Gamma-ray lines in the Fermi-LAT data?

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Gamma-ray lines are traditional smoking gun signatures for dark matter annihilation in the Universe. In regions optimized for large signal-to-noise ratio, we identified a signal candidate for a gamma-ray line at energies around 130 GeV with a post-trials significance of $3 \sigma$. Spectral and spatial properties are not inconsistent with a dark matter signal. One year has passed since the initial papers, and I give here a brief summary and an update on the status of the 130 GeV feature in the un-reprocessed P7 gamma-ray data of the Fermi-LAT.

1. Introduction

One of the main challenges in searches for a signal from dark matter annihilation is the signal-background discrimination. The dark matter signal is expected to be faint in most scenarios, and often much weaker than the systematic uncertainties associated with the Galactic diffuse emission and unresolved point sources. Smoking-gun signatures like gamma-ray lines, or related sharp features from internal Bremsstrahlung processes or cascade decays, could hence become the cornerstone for an unequivocal disconfirmation Bremsstrahlung processes or cascade decays, could hence become the cornerstone for an unequivocal discovery of a dark matter signal in the gamma-ray sky.

Our recent identification of a line-like feature with a post-trials significance of $3 \sigma$ around energies of 130 GeV in the Galactic center data of the Fermi Large Area Telescope (LAT) (Bringmann et al. [2012] and Weniger [2012]) gave rise to a large number of papers, studying possible explanations in terms of dark matter annihilation, mono-energetic pulsar winds (Aharonian et al. [2012]), and instrumental effects (Finkbeiner et al. [2013], Hektor et al. [2012], Whiteson [2012, 2013]). The signal candidate was subsequently confirmed independently by Tempel et al. [2012] and Su and Finkbeiner [2012a] (for a recent review on indirect dark matter searches with gamma rays see Bringmann and Weniger [2012]).

In this proceedings contribution, I will briefly summarize the results from the initial analysis and some of the follow-up work in section 2, give an update in section 3 and conclude in section 4.

2. Identification and developments

Most searches for gamma-ray lines from WIMP (weakly interacting massive particle) annihilation are technically a shape analysis of the gamma-ray flux measured in regions of interest (ROIs) with a large signal-to-noise ratio for dark matter signals. The spectral analysis is usually confined to a small energy range around the line energy of interest, such that the smooth background spectra can then be approximated by a single power-law. The basic idea is here to trade systematic uncertainties in the background flux for statistical errors.

In Bringmann et al. [2012], Weniger [2012], we used an adaptive method to find ROIs optimized for different profiles of the Galactic dark matter halo. As template for the background morphology, we took the gamma-ray flux measured at 1–20 GeV; for a given dark matter signal profile, the optimal ROI was than uniquely determined using a simple deterministic algorithm that optimizes the signal-to-noise ratio. For non-cored dark matter profiles, these ROIs take roughly the shape of an hourglass. One of these ROIs (for a slightly contracted profile) is shown in the left panel of Fig. 1 by the black line (c.p. Weniger [2012]).

The differential flux of gamma rays measured in this ROI is shown in the right panel of Fig. 1. Already by eye, one can identify a surprisingly clear line-like excess at energies around 130 GeV. The two solid lines to the right represent a power-law only (power-law + line signal) fit to the data, restricted to the energy range 80–210 GeV. The formal significance for a line feature was found to be $4.6 \sigma$ (Weniger [2012]; even higher $> 5 \sigma$ significances were found in the template analysis by Su and Finkbeiner [2012a]). To illustrate the sharpness of the feature, the gray dotted line at the left shows a spectrum with super-exponential cutoff; the gray dashed line shows the inverse Compton scattering (ICS) radiation generated by a mono-energetic electron population, scattering with star light at the Galactic center. Even this highly idealized ICS emission is disfavoured w.r.t. to a monochromatic gamma-ray line by about $3 \sigma$ (with $TS \approx 12$ instead of $TS \approx 21$ for the line).

If the 130 GeV signature is interpreted as a gamma-ray line produced by dark matter annihilation via $\chi\chi \to \gamma\gamma$, the corresponding line from $\chi\chi \to \gamma Z^0$ would be expected at a gamma-ray energy of $\approx 114$ GeV, though the strength of this line would be model dependent. Indeed, weak indications for such a second line at the $1\sigma–2\sigma$ level were found by different groups (see e.g. Su and Finkbeiner [2012a], Bringmann and Weniger [2012], Rajaraman et al. [2012]). Furthermore, it was found that the signature is extended and roughly compatible with the flux profile expected from a conventional NFW or Einasto dark matter profile (see Bringmann and Weniger [2012]). At the very center, however, the signature appears to be displaced from the Galactic center.
with a significance of about 3σ. Data exhibits a gamma-ray line feature at 130 GeV in low-incidence angle test regions, like the Galactic disk. However, the same signature was not found in other regions. This could point towards an instrumental effect generating 130 GeV lines.

Most interestingly, it was found (Finkbeiner et al. [2013], Hektor et al. [2012], Bloom [2012]) that the observational profile of the LAT does not change significantly, no consistent interpretation of the Earth limb line and the Galactic center line in terms of an instrumental effect has emerged yet. A further possible line signature at 130 GeV was found recently by Whiteson [2013] in a 5° region following the Sun.

Formally, and before trials, the most significant feature is the line at the Galactic center. Given the completely different nature of the various targets, it seems rather unlikely that all these signatures have a common instrumental or physical origin (for an in-depth discussion of some of the possible instrumental effects see Finkbeiner et al. [2013]). In any case, there is no way around waiting for additional data to see which of these signatures, if any, are real effects and which are statistical flukes in light of a large number of hidden trials.

3. Updates

Given the best-fit values for the gamma-ray line flux as determined from data taken until the 8th of March 2012 (as in Weniger [2012]), one can easily project how the signal significance should evolve as more data is added. On average, since we are in the background limited regime, the accumulated significance in units of Gaussian sigma should grow like $x(t) = \sqrt{t/t_0}$ in case of a true signal, and fall like $x(t) = x_0 \sqrt{t_0/t}$ in case of a statistical fluke; here $x_0$ is the significance measured at time $t_0$. Using the Gaussian approximation, the 68%CL error bands around this mean trend can be estimated analytically in case a signal is present.
and read
\[
x_{\text{real}}(t) = x_0 \sqrt{\frac{t}{t_0}} \pm \left[ \left( 1 + \frac{S}{B} \right) \left( 1 - \frac{t}{t_0} \right) \right]^{\frac{1}{2}}
+ x_0^2 \left( \sqrt{\frac{t}{t_0}} - \sqrt{\frac{t}{t_0}} \right)^2 \left( \frac{\Delta S}{S} \right)^2.
\]  
(1)

In the present case, the signal-to-background ratio is \( S/B \approx 35\% \), and \( \Delta S/S \approx 25\% \) is the statistical uncertainty of the measured line flux. If the signature is a statistical fluke, the expression reads instead just
\[
x_{\text{fluke}}(t) = x_0 \sqrt{\frac{t}{t_0}} \pm 1 - \frac{t}{t_0}.
\]  
(2)

In Fig. 2, we show how the accumulated significance of the signature evolved over time (black solid line). In the fit, we fixed the gamma-ray line energy to \( E_\gamma = 129.8 \) GeV, and the fits are performed in an energy range 65–260 GeV, which is slightly larger than in previous studies and gives higher statistical power (we obtain similar results for e.g. 40–400 GeV). As cut in \texttt{gtmktme} we take \texttt{DATA\_QUAL==1} like in Weniger [2012], but checked that using the recommended \texttt{DATA\_QUAL==1 && LAT\_CONFIG==1 && ABS(ROCK\_ANGLE)<52} instead does not significantly affect our results. The vertical bar indicates the 8\textsuperscript{th} of March 2012, which we use here as a starting point for a new trial-free measurement. We show results for the ROIs Reg3 and Reg4 which gave the highest significances in Weniger [2012], and for \texttt{P7CLEAN\_V6} (top) and \texttt{P7SOURCE\_V6} (bottom) class events. Data until the 22\textsuperscript{nd} of February 2013 is taken into account.

In case of \texttt{CLEAN} events, the curves are still compatible with a true signal at the 95\%CL, although the trend is clearly more pointing towards a statistical fluke. For \texttt{SOURCE} class events, the situation is
similar, although here the trend is less pronounced and the current significance lies exactly between the expectations for a fluke and a signal. We caution not to overinterpret these figures: A decrease of the significance is possible over a short period of time even for a real signal. But, if the significance continues to drop at this rate, 6–12 month of additional data should be enough to disqualify the 130 GeV feature from being a steady monochromatic line on top of a power-law background.

We emphasize that following the time evolution of the significance within the ROIs that were used in the initial analysis (and which were well defined a-priori regions optimized for dark matter searches, without any optimization on the target sample itself) is the cleanest way to access the statistical significance and stability of the signature. It allows a clear prediction for the time evolution of the tentative line signal, free of any hidden trials, and free of ambiguities in choosing ROIs and details of the fitting methods. And with the accumulation of more data, the signature will either pass that test or it will fail.

4. Conclusions

Our recent identification of a line-like signature around 130 GeV in the Galactic center data of the Fermi-LAT raised an enormous interest, as it could be the long awaited smoking gun signature for annihilation of WIMP dark matter particles in the Universe. The signature was independently confirmed by many groups, and numerous studies accessed model-building aspects of the tentative line signal, studied possible instrumental indications, and searched for corroborating evidence from Galaxy clusters and dark matter subhalos.

Since the initial papers, exactly one year has passed by now, and it is time to discuss how the signature evolved during that year. For the ROIs that we used in the early papers, the expected signal event rate is about ~1/month, and one finds clear, trial free and unambiguous predictions for how the signature should behave if it is a real monochromatic line on top of a power-law background. We confront these predictions with the data in Fig. 2. In case of P7CLEAN_V6 events, the time evolution of the accumulated significance clearly points more towards a statistical fluke; in case of P7SOURCE_V6 events, it lies exactly between the expectations for a real signal and a fluke. In all cases, the time evolution is still compatible with a real signal at the 95% CL. However, should the significance continue to drop at the same rate, 6–12 month of additional data will be enough to exclude the possibility of a real gamma-ray line signal with high confidence.

The release of reprocessed P7 data by the Fermi-LAT team is expected to happen soon, and it will allow a fresh look at all aspects of the 130 GeV feature. The Air Cherenkov Telescope HESS-II should be able to confirm or rule out the signature with high significance with less than 100 hours of Galactic center observations [Bergstrom et al. 2012], but results are unlikely to be released before late 2014. The availability of P8 events, based on a set of completely rewritten event reconstruction algorithms for the LAT, is anticipated for later this year. It will likely become a landmark for deciding whether one should give up on the 130 GeV feature, or whether it becomes imperative to further investigate it with dedicated observations of the Galactic center in the upcoming years.

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