Title: Interpreting recent dark matter hints

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Abstract: Recent PAMELA and ATIC results may represent a breakthrough in dark matter searches beyond its gravitational imprint. After briefly reviewing the possible (classes of) explanations for the observed excesses in positron and electron cosmic ray fluxes I will focus on a two component dark matter model that may provide an explanation for large boost factors needed in the dark matter annihilation interpretation of the signals.

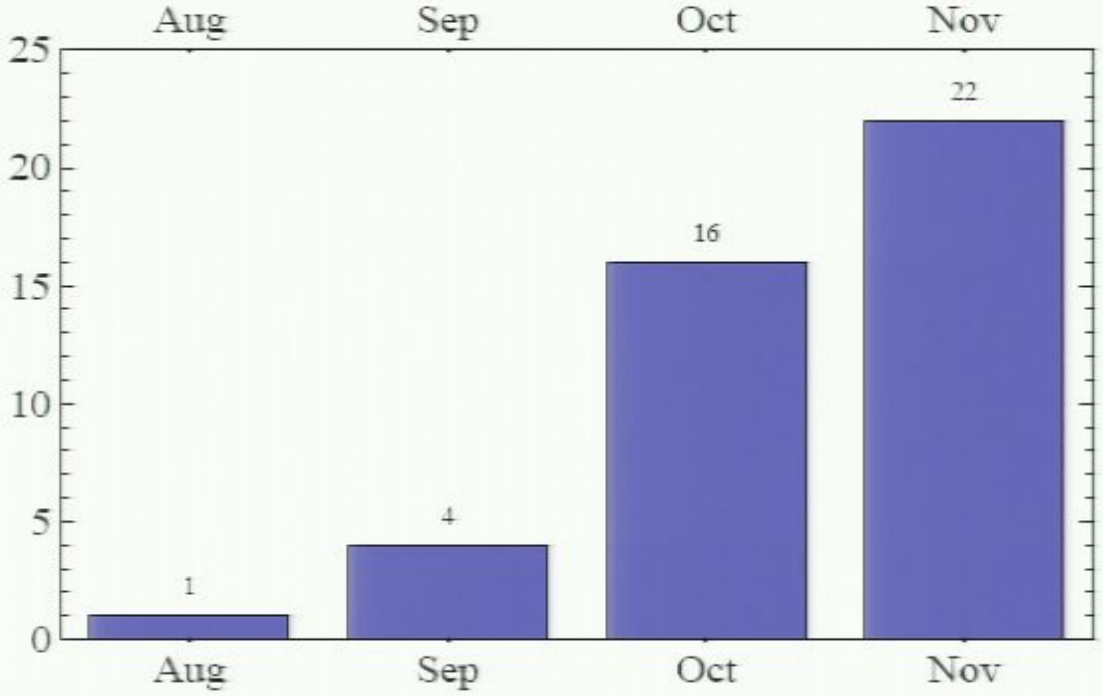
Interpreting dark matter hints

Jure Zupan

CERN & IJS & Univ. of Ljubljana

Papers, papers and more papers

- since summer conferences a flood of papers
- at least 43 so far (not all show up on spires cites)



- Pamela data (0810.4995) appeared on arXiv Oct. 28
- my talk: a snapshot of the situation now

Outline

- Data: Pamela, ATIC, HESS
- challenges
  - boost factors
  - annihilation modes
- proposed solutions
- new challenges from the past week

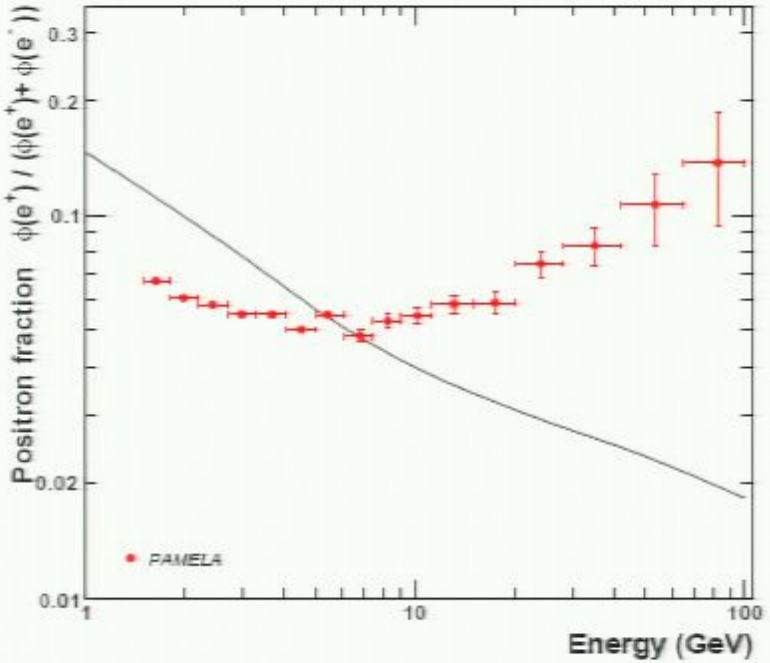
Pamela

- Pamela=Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
- satellite mission, launched june 2006
- expected sensitivity

Particle	Energy Range
Antiproton flux	80 MeV - 190 GeV
Positron flux	50 MeV - 270 GeV
Electron flux	up to 400 GeV
Proton flux	up to 700 GeV
Electron/positron flux	up to 2 TeV
Light nuclei (up to Z=6)	up to 200 GeV/n
Light isotopes (D, 3He)	up to 1 GeV/n
Antinuclei search	(better than 10^{-7} in antiHe/He)

Pamela-positrons

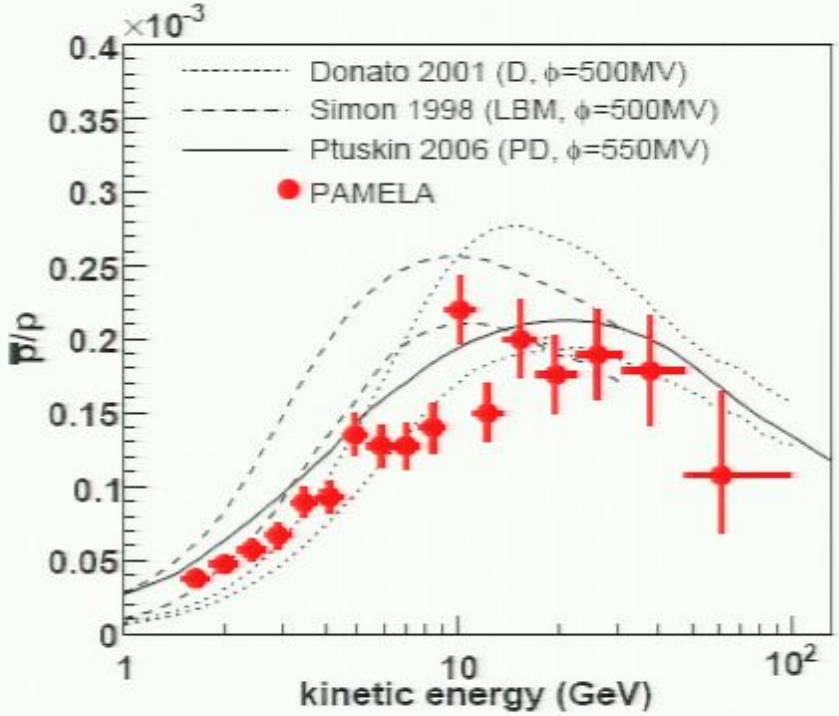
- turn-up in the positron fraction above $10\mathrm{GeV}$ 0810.4995
- comparison with the expected background (secondary production - Moskalenko& Strong [Galprop])
- low energy (< 10 GeV) sensitive to solar modulation



Pamela-antiprotons

0810.4994

- no excess seen in the antiproton fraction spectrum



LBM=Leaky Box Model, D=Diffusion model, PD=Plain Diffusion model

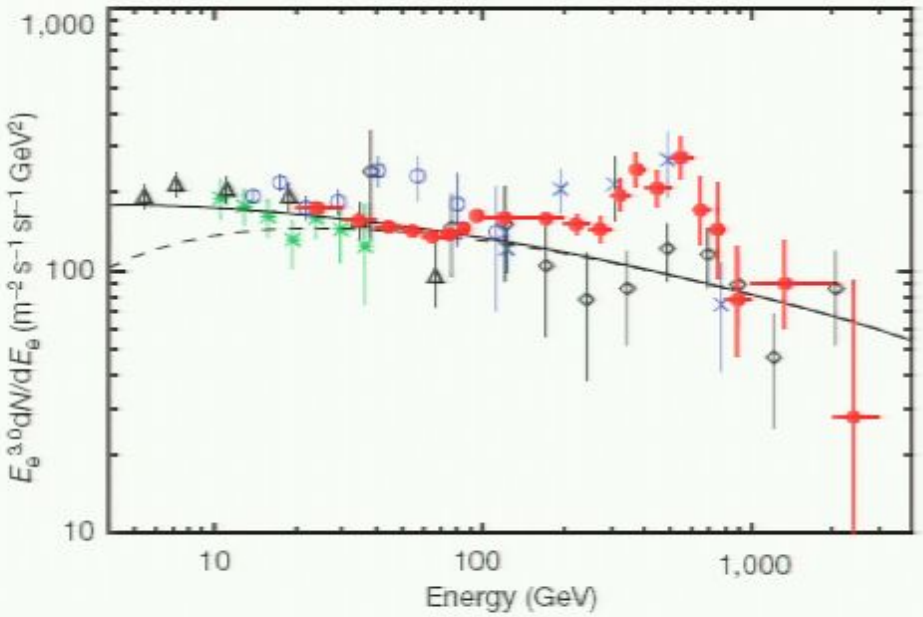
ATIC

- ATIC=Advanced Thin Ionization Calorimeter
- long duration balloon flights over Antarctica
- capable of measuring the incident cosmic ray $|e|$ and energy over an energy range of $50\mathrm{GeV}$ to $> 100\mathrm{TeV}$
- does not distinguish electrons from positrons

ATIC-electrons+positrons

Nature, 456, 07477

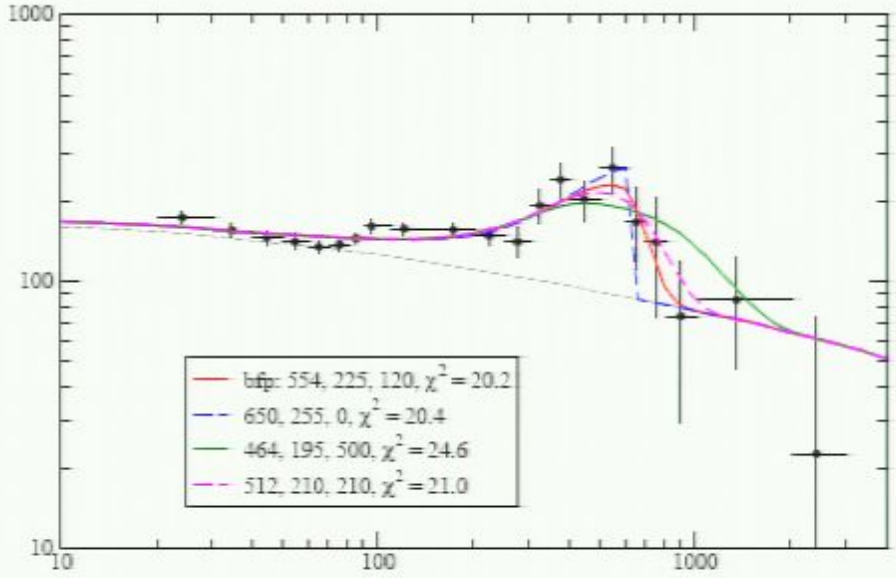
- released last week: $\gtrsim 4\sigma$ excess in $\Phi(e^+ + e^-)$

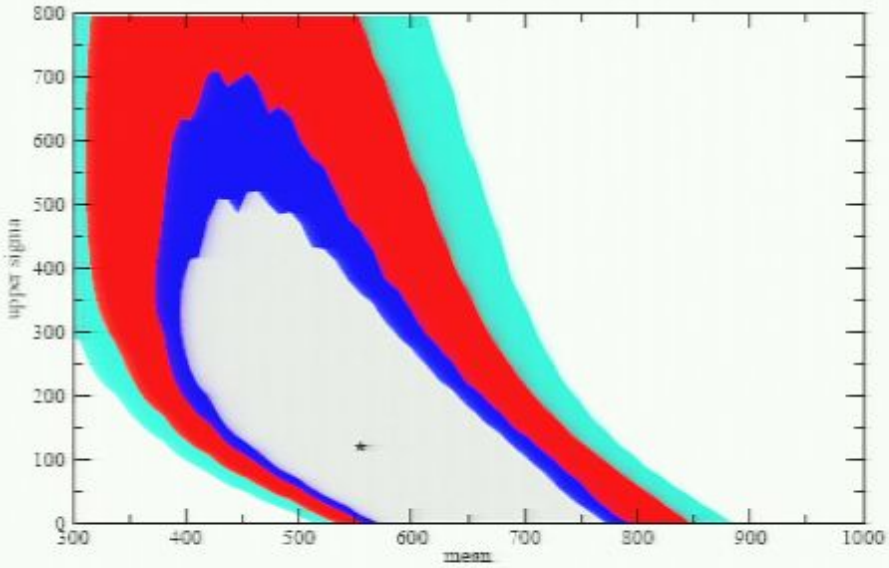


- ATIC
- AMS
- △ HEAT
- ○ BETS
- × PPB-BETS
- ◇ emulsion chambers
- — GALPROP prediction
- – – estimate of solar modulation

Cut-off?

- Do we see a cut-off in ATIC data? Niro, Fairbairn, Schwetz, JZ, unpubl.
- a fit to an asymmetric gaussian, bck. from Galprop





- numbers on the left plot: mean, $\sigma_{\rm lower}$, $\sigma_{\rm upper}$, χ^2
- other func. forms also support cut-off (or steep change in power law)

Interpretations

- astrophysical sources: local supernovae remnants (pulsars)?
- signal of nongravitational dark matter interactions?

Astrophysical source?

- a local pulsar suggested as a source

Hooper, Blasi, Serpico, 2008; Serpico 2008;+ refs in

- need to be young $\sim 100k\text{years}$
- known sources do not give large enough e^+ flux

ATIC, Nature, 456, 07477

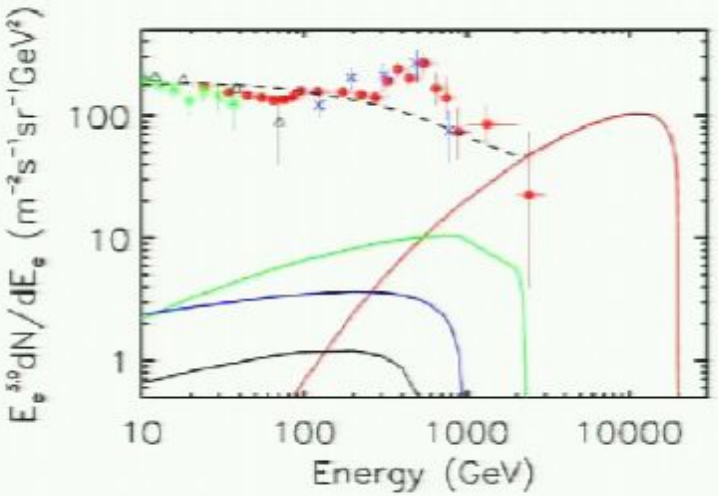


Figure s10. The possible contribution to the electron spectrum from nearby sources: Vela (red). Monogem (green). Loop 1 (blue) and Geminga (black).

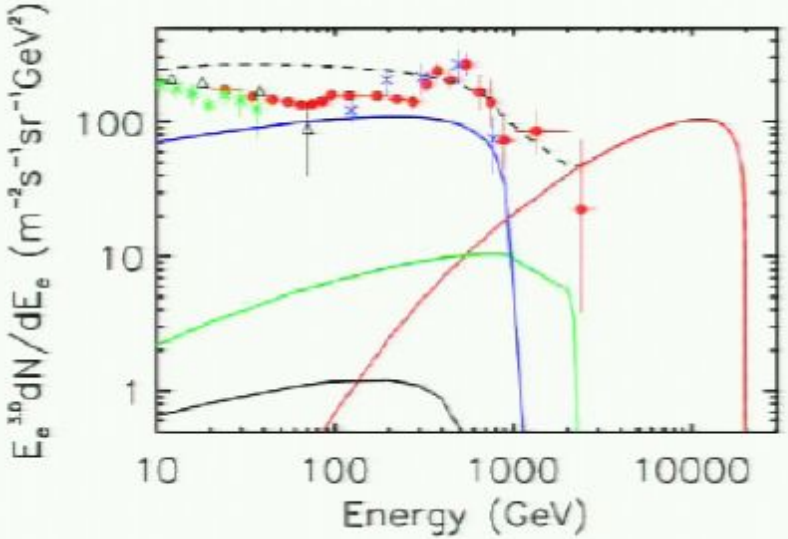


Figure s11. Predicted electron spectrum for a Loop 1 source with its intensity scaled by a factor of 30.

DM signal?

- assume for the moment that the signal due to annihilation

$$\chi + \chi \to X_{SM},$$

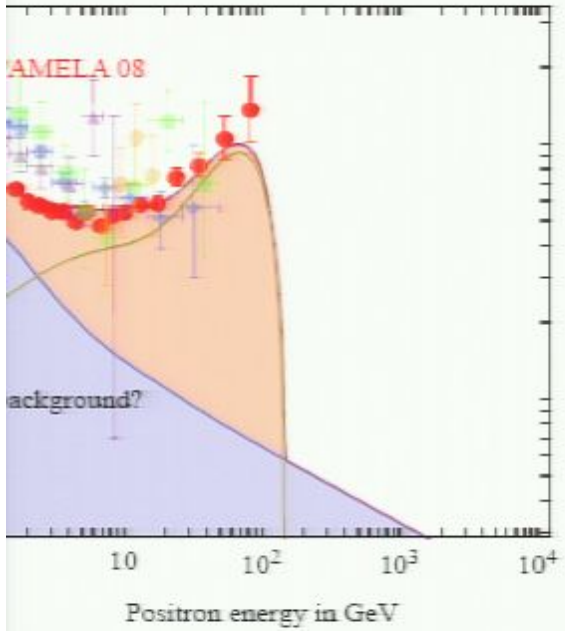
where $X_{SM} = e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \bar{q}q, \bar{b}b, \bar{t}t, WW, ZZ, hh$

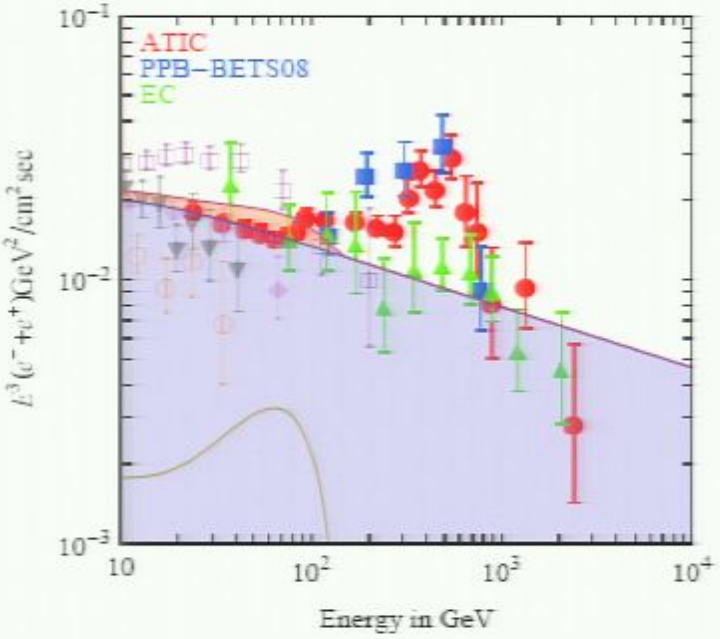
- Cirelli et al. performed model independent analysis
- find two preferred solutions
  - $1\mathrm{TeV}$ DM with $\chi + \chi \to l^+l^-$
  - $> 10\mathrm{TeV}$ DM with $\chi + \chi \to WW$

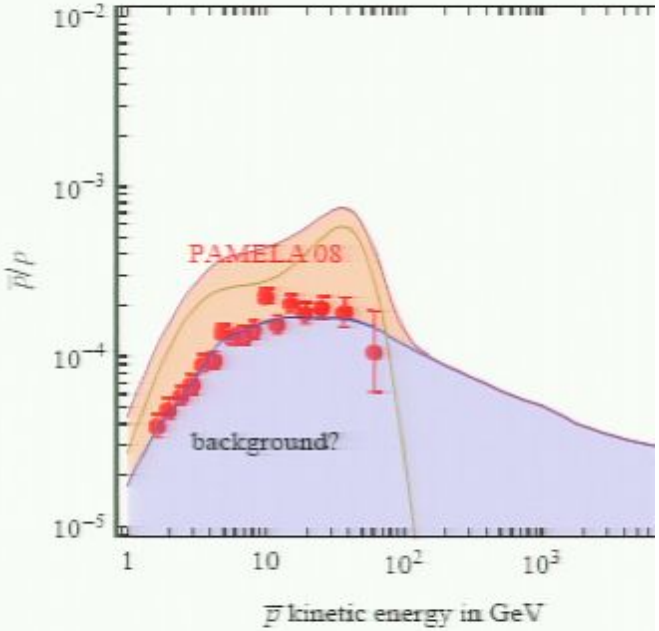
150 GeV DM

Cirelli, Kadastik, Raidal, Strumia 08

DM with $M = 150$ GeV that annihilates into W^+W^-



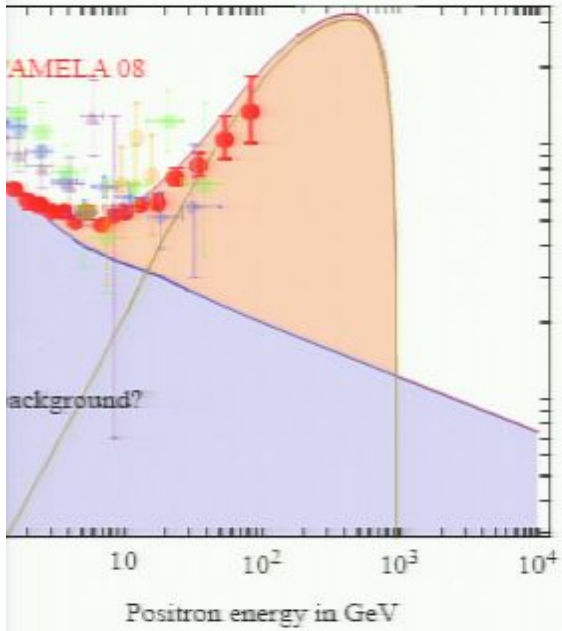


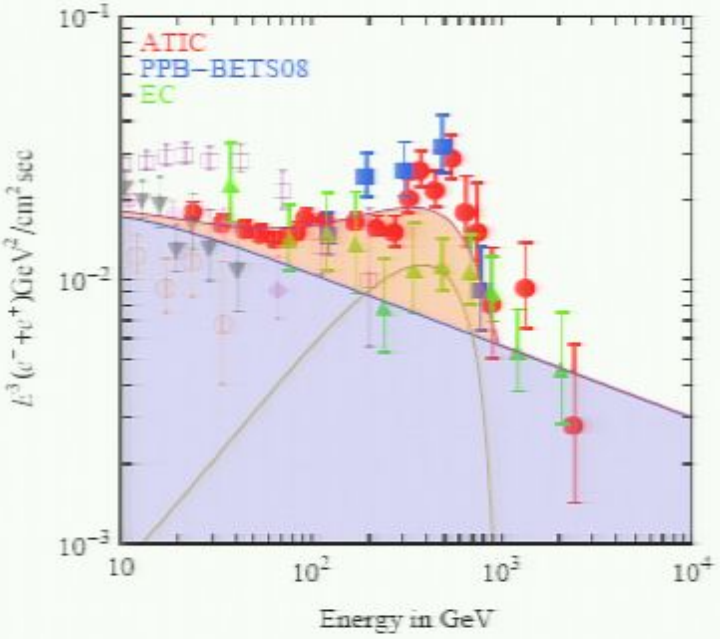


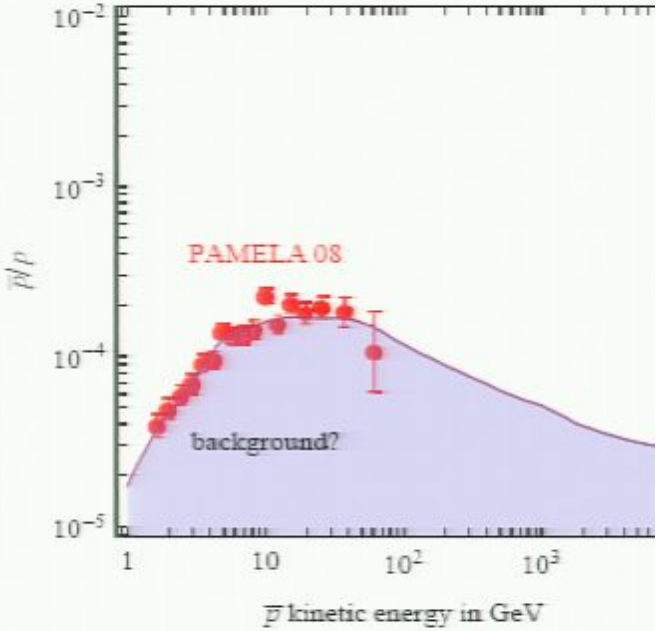
1 TeV DM

Cirelli, Kadastik, Raidal, Strumia 08

DM with $M = 1$ TeV that annihilates into $\mu^+\mu^-$



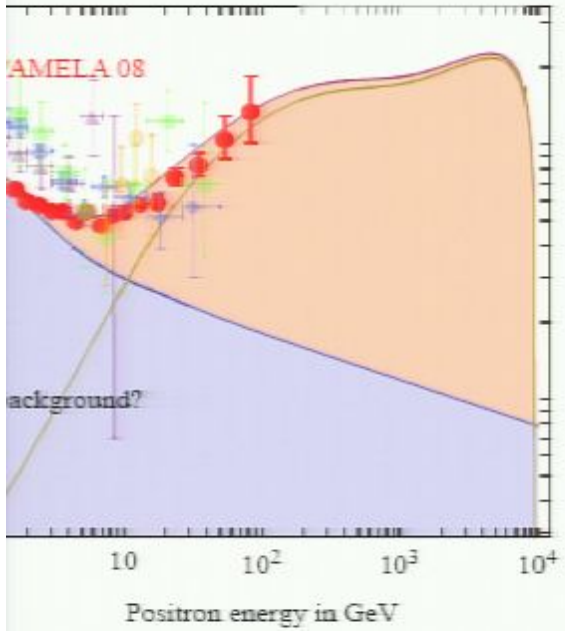


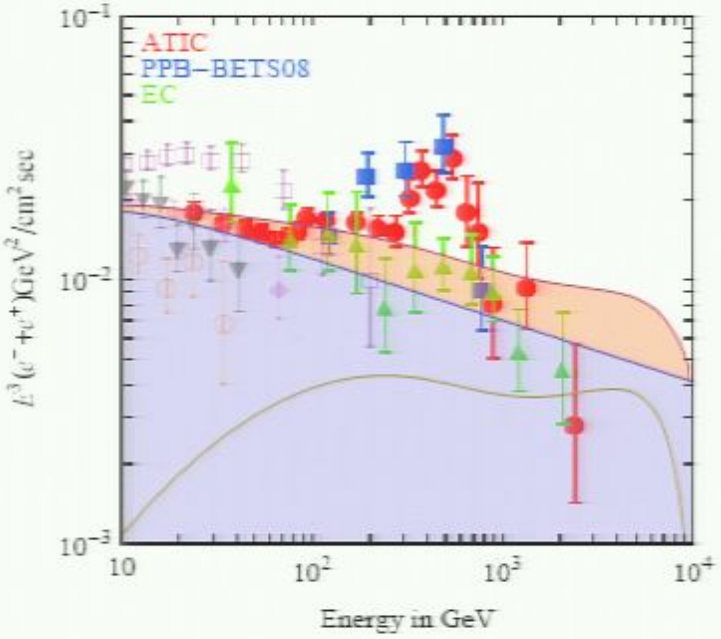


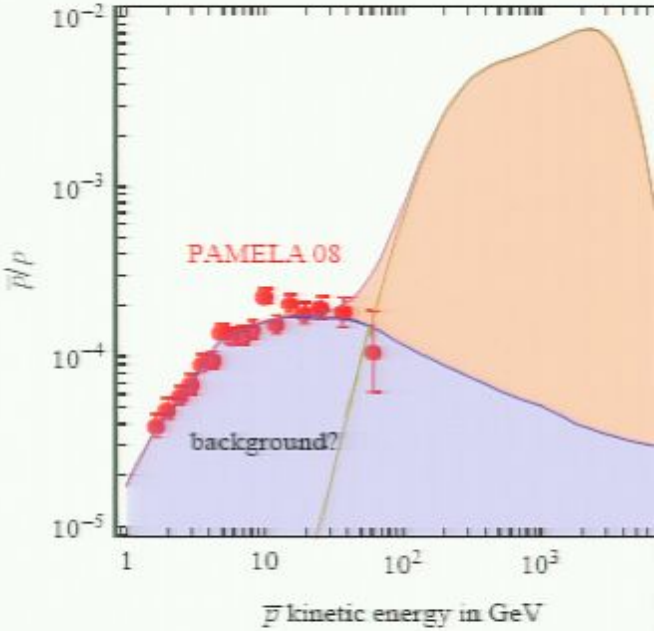
10 TeV DM

Cirelli, Kadastik, Raidal, Strumia 08

DM with $M = 10$ TeV that annihilates into W^+W^-







Challenges

two challenges if DM annihilation $\chi\chi \to X_{SM}$

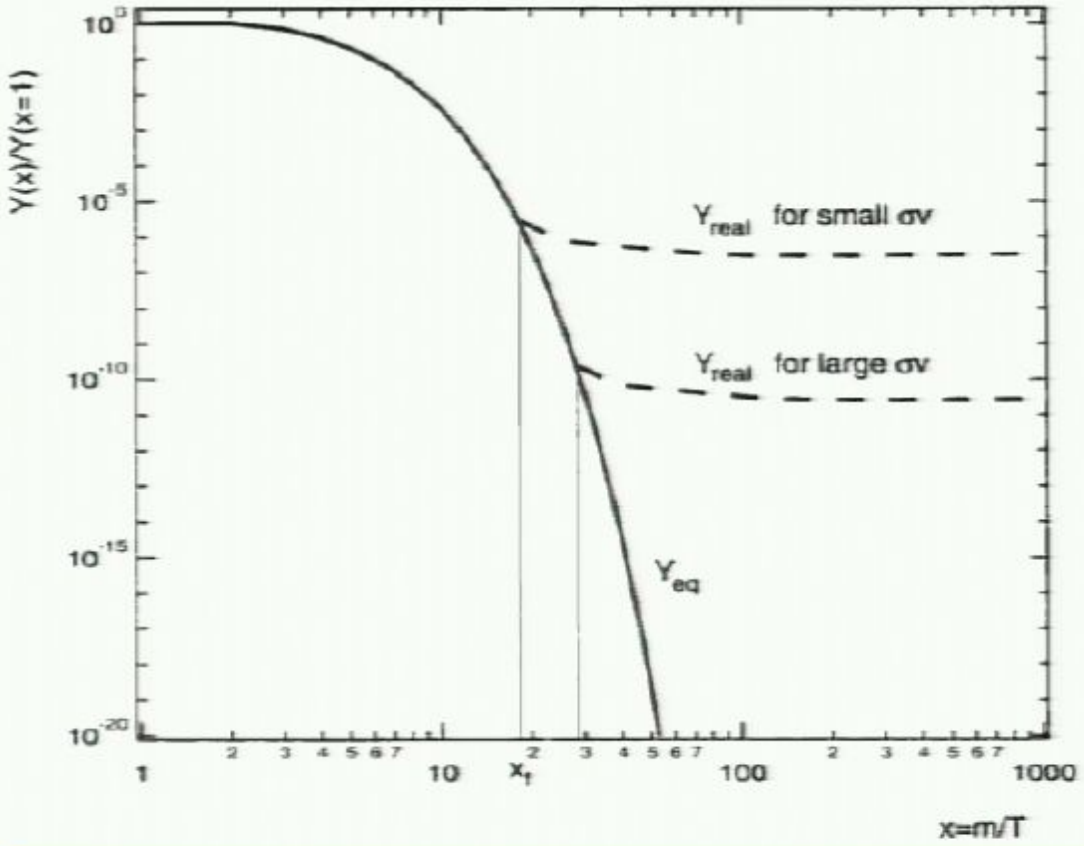
- signal in leptons (e^+) but not in quarks ($\bar{p}$)
- the annihilation cross section larger than expected for a thermal relic

Thermal relic

- if simple thermal relic then

$$\Omega_{\rm DM} \propto 1/\langle \sigma_A v \rangle_{\rm F} \Rightarrow \langle \sigma_A v \rangle_{\rm F} \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$$

$Y = n/s$



Boost factor

- if simple thermal relic then
  $\Omega_{\rm DM} \propto 1/\langle\sigma_A v\rangle_{\rm F} \Rightarrow \langle\sigma_A v\rangle_{\rm F} \simeq 3\times 10^{-26}{\rm cm}^3/{\rm s}$
- Pamela and ATIC measure

$$\Phi_{e^+} \propto \langle\sigma_A v\rangle \rho^2_{\rm DM}/m^2_{\rm DM}$$

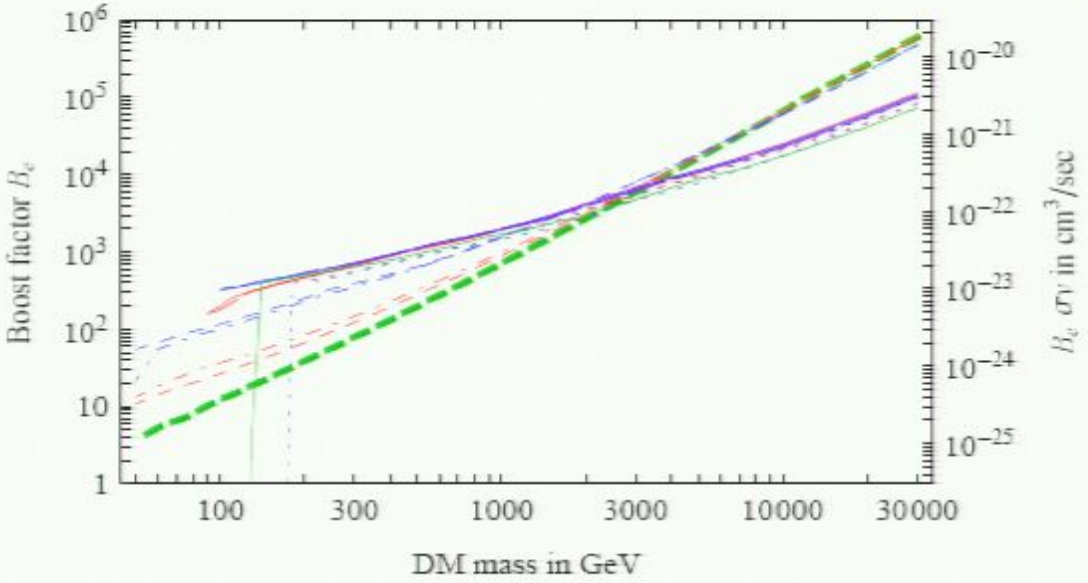
- define a "boost factor"

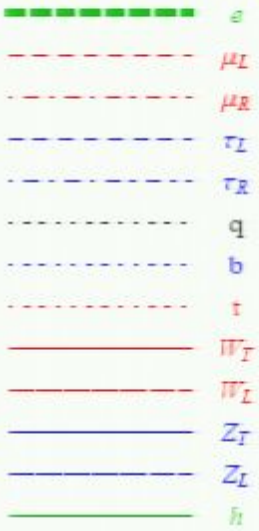
$$B \equiv \frac{\langle\sigma_A v\rangle \rho^2_{\rm DM}}{\langle\sigma_A v\rangle_F (\bar{\rho}_{\rm DM})^2}$$

Boost factors

- model independent (EFT) analysis for Pamela

Cirelli, Kadastik, Raidal, Strumia 2008





- astrophysical boost factor (due to DM halo substructure) below 10
- $\Rightarrow$ if DM annihilation then not a simple thermal relic

Unitarity bound

- unitarity bound also imposes the upper bound on DM mass

Niro, Fairbairn, Schwetz, JZ, unpubl.

- s-wave annihilation: $\sigma v \leqslant 4\pi/(vM^2)$
- this bounds the possible boost factor

$$B \leqslant \frac{4\pi}{vM^2\langle\sigma v\rangle_F} = 5\cdot 10^6\left(\frac{1\mathrm{TeV}}{M}\right)^2\left(\frac{10^{-3}}{v}\right)$$

- from model indep. bound on previous slide for leptonic decays

$$M \leqslant 8-9\ \mathrm{TeV}$$

($M \leqslant 12\mathrm{TeV}$ for hadronic decays)

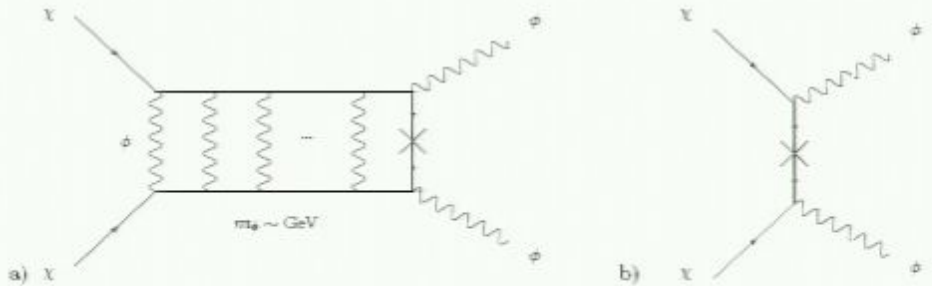
Large boost factors

- Sommerfeld enhancement due to a new long range attractive interaction between WIMPs
  Hisano et al. 03-06; Cirelli et al. 07-08; Pospelov, Ratz 08;Arkani-Hamed et al. 08; Fox, Poppitz 08; Pospelov 08; Bai, Hambye 08; Nomura, Thaler 08; Ackerman et al 08;
- annihilation through resonances
- recombination through WIMP-onium — Pospelov, Ratz 2008
- nonthermal DM: 2DM model — Fairbairn, JZ, 2008
- decaying DM
  Chen, Takahashi, Yanagida, 08; Ibarra, Tran 08; Hamaguchi, Nakamura, Shirai Yanagida 08; Yin, Yuan, Liu, hang, Bi, Zhu 08
- different temperature in the DM sector and in the visible sector — Nelson and Spitzer

Sommerfeld enhancement

Hisano et al. 03-06; Cirelli et al. 07-08; Pospelov, Ratz 08;Arkani-Hamed et al. 08; Han 08; Fox, Poppitz 08; Pospelov 08; Bai, Hambye 08; Nomura, Thaler 08; Ackerman et al 08;

- seems the most popular model-builders' choice
- additional attractive interaction enhances annihilation in NR limit



- χ- DM with mass M, ϕ mediates the interac., mass m_ϕ
- leads to a Yukawa potential $V(r) = -\alpha e^{-m_\phi r}/r$
- annihil. $\chi + \chi \to X_{\rm SM}$: $\sigma v \sim \pi \alpha'^2/M^2$
  - from relic abundance $\alpha' \sim 0.03(M/1{\rm TeV})$
  - for "secluded models" $\chi + \chi \to \phi + \phi \to X_{\rm SM} \Rightarrow \alpha = \alpha'$

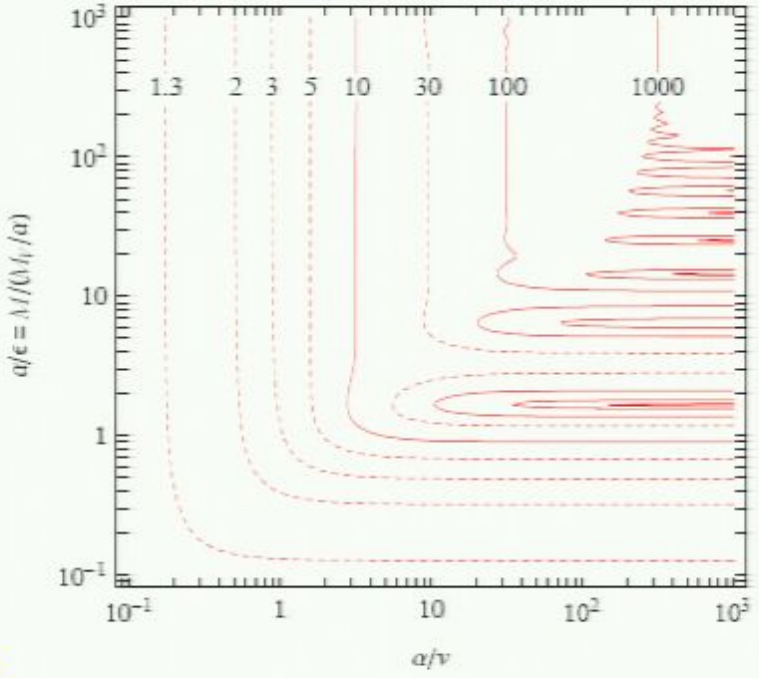
Pospelov, Ritz, Voloshin 07

Sommerfeld enhancement II

several interesting limits

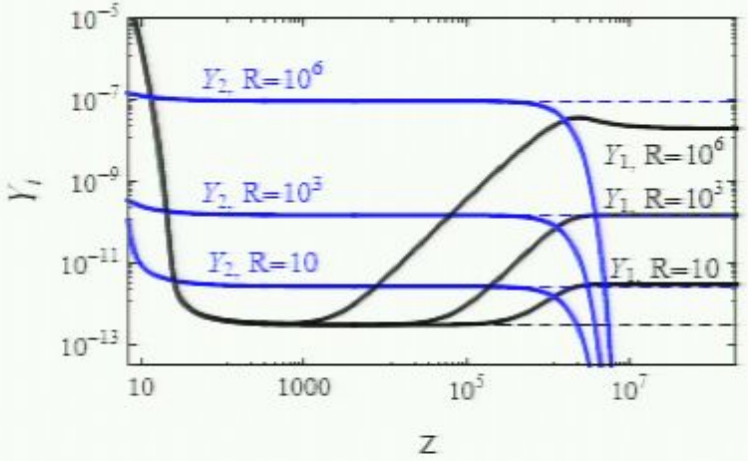
- $v^2 \gg \alpha m_\phi / M$: $\Rightarrow 1/r$ potential $\Rightarrow S = \frac{\pi\alpha}{v} \sim 10^2 \frac{\alpha}{0.03} \frac{10^{-3}}{v}$
  - for "secluded models" with $M \sim 1\mathrm{TeV}$ not large enough (valid for $m_\phi < 30\mathrm{MeV}(M/1\mathrm{TeV})$)
- generically for $v \to 0$:
  $$S = \alpha M / m_\phi$$
  - for "secluded models":
    $$S < 10^3$$
- if a zero-energy bound state $\Rightarrow$ larger S possible
- scattering through WIMP-onium
  $$\chi + \chi \to (\chi - \mathrm{onium}) + \phi \to 3\phi$$
  Pospelov, Ratz 08

Cirelli et al. 0809.2409



2-component DM

- an example of DM not a simple thermal relic Fairbairn, JZ, 08
- two components: χ_2, χ_1
  - χ_2 is metastable, decays after freeze-out
    $\chi_2 \to \chi_1 + X_{SM}$
  - χ_1 is the DM that we observe now - and also gives Pamela/ATIC signal
  - this setup decouples $\langle \sigma_A v \rangle_F$ from $\Omega_{\rm DM}$



$$\frac{Y_1(\infty)}{Y_1^{\rm Th.rel.}} \simeq 1 + N_{\rm dec} R \left(1 - \frac{1}{z_1^F} \log R\right)$$

$$R = \frac{m_1}{m_2} \frac{\langle \sigma_{A1} v_1 \rangle}{\langle \sigma_{A2} v_2 \rangle}, \; z = m_1/T, \; Y_i(z) = n_i(z)/s(z)$$

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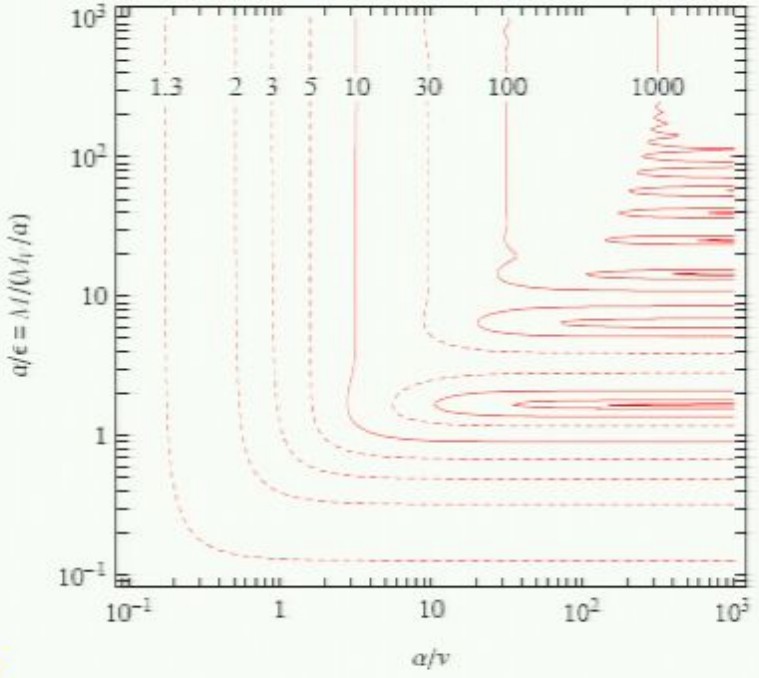

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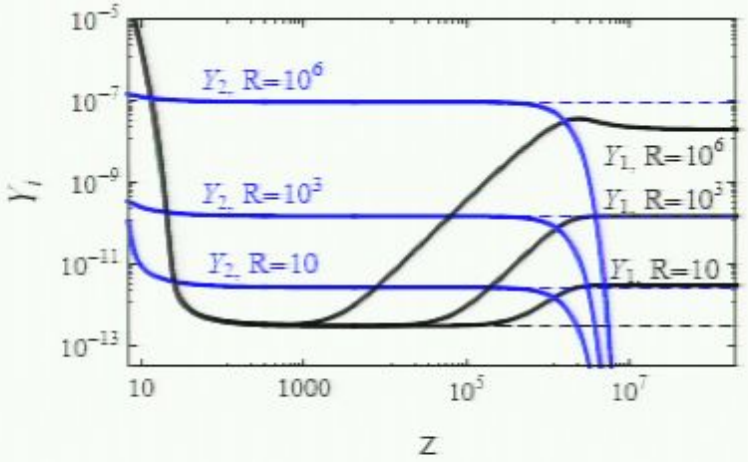

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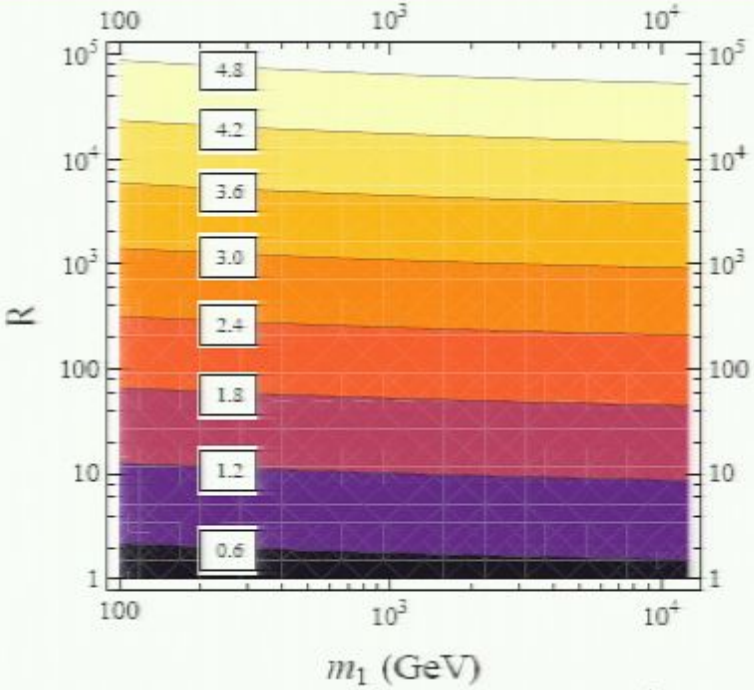
2DM II



$$B = 10^n,$$

n-contours shown

- the boost factors $B = \frac{\langle \sigma_{A1} v_1 \rangle}{\langle \sigma_A v \rangle_F} \simeq \frac{z_{1F}^{2DM}}{z_F^{CDM}} \sqrt{\frac{g_*^{CDM}}{g_*^{2DM}}} \frac{Y_1(\infty)}{Y_1^{Th.rel.}}$
- to avoid wash-out χ_2 should decay after freeze-out

  $\Gamma_2 \ll 10^{-17}\mathrm{GeV} \cdot \frac{1}{B} \cdot \left(\frac{m_1}{100\mathrm{GeV}}\right)^2 \Leftrightarrow, \tau_2 \gg 10^{-8} s$
- from nucleosynthesis $\tau_2 < 1s$

2DM III

- a simple possibility: χ_1 charged under Z_2, χ_2 under Z_2', SM neutral under $Z_2 \times Z_2'$
- take χ_1 and χ_2 scalars, singlets under $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_\chi = \mathcal{L}_{\rm kin} + c_1 \chi_1^2 \chi_2^2 + c_2 (H^\dagger H) \chi_1^2 + c_3 (H^\dagger H) \chi_3^2 + c_4 \chi_1^4 + c_5 \chi_2^4$$

- χ_1 and χ_2 thermalise through inter. with the SM higgs
- for large boost factors: $c_2 \gg c_1$ is needed
- Z_2' broken by dim 5 ops: $\frac{1}{\Lambda}(H H^\dagger)\chi_1^2 \chi_2$, $\frac{1}{\Lambda}\partial_\mu \chi_1 \partial^\mu \chi_1 \chi_2$, $\frac{m_1^2}{\Lambda}\chi_1^2 \chi_2$, $\frac{1}{\Lambda}(\bar{\psi}\{1, \gamma_5\}\psi)\chi_2$, $\frac{m}{\Lambda}(H^\dagger H)\chi_2$,
- give a decay width $\Gamma_2 \simeq m^3/(16\pi\Lambda^2)$

$$\Rightarrow \Lambda \gg \sqrt{m_{Pl}\, m/16\pi} = 5 \times 10^{10} \mathrm{GeV} \cdot \left(\frac{m}{1\mathrm{TeV}}\right)$$

Different temperatures

- a version of "secluded model", hidden sector χ_i interacts with SM only through ϕ, ϕ then decays to SM (Nelson, Spitzer, 08)

$$\chi_1 + \chi_1 \to \phi\phi \to X_{\rm SM}$$

- Thermal history:
  - (i) hidden and visible sector decouple
  - (ii) χ_i annihilate to $\chi_1 \Rightarrow T_{\rm hidden} > T_{visible}$
  - (iii) χ_1 decouples from ϕ
  - (iv) ϕ decays
- the calculation of relic abundance of χ_1 is modified
- exists an upper bound: $B \lesssim 5$
- is not favored by ATIC

Decaying DM

Chen, Takahashi, Yanagida, 08; Ibarra, Tran 08; Hamaguchi, Nakamura, Shirai Yanagida 08; Yin, Yuan, Liu, hang, Bi, Zhu 08

- a DM that is metastable on cosmological time scales
- typically $\tau \sim 10^{26} s \Leftrightarrow \Gamma \sim 10^{-51}\mathrm{GeV}$ needed to explain PAMELA/ATIC
- if from dim $n+4$ operator

$$\Gamma \sim \frac{m^{2n+1}}{16\pi\Lambda^{2n}}$$

- for dim 5 op.: $\Lambda \sim 10^{29}\mathrm{GeV}\left(\frac{m}{1\mathrm{TeV}}\right)^{3/2}$
- for dim 6 op.: $\Lambda \sim 10^{16}\mathrm{GeV}\left(\frac{m}{1\mathrm{TeV}}\right)^{5/4}$

The leptonic mode challenge

- kinematical suppression: used in "secluded" models of DM
  - two (or more) species of DM, one heavy χ and one light ϕ
  - the positrons signal from

$$\chi + \chi \rightarrow \phi\phi \rightarrow X_{SM}$$

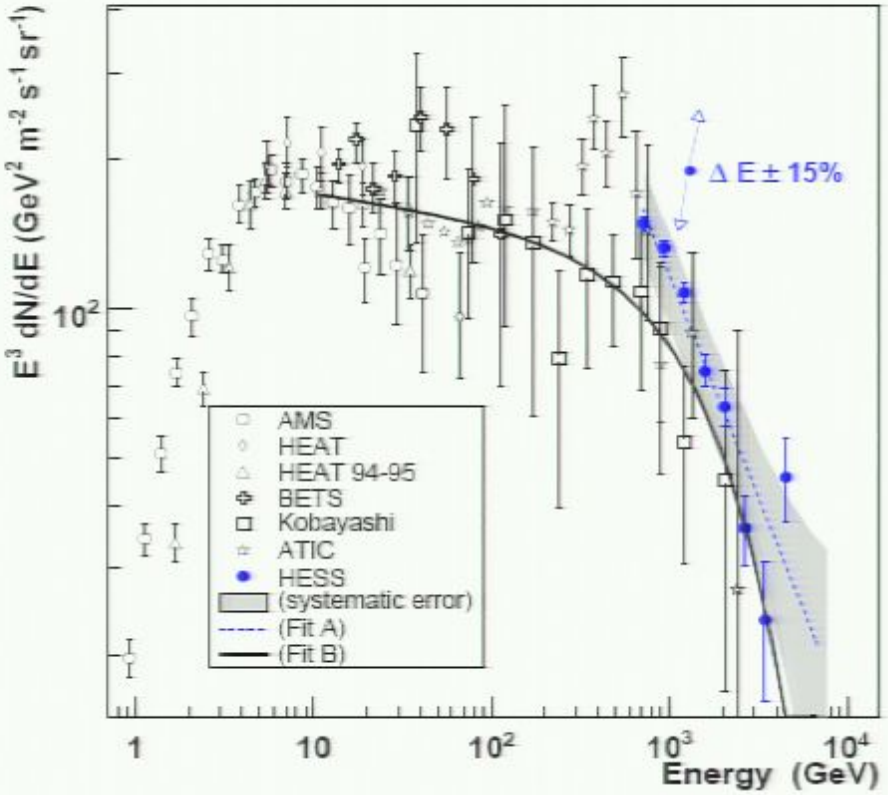
  - take $m_\phi < m_p$ then $\phi \rightarrow pX$ not possible
- leptophilic models: here the DM (or ϕ in "secluded" models) couples only to leptons due to a symmetry

Challenges of the last week

- new data from HESS on $e^+ + e^-$ flux above 1 TeV
- comparison with the observed γ flux from
  - galactic center
  - galactic ridge
  - Sagittarius dwarf spheroidal galaxy

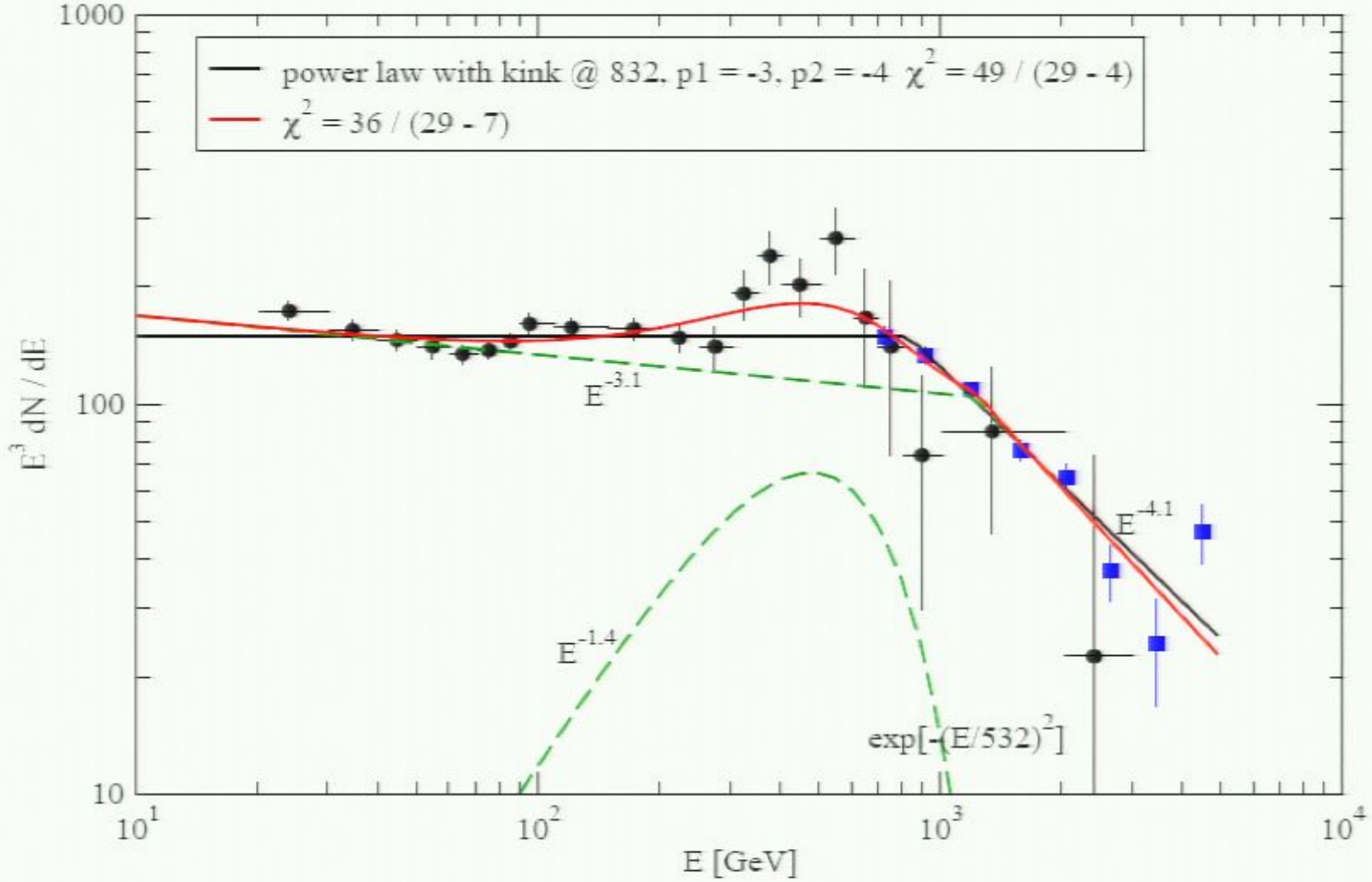
HESS data

- shows a change in power-law above $\sim 2\mathrm{TeV}$ 0811.3894



Still a bump?

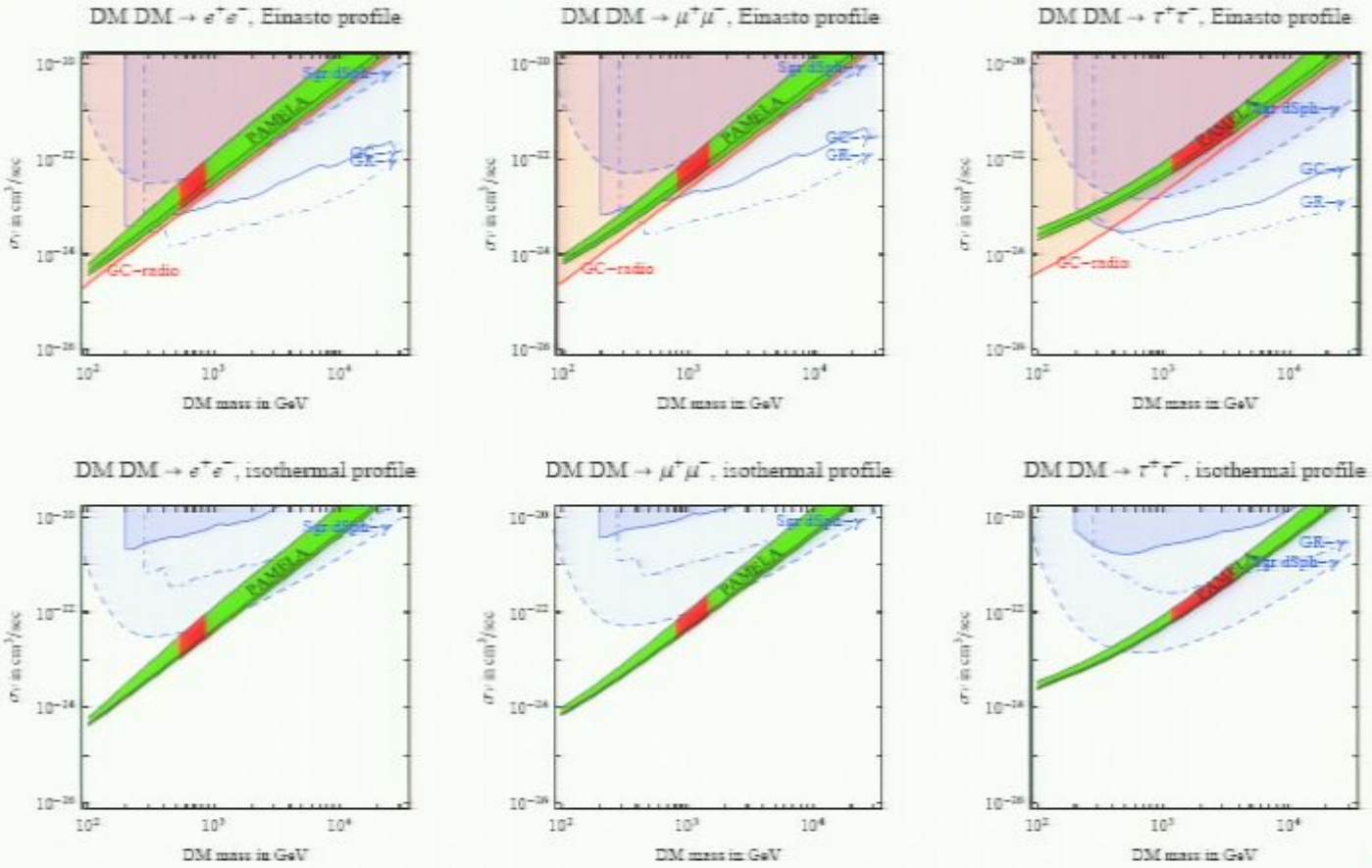
Niro, Fairbairn, Schwetz, JZ, unpubl.



DM annihilation and γ

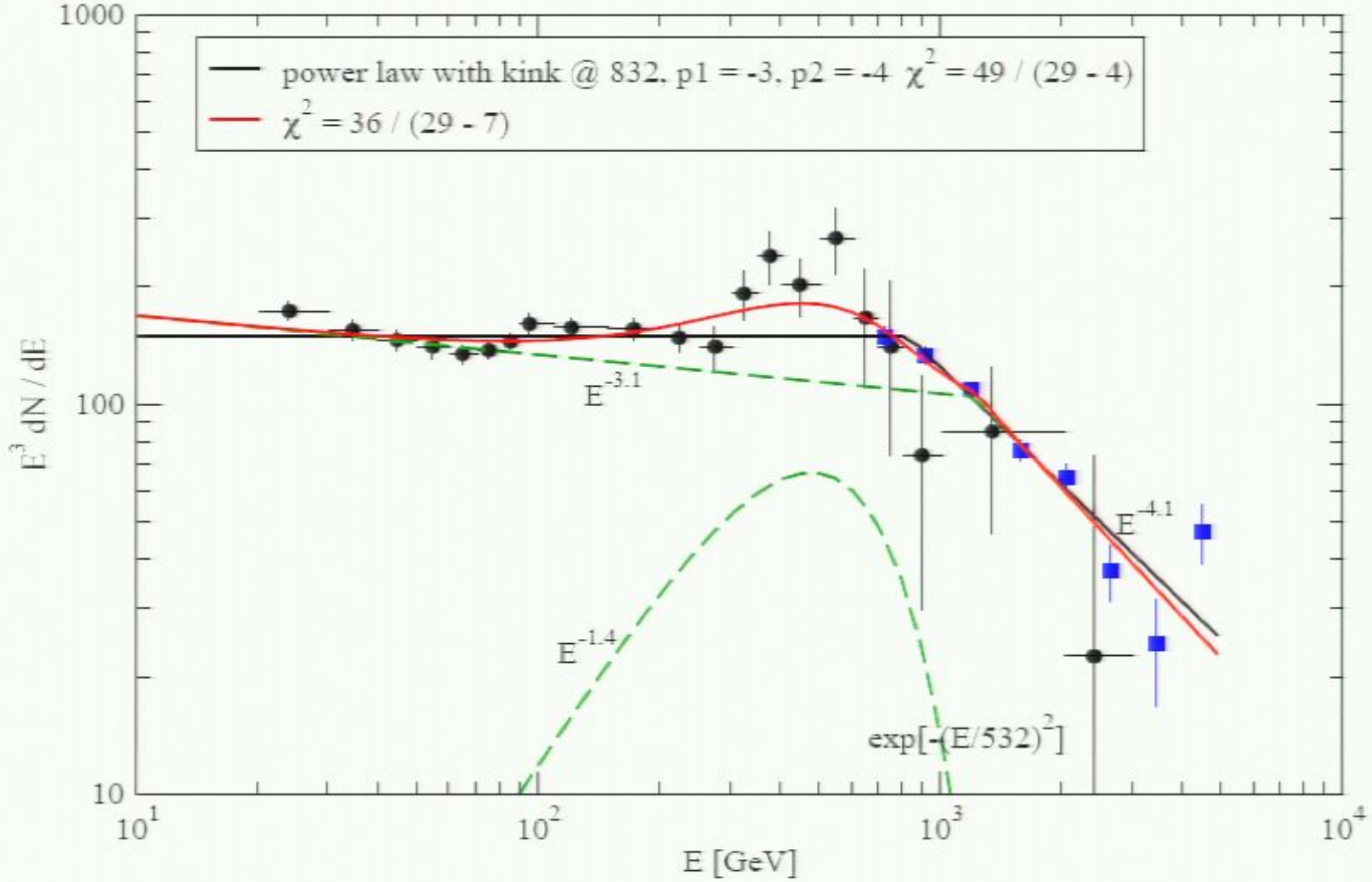
Bertone, Cirelli, Strumia, Taoso, 0811.3894

- $\chi\chi \to e^+e^-$ associated with bremsstrahlung+ sinchrotron radiation
- in conflict with HESS for most popular DM profiles



Still a bump?

Niro, Fairbairn, Schwetz, JZ, unpubl.



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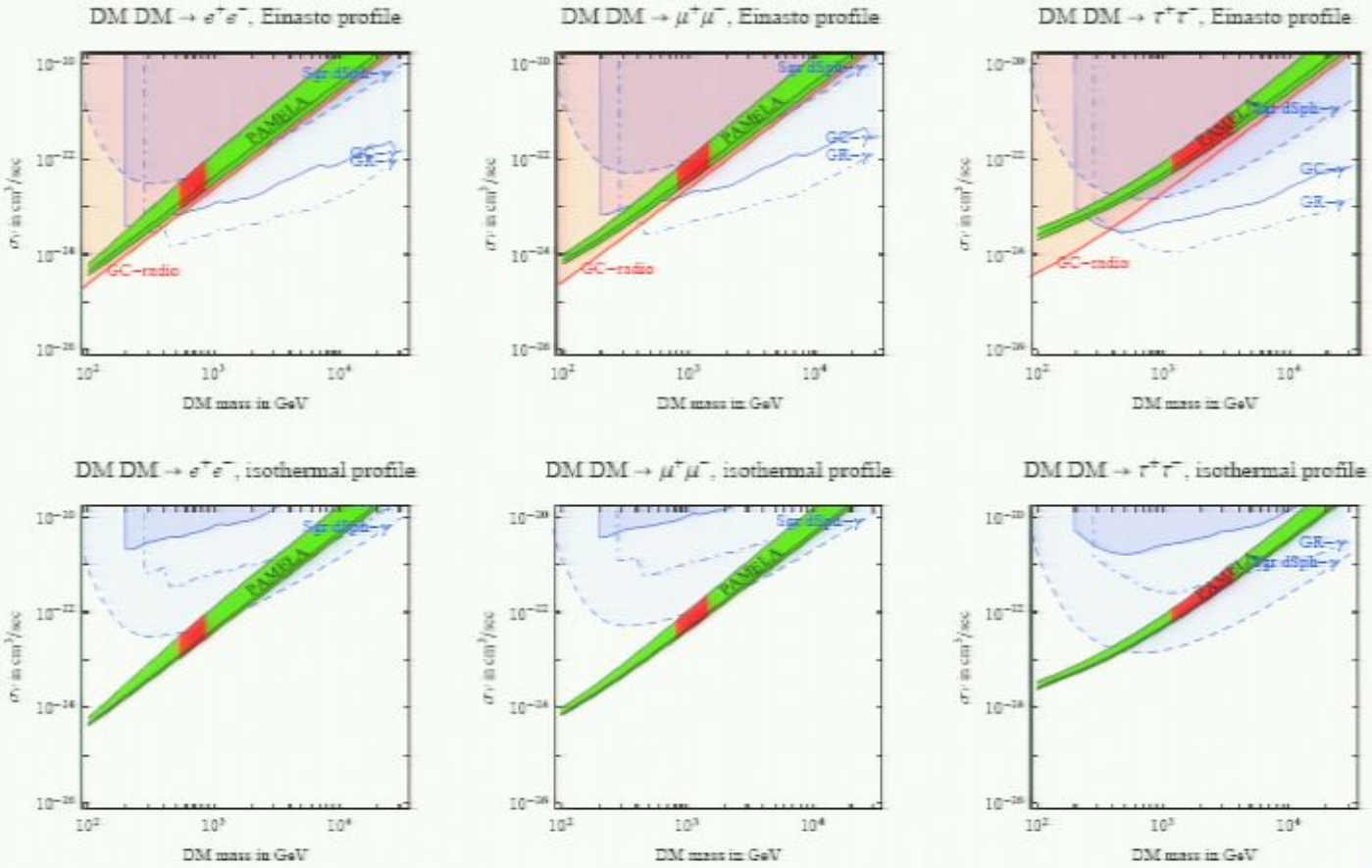
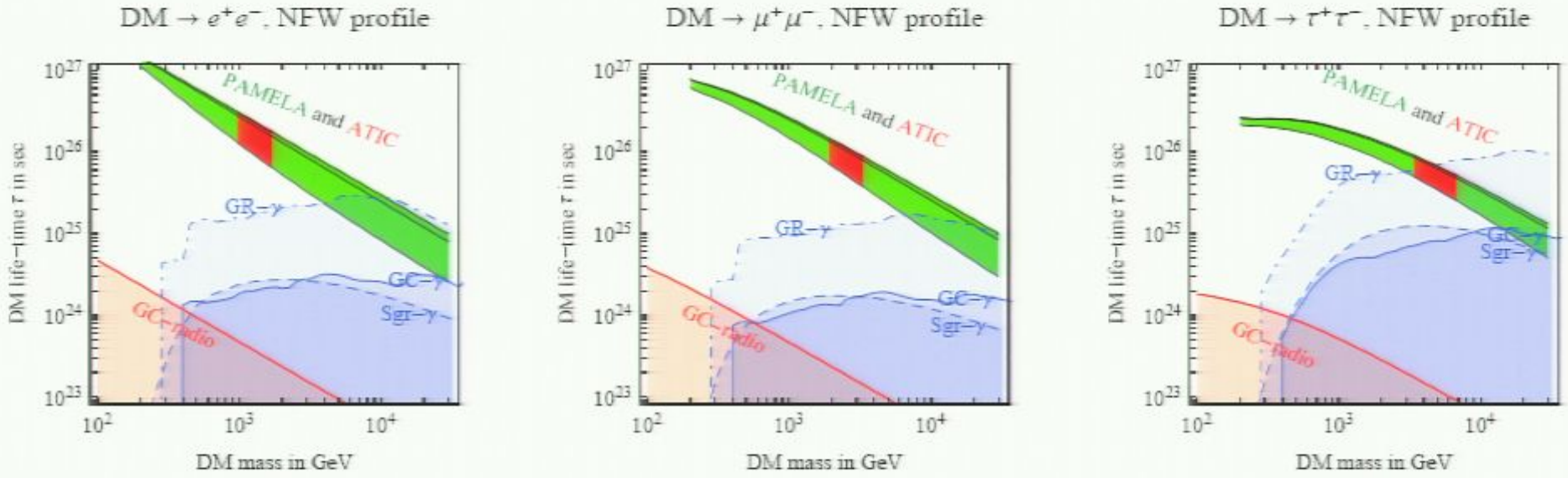


decaying DM and γ

Nardi, Sannino, Strumia, 0811.4153

- less problematic, the reason:
  - for decay $\Phi_{e^+} \propto \rho_{DM}$, while for annih. $\Phi_{e^+} \propto \rho^2_{DM}$
  - $\Rightarrow$ higher signal from dense regions (center of the galaxy, etc)
- for Navarro, Frenk and White profile:



Conclusions

- a very active field - are we seeing a DM signal?
- presented a 2 component DM model that can explain large "boost factors"

Pamela-positrons comparison

0810.4995