THREE (+) EXCEPTIONS FOR THERMAL DARK MATTER

AND THE 130 GEV FERMI LINE

Based on 1208.0009 with S. Tulin and H. Yu

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EVIDENCE FOR DM OVERWHELMING

All evidence points toward







HOW DARK IS DARK MATTER?

• Which probe is the most constraining?



SEARCH VIA ANNIHILATIONS

How do we get photons from DM annihilation?



1. Direct



2. Final State Radiation



3. Inverse Compton

A FERMI LINE?



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A FERMI LINE(S)?



A SYSTEMATIC?





Finkbeiner and Weniger

A SYSTEMATIC?

	23.0 - 24.6 GeV		24.6 - 26.3 GeV		26.3 - 28.1 GeV		28.1 - 30.1 GeV		30.1 - 32.2 GeV
15	Nγ= 2.53 TS= 0.56	15	Nγ= 0.00 TS= 0.00	15	Nγ= 7.65 TS= 4.45	15	Nγ= 0.00 TS= 0.00	15	Nγ= 0.00 TS= 0.00
10		10		10		10		10	
5		5		5		5		5	
5		5		5		5		5	
0		0 2	0 10 0 -10 -2	0	0 10 0 -10 -2	0	0 10 0 -10 -2	0	0 10 0 -10 -20
15	32.2 - 34.5 GeV	15	34.5 - 36.9 GeV	15	36.9 - 39.5 GeV	15	39.5 - 42.2 GeV	15	42.2 - 45.2 GeV
	Nγ= 0.00 TS= 0.00		Nγ= 0.00 TS= 0.00		Nγ= 0.00 TS= 0.00		Nγ= 0.00 TS= 0.00		Nγ= 2.15 TS= 0.72
10		10		10		10		10	
5		5		5		5		5	
			M		A.,				Abo, al m
20	0 10 0 -10 -2	0 2	0 10 0 -10 -2	0 20	0 10 0 -10 -2	0 2	0 10 0 -10 -2	20 2	0 10 0 -10 -20
15 p	45.2 - 48.4 GeV	15	48.4 - 51.7 GeV	15	51.7 - 55.4 GeV	15	55.4 - 59.2 GeV	15	59.2 - 63.4 GeV
10	Nγ= 1.07 TS= 0.20	10	Νγ= 0.00 ΤS= 0.00	10	Νγ= 0.00 ΤS= 0.00	10	Νγ= 3.72 15= 3.27	10	$N\gamma = 1.81$ $IS = 0.94$
		10		10		10		10	
5		5		5		5		5	
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20	0 10 0 -10 -2 63.4 - 67.8 GeV	20 2	0 10 0 -10 -2 67.8 - 72.6 GeV	0 20	0 10 0 -10 -2 72.6 - 77.7 GeV	0 2	0 10 0 -10 -2 77.7 - 83.1 GeV	20 2	0 10 0 -10 -20 83.1 - 88.9 GeV
15	Nγ= 0.37 TS= 0.04	15	Nγ= 1.12 TS= 0.63	15	Nγ= 1.41 TS= 0.80	15	Nγ= 0.90 TS= 0.45	15	Nγ= 0.00 TS= 0.00
10		10		10		10		10	
5		5		5		5		5	
0	boll to all and the	0		0	All rom A Ander	0		0	
15.0	88.9 - 95.1 GeV	15	95.1 - 101.8 GeV	150	101.8 - 108.9 GeV	151	108.9 - 116.6 GeV	1 1 5	116.6 - 124.7 GeV
13	Nγ= 0.00 TS= 0.00	13	Nγ= 1.17 TS= 0.88	13	Nγ= 0.00 TS= 0.00	13	Nγ= 3.73 TS= 7.73	15	Nγ= 0.00 TS= 0.00
10		10		10		10		10	
5		5		5		5	.Л	5	
0 E 20) 10 0 -10 -2	0	0 10 0 -10 -2	0	0 10 0 -10 -2	01	0 10 0 -10 -2	0202	0 10 0 -10 -20
15	124.7 - 133.4 GeV	15	133.4 - 142.8 GeV	15	142.8 - 152.8 GeV	15	152.8 - 163.5 GeV	15	163.5 - 174.9 GeV
10	Nγ= 10.31 TS=32.66	10	Nγ= 0.83 TS= 0.58	10	Nγ= 0.00 TS= 0.00	10	Nγ= 0.00 TS= 0.00		Nγ= 0.00 TS= 0.00
10	ĥ	10		10		10		10	
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20) 10 0 -10 -2	0 2	0 10 0 -10 -2	0 20	0 10 0 -10 -2	0 2	0 10 0 -10 -2	20 2	0 10 0 -10 -20

Finkbeiner and Su

SHOULD WE BUILD MODELS FOR THE FERMI LINE?

- Unlikely a statistical fluke
- However, like other Gaussian anomalies, we learn about models of DM by MR being faced with an Unconventional anomaly
- Take the line seriously and see what it takes to build a model

Models	Before trials	After trials (one line)
Gaussian (centered)	5.0σ	3.7σ
aussian (off center, $\theta > 40^{\circ}$)	5.5σ	3.7σ
unbinned ℓ	5.2σ	3.2σ
unbinned $\ell \ (\theta > 40^{\circ})$	4.9σ	2.8σ
unbinned b	4.8σ	3.5σ
unbinned $b \ (\theta > 40^{\circ})$	4.6σ	3.2σ
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ
- NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ
Einasto (off center)	6.6σ	5.1σ

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WHAT DOES A MODEL FOR THE FERMI LINE DO?

- Avoid continuum constraints
- Give a *large* rate
- Obtain correct relic density (if interested in thermal DM)

1. AVOID CONTINUUM CONSTRAINT

 DM doesn't carry a charge; coupling to photons comes through loops of charge particles



Cut the loop and you get continuum photons

1. AVOID CONTINUUM CONSTRAINT





2. Final State Radiation 3. Inverse Compton

• Annihilation to charged states dominates by $\frac{R_{SM}}{R_{\gamma\gamma}} \sim (\pi/\alpha)^2 \approx 10^5$







$$R^{\rm th} \equiv \frac{\sigma_{\rm ann}}{2\,\sigma_{\gamma\gamma} + \sigma_{\gamma_Z}}$$

 $R_{\rm wino}^{\rm th} \simeq 200$ and $R_{\rm Higgsino}^{\rm th} \simeq 700$



 However, p-wave does not allow one to obtain thermal DM v ~ 0.3
⟨σv⟩_{tree,p-wave} ~ 10⁻²⁷ cm³/s × 10⁵ × 0.3² ≠ 3 × 10⁻²⁶ cm³/s

THREE EXCEPTIONS

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- Some way to:
 - suppress continuum photons
 - obtain the observed abundance of DM



If we believe Hooper's results, then even if winos are only about 1/10 of all the dark matter there is some tension with the galactic center, and the corresponding photon lines would be at the 10^{-28} cm³/s level, too small to explain the observation. The suggestion of Acharya et al. [?] is then **ruled out**, in an especially decisive way if Hooper's bound is correct.

Direct detection: Any dark matter that a minipilate to γ of γZ can in principle show a photon sin direct-detection experiments through either a loop process (exchanging two photons or a photon and a Z with the nucleus) or the $2 \rightarrow 3$ process $\chi N \rightarrow \chi N \gamma$. However, these will typically be small enough that there is no limit (in fact, they may be small enough that the neutrino background swamps any possible detection, possibly with the exception of directional direct detection). Estimates for a particular model appear in [?], and are several orders of magnitude below the current limits

I expect that any model consistent with Hooper's tree-level continuum gamma-ray constraints will also be safe, or at worst borderline, from direct detection through Higgs exchange. Can we make this statement more precise? This is interesting even independent of the gamma-ray line, since it suggests that ferm IAD is toing roughly as Well as Xenon at constraining models.

Neutrinos: Annihilation to Z bosons in the sun lead to a flux of neutrinos that may be detectable on Earth. What are the numbers? Edit: I think it's hopeless but still abundance of should maybe write down some numbers.

$$x \dots f$$

Figure 3: Illustrating the role of charge particles in arguments about the γ -ray line.

3. Asymmetric Dark Matter

Buckley, Hooper Bai, Shelton Fan, Reece

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EXCEPTION 1: COANNIHILATION



- Relic density set by annihilation with heavier state; relic abundance fixed by mass splitting
- Heavier state not present today; must annihilate through virtual state
- Natural example is dipole moment

EXCEPTION 1: COANNIHILATION

$$\mathscr{L}_{\text{int}} = \frac{\mu_{\gamma}}{2} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 F_{\mu\nu} + \frac{\mu_Z}{2} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 Z_{\mu\nu}$$

Natural place to look is in monopoles







EXCEPTION 1: COANNIHILATION

• Other toy models are realizable



 $\mathscr{L}_{\text{int}} = \bar{\chi}_2(g_S + g_P\gamma_5)\chi_1\phi + \bar{f}(g'_S + g'_P\gamma_5)f'\phi + \text{h.c.}$

EXCEPTION 2: FORBIDDEN CHANNELS

- Make the charged particle in the loop heavier than the DM
- No direct annihilation; avoid continuum constraints
- Dial neutral-charged mass splitting to obtain correct relic abundance

EXCEPTION 2: FORBIDDEN CHANNELS

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EXCEPTION 3: ASYMMETRIC DARK MATTER

- Stop the annihilation in the early universe dead in its tracks: remove the antimatter
- How do we regain annihilations today? Oscillations!

Matter Anti-Matter



Dark

OSCILLATING ADM

- Asymmetry may be erased
- Any violation of DM number can lead to darkanti-dark oscillations
- Like ν oscillations
- Become important when³ mass exceeds Hubble expansion



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EXCEPTION 3: ASYMMETRIC DARK MATTER

- Still need to suppress continuum today
- Make use of p-wave





^[6] E Aprile at al [YENON100 Collaboration] "Dark Matter Results fro

EXCEPTION 5: INTERNAL BREMSTRAHLUNG

 Photon from IB can look nearly monochromatic





0.01

0.02

0.05

0.10

0.20

 $x = E / m_{\chi}$

0.50

1.00

2.00



• With IB photon, it becomes s-wave

SUMMARY

- Fermi line: compelling signal for DM or a systematic?
- General take home message: not very difficult to construct models that fit this feature, though MSSM-type models must be very particular
- Good news: experimentally resolvable on a short time scale