Astrophysical issues in indirect DM detection

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Outline

* Introduction

* Practical examples of astrophysical issues (at the Galactic scale)
  => size of the GCR diffusion zone: relevant to antiprotons, antideuterons, (diffuse gamma-rays)
  => positron fraction: clarifying the role of local astrophysical sources
  => impact of DM inhomogeneities: boost + reinterpreting current constraints
  => diffuse gamma-rays

* Perspectives
Main arguments:
- Annihilation final states lead to: gamma-rays + antimatter
- $\gamma$-rays: lines, spatial + spectral distribution of signals vs bg
- Antimatter cosmic rays: secondary, therefore low bg
- DM-induced antimatter has specific spectral properties

But:
- Do we control the backgrounds?
- Antiprotons are secondaries, not necessarily positrons
- Do the natural DM particle models provide clean signatures?
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Transport of Galactic cosmic rays
The standard picture

\[ \partial_t \frac{dn}{dE} = Q(E, \vec{x}, t) \]
\[ + \left\{ \vec{\nabla} \left( K(E, \vec{x}) \vec{\nabla} - \vec{V}_c \right) \right\} \frac{dn}{dE} \]
\[ - \left\{ \partial_E \left( \frac{dE}{dt} - \partial_E E^2 K_{pp} \partial_p E^{-2} \right) \right\} \frac{dn}{dE} \]
\[ - \left\{ \Gamma_{\text{spal}} \right\} \frac{dn}{dE} \]

From Haslam et al data (1982)
Dark matter has long been discovered!

Agnese + (2013)  
DAMA, CoGenT, CRESST ... + CDMSII(Si) versus XENON-10, XENON-100  
→ DM around 10 GeV

Around the GC  
Weniger +, Finkbeiner + (2012)  
→ DM around 130 GeV

511 keV, Knödlseder/Weidenspointner + (2005 - 2008)  
Boehm, Hooper + (2004) → DM around 1 MeV

HEAT/PAMELA/AMS positron excess  
Bergström +, Cirelli + (2008) → DM around 300-1000 GeV

Hooper + (2012): gamma-rays + radio at GC  
→ DM around 10 GeV
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All point toward different mass scales:
1 MeV / 10 GeV / 130 GeV / 500 GeV

Hard to explain with a single DM candidate
(except maybe for XDM, Weiner ++ 2004-2012, Cline +, etc.)

Around the GC
Weniger +, Finkbeiner + (2012)
→ DM around 130 GeV

X-ray binaries + radioactive species
511 keV, Knödlseder/Weidenspointner + (2005 - 2008)
Boehm, Hooper + (2004) → DM around 1 MeV

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Close to threshold: Systematics?

Pulsars?

Astro contribs?

Near threshold: Systematics?
* Instrumental effects (not our job)

* Check consistency with complementary signals
  => multi-messenger analyses (multiwavelength photons, antimatter CRs, neutrinos)
  => multi-source analyses (MW, Dwarf galaxies, )
  => (other detection methods: LHC+direct+indirect+early universe+etc.)

* Understand / quantify theoretical uncertainties (for discovery as well as constraints)
  => eg CR transport, DM distribution, Galactic components

* Understand / quantify backgrounds
  => astrophysical sources / mechanisms

**NB:** Fermi + HESS2 + AMS02 + CTA => beginning of precision era in GeV-TeV astrophysics
Focus on antinuclei: antiproton constraints

DAMA+CDMS+COGENT mass regions 
(+ GC fit by Hooper+)
=> WIMP mass ~10 GeV

Couplings to quarks => annihilation may produce antiprotons (not generic for Majorana fermions, only s-wave contributions)
Large antiproton flux expected (scales like 1/m^2)

** Uncertainties due to the size of the diffusion zone?

Lavalle (2010)
Impact of the size of the diffusion zone


=> attempts to bracket theoretical uncertainties

Besides best fit transport model (dubbed med), proposal for 2 extreme configurations:

\[ \min: L = 1 \text{ kpc} \]
\[ \max: L = 15 \text{ kpc} \]

minimizing and maximizing the DM-induced fluxes, respectively.

NB: much less effect on high-energy positrons (Lavalle+ 07, Delahaye+ 08) – short propagation scale.

The game people usually play:
1) you want your model to survive antiproton constraints:
   => take a small L
2) you want to advertise your model for detection:
   => take L from med to max.
Where do constraints on L come from?

Putze+ (2011)

Secondary/Primary ratios:

Degeneracy between K and L!

On the blackboard
Where do constraints on $L$ come from?

Putze+ (2011)

Strong+ (2004)

Breaking degeneracy with radioactive secondaries
$\Rightarrow$ lifetime too short to reach $L$
Uncertainties in the diffusion halo size?
Quick digression towards positrons

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

\[ \phi_{e^+} \propto \frac{1}{\sqrt{K_0}} \]

\[ \frac{K_0}{L} \approx C_{st} \]

Small L models in tension with positron data

=> L > 1 kpc => Very conservative statement!

Perspectives:
- PAMELA/AMS data still to come

=> Ongoing work with Maurin and Putze
What else on K and L?  
(on the spectral hardening)

Could be due to a change in diffusion properties (eg Blasi+ 12)

=> K has different slope > 100 GeV  
(from 0.7 to 0.3)

=> impact on secondary CR production

ATIC Collab (2006-2012)
Cream Collab (2010-2011)

Blasi+ (2012)
Short comments on the positron fraction

We know pulsars can make it in principle. Going to realistic modeling is complicated (eg Delahaye et al 10).

=> separate distant/local sources, and accommodate the full data (e-, e+, e+e-, e+/e+e-) …

=> Pulsar wind nebulae (PWNe) as positron/electron sources

=> SNRs as electron sources (each PWN must be paired with an SNR)

=> you may fit amplitudes / spectral indices … then what?

** Observational constraints!

=> use pulsar period, multiwavelength data for all observed sources … but … not that simple.
Modeling the electron/positron sources?

Different timescales:
1) E-loss time > source age > transport time
2) transport time >> photon time
=> cannot directly use photon data
=> requires dynamical models for sources (time evolution)

Very complicated problem:
1) photon data: CRs which are mostly still confined in sources (escape issue)
2) coupled evolution of magnetic fields and CR density

Some attempts at the source level (eg Ohira+ 10-11), but much more work necessary.

Work in prep. with Y. Gallant and A. Marcowith (LUPM).

Crab nebula (ESA) (just for illustration, not relevant for e+/e-)

Horns & Aharonian (04) Crab SED

photon obs. time = \( \frac{d}{c} \approx 300 \text{ yr} \left[ \frac{d}{100 \text{ pc}} \right] \)

transport time \( \approx \frac{d^2}{K(E)} \approx 30 \text{ kyr} \left[ \frac{E}{1 \text{ TeV}} \right]^{-1/2} \left[ \frac{d}{100 \text{ pc}} \right]^2 \)

E-loss time \( = \int_{E}^{E_{s}} dE' b(E') \approx 300 \text{ kyr} @ 1 \text{ TeV} \)
Anisotropy as a test?

**Caveats:**

* model-dependent (diffusion halo size again!)
* contributions of other sources (e.g., dipole from GC/antiGC asymmetry in the source distribution)
* cancellations might occur in the dipole

**Still:**

* physically meaningful information
* should be provided for all CR species separately (e.g., positrons, antiprotons, etc.)
* will provide constraints to the full transport model
* AMS may reach the necessary sensitivity
DM interpretation of the positron excess?
(if you still want to believe ...)

Method:
* background (!!!) + annihilation cross-section as free params.

Conclusions:
* severe antiproton constraints => multi-TeV or leptophilic models

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But ... local DM: 0.3 → 0.4 GeV/cm³, DM subhalos => BF ~ 2-3
=> factor of 4-5 possible
Boost factor? ... well, in fact, boost factors

\[ B = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1 \]

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2) **Cosmic rays**: stochastic motion, define energy-dependent propagation scale.
   - a) Large propagation scale: if enough to feel regions close to GC, then \( \mathcal{B} \sim 1 \)
   - b) Small propagation scale: if we are sitting on a clump, then \( \mathcal{B} \gg 1 \), otherwise \( \mathcal{B} \) moderate
Impact of subhalos on the positron flux

If DM is cold, subhalos must exist and survive tidal stripping (e.g., Berezinsky+ 05).

Very small masses can be achieved, fixed by the WIMP free streaming scale (e.g., Bringmann 09).

Properties studied in cosmological simulations, but limited by resolution => \( M > 104 \) Msun only.

Latest dedicated studies show profiles more cuspy than NFW at cut-off mass (e.g., Ishiyama+ 10, Anderhalden+ 13).

=> PAMELA could be explained by 100 GeV WIMPs (not AMS).
Assumptions:
- homogeneous/isotropic diffusion coefficient
- continuous distribution of sources; CRs escape sources with ad-hoc broken power laws (indices are free parameters)
- ISM from HI, H2 (CO), HII (Lazio & Cordes), dust correlations … maps

Results:
- global fit to the data not too bad (10-20% residuals), except GC and G-edges (30-40%)
- large magnetic halo preferred, $L \sim 10$ kpc
- Caveats: potentially large (and degenerate) systematic errors, but physical interpretation meaningful $\Rightarrow$ encouraging
Diffuse emission and CRs: theoretical uncertainties

(T. Delahaye, IFT-LAPTh)

3D model of H2

Diff with Galprop (hadronic contribution)
~ 50% in the disk!

Impact of ISM modeling

1102.0744

Advantages
* Good sensitivity, sampling & uniformity of CO survey
* Kinematic resolution toward GC

Limitations
* Limited resolution of SPH simulations (problem near GC)
* Single value of $X_{CO}$

Comments
* Very thorough & lucid analysis
* Globally reliable, except within ~ 1 kpc from GC
* Model available online

Julien Lavalle, Service de Physique Théorique, ULB, 19 IV 2013
**Diffuse emission: a top bottom approach**

Cosmological simulation:
self-consistent modeling of a galaxy (DM, gas, stars)

**Advantages:**
* all ingredients are identified and localized (sources and gas)
  * check the relevance of current assumptions

**Limits:** spatial resolution

=> preliminary results encouraging, work in progress

**Skymaps:**
DM (100 GeV b-bbar) – astro processes – DM/astro

Compare e.g. with Weniger 12
(optimized region for 130 GeV line)
Conclusions

- Current GCR models allow for a reasonable understanding of (i) the local CR budget and (ii) the Galactic diffuse emission(s)
- Nota: there is no “standard model” for GCRs! (many inputs, lucidity is required)
- Not accurate enough for specific regions (e.g. GC), but still very useful
- Current models have reached their limits
  => prediction power saturates, need to put more physics in ... at the price of increasing theoretical uncertainties (though expected to decrease in the future)

For DM:
- Best targets remain:
  1) DSPhs as observed in gamma-rays + gamma-ray lines
  2) neutrinos from the Sun
- Antimatter CRs + diffuse emissions more relevant to constraints: astrophysics pollutes a lot, and is not completely controlled yet
*** Complementarity with other detection methods (direct/LHC) is definitely the best strategy.
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