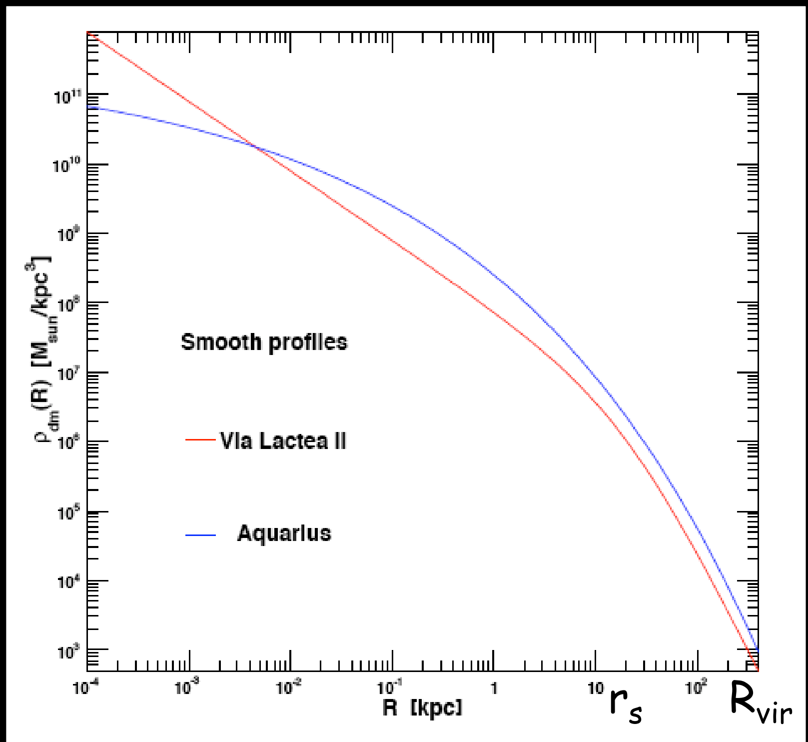
MW-like halos at z=0

Via Lactea 2, Diemand et al

Aquarius, Springel et al

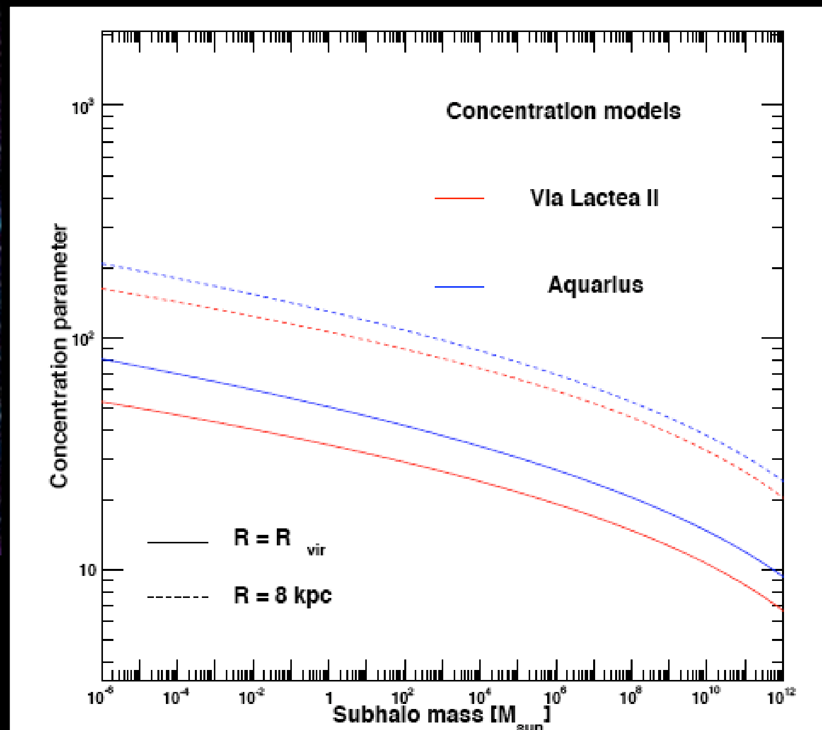
Modeling the structure of dark matter halos from N-body simulations ($M > 10^5\ M_{sun}$)

→ **Halo and subhalo profile shape and concentration**



NFW VS Einasto

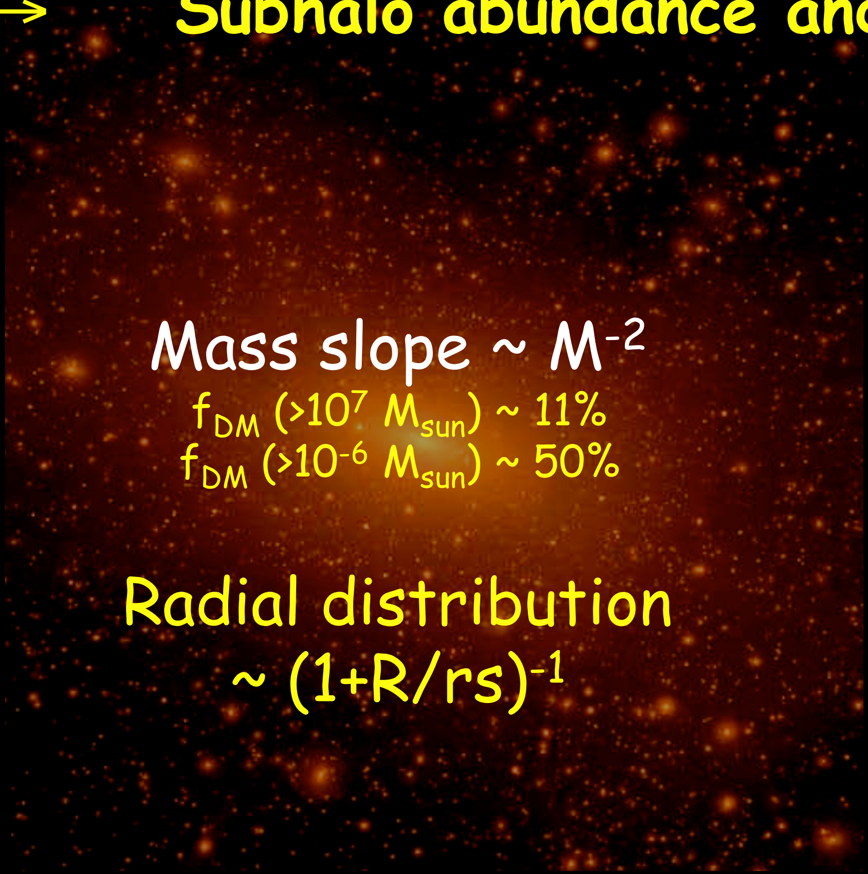
Concentration parameter (R_{vir}/r_s) has radial dependence
higher concentration -> higher flux!

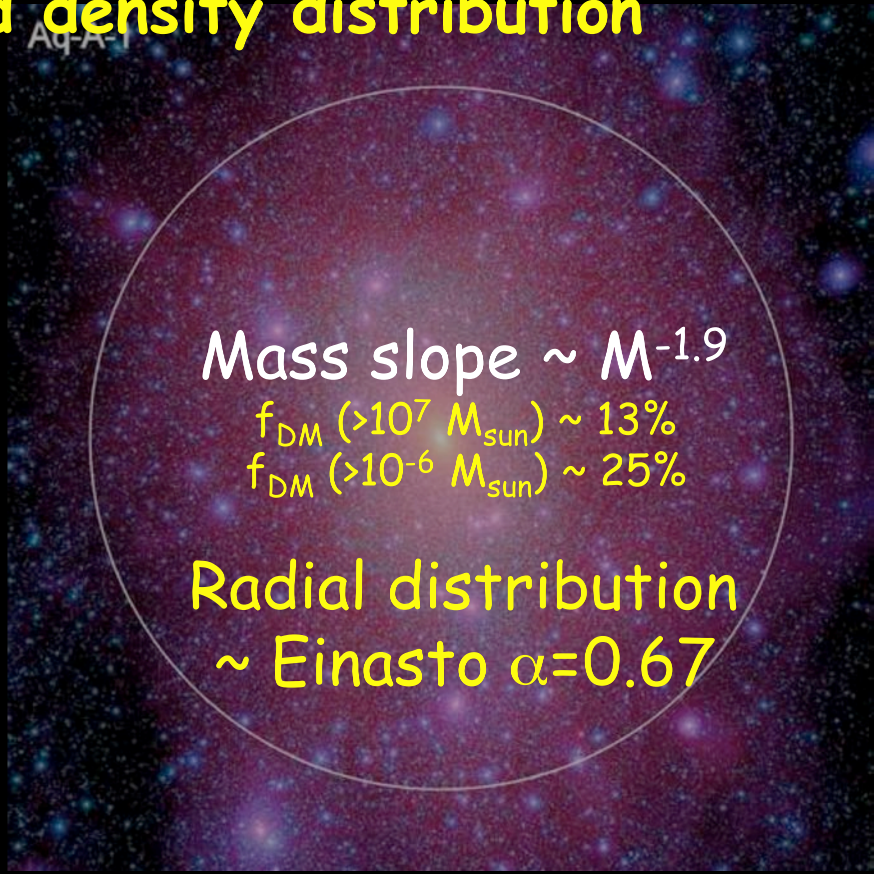


LP, Lavalle, Bertone & Branchini 2009

Modeling the structure of dark matter halos from N-body simulations ($M > 10^5\ M_{sun}$)

→ **Subhalo abundance and density distribution**





Mass slope ~ M^{-2}

f_{DM} ($>10^7\ M_{sun}$) ~ 11%

f_{DM} ($>10^{-6}\ M_{sun}$) ~ 50%

Radial distribution

~ $(1+R/rs)^{-1}$

Mass slope ~ $M^{-1.9}$

f_{DM} ($>10^7\ M_{sun}$) ~ 13%

f_{DM} ($>10^{-6}\ M_{sun}$) ~ 25%

Radial distribution

~ Einasto α=0.67

Roche criterion sets the effect of tidal forces

Indirect detection of γ-rays:

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

$$\Phi_{PP} = \frac{1}{4\pi}\frac{\sigma_{ann}v}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_f \frac{dN_f^\gamma}{dE_\gamma}BR_f$$

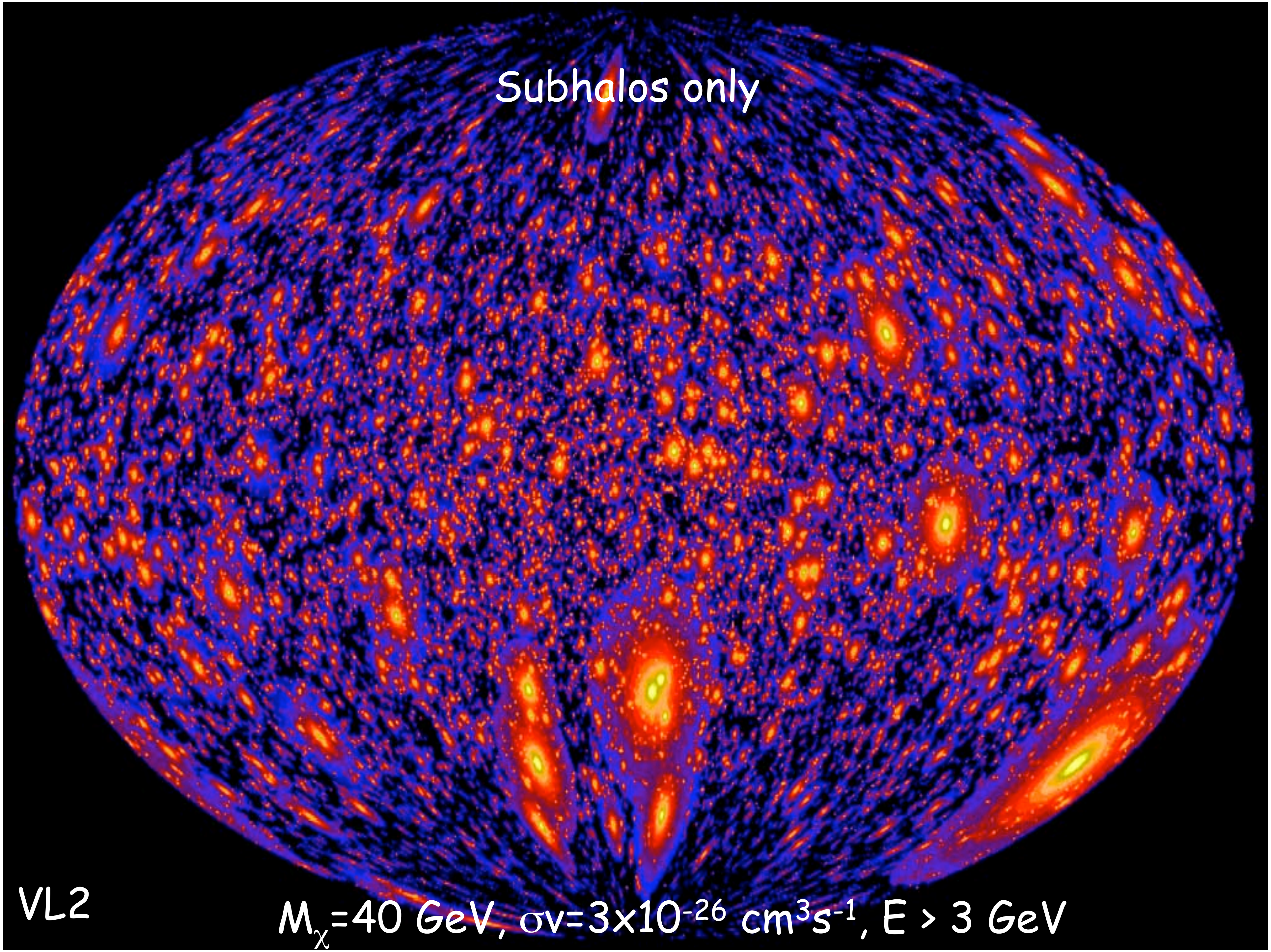
Step 1: **MW smooth**

Single subhalo contribution

$$\Phi_{COSMO}^{halo}(M,R,r) \propto \int_{V.o.s.} dV\left[\frac{\rho_{DM}^2\left(M,c(M,R),r(d,V(\lambda',\theta',\varphi'),\psi)\right)}{d^2}\right]$$

We created Monte Carlo simulations of the brightest and closest subhalos

Each source is characterized by its energy spectrum


Subhalos only
VL2
M_χ=40 GeV, σv=3x10^{-26} cm^{3}s^{-1}, E > 3 GeV

Indirect detection of γ-rays:

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$$\Phi_{PP} = \frac{1}{4\pi}\frac{\sigma_{ann}v}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_f \frac{dN_f^\gamma}{dE_\gamma}BR_f$$

Step 2: **Integrated contribution of all the halos (sources) along the LOS**

$$\Phi_{COSMO}(\psi,\Delta\Omega) \propto \int_M dM \int_c dc \iint_{\Delta\Omega} d\vartheta d\varphi \int_{l.o.s} d\lambda \Big[\rho_{sh}(M, R(R_{sun},\lambda,\psi,\vartheta,\varphi)) \cdot P(c) \cdot \Phi_{COSMO}^{halo}(M, c(M,R), r(\lambda,\lambda',\psi,\vartheta',\varphi'))\Big]$$

We modeled the LOS integral and integrated the signal over all sources

Indirect detection of γ-rays:

$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

Step 3: **Integrated contribution of EXTRAGALACTIC halos and subhalos**

Computing the cosmological γ-ray flux due to DM annihilation in halos...

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{m_\chi^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0(1+z))}{dE}e^{-\tau(z,E_0)}$$

Enhancement due to halo weighted for the halo mass function $\propto \frac{d\log N}{d\log M}\Delta_M^2$

... and subhalos...

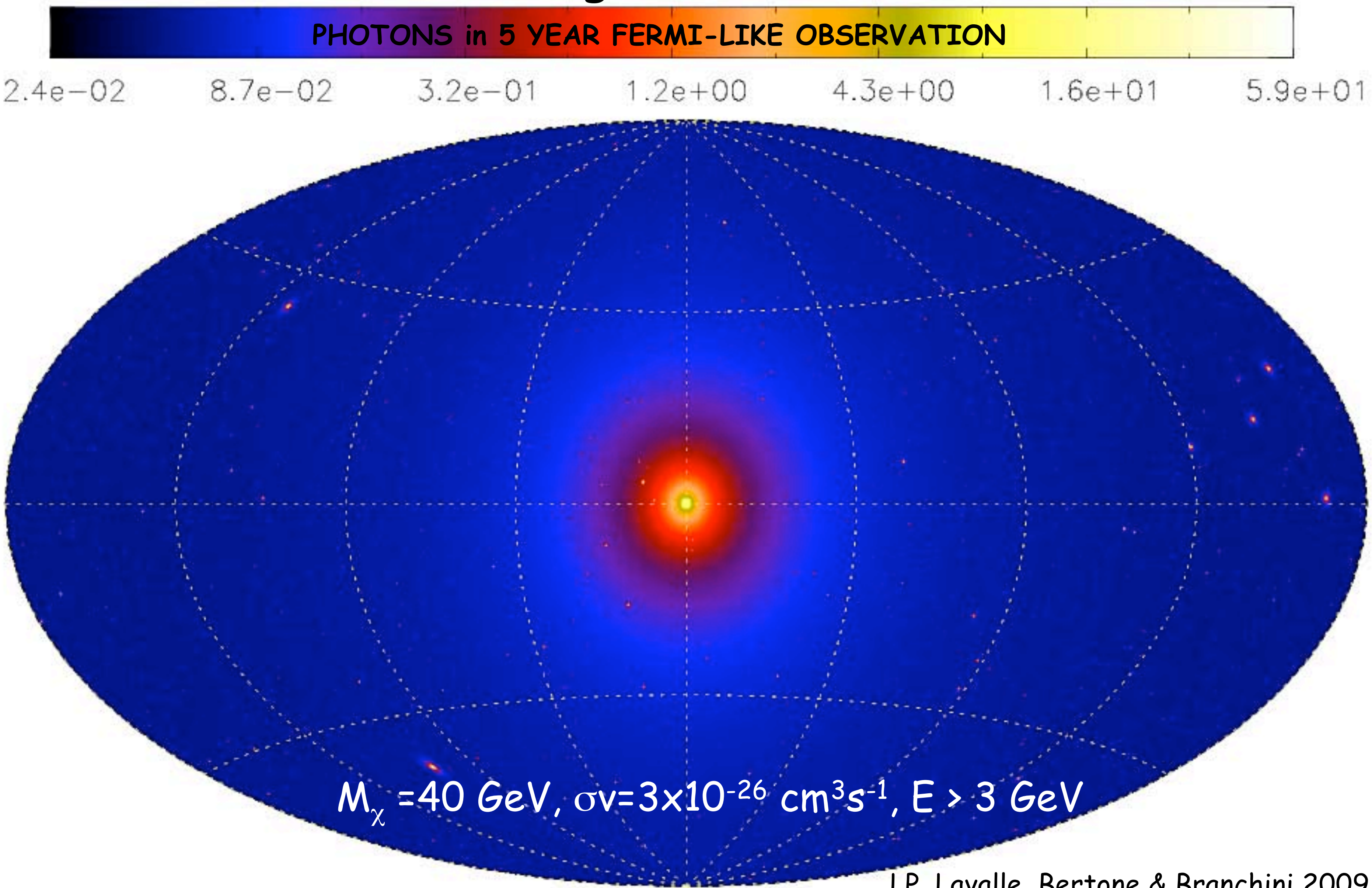
$$M\Delta_M^2 \rightarrow \int_{M_{min}} dM_{sub}\int_0^{R_{vir}(M)} 4\pi R^2 dR\int dc P(c) M_{sub}\rho_{sh}(M_{sub},M,R)c(M_{sub},R)^3\frac{I_2(c)}{I_1^2(c)}$$

Normalized to subhalo mass fraction f(M)

$$\propto \int_{LOS}\rho_{sub}^2(M_{sub})$$

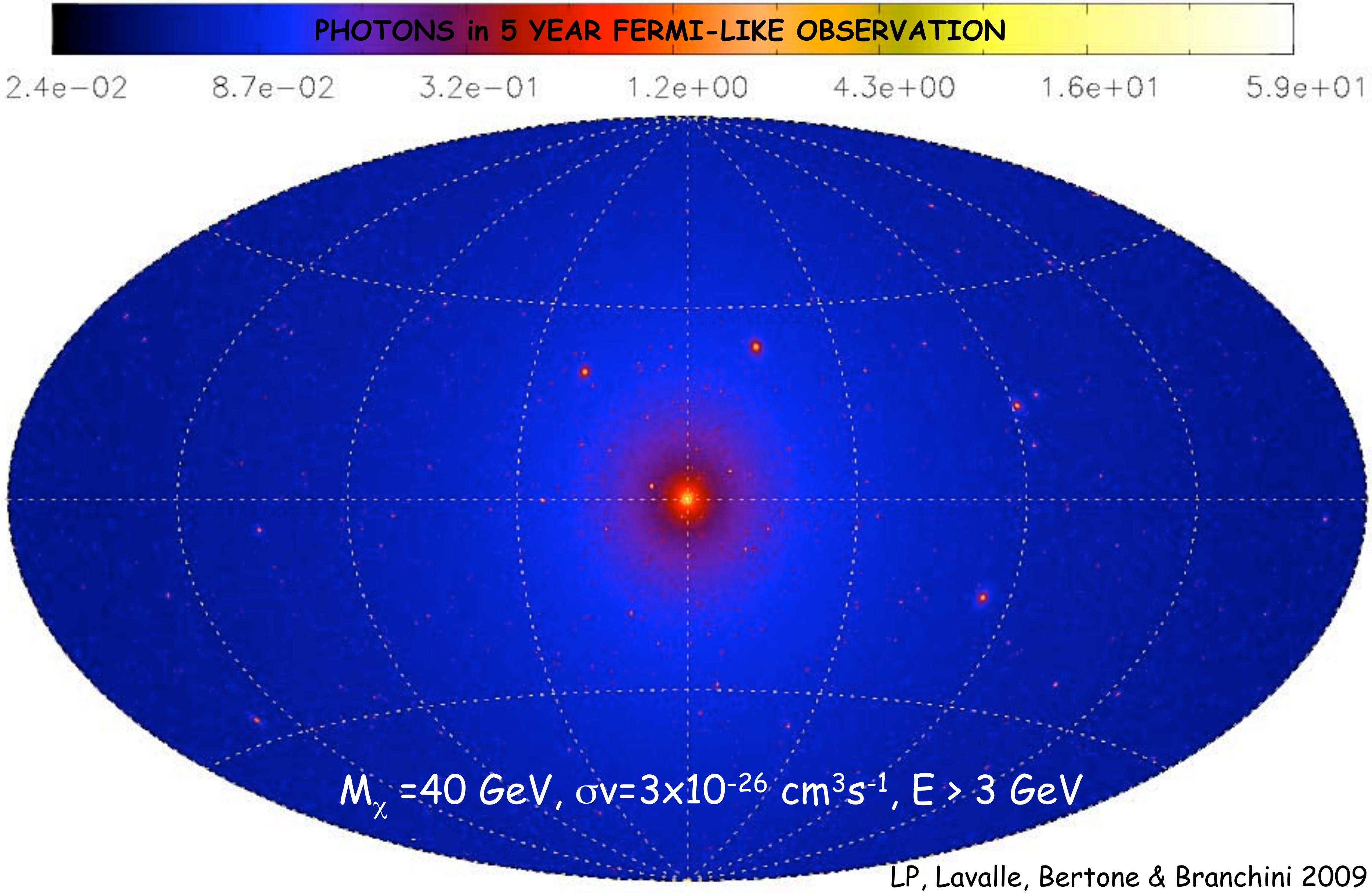
We modeled the LOS integral and integrated the signal over all sources

The γ-ray sky (Aquarius)
Galactic and extragalactic: smooth + subhalos



LP, Lavalle, Bertone & Branchini 2009

The γ-ray sky (Via Lactea 2)
Galactic and extragalactic: smooth + subhalos



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The γ-ray sky
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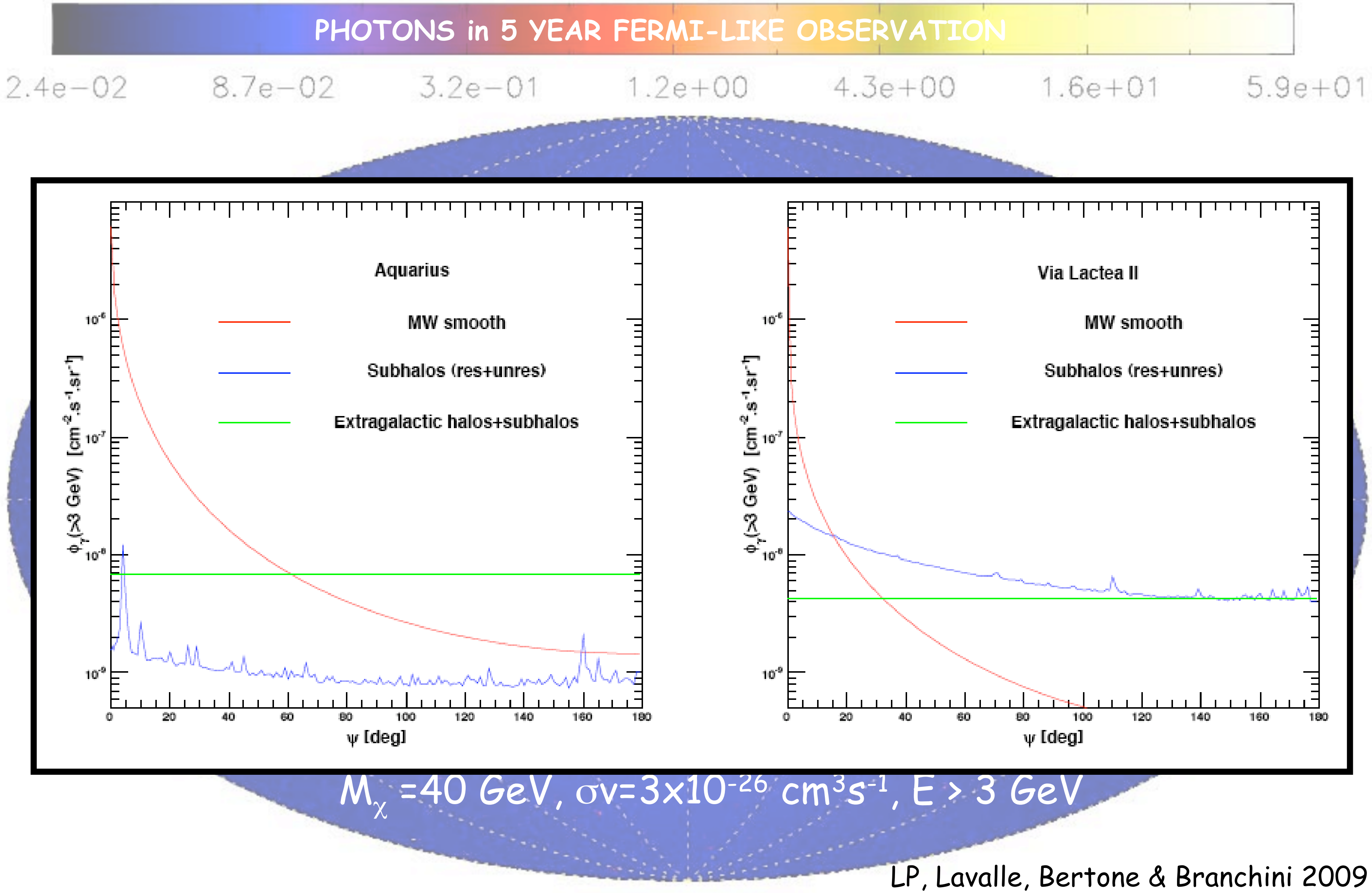
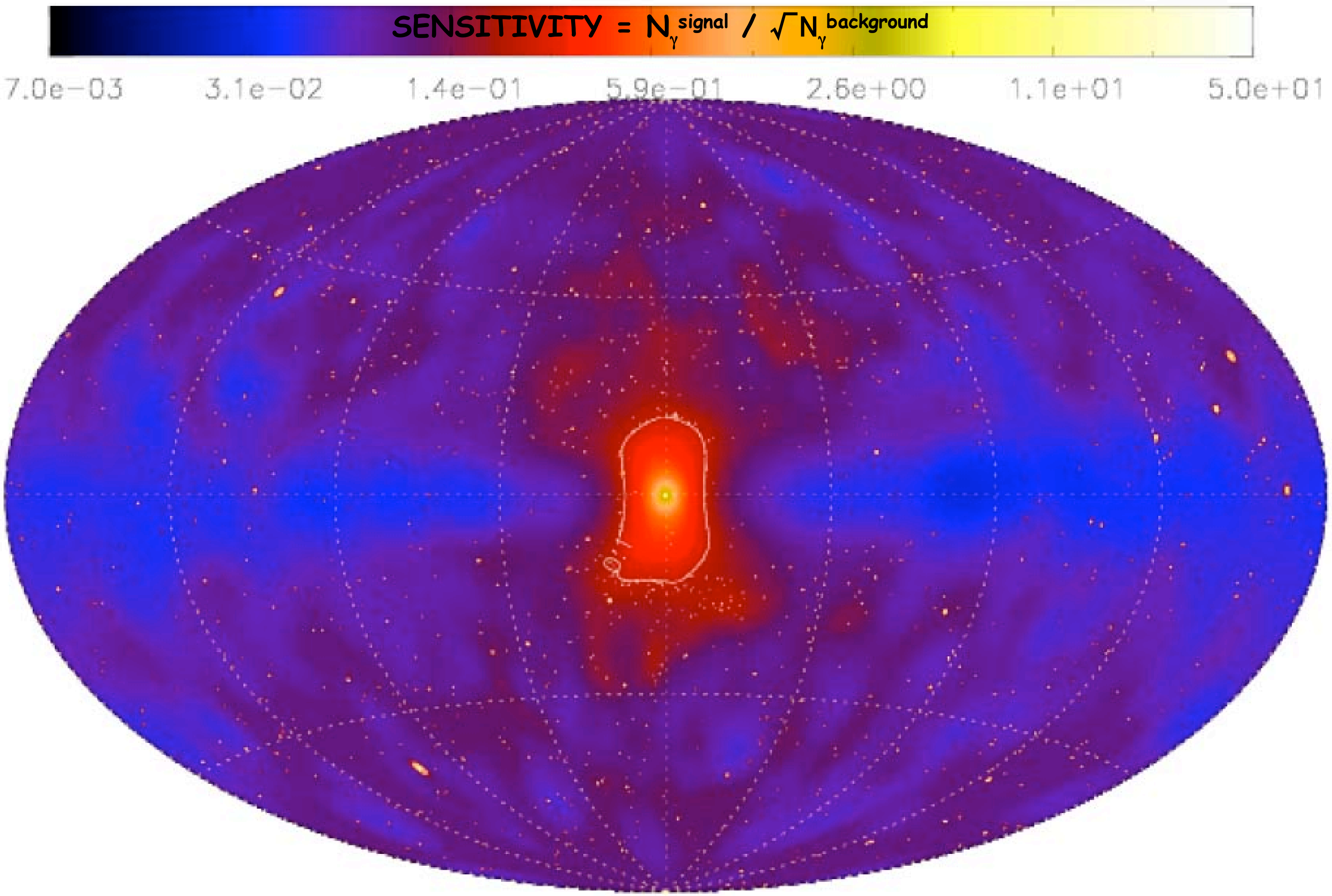


M_χ =40 GeV, $\sigma v=3\times10^{-26}$ cm^3s^{-1}, E > 3 GeV

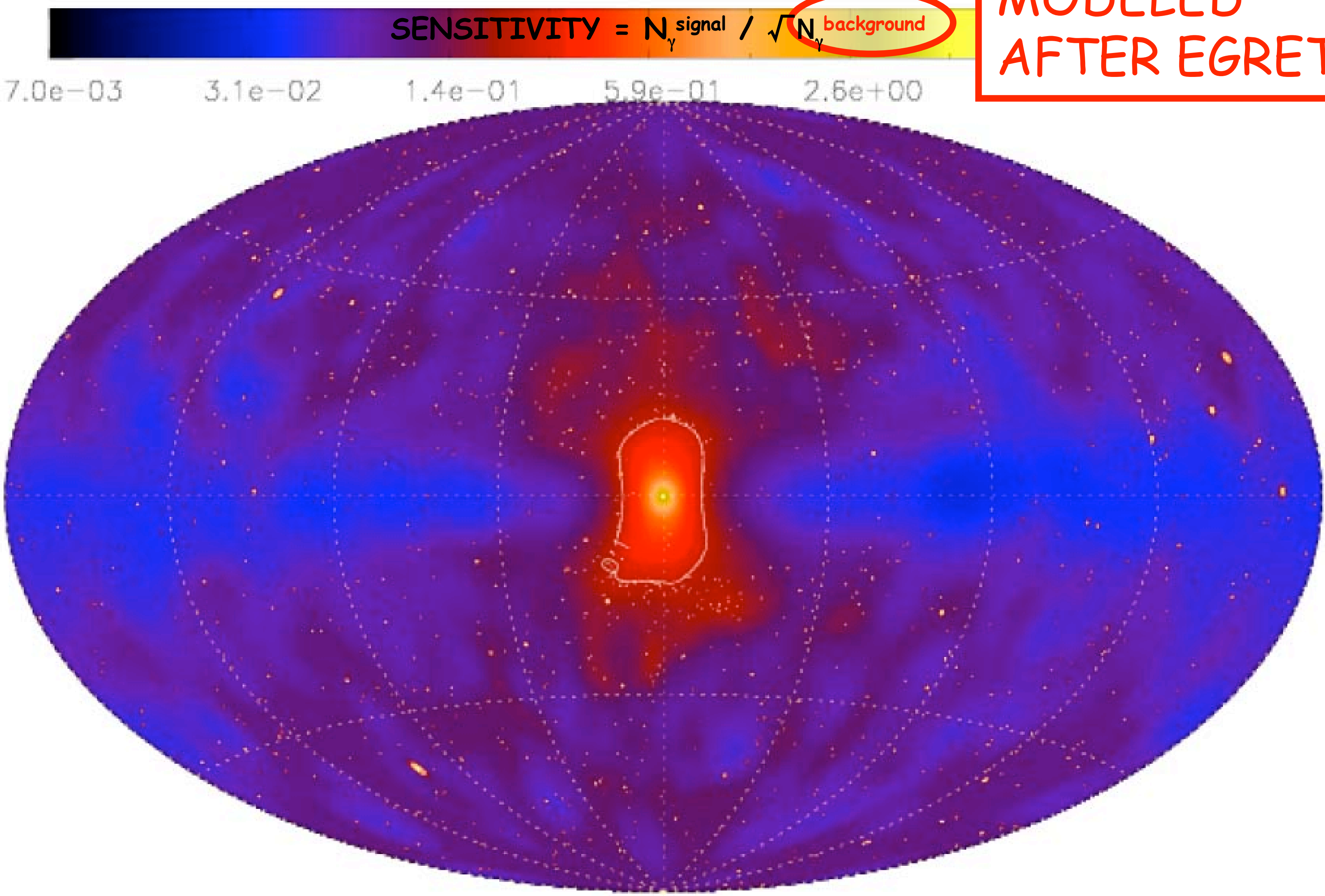
LP, Lavalle, Bertone & Branchini 2009

Is the γ-ray sky from DM annihilation DETECTABLE?



LP, Lavalle, Bertone & Branchini 2009

Is the γ-ray sky from DM annihilation DETECTABLE?



MODELED AFTER EGRET!!

LP, Lavalle, Bertone & Branchini 2009

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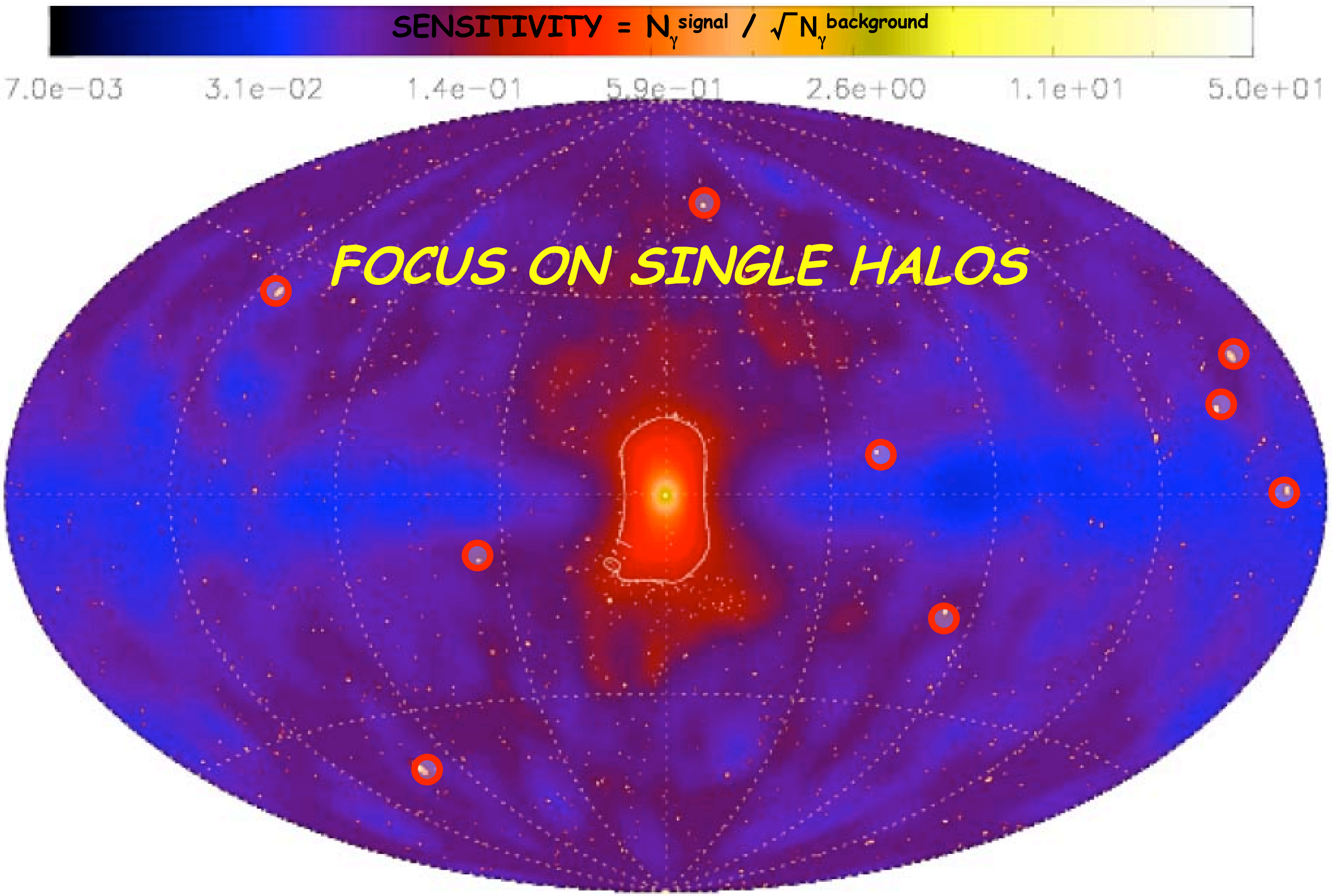

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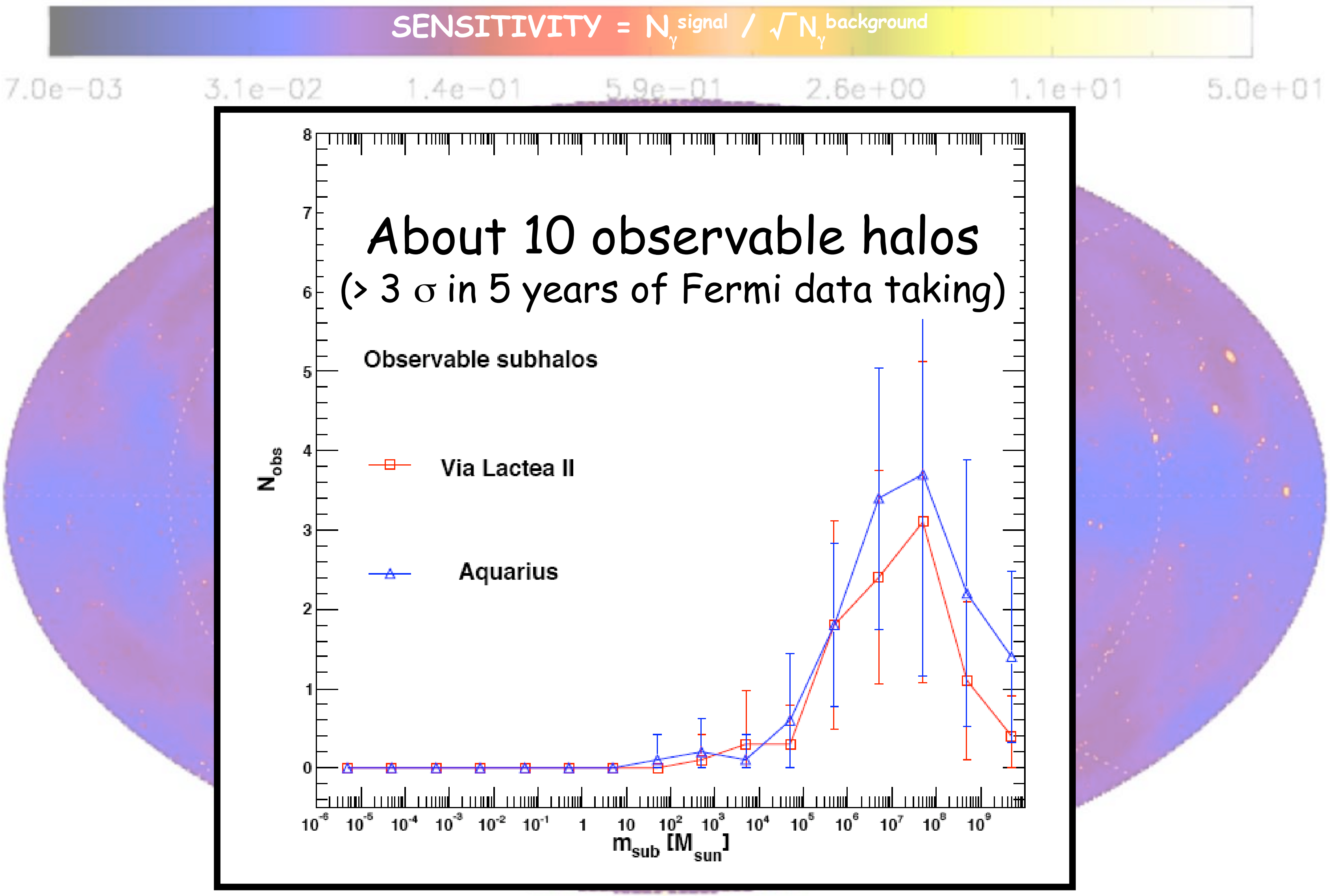

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Next step: Compare with Fermi MAP

first 3 months: 205 sources > 0.3 GeV > 10 σ

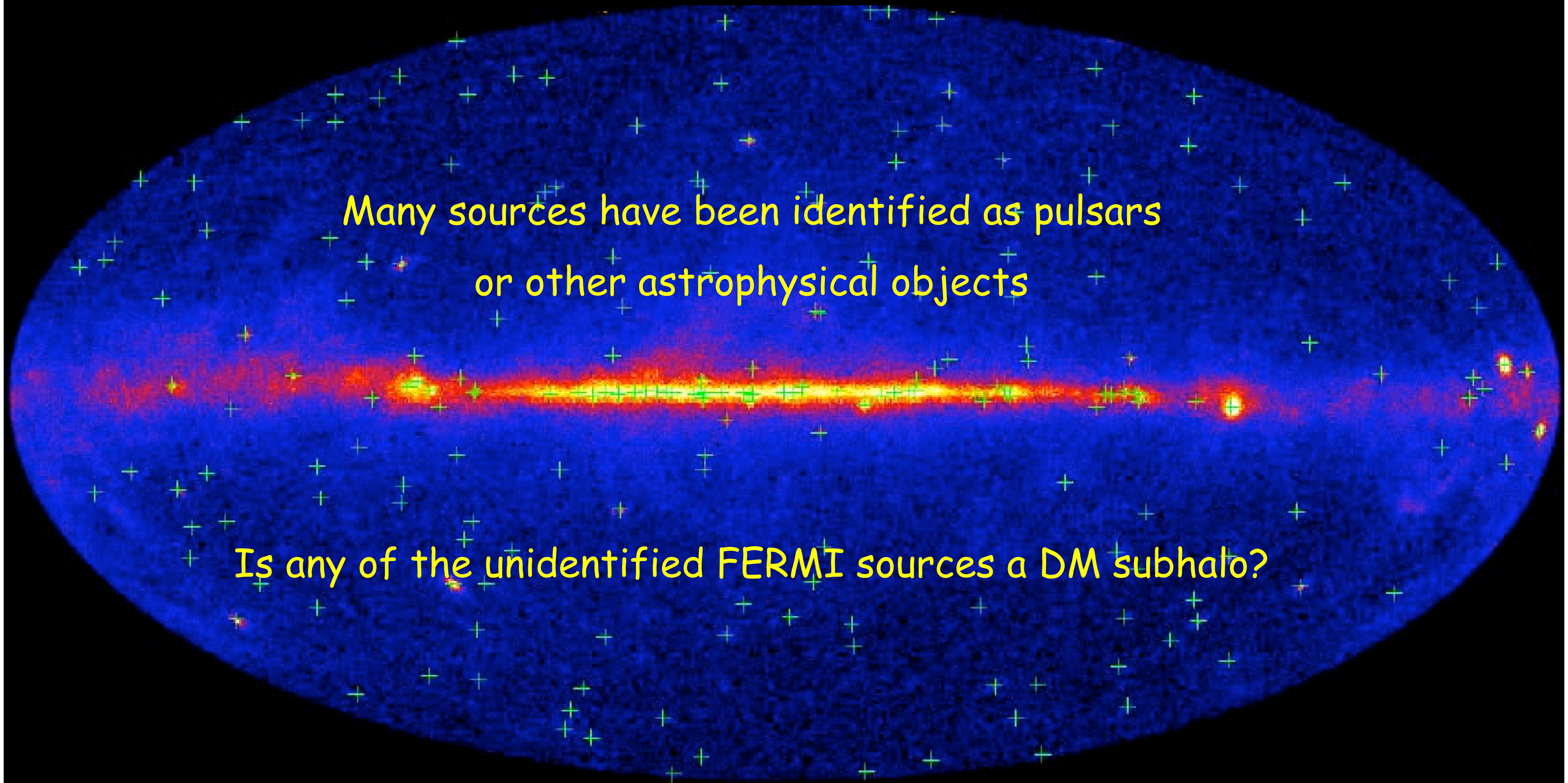
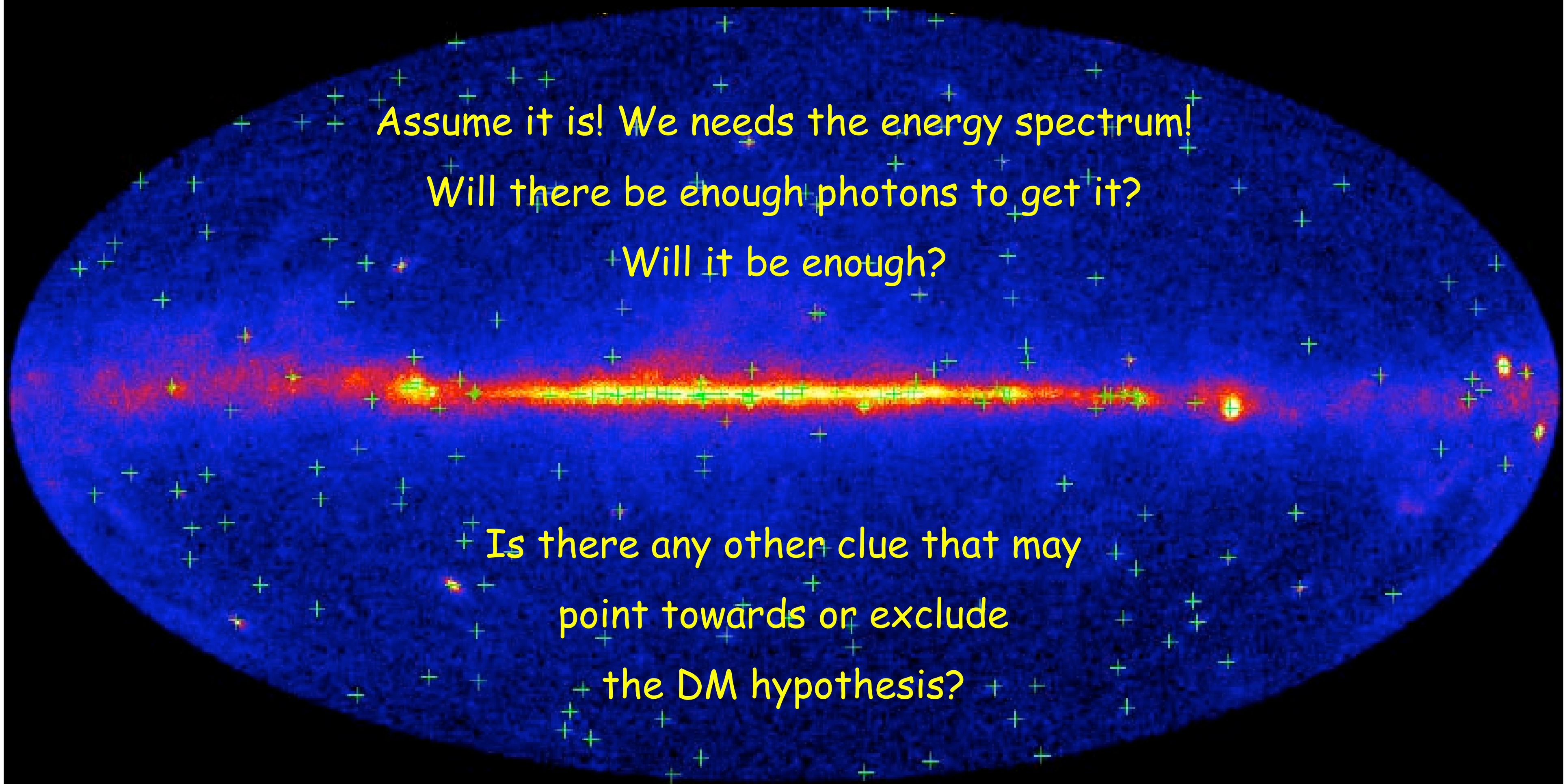


Figure from D. Smith @ TANGO in Paris

Is it so “easy”?


Assume it is! We needs the energy spectrum!
Will there be enough photons to get it?
Will it be enough?
Is there any other clue that may
point towards or exclude
the DM hypothesis?

Indirect detection of dark matter:

The role of substructures

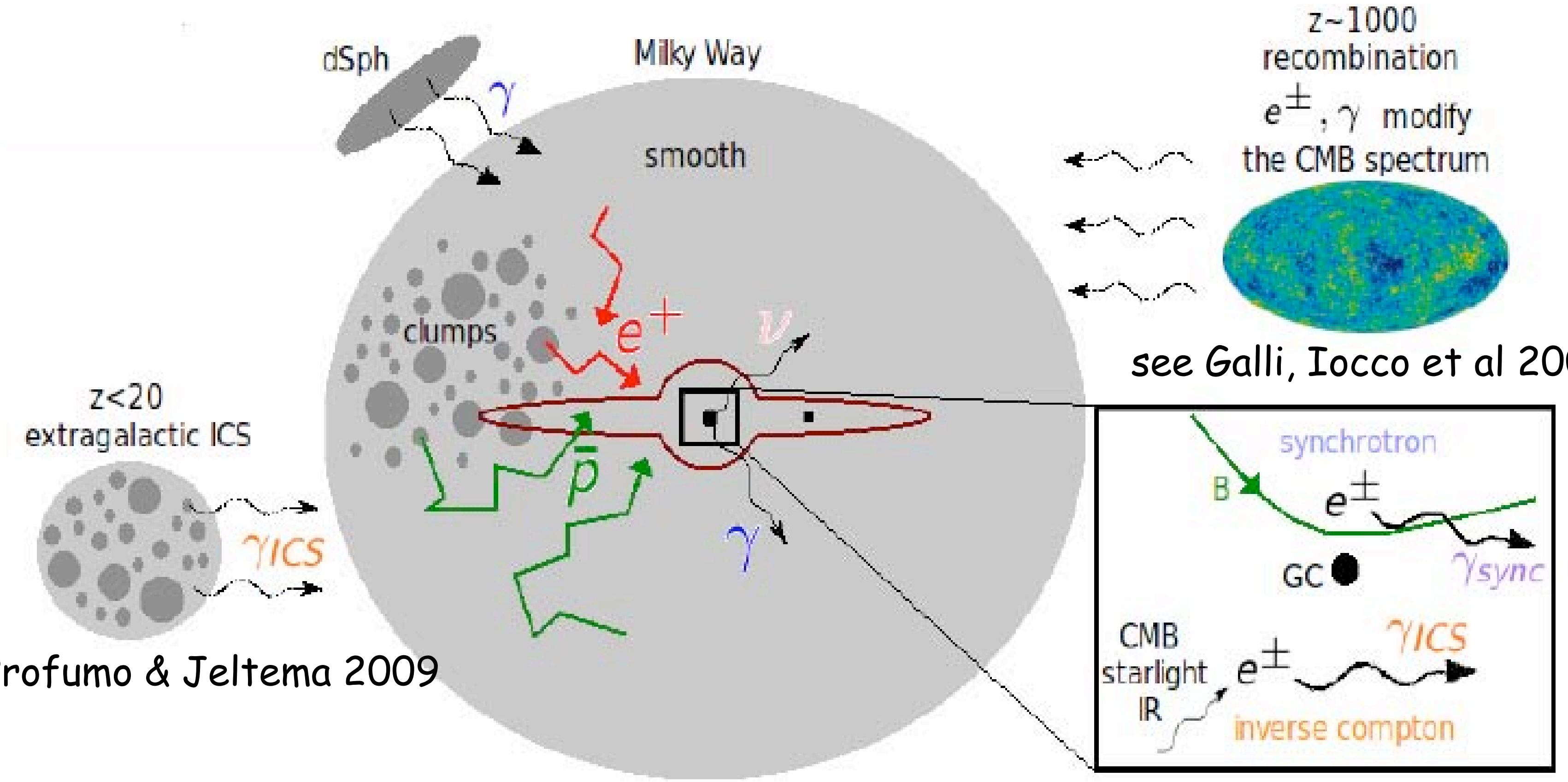
Subhalo population of our galaxy:

-Prospects for detection in γ-rays

-Multi-wavelength analysis

The multiwavelength/multimessenger/multitarget approach

Φ = ParticlePhysics x Cosmology/Astrophysics x Transport

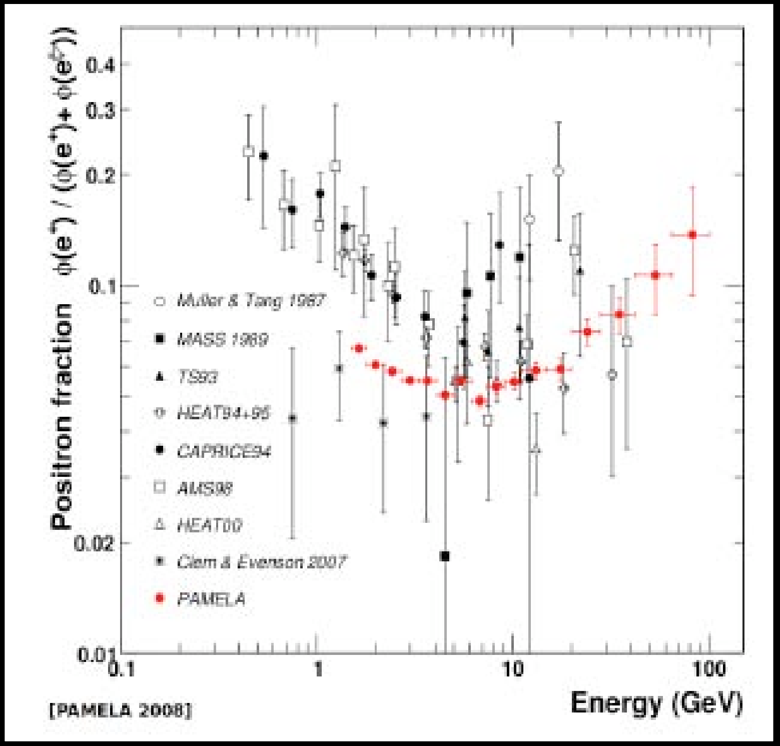


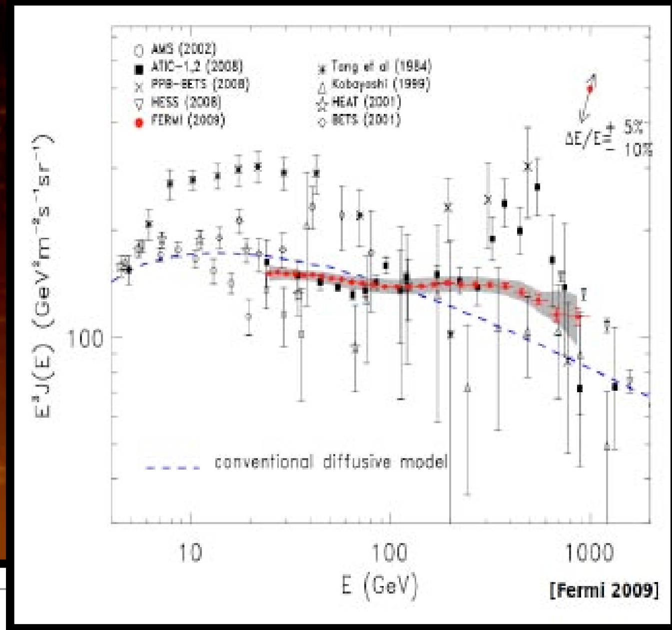
see Galli, Iocco et al 2009

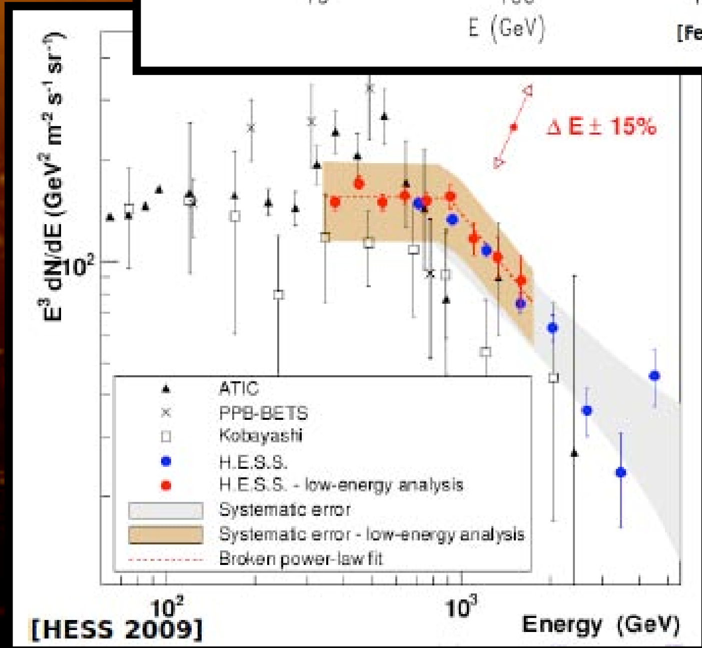
see Profumo & Jeltema 2009

Slide: courtesy of M. Pato

We already had a case of "Possible Indirect Detection"







e^+e^- measurements triggered a wealth of DM model building which is good independently on the nature of the excesses (that is probably astrophysical)

Possible Indirect Detection trigger: cosmic ray data

DARK MATTER HYPOTHESIS: THEORY

Particle physics and astrophysics boost: Sommerfeld effect

THE DATA

γ-ray

cosmic rays

radio

CMB

-Verification
-Constraints
-Expected sensitivities

DARK MATTER HYPOTHESIS: TEST

Multi-multi-multi approach (environment: DM structures)

PHENOMENOLOGY

γ-rays / radio / antimatter

The radio sky
GC, no subhalos

Assume a magnetic field

7.2 mG	$r<0.04$pc
7.2 mG$(r/0.04\text{pc})^{-2}$	$0.04\text{pc}<r<3.38$pc
1 μG	$r>3.38$pc

Compute synchtrotron power à la Bertone 2008

$$n_{e\pm}(\vec{x},E_{e\pm}) = \frac{\sigma v}{2m_{DM}^2}\rho_{DM}^2(\vec{x})\frac{N_{e\pm}(>E_{e\pm})}{b_{syn}(\vec{x},E_{e\pm})}$$

$$\nu\frac{dW_{syn}}{d\nu} = \frac{\sigma v}{2m_{DM}^2}\int_{\Delta\Omega} d\Omega\int_{los} ds\rho_{DM}^2(\vec{x})E(\vec{x},\nu)\frac{N_{e\pm}(>E_{e\pm})}{2}$$

The antimatter sky

Compute the number density à la Delahaye 2008

$$n_{CR}(t,\vec{x},E_{CR}) \equiv \frac{d^2N_{CR}}{dVdE_{CR}}$$

electrons and positrons

losses: ICS + synchrotron

$$\frac{\partial n_{e+}}{\partial t} - K_{e+}(E_{e+})\nabla^2 n_{e+} - \frac{\partial}{\partial E_{e+}}\left(b(E_{e+})n_{e+}\right) = Q_{e+}(\vec{x},E_{e+})$$

diffusion (cilindric) source term

protons and antiprotons

destruction in the disk

$$\frac{\partial n_{\bar{p}}}{\partial t} - K_{\bar{p}}(T_{\bar{p}})\nabla^2 n_{\bar{p}} - \frac{\partial}{\partial z}\left(\mathrm{sgn}(z)V_c n_{\bar{p}}\right) = Q_{\bar{p}}(\vec{x},T_{\bar{p}}) - 2h\delta_D(z)\Gamma_{ann}^{p\bar{p}}(T_{\bar{p}})n_{\bar{p}}$$

galactic winds

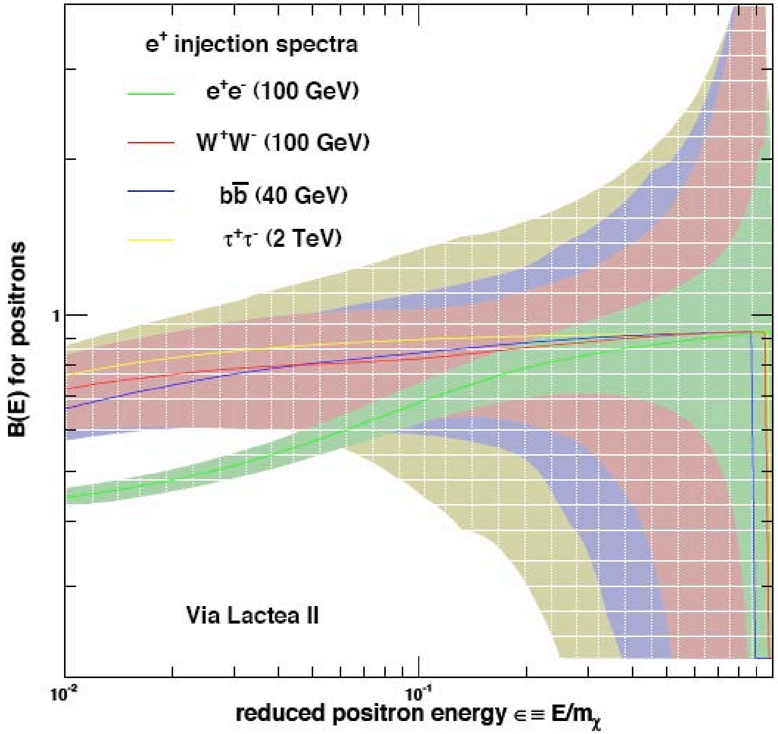
Compute fluxes and boosts à la Lavalle 2008

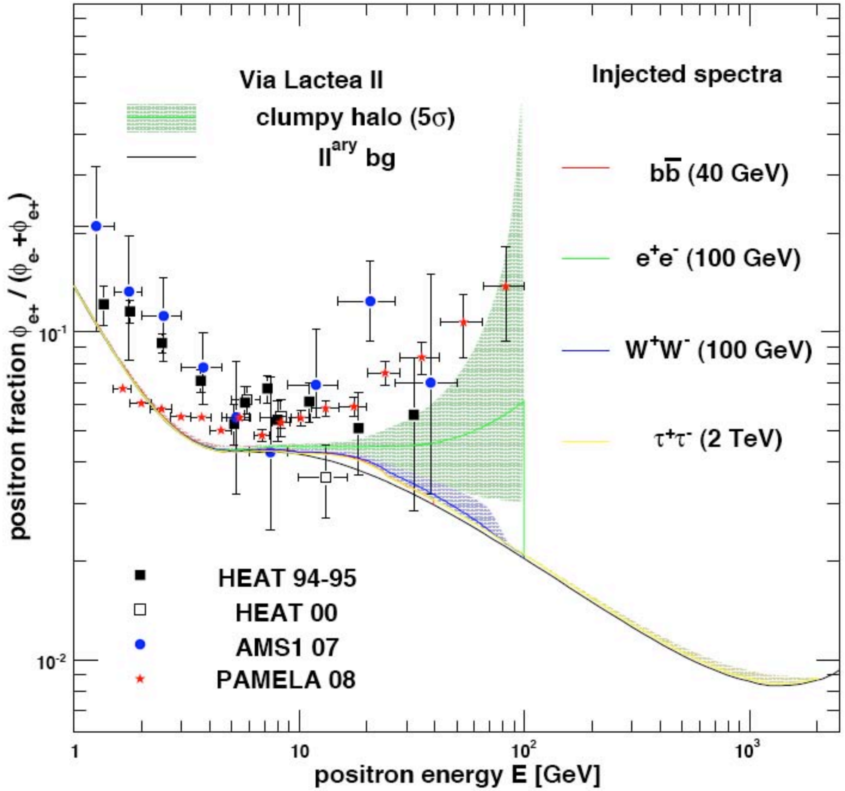
$$\phi_{CR,sm}(E_{CR}) \propto <\sigma v> \int_{E_{CR}}^{\infty} dE \frac{dN_{CR}}{dE} \int_{diff.zone} d^3\vec{x} \left(\frac{\rho_{sm}(\vec{x})}{\rho_{sun}}\right)^2 G_{sun}^{CR}(\vec{x},\lambda_D)$$

↕

$$<\phi_{CR,cl}>(E_{CR}) \propto <\sigma v> N_{cl} \int_{E_{CR}}^{\infty} dE \frac{dN_{CR}}{dE} \int_{diff.zone} d^3\vec{x} <\xi>_M (R) \frac{dP_V}{dV}(R) G_{sun}^{CR}(\vec{x},\lambda_D) = N_{tot}^{sub} <\phi_{sub}>$$

The antimatter sky





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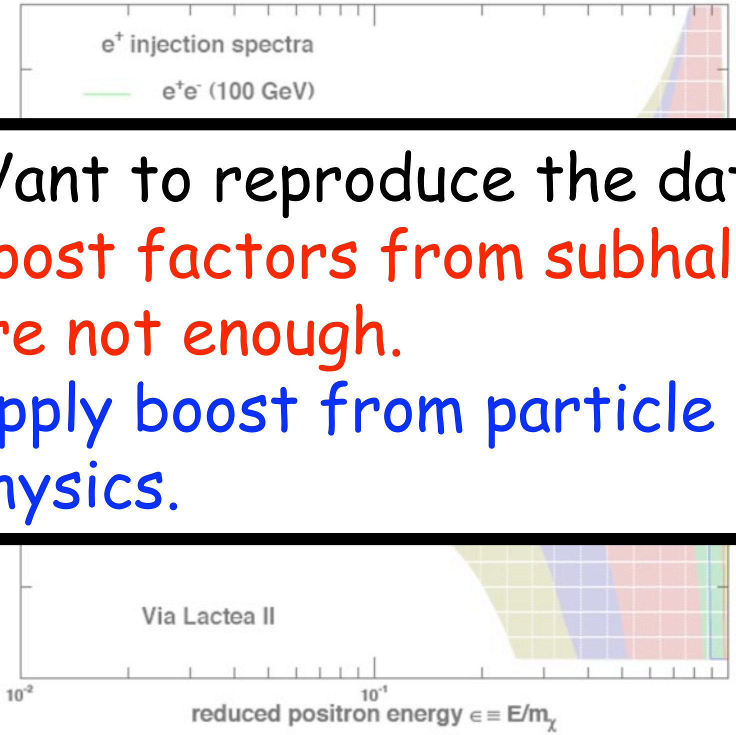
LP, Lavalle, Bertone & Branchini 2009

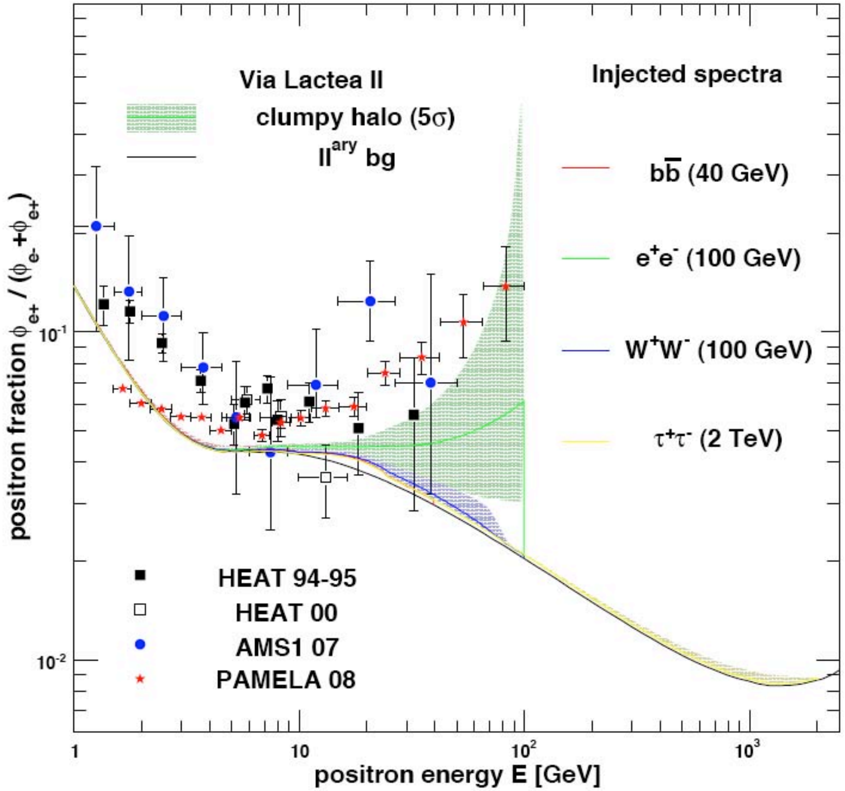
The antimatter sky



Want to reproduce the data?

Boost factors from subhalos are not enough.

Apply boost from particle physics.



Compute fluxes and boosts à la Lavalle 2008

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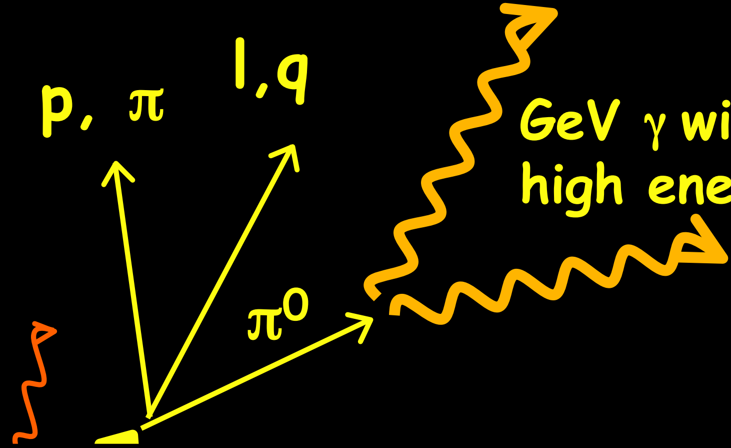
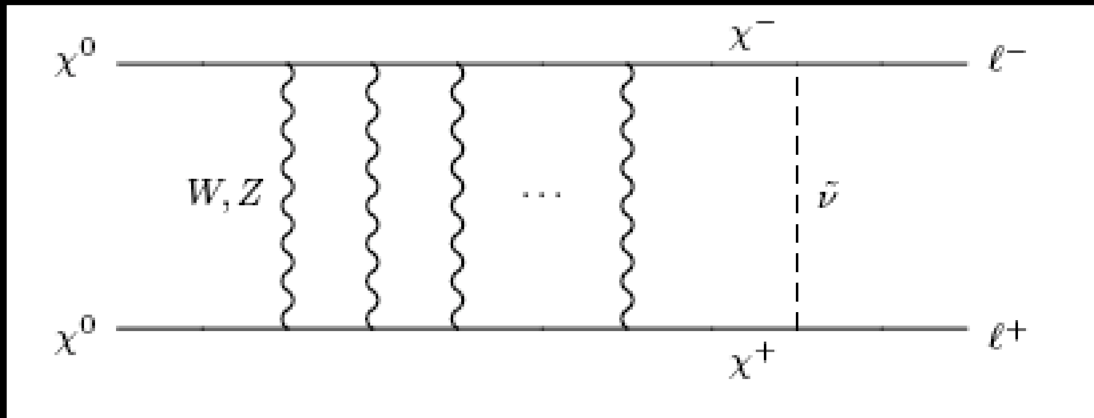
LP, Lavalle, Bertone & Branchini 2009

Φ_{pp} : MODEL THE BOOST FACTOR FROM SOMMERFELD EFFECT





WIMP DM
GeV to TeV

keV γ
from ICS and S

It mimics an attractive force which arises when the two DM particles get close and are slow. Annihilation proceeds through the exchange of massive vector bosons

$$\sigma_{ann}v = S(\sigma_{ann}v)_{thermal}$$

Particle Physics BF: Sommerfeld enhancement

Sommerfeld effect produces a local enhancement of the annihilation cross-section which depends on the DM velocity and mass, and does not touch the thermal value

$$\frac{1}{m_{DM}}\frac{d^2\psi(r)}{dr^2} = -m_{DM}\beta^2\psi(r) - \frac{\alpha}{r}e^{-m_V r}$$

β dependence

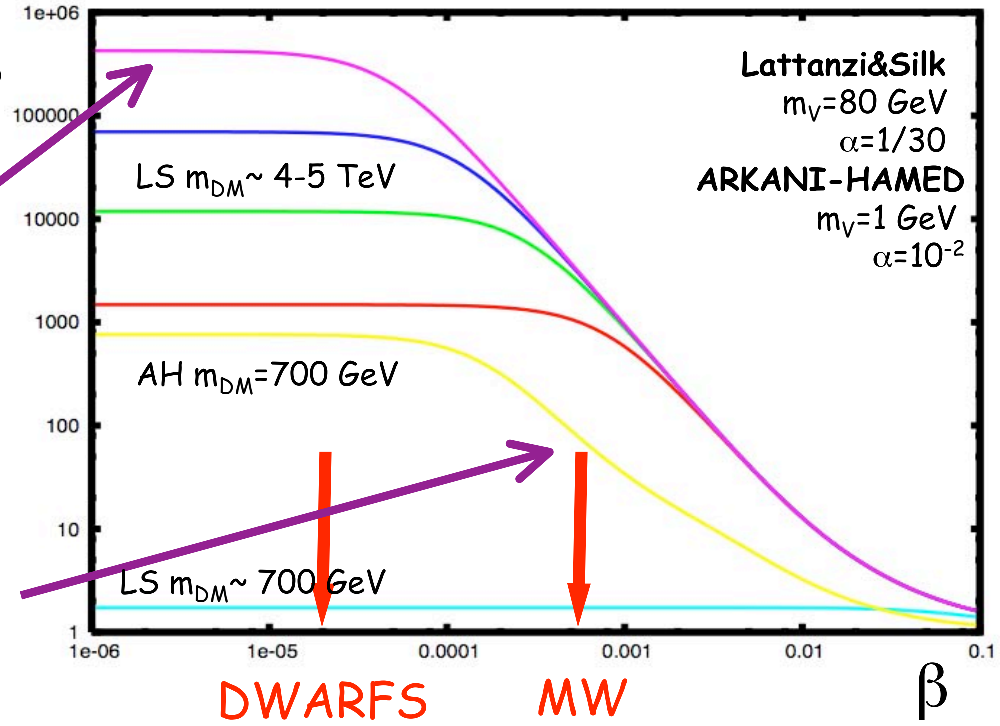
enhancement S

$$\beta << \sqrt{\frac{\alpha m_V}{m_{DM}}} \rightarrow S = S_{max}$$

saturation

$$\sqrt{\frac{\alpha m_V}{m_{DM}}} < \beta < \alpha \rightarrow S = \frac{\pi\alpha}{\beta}(1 - e^{-\pi\alpha/\beta})^{-1}$$

1/v behaviour



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$$\frac{1}{m_{DM}}\frac{d^2\psi(r)}{dr^2} = -m_{DM}\beta^2\psi(r) - \frac{\alpha}{r}e^{-m_V r}$$

$\beta << \sqrt{\frac{\alpha ...}{m ...}}$

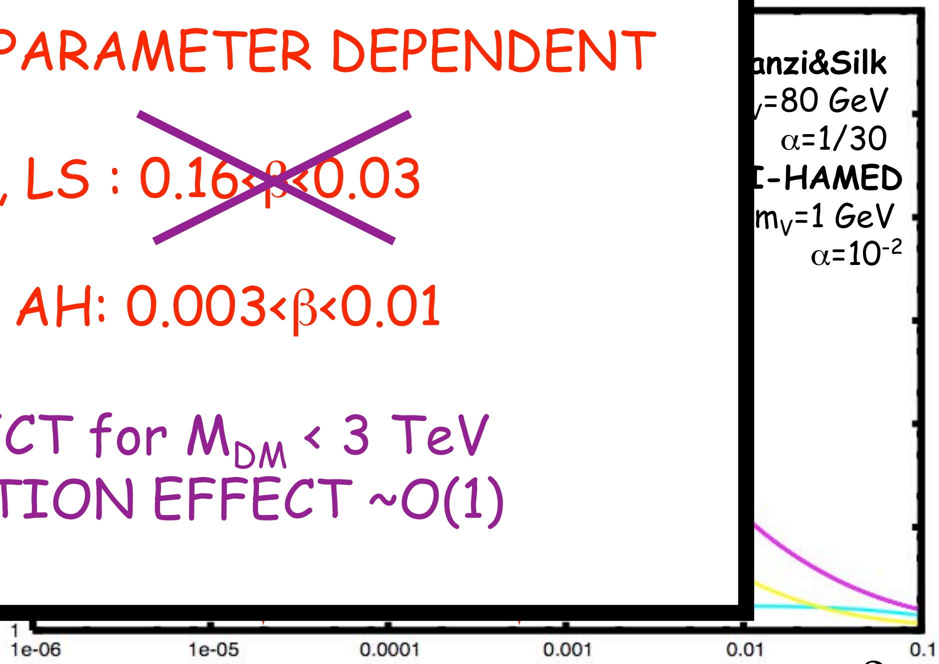
$\sqrt{\frac{\alpha m_V}{m_{DM}}} < \beta$

NOTE: 1/v EFFECT IS PARAMETER DEPENDENT

m_{DM}=100 GeV , LS : 0.16<β<0.03

AH: 0.003<β<0.01

LS: NO 1/v EFFECT for M_{DM} < 3 TeV
SMALL SATURATION EFFECT ~O(1)

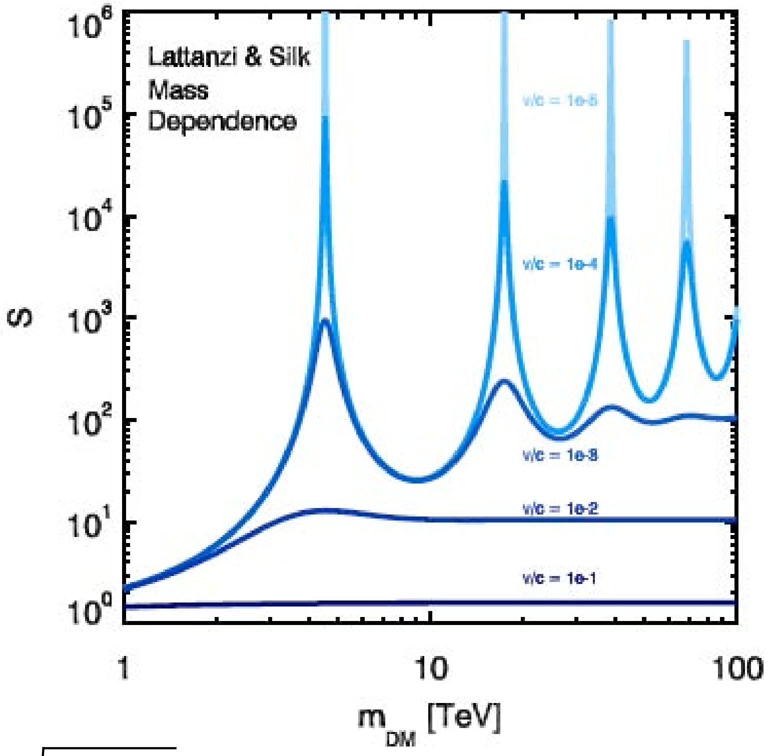


DWARFS MW β

Particle Physics BF: Sommerfeld enhancement

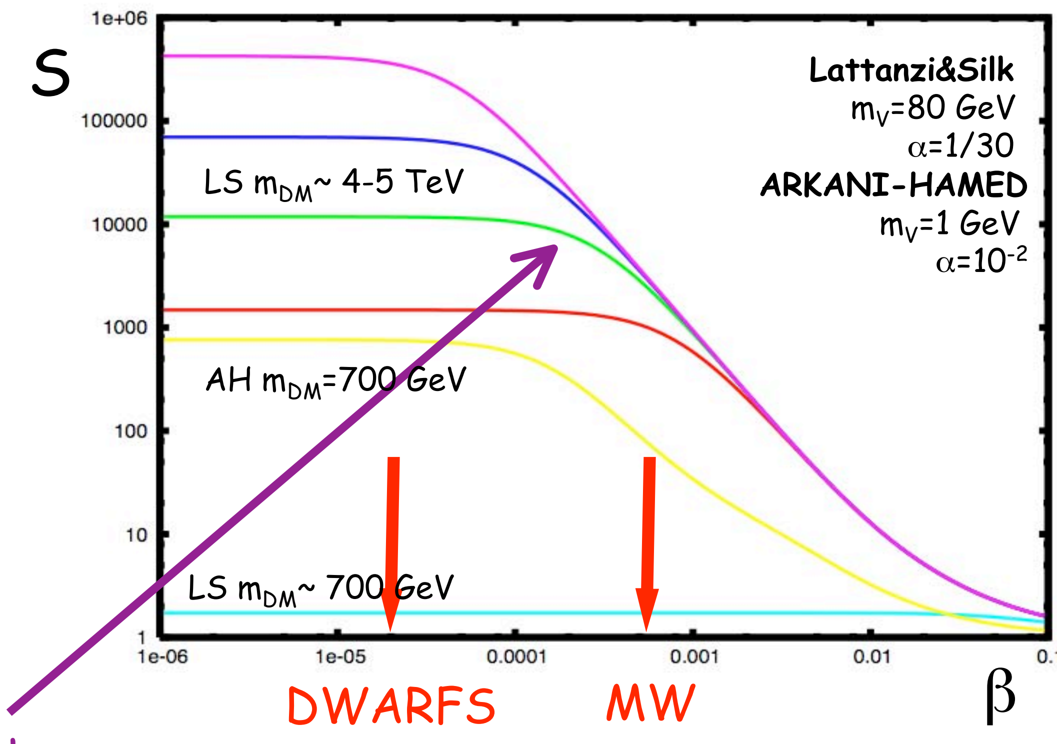
Sommerfeld effect produces a local enhancement of the annihilation cross-section which depends on the DM velocity and mass, and does not touch the thermal value

mass dependence (resonance)



$$\sqrt{\frac{\alpha m_{DM}}{m_V}} = (2n+1)\frac{\pi}{2} \rightarrow S = \frac{\alpha m_V}{m_{DM}} \frac{1}{\beta^2}$$

β dependence



1/v² effect

Particle Physics BF and astrophysics BF:
Sommerfeld enhancement and subhalos

Dwarf galaxies and galactic subhalos have low velocity dispersions, hence the Sommerfeld enhancement should be convolved with the sub-subhalo contribution

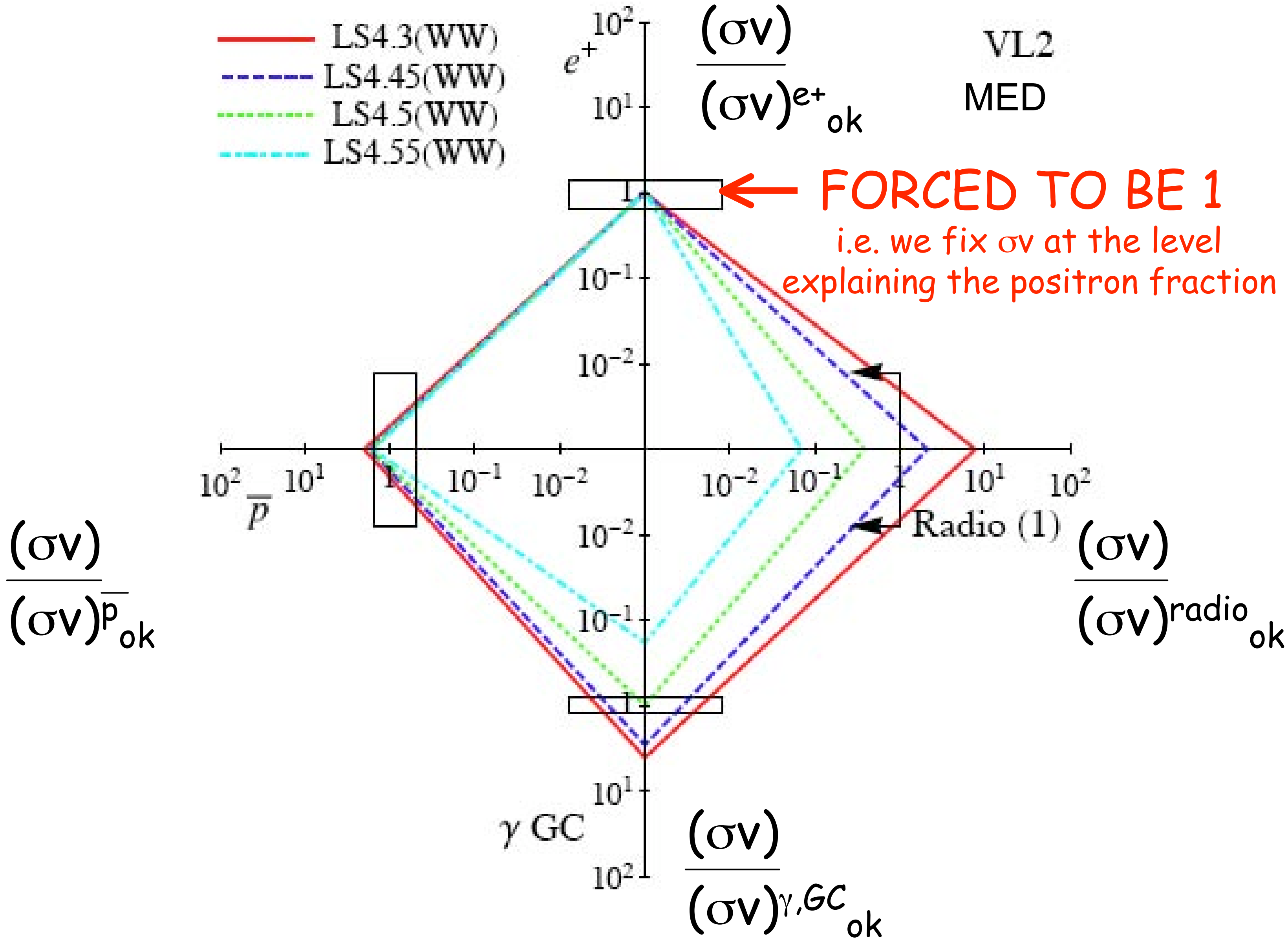
$$\sigma_{ann} v = (\sigma_{ann} v)_{thermal} S(\beta(r))$$

$$\Phi = T(E,d) \frac{(\sigma_{ann} v)_{thermal}}{2m_\chi^2} \int_{E_0}^{m_\chi} \sum_f \frac{dN_f^\gamma}{dE_\gamma} BR_f \int_{l.o.s} d\lambda S(\beta(M,r)) \rho_{DM}^2 \left(M, c(M,r), R\right)$$

This holds for all annihilation products

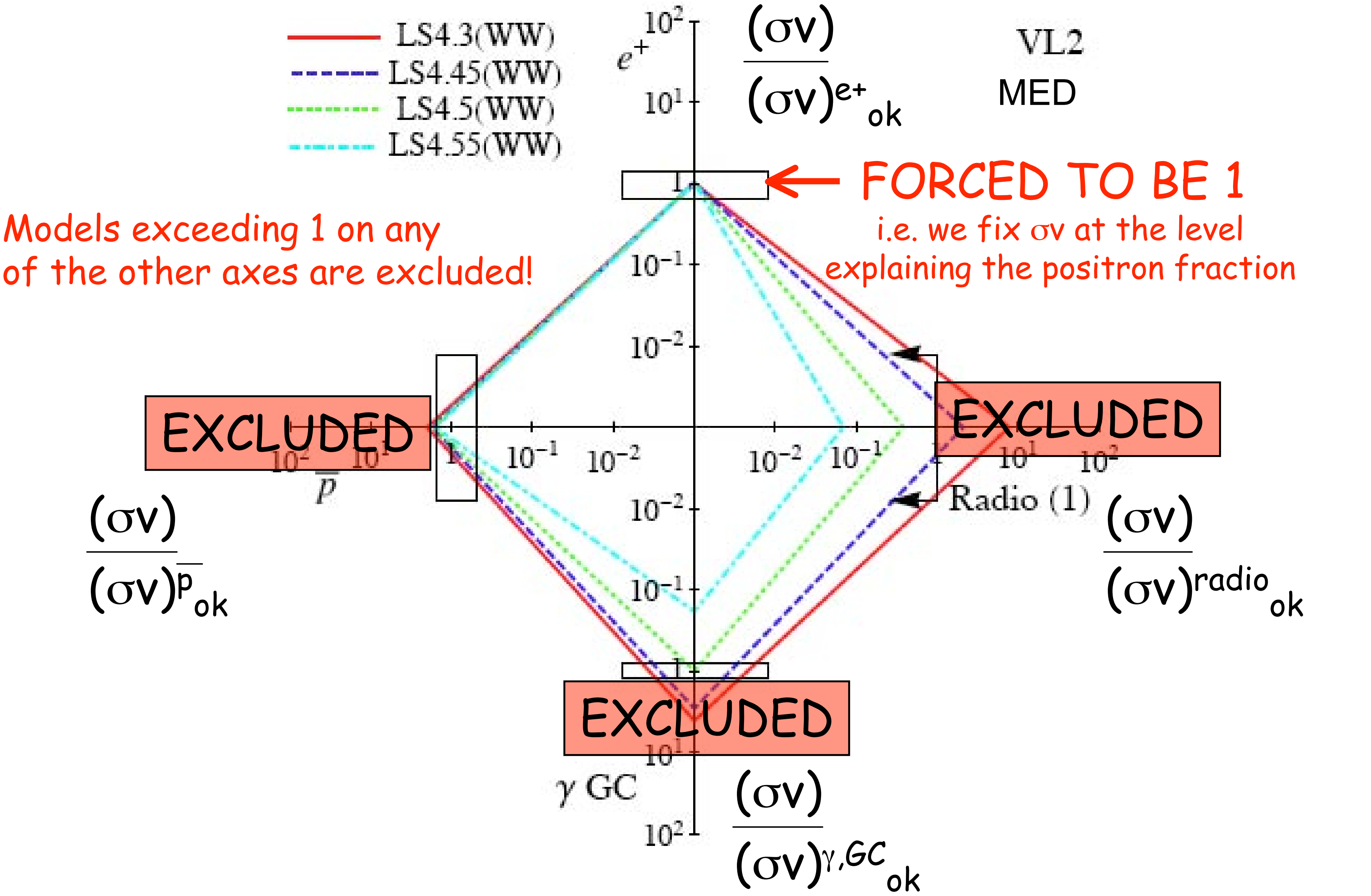
We can perform a multi-wavelength analysis
to constrain models
APPLYING BOOSTS TO BOTH Φ_{PP} AND Φ_{COSMO}

Compact way of plotting multi-wavelength constraints APPLIED TO POSITRON FRACTION



Pato, LP, Bertone 2009

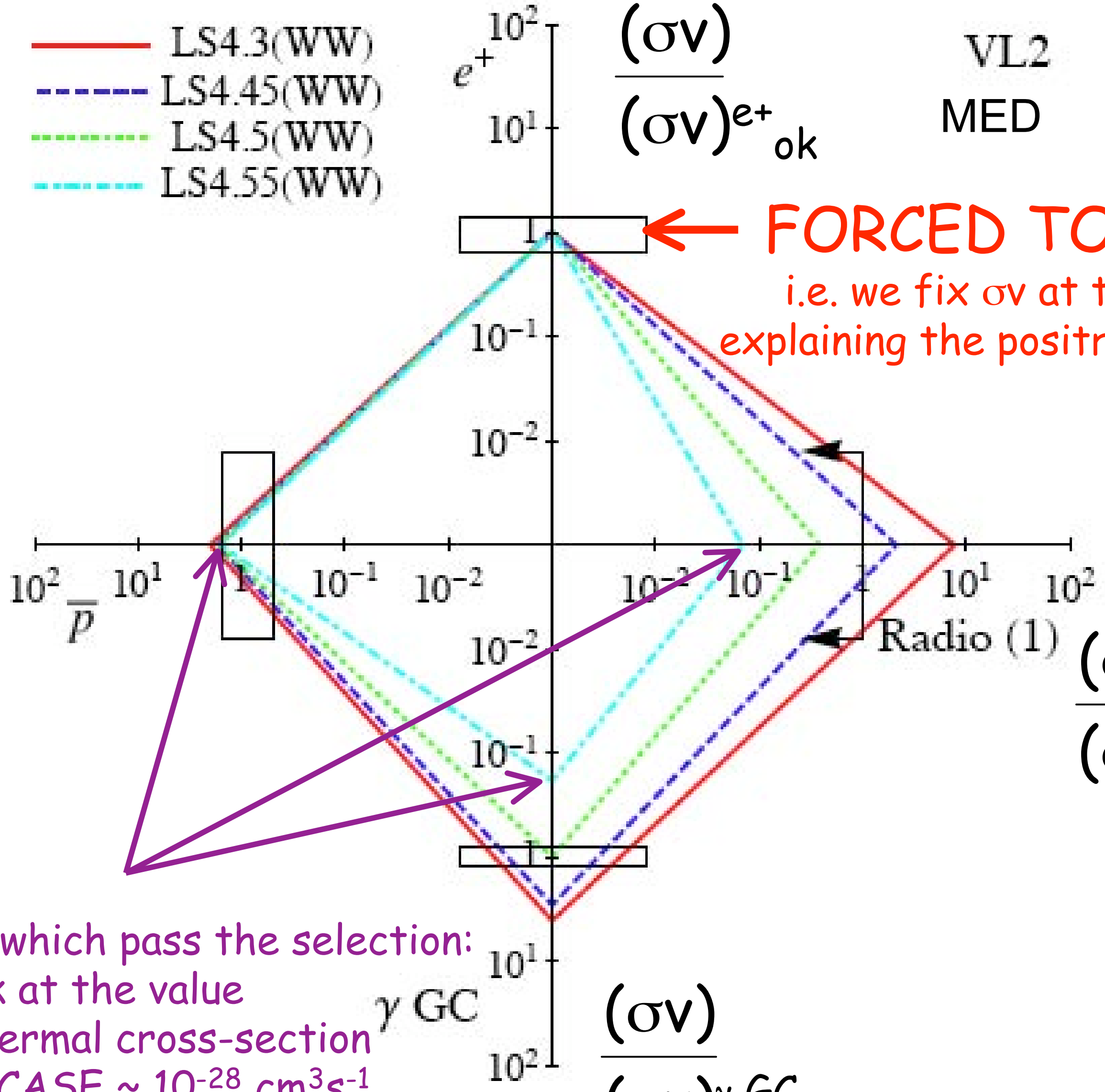
Compact way of plotting multi-wavelength constraints APPLIED TO POSITRON FRACTION



Pato, LP, Bertone 2009

Compact way of plotting multi-wavelength constraints APPLIED TO POSITRON FRACTION

our model B



$\frac{(\sigma v)}{(\sigma v)^{e+}_{ok}}$

FORCED TO BE 1

i.e. we fix σv at the level explaining the positron fraction

$\frac{(\sigma v)}{(\sigma v)^{\overline{p}}_{ok}}$

$\frac{(\sigma v)}{(\sigma v)^{radio}_{ok}}$

$\frac{(\sigma v)}{(\sigma v)^{\gamma,GC}_{ok}}$

For the models which pass the selection:
look at the value
for the thermal cross-section
IN THIS CASE ~ 10^{-28} cm^3s^{-1}

Too low for standard cosmology...

Pato, LP, Bertone 2009

Conclusions

Detection of individual structures

In the best case scenario high mass halos are "detectable"
Result poorly dependent on small mass extrapolation

Multi-wavelength constraints

Coherent prediction of signals from all annihilation products
is now necessary in order to constrain (or discover)
particle physics and cosmological DM models

Upcoming data

This is more than ever important in these years
when data from satellites, Cherenkov Telescopes,
accelerators and Direct detection are about to allow
an unprecedented insight on the DM puzzle