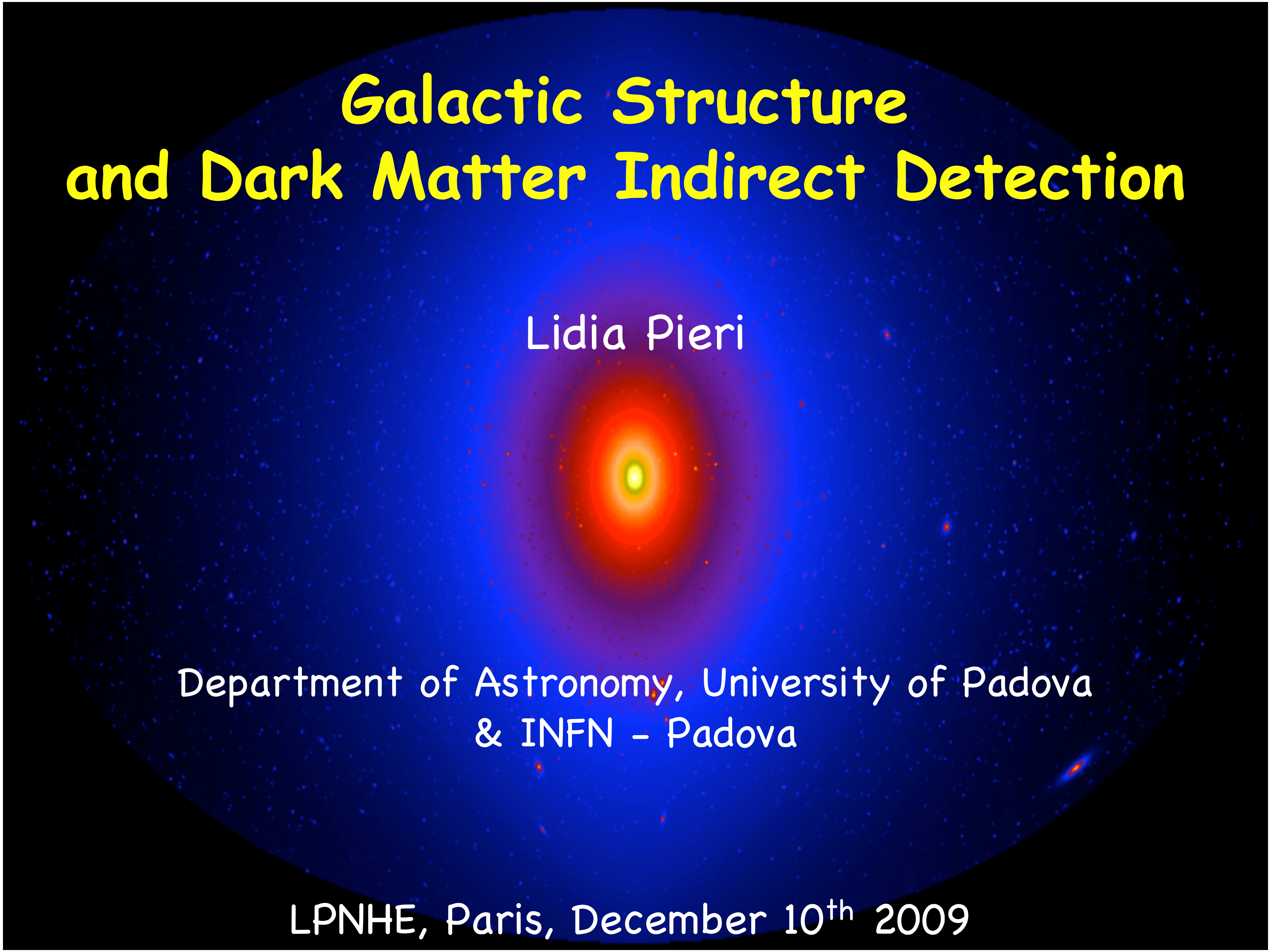


Galactic Structure and Dark Matter Indirect Detection

Lidia Pieri

Department of Astronomy, University of Padova & INFN - Padova

LPNHE, Paris, December 10th 2009

General outline

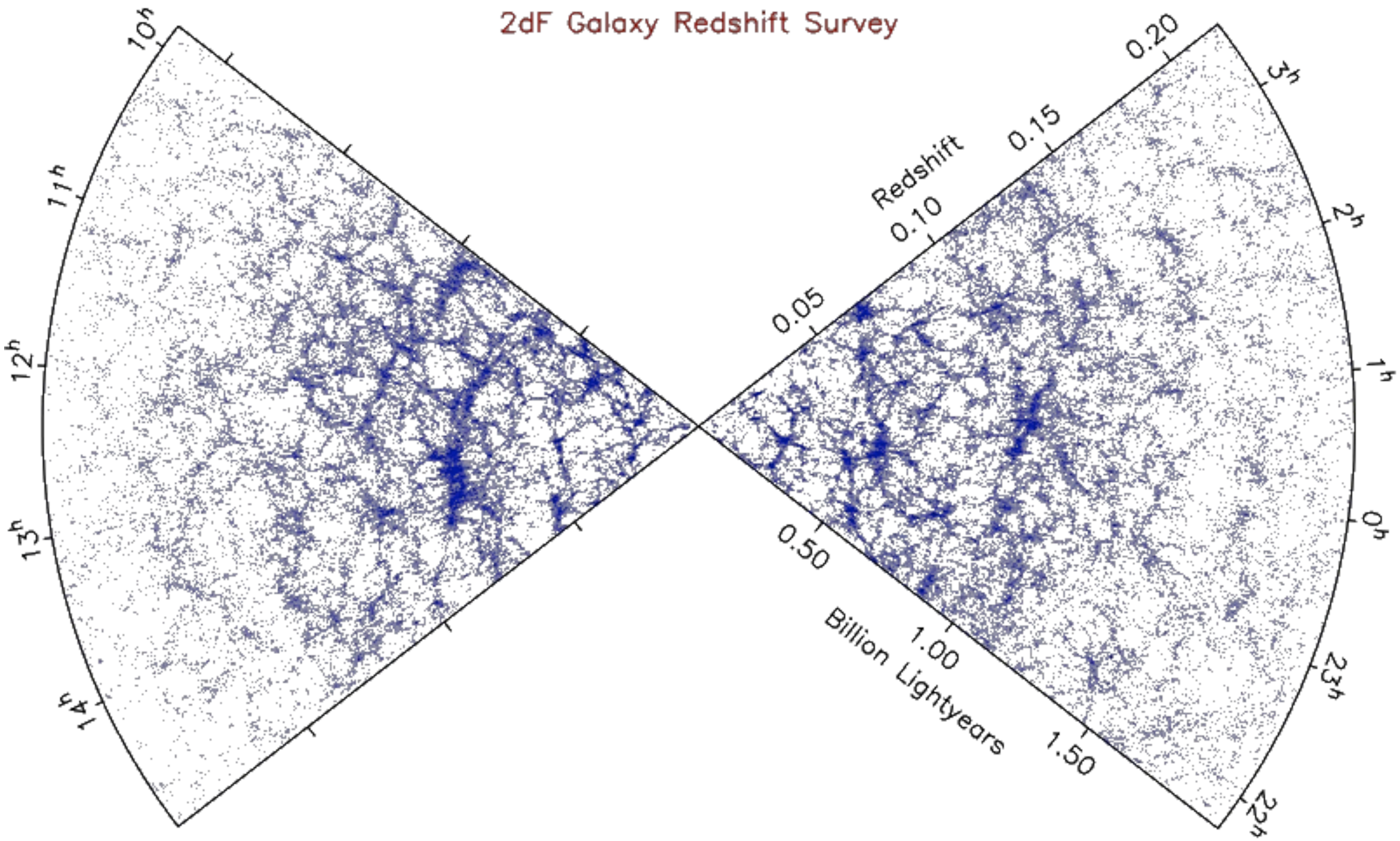
Indirect detection of dark matter:
Theoretical motivation

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

Evidences for Dark Matter on the largest scales

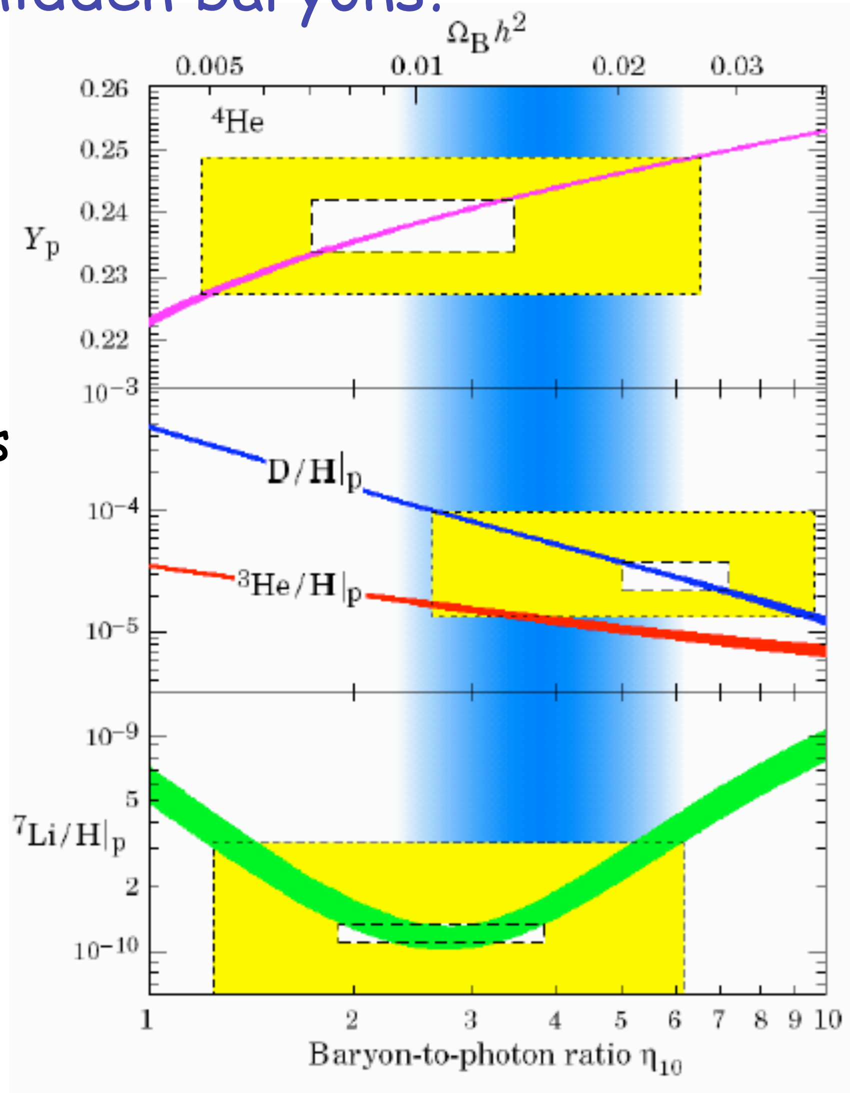


Measurements of galaxy clusters abundance and peculiar (relative) velocity require gravitational potential from a mass ~ 500 to 900 times the luminous one.

Is this mass due to hidden baryons?

Big Bang Nucleosynthesis constraints the average baryonic content of the Universe.
To agree with the measured abundances of helium, deuterium, and lithium, the baryonic content of the Universe must be 4%, wrt a flat Universe.

Yet we see 5 ‰ in stars

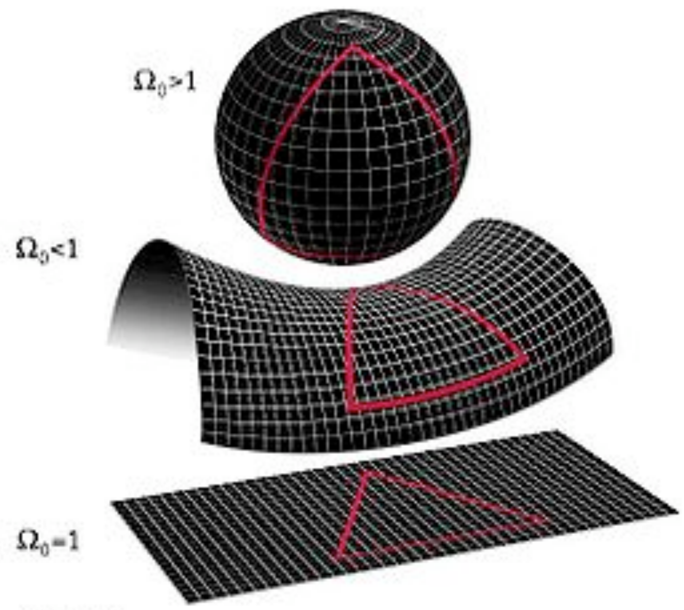


There must be a series of baryonic objects we don't see, such as dim brown or red dwarf, Jupiter like objects, black hole, Warm-Hot Intergalactic Medium… but up to 4%

Other two missing pieces of the puzzle

The Universe is flat
tested by CMB measurements

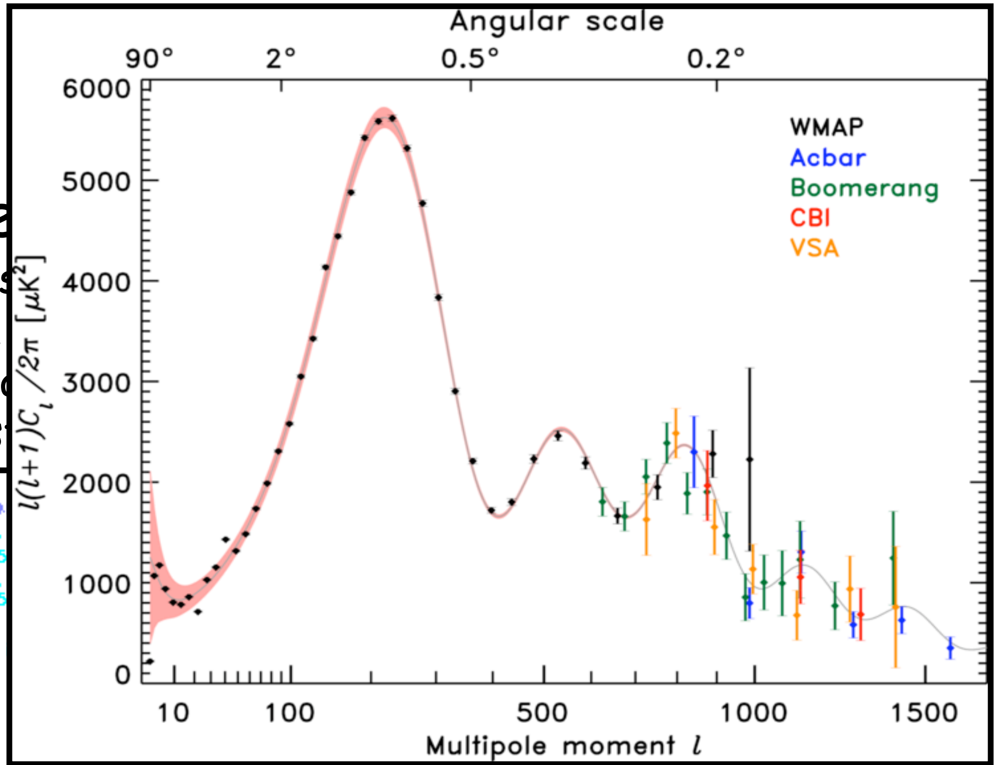
The last scattering surface fixes the scale of inomogeneities at recombination, i.e. when atomic hydrogen is formed. A spatial temperature fluctuation on the last scattering surface appears to us as an anisotropy on the sky. The conversion from physical scale into angular scale depends on the curvature of the universe and the distance to the last scattering surface.



The Universe is in accelerated expansion
tested by supernovae redshift (distance) measurements

Gravity only would slow down the expansion as the Universe dilutes
Supernovae are standard candles since their luminosity is well known and their distance can be accurately determined, and found to be inconsistent with a slowing-down expansion

Other two missing pieces of the puzzle



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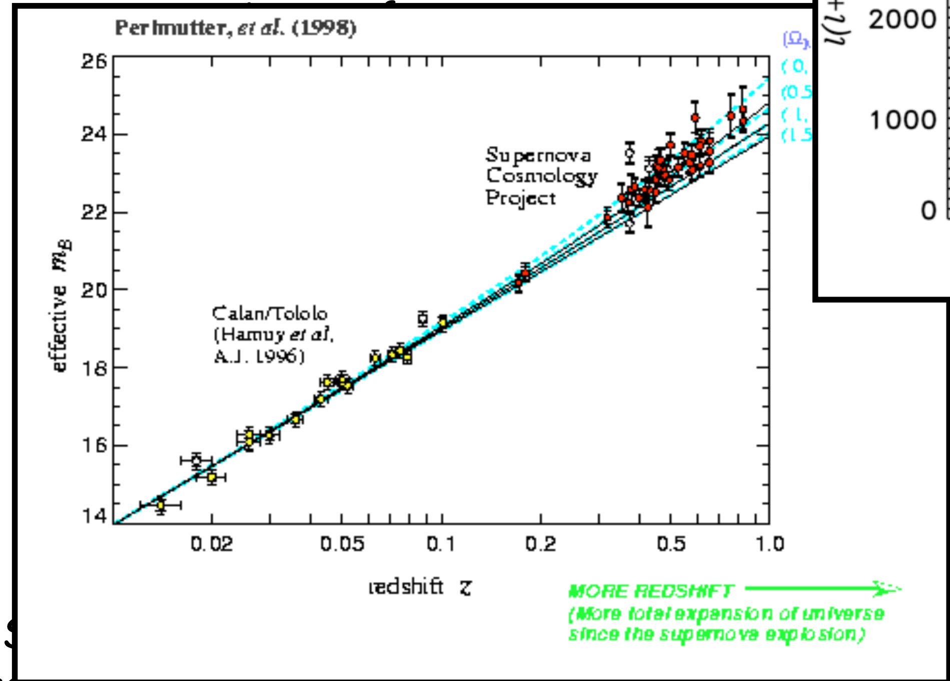


elerated expansion

(distance) measurements

ansion as the Universe dilutes
S inosity is well known and their distance
can be accurately determined, and found to be inconsistent with a slowing-down expansion

Cosmological framework

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

measures

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

Ω_b ~ 0.005 (galaxies)

Ω_b ~ 0.04 (BBN)

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

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

Cosmological framework

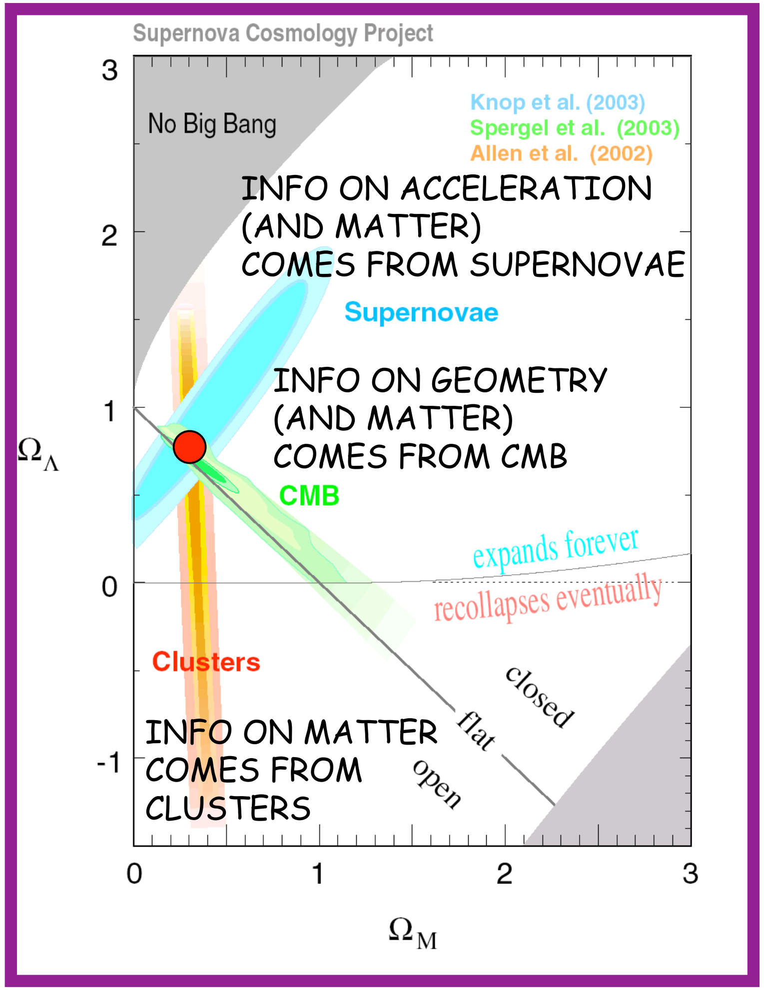
The Standard Model of the Universe, as derived from data on large scale structures, distant supernovae, CMB, etc.
predicts a flat, accelerating Universe

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*

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



Resuming: the cosmological pie

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

known particles unknown

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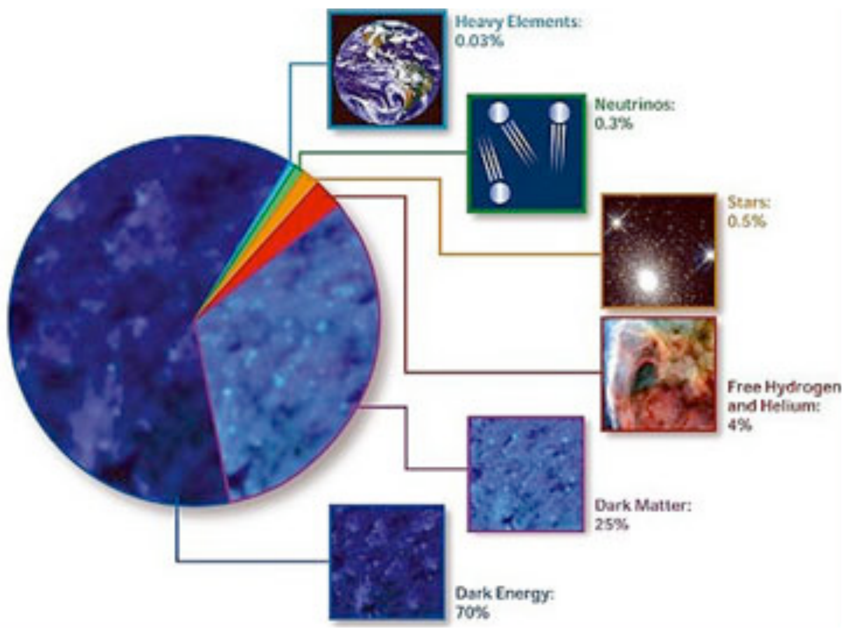
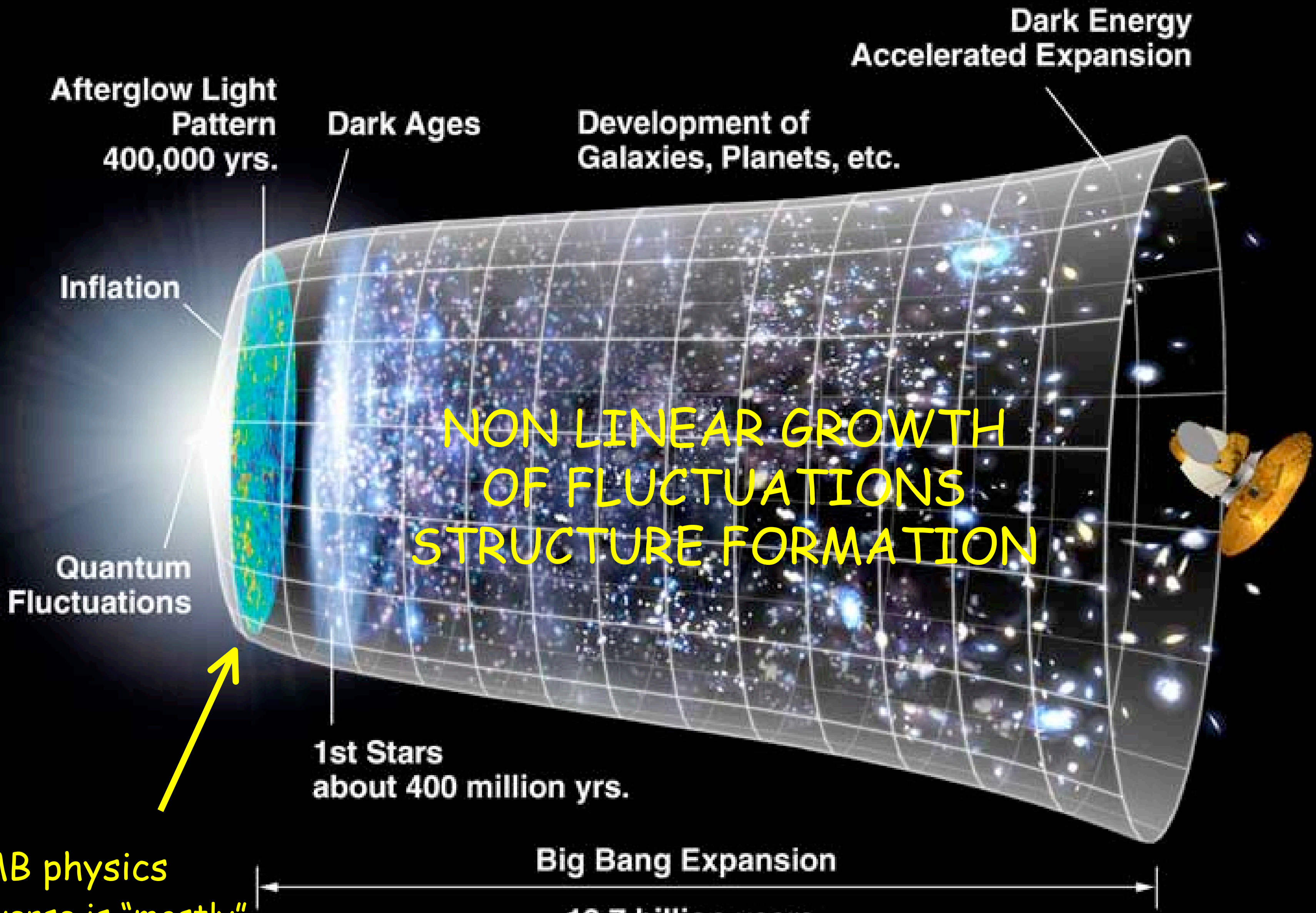
$\Omega_\Lambda \sim 0.73$

$\Omega_{DM} \sim 0.23$

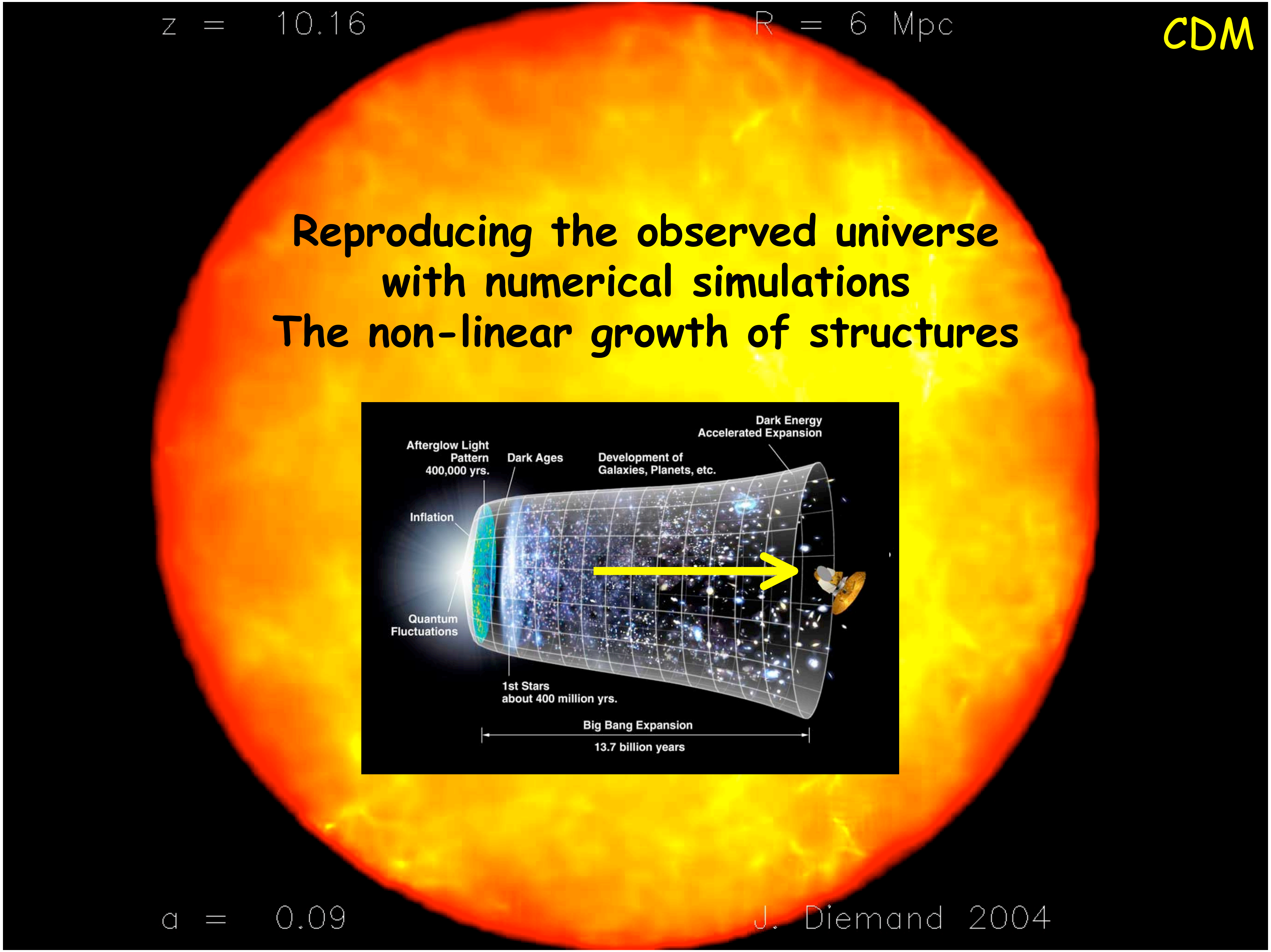


The thermal history of the universe



CMB physics

Universe is "mostly"
homogeneous and isotropic, but seeds of structures are already there


z = 10.16
R = 6 Mpc
CDM
Reproducing the observed universe
with numerical simulations
The non-linear growth of structures
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
a = 0.09
J. Diemand 2004

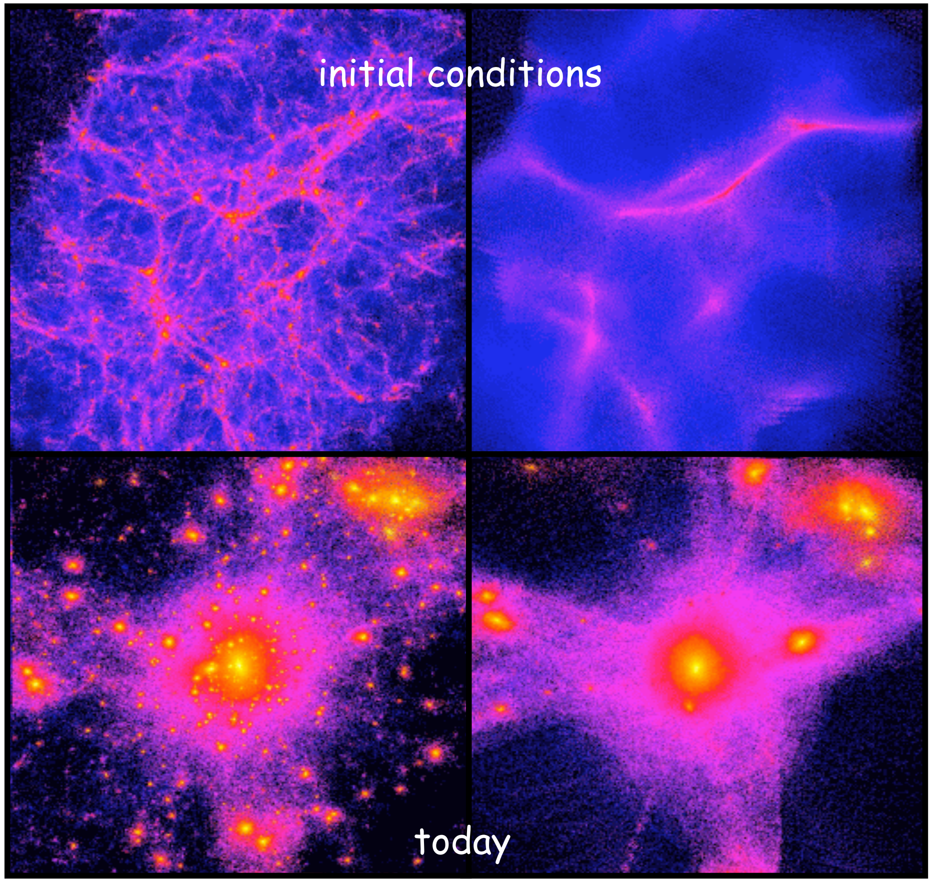
Which DM theory better reproduces the observed Universe?

The evolution of DM halos
Primordial density fluctuations grow and collapse in gravitationally bound structures which eventually Virialize and form halos.

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.

non-relativistic particles form smaller halos

relativistic particles have larger kinetic energy and need larger mass to be gravitationally bound

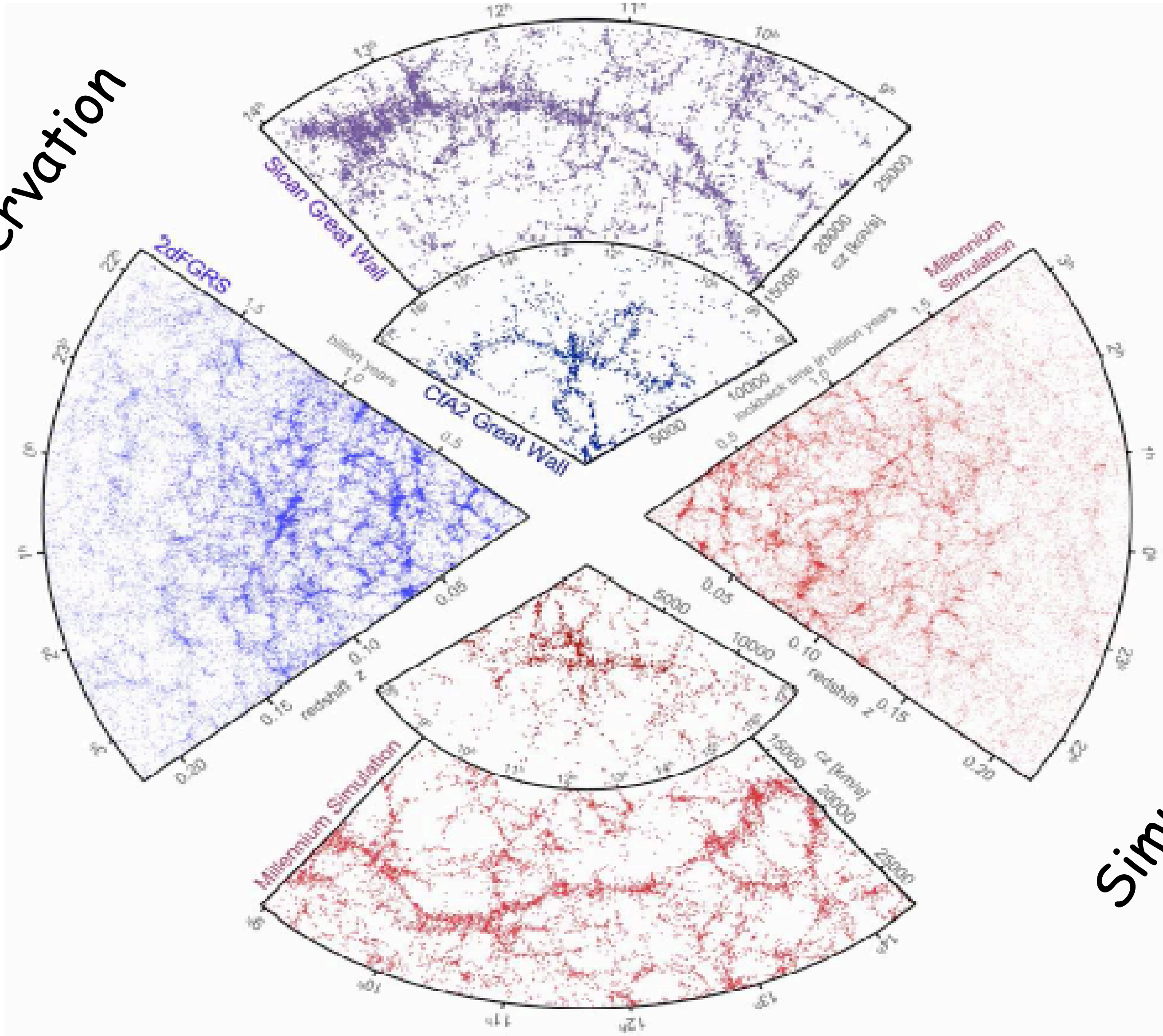


Cold dark matter

Hot dark matter

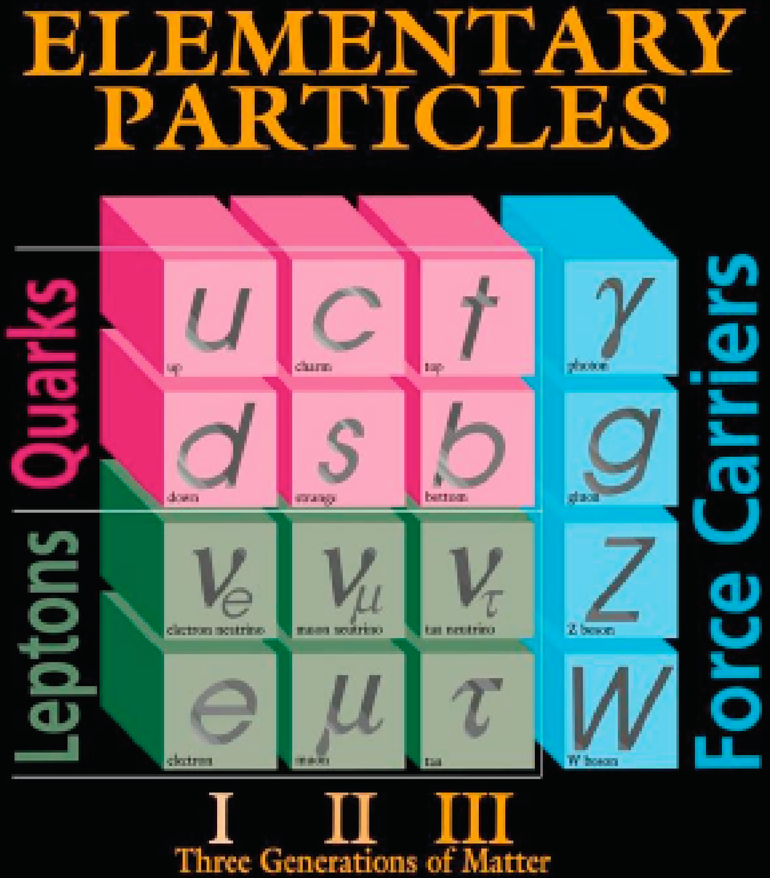
CDM N-body simulations reproduce the observed Universe

Observation



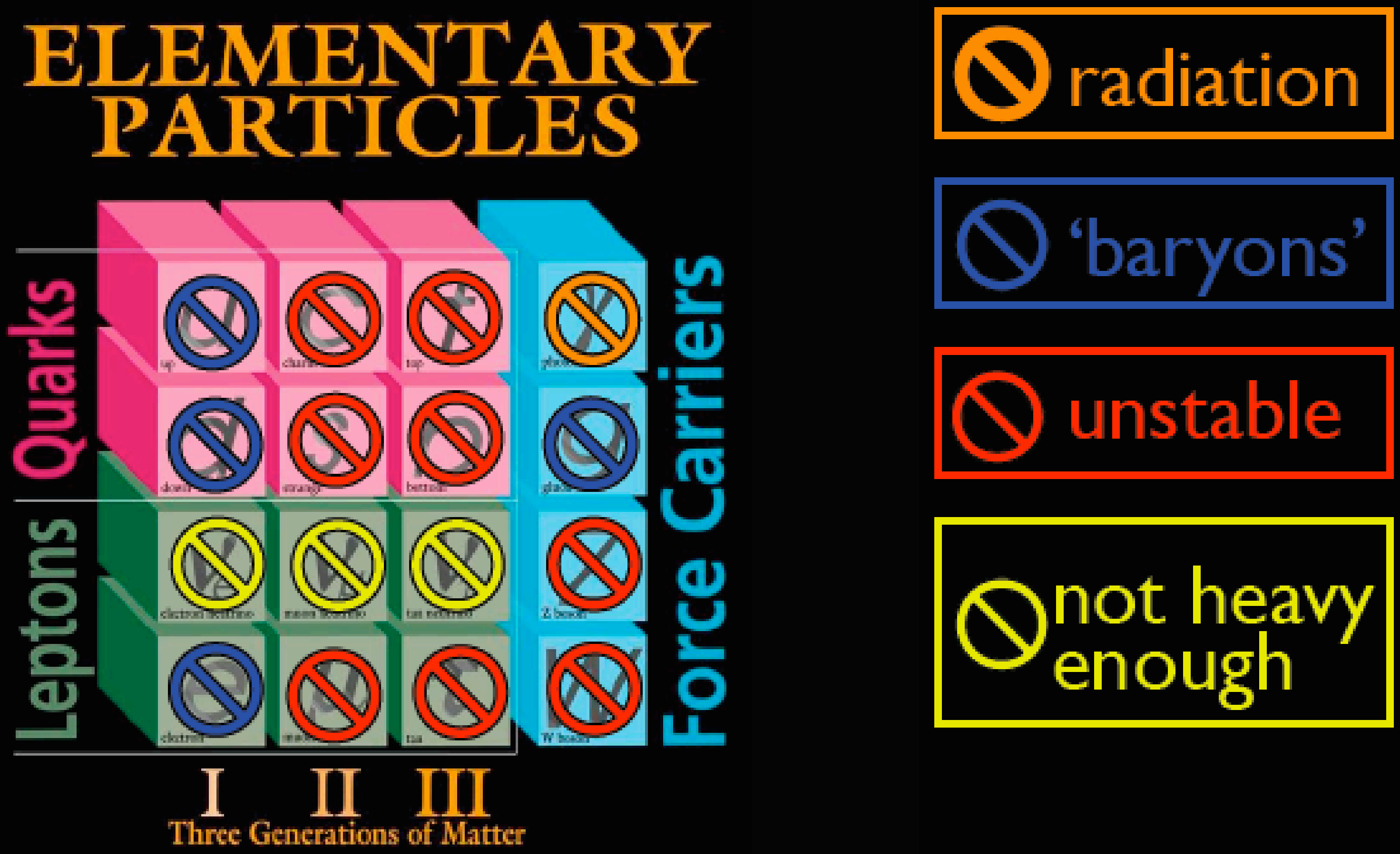
Simulation

Which candidate for the dark matter?



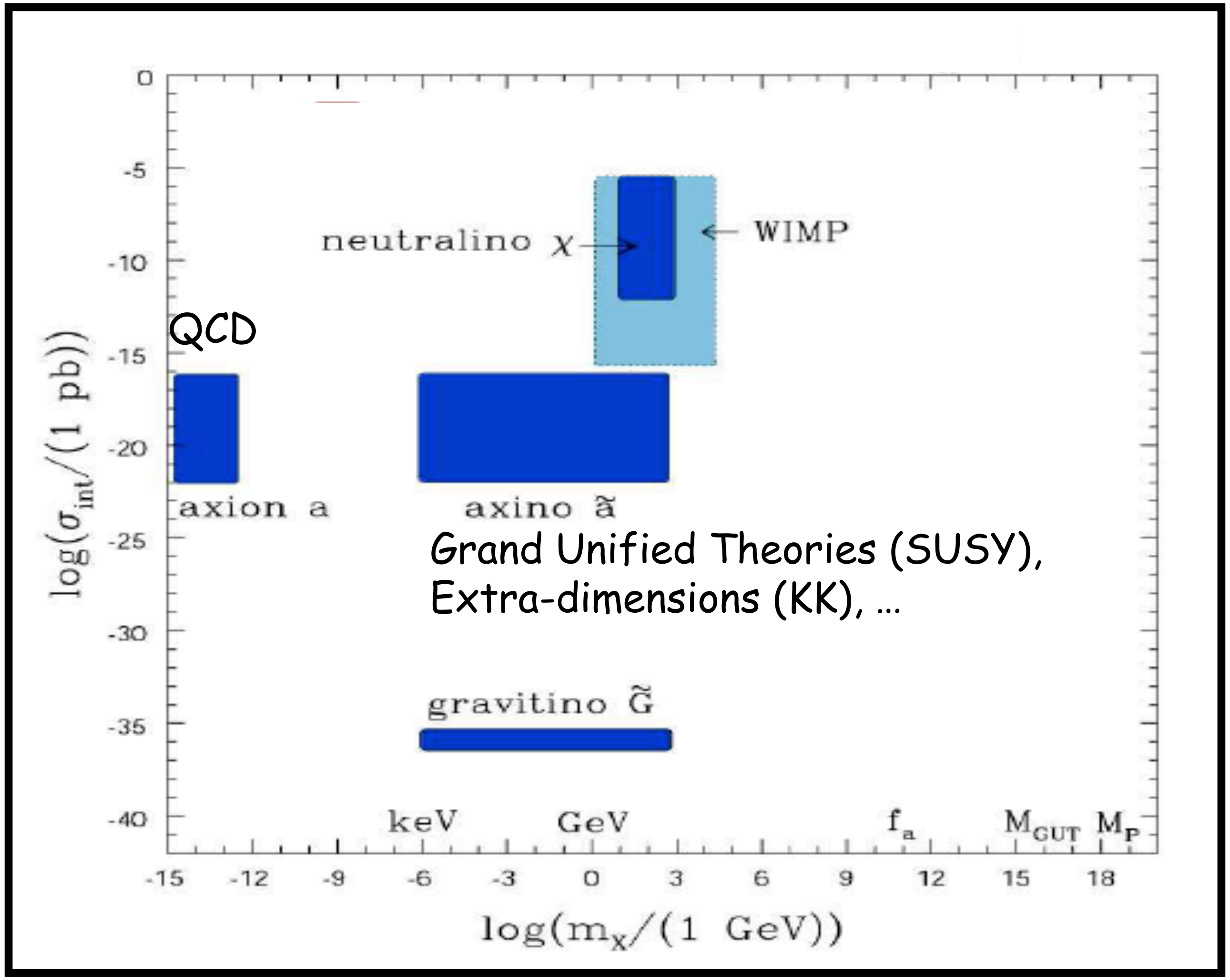
Standard Model particles

Which candidate for the dark matter?

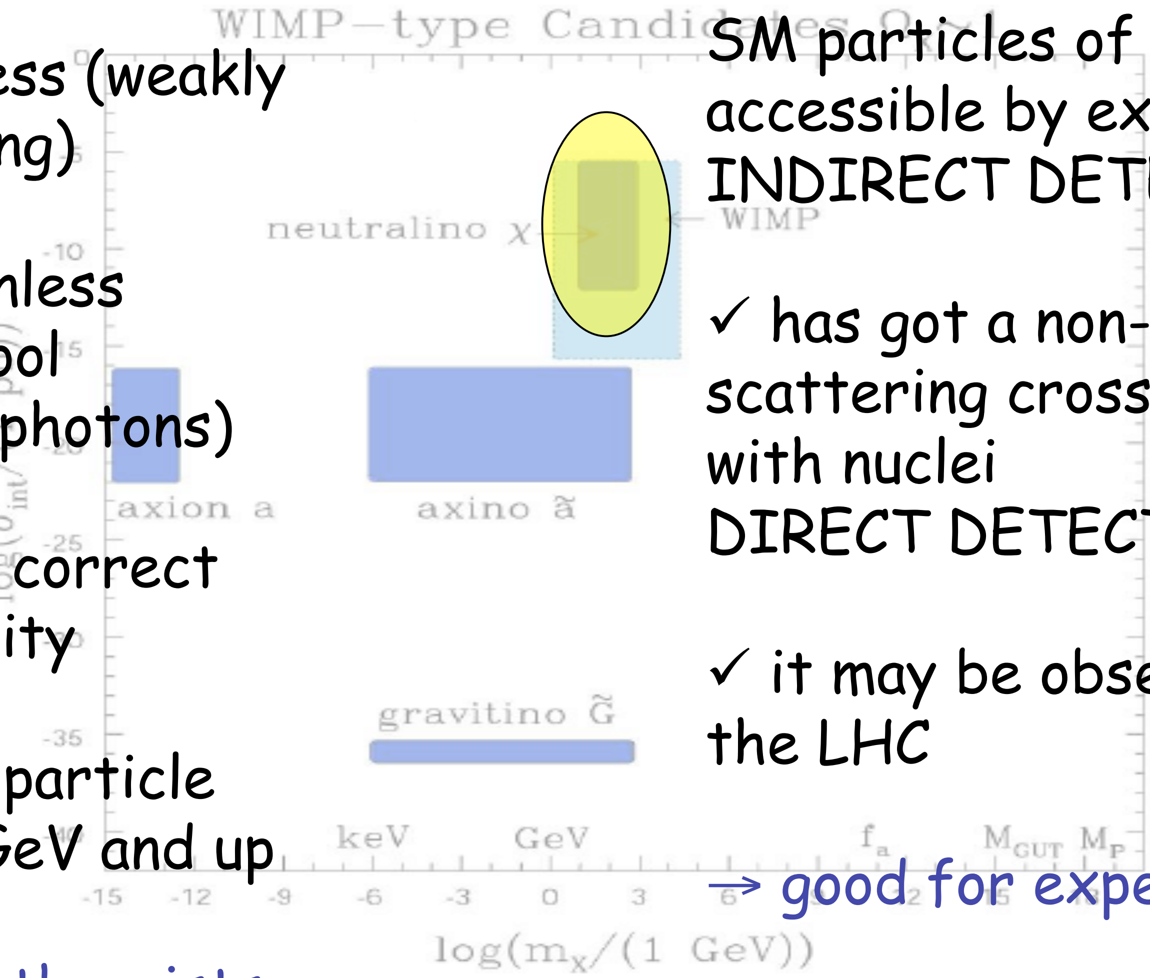


Standard Model particles cannot be DM

Cold Dark Matter candidates



Is the Neutralino the theoretical miracle?
Joins particle physics and cosmology



✓ stable (lightest)

✓ collisionless (weakly interacting)

✓ dissipationless (cannot cool radiating photons)

✓ gives the correct relic density

✓ is a CDM particle M ~ 100 GeV and up

→ good for theorists

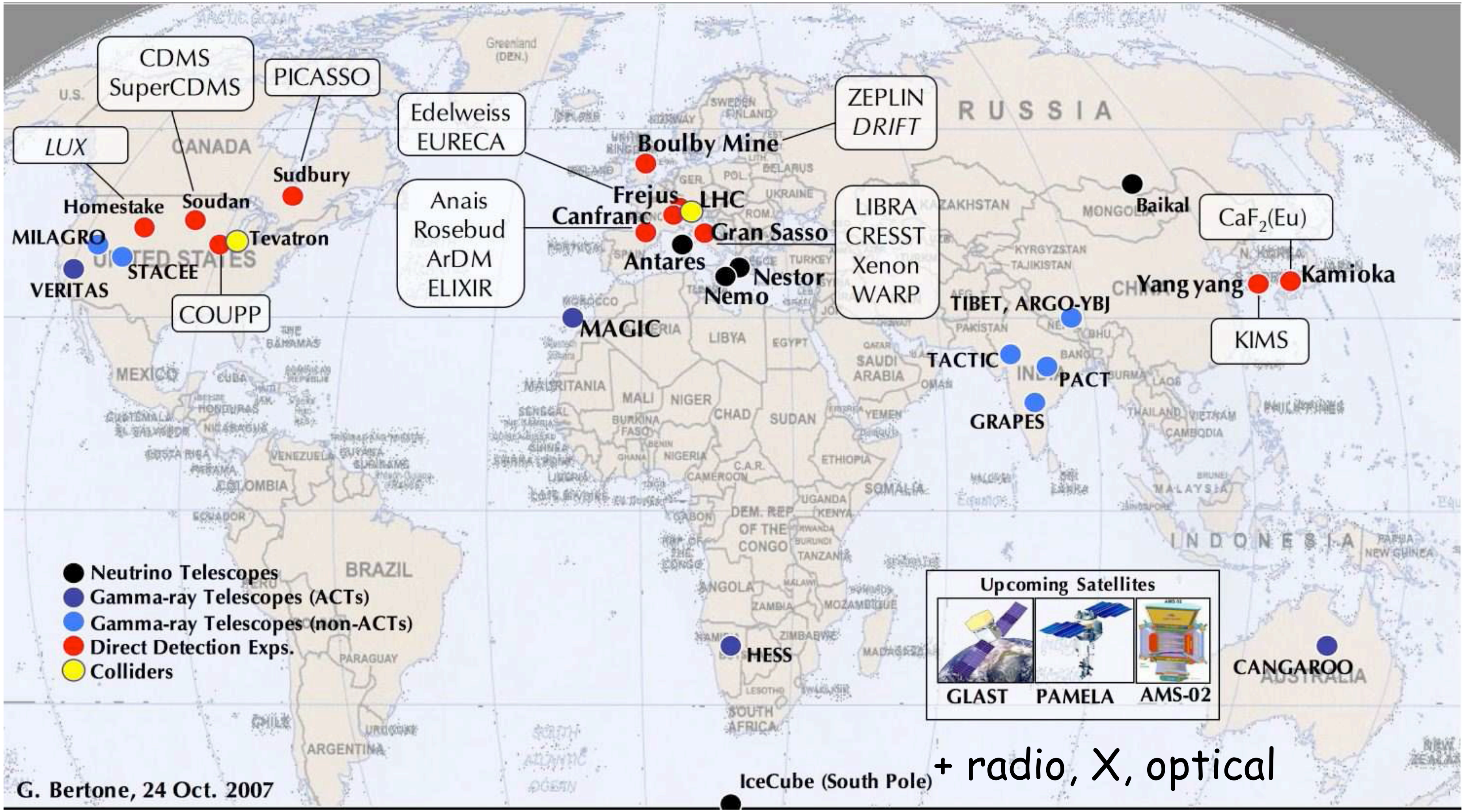
✓ it self-annihilates into SM particles of energies accessible by experiments INDIRECT DETECTION

✓ has got a non-null scattering cross section with nuclei DIRECT DETECTION

✓ it may be observed at the LHC

→ good for experimentalists

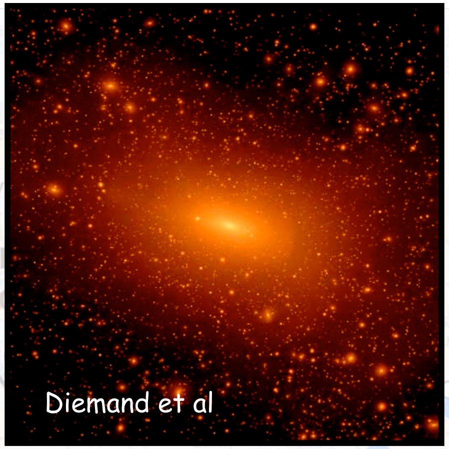
BIG EXPERIMENTAL EFFORTS

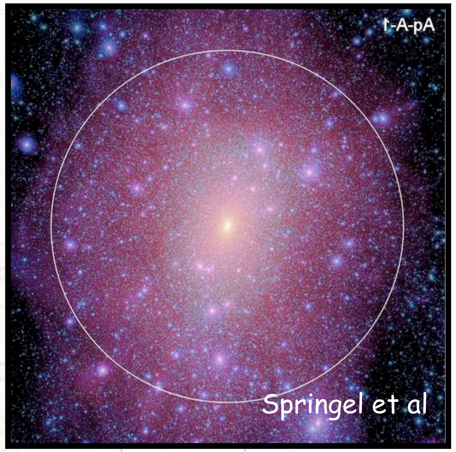


- accelerators   Many possible patterns for final states (jets and missing energy) m_χ< 1-2 TeV
- direct searches χ elastic diffusion on nuclei (nucleus recoil energy) 30 GeV < m_χ< 100-200 GeV
- indirect searches ($\chi\chi$ annihilation)
  - in close massive objects (Earth, Sun) → neutrinos
  - in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

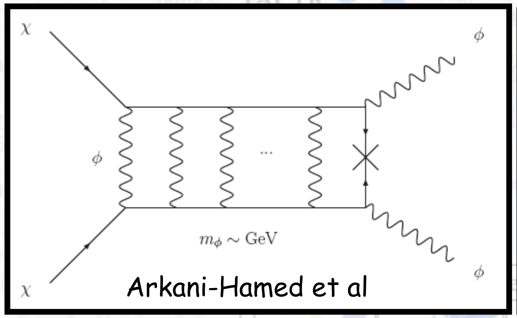
AND ACTIVE THEORETICAL MODELING

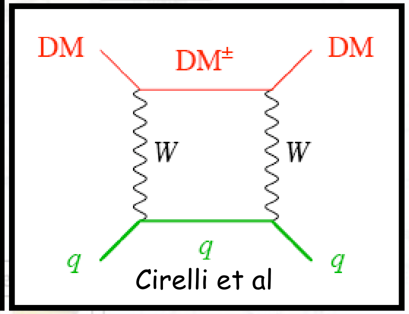
Numerical simulations of our galaxy

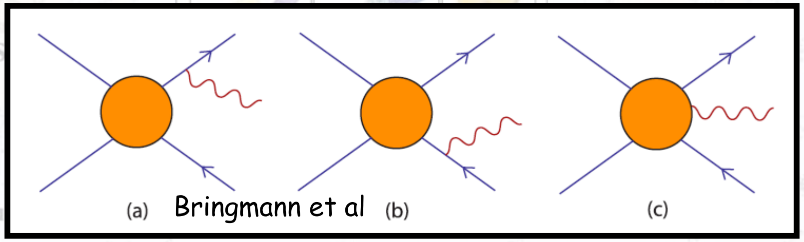




Particle physics modeling: new candidates explored, new effects added (Sommerfeld enhancement of the annihilation cross-section, Internal bremmstrahlung, etc.)







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Indirect detection of dark matter:

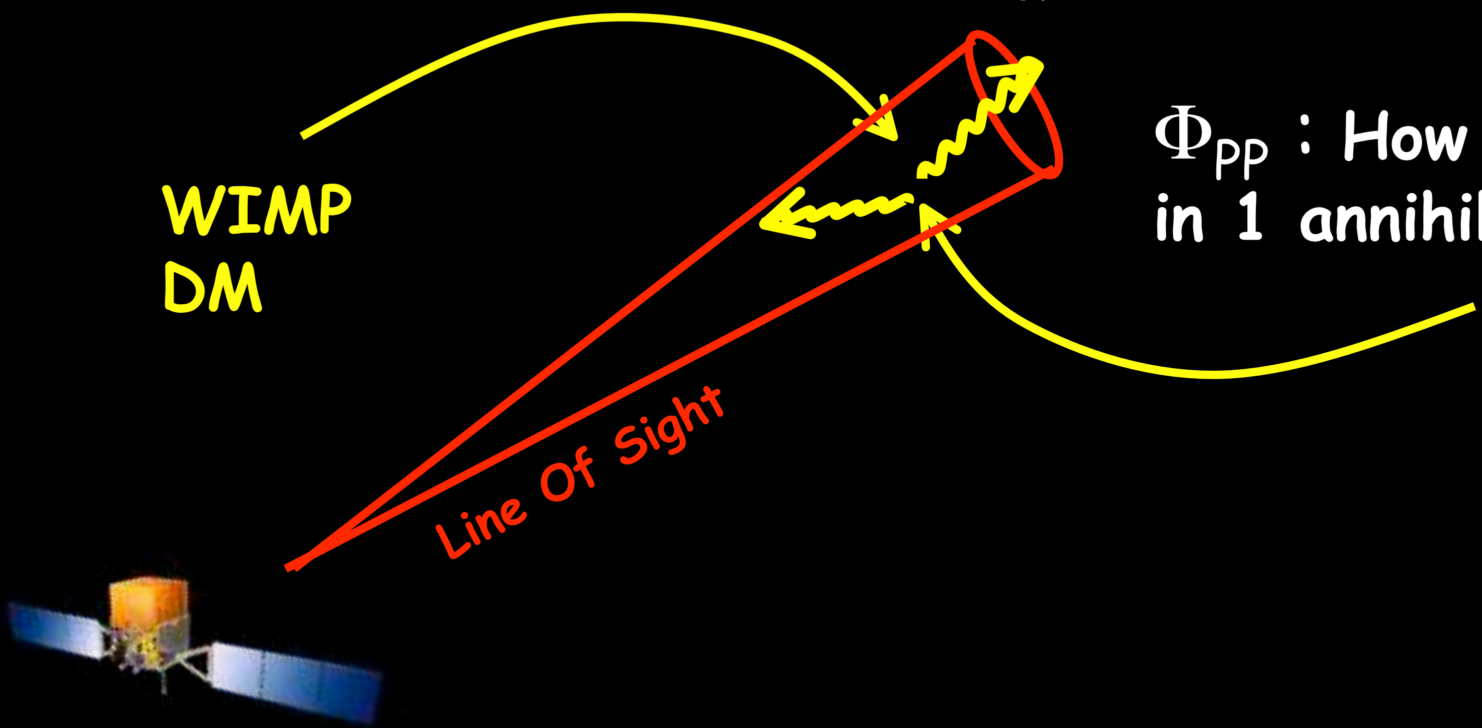
The role of substructures

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

Indirect detection of γ-rays

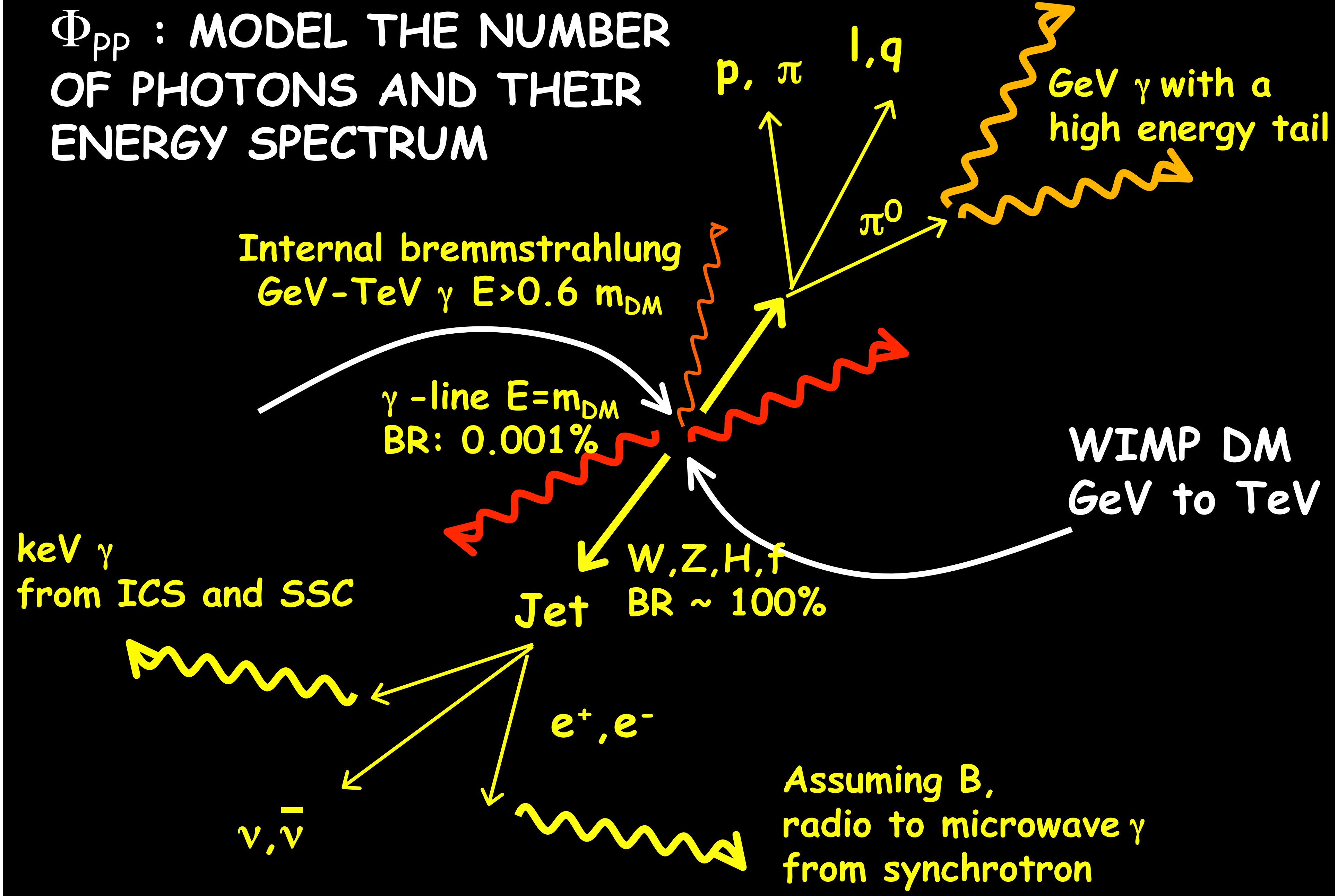
$$\Phi_\gamma = \Phi_{\text{particle physics}} \times \Phi_{\text{cosmology}}$$

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



Φ_{PP} : How many γs in 1 annihilation

Φ_{PP} : MODEL THE NUMBER OF PHOTONS AND THEIR ENERGY SPECTRUM



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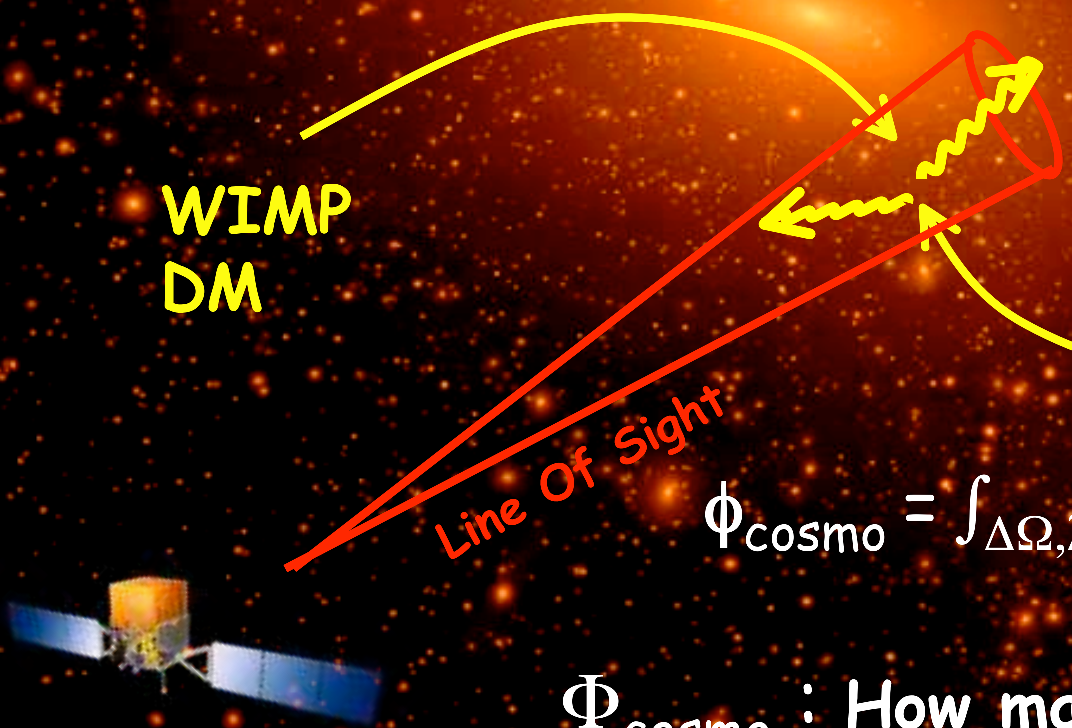
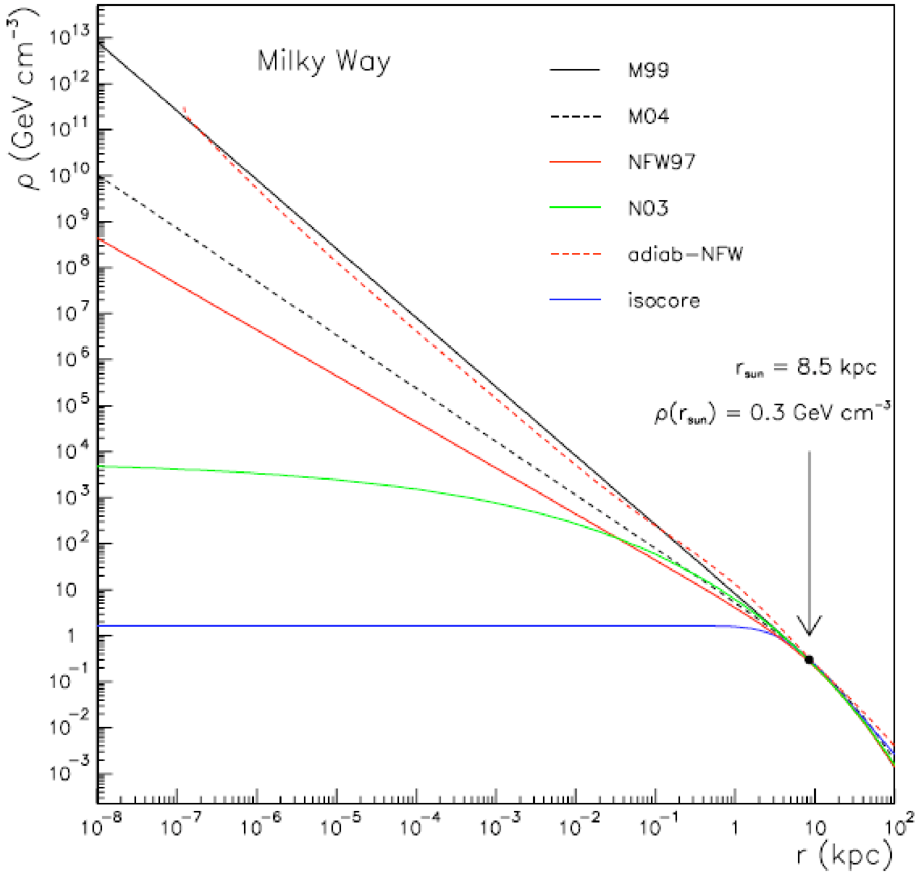


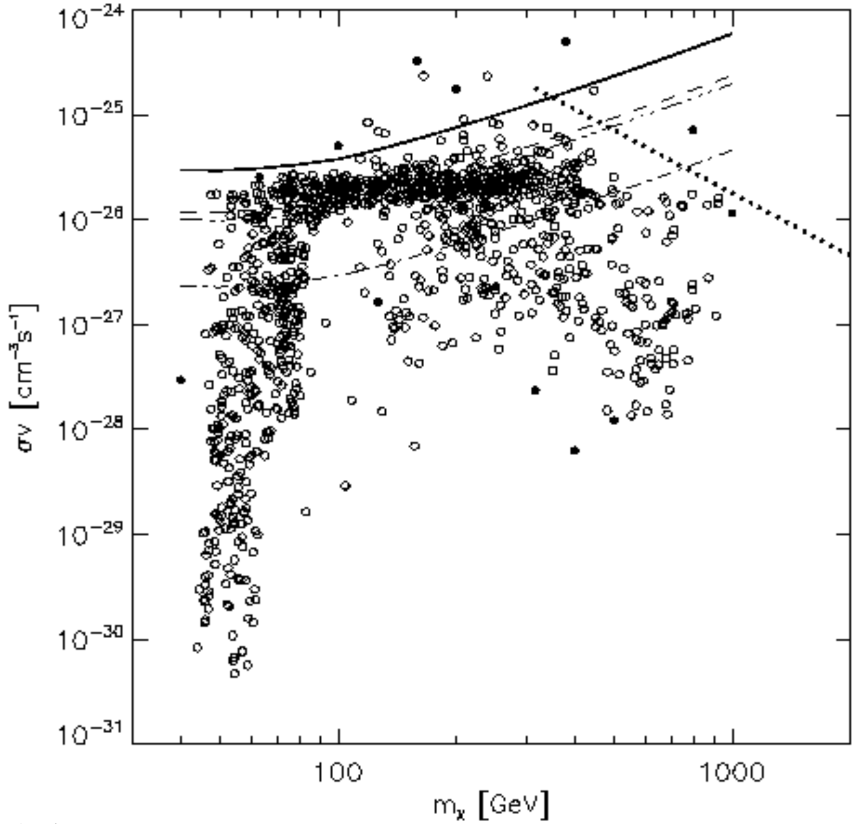
$$\phi_{cosmo} = \int_{\Delta\Omega,\lambda} \frac{\rho^2_{DM}(r(\Delta\Omega,\lambda))}{\lambda^2} d\lambda d\Omega$$

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

Free parameters from one single halo

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



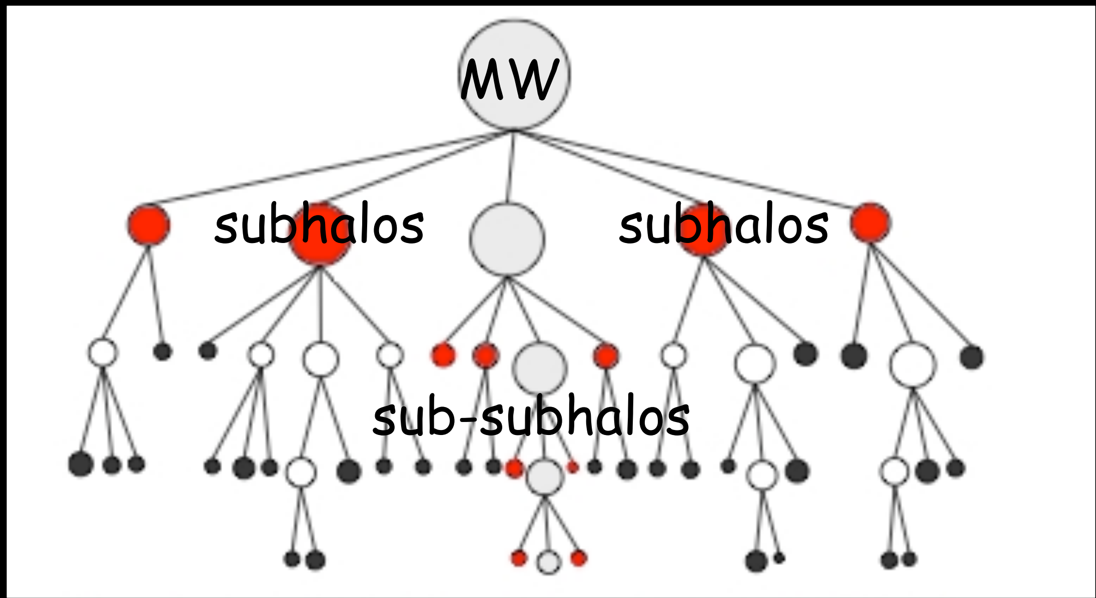


$$\Phi^{halo}_{COSMO}(M,R,r) \propto \int_{l.o.s.} d\Omega d\lambda \left[\frac{\rho^2_{DM}(M,c,r,\psi)}{d^2}\right]$$

Fornengo, LP, Scopel 2004, LP, Pizzella et al 2008, LP, Bertone, Branchini 2008, Fornasa, LP, Bertone, Branchini 2009 etc.

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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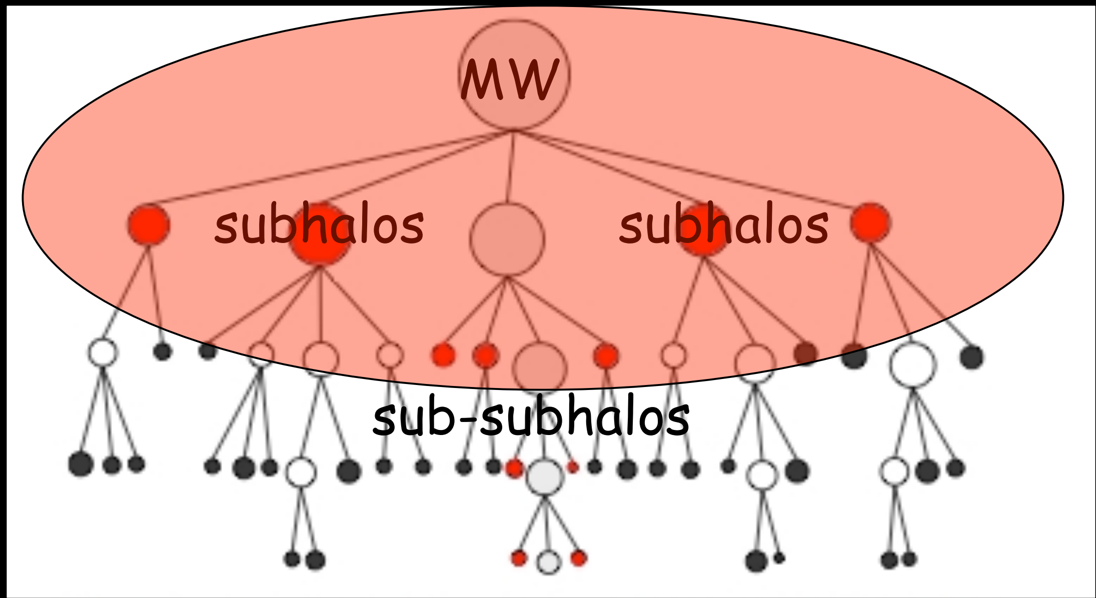

N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

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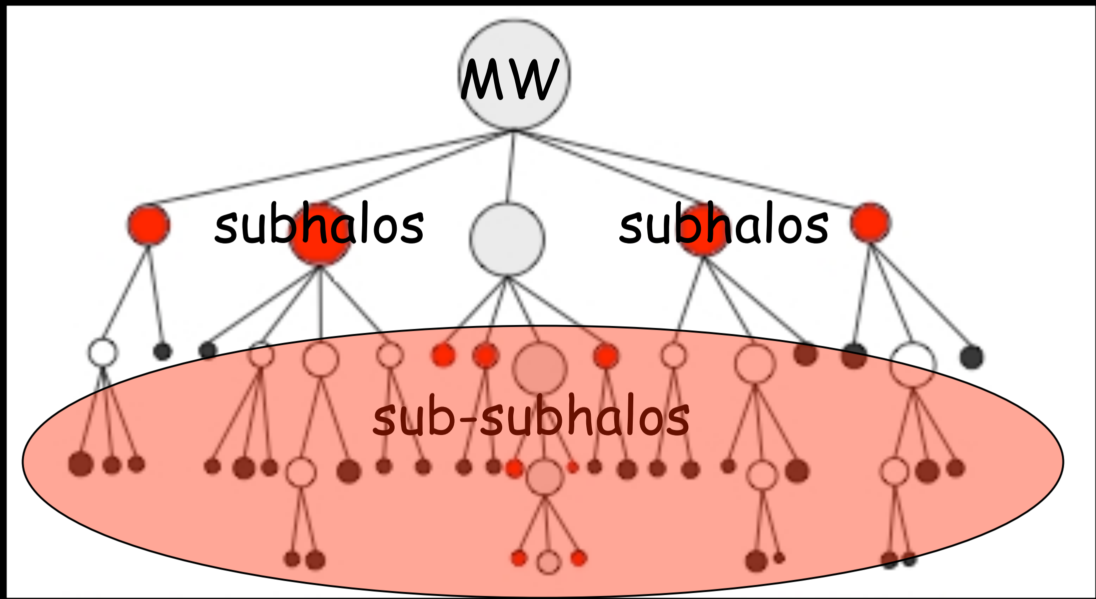
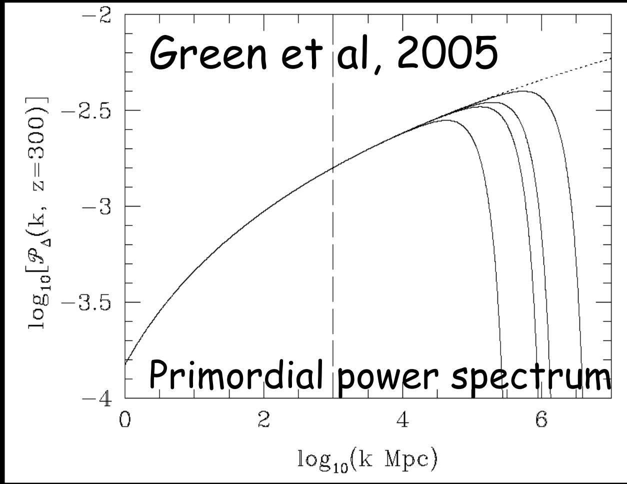


N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

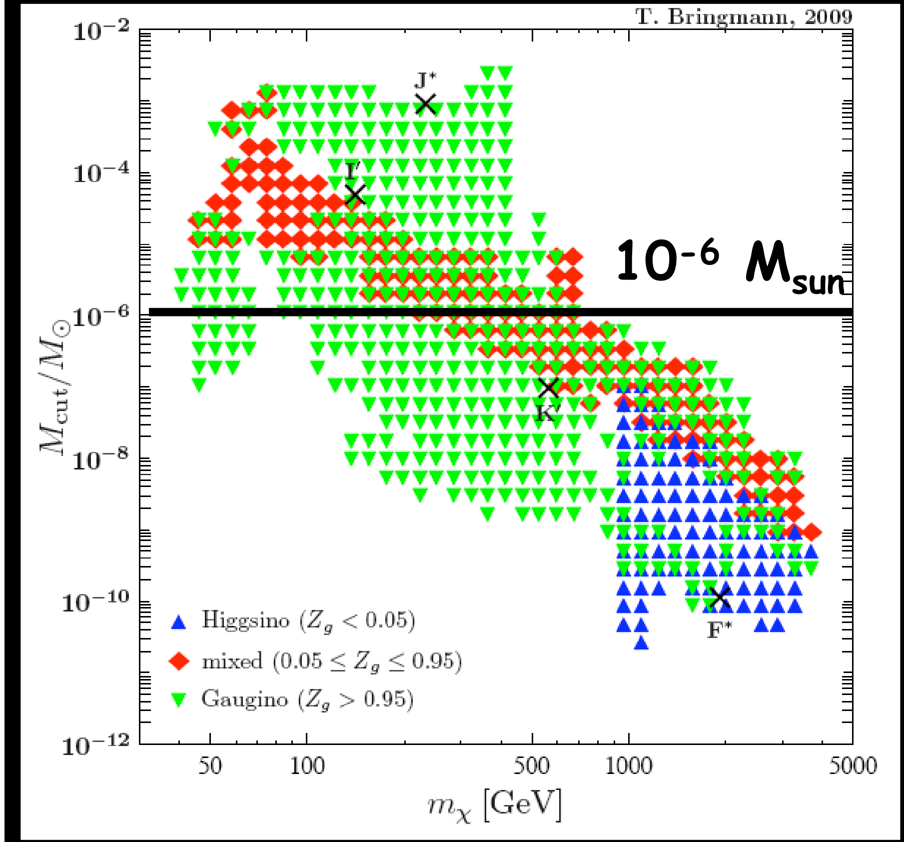
Microphysics and theory of structure formation sets the mass of the smallest halo
because there is no enough cpu power to simulate small halos from collapse till today.

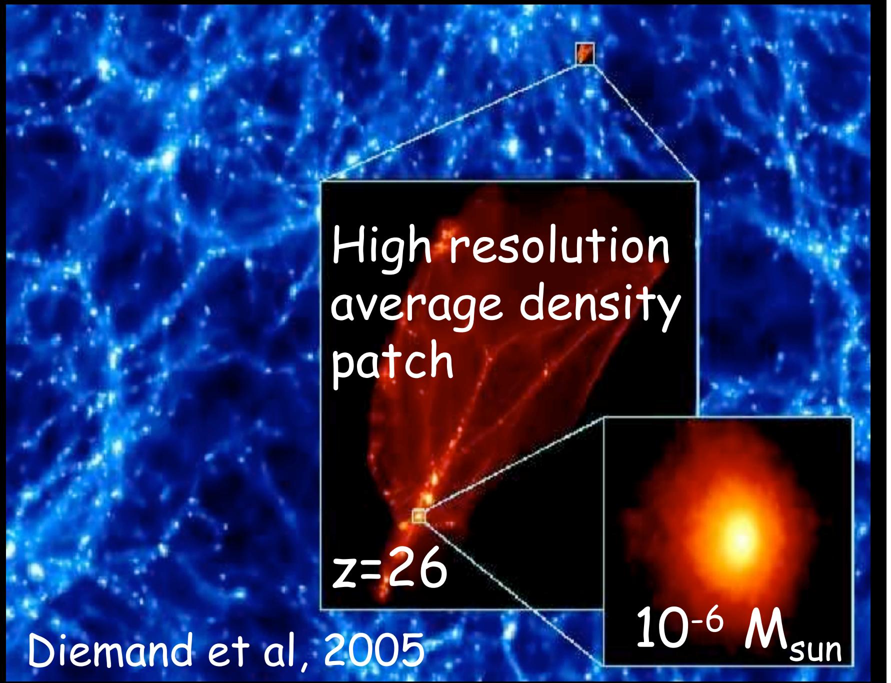
Modeling the structure of dark matter halos from theory of structure formation ($M < 10^5\ M_{sun}$)

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

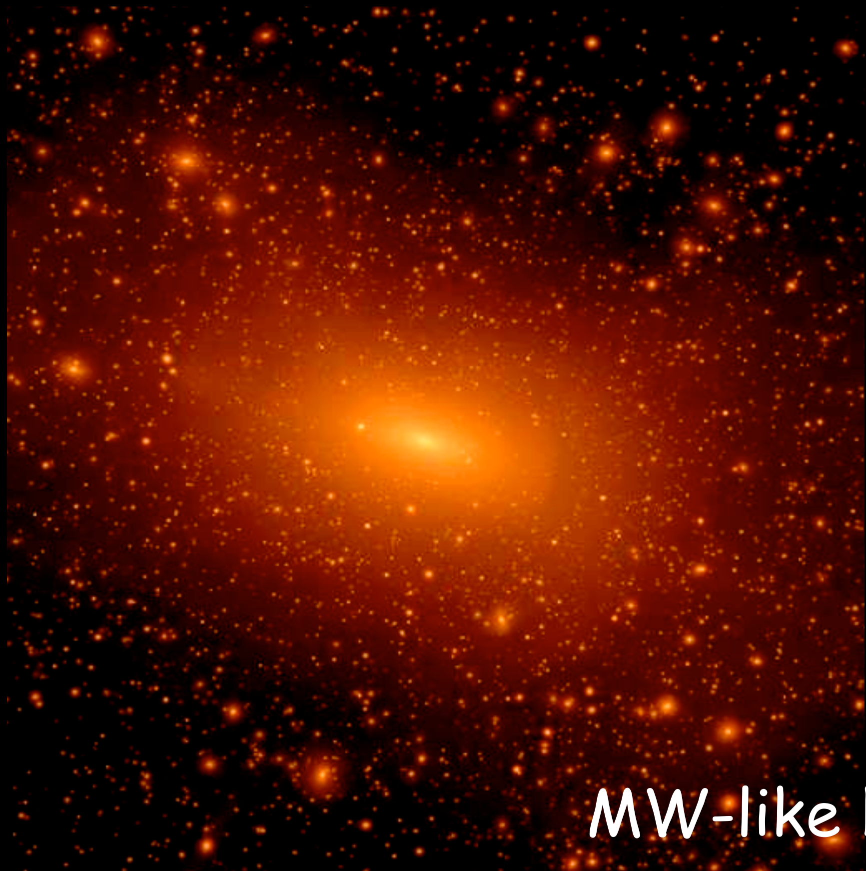


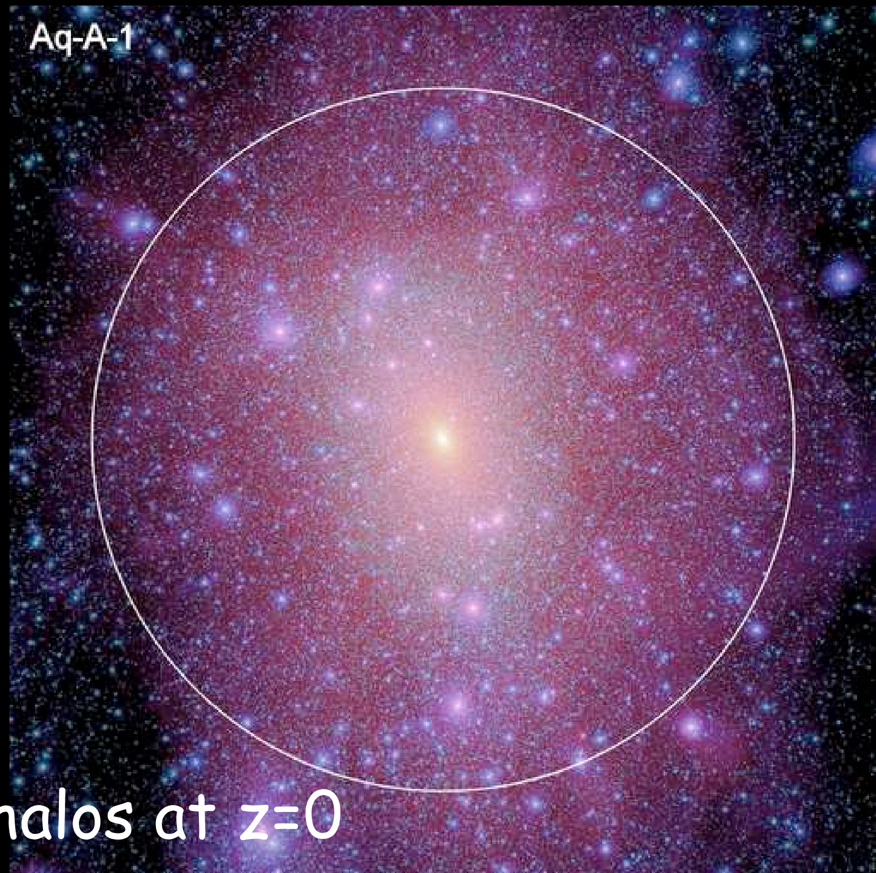
Typical M_{min} for a WIMP = $10^{-6}\ M_{sun}$





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





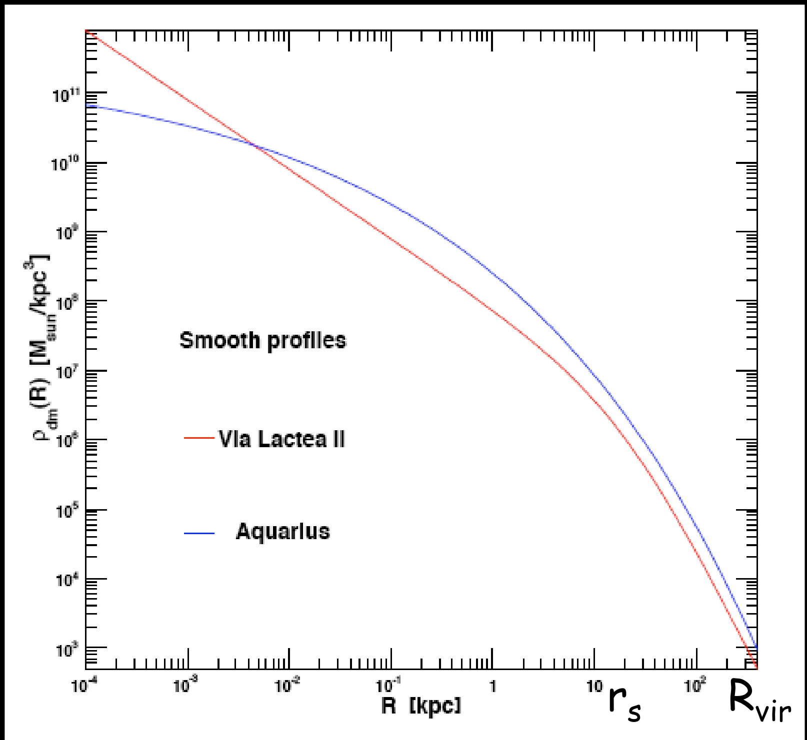
MW-like halos at z=0

Via Lactea 2, Diemand et al

Aquarius, Springel et al

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

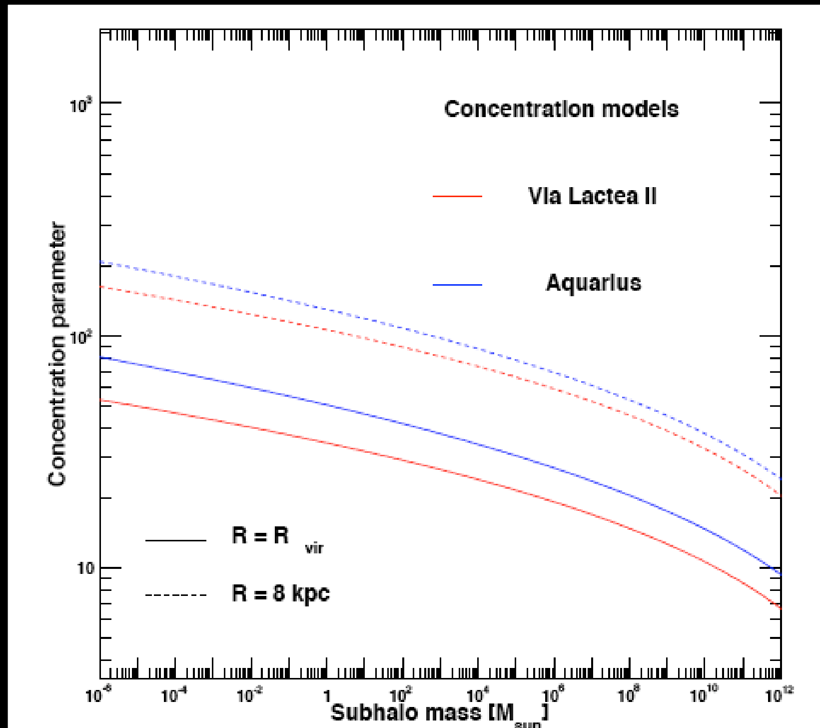
→ **Halo and subhalo profile shape and concentration**



NFW VS Einasto

Concentration parameter (R_{vir}/r_s) has radial dependence

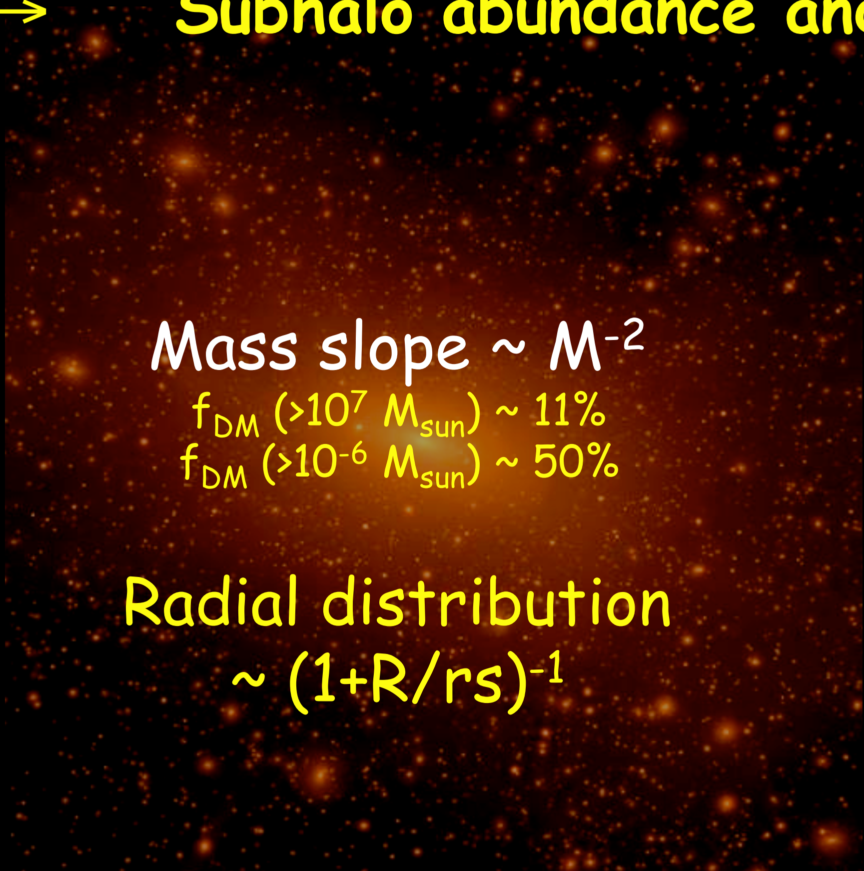
higher concentration -> higher flux!

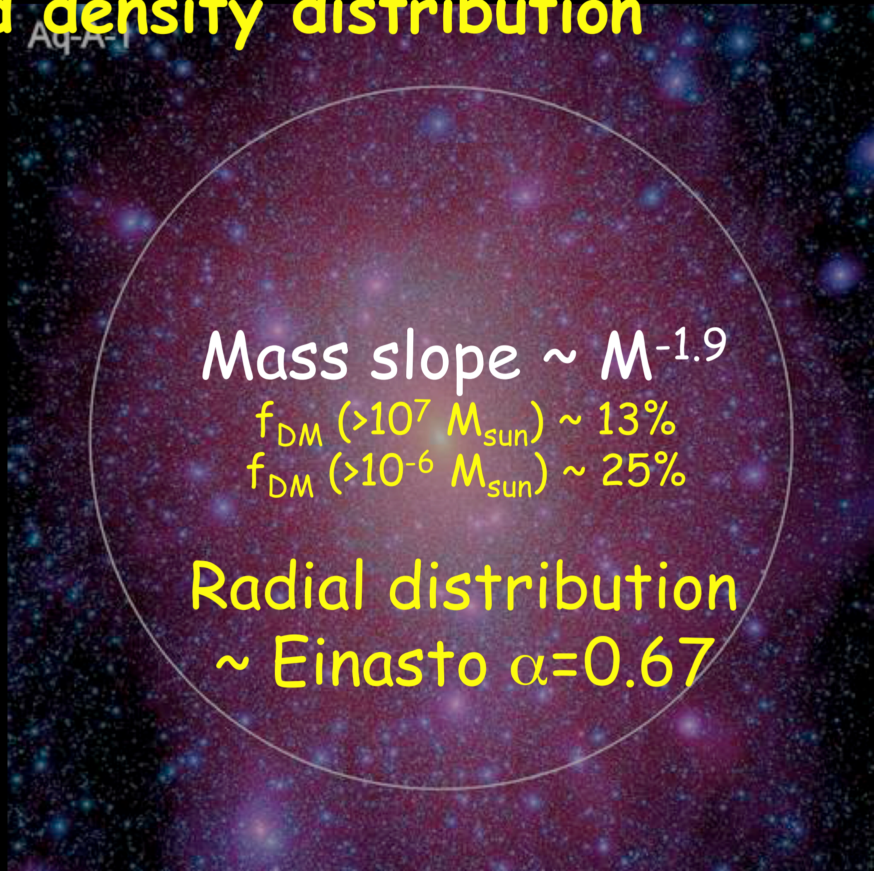


LP, Lavalle, Bertone & Branchini 2009

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

→ **Subhalo abundance and density distribution**





Roche criterion sets the effect of tidal forces

Indirect detection of γ-rays:

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

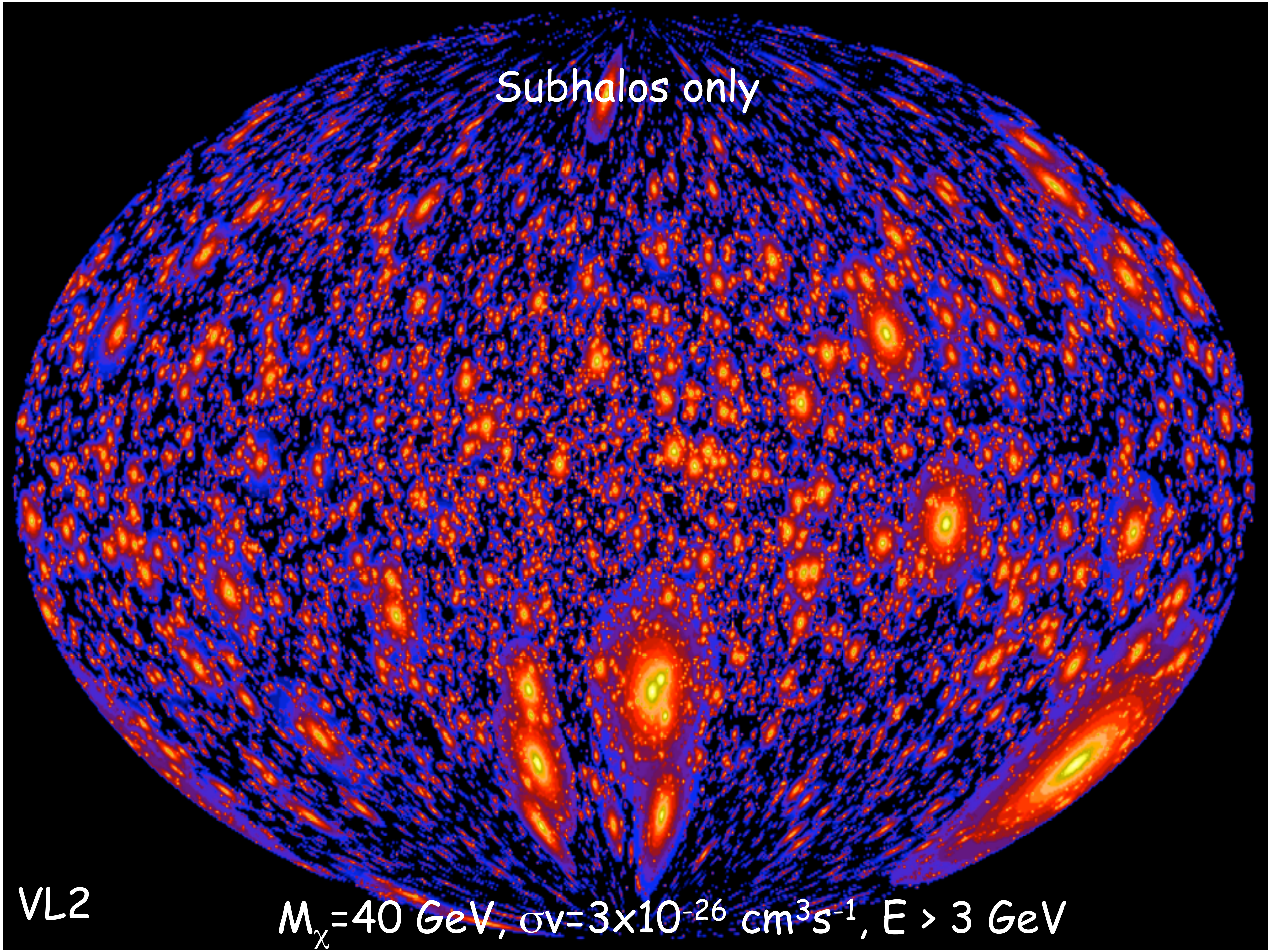
$$\Phi_{PP} = \frac{1}{4\pi}\frac{\sigma_{ann}v}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_f \frac{dN_f^\gamma}{dE_\gamma}BR_f$$

Step 1: **MW smooth**
Single subhalo contribution

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

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:

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

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

Step 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...

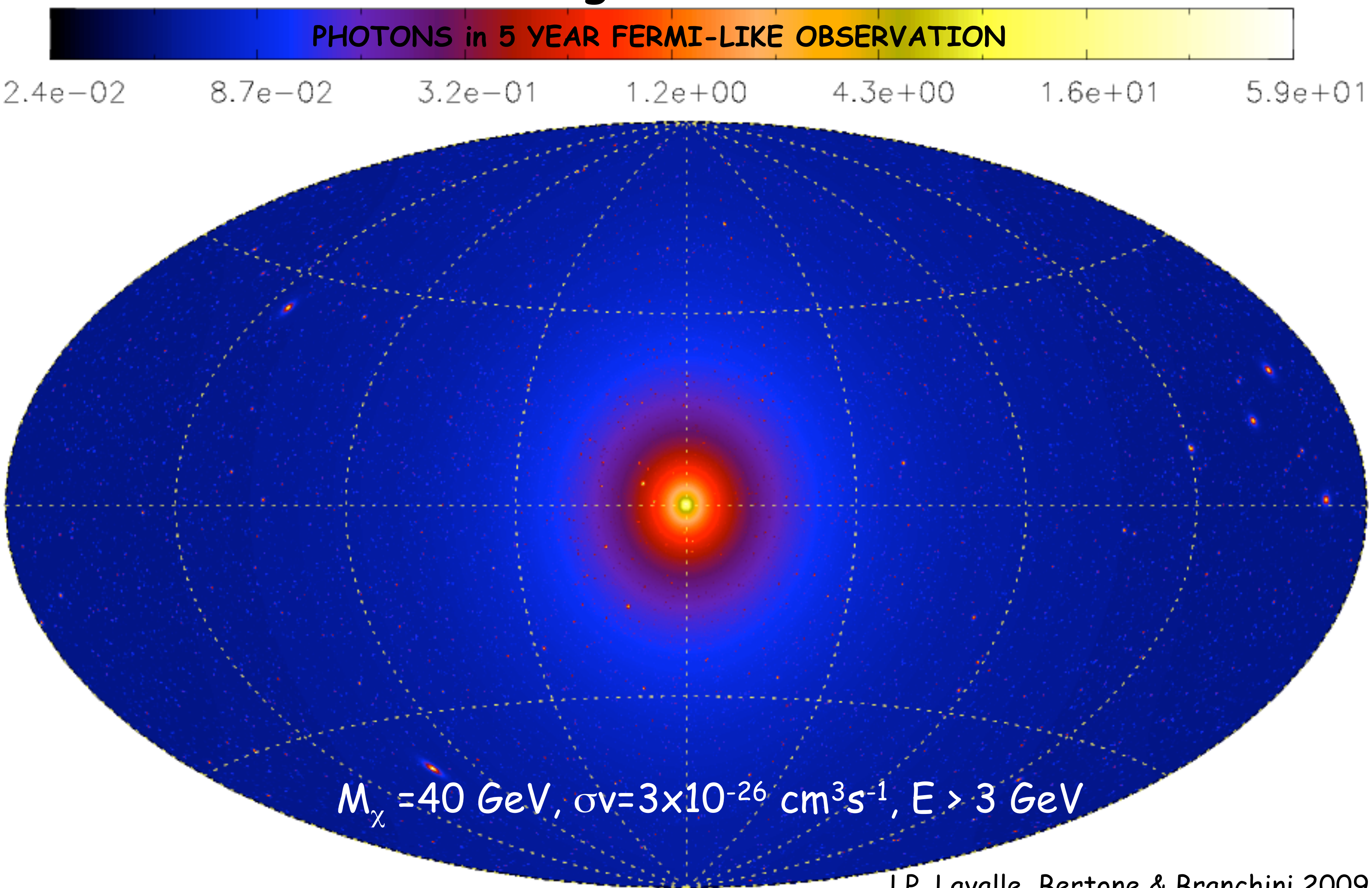
$$M\Delta_M^2 \rightarrow \int_{M_{min}} dM_{sub} \int_0^{R_{vir}(M)} 4\pi R^2 dR \int dc P(c) M_{sub} \rho_{sh}(M_{sub}, M, R) c(M_{sub}, R)^3 \frac{I_2(c)}{I_1^2(c)}$$

Normalized to subhalo mass fraction f(M)

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

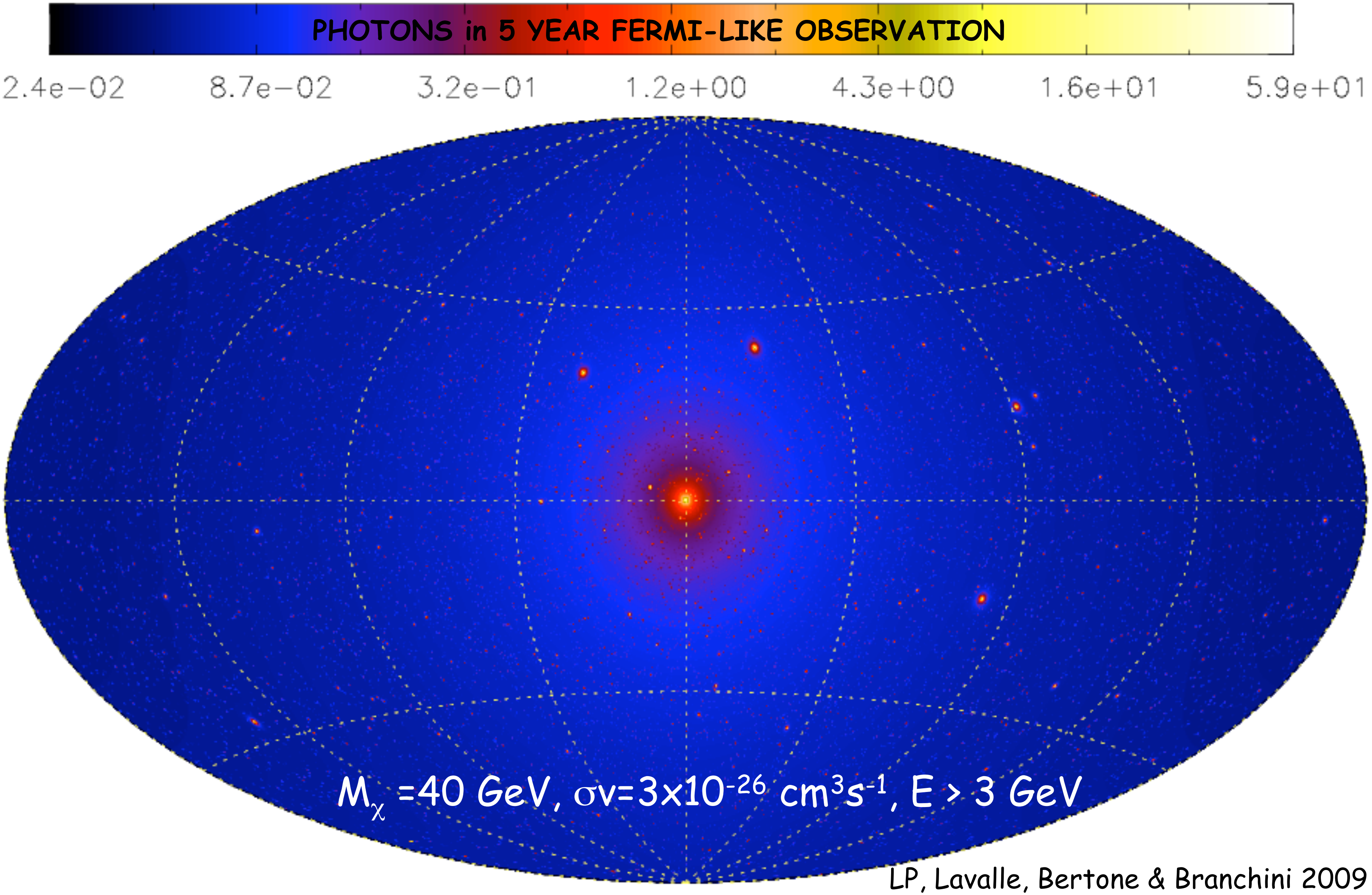
We modeled the LOS integral and integrated the signal over all sources

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



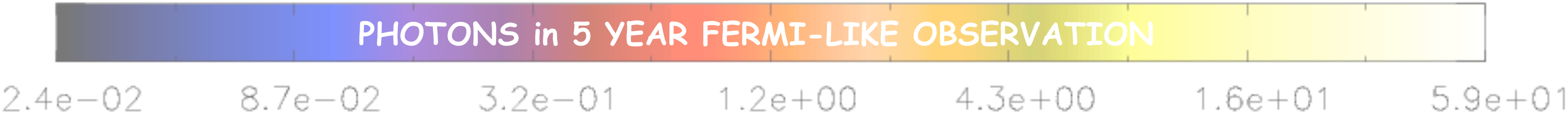
LP, Lavalle, Bertone & Branchini 2009

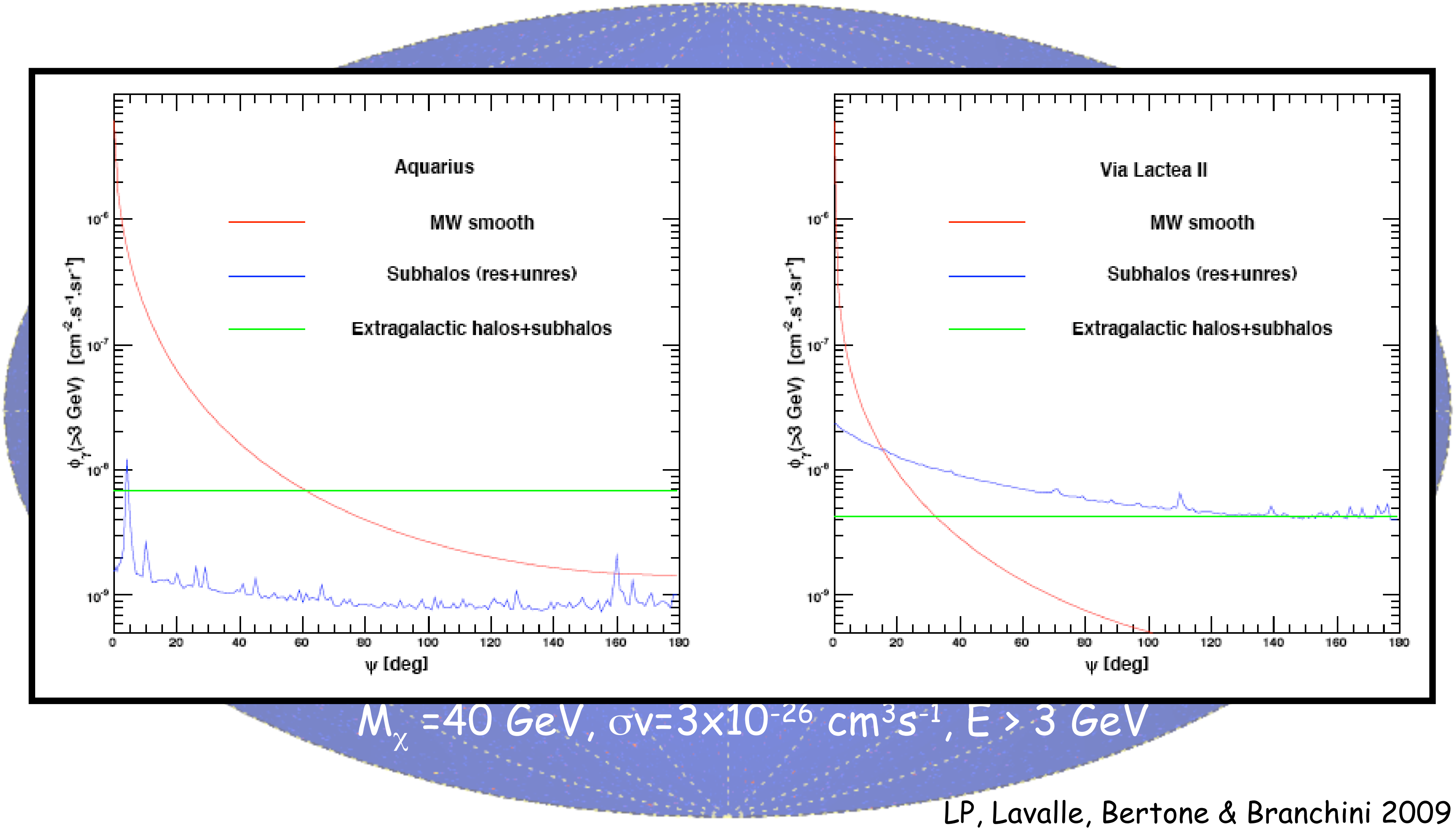
The γ-ray sky (Via Lactea 2)
Galactic and extragalactic: smooth + subhalos



LP, Lavalle, Bertone & Branchini 2009

The γ-ray sky
Galactic and extragalactic: Smooth + subhalos

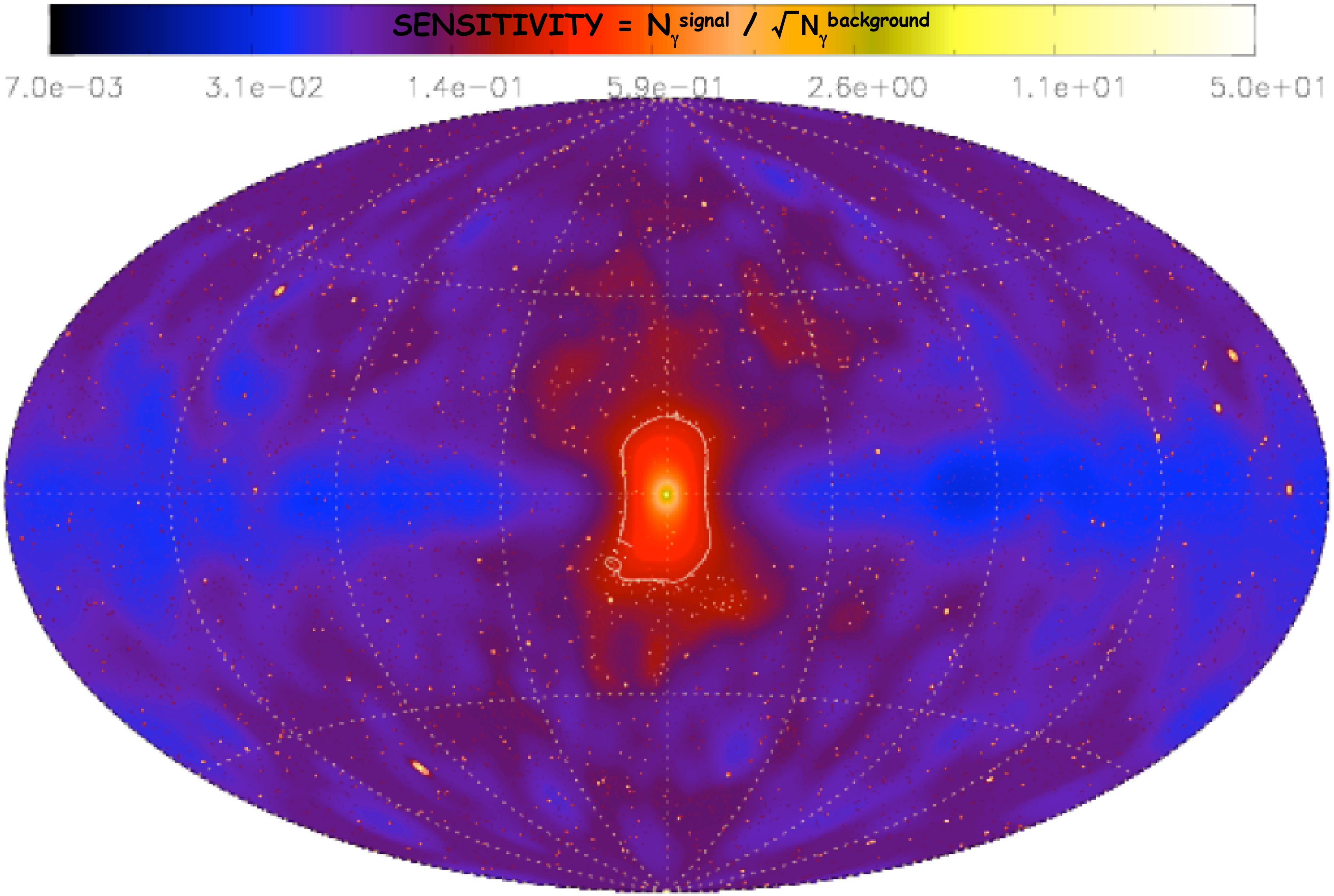




M_χ =40 GeV, $\sigma v = 3\times10^{-26}$ cm^3s^{-1}, E > 3 GeV

LP, Lavalle, Bertone & Branchini 2009

Is the γ-ray sky from DM annihilation DETECTABLE?



LP, Lavalle, Bertone & Branchini 2009

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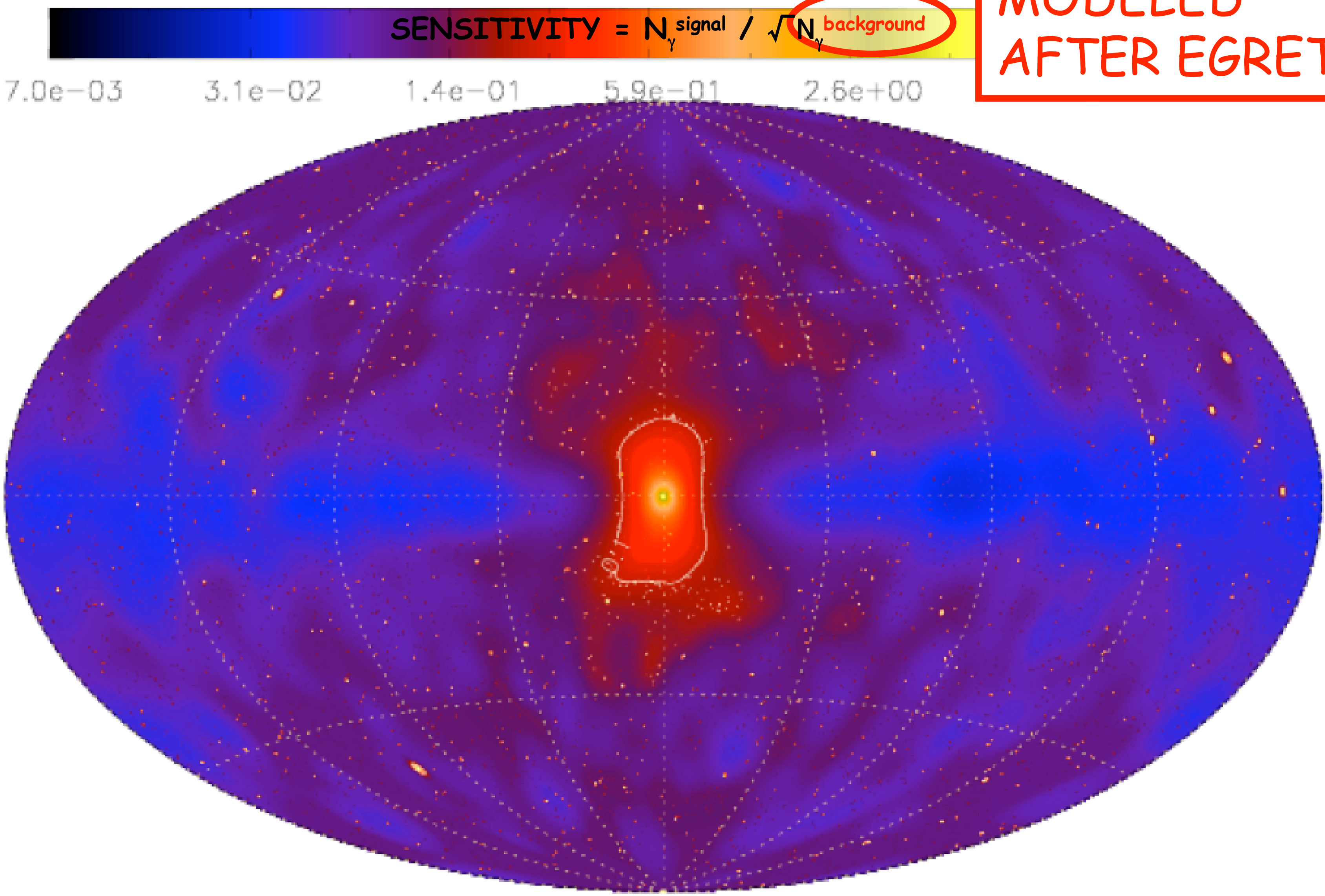


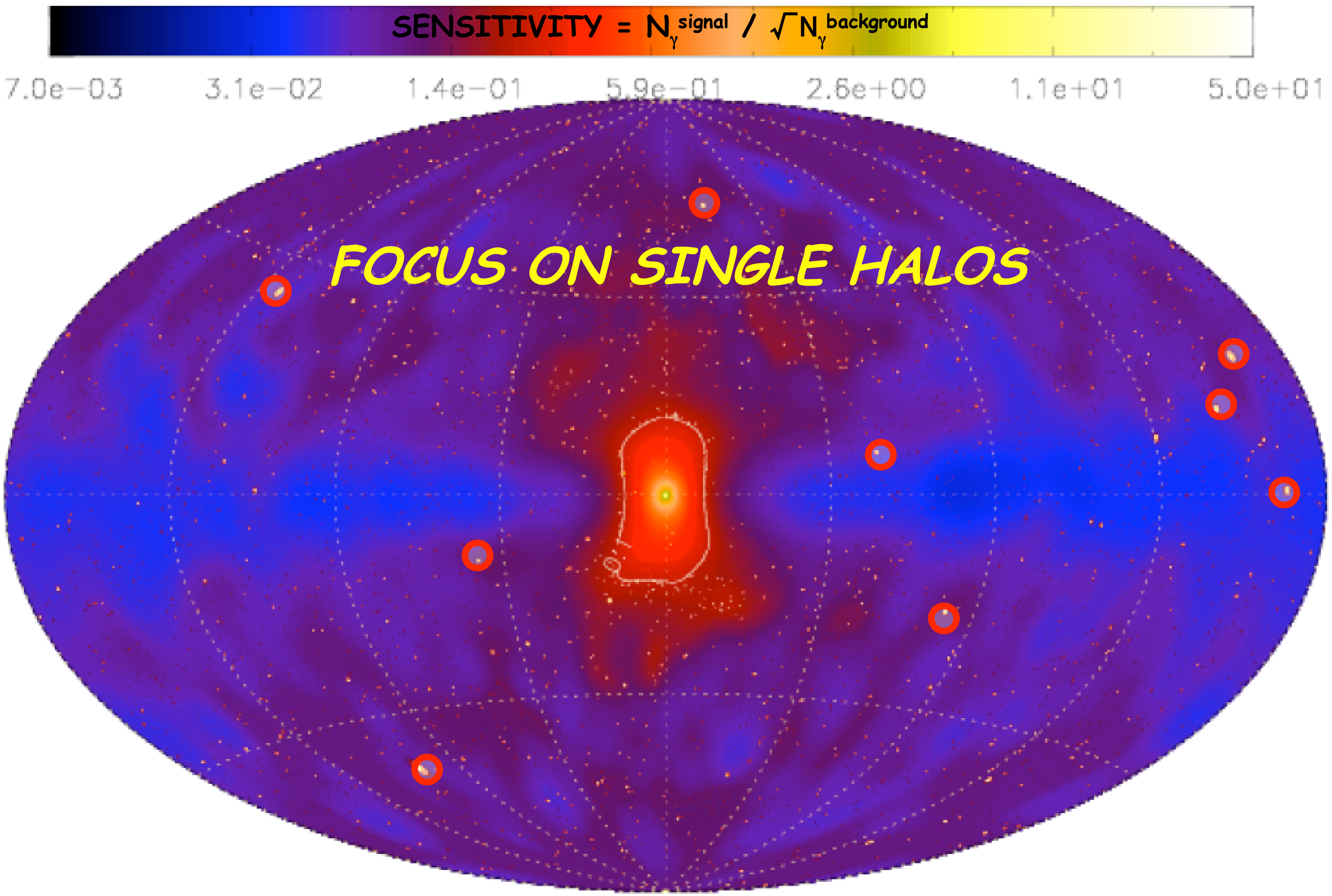
MODELED AFTER EGRET!!

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?



LP, Lavalle, Bertone & Branchini 2009

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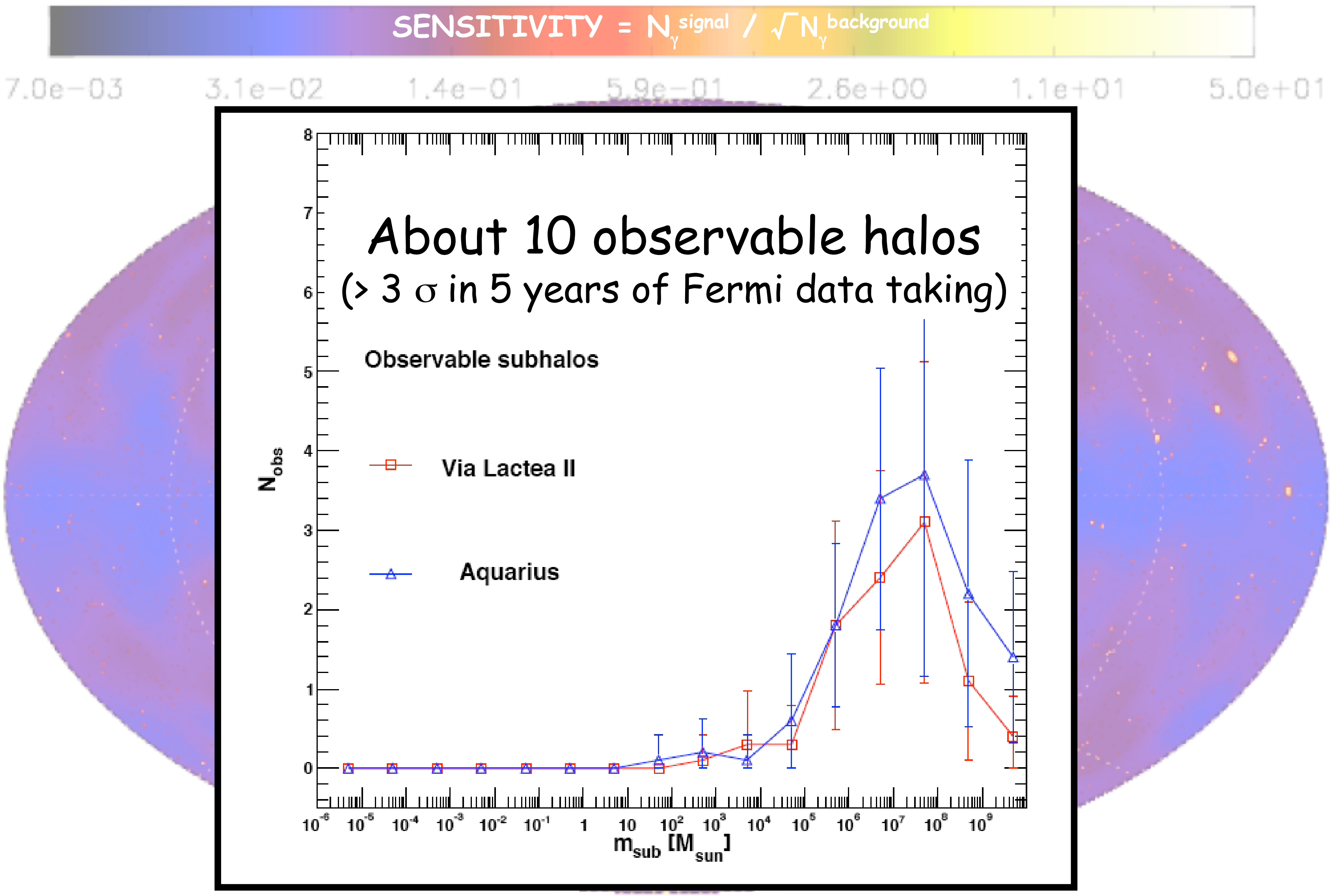
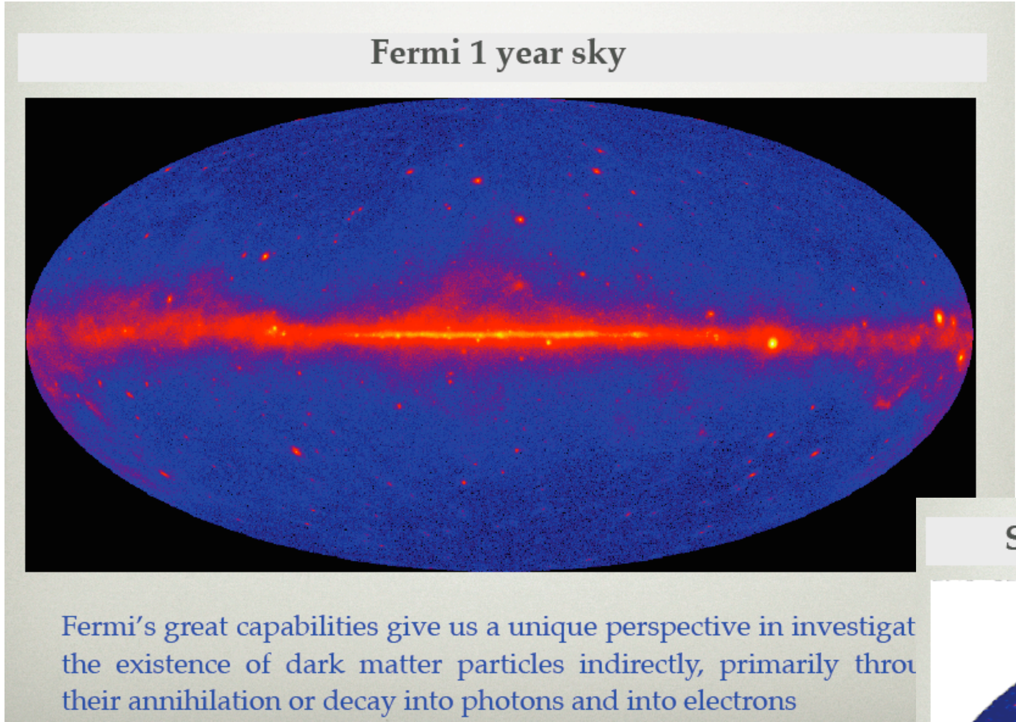
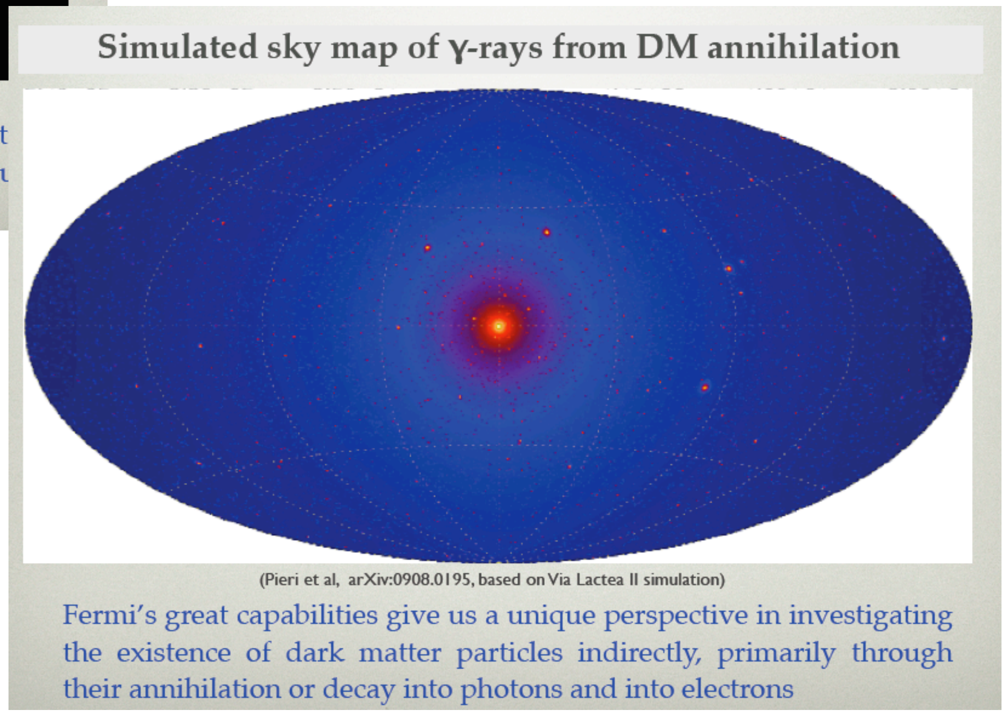


LP, Lavalle, Bertone & Branchini 2009

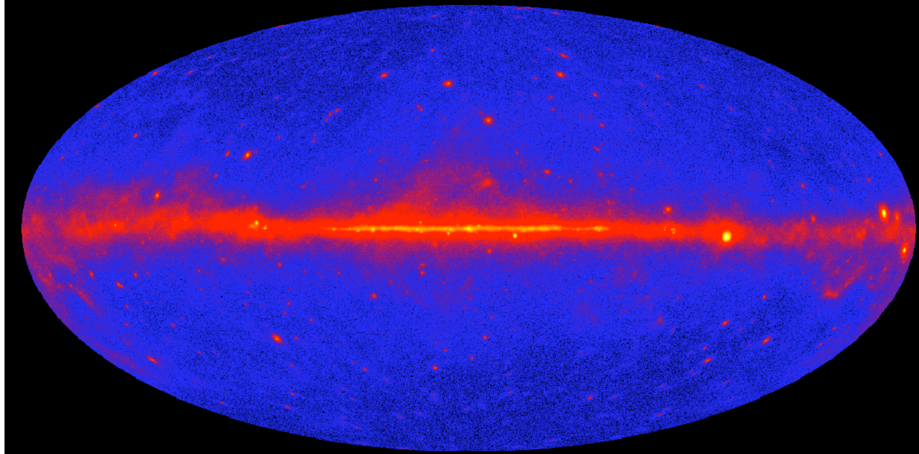
to be compared with Fermi 1-year data





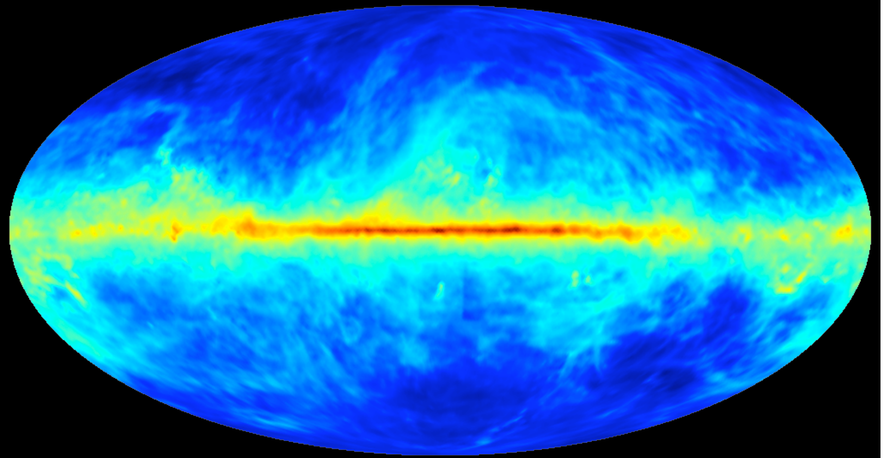
First slides from DM presentation
at Fermi symposium,
Nov. 2009, credit: Simona Murgia

to be compared with Fermi 1-year data after background subtraction



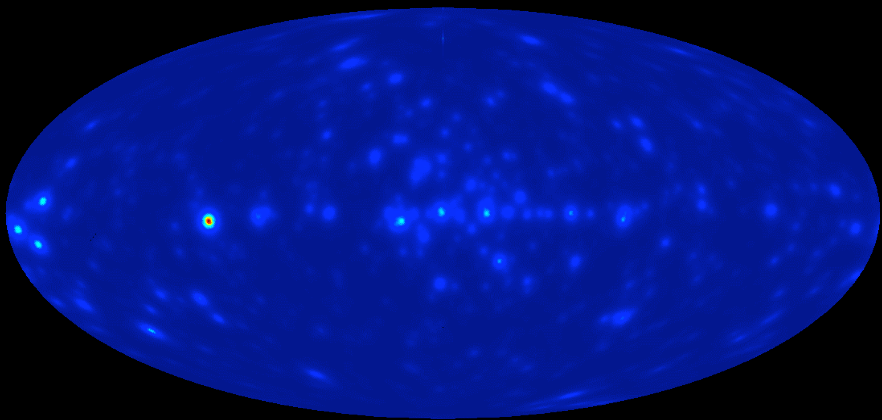
Fermi data

–



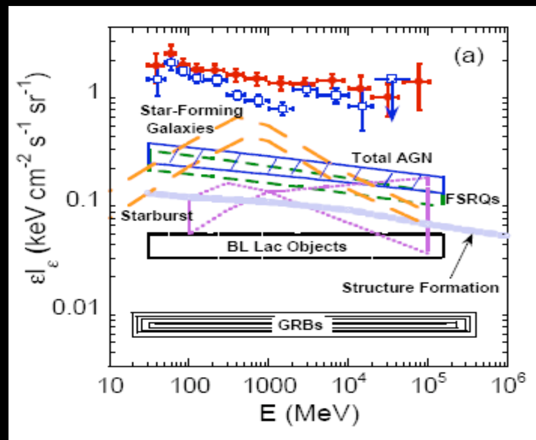
galactic diffuse

–



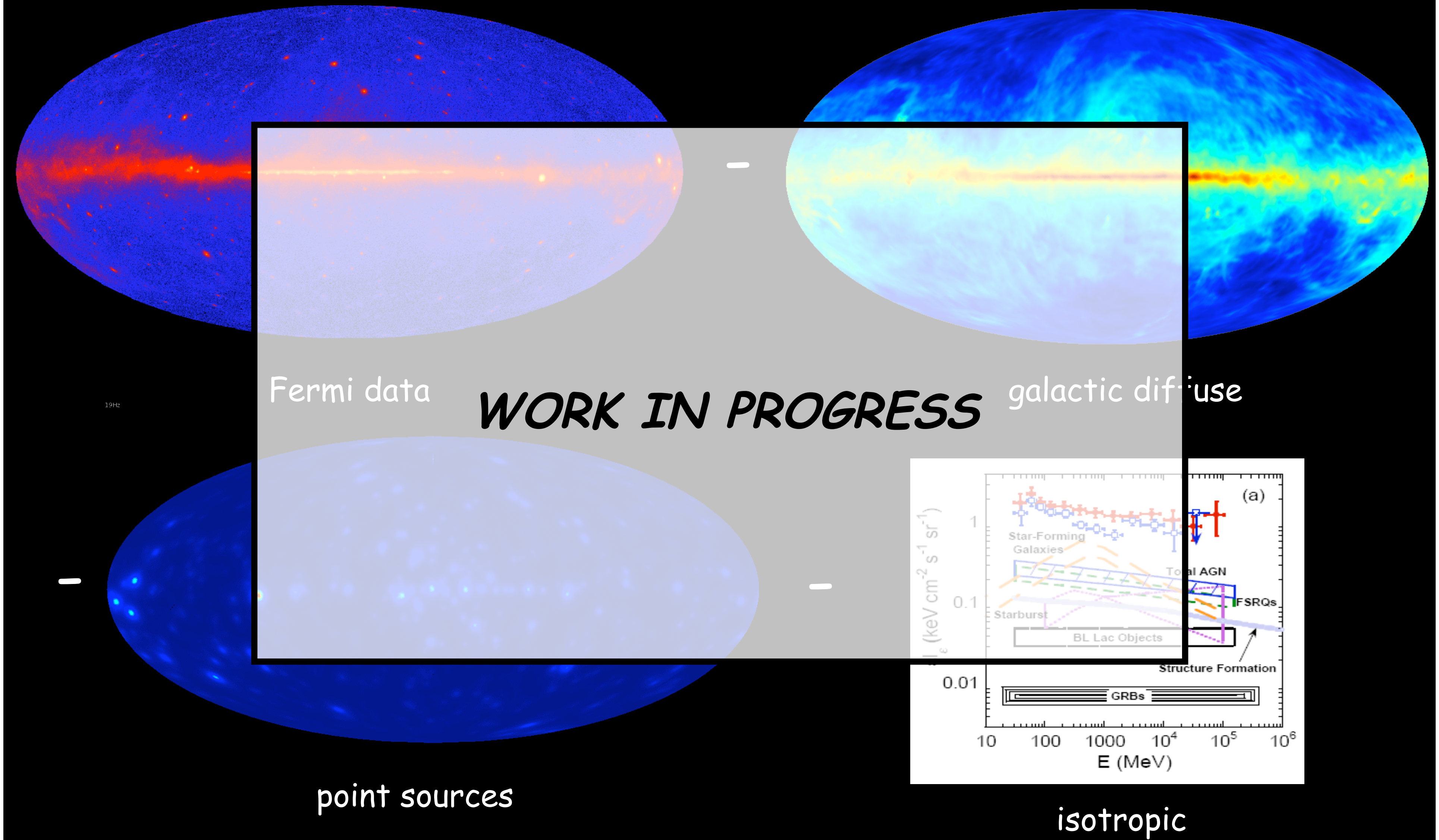
point sources

–



isotropic

to be compared with Fermi 1-year data after background subtraction



Indirect detection of dark matter:

The role of substructures

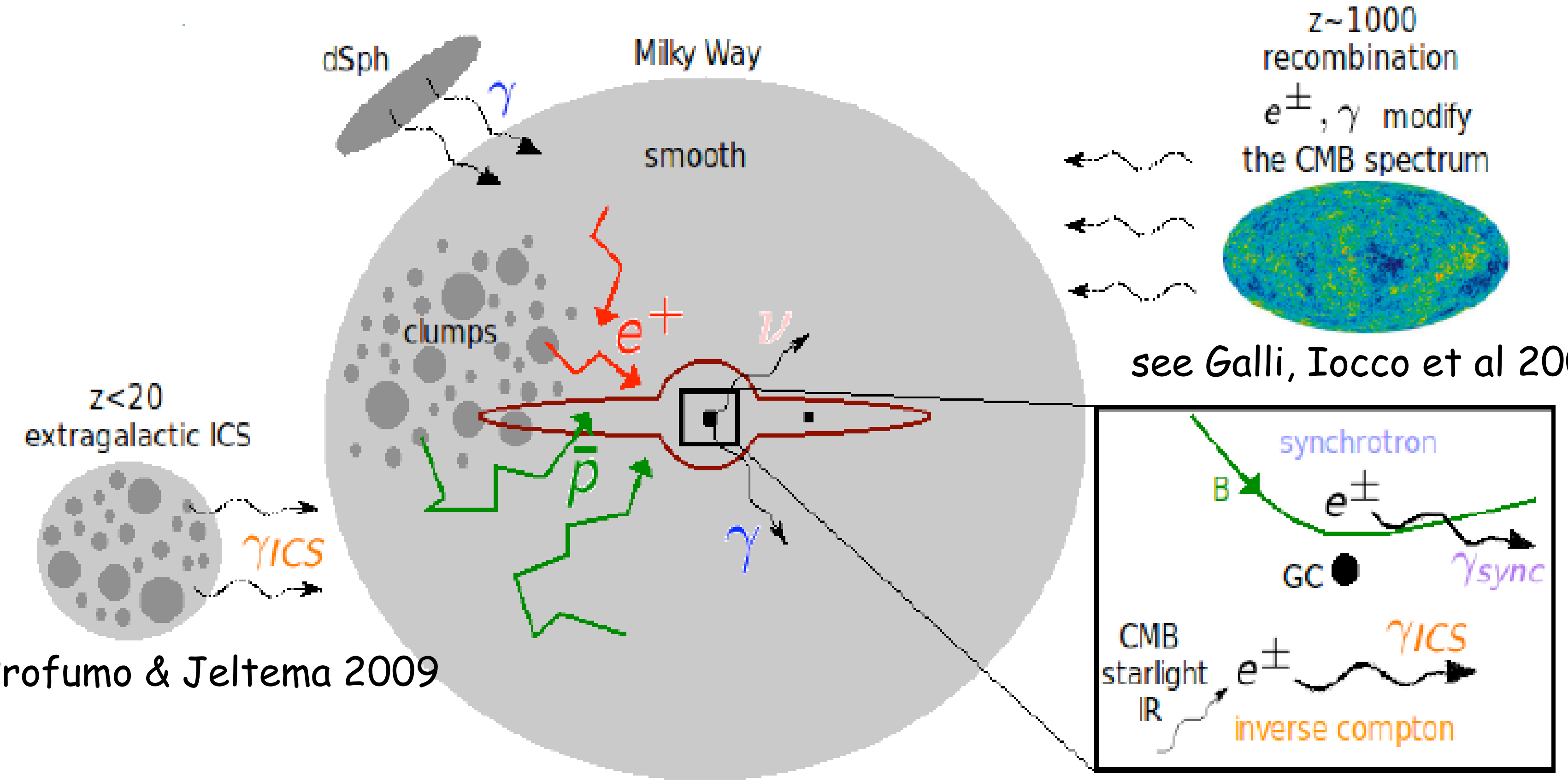
Subhalo population of our galaxy:

-Prospects for detection in γ-rays

-Multi-wavelength analysis

The multiwavelength/multimessenger/multitarget approach

Φ = ParticlePhysics x Cosmology/Astrophysics x Transport

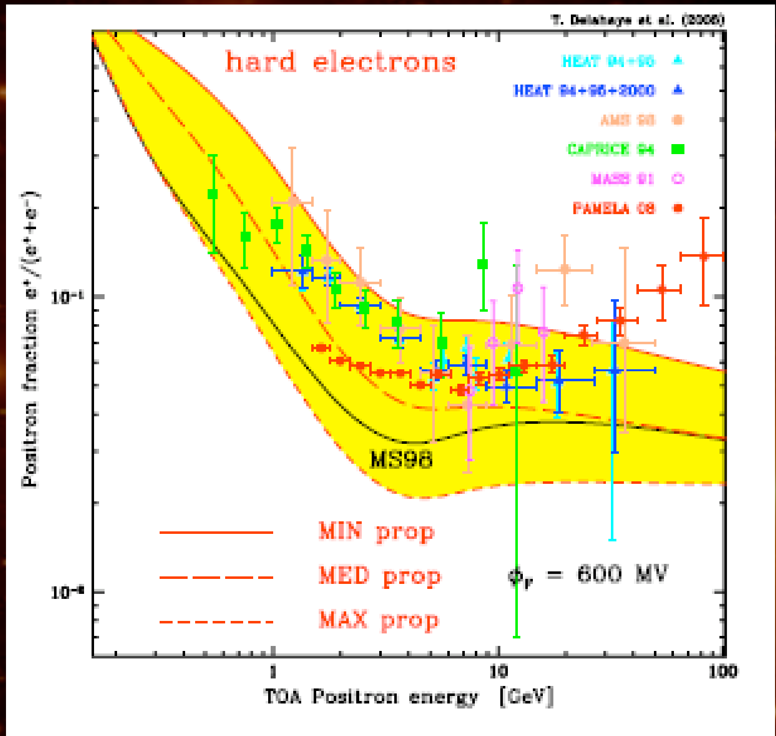


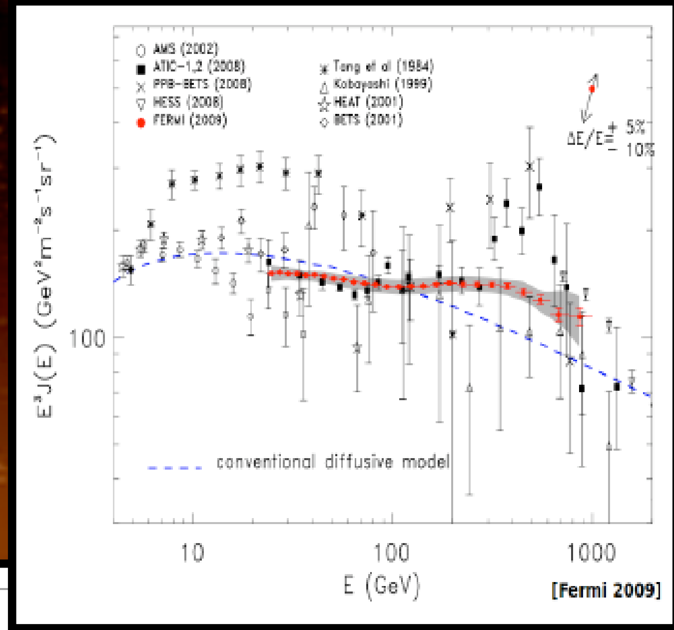
see Galli, Iocco et al 2009

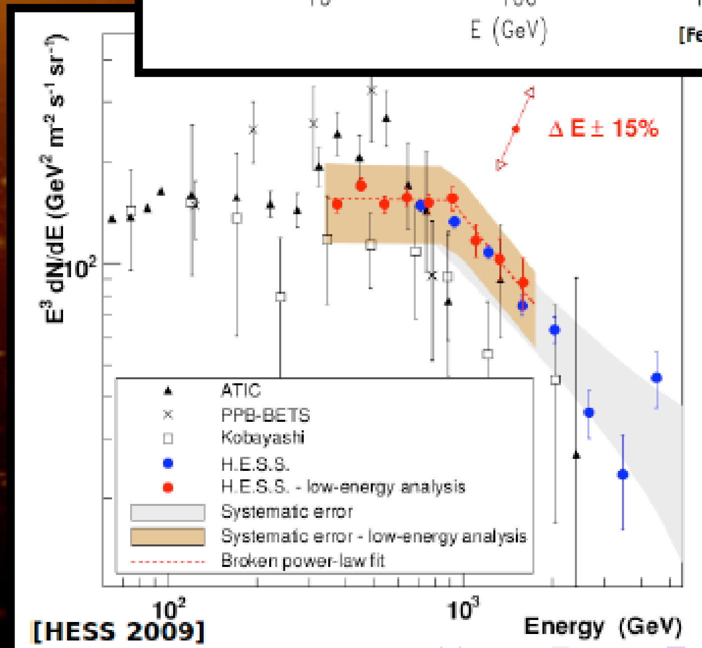
see Profumo & Jeltema 2009

Slide: courtesy of M. Pato

The case of a "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)

A new approach is needed

DARK MATTER THEORY (PP and COSMO)

looking for a good candidate, as well as for boosting effects from particle physics and astrophysics

THE DATA

cosmic rays

γ-rays

radio photons

anisotropies

CMB…

DARK MATTER HYPOTHESIS: PHENOMENOLOGICAL TEST

multi-messenger
multi-observer
multi-wavelength

Verification, Constraints, Expected sensitivities

The radio sky
GC, no subhalos

Assume a magnetic field

7.2 mG	r<0.04pc
$7.2\ \mathrm{mG}(r/0.04\mathrm{pc})^{-2}$	0.04pc<r<3.38pc
$1\ \mu\mathrm{G}$	r>3.38pc

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

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

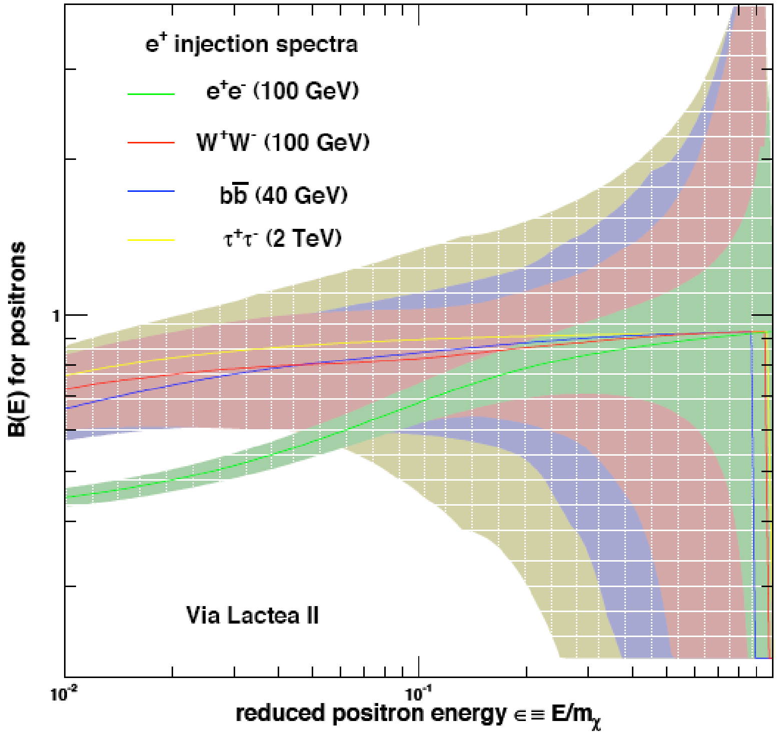
galactic winds

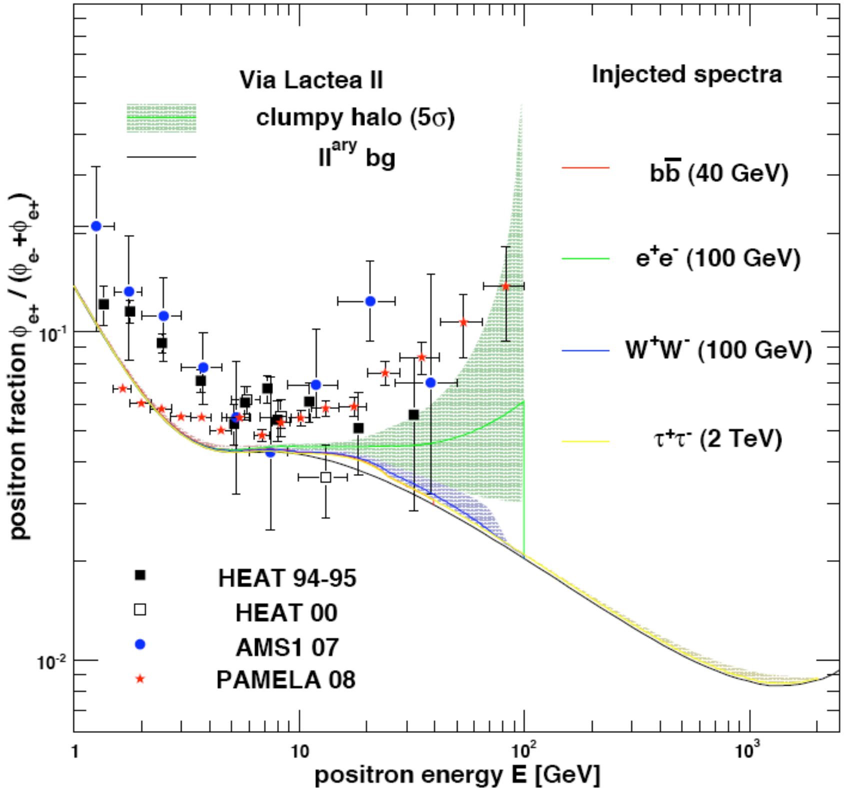
Compute fluxes and boosts à la Lavalle 2008

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

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

The antimatter sky





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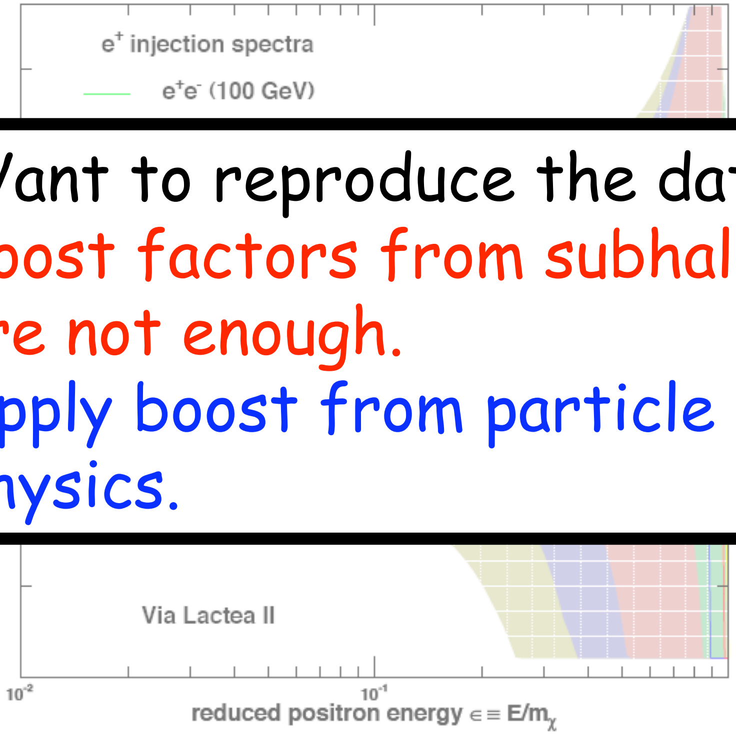
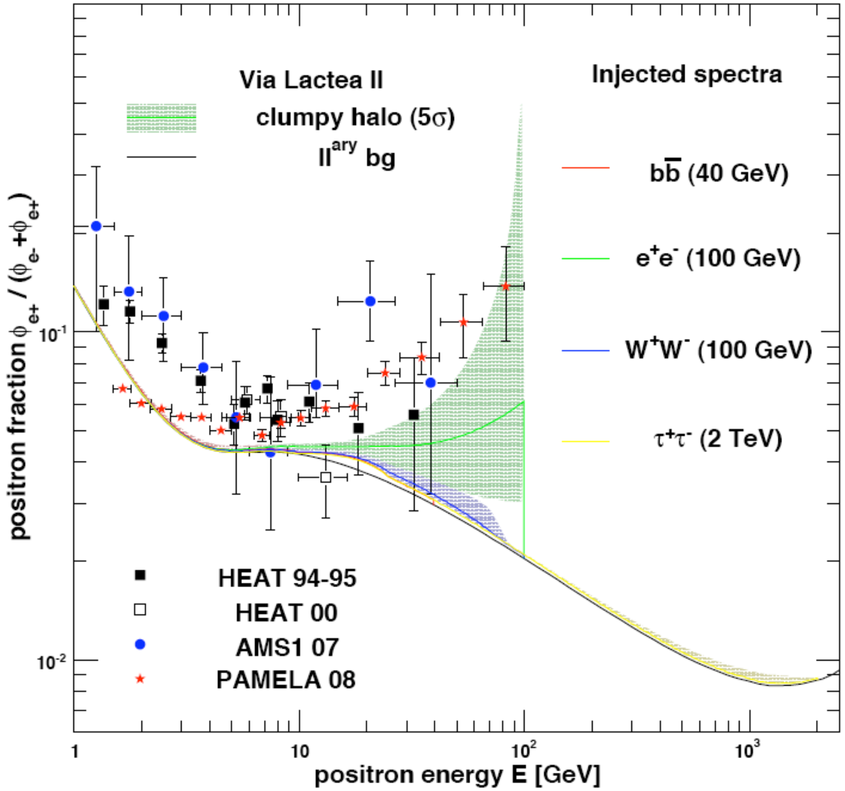
LP, Lavalle, Bertone & Branchini 2009

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

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

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LP, Lavalle, Bertone & Branchini 2009

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

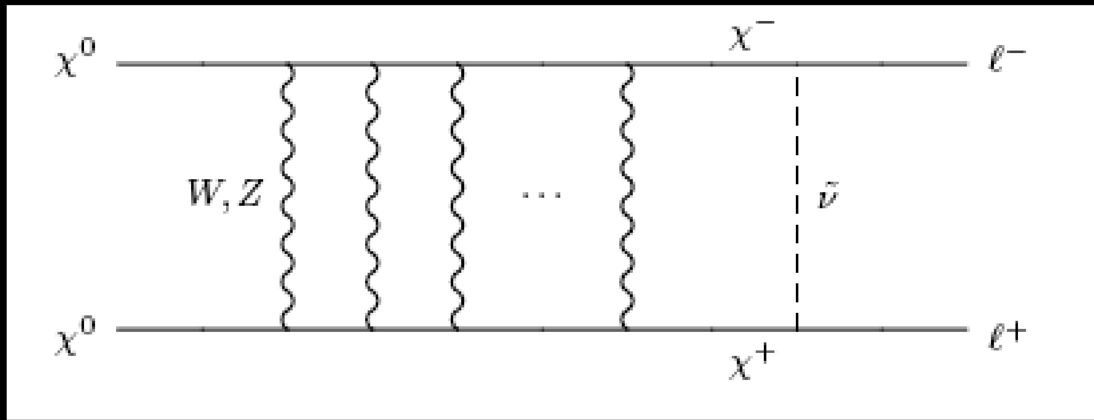
p, π

l,q

GeV γ with a high energy tail

π^0

Internal bremmstrahlung
GeV-TeV γ E>0.6 m_{DM}



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

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

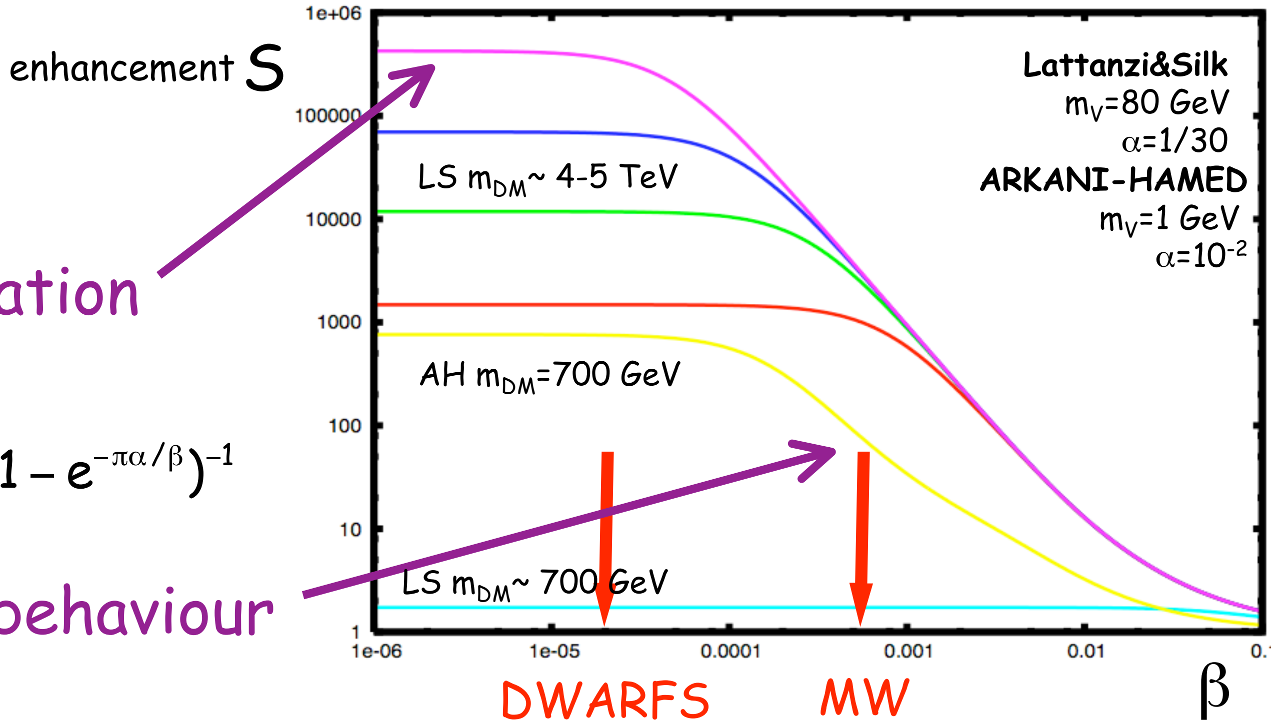
$$\beta << \sqrt{\frac{\alpha m_V}{m_{DM}}} \rightarrow S = S_{max}$$

saturation

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

1/v behaviour

β dependence



Particle Physics BF: Sommerfeld enhancement

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

NOTE: 1/v EFFECT IS PARAMETER DEPENDENT

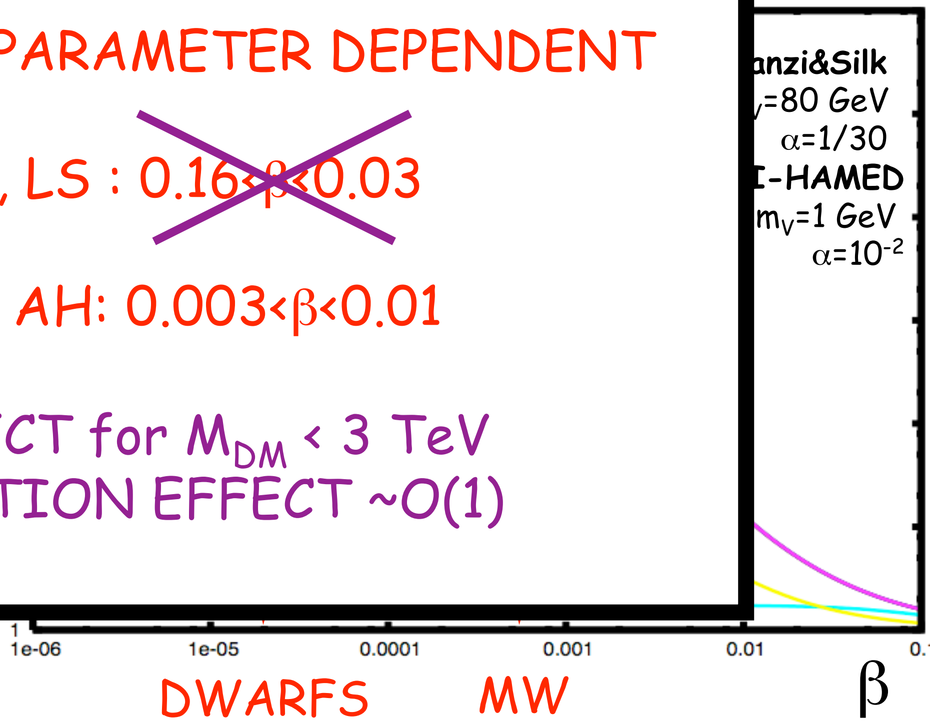
~~m_{DM}=100 GeV , LS : 0.16<β<0.03~~

AH: 0.003<β<0.01

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

$\beta <<$

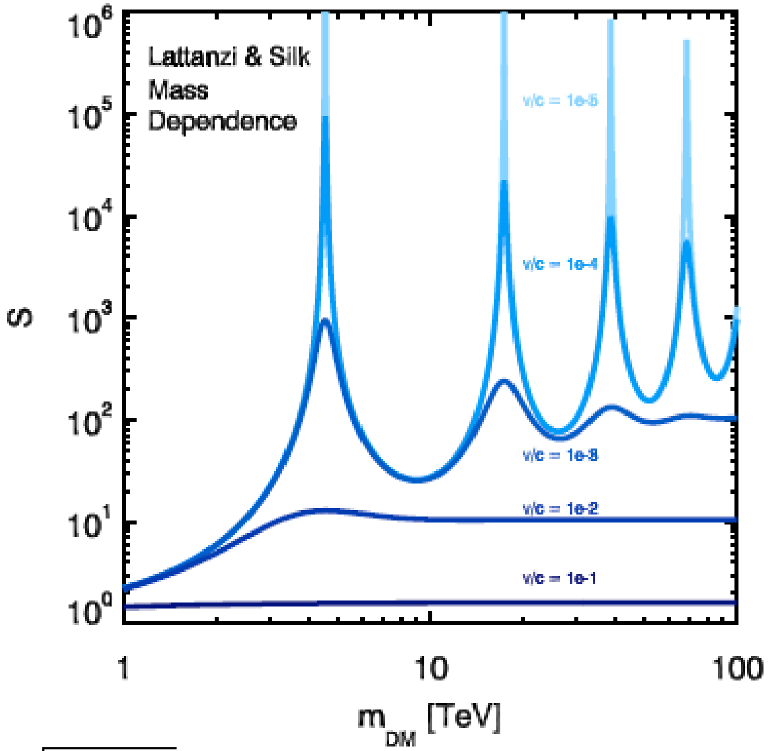
$\sqrt{\frac{\alpha m_V}{m_{DM}}} < \beta$



Particle Physics BF: Sommerfeld enhancement

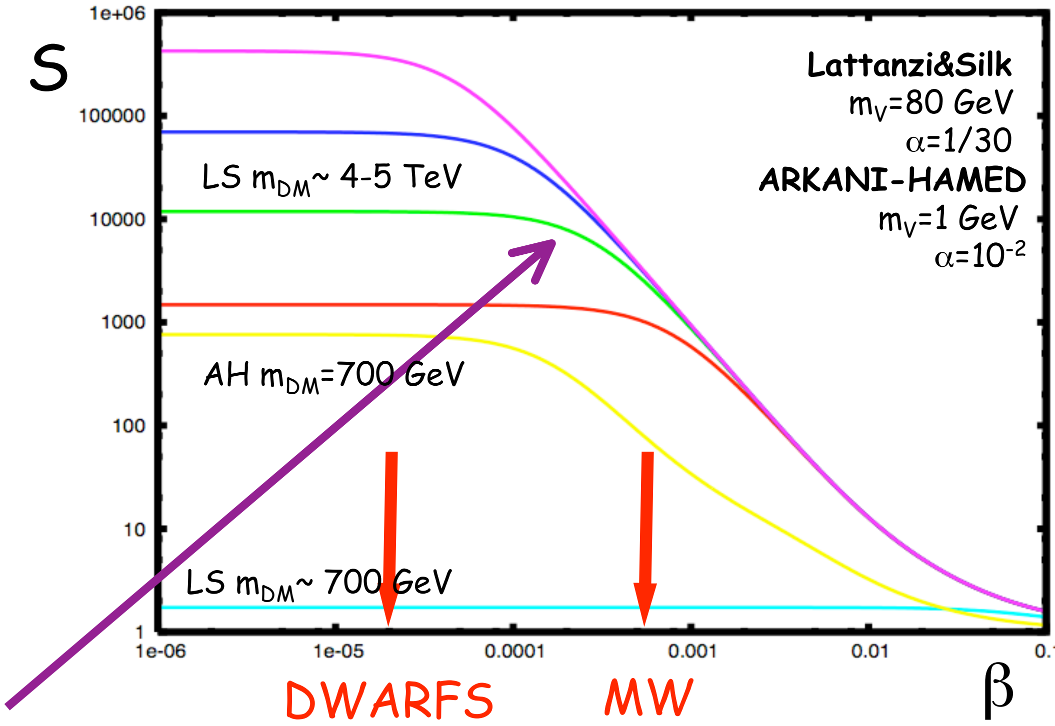
Sommerfeld effect produces a local enhancement of the annihilation cross-section which depends on the DM velocity and mass, and does not touch the thermal value

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

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

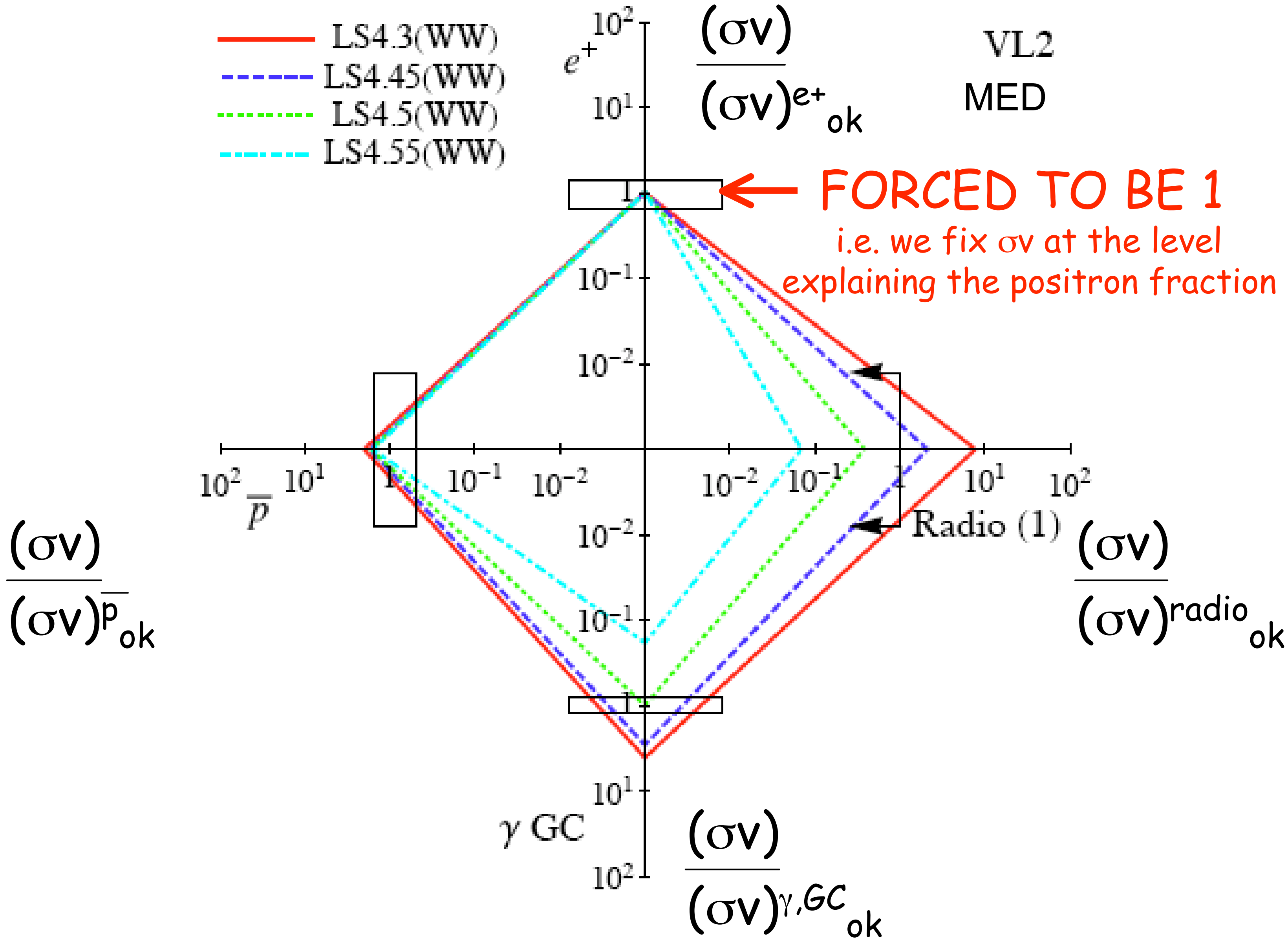
$$\Phi = T(E,d) \frac{(\sigma_{ann} v)_{thermal}}{2m_\chi^2} \int_{E_0}^{m_\chi} \sum_f \frac{dN_f^\gamma}{dE_\gamma} BR_f \int_{l.o.s} d\lambda S(\beta(M,r)) \rho_{DM}^2 \left(M, c(M,r), R \right)$$

This holds for all annihilation products

We can perform a multi-wavelength analysis to constrain models

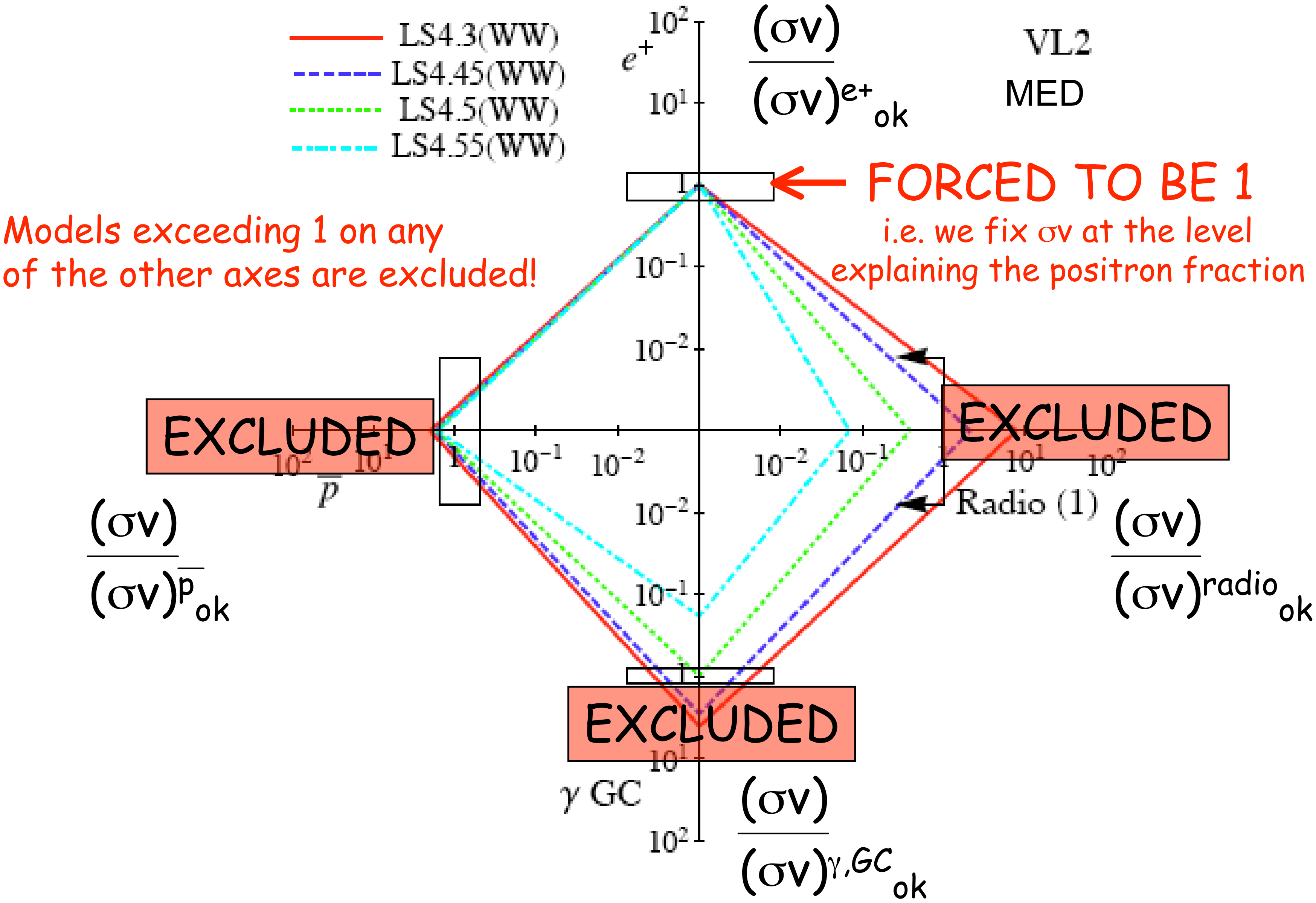
APPLYING BOOSTS TO BOTH Φ_{PP} AND Φ_{COSMO}

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

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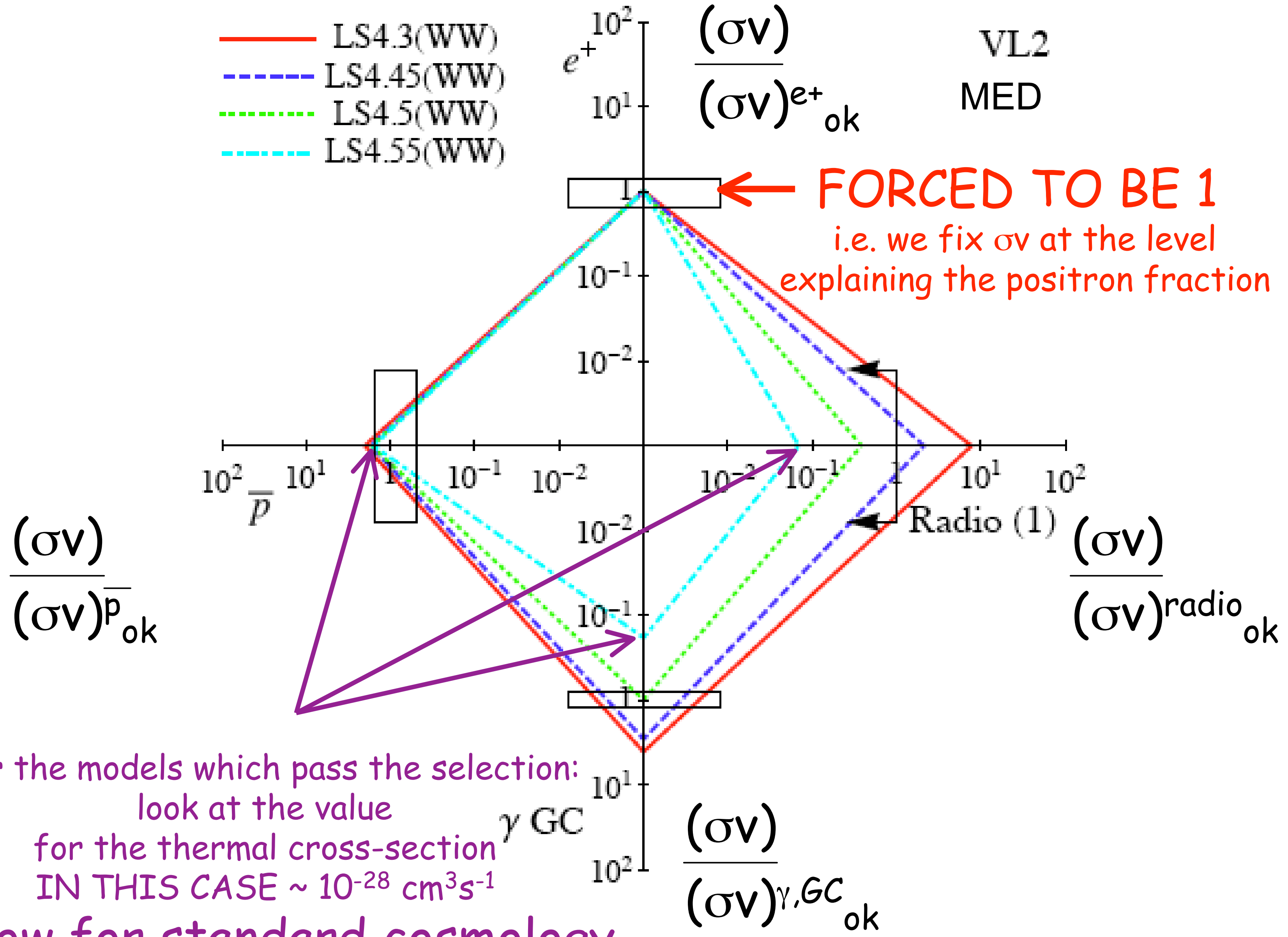
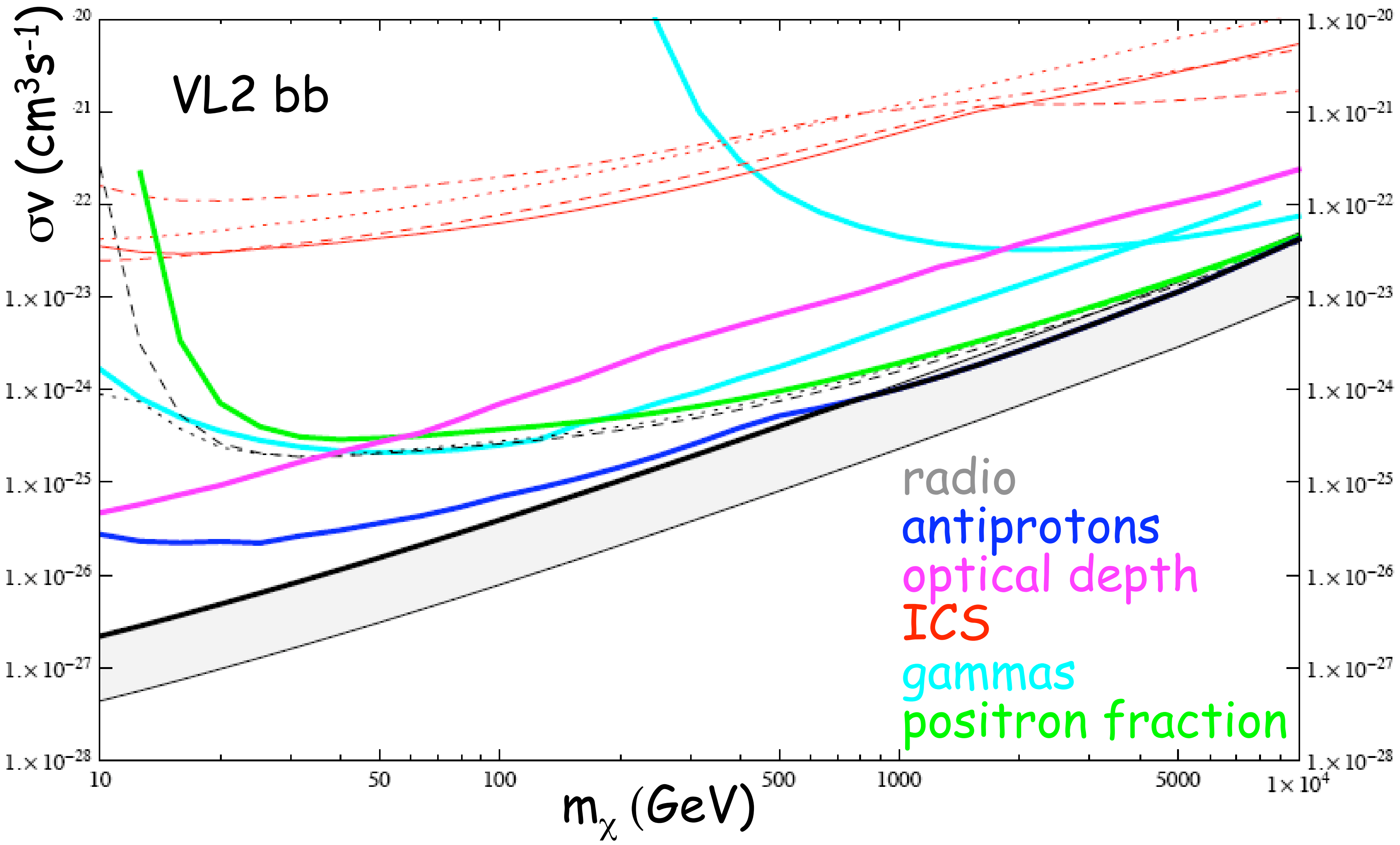


Too low for standard cosmology...

Pato, LP, Bertone 2009

Warning: any model, to be observed, must be compatible with multi-messenger constraints



Catena, Fornengo, Masiero, Pato, Pieri, *in preparation*

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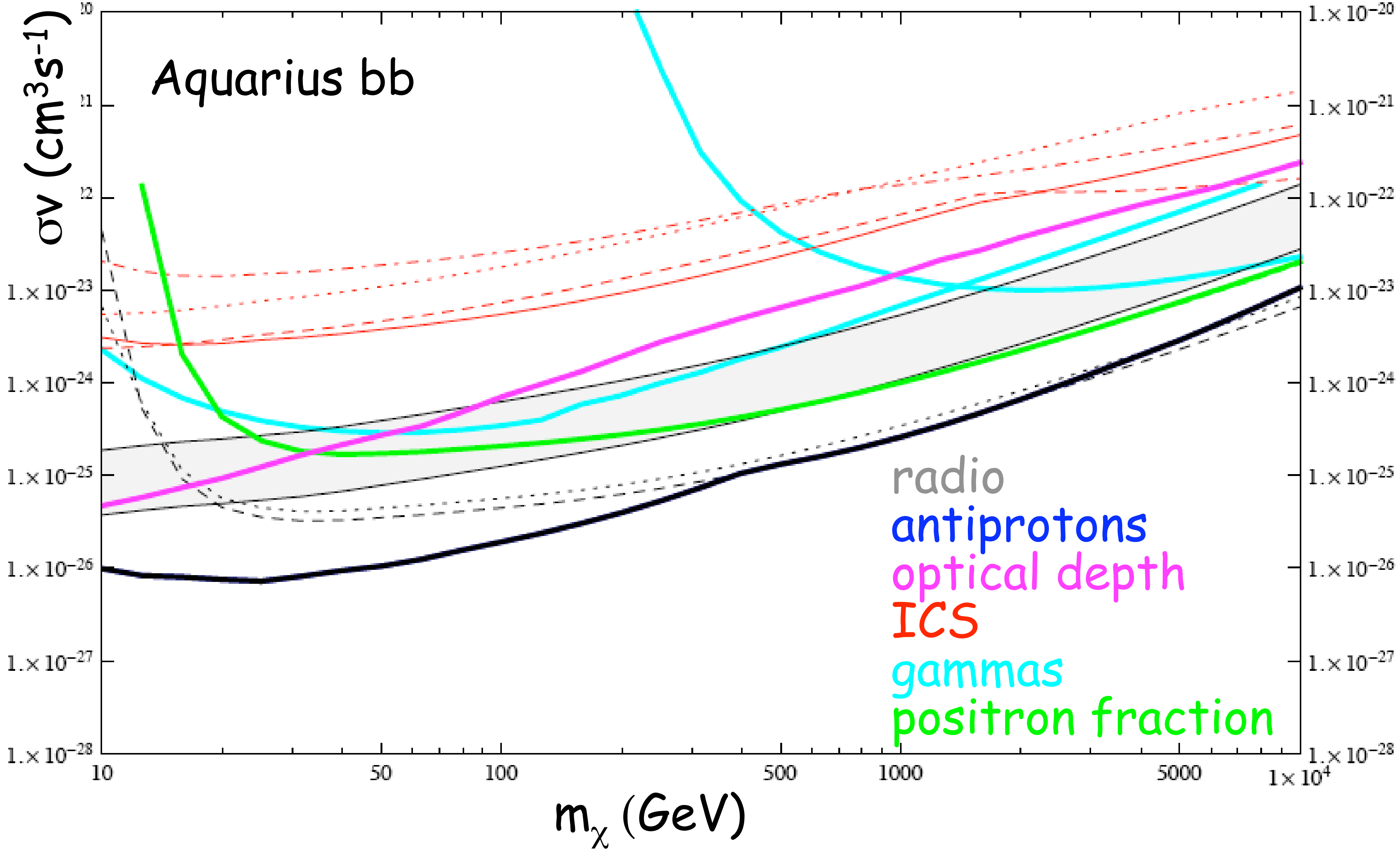

Catena, Fornengo, Masiero, Pato, Pieri, *in preparation*

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