Astrophysical observables for Dark Matter

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Outline

- Microlensing and rotation curve constraints to the DM distribution in our Galaxy

  → All types of DM, a "topography" study

  → Simulations, direct detection experiments

- CMB constraints on self-annihilation cross sections

  → Self-annihilating DM, model-independent analysis

  → Indirect searches

Dark Matter distribution in the Milky Way: microlensing and dynamical constraints

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Based on **arXiv:1107.5810** ***(JCAP in press)***

In collaboration with:

G. Bertone, P. Jetzer, M. Pato

Basic idea: take home

Rotation curves (all matters)

-

Microlensing optical depth (only compact bodies)

=

Diffuse components (DM and Gas)

[Binney & Evans '01]

Outline

- Microlensing, an introduction

  → Optical depth τ

- Modelling baryons in the MW

  → Modelling the DM, parameters

- Rotation curve observations, an overview

- Results: constraining Adiabatic Contraction and fitting the DM to rotation curve

Microlensing: principles

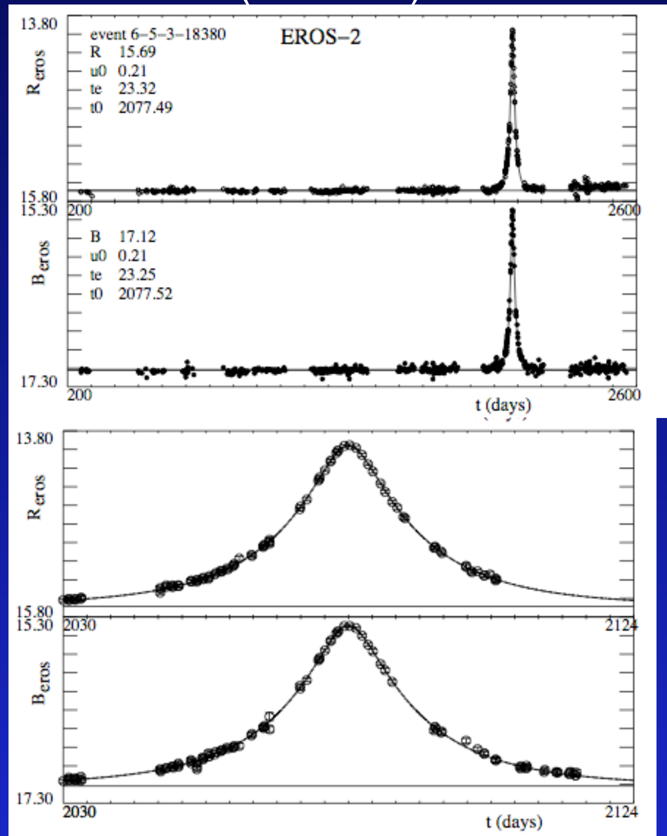
compact object (lens)
between us and source
creates two unresolved object
result: light magnification *A(t)*

$$A(t) = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}}$$

Lens need to be close to *los*:
Einstein radius

$$R_E = 2.85\ \mathrm{AU}\sqrt{\frac{MD_d[1-(D_d/D_s)]}{1\ \mathrm{kpc}}}$$

Optical/NIR surveys:
I field (620-920) nm
B field(420-720) nm



[EROS 2006]

<u>Microlensing caused by compact objects only</u>

Microlensing optical depth τ

The integrated probability of having a luminosity enhancement: events with A>1.34

Observationally:

$$\tau = \frac{1}{N_{\rm obs}\Delta T_{\rm obs}} \frac{\pi}{2} \sum_{\rm events} \frac{t_{\rm E}}{\epsilon(t_{\rm E})}$$

Theoretically,

we need models for the source ad lens distribution

$$\tau(\ell, b, D_s) = \frac{4\pi G}{c^2} \int_0^{D_s} dD_l \; \rho_l(\ell, b, D_l)\, D_l \left(1 - \frac{D_l}{D_s}\right)$$

$$\langle\tau\rangle(\ell, b) = \frac{\int_0^{r_\infty} dD_s \; \tau(\ell, b, D_s)\, dn_s/dD_s}{\int_0^{r_\infty} dD_s \; dn_s/dD_s}$$

Notice that τ depends on total mass of population, no IMF!!!

Microlensing observations of GC

MACHO CGR = average of 9 fields

$$(\ell, b) = (1.50^\circ, -2.68^\circ)$$

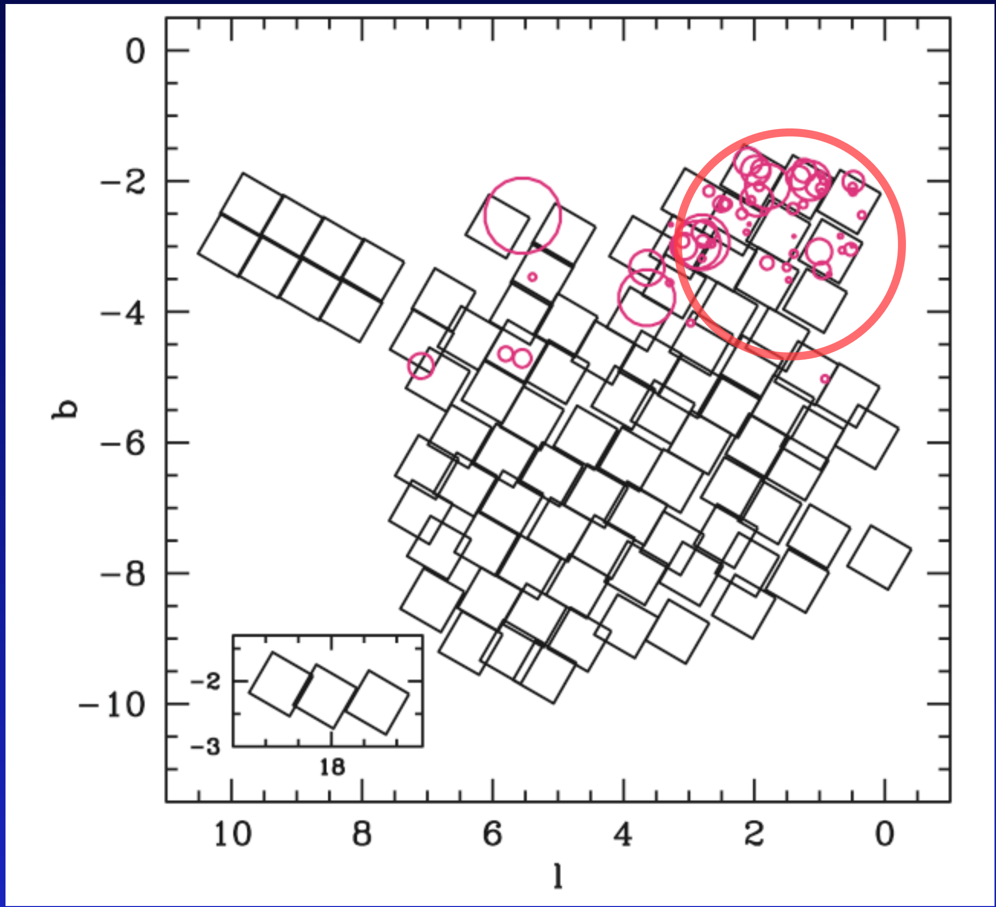
$$\langle\tau\rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$$

few < t_E/days < 700

10^{-3} < M_l/Msun < 80

Sources: red clump giant in the bulge

Insensitive to recently discovered Jupiter mass objects, However, below uncertainty: 0.1% mass content



MACHO [Popowski et al. 2005]

Galactic (baryonic) models

Ingredients:
Exponential/Gaussian bulge (with bar)
+ thin / thick disk
Bar at R < 2.5 kpc: bar angle $\alpha \approx 25°$

- **Model 1:** E2 bulge and thin+thick disk;
- **Model 2:** G2 bulge and thin+thick disk;
- **Model 3:** G2 bulge and thin disk;
- **Model 4:** Zhao bulge and thin disk; and

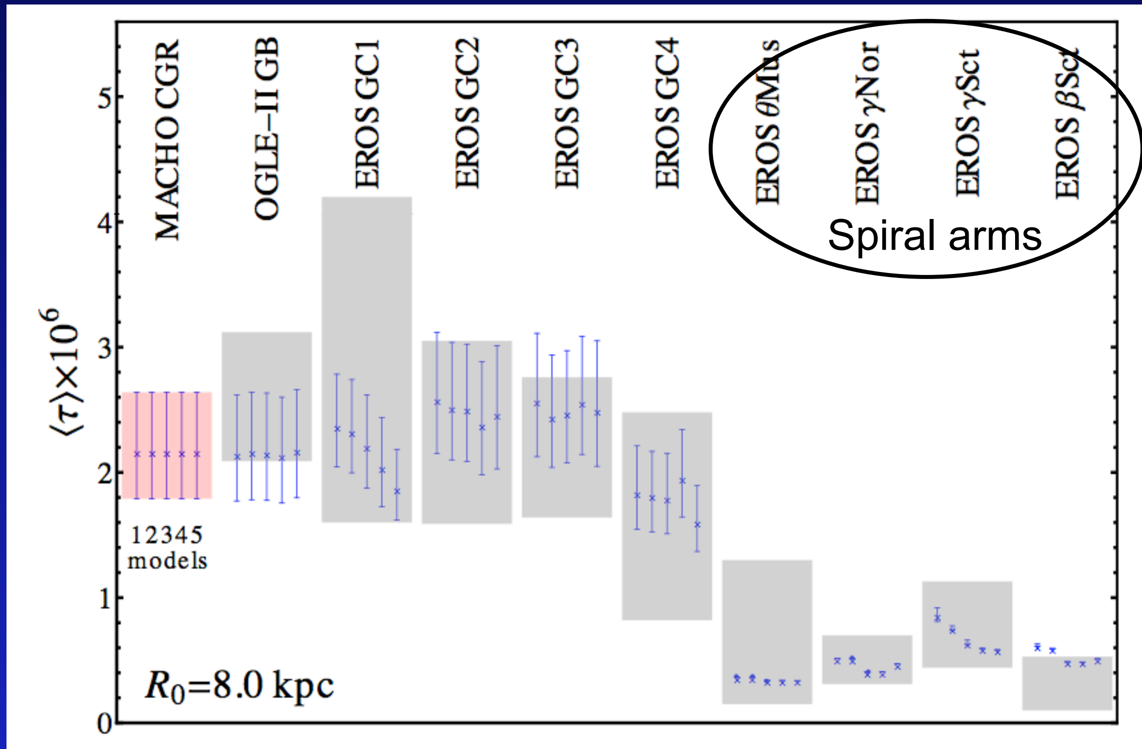
Model 5: bar + disk + gas

Shape fixed, density normalization ρ_b
calibrated to fit the MACHO observations

Galactic baryonic models

They fit quite well other microlensing observations:

GC and beyond!!



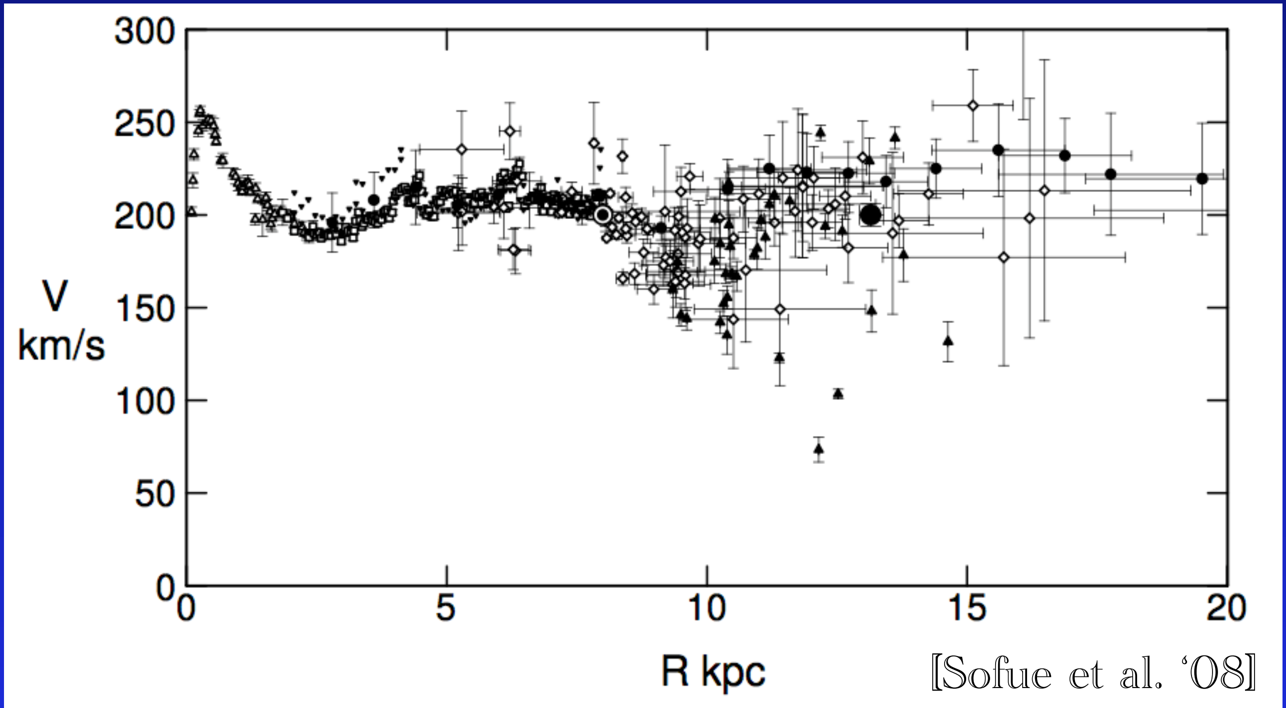
Mass ditribution used to obtain gravitational potential (circular velocities) using non-spherical Poisson equation; <u>Not adding DM</u> yet (see the following…)

Rotation curves: observations

Gas clouds moving in the disk: inner Galaxy
HI or CO line used as tracers
circular velocity assumption

$$v_c(R_0 \sin\ell) = v_t(\ell) + v_0 \sin\ell \qquad v_0 \equiv v_c(R_0)$$

Need to adopt *(R_0, v_0)*: different values in literature
unified rotation curve for *(8 kpc, 200km/s)*



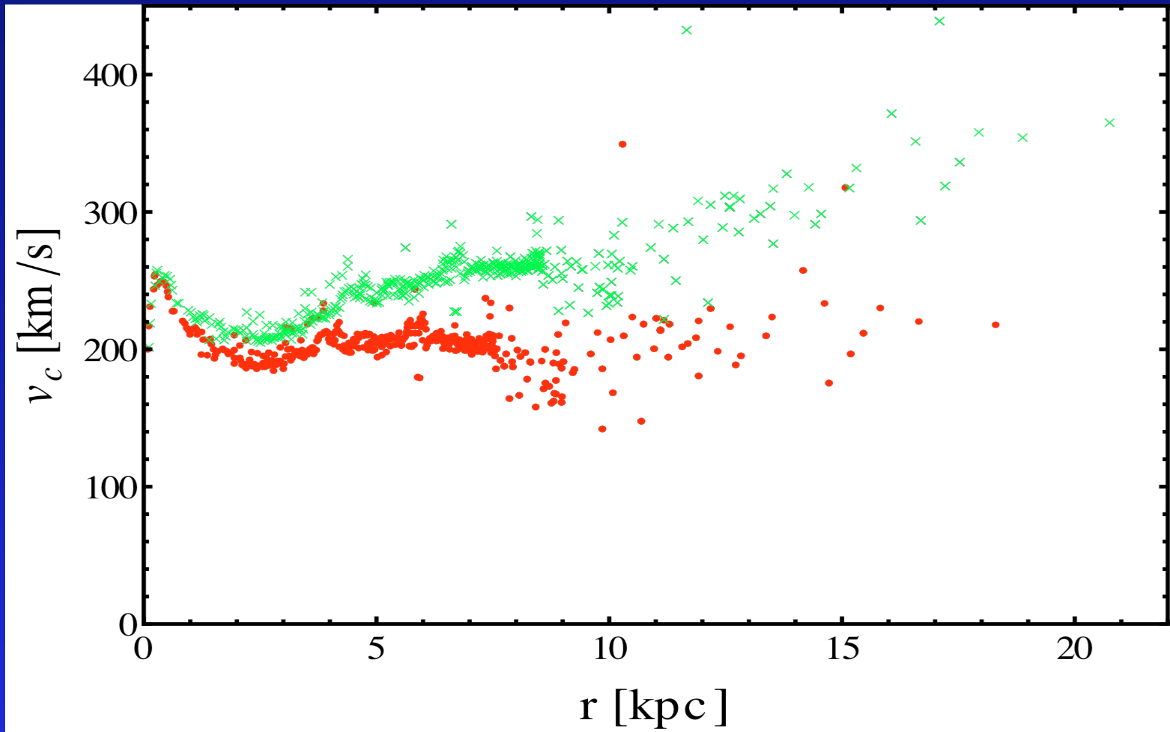
Rotation curve: uncertainties

We bracket the uncertainty in the determination of (R_0,v_0)
7.5 kpc < R_0 < 8.5kpc
200 km/s < v_0 < 260 km/s

Transformations valid only in the inner circle (safe, see later)

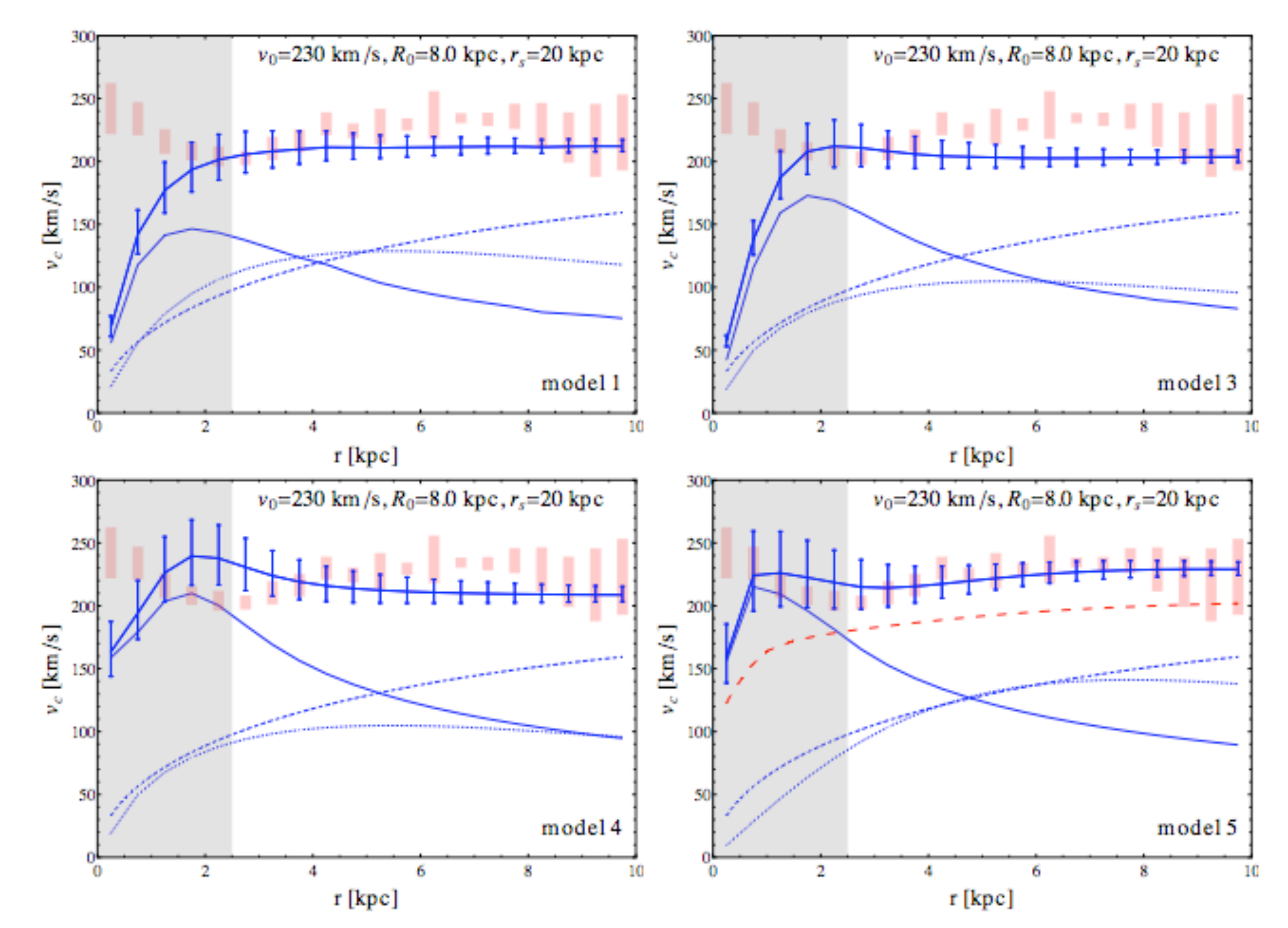
$$R' = R\frac{R'_0}{R_0}$$

$$v'_t = v_t + \frac{R}{R_0}(v'_0 - v_0)$$



Checking our baryonic models

(and adding DM)



With DM: NFW r_s=20kpc ; α=1 ; ρ_0 = 0.4 GeV/cm3

Let's use this to constrain DM!

Rotation Curves (all matters)

-

Microlensing optical depth (only compact bodies)

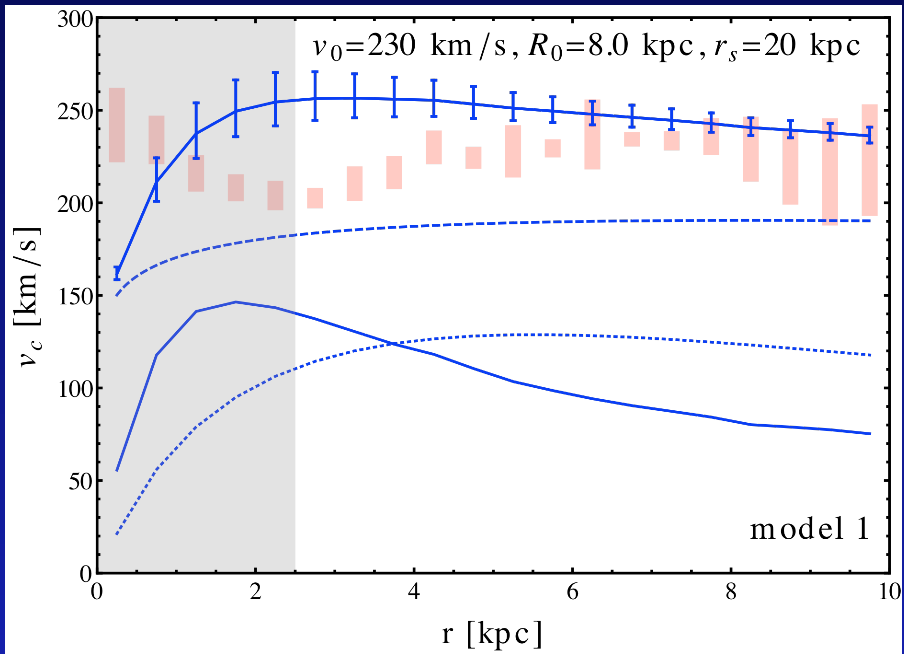
=

Diffuse components (DM and Gas)

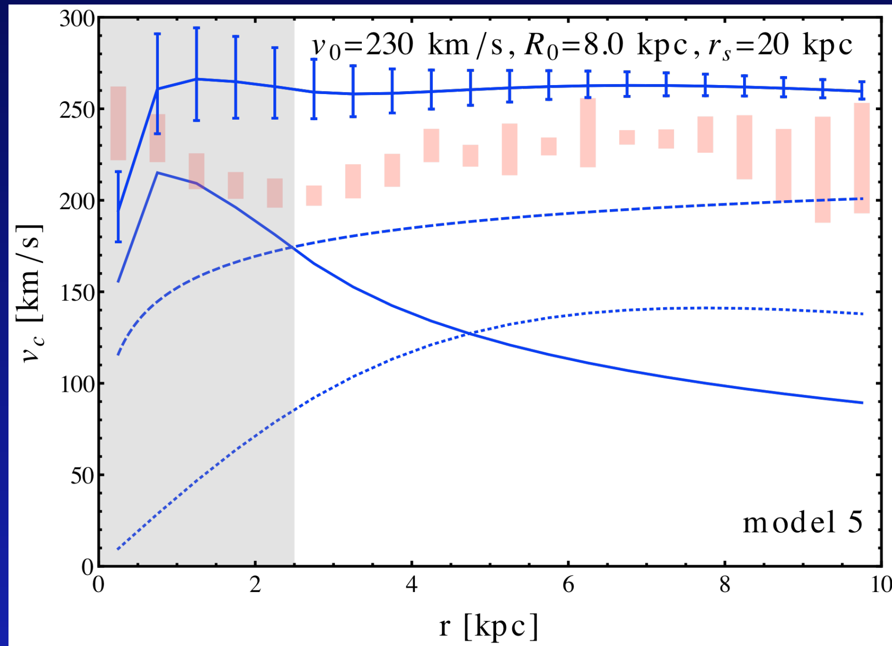
[Binney & Evans '01]

Test failure: 2 sigma overshoot

NFW $(\alpha,\rho_0) = (1.8,0.4)$



Einasto $(\alpha,\rho_0) = (0.05,0.5)$

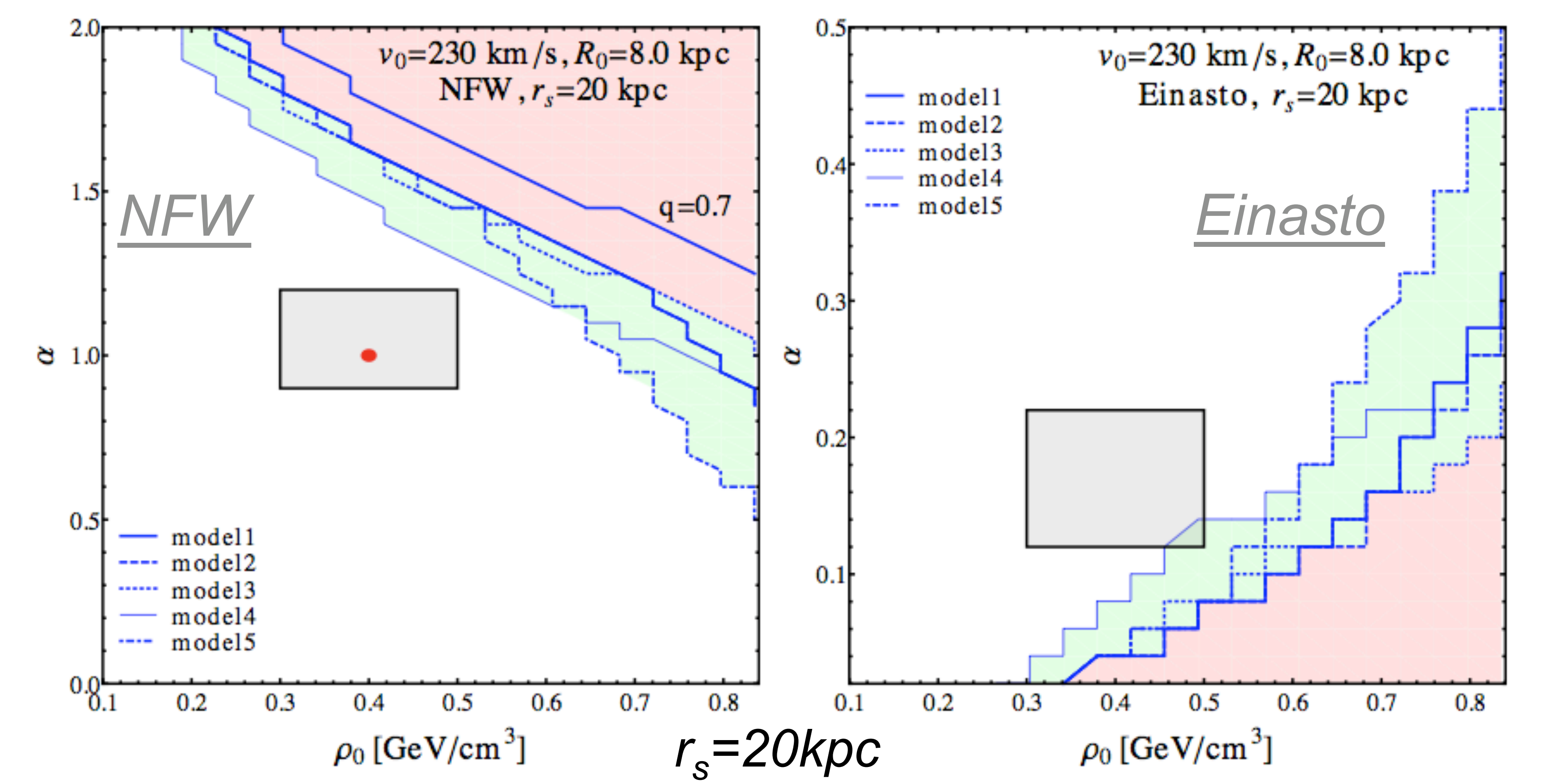


Observational velocity uncertainties:
statistical + systematic
(average of literature spread in 0.5 kpc bin)

Theoretically reconstructed uncertainties:
MACHO 2005 statistical propagated

The constraints that follow are quite <u>conservative</u>

Constraining the parameter space: the “fiducial” configuration



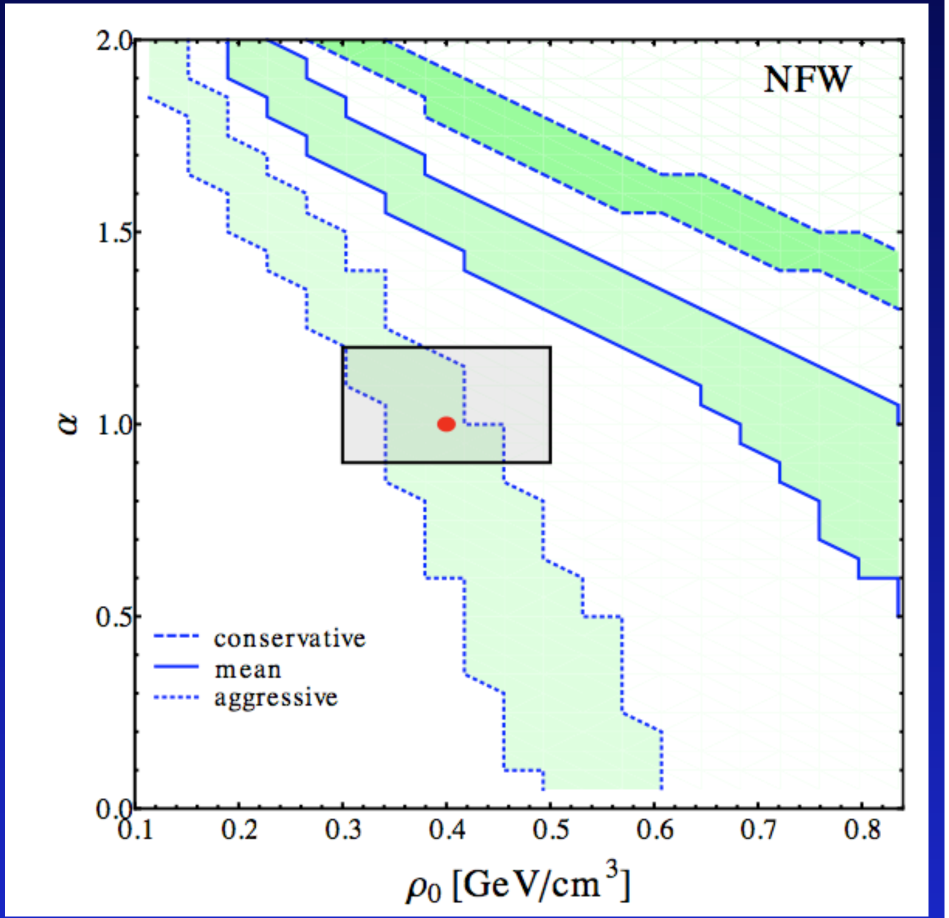
Constraints come from 2.75kpc, 7.75kpc bins,
thus no worries about kinematic transformations

Constraints dependence on parameters

What DM configurations
can we esclude if we change
Solar radius and local velocity?

Rescaling:

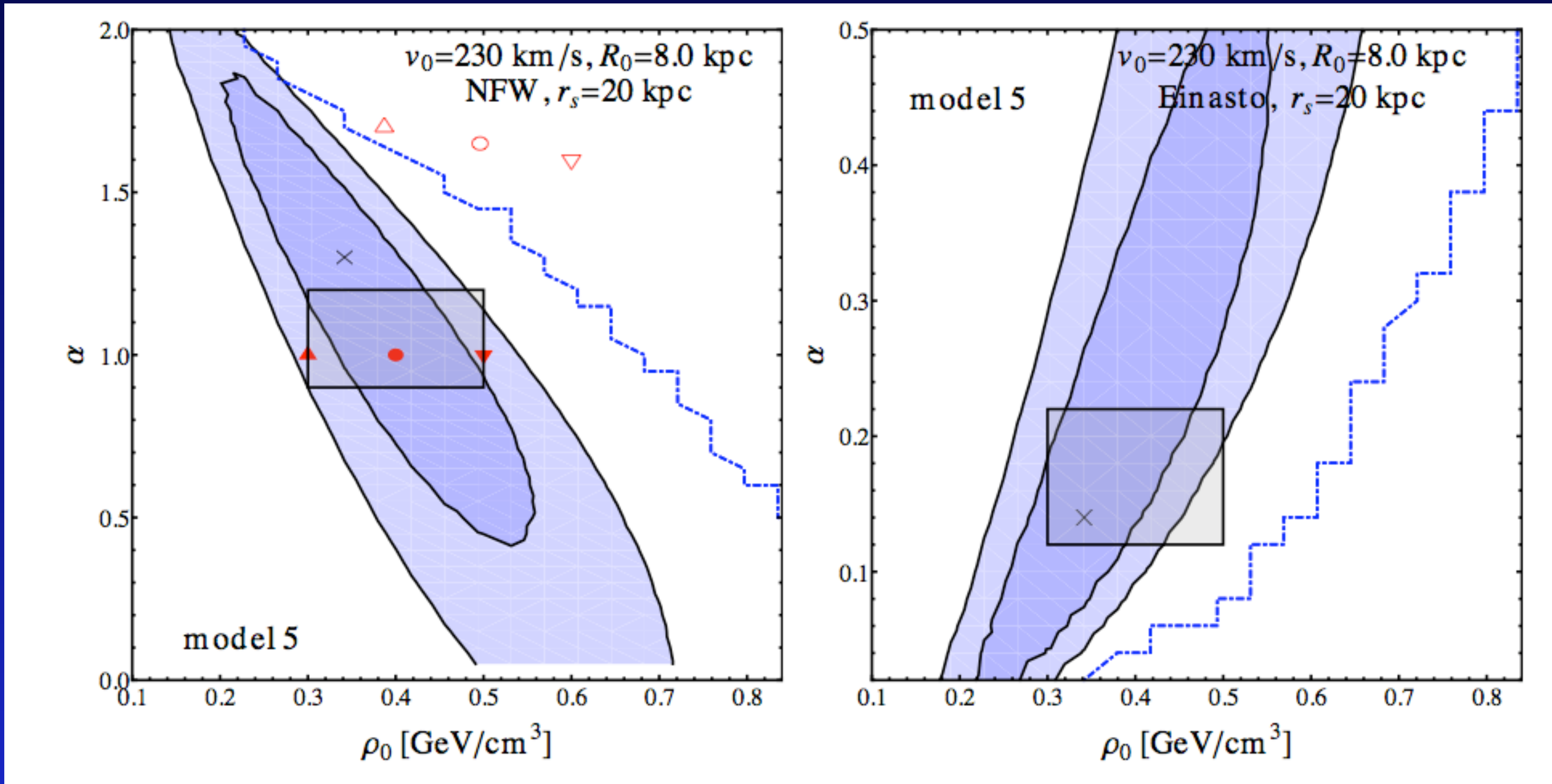
-) rotation curve
-) baryon modelling
-) DM halo



Conservative (r_s, R_0, v_0) = (35,7.5,260)
Mean (r_s, R_0, v_0) = (20,8.0,230)
Aggressive (r_s, R_0, v_0) = (10,8.5,200)

Fitting the best DM parameters

using Model 5 (includes gas, best shape fitting)



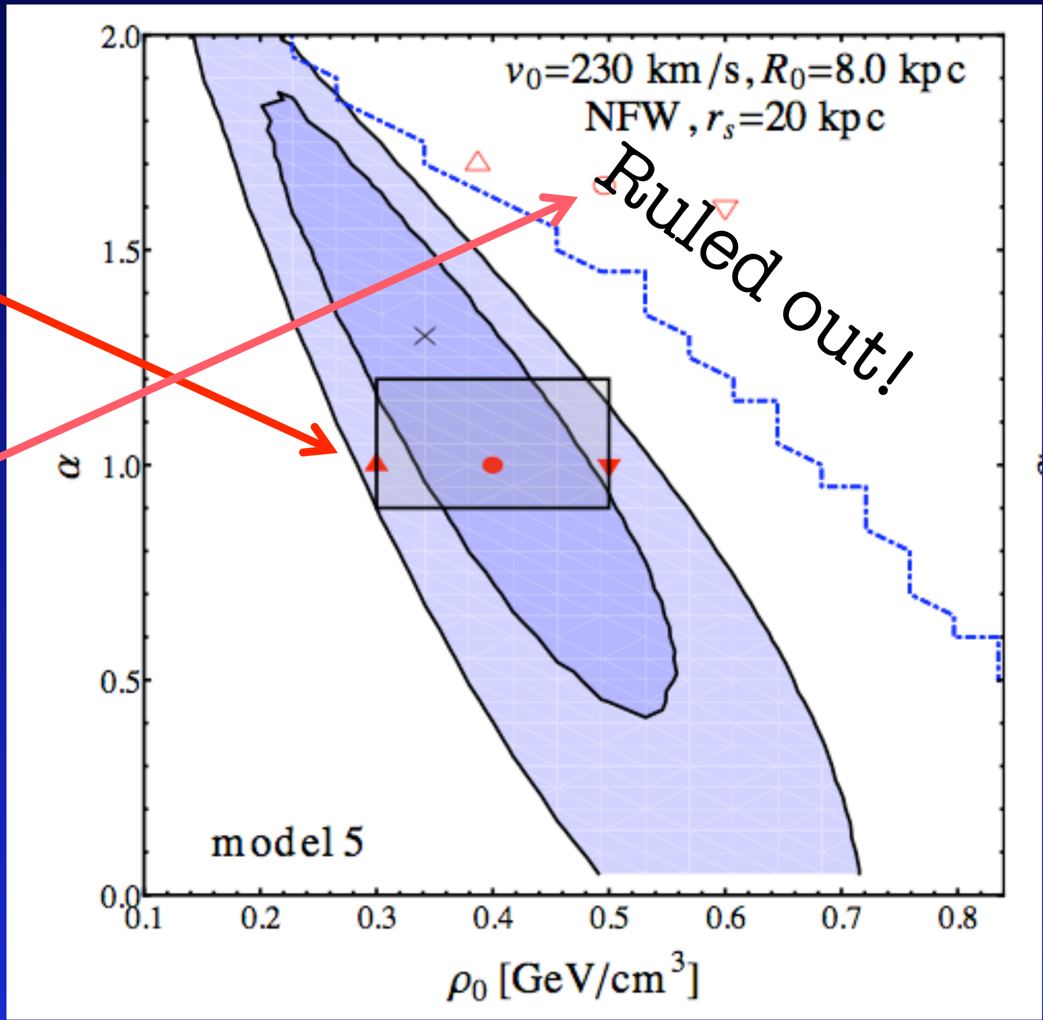
Excellent agreement with simulation parameter space,
And determination of ρ_0 [Catena & Ullio '09]

Adiabatic Contraction
the embarassing guest

Starting point

apply adiabatic invariant
M(R)R=const

Blumenthal flavor of AC:
still need to test
Gnedin/Gustafsson
models



Concluding

- Combining Microlensing observations of galactic Bulge with observations of rotation curves, possible to have information about DM distribution in the Galaxy

- Agreement with NFW and Einasto suggested by numerical simulations

- Rule out extreme flavor of Adiabatic Contraction

- Using a specific baryonic model, possible to find the best fitting NFW/Einasto parameters, obtaining

the 1 σ interval ρ_0=[0.20-0.55] for spherical halos

(R_0=8kpc, v_0=230km/s, r_s=20kpc , varying α)

Est via sublimis caelo manifesta sereno
Lactea nomen habet, candore notabilis ipso

[Ovidius, Metamorphoses *I-168*]

Updated CMB constraints on DM annihilation cross-sections

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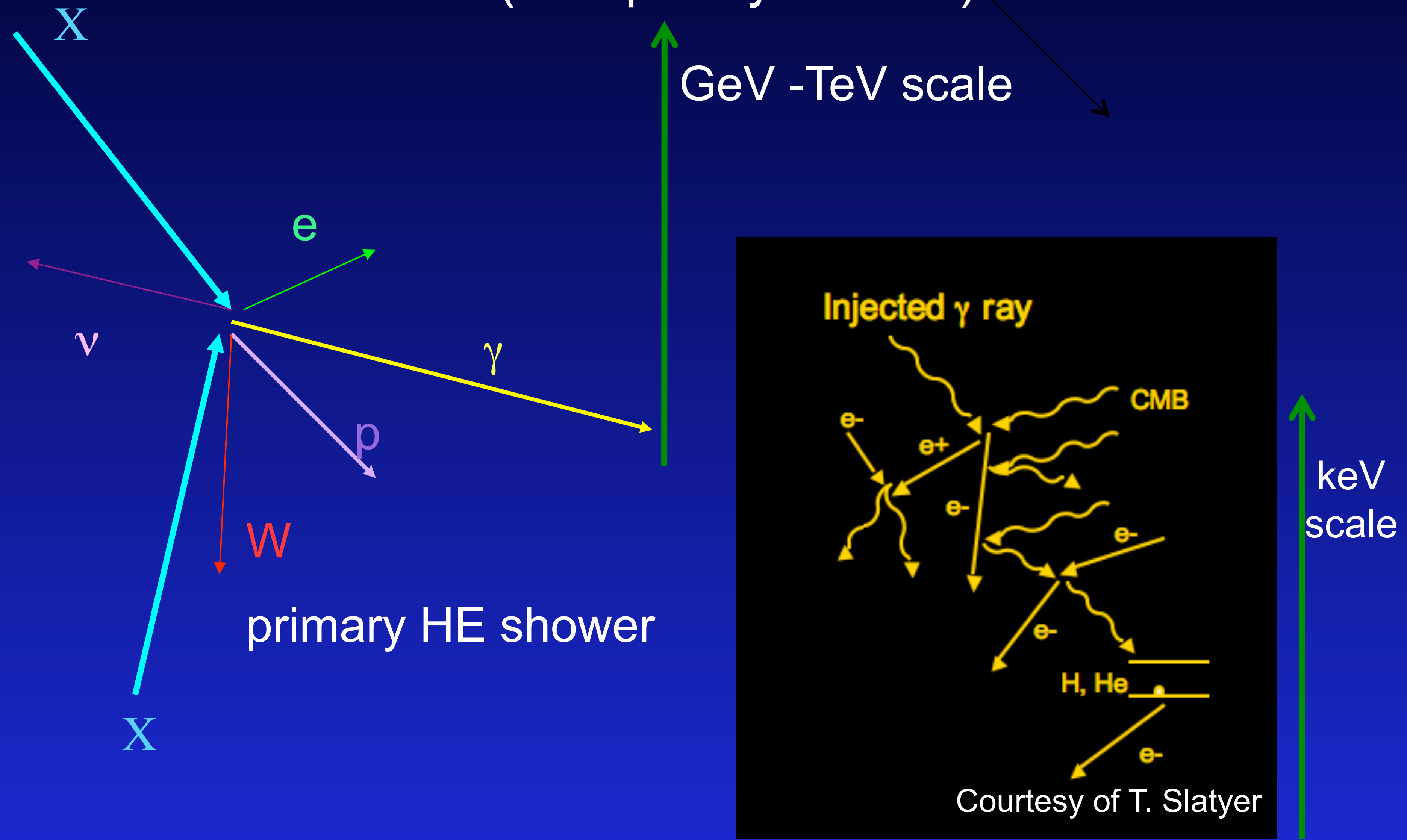
Marie Curie fellow at

Institut d'Astrophysique de Paris

Based on PRD82 (2009), PRD84 (2011)
in collaboration with: G. Bertone, S. Galli, A. Melchiorri

DM annihilation and the IGM
(and plenty of time)



heating and *ionization*

Isotropically averaged cosmological DM annihilation

Smooth component

$$A^{\mathrm{sm}}(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \rho_{\mathrm{DM},0}^2 (1+z)^6$$

Structure component

$$A^{\mathrm{struct}}(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \int \int dM \frac{dn}{dM}(z, M) (1+z)^3 \, 4\pi r^2 \, \rho_i^2(r, M(z)) \, dr$$

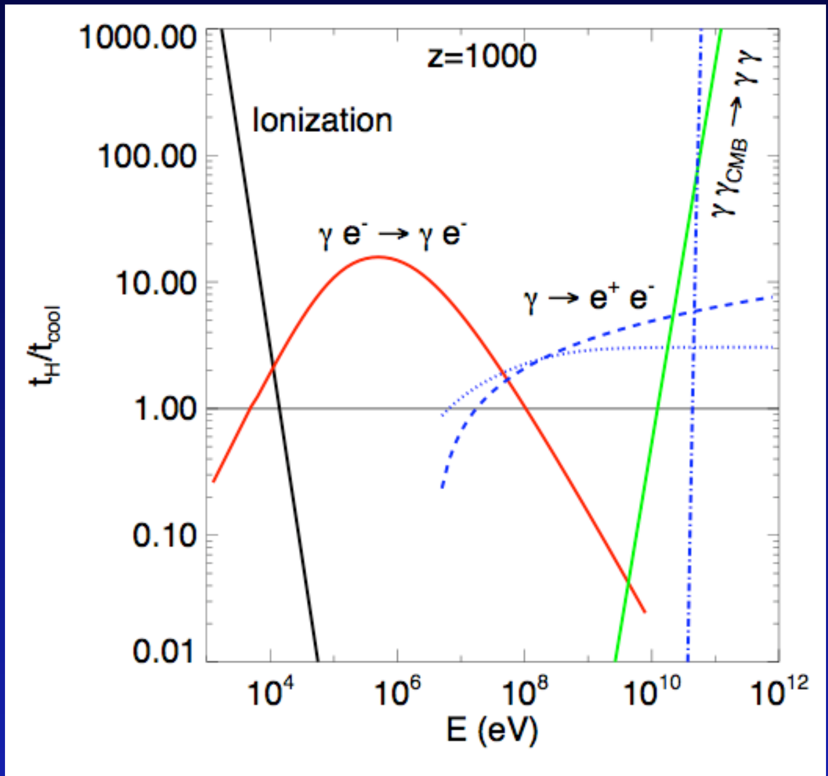
Structure formation history
(Press-Schechter / Sheth-Tormen)

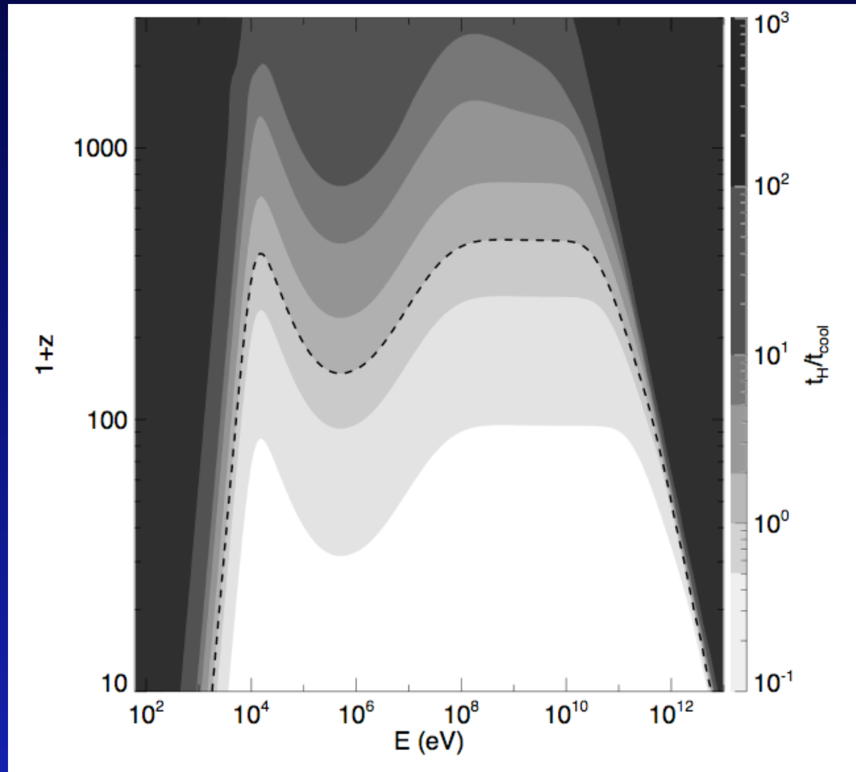
DM density halo profile
Burkert / Einasto / NFW

$$A(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \rho_{\mathrm{DM},0}^2 (1+z)^6 \, (1 + \mathcal{B}_{\mathrm{M}}(z))$$

Only after structure formation $z \leq \approx 100$

…and its absorption by the surrounding gas
(coupling DM induced shower to IGM)





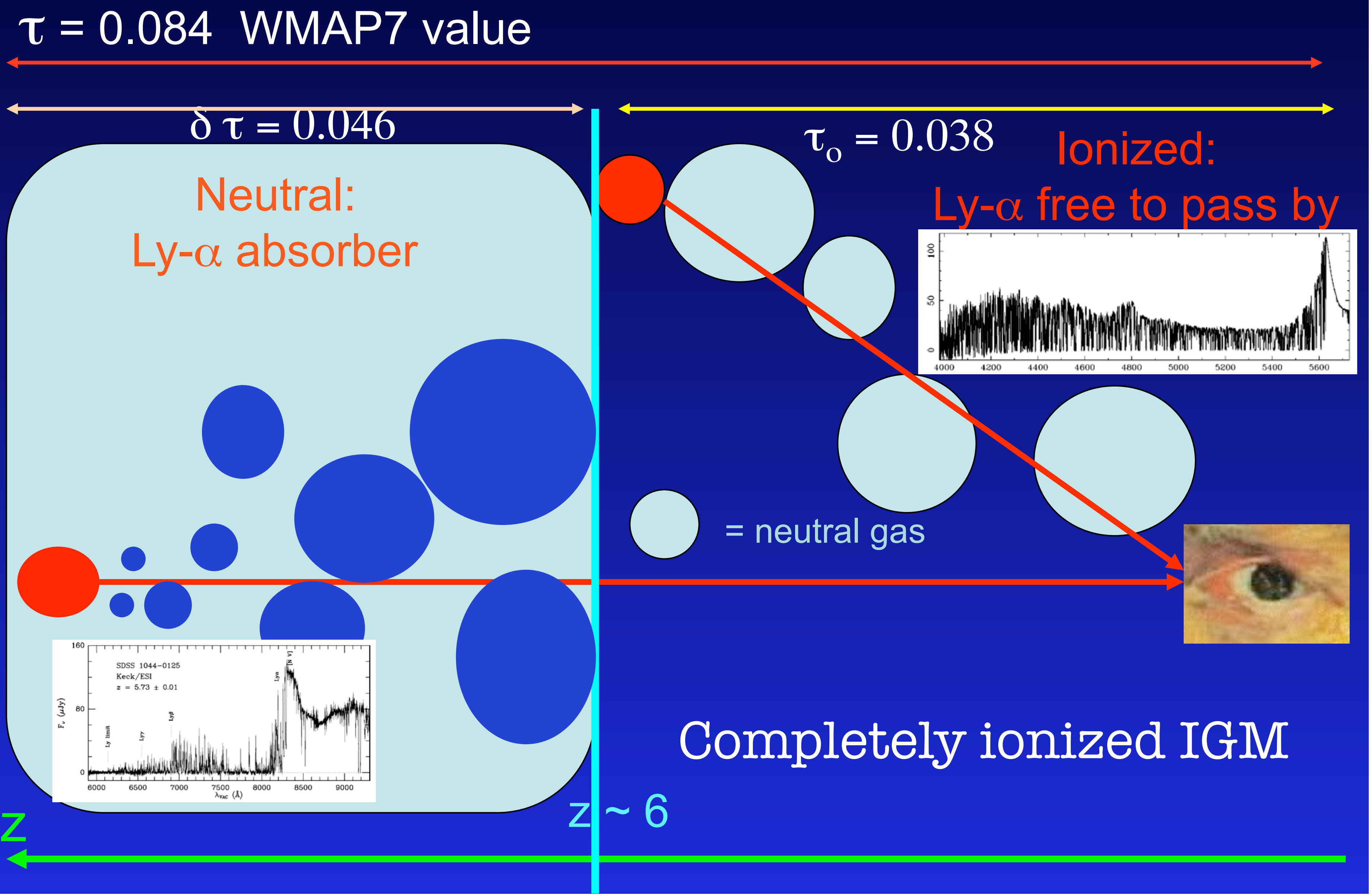
Photoionization, IC scattering, pair production (on CMB γ and matter), γγ scattering

"Opacity window" of the Universe

[Slatyer et al. `09]

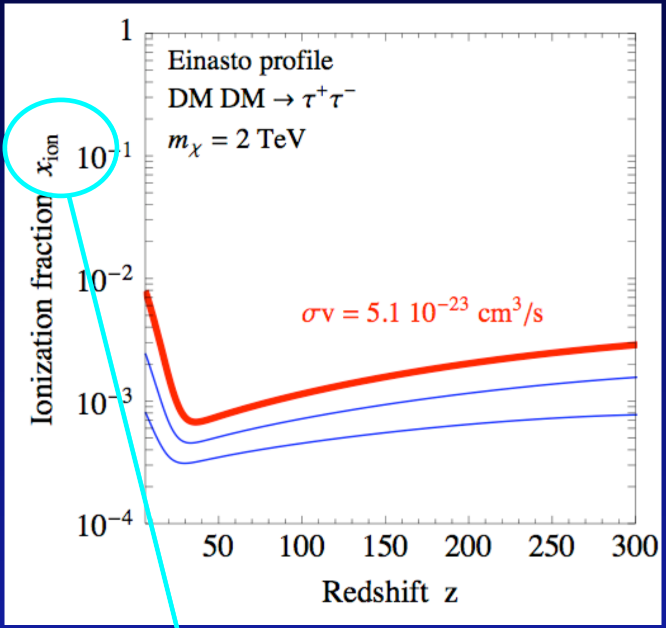
Electron optical depth τ

$$\tau = -\int n_e(z)\,\sigma_{\rm T}\,\frac{dt}{dz}$$

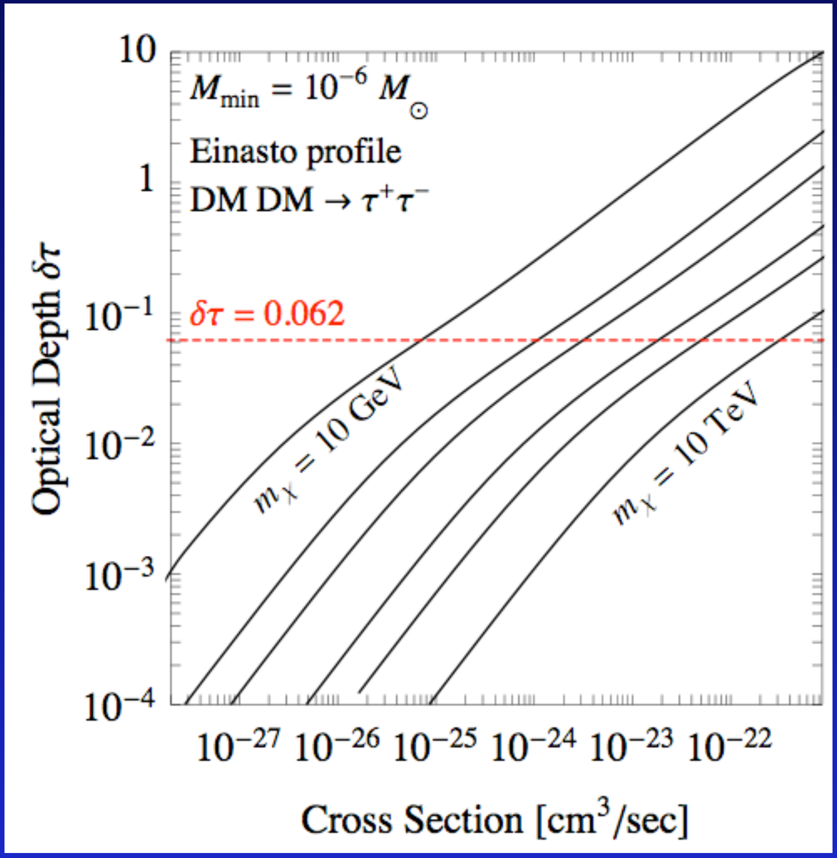


τ constraints

(DM annihilations can overproduce free e^-)



To be integrated!



In this models:

no astrophysical sources (z > 6)

Extra-conservative bounds!

[Cirelli, FI, Panci `09]

Isotropically averaged cosmological DM annihilation

Smooth component

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Structure component

$$A^{\rm struct}(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \int \int dM \frac{dn}{dM}(z,M) (1+z)^3\, 4\pi r^2\, \rho_i^2(r, M(z))\, dr$$

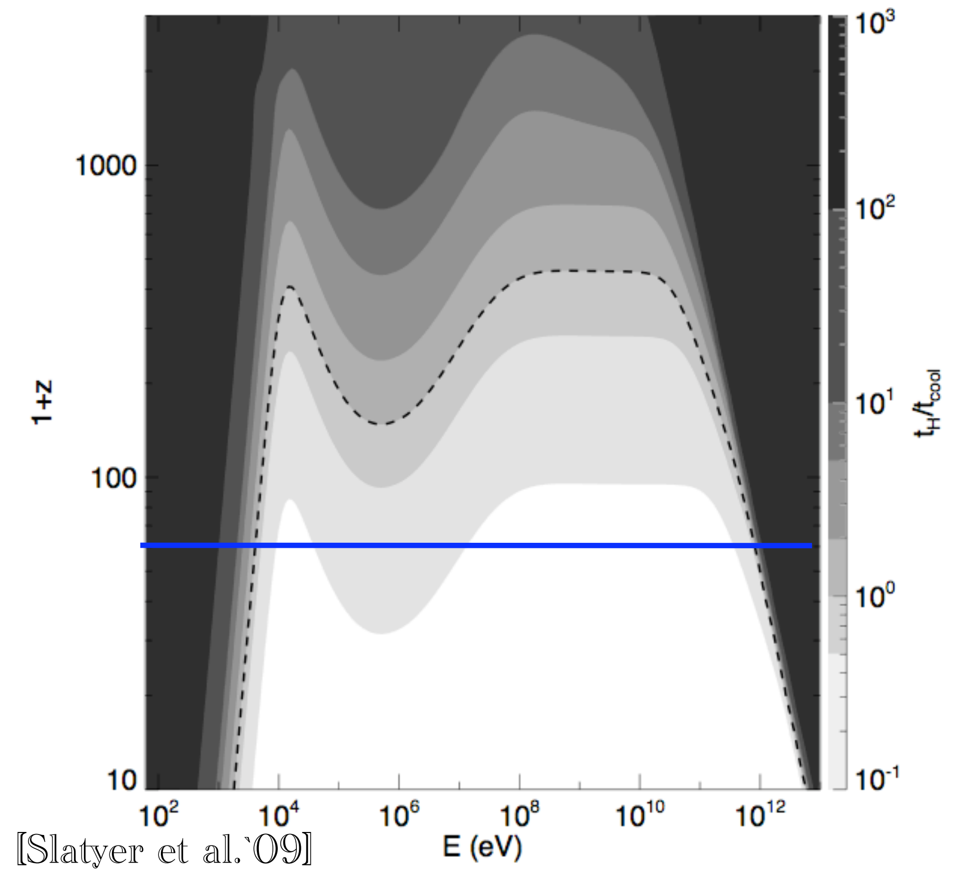
Structure formation history (Press-Schechter / Sheth-Tormen)

DM density halo profile Burkert / Einasto / NFW

$$A(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \rho_{\rm DM,0}^2 (1+z)^6 \,(1 + \mathcal{B}_{\rm M}(z))$$

Only after structure formation $z \lesssim \approx 100$

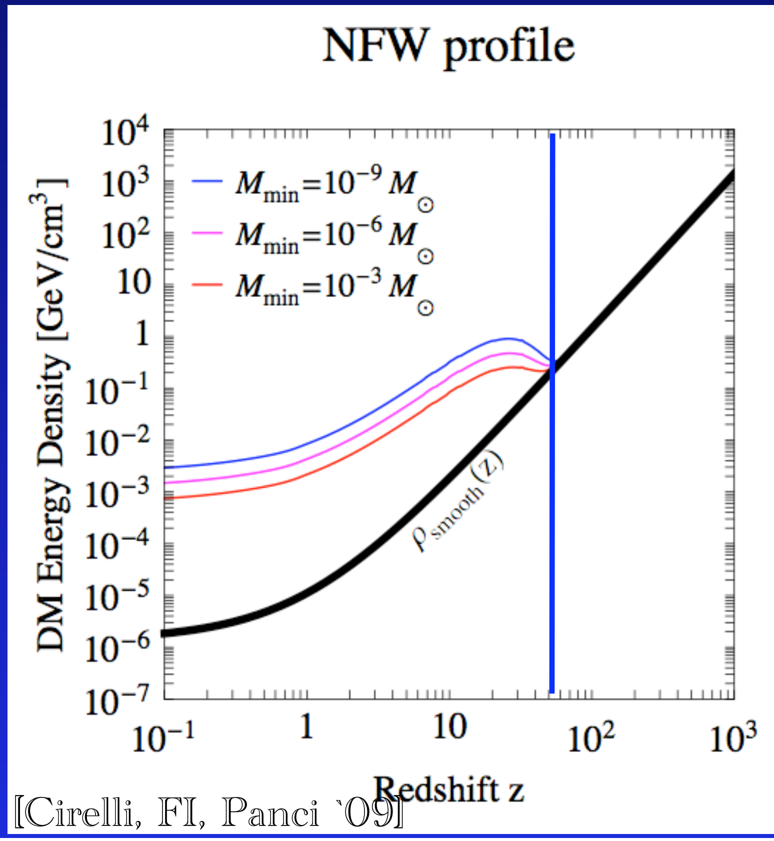
Transparency of the Universe & structure formation



HE shower gets efficiently absorbed

at high z

Structure formation takes place in a late Universe (z < 60)



Self-annihilating DM and the IGM

The smooth DM component annihilates with a rate (per volume)
(easily re-writable for decaying DM)

$$\frac{dI}{dt}(z) = n^2_{DM}(z)\langle\sigma v\rangle m_\chi c^2$$

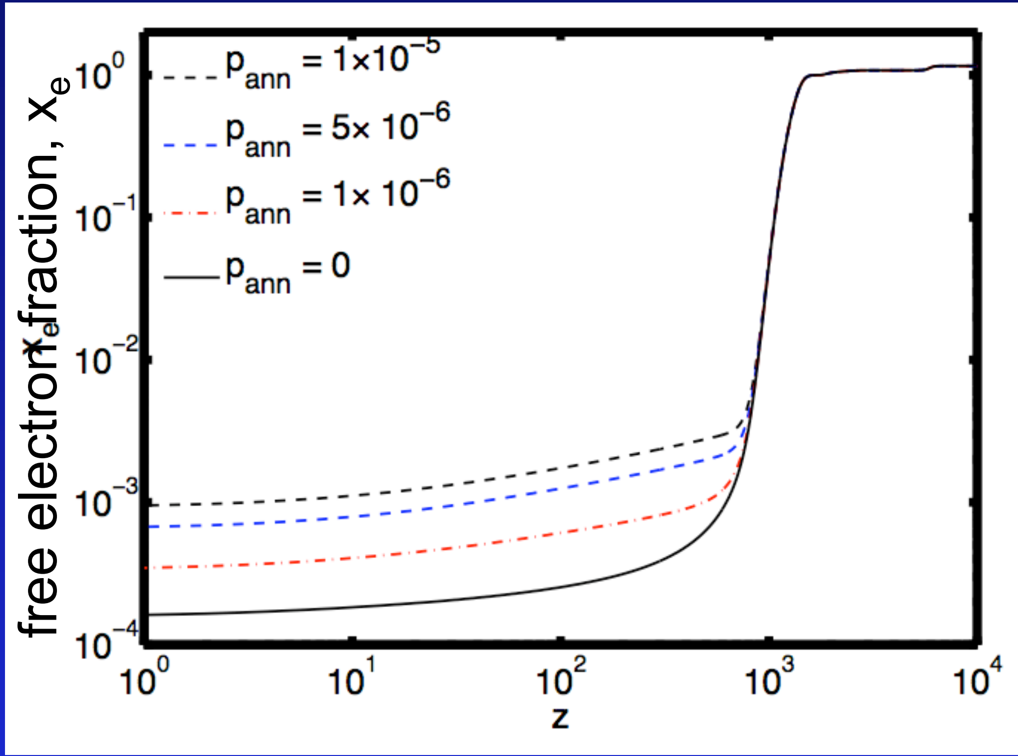
depositing energy in the gas (IGM) at a rate

$$\frac{dE}{dt}(z) = \rho_c^2 c^2 \Omega^2_{DM}(1+z)^6 f \frac{\langle\sigma v\rangle}{m_\chi}$$

The only DM-related parameter is

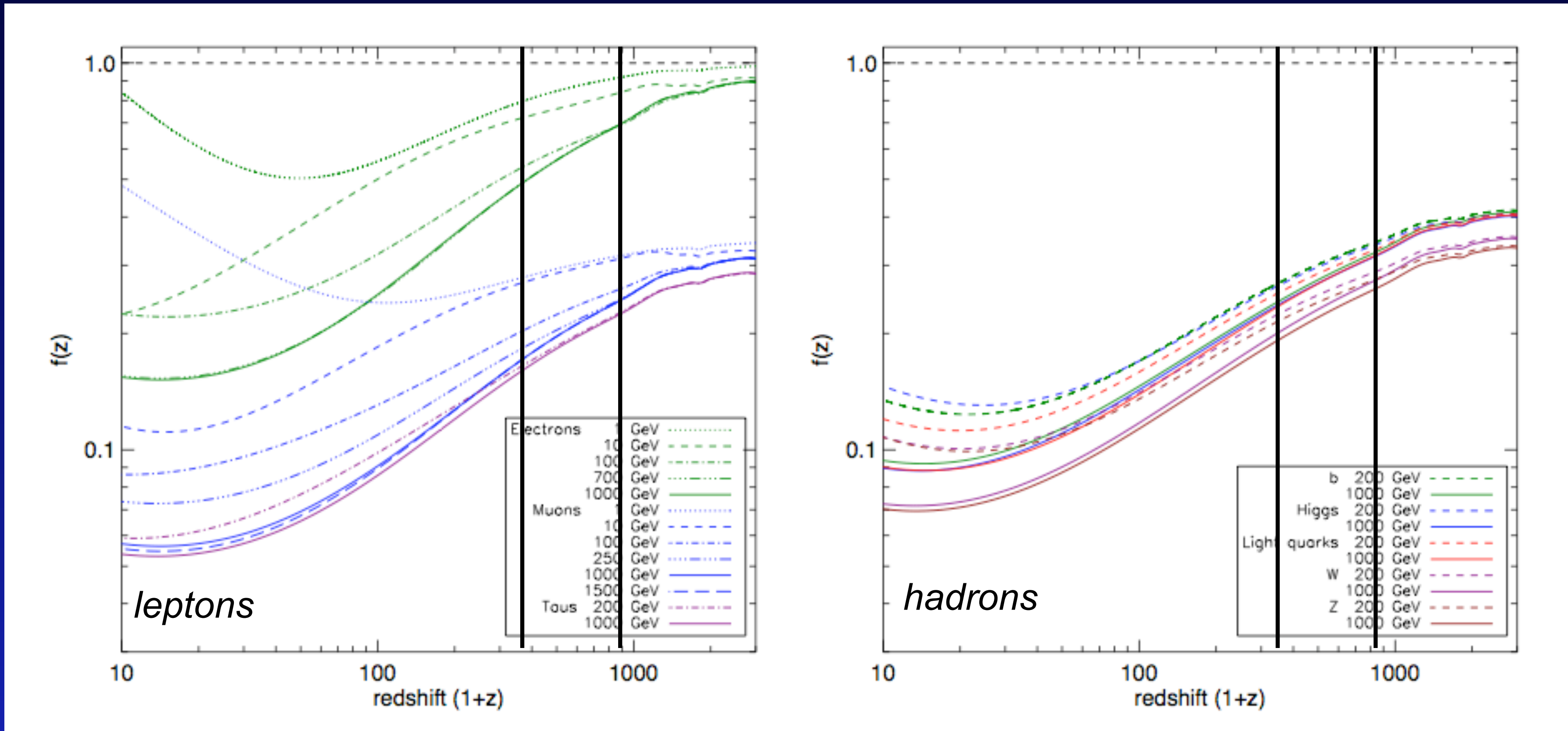
$$p_{\rm ann} \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}$$

Main effect of injected energy: ionization of the IGM



[Galli, FI, Bertone, Melchiorri `09]

Evaluating “ $f(z)$ ”



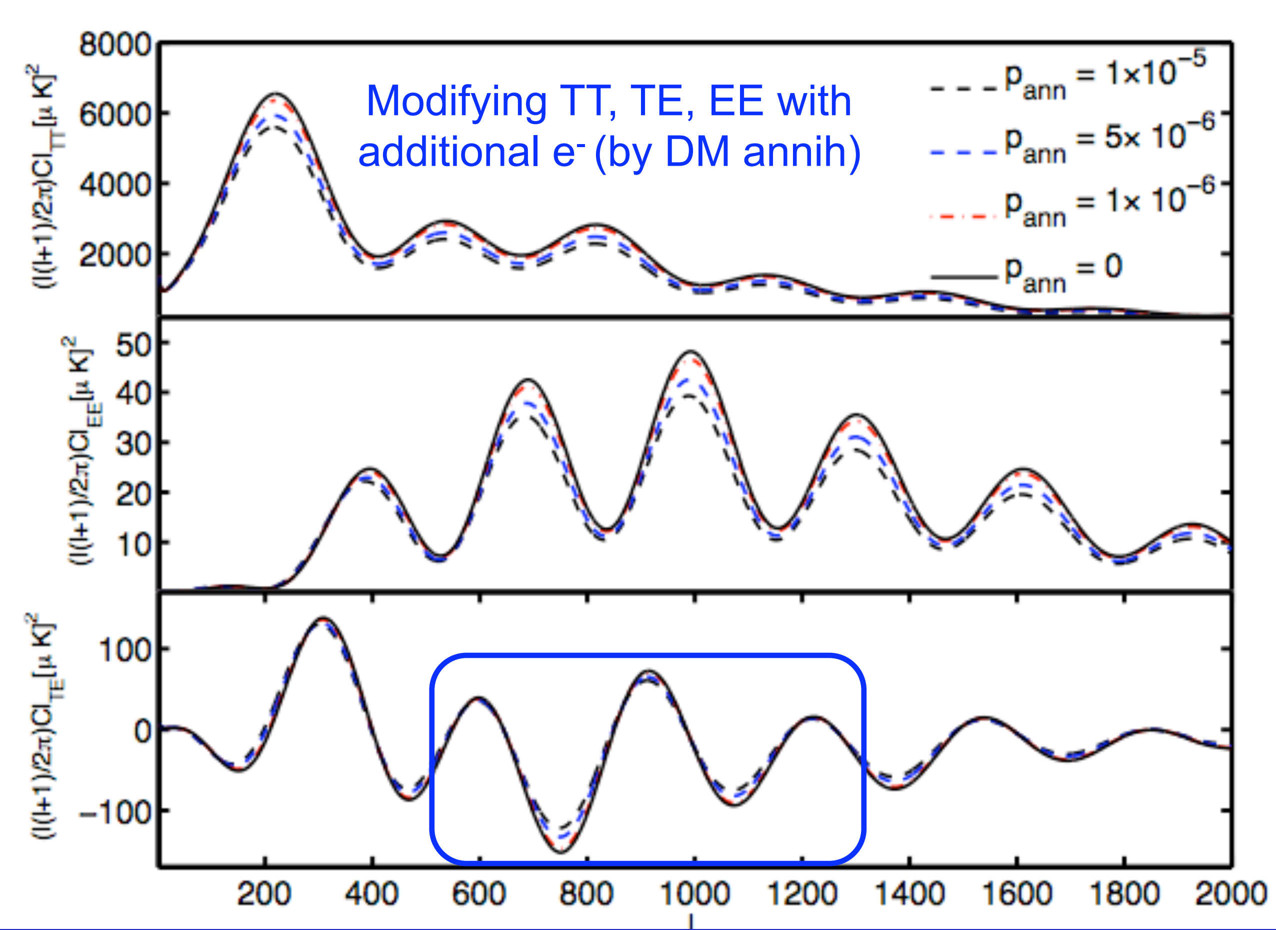
Previous analysis based on constant “ f “ ; not-so-bad! see *[Finkbeiner + ’11]* for PCA motivation of *f=f(600)*

All channels,
all secondaries,
redshift dependence

Branching ratio of DM annihilation crucial for determining absorption

[Slatyer et al. 09]

Self-annihilating DM and the CMB



Degeneracy of p_{ann} with cosmological parameters $(\omega_b, n_s, \omega_{dm})$

[Padmanabhan & Finkbeiner 05]

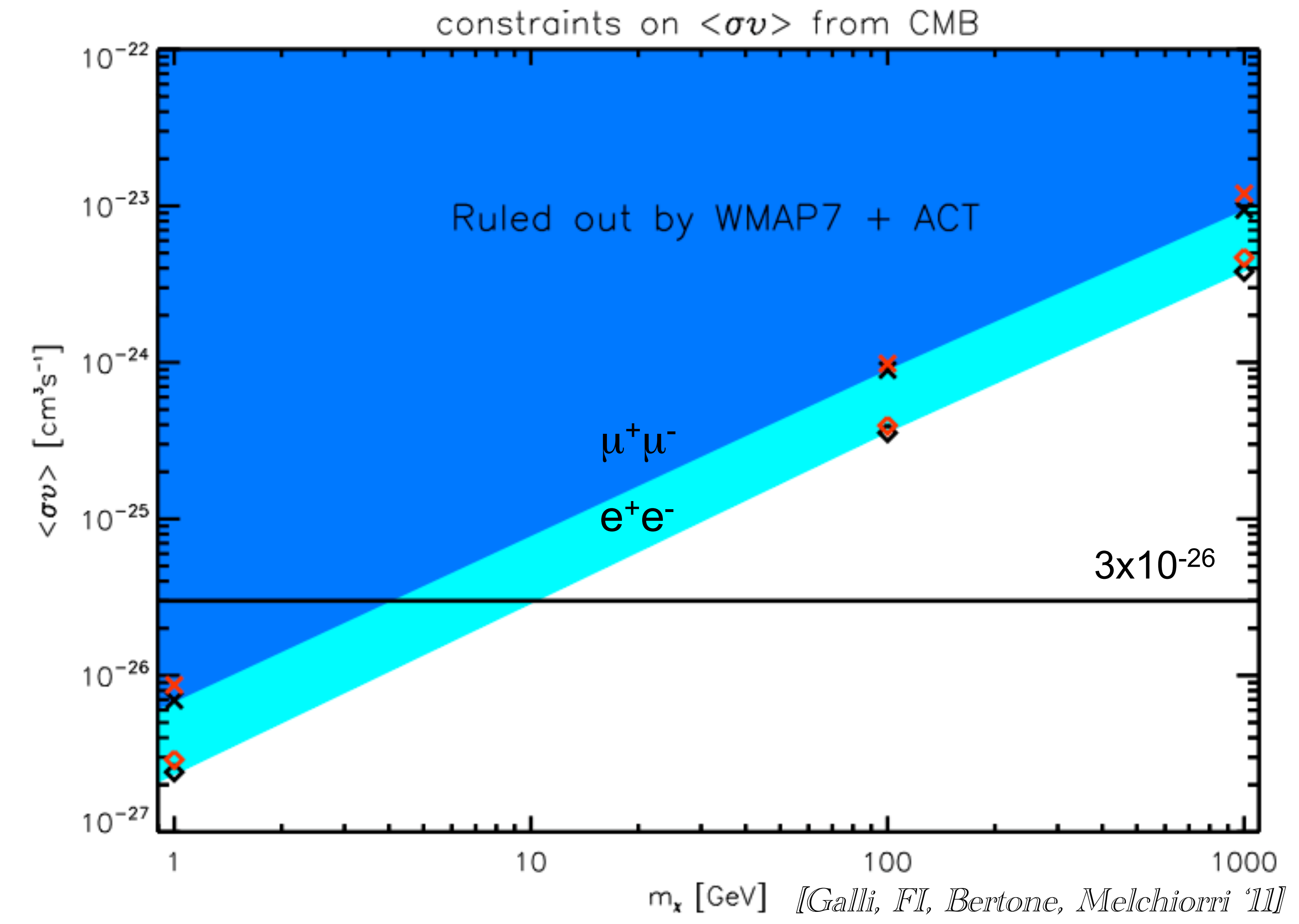
RUN OF COMPLETE Cosmomc analysis

@ z >1000 , already many e^-
no effects
energy injection is small

[Galli, FI et al. `09,'11]

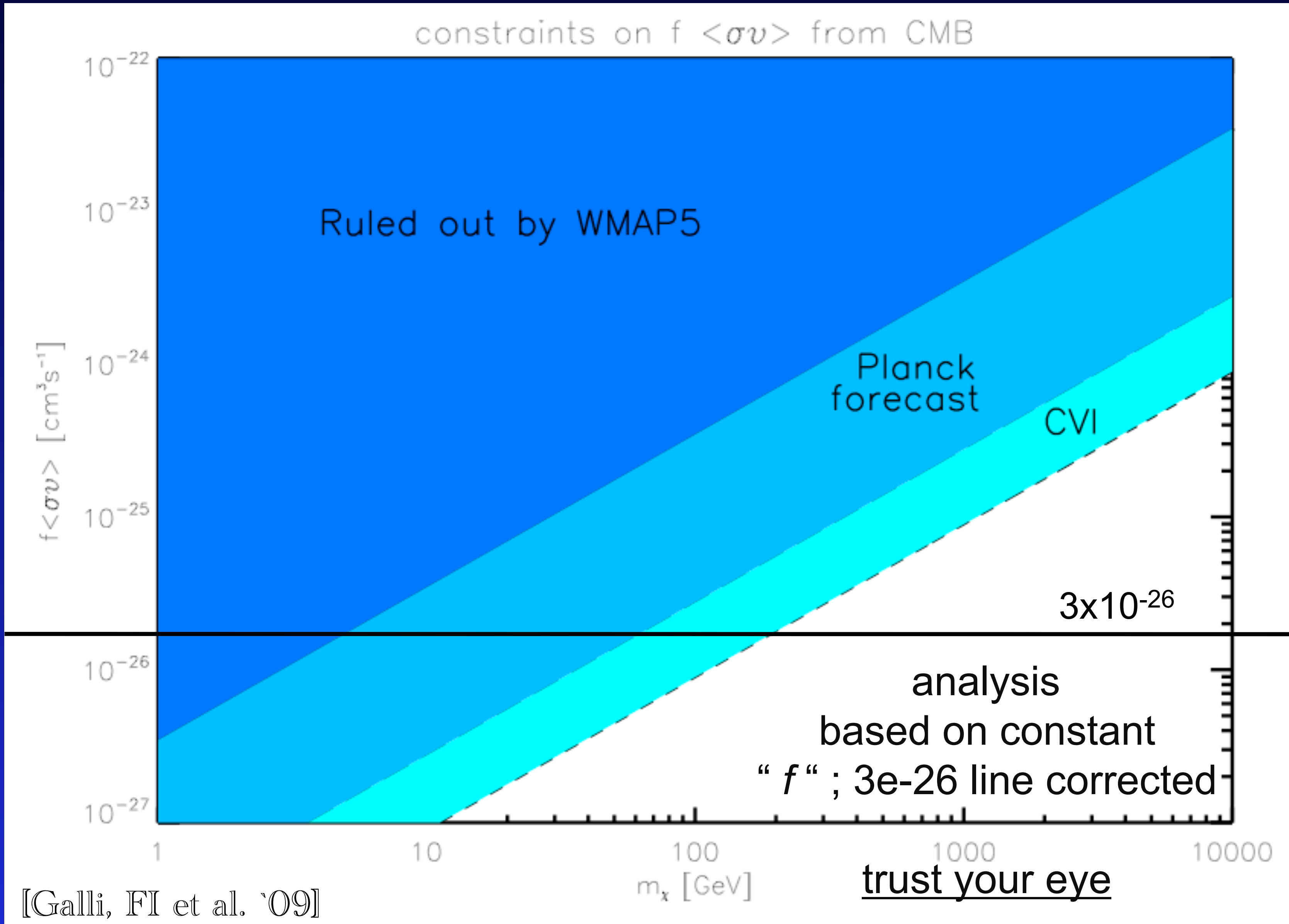
Constraints from WMAP7+ACT

(l_{max}=3500)

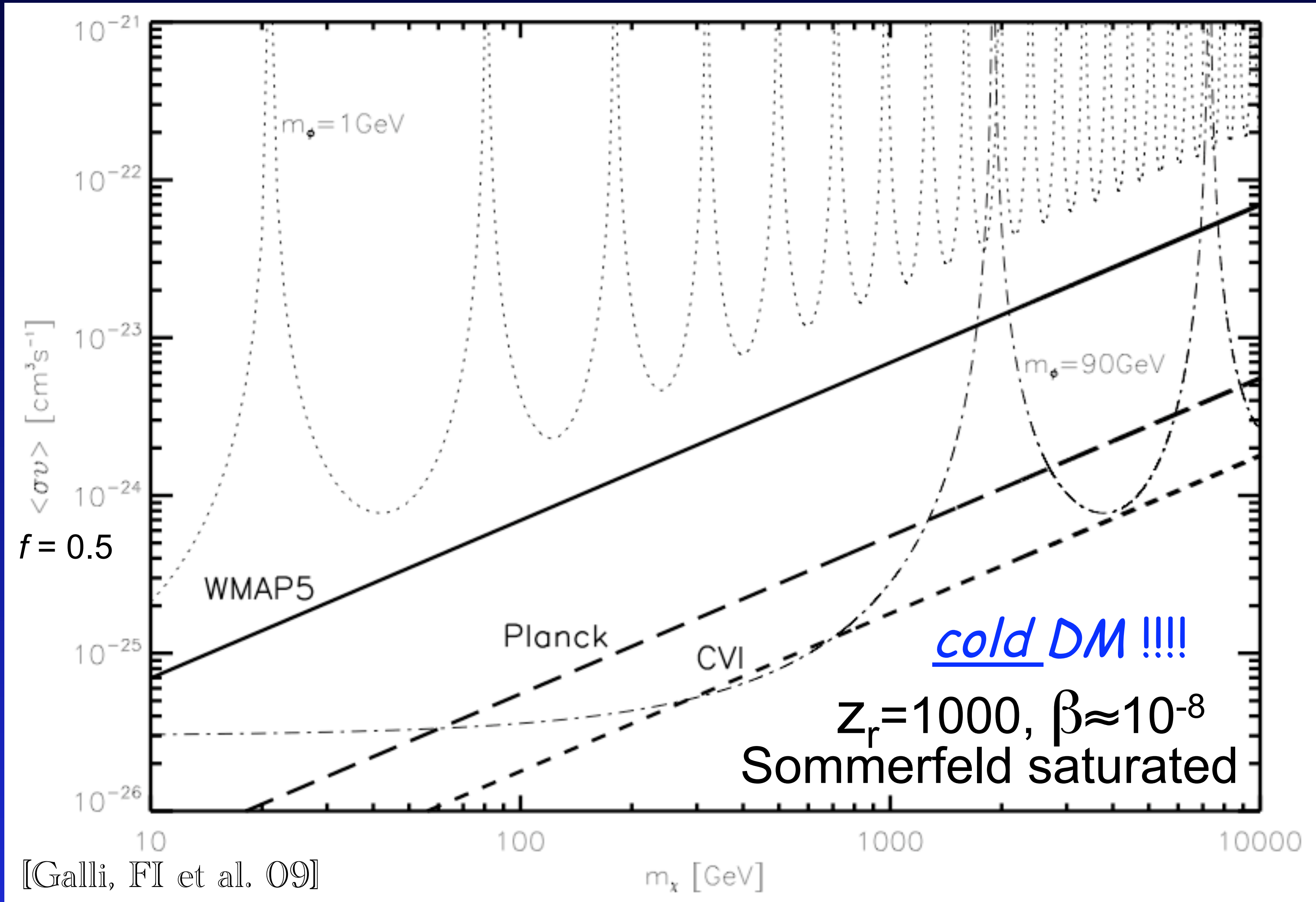


Similar analysis by [Hutsi et al '11]*, no ACT data, different f(z)*

Forecasts for Planck

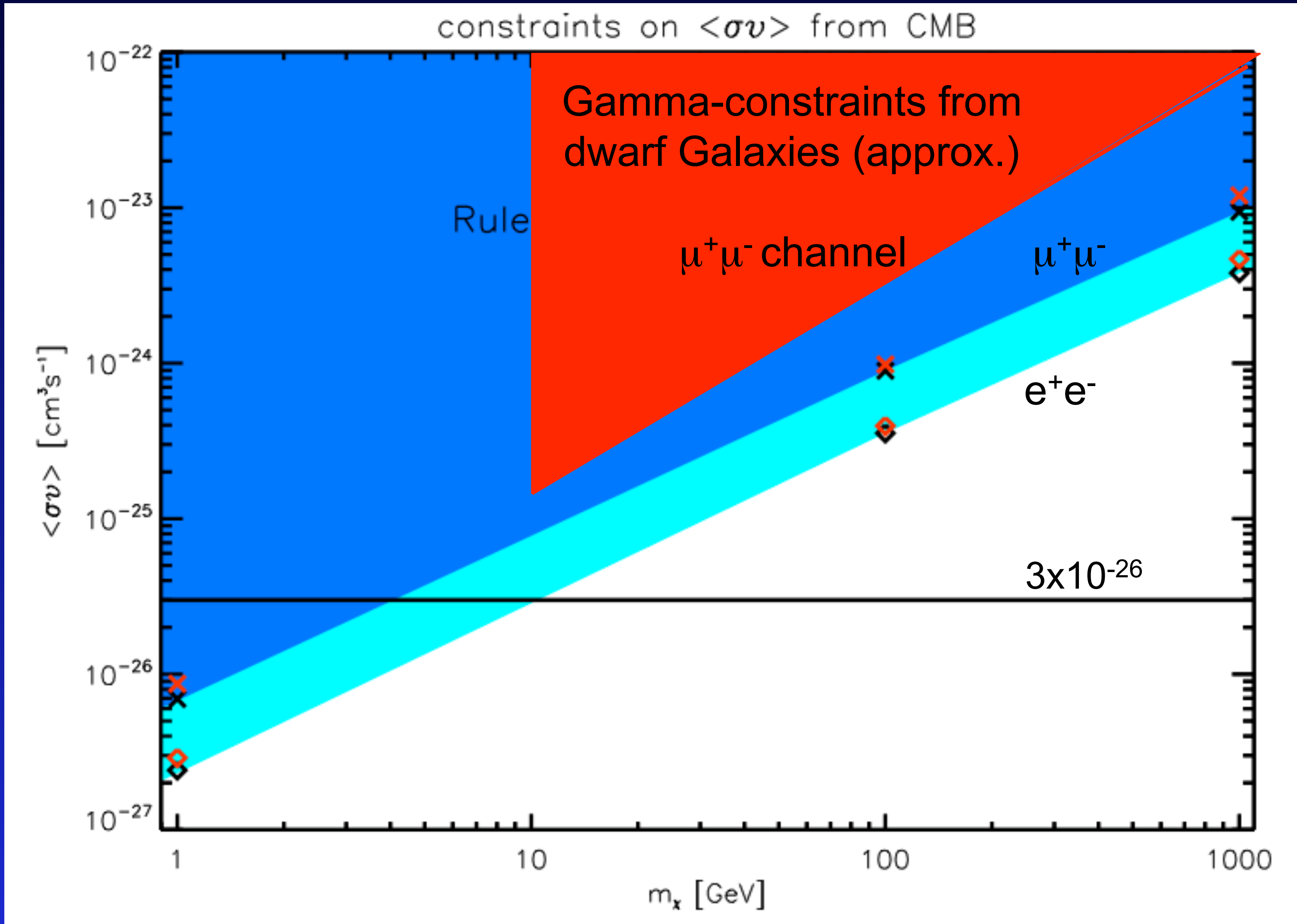


Constraining Sommerfeld Enh. with CMB



See also [Slatyer et al '11] for a discussion of this

Comparing constraints



Dwarf-Galaxies constraints on other channels vary, see Llena-Garde, for the Fermi Collaboration

Concluding

- CMB is a powerful tool to constrain DM annihilation properties

- Independent from "usual suspect" unknowns: halo profile, central slope, minimal mass, structure formation history. Cosmology only!

- Exquisite tool to test Sommerfeld enhancement

- If Planck sees something, refrain from rejoying: *breath* and *think* before submitting to archive