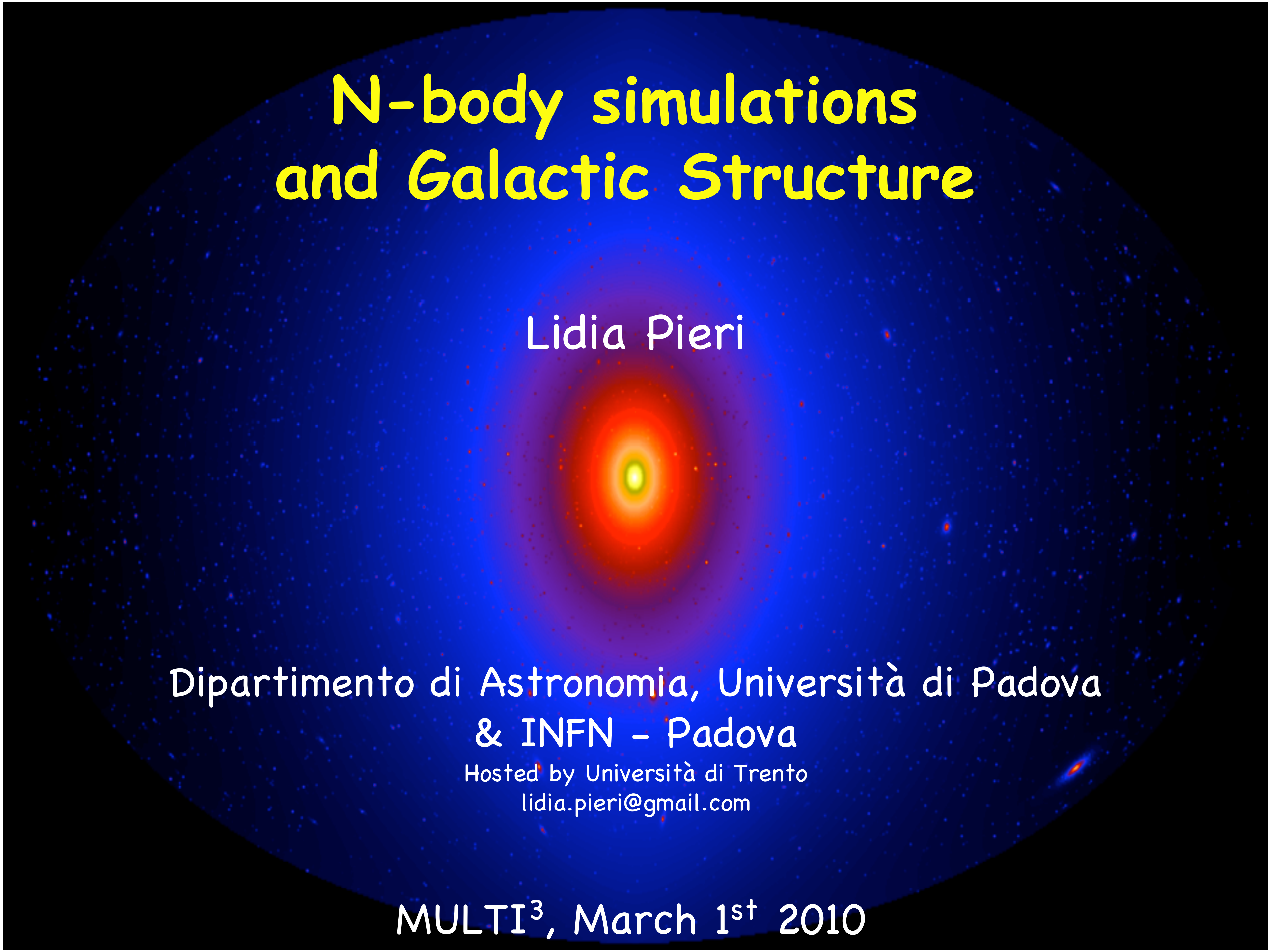

N-body simulations and Galactic Structure

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Hosted by Università di Trento
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MULTI^3, March 1st 2010

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

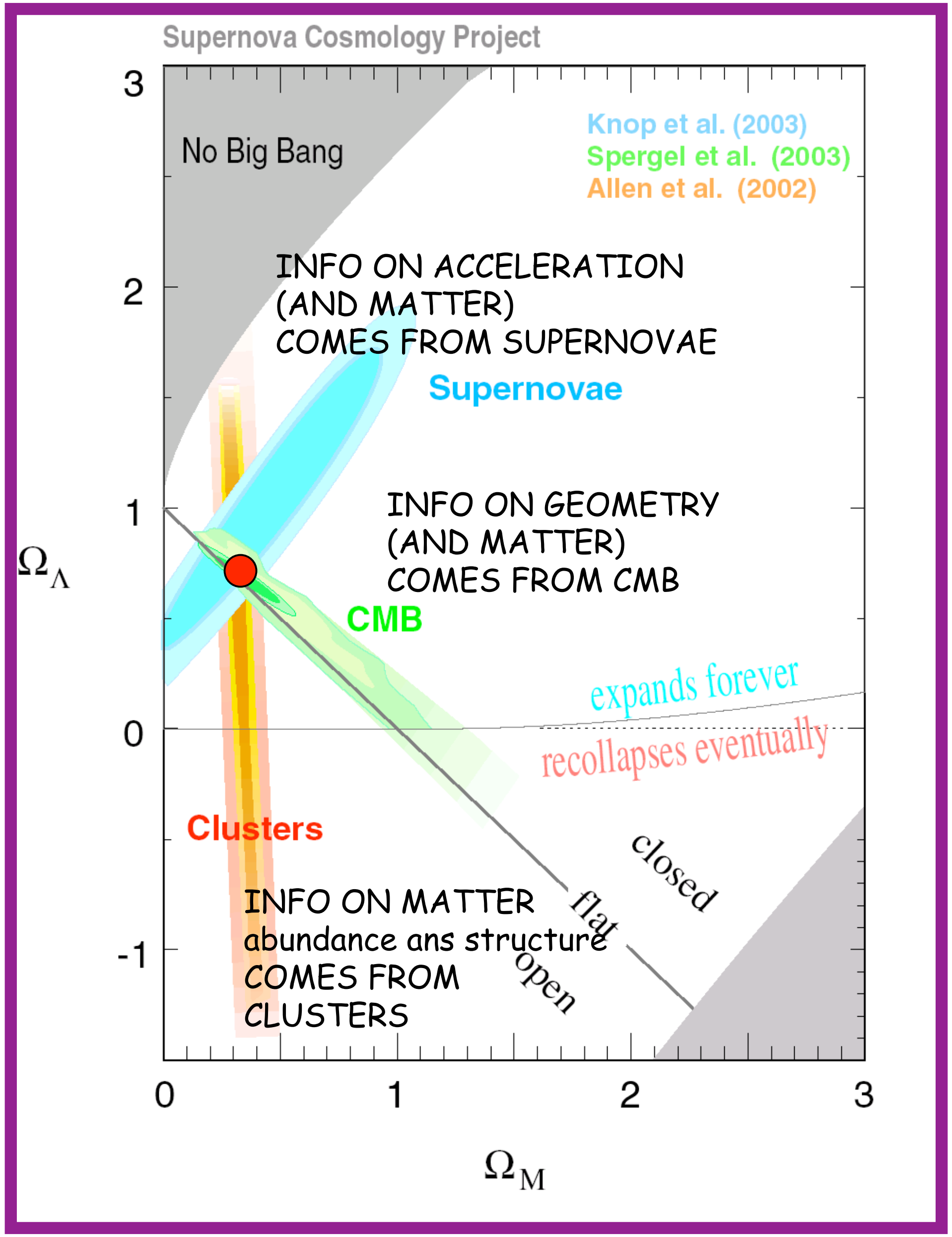
- an unknown form of repulsive energy, or dark energy

$\Omega_\Lambda \sim 0.73$

- an unknown type of non baryonic matter, or

DARK MATTER

$\Omega_{DM} \sim 0.23$



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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

VS the observed minor components

Ω_b ~ 0.005 (galaxies)

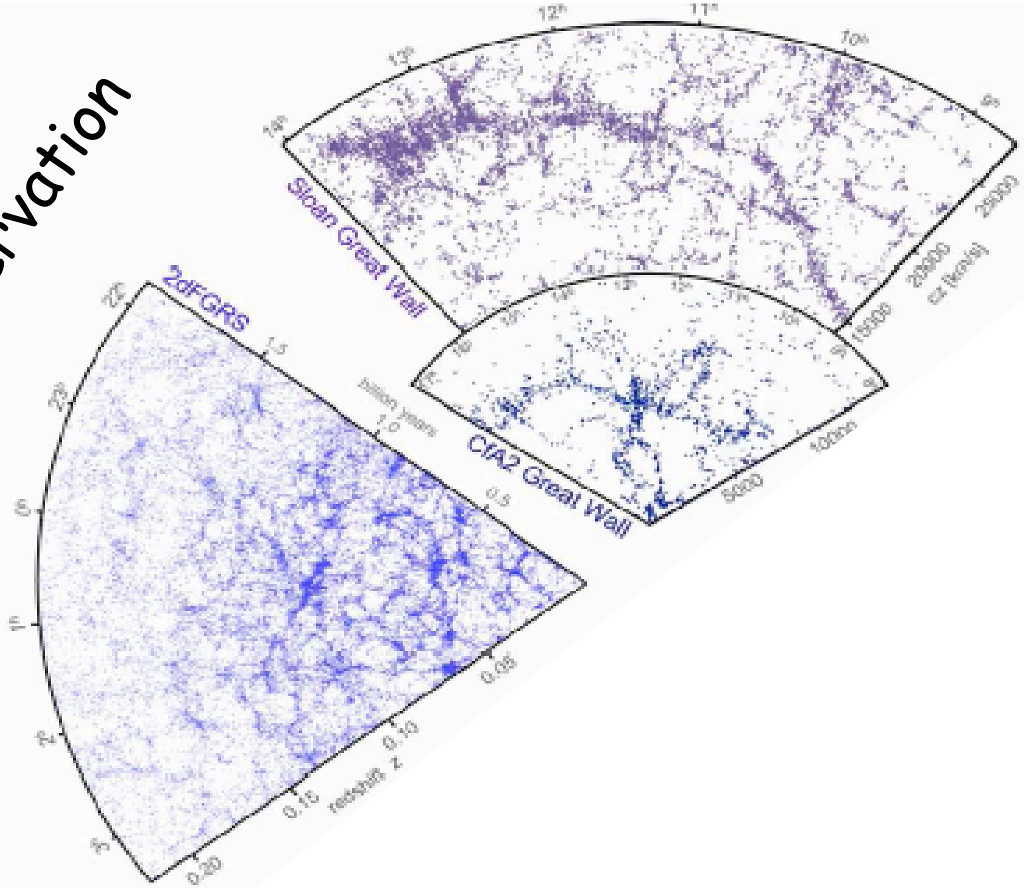
Ω_b ~ 0.04 (BBN)

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

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

Infos on matter abundance and structure come from large scale structure observation

Observation



Can theory of structure formation reproduce the observed Universe?

Theory of structure formation and N-body simulations

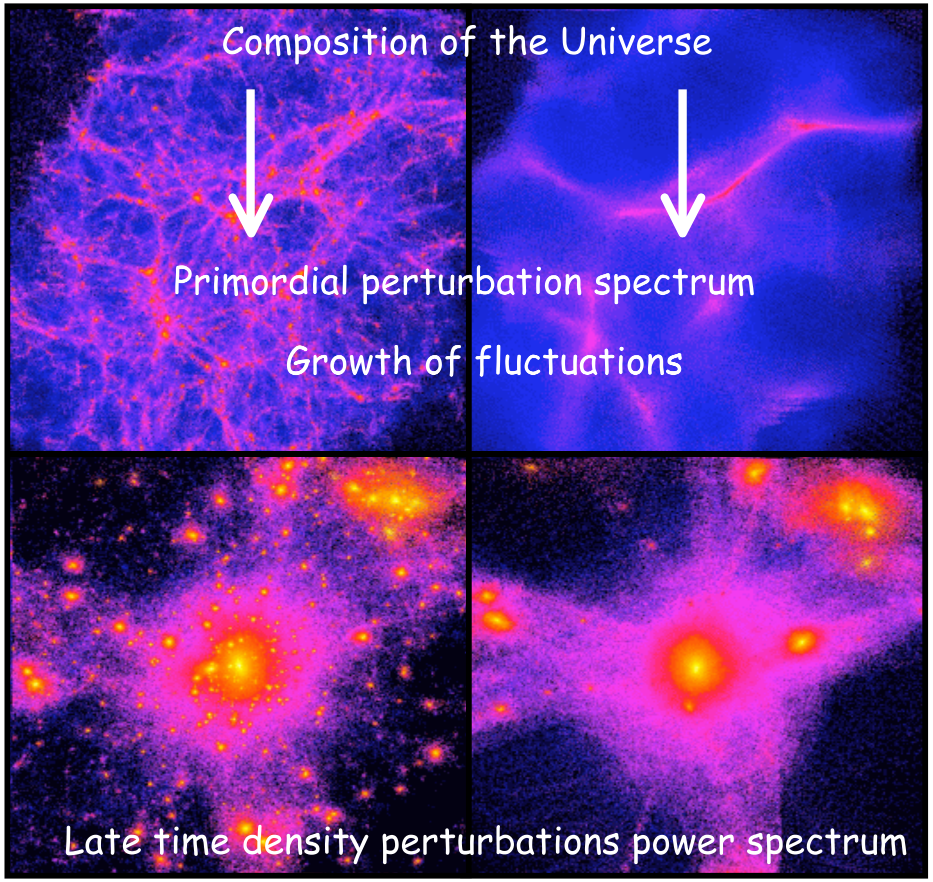
DM halos
Primordial density fluctuations grow and collapse in gravitationally bound structures which eventually virialize and form halos.

Particle nature of DM determines primordial power spectrum and assembly hystory.
Baryons are captured in the dark matter potential well and form galaxies, clusters, etc.

Once the power spectrum is fixed, the evolution is driven by gravitational force, and can be followed via numerical N-body simulations.

non-relativistic particles form smaller halos

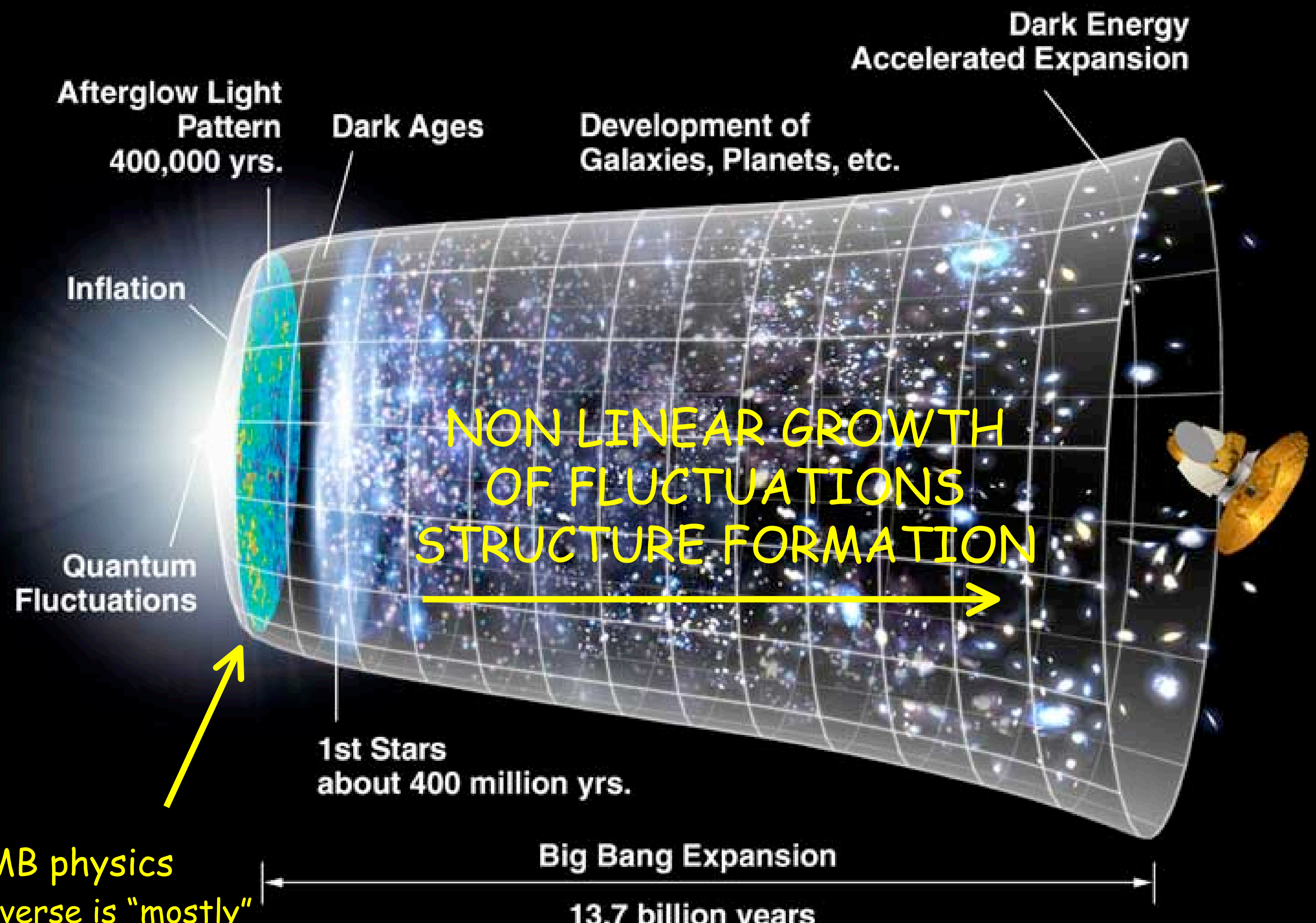
relativistic particles have larger kinetic energy and need larger mass to be gravitationally bound



Cold dark matter

Hot dark matter

The thermal history of the universe



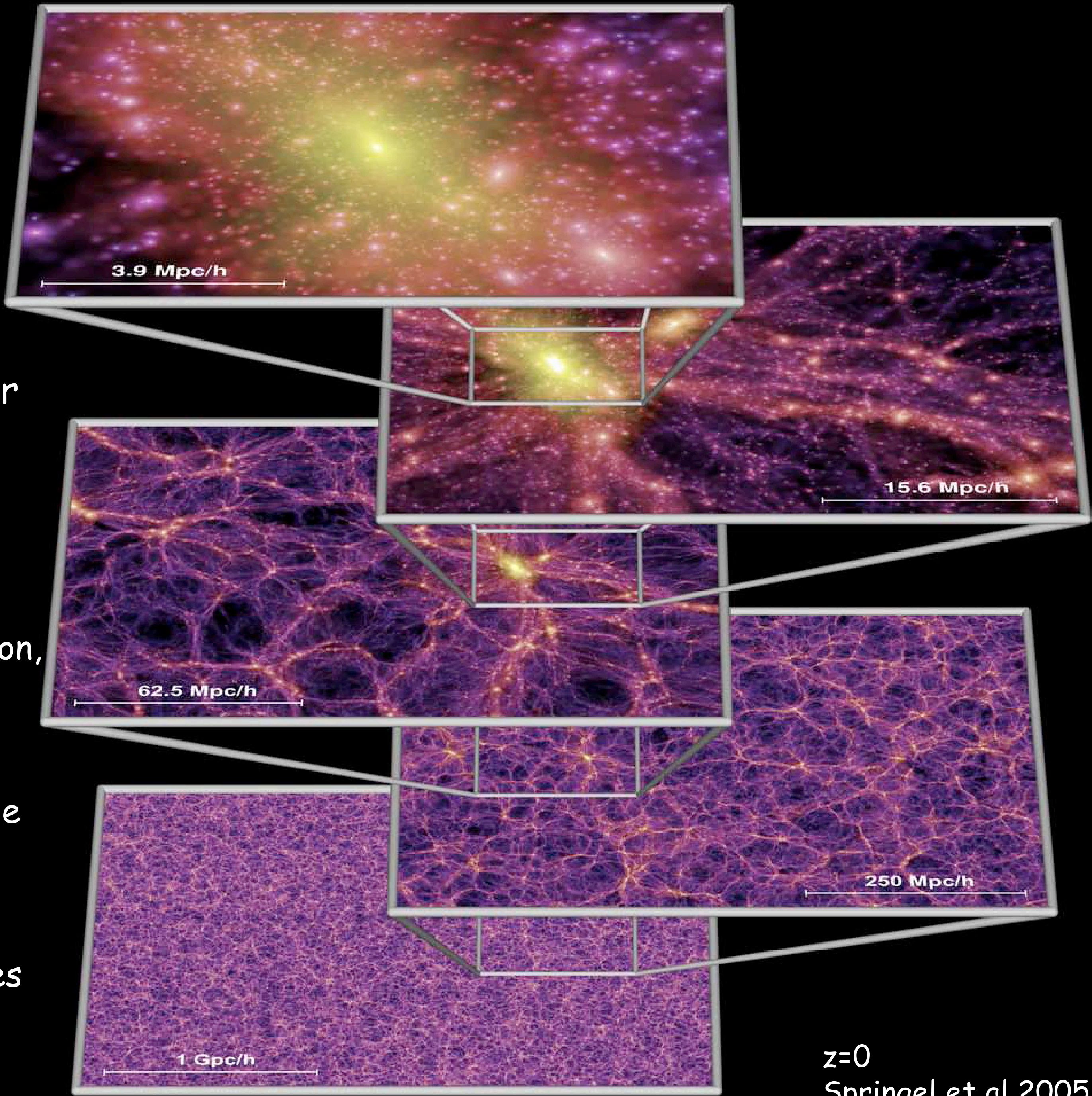
CMB physics

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

MILLENNIUM
Simulation
CDM universe

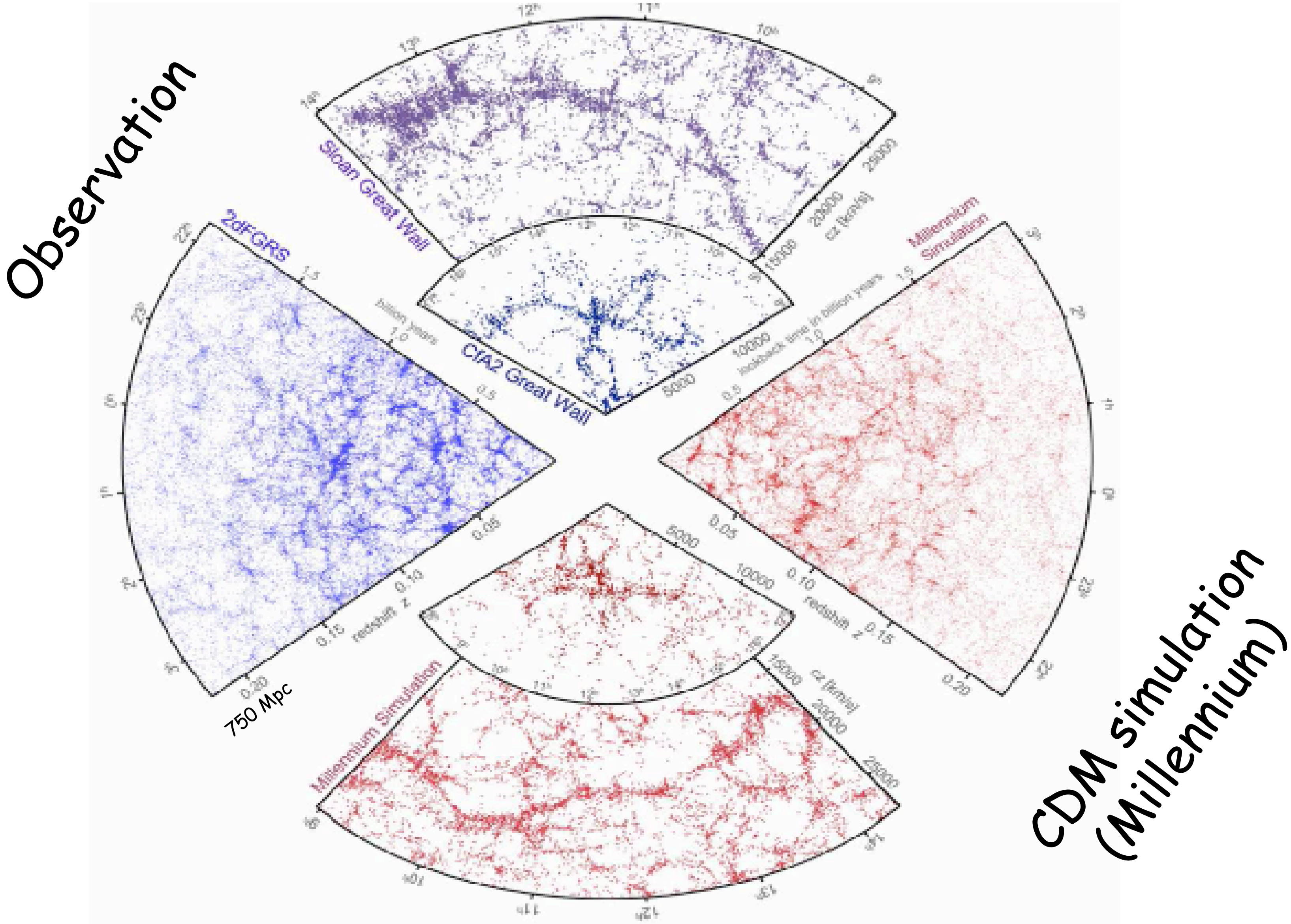
Simulates halos on cosmological scales, then resimulates a smaller patch with higher mass resolution.

Tracks the formation of galaxies and quasars in the simulation, by implementing a semianalytic model to follow gas, star and supermassive black hole processes within the merger history trees of dark matter halos and their substructures



z=0
Springel et al 2005

CDM N-body simulations better reproduce the data



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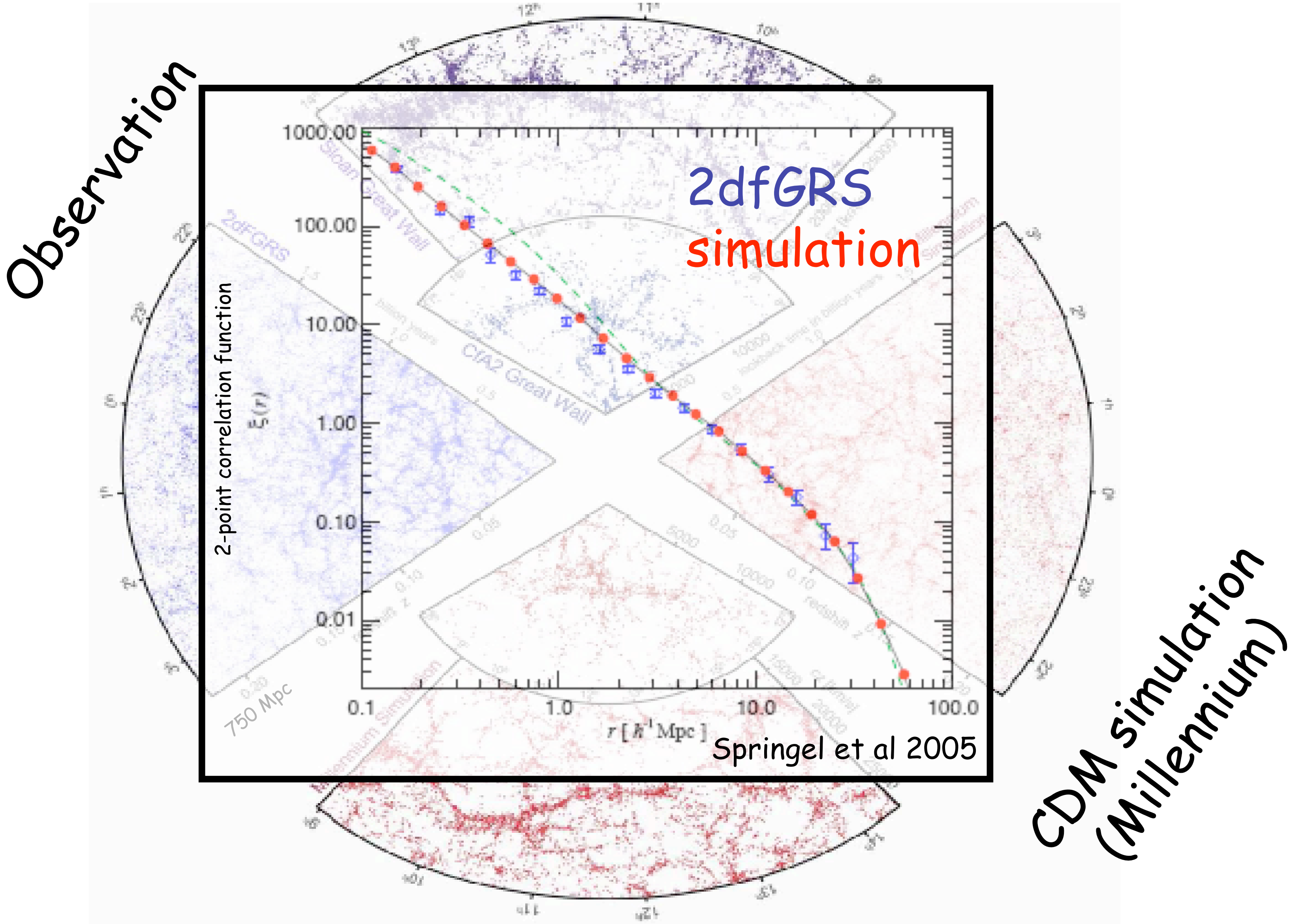
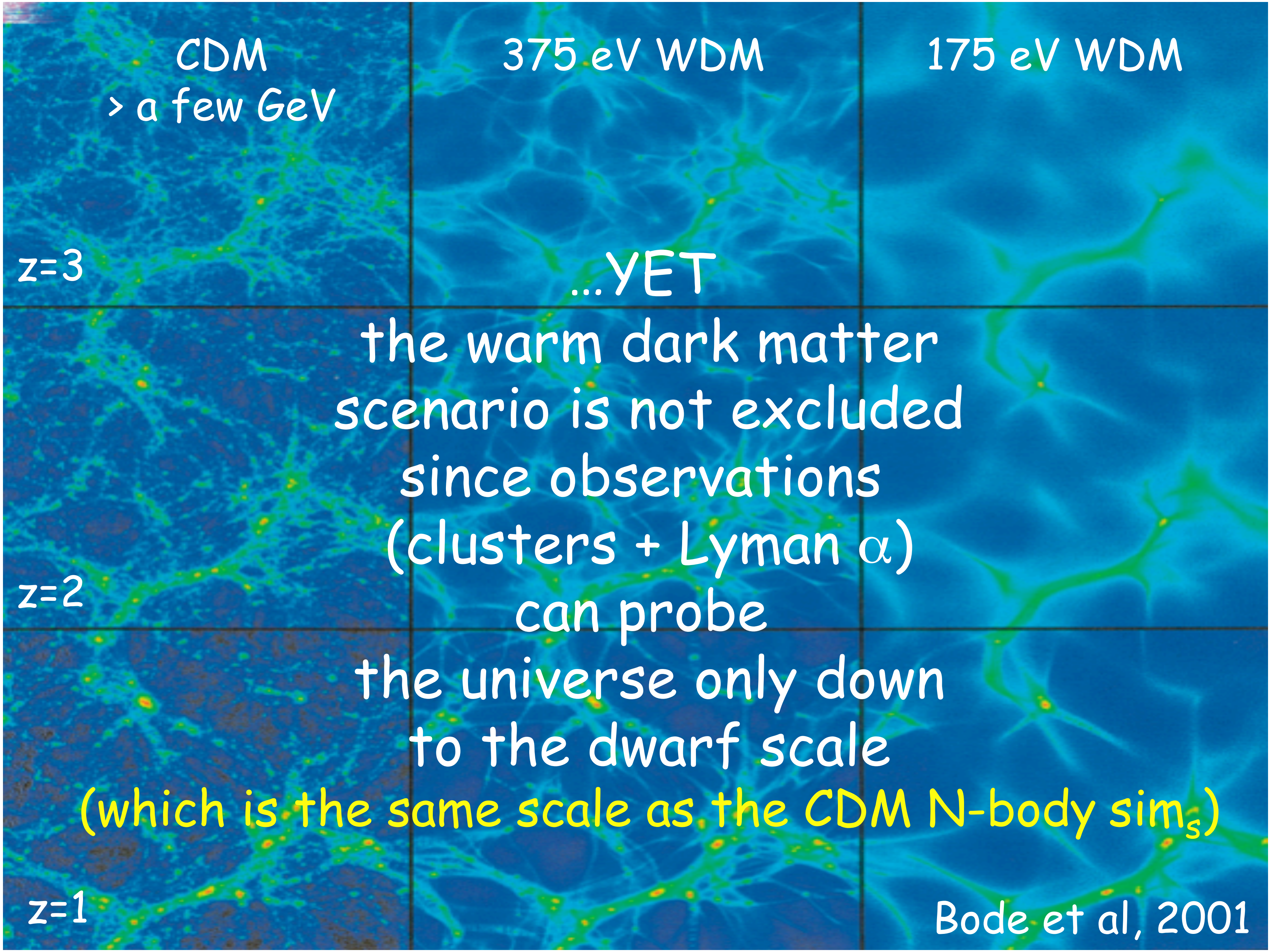
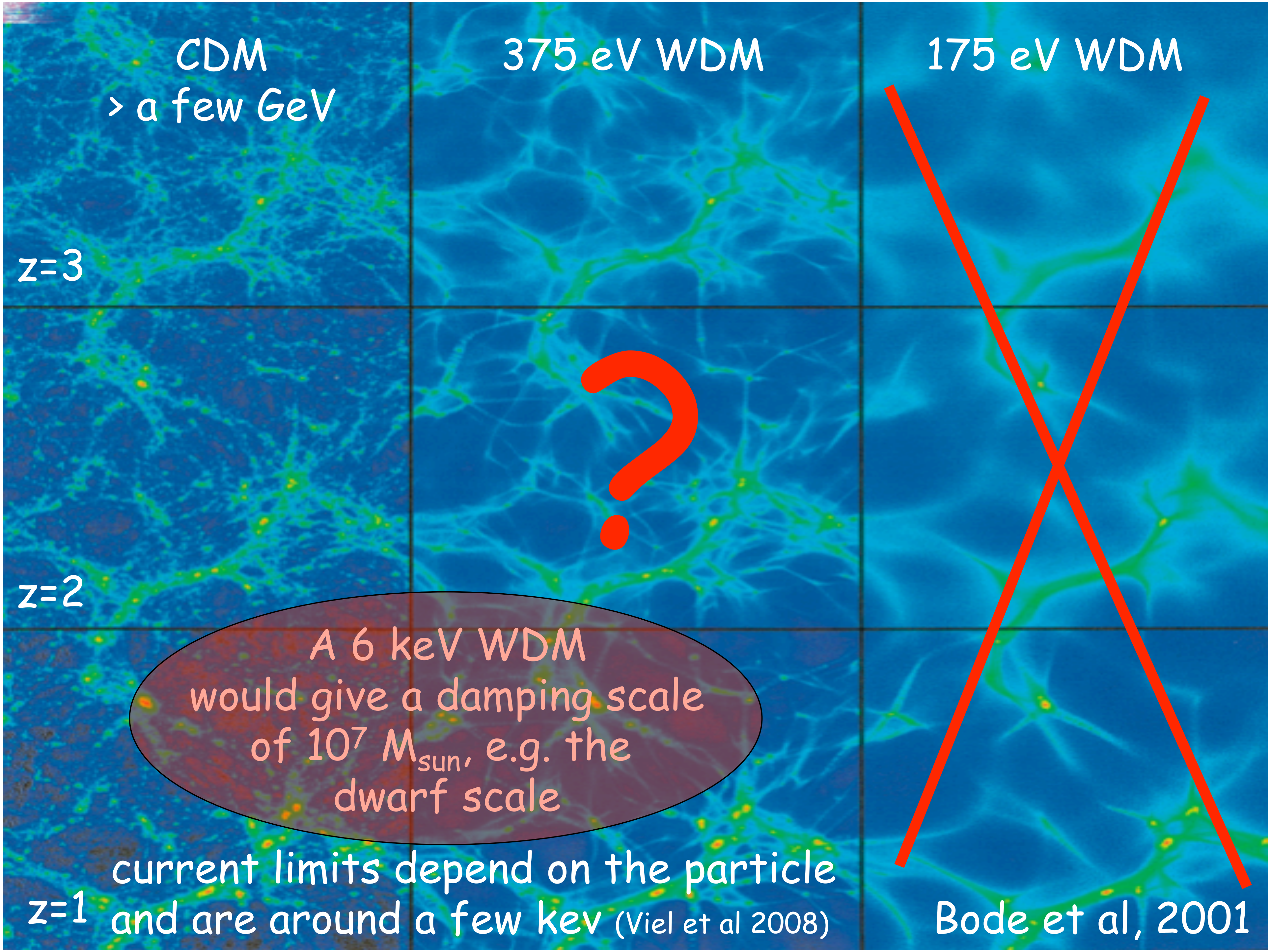
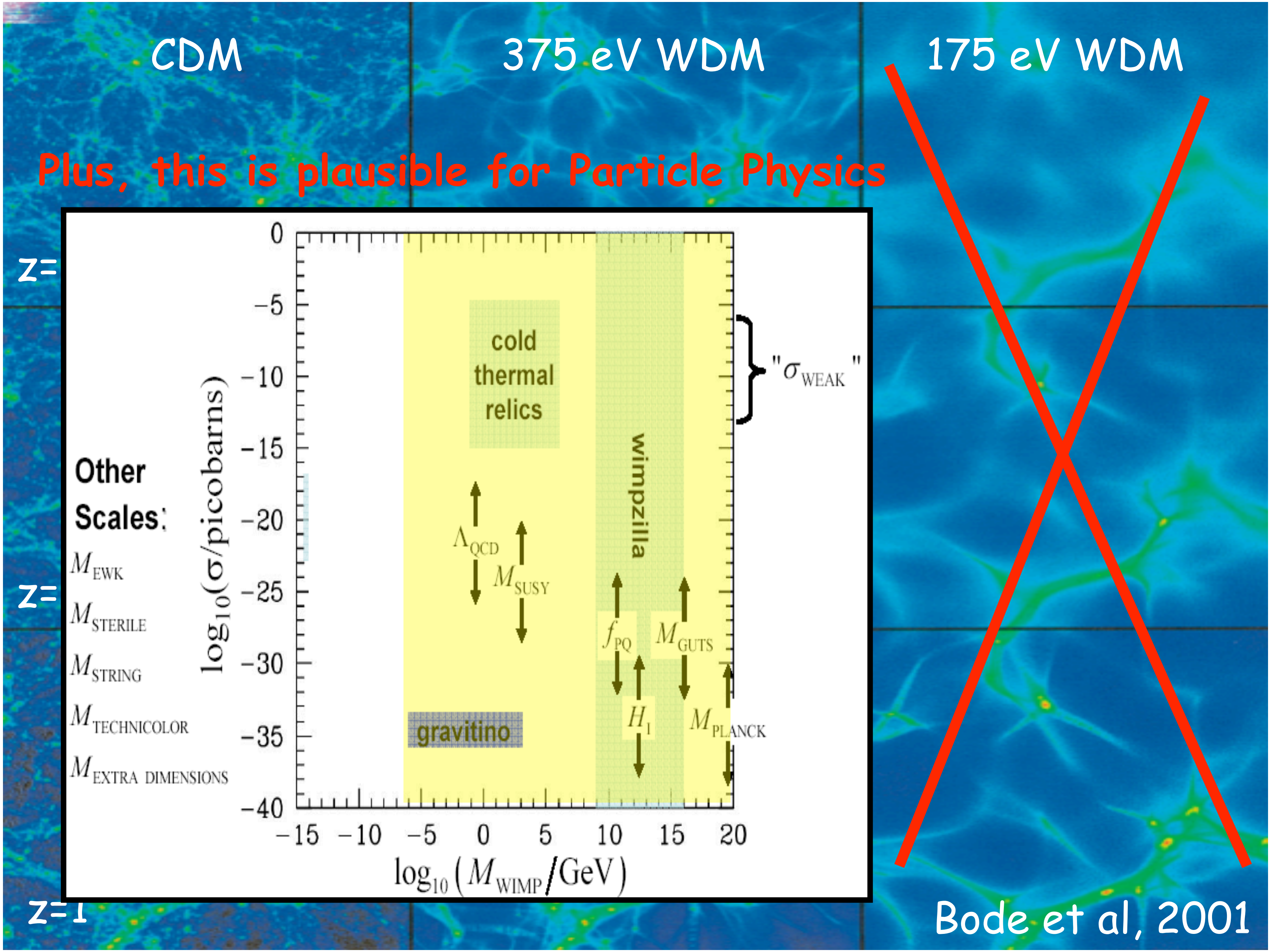



CDM
> a few GeV
375 eV WDM
175 eV WDM
z=3
...YET
the warm dark matter
scenario is not excluded
since observations
(clusters + Lyman α)
can probe
the universe only down
to the dwarf scale
(which is the same scale as the CDM N-body sims)
z=2
z=1
Bode et al, 2001


CDM
> a few GeV
375 eV WDM
175 eV WDM
z=3
z=2
z=1
?
A 6 keV WDM
would give a damping scale
of 10^7 M_{sun}, e.g. the
dwarf scale
current limits depend on the particle
and are around a few kev (Viel et al 2008)
Bode et al, 2001

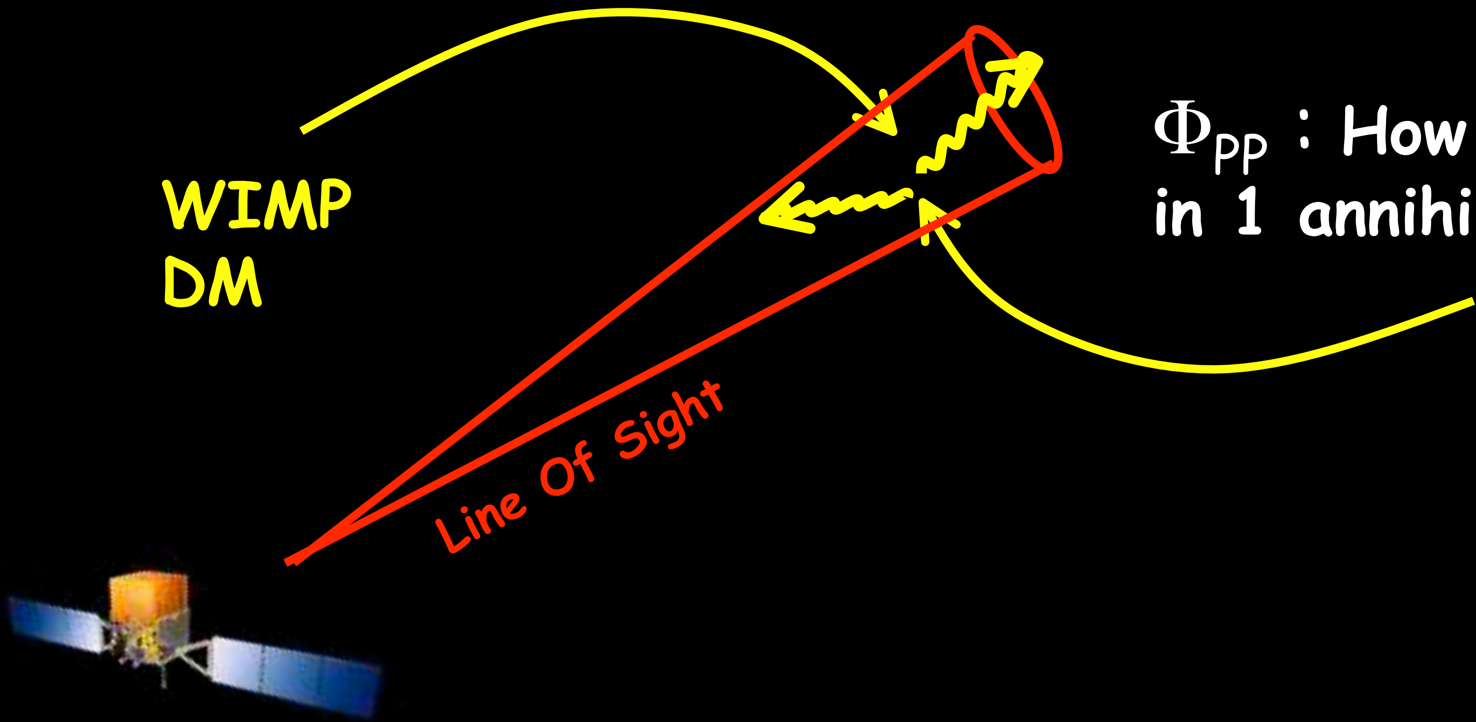


CDM
375 eV WDM
175 eV WDM
Plus, this is plausible for Particle Physics
z=
z=
z=1
Other Scales:
M_{EWK}
$M_{STERILE}$
M_{STRING}
$M_{TECHNICOLOR}$
$M_{EXTRA\ DIMENSIONS}$
$\log_{10}(\sigma/\text{picobarns})$
0
−5
−10
−15
−20
−25
−30
−35
−40
cold thermal relics
wimpzilla
"σ_{WEAK}"
Λ_{QCD}
M_{SUSY}
f_{PQ}
M_{GUTS}
H_1
M_{PLANCK}
gravitino
−15
−10
−5
0
5
10
15
20
$\log_{10}(M_{WIMP}/\text{GeV})$
Bode et al, 2001

DM structure is a fundamental ingredient for DM detection

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

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



Φ_{PP} : How many γs in 1 annihilation

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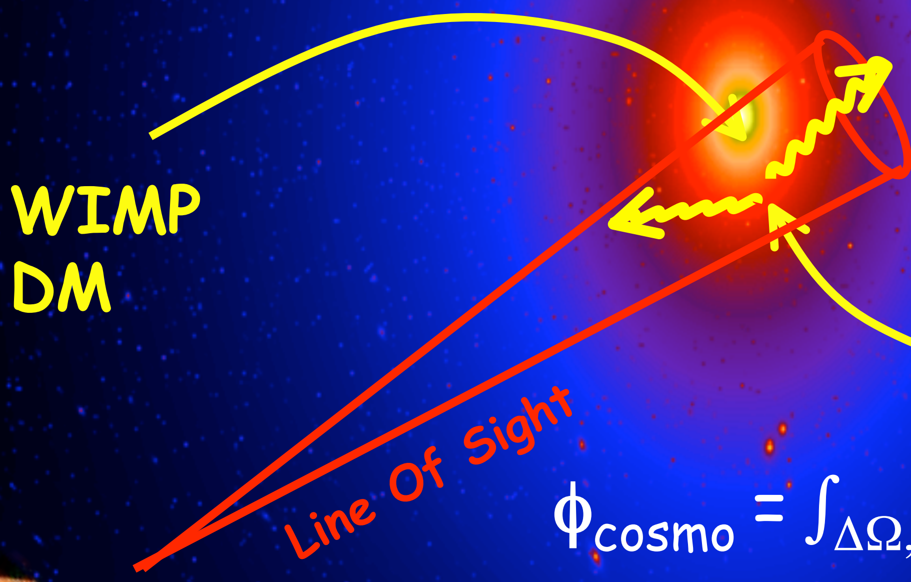
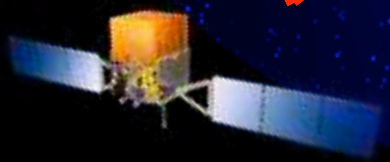


Φ_{PP} : How many γs in 1 annihilation

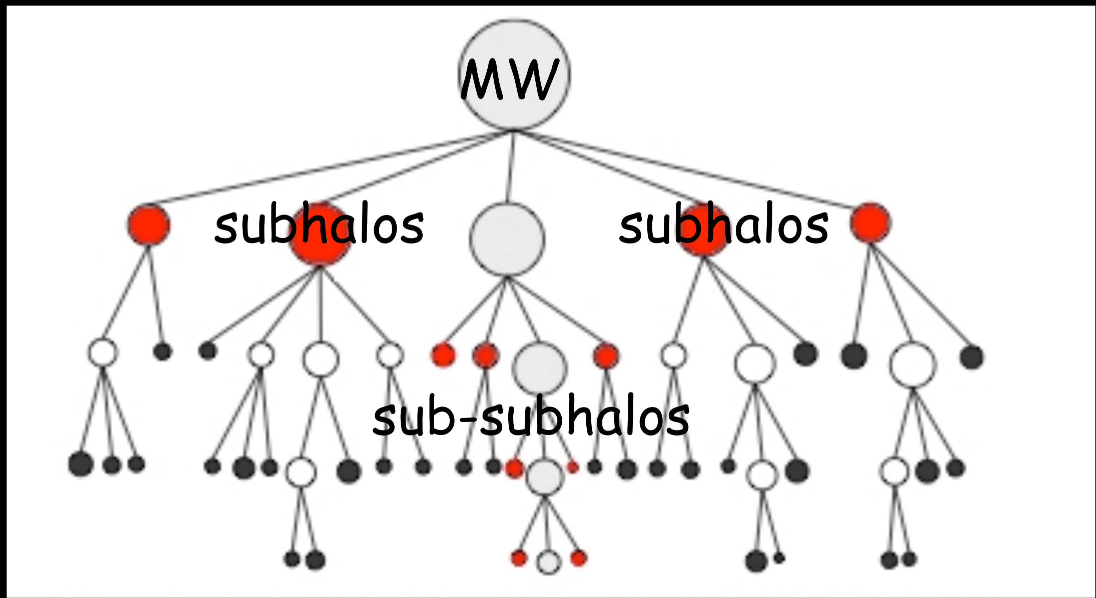
$$\phi_{cosmo} = \int_{\Delta\Omega,\lambda} \frac{\rho^2_{DM}(r(\Delta\Omega,\lambda))}{\lambda^2}\,d\lambda\,d\Omega$$



Φ_{cosmo} : How many annihilations ⇔ How many and which 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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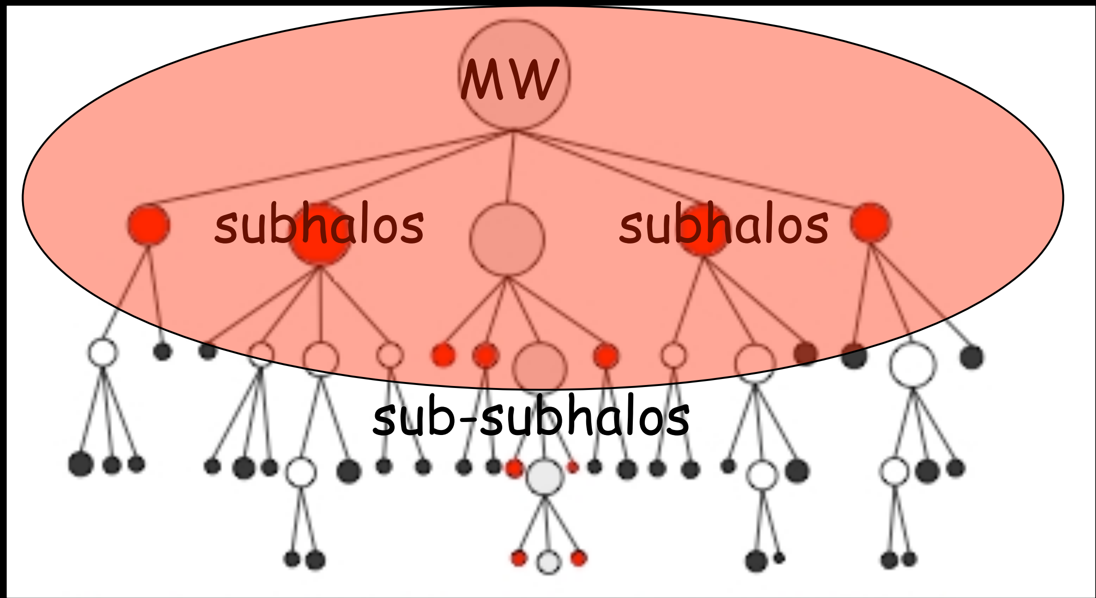

N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

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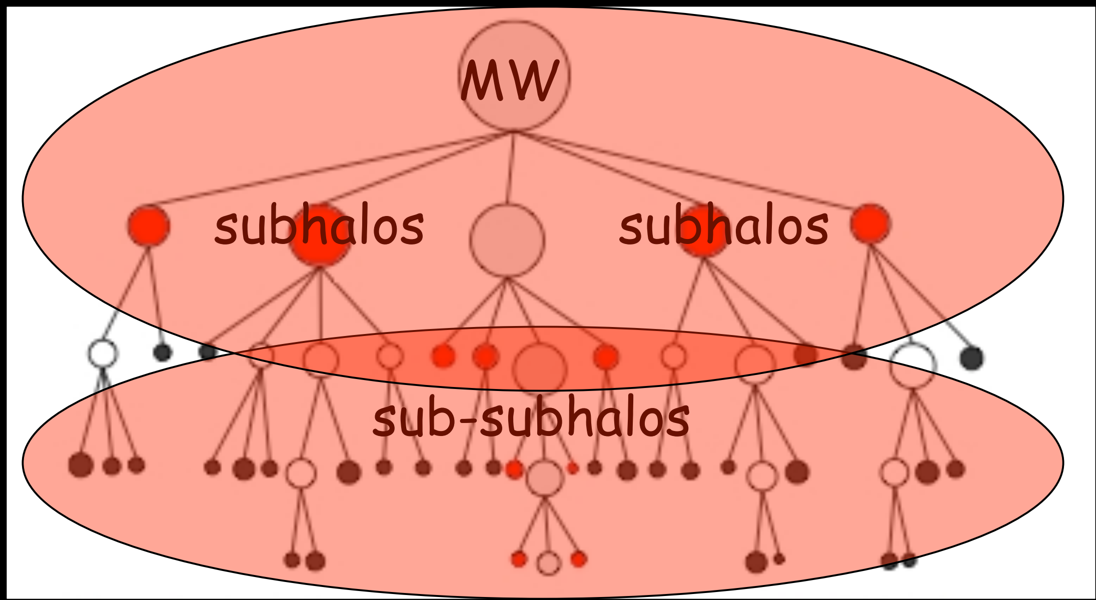
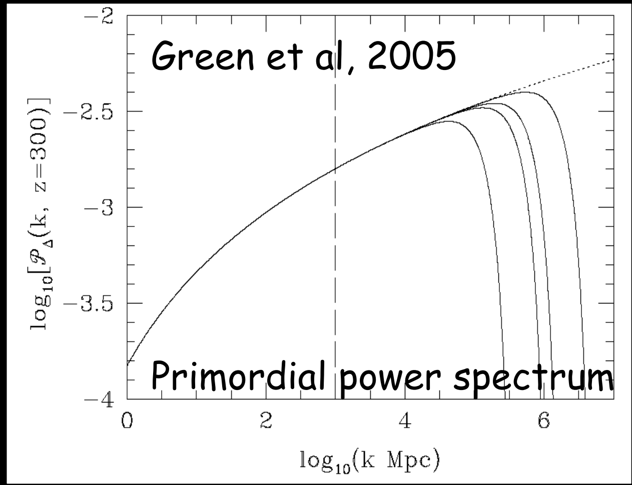


N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

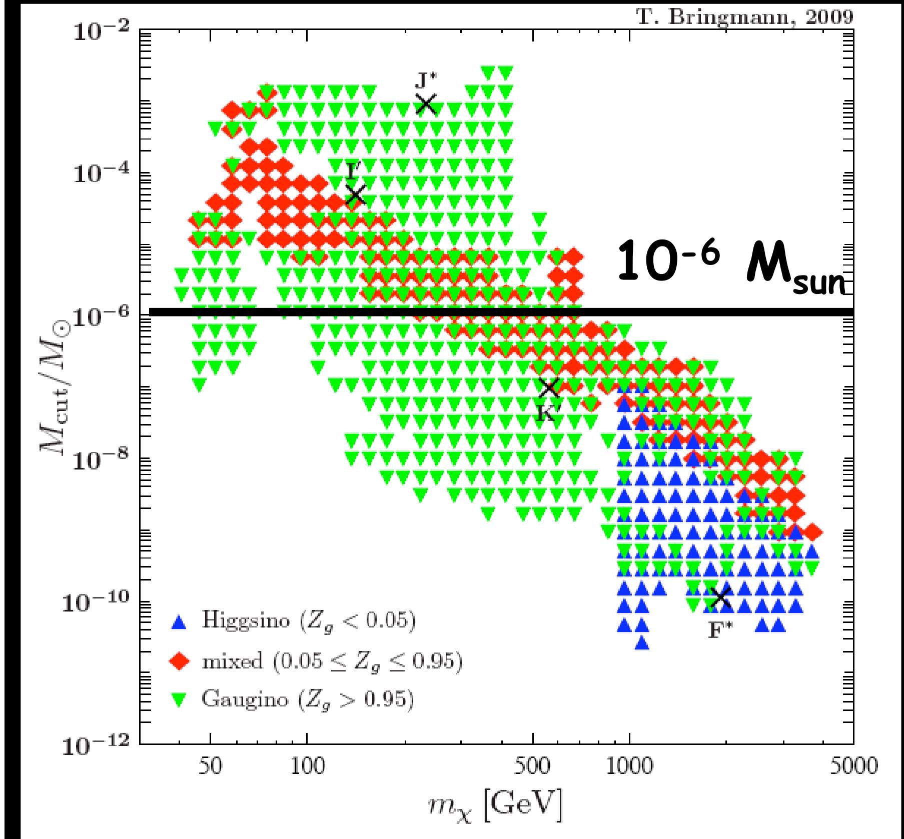
Microphysics and theory of structure formation sets the mass of the smallest halo
because there is no enough cpu power to simulate small halos from collapse till today.

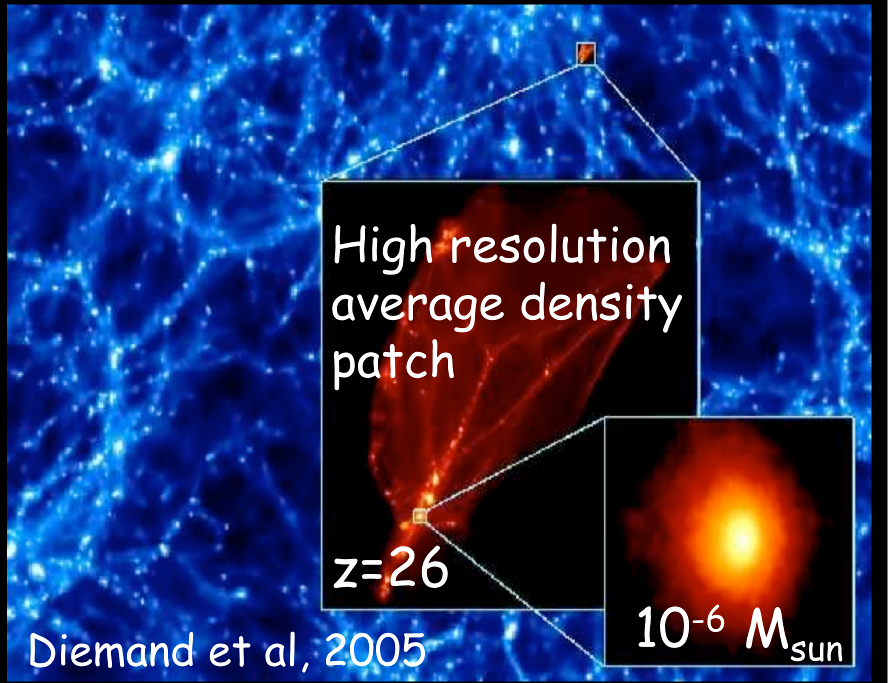
Modeling the structure of dark matter halos from theory of structure formation ($M < 10^5\ M_{sun}$)



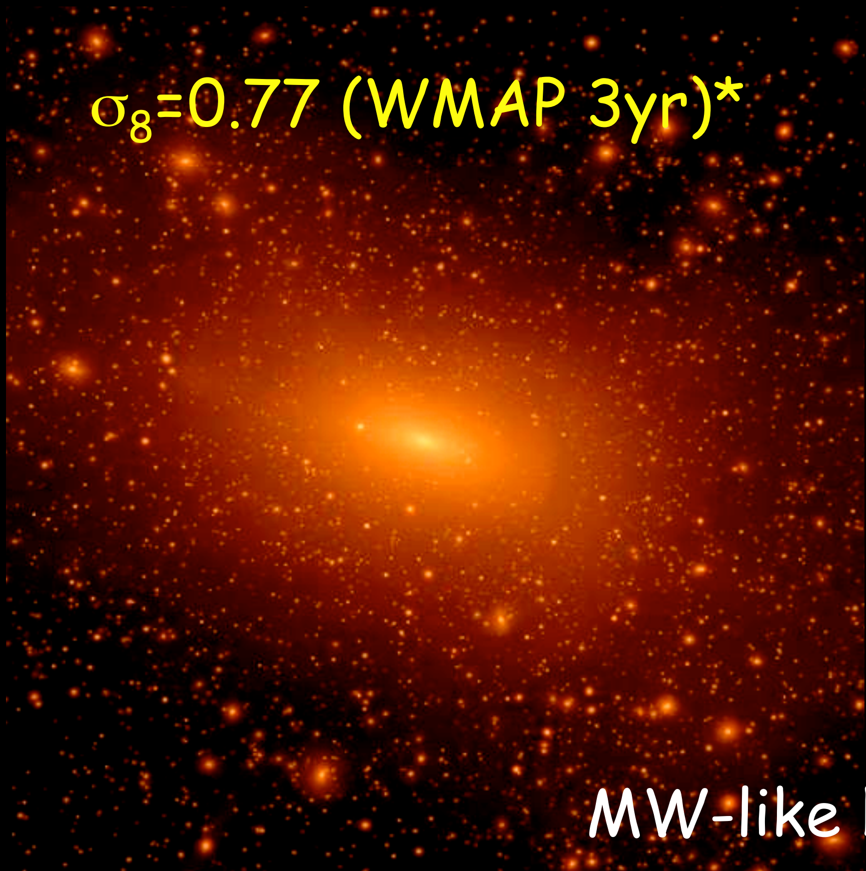
Theory: Damping of the primordial power spectrum due to CDM free streaming or acoustic oscillations after kinetic decoupling

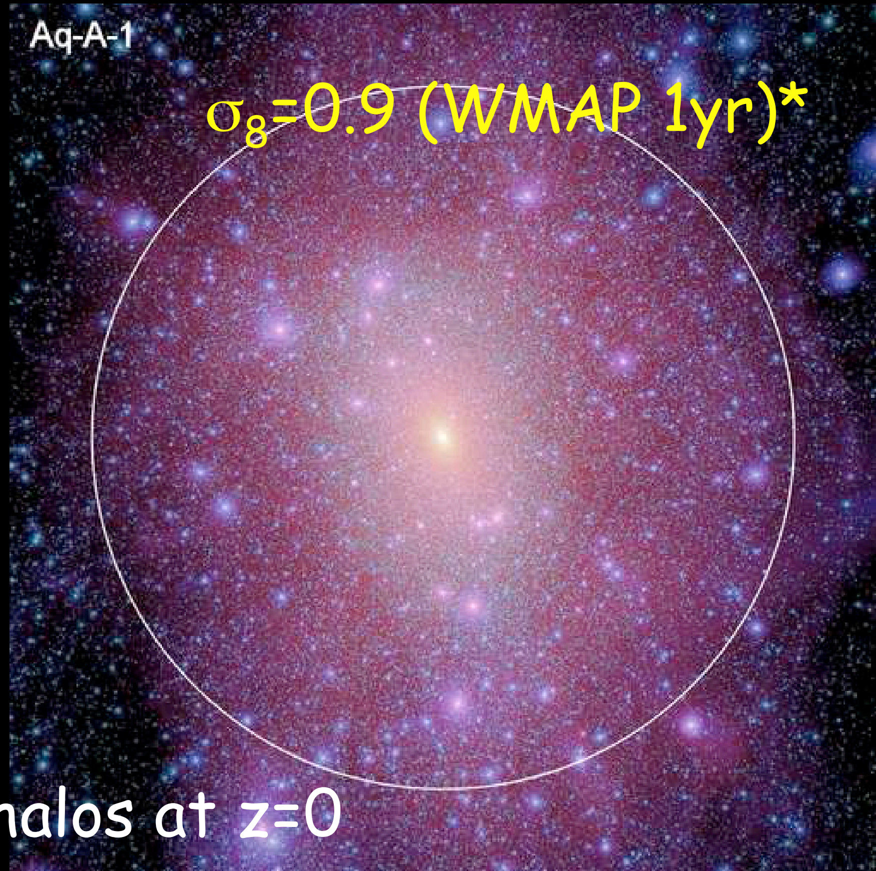
Typical M_{min} for a WIMP = $10^{-6}\ M_{sun}$





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





MW-like halos at z=0

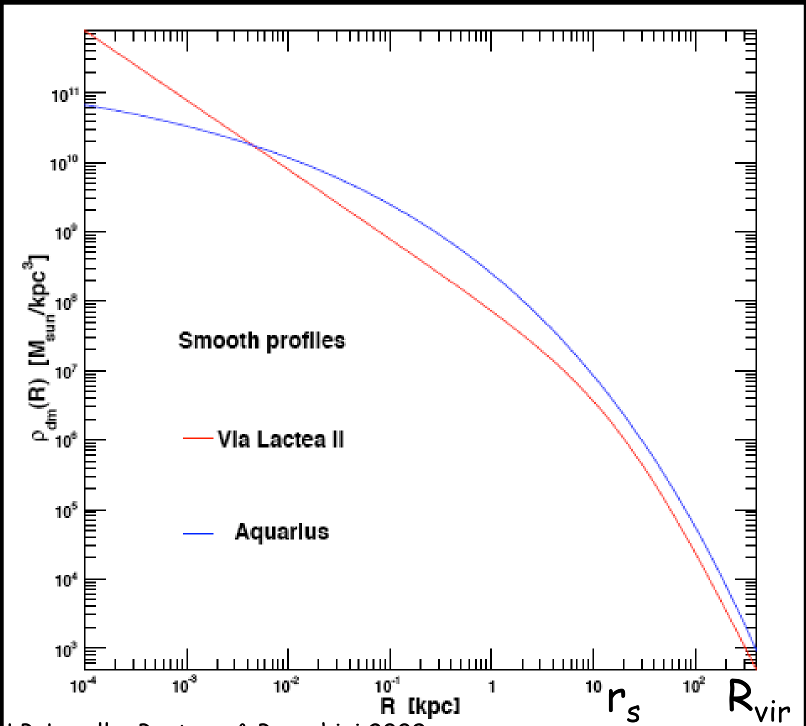
Via Lactea 2, Diemand et al

Aquarius, Springel et al

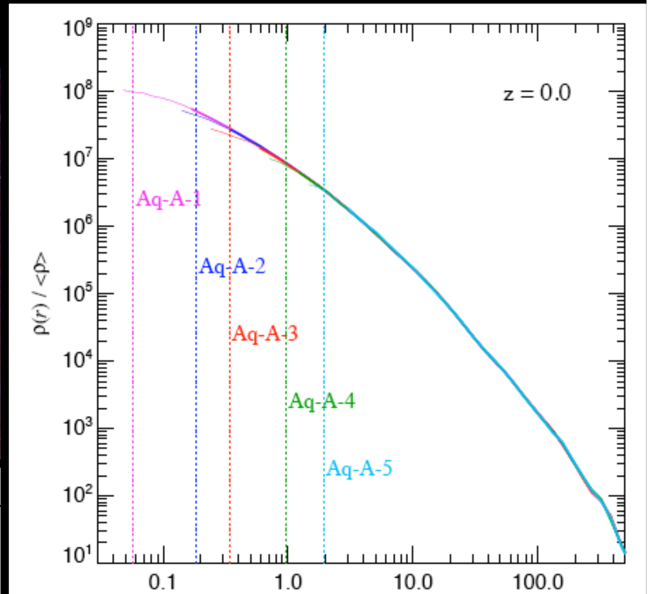
*Note σ_8=0.8 (WMAP 7yr)

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

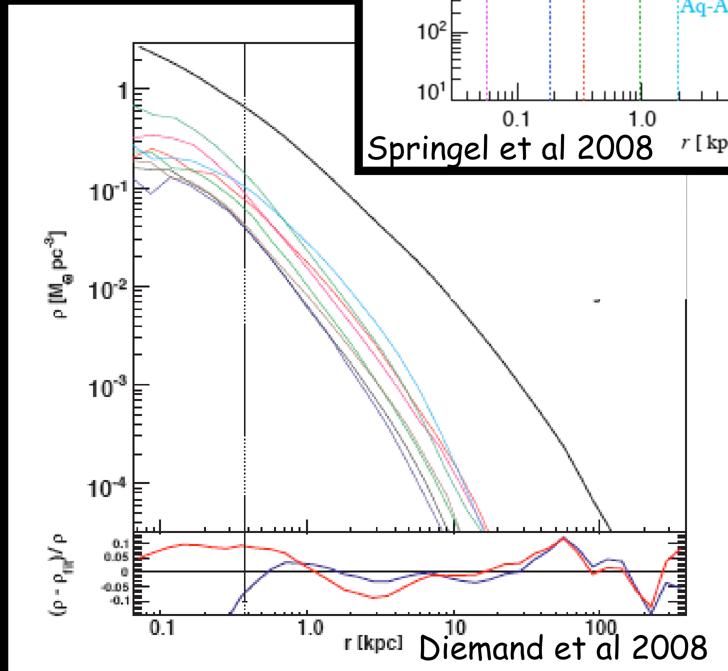
→ Halo and subhalo profile shape



J.P. Lavalle, Bertone & Branchini 2009



Springel et al 2008



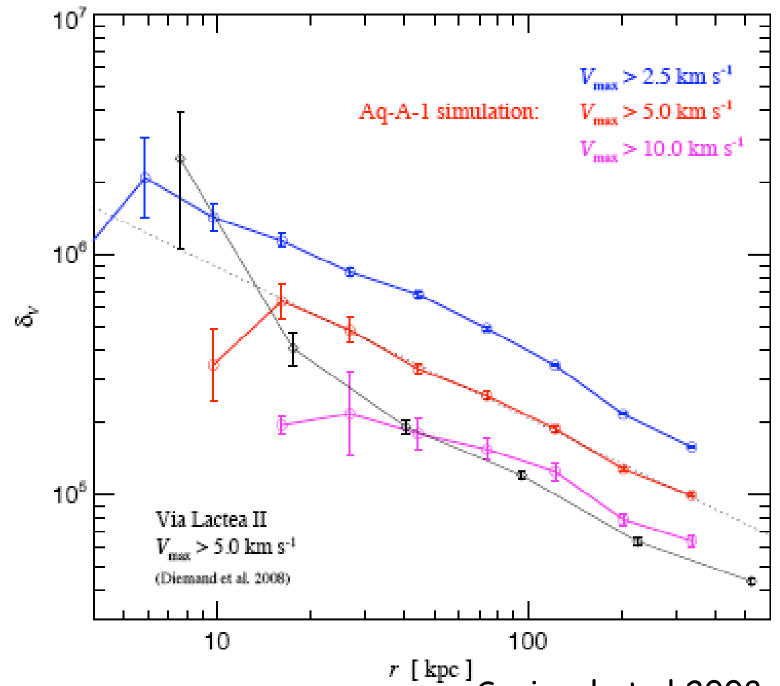
Diemand et al 2008

NFW VS Einasto

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

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

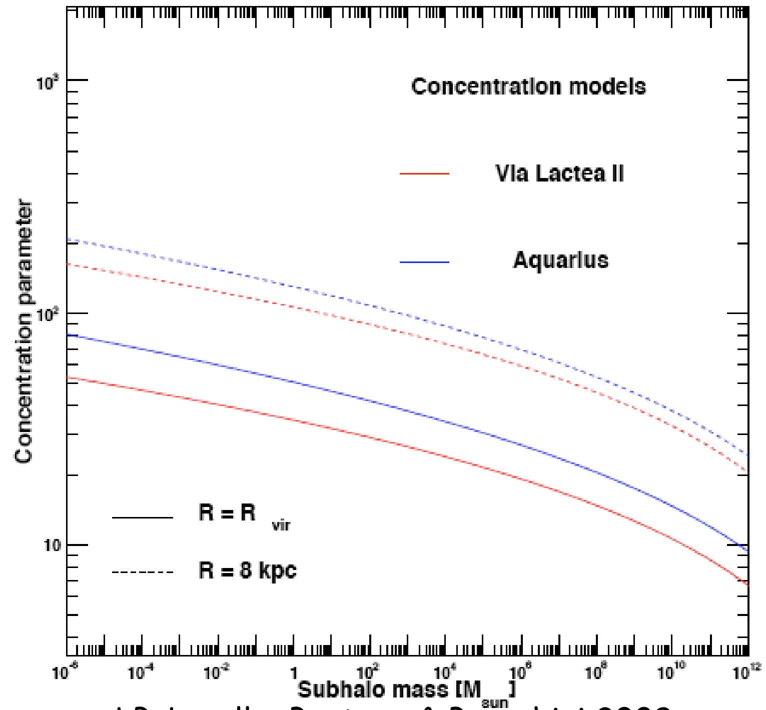
Concentration parameter differ (because of σ_8)



Springel et al 2008

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

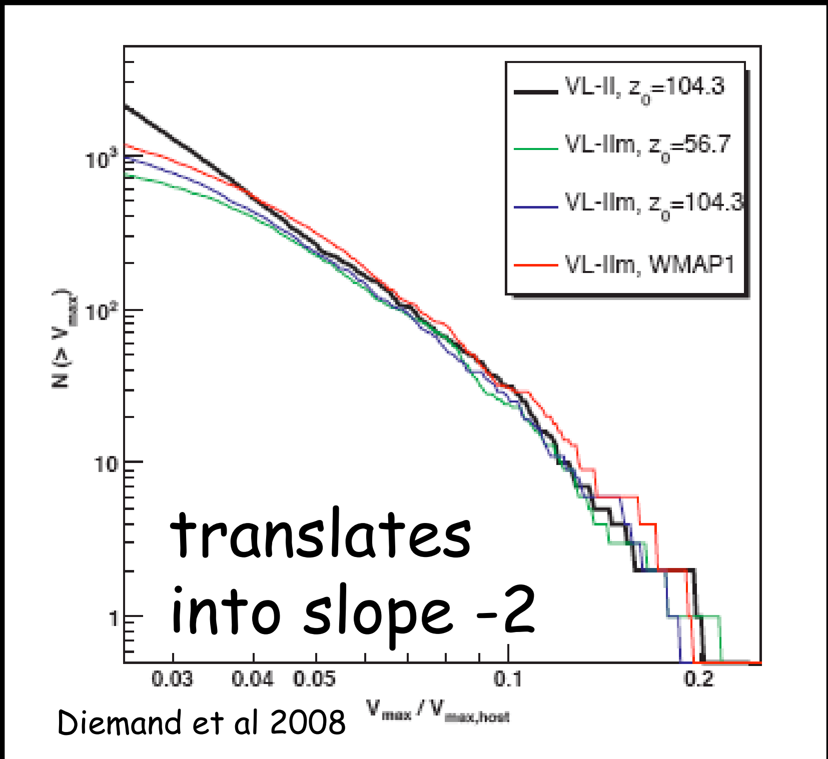
higher concentration -> higher flux!

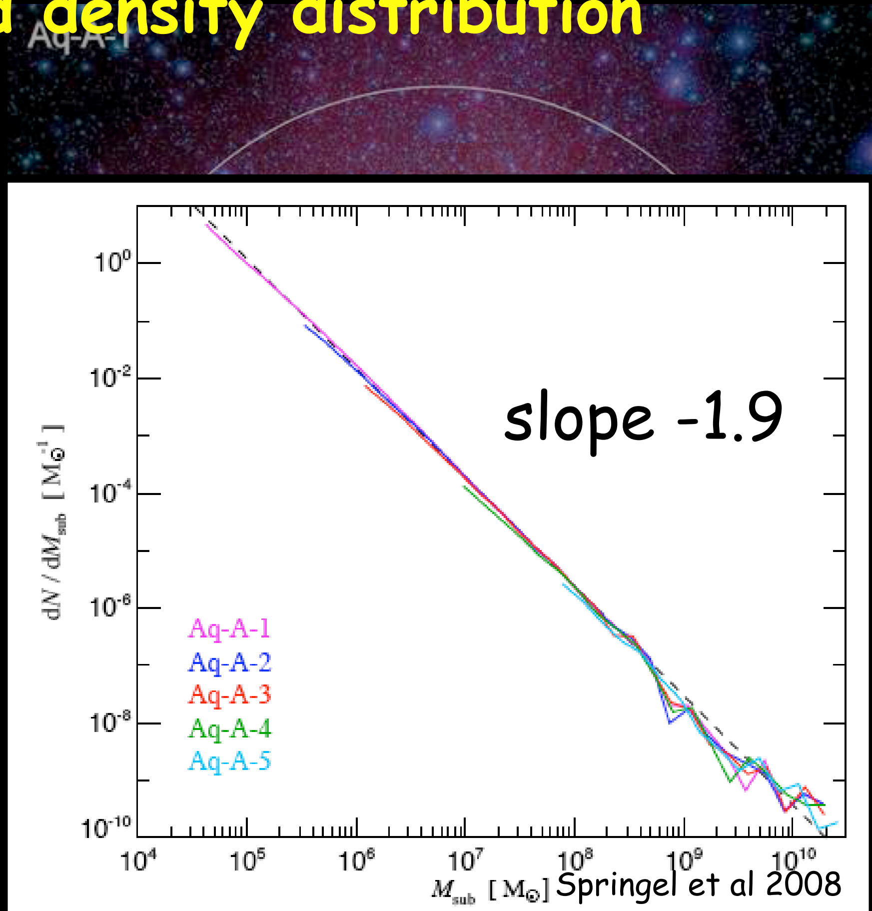


LP, Lavalle, Bertone & Branchini 2009

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

→ **Subhalo abundance and density distribution**





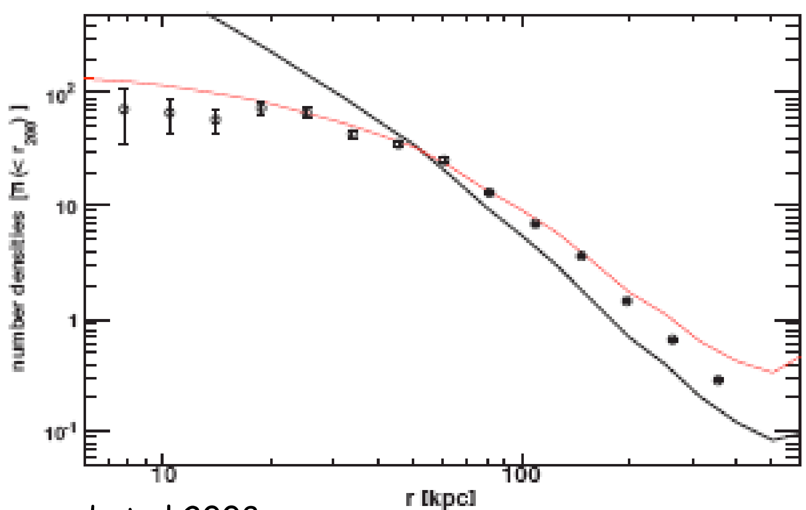
Note the different subhalo definition (v_{max} VS mass)

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

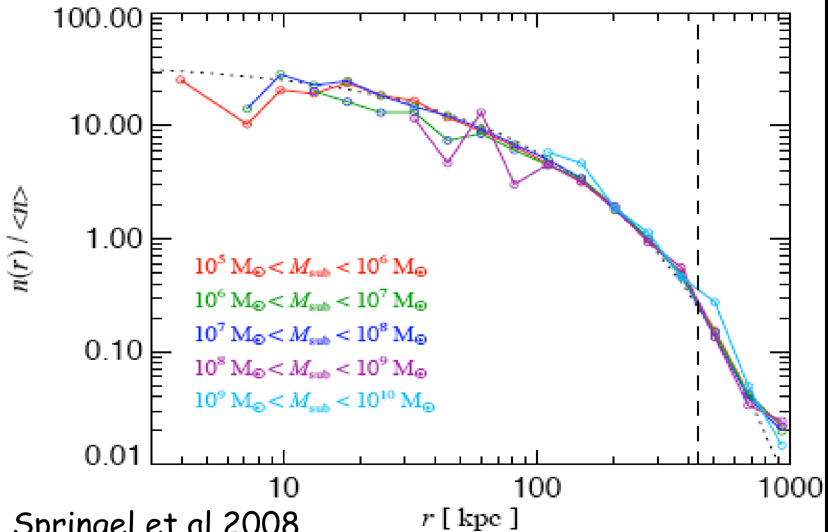
→ Subhalo abundance and density distribution

Aq-A-1

Mass slope ~ M^{-2}		Mass slope ~ $M^{-1.9}$
f_{DM} (>$10^7\ M_{sun}$) ~ 11%	difference due to σ_8	f_{DM} (>$10^7\ M_{sun}$) ~ 13%
f_{DM} (>$10^{-6}\ M_{sun}$) ~ 50%	difference due to extrapolation	f_{DM} (>$10^{-6}\ M_{sun}$) ~ 25%
Radial distribution ~ $(1+R/rs)^{-1}$		Radial distribution ~ Einasto α=0.67



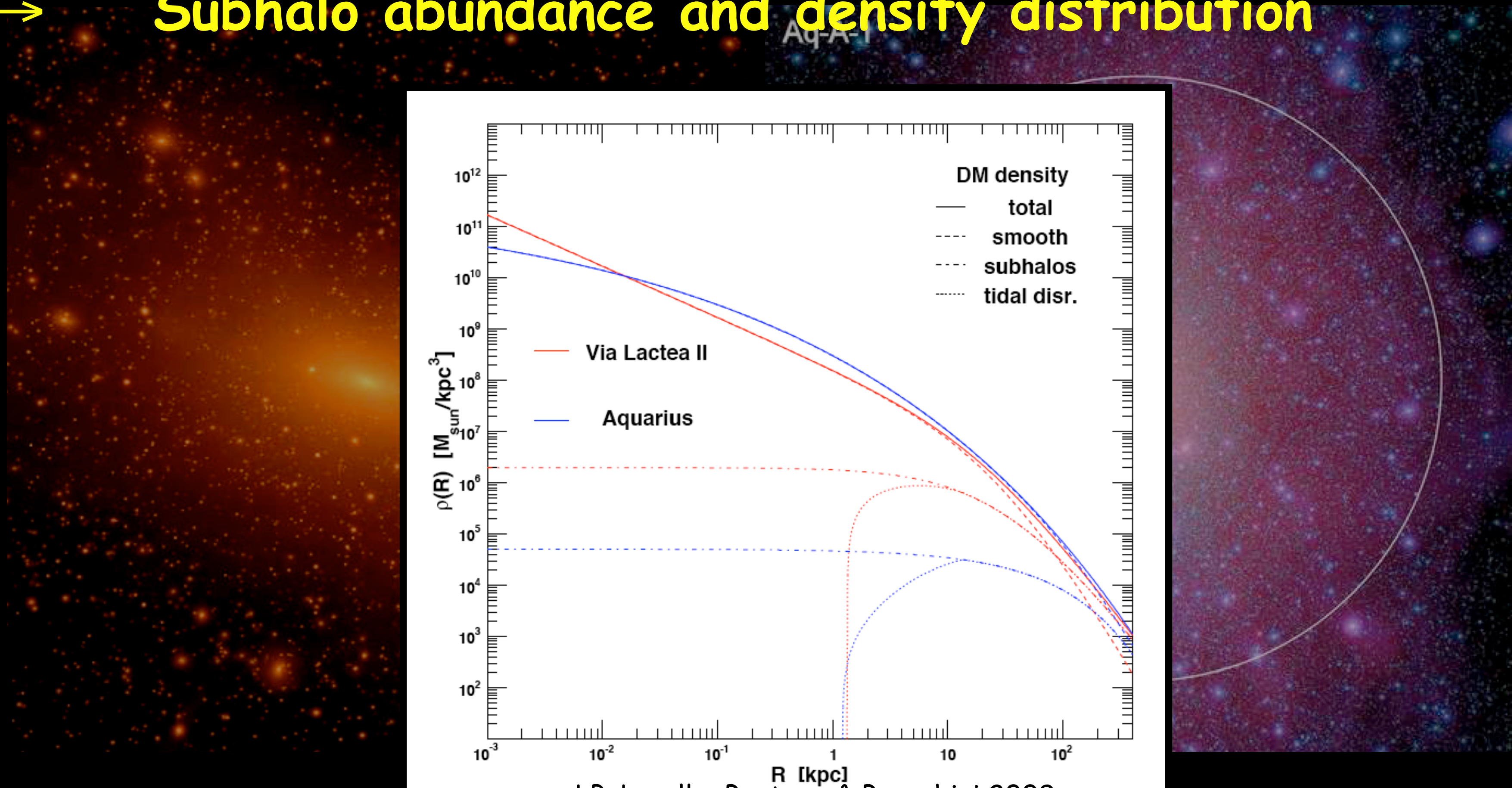
Diemand et al 2008



Springel et al 2008

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

→ **Subhalo abundance and density distribution**



LP, Lavalle, Bertone & Branchini 2009

Roche criterion sets the effect of tidal forces

Predictions

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

Step 1: MW smooth and single subhalo contribution

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

Step 2: Integrated contribution of all the GALACTIC halos along the LOS

$$\Phi^{allhalos}{}_{COSMO}(\psi, \Delta\Omega) \propto \int_M dM \int_c dc \iint_{\Delta\Omega} d\vartheta d\varphi \int_{l.o.s} d\lambda \rho_{sh}(M,R) \cdot P(c) \Phi^{halo}_{COSMO}$$

Predictions

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

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…

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

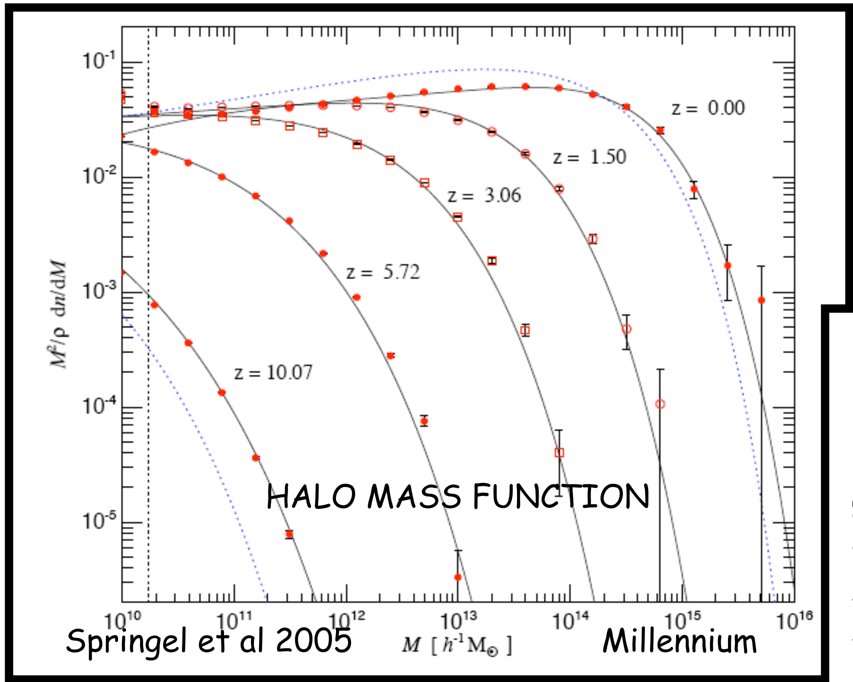
Normalized to subhalo mass fraction f(M)

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

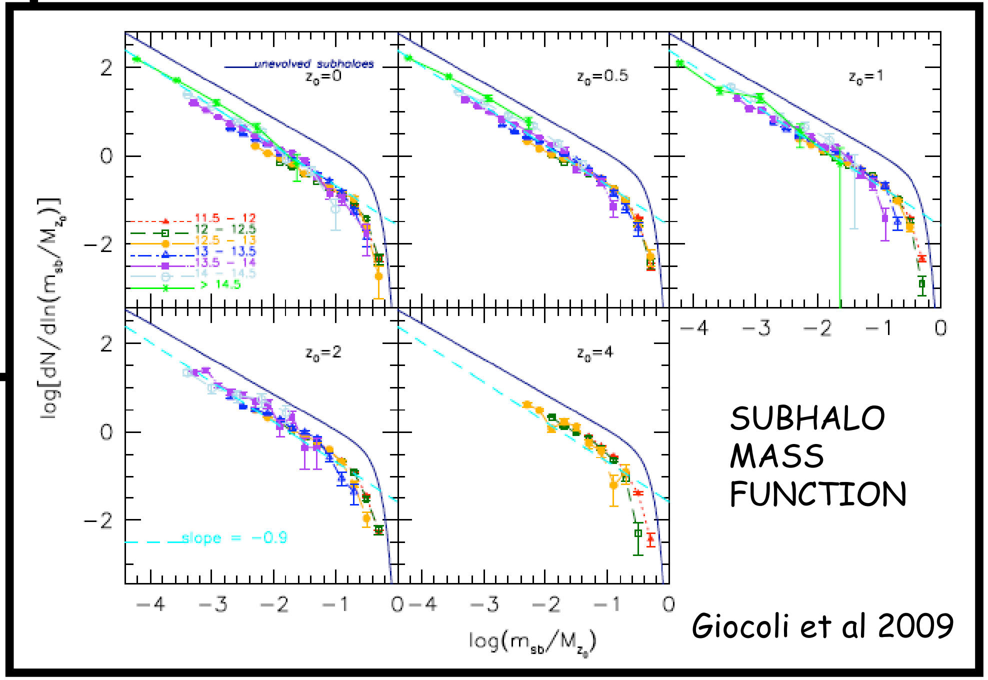
Predictions

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

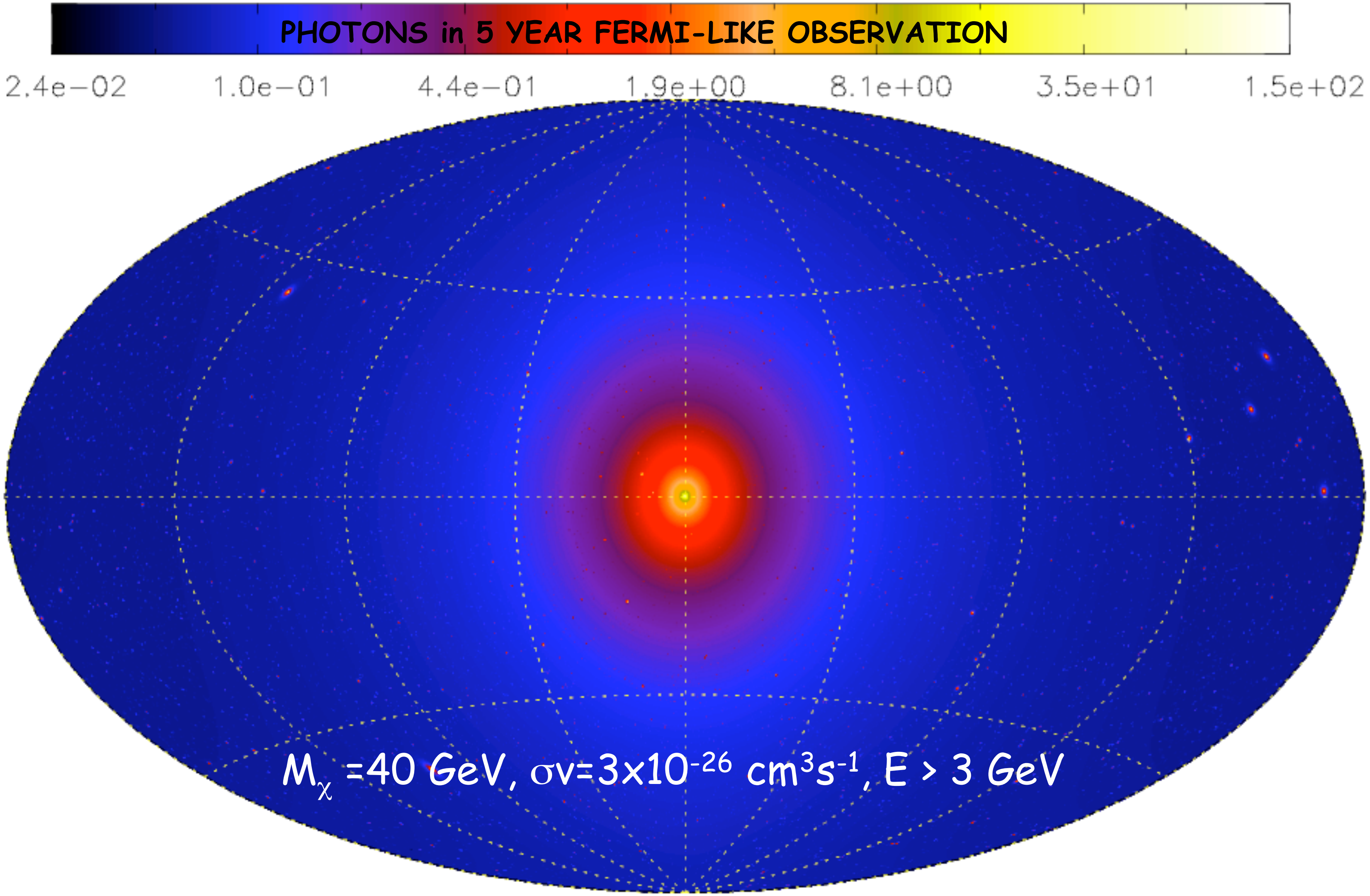
Step 3: **Integrated contribution of EXTRAGALACTIC halos and subhalos**



Mass function as predicted by TSF is found in N-body

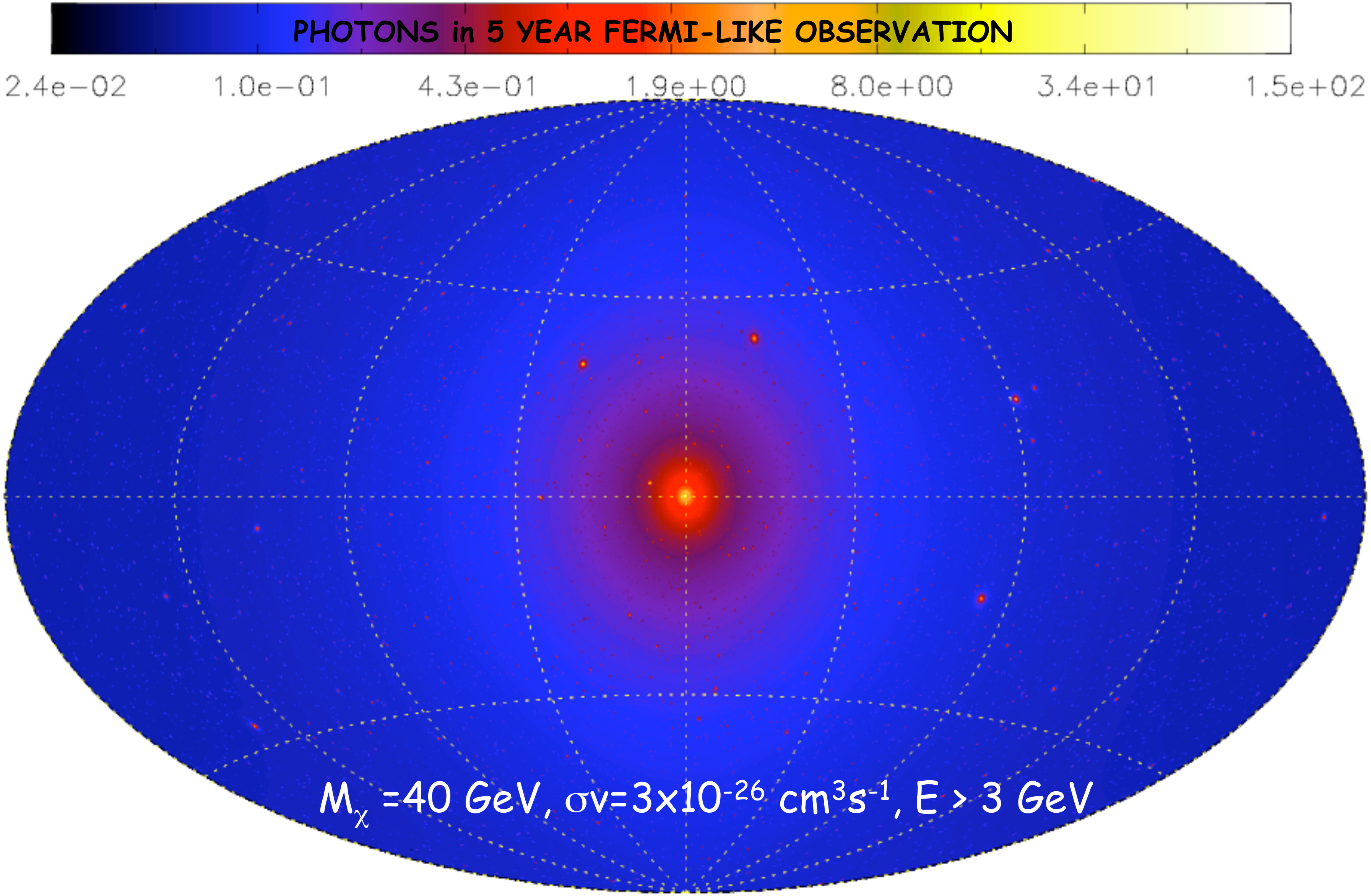


The γ-ray sky (Aquarius)
Galactic and extragalactic: smooth + subhalos



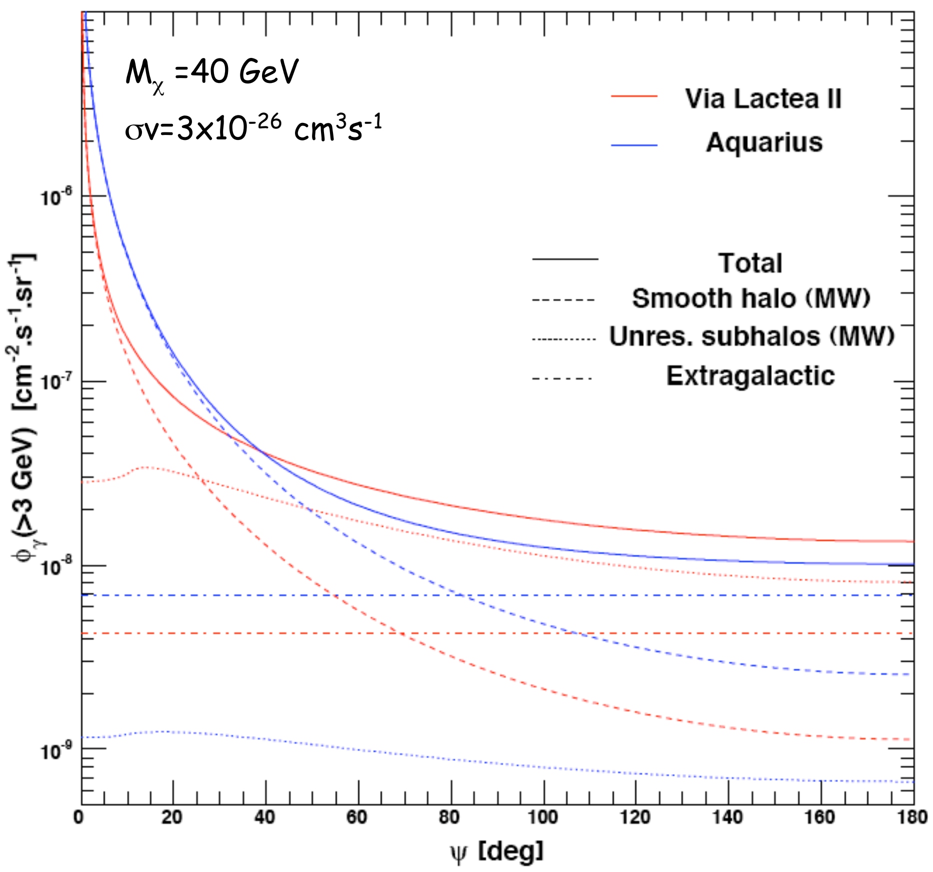
LP, Lavalle, Bertone & Branchini 2009

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



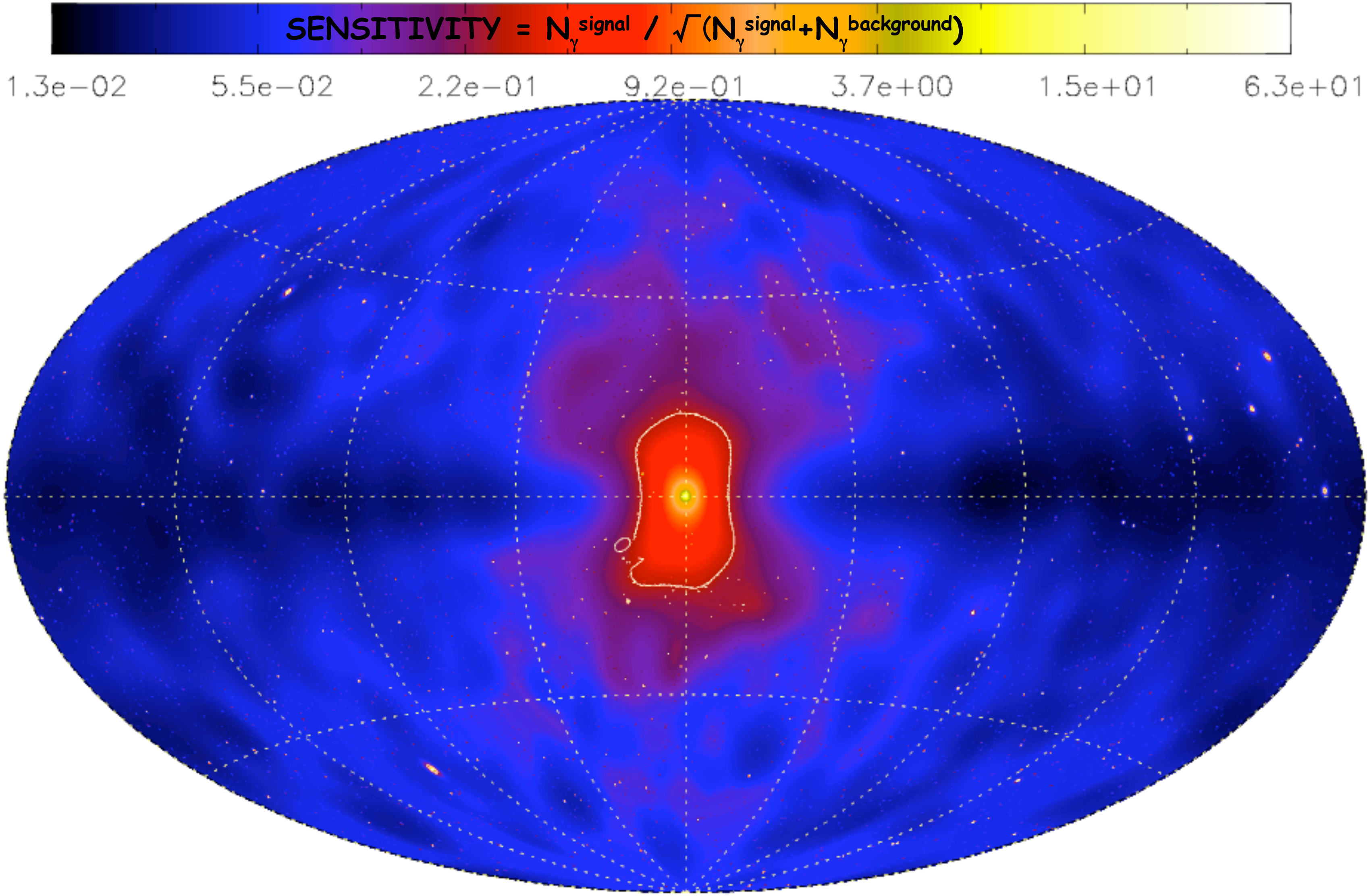
LP, Lavalle, Bertone & Branchini 2009

The γ-ray sky
Galactic and extragalactic: smooth + clumpy



LP, Lavalle, Bertone & Branchini 2009

Is the γ-ray sky from DM annihilation DETECTABLE?



LP, Lavalle, Bertone & Branchini 2009

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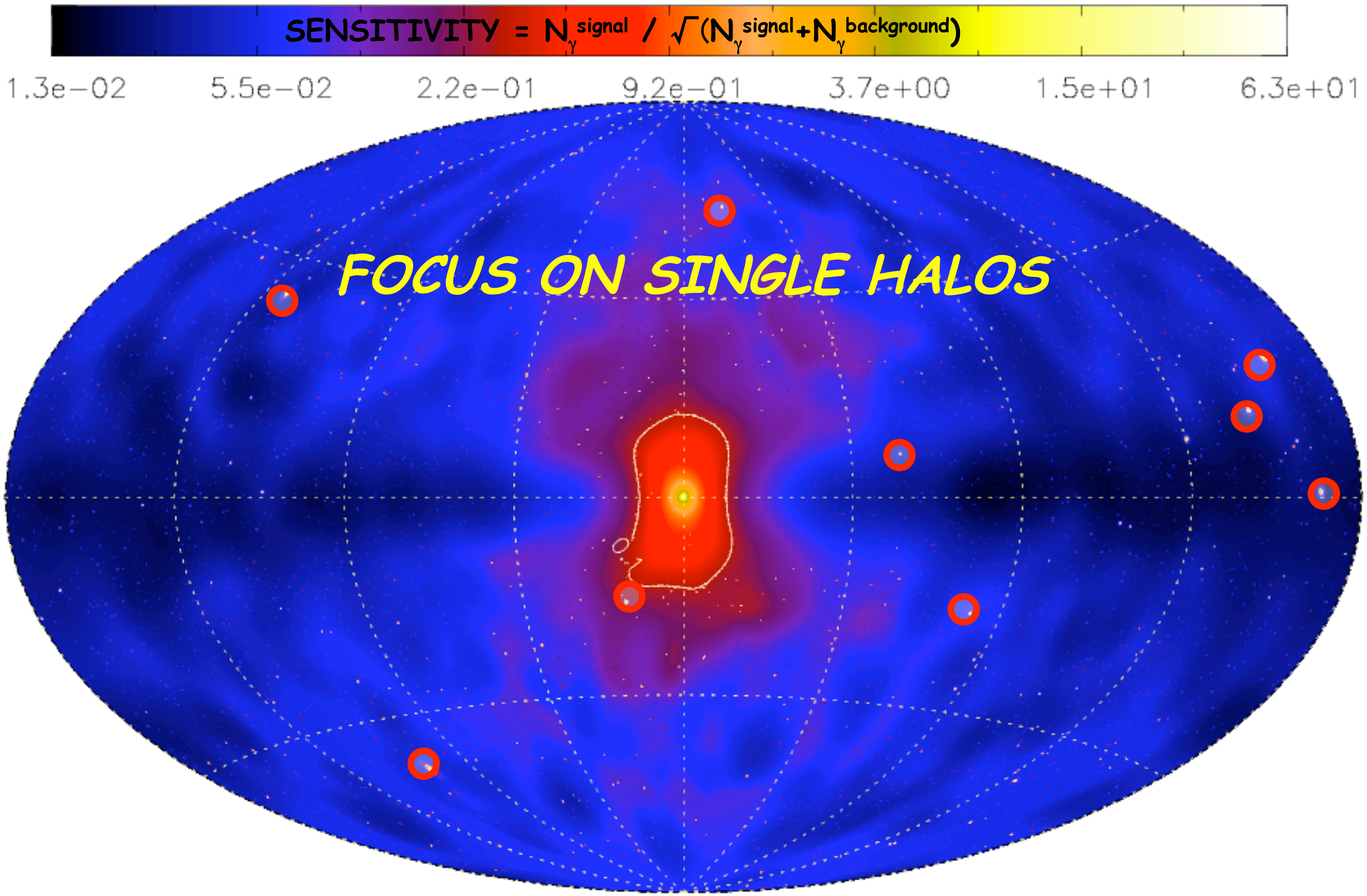

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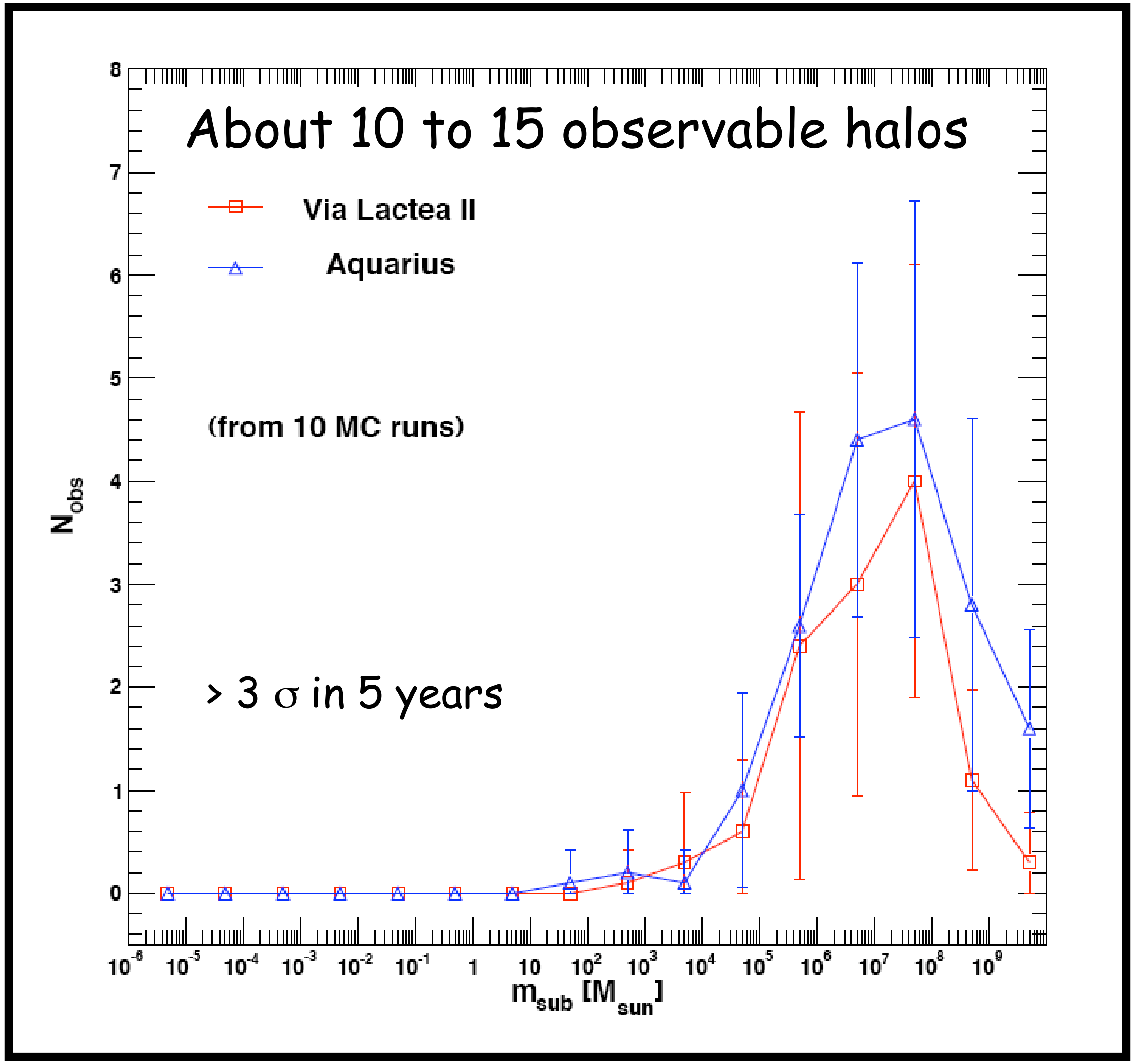
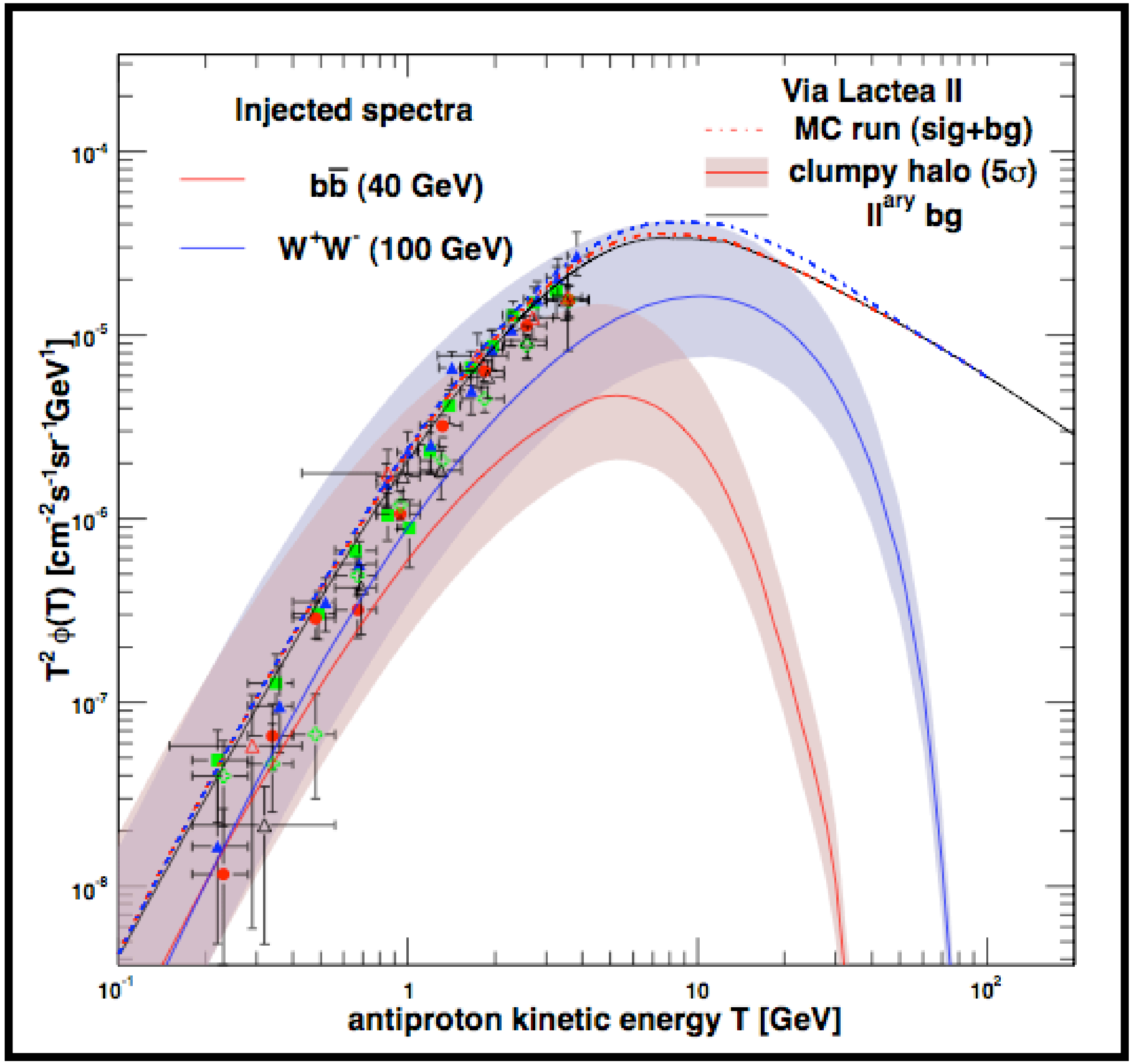


LP, Lavalle, Bertone & Branchini 2009

Check with the antiproton flux deriving from observable subhalos.. And it is OK..



This is an example of combining multi-messenger results in order to get stable predictions or exclude particle models

See, e.g., Pato, LP & Bertone 2009
Catena,Fornengo,Pato,LP & Masiero 2010
Colafrancesco, Lieu ,Marchegiani, Pato & LP 2010

to appear in LP, Lavalle, Bertone & Branchini 2009 - revised

Beyond the first monopole
angular correlations on the diffuse γ-ray background

INGREDIENTS:

Take the γ-ray flux due to DM annihilation in the galactic subhalos

AND

the cosmological γ-ray flux due to DM annihilation

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

and compute the coefficients of the decomposition in spherical armonics

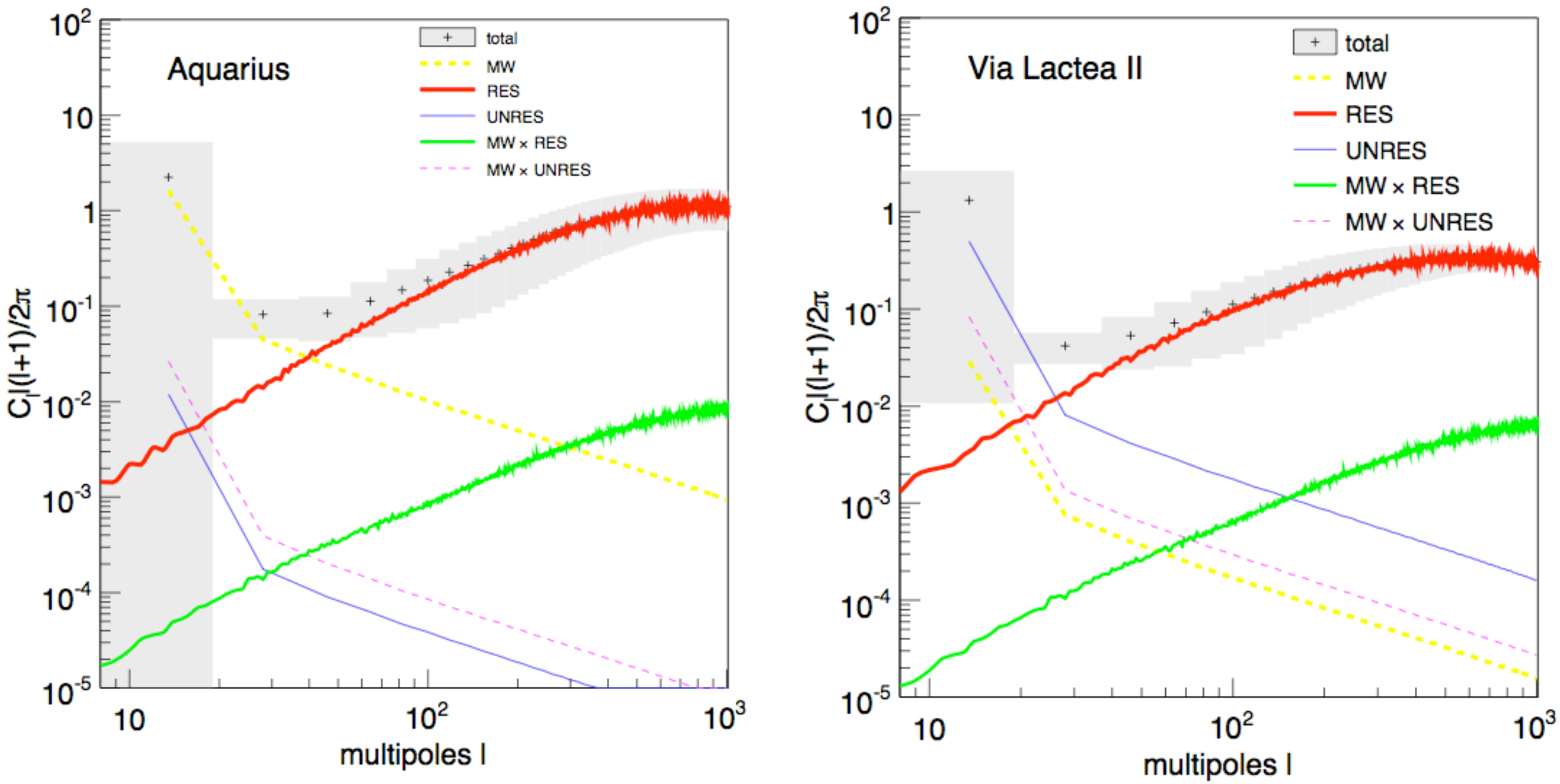
$$\left\langle \frac{d\phi}{dE d\Omega} \right\rangle a_{l,m} = \int d\Omega \left(\frac{d\phi}{dE d\Omega} - \left\langle \frac{d\phi}{dE d\Omega} \right\rangle \right) Y_{l,m}(\theta,\varphi)^*$$

$$C_l = \frac{\sum_{m=0}^{l} \left| a_{l,m} \right|^2}{2l+1}$$

Angular correlations on the diffuse γ-ray background

Galactic subhalos

-checked against different number of simulated Galactic subhalos-



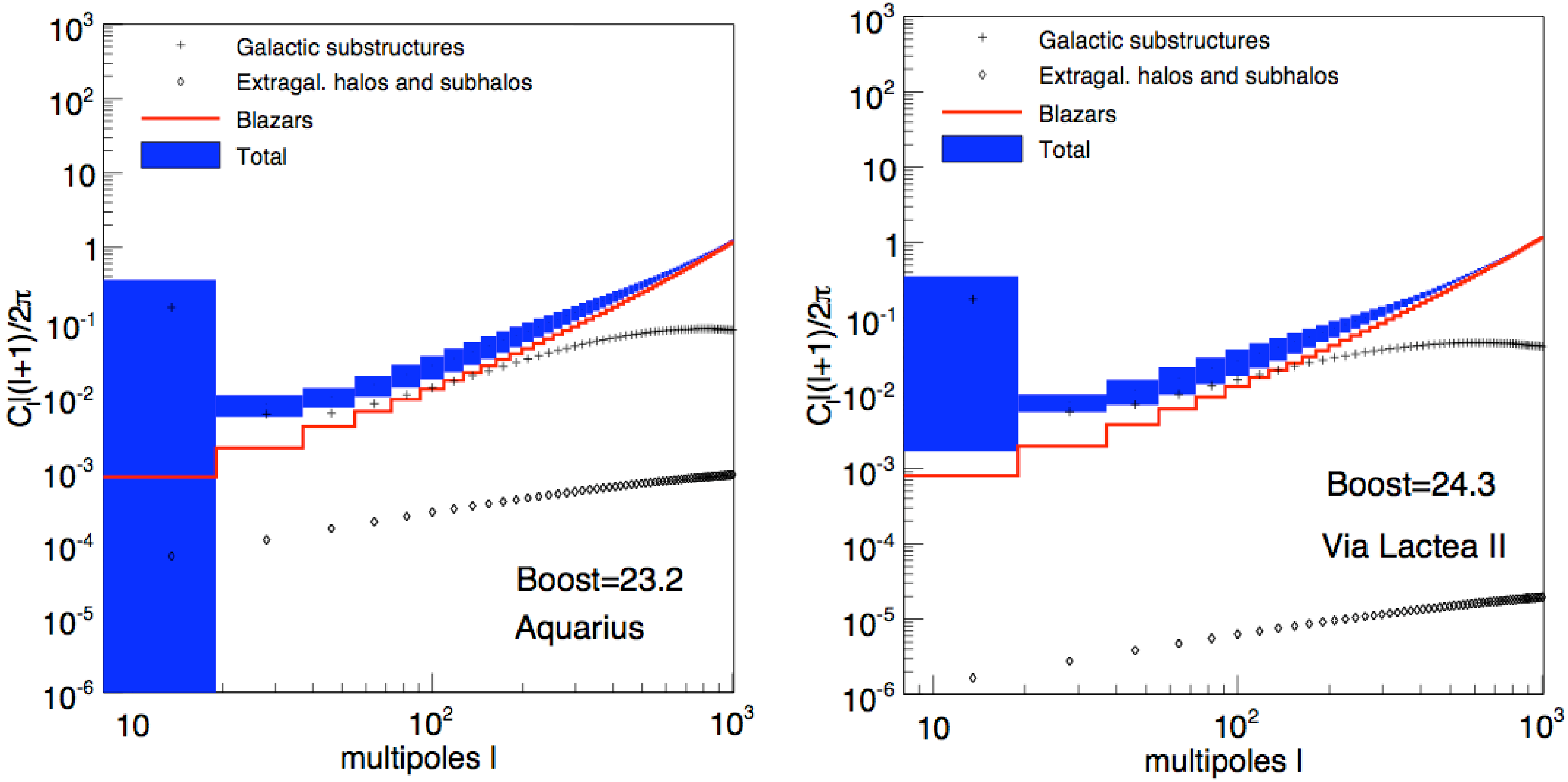
M_χ=40 GeV, $\sigma v = 3\times10^{-26}$ cm^{3}s^{-1}, E = 10 GeV

Ando, Bertone, Branchini, Fornasa, LP *in preparation*

Angular correlations on the diffuse γ-ray background (toy model: assume EGB = 60% EGRET EGB)

Comparison with EGB à la Ando&Komatsu

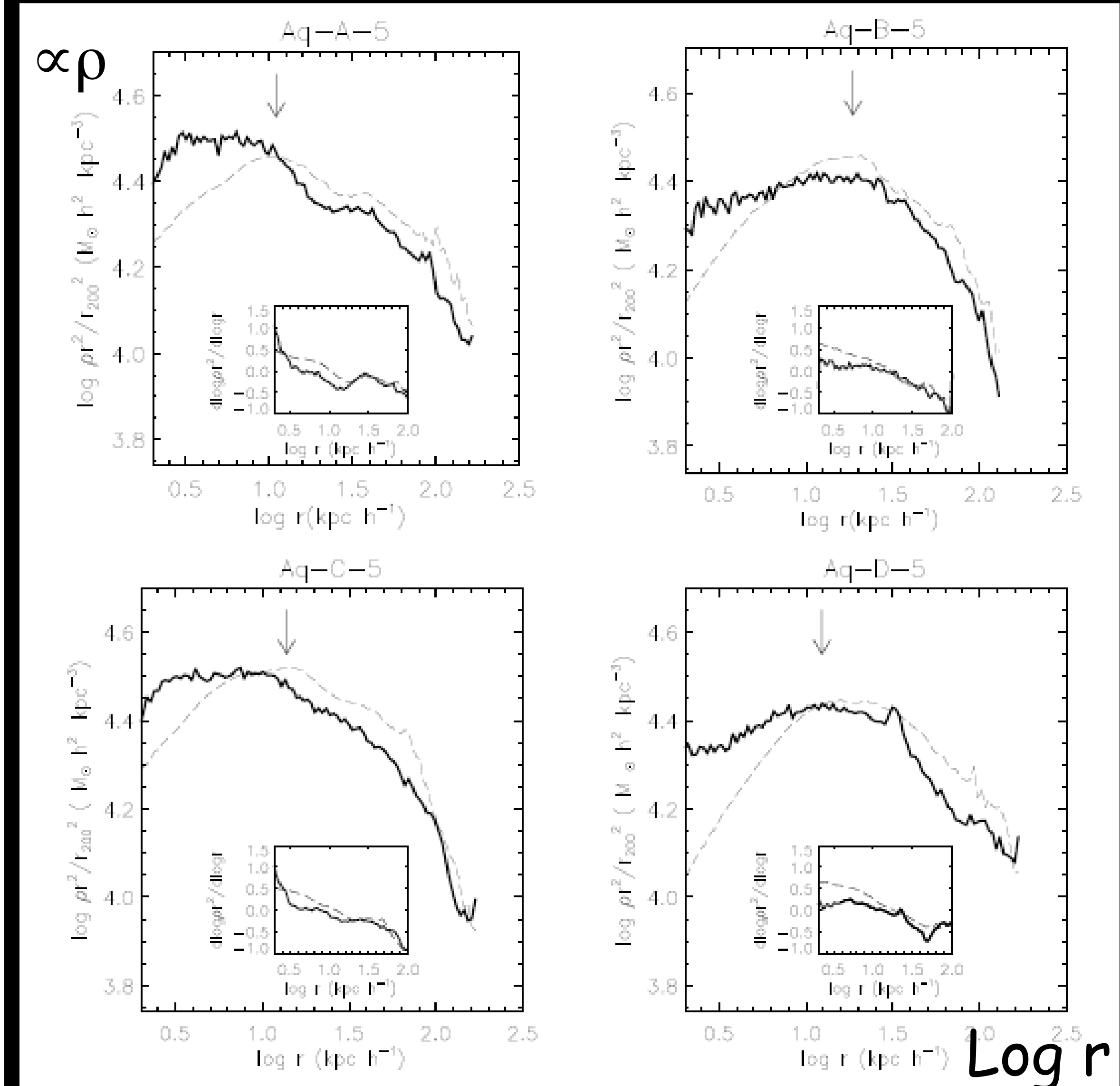
-we take the shape for blazar and extragalactic DM from them-



M_χ=40 GeV, $\sigma v = 3\times10^{-26}$ cm^3s^{-1} boosted to be 60% of EGB, E = 10 GeV

Ando, Bertone, Branchini, Fornasa, LP *in preparation*

The frontier : simulations including baryons



Tissera et al. 2009 resimulated 6 Aquarius MW-like halos including metal-dependent cooling, star formation and supernova feedback

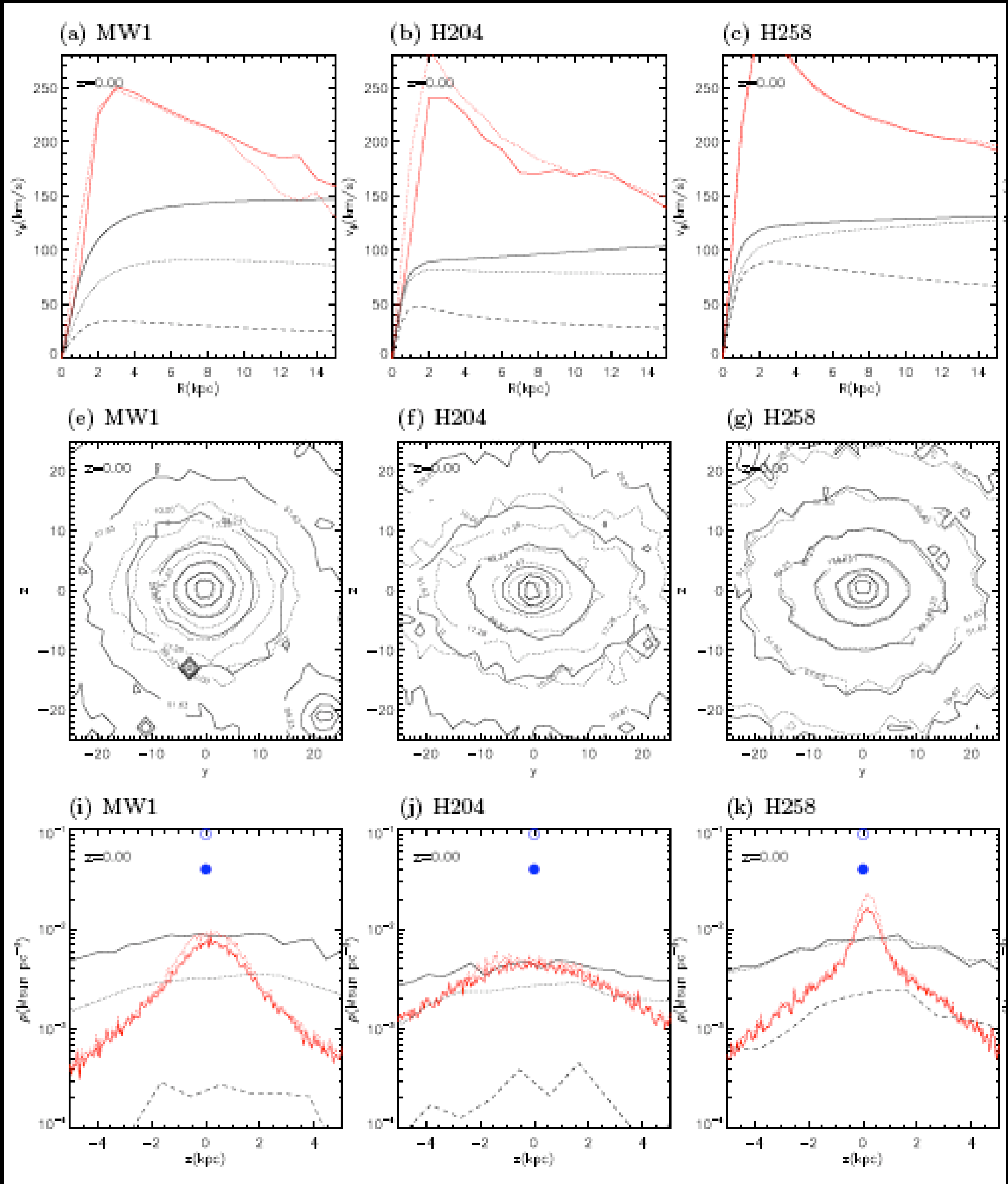
Found steeper DM profiles

Specific results depend on merging history

Agertz et al 2010 (Ben Moore group) are producing high resolution simulations of the MW including baryons..

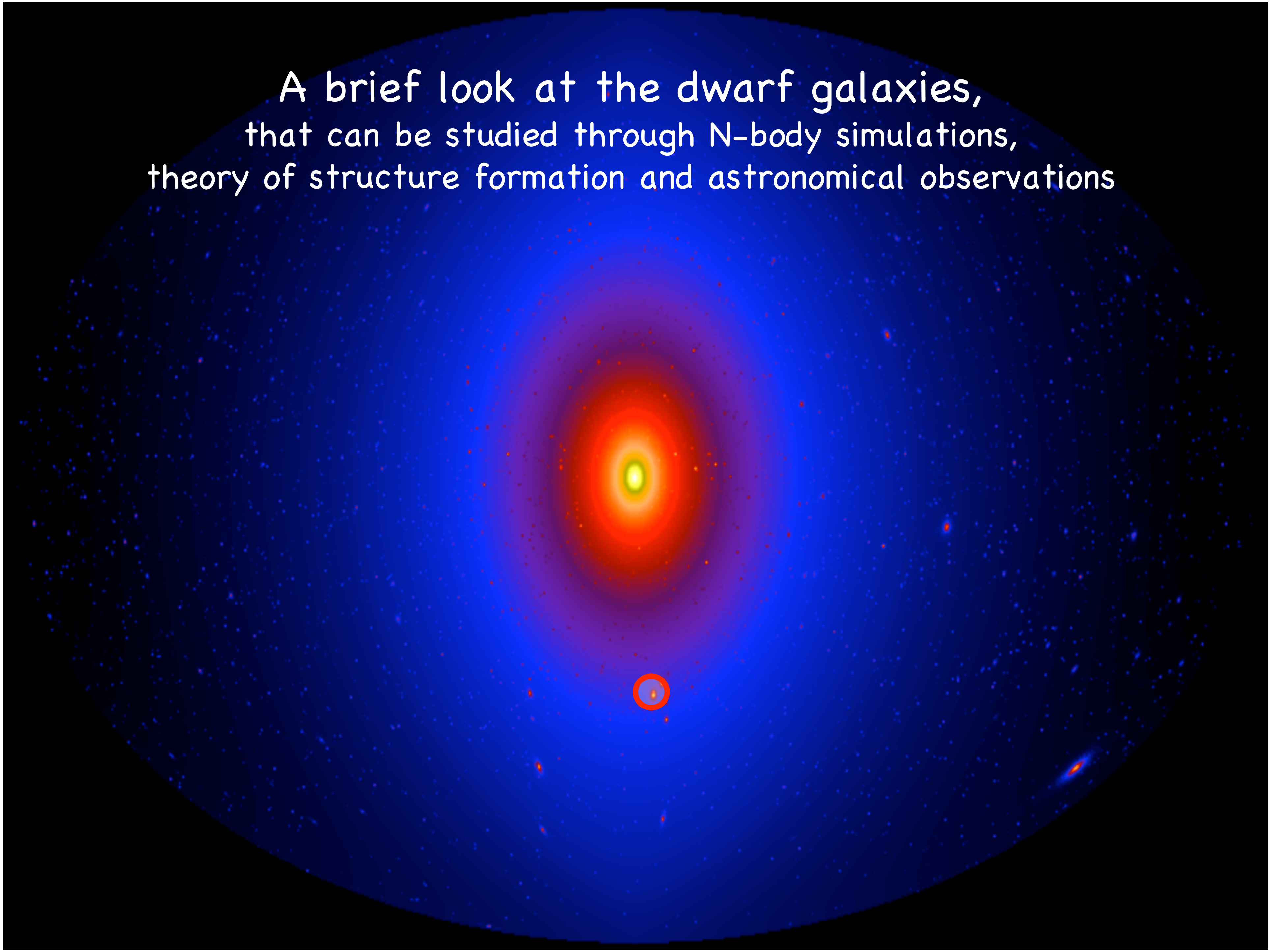
Stay tuned (Agertz,Bertone, Pato, LP, Diemand, Moore, 2010)

The case : the dark disc



Read et al. 2009
found that baryons in the disk causes merging satellites to be dragged towards the disk and be torn apart, resulting in a dark matter disk, which gives anisotropic DM velocity distribution at the solar neighbourough with interesting implications on WIMP capture and annual modulation signal.

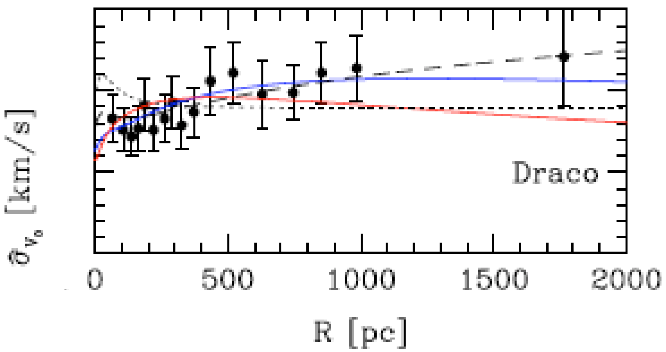
Specific results depend on merging history


A brief look at the dwarf galaxies,
that can be studied through N-body simulations,
theory of structure formation and astronomical observations

Dwarf galaxies are the only objects whose density profiles are nicely inferred by astronomical measurements

-> small astrophysical uncertainty

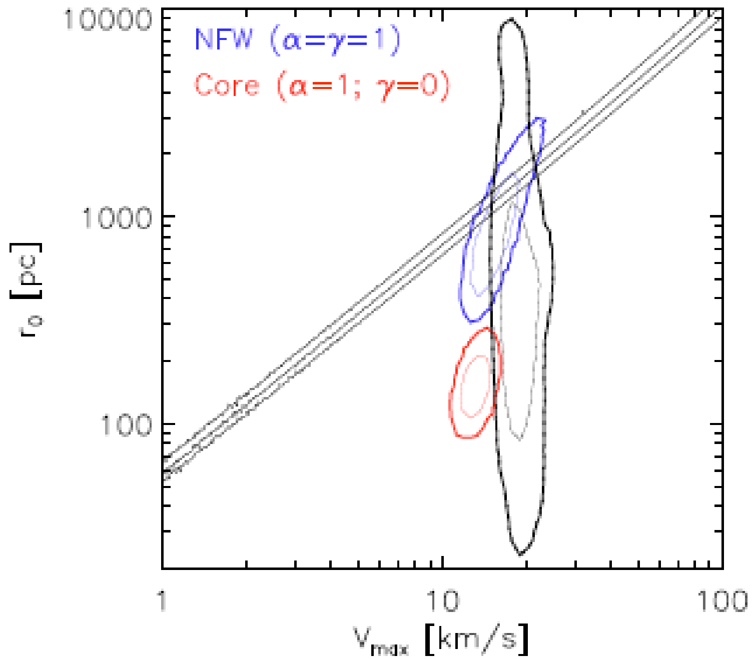
from velocity dispersions..



... to density profiles.

Universal behaviour!

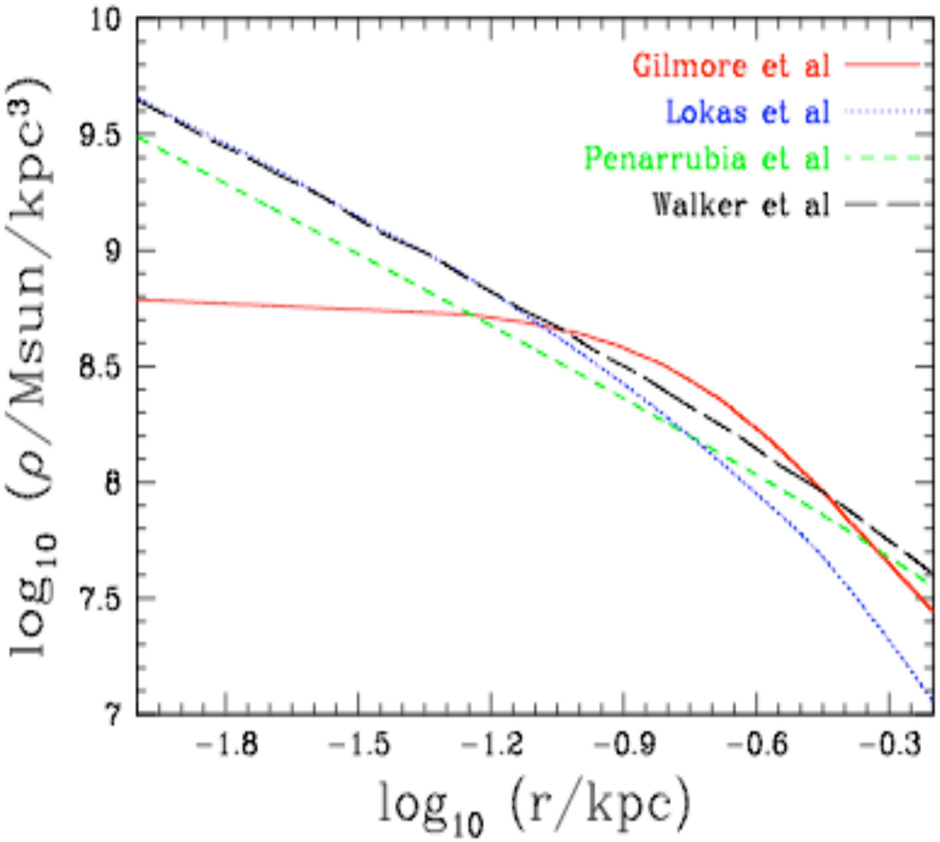
NFW preferred by χ^2 analysis

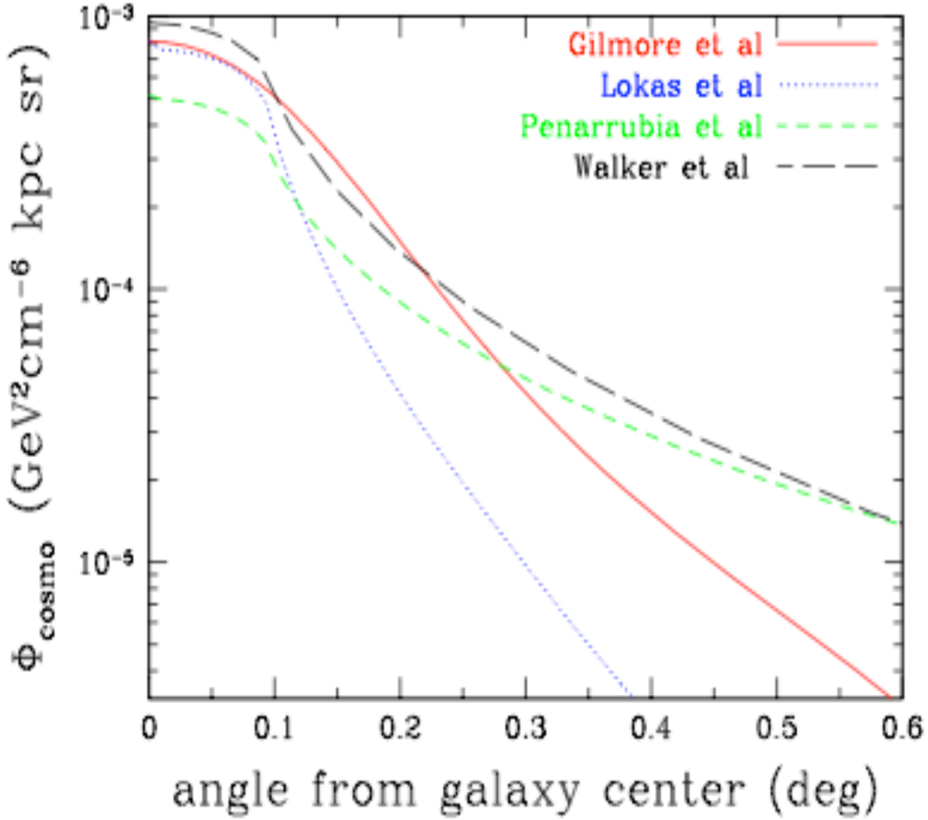


Walker et al, 2009

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

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

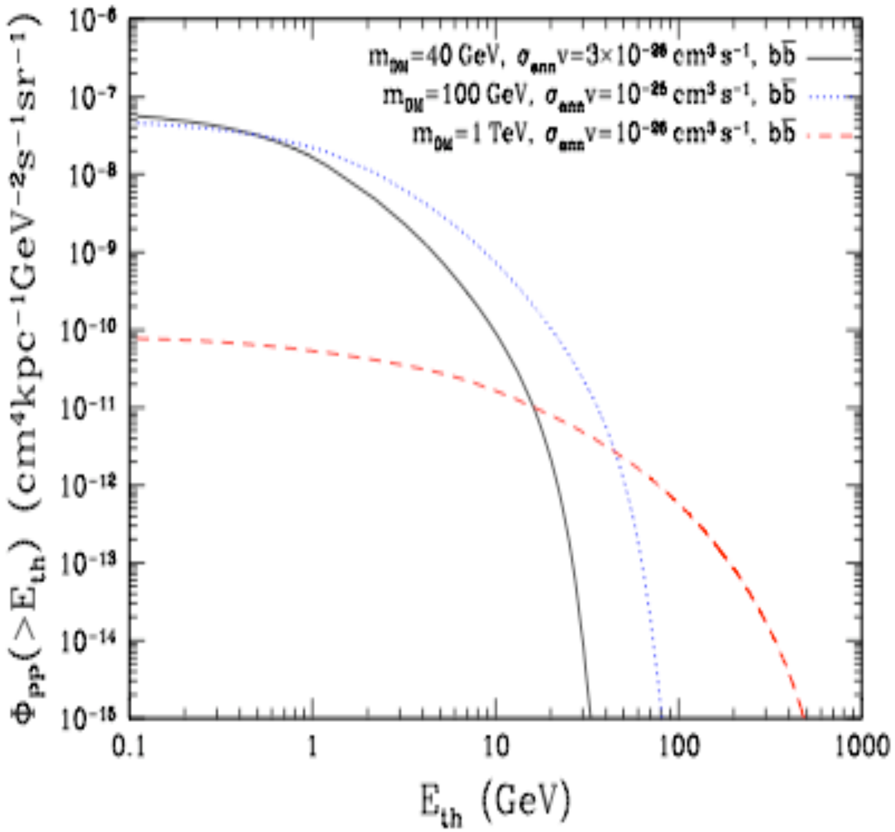


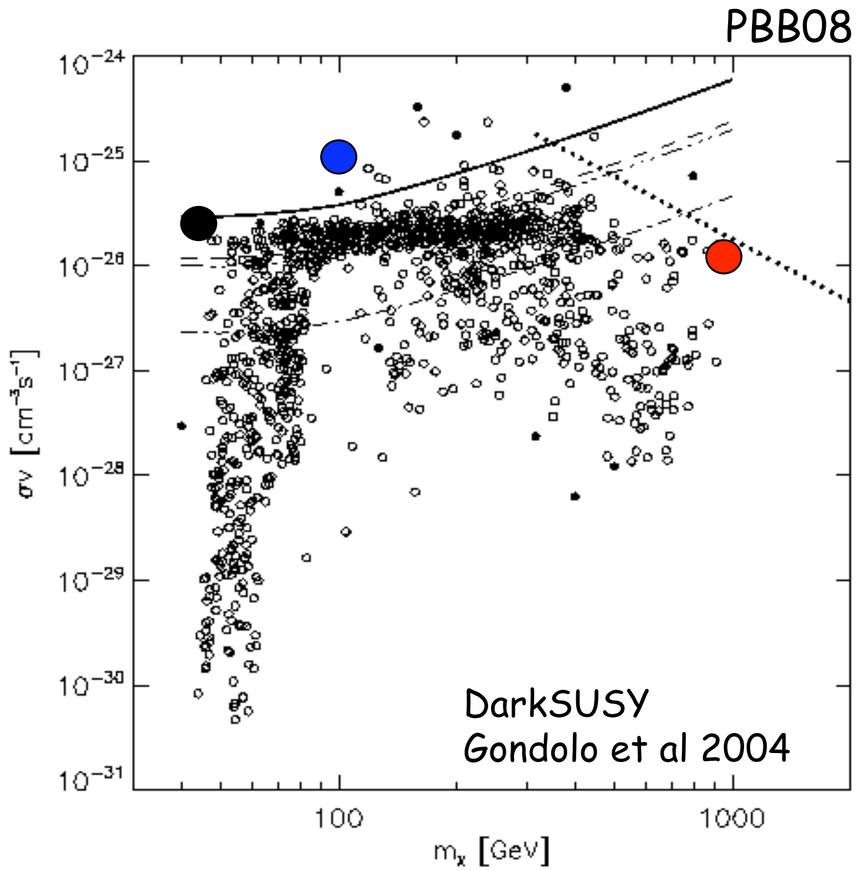


LP, Pizzella, Corsini, Dalla Bontà & Bertola 2008

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

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

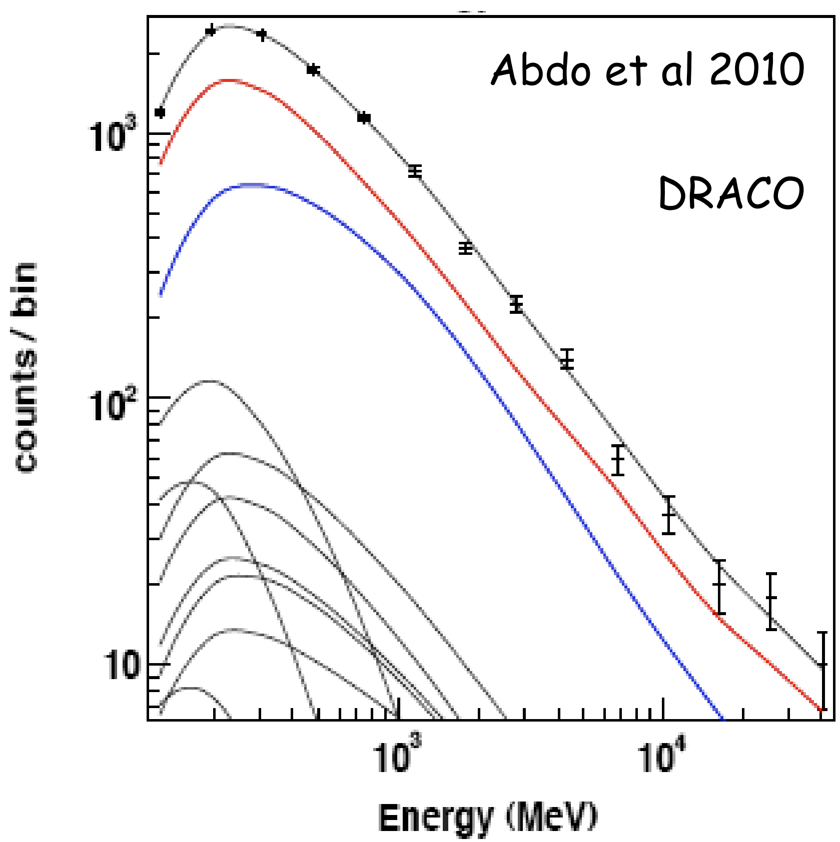




LP, Pizzella, Corsini, Dalla Bontà & Bertola 2008

Comparing predictions with Fermi performances

DRACO Φ_{γ}^{max} (> 100 MeV) = (4.5±1.5) x 10^{-11} cm^{-2} s^{-1}

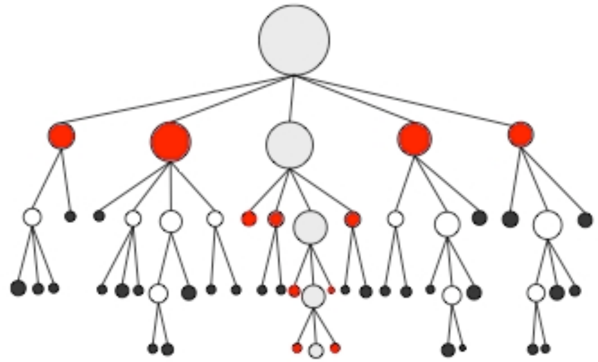


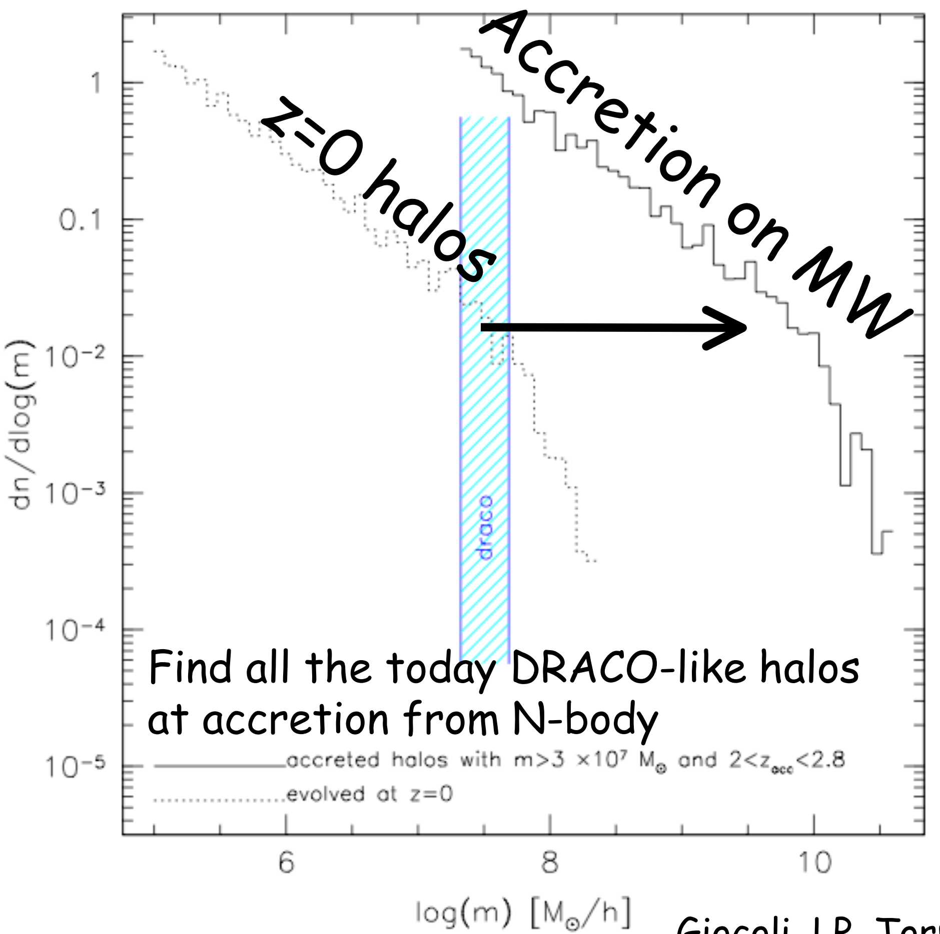
$\phi_{\gamma,Fermi}^{95\%CL}(>100MeV,1yr)$
$(0.1-2)\times10^{-9}\,cm^{-2}s^{-1}$

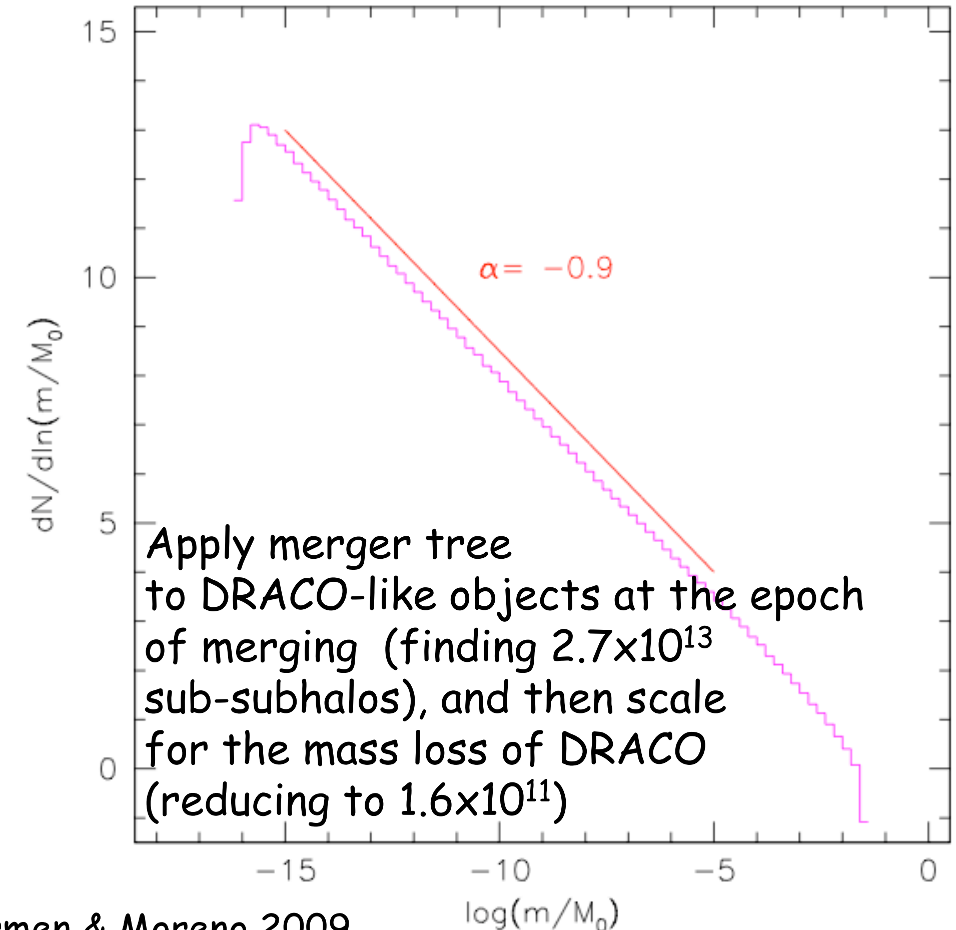
DRACO and other dwarfs are now only <u>slightly</u> below the detection limit
(for our PP scenarios)

And very clean astro-objects
poor astrophysical background
stable astrophysical predictions

Can an astrophysical boost factor affect our computation?

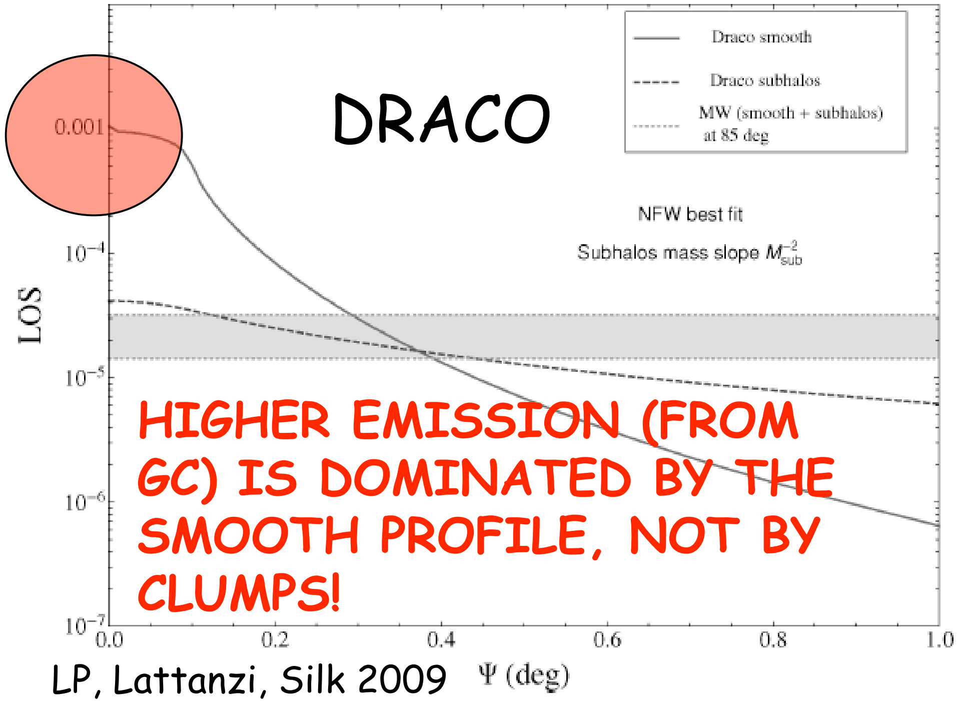






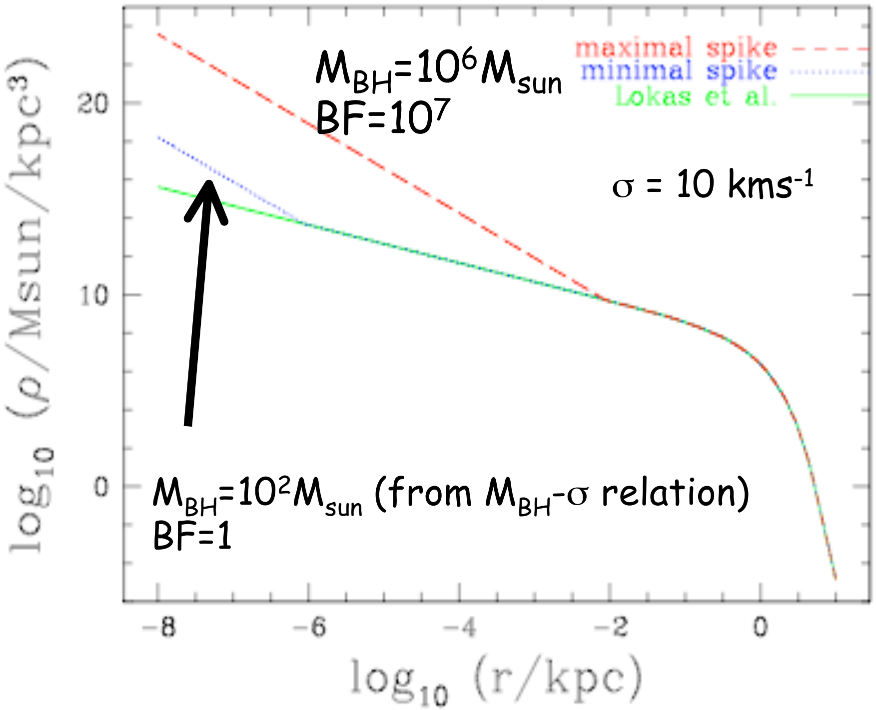
Giocoli, LP, Tormen & Moreno 2009

Stability of Draco predictions: boost factors?



LP, Lattanzi, Silk 2009

LP, Pizzella, Corsini, Dalla Bontà & Bertola 2008



NFW fit to DRACO velocity dispersion (Walker et al 2008)
$M=5 \times 10^9\ M_{sun}$
$c=22$, $r_s=2$ kpc
$\rho_s=2.16 \times 10^7\ M_{sun}\ kpc^{-3}$

A Black Hole, if any, is not likely to give any significant boost

Conclusions

N-body simulations and theory of structure formation have allowed us to model the galactic structure and to infer predictions useful for DM detection

The inclusion of baryons in N-body simulations and the advent of new astrophysical and hopefully accelerator data could soon shade light on DM