The cosmic ray antiproton signal at TeV energies

Pierre Salati – Université de Savoie & **LAPTH**

1) High energy antiproton : a new window

2) The antiproton signal of TeV WIMPs

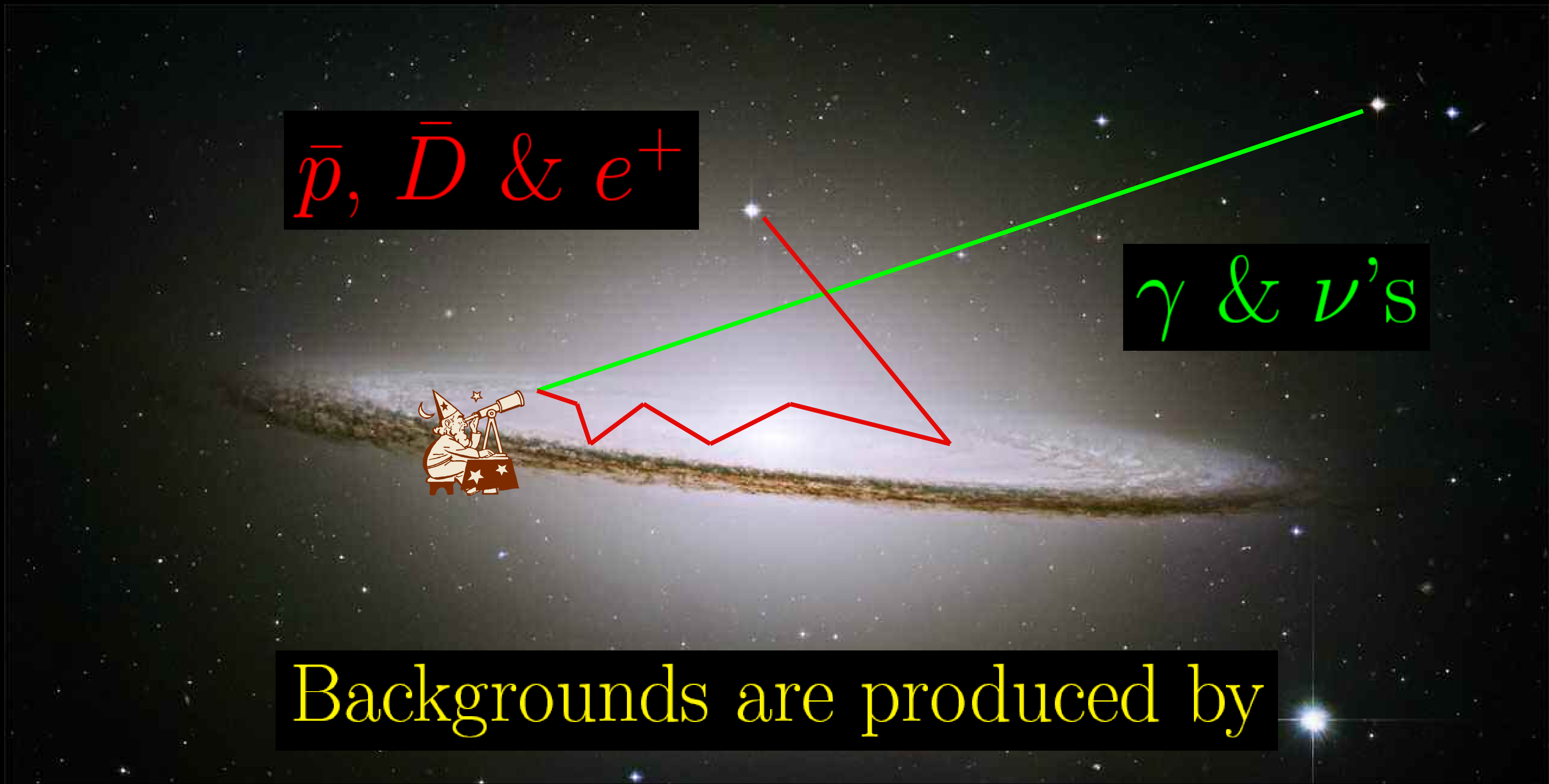
3) DM mini–spikes around IMBHs

T. Bringmann & **P.S.**, PRD **75** (2007) 083006

P. Brun, G. Bertone, J. Lavalle, **P.S.** & R. Taillet, arXiv:0704.2543

TeV Particle Astrophysics 2007 – Venezia – August 28, 2007

1) High energy antiproton : a new window



standard processes within the Galactic disk !

Cosmic–rays diffuse in space and energy

- Diffusion and convection in space

$$\vec{J} \; = \; - \, K \, \vec{\nabla} \Psi \; + \; \Psi \, \vec{V_C}$$

- Second order Fermi mechanism

$$J_E \; = \; b^{\mathrm{loss}}(E) \, \Psi \; - \; K_{EE}(E) \, \partial_E \Psi$$

- Steady state holds with $\partial_t \Psi = 0$

Thickness L

$$K(E) = K_0 \, \beta \times \mathcal{R}^{\delta} \qquad \Downarrow \qquad K_{EE} = \frac{2}{9} {V_a}^2 \frac{E^2 \beta^4}{K(E)}$$

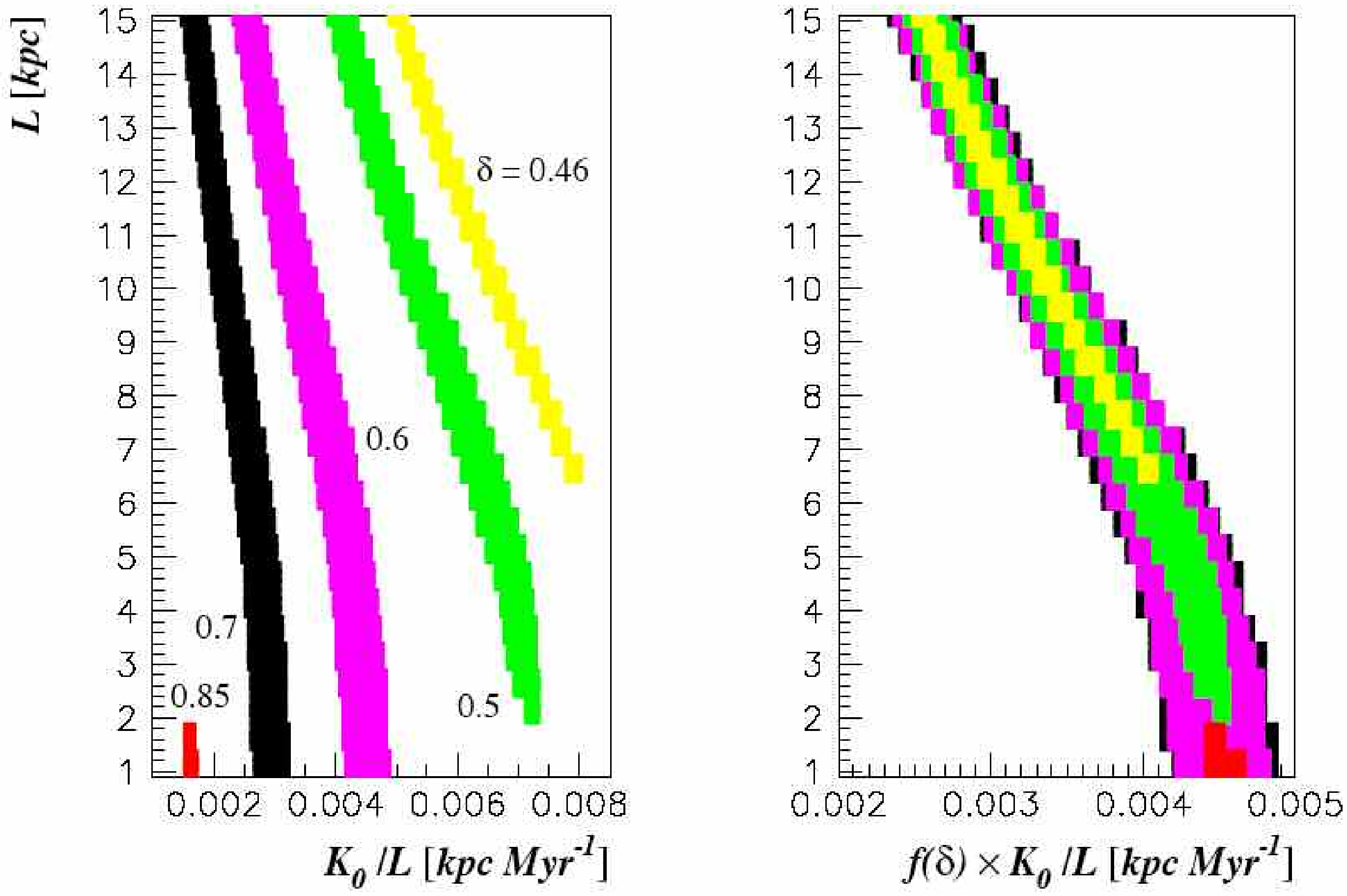
$$V_C \, \partial_z \Psi \; - \; K \, \Delta \Psi \; + \; \partial_E \left\{ b^{\mathrm{loss}}(E) \, \Psi \; - \; K_{EE}(E) \, \partial_E \Psi \right\} \; = \; Q$$

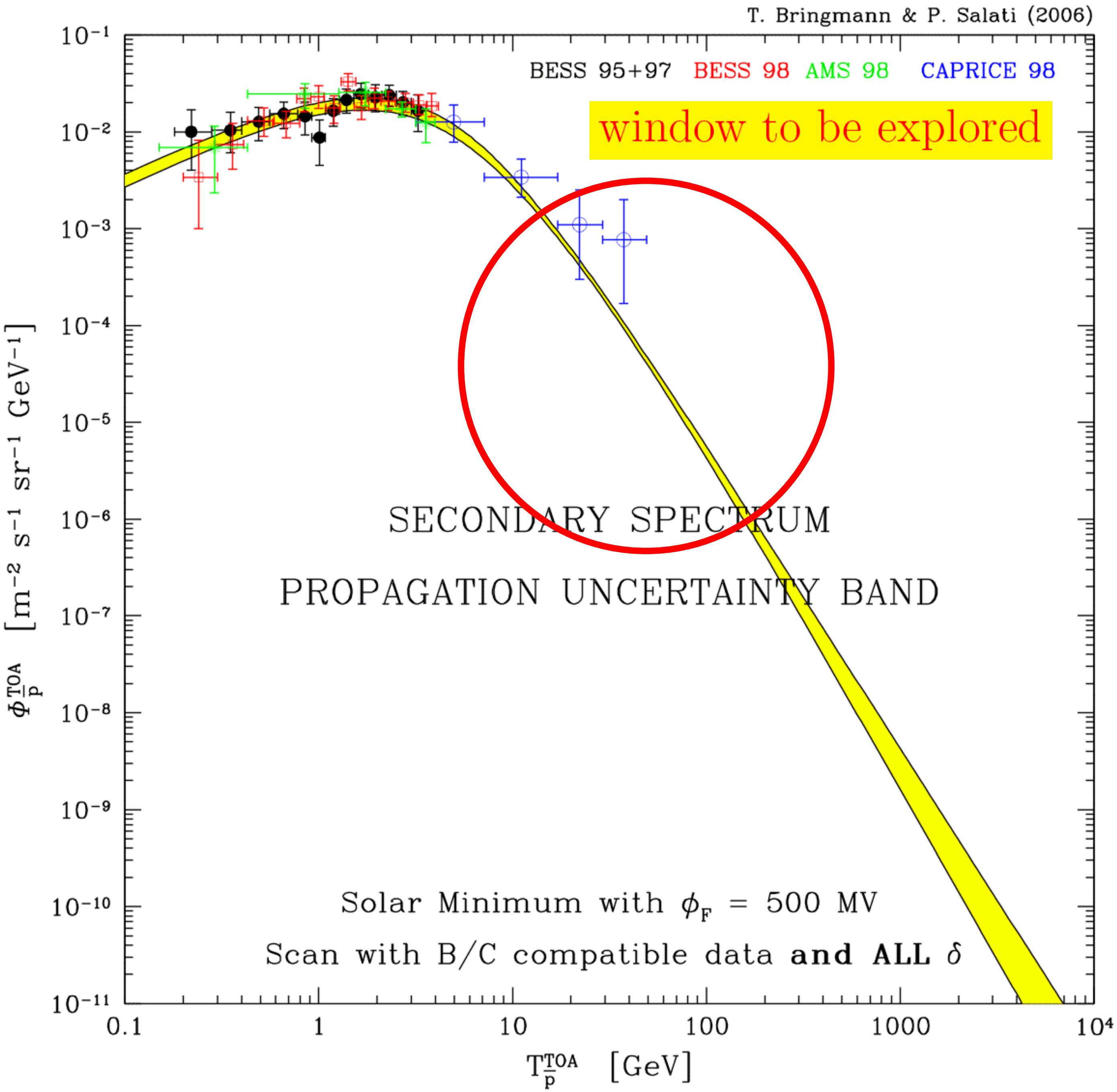
THE ASTROPHYSICAL JOURNAL, 555:585–596, 2001 July 10

D. Maurin et al.

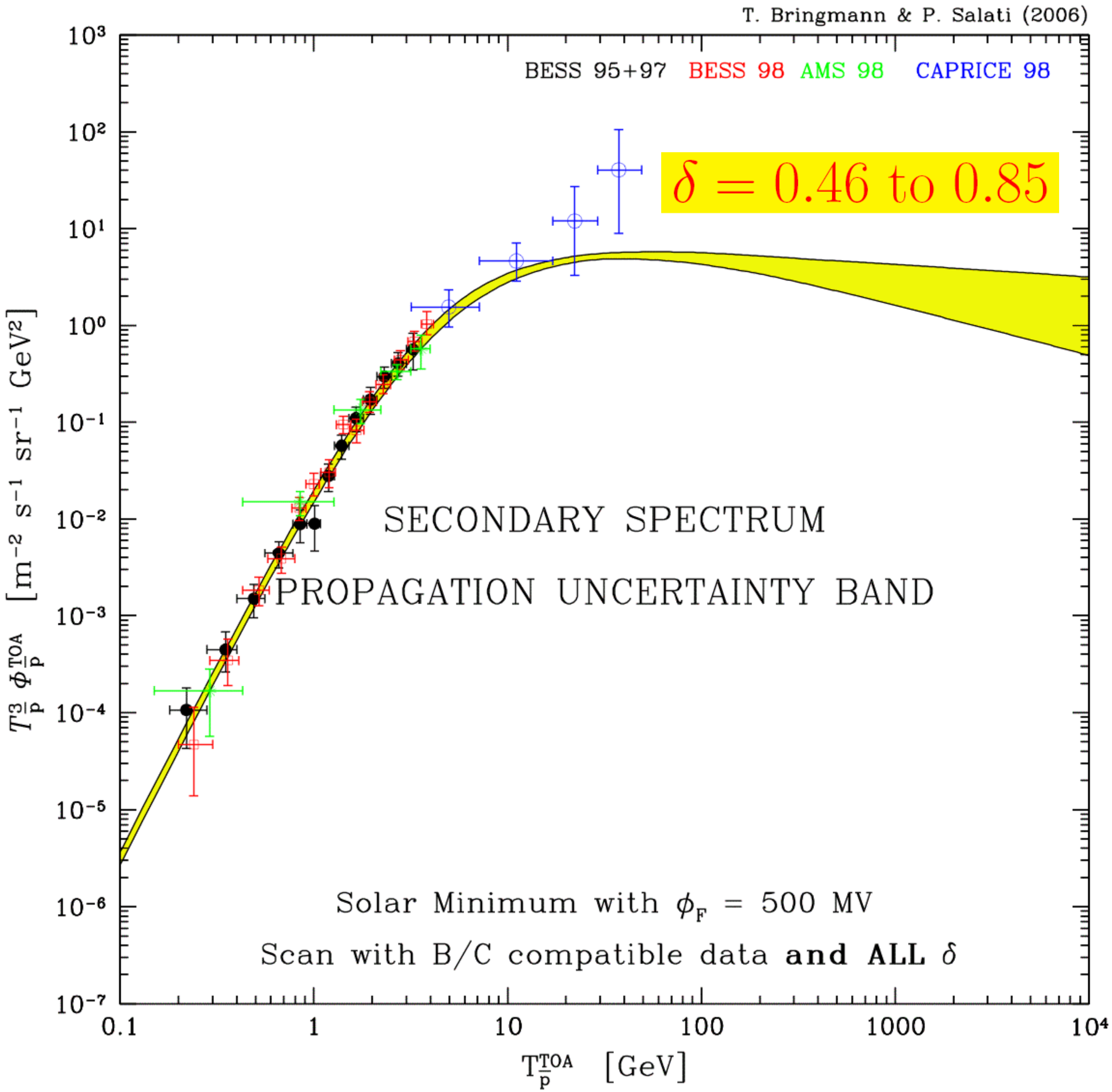
$$K(E) = K_0\,\beta \times \mathscr{R}^{\delta}$$

Iso-χ^2 contours for B/C ($\chi^2 < 40$)





T. Bringmann & P. Salati (2006)
BESS 95+97 BESS 98 AMS 98 CAPRICE 98
window to be explored
SECONDARY SPECTRUM
PROPAGATION UNCERTAINTY BAND
Solar Minimum with ϕ_F = 500 MV
Scan with B/C compatible data **and ALL** δ
$\Phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
10^4



T. Bringmann & P. Salati (2006)
BESS 95+97 BESS 98 AMS 98 CAPRICE 98
$\delta = 0.46$ to 0.85
SECONDARY SPECTRUM
PROPAGATION UNCERTAINTY BAND
Solar Minimum with ϕ_F = 500 MV
Scan with B/C compatible data **and ALL** δ
$T_{\bar{p}}^3\, \Phi_{\bar{p}}^{TOA}$ [$m^{-2}\, s^{-1}\, sr^{-1}\, GeV^2$]
$T_{\bar{p}}^{TOA}$ [GeV]

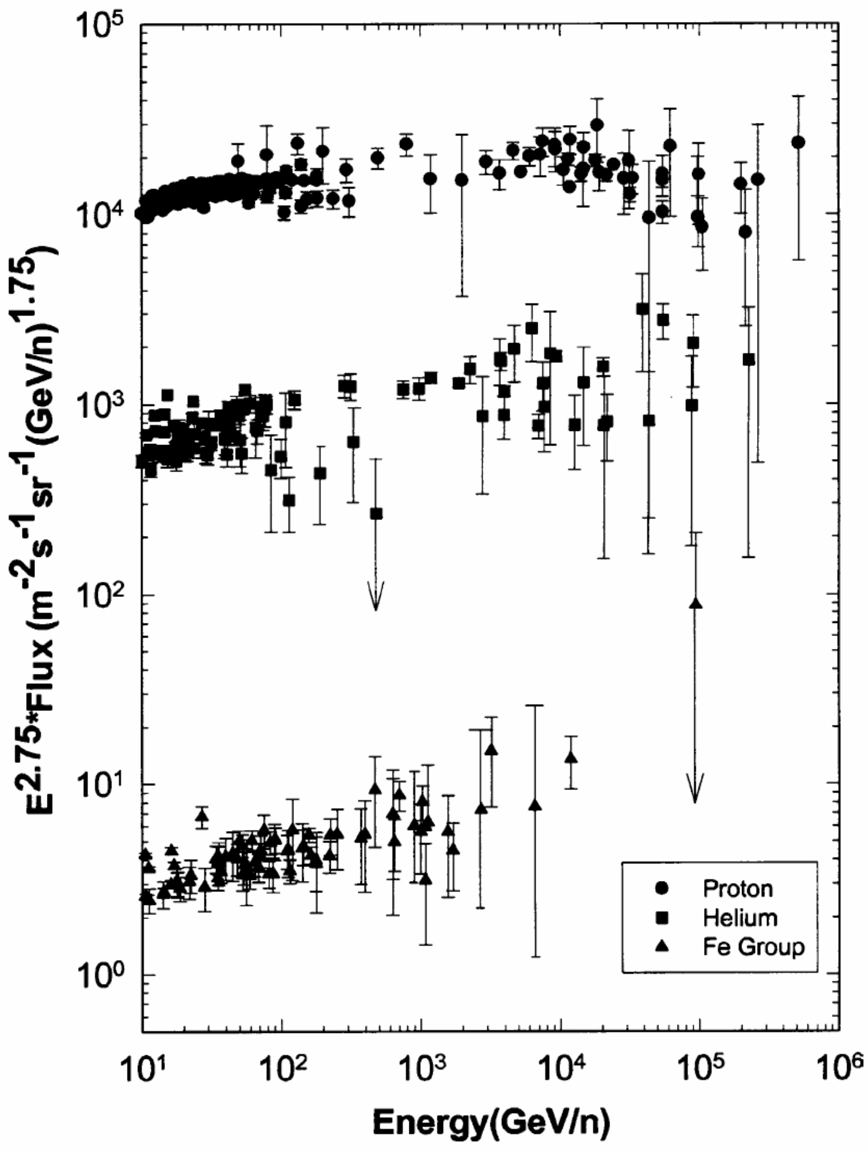
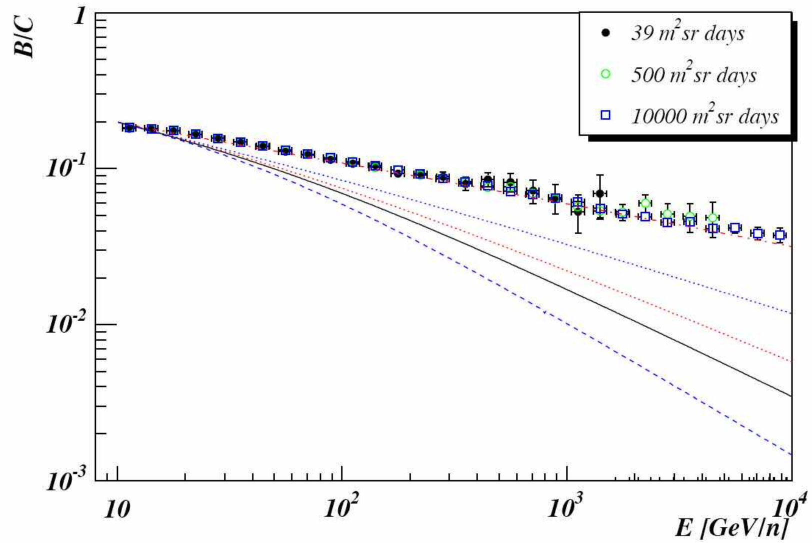
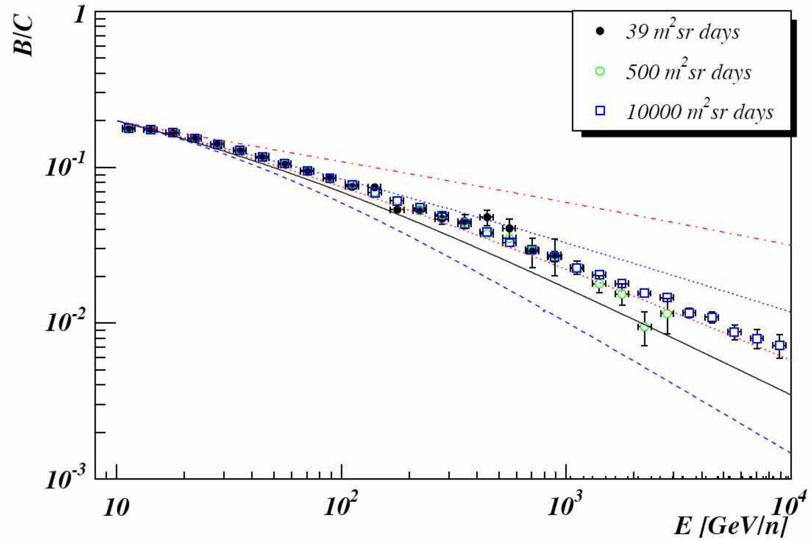


Fig. 1. Compiled data from direct measurements.

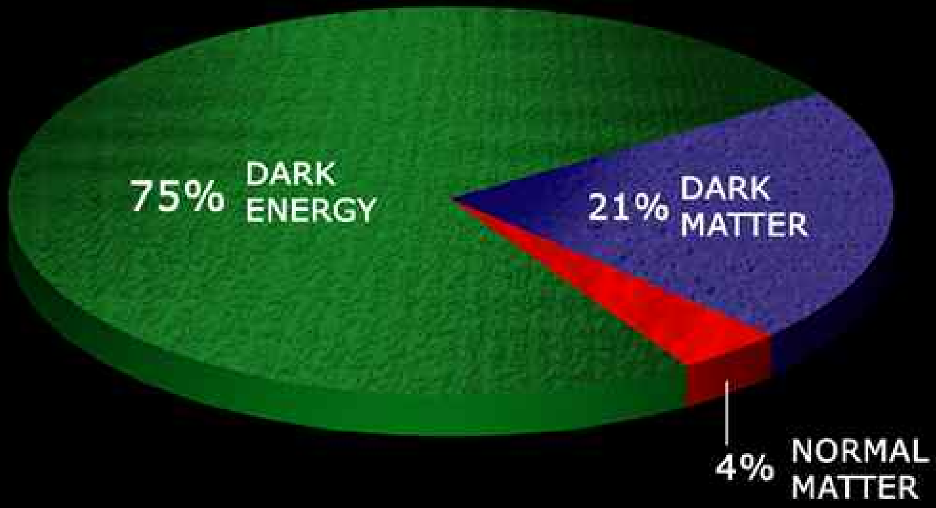
CREAM





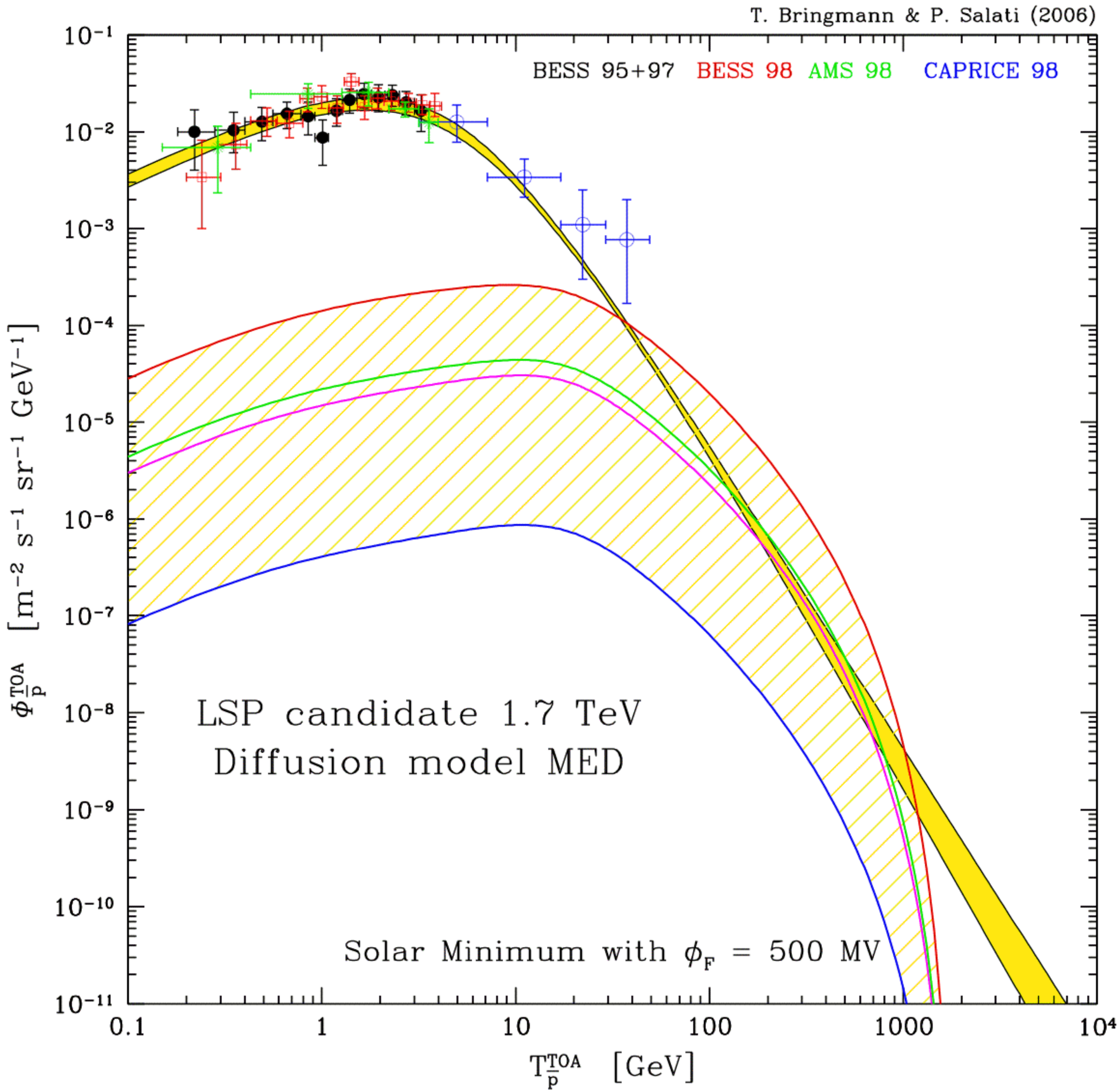
A. Castellina & F. Donato astro-ph/0504149

2) The antiproton signal of TeV WIMPs

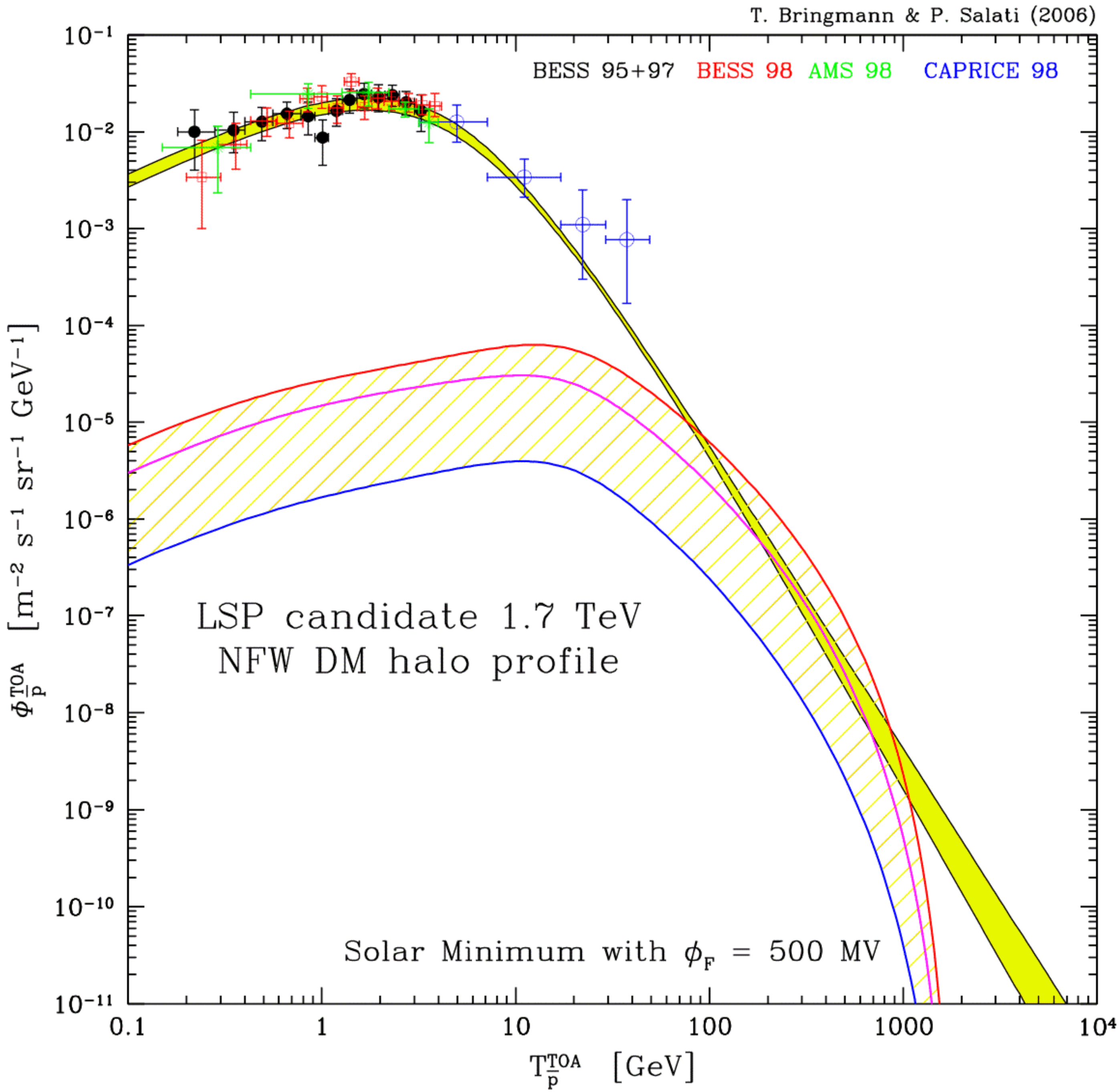


$$\chi + \chi \rightarrow f\bar{f},\, W^+W^-, \ldots \rightarrow \bar{p},\, \bar{D},\, e^+,\, \gamma\ \&\ \nu\text{'s}$$

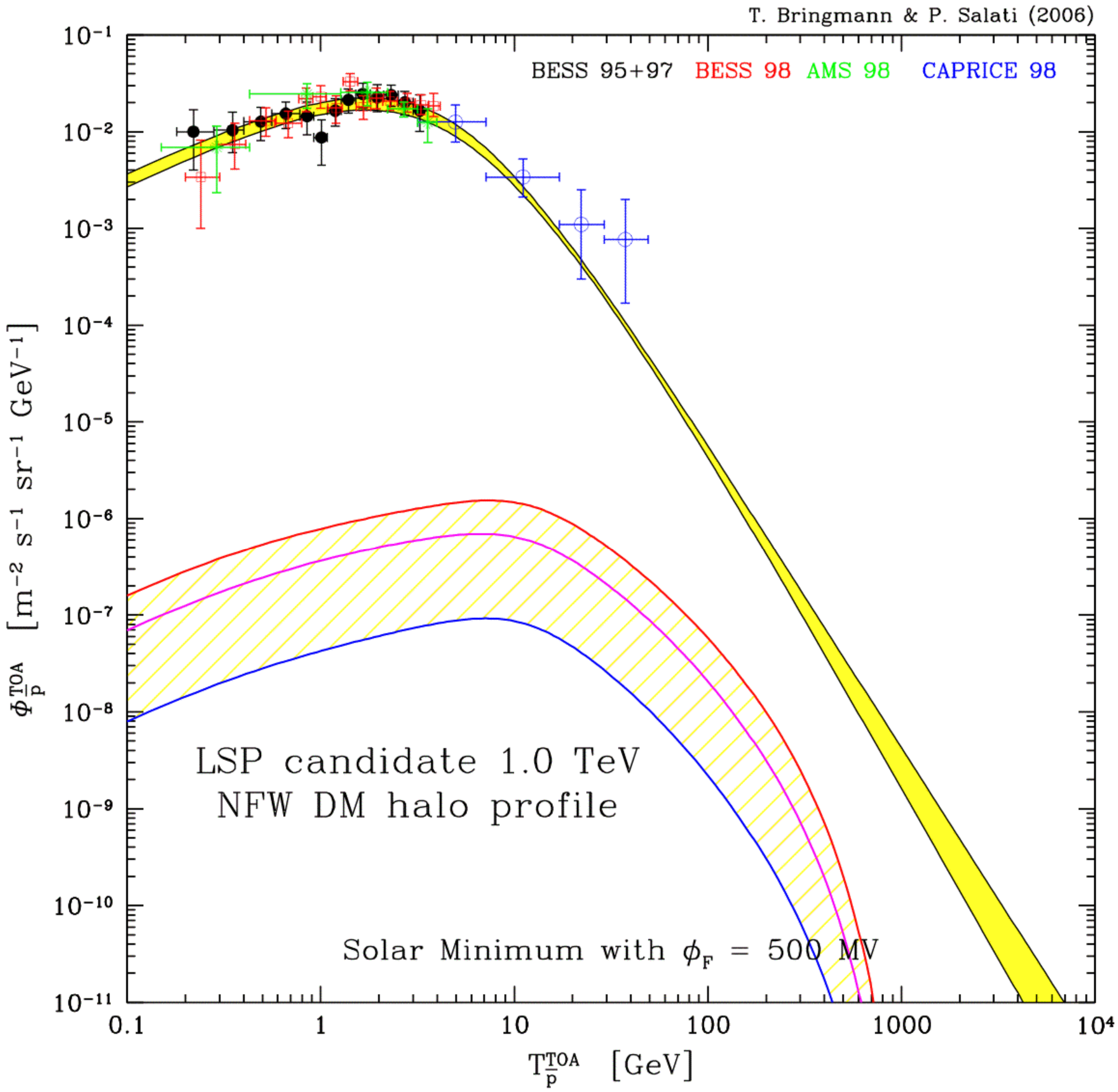
Weakly Interacting Massive particles – WIMPs – could be the major component of the haloes of galaxies. Their mutual annihilations would produce extra high–energy cosmic rays : the DM messengers



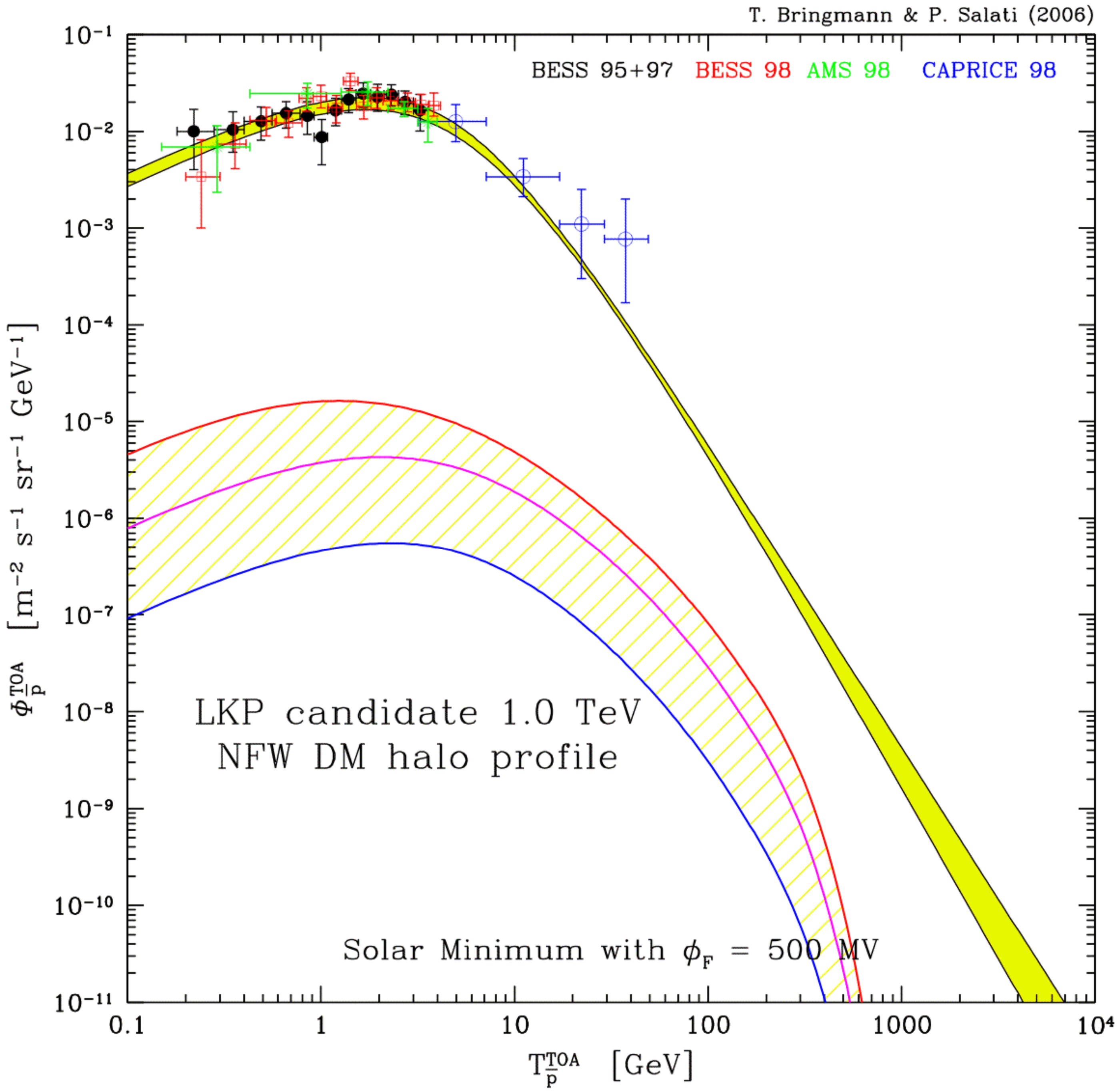
T. Bringmann & P. Salati (2006)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
LSP candidate 1.7 TeV
Diffusion model MED
Solar Minimum with ϕ_F = 500 MV
$\Phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]



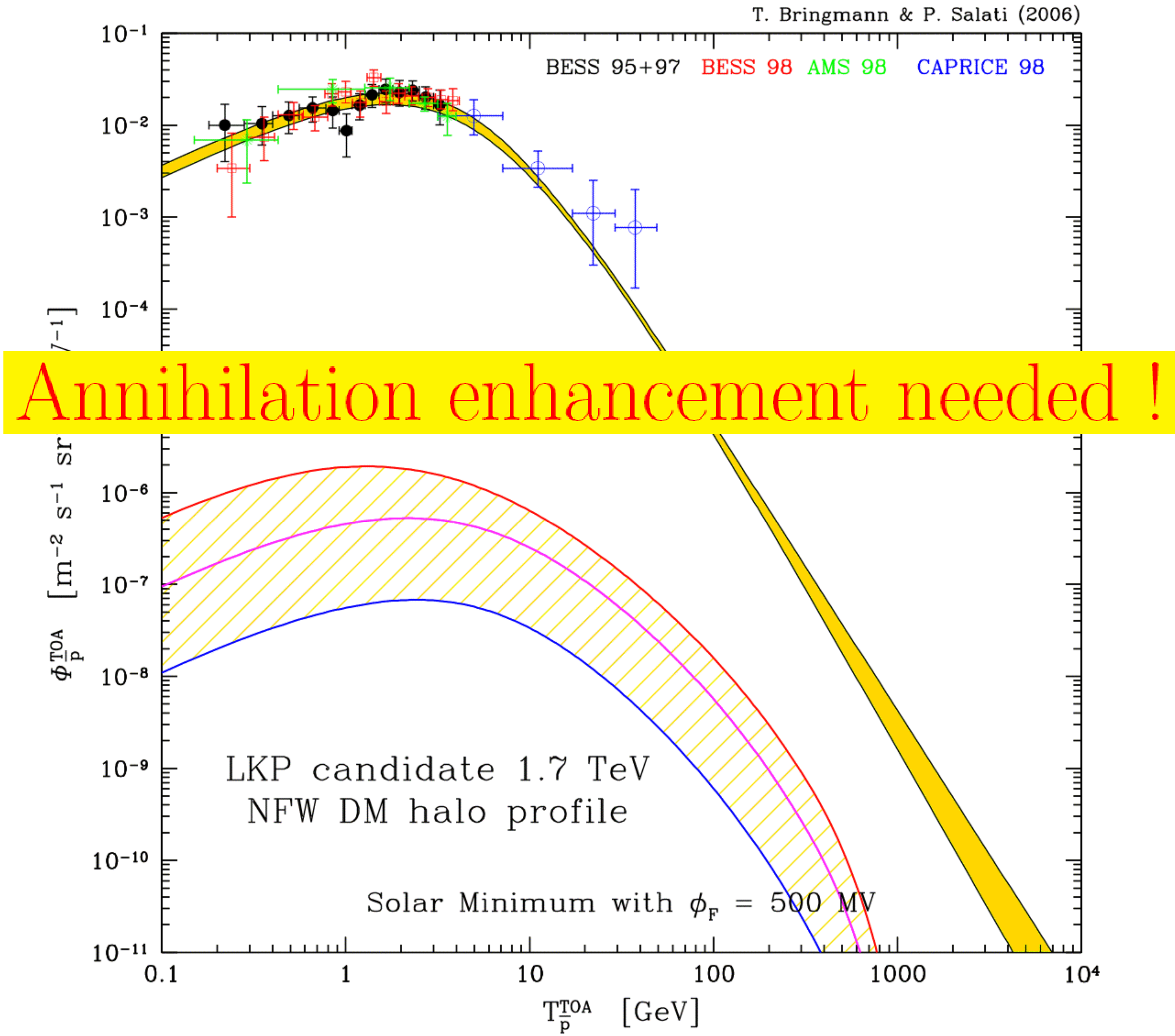
T. Bringmann & P. Salati (2006)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
LSP candidate 1.7 TeV
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
$\Phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
10^4

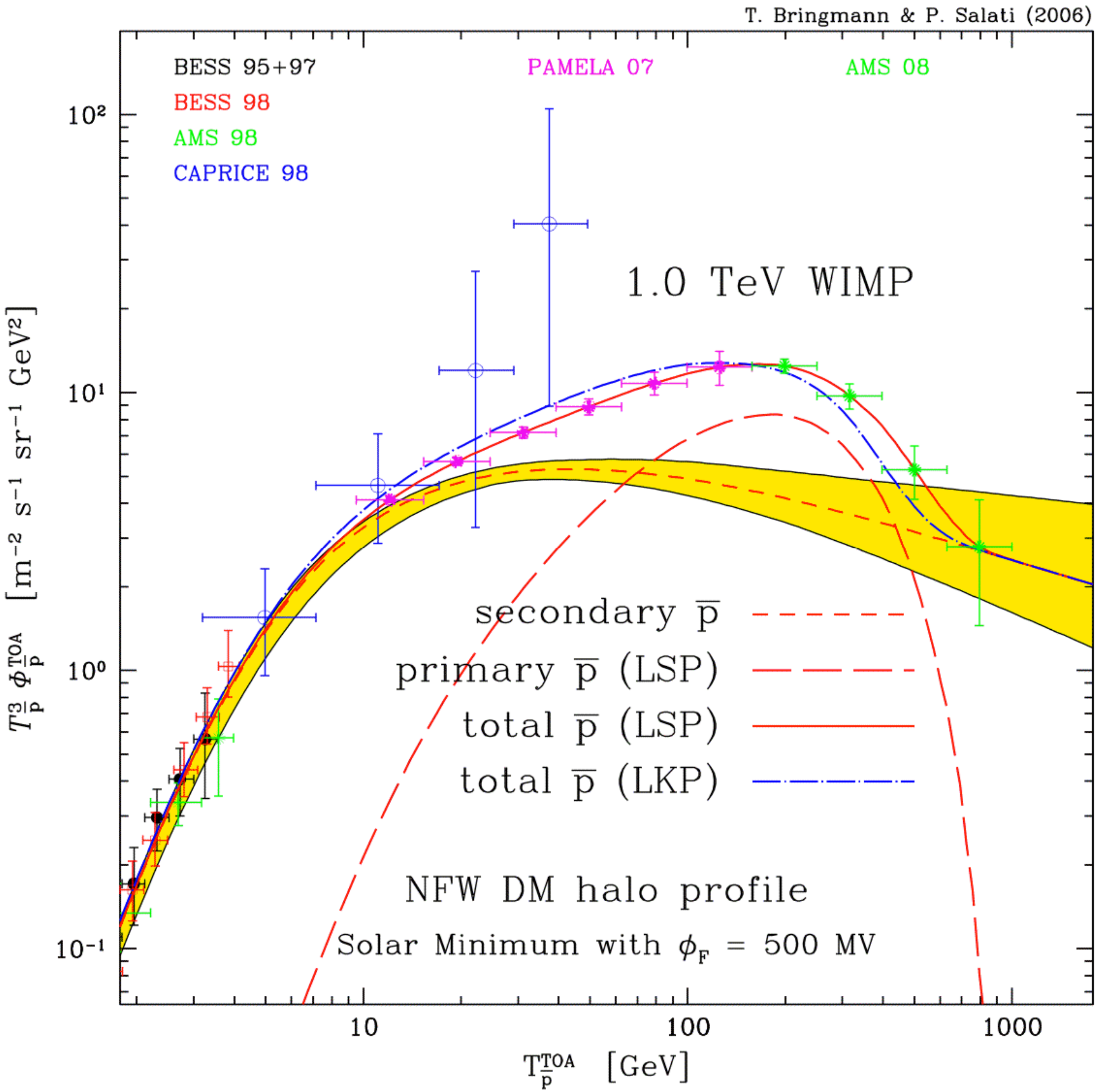


T. Bringmann & P. Salati (2006)
BESS 95+97 BESS 98 AMS 98 CAPRICE 98
LSP candidate 1.0 TeV
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
$\Phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
10^{4}

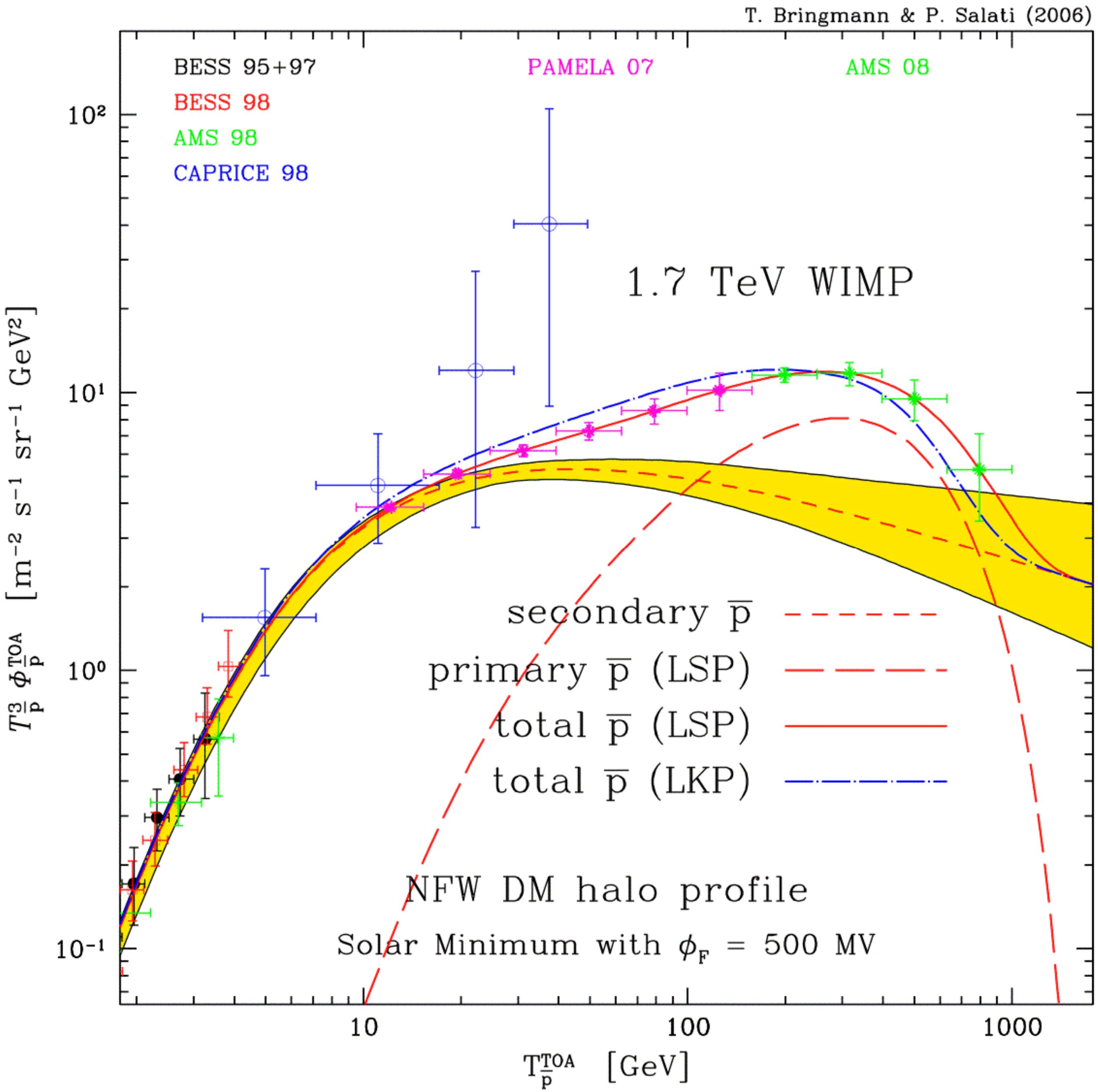


T. Bringmann & P. Salati (2006)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
LKP candidate 1.0 TeV
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
$\Phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
10^4


T. Bringmann & P. Salati (2006)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
Annihilation enhancement needed !
LKP candidate 1.7 TeV
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
$\phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr
$T_{\bar{p}}^{TOA}$ [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
10^4



T. Bringmann & P. Salati (2006)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
PAMELA 07
AMS 08
1.0 TeV WIMP
secondary p̄
primary p̄ (LSP)
total p̄ (LSP)
total p̄ (LKP)
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
10^2
10^1
10^0
10^{-1}
10
100
1000
$T_{\bar{p}}^{TOA}$ [GeV]
$T_{\bar{p}}^3 \, \phi_{\bar{p}}^{TOA}$ [m^{-2} s^{-1} sr^{-1} GeV^2]


T. Bringmann & P. Salati (2006)
BESS 95+97
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AMS 98
CAPRICE 98
PAMELA 07
AMS 08
1.7 TeV WIMP
secondary p̄
primary p̄ (LSP)
total p̄ (LSP)
total p̄ (LKP)
NFW DM halo profile
Solar Minimum with ϕ_F = 500 MV
$T^3_{\bar{p}}\ \Phi^{TOA}_{\bar{p}}$ [m^{-2} s^{-1} sr^{-1} GeV^2]
$T^{TOA}_{\bar{p}}$ [GeV]
10
100
1000
10^2
10^1
10^0
10^{-1}

3) DM mini–spikes around intermediate mass black holes

G. Bertone, A.R. Zentner & J. Silk, PRD **72** (2005) 103517

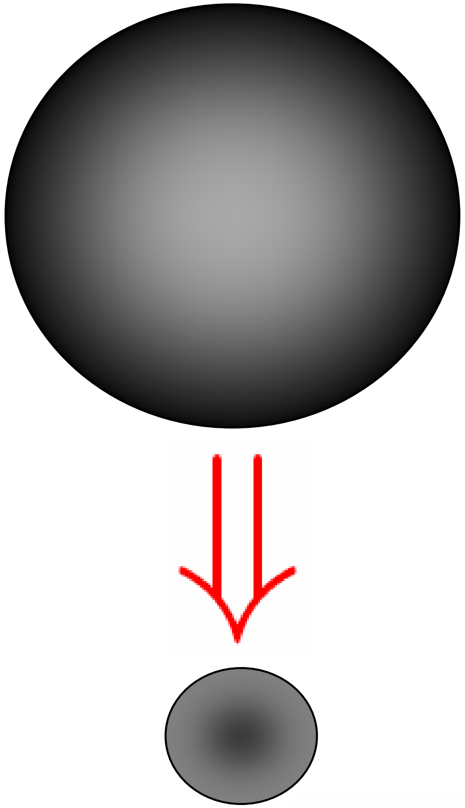
When the first DM halos form, gas cools and collapses as pressure supported disks

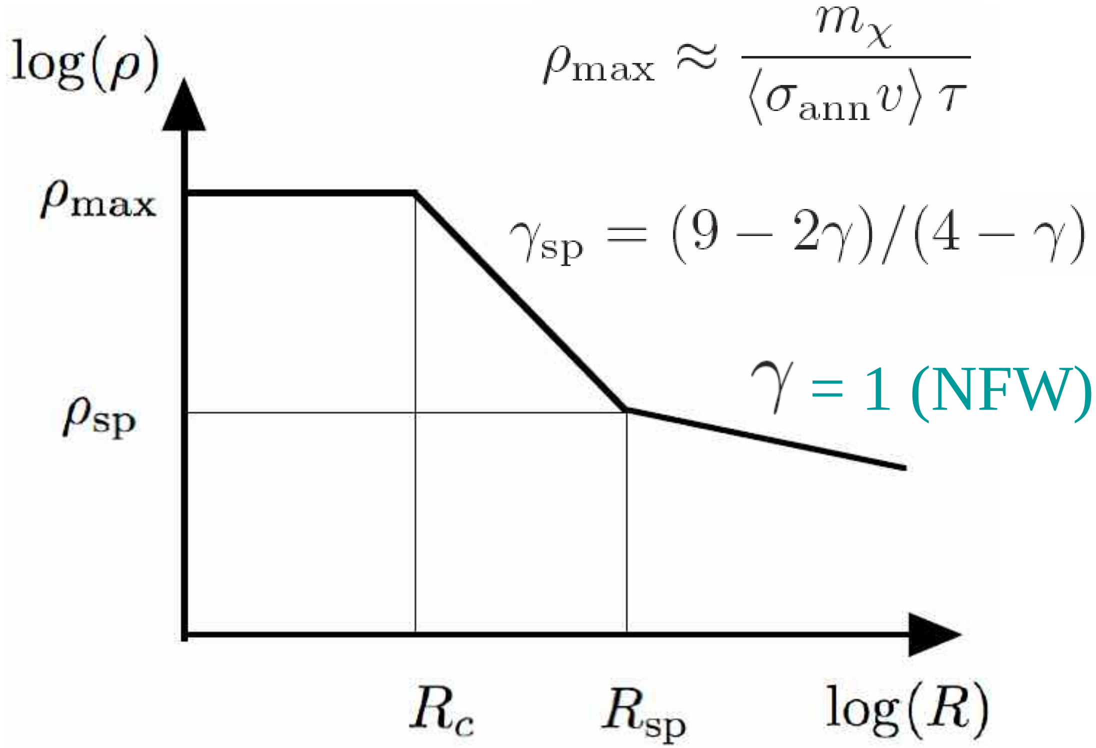
A baryonic mass of $\sim 10^5$ $M_\odot$ looses its angular momentum

It is transferred at the center to form an Intermediate Mass Black Hole

During the process, DM is adiabatically compressed onto this central object

Adiabatic DM compression around the IMBH





Large annihilation volume

DM mini-spike $\propto \langle \sigma_{\rm ann} v \rangle^{2/7} \, m_\chi^{-9/7}$

$\equiv \frac{\rho_{\rm max}}{\rho_{\rm sp}} \Big\}^{3/7}$

Compensation between $\rho_{\rm max}$ & $\langle \sigma_{\rm ann} v \rangle$

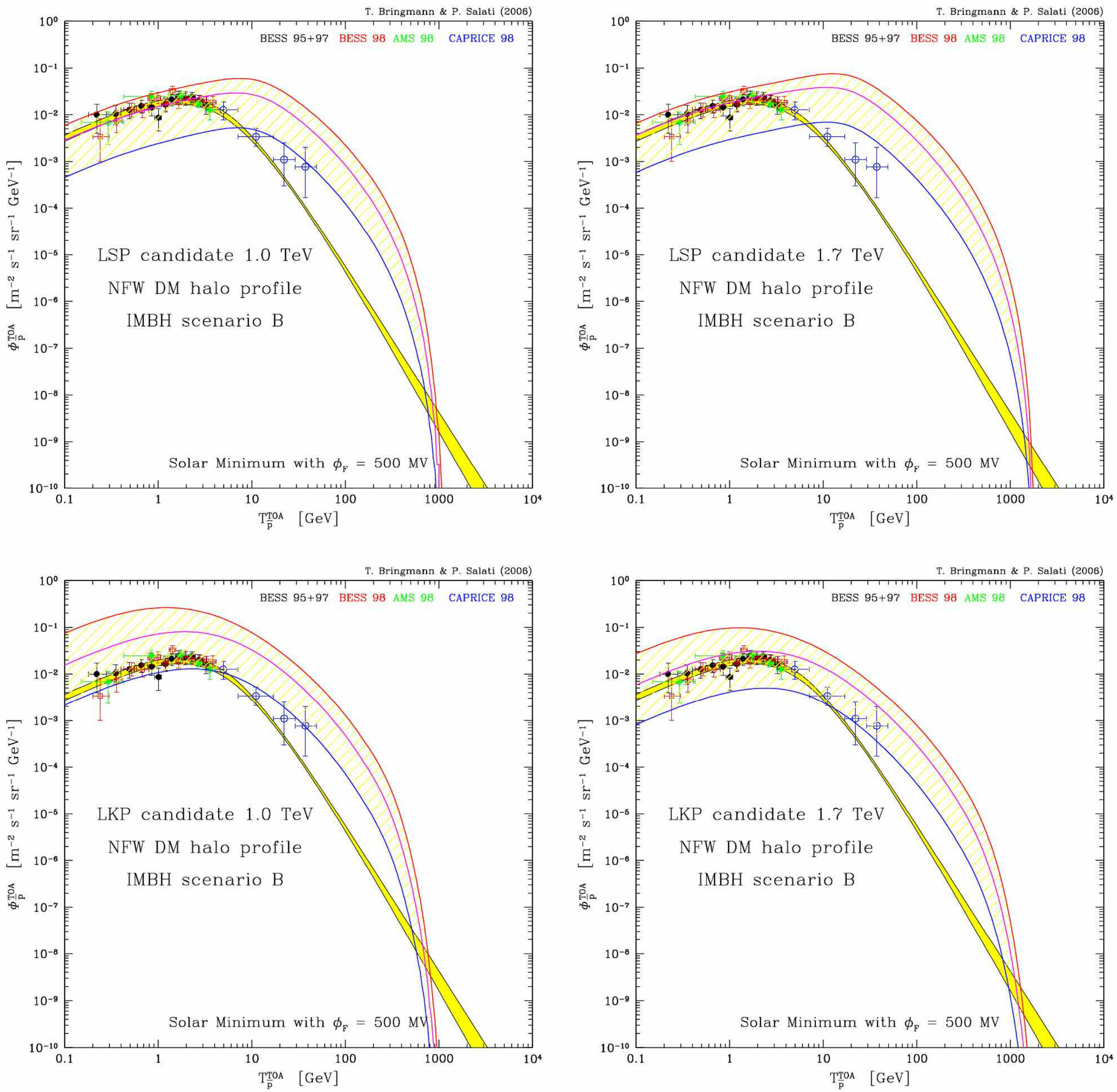


FIG. 6: Same as Fig. 5, now with an NFW profile and a typical population of IMBHs in the galactic halo.

MC distributions of the annihilation volume ξ and position $\mathbf{x}$

$q(\xi)$

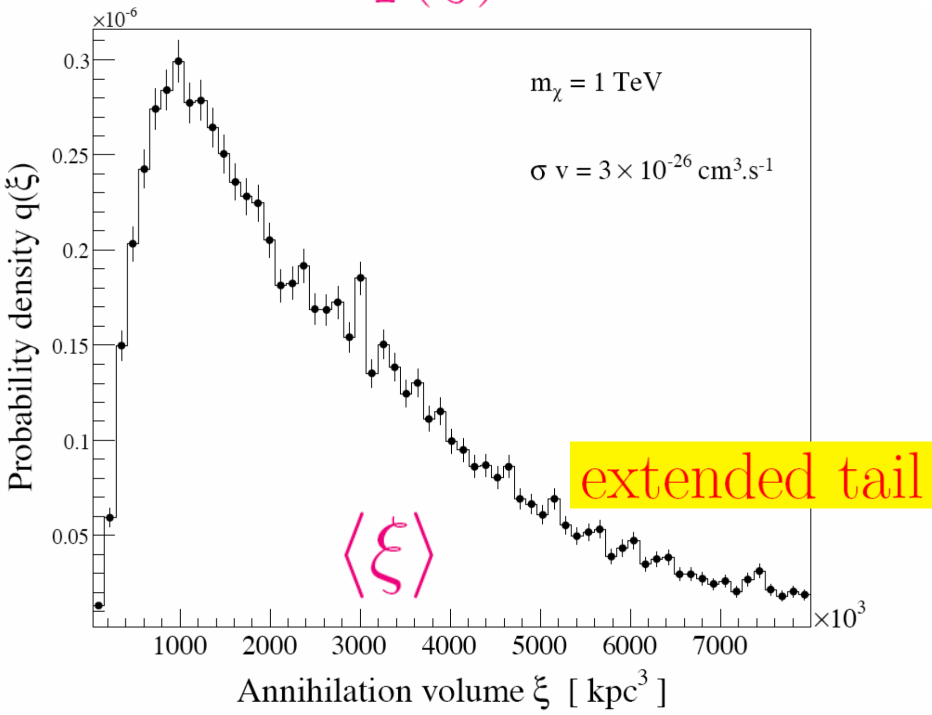


FIG. 3: The probability law $q(\xi)$ for the annihilation volume has been derived from the Monte-Carlo results of Ref. [40]. We found no correlation with the mini-spike position.

$p(\mathbf{x})$

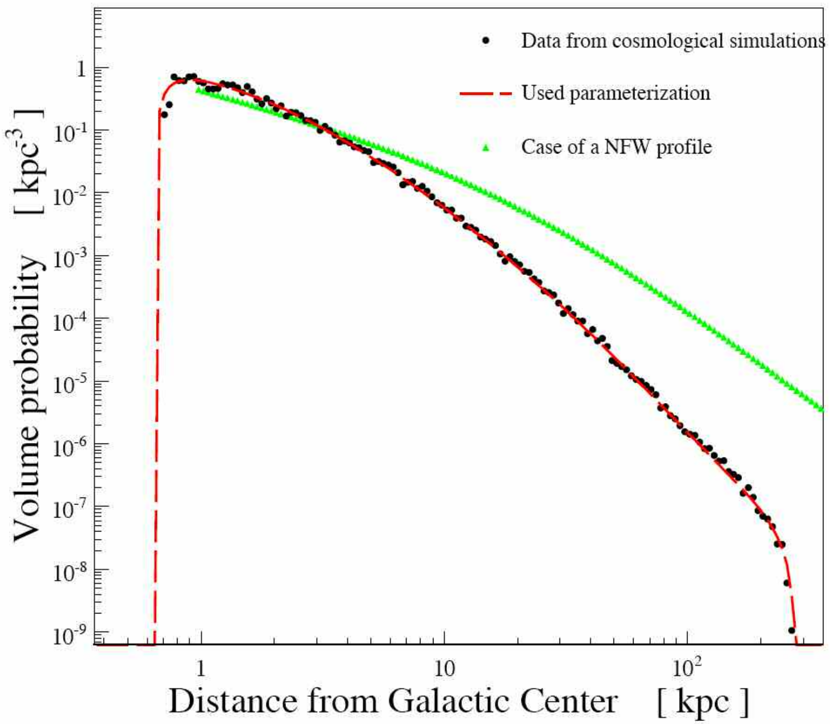
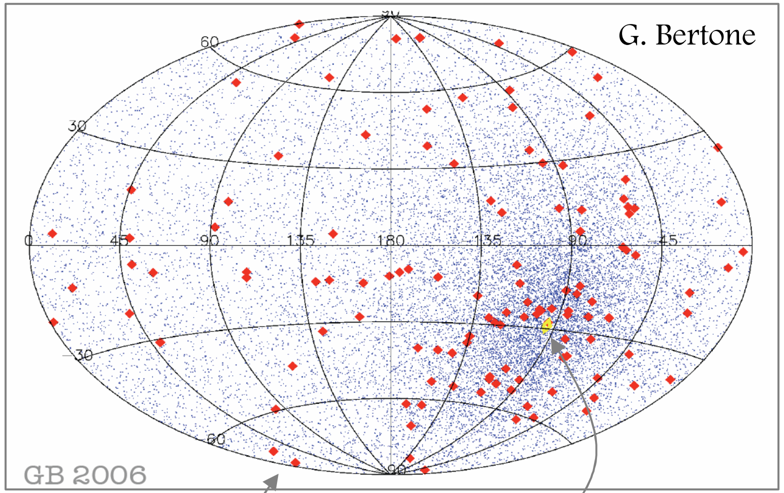


FIG. 4: Radial distribution of the mini-spikes, as extracted from the numerical results of Ref. [40].

$$\langle \xi^n \rangle = \int_0^{+\infty} \xi^n \, q(\xi) \, d\xi \quad \& \quad \langle G^n \rangle = \int_{\mathrm{DZ}} \{G(\mathbf{x})\}^n \, p(\mathbf{x}) \, d^3\mathbf{x}$$

● : one realization

• : iterations



Galactic center

Each black hole has specific parameters

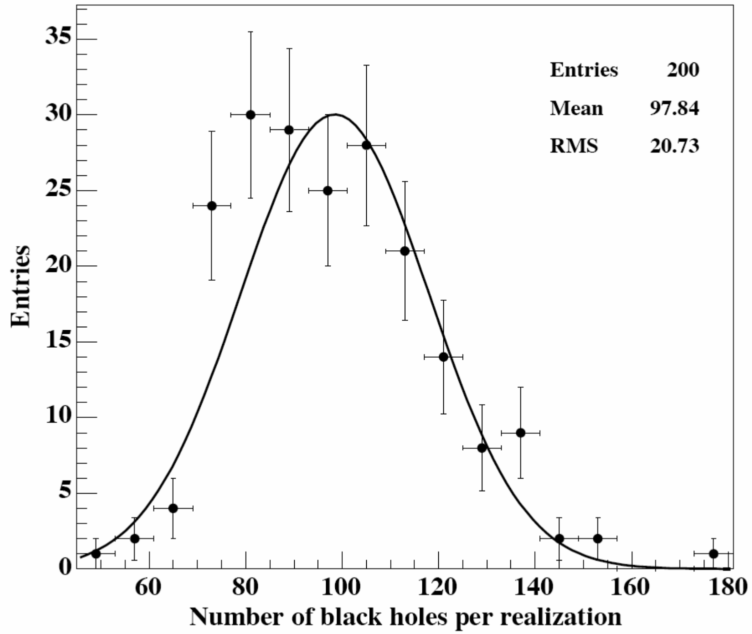


FIG. 1: Distribution of the Monte-Carlo realizations of the galactic mini-spike population – extracted from Ref. [40] – as a function of the number $N_{\rm BH}$ of objects within a galactocentric radius of 100 kpc.

$$B_{\rm eff} = 1 + \frac{\langle \phi_r \rangle}{\phi_s} = 1 + N_{\rm BH} \frac{\langle \xi \rangle \langle G \rangle}{\mathcal{I}}$$

$$\frac{\sigma_B}{B_{\rm eff}} = \frac{\sigma_r / \phi_s}{1 + \langle \phi_r \rangle / \phi_s} \simeq \frac{\sigma_r}{\langle \phi_r \rangle}$$

$$\frac{\sigma_r^2}{\langle \phi_r \rangle^2} = \frac{1}{\langle N_{\rm BH} \rangle} \left\{ \frac{\langle \xi^2 \rangle}{\langle \xi \rangle^2} \frac{\langle G^2 \rangle}{\langle G \rangle^2} - 1 \right\} + \frac{\sigma_N^2}{\langle N_{\rm BH} \rangle^2}$$

Boost distributions

Positrons

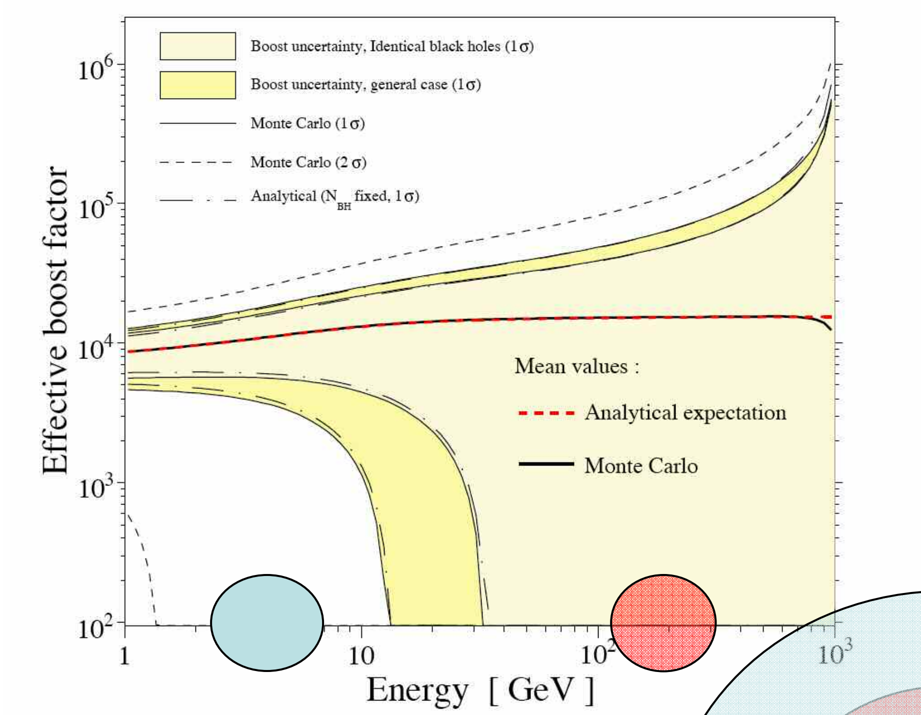


FIG. 5: Results from the Monte-Carlo simulations of the IMBHs population inside the Milky Way are compared to the analytical computations of the effective boost factor and its dispersion, for $m_\chi = 1$ TeV.

1 TeV positron line

Antiprotons

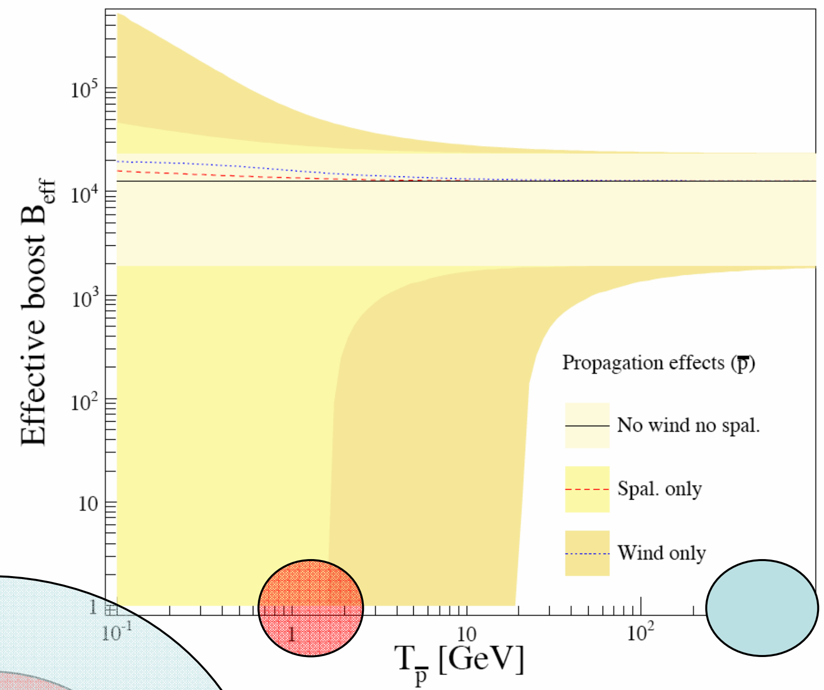
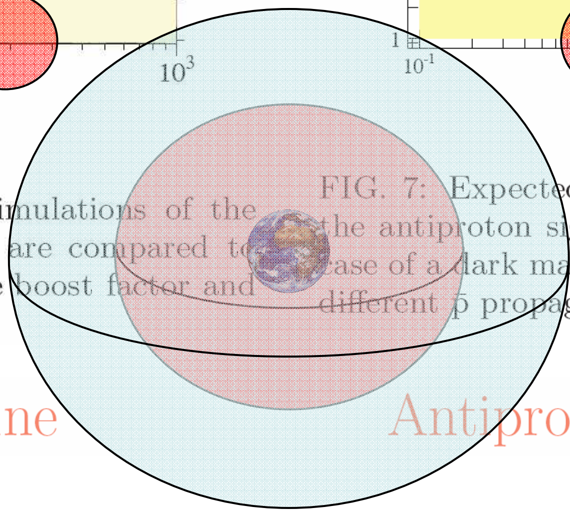
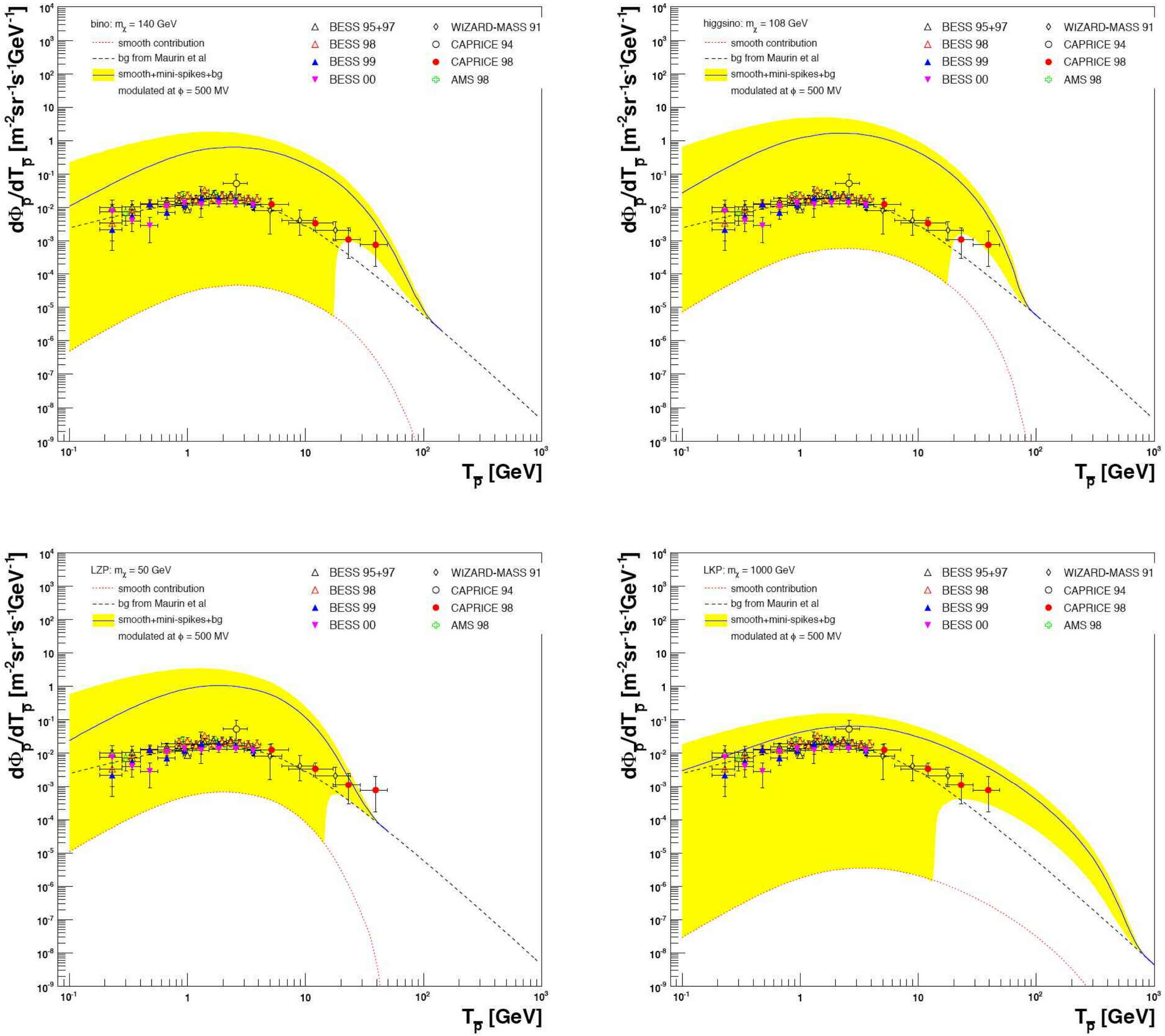


FIG. 7: Expected value and variance of the boost factor of the antiproton signal as a function of kinetic energy, in the case of a dark matter particle with mass $m_\chi = 1$ TeV and for different $\bar{p}$ propagation configurations.

Antiprotons injected at $E_S \simeq E$





bino: m_χ = 140 GeV
higgsino: m_χ = 108 GeV
LZP: m_χ = 50 GeV
LKP: m_χ = 1000 GeV
smooth contribution
bg from Maurin et al
smooth+mini-spikes+bg
modulated at ϕ = 500 MV
BESS 95+97
BESS 98
BESS 99
BESS 00
WIZARD-MASS 91
CAPRICE 94
CAPRICE 98
AMS 98
$d\Phi_{\bar{p}}/dT_{\bar{p}}$ [$m^{-2}sr^{-1}s^{-1}GeV^{-1}$]
$T_{\bar{p}}$ [GeV]

Conclusions and perspectives

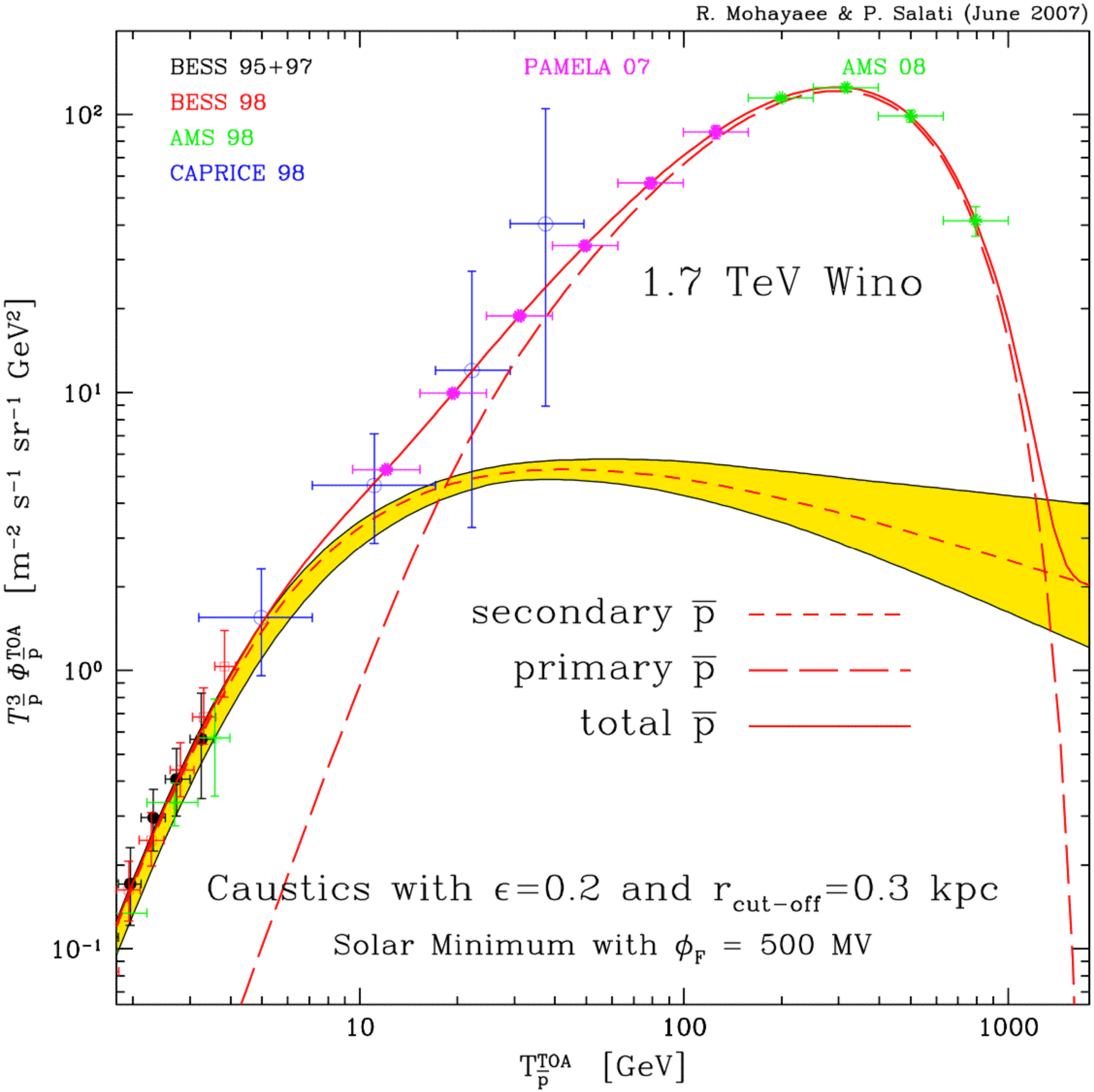
• Our predictions of the DM indirect signals are plagued by large uncertainties. We need observations ! In particular CREAM for δ and ^{10}Be/^{9}Be for K_0.

• The 10 GeV to 1 TeV antiproton window is promising. Will the Caprice excess be confirmed by PAMELA and AMS?

• A few particle physics models lead to a visible signal. In general, large boost factors are needed though.

• The DM mini–spike scenario is associated to very large boost factors with a signal exceeding – on average – the observations. However, beware of the large variance !

• In the case of caustics, the signal is enhanced by a factor of ~ 30 if $r_{\rm cut\,off}$ is as small as 0.3 kpc. But is it reasonable ?



R. Mohayaee & P. Salati (June 2007)
BESS 95+97
BESS 98
AMS 98
CAPRICE 98
PAMELA 07
AMS 08
1.7 TeV Wino
secondary p̄
primary p̄
total p̄
Caustics with ϵ=0.2 and r_cut-off=0.3 kpc
Solar Minimum with φ_F = 500 MV
10²
10¹
10⁰
10⁻¹
10
100
1000
T_p̄^TOA [GeV]
T_p̄^3 Φ_p̄^TOA [m⁻² s⁻¹ sr⁻¹ GeV²]

Space diffusion dominates in the master equation

$$V_C \, \partial_z \Psi \; - \; K \, \Delta \Psi \; + \; \partial_E \left\{ b^{\rm loss}(E) \, \Psi \; - \; K_{EE}(E) \, \partial_E \Psi \right\} \; = \; Q$$

Poisson equation $K \, \Delta \Psi \; + \; Q \; = \; 0$

$$\Downarrow$$

Long range with $G_{\bar{\rm p}}^{\rm 3D}(r) \; = \; \dfrac{Q}{4 \pi K r}$

- Evaporation at the vertical boundaries $\pm L$
- Leakage at the radial boundaries $R = 20$ kpc
- Evaporation from convective wind V_C
- Annihilations inside the MW gaseous disk
- Energy losses and mild diffusive reacceleration

4) The hidden realm of Vlasovia and DM caustics

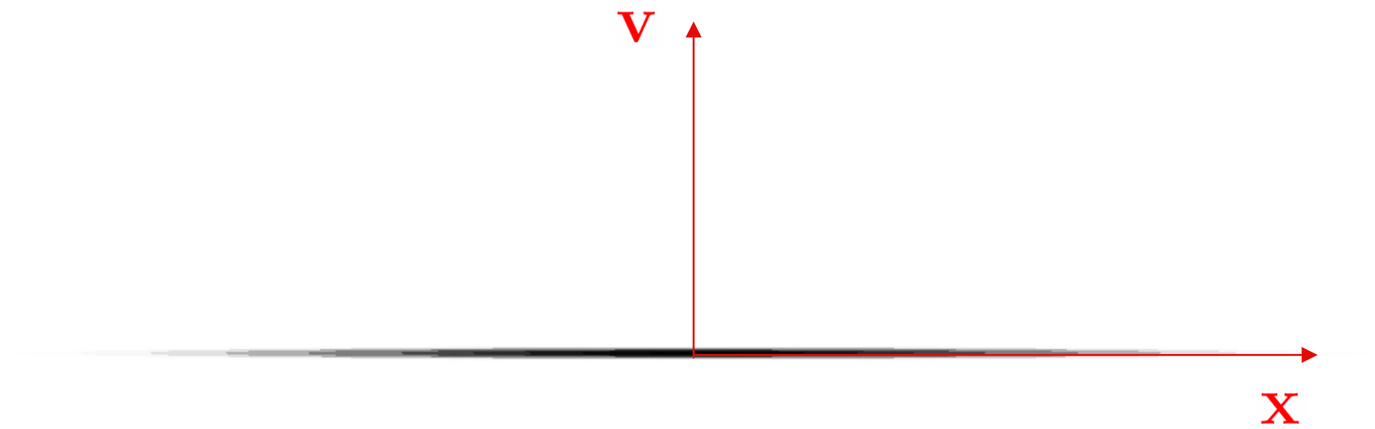
The **Vlasov** equation holds in phase space

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla_{\mathbf{x}} f \; - \; \nabla_{\mathbf{x}}\Phi\cdot\nabla_{\mathbf{v}} f \; = \; 0 \text{ (no collision)}$$

$$\Delta\Phi \; = \; 4\pi G \int \mathrm{d}^{\mathrm{D}}\mathbf{v}\, f(\mathbf{x},\mathbf{v},t) \text{ (Poisson equation)}$$

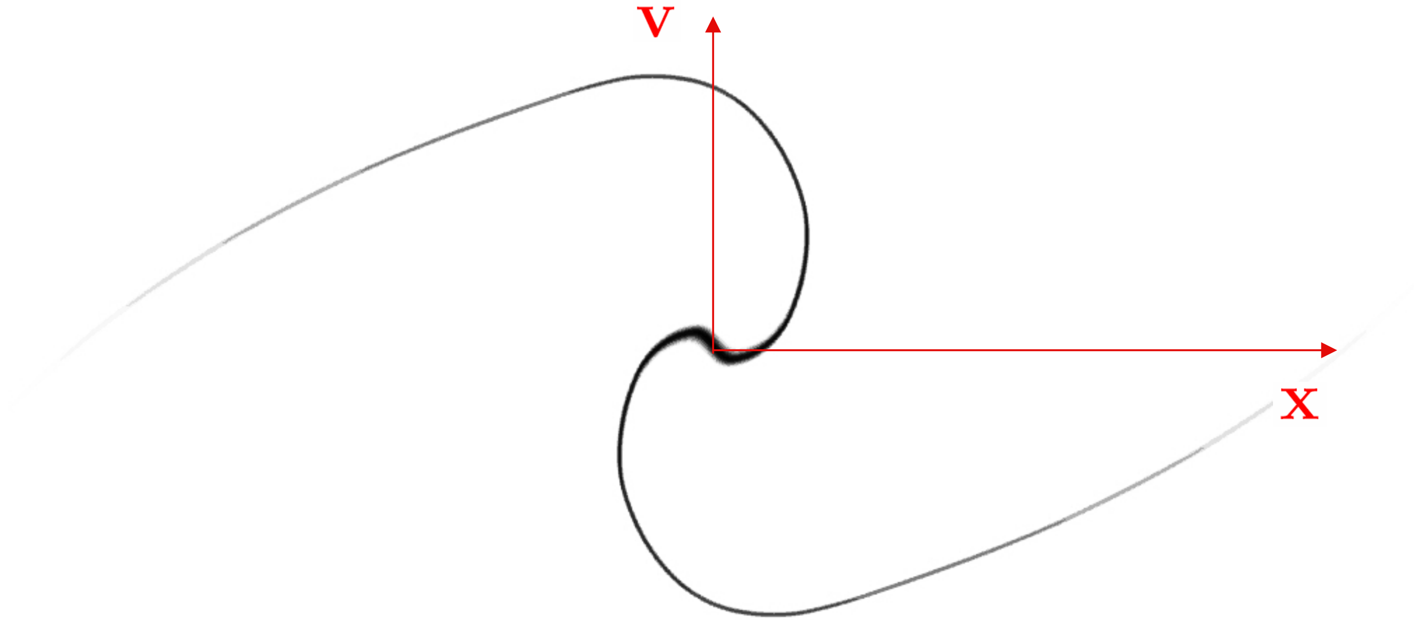
S. Colombi (IAP, Paris) & J. Touma (CAMS, Beirut)

Cold Initial Conditions

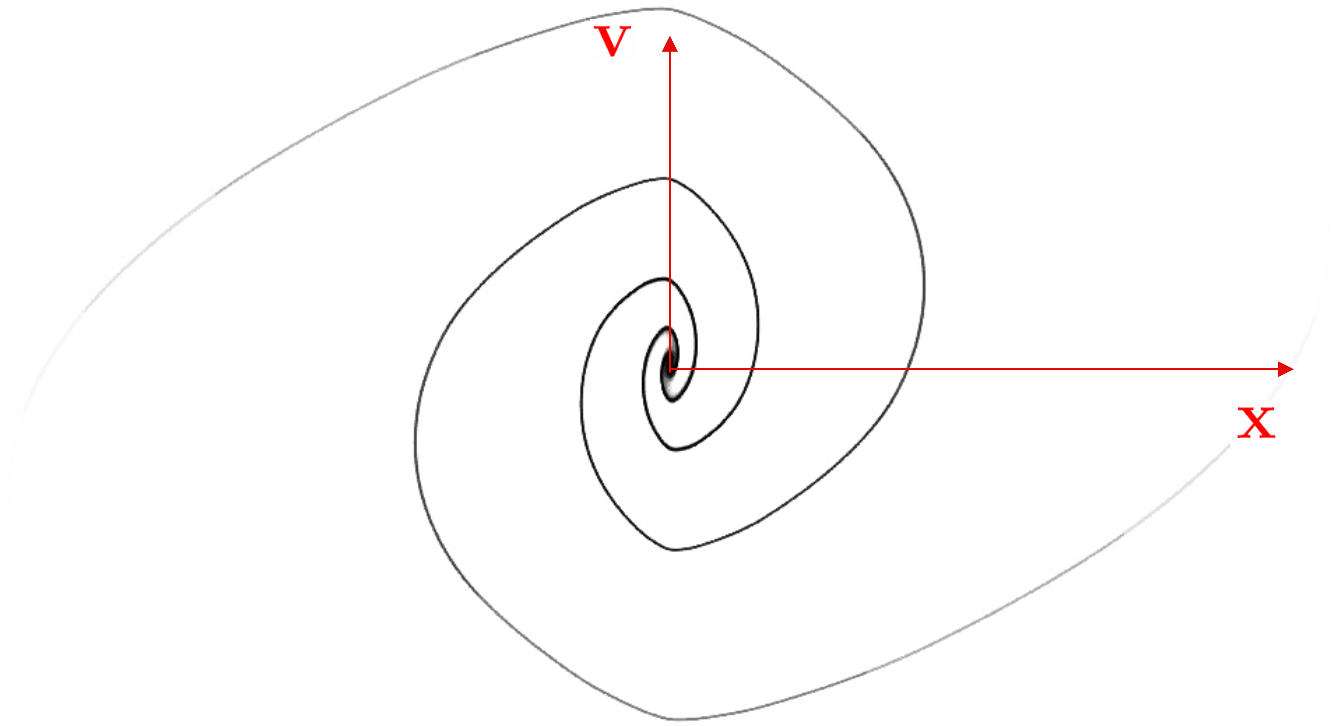


Evolution under 1-D gravity in phase space

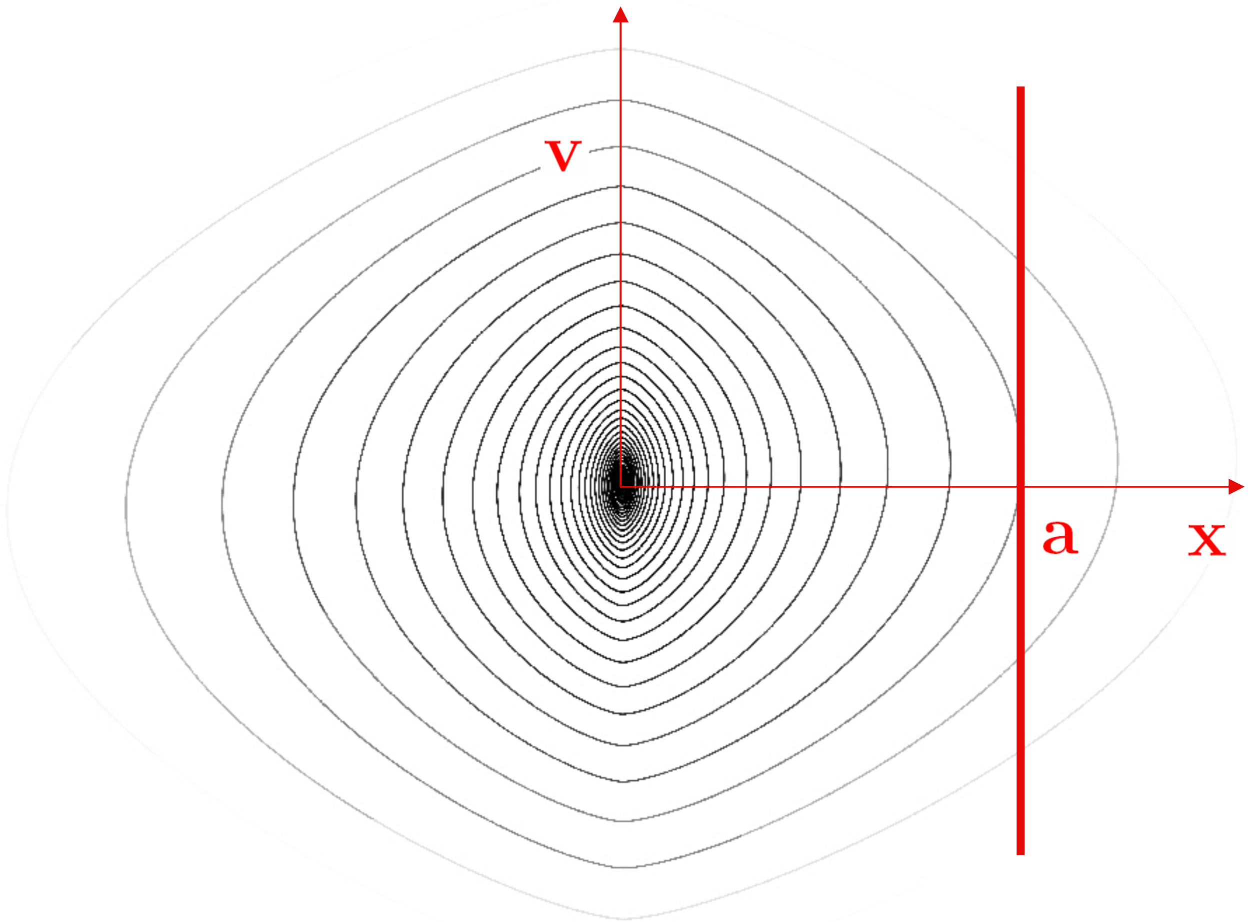
S. Colombi (IAP, Paris) & J. Touma (CAMS, Beirut)



S. Colombi (IAP, Paris) & J. Touma (CAMS, Beirut)

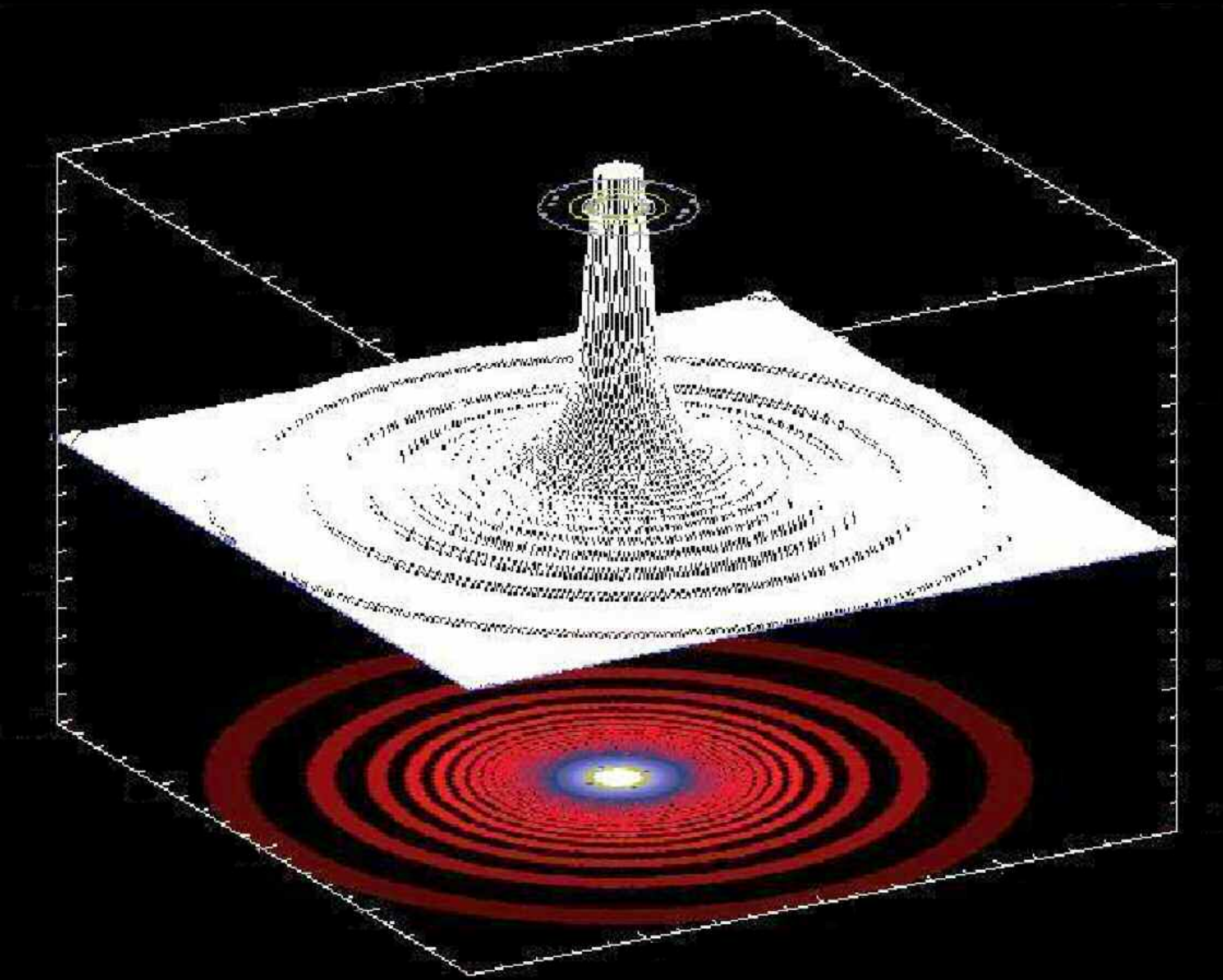


S. Colombi (IAP, Paris) & J. Touma (CAMS, Beirut)

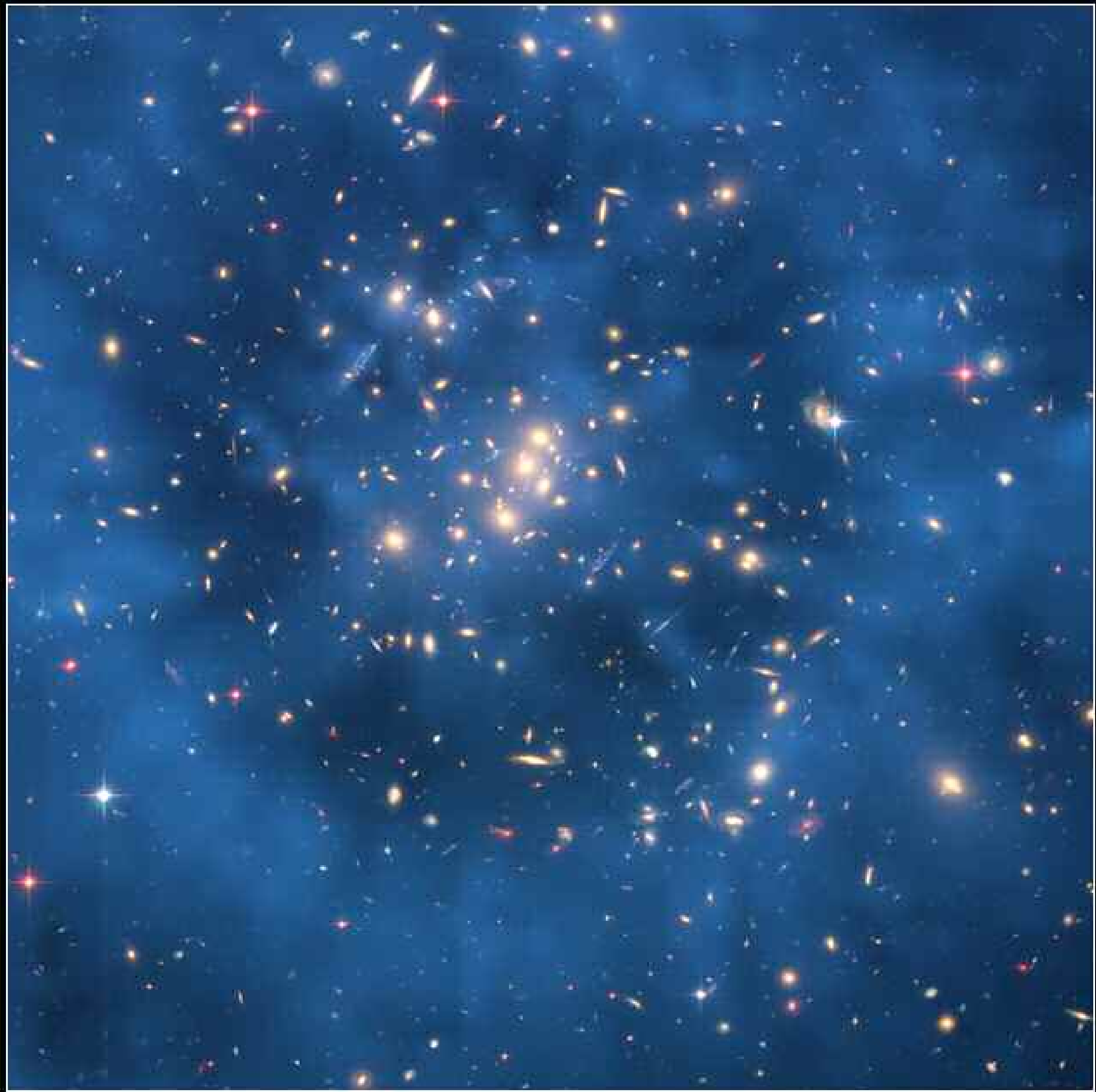


$$\rho(\mathbf{a}) = \int \mathrm{d}\mathbf{v}\, f(\mathbf{a},\mathbf{v}) \text{ is infinite !}$$

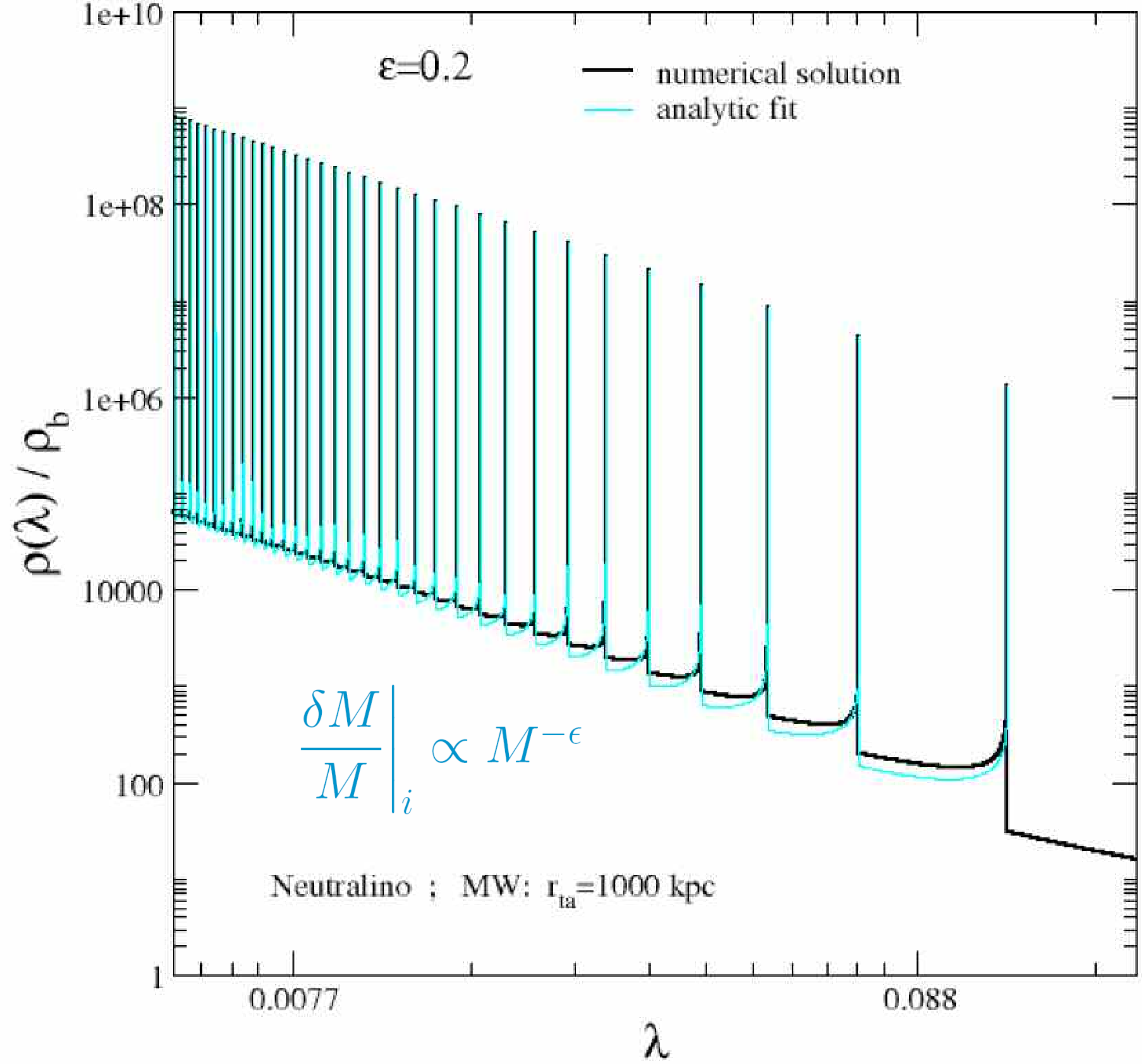
Self-similar infall model – E. Bertschinger, ApJ **58** (1985) 39



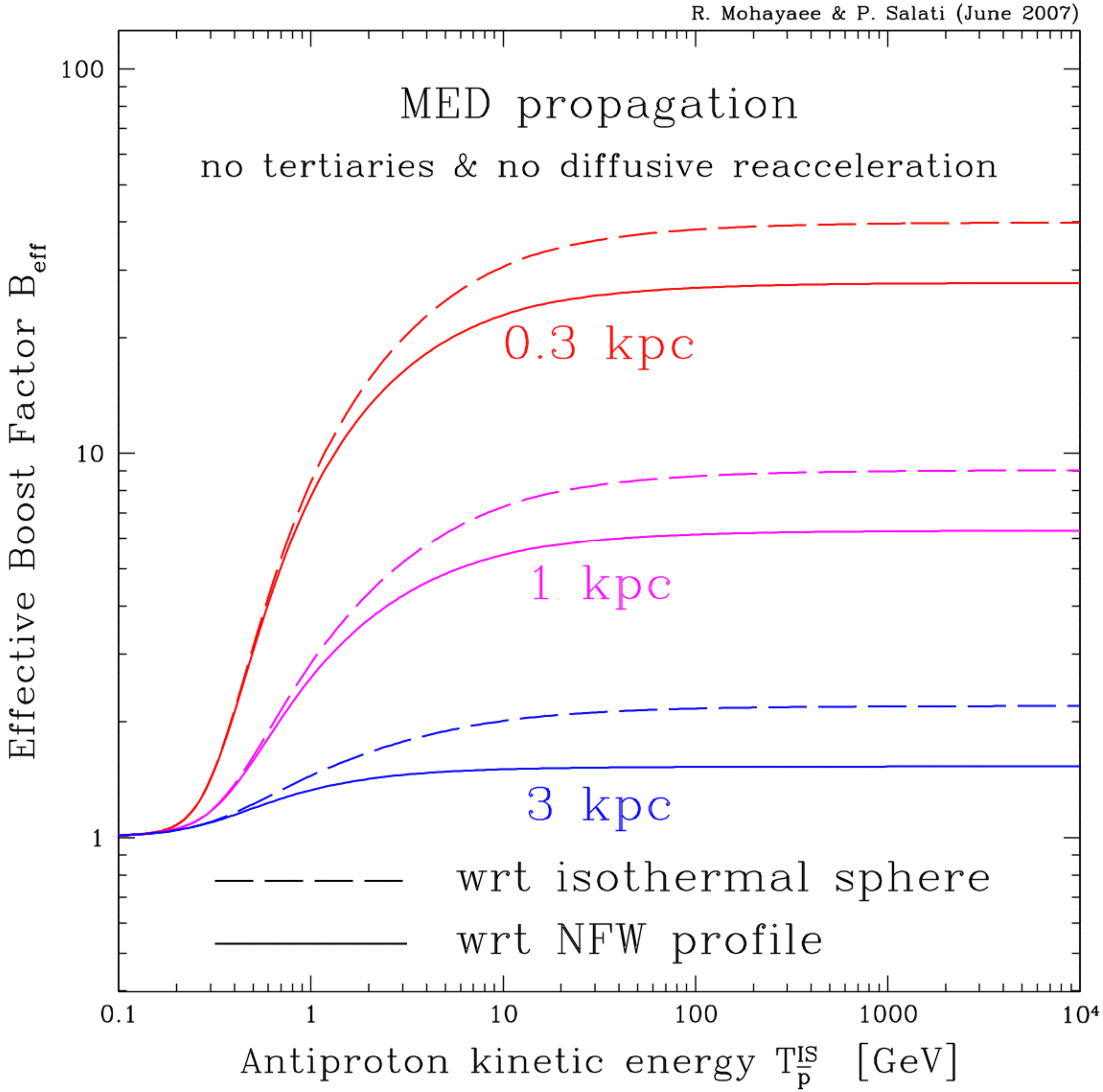
Dark Matter Ring in Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC



NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17b



λ_D is much larger than the intra-caustic distance



R. Mohayaee & P. Salati (June 2007)
MED propagation
no tertiaries & no diffusive reacceleration
0.3 kpc
1 kpc
3 kpc
wrt isothermal sphere
wrt NFW profile
Effective Boost Factor B_{eff}
100
10
1
0.1
1
10
100
1000
10^4
Antiproton kinetic energy $T_{\bar{p}}^{IS}$ [GeV]