Dark matter annihilation and non-thermal processes in Galaxy clusters

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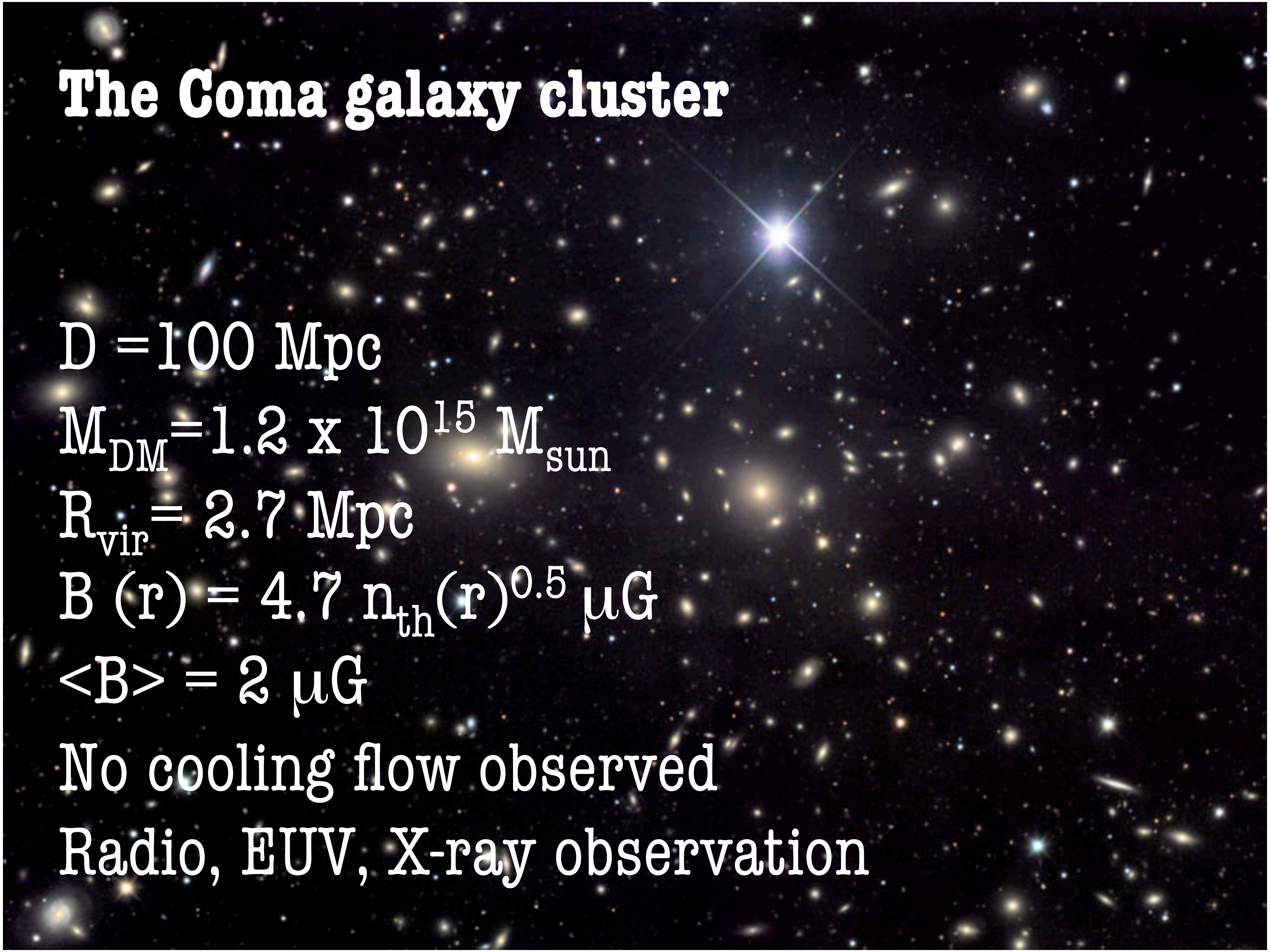
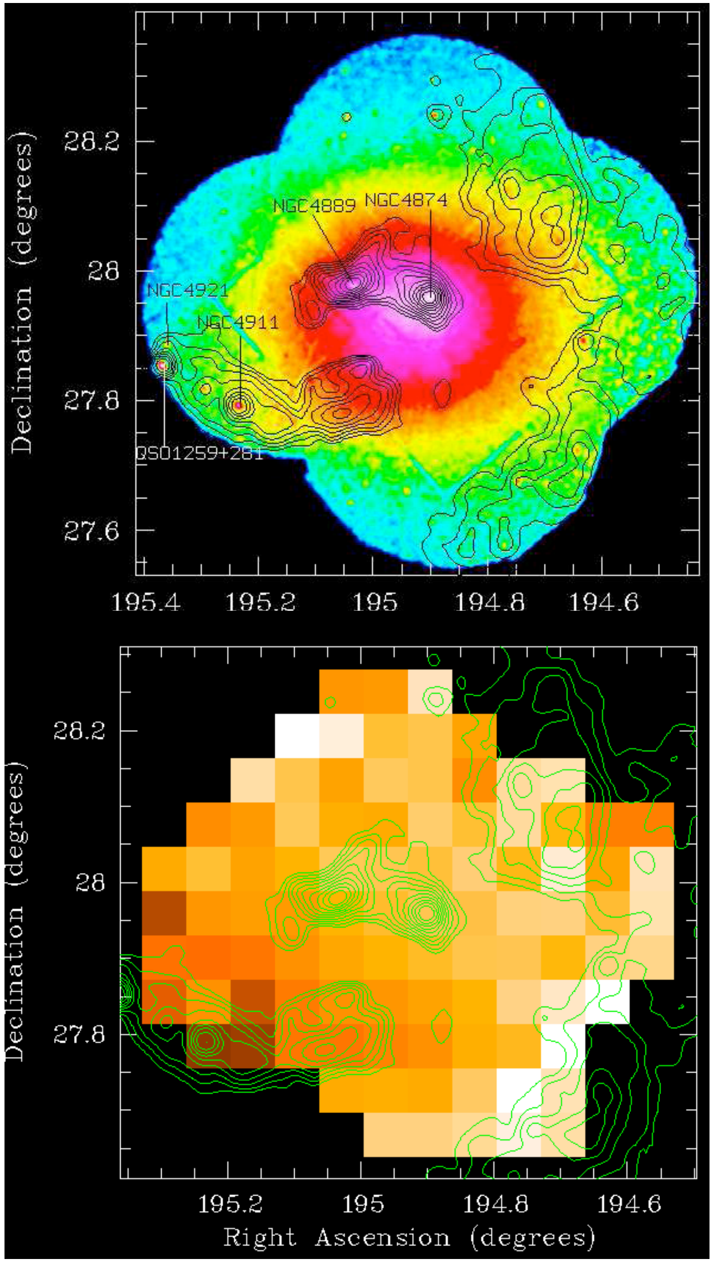
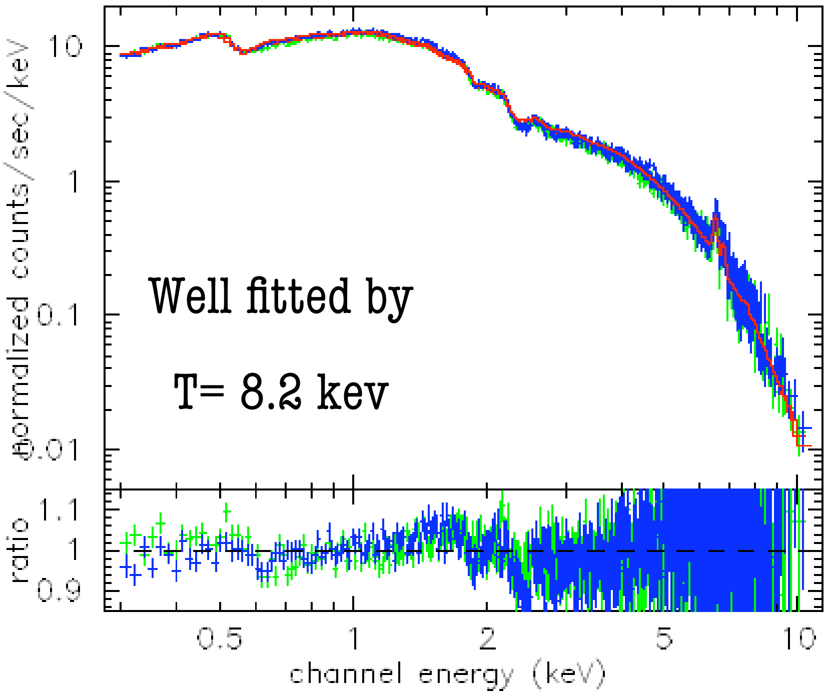
GGI workshop on Dark Matter
May 7th 2010

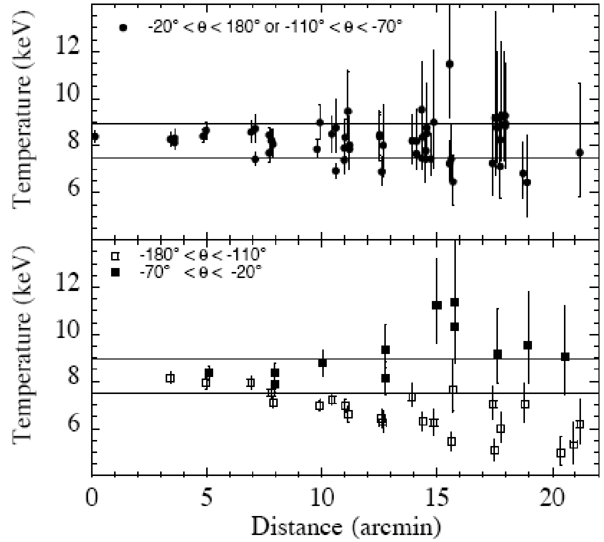

The Coma galaxy cluster
D =100 Mpc
M_{DM}=1.2 x 10^{15} M_{sun}
R_{vir}= 2.7 Mpc
B (r) = 4.7 $n_{th}(r)^{0.5}$ μG
<B> = 2 μG
No cooling flow observed
Radio, EUV, X-ray observation

The thermal component (from X-rays)

XMM [0.3 -2] kev



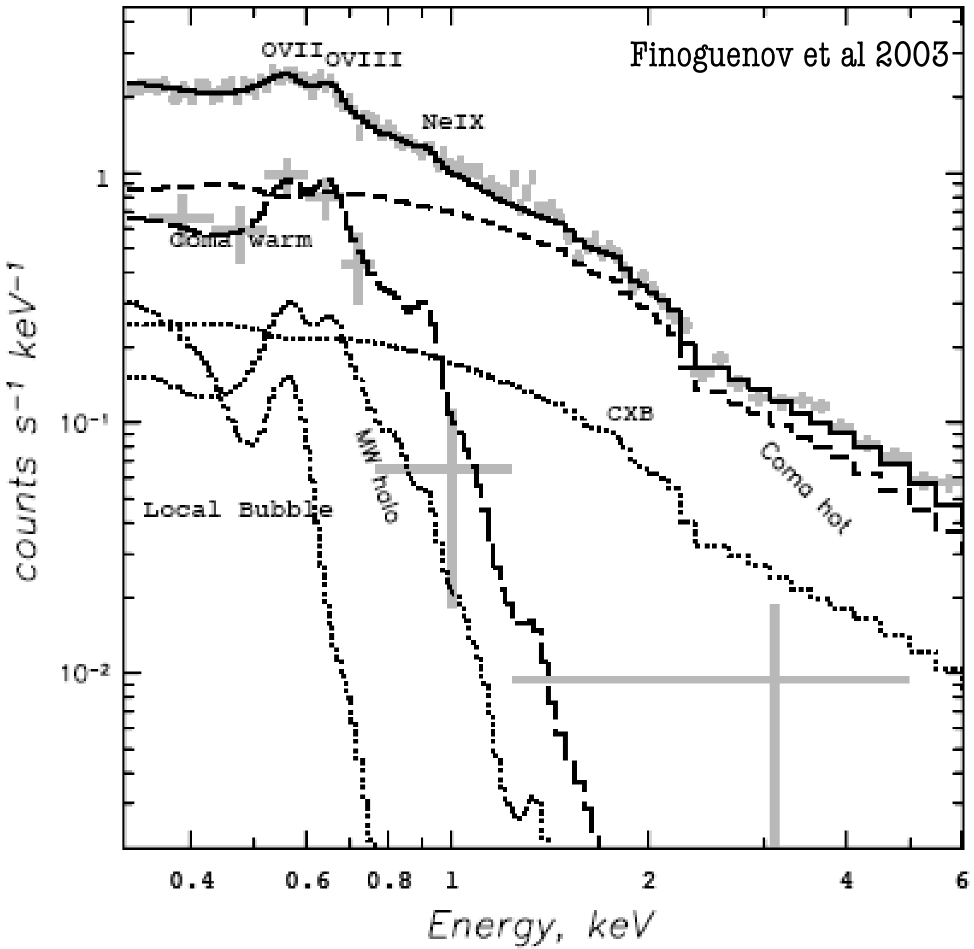




Arnaud et al 2001

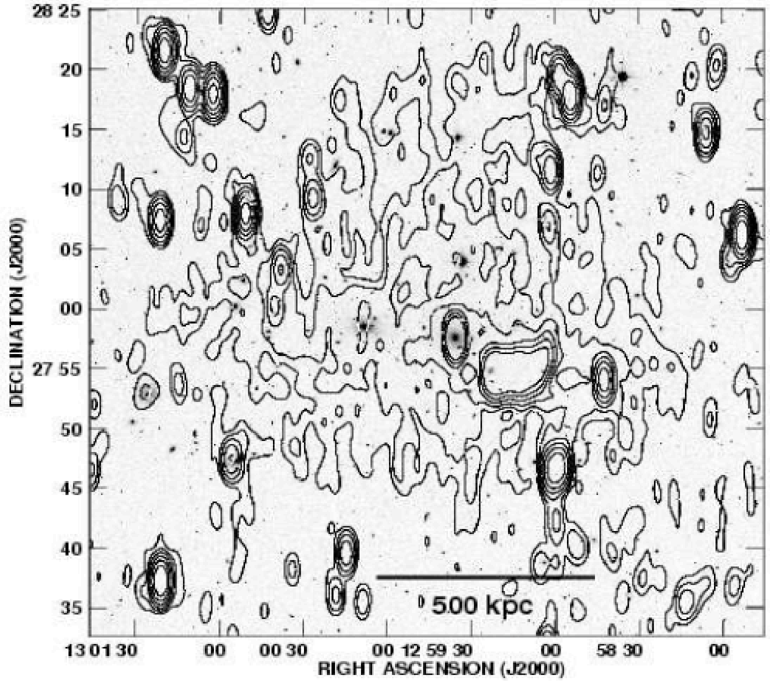
Maybe a second thermal component
The soft-X-ray excess in the outskirts of Coma (r > 1 Mpc)

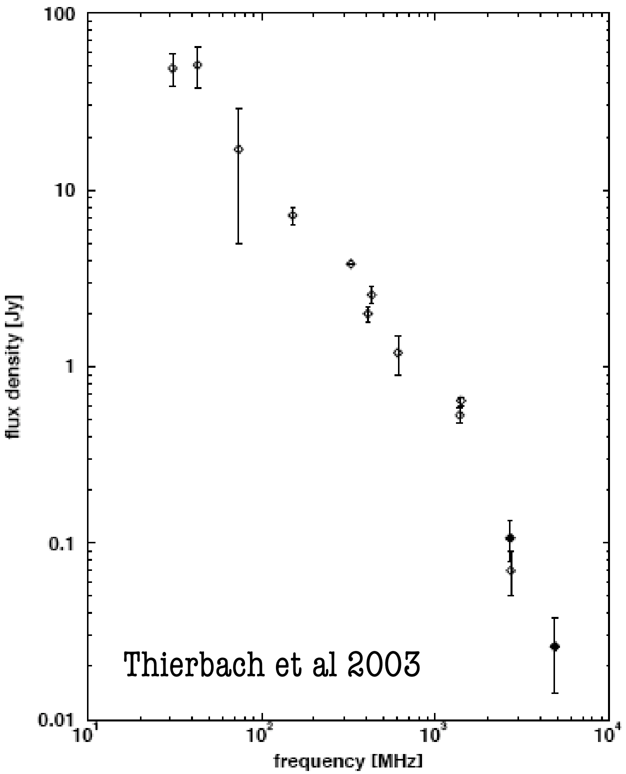
Fitted by a second thermal component of T = 0.22 keV
consistent with Warm-Hot Intergalactic Medium filaments found in numerical simulation of cluster formation



Non-thermal components: the radio halo of Coma (r < 1 Mpc)

Giovannini et al 1993





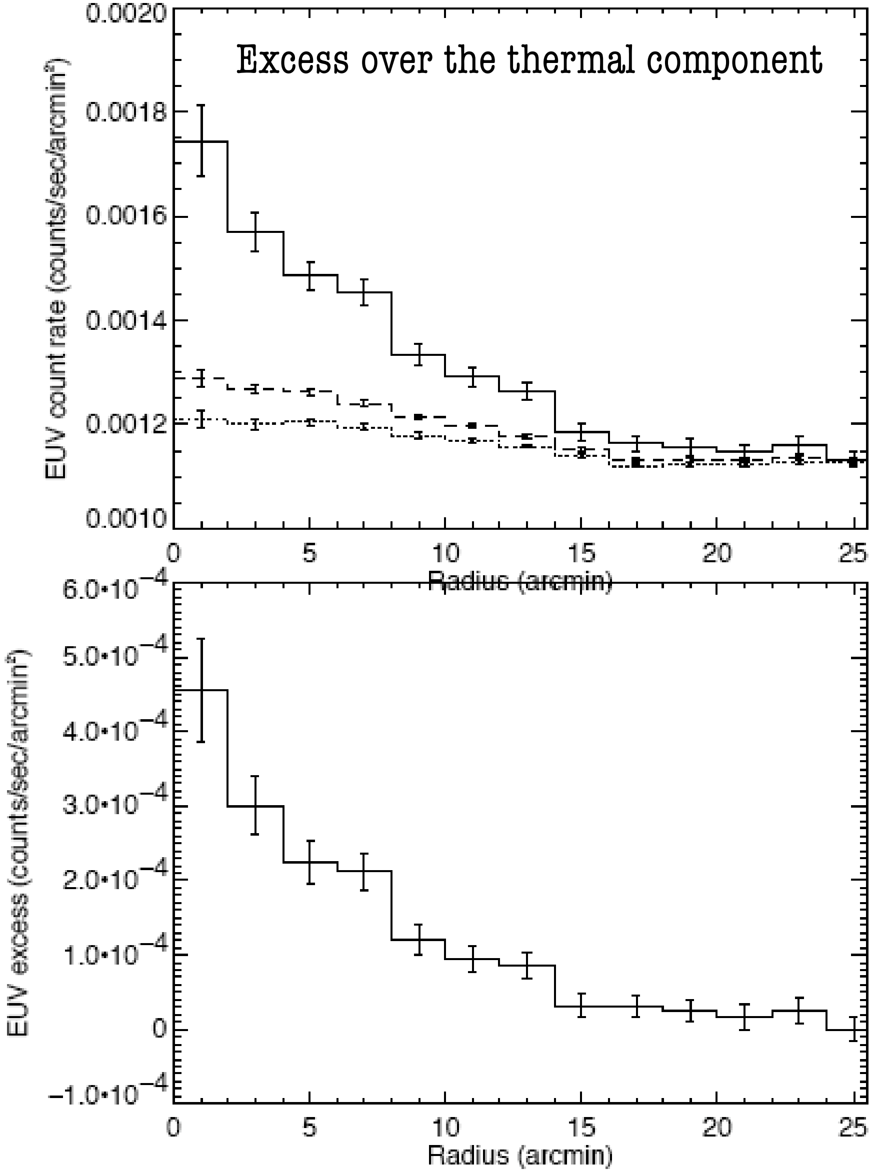
Diffused over Mpc scale - Requires a population of relativistic non-thermal electrons $\gamma > 10^4$ for B ~ 0.1,1 μG

(Note, Faraday Rotation Measurements suggest <B> ~ 2 μG - Bonafede et al. 2010)

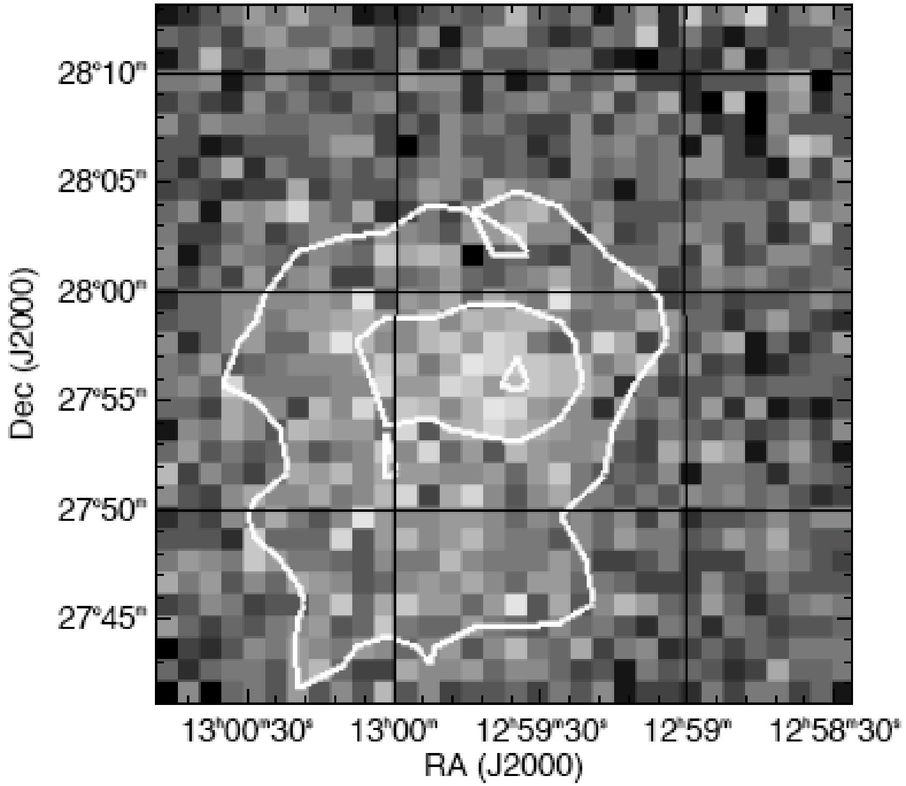
Primary or reacceleration model: electrons produced by AGN activity (quasars, radio galaxies) or star formation (supernovae, galactic wind, etc). Synchrotron and ICS radiation losses should be balanced by reacceleration (shock waves or magneto-hydrodinamics turbolences) - see Brunetti et al 2004 -

Secondary model: electrons produced in inelastic nuclear collisions between relativistic CR protons and thermal ions of the intracluster medium. B > few μG is needed + associated photon and neutrino production - see Blasi & Colafrancesco 1999 -

The extreme UV excess in the center of Coma (r < 1 Mpc)



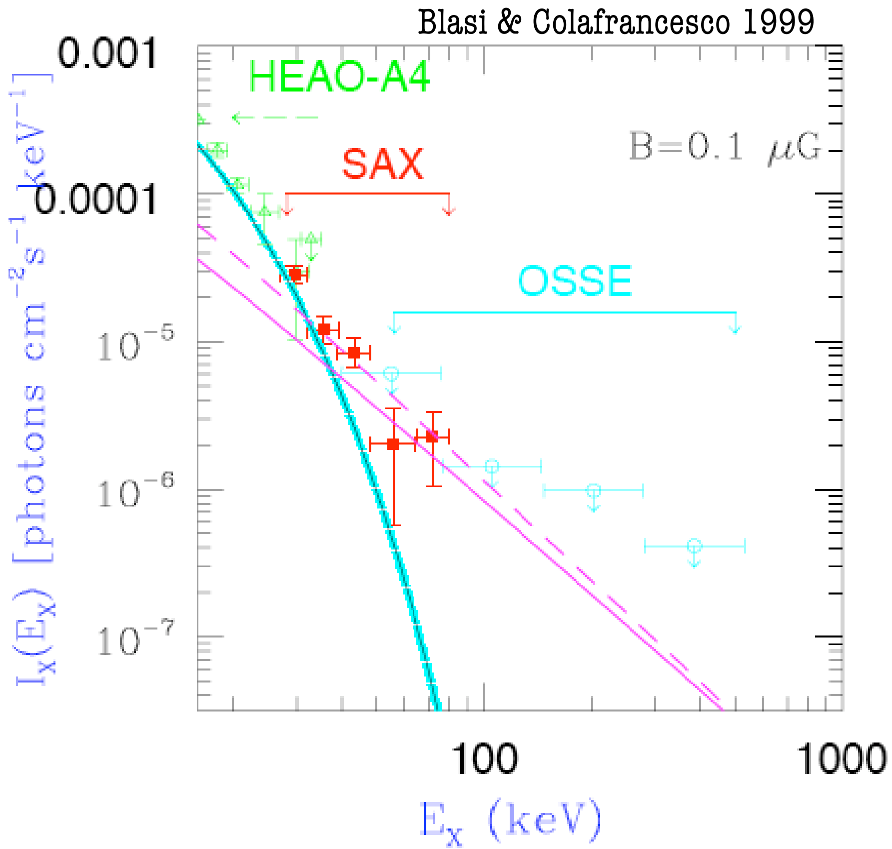
Possibly generated by a secondary population of relativistic electrons - produced through inelastic collisions of CRs with cluster plasma (secondary model) - which inverse Compton scatter off CMB photons

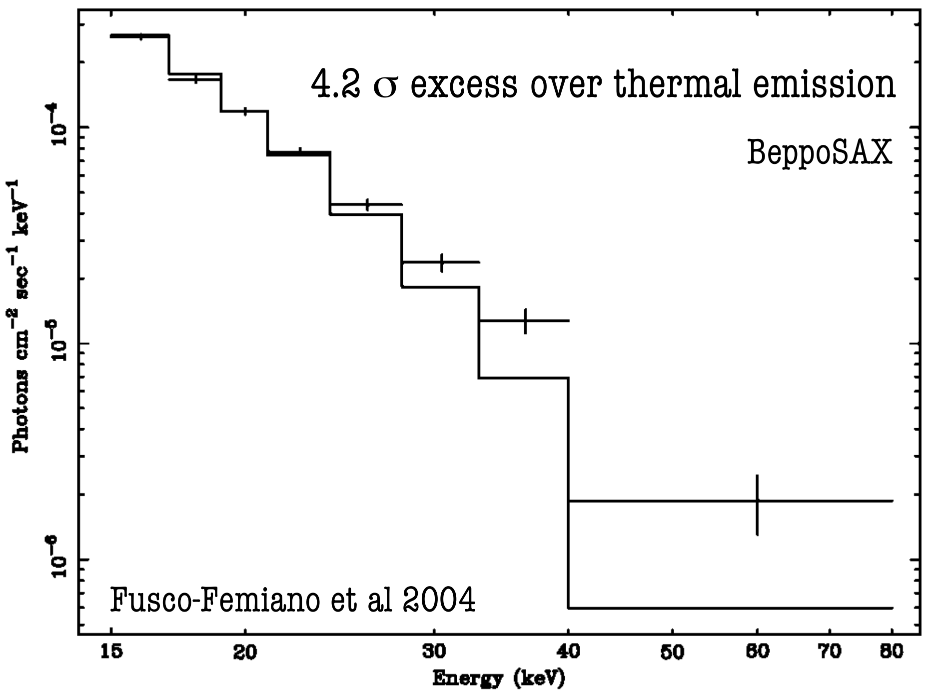


[0.13 - 0.18] kev

Bowyer et al 2004

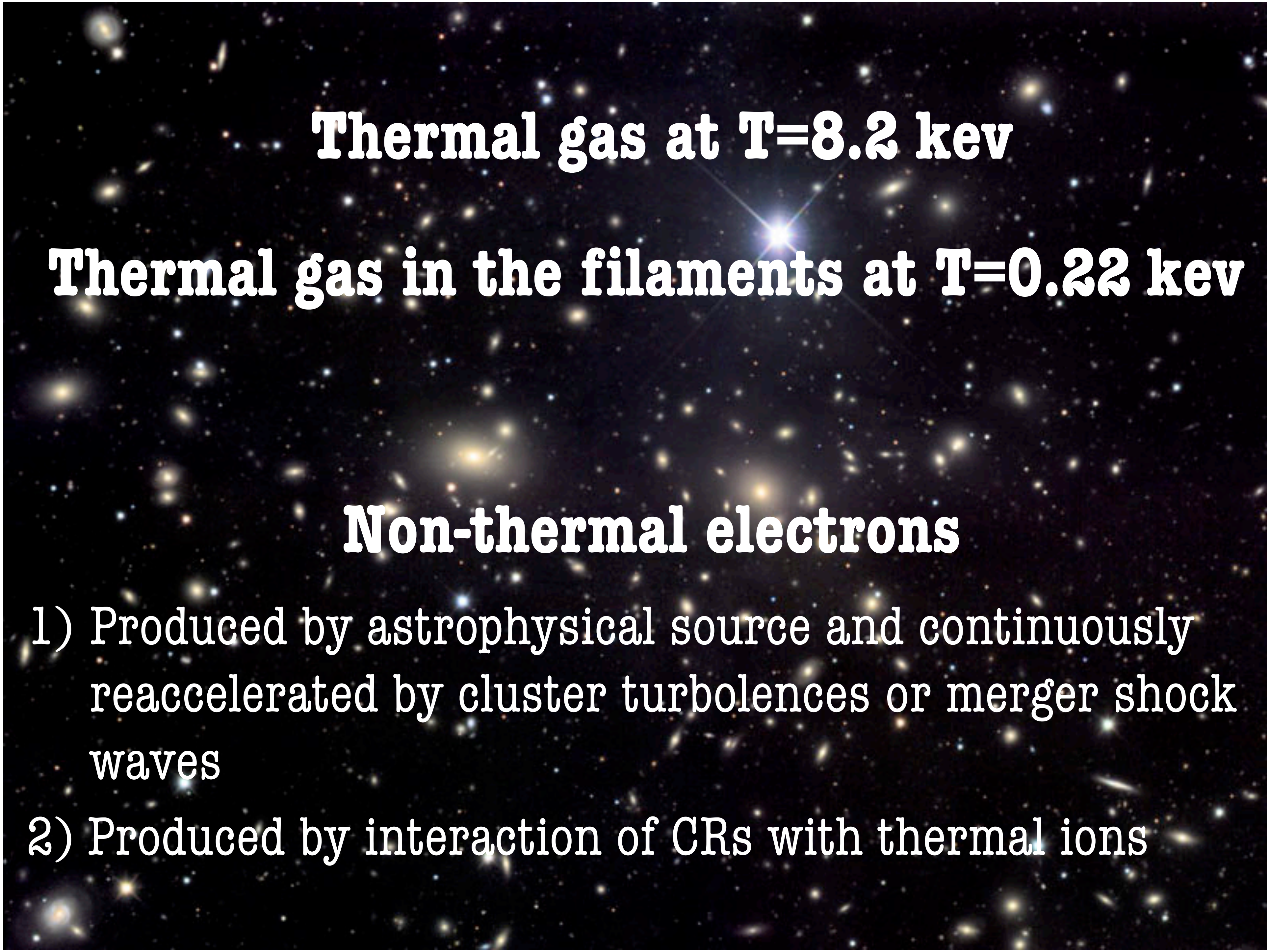
The hard X-ray excess in the center of Coma (r < 1 Mpc)





Possibly generated by ICS off CMB of the same electrons responsible for the radio halo (primary or secondary). Warning: in case of secondary model, the magnetic field needed may overproduce γ-rays (Blasi&Colafrancesco 1999)

Alternative: maybe due to a supra-thermal electron tail developed in the thermal electron distribution due to stochastic acceleration in the turbulent intra-cluster medium (Ensslin et al 1998)



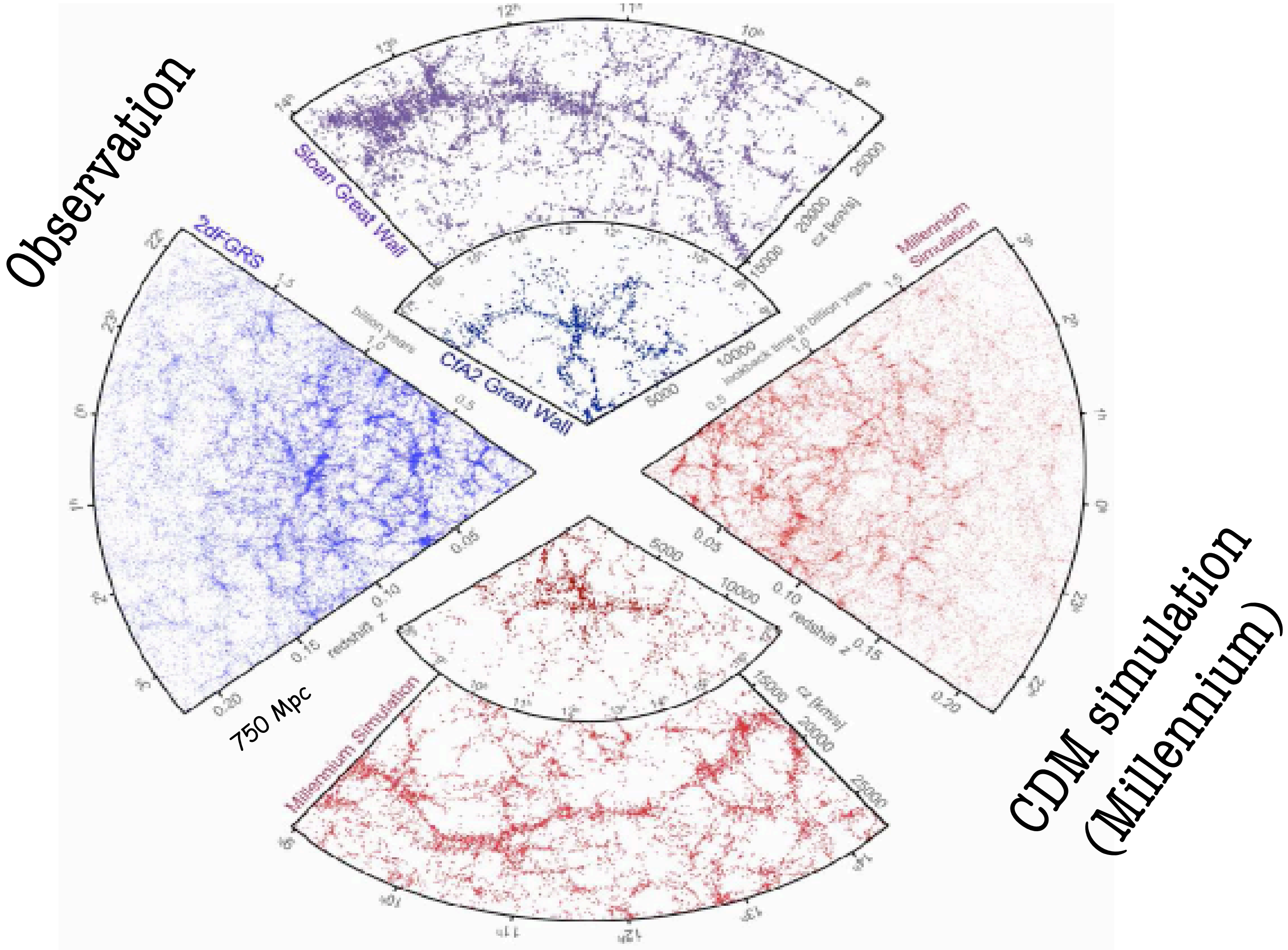
Thermal gas at T=8.2 kev

Thermal gas in the filaments at T=0.22 kev

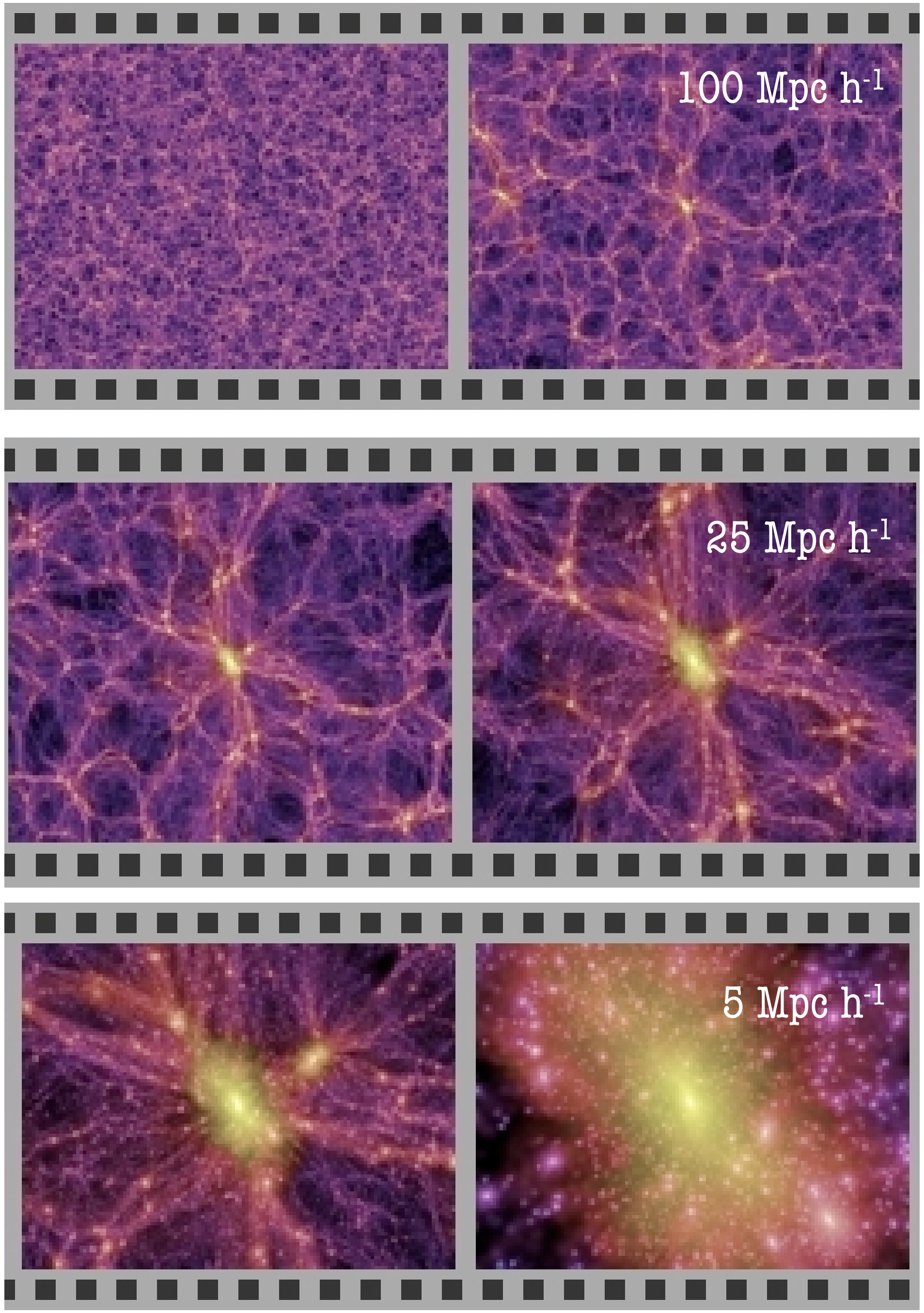
Non-thermal electrons

1) Produced by astrophysical source and continuously reaccelerated by cluster turbolences or merger shock waves
2) Produced by interaction of CRs with thermal ions

An Alternative Non Thermal Hypothesis:
(although non asked for...)
Relativistic electrons are produced by DM annihilation



MILLENNIUM Simulation
CDM universe
Springel et al. 2005



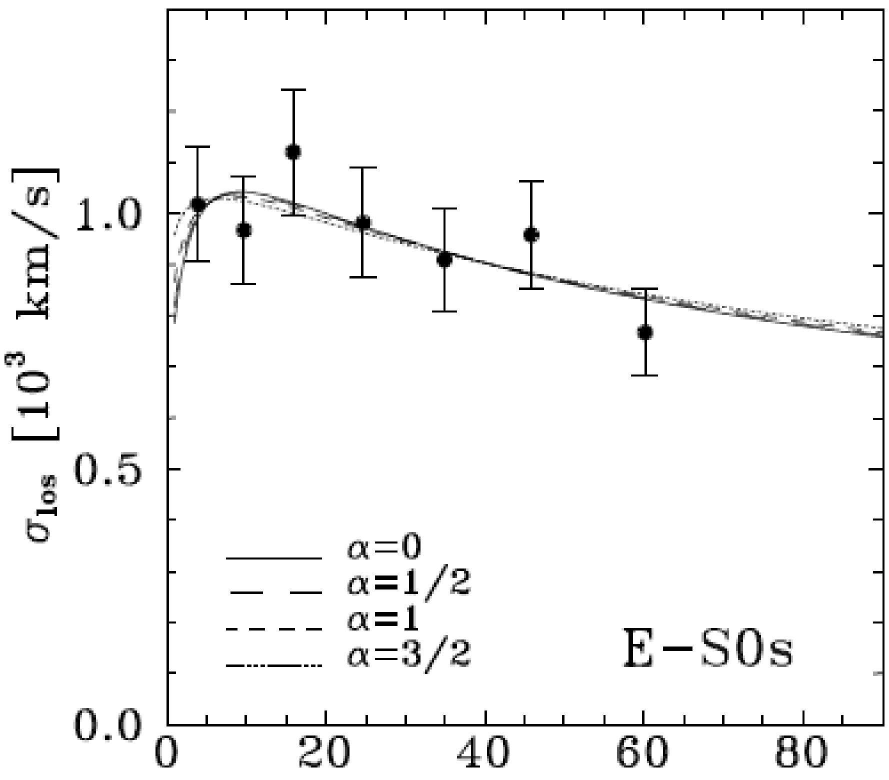
Simulates halos on cosmological scales, then resimulates a smaller patch with higher mass resolution down to cluster scale.

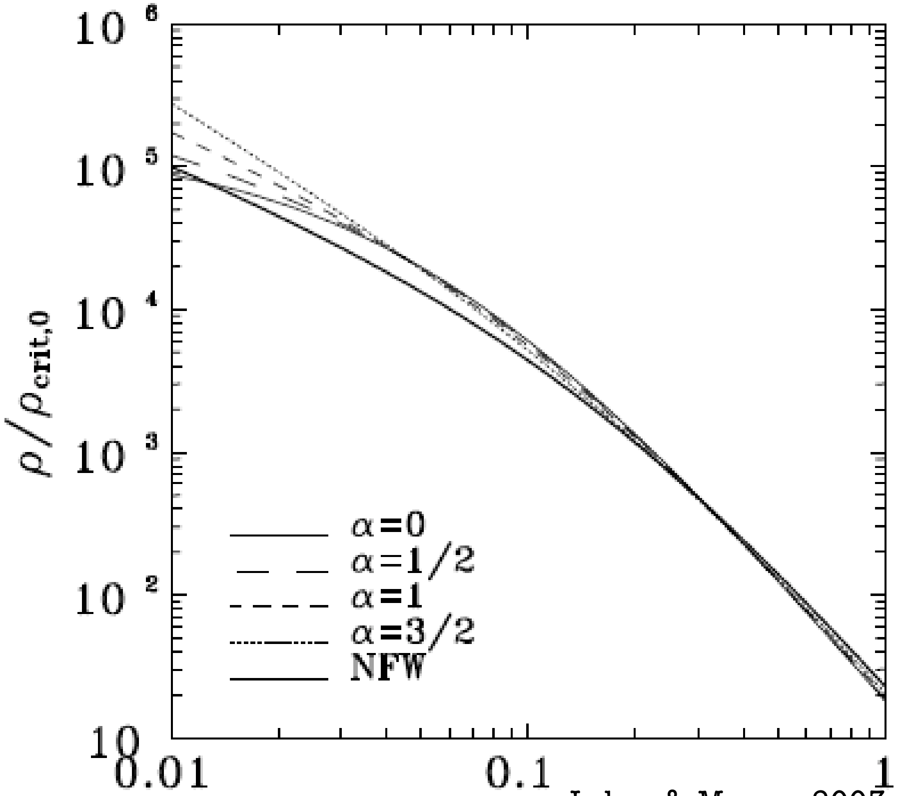
Tracks the formation of galaxies and quasars in the simulation, by implementing a semianalytic model to follow gas, star and supermassive black hole processes within the merger history trees of dark matter halos and their substructures

z=0

An Alternative Non Thermal Hypothesis:
(although non asked for...)
Relativistic electrons are produced by DM annihilation

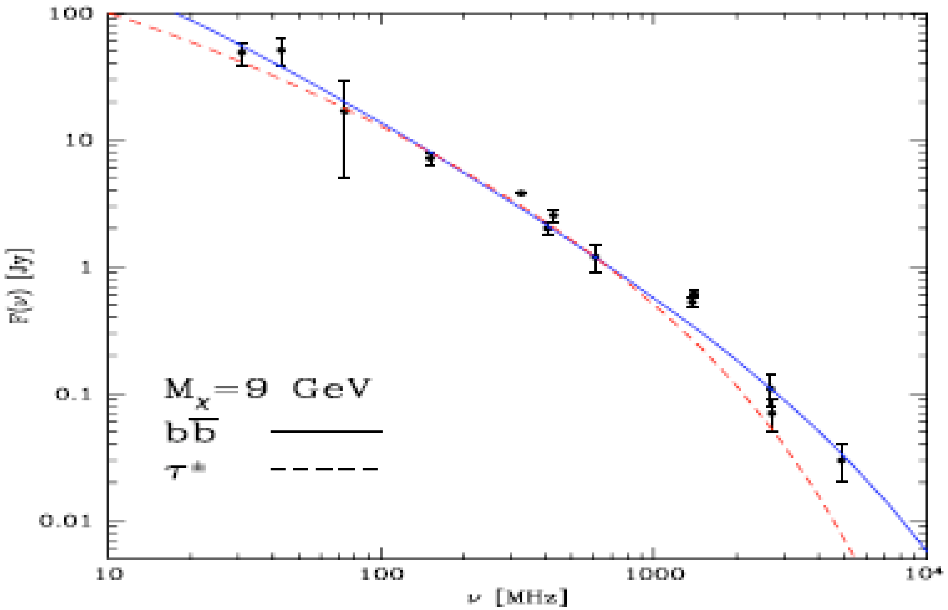
DM Density profiles can be inferred from astronomical measurements
or derived from numerical simulations

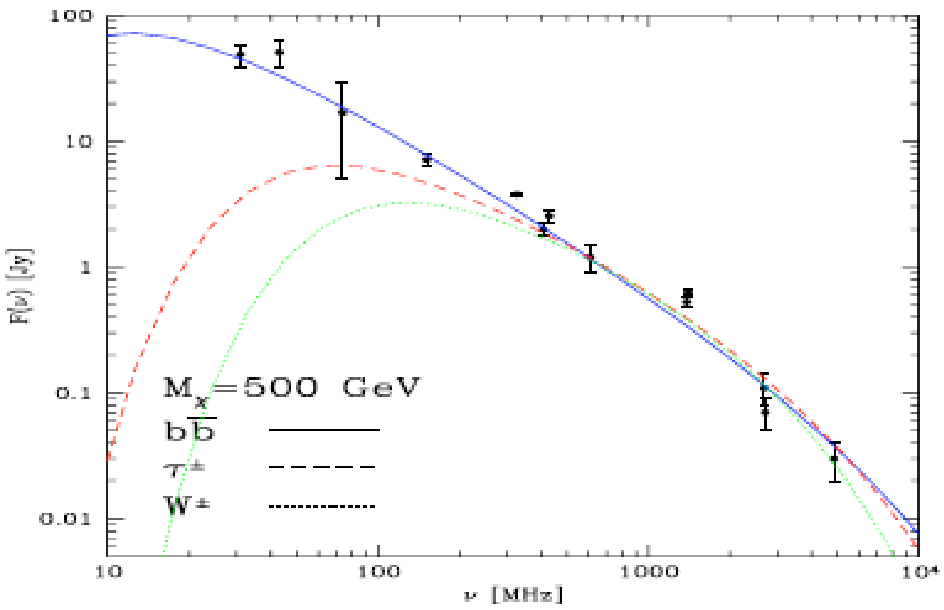




Lokas & Mamon 2003
Bullock et al 2001

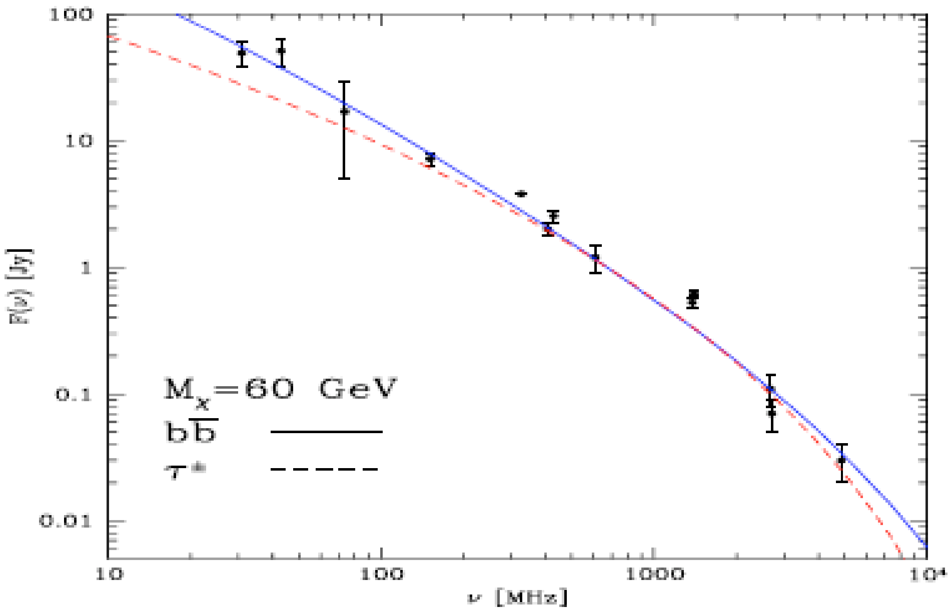
DM best fit to the radio halo spectrum of Coma





1st step:

Magnetic field and particle physics are left as free parameters to fit the radio halo of Coma

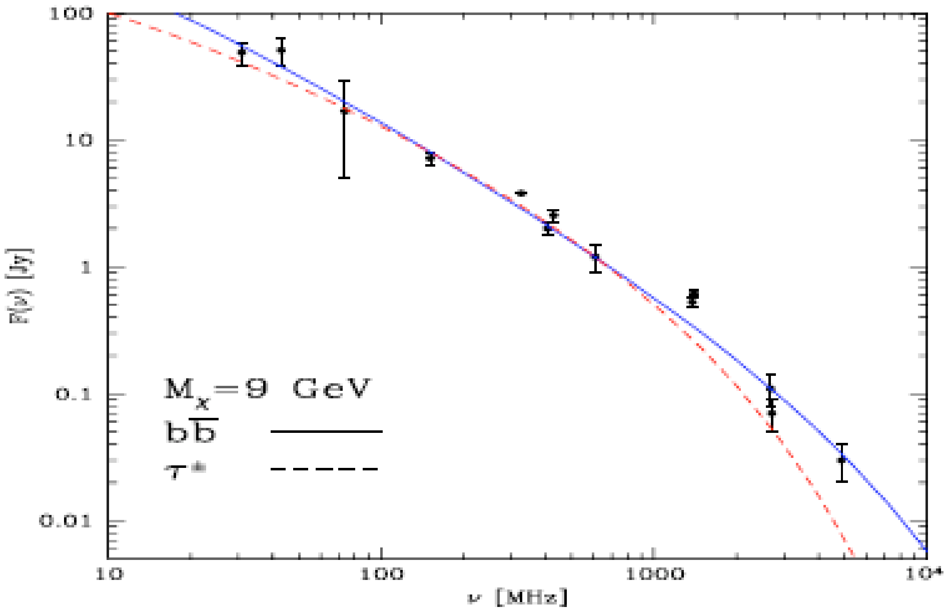


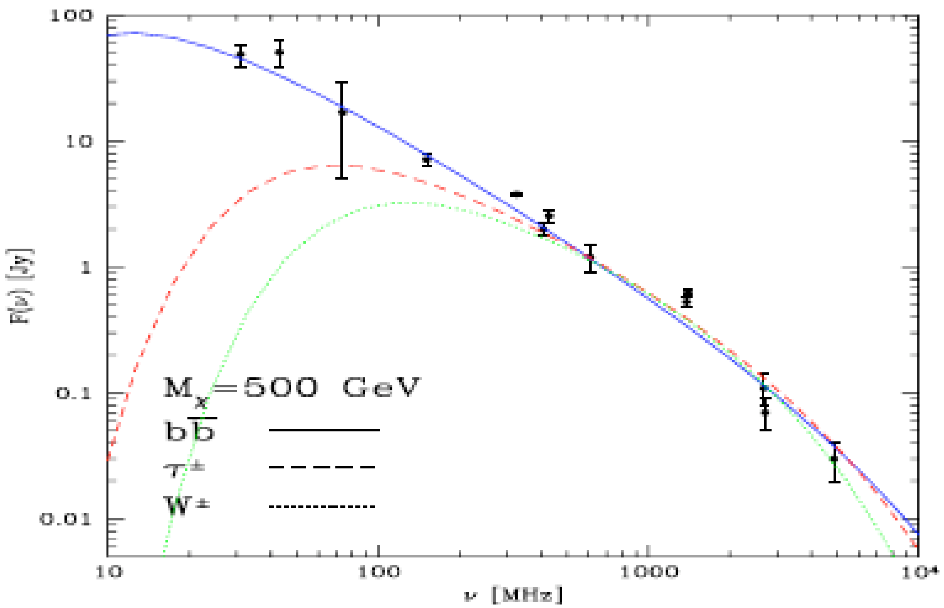
Colafrancesco, Lieu, Marchegiani, Pato & LP 2010

Compute electron equilibrium density

$$\frac{dn_e}{dE}(r,E) = \frac{1}{b(E)} \int_E^{M_\chi} dE' \, \widehat{G}\left(r, v - v'\right) Q_e(r,E')$$

DM best fit to the radio halo spectrum of Coma





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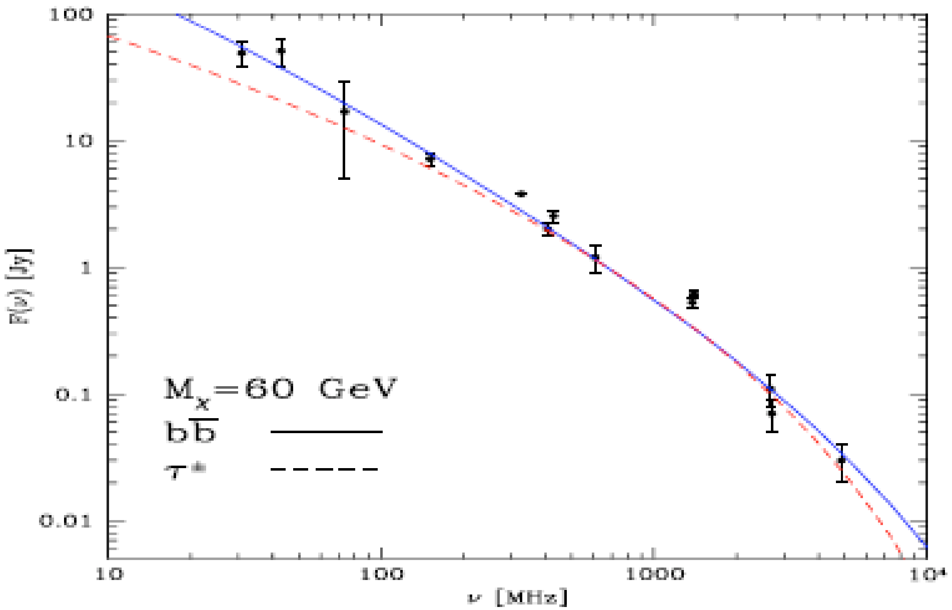


Colafrancesco, Lieu, Marchegiani, Pato & LP 2010

Compute synchrotron power,

$$P_{\rm synch}\left(\nu,E,r\right)=\int_0^\pi d\theta\frac{\sin\theta}{2}2\pi\sqrt{3}r_0 mc\nu_0\sin\theta F\left(x/\sin\theta\right)$$

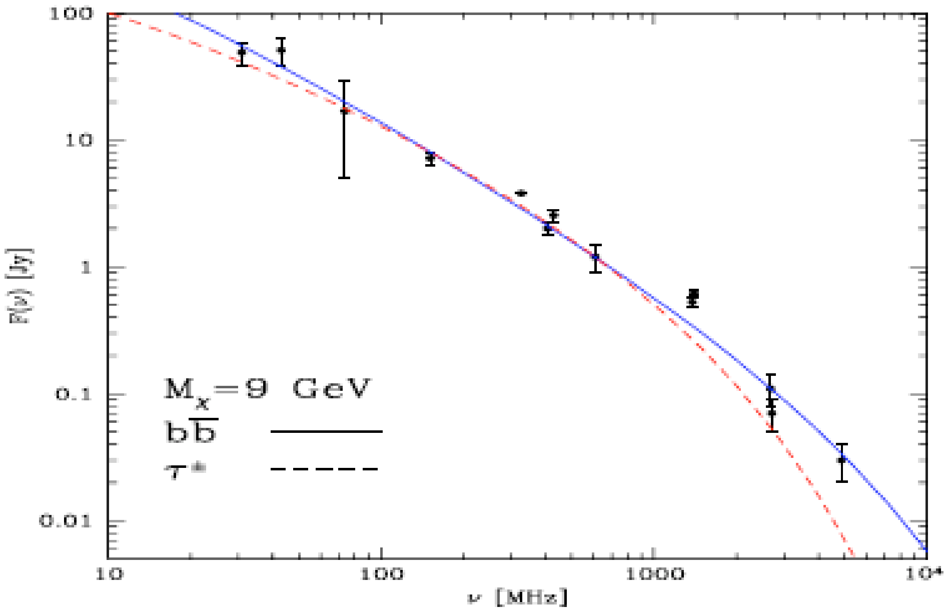
local emissivity

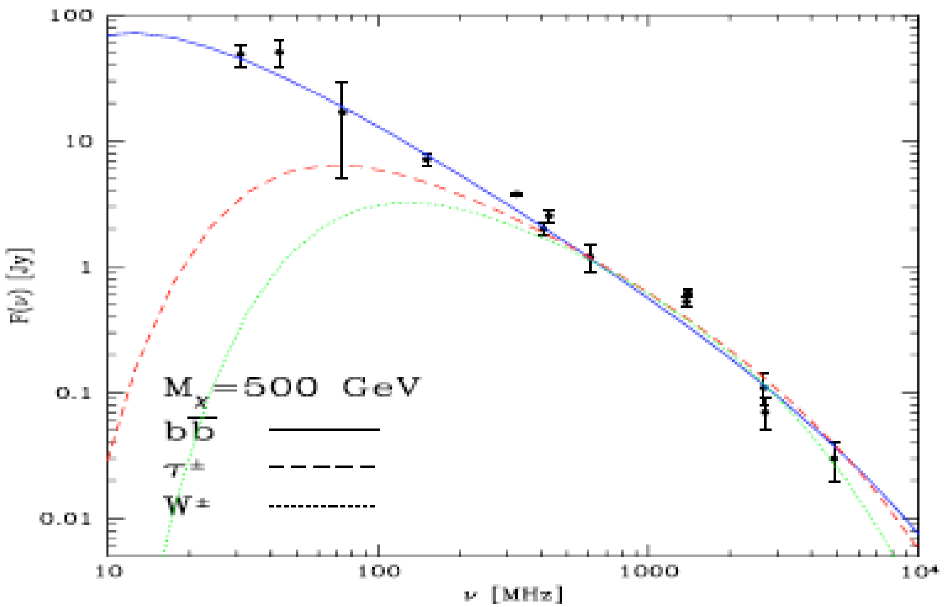
$$j_{\rm synch}\left(\nu,r\right)=\int_{m_e}^{M_\chi}dE\,\left(\frac{dn_{e^-}}{dE}+\frac{dn_{e^+}}{dE}\right)P_{\rm synch}\left(\nu,E,r\right)$$

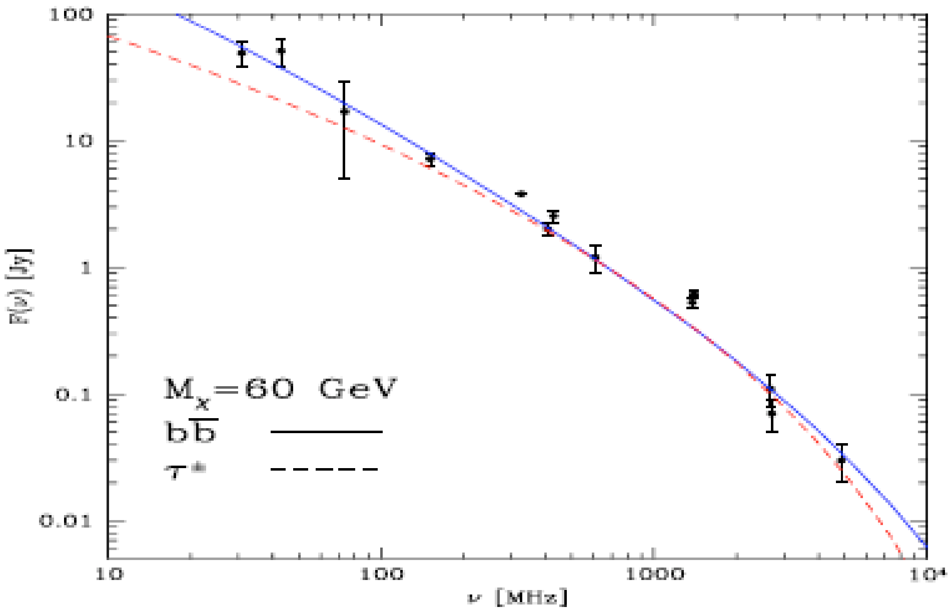
and flux density spectrum

$$S_{\rm synch}(\nu)=\int d^3r\,\frac{j_{\rm synch}\left(\nu,r\right)}{4\pi\,D^2_{\rm Coma}}$$

DM best fit to the radio halo spectrum of Coma







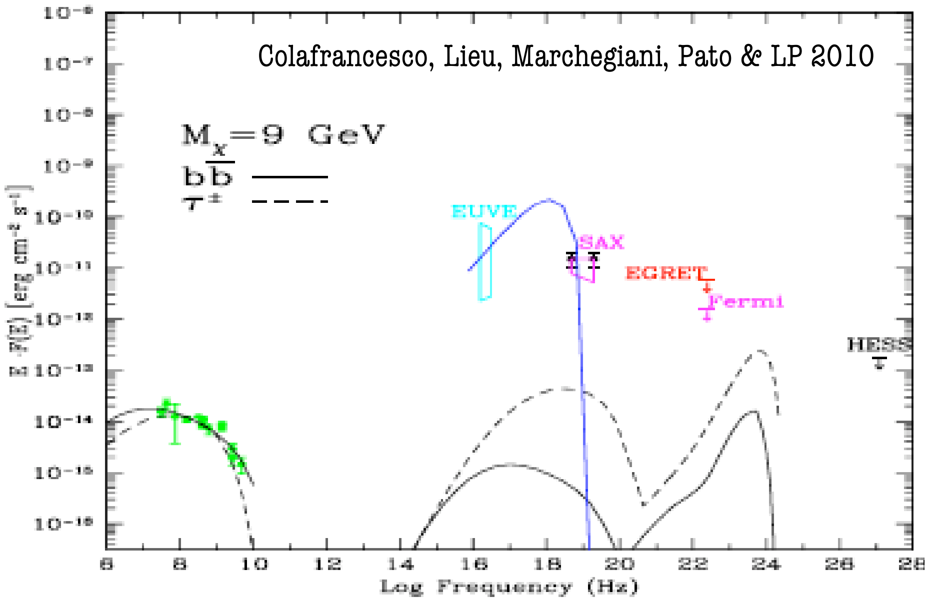
1st step:

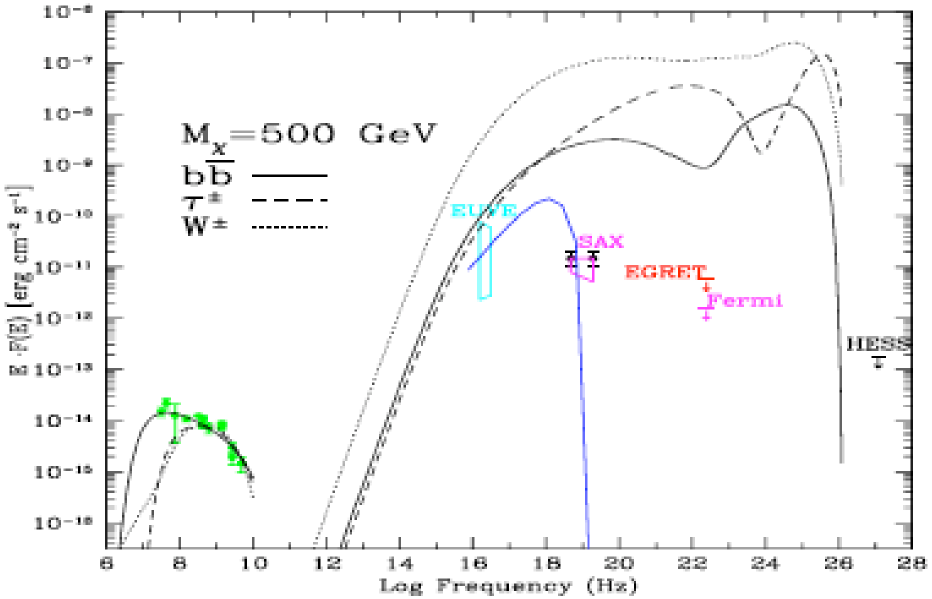
Magnetic field and particle physics are left as free parameters to fit the radio halo of Coma

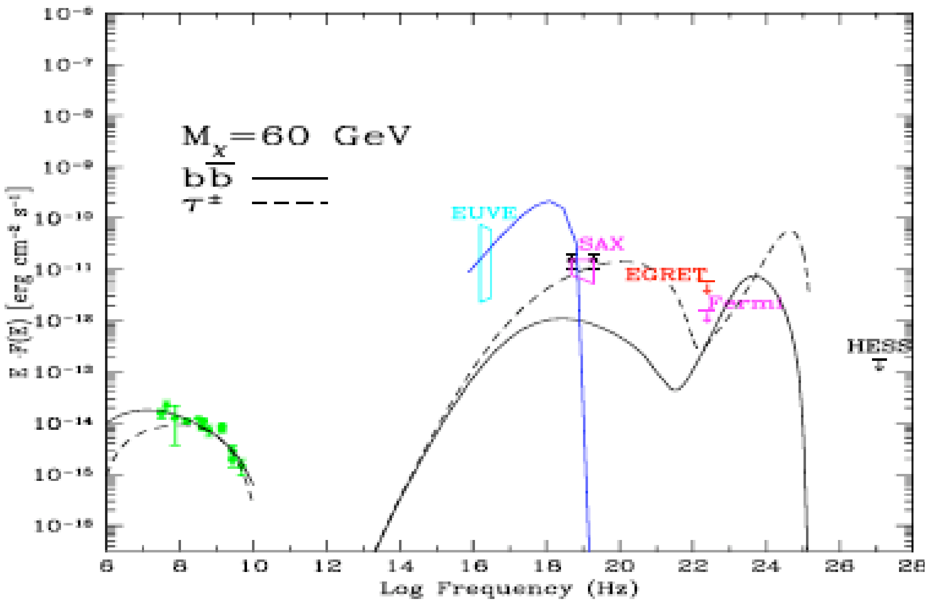
Fig. 2. The radio halo spectrum of Coma and the best fits of three DM models with $M_\chi = 9$ GeV (upper panel) for $b\bar{b}$ (solid with $\sigma V = 1.7 \cdot 10^{-25}$ cm^3 s^{-1} and $B_0 = 20$ μG) and $\tau^\pm$ (dashed with $\sigma V = 5.6 \cdot 10^{-25}$ cm^3 s^{-1} and $B_0 = 2.2$ μG), $M_\chi = 60$ GeV (mid panel) for $b\bar{b}$ (solid with $\sigma V = 8.5 \cdot 10^{-23}$ cm^3 s^{-1} and $B_0 = 0.5$ μG) and $\tau^\pm$ (dashed with $\sigma V = 9.0 \cdot 10^{-22}$ cm^3 s^{-1} and $B_0 = 0.1$ μG), and with $M_\chi = 500$ GeV (lower panel) with $b\bar{b}$ (solid with $\sigma V = 2.0 \cdot 10^{-18}$ cm^3 s^{-1} and $B_0 = 0.01$ μG), $\tau^\pm$ (dashed with $\sigma V = 1.9 \cdot 10^{-17}$ cm^3 s^{-1} and $B_0 = 0.002$ μG) and $W^\pm$ (dotted with $\sigma V = 1.3 \cdot 10^{-16}$ cm^3 s^{-1} and $B_0 = 0.001$ μG). Data from Thierbach et al. (2003). The results are obtained using $B(r) \propto n_{th}(r)$ and NFW smooth DM profiles, without considering the effect of substructures.

Colafrancesco, Lieu, Marchegiani, Pato & LP 2010

Multiwavelenght DM interpretation or exclusion?







2nd step:

The multiwavelength yield is compared with available measurements or upper limits

Compute Inverse Compton Scattering,

$$P_{\rm IC}\left(E_\gamma, E\right) = c\, E_\gamma \int d\epsilon\, n(\epsilon)\, \sigma(E_\gamma, \epsilon, E)$$

$$j_{\rm IC}\left(E_\gamma, r\right) = \int dE \left(\frac{dn_{e^-}}{dE} + \frac{dn_{e^+}}{dE}\right) P_{\rm IC}\left(E_\gamma, E\right)$$

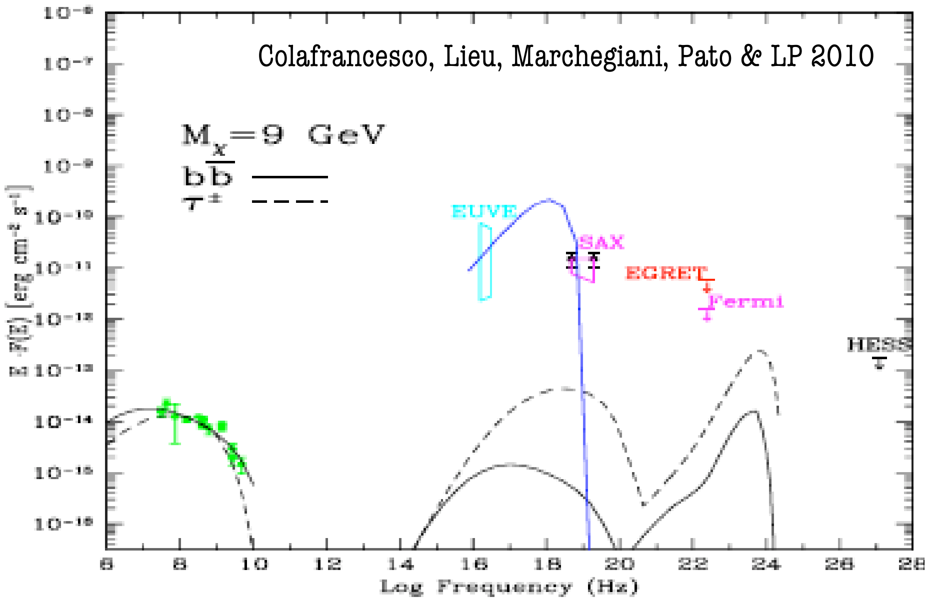
$$S_{\rm IC}(E_\gamma) = \int d^3r\, \frac{j_{\rm IC}\left(E_\gamma, r\right)}{4\pi\, D^2_{\rm Coma}}$$

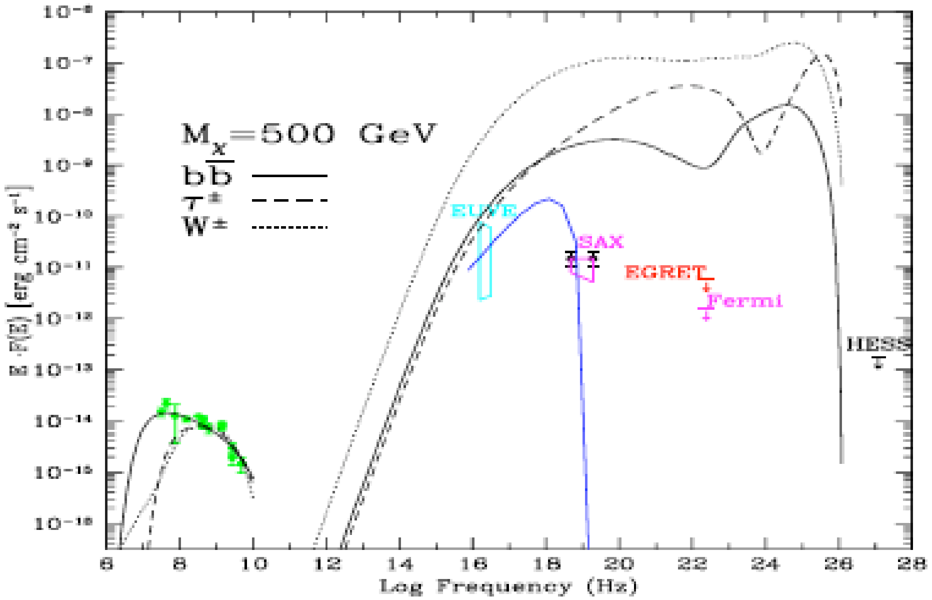
non-thermal bremsstrahlung

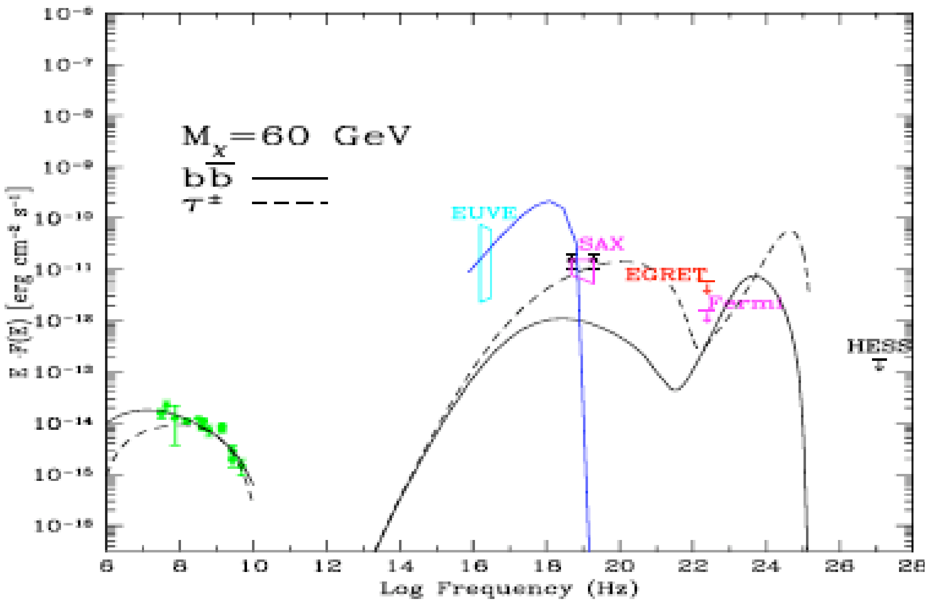
$$P_{\rm B}\left(E_\gamma, E, r\right) = c\, E_\gamma \sum_j n_j(r)\, \sigma_j(E_\gamma, E)$$

and prompt γ-ray emission (more later)

Multiwavelenght DM interpretation or exclusion?





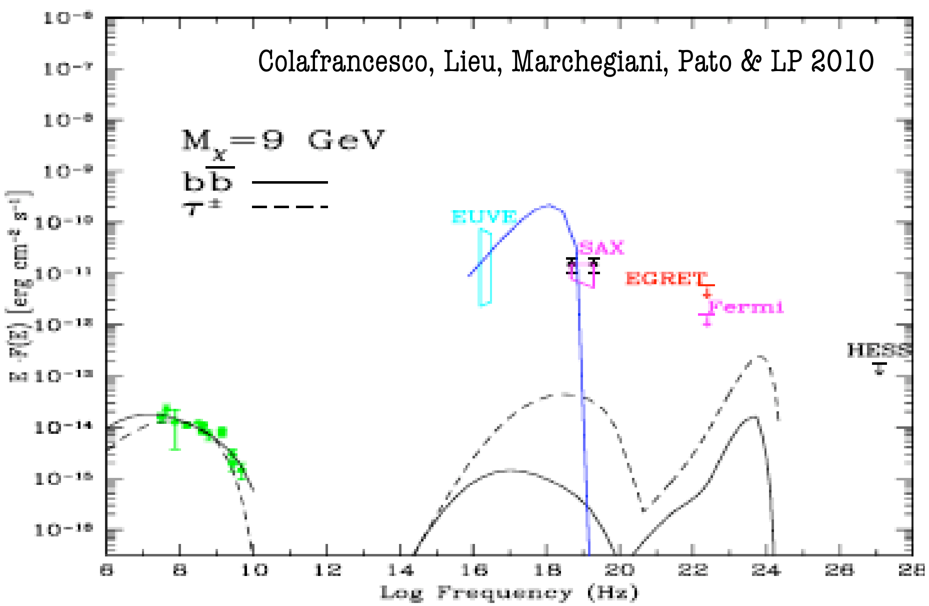


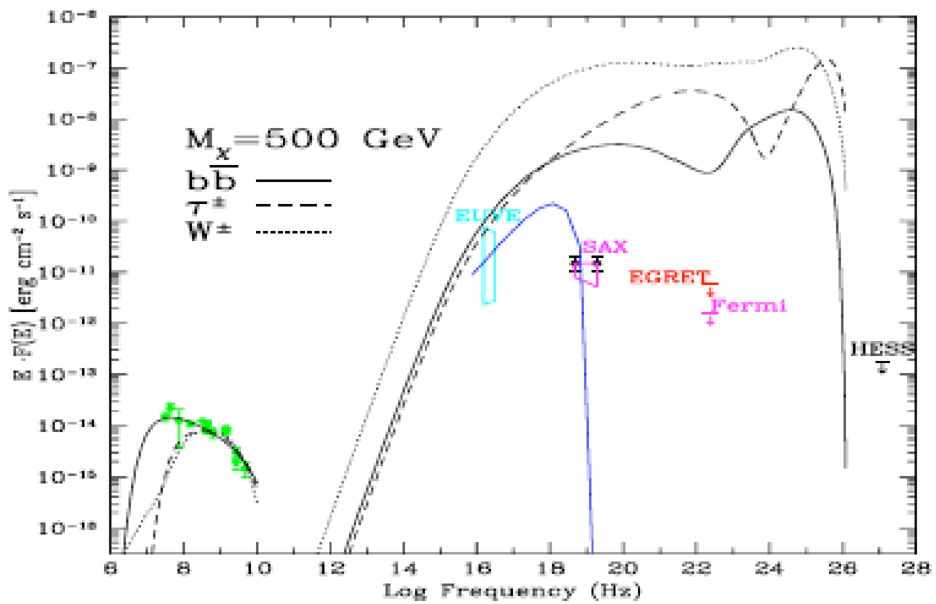
2nd step:

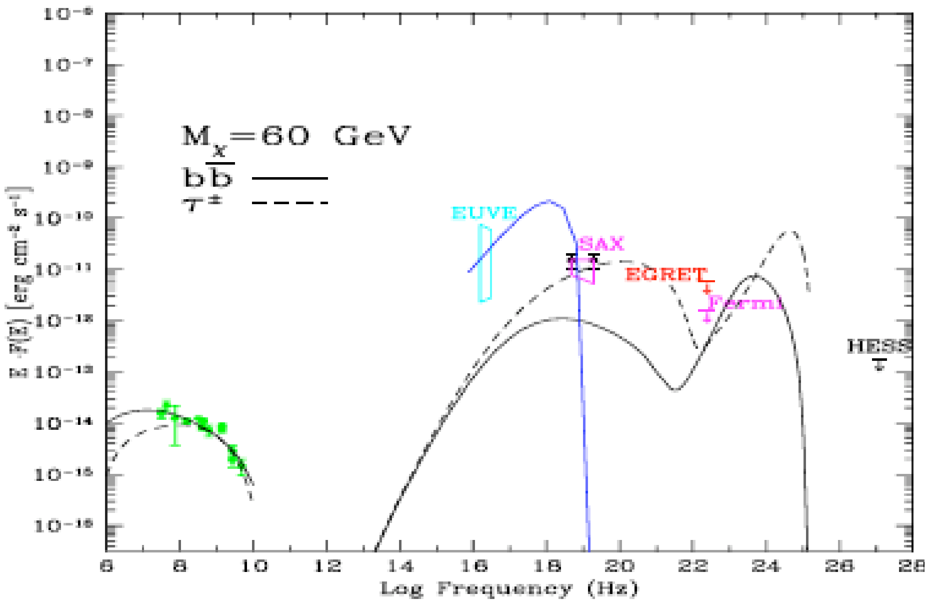
The multiwavelength yield is computed not to exceed other measurements

Fig. 4. The SED of the DM-induced e.m. signals in Coma as predicted by the three DM models. Upper panel: $M_\chi = 9$ GeV (solid: $b\bar{b}$; dashed: $\tau^\pm$); mid panel: $M_\chi = 60$ GeV (solid: $b\bar{b}$; dashed: $\tau^\pm$); lower panel: $M_\chi = 500$ GeV (solid: $b\bar{b}$; dashed: $\tau^\pm$; dotted: $W^\pm$) The values of σV and B_0 for the different models are the same used in Fig.2. The hatched regions in the X-ray domain represent data from PDS/BeppoSAX (Fusco-Femiano et al. 2004), HEXTE/RXTE (Rephaeli et al. 1999) and EUVE (Lieu et al. 1999). We also report the EGRET (Reimer et al 2003), Fermi (Mori 2009) and HESS (Aharonian et al. 2009a) upper limits on Coma. The blue line is a thermal bremsstrahlung model for Coma with $kT = 8.2$ keV (Briel et al. 1992). The results are obtained using $B(r) \propto n_{th}(r)$ and NFW smooth DM profiles, without considering the effect of substructures.

Multiwavelenght DM interpretation or exclusion?







2nd step:

The multiwavelength yield is computed not to exceed other measurements

No evidence for a combined explanation of non-thermal excesses in terms of Dark Matter annihilation

Compatibility with the cluster heating rate

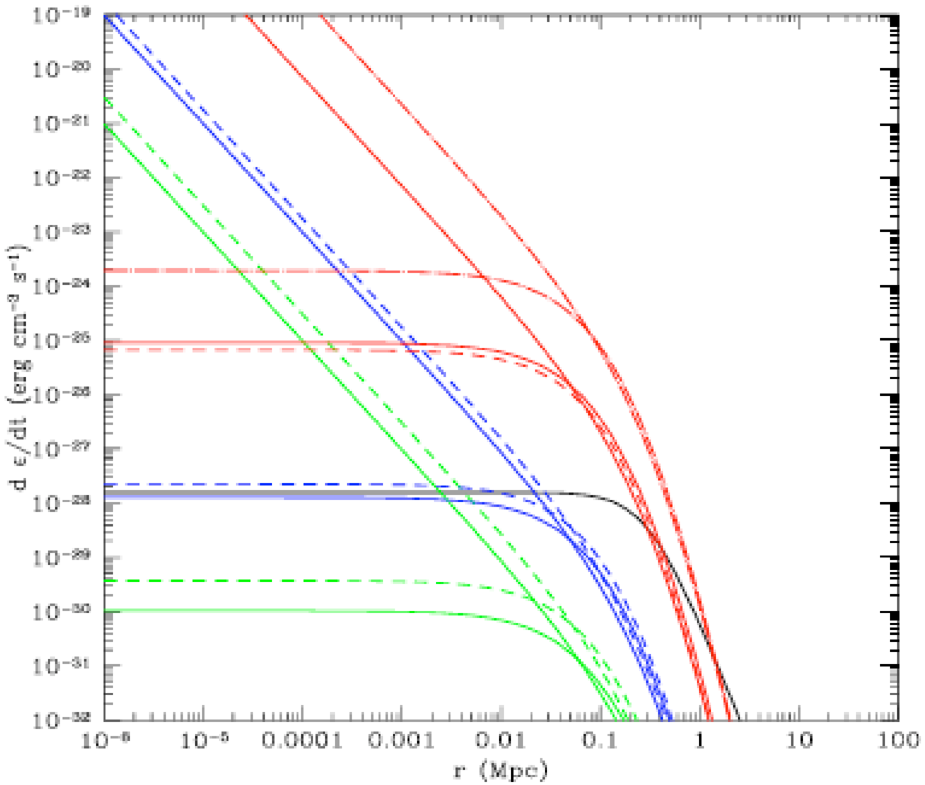


Fig. 5. The heating rate induced by DM secondary particles in Coma as predicted by the three DM models with $M_\chi = 9$ GeV, $M_\chi = 60$ GeV and $M_\chi = 500$ GeV for $b\bar{b}$ (solid), $\tau^\pm$ (dashed), W$^\pm$ (dot-dashed) compositions. We consider an NFW DM profile (green, blue and red peaking curves for 9, 60 and 500 GeV respectively) and a cored DM profile (green , blue and red flattening curves for 9, 60 and 500 GeV respectively). The values of σV and B_0 for the different models are the same used in Fig.2. The solid black curve shows the bremsstrahlung cooling rate of the intra-cluster gas at a temperature of 8.2 keV. The results are obtained using $B(r) \propto n_{th}(r)$ and smooth DM profiles, without considering the effect of substructures.

3rd step:

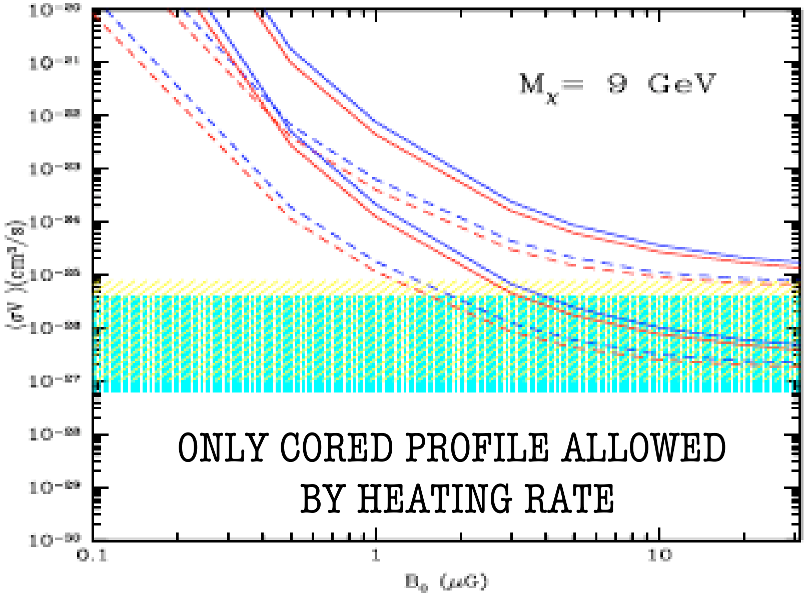
The heating rate of the inctracluster gas due to Coulomb collision of low-energy non-thermal electrons should not exceed the bremmstrahlung cooling rate of thermal electrons

otherwise the heated gas would get a temperature higher than the one observed in the cluster, which is related to the cooling rate of thermal gas.
We would observe a fast gas heating and expansion, while the cluster is thermally stable.

$$\frac{dE}{dtdV} = \int dE \frac{dn_e}{dE} \cdot \left(\frac{dE}{dt}\right)_{Coul}$$

Colafrancesco, Lieu, Marchegiani, Pato & LP 2010

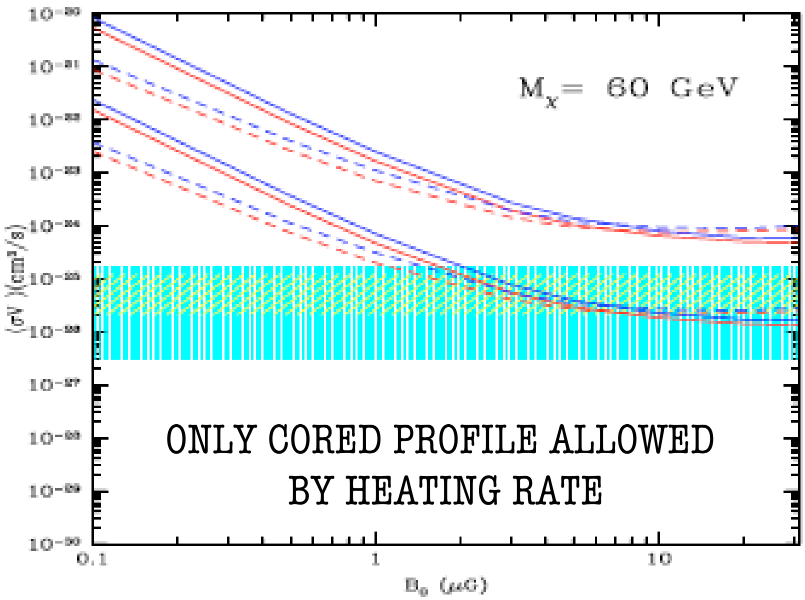
Compatibility with multimessenger constraints

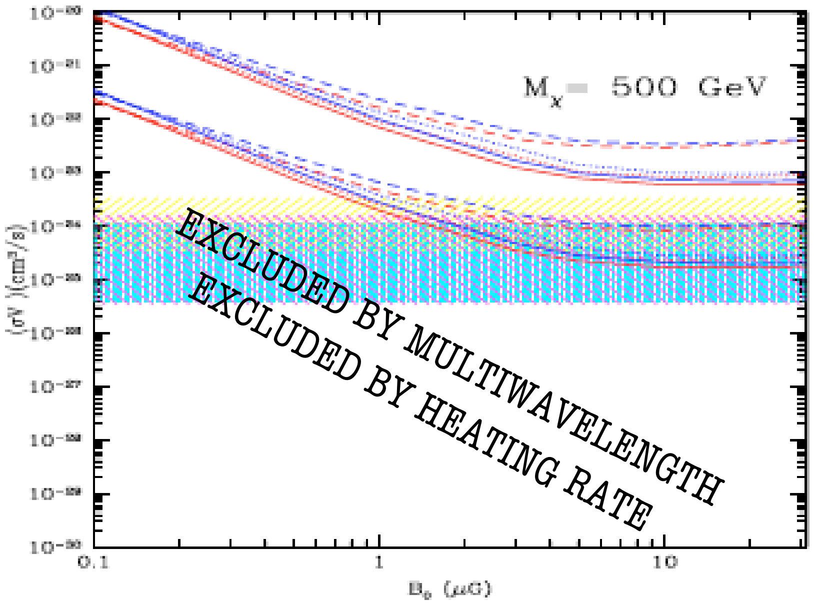


4th step (also called the killer step):

Cross-sections are compared with available constraints from GC γs, diffuse γs, antimatter, CMB, radio ... which excludes ANY dark matter interpretation for smooth profiles

Look at the upper curves: smooth cluster halo
All DM explanation are excluded





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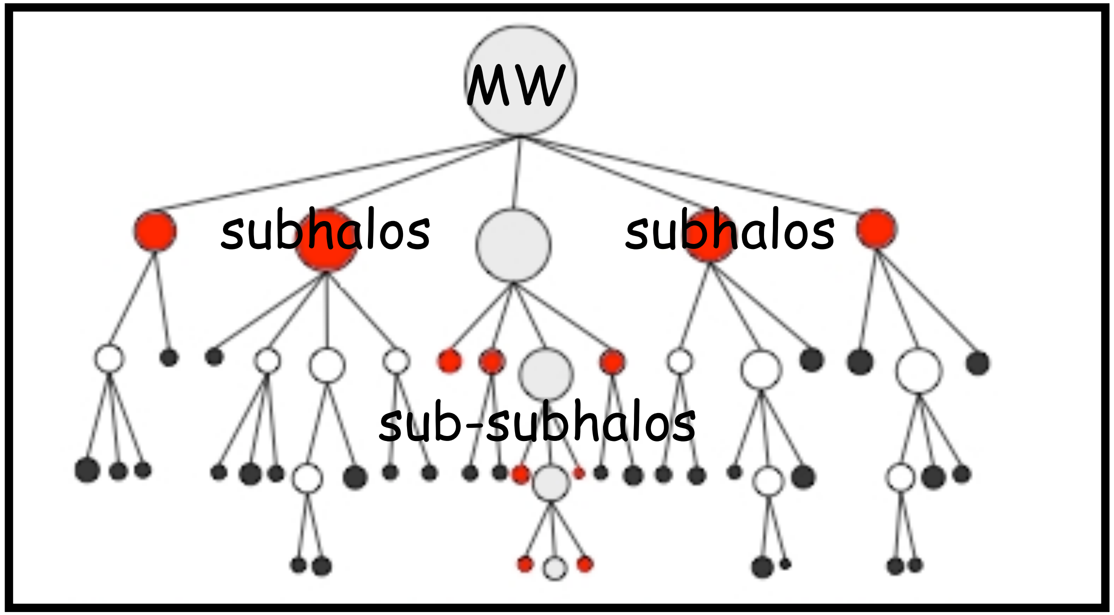
Adding subhalos: modeling the structure of dark matter halos

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)



Make use of simulations on galactic scale and use self-similarity arguments to infer cluster properties.

Note: self-similarity proven from cluster to galactic scale

Adding subhalos: modeling the structure of dark matter halos

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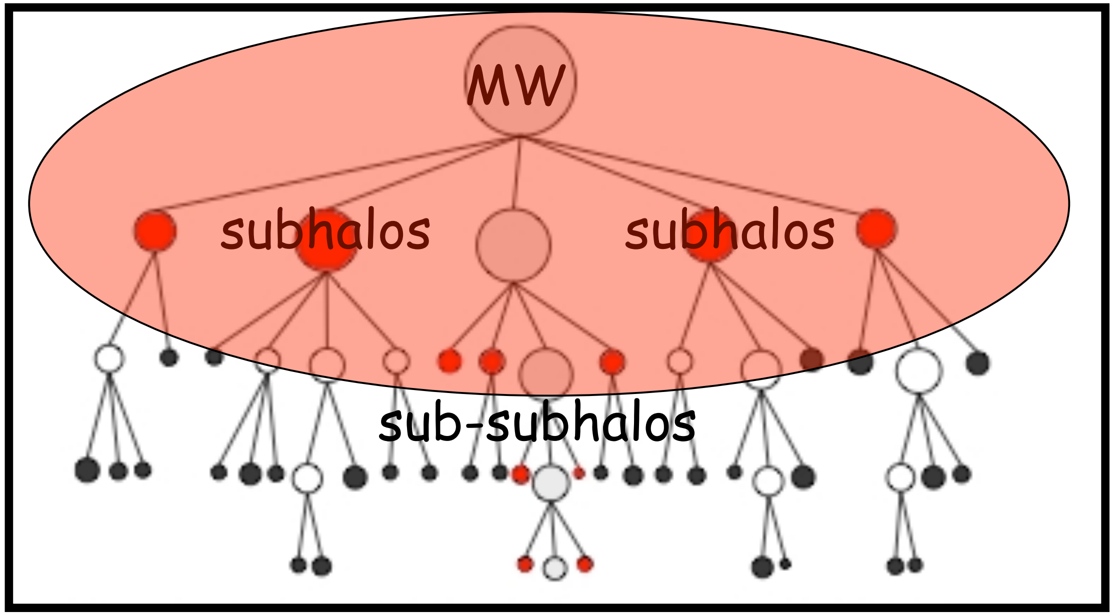

N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

Adding subhalos: modeling the structure of dark matter halos

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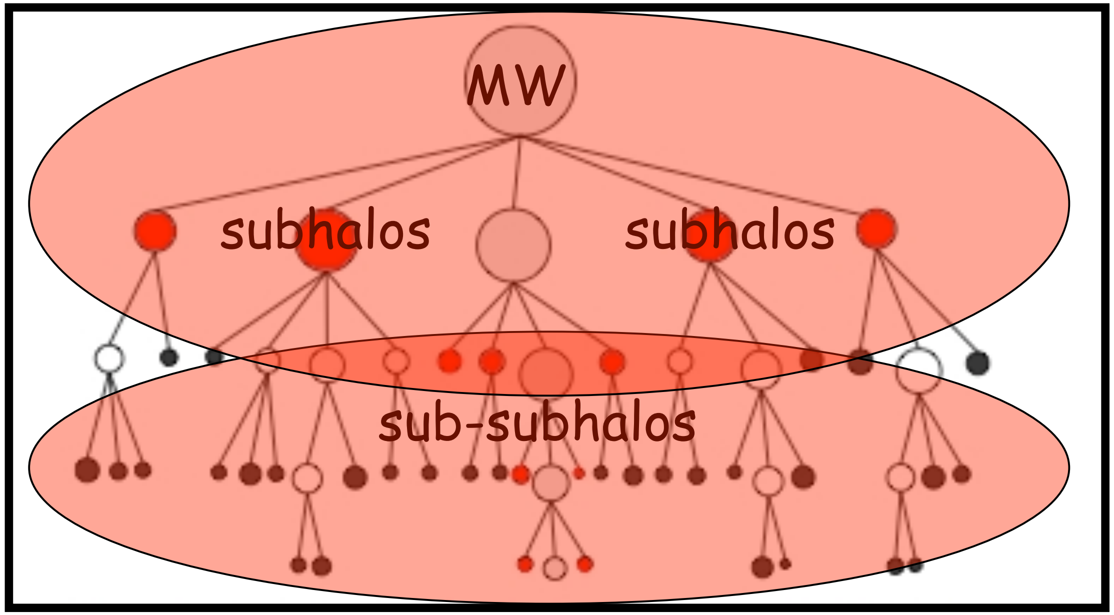


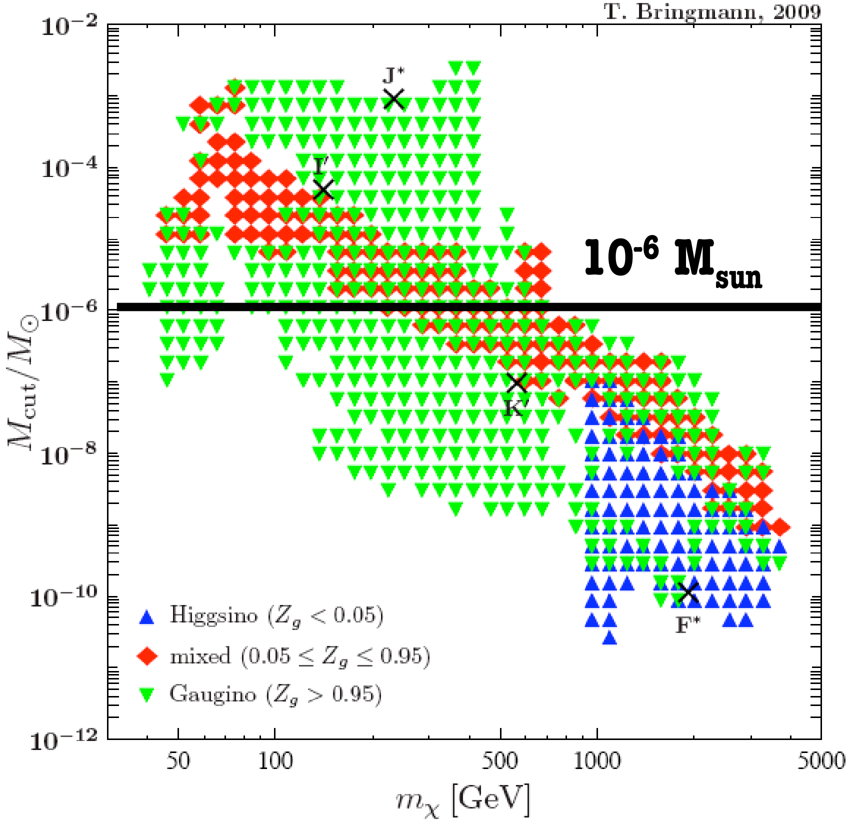
N-body simulations study the smooth halo and the larger halos ($M > 10^5\ M_{sun}$).

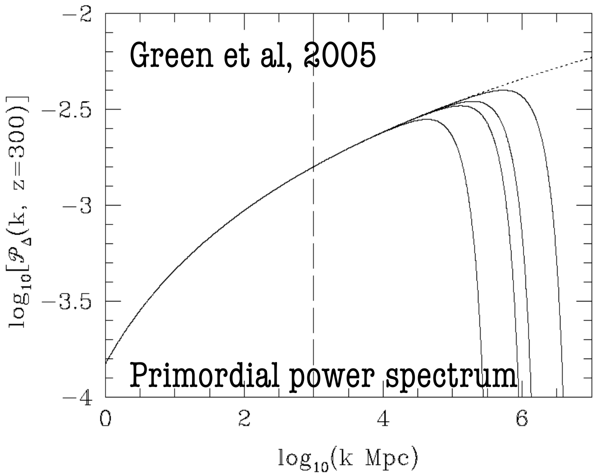
Microphysics and theory of structure formation sets the mass of the smallest halo
because there is no enough cpu power to simulate small halos from collapse till today.

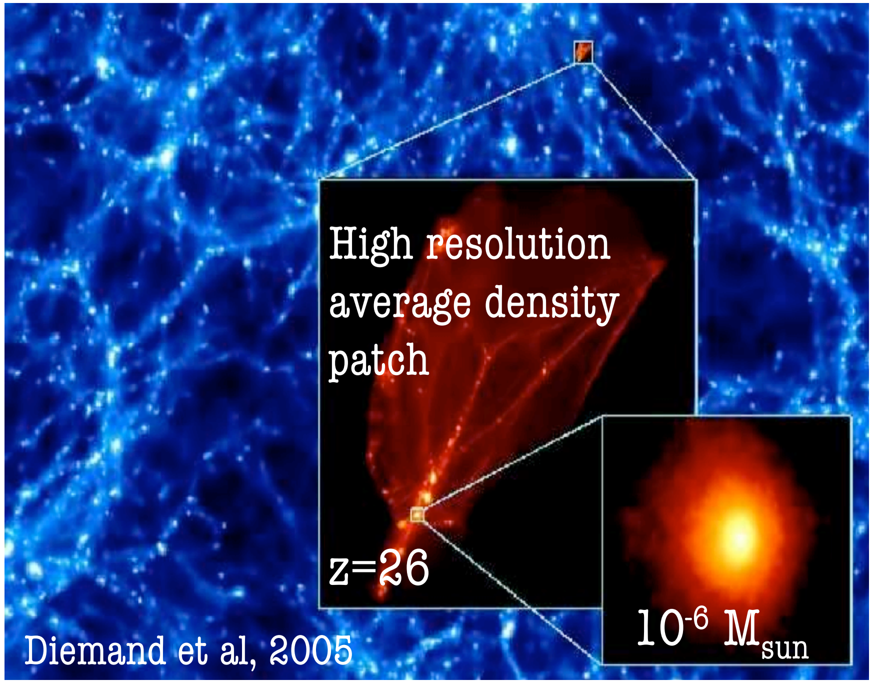
Modeling the structure of dark matter halos from theory of structure formation (M< 10^5 M_{sun})

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

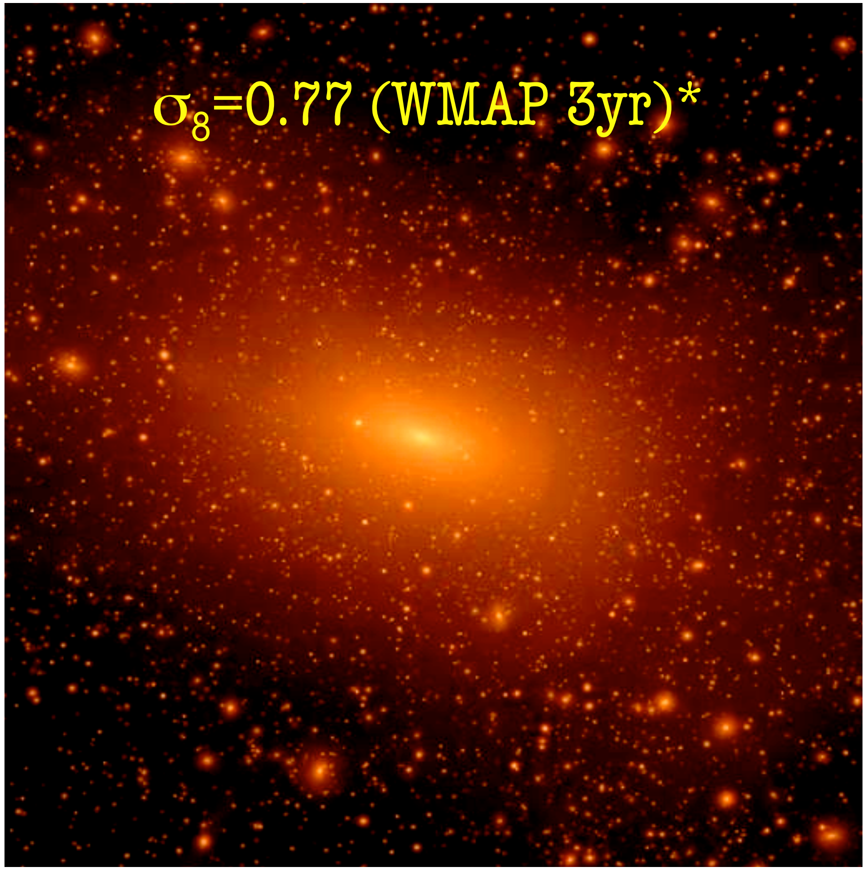
Typical M_{min} for a WIMP = 10^{-6} M_{sun}

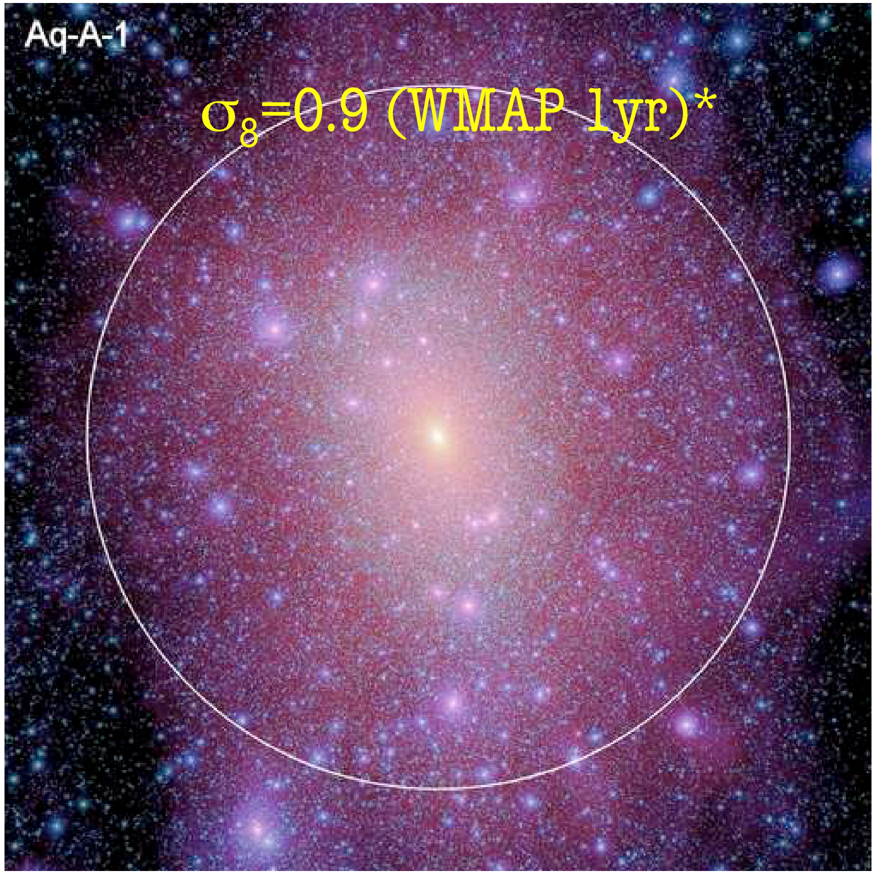






Modeling the structure of dark matter halos from N-body simulations ($M > 10^5\ M_{sun}$)





MW-like halos at z=0

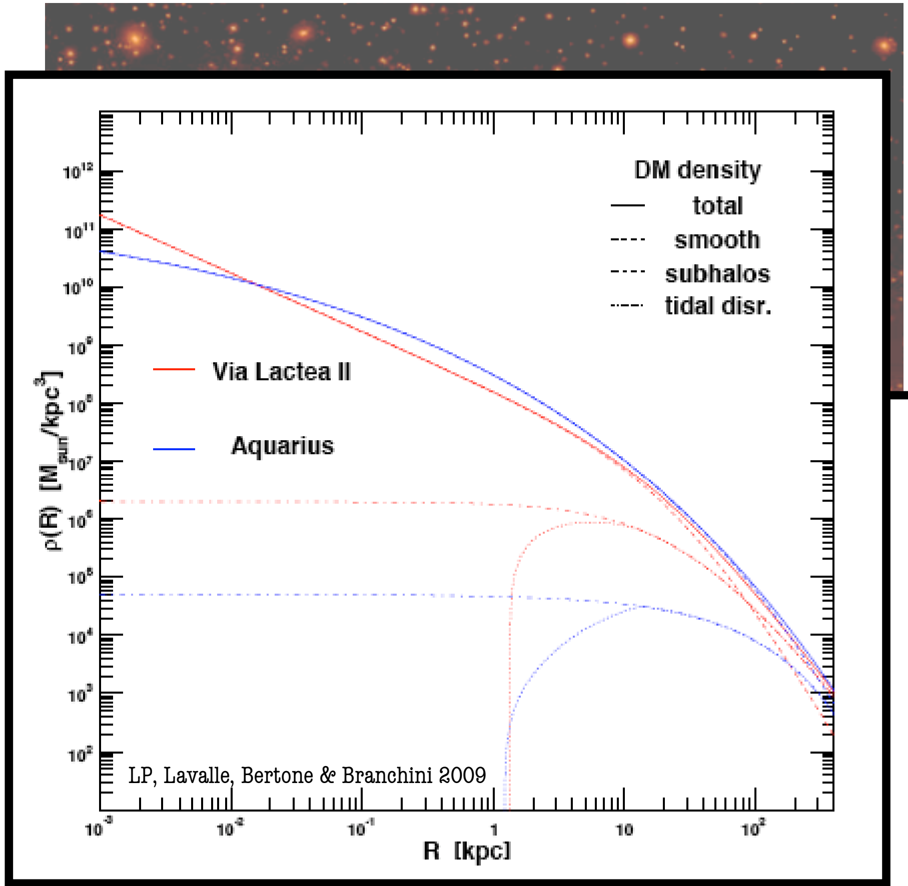
Via Lactea 2, Diemand et al

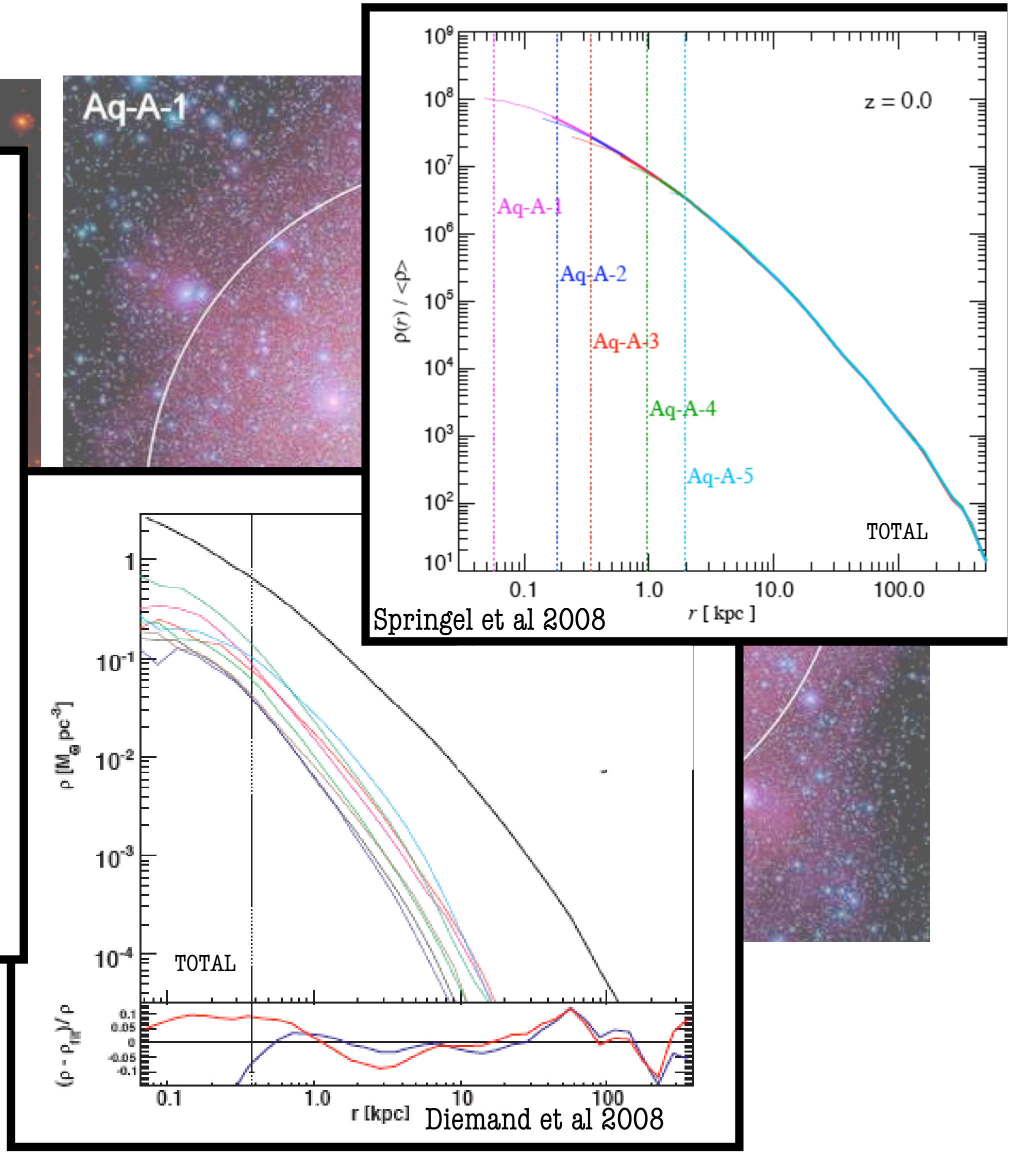
Aquarius, Springel et al

*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

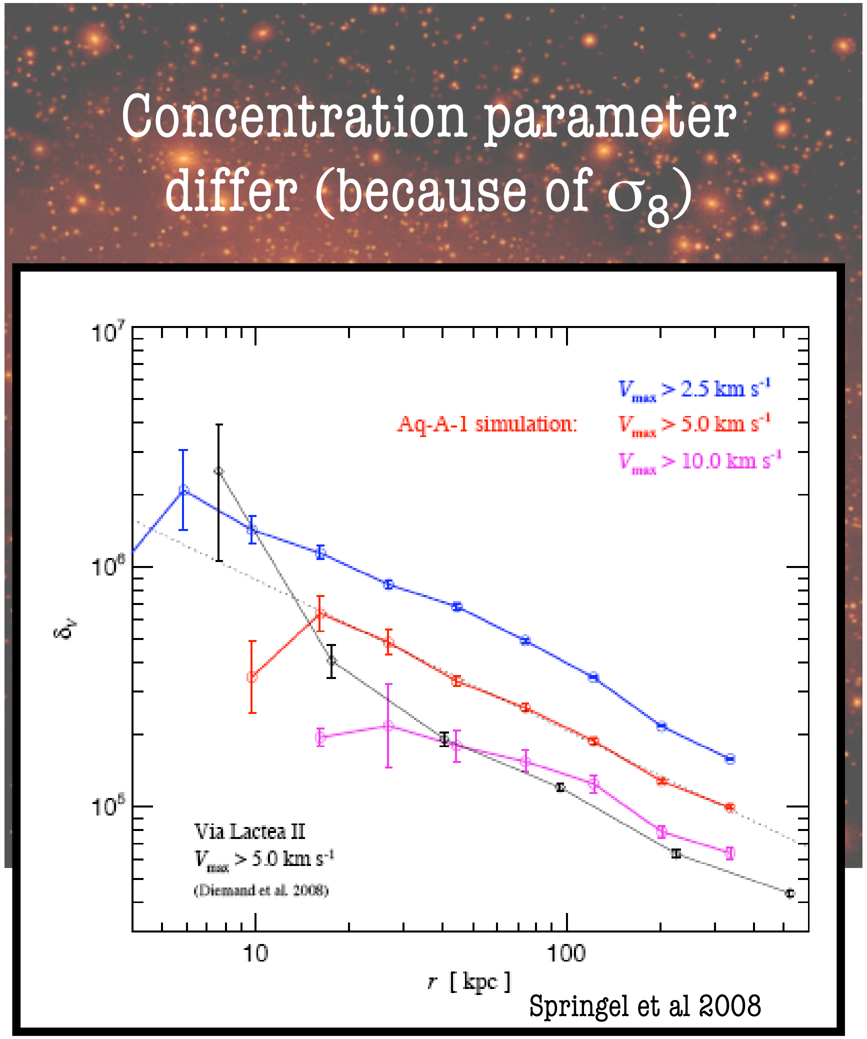


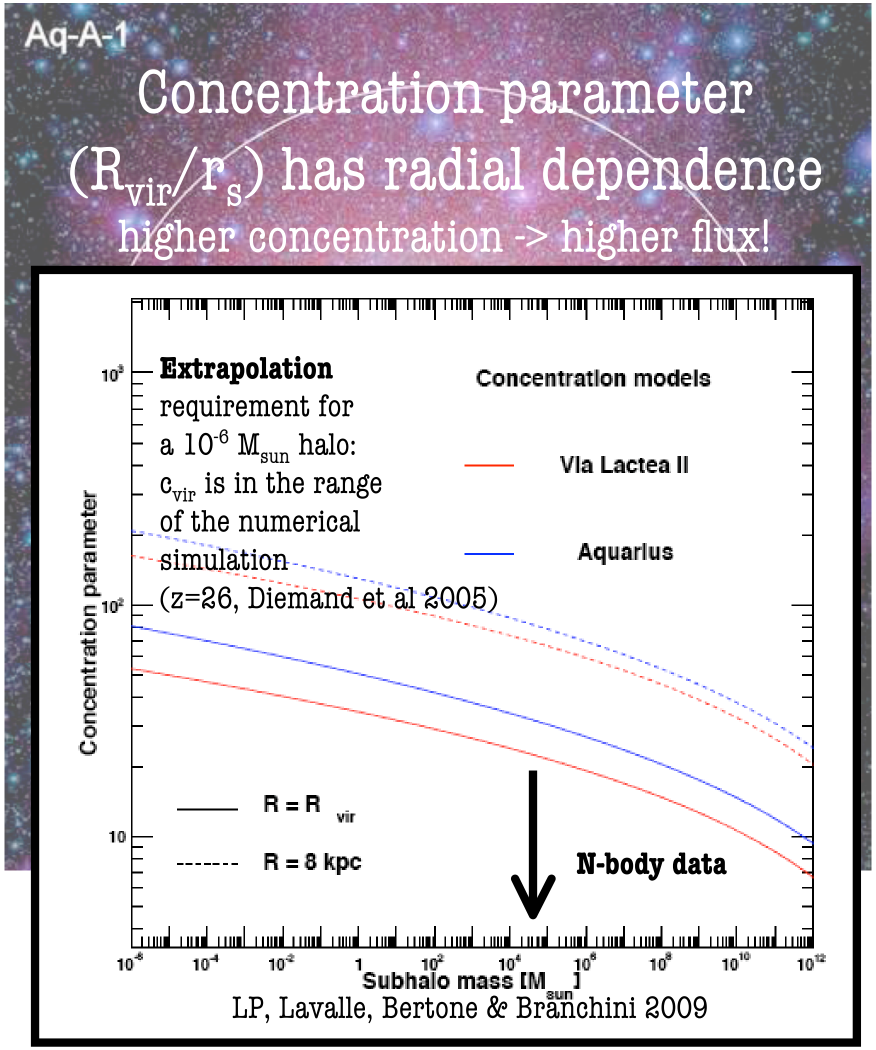


Warning: NFW or Einasto are total profiles (smooth + subhalo)

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

Halo and subhalo profile shape and concentration





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

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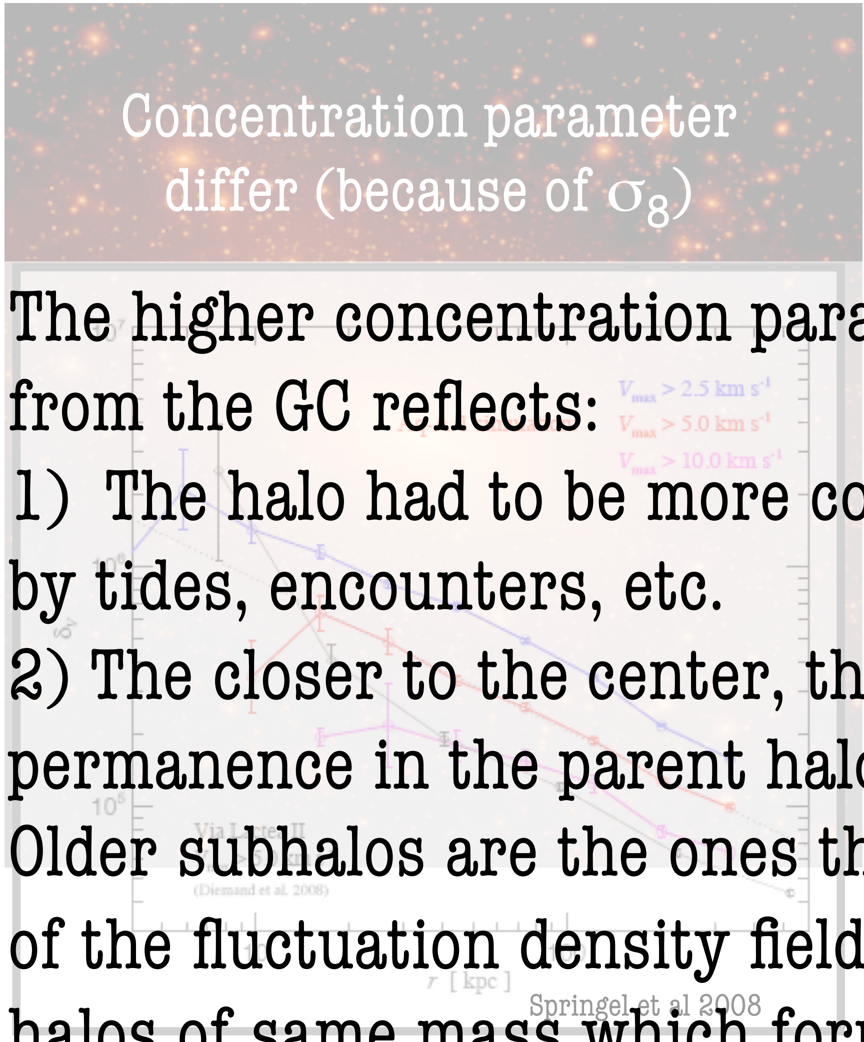
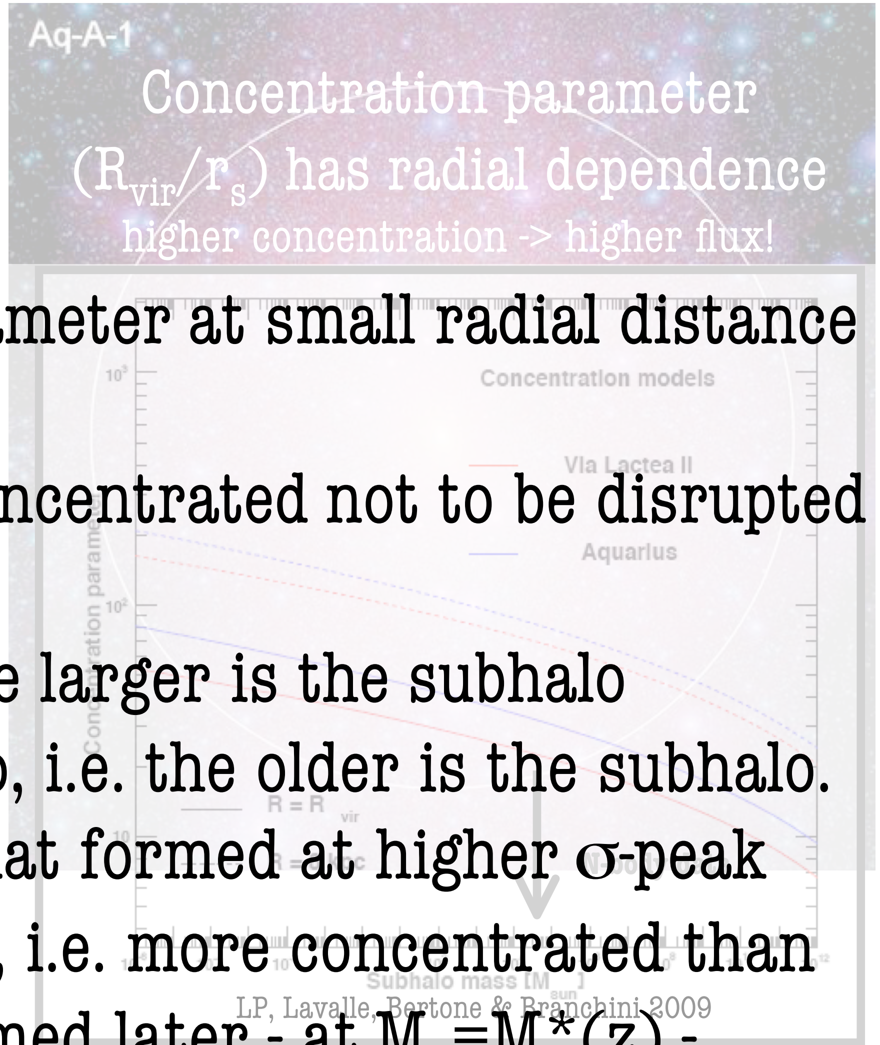


Concentration parameter differ (because of σ_8)



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

higher concentration -> higher flux!

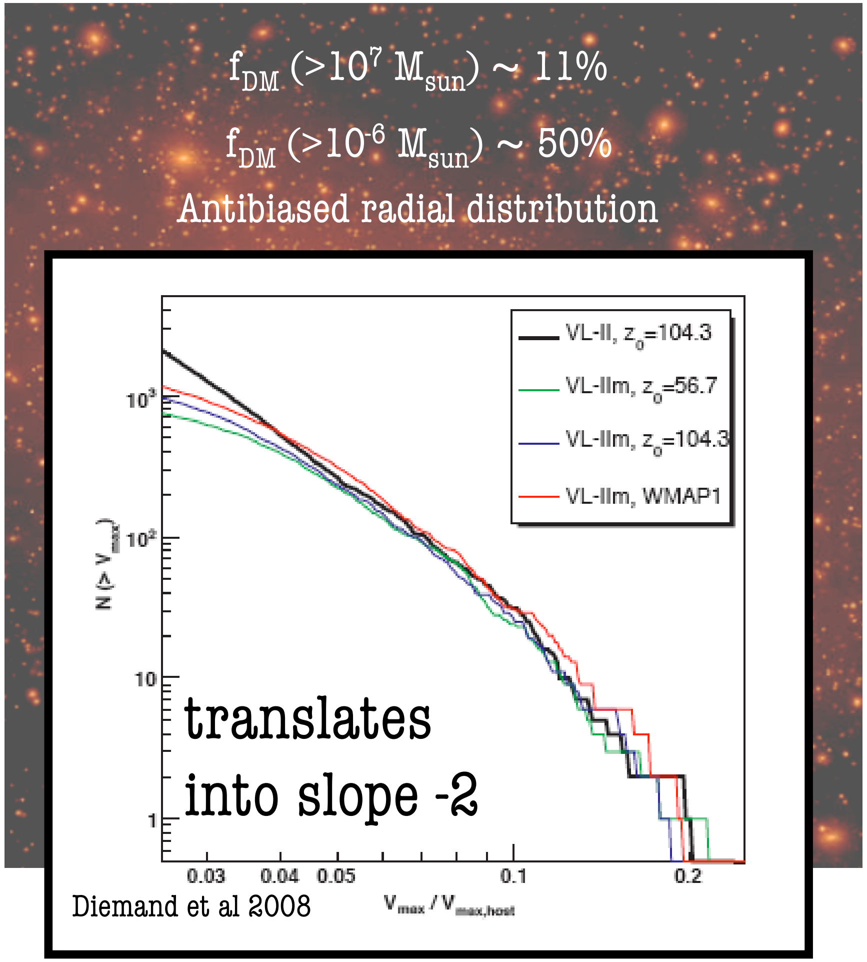
The higher concentration parameter at small radial distance from the GC reflects:

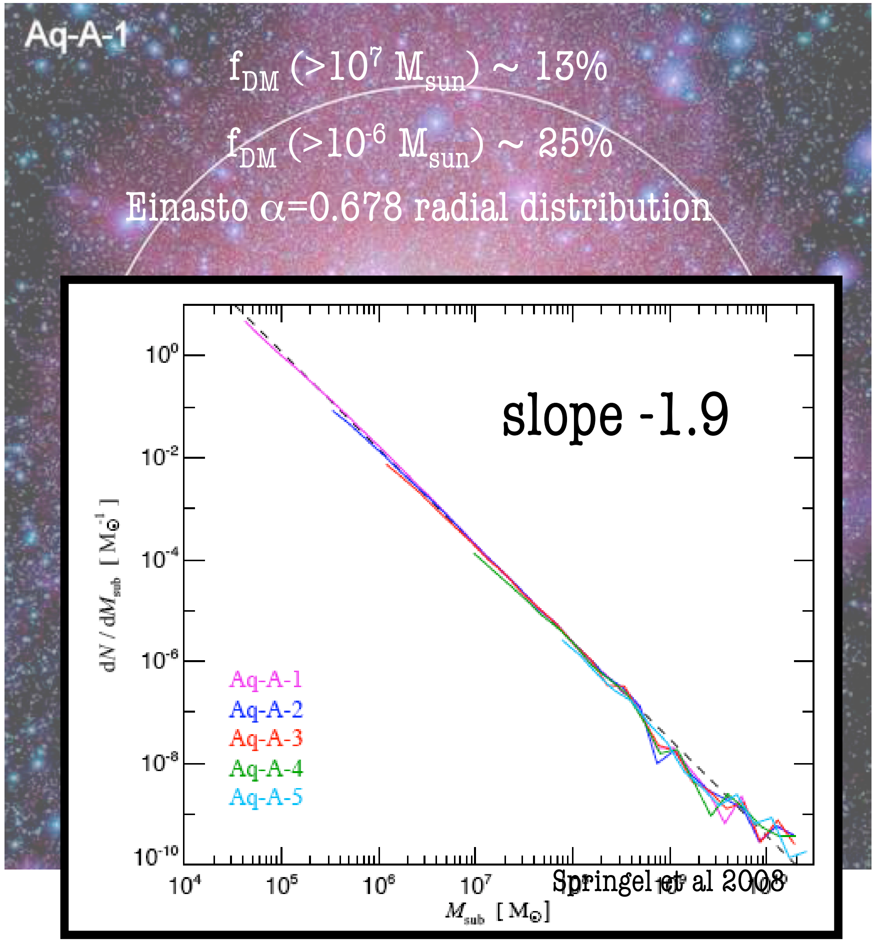
1) The halo had to be more concentrated not to be disrupted by tides, encounters, etc.

2) The closer to the center, the larger is the subhalo permanence in the parent halo, i.e. the older is the subhalo. Older subhalos are the ones that formed at higher σ-peak of the fluctuation density field, i.e. more concentrated than halos of same mass which formed later - at $M_h = M^*(z)$ -

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

Subhalo abundance and density distribution

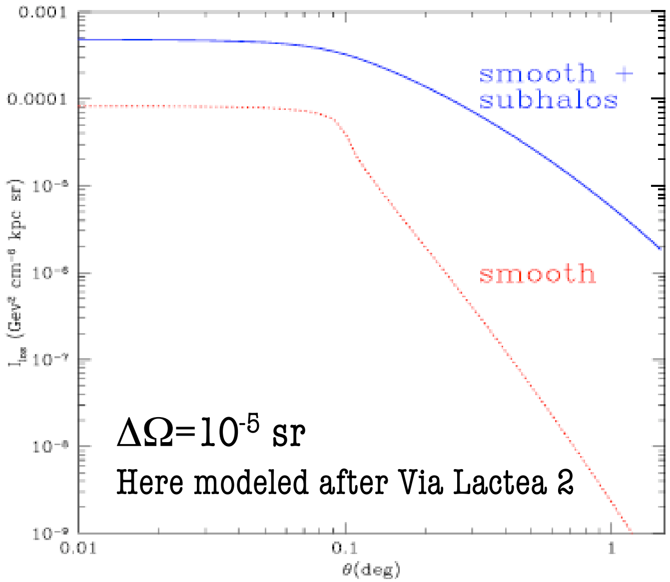


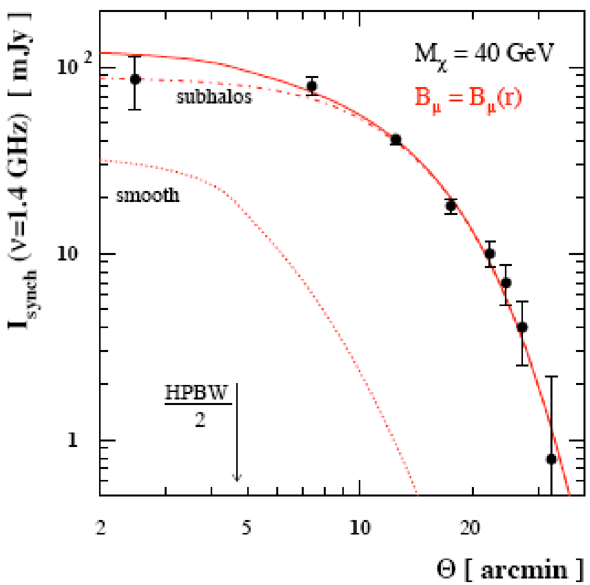


Note the different subhalo definition (v_{max} VS mass)
Slope -1.95 is consistent with both simulations within the fit errors

Compatibility with multimessenger constraints adding subhalos

Colafrancesco, Lieu, Marchegiani, Pato & LP 2010



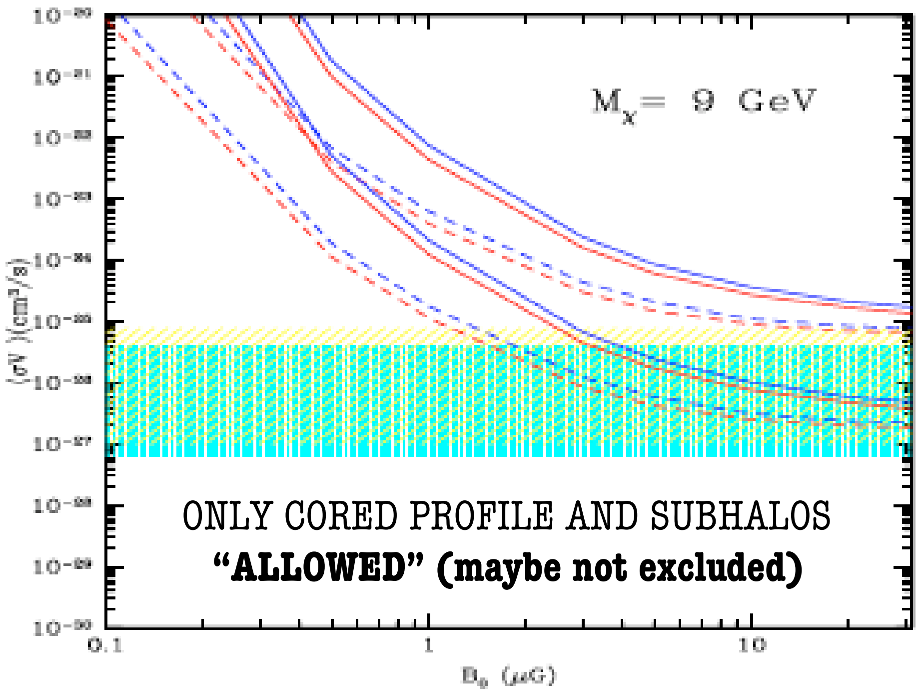


Colafrancesco, Profumo & Ullio 2006

Subhalo population

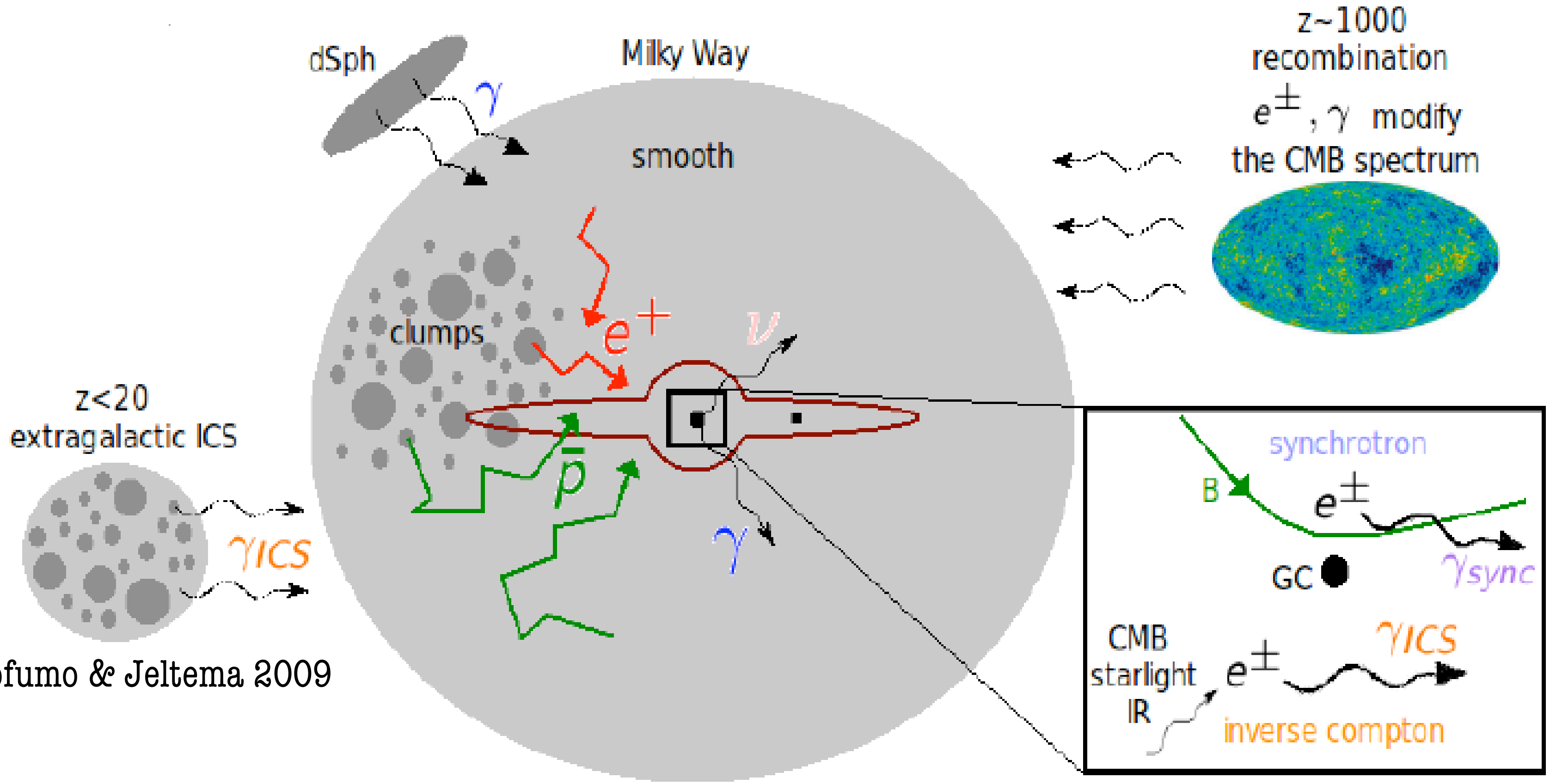
In presence of a population of substructures with $M_{min}=10^{-6}$ Msun and radial dependence of the concentration parameter, a boost of ~ 35 still let some models allowed, providing a favourable environment (MW DM structure and propagation model)

Note that subhalos are also needed to explain the surface brigthness profile of the radio halo



The multiwavelength/multimessenger/multitarget approach

Φ = ParticlePhysics x Cosmology/Astrophysics x Transport



see Profumo & Jeltema 2009

Slide: courtesy of M. Pato

The γ-ray sky

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

MW smooth and single subhalo contribution

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

Integrated contribution of all the GALACTIC halos along the LOS

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

Integrated contribution of EXTRAGALACTIC halos and subhalos

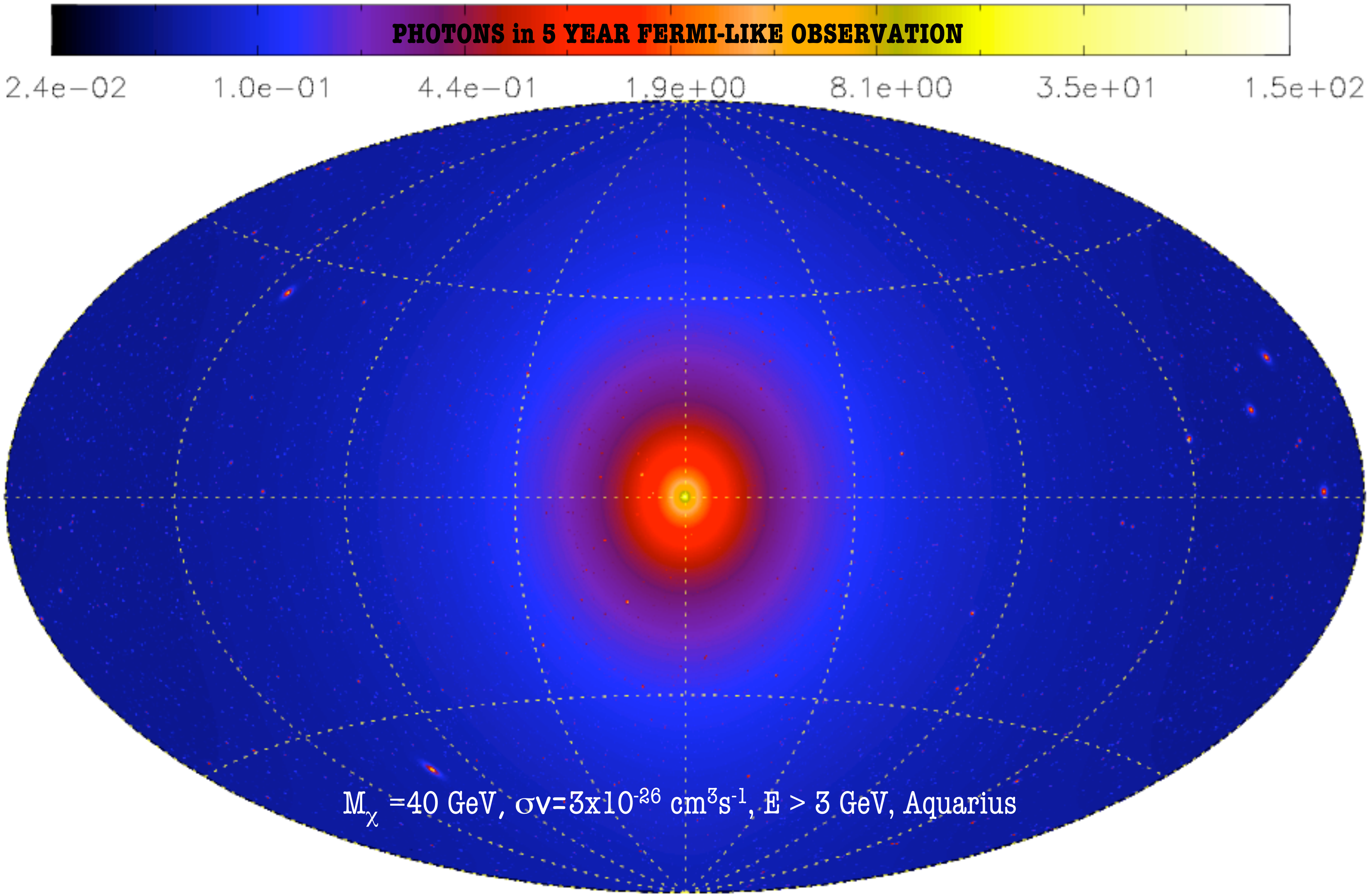
Computing the cosmological γ-ray flux due to DM annihilation in halos and subhalos

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

Enhancement due to halo weighted for the halo and subhalo mass function

$$\propto \frac{d\log N}{d\log M} \Phi^{halo}_{COSMO}$$

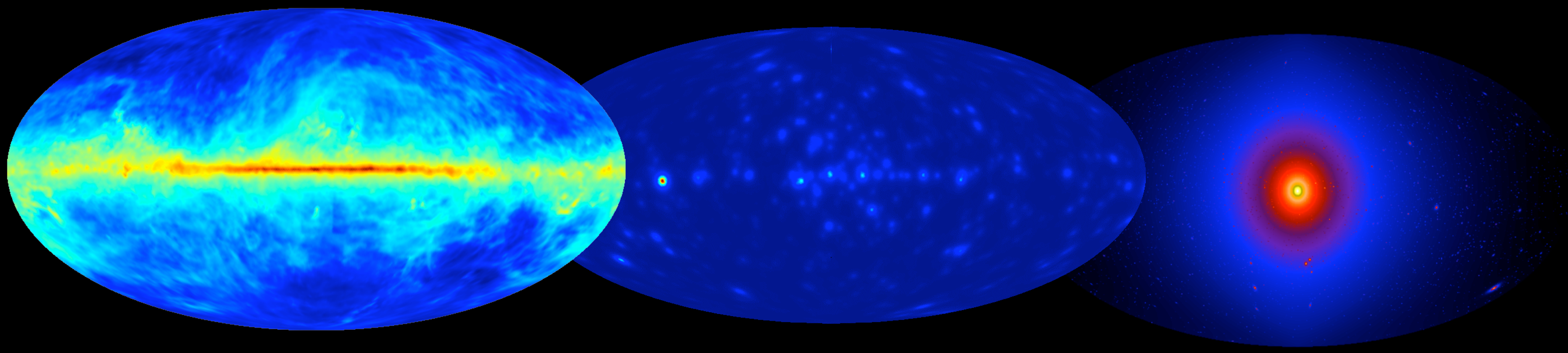
The γ-ray sky
Galactic and extragalactic: smooth + subhalos



LP, Lavalle, Bertone & Branchini 2009

to be compared with the available data after background subtraction

ingredients

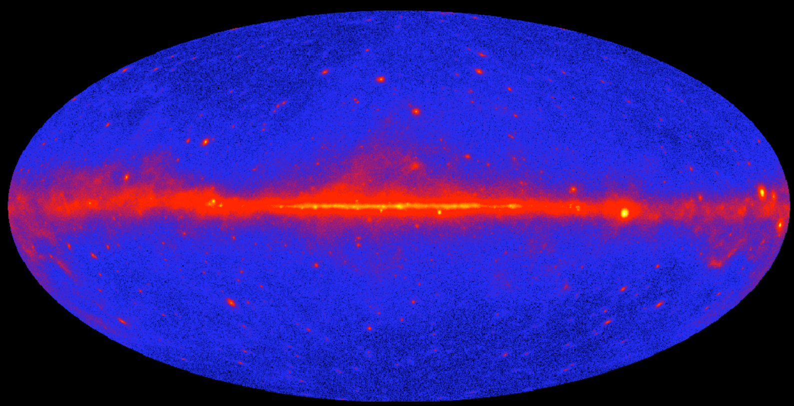


galactic diffuse model (+ isotropic)

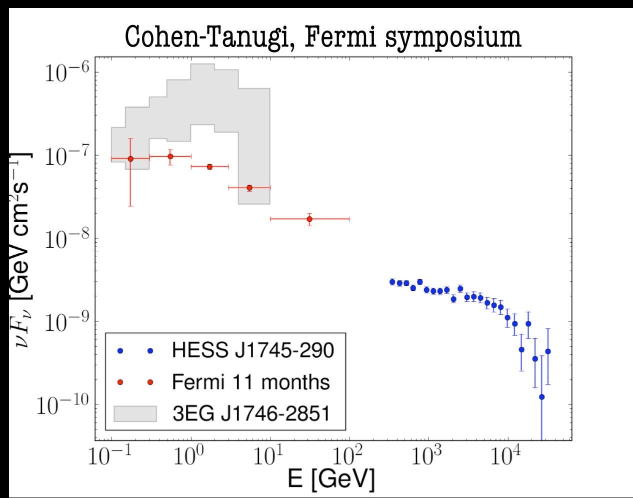
point sources data

dark matter model

data



Fermi data



Galactic Center data

The antimatter sky - coherent halo description wrt γ-rays

Compute the number density à la Delahaye et al. 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

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

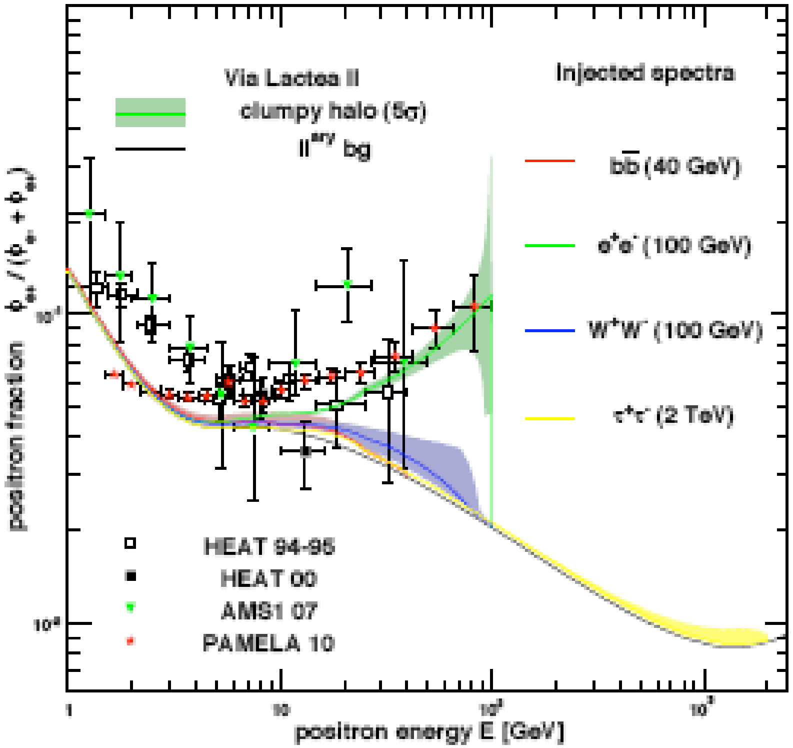
galactic winds

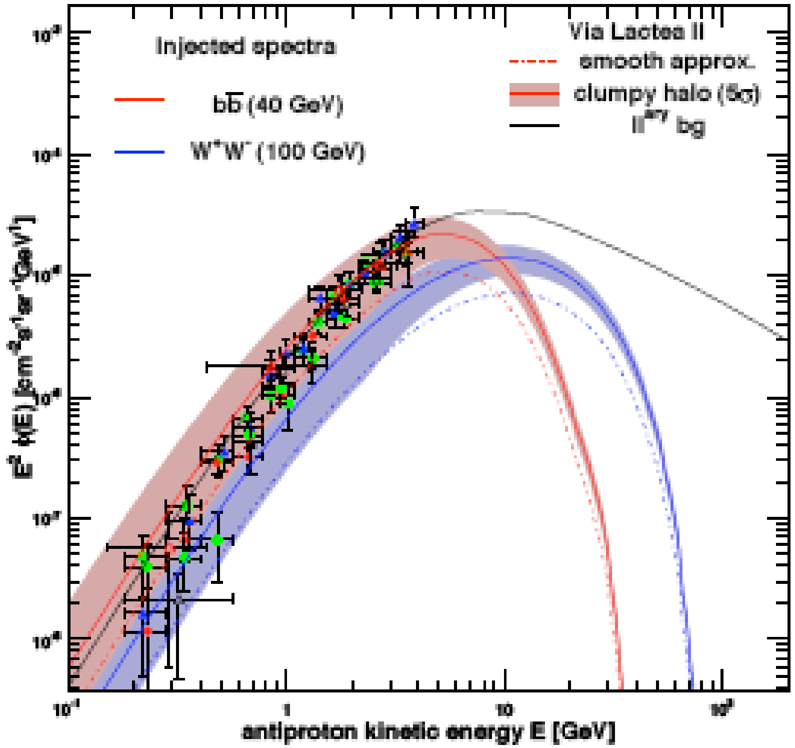
Compute fluxes and boosts à la Lavalle et al. 2008

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

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

The antimatter sky - coherent halo description wrt γ-rays





Compute fluxes and boosts à la Lavalle et al. 2008

LP, Lavalle, Bertone & Branchini 2009

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

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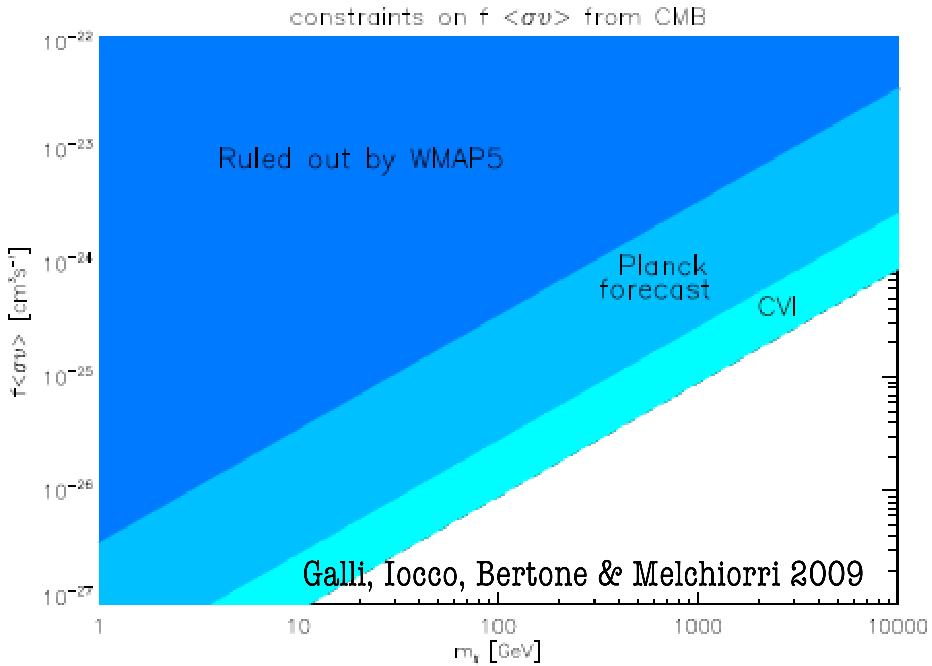
Constraints from CMB
- no structure dependence -

Injection of DM annihilation around z=1000
would affect recombination and hence modify the CMB

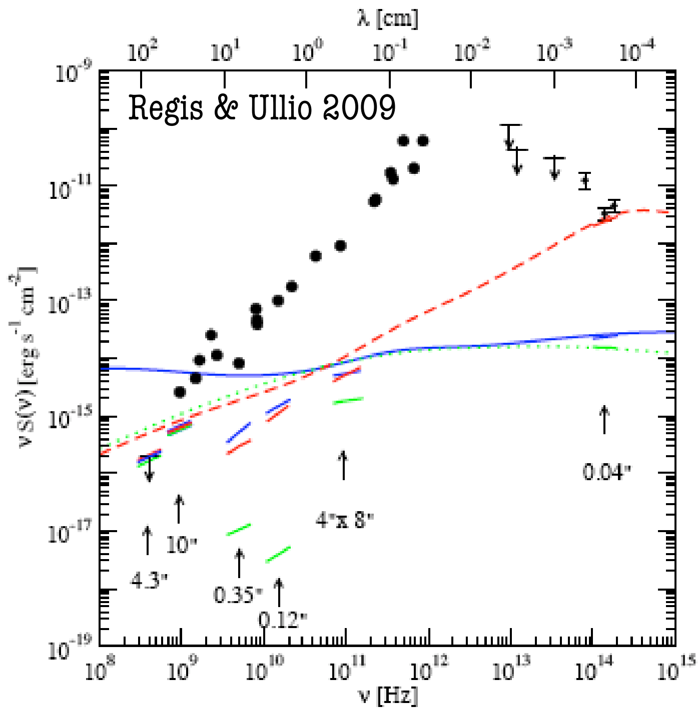


The radio sky
GC modeled coherently
with γ-rays and antimatter

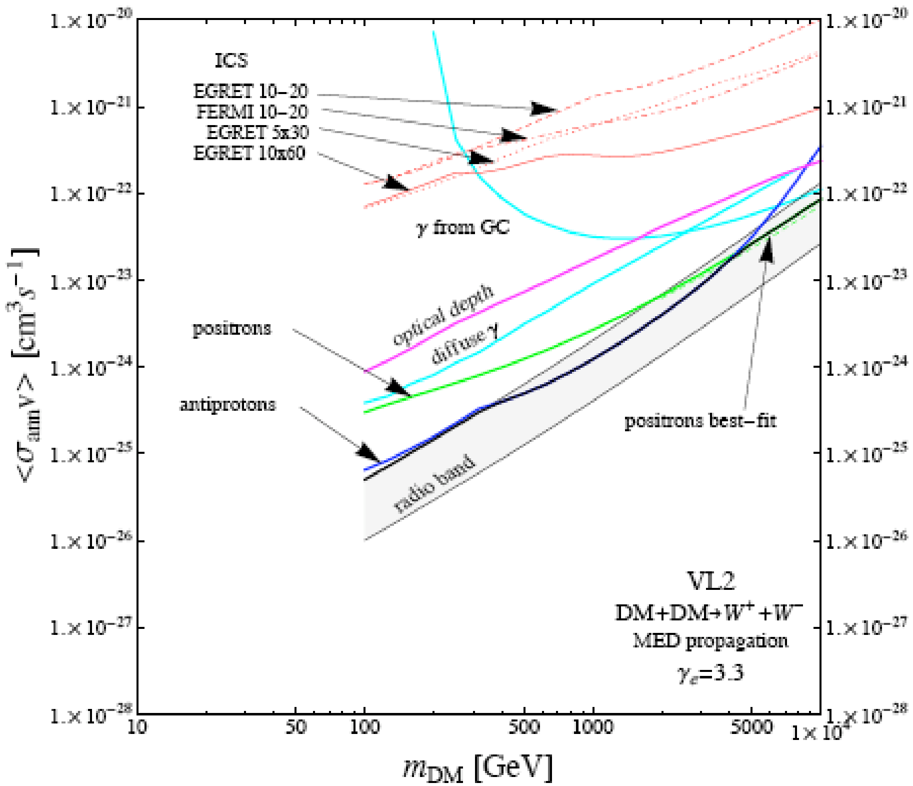
Compute synchtrotron power

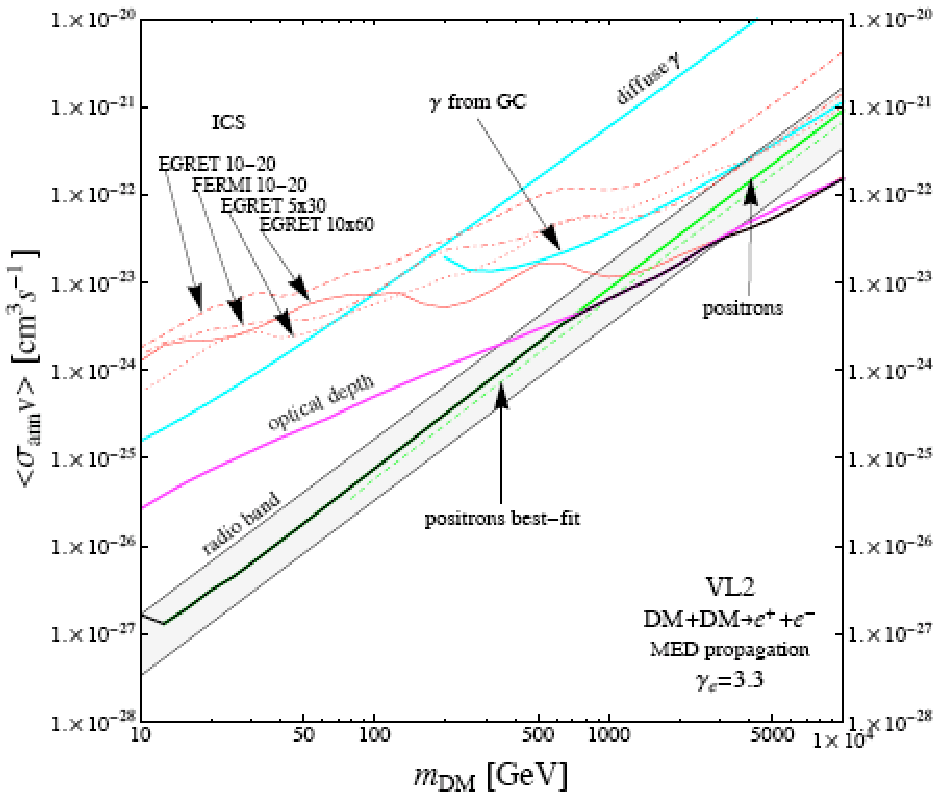
$$n_{e\pm}(\vec{x},E_{e\pm}) = \frac{\sigma v}{2m_{DM}^2}\rho_{DM}^2(\vec{x})\frac{N_{e\pm}(>E_{e\pm})}{b_{syn}(\vec{x},E_{e\pm})}$$

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



Multi³ constraints on annihilation cross-section



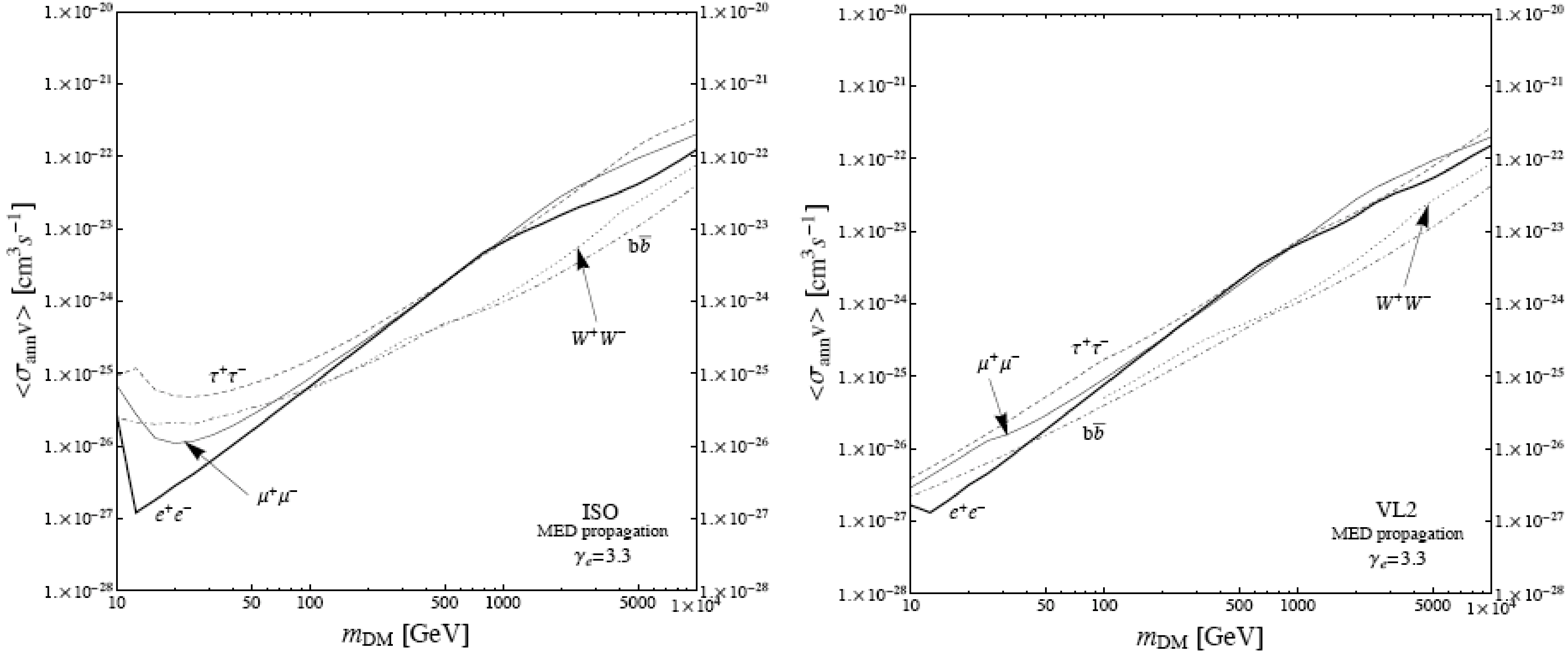


Catena, Fornengo, Pato, LP & Masiero 2010

Different messenger play different roles for different channels

Yet the amount of exclusion is almost the same..

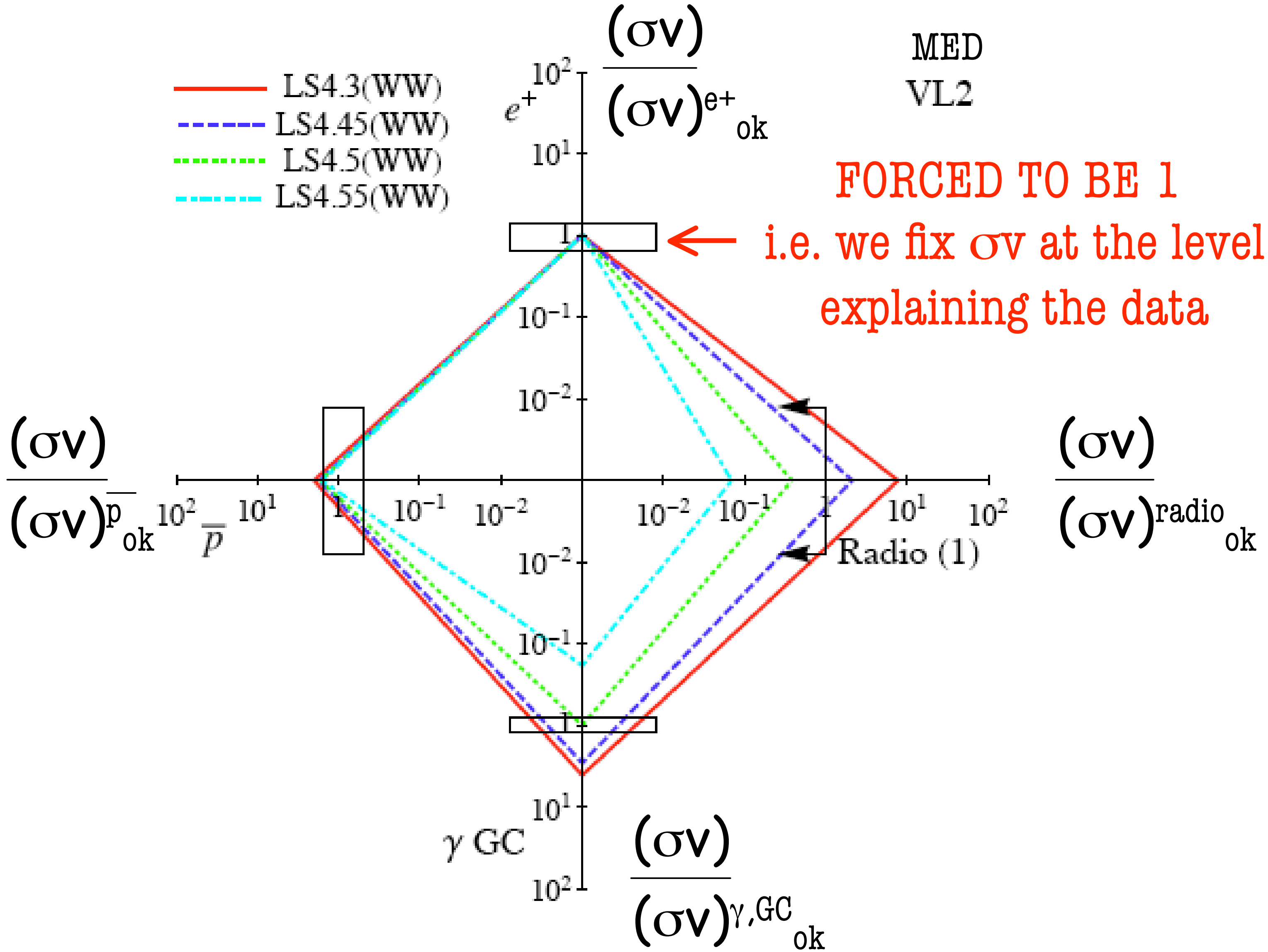
Multi^3 constraints on annihilation cross-section



Catena, Fornengo, Pato, LP & Masiero 2010

In order to get bands of exclusion we change profile
(Via Lactea II or Aquarius with subhalos, isocored without subhalos) and
propagation parameters (inside the MIN-MED-MAX propagation model)

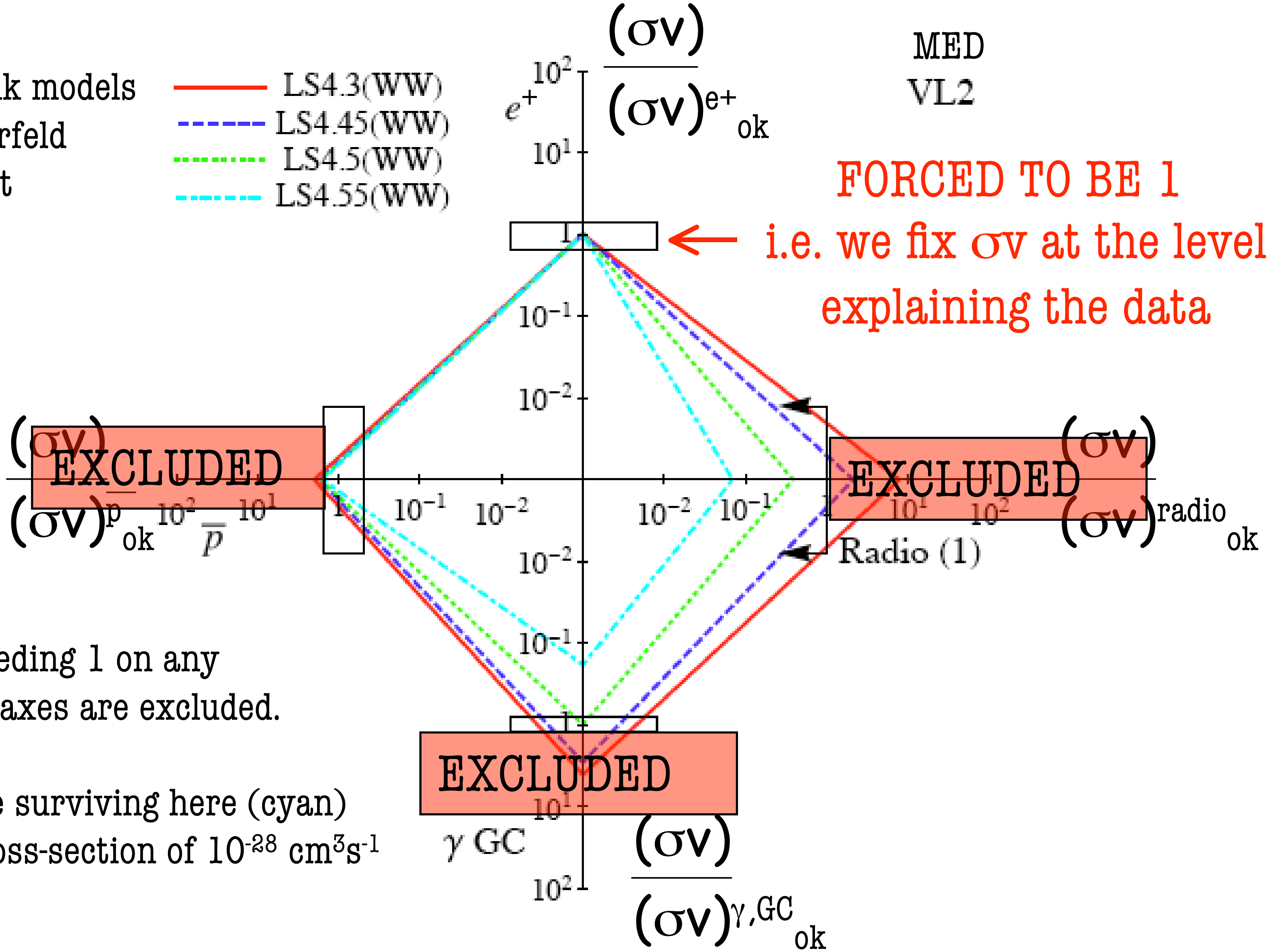
Compact way of plotting multi-wavelength constraints
APPLIED TO POSITRON FRACTION



Pato, LP, Bertone 2009

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

Lattanzi&Silk models with Sommerfeld enhancement



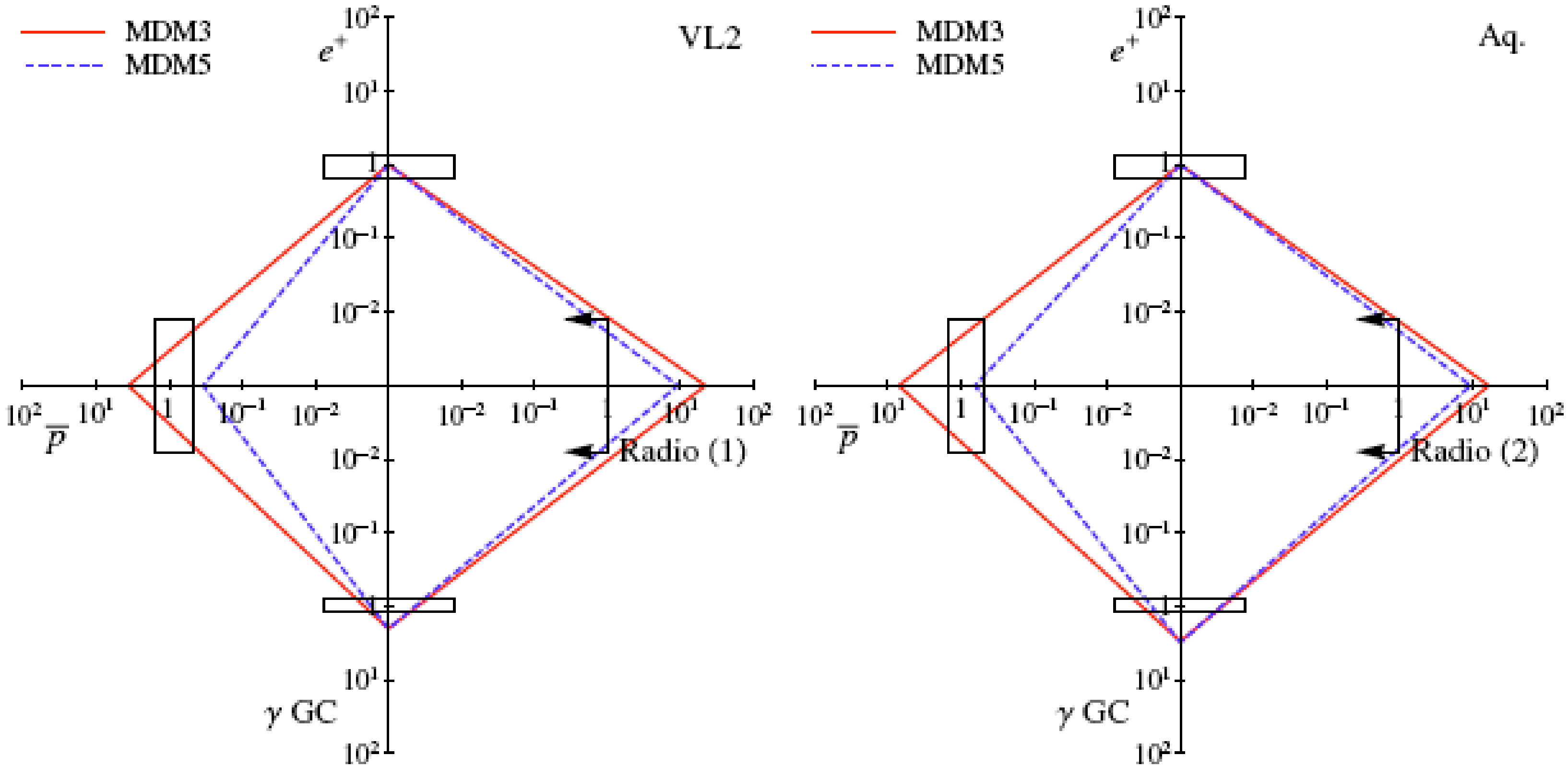
Models exceeding 1 on any of the other axes are excluded.

The only one surviving here (cyan) has got a cross-section of 10^{-28} cm^{3}s^{-1}

Pato, LP, Bertone 2009

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

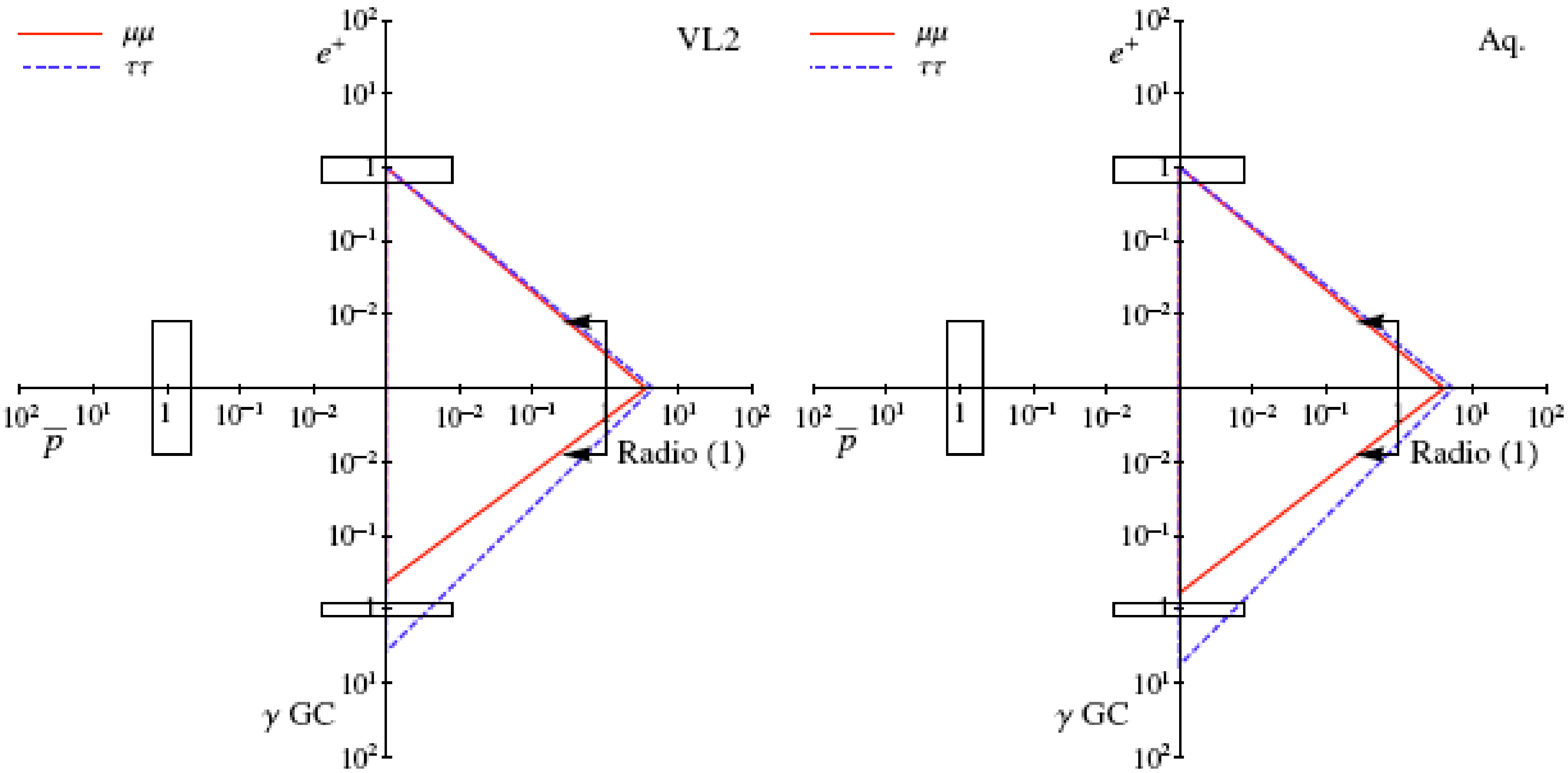
Minimal Dark Matter models are excluded



Pato, LP, Bertone 2009

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

Leptonic models are excluded

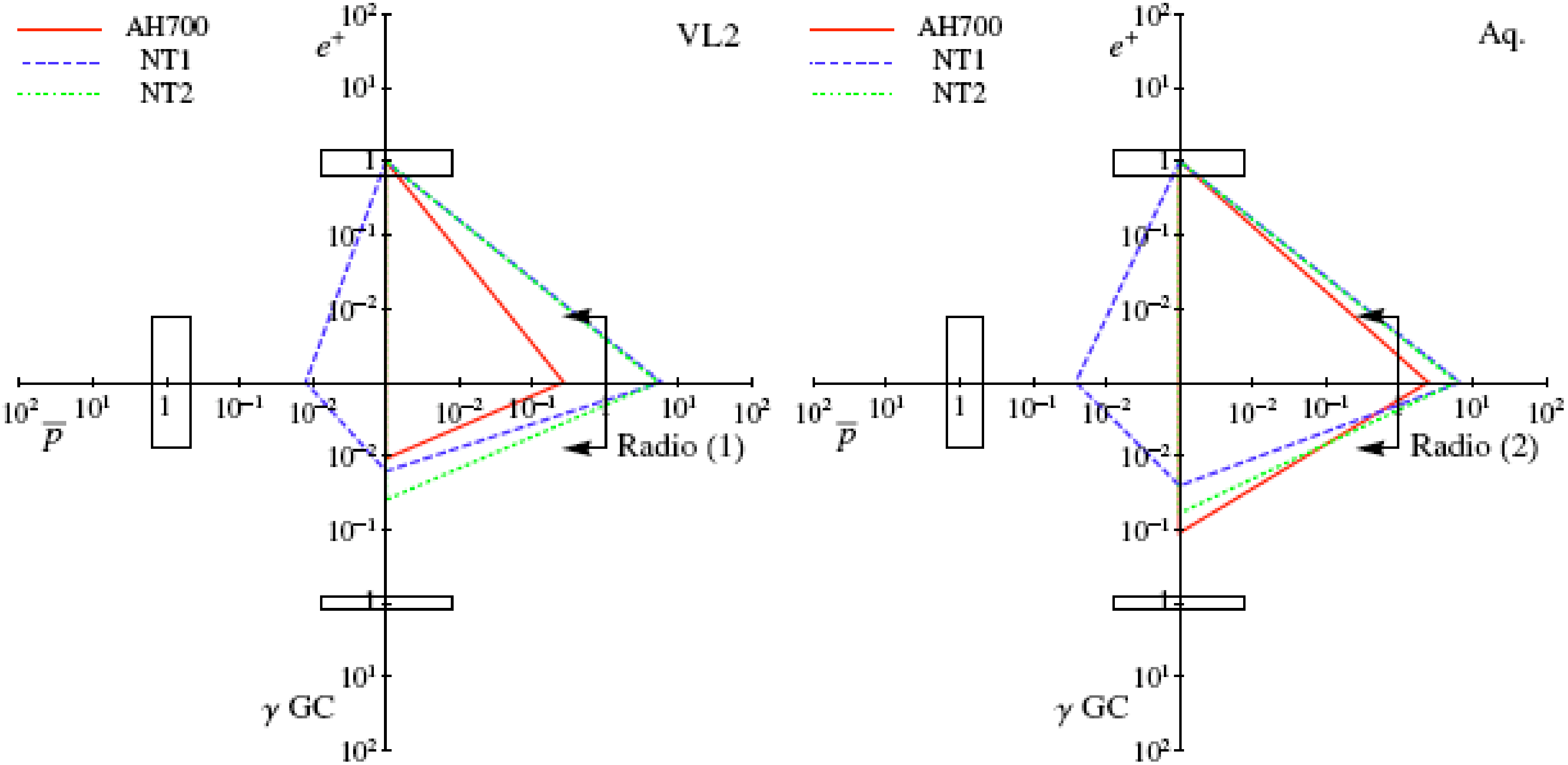


Pato, LP, Bertone 2009

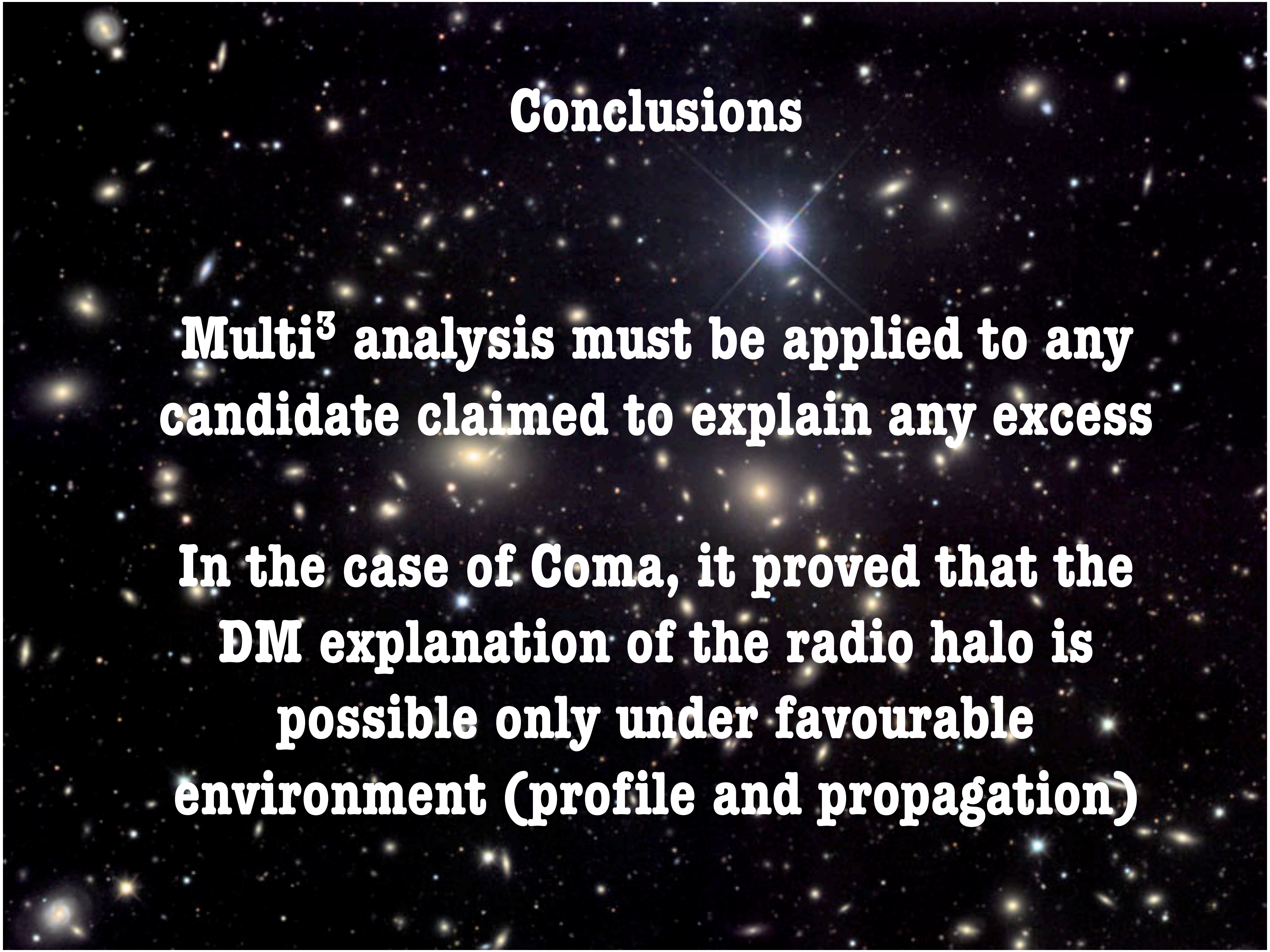
Compact way of plotting multi-wavelength constraints
APPLIED TO POSITRON FRACTION

Nomura&Thaler models are excluded

Arkani-Hamed et al. model is the only one surviving



Pato, LP, Bertone 2009



Conclusions

Multi^3 analysis must be applied to any candidate claimed to explain any excess

In the case of Coma, it proved that the DM explanation of the radio halo is possible only under favourable environment (profile and propagation)