Current status of

Indirect Searches for Particle Dark Matter

Torsten Bringmann

UiO: University of Oslo
Dark matter all around

overwhelming evidence on all scales!
**Weakly Interacting Massive Particles**

- **well-motivated** from particle physics [SUSY, EDs, …]

- **WIMP “miracle”**

  
  \[ T_{\text{cd}} \sim m_\chi / 25 \]

  chemical decoupling ("freeze-out")

  \[ \Omega_\chi \]

  relic density

- **Freeze-out ≠ decoupling**

  
  \[ T_{kd} \sim m_\chi / (10^2 \ldots 10^5) \]

  kinetic decoupling

  \[ M_{\text{cut}} \sim \text{size of smallest subhalos} \]

  e.g. TB, NJP '09

\[ M_{\text{cut}} \text{ strongly model-dependent} \]

- \( \sim (10^{-11} - 10^{-4}) M_\odot \) in SUSY
- up to dwarf-scale size for MeV-mediators!

\[ \text{i.e. not} \sim 10^{-6}! \]

See talk by K. Freese…
Strategies for WIMP searches

直接 (directly) 间接 (indirectly) 纳米粒子探测器 (at colliders)

⇒ all complementary!
Indirect DM searches

DM has to be (quasi-)stable against decay...
... but can usually pair-annihilate into SM particles
Try to spot those in cosmic rays of various kinds

The challenge: i) absolute rates
\[ \sim \] regions of high DM density
ii) discrimination against other sources
   low background; clear signatures
Indirect detection of WIMPs

DM indirect detection:

"Boost factor"
- each decade in $M_{\text{subhalo}}$ contributes very roughly the same
- depends on uncertain form of microhalo profile ($c_V$ ...) and $dN/dM$

$\Phi_{SM} \propto \langle \rho_x^2 \rangle = (1 + BF) \langle \rho_x \rangle^2$

Fig.: Bergström, NJP '09

\( \text{(still) important to include realistic value for } M_{\text{cut}} \)
The ‘golden’ channel

Gamma rays:

- Rather **high rates**
- **No attenuation** when propagating through halo
- **No assumptions** about diffuse halo necessary
- **Point directly to the sources:** clear spatial signatures
- **Clear spectral signatures** to look for
Gamma-ray flux

The expected **gamma-ray flux** \([\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]\) from a source with DM density \(\rho\) is given by

\[
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta \psi) = \int_{\Delta \psi} \frac{d\Omega}{\Delta \psi} \int_{\text{l.o.s.}} d\ell(\psi) \rho^2(\mathbf{r}) \langle \sigma v \rangle_{\text{ann}} \frac{8 \pi m_\chi^2}{\sum f B_f \frac{dN_f^\gamma}{dE_\gamma}}
\]

**for point-like sources:**

\[

\cong (D^2 \Delta \psi)^{-1} \int d^3 r \rho^2(\mathbf{r})
\]

\(\Delta \psi\): angular res. of detector  
\(D\): distance to source

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**astrophysics**

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**particle physics**

\(\langle \sigma v \rangle_{\text{ann}}\): total annihilation cross section  
\(m_\chi\): WIMP mass \((50 \text{ GeV} \lesssim m_\chi \lesssim 5 \text{ TeV})\)  
\(B_f\): branching ratio into channel \(f\)  
\(N_f^\gamma\): number of photons per ann.

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**high accuracy**

**spectral information**

**angular information**  
+ rather uncertain **normalization**
the impact of non-spherical halos on DM signals, charged particles signals are not expected to be a current standard assumption in the literature and we therefore prefer to stick to it in order to allow for those cases.

Next, we need to determine the parameters as to precisely reproduce the scale density) that enter in each of these forms. Instead of taking them from the individual

Figure 1: 

Difference in annihilation flux several orders of magnitude for the galactic center

[NB: figure does not take into account cut-off due to self-annihilation! ]

Situation much better for e.g. dwarf galaxies

Large uncertainties “only” in the very central region.

local DM density: \( \rho_\odot \sim 0.4 \text{ GeV/cm}^3 \)

DM distribution

Indirect Searches for Particle Dark Matter

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Annihilation spectra

Secondary photons
- many photons but
- featureless & model-independent
- difficult to distinguish from astro BG
  good constraining potential

Primary photons
- direct annihilation to photons
- model-dependent ‘smoking gun’ spectral features near $E_\gamma = m_\chi$
  discovery potential
More particle physics input

**Sommerfeld effect**
- strong enhancement of annihilation rates for light mediators / heavy DM
  - (particularly relevant for line signals)
  - related effect: bound state formation

**Radiative corrections**
- strong enhancement possible
  - (in particular if tree-level rates are suppressed)
- electromagnetic IB: line-like
  - spectral signatures or sharp steps
- electroweak IB: enhancement of continuum part; can change composition of final stable particles

[disclaimer: list of relevant papers would fill the whole slide…]

These contributions are highly model-dependent!

[Recent example: full calculation for MSSM]

also ~same for “model-independent” SU(2) corrections!
[as implemented e.g. in PPPC 4 DM ID (Cirelli+, JCAP ’11)]

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A new signature?

- **Resonances** can single out spectral features
  - counter example for “flux = particle factor x astrophysical factor”!
  - particularly relevant for extra-dimensional scenarios
    - example: universal extra dimensions (Appelquist, Cheng & Dobrescu, PRD ‘01)

- (Kerr) **Black holes** can accelerate DM particles to $\sqrt{s} \gg 2m_{DM}$  
  - but beware of many caveats: ongoing discussion…

- Potential **smoking gun** signature for extra-dimensional origin of DM: equidistant line signals!
Astrophysical processes present significant backgrounds:

Possible targets include:

- **The Galactic center**: brightest source in sky, but large backgrounds
- **Dwarf galaxies**: DM dominated, M/L≈1000; fluxes soon in reach
- **The Galactic halo**: good statistics, angular information; significant backgrounds
- **DM clumps**: easy discrimination (once found); bright enough?
- **Galaxy clusters**: large substructure boost; good discovery potential, limits model-dependent
- **Extragalactic background**: cosmological signal; hard to model, potentially very constraining

Talk by M. Sanchez-Conde!
Look for secondary photons from DM
[typical assumption: 100% annihilation into $\bar{b}b$]

Fig.: Wood+, 1507.03530

Indirect searches ever more competitive!
A signal from the GC?

- **Excess emission** in inner Galaxy and Galactic center region:
  - extremely high statistical evidence
  - relatively sharp peak around 1-3 GeV
  - rotationally symmetric
  - roughly $r^{-2.5}$ emission profile
  - extends at least from $\sim 10$pc to $\sim 1$kpc

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**Calore, Cholis & Weniger, JCAP’15**
**Daylan et al., 1402.6703**

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Goodenough & Hooper, 0910.2998
Hooper & Goodenough, PLB ’11
Hooper & Linden, PRD ’11
Abazajian & Kaplinghat, PRD ’12
Macias & Gordon, PRD ’14
Hooper, PDU ’13
Hooper & Slatyer, PDU ’13
Huang, Urbano & Xue, 1307.6862
Abazajian, Canac, Horiuchi & Kaplinghat, 1402.4090

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**Indirect Searches for Particle Dark Matter – 15**

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DM interpretation

Constraints

- collider & direct detection experiments lead to highly model-dependent constraints
- indirect searches:
  - model-independent severe constraints
    - (NB: astrophysical uncertainties smaller than typical because DM profile is ~fixed!)
    - see also new Fermi dwarf limits!

Astrophysical explanations...

- milli-second pulsars: need large population
- “recent” bursts injecting high-energy population of electrons or protons:
  - spectral fit worse (at least for p); spherical out to kpc scales?
  - Recent strong evidence (> 4σ) for unresolved point sources (=MSPs?)

Alves+, PRD ‘14
Berlin, Hooper & McDermott, PRD ‘14
Izaguirre, Krnjaic & Shuve, PRD ‘14
Kong & Park, NPB ‘14
Han, Liu & Su, JHEP ‘14

Hooper et al., PRD ‘13

Petrovic, Serpico & Zaharijas, 1405.7928
Carlson & Profumo, 1405.7685

Ackermann+, 1503.02641
Bartels, Krishnamurthy & Weniger, 1506.05104
Lee+, 1506.05124
Line searches

No signals, but ever better **limits**
- Fermi: 0.2-500 GeV  
  Ackermann et al., PRD '15
- HESS GC analysis: 0.5-25 TeV  
  Abramowski et al., PRL '13

Line-feature around **130 GeV**:
- Bringmann et al., 1203.1312
- Weniger, 1204.2797
- Tempel, Hektor & Raidal, 1205.1045
- Su & Finkbeiner, 1206.1616

→ **Signal interpretation now excluded**

Huge potential to improve limits:
- CTA, Gamma-400, CALET, DAMPE, …
3.5 keV X-ray line seen in
- Andromeda galaxy & Perseus cluster
  Boyarski, Ruchayskiy, Iakubovskyi & Franse, PRL ‘14
- instrumental lines “removed” through stacking
- known atomic transitions cannot account for the strength of the signal
  Jeltema & Profumo, 1408.1699
  Boyarski et al., 1408.4388
  Bulbul et al., 1409.4143

DM interpretation
- Decaying 7 keV sterile neutrino
- decaying axions
- eXciting DM
- millicharged DM
- atomic DM
- …
DM or not DM…

**Expect** to see a line even from the GC!

- Take *Chandra* observations, remove point-sources
- model continuum emission and known lines

But with *XMM* Newton data, there **is** a line at the GC!?  

Stacking galaxies reveals **no line**

- inconsistent with ("standard") DM interpretation at >10σ!  
- but axions still alive

**Need more data:** *XMM* observations of Draco, Astro-H…

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Indirect DM searches

Neutrinos:
- **Unperturbed** propagation like for photons
- But DM signal significance (for the same target) usually considerably worse
- **New feature**: signals from the center of sun or earth!

Fig. from J. Edsjö
Neutrino signals

\[ \dot{N} = C - C A N^2 - C^E N \]

*Neutrino signal from center of earth not competitive with direct detection (equilibrium typically not yet reached)*

*Neutrino signal from sun leads to very competitive limits on spin-dependent scattering rates*

Annihilation rate:

\[ \Gamma_A = \frac{1}{2} C \tanh^2 \left( \frac{t}{\sqrt{C A C}} \right) \]

\[ \frac{C}{2} \text{ in equilibrium} \]

(=maximal signal)
GCRs are confined by galactic magnetic fields
Random distribution of field inhomogeneities
\[ \rightsquigarrow \] propagation well described by diffusion equation
After propagation, no directional information is left
Also the spectral information tends to get washed out
Equal amounts of matter and antimatter
\[ \rightarrow \] focus on antimatter (low backgrounds!)
Positrons

Excess in cosmic ray positron data has triggered some excitement:

Are we seeing a DM signal ???
DM explanations

Model-independent analysis:
- strong constraints on hadronic modes from $\bar{p}$ data
- $\chi\chi \rightarrow e^+e^-$ or $\mu^+\mu^-$ favoured
- large boost factors generic $- \mathcal{O}(10^3)$

→ highly non-conventional DM!
  + significant radio/IC constraints...

and: many good astrophysical candidates for primary sources in the cosmic neighbourhood:
- pulsars Grasso et al., ApP '09, Yüksel et al., PRL '09, Profumo, 0812.4457
- old SNRs Blasi, PRL '09, Blasi & Serpico, PRL '09

→ Very challenging to probe DM with positrons...
Re-assessing the $e^+$ channel

**Observation #1:**

*Sharp spectral features do exist, for leptonic channels, even after propagation!*

**Observation #2:**

*AMS provides data*

1. With extremely high statistics
2. For which a simple (5 param) smooth BG model provides an excellent fit

Perfect conditions for a spectral fit!

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Spectral fit with positrons

~same procedure as for gamma rays...

[profile likelihood; no sliding energy window, 5 params for BG instead of 2]

\[
\langle \sigma v \rangle \propto \rho^2 \frac{m^2}{M^2} \ln \frac{m}{M} \frac{M}{m} \frac{m}{M} \frac{1}{f}
\]

\( m \equiv m_\chi \)

\( f \equiv f_{\text{eff}} \)

\( m_{\text{eff}} \)

\( m \ll m_{\text{eff}} \)

\( m^2 \ll M^2 \)

\( f \ll 1 \)

\( m \ll M \)

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Other wavelengths

$e^\pm$ also open up a large new window for indirect searches:

- Inverse Compton
- Gamma rays (or hard X-ray)
- Magnetic field
- Synchrotron
- Radio (or soft X-ray)

408 MHz flux upper limit inside 4" cone gives particularly strong limits for spiky profiles

NB: recent B-field measurement $-B \gtrsim 8\text{mG} @ 0.1\text{pc}$ seems to make main assumption of ~instant energy losses very realistic!

Regis & Ullio, PRD '08

Gondolo, PLB '00
Bertone, Sigl & Silk, MNRAS '01

Eatough et al., Nature '13

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Radio limits

Strong magnetic fields imply almost instantaneous energy loss by synchrotron radiation

Dominant uncertainty is not $B$, but the DM profile in the innermost galaxy!

TB, Vollmann & Weniger, PRD ‘14

Indirect Searches for Particle Dark Matter — 28
Antiprotons

Small **Background** uncertainties:
- B/C fixes **propagation** parameters
- similar uncertainty from **nuclear physics**
  (mostly $p + H \rightarrow \bar{p} + X$)
- solar modulation well described by force-field approximation for $T_\bar{p} \gtrsim 0.1$ GeV

\[ \text{simple 3-parameter background model fully takes into account these uncertainties!} \]

95% c.l. **DM limits:**
- Increase $\langle \sigma v \rangle$, while profiling over the three BG params, until $\Delta(-2 \ln \mathcal{L}) = 2.71$

(see also Cirelli et al., 1407.2173)
Antiprotons from AMS

Compatible with expectations also at high energies

Still needed:
- Full data release — statistical errors do matter for DM limits!
- Data for heavier nuclei to reduce much larger propagation uncertainties for DM signal

Giesen+, 1504.04276
Evoli, Gaggero & Grasso, 1504.05175
Kappl, Reinert & Winkler, 1506.04145
Conclusions

Indirect searches have become extremely competitive

| channel          | Y-rays | antiprotons | positrons                          | radio (GC)                  | ...
|------------------|--------|-------------|------------------------------------|-----------------------------|-----
| $\langle \sigma v \rangle_{\text{therm}}$ | $m_\chi \lesssim 100$ GeV | $m_\chi \lesssim 50$ GeV | $m_\chi \lesssim 100$ GeV        | $m_\chi \lesssim \text{few} \times 100$ GeV | [assumes cuspy profile down to $\sim 0.1$ pc]  |
| probed for       | for $bb$ | for $e^+e^-$ | [for $e^+e^-$]                     |                             |     |

ID provides powerful complementary probes

Interesting current indications

- [130 GeV feature: gone]
- Reticulum? talk by S. Koushiappas!
- GeV excess @ Galactic center?
- keV-line?

The future will certainly see more claims

- risk for false alarms
- one of those might be real — so don’t dismiss them too easily!
Backup Slides
(Far) future of DM searches

Roughly one order of magnitude improvement during last decade, expect ~same for next decade
**Far** future of DM searches

- Further significant improvement possible with current technology
- In particular space-based instruments (but need very large exposures)
- Earth-based soon systematics-limited \( \leadsto \) need to e.g. reject e\(^{-}\)-background!

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Again: the GC excess

Model-independent way to test DM hypothesis: look for other messengers!

\[ \rho_\chi \propto r^{-\Gamma} \]

\[ m_\chi \text{ [GeV]} \]

<table>
<thead>
<tr>
<th>Constraint/GC Best Fit</th>
<th>GC Radio Constraints</th>
<th>Antiprotons</th>
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</thead>
<tbody>
<tr>
<td>( b\bar{b} )</td>
<td>( \Gamma = 1.04 )</td>
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<tr>
<td>( \text{radio} )</td>
<td>( \Gamma = 1.04 )</td>
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<tr>
<td>( \text{antiprotons} )</td>
<td>( \Gamma = 1.26 )</td>
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Again: the GC excess

For **leptonic channels**, positron limits important

- NB: “Democratic” scenarios completely excluded
  (i.e. same BR to all $\ell^+ \ell^-$)

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The optimist’s view: 
“**Signal around the corner**”

The pessimist’s view: 
“**Significant tension**”

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AMS positron limits

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bottom line:

For leptonic channels, positron limits important

- NB: “Democratic” scenarios completely excluded (i.e. same BR to all $\ell^+ \ell^-$)