Stefano Profumo

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

Status of Astrophysical Searches for Dark Matter

13th International Workshop on the Dark Side of the Universe

KAIST Muji Campus, Daejeon, Korea

Monday July 12, 2017

Detecting the debris of dark matter annihilation or decay

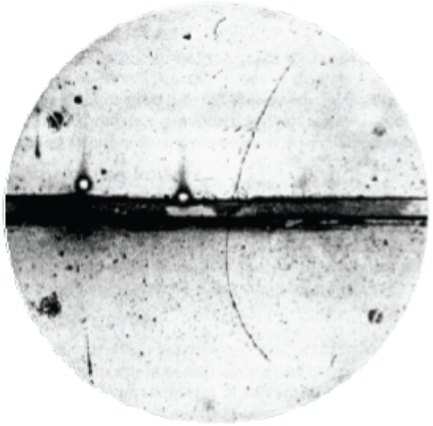
"Indirect" Dark Matter Detection

“Indirect” Dark Matter Detection

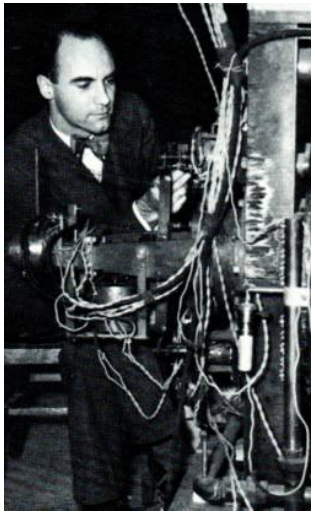
Can we do fundamental physics with indirect DM detection?

“Indirect” Dark Matter Detection

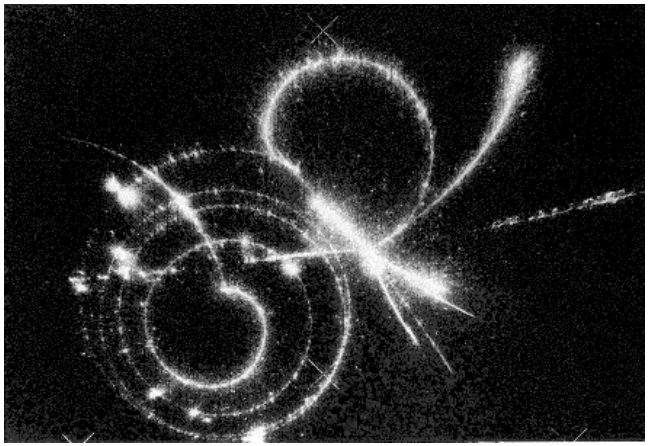
Can we do fundamental physics with astroparticle/astronomical data?



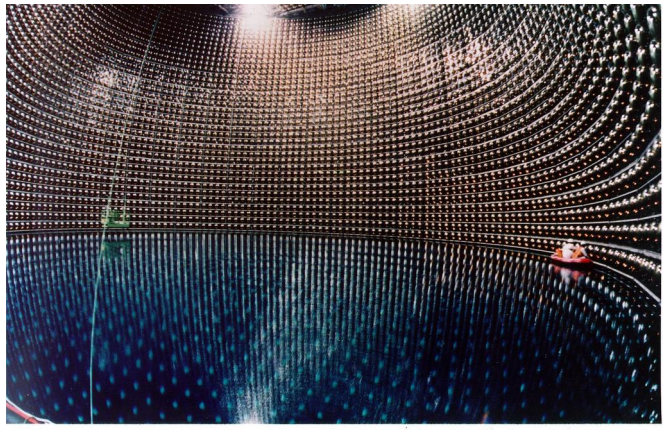
Antimatter
(positron, Anderson, 1932)



Second Generation
(muon, Anderson, 1936)



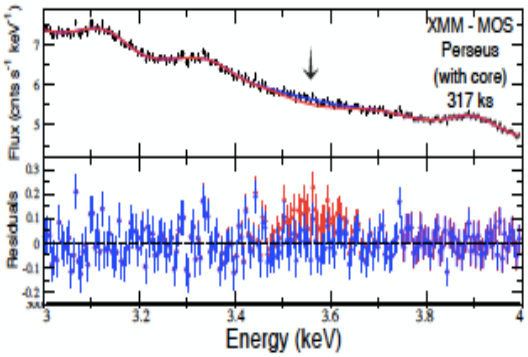
Pions ("Yukawa" particles)
(Lattes, Powell and
"Beppo" Occhialini)



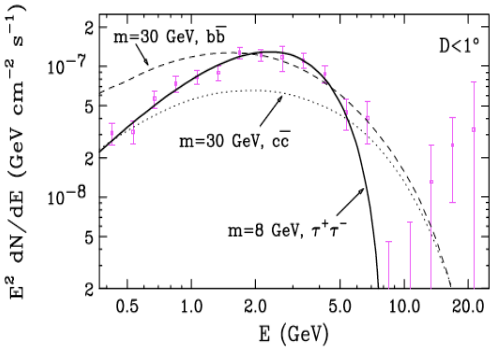
Neutrino Masses/Mixing
(2015 Nobel Prize)

Three tantalizing signals

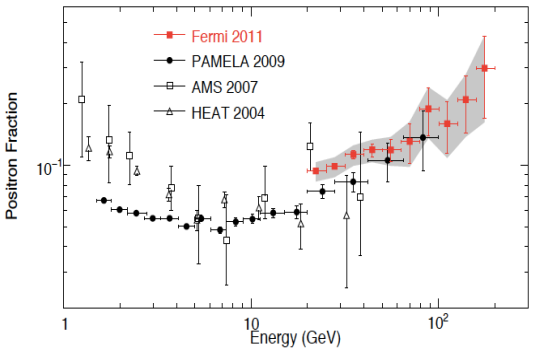
3.5 keV line



Gamma-ray excess in the Galactic Center



Cosmic-Ray Anomalies

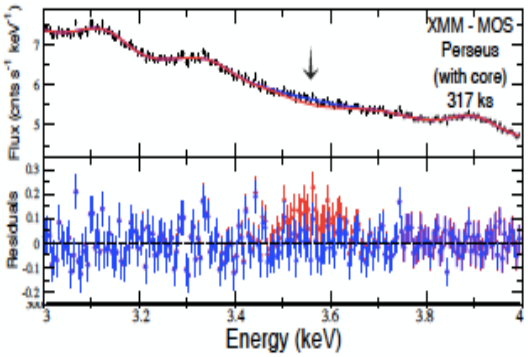


factor of 10^9 apart in energy!

…exemplifies how much we know about the particle nature of dark matter (close to nothing)

Three tantalizing signals

3.5 keV line



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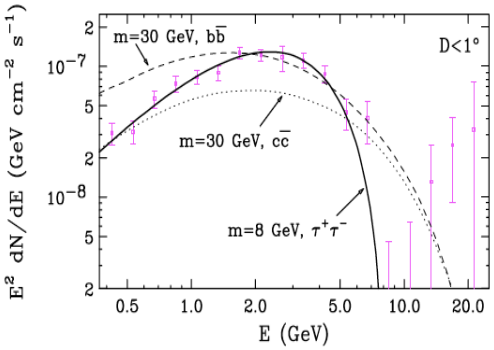

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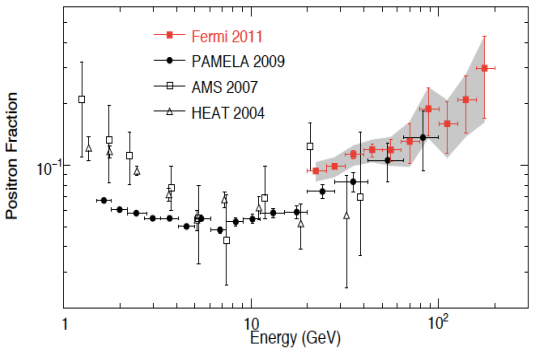


factor of 10^9 apart in energy!

…exemplifies how much we know about the particle nature of dark matter (close to nothing)

Bulbul+ (2014)

- Stacked clusters
- Perseus

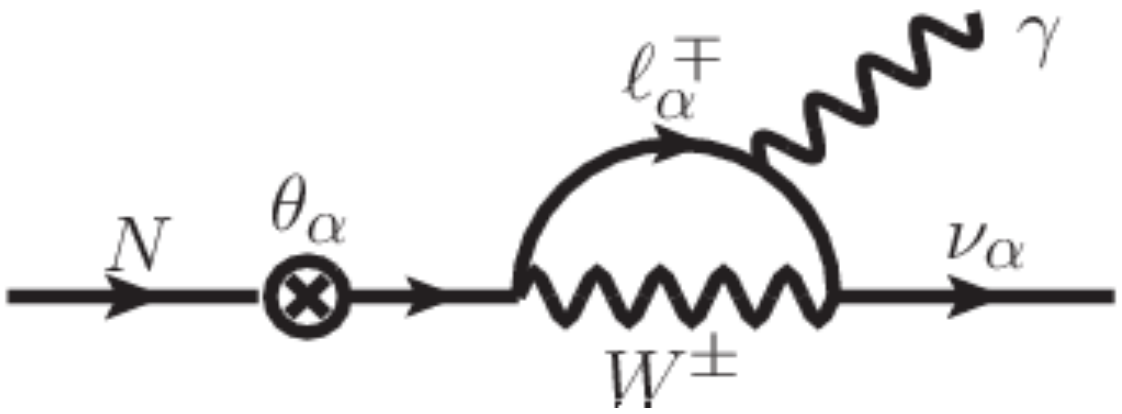
Boyarsky+ (2014)

- M31 (Andromeda)
- Perseus

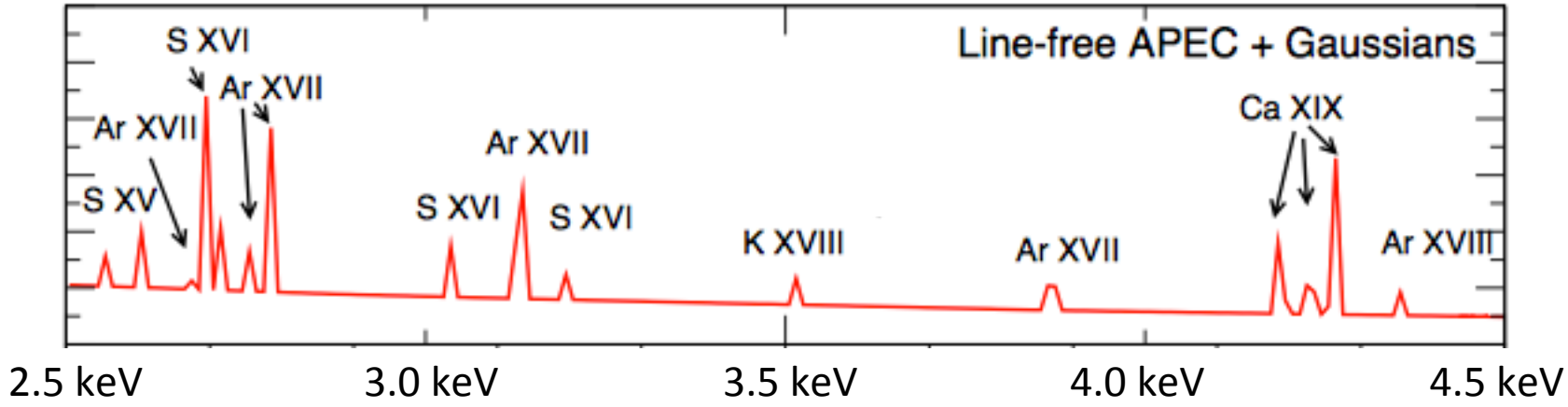
Jeltema+Profumo (2014)

- Galactic Center

X-ray lines predicted from sterile neutrinos



X-ray lines also from atomic transitions of highly-ionized Z ~ 16-20 atoms*



K XVIII has (two) lines near 3.5 keV

[K (Z=19) ion with 18-1 electrons missing, i.e. "He-like"]

* $E_z \sim 13.6\ Z^2$ eV → $Z \sim (3{,}500 / 13.6)^{1/2} \sim 16$, but $Z_{eff} < Z$…

How do we tell K apart from sterile ν or other exotica??

Try to predict K XVIII line brightness using other elemental lines

two key complications:

#1 Plasma Temperature

#2 Relative Elemental Abundances

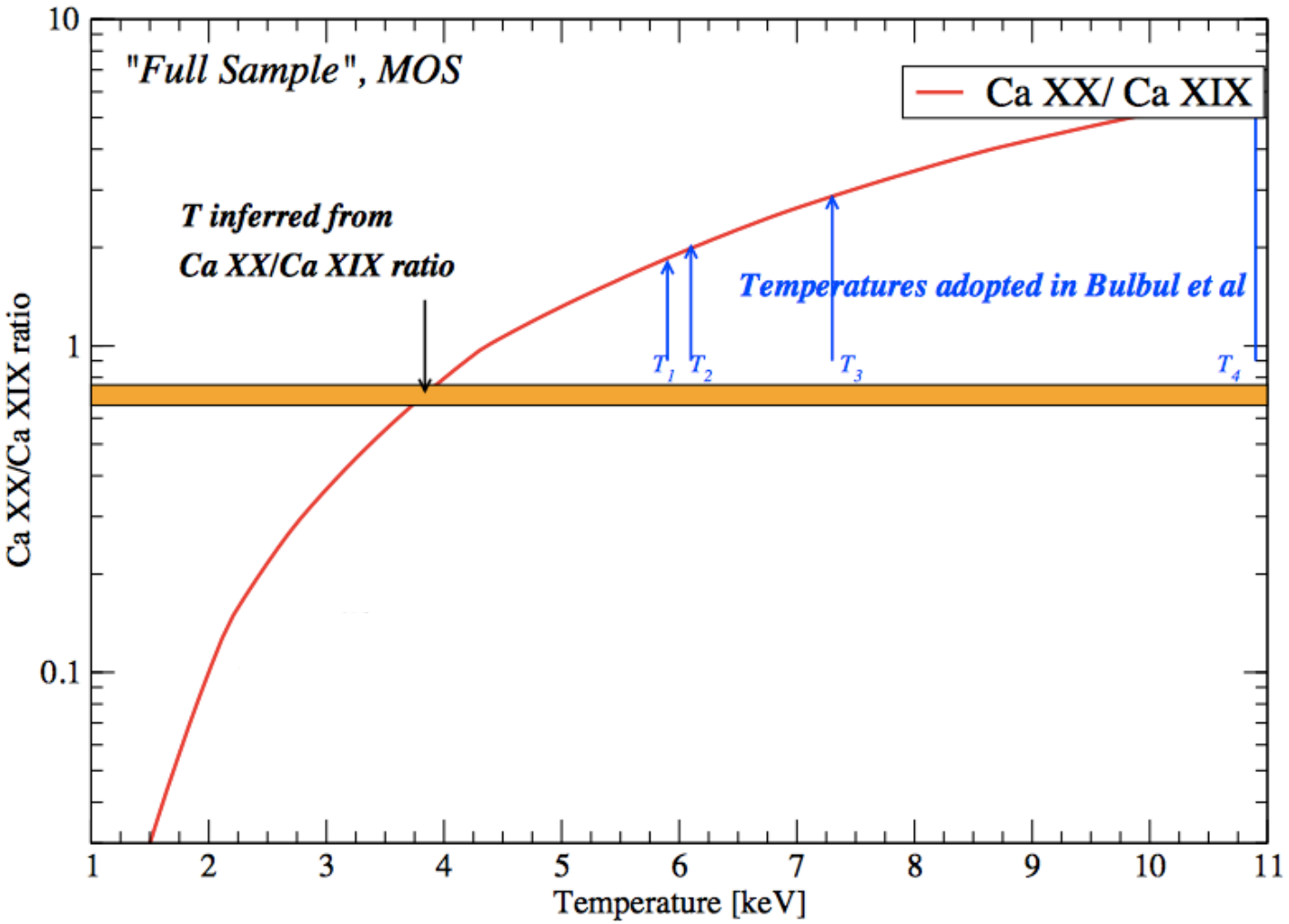
Bulbul+ argues against K XVIII since prediction for K 3.5 keV line too low (by factors ~20 for solar abundances)

…but the Bulbul+ prediction makes two key mistakes:

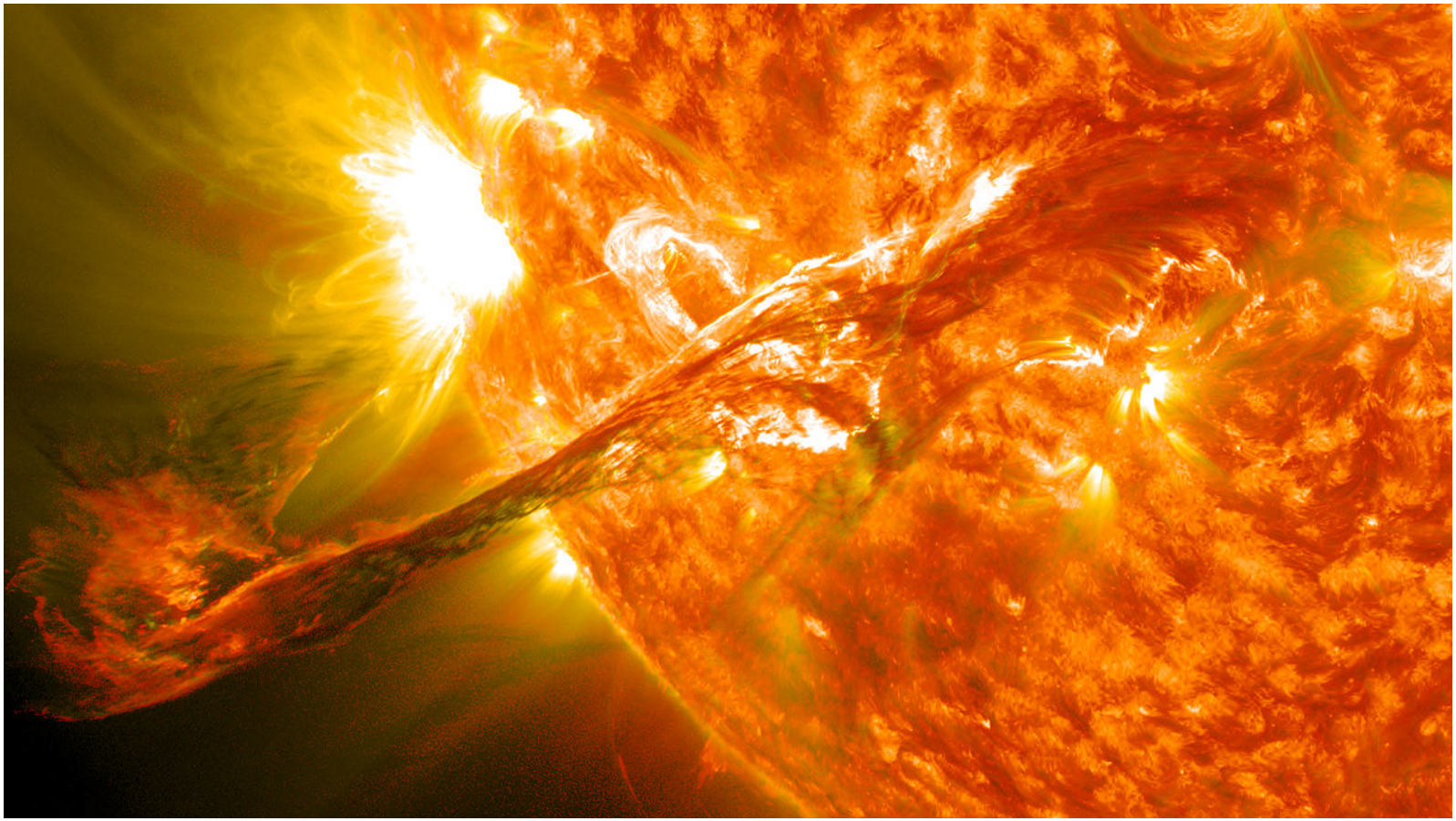
#1 Plasma Temperature

#2 Relative Elemental Abundances

Bulbul+ uses very large T highly suppresses K emission!



also, under-estimate ~10 of K abundance! (Photospheric versus Coronal)



* Phillips et al, ApJ 2015, RESIK crystal spectrometer

(4-13) x (10) >> 20

Plasma **T**

Relative **Abundances**

Required **K XVIII** “enhancement”

William of Occam
c. 1286-1347

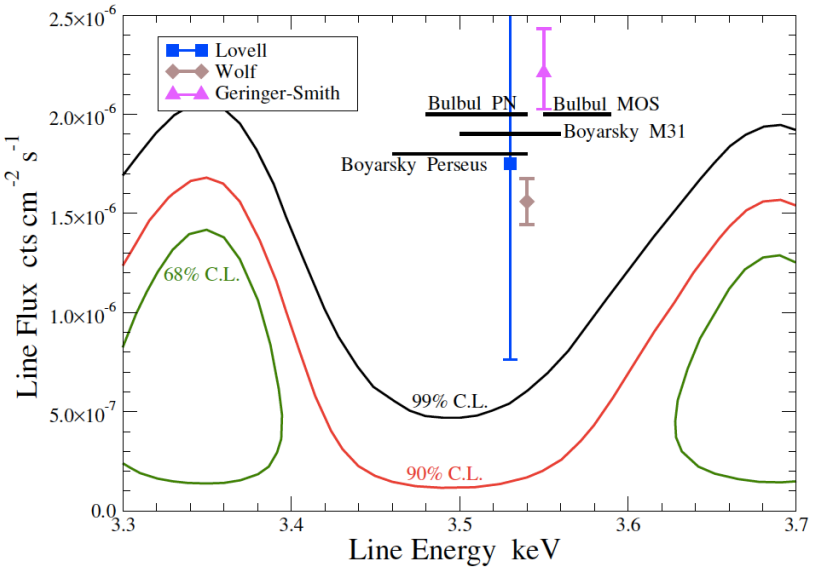
“Entia non sunt multiplicanda praeter necessitatem”

Occam is happy!

What else?

- Look for the line where there is no plasma and lots of dark matter

(conclusively nothing: >1Ms XMM observation of Draco dSph, Jeltema & Profumo 2015)



What else?

- Look for the line where there is no plasma and lots of dark matter

(conclusively nothing: >1Ms XMM observation of Draco dSph, Jeltema & Profumo 2015)

- Look for the morphology of the line

(conclusively similar to other plasma lines, Carlson, Jeltema & Profumo 2015)

What if it is Dark Matter?

simplest models (sterile neutrino) don't work

every challenge is an opportunity…
…interesting riddle for theorists!

Redman's Theorem

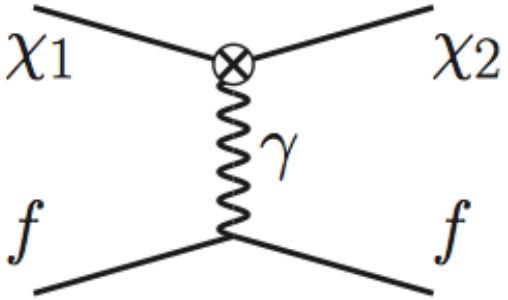
"Any competent theoretician can fit any given theory to any given set of facts" (*)

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"

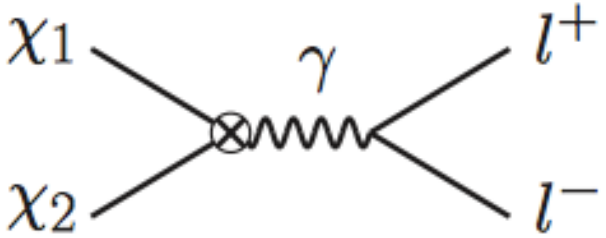
3.5 keV line …an excuse for an exciting, new mechanism for a signal from Dark Matter!

$$\chi_1 f \to \chi_2 f \longrightarrow \chi_2 \to \chi_1 \gamma$$

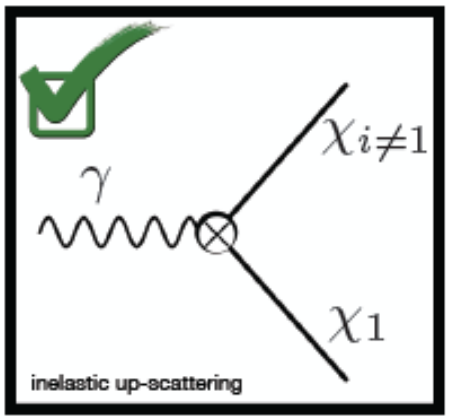


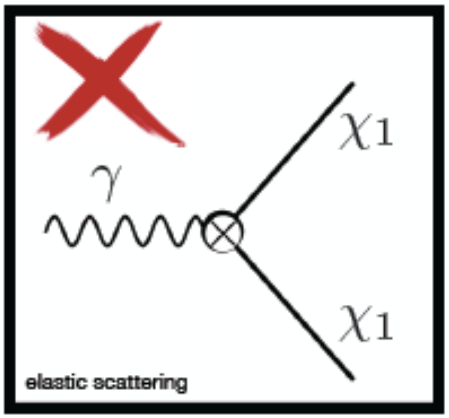
Signal ~ ρ_{DM} x ρ_{gas}

Good Thermal Relic!



D'Eramo, Hambleton, Profumo and Stefaniak, 1603.04895, PRD





C E L I B E

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D'Eramo and Profumo, in preparation

What will settle the origin of the 3.5 keV line?

Wait for new X-ray telescopes!

- Hitomi patch-up follow-up (>2020): XARM (X-ray Astr. Rec. Mission), a "directed" mission (no proprietary data)
- Athena (>2020)
- Lynx (formerly X-ray surveyor) (>2030)

K XVIII remains Occam's razor's fav. option, but wait for better observations!!

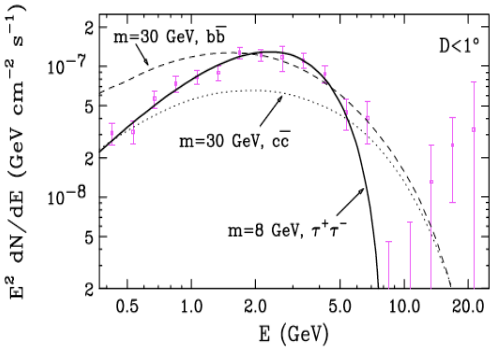
Plasma-excited DM:
New mechanism to detect DM

Lines anywhere eV …keV …GeV

Unique obs. predictions, background "free"

Structure formation? Small-scale structure?

Gamma-ray excess in the Galactic Center



Puzzling situation!

- Incontrovertible "excess" over standard diffuse gamma-ray background models
- Dark Matter explanation very "natural"
- Astrophysical counterparts (esp. MSP) possible but unlikely

What produces the Galactic Center excess?

WRONG QUESTION!

Rather: is the excess indeed there?

Are models of diffuse emission adequate to current data?

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 (~ few %)!

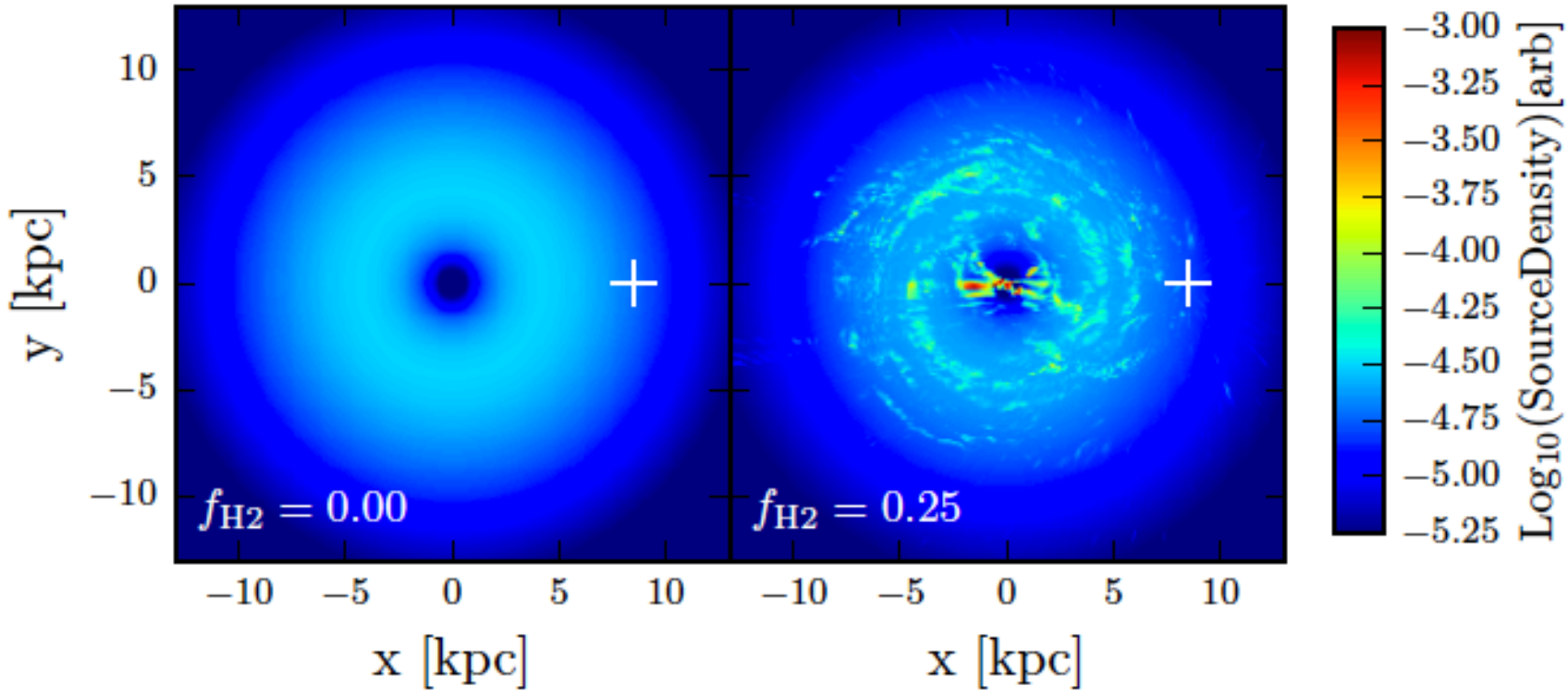
Towards the next generation of diffuse gamma-ray models

1. 3-D Gas Density Distribution
2. 3-D Cosmic-Ray Propagation
3. Cosmic Ray Bursts/Transients
4. Physically motivated Cosmic-ray source distributions

Biggest Deal: #4

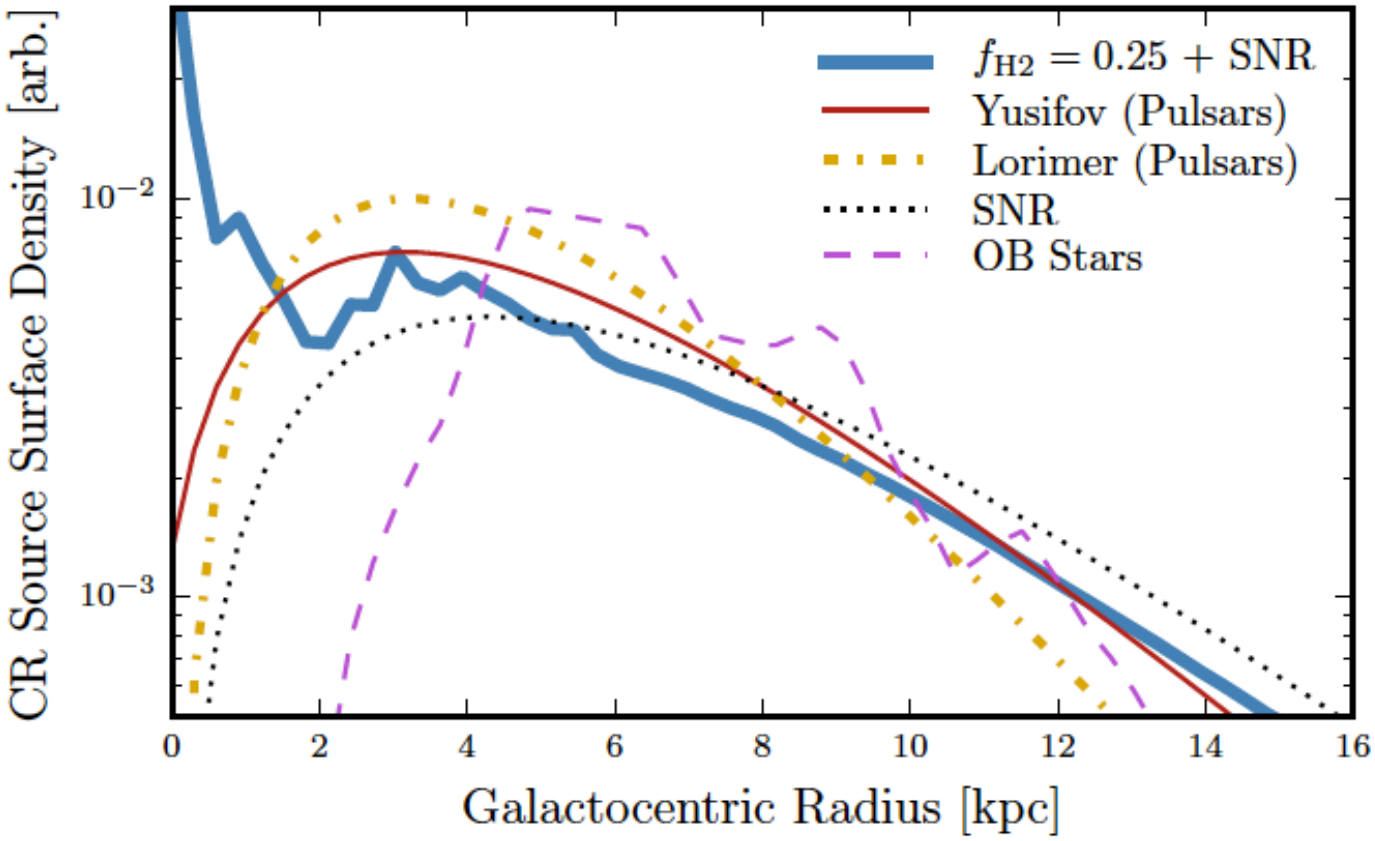
* Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584

4. Physically motivated, 3D Cosmic Ray source distributions



*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

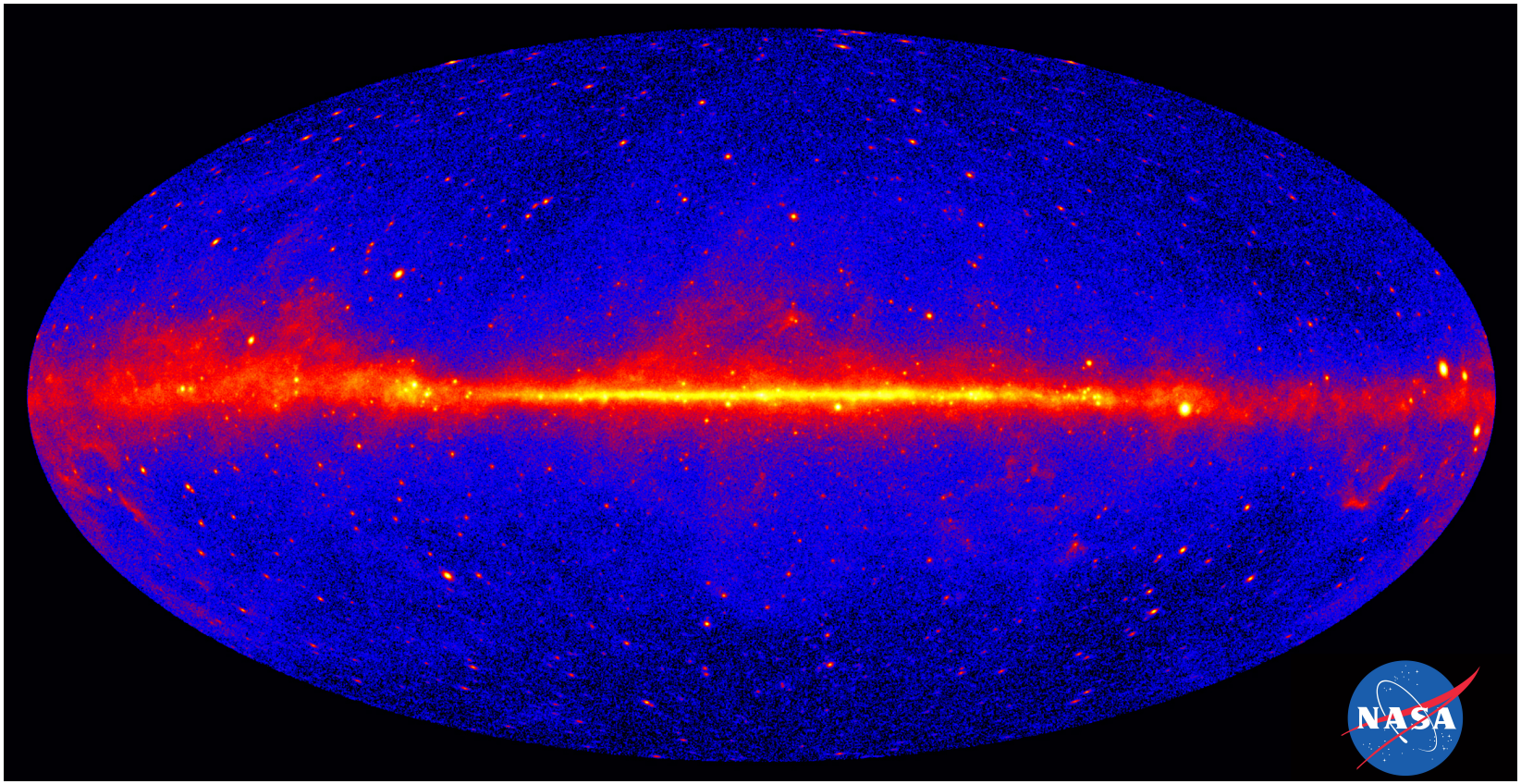
4. Physically motivated, 3D Cosmic Ray source distributions



* Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584

Good to push the (theory) envelope.

But do you get a better or worse fit to data?



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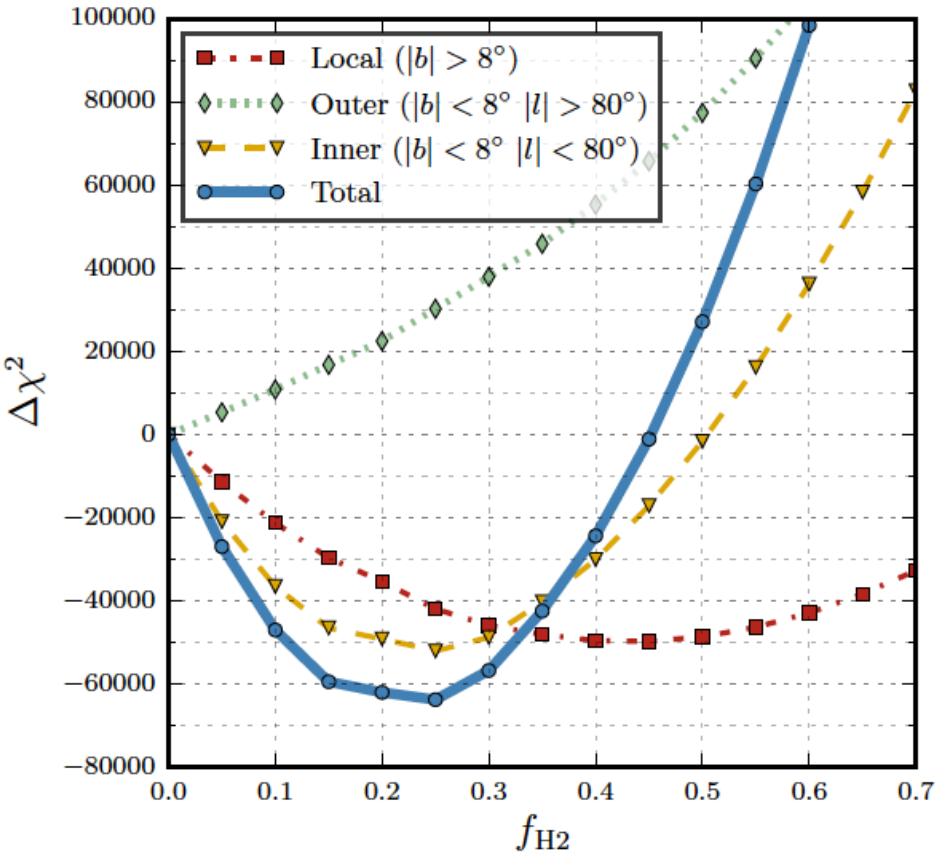
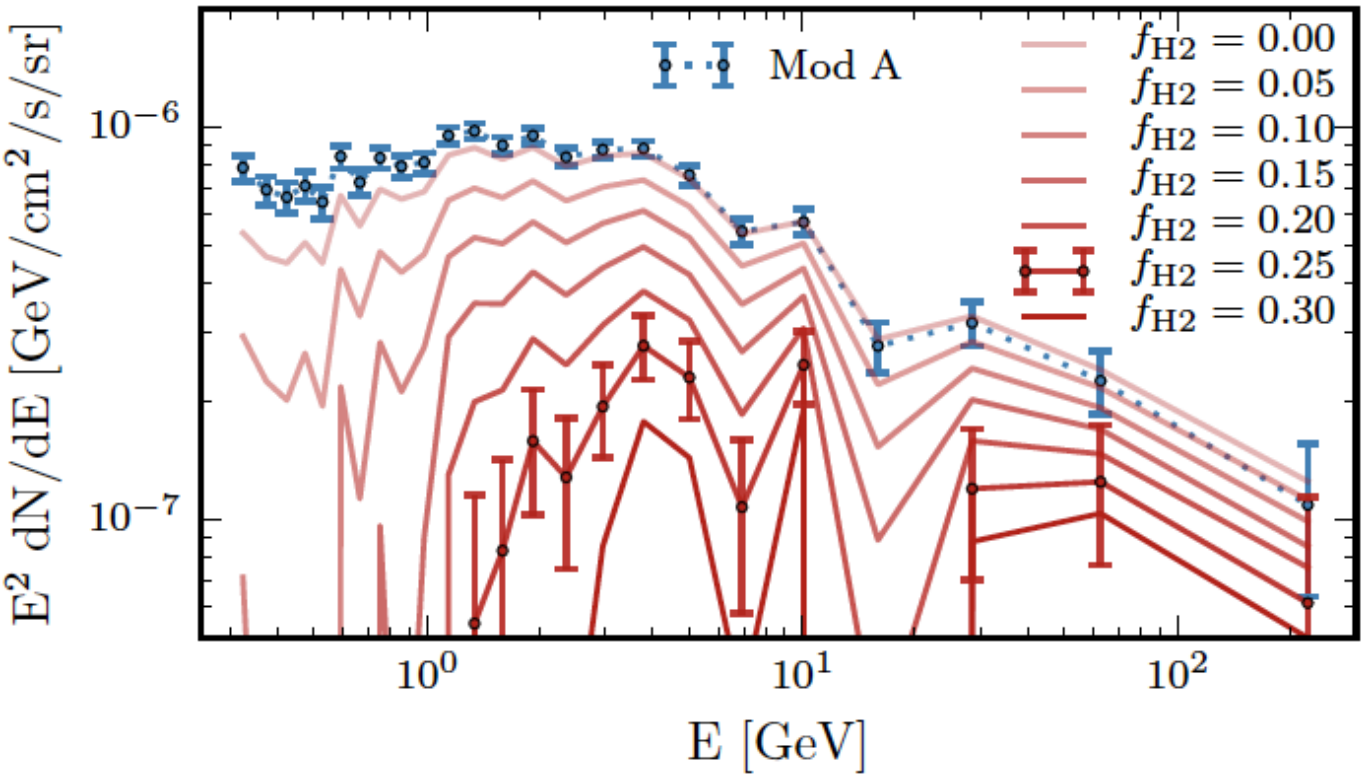


* Carlson, Linden, Profumo 1510.04698, sub. to Phys.Rev.Lett.

What do these improved models imply for the Galactic Center "Excess"?

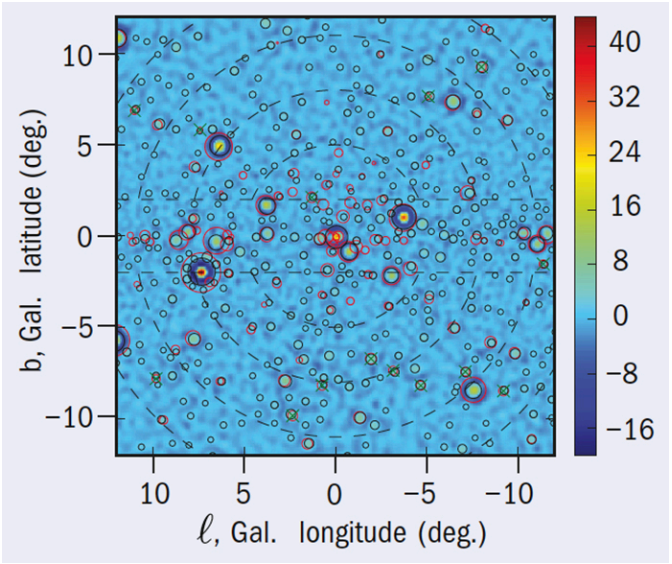


* Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584

We are making significant progress towards understanding Galactic gamma rays

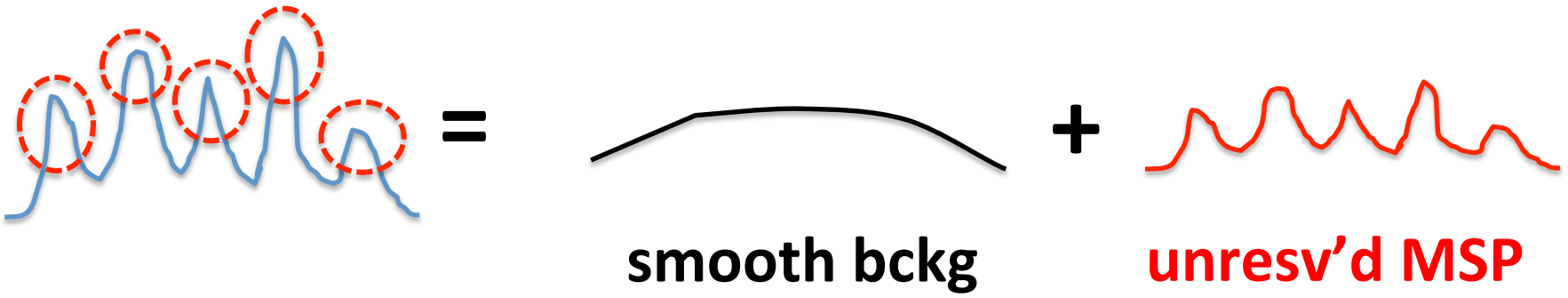
Cosmic-Ray injection and 3D models are key!

Discrimination between unresolved point sources and diffuse emission*,** also highly dependent on background model!



* Bartels et al, 2016, PRL 116 051102, ** Lee et al, 2016, PRL 116 051103

Finding excess clustering can mean…



Proxy: HI column density!!

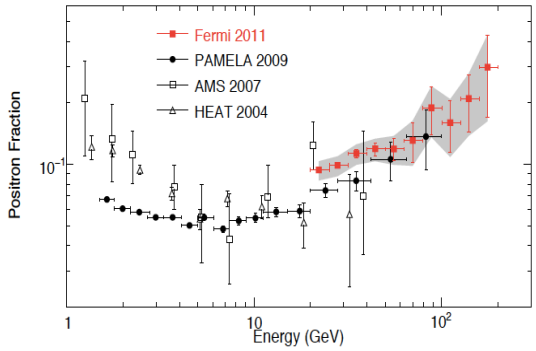
* Profumo, Reiman, Ulbricht in preparation

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

Is DM detection with gamma rays
possible at all? Yes.

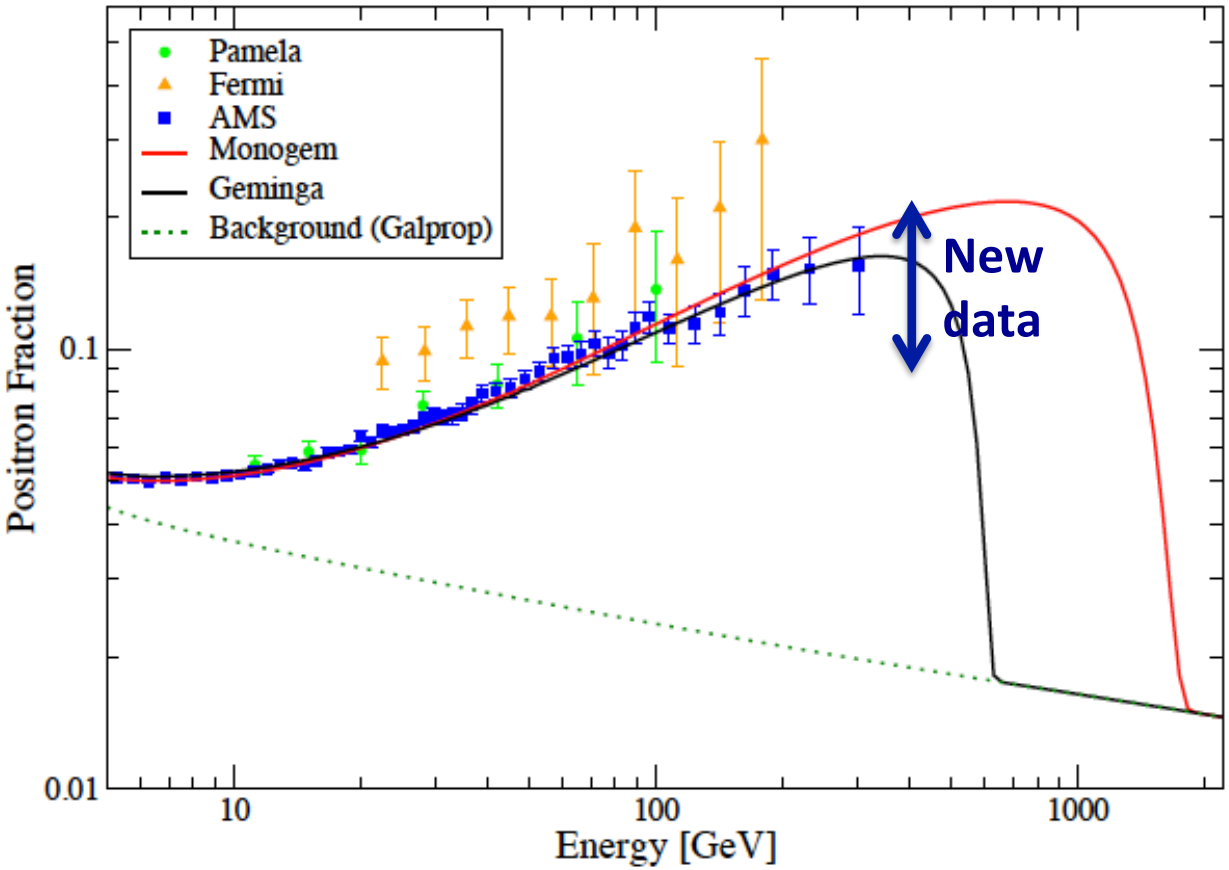
A diffuse gamma-ray line
(opportunities both at MeV and TeV)

Cosmic-Ray Anomalies



Marc Kamionkowski: “Stefano, stay away from cosmic rays. They’re too messy”

PSRs work perfectly well



only one (not-so) free parameter!

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

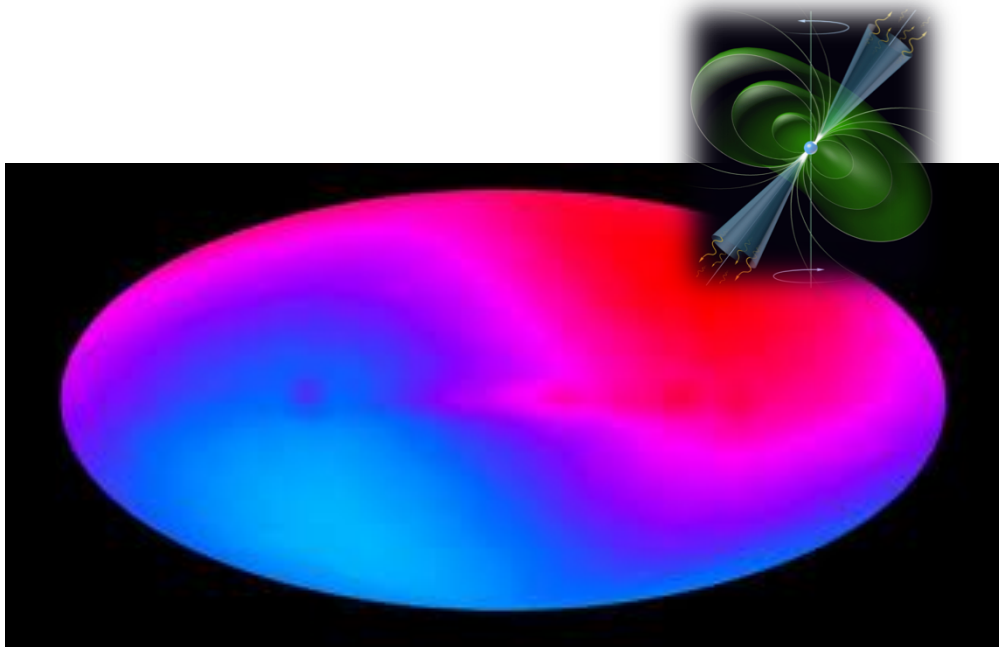
Cutoff is not a smoking gun for DM!

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

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

How can we tell PSR apart from DM?

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



No dipolar anisotropy detected so far
[but consistent with PSR interpretation]

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

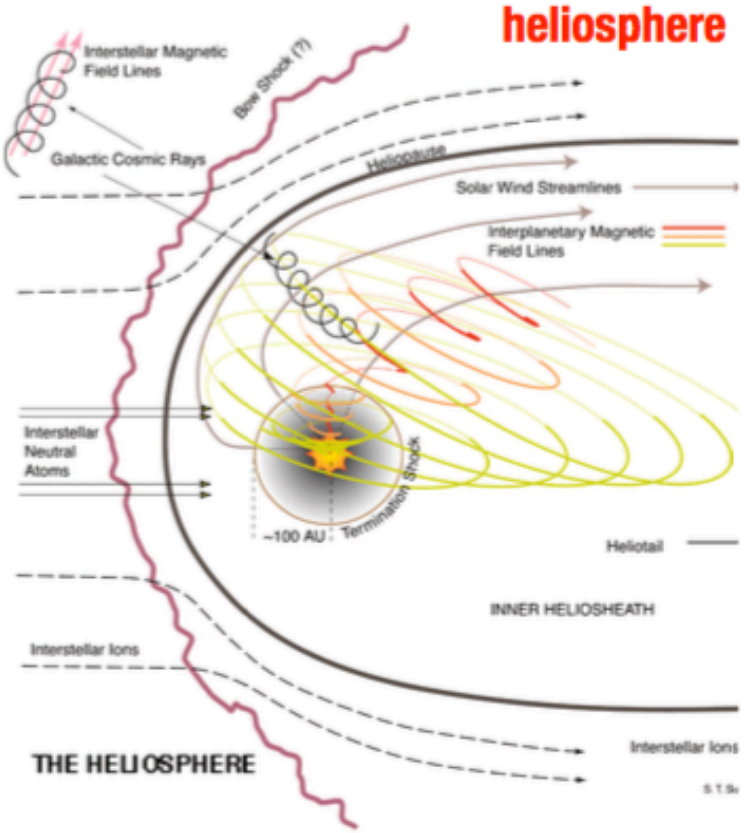
Stefano Profumo*
Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
(Dated: May 21, 2014)

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 in a nearby clump. I consider the annihilation pathway producing the smallest flux of gamma rays versus

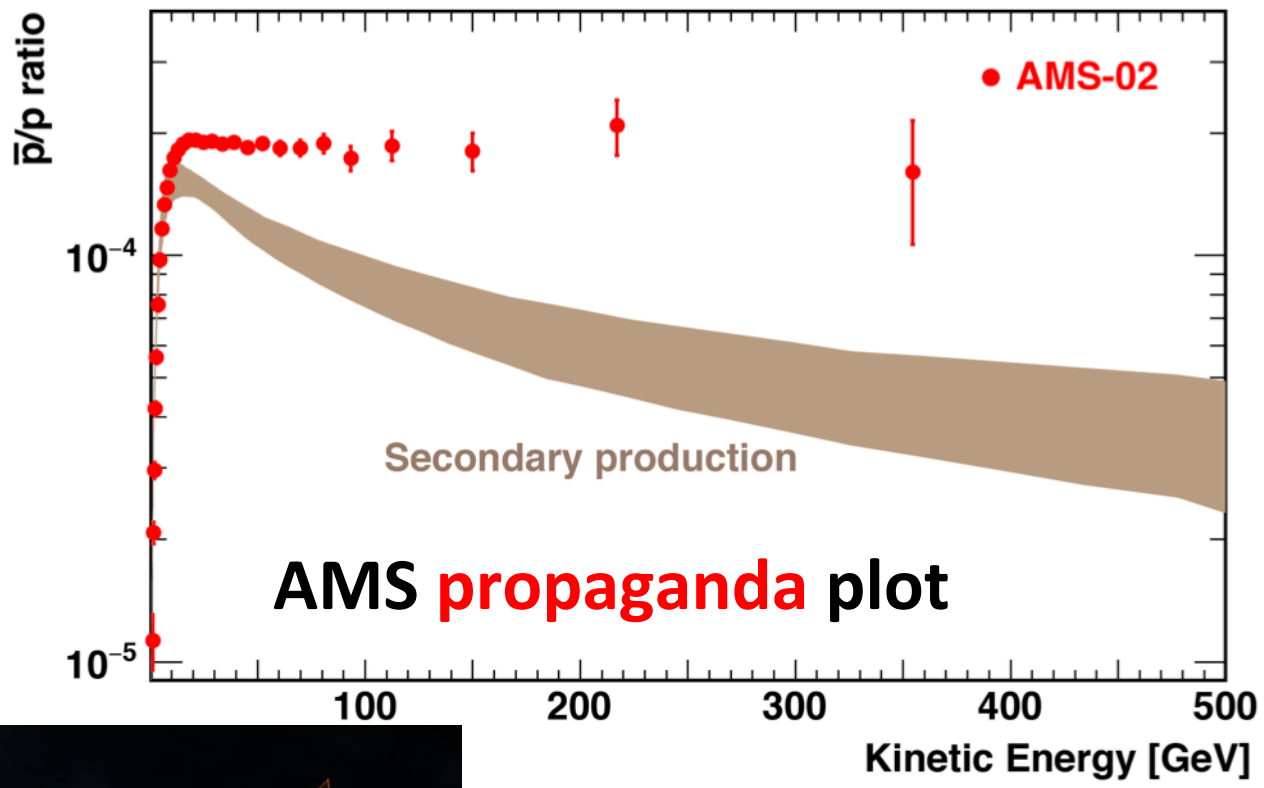
Profumo, PRD 2014

…but life might not be easy after all!

Larmor radius for heliospheric magnetic fields *B~ nT*, is of the order of the solar system size



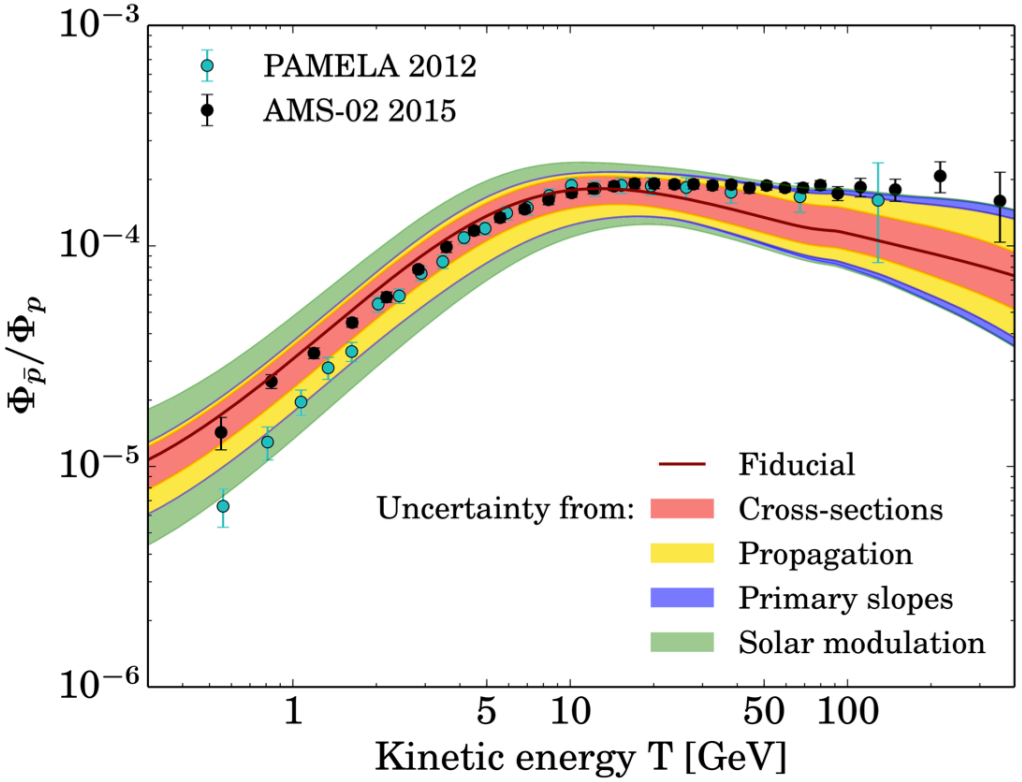
What about antiprotons?



AMS propaganda plot

Resonaances: "experts unanimously agree that the **brown smudge** in the plot above **is actually just s**t**, rather than a range of predictions from the secondary production"

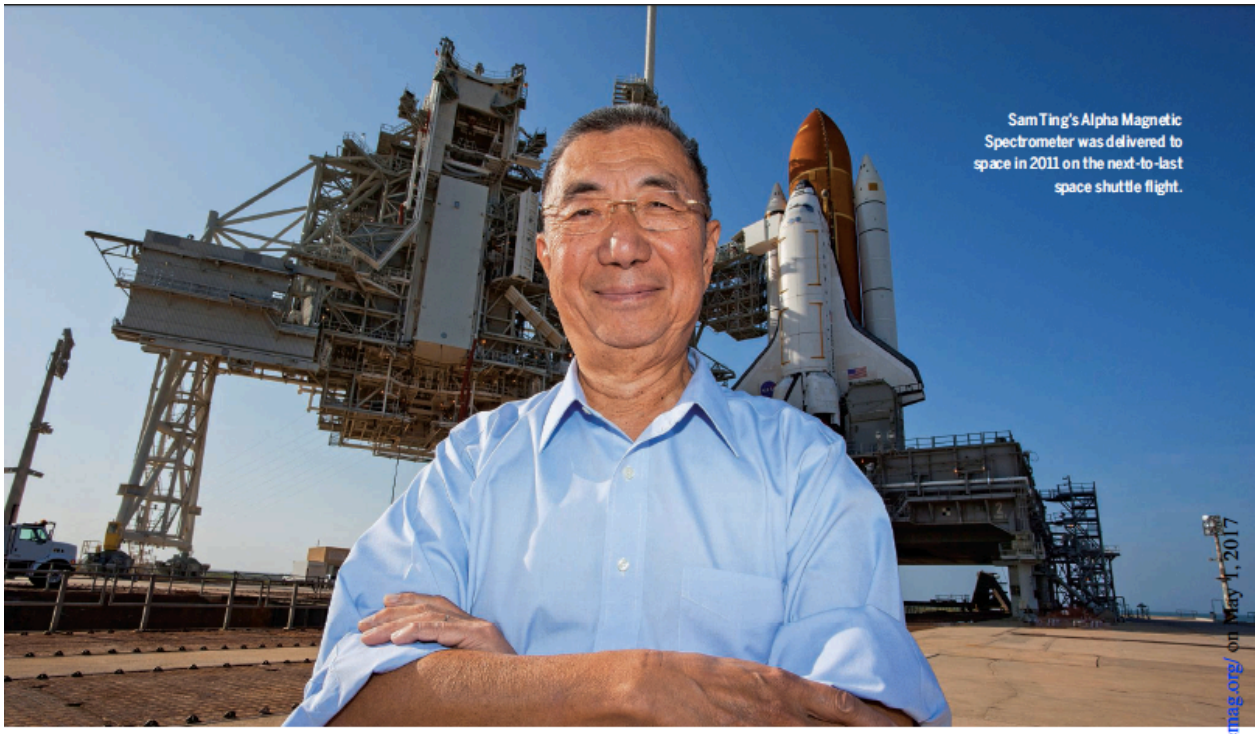
What about antiprotons?



Could the apparent "excess" come from pulsars??

see eg. Resonaances blog

What about $^{3}\overline{\text{He}}$?



Sam Ting's Alpha Magnetic Spectrometer was delivered to space in 2011 on the next-to-last space shuttle flight.

SAM TING'S LAST TEASE

How the physicist's aging space magnet, in a final flourish, may have trapped heavy antimatter

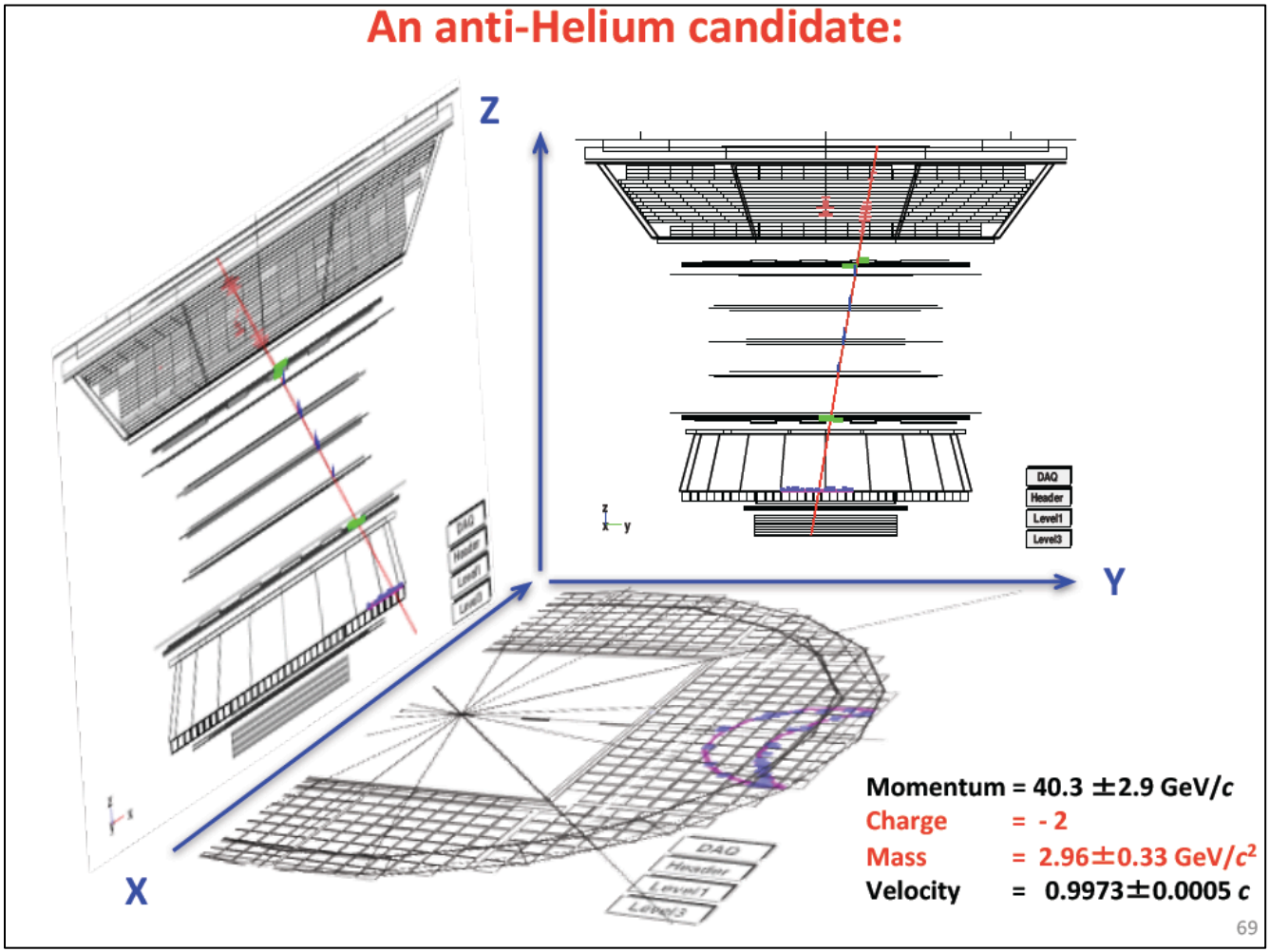
By **Joshua Sokol**

Sam Ting speaks softly and deliberately as he gets ready to deliver some juicy news to his audience. finally delivering on the promise of its original name, when "AM" stood for "antimatter."

So far, the AMS has measured the masses that the AMS may have trapped a bigger and weirder form of antimatter. The AMS, he says, has seen a handful of candidate

Science, April 2017

What about $^{3}\overline{\text{He}}$?



needs $1/10^{9}$ background discrimination…

Ting, AMS CERN, December 2016

What about $^{3}\overline{\text{He}}$?

Antihelium from Dark Matter

Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]

[1] *Department of Physics, University of California, 1156 High St., Santa Cruz, CA 95064, USA*
[2] *Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA*[**]
[3] *Department of Physics, University of Chicago, Chicago, IL 60637*
[4] *Kavli Institute for Cosmological Physics, Chicago, IL 60637*
[5] *Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany*

(Dated: March 20, 2014)

Cosmic-ray anti-nuclei provide a promising discovery channel for the indirect detection of particle dark matter. Hadron showers produced by the pair-annihilation or decay of Galactic dark matter generate anti-nucleons which can in turn form light anti-nuclei. Previous studies have only focused on the spectrum and flux of low energy antideuterons which, although very rarely, are occasionally also produced by cosmic-ray spallation. Heavier elements ($A \geq 3$) have instead entirely negligible astrophysical background and a primary yield from dark matter which could be detectable by future experiments. Using a Monte Carlo event generator and an event-by-event phase space analysis, we compute, for the first time, the production spectrum of $^{3}\overline{\text{He}}$ and $^{3}\overline{\text{H}}$ for dark matter annihilating or decaying to $b\bar{b}$ and $W^{+}W^{-}$ final states. We then employ a semi-analytic model of interstellar and heliospheric propagation to calculate the $^{3}\overline{\text{He}}$ flux as well as to provide tools to relate the anti-helium spectrum corresponding to an arbitrary antideuteron spectrum. Finally, we discuss prospects for current and future experiments, including GAPS and AMS-02.

19 Mar 2014

Coogan et al, 2014, PRD

What about $^{\overline{3}}$He?

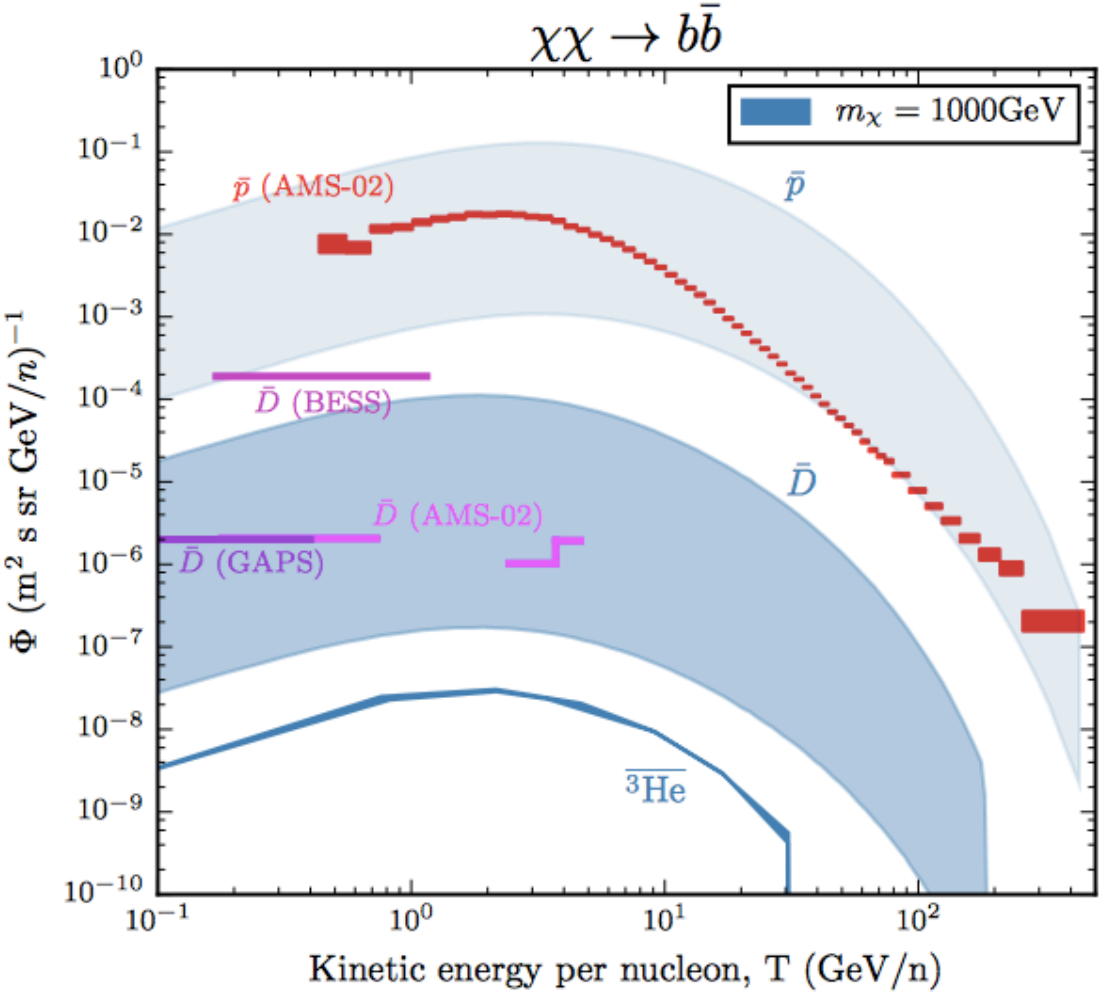
Can AMS anti-Helium events come from dark matter? Maybe!

Adam Coogan[1*] and Stefano Profumo[1†]
[1]*Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*

We demonstrate that the tentative detection of a few anti-helium events with the Alpha Magnetic Spectrometer (AMS) on board the International Space Station can in principle be ascribed to the annihilation or decay of Galactic dark matter, when accounting for uncertainties in the coalescence process leading to the formation of anti-nuclei. We show that the predicted antiproton rate, assuming the anti-helium events came from dark matter, is marginally consistent with AMS data, as is the antideuteron rate with current available constraints. We argue that a dark matter origin can be tested with better constraints on the coalescence process, better control of misidentified events, and with future antideuteron data.

Coogan and Profumo, 1705.09664

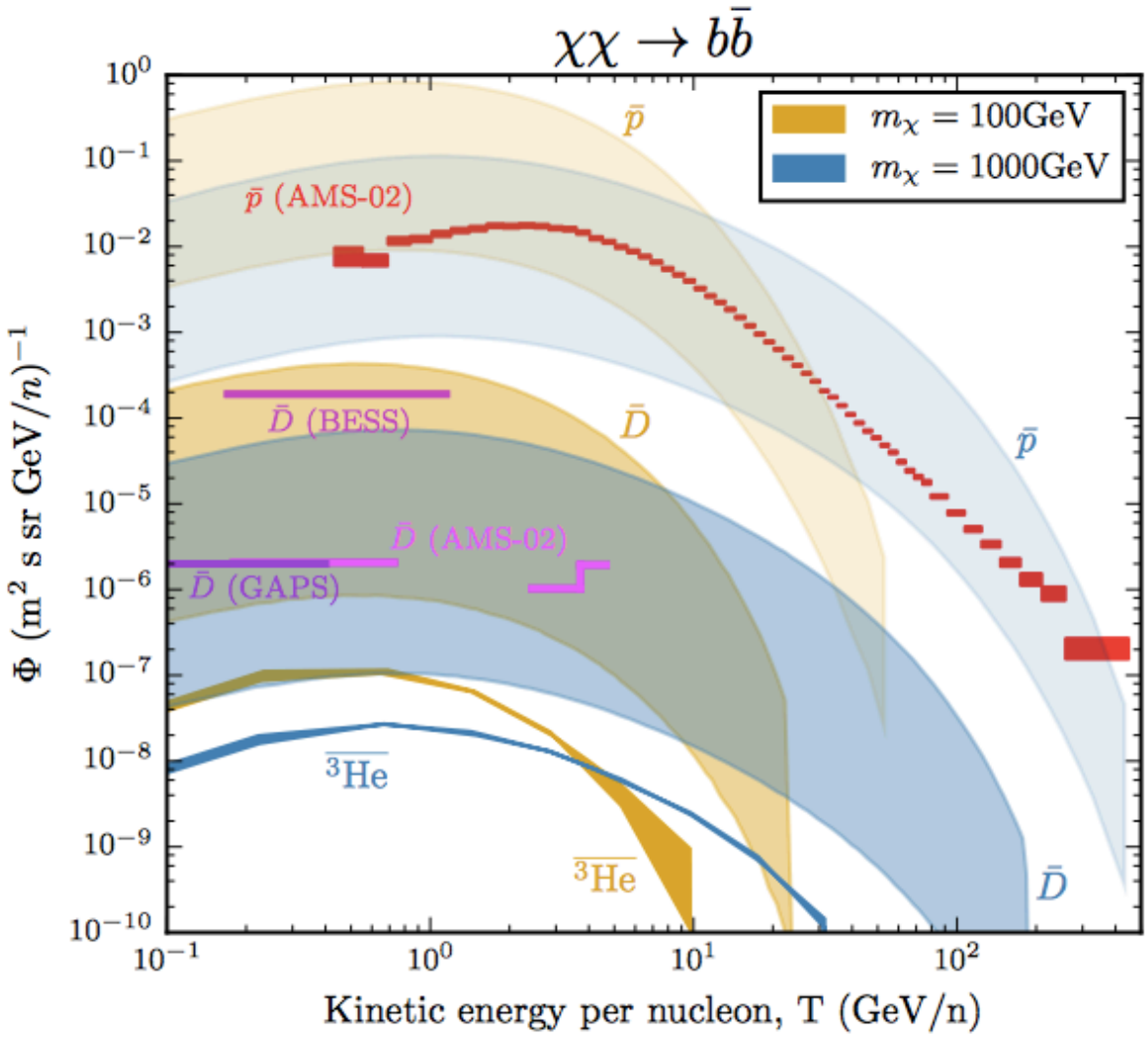
What about $^{3}\overline{\text{He}}$?



One event with 40 GeV momentum in 5 years

Coogan and Profumo, 1705.09664

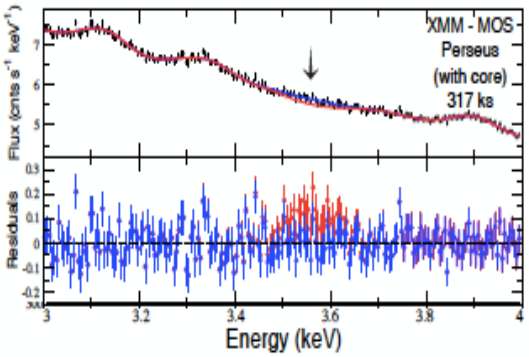
What about $^{3}\overline{\text{He}}$?



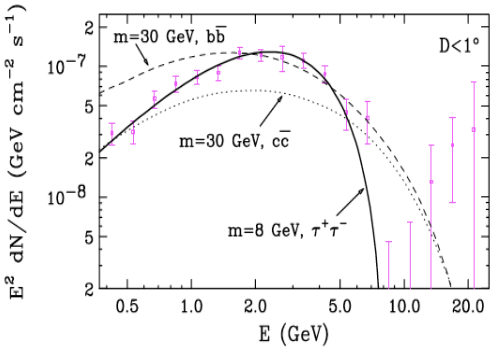
one event per year

Coogan and Profumo, 1705.09664

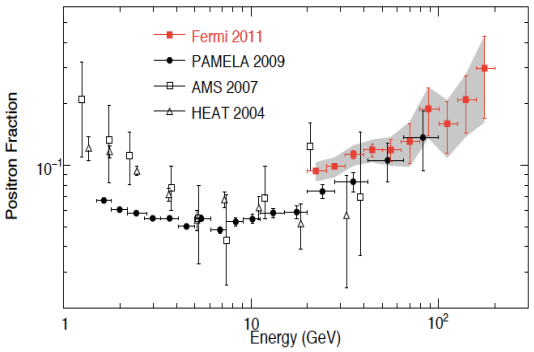
3.5 keV line



Gamma-ray excess in the Galactic Center

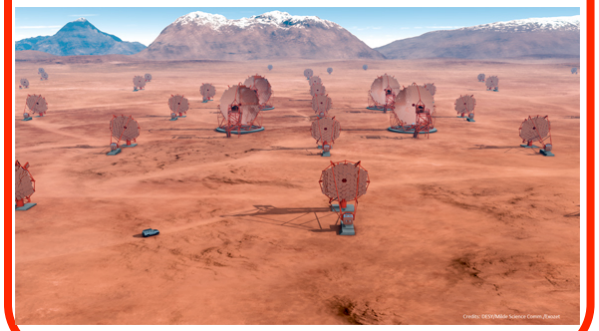


Cosmic-Ray Anomalies

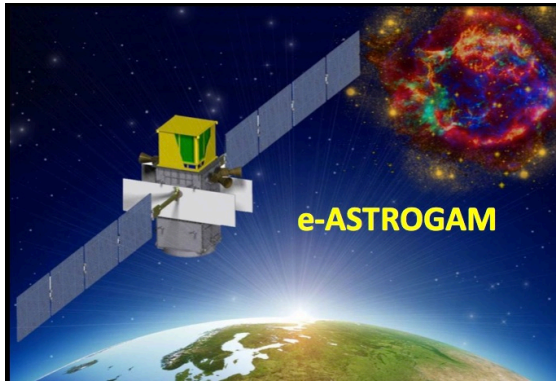


what else, then?

CTA



MeV gamma-rays



Radio Surveys

An Introduction to
Particle Dark Matter

The paradigm of dark matter is one of the key developments at the interface between cosmology and elementary particle physics. It is also one of the foundational blocks of the Standard Cosmological Model. This book offers a brand new perspective within this complex field: building and testing particle physics models for cosmological dark matter. Chapters are organized to give a clear understanding of key research directions and methods within the field. Problems and solutions question accepted knowledge of dark matter and provide guidance in the practical implementation of models. Appendices are also provided to summarize physical principles in order to enable the building of a quantitative understanding of particle models for dark matter.

This is essential reading for anyone interested in understanding the microscopic nature of dark matter as it manifests itself in particle physics experiments, cosmological observations and high-energy astrophysical phenomena. This interdi… textbook is an introduction for cosmologists and astro… interested in particle models for dark matter, as well as … physicists interested in early-universe cosmology and hi… astrophysics.

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Observable universe logarithmic
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An Introduction to Particle Dark Ma…

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An Introduction to
Particle Dark Matter

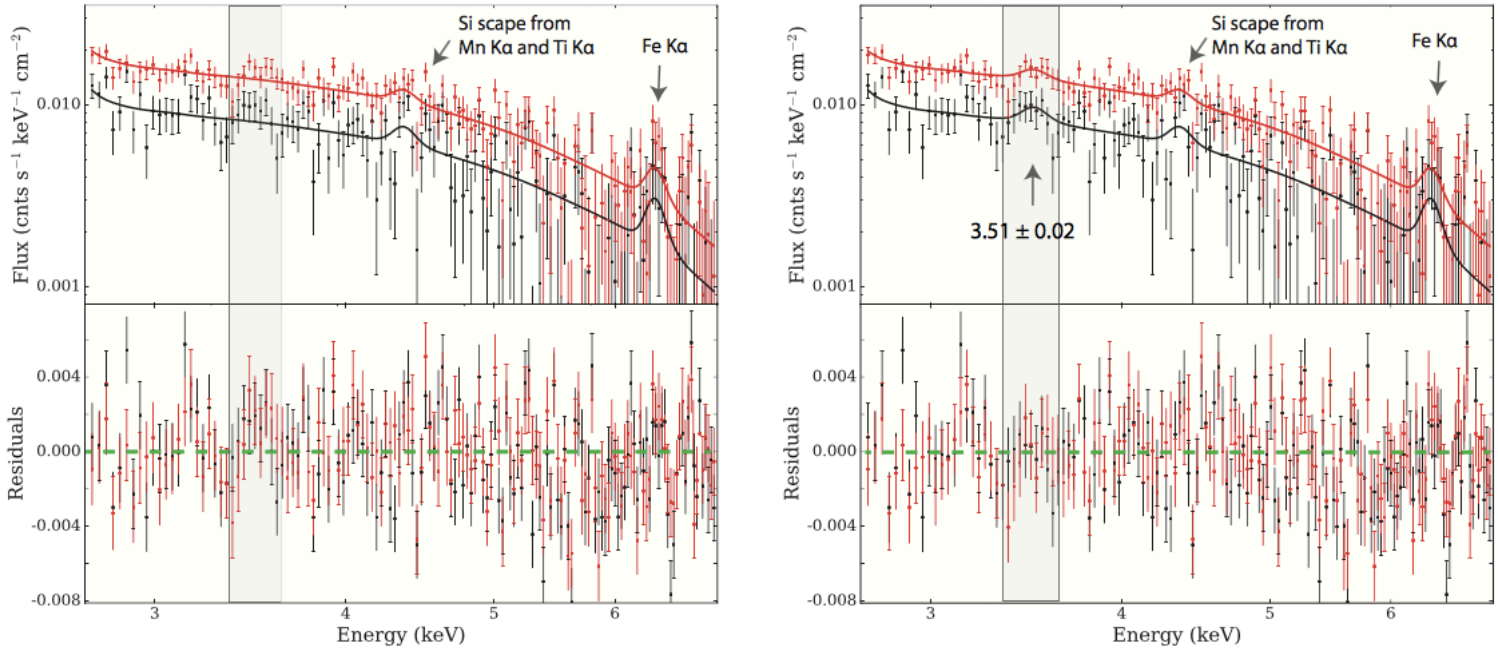
Stefano Profumo

- Not a review!
- "Blackboard"-style
- 233 Exercises
- Designed for "self-study"

World Scientific

What will settle the origin of the 3.5 keV line?

1. Analyzing X-ray data from Chandra/XMM?

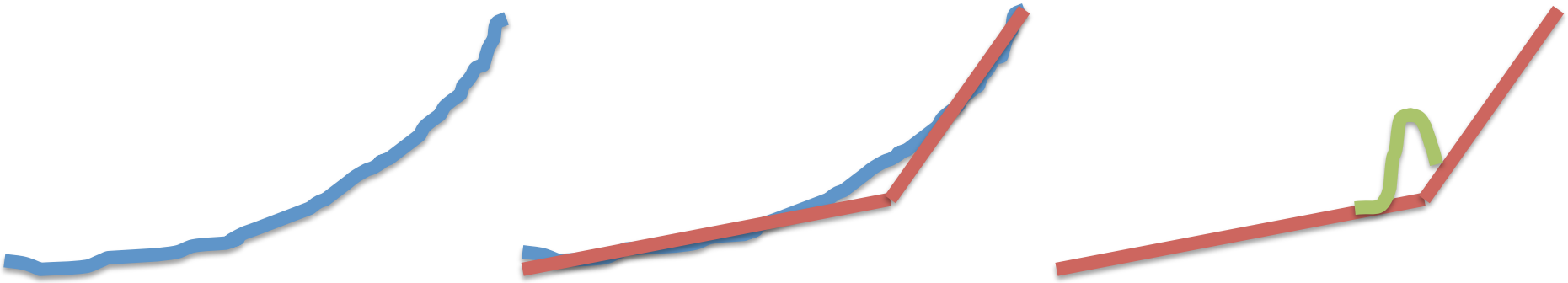


(inconclusive) claim of a 3σ significance detection in Chandra COSMOS Legacy Field South

Cappelluti et al, 1701.07932

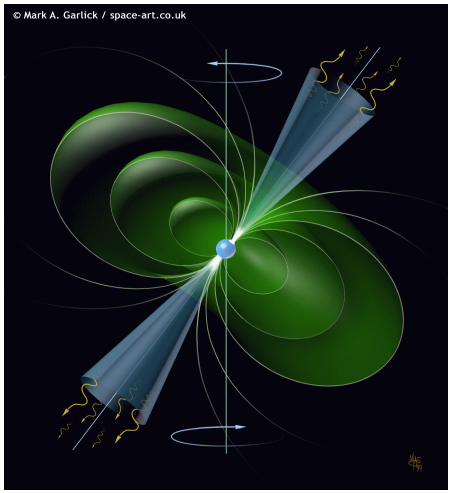
What will settle the origin of the 3.5 keV line?

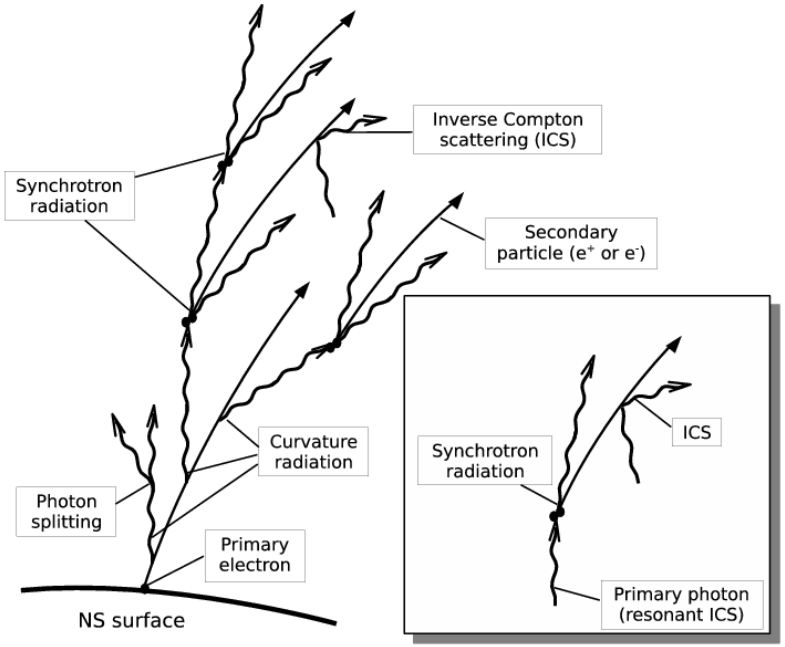
Issue: weak lines are hard to detect with poor energy resolution and poor background modeling!



Data Fit Residual

Any other stable particles from PSR?



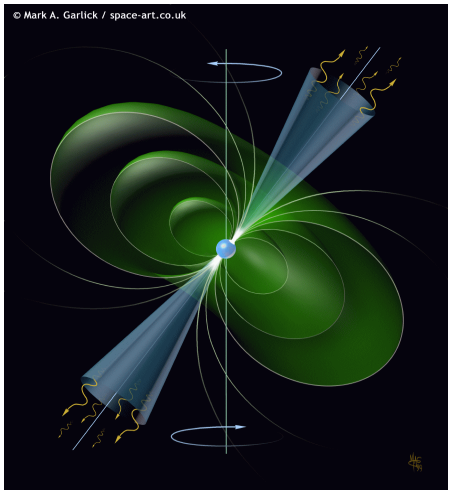


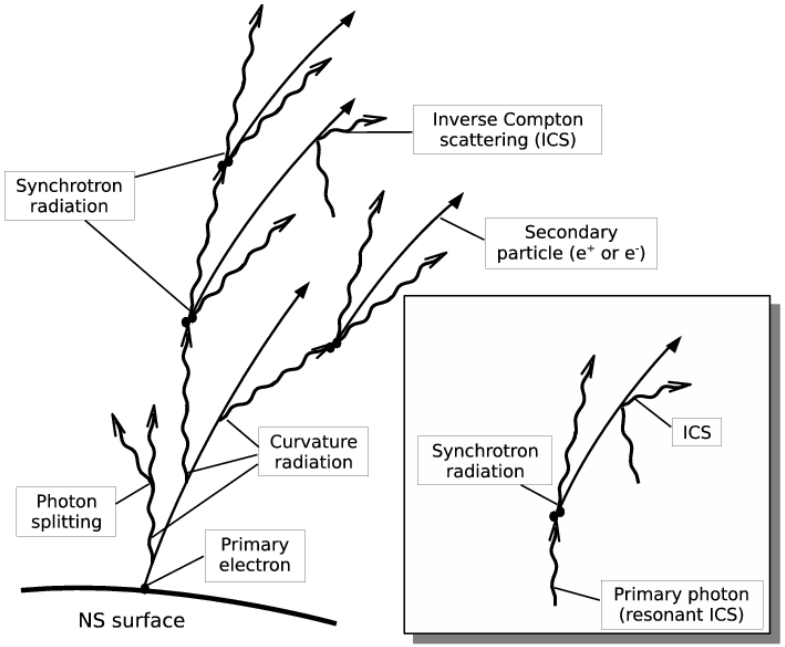
magnetosphere produces e^+e^- pairs from ~GeV photons in ~10^{13} G magnetic fields

quark-antiquark pairs are also produced, in predictable amounts, and with predictable hadronization products

D'Eramo and Profumo, in preparation

Any other stable particles from PSR?





- Up to 10 GeV neutrinos should be produced from charged pion decay
- Antiprotons should also be produced, and (like e^+e^-) subsequently accelerated in the PWN shocks

D'Eramo and Profumo, in preparation