Cosmic-ray antiproton constraints on light dark matter candidates

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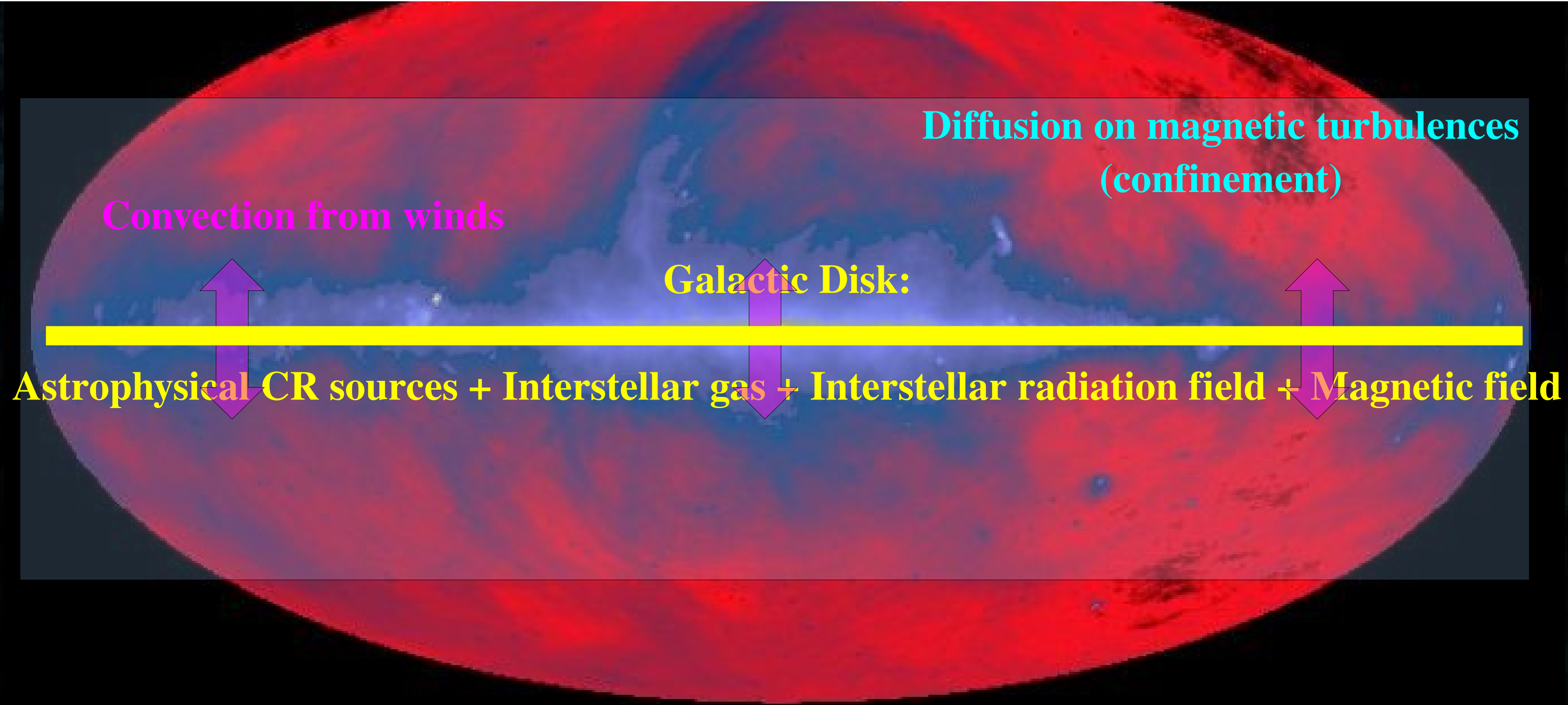
<u>Refs:</u> Cerdeno, Delahaye & Lavalle 11, arXiv:1108.1128 (NPB)
Lavalle 10, arXiv:1007.5253 (PRD)

GDR Terascale @ Marseille, 12 – X – 2011

Propagation of Galactic cosmic rays: The standard picture

e.g. Berezinsky et al 90

$$\underbrace{\partial_t \mathcal{N}}_{\text{time evolution}} = \underbrace{\mathcal{Q}(\vec{x},E,t)}_{\text{source}} + \vec{\nabla} \underbrace{\left\{ \left(K_{xx}(E)\vec{\nabla} - \vec{V}_c \right)\mathcal{N} \right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \partial_p \underbrace{\left\{ \left(\dot{p} - \frac{p}{3}\vec{\nabla}\cdot\vec{V}_c - p^2\, K_{pp}(E)\partial_p \frac{1}{p^2} \right)\mathcal{N} \right\}}_{\text{momentum current } \mathcal{J}_{pp}} - \underbrace{\frac{\tau_s + \tau_r}{\tau_s\,\tau_r}\mathcal{N}}_{\text{spallation, decay}}$$



Diffusion on magnetic turbulences (confinement)

Convection from winds

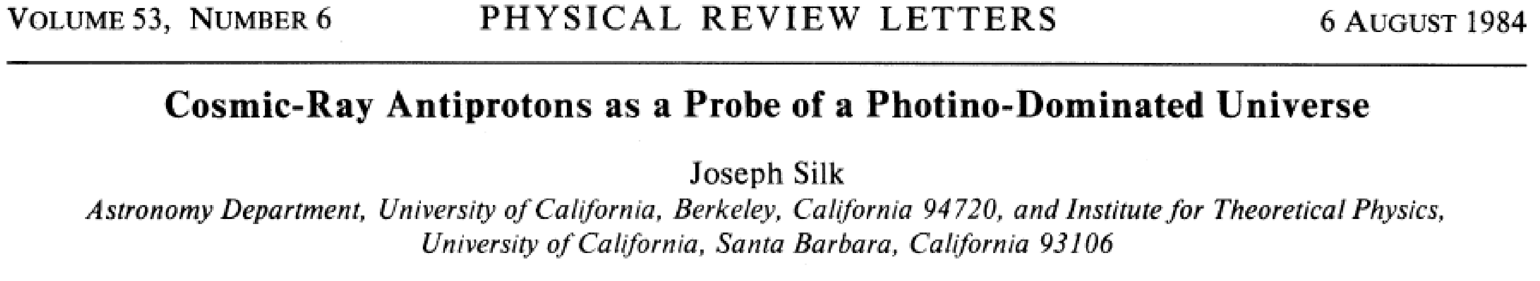
Galactic Disk:

Astrophysical CR sources + Interstellar gas + Interstellar radiation field + Magnetic field

408 MHz synchrotron, Haslam et al (1982)

In the GeV-TeV energy range, electrons lose energy quickly as they propagate, protons do not

Credit to original ideas: back to the 80's



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Cosmic-Ray Antiprotons as a Probe of a Photino-Dominated Universe

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Rudaz & Stecker (1988)

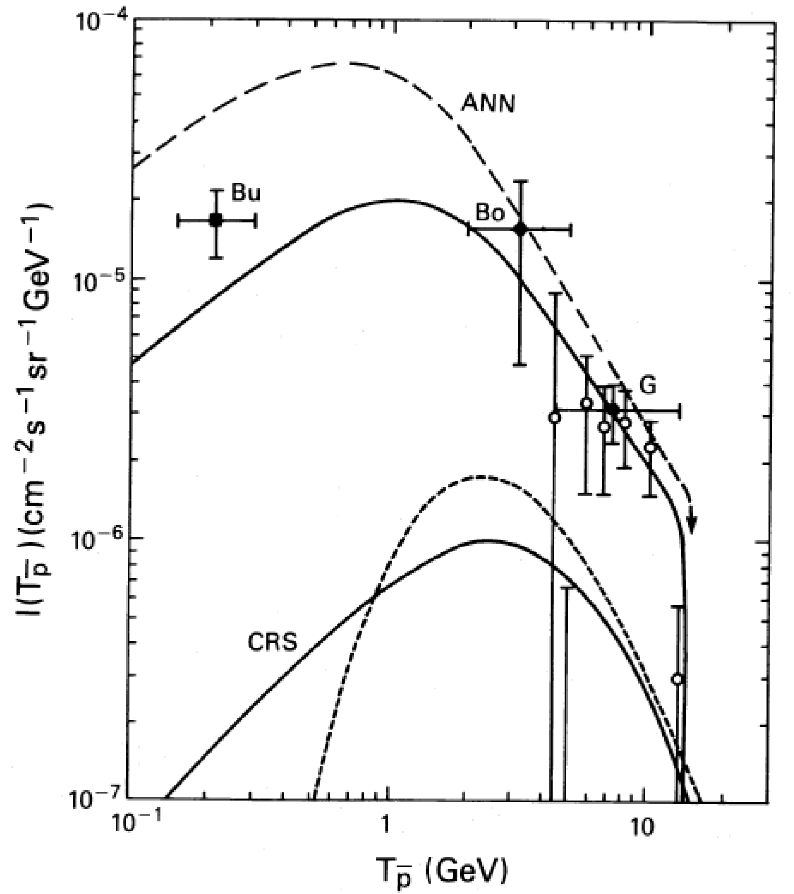


FIG. 1.—Interstellar (extra–solar system) cosmic-ray antiproton flux from $M_\chi = 15$ GeV dark matter fermion annihilation (*dashed line*) and that spectrum modulated by the solar wind as discussed in the text (*solid line*) compared with the observed fluxes as measured by Buffington *et al.* (1981) (Bu), Bogomolov *et al.* (1981) (Bo), and Golden *et al.* (1984) (G). Lower curves, marked CRS, show the predicted flux of antiprotons as cosmic-ray secondaries produced by cosmic-ray collisions in interstellar space (Protheroe 1981).

<u>Status by the end of the 80's:</u>

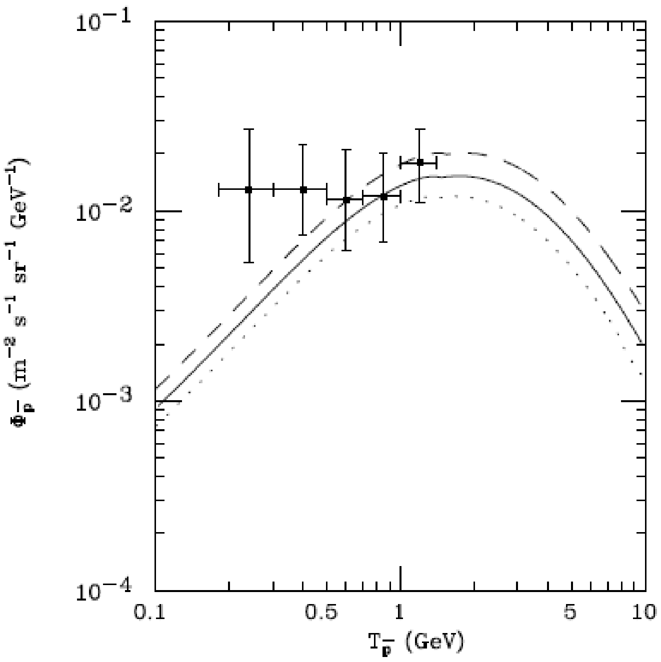
- CR antimatter signals => low background

- A few data on the CR antiproton flux (eg. Buffington+81, Bogomolov+81, Golden+84)

- Secondary predictions (eg. Protheroe 81) too low

- Primary source required: dark matter may fit.

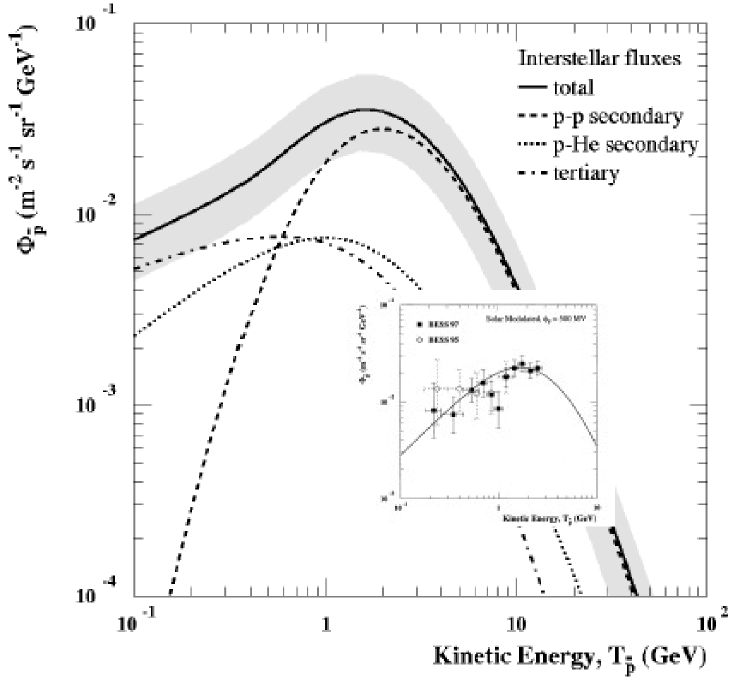
Secondary antiprotons

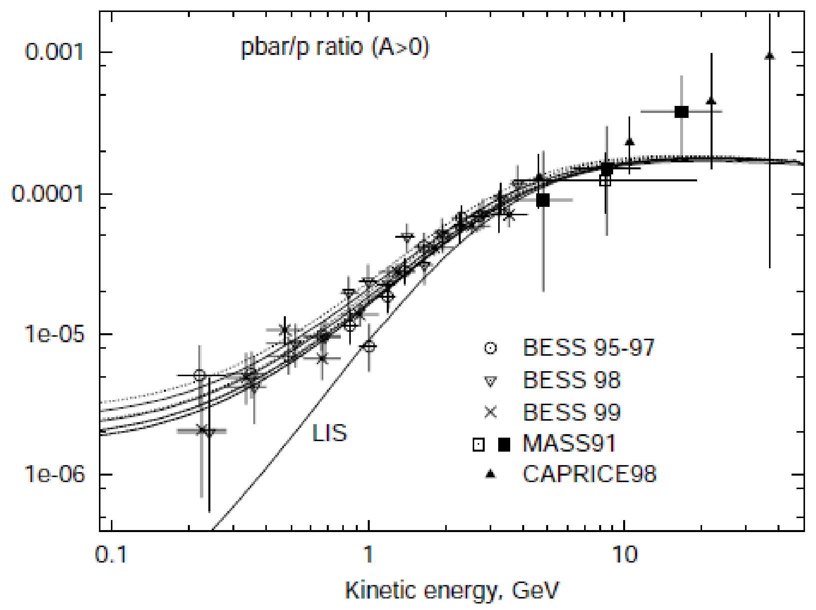


Bottino+98
(no tertiaries)

Cosmic rays
+ interstellar gas
→ antiprotons

Bergström+99
(tertiaries incl.)

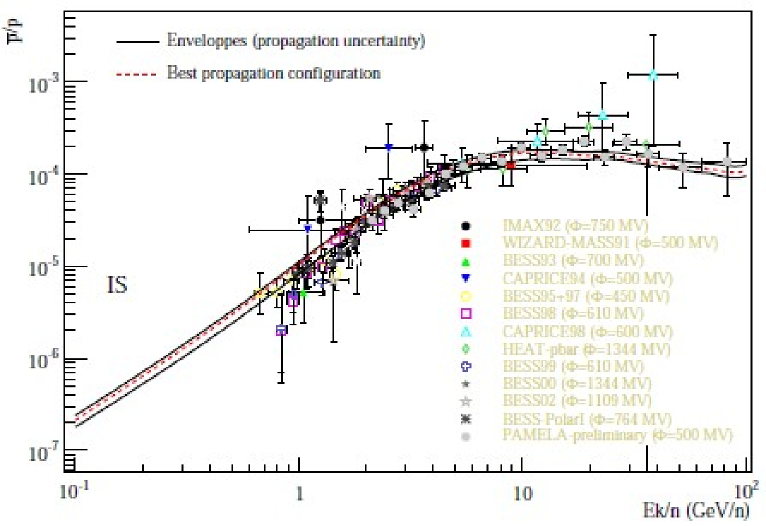




Moskalenko+02
(Galprop)

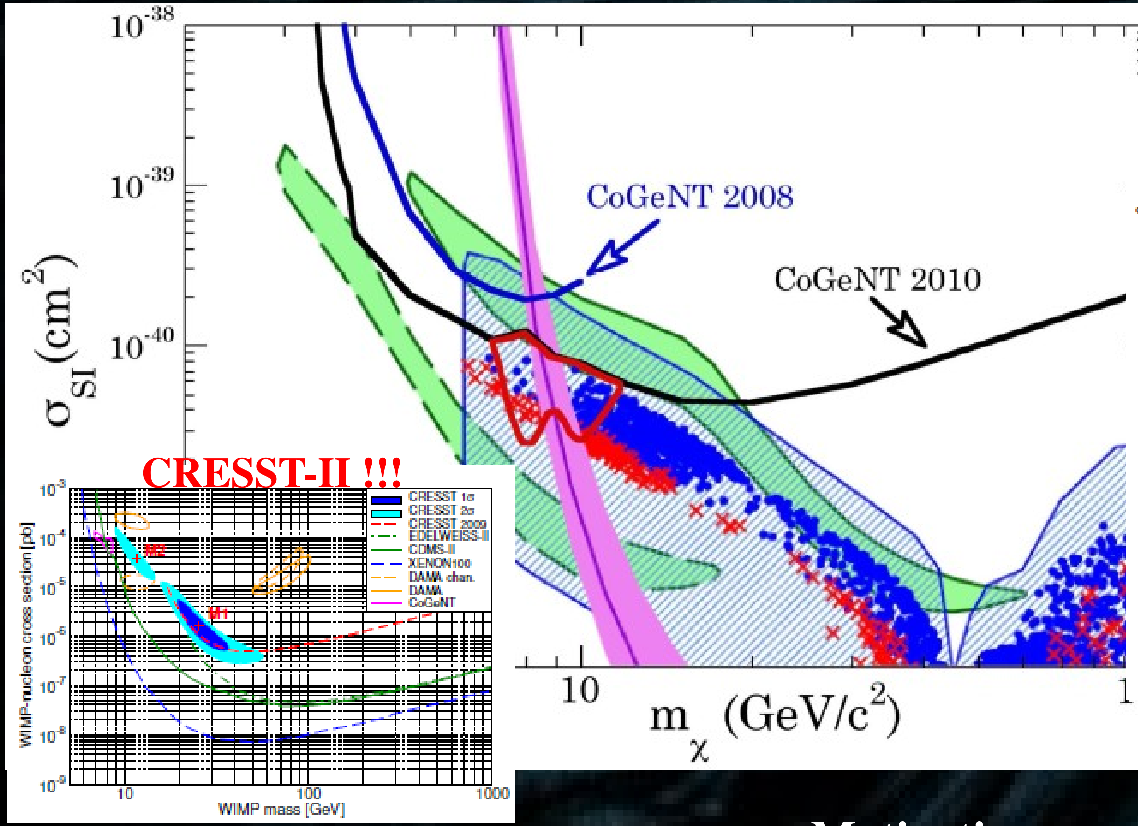
CONSISTENT WITH CURRENT DATA, eg BESS, PAMELA (AMS awaited)

Donato+01,
Bringmann & Salati 07

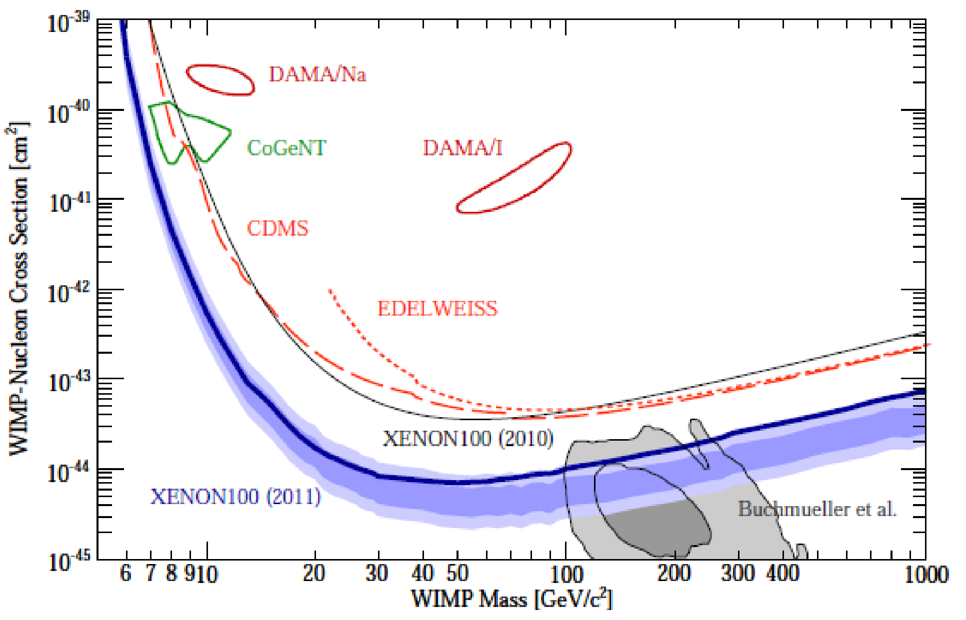


The case for light WIMPs

CoGeNT (Collar+10-11)



XENON-10-100 (Aprile+10-11)

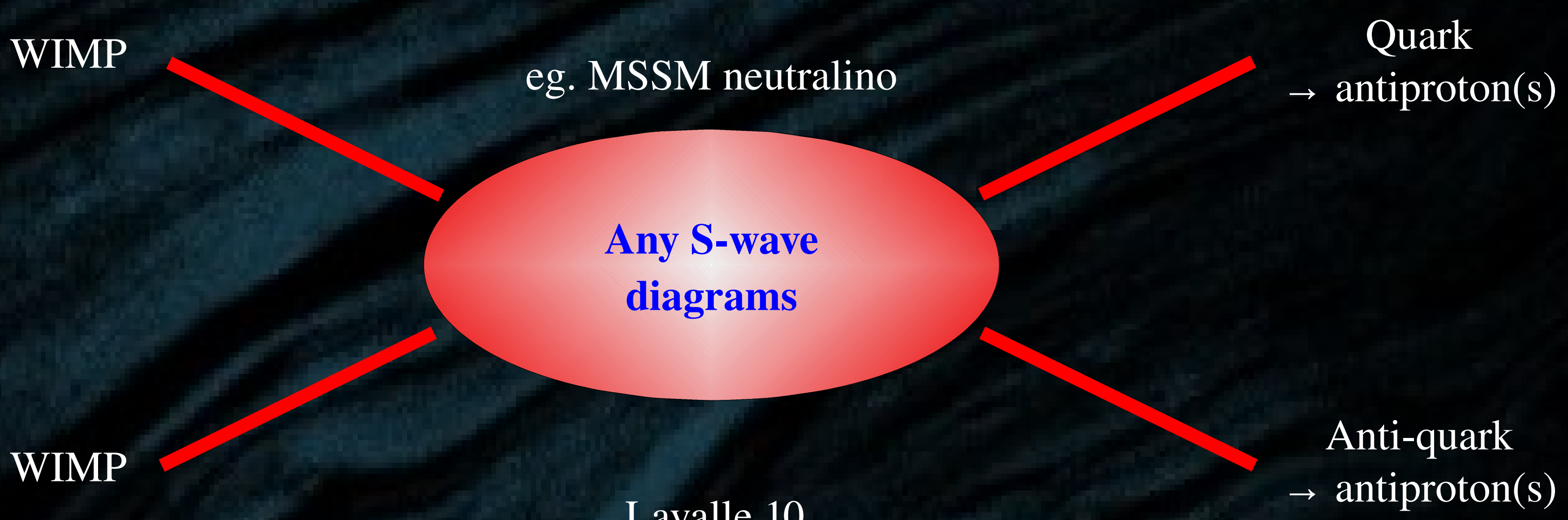


Motivations are above:

CoGeNT (Collar+10-11), DAMA (Bernabei+00-11), CRESST (Angloher+11)
Predictions in the plot by Bottino+10 (non-unified gaugino masses models)
Favored mass range: ~ 10 GeV

But see also: CDMSII (Ahmed+10), XENON-10-100 (Aprile+10-11), SIMPLE (Felizardo+11)

Light WIMPs: direct annihilation into quarks



WIMP

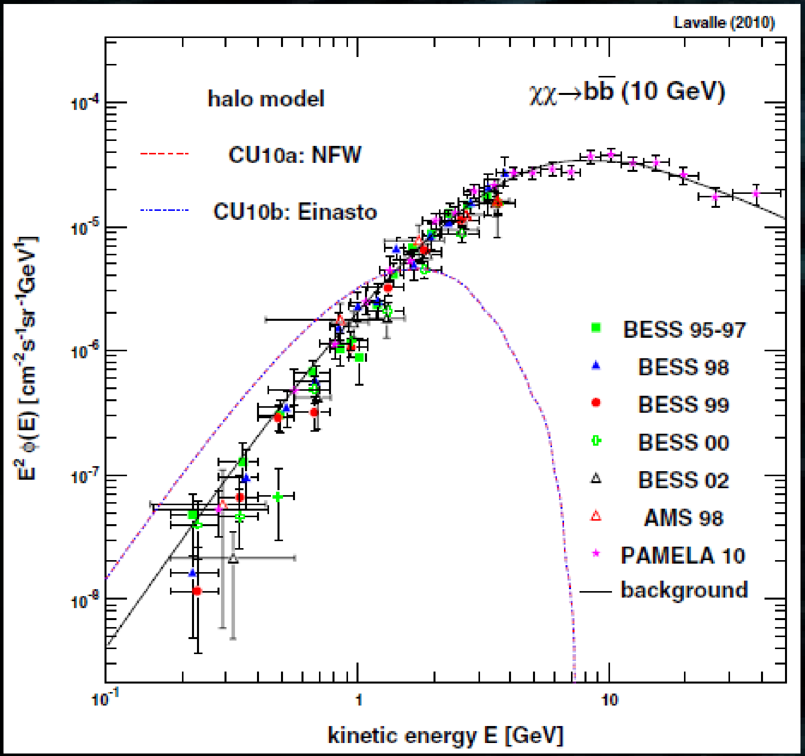
eg. MSSM neutralino

Quark
→ antiproton(s)

Any S-wave diagrams

WIMP

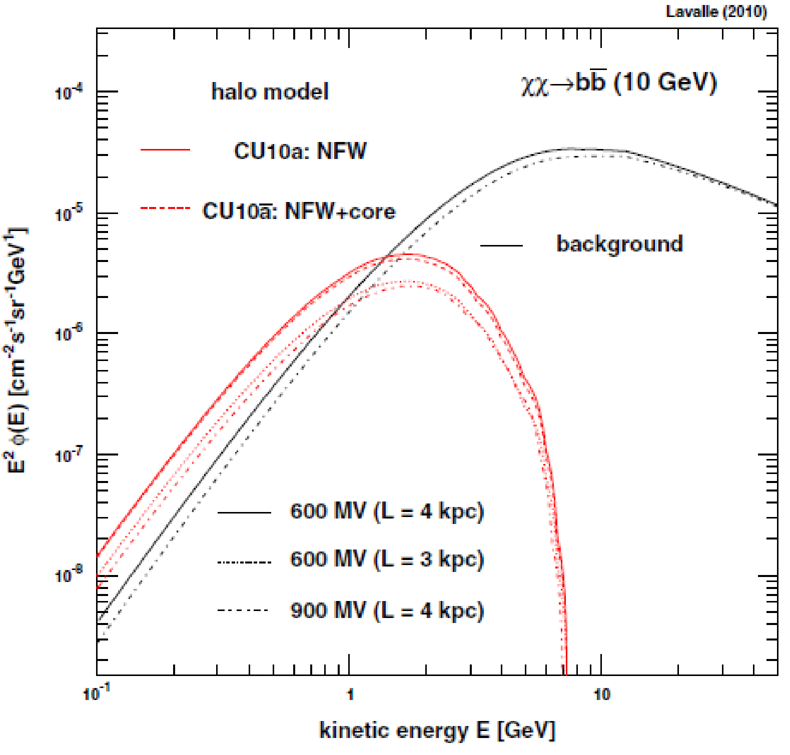
Anti-quark
→ antiproton(s)



Lavalle 10
(see also Bottino+05)

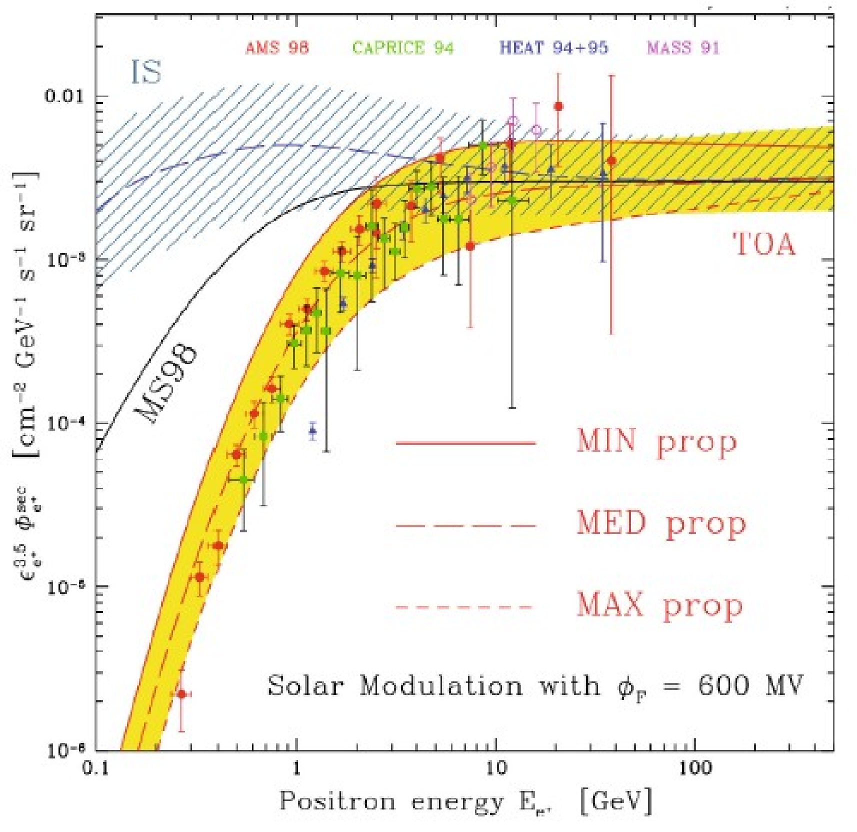
6 GeV < mass < 15 GeV
→ **big trouble with data**
$\langle\sigma v\rangle < 10^{-26}$ cm^3/s

Ingredients:
- NFW halo
(Catena & Ullio 10)
- Diff halo size:
L=3-4 kpc
(eg. Putze, Maurin+10-11)



Uncertainties in the diffusion halo size? Quick digression towards positrons

Secondary positrons
(eg. Delahaye+09, Lavalle 11)



$$\phi_{e^+} \propto 1/\sqrt{K_0}$$

$$\frac{K_0}{L} \approx \mathrm{Cst}$$

Small halo models in serious trouble with positron data

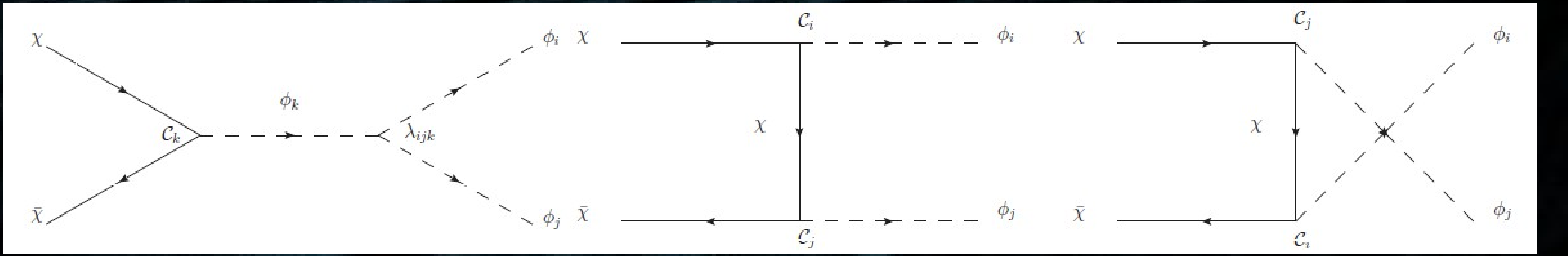
++ Positron fraction => primary source required

L > 1 kpc => Very conservative statement!

Perspectives:

- PAMELA data to come (low solar activity period)
- Pheno/theory: Improve models!
  [L-models not consistent for DM, L>3 kpc OK when K(E,z) is used instead]

Singlet extensions of the MSSM: make all of them light




Light dark matter in the singlet-extended MSSM

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Physics Letters B 695 (2011) 169–173

Add a singlet superfield coupled to the Higgs superfields
=> can get light singlino-dominated neutralino (WIMP)
+ enriched Higgs sector (light CP-even and CP-odd bosons)
[see eg. Ellwanger+ 97-11]

See also: Belikov+10,
Draper+10 (NMSSM),
Albornoz-Vasquez+11

Set relic density

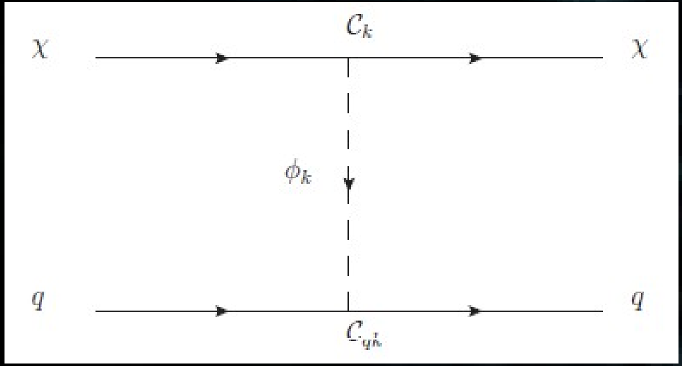
$$\chi + \bar\chi \xrightarrow{\text{s:}h;\ \text{t:}\chi} a + a \quad \text{(P-wave)}$$

$$\chi + \bar\chi \xrightarrow{\text{s:}h;\ \text{t:}\chi} h + h \quad \text{(P-wave)}$$

$$\chi + \bar\chi \xrightarrow{\text{s:}a;\ \text{t:}\chi} a + h \quad \text{(S+P-waves)}$$

Sets indirect detection signals

Direct detection: CP-even exchange



Effective low energy interacting Lagrangian:

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}\sum_i \bar\chi\, C_{\chi i}\,\chi\,\phi_i - \sum_{i,j,k}\frac{\lambda_{ijk}}{\eta_{ijk}}\,\phi_i\,\phi_j\,\phi_k \;+ \text{h.c.},$$

Direct detection of singlino-like WIMP

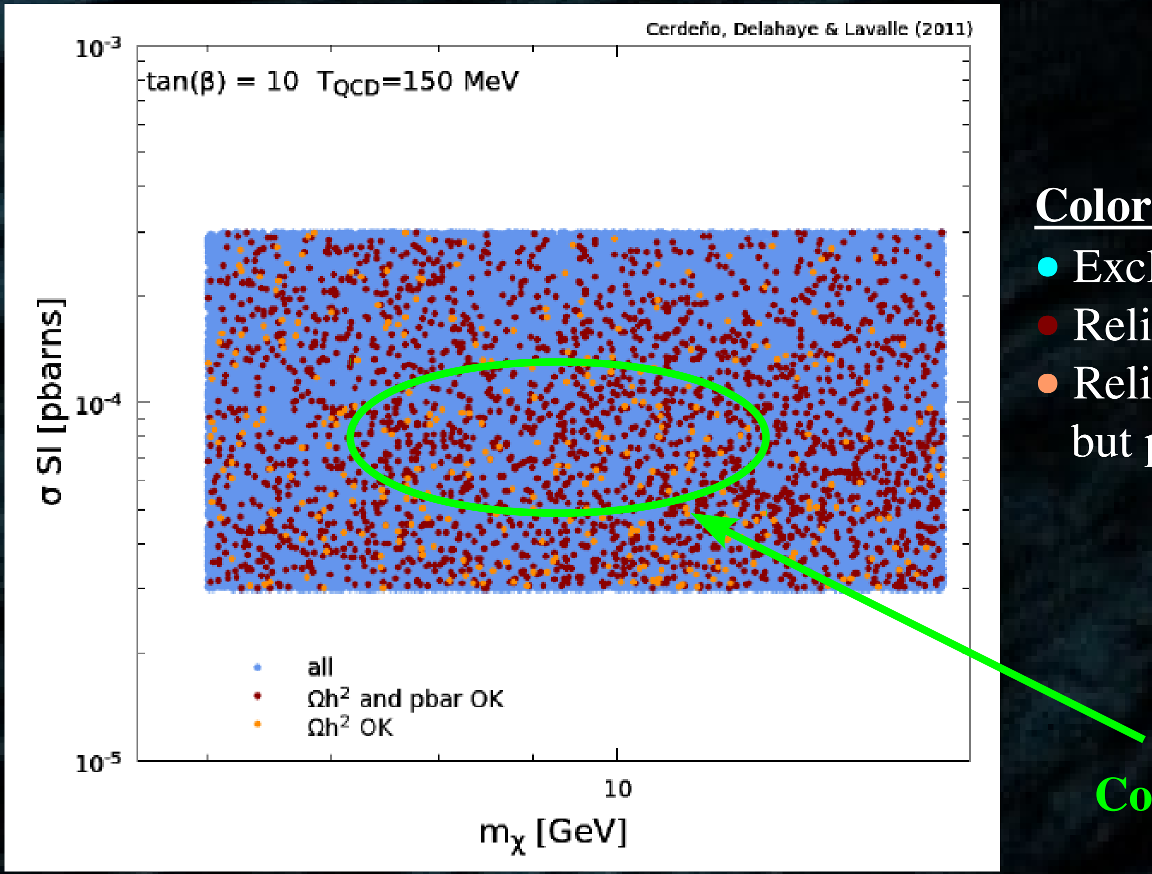
Setup:

- Singlino-like WIMP
- Realistic Higgs sector with mixing angles: additional singlet-like CP-even (h) and CP-odd (a) light Higgs bosons

Constraints:

- Some collider constraints (=> large singlet fraction)
- Direct detection signal dominated by h exchange (MSSM Higgs decoupled)
- DD signal region encompasses CoGeNT
- 2 mchi > ma + mh

Cerdeno, Delahaye & JL 11



CoGeNT region

Color index:

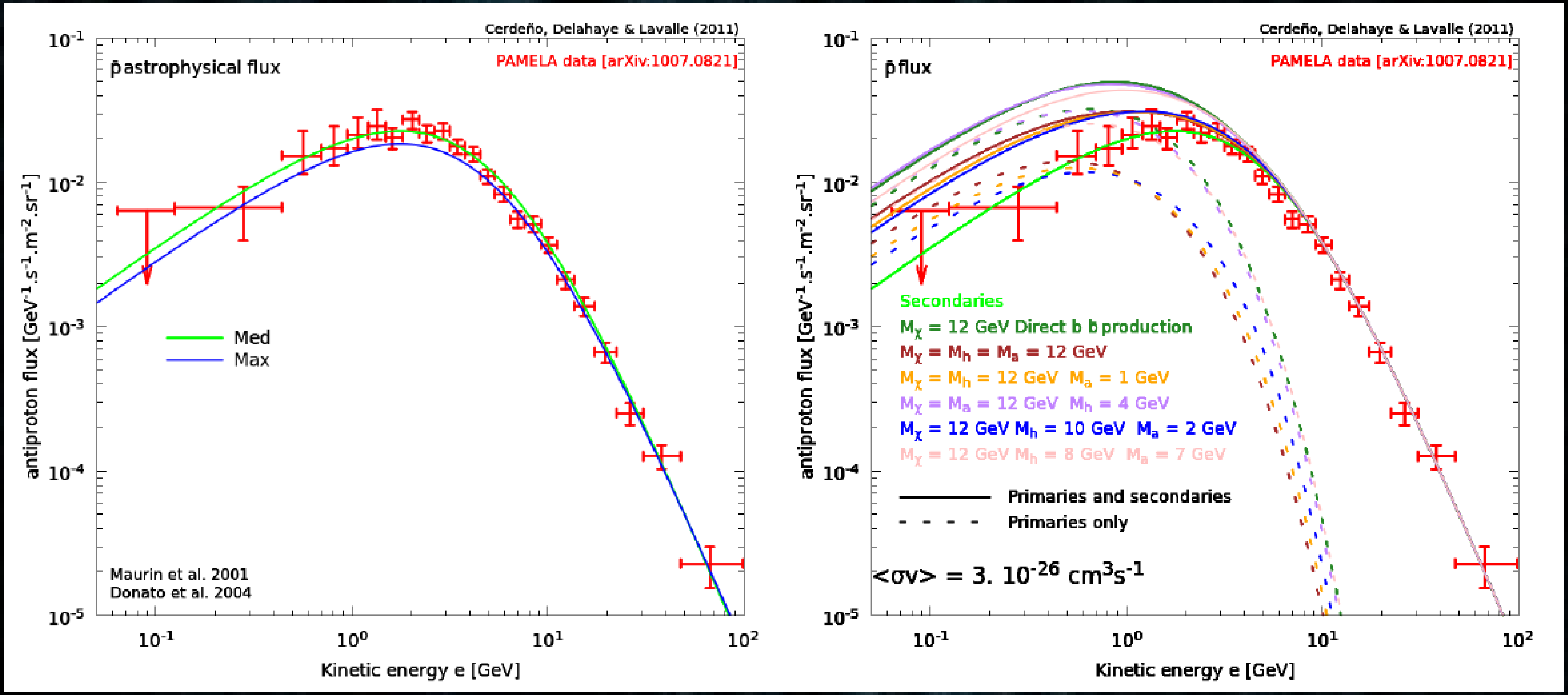
- ● Excluded relic d.
- ● Relic d. OK
- ● Relic d. OK but pbar excess

Free parameters:

- Masses
- Couplings
- tanbe

Setting the antiproton constraints

Cerdeno, Delahaye & JL 11



The data:

PAMELA only
[low solar activity
++ competitive errors]

Propagation and secondaries:

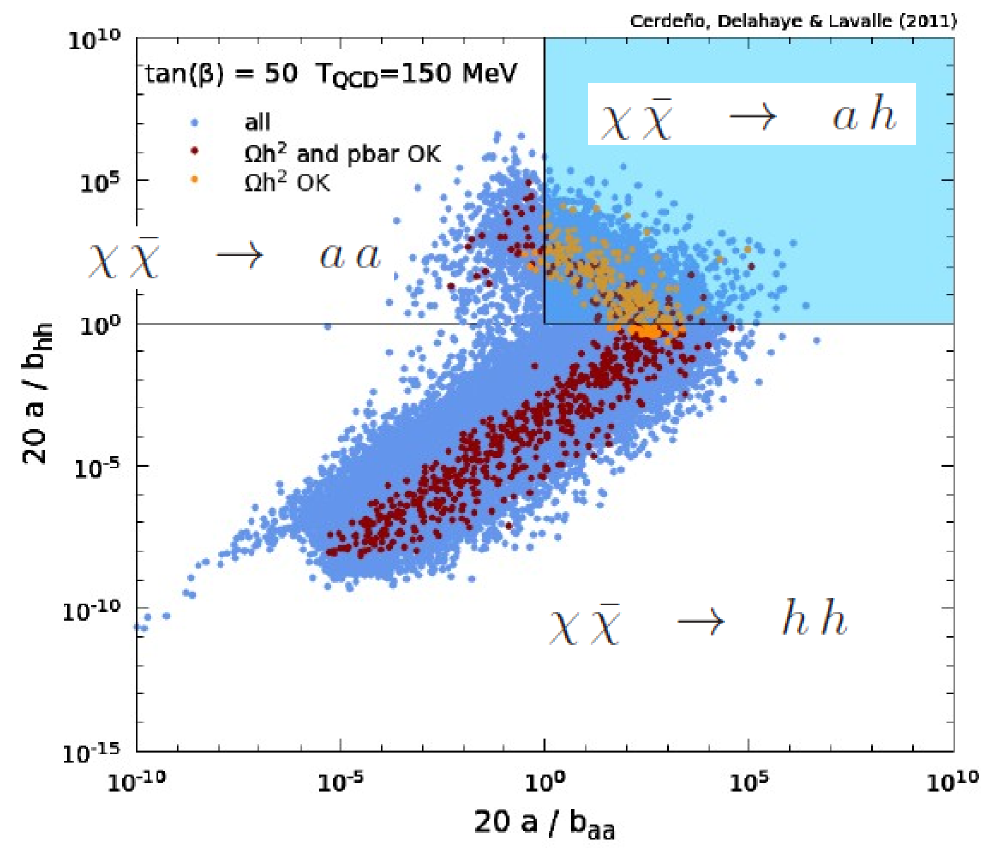
Maurin+01 best fit (*med*)
Donato+01 secondary flux
Conservative sol. mod.: 600 MV

Primary spectra:

a, *h* will decay to quarks
=> fragmentation with Pythia
++ Lorentz boost (*a*, *h* not produced at rest)

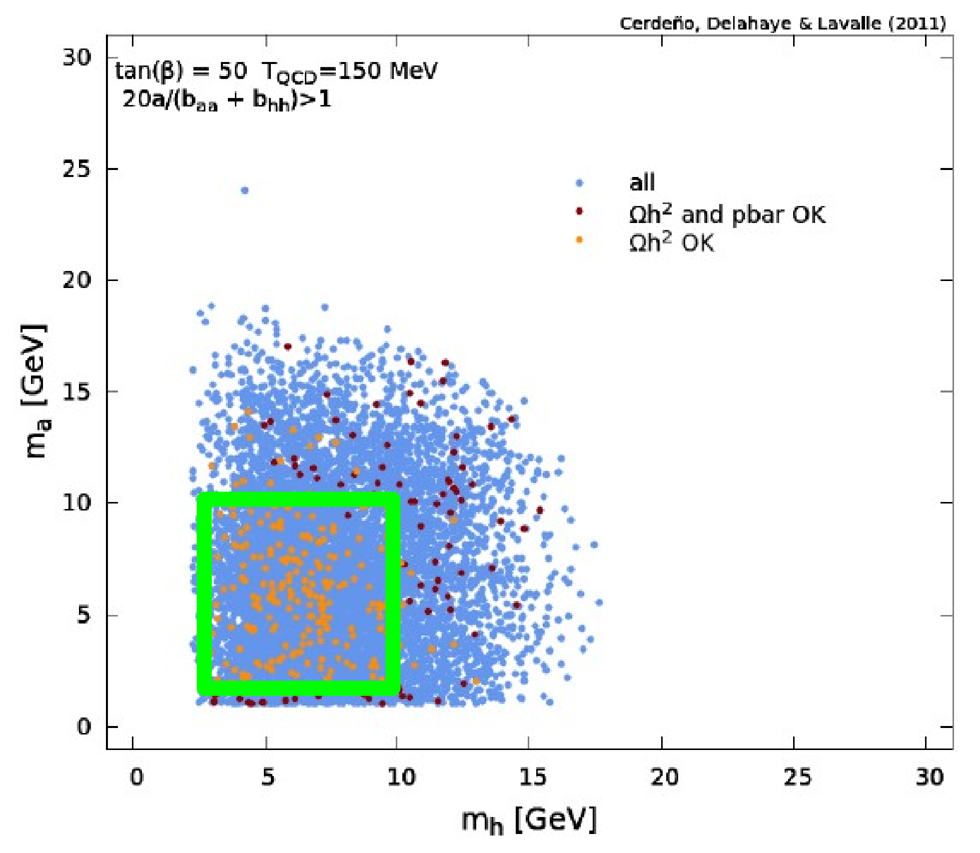
Understanding the results: S-to-P wave ratio and mass range

Indirect detection signal => pure S-wave required



$$\langle\sigma v\rangle \approx a + b/\{x \equiv m_\chi/T\}$$

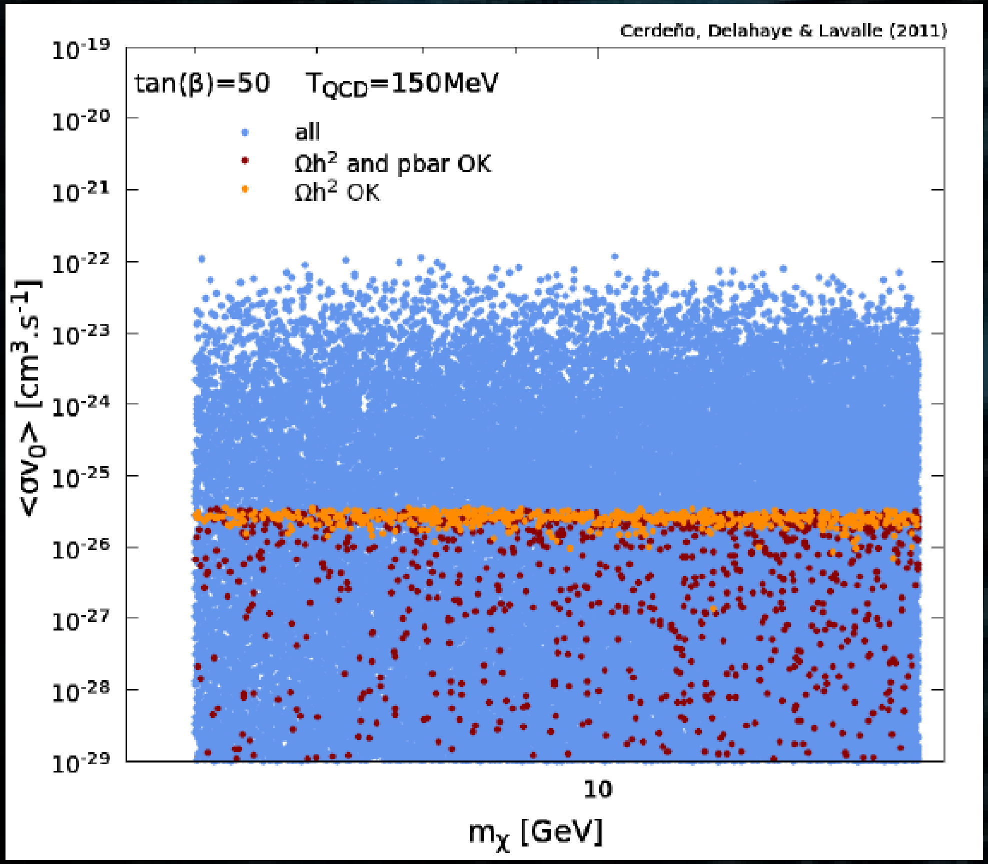
Light Higgs bosons masses

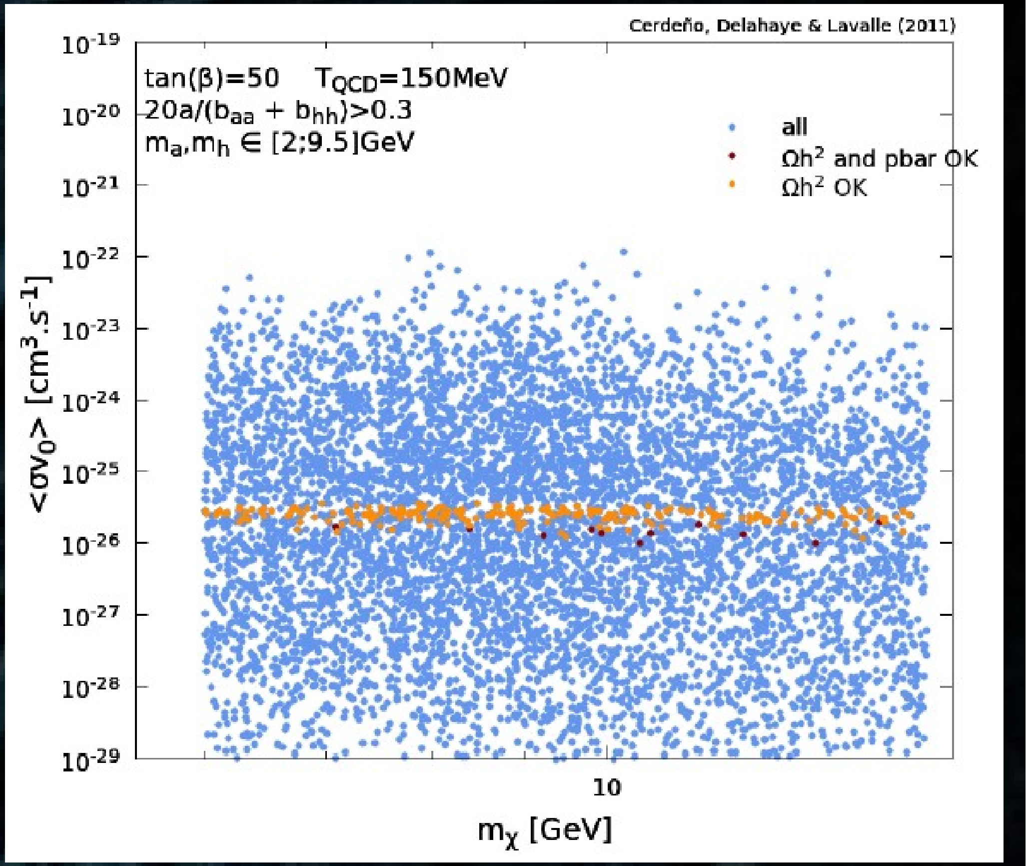


m < 2 mp or m~2 mb~10 GeV do not produce antiprotons

In terms of annihilation cross section

Cerdeno, Delahaye & JL 11

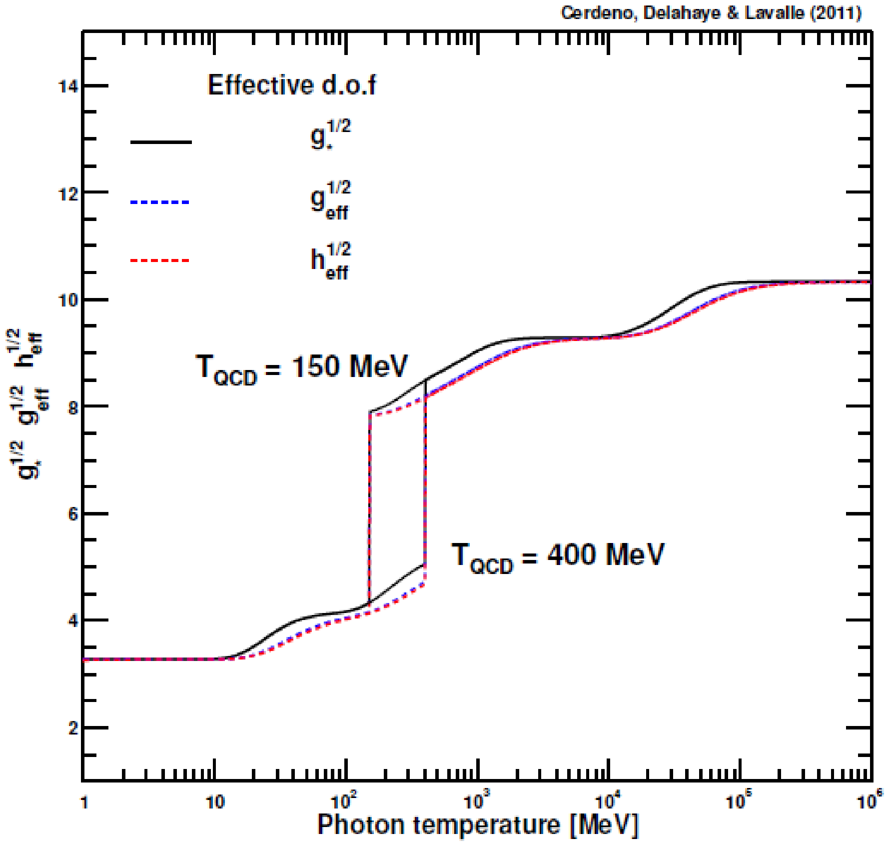


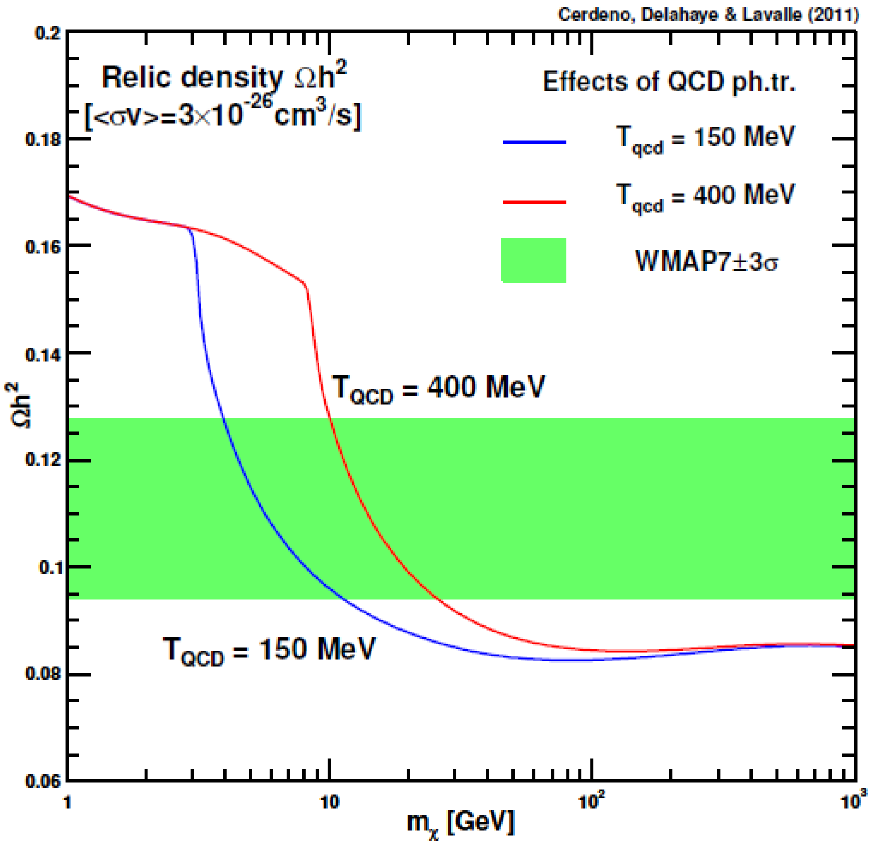


Select S-wave dominated annihilation
++ light Higgs bosons' mass range

$$\longrightarrow \quad \langle \sigma v \rangle_0 \lesssim 1.5 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

Relic density: QCD phase transition effect



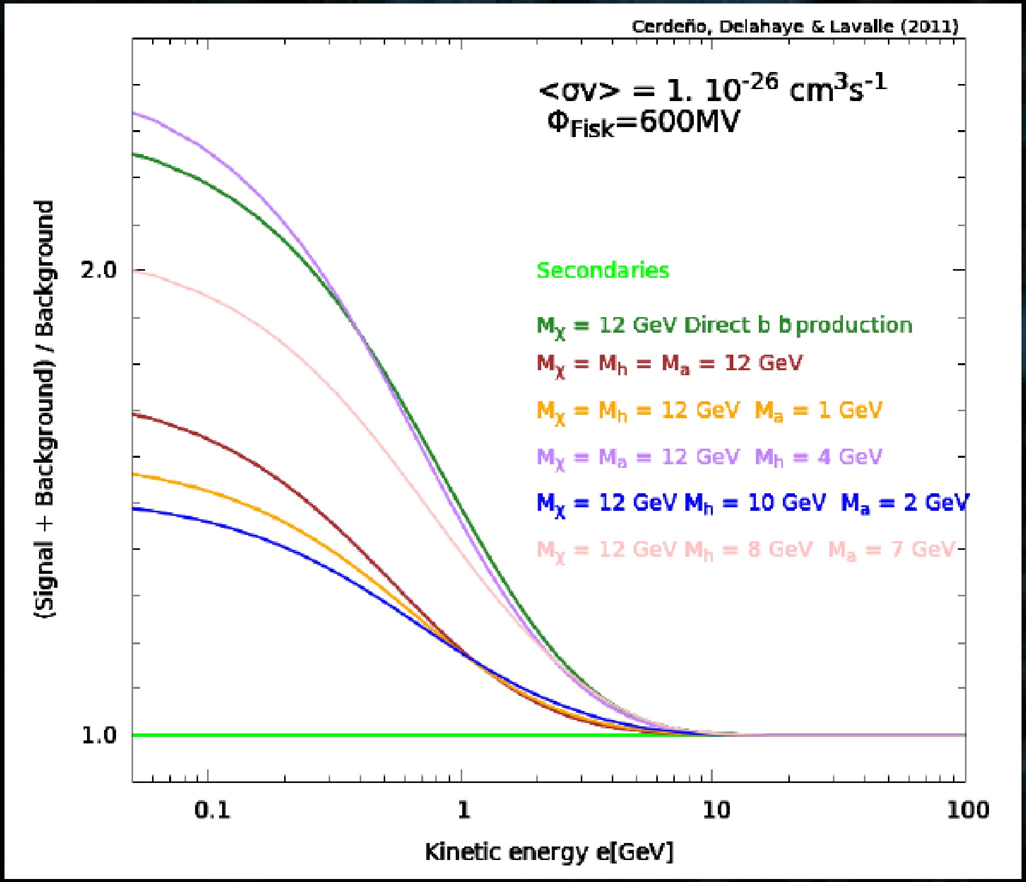


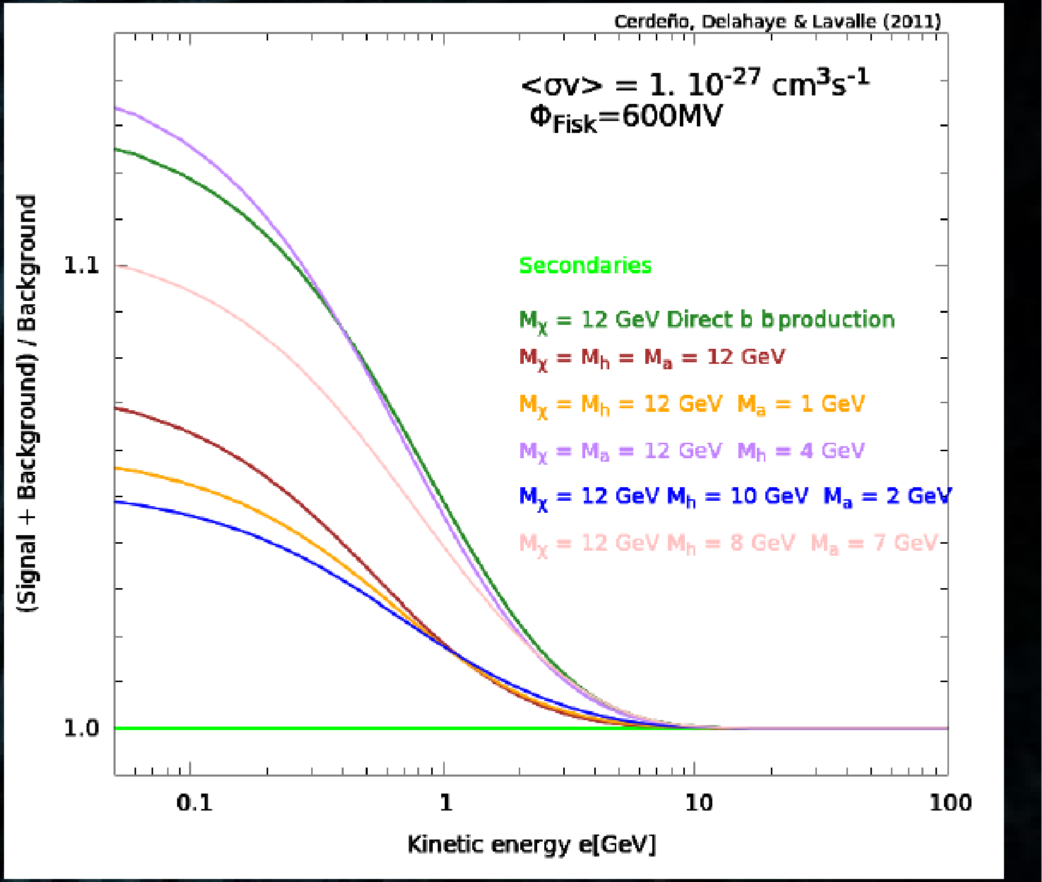
$$x_f \equiv \frac{m_\chi}{T_f} \approx 20 \;\text{ for WIMPs}$$
$$m_\chi \approx 8\text{ GeV} \Longrightarrow T_f \approx 400\text{ MeV} \approx T_{\rm qcd}$$

$$\Omega_\chi \propto \frac{1}{g_\star^{1/2}(x_f)\,\langle\sigma v\rangle_{x_f}}$$

Can we do better ?

Typical signature = low energy spectral break


Cerdeño, Delahaye & Lavalle (2011)


Cerdeño, Delahaye & Lavalle (2011)

PAMELA, AMS: achieve 5% error @ 100 MeV
Theory: improve solar modulation treatment!

Conclusions

- Cosmic-ray antiprotons provide strong constraints to light WIMP candidates with ~10 GeV masses (no boost required from eg. DM substructures)

- This applies to an S-wave dominated annihilation at freeze out + quarks among final states
=> P-wave dominated models do escape the antiproton constraints

- Direct annihilation into quarks more strongly constrained:
$\langle \sigma \, v \rangle < 5 \times 10^{-27}$ cm^3/s, typically (100% into quark pairs)

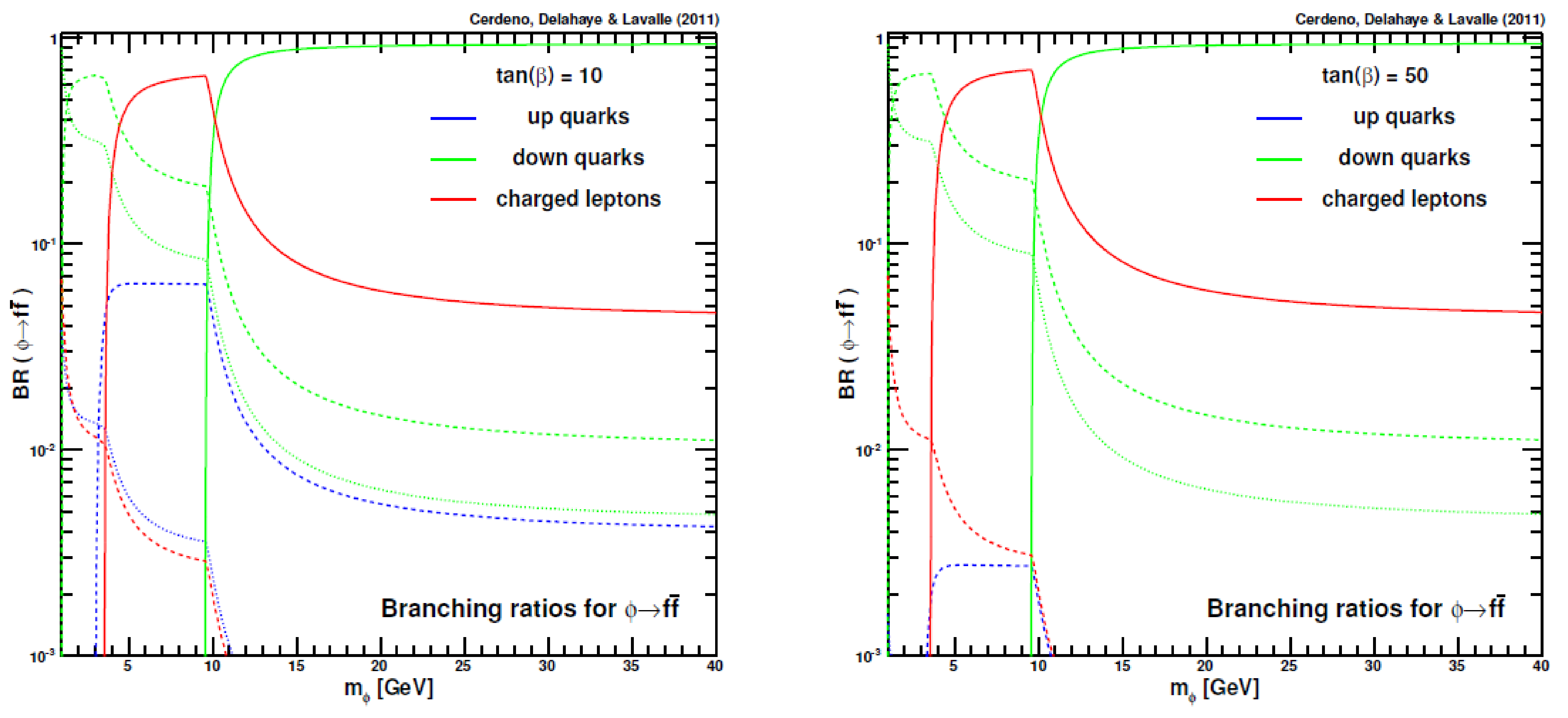
- Singlino-like WIMP candidates with unusual annihilation final states also strongly constrained in some cases [annihilation into CP-even + CP-odd <= 2 mchi > ma + mh]
=> constraints apply to any model annihilating into 2 exotic and unstable scalar/gauge fields

- Limits could be significantly improved if PAMELA/AMS achieve 5% error @ 100 MeV
=> look for low energy spectral break
=> complementary discovery channel ?

- Complementarity with gamma-rays + radio in prep. !

Backup slides

Light Higgs bosons' couplings to SM fermions

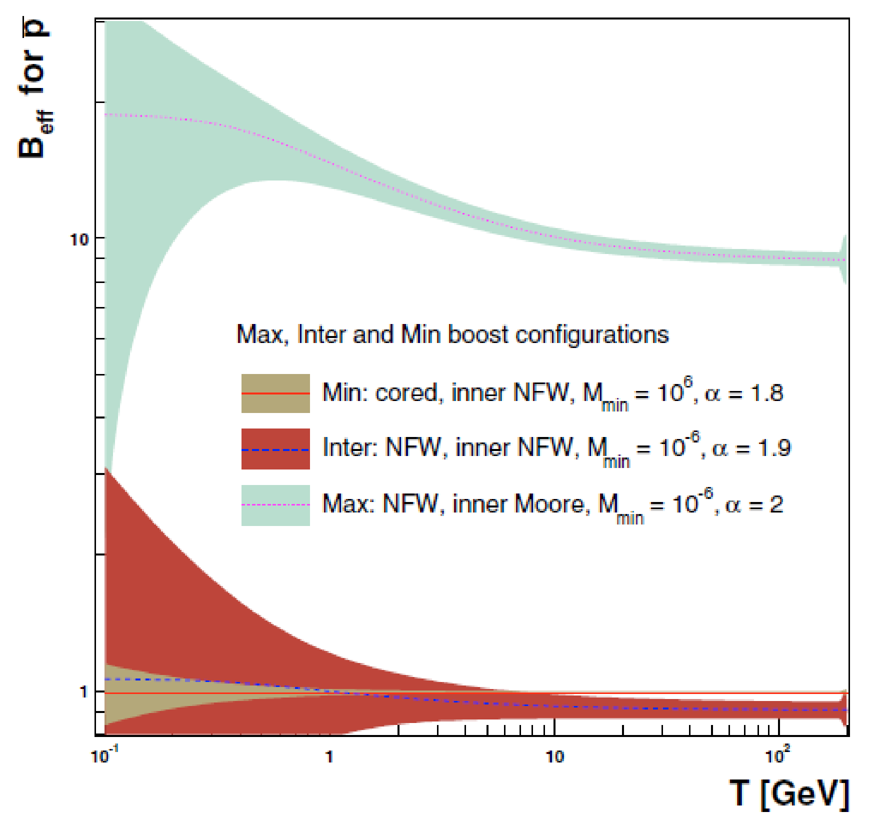


$$
\begin{aligned}
h &= s_\varphi\,[s_\theta\,\mathrm{Re}(H_d) - c_\theta\,\mathrm{Re}(H_u)] + c_\varphi\,\mathrm{Re}(S)\\
a &= s_{\varphi_a}\,[s_{\theta_a}\,\mathrm{Im}(H_d) - c_{\theta_a}\,\mathrm{Im}(H_u)] + c_{\varphi_a}\,\mathrm{Im}(S)\\
&= s_{\varphi_a}\,[A_{\mathrm{MSSM}}] + c_{\varphi_a}\,\mathrm{Im}(S)\,,
\end{aligned}
$$

$$
\begin{aligned}
C_{\phi_i,\mathrm{up,up}} &= -\frac{g\,m_u}{2\,M_W\,s_\beta}\left\{s_\varphi\,c_\theta - i\,\gamma_5\,s_{\varphi_a}\,c_{\theta_a}\right\}\\
C_{\phi_i,\mathrm{down,down}} &= -\frac{g\,m_d}{2\,M_W\,c_\beta}\left\{s_\varphi\,s_\theta - i\,\gamma_5\,s_{\varphi_a}\,s_{\theta_a}\right\}\,,
\end{aligned}
$$

Considering dark matter subhalos

JL, Yuan, Maurin & Bi (08)



Pieri, JL, Bertone & Branchini 10