Title: New Physics and Astrophysical Searches for Dark Matter

Date: May 05, 2015 11:00 AM

URL: http://pirsa.org/15050032

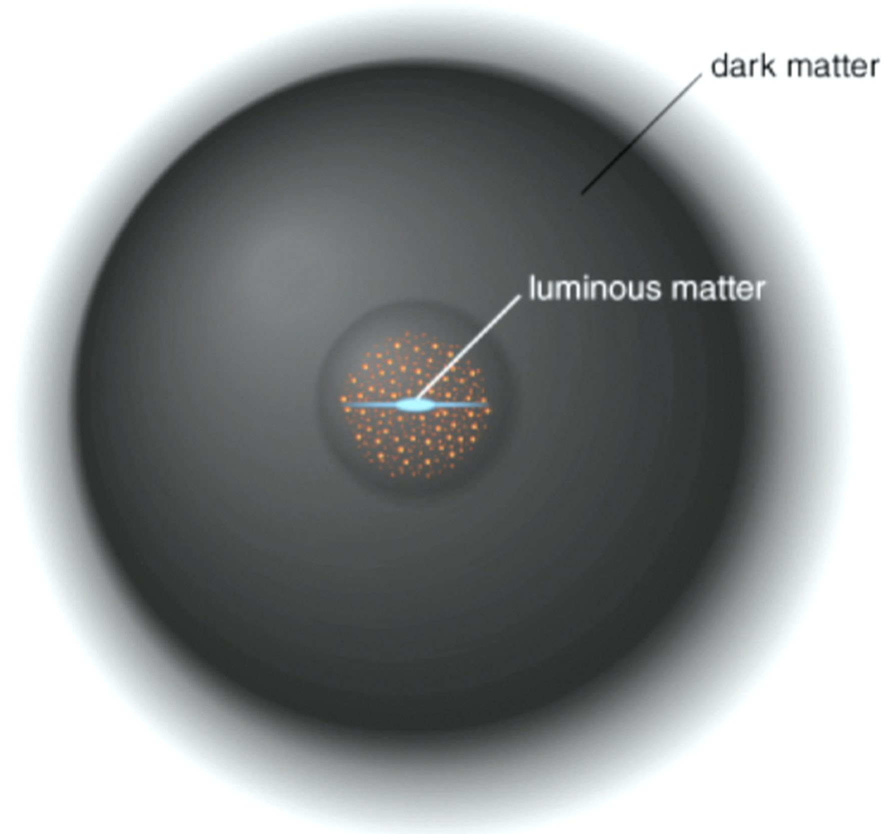
Abstract: <p>Can we learn about New Physics with astronomical and astro-particle data? Understanding how this is possible is key to unraveling one of the most pressing mysteries at the interface of cosmology and particle physics: the fundamental, particle nature of the dark matter.
I will discuss some of the recent puzzling findings in astro-particle and astronomical observations that might be related to signals from dark matter. I will first review the status of explanations to the cosmic-ray positron excess, emphasizing how we might be able to discriminate between astrophysical sources and dark matter.
I will then discuss the evidence for an X-ray line at 3.5 keV, and present new results on systematic effects and on the role of previously underestimated astrophysical lines.
Finally, I will discuss a reported excess of gamma rays from the central regions of the Galaxy. I will address the question of whether we are possibly observing a signal from dark matter annihilation, how to test this hypothesis, and which astrophysical mechanisms constitute the relevant background.

</p>

Stefano Profumo
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

New Physics and Astrophysical Searches for Dark Matter

Perimeter Institute
Tuesday May 5, 2015


dark matter
luminous matter

a new
elementary particle

what is an elementary particle?

what is an

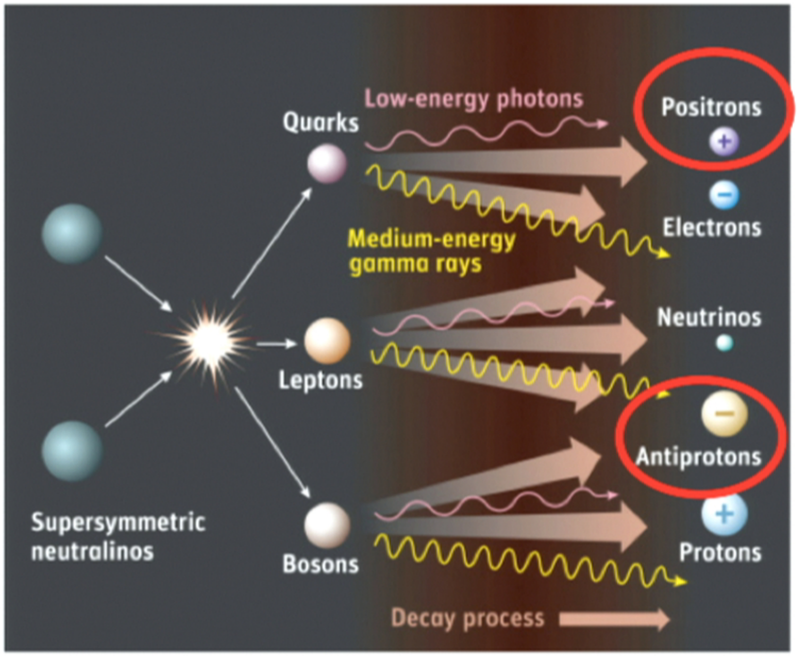
elementary particle?

an irreducible, unitary representation of the Poincaré Group

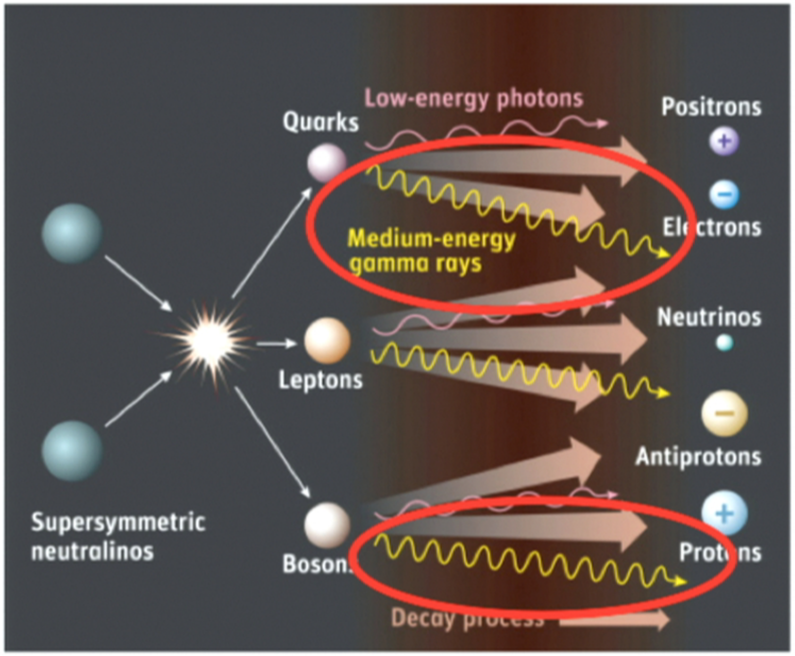
(m, J)

(m, J)

is this new dark matter particle coupled to the "visible world"?


Low-energy photons
Quarks
Positrons
Electrons
Medium-energy
gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric
neutralinos
Bosons
Protons
Decay process

Antimatter



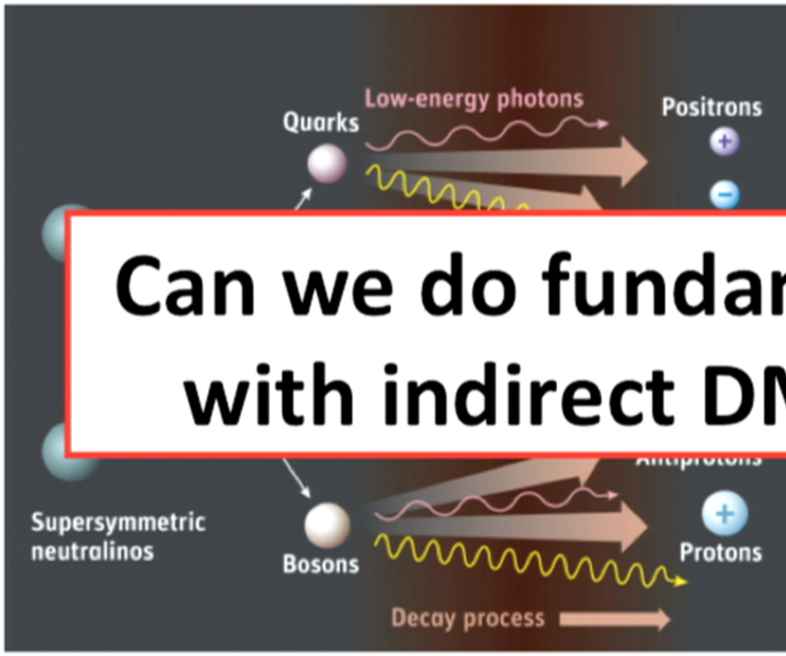
Antimatter

- ✓ Rare
- x Propagation

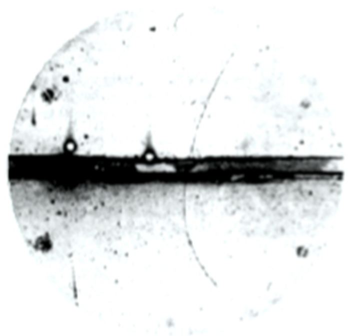
Photons

- ✓ Travel Straight

“Indirect” Dark Matter Detection



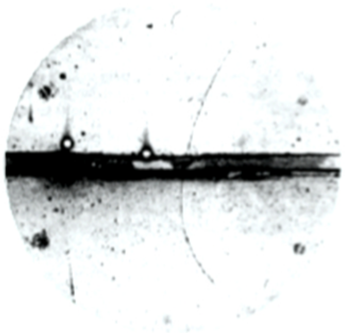
Can we do fundamental physics with indirect DM detection?



Antimatter
(positron, Anderson, 1932)

Second Generation
(muon, Anderson, 1936)

Pions ("Yukawa" particles)
(Lattes, Powell and
"Beppo" Occhialini)



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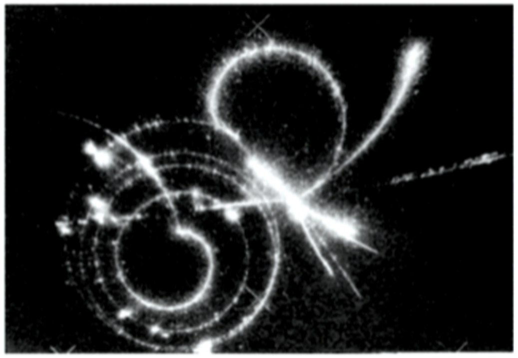

Pions ("Yukawa" particles)
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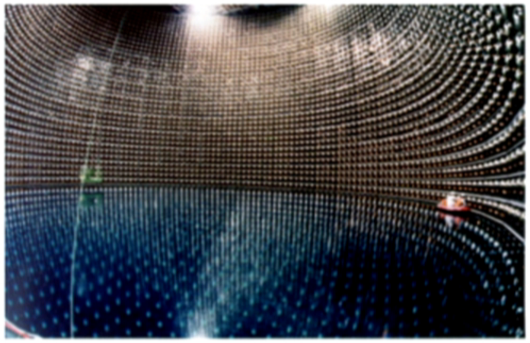
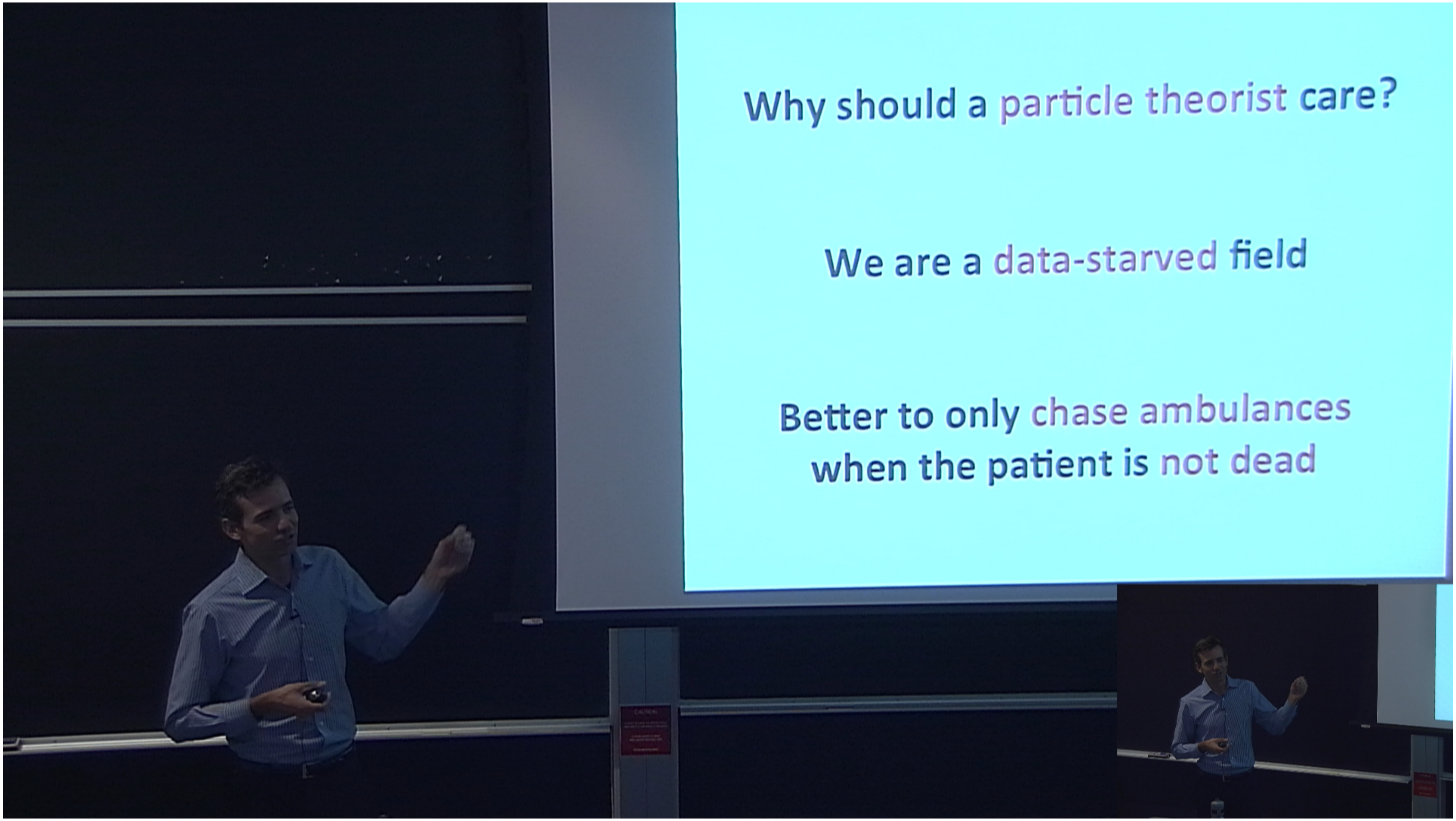


Neutrino Masses

Why should a particle theorist care?

We are a data-starved field


Why should a particle theorist care?
We are a data-starved field
Better to only chase ambulances
when the patient is not dead

one of the most popular* signals attributed to Dark Matter:

Cosmic-Ray Positron Excess

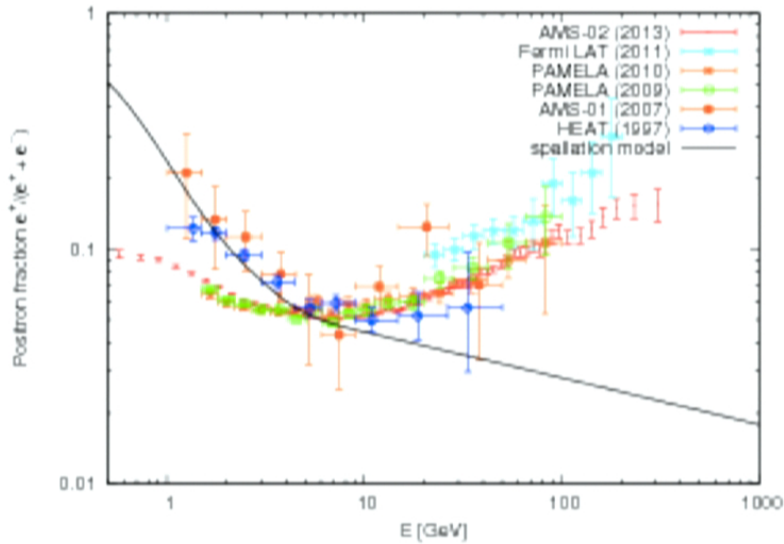
*approximately 1500 citations; ~1200 discuss dark matter

Rising Positron Fraction with energy cut-off at Dark Matter particle mass envisioned as smoking gun

[Tylka 1989, Turner and Wilczek, 1990]

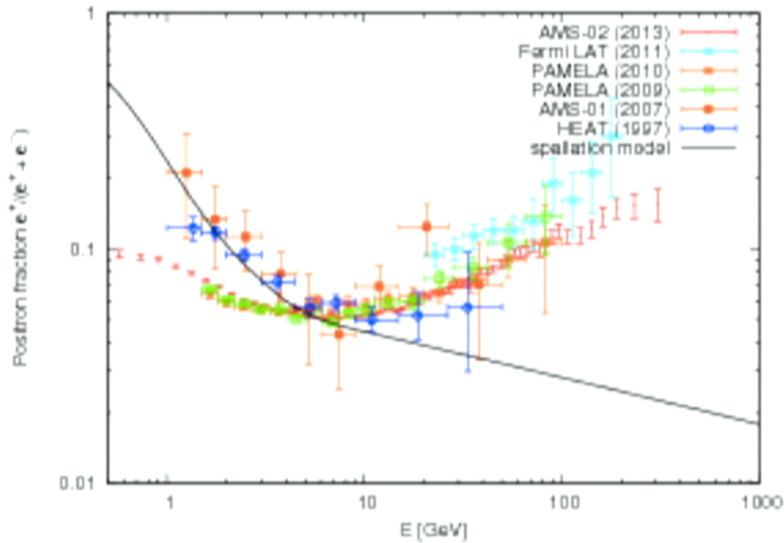
First hint of a rising positron fraction:

✓ **HEAT 1997**

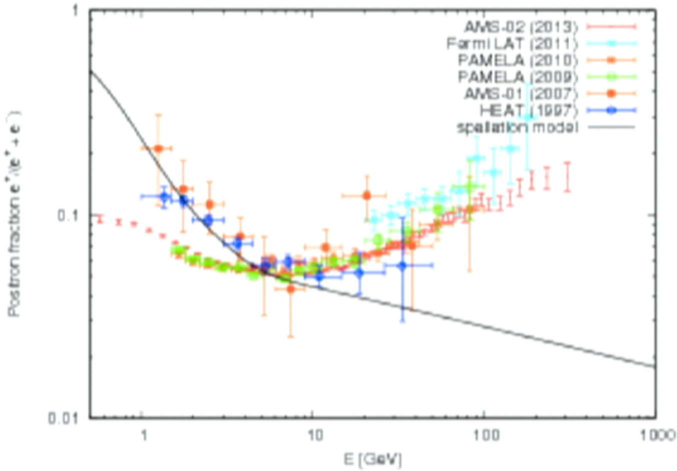


First hint of a rising positron fraction:

- ✓ **HEAT 1997**
- ✓ **Pamela 2009**
- ✓ **Fermi 2010**

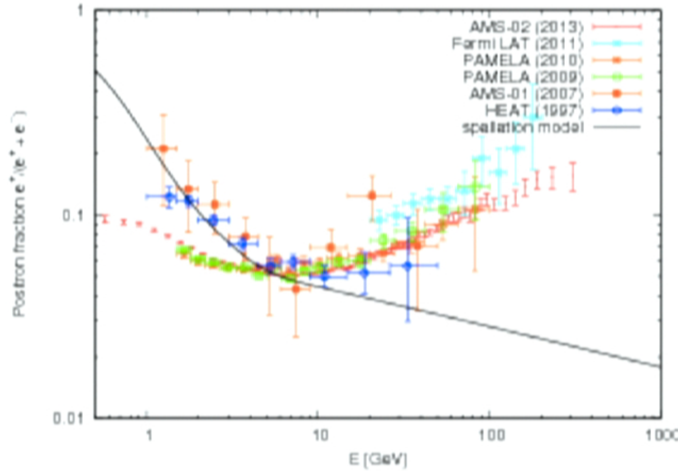


Decreasing positron fraction assumes exclusive secondary origin



Decreasing positron fraction assumes exclusive secondary origin

[*Physics: D(E) ~ E^{δ}*]



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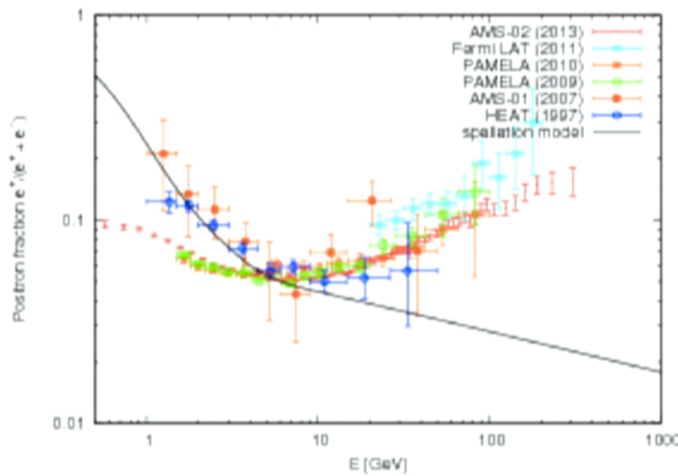
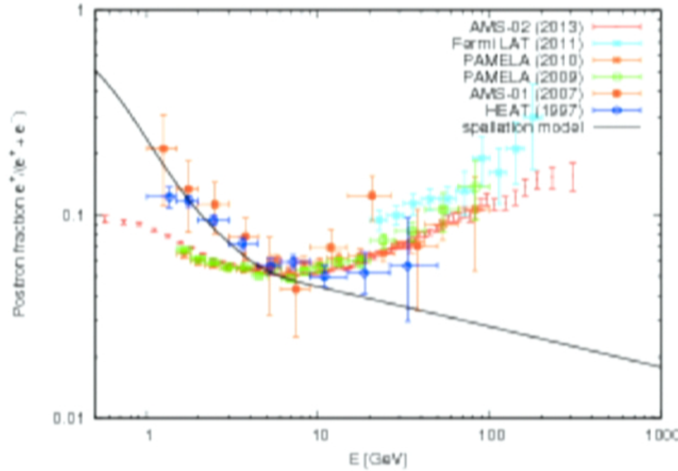


Hence rising fraction = excess
Caveats:

- **in-source secondary reacceleration**

Decreasing positron fraction assumes exclusive secondary origin

[*Physics: D(E) ~ E^{δ}*]

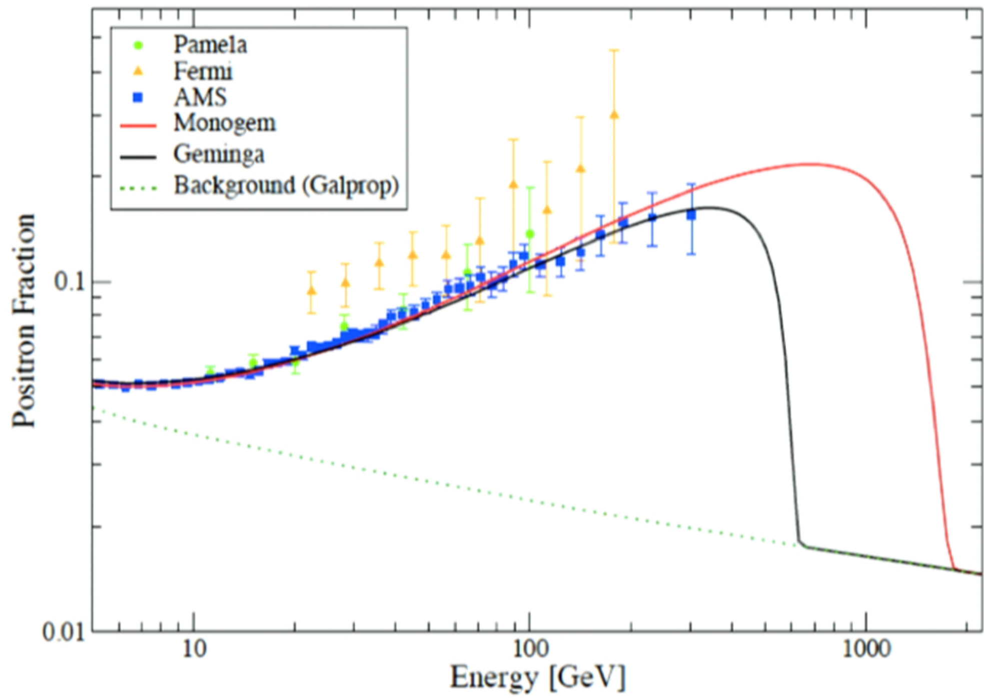


Hence rising fraction = excess

Caveats:

- **in-source secondary reacceleration**
- **primary production (e.g. PSR)**

PSRs work perfectly well



Linden and Profumo, 1304.1791, **Astrophys.J. 772 (2013) 18**

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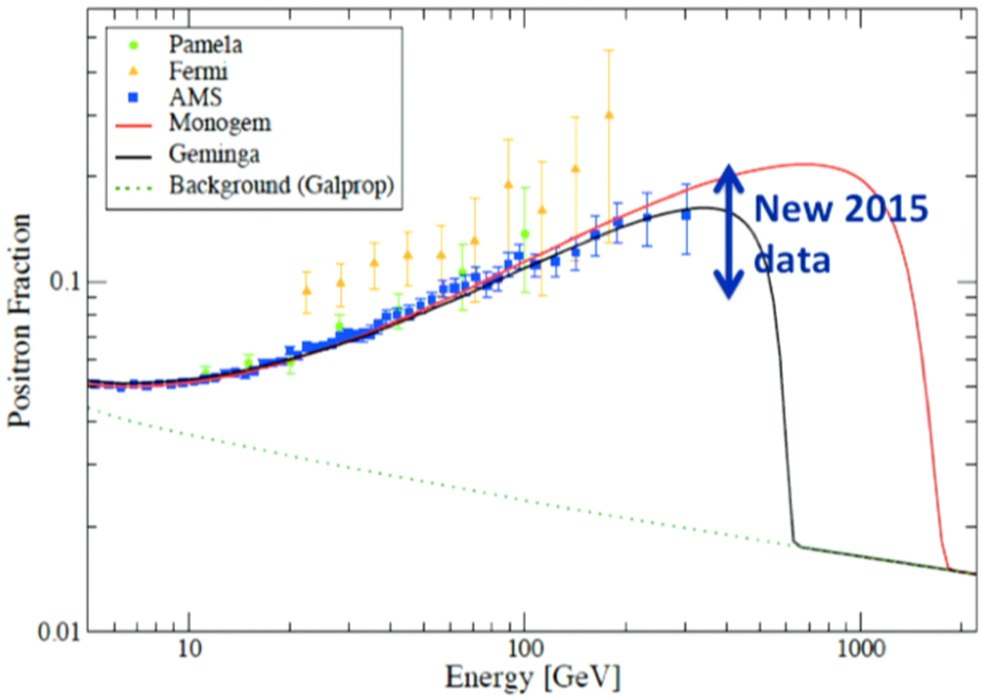

hardly any free parameter!

Linden and Profumo, 1304.1791, **Astrophys.J. 772 (2013) 18**

Cutoff is not a smoking gun for DM!

$$\frac{dE}{dt} = -bE^2$$

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$$\frac{dE}{dt} = -bE^2 \qquad \int_{\infty}^{E_{max}} \frac{dE}{E^2} = -bT_{PSR}$$

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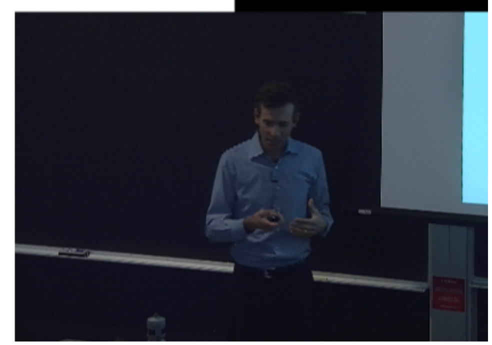
Observing a cutoff will likely help pinpointing relevant PSR(s)



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Observing a cutoff will likely help pinpointing relevant PSR(s)

Known PSR OK

[new e.g. gamma-ray PSR also important, Gendelev+Profum

Explaining the positron excess with Dark Matter is problematic

But for theorists problems are opportunities

Cutoff is not a smoking gun for DM!

$$\frac{dE}{dt} = -bE^2 \qquad \int_{\infty}^{E_{\max}} \frac{dE}{E^2} = -bT_{PSR} \qquad E_{\max} = \frac{1}{bT_{PSR}}$$

Observing a cutoff will likely help pinpointing relevant PSR(s)

Known PSR OK

[new e.g. gamma-ray PSR also important, Gendelev+Profumo 2010]

Redman's Theorem

"Any competent theoretician can fit any given theory to any given set of facts" (*)

Roderick O. Redman
(b. 1905, d. 1975)
Professor of Astronomy
at Cambridge University

(*) Quoted in M. Longair's "High Energy Astrophysics", sec 2.5.1 "The psychology of astronomers and astrophysicists"

- Large annihilation rate today, smaller in early universe

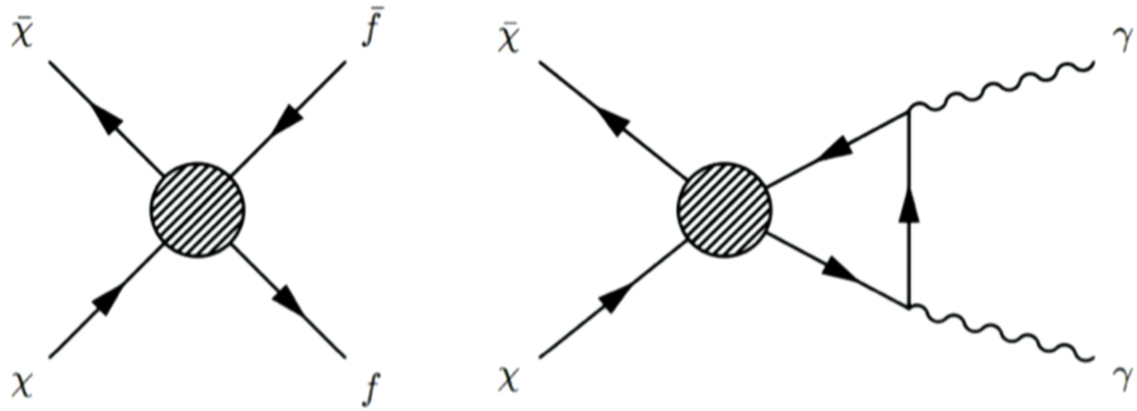
- Suppress hadronic annihilation modes

- Large annihilation rate **today**, smaller in **early universe**

- Suppress **hadronic** annihilation modes

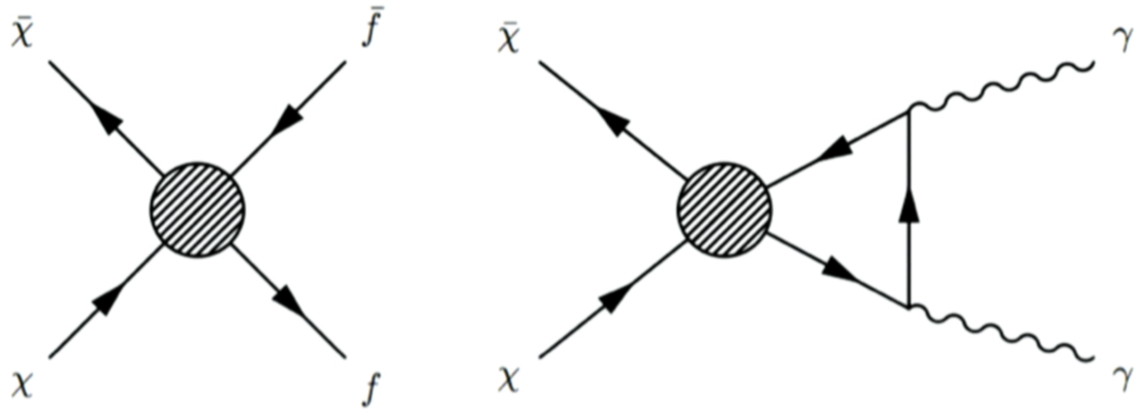
- Hide **secondary** radiation

An example: close the lepton loop!



Coogan, Profumo and Shepherd (2015)

An example: close the lepton loop!



Name	Operator	X
SS	$\bar{\chi}\chi\bar{f}f$	γ
PS	$\bar{\chi}\gamma^5\chi\bar{f}f$	
SP	$\bar{\chi}\chi\bar{f}\gamma^5 f$	
PP	$\bar{\chi}\gamma^5\chi\bar{f}\gamma^5 f$	
RR	$\bar{\chi}\gamma^\mu P_R\chi\bar{f}\gamma_\mu P_R f$	γ
RL	$\bar{\chi}\gamma^\mu P_R\chi\bar{f}\gamma_\mu P_L f$	
LR	$\bar{\chi}\gamma^\mu P_L\chi\bar{f}\gamma_\mu P_R f$	
LL	$\bar{\chi}\gamma^\mu P_L\chi\bar{f}\gamma_\mu P_L f$	

Name	Operator	X
VV	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$	Z
AV	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu f$	
VA	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu\gamma^5 f$	
AA	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma^5 f$	γ
RV	$\bar{\chi}\gamma^\mu P_R\chi\bar{f}\gamma_\mu f$	Z
LV	$\bar{\chi}\gamma^\mu P_L\chi\bar{f}\gamma_\mu f$	
RA	$\bar{\chi}\gamma^\mu P_R\chi\bar{f}\gamma_\mu\gamma^5 f$	γ
LA	$\bar{\chi}\gamma^\mu P_L\chi\bar{f}\gamma_\mu\gamma^5 f$	
VR	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu P_R f$	Z
VL	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu P_L f$	
AR	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu P_R f$	γ
AL	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu P_L f$	

Coogan, Profumo and Shephe

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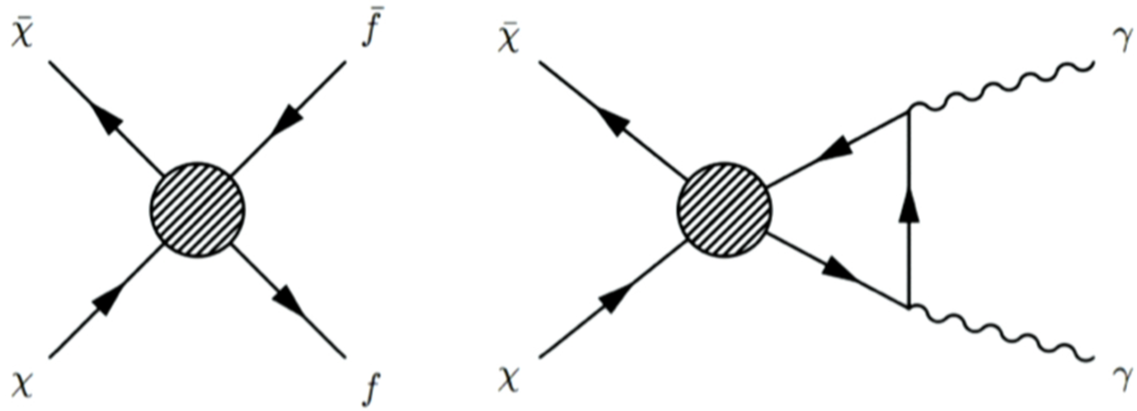

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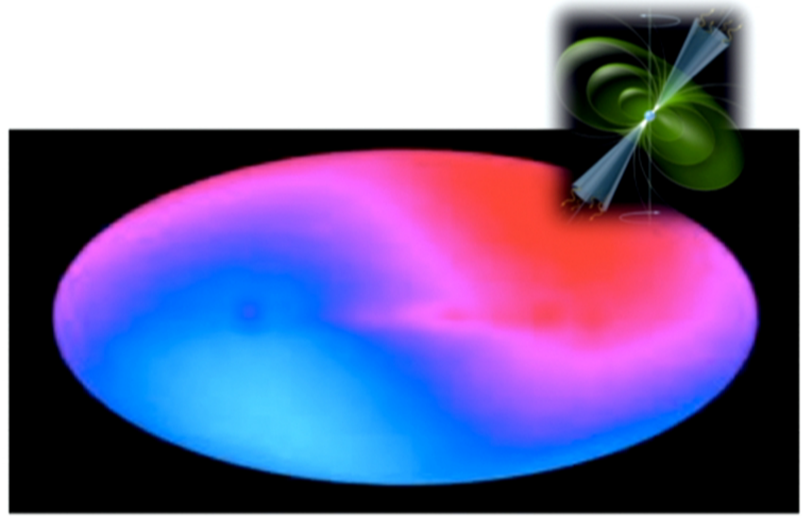
AR	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu P_R f$	γ
AL	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu P_L f$	

AA, AL, AR, AV ruled out!

Coogan, Profumo and Shepherd (2015)

How can we tell PSR apart from DM?

Use arrival direction of $e^{\pm}$!



How can we tell PSR apart from DM?

General theorem: if anisotropy is directed, it cannot be Dark Matter

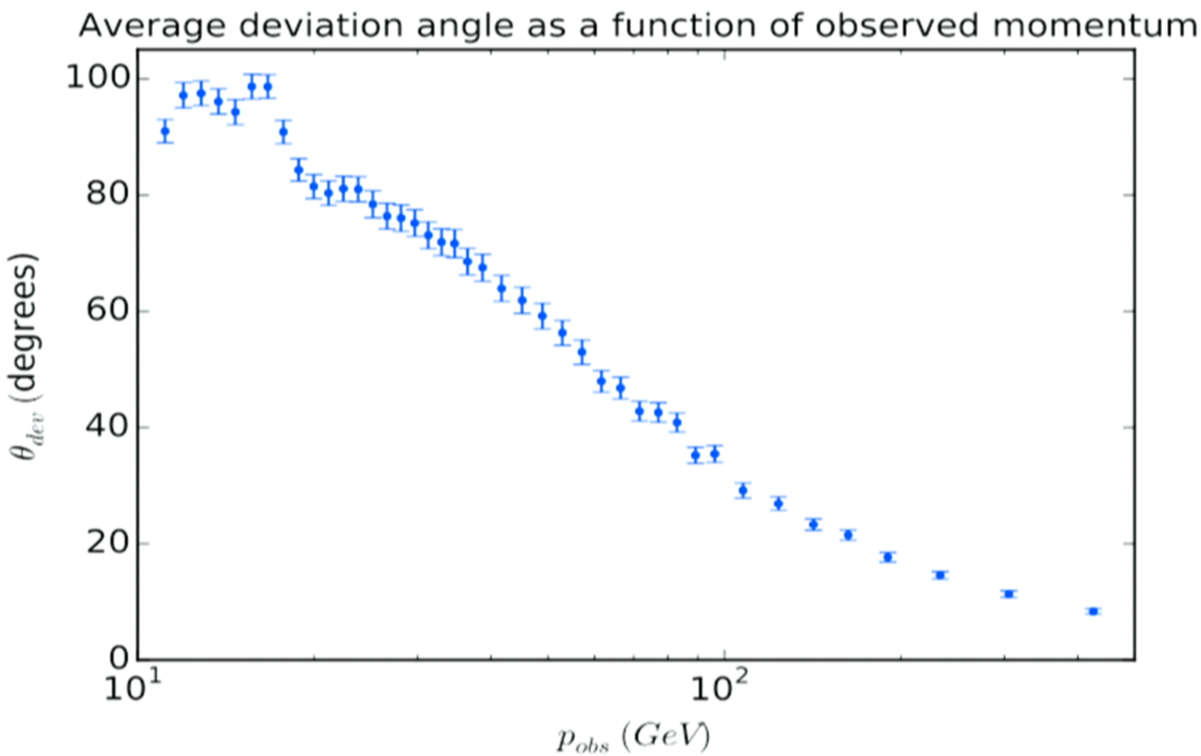
The detection of a cosmic-ray electron-positron anisotropy is a sufficient (but not necessary) condition to discard a Dark Matter origin for the anomalous positron fraction

Stefano Profumo*
Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
(Dated: May 21, 2014)

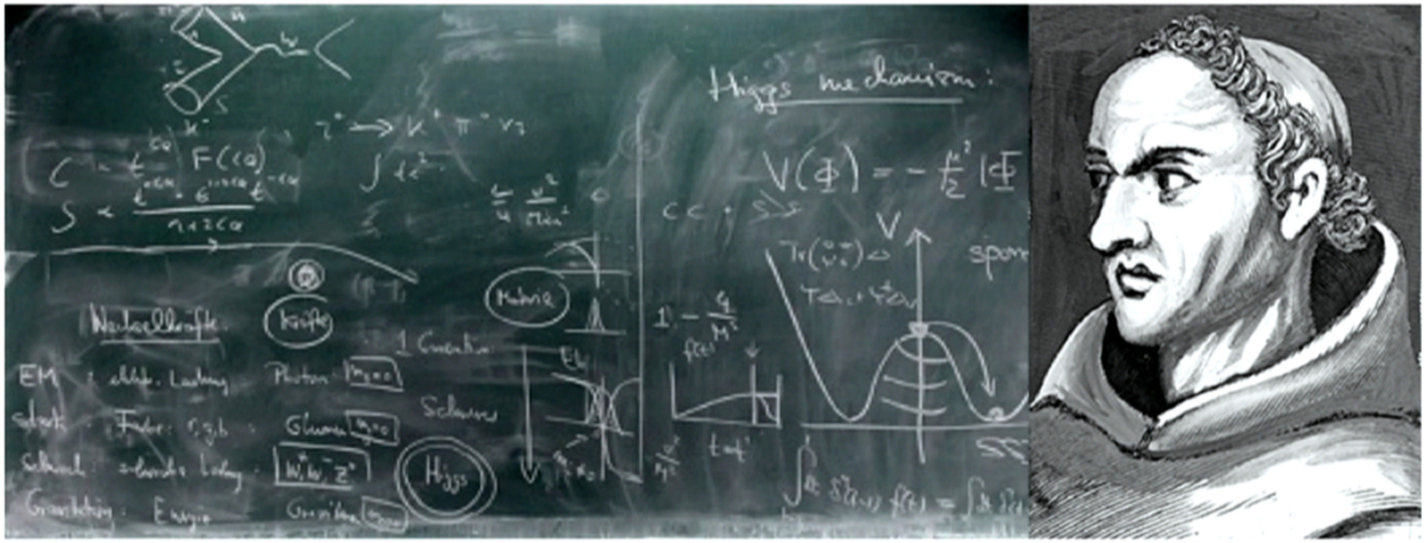
I demonstrate that if an anisotropy in the arrival direction of high-energy cosmic-ray electrons and positrons is observed, then dark matter annihilation is ruled out as an explanation to the positron excess. For an observable anisotropy to originate from dark matter annihilation, the high-energy electrons and positrons must be produced

Profumo 2014

…but life might not be easy after all!



Coogan and Profumo, in preparation



Rare picture of William of **Occam**, **perplexed** by **XXI century particle theorists** working on **dark matter**

WIRED

DANIELLE VENTON 04.22.15 1:00 PM

SCIENCE IS CLOSING IN ON DARK MATTER, BUT BEWARE THE HYPE

much hype during last few months from discovery of a 3.5 keV X-ray line

SKY

Mysterious X-rays Might Hint at Dark Matter

By: **Monica Young** | July 8, 2014

UNIVERSE TODAY

New Signal May Be Evidence of Dark Matter, Say Researchers

by VANESSA JANEK *on* DECEMBER 15, 2014

much hype during last few months from discovery of a 3.5 keV X-ray line

SKY

Mysterious X-rays Might Hint at Dark Matter

By: **Monica Young** | July 8, 2014

UNIVERSE TODAY

New Signal May Be Evidence of Dark Matter,

X-ray observations shed new light on dark matter

gizmag

By Brian Dodson

March 10, 2014

much hype during last few months from
discovery of a 3.5 keV X-ray line

The Register®
Biting the hand that feeds IT

Boffins say dark matter found with X-ray

Bulbul+ (2014)
- Stacked clusters
- Perseus

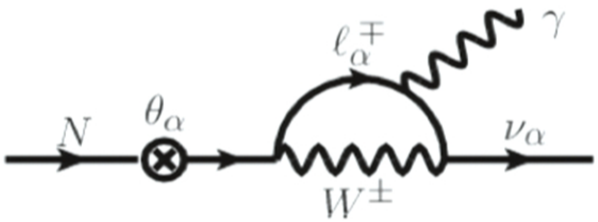
Boyarsky+ (2014)
- M31
- Perseus

Jeltema+Profumo (2014)
- Galactic Center

X-ray lines predicted from sterile neutrinos

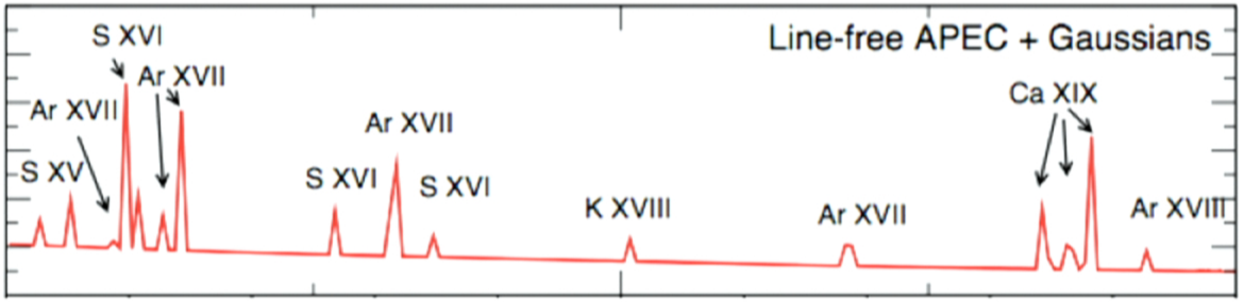
- $SU(2)_L$ gauge singlet, but (small) mixing angle with active neutrinos
- Viable DM candidates (Dodelson-Woodrow production; "warm" DM)

X-ray lines predicted from sterile neutrinos



- $SU(2)_L$ gauge singlet, but (small) mixing angle with active neutrinos
- Viable DM candidates (Dodelson-Woodrow production; "warm" DM)
- Possibly connected with baryogenesis (νMSM)
- Would decay via mixing with active neutrinos

X-ray lines also from atomic transitions of highly-ionized Z ~ 20 atoms



K XVIII has two lines near 3.5 keV

How do we tell K apart from sterile ν??

Try to predict K XVIII line brightness using other elemental lines

two key complications:

#1 Plasma Temperature

Bulbul+ argues against K XVIII
since prediction for K 3.5 keV line too low
(by factors ~20 for solar abundances)

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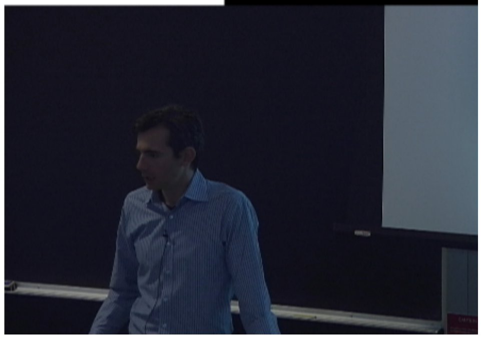
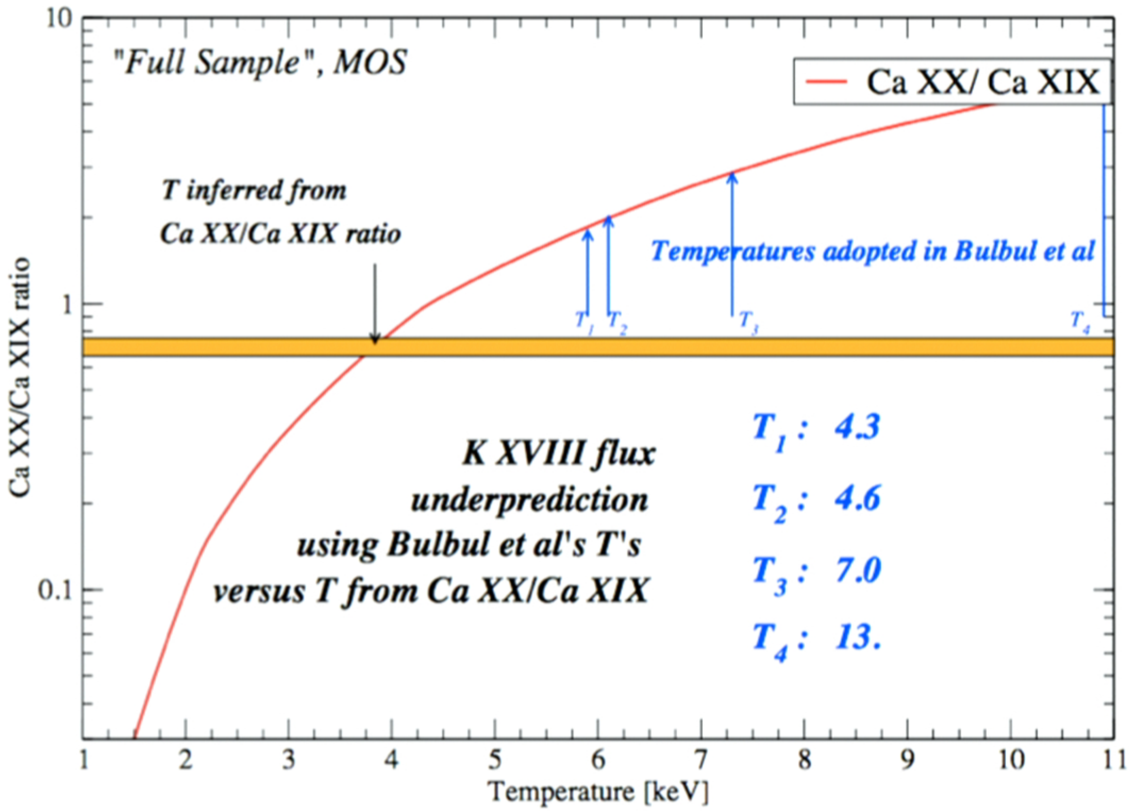


however, Bulbul+ uses very large T, which suppress K emission!



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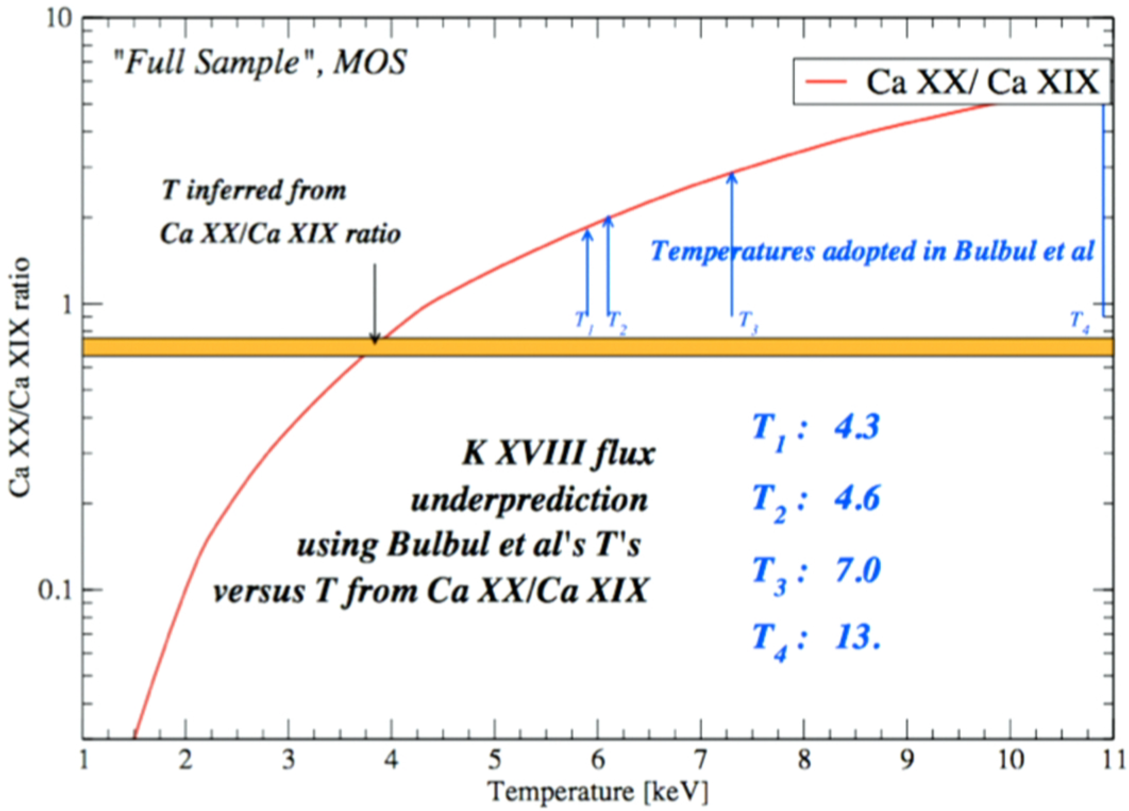


#1 look elsewhere: depressing

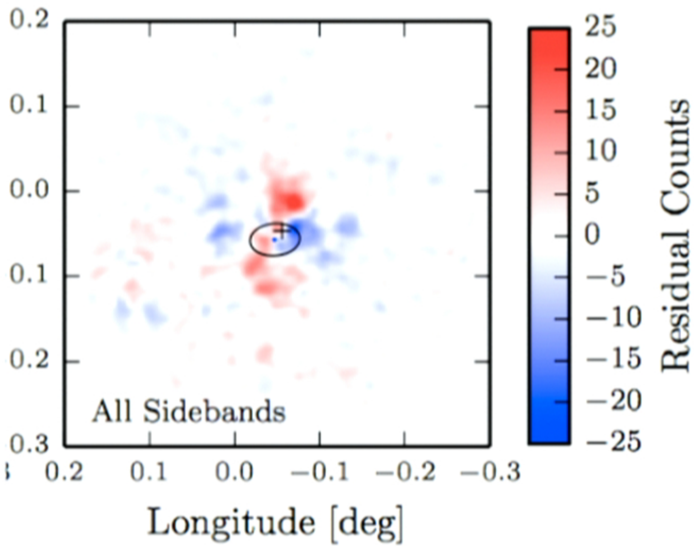
- no signal from dSph*

*Malyshev et al 2014

#1 look elsewhere: depressing

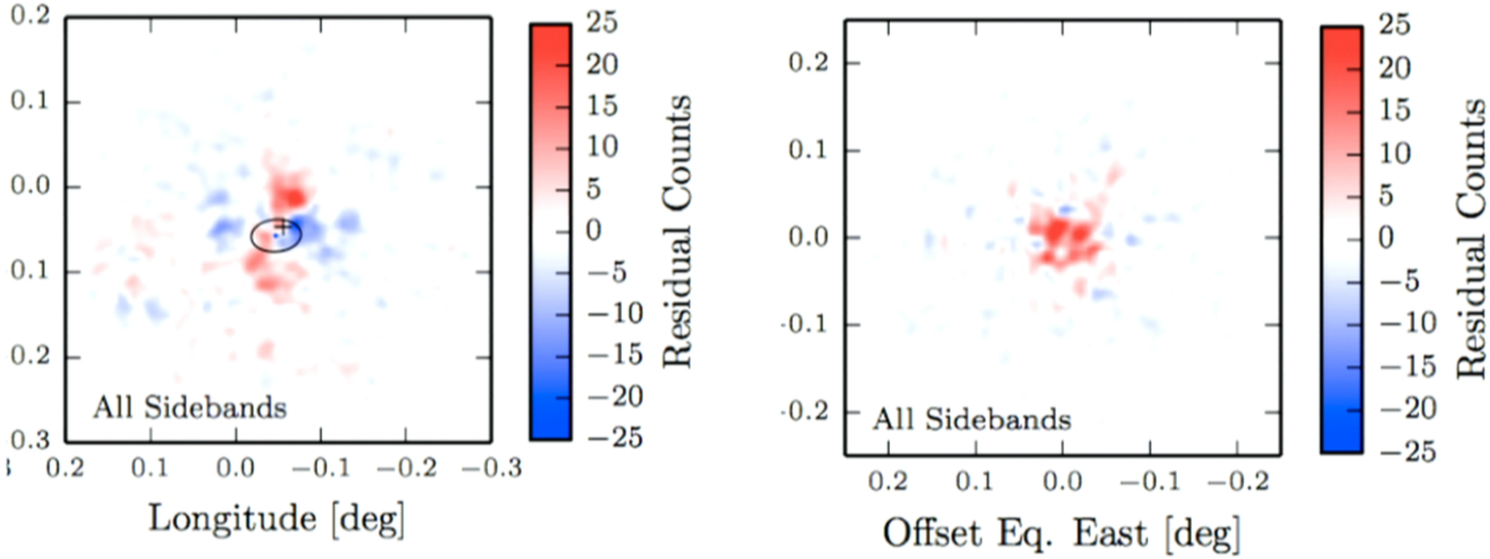
- no signal from dSph*
- no signal from stacked galaxies and groups, low-T plasma**
- no signal from M31***

*Malyshev et al 2014
** Anderson et al 2014
*** Jeltema and Profumo 2014 (2)



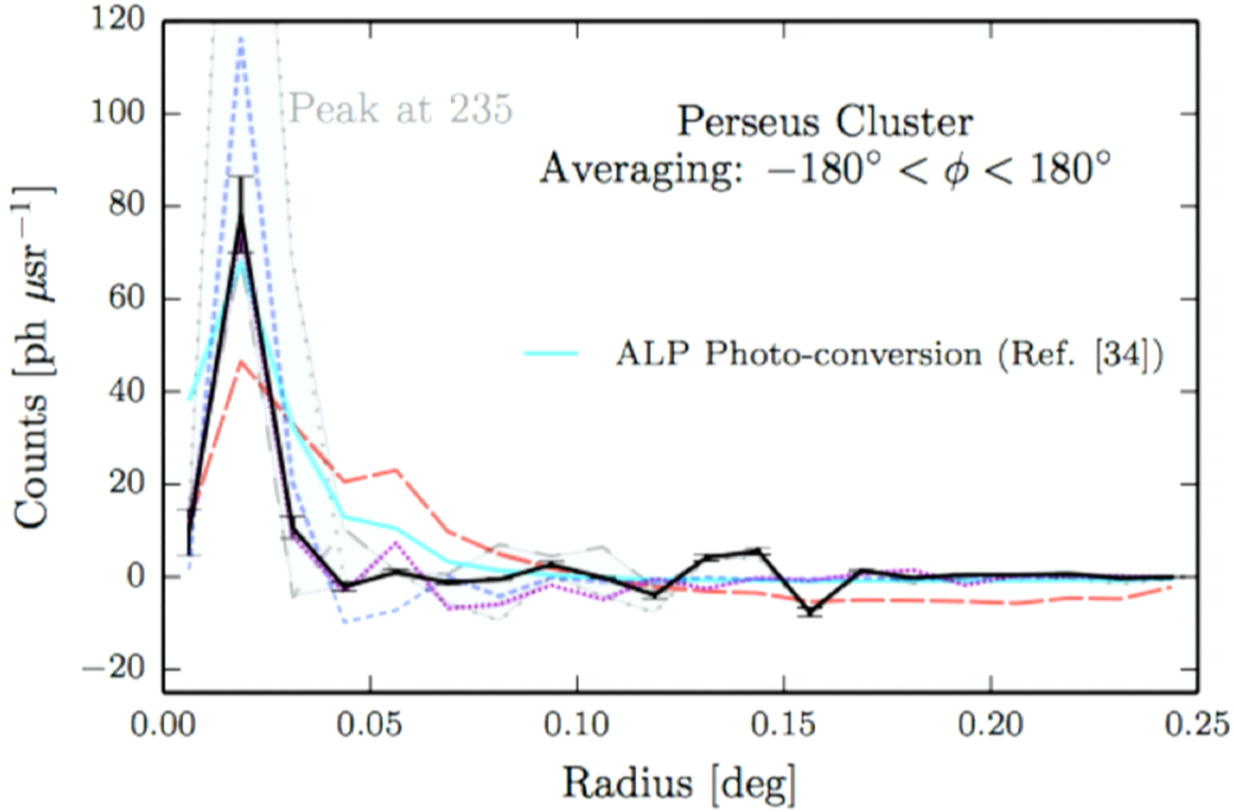
Milky Way

Carlson, Jeltema and Profumo, 2015

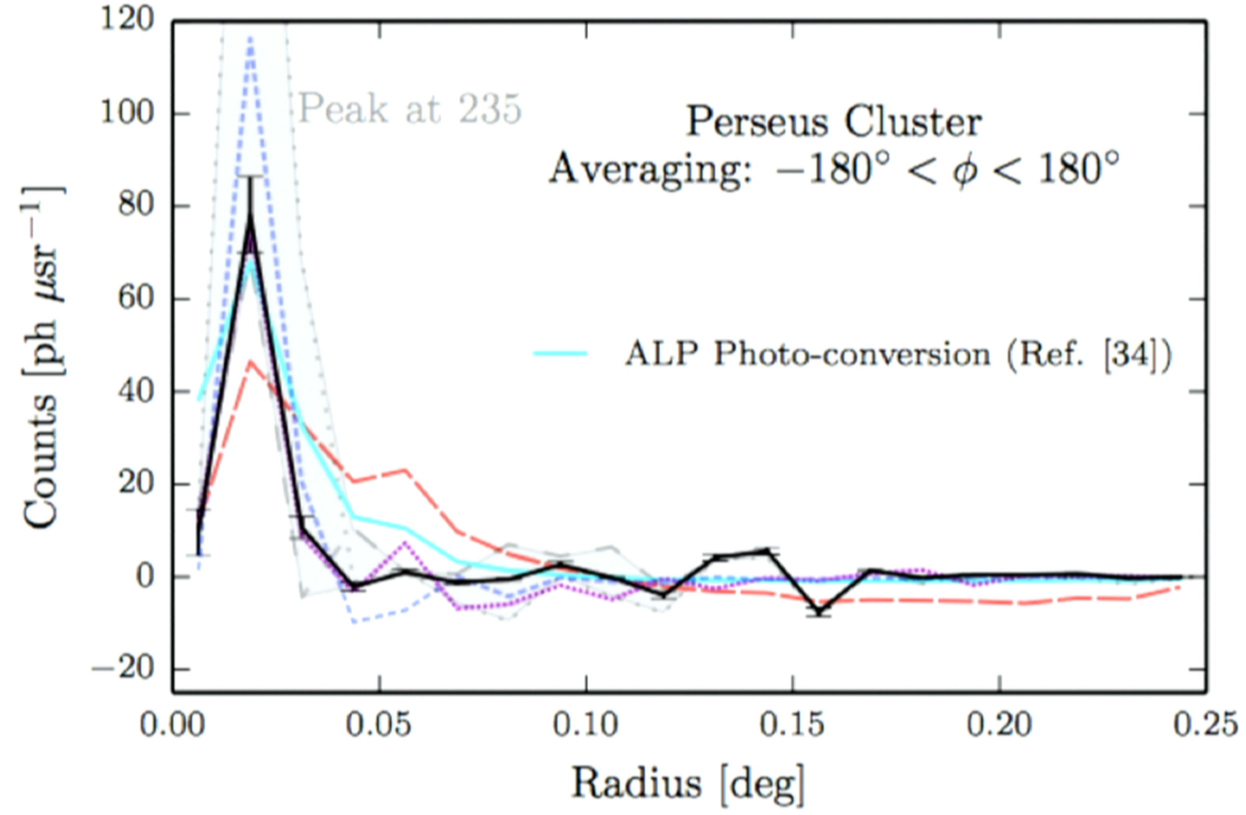


Milky Way Perseus

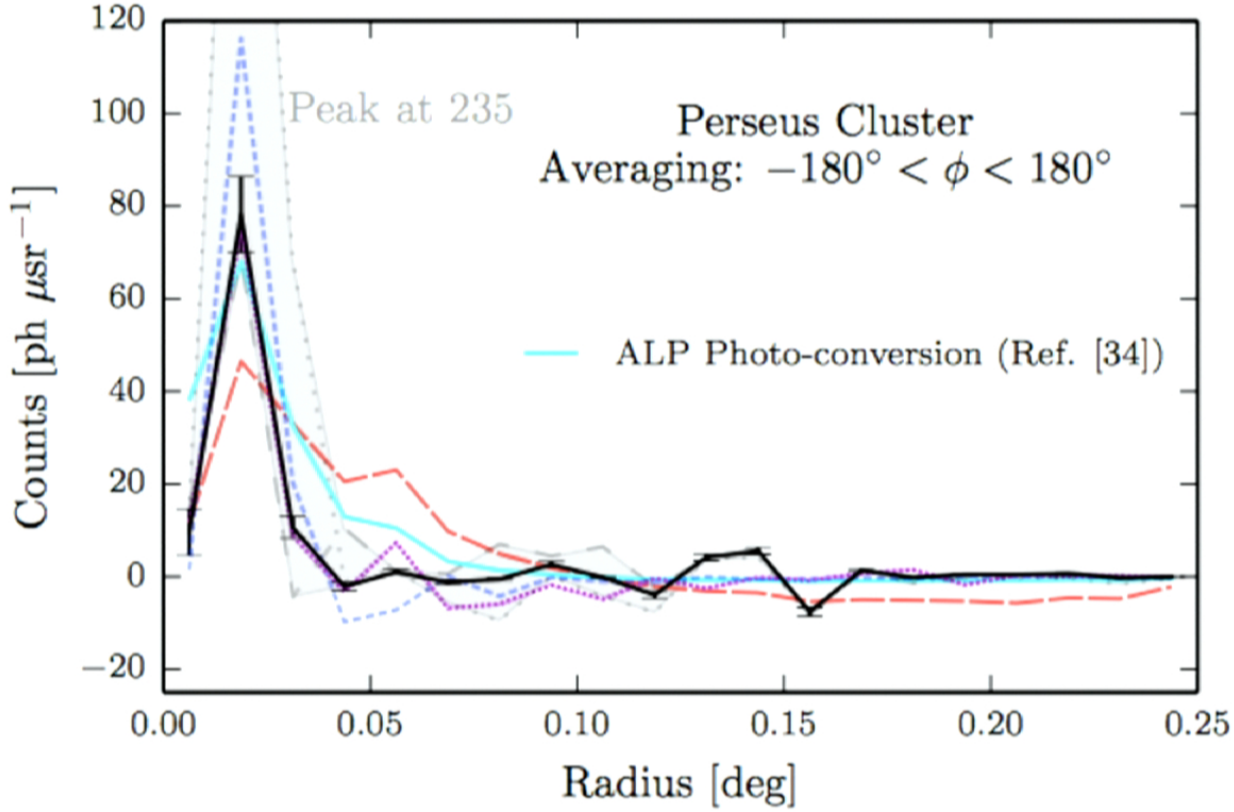
Carlson, Jeltema and Profumo, 2015



Carlson, Jeltema and Profumo, 2015



Carlson, Jeltema and Profumo, 2015



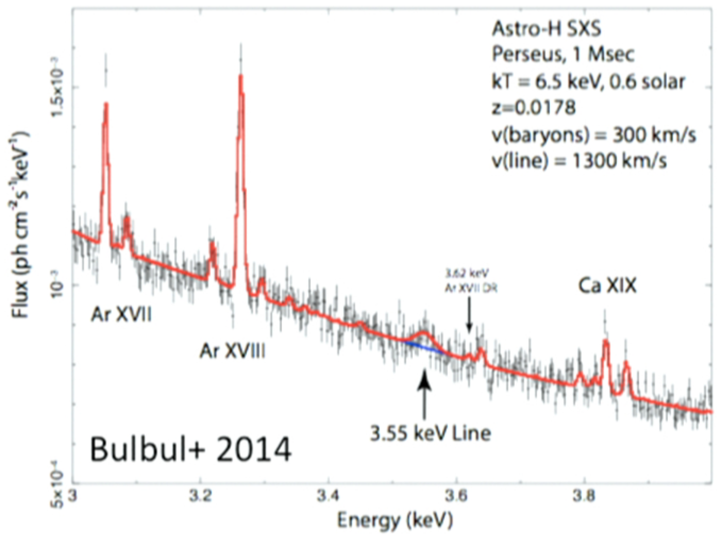
axion-like particles survive the morphology test

decaying DM strongly disfavored

Carlson, Jeltema and Profumo, 2015

Sterile Neutrino Dark Matter decay strongly disfavored

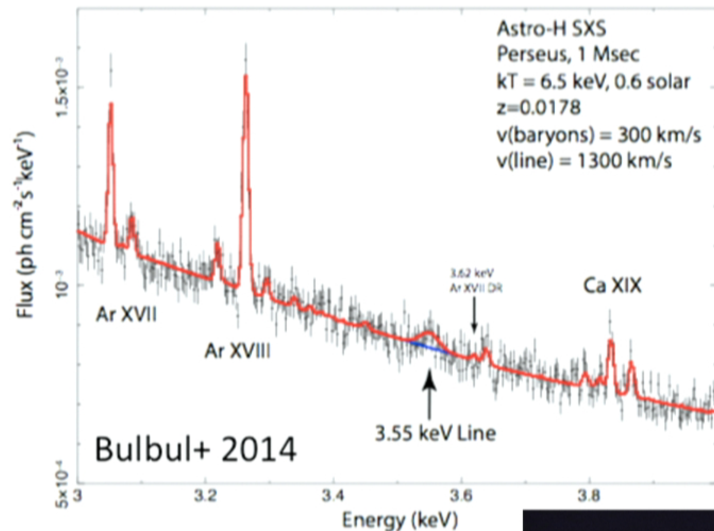
Final word: Astro-H
Soft X-ray Spectrometer



- Tell K XVIII line apart based on energy resolution
- Observe line broadening by velocity dispersion

Sterile Neutrino Dark Matter decay strongly disfavored

Final word: Astro-H Soft X-ray Spectrometer



- Tell K XVIII line apart based on energy resolu
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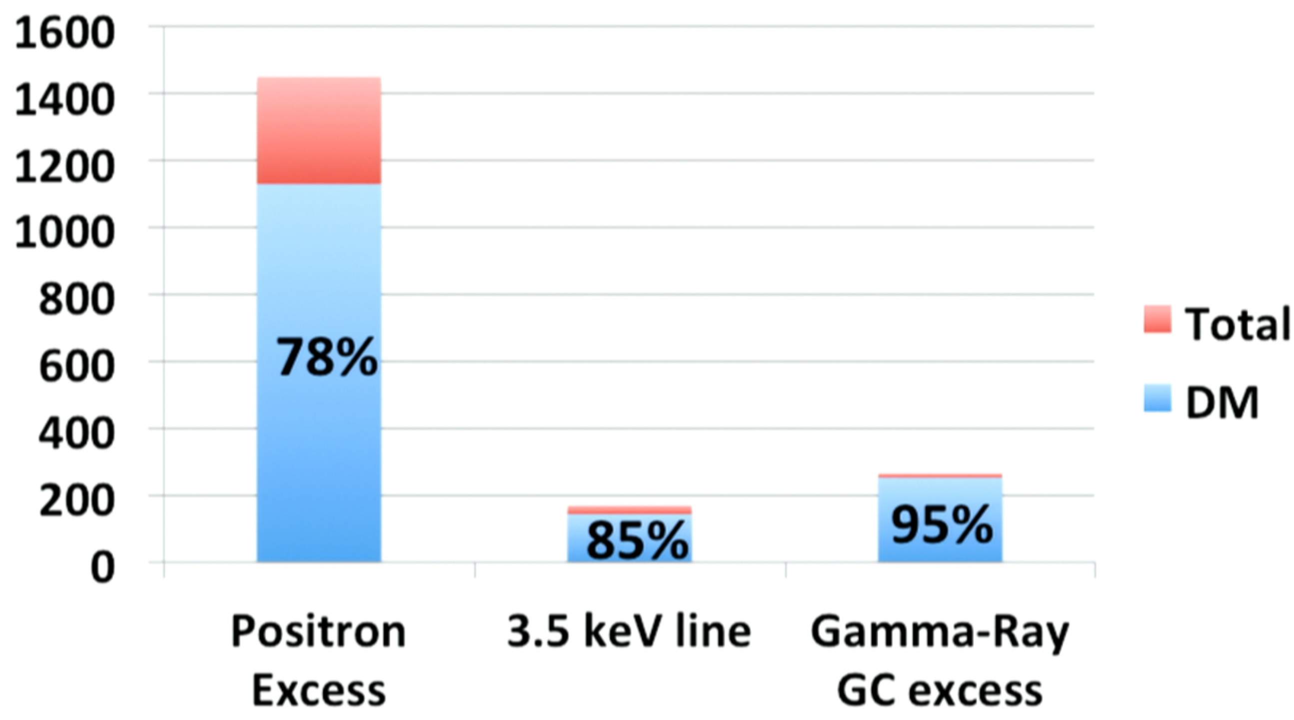
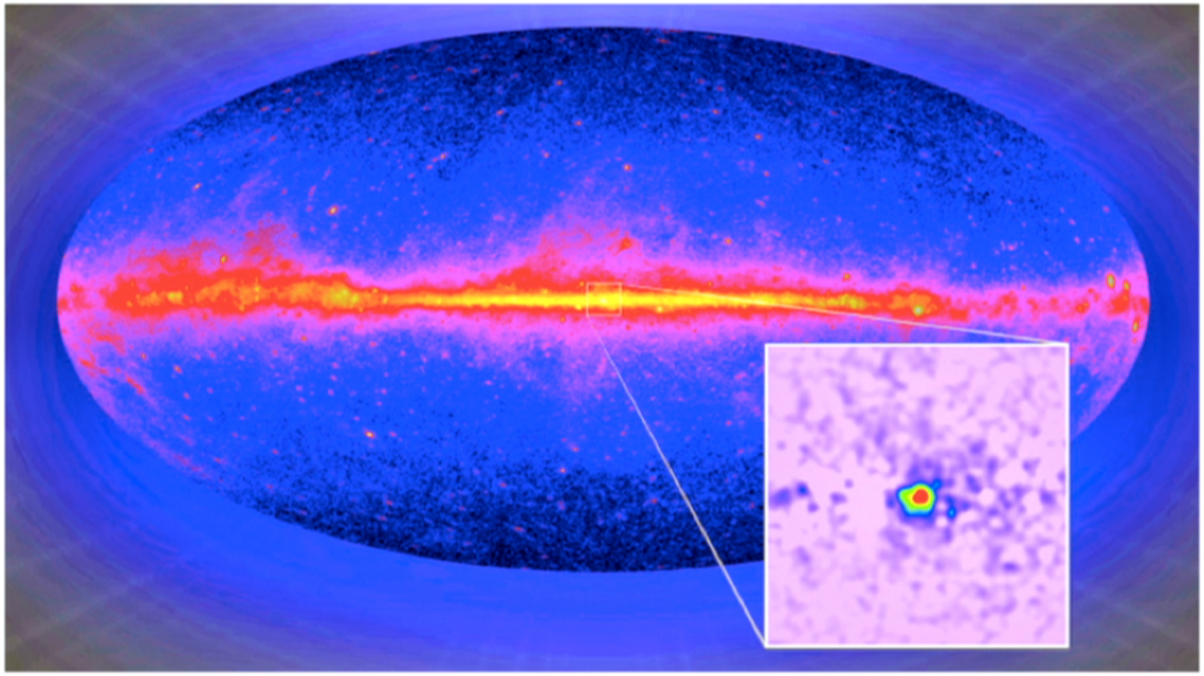
The Darkest Signal:
Galactic Center Gamma-Ray Excess



After early reports (primarily by Hooper et al) **Galactic Center Excess** reported independently, and with a variety of different assumptions for background etc, by Daylan et al (Harvard+MIT+Fermilab); Abazijian et al (UCI); Macias and Gordon (NZ)




The Economist
APRIL 28TH - MAY 4TH 2001
IS INEQUALITY GROWING?
TARGET-CRAZY LABOUR
Why Silvio Berlusconi is unfit to lead Italy

What **produces** the Galactic Center **excess**?

Fitting the excess with
Dark Matter Annihilation **not problematic**

- ✓ **Morphology** ~OK
- ✓ **Spectrum** ~OK
- ✓ Constraints from **dSph, radio, CMB**
  ~sort of OK

What produces the Galactic Center excess?

Most obvious astrophysical counterpart (unresolved pulsars) does not work

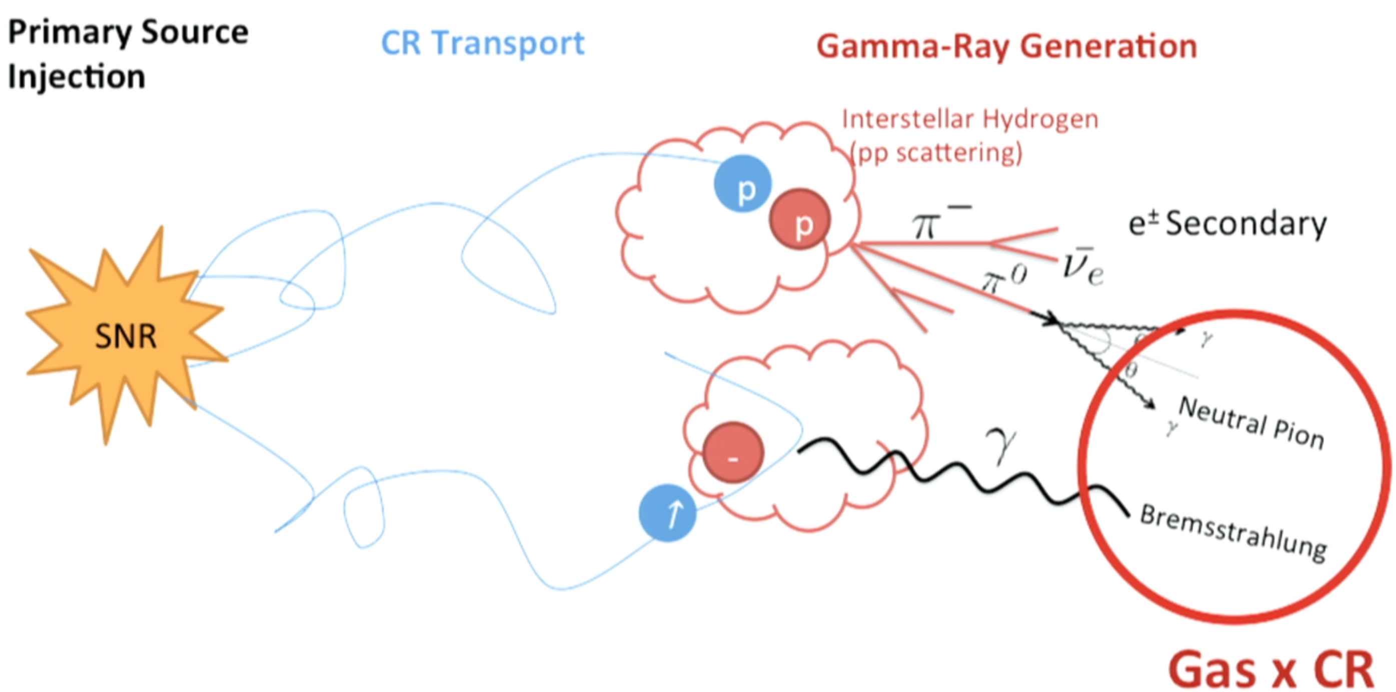
What produces the Galactic Center excess?

WRONG QUESTION!

Rather: is the excess indeed there?

Are models of diffuse emission adequate to current data?

Two key ingredients of diffuse emission



All groups that find an excess assume:

1. 2-D Gas Density Distribution
2. 2-D Cosmic-Ray Propagation
3. Steady State

All groups that find an excess assume:

1. 2-D Gas Density Distribution
2. 2-D Cosmic-Ray Propagation
3. Steady State
4. Simplistic Cosmic-ray source distribution

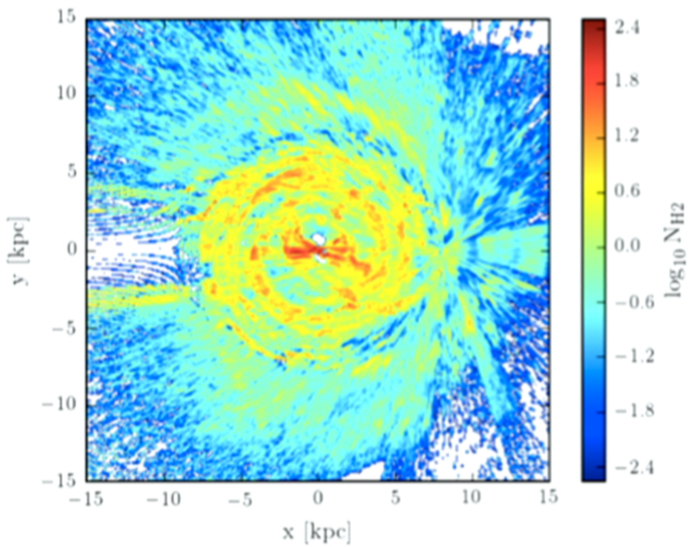
Every assumption costs a systematic effect of the same order as the excess!

Towards the next generation of diffuse gamma-ray models

1. 3-D Gas Density Distribution
2. 3-D Cosmic-Ray Propagation

Carlson, Linden, Profumo, Queiroz in preparation

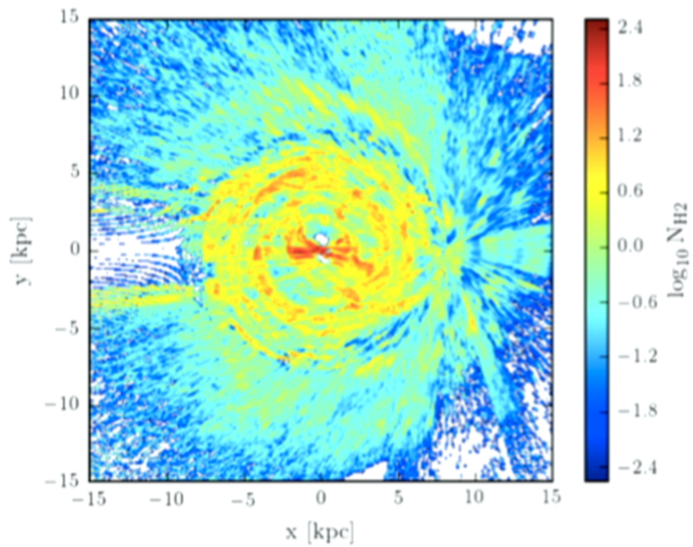
1. 3-D Gas Density Distribution



H2 column density

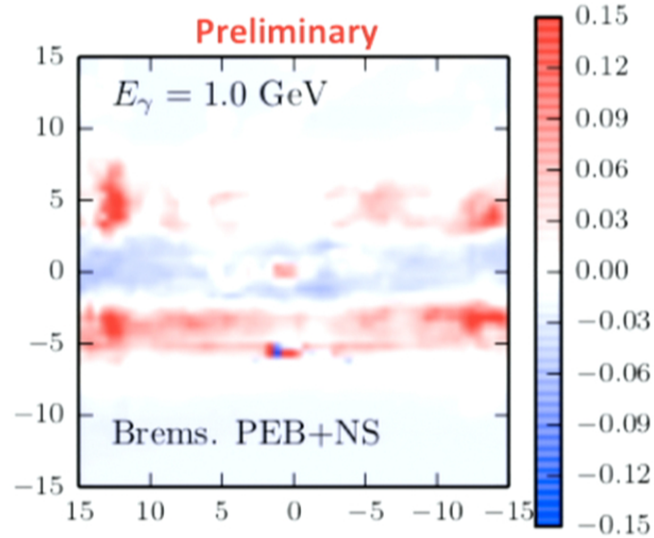
Carlson, Linden, Profumo, Queiroz in preparation

1. 3-D Gas Density Distribution



H2 column density

Preliminary



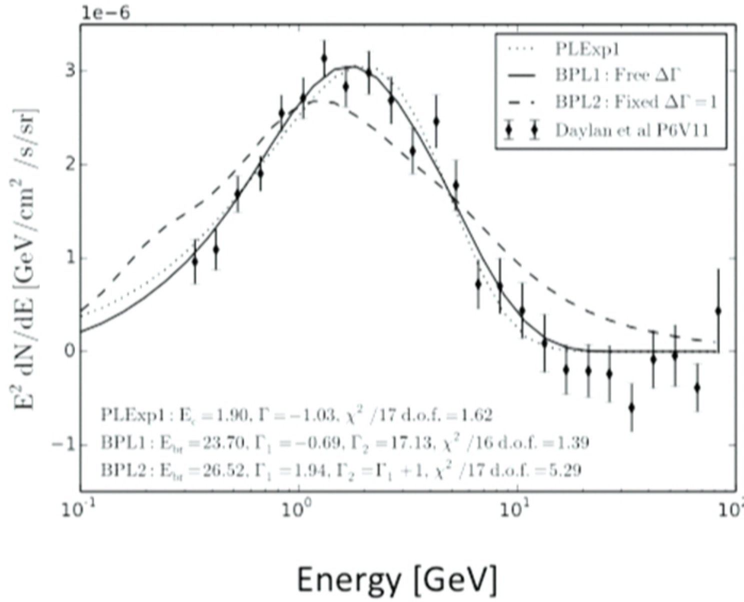
~3-10% effect

Carlson, Linden, Profumo, Queiroz in preparation

2. 3-D Cosmic-Ray Propagation

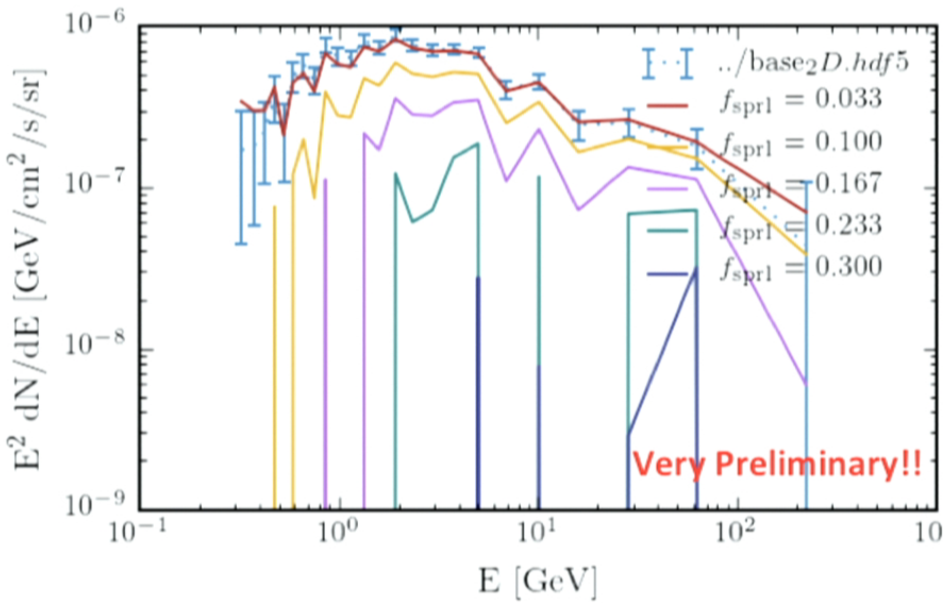
Carlson, Linden, Profumo, Queiroz in preparation

3. Steady State



Carlson and Profumo, PRD 2014

4. Physically motivated Cosmic-ray source distributions



Placing ~20% of CR sources in H2 regions absorbs the excess ~entirely!

Carlson, Linden, Profumo, Queiroz in preparation

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I remain skeptic about establishing
a conclusive Dark Matter
detection signal from the Galactic Center

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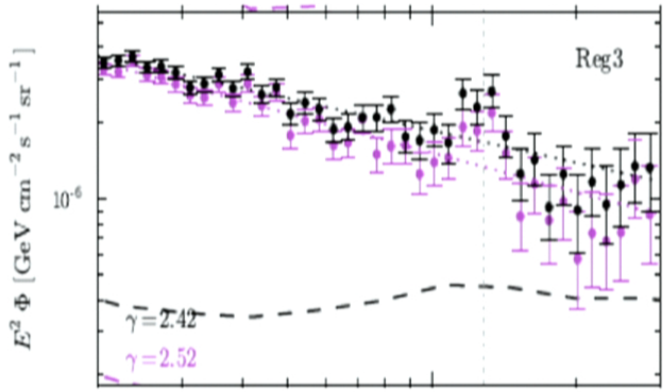
Is this possible at all?

Yes.

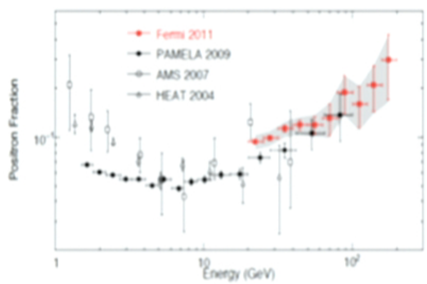


Unfortunately, the 130 GeV line was a statistical fluke

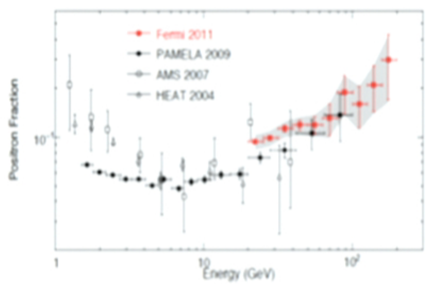
- too narrow right off the bat
- significance did not increase with time
- Pass 8 does not see any line

Weniger 2012

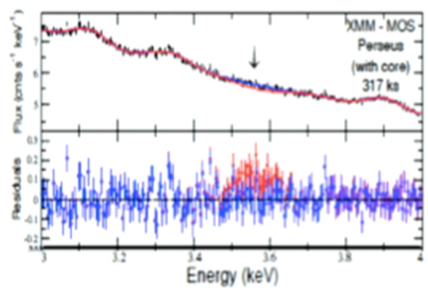
Cosmic-Ray Positron Excess



Cosmic-Ray Positron Excess



3.5 keV line



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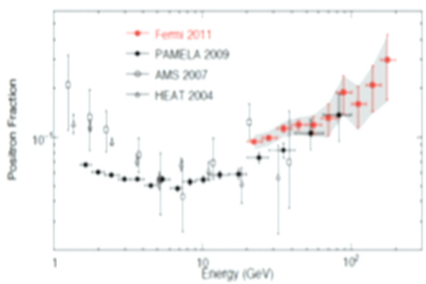

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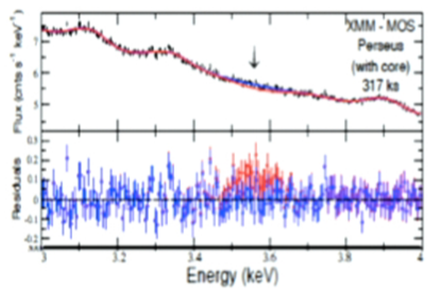
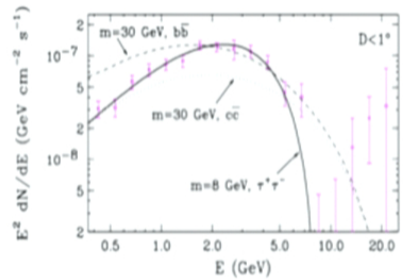


Gamma-ray excess in the Galactic Center



13-TeV LHC

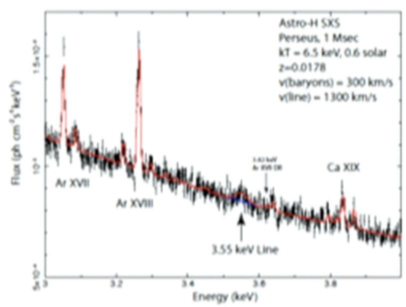
13-TeV LHC

Radio Surveys

13-TeV LHC

Radio Surveys

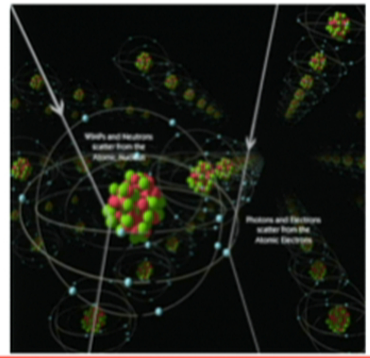
Astro-H



CTA

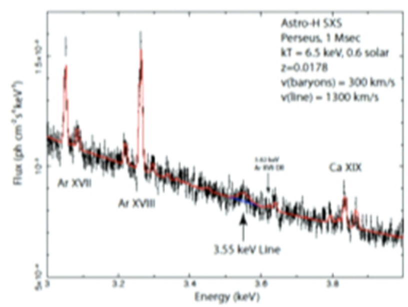
13-TeV LHC

G-2 Direct Detection



Radio Surveys

Astro-H



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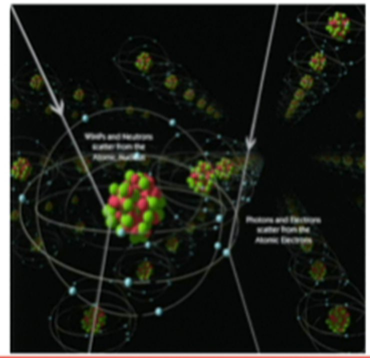

Radio Surveys

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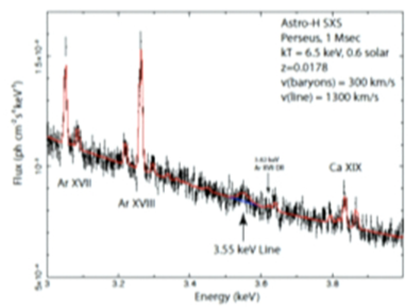

CTA

The promenades of Euclid

...an appropriate adage for indirect dark matter detection :

"Everything we see hides another thing,

we always want to see what is hidden by what we see"

R. Magritte

[slide concept: Pasquale Serpico]