Cosmic-ray antiproton constraints on light dark matter candidates

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

TAUP @ München, 5 to 9 – IX – 2011

UAM UNIVERSIDAD AUTONOMA DE MADRID
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ift
MultiDark Multimessenger Approach for Dark Matter Detection

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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and

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THE ASTROPHYSICAL JOURNAL, 325:16–25, 1988 February 1

Rudaz & Stecker (1988)

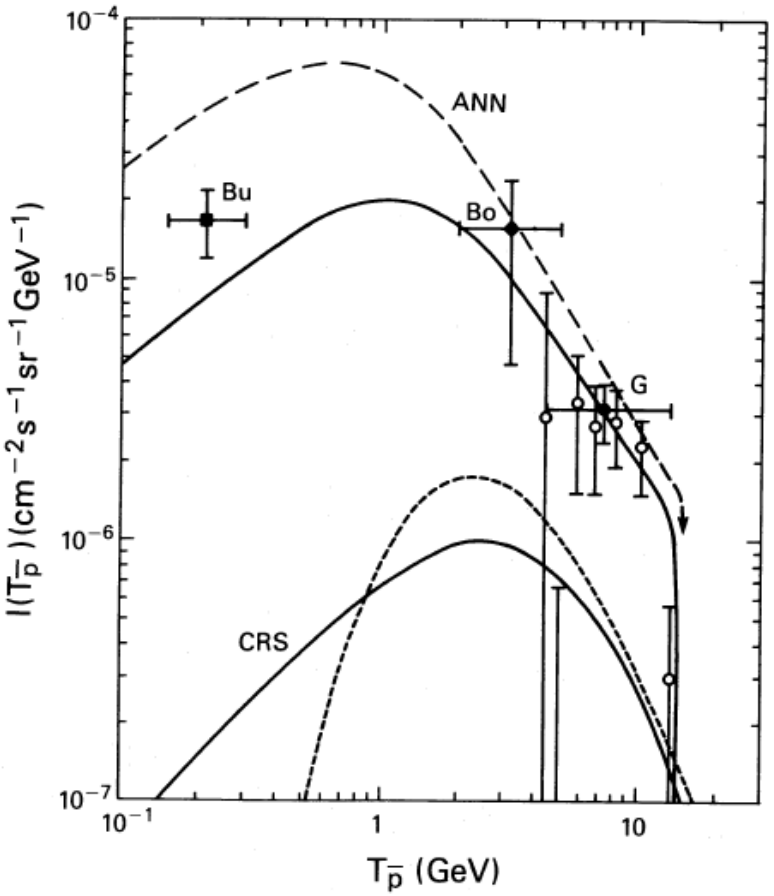
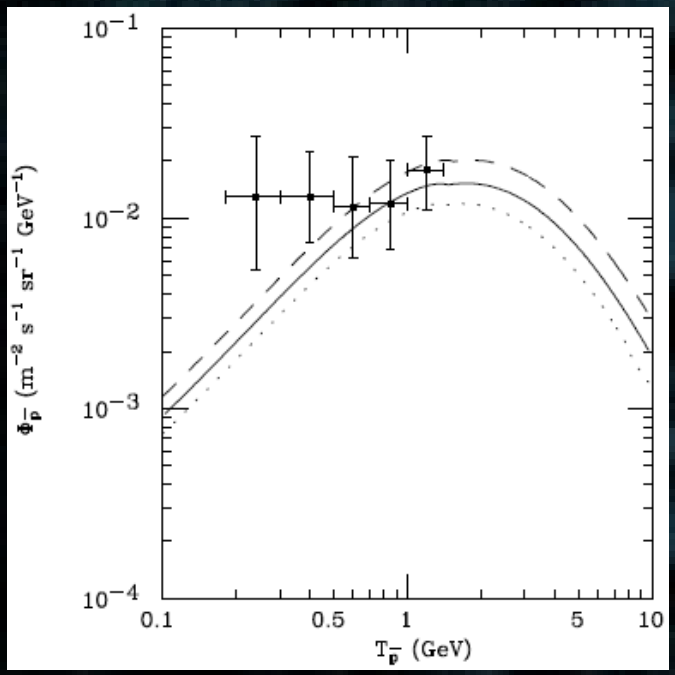


FIG. 1.—Interstellar (extra–solar system) cosmic-ray antiproton flux from $M_\chi = 15$ GeV dark matter fermion annihilation (*dashed line*) and that spectrum modulated by the solar wind as discussed in the text (*solid line*) compared with the observed fluxes as measured by Buffington *et al.* (1981) (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.

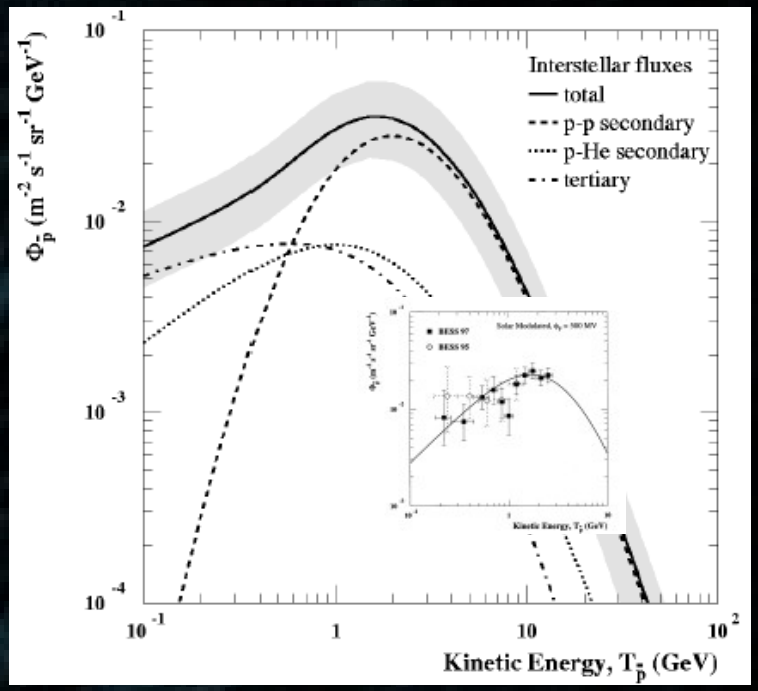
Secondary antiprotons



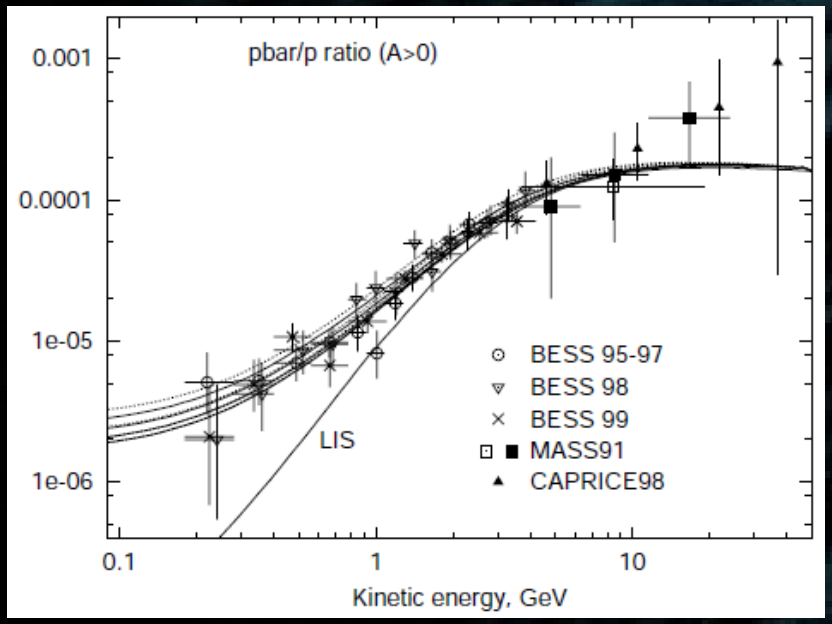
Bottino+98
(no tertiaries)

Cosmic rays
+ interstellar gas
→ antiprotons

Bergström+99
(tertiaries incl.)

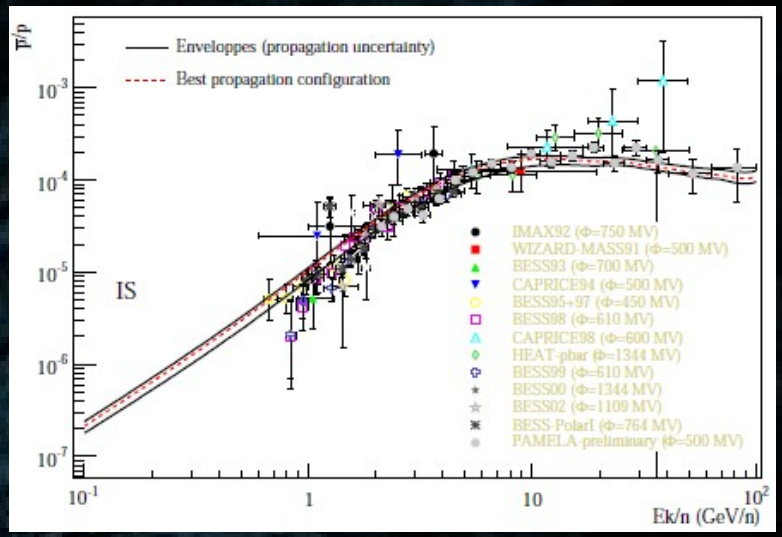


Moskalenko+02
(Galprop)



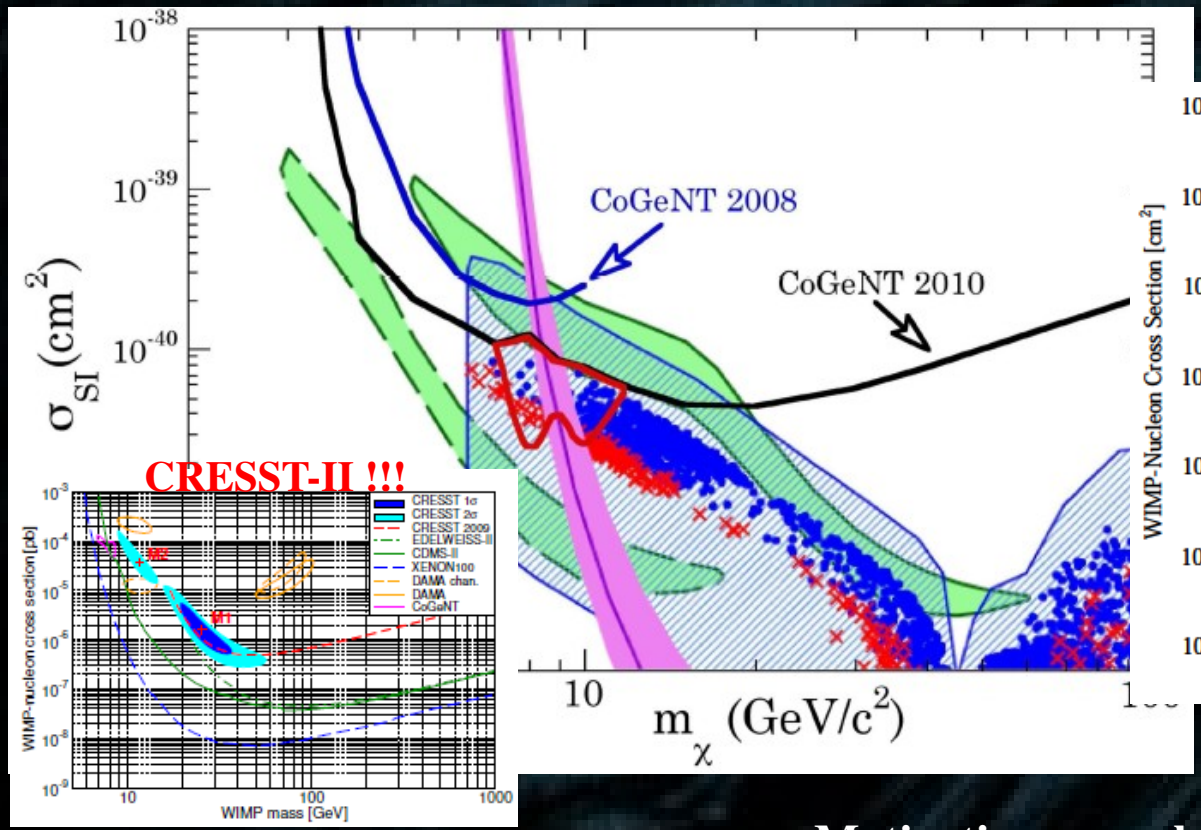
CONSISTENT WITH CURRENT DATA, eg BESS, PAMELA (AMS awaited)

Donato+01,
Bringmann & Salati 07

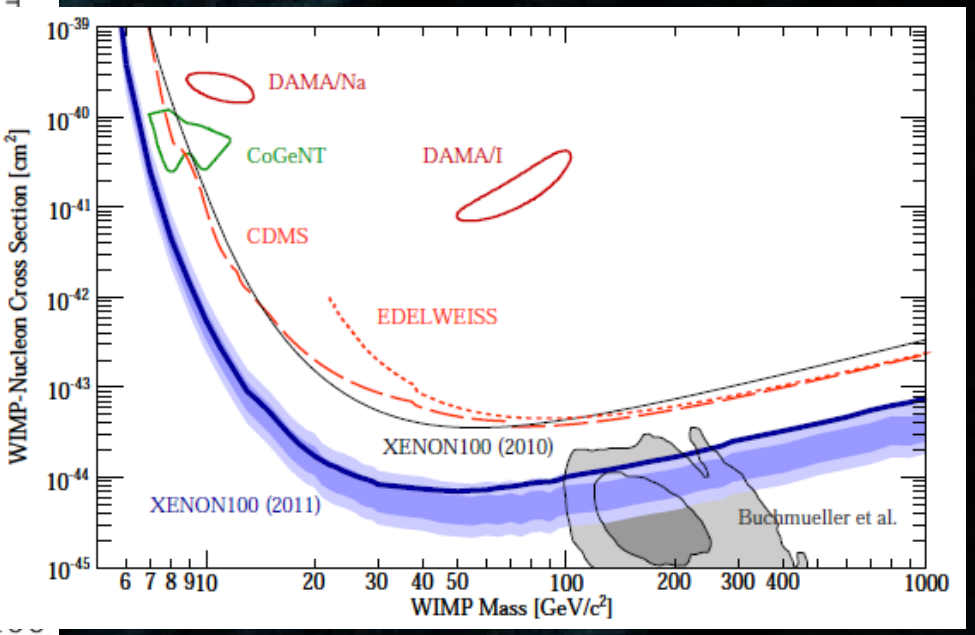


The case for light WIMPs

CoGeNT (Collar+10-11)



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



<u>Motivations are above</u>:

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

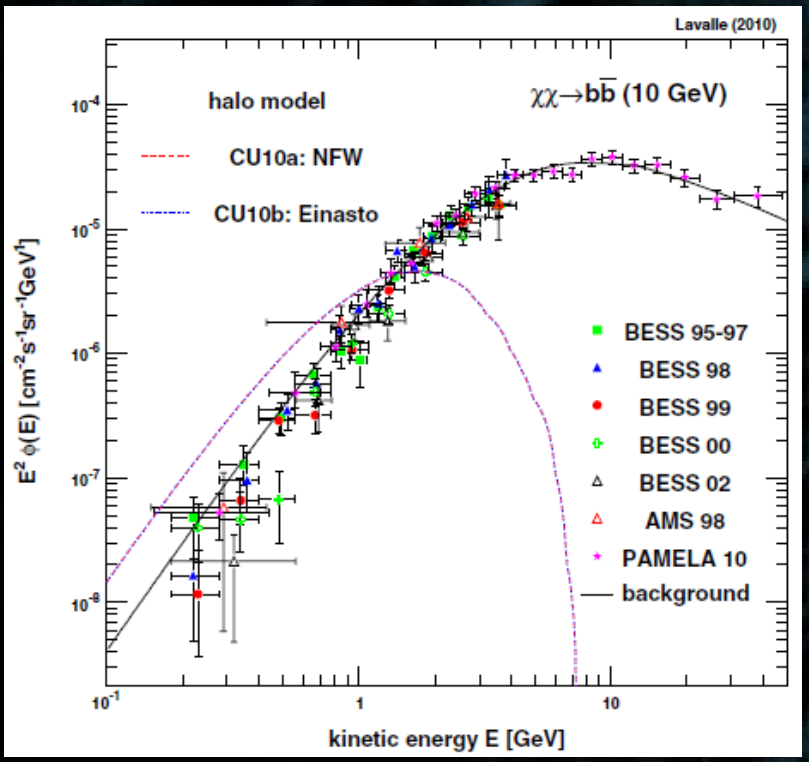
eg. MSSM neutralino

Quark
→ antiproton(s)

Any S-wave diagrams

WIMP

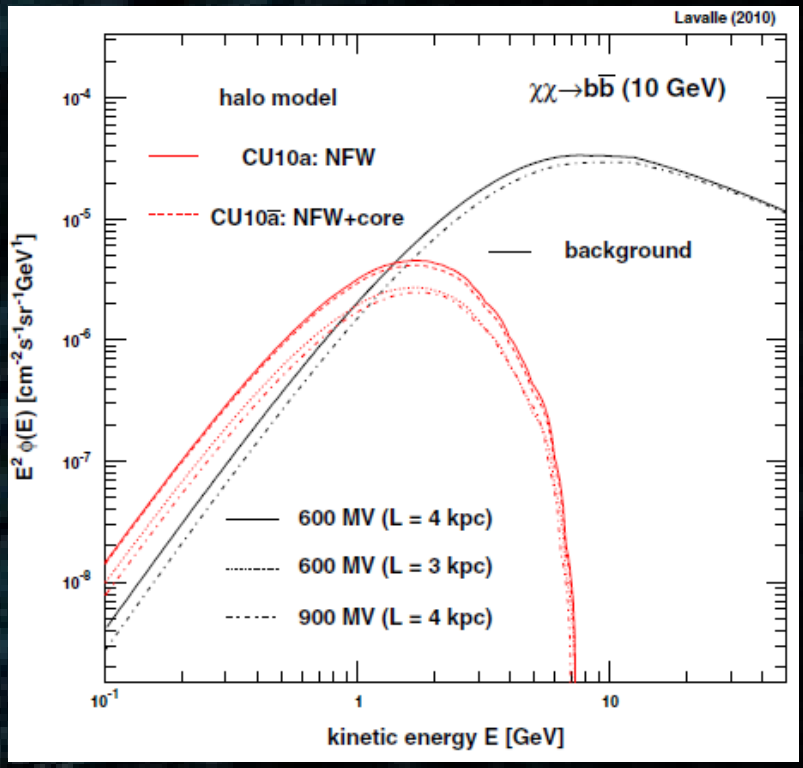
Anti-quark
→ antiproton(s)



Lavalle 10
(see also Bottino+05)

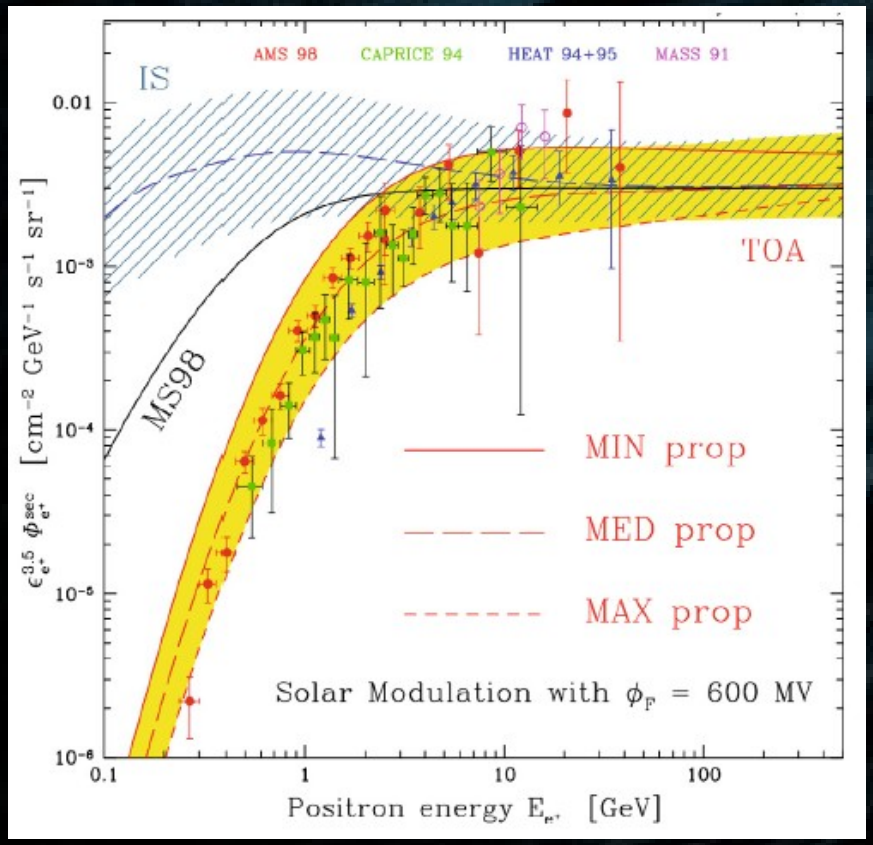
6 GeV < mass < 15 GeV
→ **big trouble with data**
$\langle\sigma v\rangle < 10^{-26}$ cm^3/s

<u>Ingredients:</u>
- 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

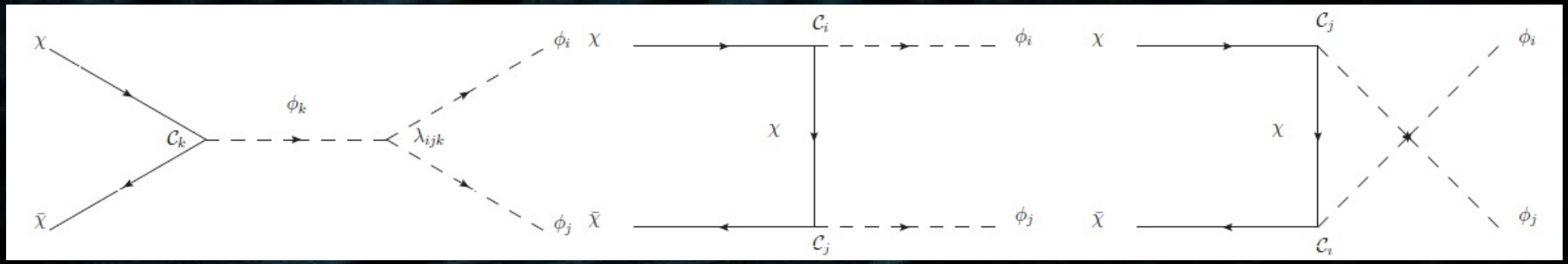
++ Positron fraction => primary source required

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

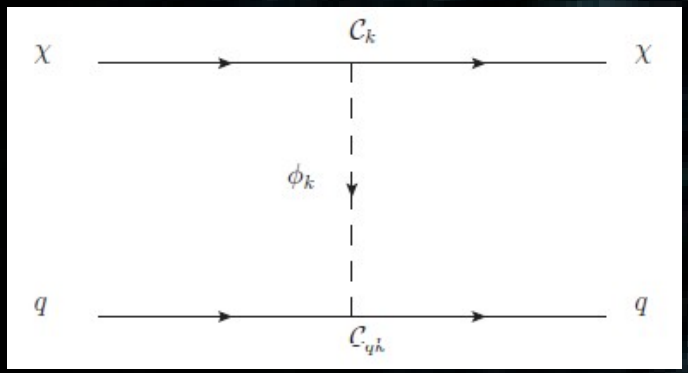
$$\chi + \bar{\chi} \xrightarrow{\text{s:}h;\ \text{t:}\chi} a + a \quad \text{(P-wave)}$$

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

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

Sets indirect detection signals

Direct detection: CP-even exchange



Effective low energy interacting Lagrangian:

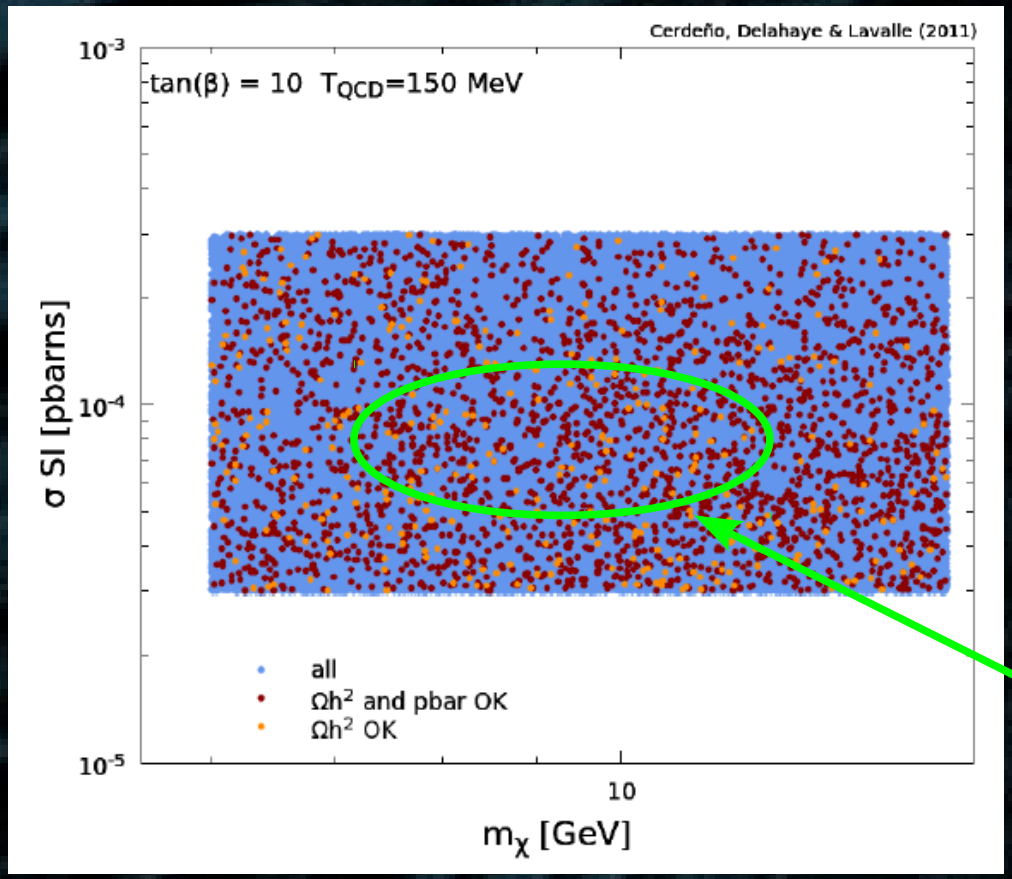
$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}\sum_i \bar{\chi}\, \mathcal{C}_{\chi i}\, \chi\, \phi_i - \sum_{i,j,k} \frac{\lambda_{ijk}}{\eta_{ijk}}\, \phi_i\, \phi_j\, \phi_k \; + \text{h.c.},$$

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 > m*a* + m*h*

Cerdeno, Delahaye & JL 11



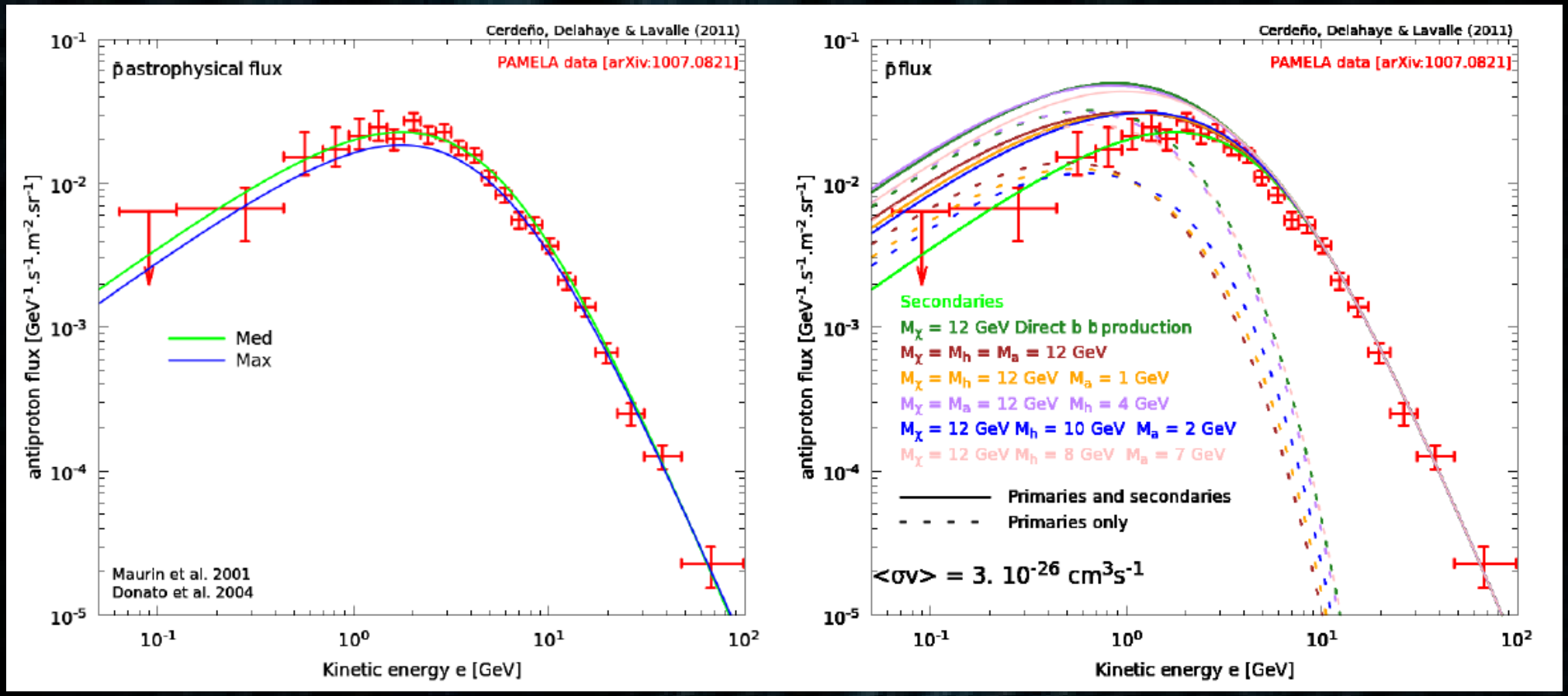
Color index:
- Excluded relic d.
- Relic d. OK
- Relic d. OK but pbar excess

CoGeNT region

Free parameters:
- Masses
- Couplings
- tanbe

Setting the antiproton constraints

Cerdeno, Delahaye & JL 11



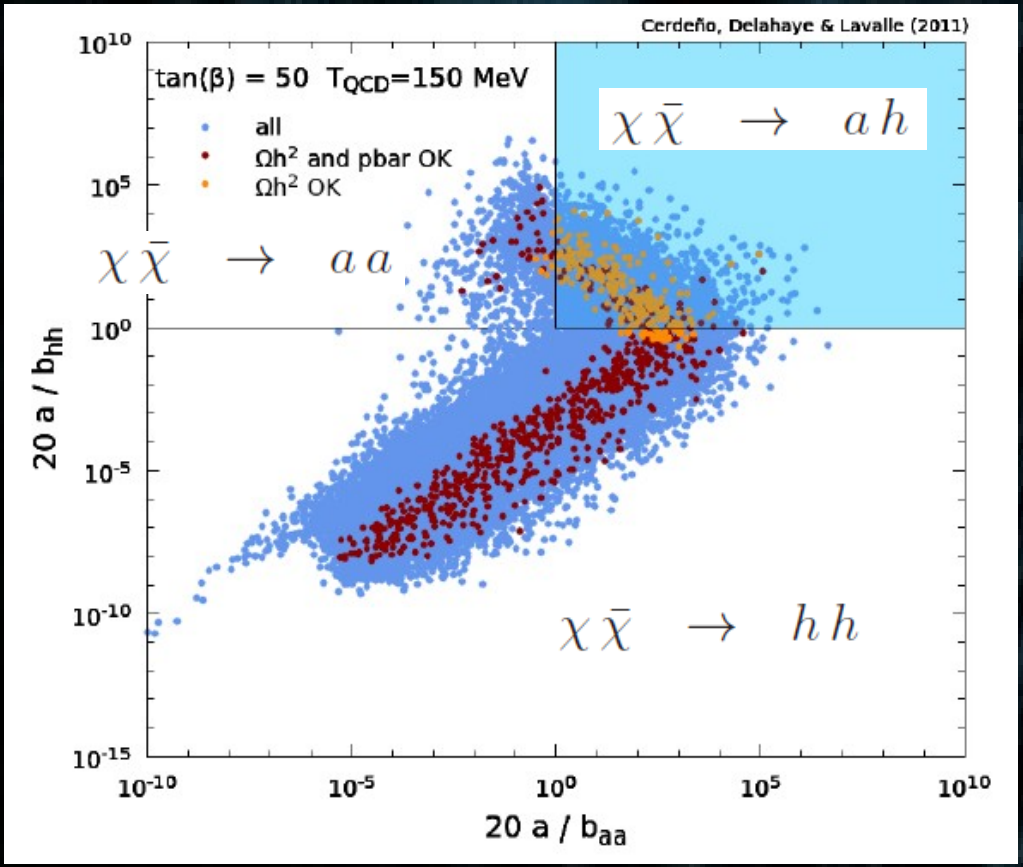
The data:
PAMELA only
[low solar activity
++ competitive errors]

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)

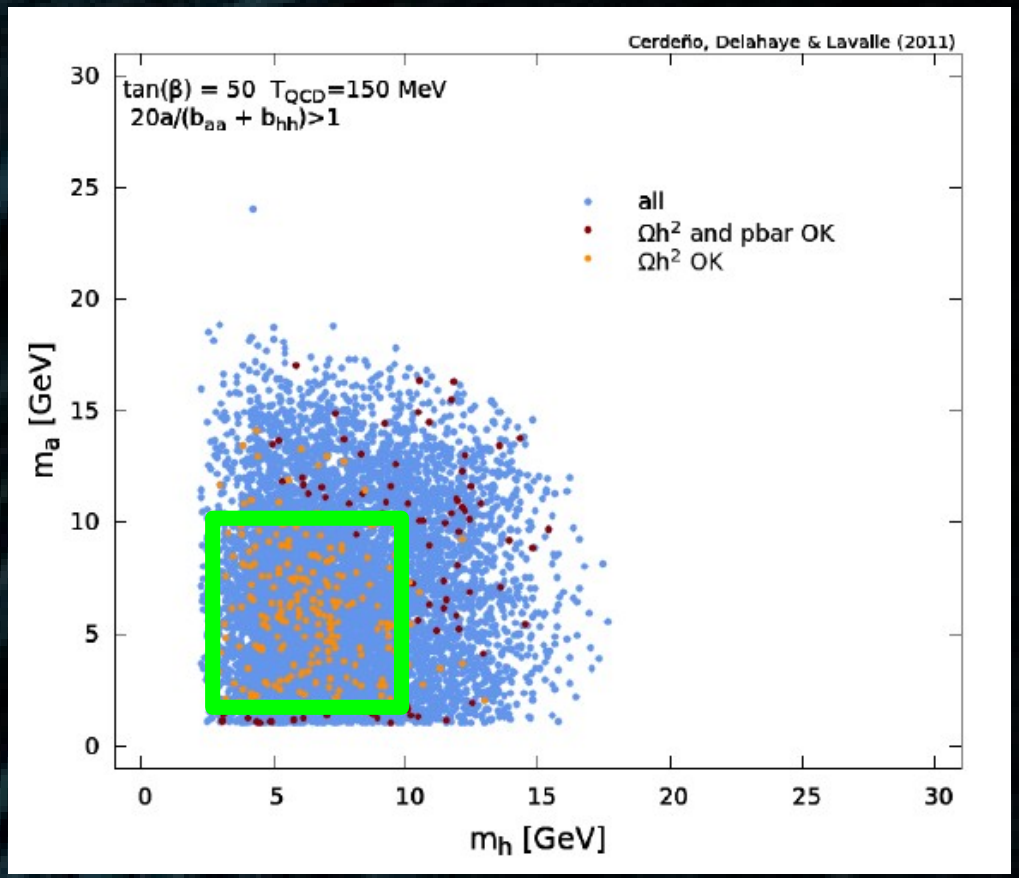
Understanding the results: S-to-P wave ratio and mass range

Indirect detection signal => pure S-wave required



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

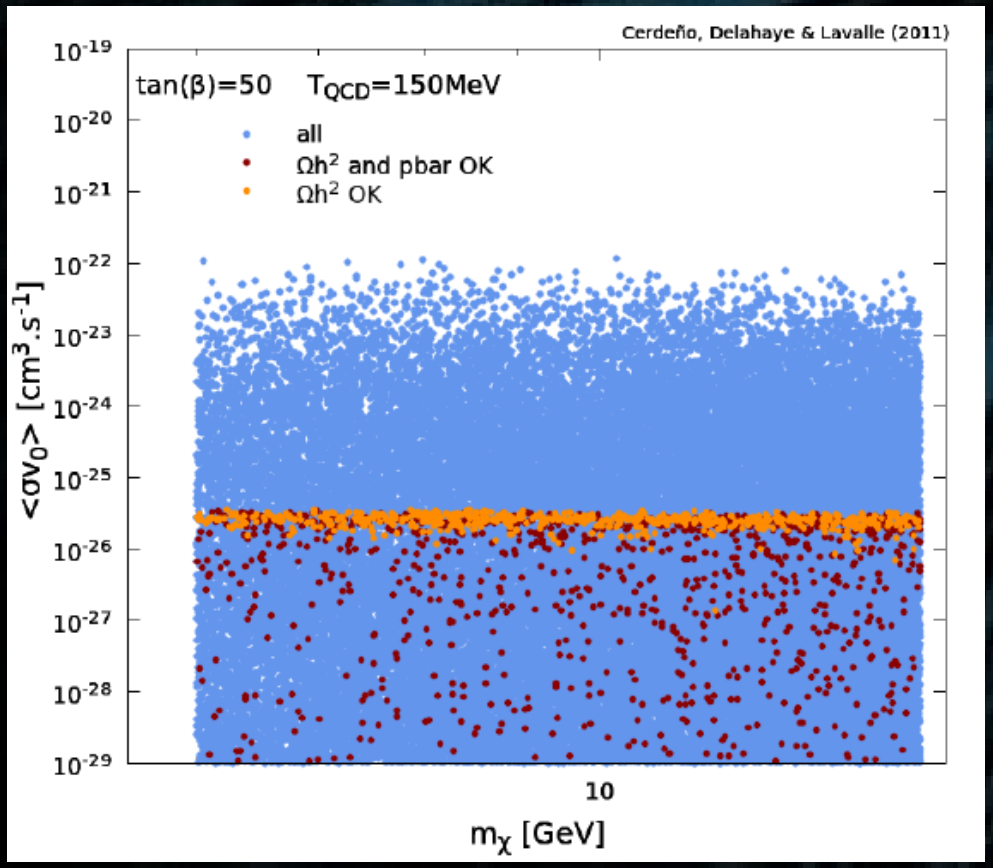
Light Higgs bosons masses

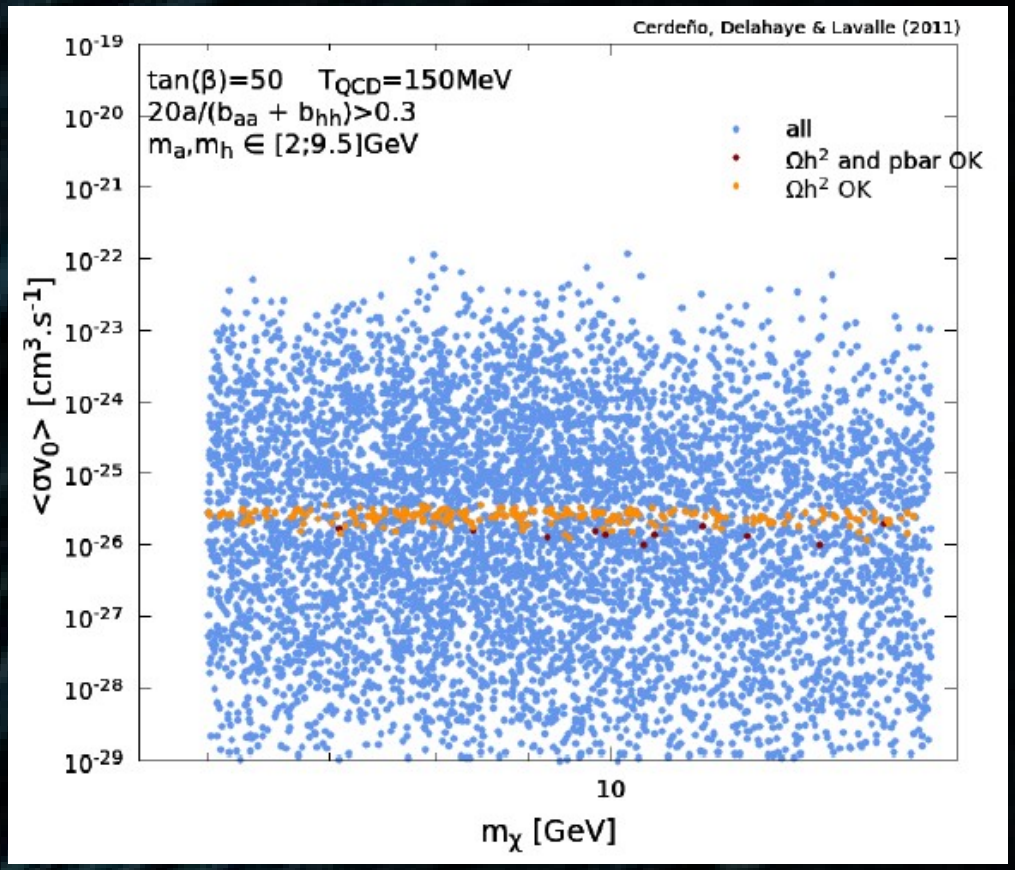


m < 2 mp or m~2 mb~10 GeV do not produce antiprotons

In terms of annihilation cross section

Cerdeno, Delahaye & JL 11



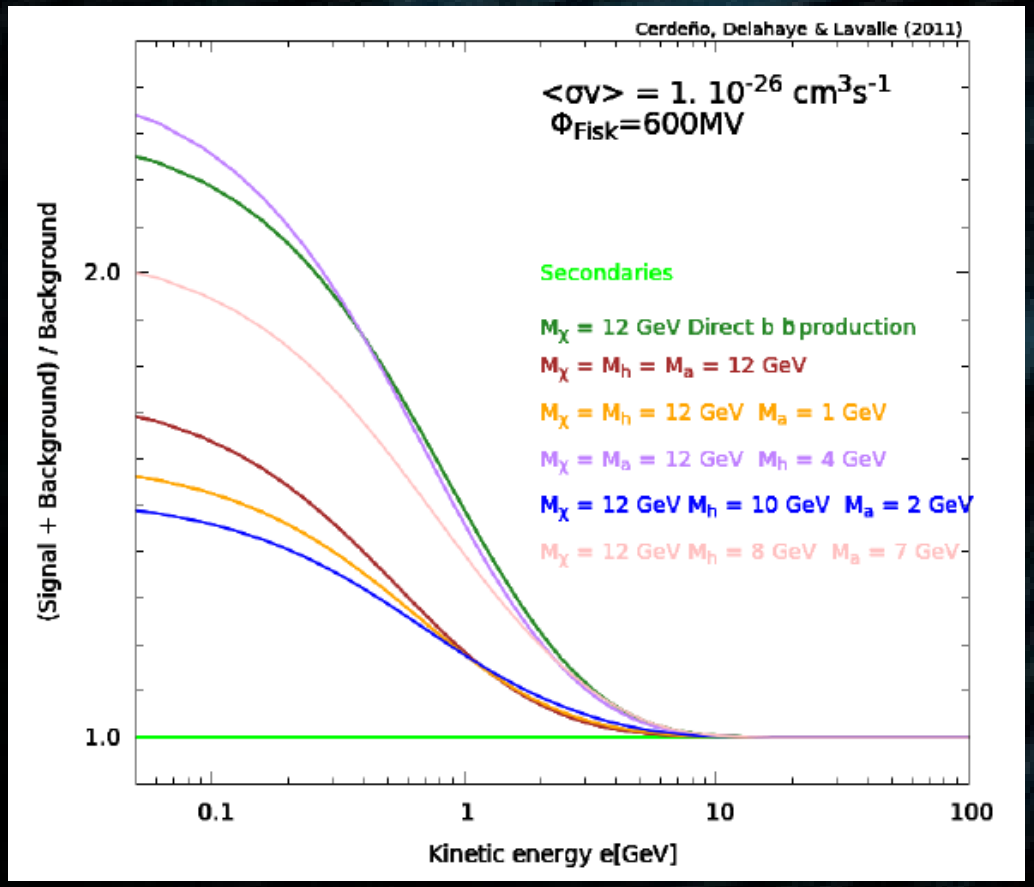


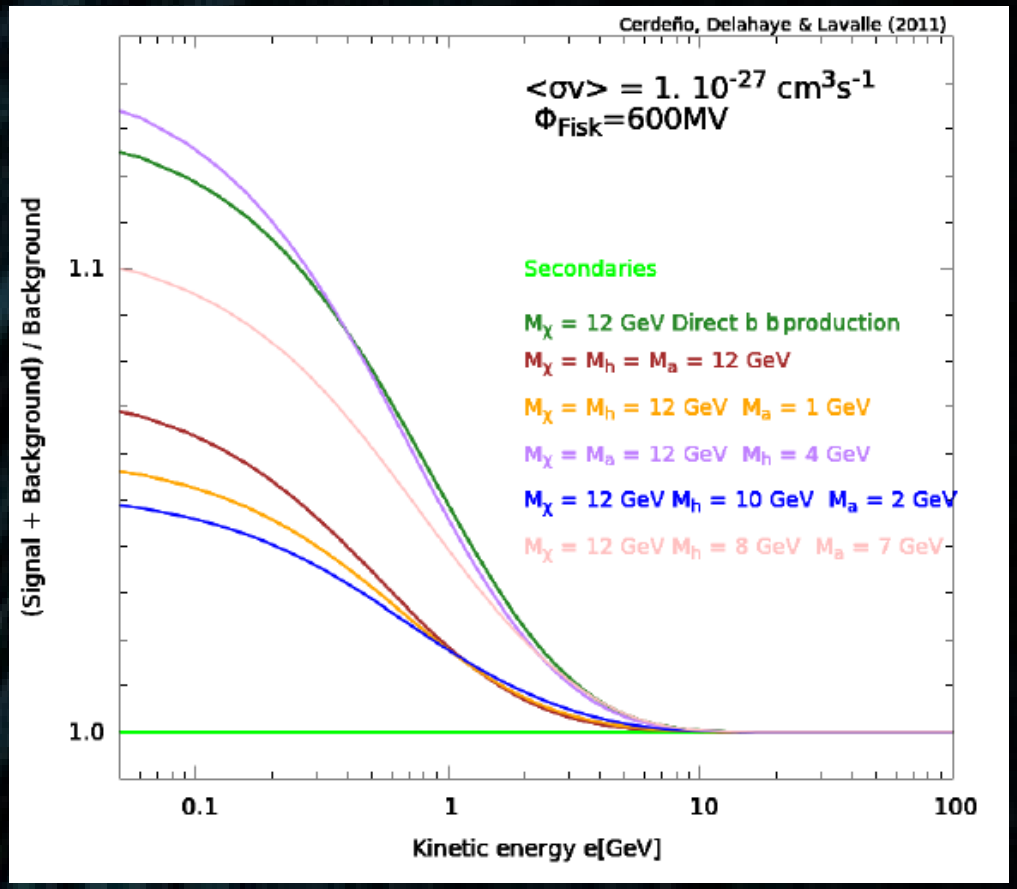
Select S-wave dominated annihilation
++ light Higgs bosons' mass range

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

Can we do better ?

Typical signature = low energy spectral break





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

Conclusions

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

- This requires 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:
$\langle \sigma v \rangle < 8 \times 10^{-27}$ cm^3/s, typically (100% into quark pairs)

- Singlino-like WIMP candidates also strongly constrained in some cases
[annihilation into CP-even + CP-odd <= 2 mchi > ma + mh]

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

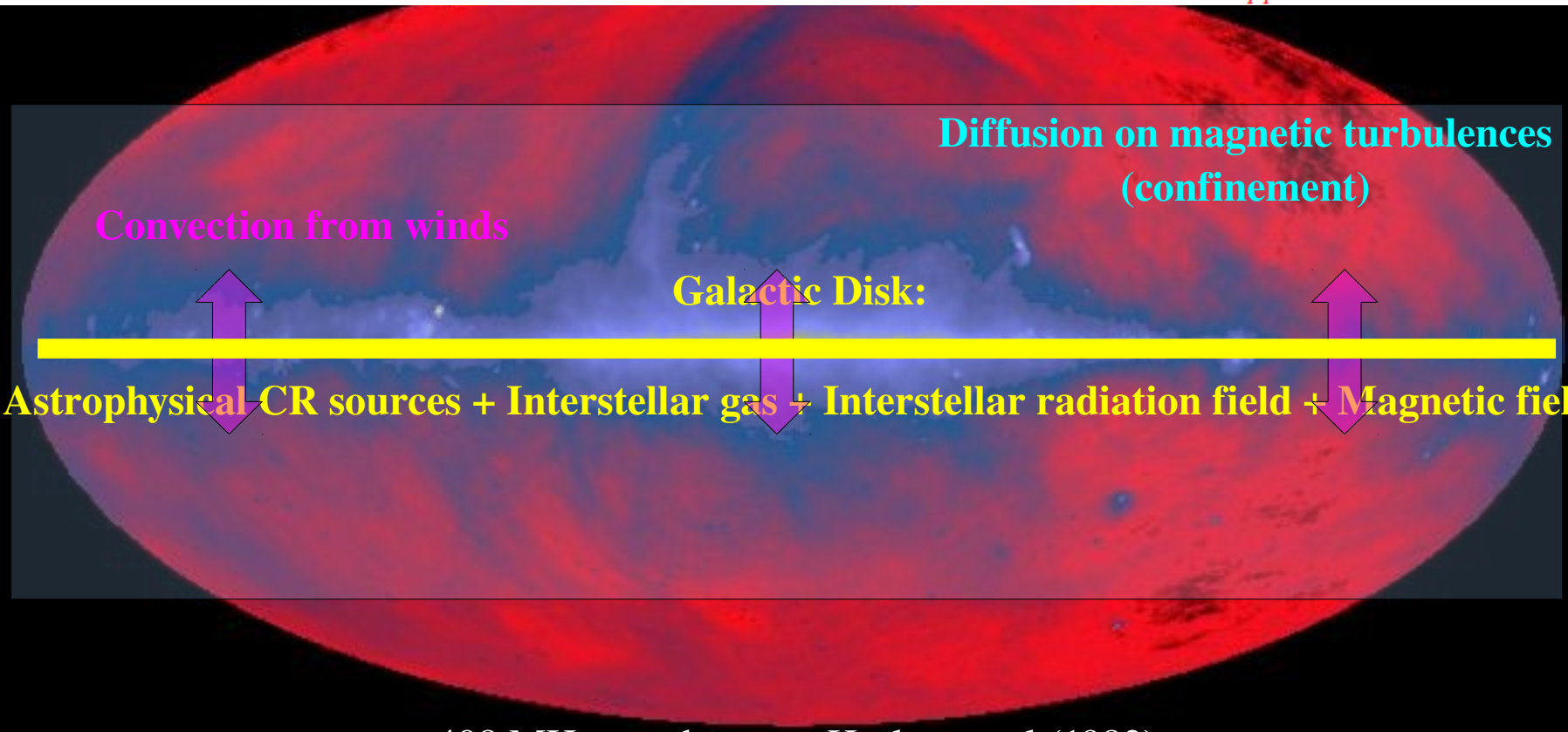
- Complementarity with gamma-rays + radio in prep. !

Backup slides

Propagation of Galactic cosmic rays: The standard picture

e.g. Berezinsky et al 90, Ptuskin's talk, Putze's talk

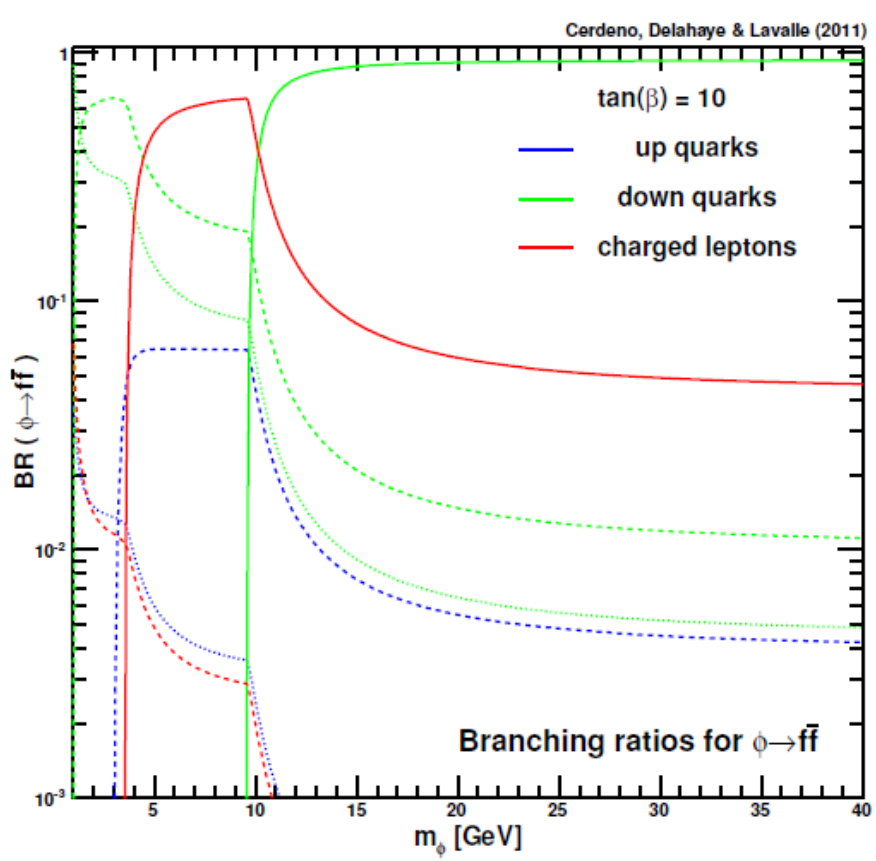
$$\underbrace{\partial_t \mathcal{N}}_{\text{time evolution}} = \underbrace{\mathcal{Q}(\vec{x}, E, t)}_{\text{source}} + \underbrace{\vec{\nabla}\left\{\left(K_{xx}(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \underbrace{\partial_p\left\{\left(\dot{p}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

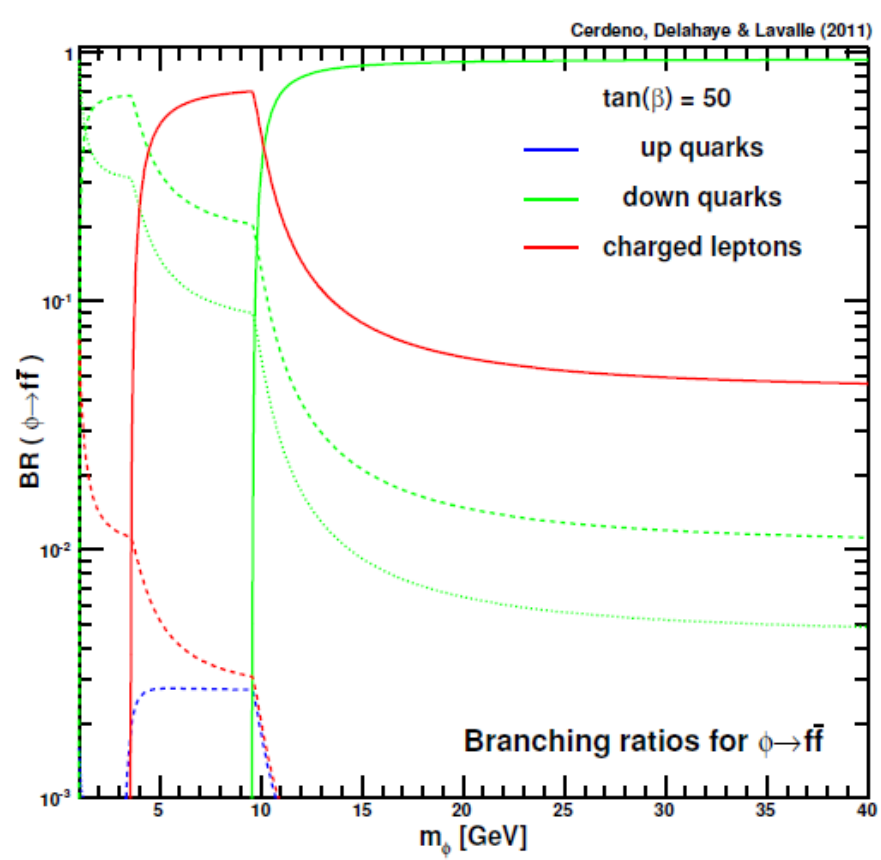


408 MHz synchrotron, Haslam et al (1982)

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

Light Higgs bosons' couplings to SM fermions

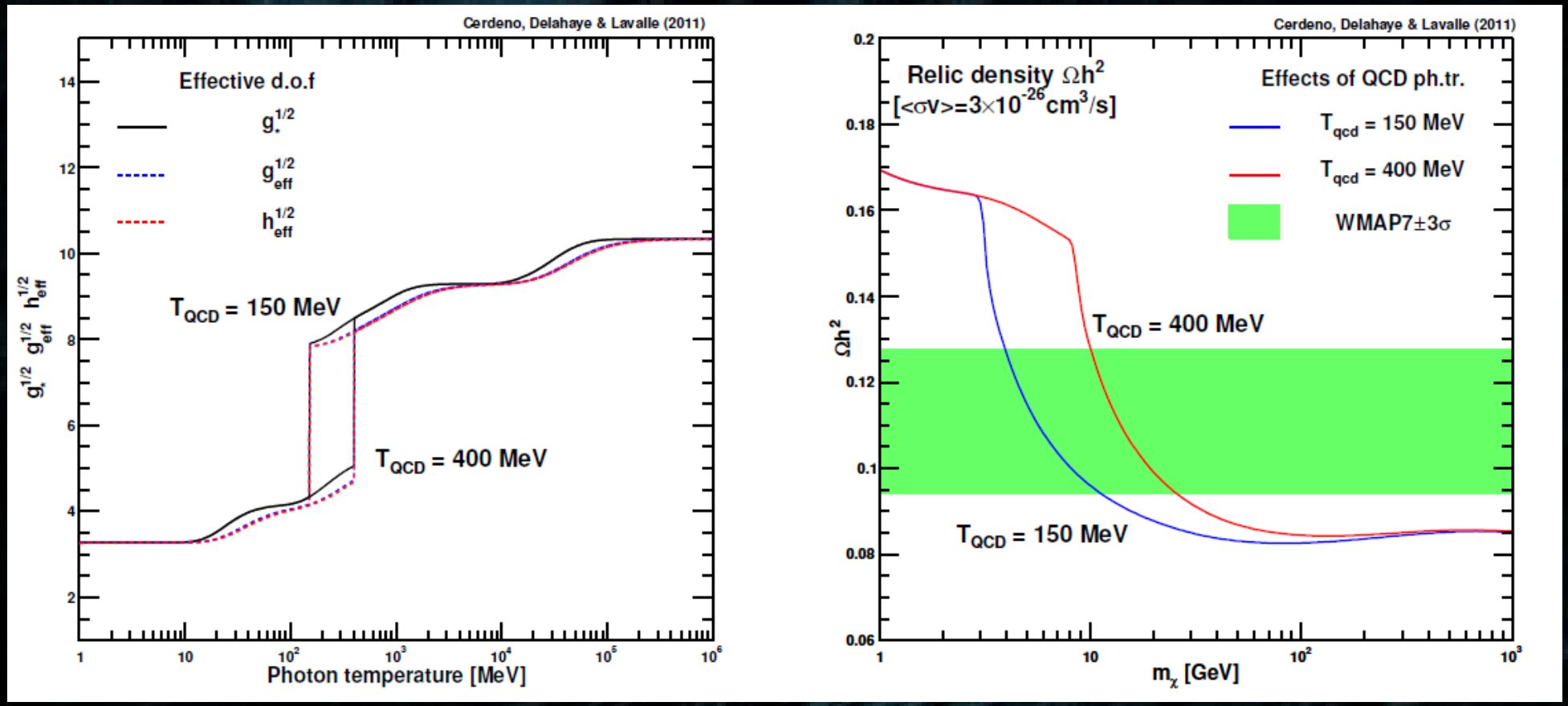




$$
\begin{aligned}
h &= s_\varphi \, [s_\theta \, \mathrm{Re}(H_d) - c_\theta \, \mathrm{Re}(H_u)] + c_\varphi \, \mathrm{Re}(S) \\
a &= s_{\varphi_a} \, [s_{\theta_a} \, \mathrm{Im}(H_d) - c_{\theta_a} \, \mathrm{Im}(H_u)] + c_{\varphi_a} \, \mathrm{Im}(S) \\
&= s_{\varphi_a} \, [A_{\mathrm{MSSM}}]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

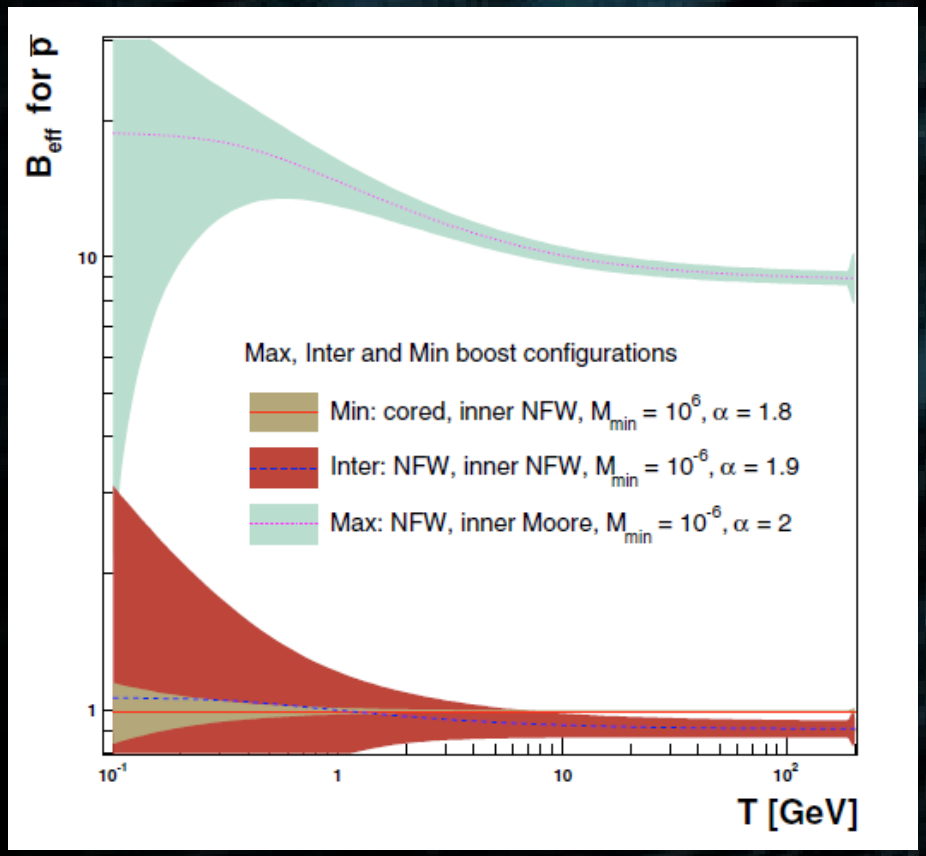
$$
\begin{aligned}
C_{\phi_i,\mathrm{up,up}} &= -\frac{g \, m_u}{2 \, M_W \, s_\beta} \left\{ s_\varphi \, c_\theta - i \, \gamma_5 \, s_{\varphi_a} \, c_{\theta_a} \right\} \\
C_{\phi_i,\mathrm{down,down}} &= -\frac{g \, m_d}{2 \, M_W \, c_\beta} \left\{ s_\varphi \, s_\theta - i \, \gamma_5 \, s_{\varphi_a}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

Relic density: theoretical uncertainties



Considering dark matter subhalos

JL, Yuan, Maurin & Bi (08)



Pieri, JL, Bertone & Branchini 10