Indirect Detection of Dark Matter

Pat Scott

Imperial College London

Slides available from tinyurl.com/patscott

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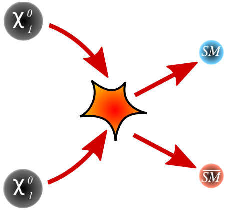
What is indirect detection?

Looking for Standard Model particles produced by dark matter annihilation or decay.

- neutrinos – IceCube, Super-K, KM3NET
- anti-protons – PAMELA, AMS-02, CALET
- anti-deuterons – AMS-02, GAPS
- e^+e^- – PAMELA, Fermi, AMS-02, CALET
  $\rightarrow$ secondary radiation: inverse Compton, synchrotron, bremsstrahlung
- gamma-rays – Fermi-LAT, HESS, CTA
- secondary impacts on the CMB, reionisation
- 'indirect direct detection' $\rightarrow$ impacts on solar and stellar structure



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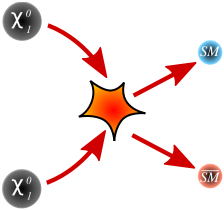

This talk will summarise the latest limits and anomalies from each of the red sectors

Liberally infused with opinions, biases towards what I think is most interesting right now, etc.

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What is indirect detection?

Looking for Standard Model particles produced by dark matter annihilation or decay.

Increasing controversy

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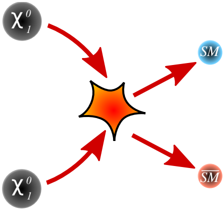

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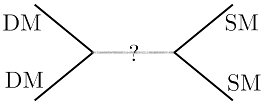
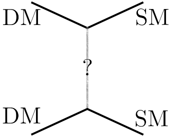
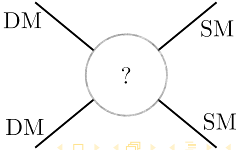
What does indirect detection do for us (theoretically)?

Indirect detection probes:

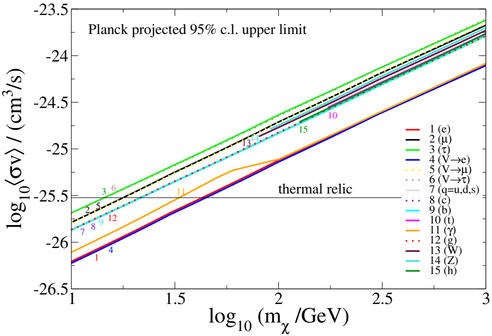
- DM mass m_χ
- annihilation cross-section $\langle \sigma v \rangle$ + branching fractions to different SM final states
  $\rightarrow$ mediator mass + mediator couplings to DM and SM
- decay width Γ_χ + branching fractions to different SM final states
  $\rightarrow$ DM couplings to SM
- scattering cross-section with nuclei
  (neutrinos + stellar 'indirect direct detection' only)
  $\rightarrow$ mediator mass + mediator couplings to DM and SM







How (not) to interpret indirect detection in BSM models



Cline & PS *JCAP* 2013

- Indirect limits always presented in terms of hard process final states
- Actual experiments do not measure those final states – they detect one type of SM particle produced later: γs, νs, etc
- Limits as presented cannot be combined and applied to models with mixed final states (= all non-toy models)
- Proper treatment of indirect detection for BSM searches requires full phenomenological recast abilities
  $\rightarrow$ full experimental *and* theoretical treatment at the same time

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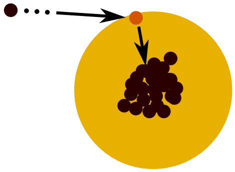
The cartoon version:

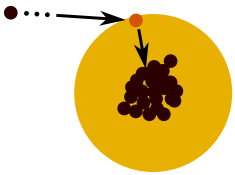
Neutrinos – how does it work?



The cartoon version:

1. Halo WIMPs crash into the Sun

Neutrinos – how does it work?



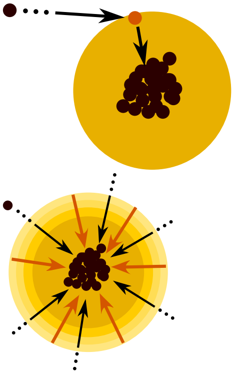
The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound

Neutrinos – how does it work?

The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core



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The cartoon version:

1. Halo WIMPs crash into the Sun
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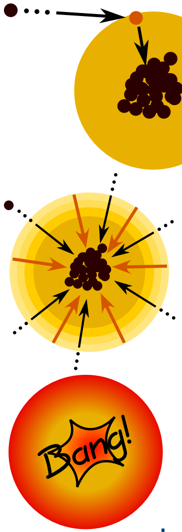
4. Annihilate with each other, producing neutrinos



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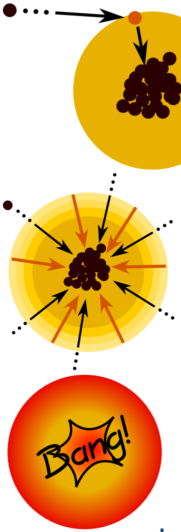
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water



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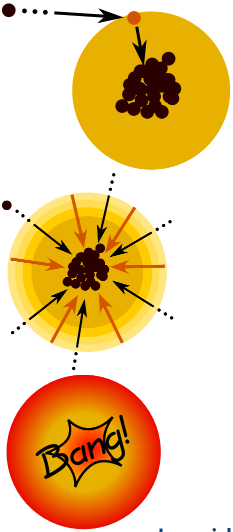
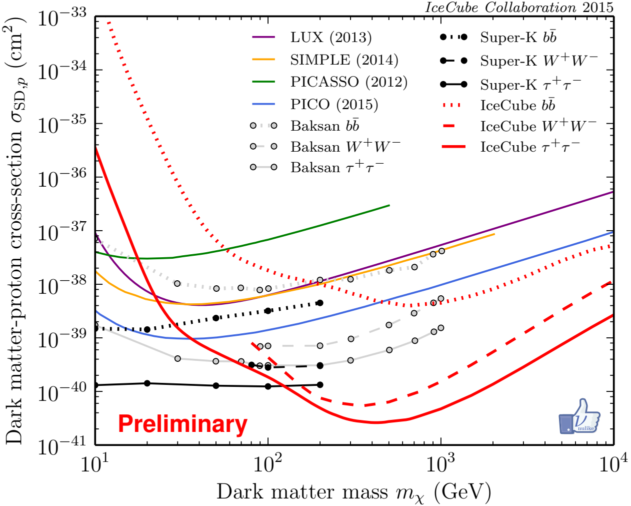
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc





IceCube Collaboration (+PS, Savage, Edsjö) *in prep*

`nulike`: model-independent unbinned limit calculator for generic BSM models

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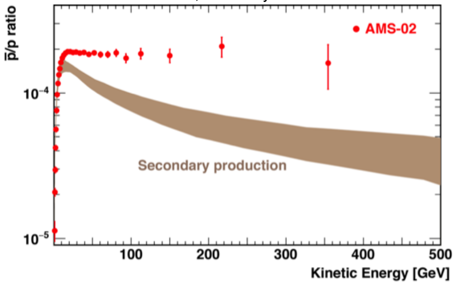
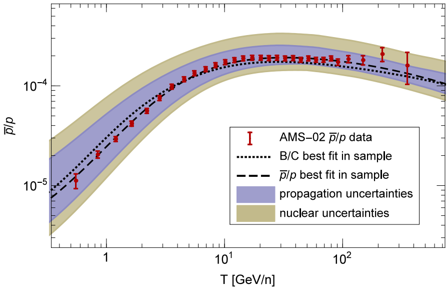
AMS-02 *claims* to have seen something DM-like in $\bar{p}$ . . .

AMS-02, AMS Days 2015



Kappl et al, arXiv:1506.04145



Improved fit of cosmic ray diffusion using AMS boron to carbon ratio (B/C) suggests otherwise.

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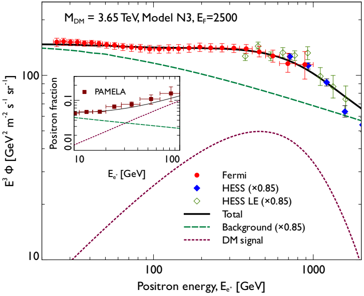
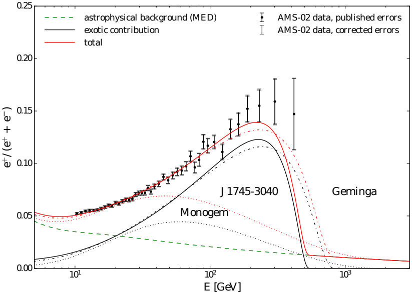
- Excess over expected background (secondary) positron ratio observed
- First seen by PAMELA, confirmed by *Fermi* then AMS-02. Still unexplained.
- Could be evidence of dark matter, could be caused by pulsars

Bergström, Edsjö & Zaharijas 2009



Boudaud et al *A&A* 2015



Resolutions?

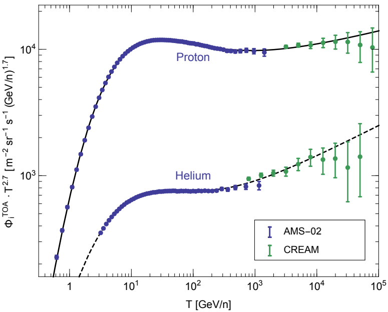
There are other issues:

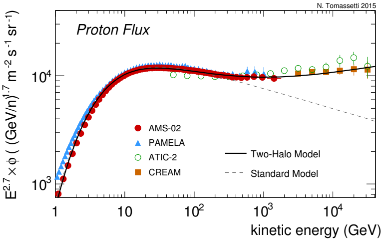
- Evidence of a break at $\sim$300 GeV in p and He spectra
- Not in heavier nuclei (ATIC, CREAM, AMS-02)

$\longrightarrow$ hard to explain with DM
$\longrightarrow$ can explain with:
- pulsars
- modified propagation
- modified acceleration

Future: CALET will test up to 20 TeV – should tell if there really is a turnover in the positron fraction

Kappl et al, arXiv:1506.04145





Types of gamma-ray spectra

- 3 main gamma-ray channels:

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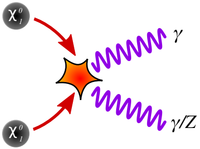
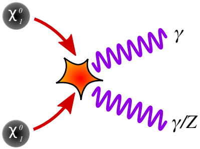
Types of gamma-ray spectra



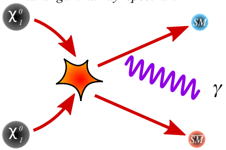
- 3 main gamma-ray channels:
  - monochromatic lines

Types of gamma-ray spectra

2 photons (or Z+photon): monochromatic lines



Internal bremsstrahlung: hard gamma-ray spectrum



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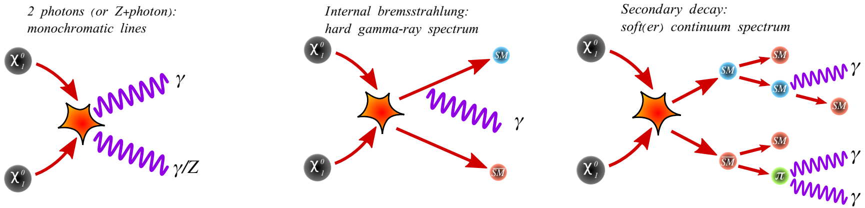

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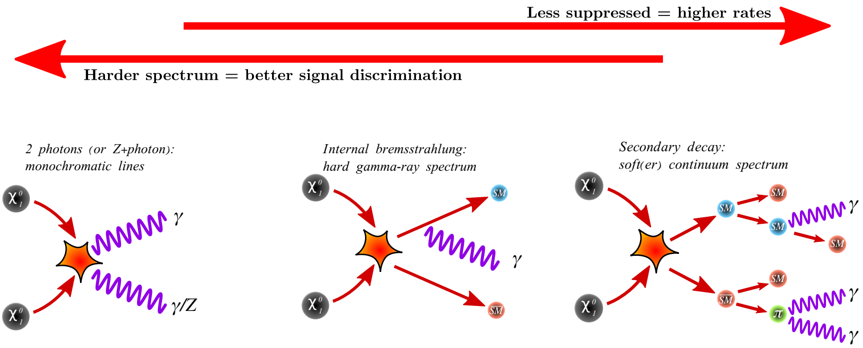

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Gamma rays – Targets

- $\Phi \propto$ annihilation rate $\propto \rho^2_{\rm DM}$

Likely targets:

- Galactic centre - large signal, large BG
- dwarf galaxies - low statistics, low BG
- Galactic halo - moderate signal, moderate BG
- clusters/extragalactic diffuse - large modelling uncertainties, low signal, low BG
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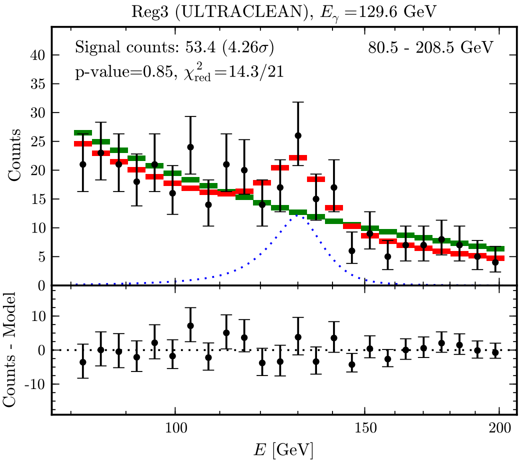

Weniger, *JCAP* 2012

Once upon a time (∼2012 actually) there was a 4σ+ line at the Galactic Centre…

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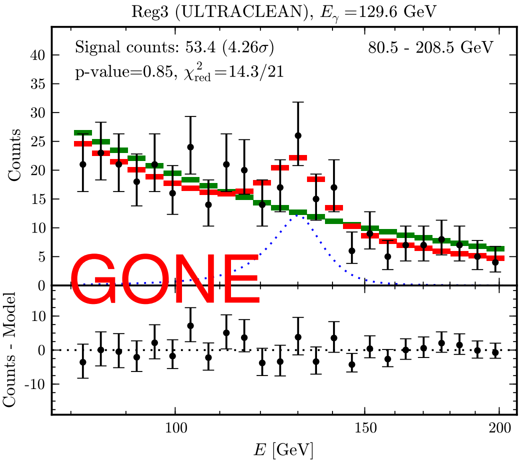

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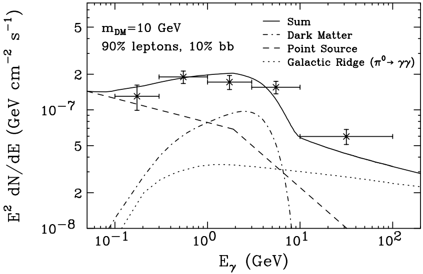
Once upon a time (∼2012 actually) there was a 4σ+ line at the Galactic Centre. . .

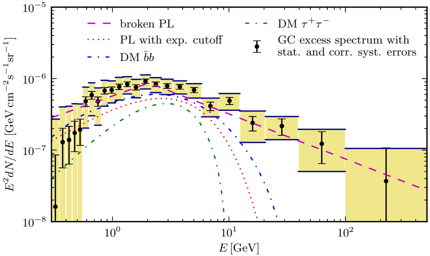
It went away. Fin.

Broad excess over naive background diffuse models at $E\sim$GeV

Hooper & Linden, arXiv:1110.0006



Calore et al, arXiv:1409.0042



So is there *really* an excess? Depends on your point of view
$\rightarrow$ lots of background and foreground freedom not yet explored

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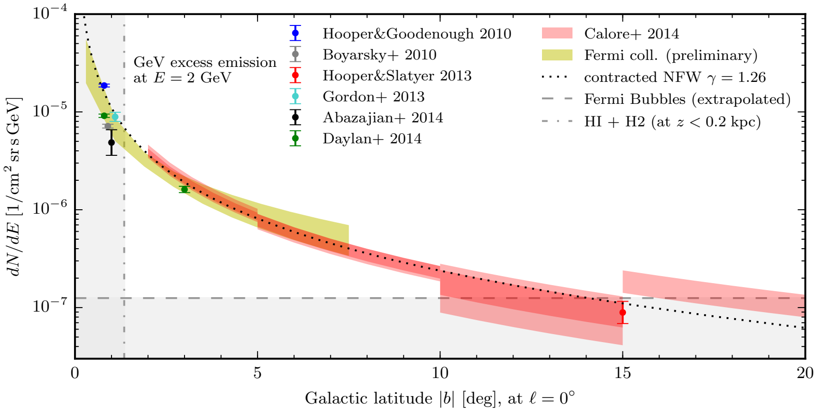
Gamma rays – Galactic Centre

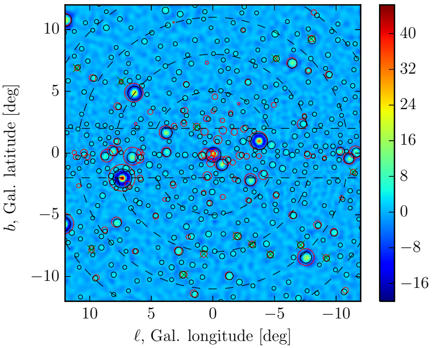
It does roughly follow expected morphology of the DM halo though…



Calore et al, arXiv:1411.4647

Photon clustering analyses – smooth emission or point sources?

Bartells et al, arXiv:1506.05104



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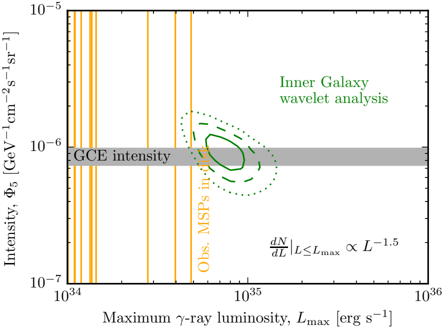
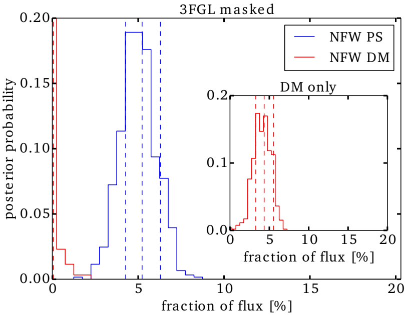
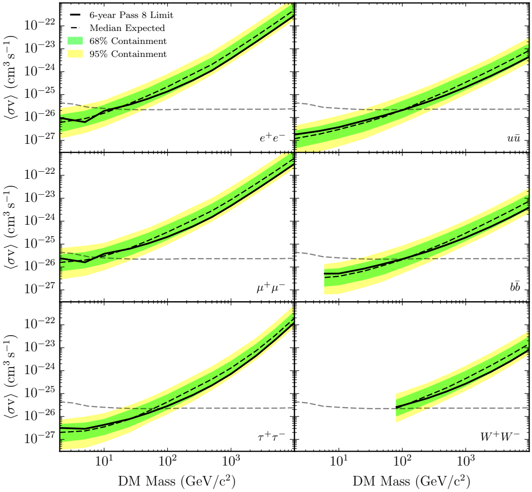


Lee et al, arXiv:1506.05124



Looks like probably point sources just below threshold

Gamma rays – Dwarfs



Fermi-LAT arXiv:1503.02641

- Pass 8 event reconstruction
- 6 years of data
- 15 dwarfs

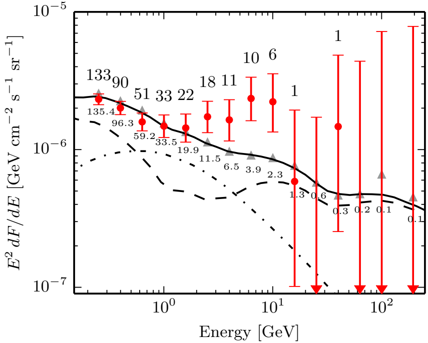
Gold standard for indirect detection.

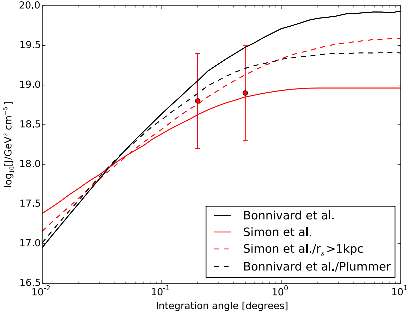
Excludes canonical thermal cross-section up to $m_\chi \sim 100$ GeV.

Note model dependence though!

Gamma rays – Dwarfs – Reticulum II

8 new southern dwarf galaxies already in Dark Energy Survey after 1 yr – some look useful, especially Reticulum II





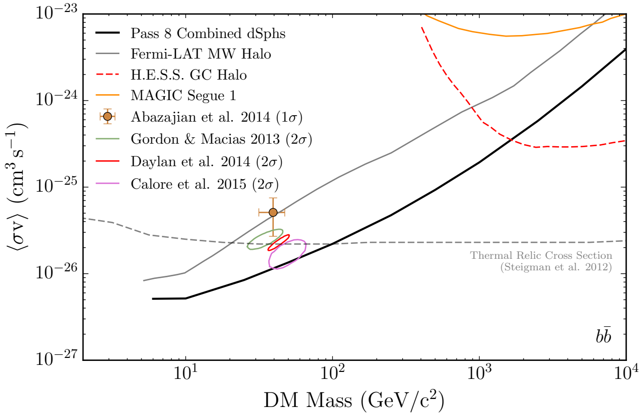
About a 2σ excess, depending on background assumptions and data class

$\longrightarrow$ May be interesting to see how this pans out once J factors are more settled

Geringer-Sameth et al *PRL* 2015
Bonnivard et al *ApJL* 2015
Simon et al *ApJ* 2015
Koushiappas, talk at *TeVPA* 2015

Gamma rays – Galactic centre ‘excess’ state of play

Fermi-LAT arXiv:1503.02641



- Safest money is on pulsars (. . . again. . .)
- Unlikely to be smooth component of DM – but ***maybe*** minihalos

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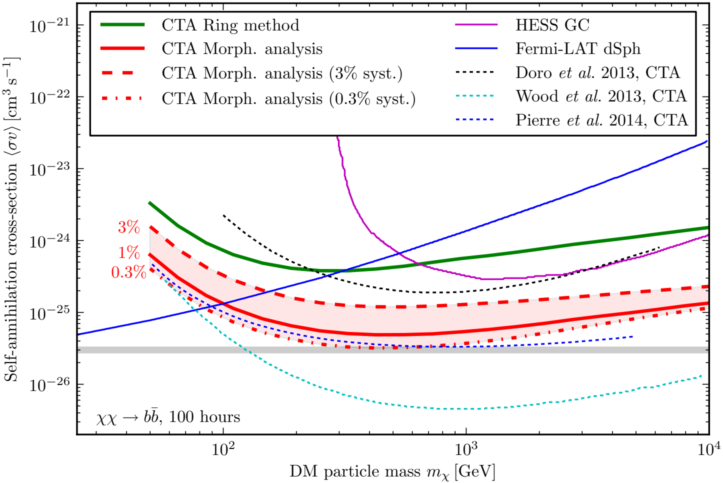
Future prospects – CTA

Silverwood, Weniger, PS, Bertone *JCAP* 2015



→ CTA will be helpful, but its abilities tend to be oversold

Summary I: current status

Indirect detection is now a mature field: ν, γ, charged cosmic rays, CMB + stars

There are anomalies:

- Positron excess persists
- Claimed anti-proton excess seems a bit of a beat up
- Galactic Centre gamma-ray excess probably exists
- Dark matter explanations looking increasingly unlikely vs pulsars

$\rightarrow$ Indirect detection has arrived at the party. . . but DM is still fashionably late.

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Summary II: where to next?

Definitive first detection of DM now seems unlikely to come from indirect searches

- $\Longrightarrow$ We need to cross-correlate indirect searches with each other and with other searches
- must be done in such a way that all data are consistently applied per model to different BSM scenarios
- $\Longrightarrow$ Global fits (`Fittino, MasterCode, GAMBIT`) $\Longrightarrow$ using 'pheno translators': `nulike, gamlike`, etc (cf. situation with `HiggsBounds, HiggsSignals`)

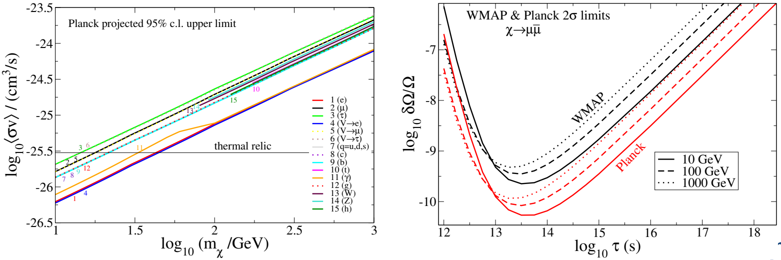
Backup slides

Energy injection from DM annihilation/decay at $z \sim 600$

$\rightarrow$ Would change ionisation balance via γs and e^+e^- interaction with electrons and H

$\rightarrow$ Changes timing + extent of recombination

$\rightarrow$ Distortion of CMB angular power spectrum



Cline & PS *JCAP* 2013

The IceCube Neutrino Observatory

- 86 strings
- 1.5–2.5 km deep in Antarctic ice sheet
- $\sim$125 m spacing between strings
- $\sim$70 m in DeepCore (10$\times$ higher optical detector density)
- 1 km^3 instrumented volume (1 Gton)