



Stefano Profumo

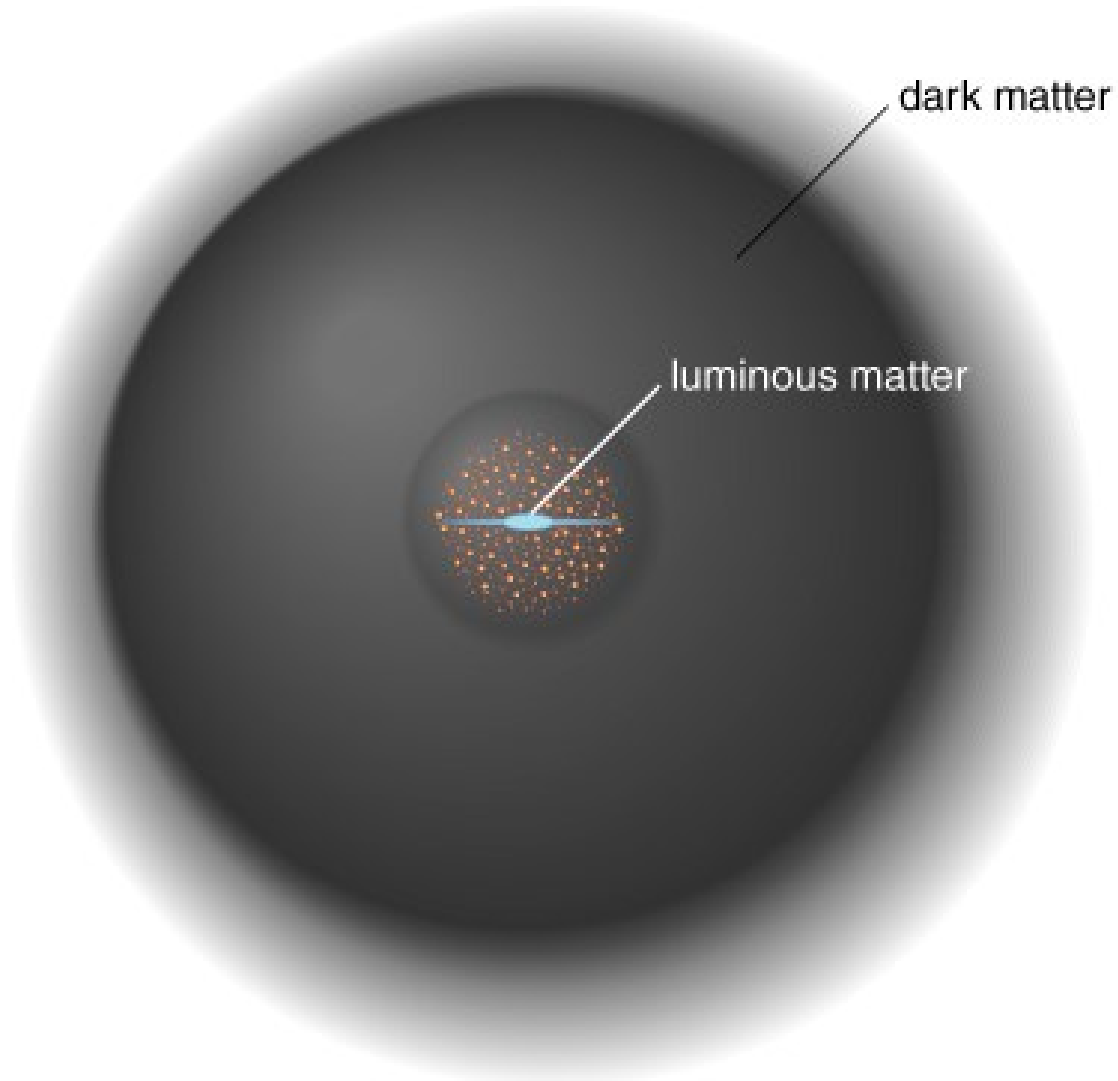
**Santa Cruz Institute for Particle Physics
University of California, Santa Cruz**

A Dark Needle in a Bright Haystack **Two Stories of Astrophysical Searches for Dark Matter**

Revealing the history of the universe with underground particle and nuclear research 2016

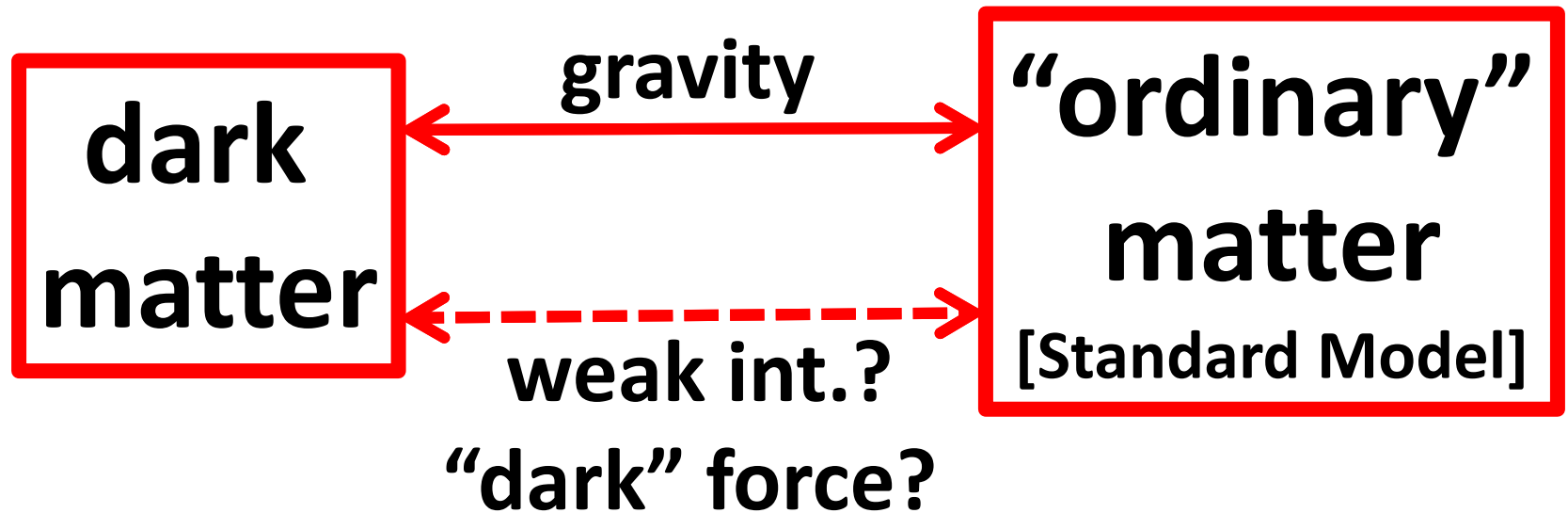
Tokyo University

Thursday, May 12, 2016

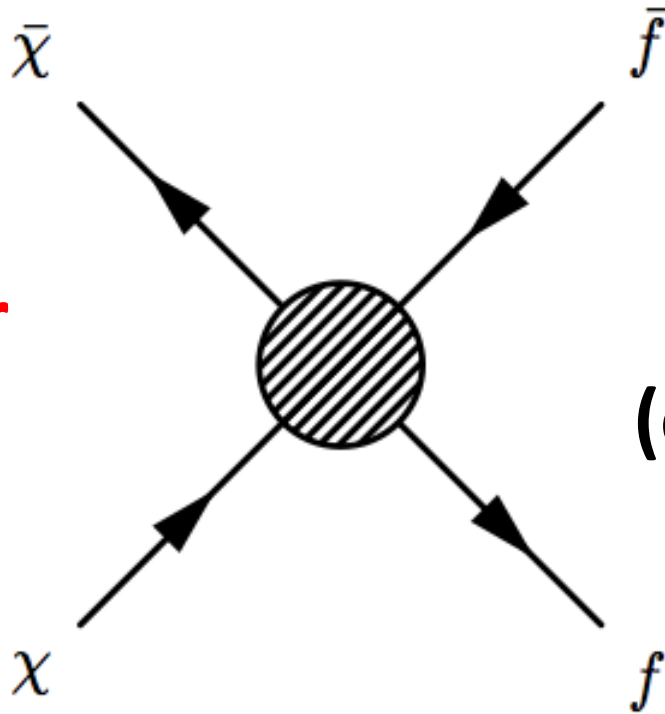


4/5

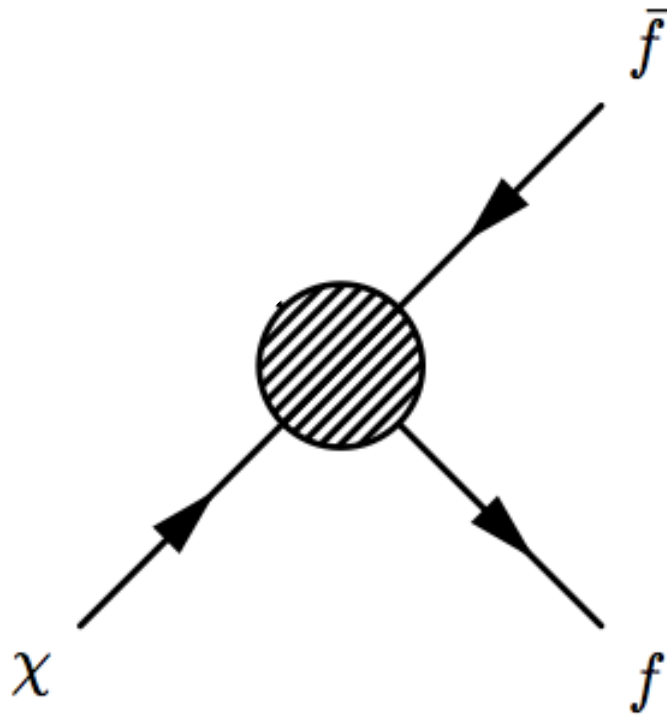
**a new
elementary particle**



**Dark Matter
Particles**



**Standard Model
(ordinary) Particles**



long-lived, but **metastable**

**Detecting the debris of
dark matter annihilation or decay**

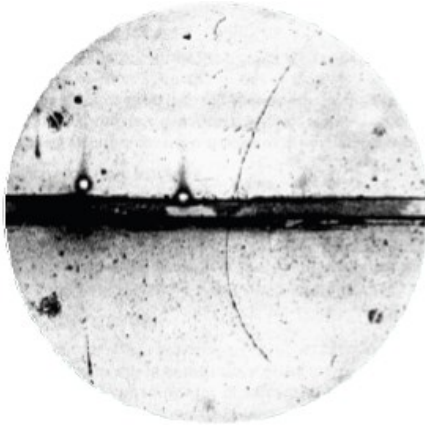
“Indirect” Dark Matter Detection

“Indirect” Dark Matter Detection

**Can we do fundamental physics
with indirect DM detection?**

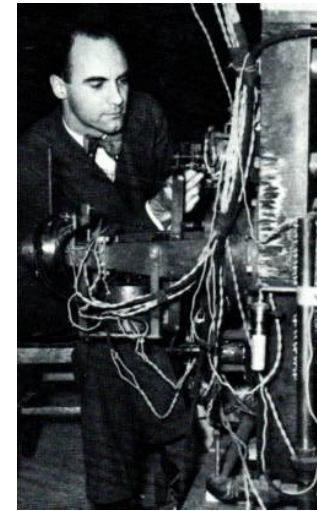
“Indirect” Dark Matter Detection

**Can we do fundamental physics
with **astroparticle/astronomical** data?**



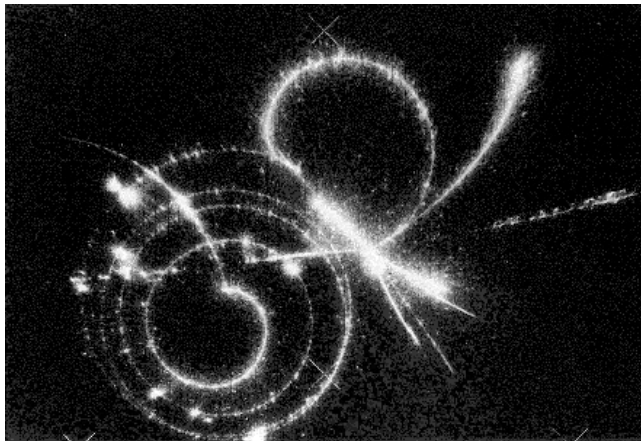
Antimatter

(positron, Anderson, 1932)

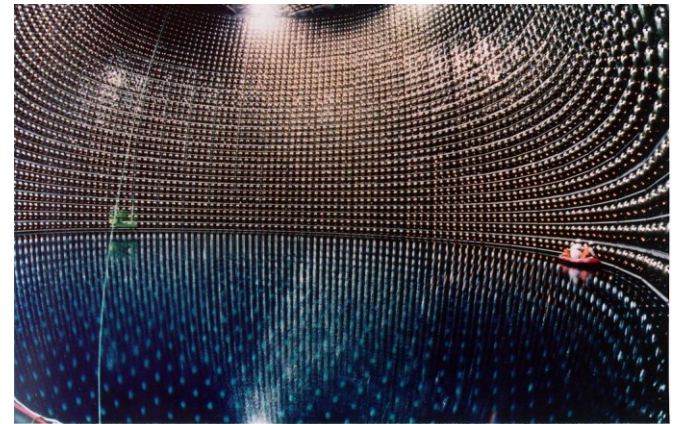


Second Generation

(muon, Anderson, 1936)



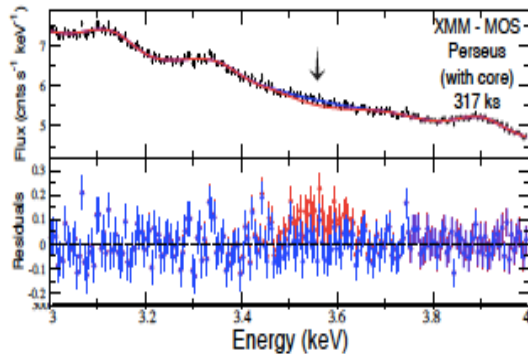
Pions (“Yukawa” particles)
(Lattes, Powell and
“Beppo” Occhialini)



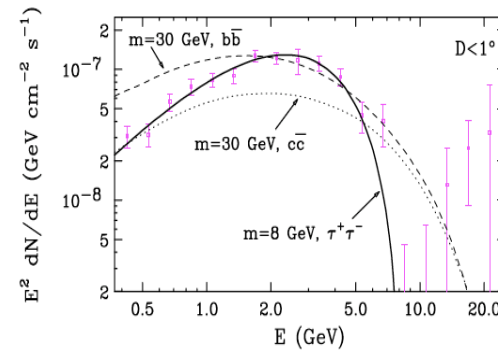
Neutrino Masses/Mixing
(2015 Nobel Prize!)

Two tantalizing signals

3.5 keV line



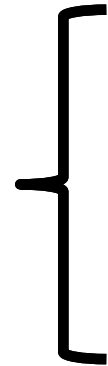
Gamma-ray excess in the Galactic Center



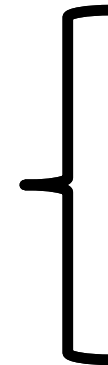
factor of **1,000,000** apart in **energy**!

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

Bulbul+ (2014)

- 
- **Stacked clusters**
 - **Perseus**

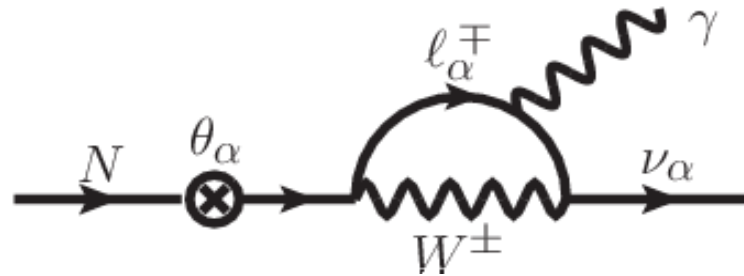
Boyarsky+ (2014)

- 
- **M31 (Andromeda)**
 - **Perseus**

Jeltema+Profumo (2014)

- 
- **Galactic Center**

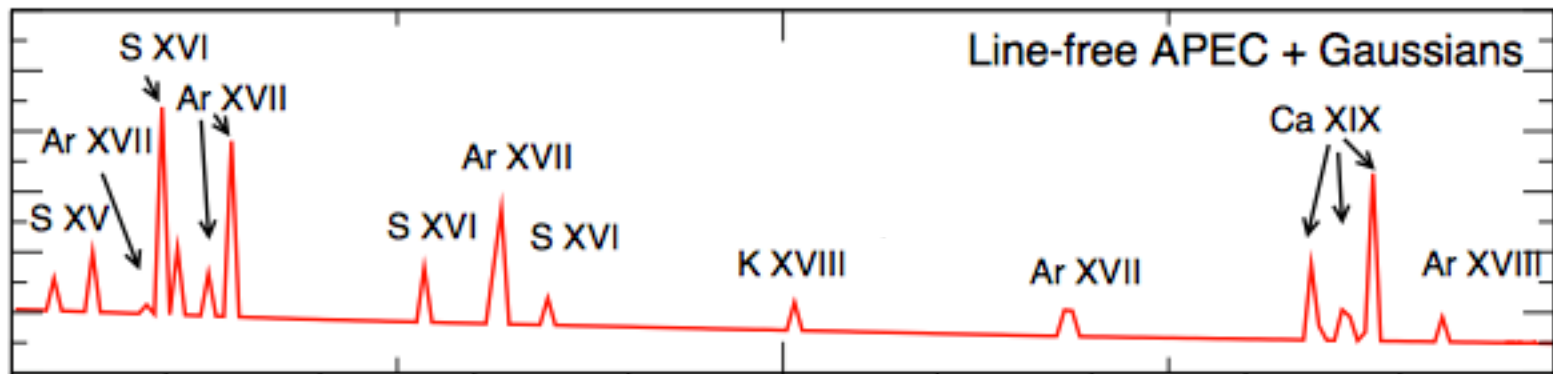
X-ray lines predicted from **sterile neutrinos**



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

3.5 keV lines (roughly) **compatible** with this!

X-ray lines also from atomic transitions of highly-ionized $Z \sim 20$ atoms*



K XVIII has two lines near **3.5 keV**
[K ($Z=19$) ion with 18-1 electrons missing, i.e. “He-like”]

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

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

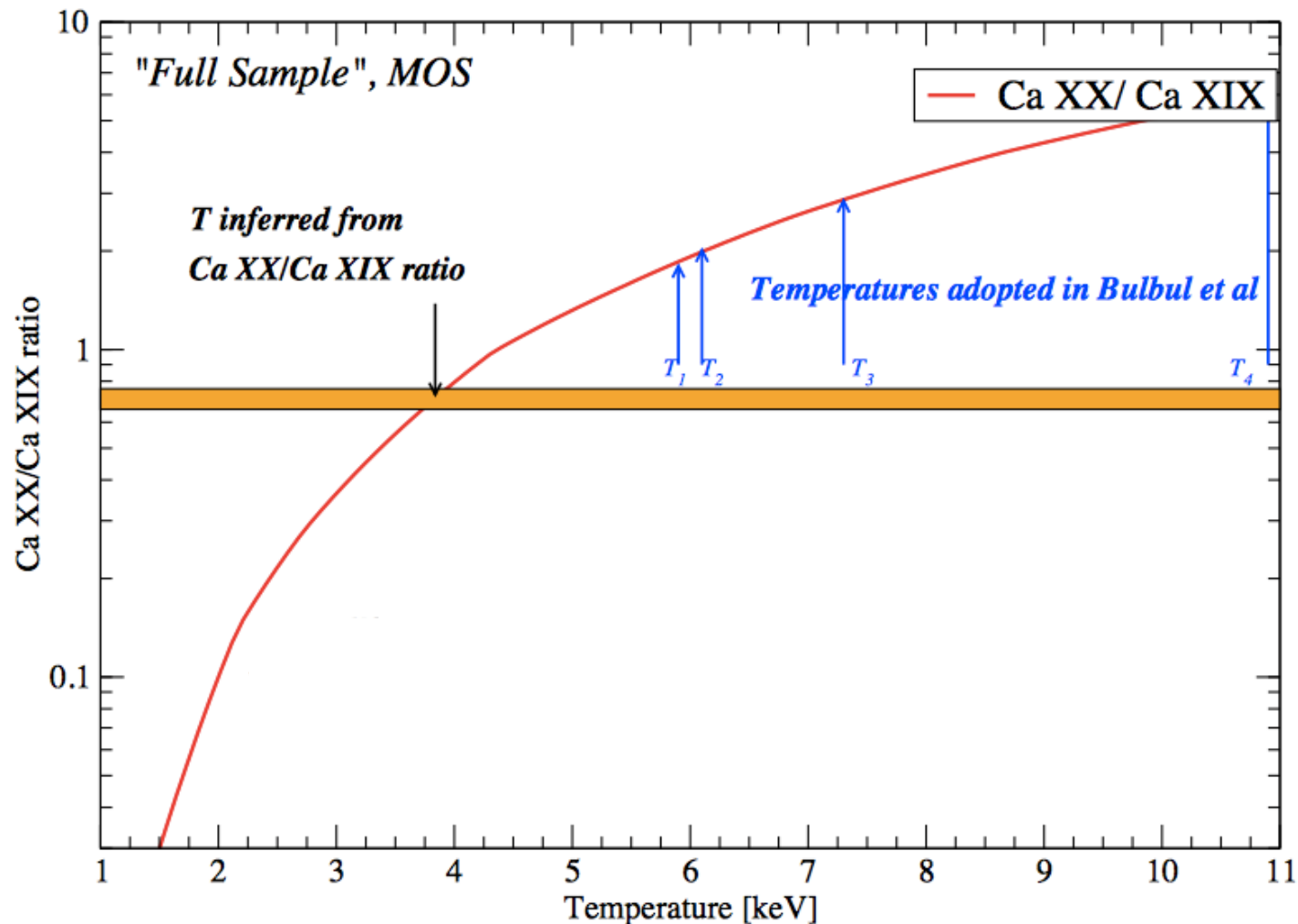
Bulbul+ argues against K XVIII
since prediction for K 3.5 keV line too low
(by factors ~ 20 for solar abundances)

...but this prediction makes two
key mistakes:

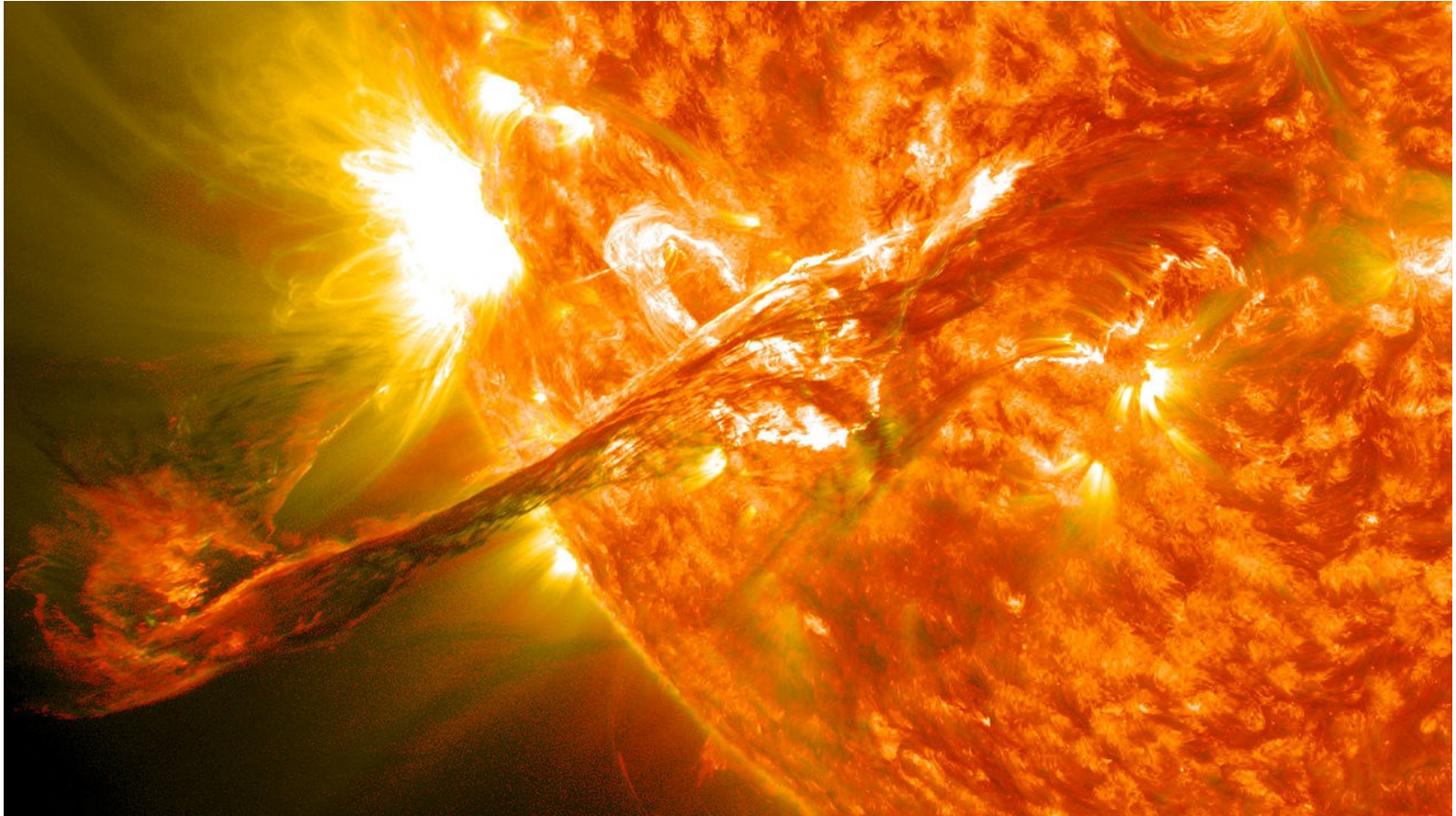
#1 Plasma Temperature

#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

**Jeltema+Profumo (2014) showed that
for clusters, and for our Galaxy
KXVIII could explain the 3.5 keV line**

Other tests?

(1) look elsewhere!

(2) use something different than spectrum!

(1) look elsewhere: **depressing**

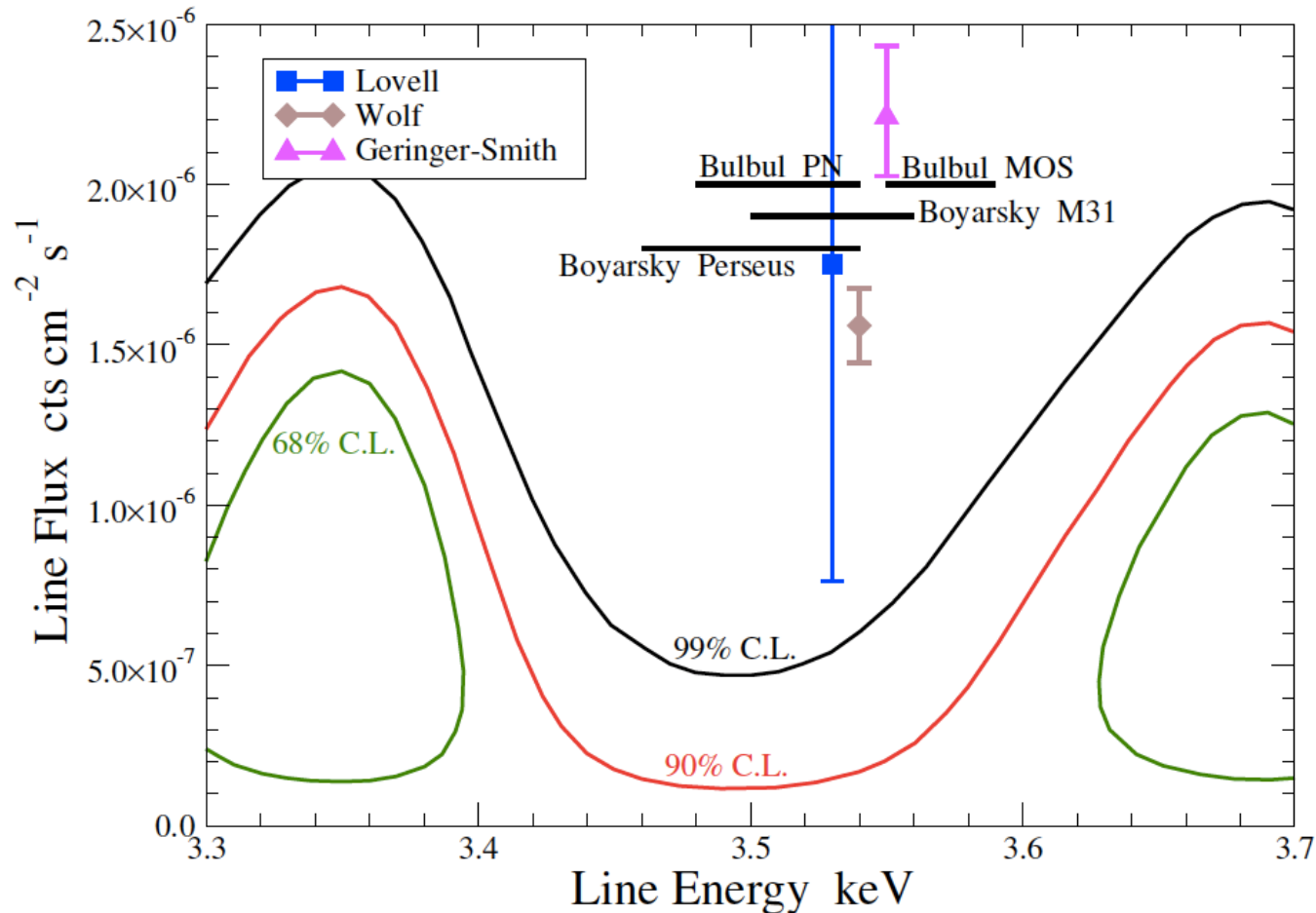
- no signal from **dSph***
- no signal from stacked **galaxies** and **groups**, low-T plasma**
- no signal from **M31*****

*Malyshev et al 2014

** Anderson et al 2014

*** Jeltema and Profumo 2014

➤ **no signal** from dedicated **1.4 Ms**
XMM observation of **Draco** dSph*

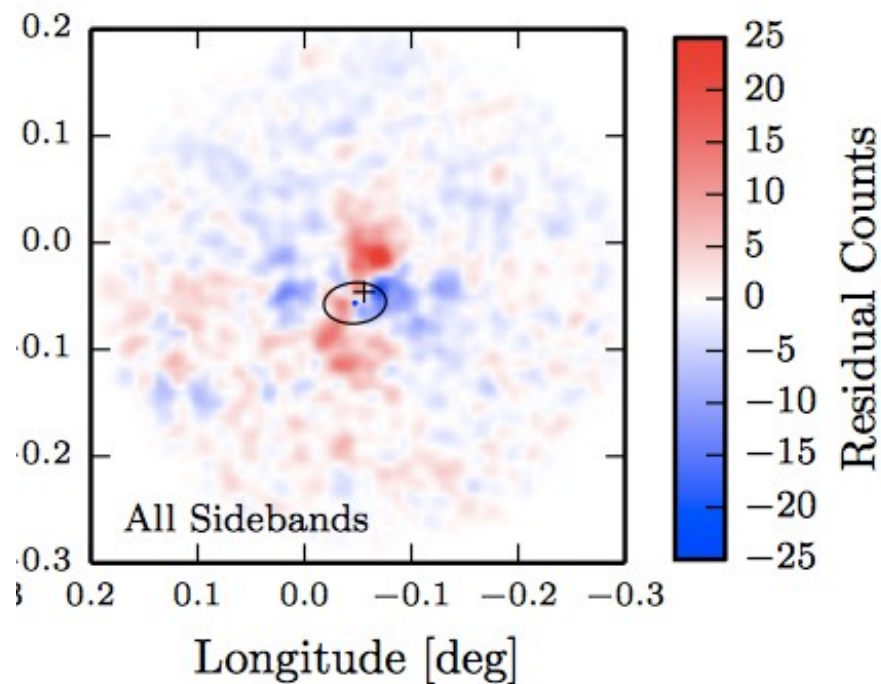


* Jeltema and Profumo, MNRAS (2015)

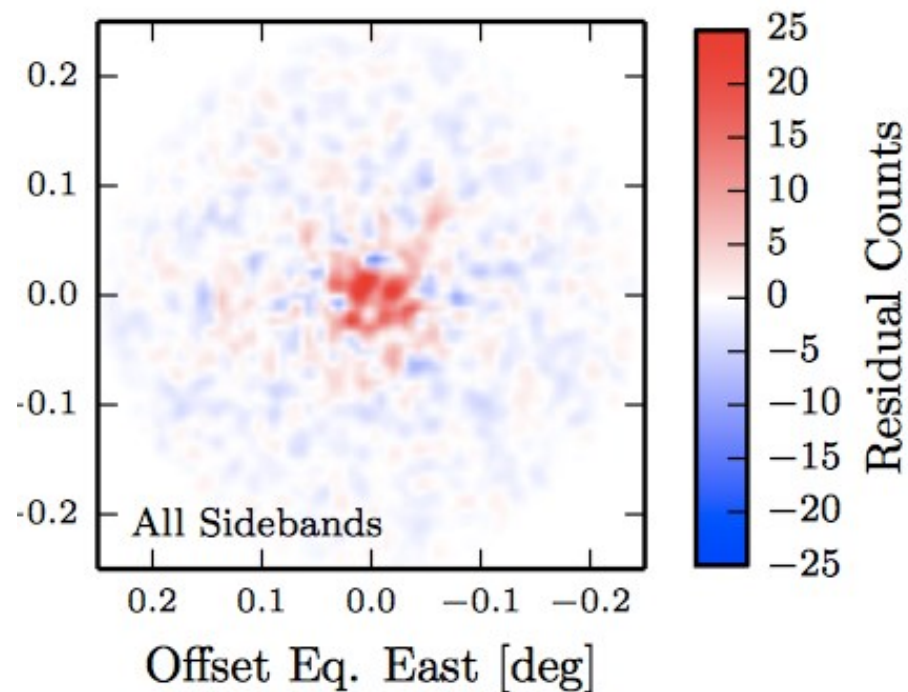
**(2) use something
different than spectrum!**

Morphology!

**Look at where the
3.5 keV photons come from!**



Milky Way



Perseus

Morphology: looks like thermal line
decaying DM strongly disfavored

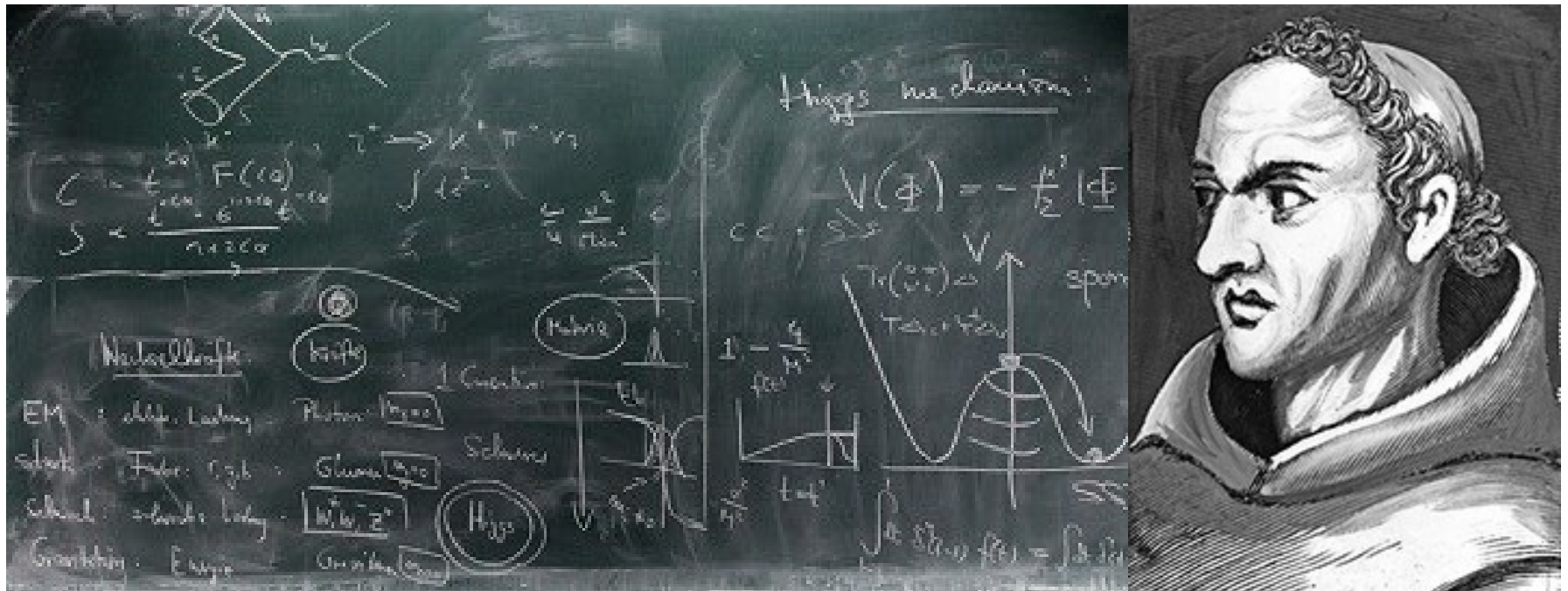
Recap!

	<u>Signal?</u>	<u>Morphology?</u>	<u>K XVIII</u>
Clusters [Perseus]	✓	~Cool core	✓
Galactic Center	✓	~Quadrupolar	✓
dSph [Draco]	✗	N/A	N/A

Dark Matter, or Potassium?



Entia **non** sunt **multiplicanda** praeter **necessitatem**
(William of Occam, c. 1286-1347)



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

What if it is Dark Matter?

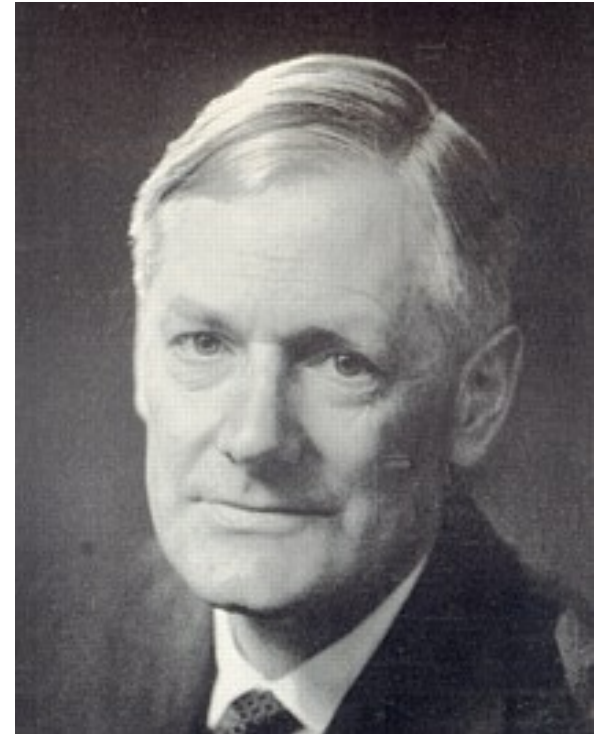
simplest models (sterile neutrino) don't work

**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” (*)**

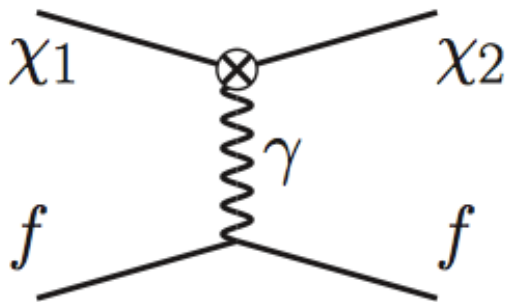
() Quoted in M. Longair's
“High Energy Astrophysics”, sec 2.5.1
“The psychology of astronomers
and astrophysicists”*



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

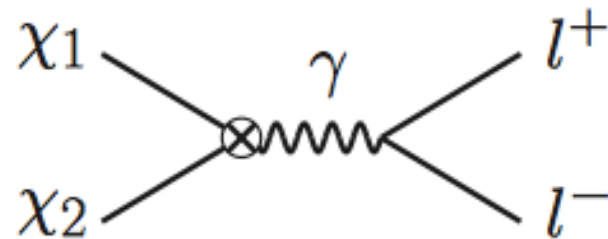
3.5 keV line ...an **excuse for an exciting,
new mechanism for a **signal** from **Dark Matter**!**

$$\chi_1 f \rightarrow \chi_2 f \longrightarrow \chi_2 \rightarrow \chi_1 \gamma$$



$$\text{Signal} \sim \rho_{\text{DM}} \times \rho_{\text{gas}}$$

Good Thermal Relic!



Why should you be **excited** by **our model**?

1. Brand **new** indirect **detection channel**!
2. **Unmistakable** signature, **background free**
3. “**Good**” model: economical, natural
UV completion, **thermal relic DM**
4. Bunch of **cool physics**!

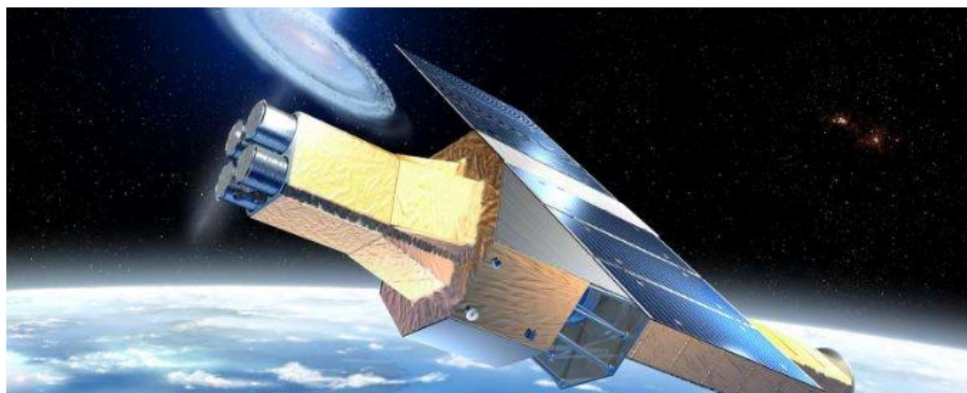
A highly falsifiable scenario

- Line **Shape** – geometric average of thermal, DM velocities
(can be resolved by Hitomi/Astro-H)



Why X-ray astronomers are anxious for good news from troubled Hitomi satellite

April 5, 2016 by Kevin Schawinski, Swiss Federal Institute Of Technology Zurich, The Conversation

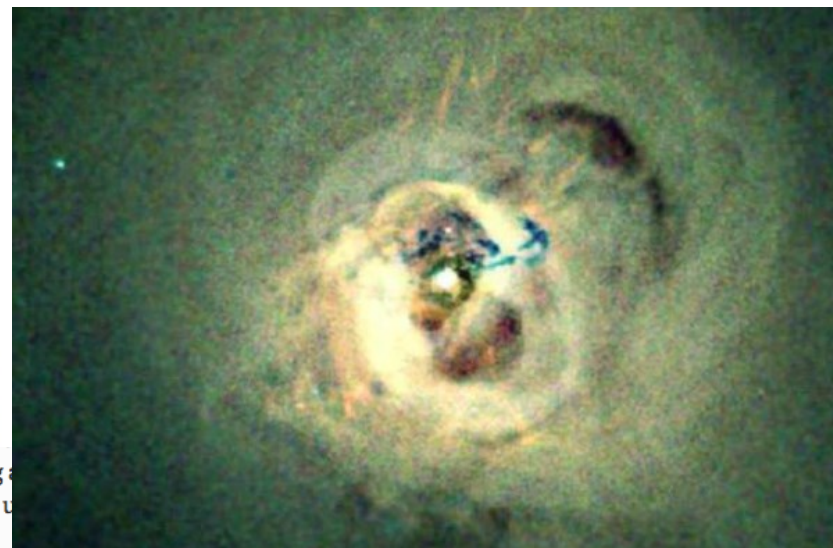


on a Japanese rocket in mid-February, could be experiencing a problem after an unexpected shift in its position may have rendered it unable to generate solar power, it said.

The satellite is supposed to be orbiting about 580 km (360 miles) above the Earth's surface, but JAXA said the satellite may also have deviated from its intended path.

The Japan Times

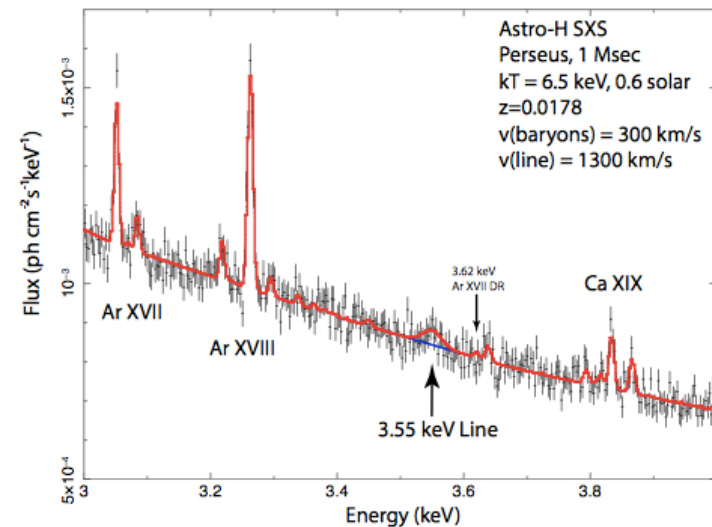
Astro-H SXS
Perseus, 1 Msec
 $kT = 6.5 \text{ keV}$, 0.6 solar
 $z=0.0178$
 $v(\text{baryons}) = 300 \text{ km/s}$
 $v(\text{line}) = 1300 \text{ km/s}$



in Ito after Saitama girl,
15, missing two years
flees captivity, alerts
cops

A highly falsifiable scenario

- Line **Shape** – geometric average of thermal, DM velocities (can be resolved by Hitomi/Astro-H)
- Unique **morphology**
- Unique **target**-dependence
- **Lines** could appear **anywhere** from eV (**visible**) to **UV**, to **X-ray**



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

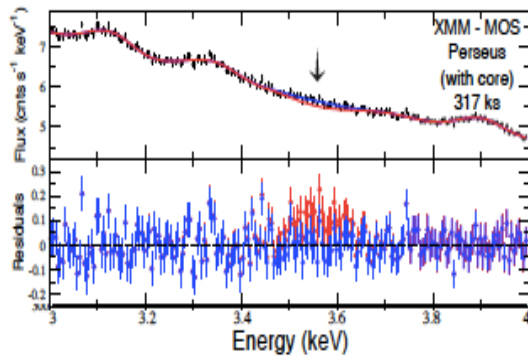
Plasma-excited DM:
New mechanism to detect DM

Lines anywhere eV...keV

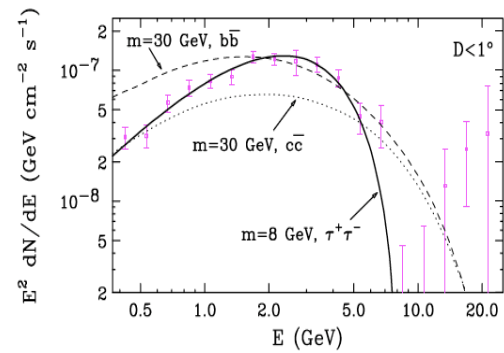
Unique obs. predictions, **background "free"**

Structure formation? **Small-scale** structure?

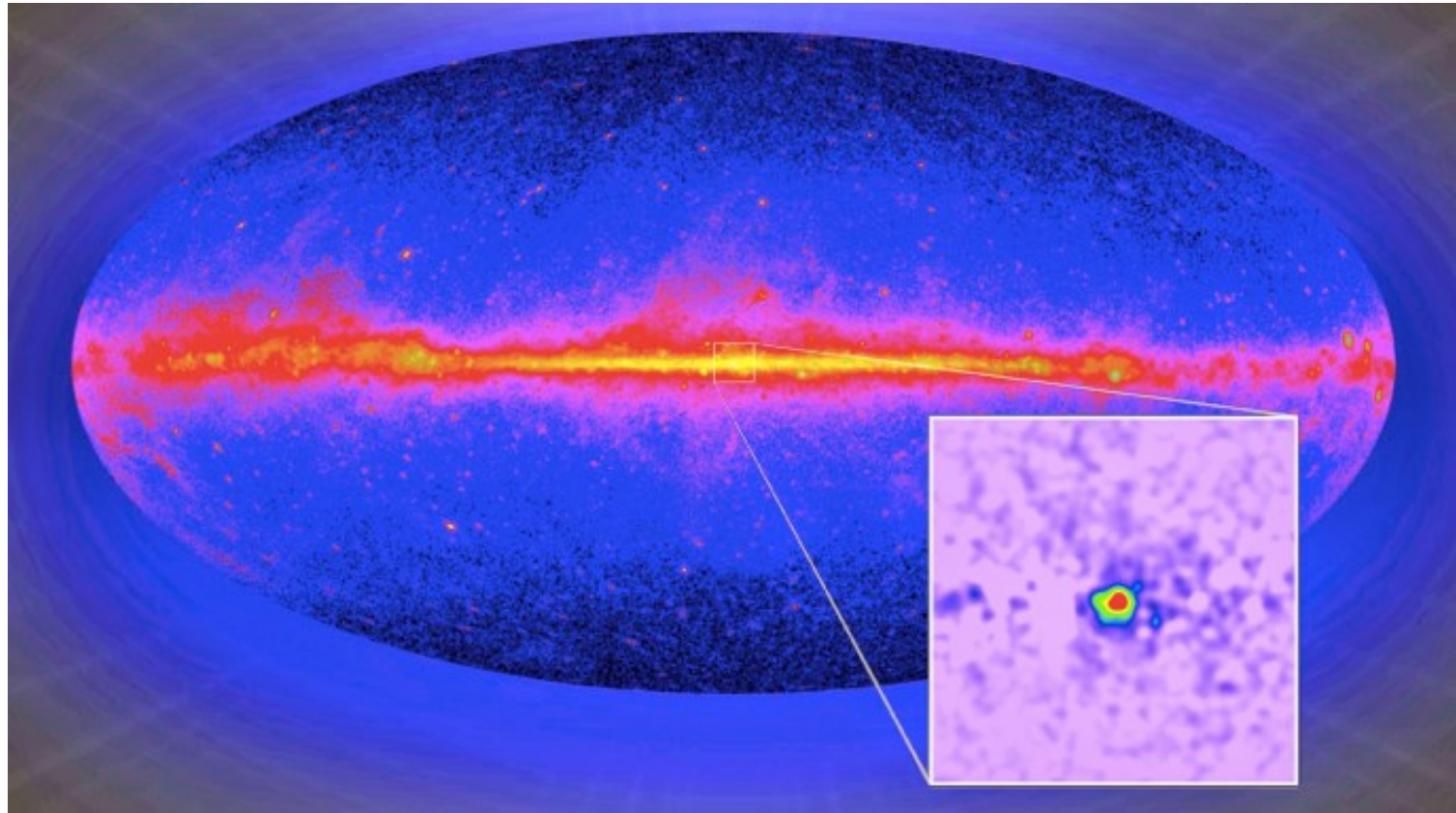
3.5 keV line



Gamma-ray excess in the Galactic Center



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); Abazajian et al (UCI); Macias and Gordon (NZ)



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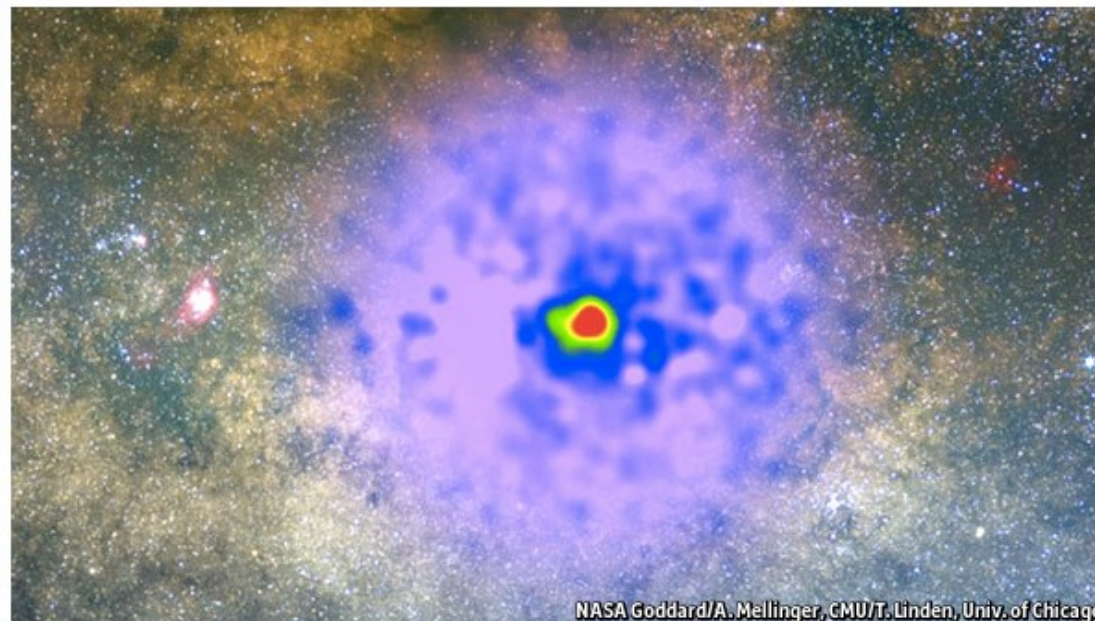
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Dark Matter
in Milky Way

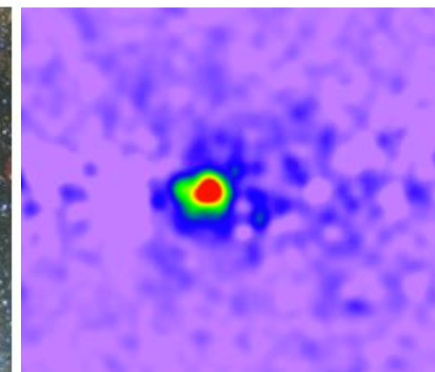
Excess gamma-ray light at the g

Apr 8, 2014 | By Clara Moskowitz

SAVANNAH, Ga.—Gamma rays from the center of the Milky Way are the result of dark matter particles, scientists say. If so, the signal detected by NASA's Fermi space telescope is the first-ever indirect detection of particles that make dark matter a stealthy and elusive substance that contributes most of the mass of the universe.



NASA Goddard/A. Mellinger, CMU/T. Linden, Univ. of Chicago



A false-colour image of the centre of the Milky Way, taken by the Fermi space telescope, with all known gamma-ray sources removed, leaving only excess emissions that may arise from dark matter annihilations (Image: T. Linden, University of Chicago)

This picture, physicists think, shows telltales of dark matter: mysterious stuff which makes up five times as much of the universe as the more familiar matter of atoms. The image, based on data from Fermi, an American satellite, and created by Dan Hooper, an astrophysicist at Fermilab, in Illinois, superimposes onto a picture of the visible substance of the Milky Way's centre a map of part of its gamma-ray production—the part in excess of

**The Economist has the tendency
to get things right**

**The
Economist**

APRIL 28TH - MAY 4TH 2001

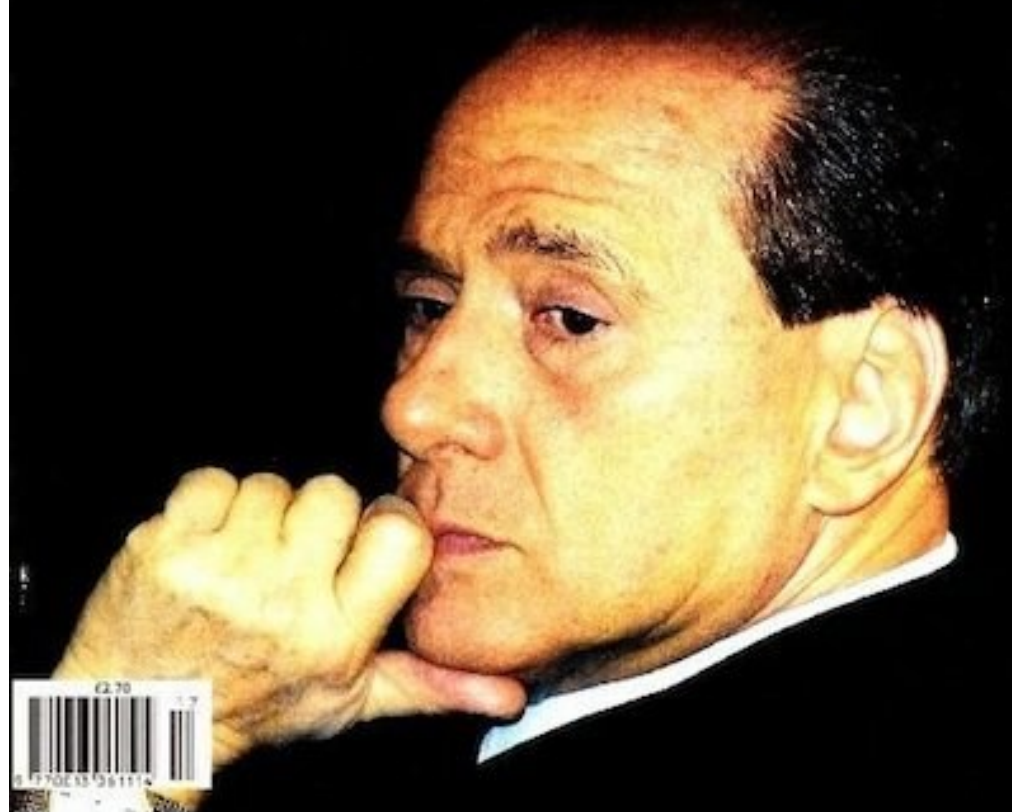
**IS INEQUALITY
GROWING?**

pages 95-97 and 106

**TARGET-CRAZY
LABOUR**

pages 22 and 31

Why Silvio Berlusconi is unfit to lead Italy



INSIDE: A SPECIAL REPORT ON CHINA'S COMING DEBT BUST

The Economist

MAY 7TH - 13TH 2016

Lessons from Leicester

Our crony-capitalism index

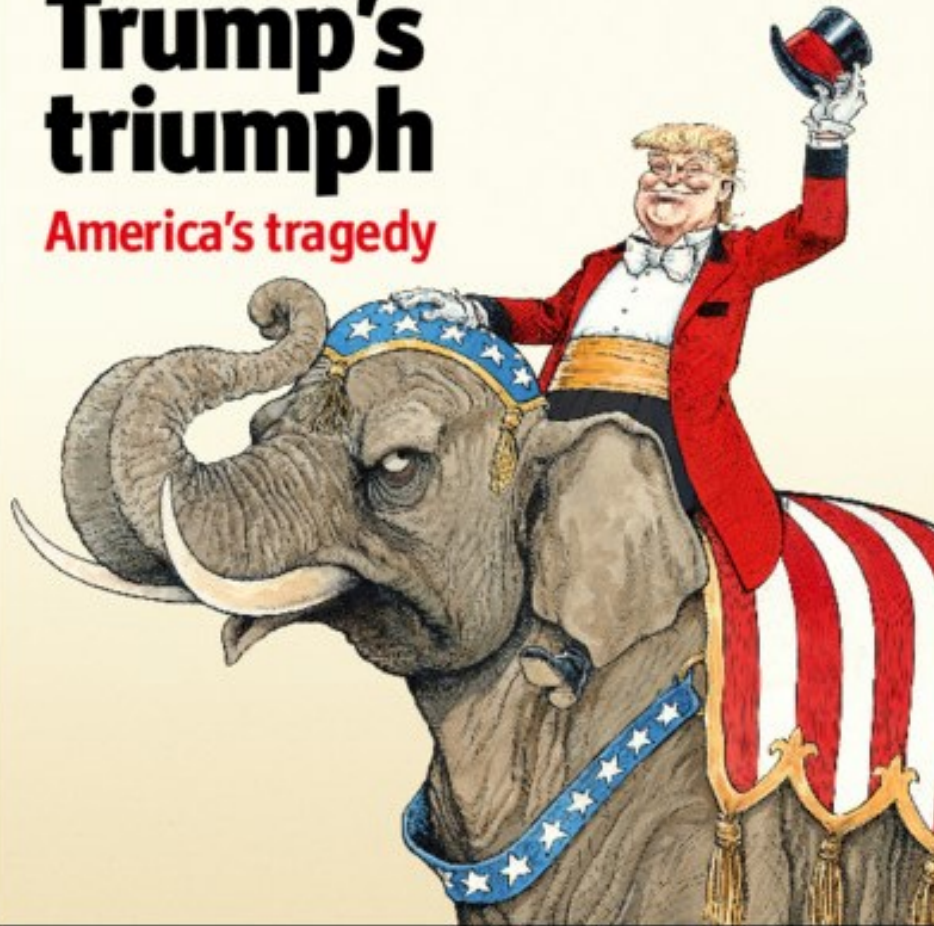
Venezuela lights candles for Chávez

Beyoncé and the market for Lemonade

Will your surgeon be a robot?

Trump's triumph

America's tragedy



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**

- ✓ **Morphology NOT OK**
- ✓ **Spectrum NOT OK**
- ✓ **Not enough!**

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

WRONG QUESTION!

Rather: **is the excess** indeed **there**?

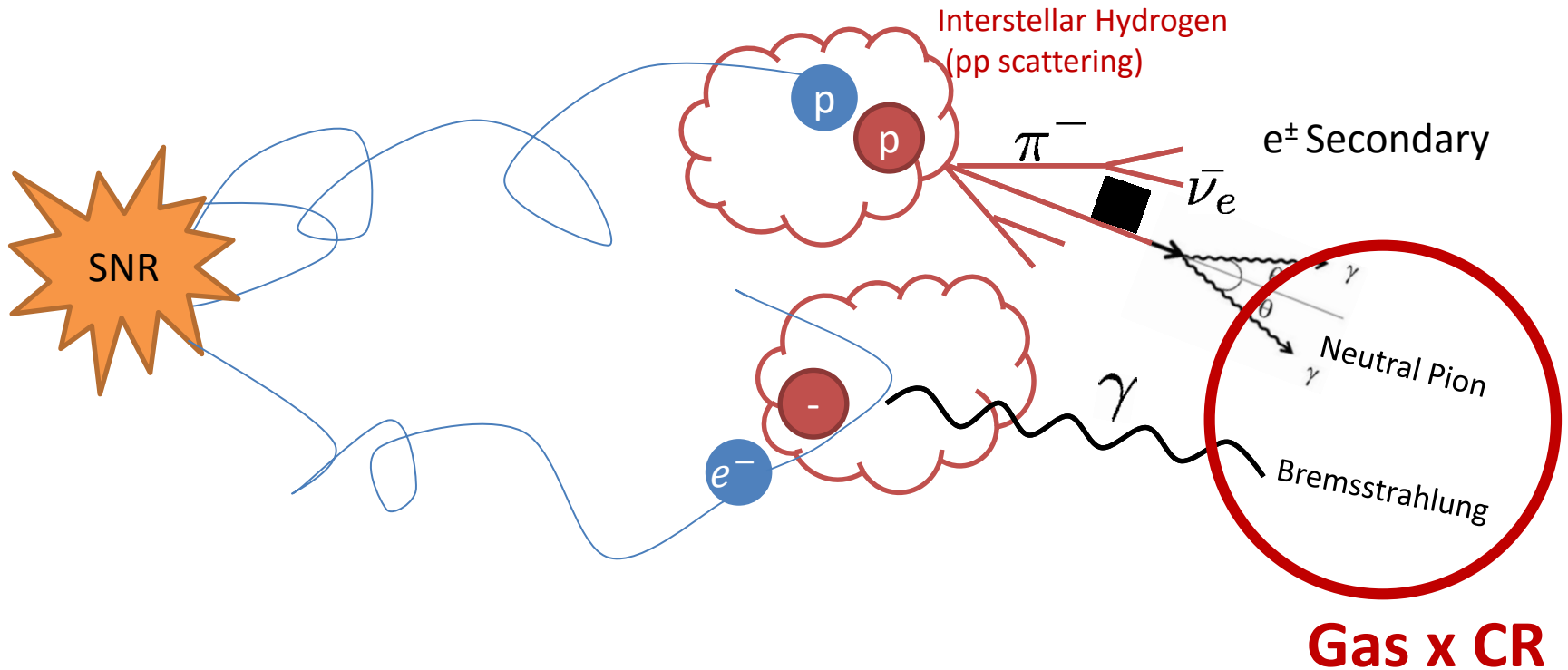
Are models of **diffuse** emission
adequate to current **data**?

Ingredients of diffuse emission

Primary Source
Injection

CR Transport

Gamma-Ray Generation



All groups that find an excess **assume:**

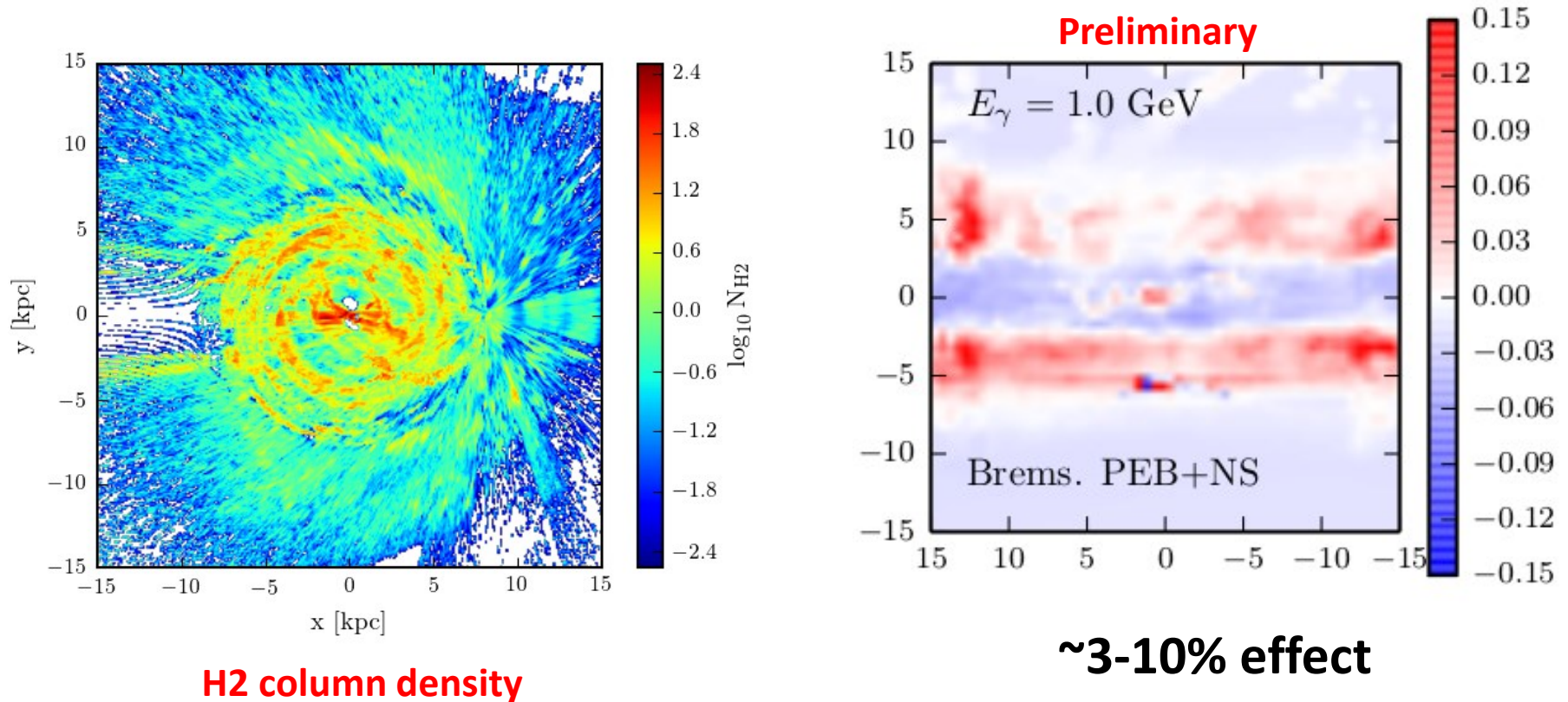
- 1. 2-D Gas Density Distribution**
- 2. 2-D Cosmic-Ray Propagation**
- 3. Steady State**
- 4. Simplistic Cosmic-ray source distribution**

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

Towards the **next generation** of **diffuse** gamma-ray models

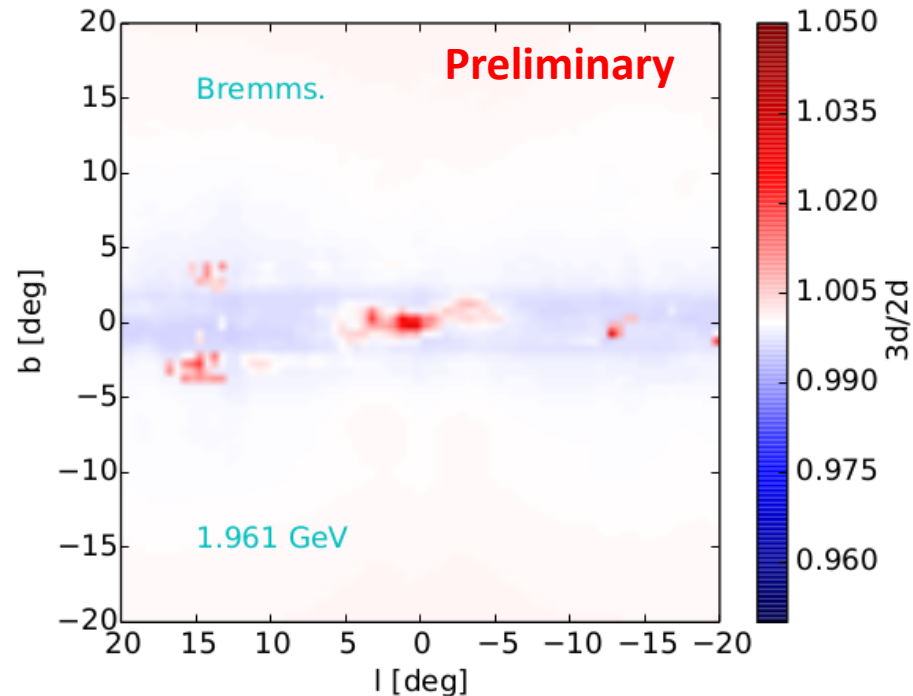
1. **3-D Gas Density** Distribution
2. **3-D Cosmic-Ray** Propagation
3. **Cosmic Ray Bursts/Transients**
4. **Physically** motivated Cosmic-ray
source distributions

1. 3-D Gas Density Distribution



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

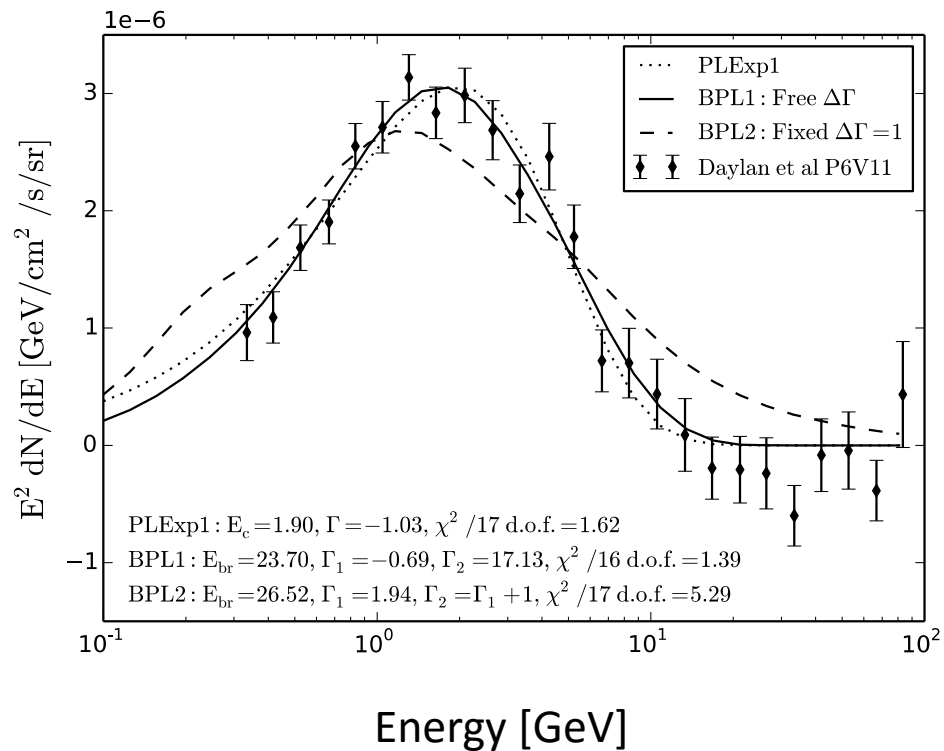
2. 3-D Cosmic-Ray Propagation



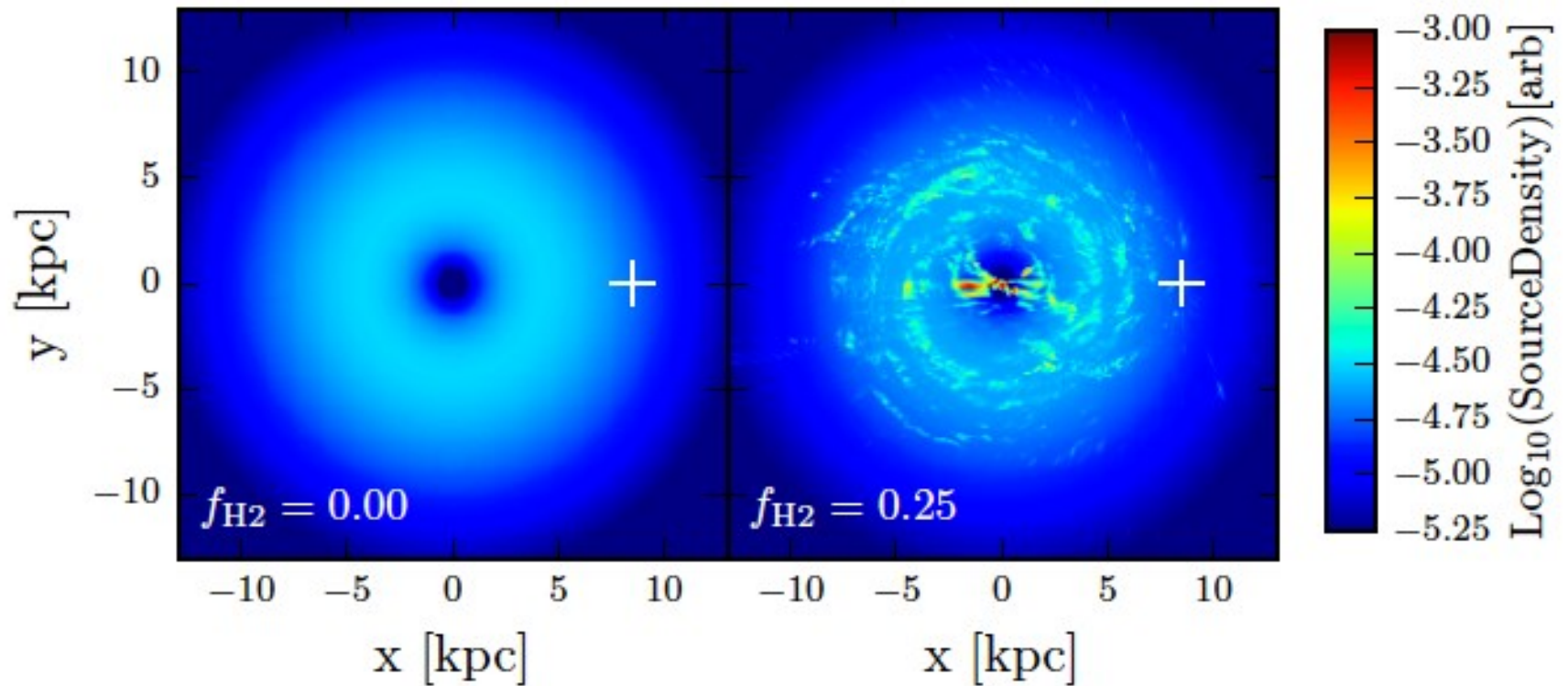
few % effect

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

3. Steady State

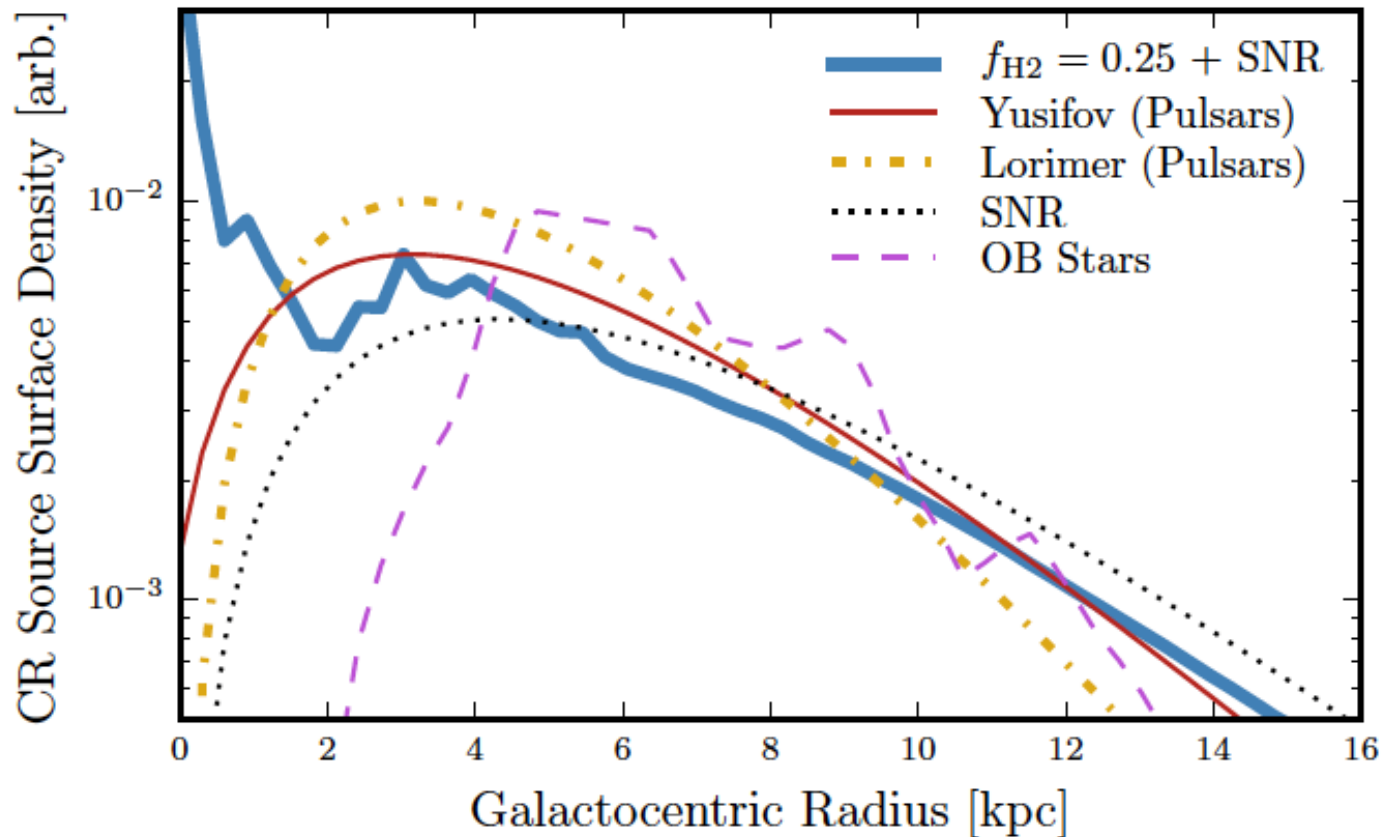


4. **Physically** motivated, **3D** Cosmic Ray source distributions



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

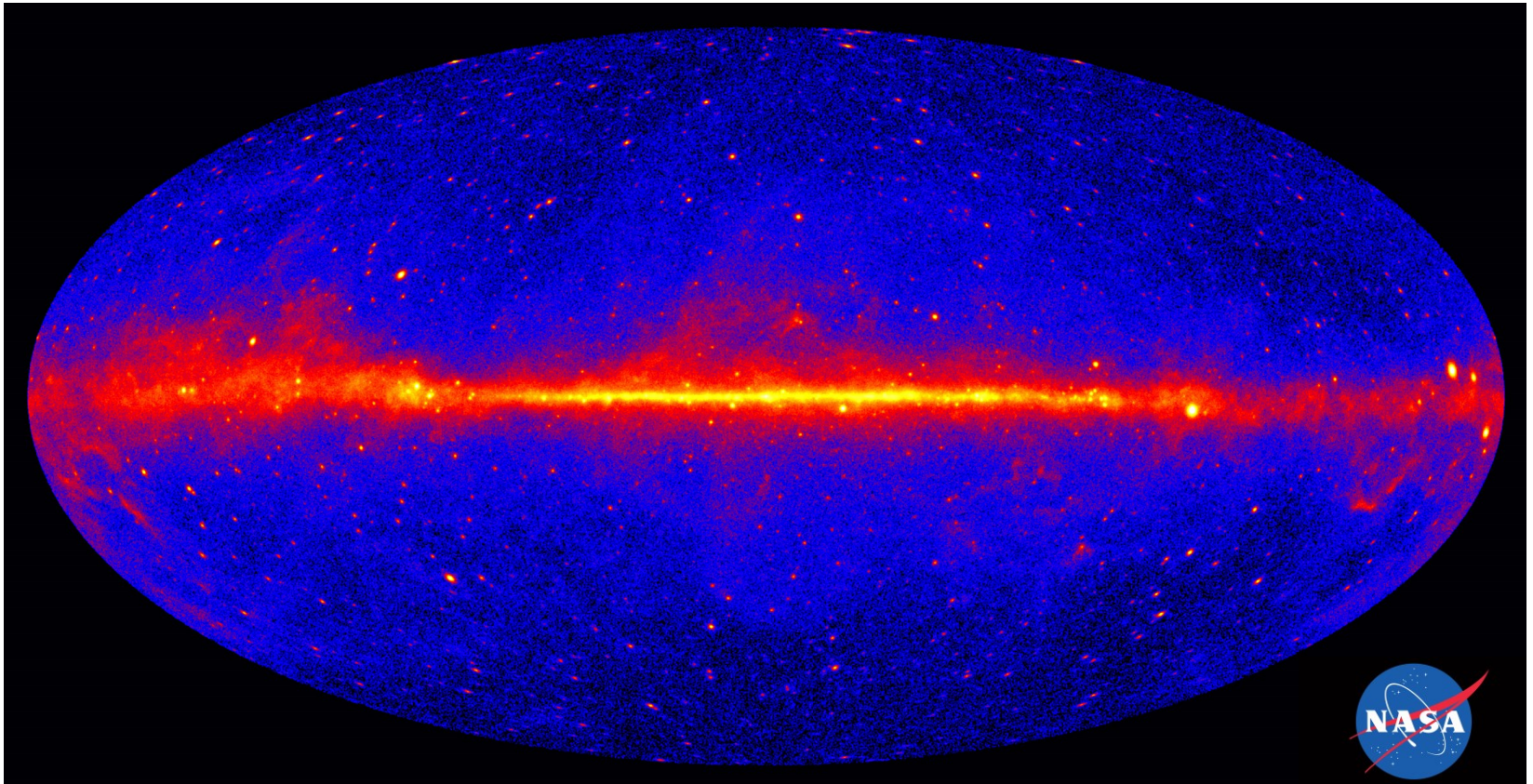
4. **Physically** motivated, **3D** Cosmic Ray source distributions



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

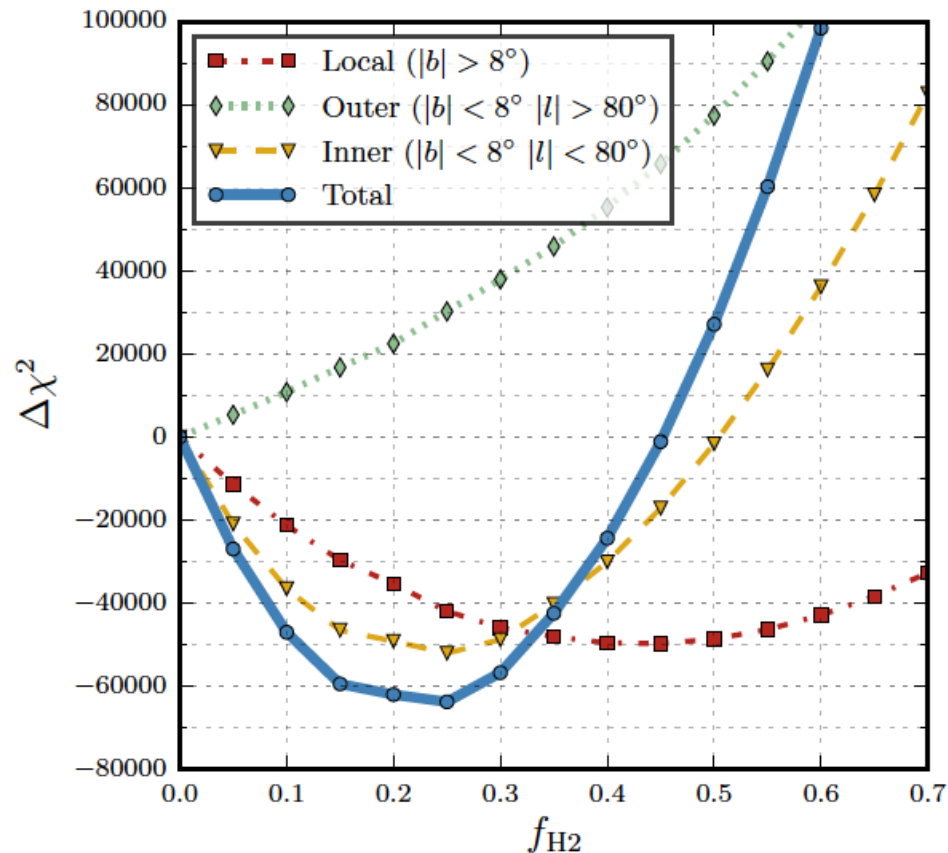
Good to push the (**theory**) **envelope**.

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



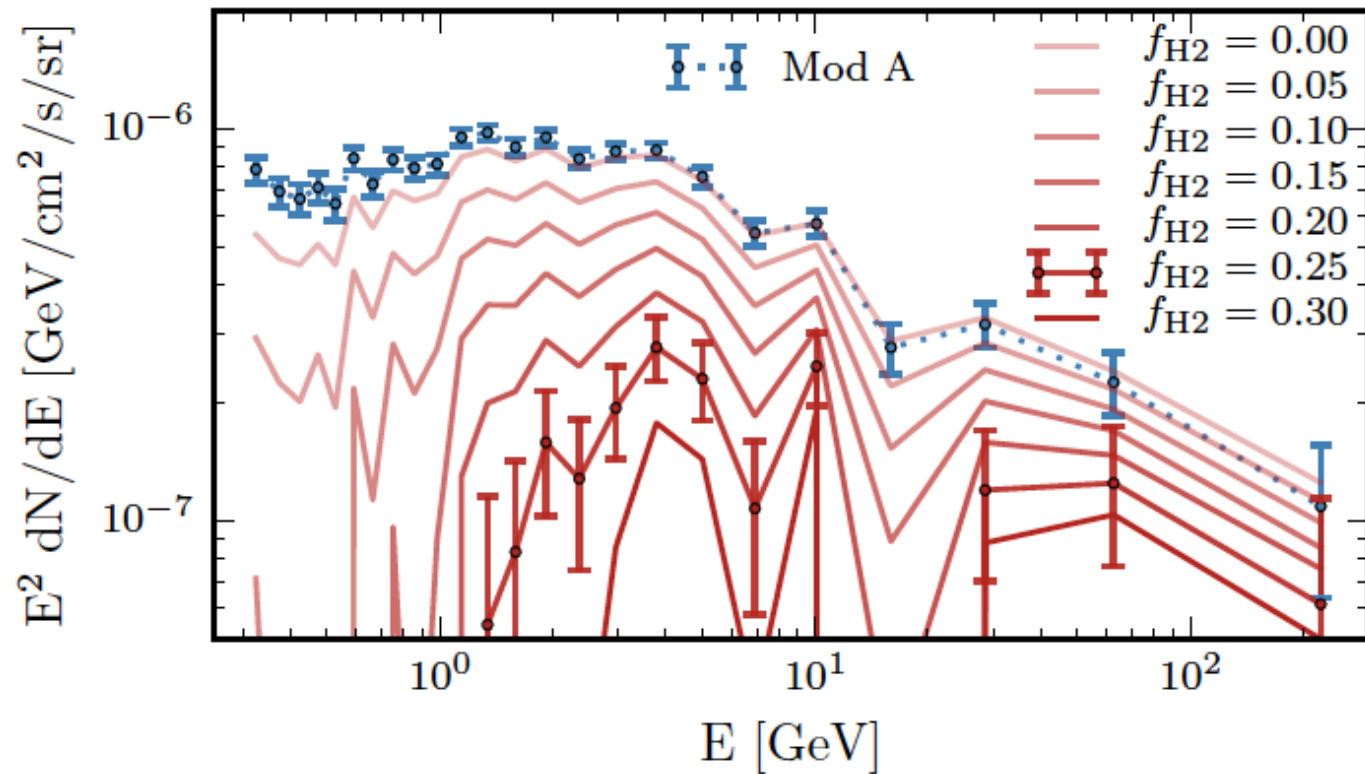
Good to push the (theory) envelope.

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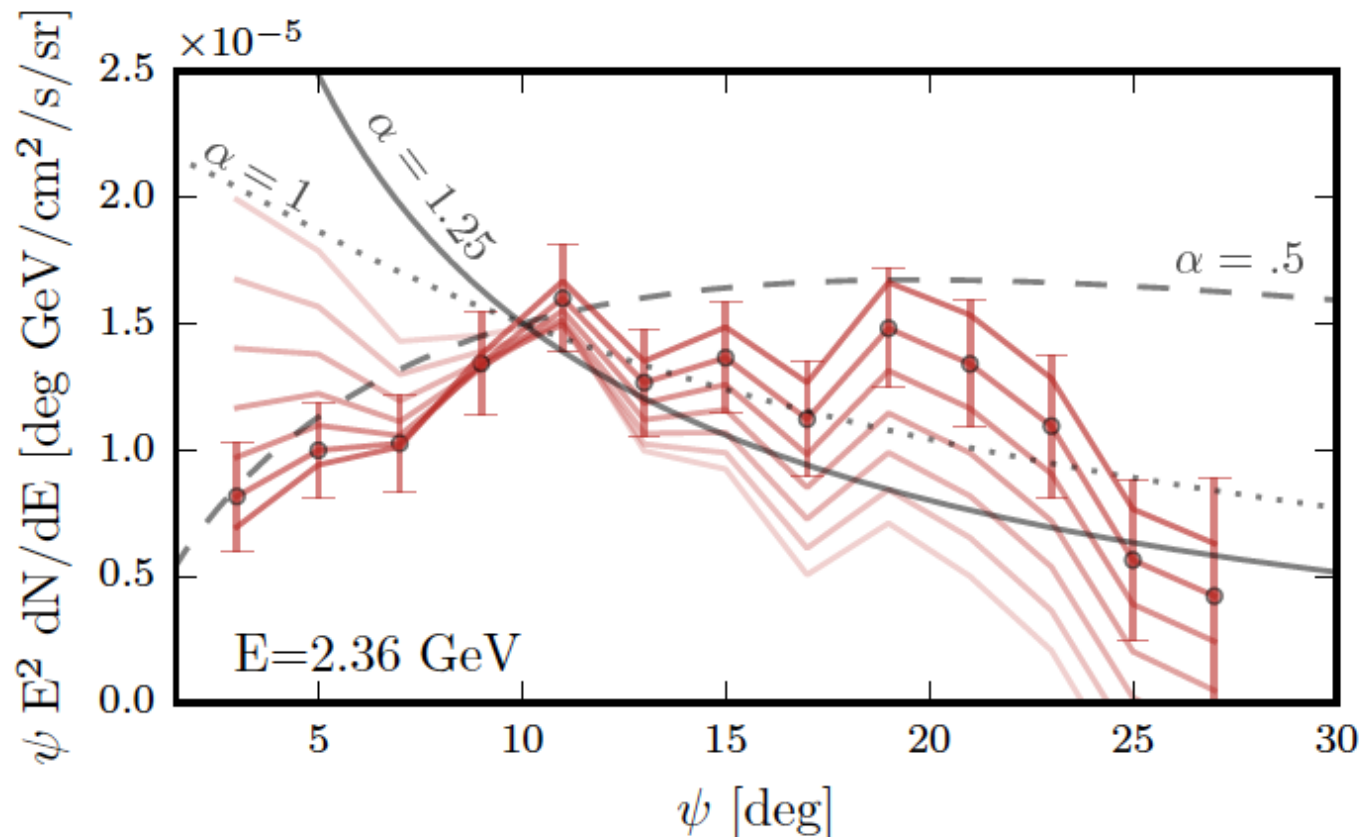
* Carlson, Linden, Profumo 1510.04698, sub. to Phys.Rev.Lett.

What do these **improved models** imply for the Galactic Center “**Excess**”?



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

What do these **improved models** imply for the Galactic Center “**Excess**”?

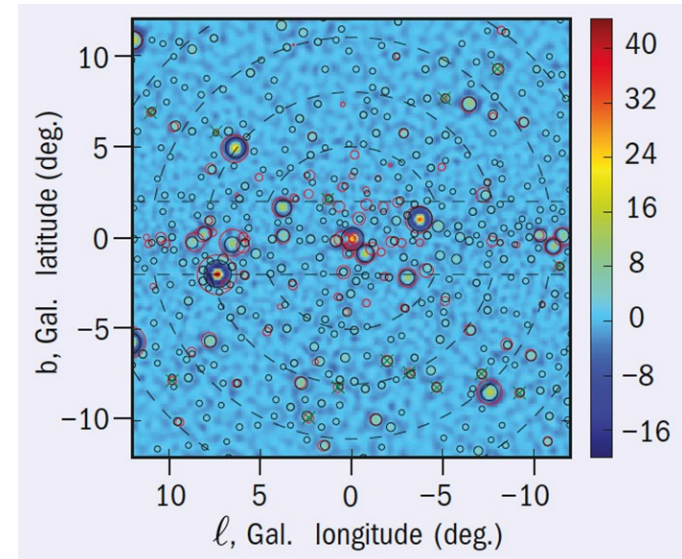


* Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584

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
emission model!



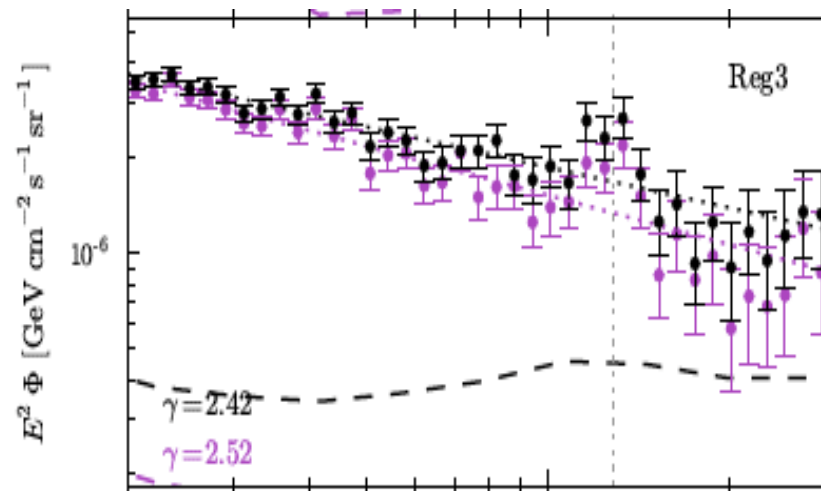
* Bartels et al, 2016, PRL 116 051102, ** Lee et al, 2016, PRL 116 051103

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 monochromatic gamma-ray line
with a diffuse morphology
has no astrophysical counterparts***

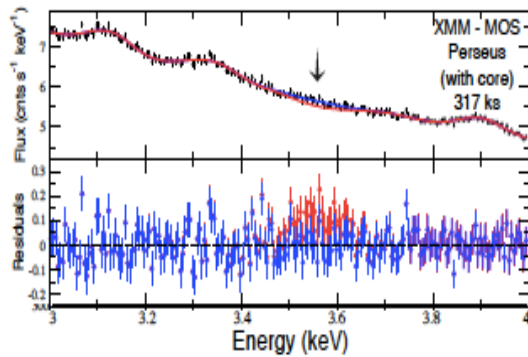
***Carlson, Linden, Profumo, JCAP 2013**



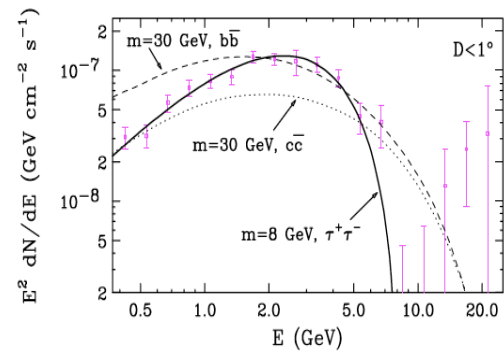
Unfortunately, the 130 GeV line was a
statistical fluke

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

3.5 keV line

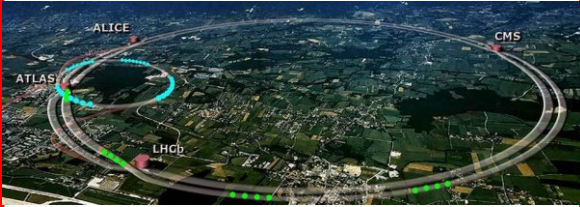


Gamma-ray excess in the Galactic Center

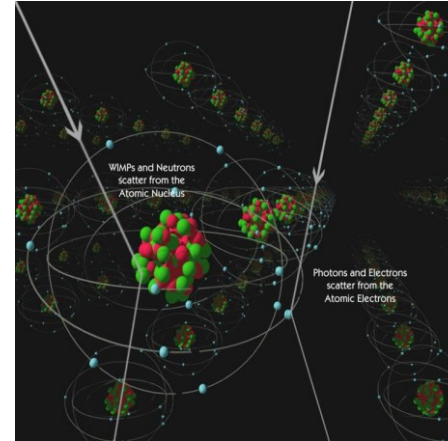


what else, then?

13-TeV LHC



G-2 Direct Detection



Radio Surveys



CTA





...an appropriate adage for
dark matter detection :

“Everything we see
hides **another thing**,

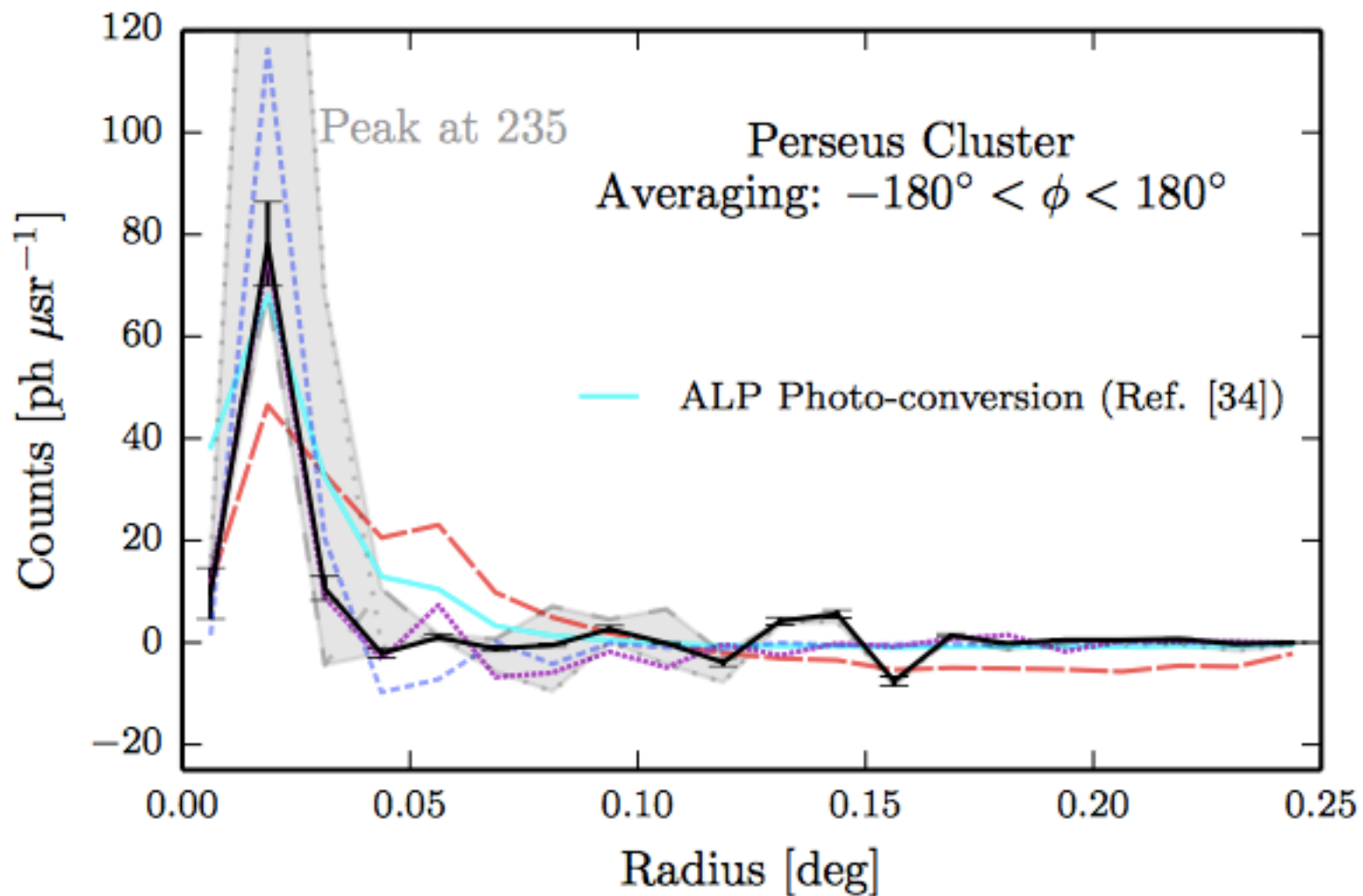
we always want to **see**
what is **hidden**
by what we see”

R. Magritte

The promenades of Euclid

Summary: “Exotic” 3.5 keV line Models

<u>Example Model</u>	<u>Signal Morph.</u>	<u>OK?</u>
Sterile ν	ρ_{DM}	NO (morph, dSph)
axion-like particles (ALP)	$\rho_{\text{DM}} \times B^2$	Yes! (but weak link to DM)
Plasma-Excited Dipole	$\rho_{\text{DM}} \times \rho_{\text{gas}}$	Yes! (and OK thermal relic!)



axion-like particles survive the morphology test
decaying DM strongly disfavored

much hype (~300 papers) for the
discovery of a 3.5 keV X-ray line



Mysterious X-rays Might Hint at Dark Matter

By: Monica Young | July 8, 2014



Boffins say dark matter found with X-ray

light on dark matter

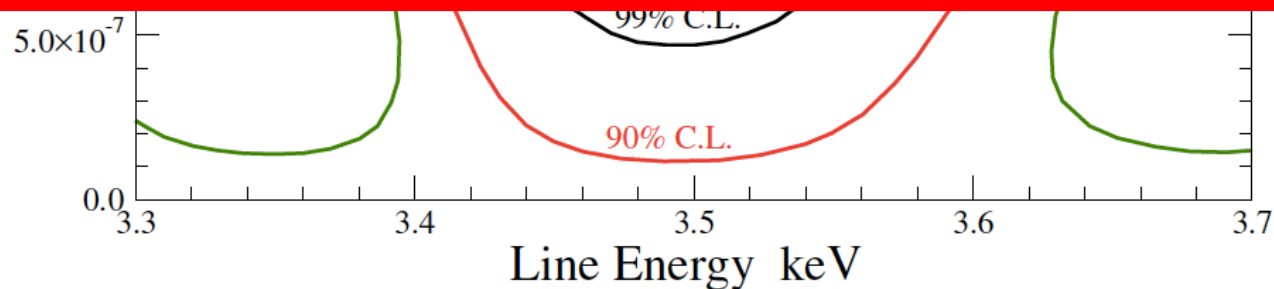
By Brian Dodson
March 10, 2014

gizmag

- **no signal** from dedicated **1.4 Ms**
XMM observation of **Draco dSph***

An example of a **zealous Referee**:

"Finally, I would like to let you know that, after I was asked to referee this paper, I decided to **download the data and examine the spectrum myself**. I largely agree with your conclusions regarding the **absence of a notable feature at ~3.5 keV**, as well as your **limits** on the line flux in this region."



* Jeltema and Profumo, MNRAS (2015)