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Stefano Profumo

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

Astrophysical Searches for Dark Matter: A Status Report

Olivefest Workshop, Minneapolis, MN

Friday May 19, 2017

Three tantalizing signals

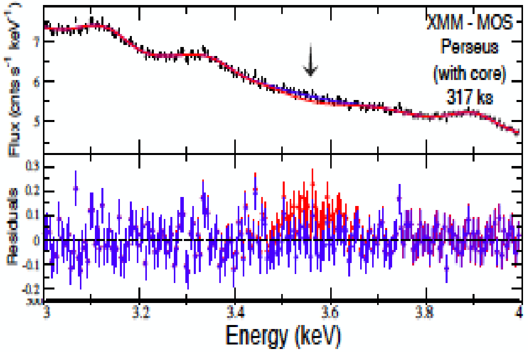
Three (less tantalizing) reasons why I'm grateful to Keith

- Keith’s papers (esp. on **SUSY DM**) got me interested into, and steered me to **hep-ph**

- Keith’s papers (yes, he has written **a lot**; here esp. on BBN, inflation) got me interested in **astroparticle/cosmology**

- Keith’s **life advices** (topics range from dealing with little kids, to biking, to how to survive very cold winters)

3.5 keV line


XMM - MOS
Perseus
(with core)
317 ks
Flux (cnts s⁻¹ keV⁻¹)
Residuals
Energy (keV)
3
3.2
3.4
3.6
3.8
4

Bulbul+ (2014)

- Stacked clusters
- Perseus

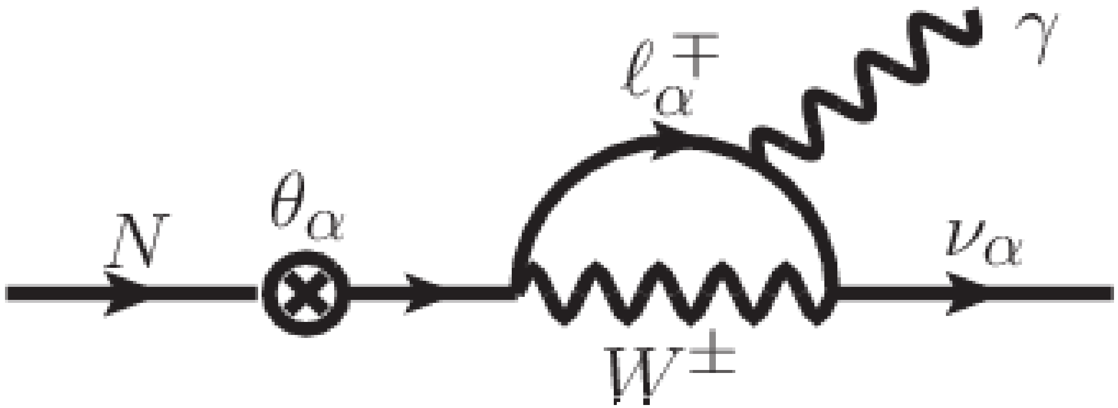
Boyarsky+ (2014)

- M31 (Andromeda)
- Perseus

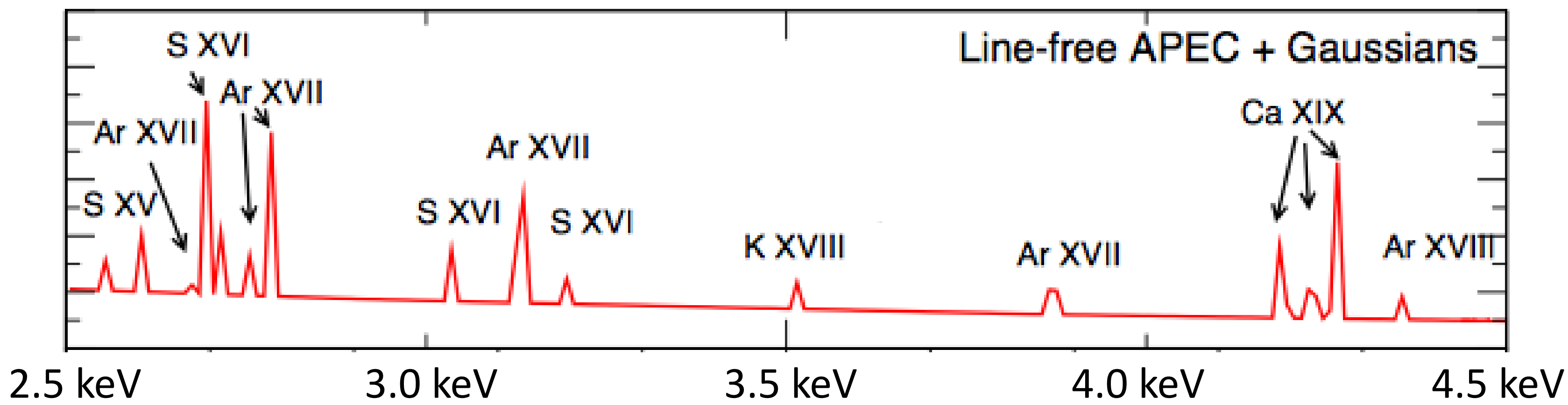
Jeltema+Profumo (2014)

- 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

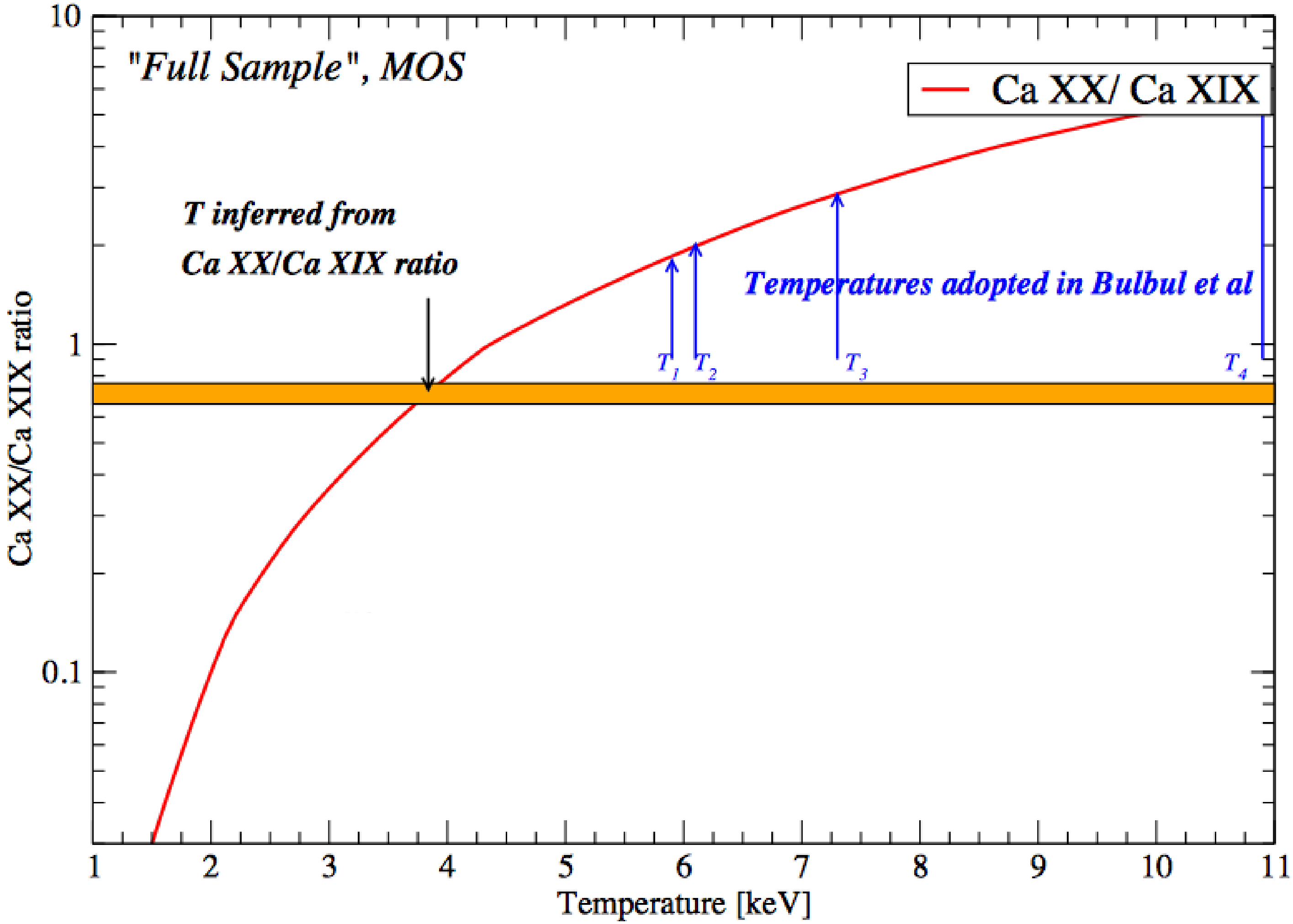
Bulbul+ argues against K XVIII since prediction for K 3.5 keV line too low (by factors ~20 for solar abundances)

…but this prediction makes two key mistakes:

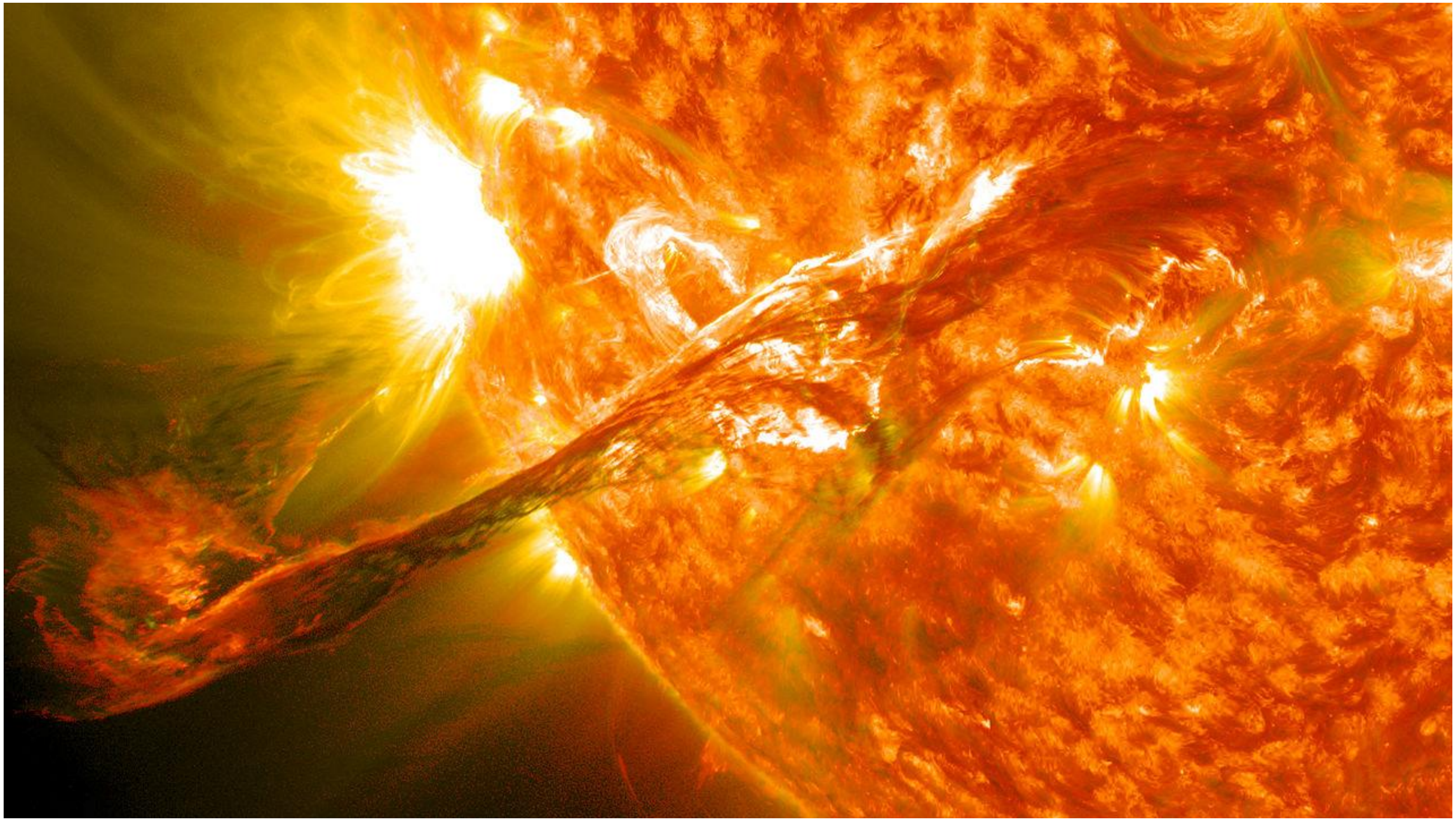
#1 Plasma Temperature

#2 Relative Elemental Abundances

Bulbul+ uses very large T highly suppresses K emission!



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



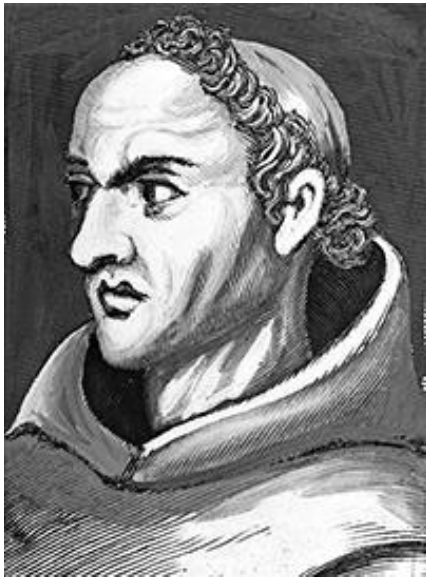
* Phillips et al, ApJ 2015, RESIK crystal spectrometer

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

Plasma **T**

Relative **Abundances**

Required **K XVIII** "enhancement"



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)

- Look for the morphology of the line

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

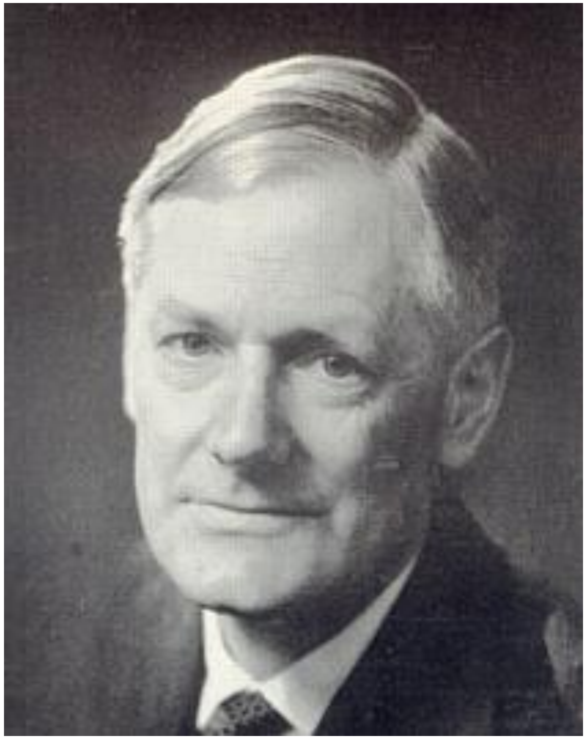
What if it is Dark Matter?

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" (*)

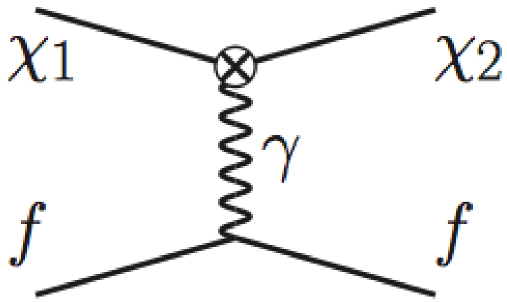


Roderick O. Redman (b. 1905, d. 1975) Professor of Astronomy at Cambridge University

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

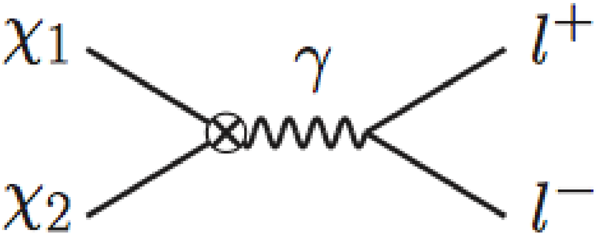
3.5 keV line …an excuse for an exciting, new mechanism for a signal from Dark Matter!

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

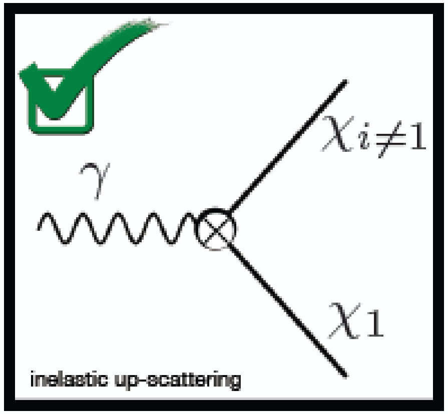


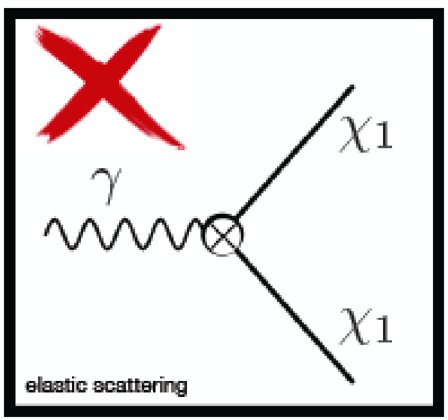
Signal ~ ρ_{DM} x ρ_{gas}

Good Thermal Relic!



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





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D'Eramo and Profumo, in preparation

K XVIII remains Occam's razor's fav. option

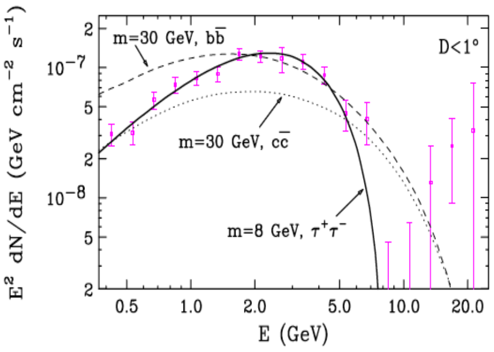
Plasma-excited DM:
New mechanism to detect DM

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 %)!

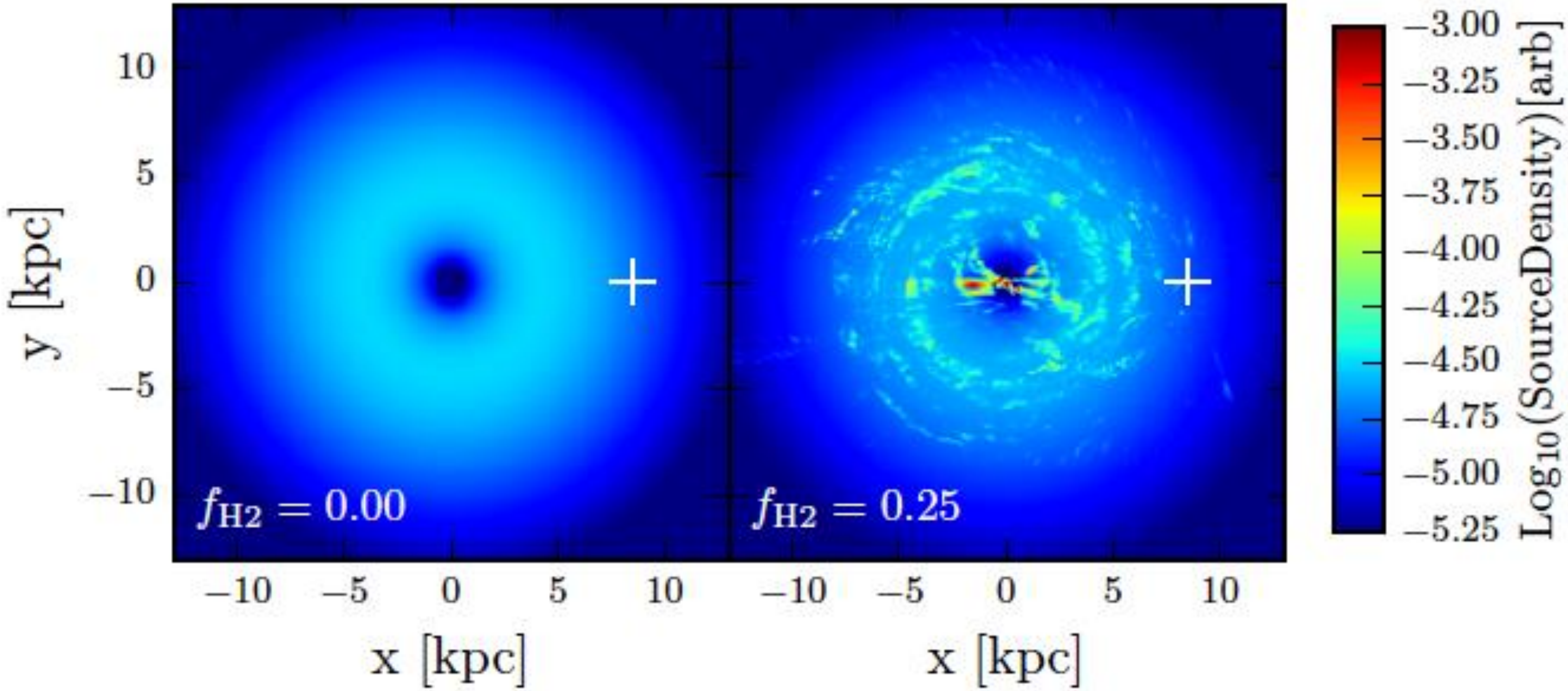
Towards the next generation of diffuse gamma-ray models

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

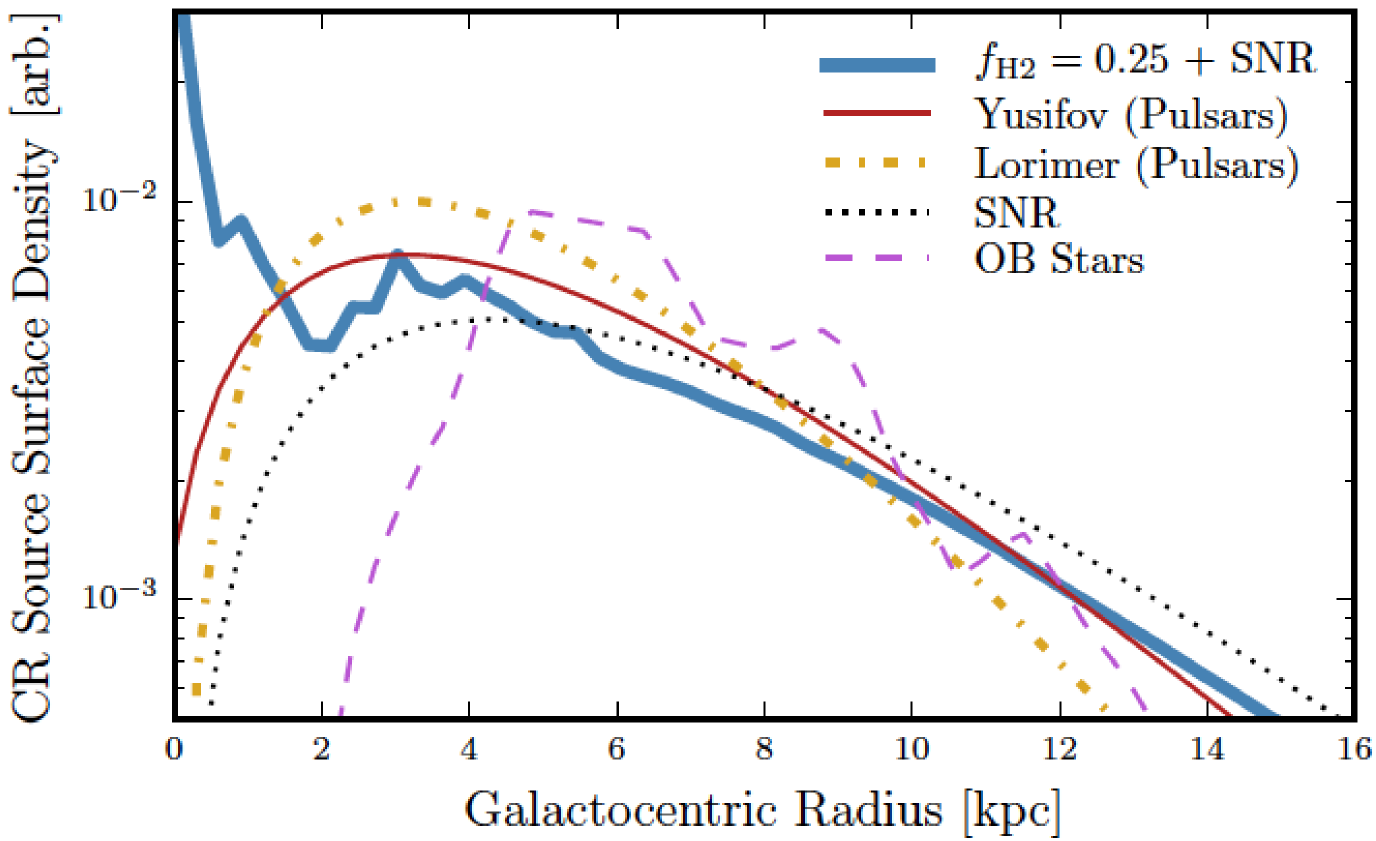
*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

4. Physically motivated, 3D Cosmic Ray source distributions



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

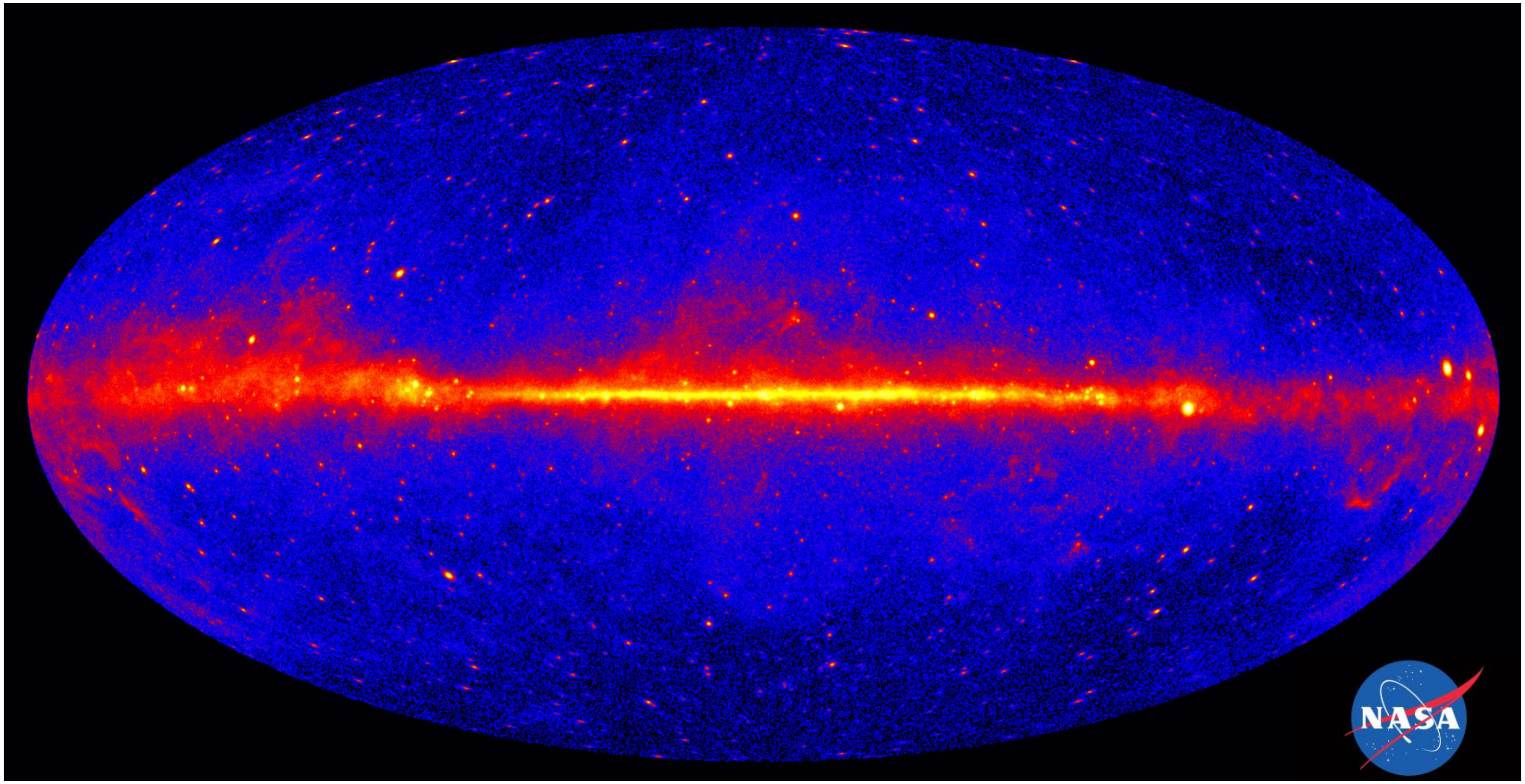
4. Physically motivated, 3D Cosmic Ray source distributions



* 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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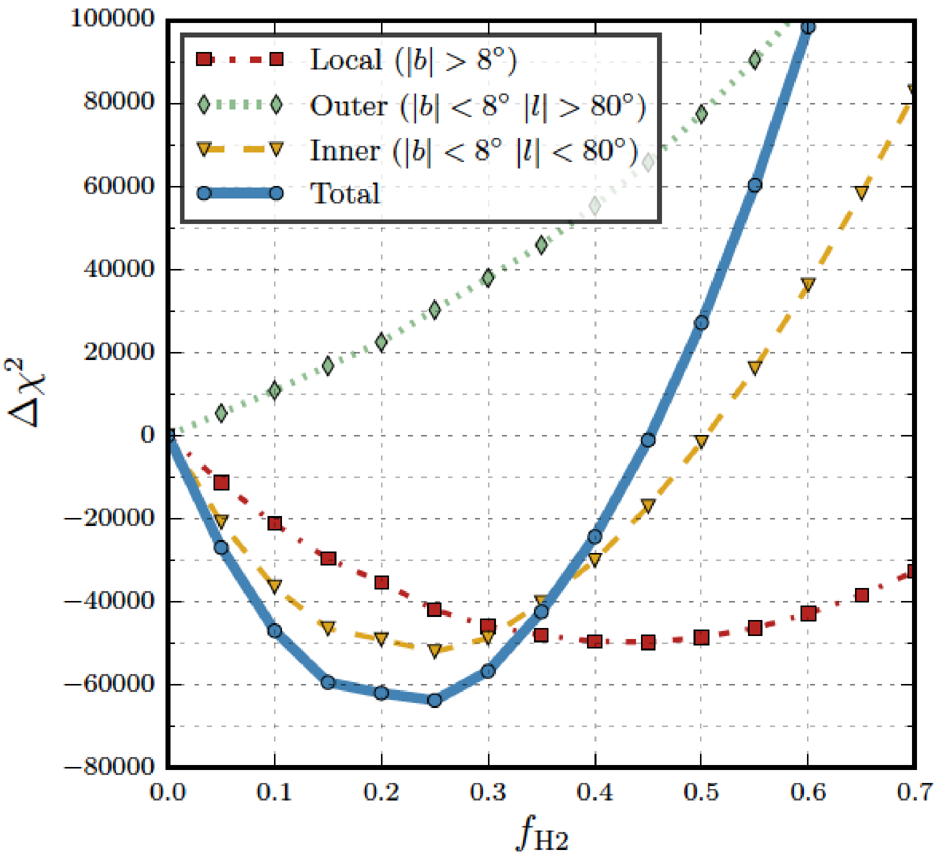
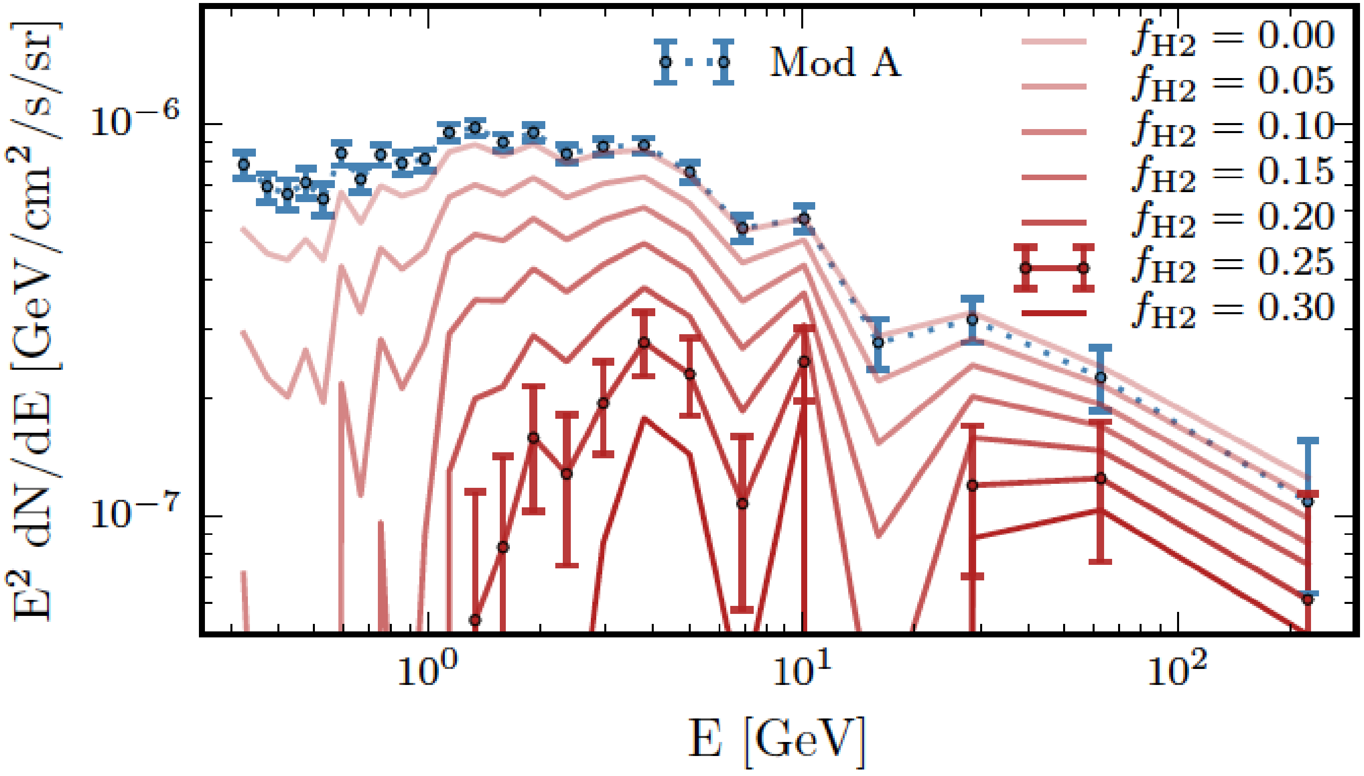


*** Carlson, Linden, Profumo 1510.04698, sub. to Phys.Rev.Lett.**

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



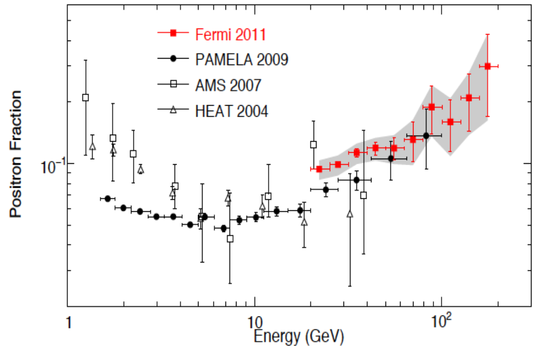
* Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584

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.

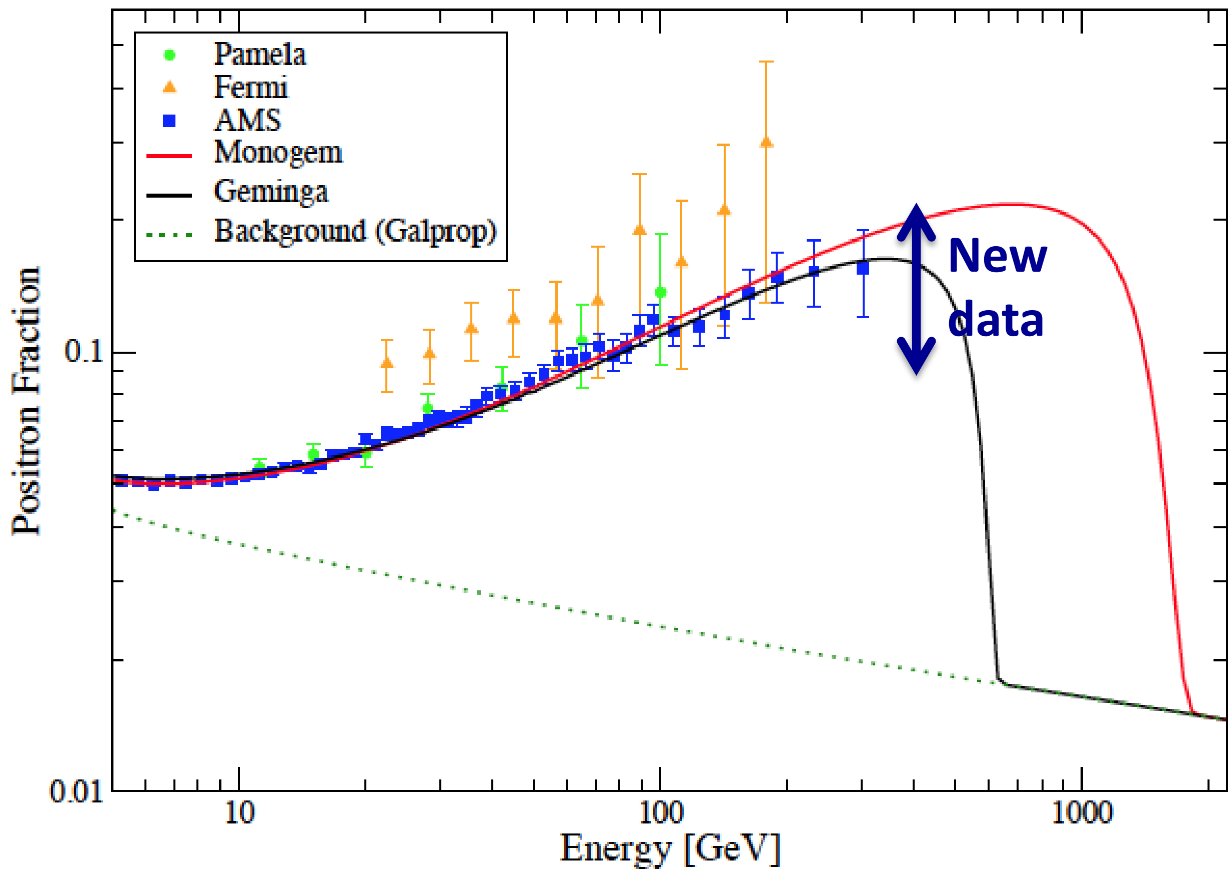
A diffuse gamma-ray line
(opportunities both at MeV and TeV)

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!

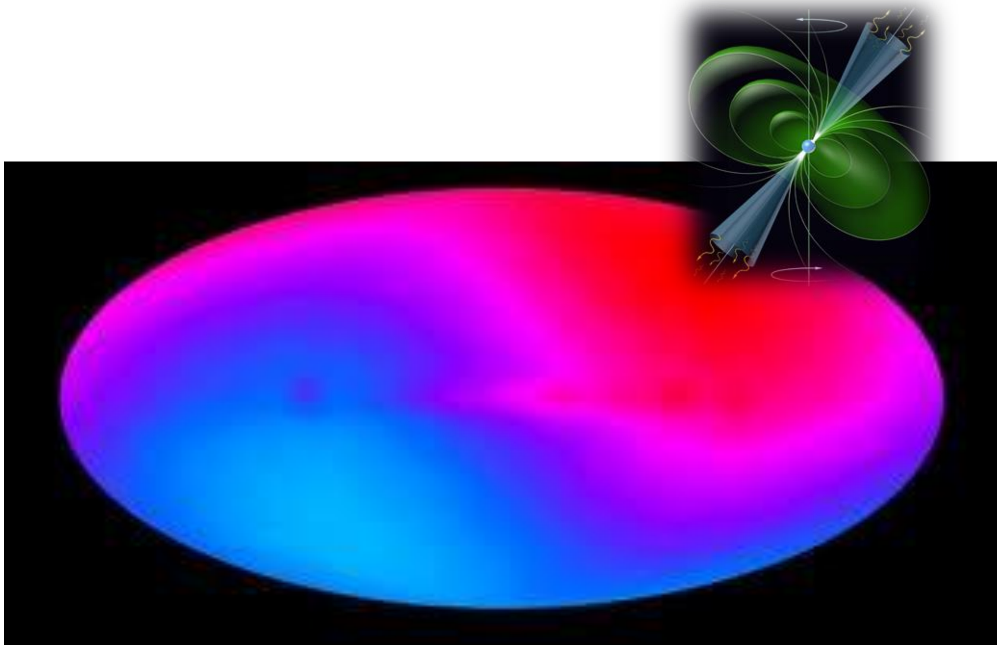
Linden and Profumo, Astrophys.J. 772 (2013) 18

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

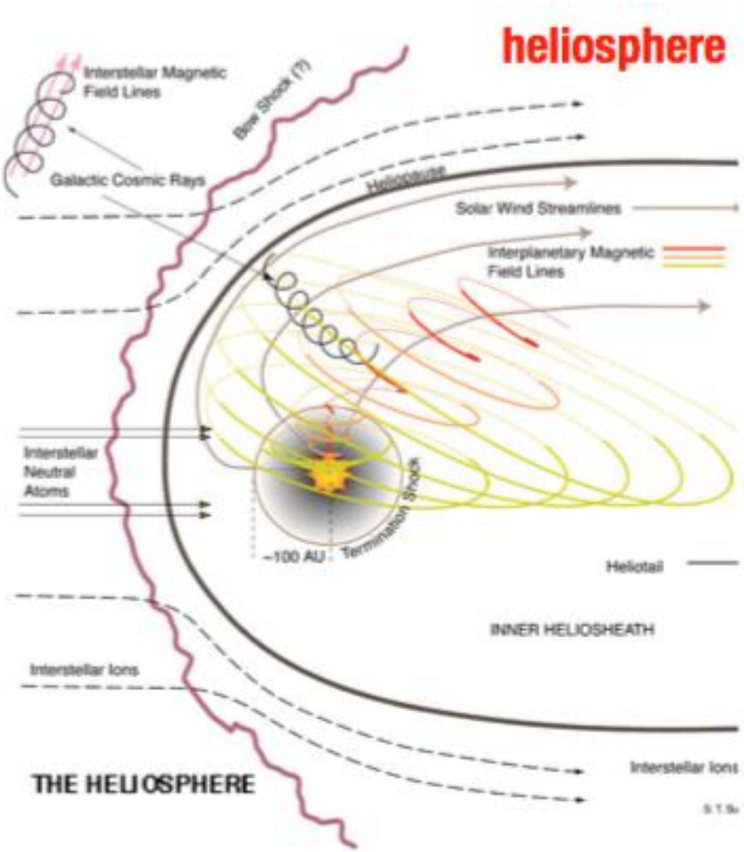
Stefano Profumo*
Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA
(Dated: May 21, 2014)

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

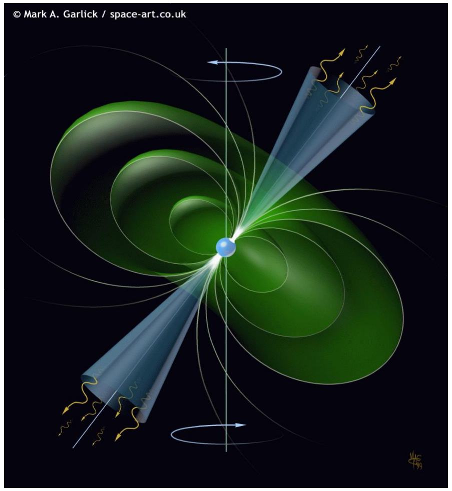
Profumo, PRD 2014

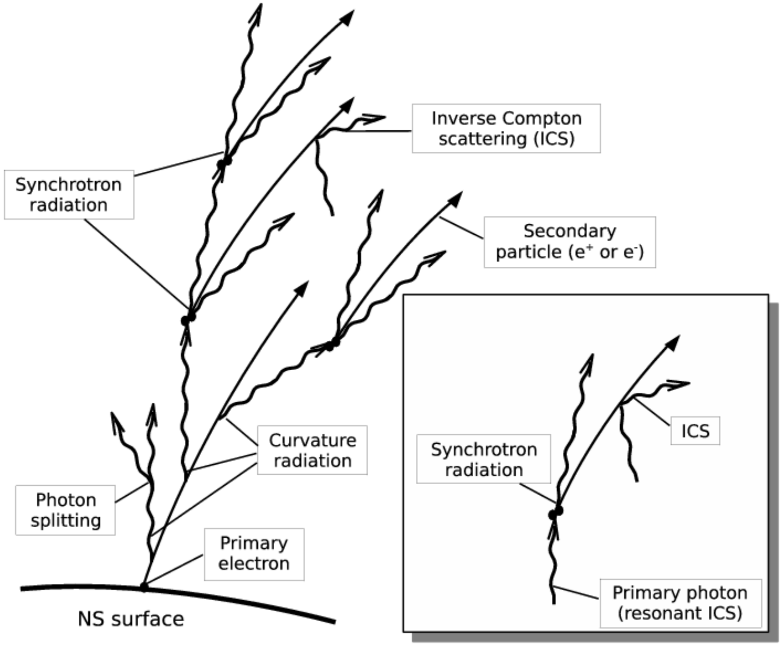
…but life might not be easy after all!

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



Any other stable particles from PSR?



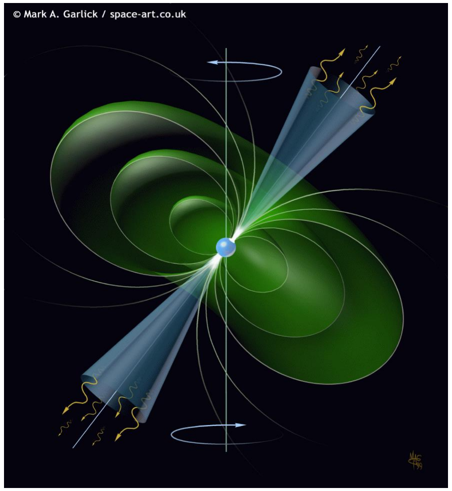


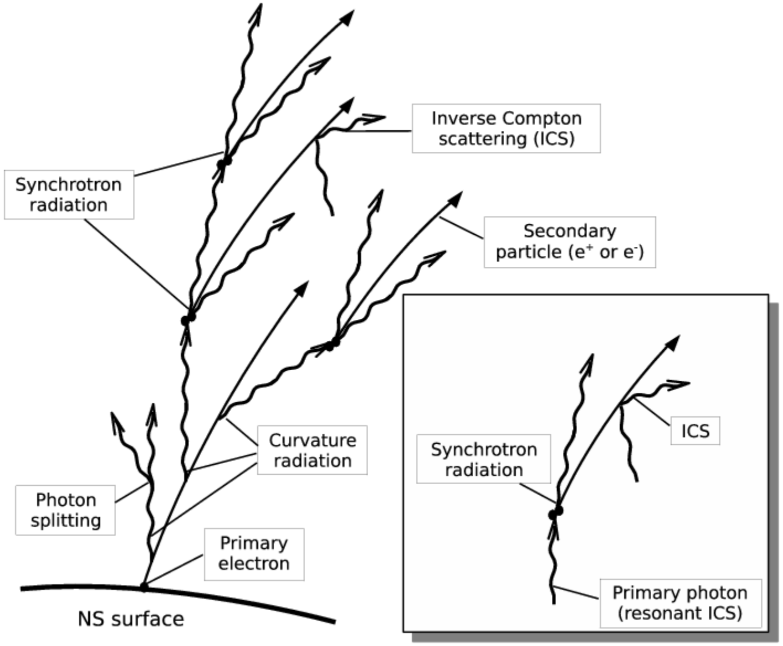
magnetosphere produces e^+e^- pairs from ~GeV photons in ~10^{13} G magnetic fields

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?



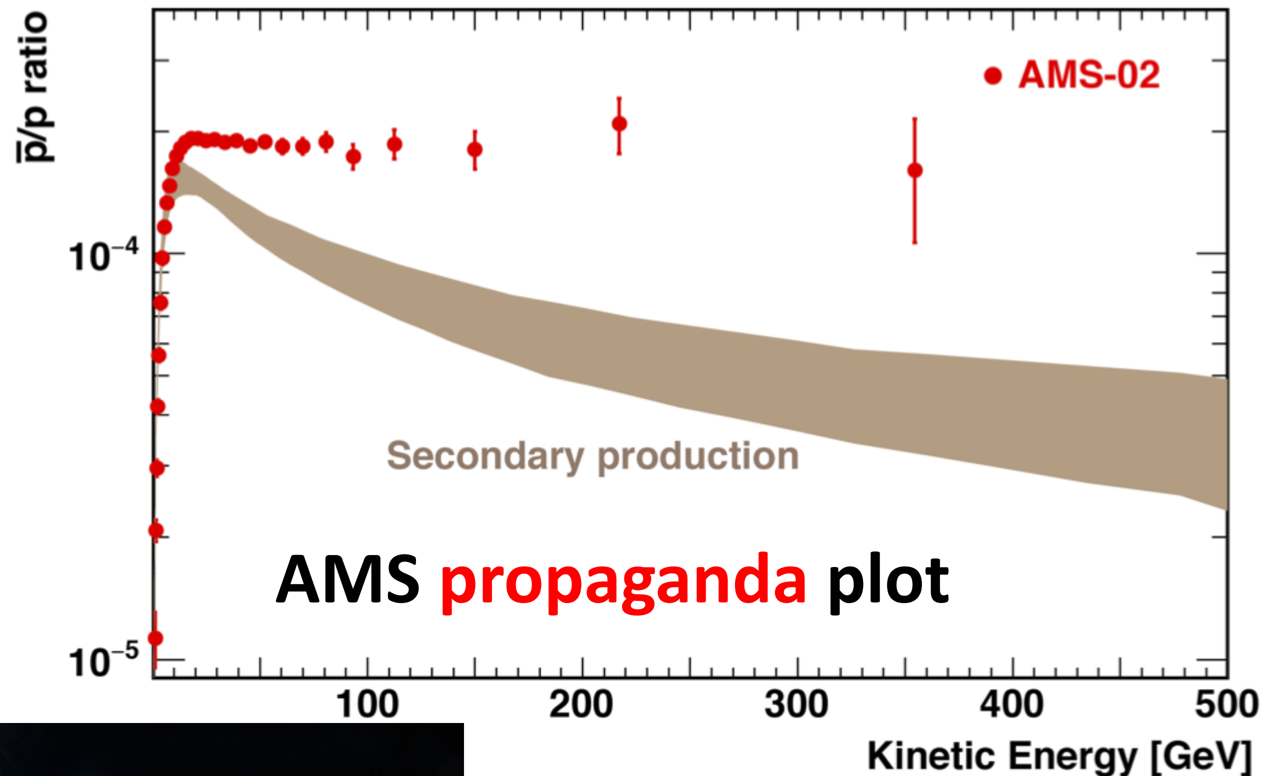


- Up to 10 GeV **neutrinos** should be produced from charged pion decay

- **Antiprotons** should also be produced, and (like e^+e^-) subsequently accelerated in the **PWN** shocks

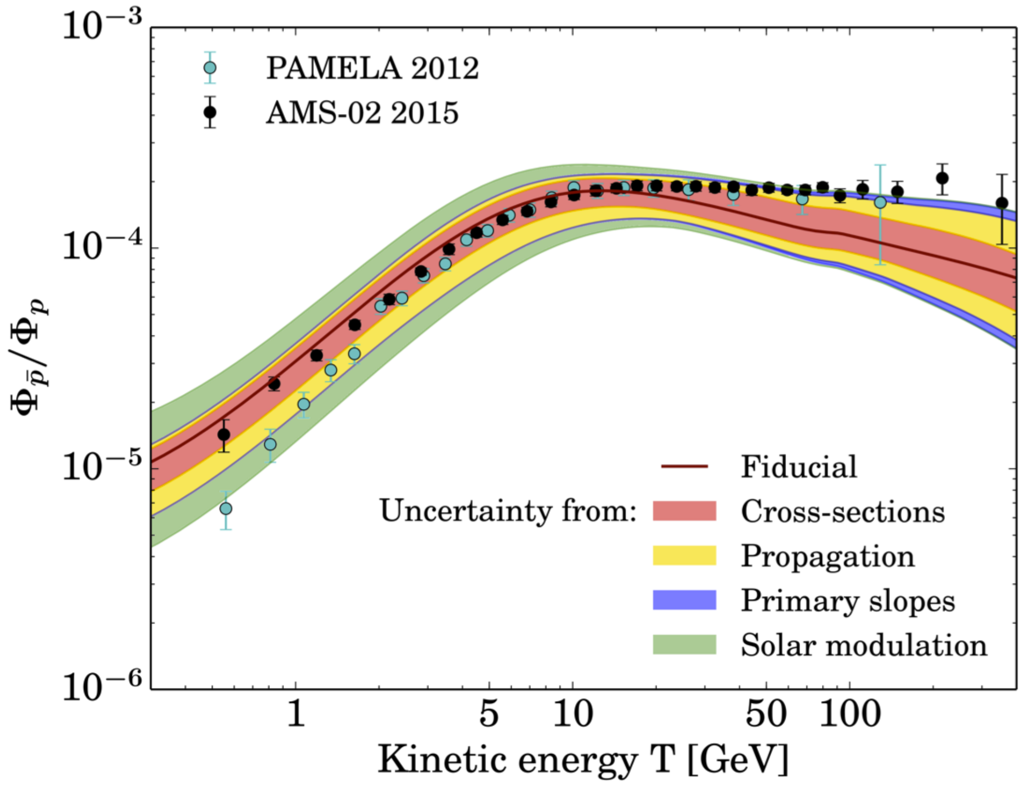
D'Eramo and Profumo, in preparation

What about antiprotons?



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}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

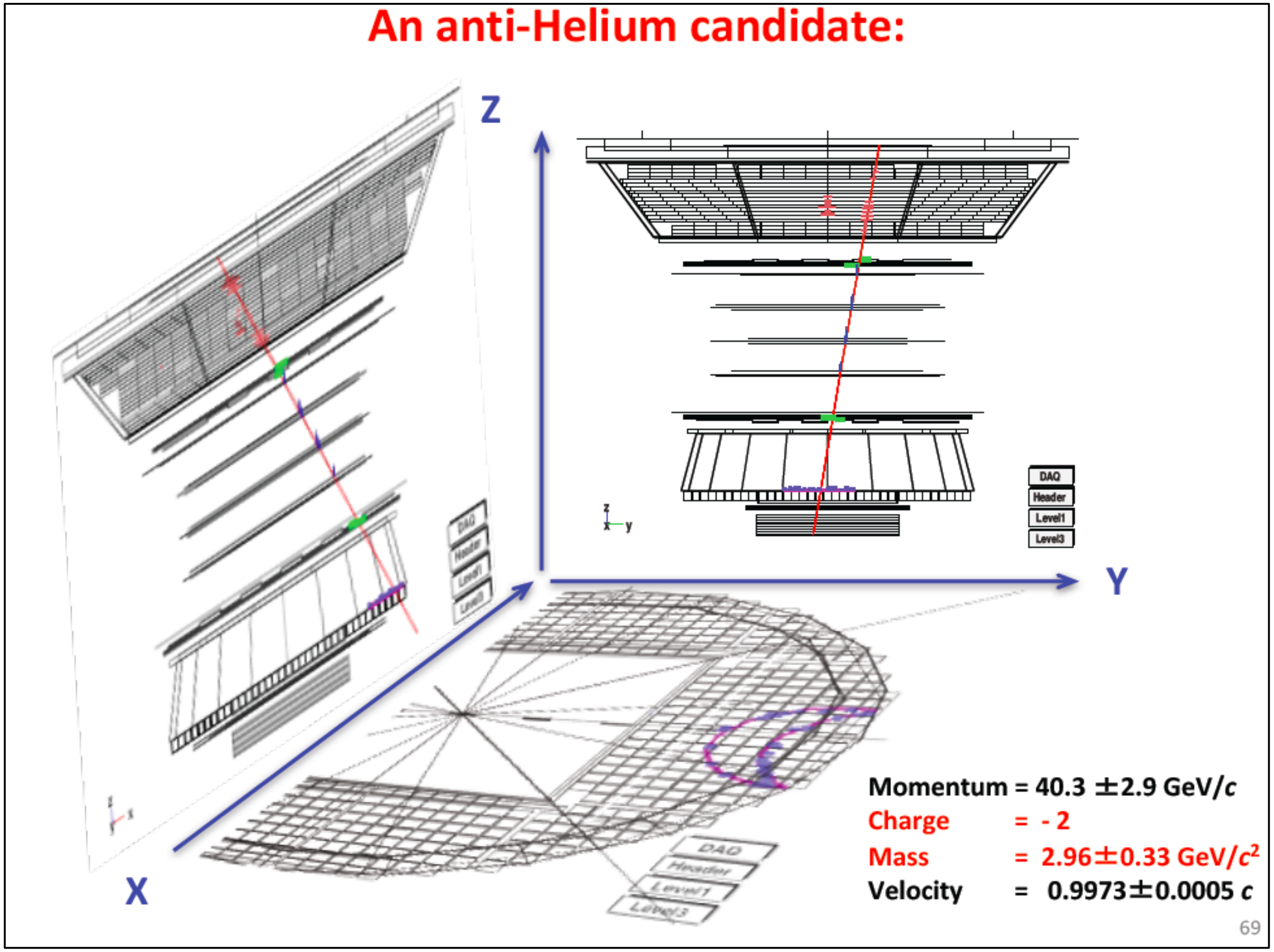
How the physicist's aging space magnet, in a final flourish, may have trapped heavy antimatter

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

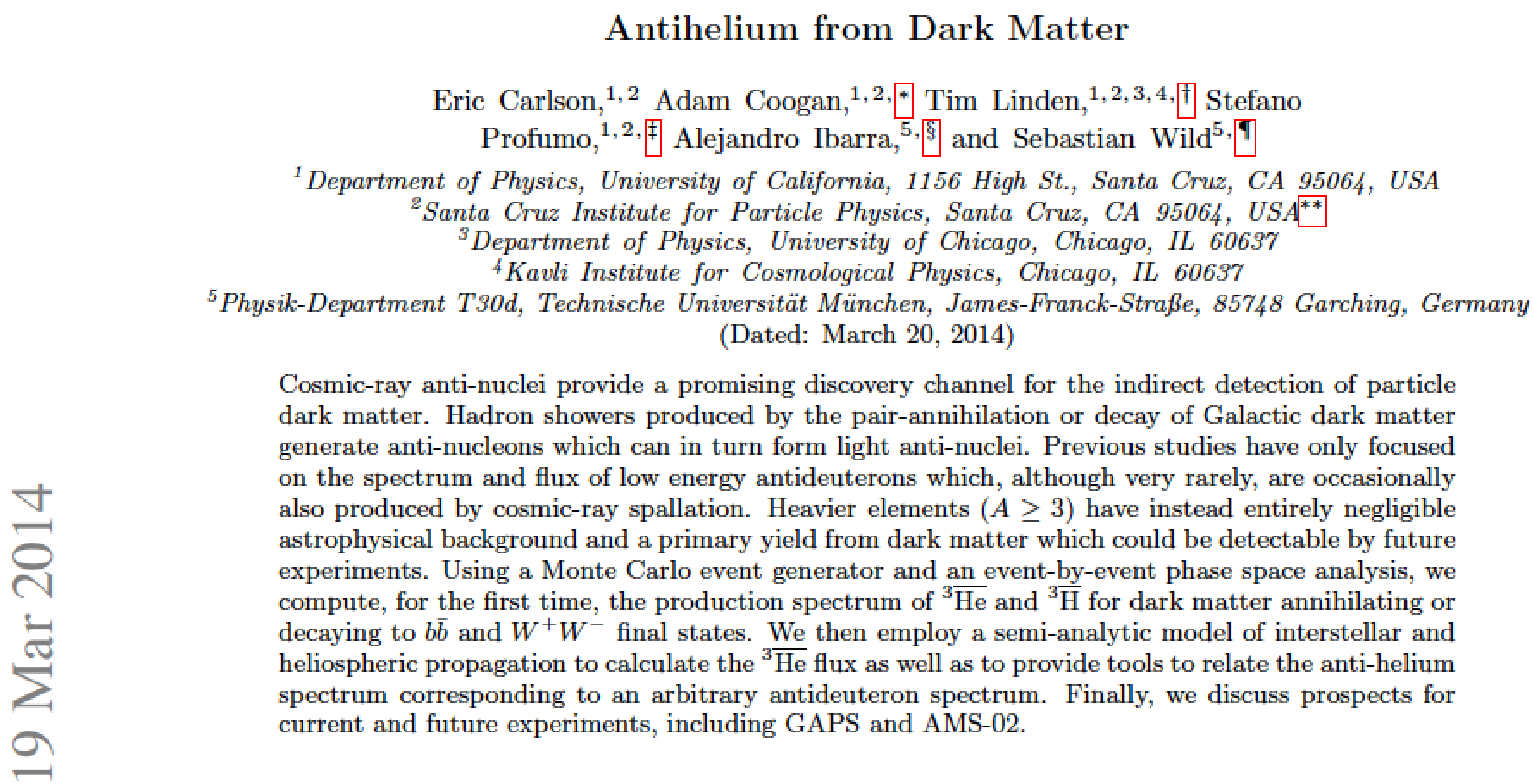
What about ^{3}He?



needs $1/10^9$ background discrimination…

Ting, AMS CERN, December 2016

What about ^{3}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,¶]

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[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

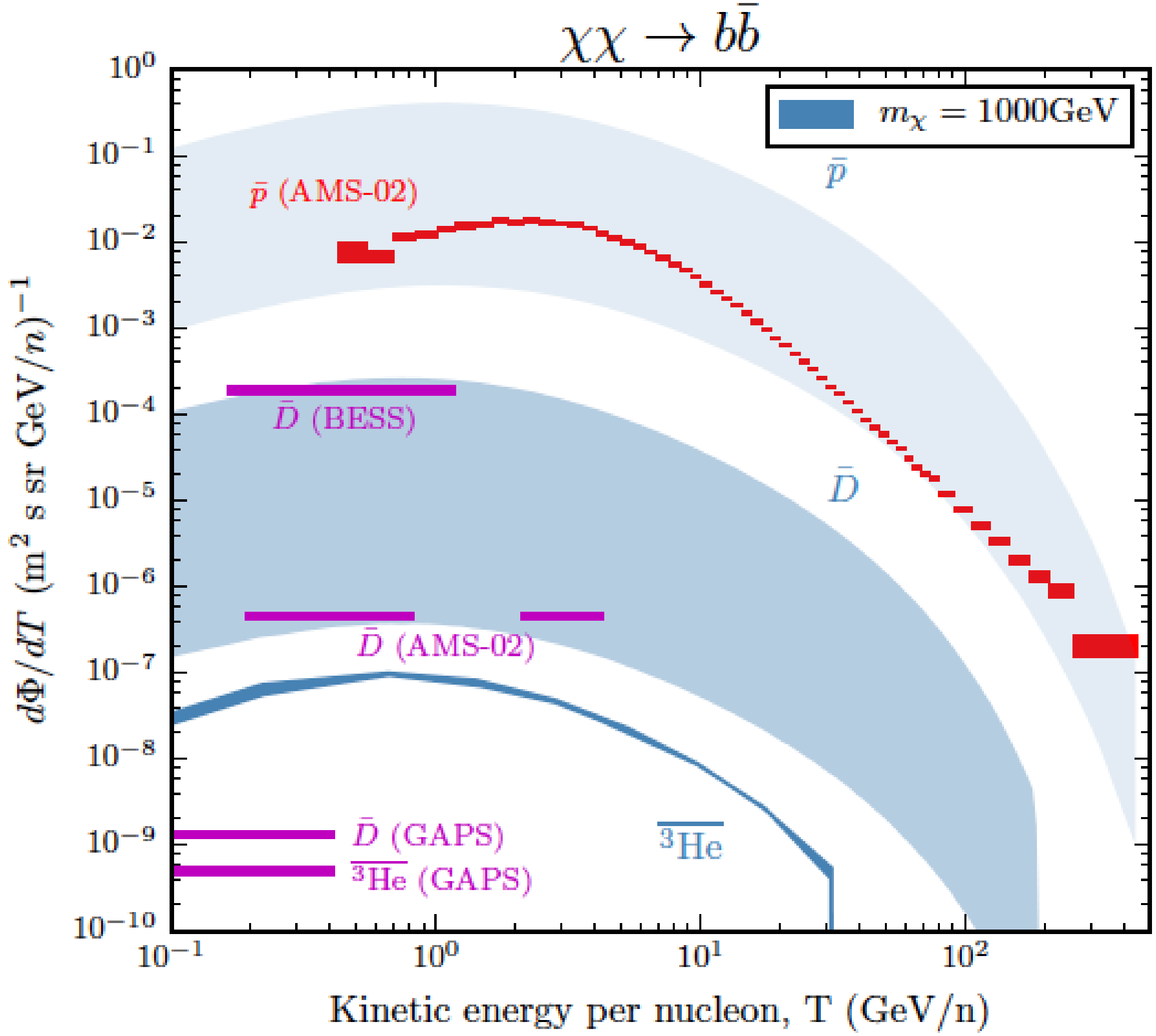
(Dated: March 20, 2014)

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 $^3\overline{\mathrm{He}}$ and $^3\overline{\mathrm{H}}$ 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 $^3\overline{\mathrm{He}}$ 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

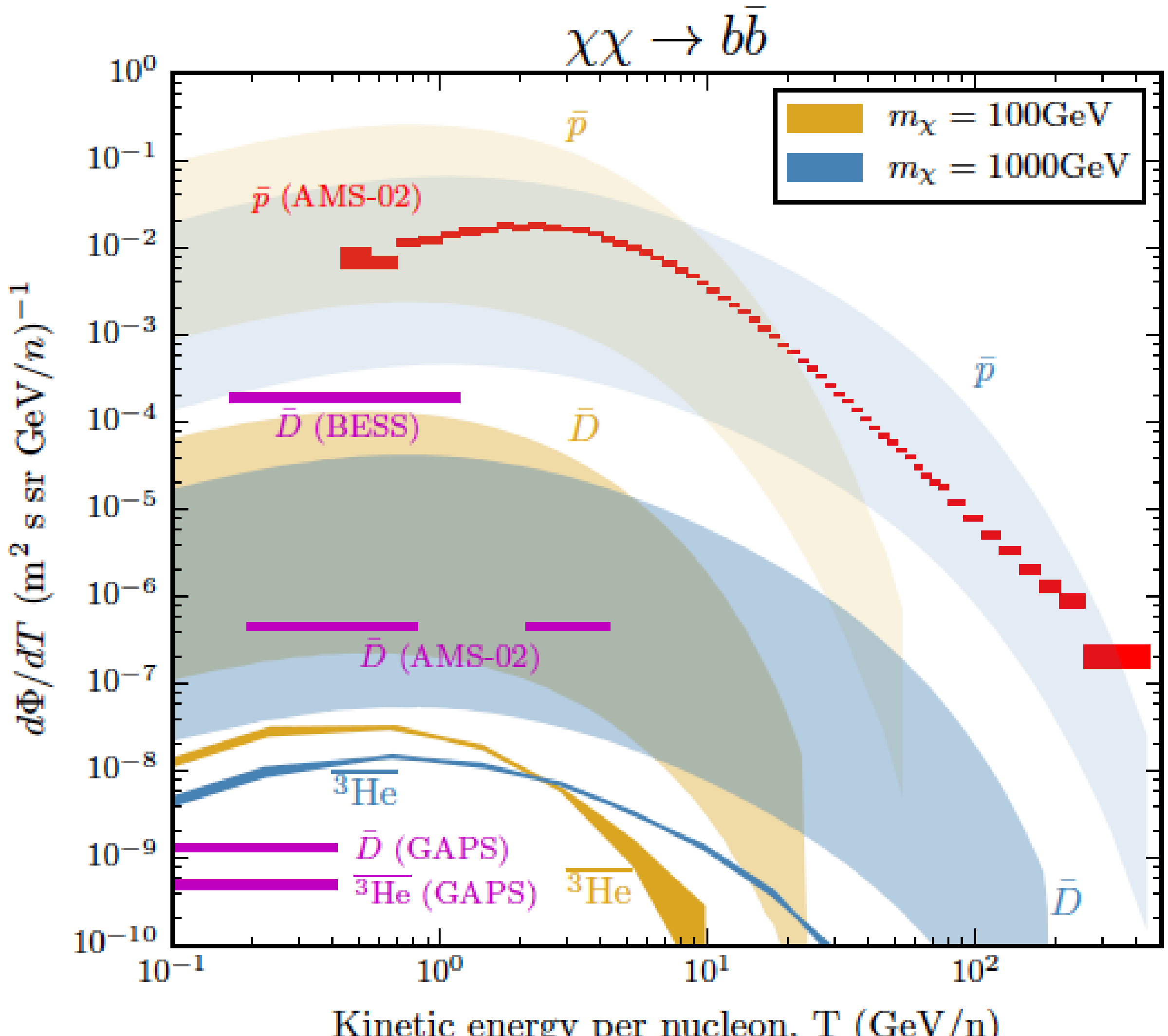
What about ^{3}He?



One event with 40 GeV momentum in 5 years

Cooga and Profumo, 2017 in preparation

What about ^{3}He?



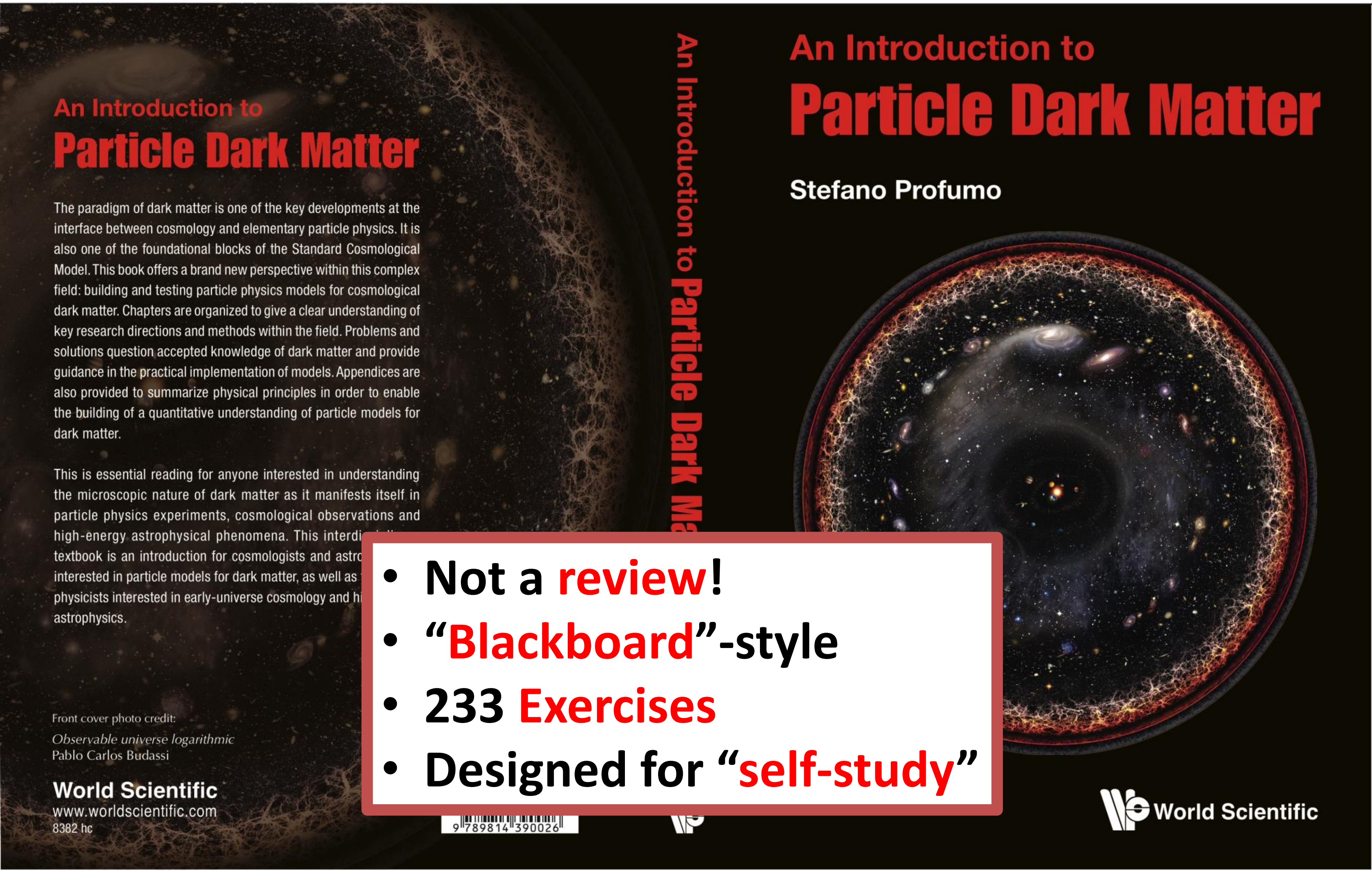
one event per year

Cooga and Profumo, 2017 in preparation

Happy Birthday and Thank You Keith!

…and a small present…

Advanced Textbooks in Physics



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