Is Dark Matter WIMPy?
Connecting Geneva with the Galactic Center

Sascha Caron
(Nikhef and RU Nijmegen)
Topic of this talk: Is this interesting for particle physics and LHC or not?

Sky map at photon energies at GeV energies visible light has 2-3 eV
Talk is based on:

A description of the Galactic Center excess in the Minimal Supersymmetric Standard Model and the Dark Matter signatures for the LHC and direct and indirect detection experiments

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Sky map at photon energies at GeV energies visible light has 2-3 eV

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(Nikhef and RU Nijmegen)
Where do GeV photons come from?
Short answer: neutral pions
Gamma ray astronomy knows several sources of gamma rays:
Examples: Pulsars, Supernova remnants etc.
Various extragalactical sources only detected with gamma rays, see pie-chart

Pulsar: rapidly rotating neutron star (very dense)
Supernova remnant: Remnant of star collapse
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Sky map at photon energies at GeV energies visible light has 2-3 eV

Astrophysics goal: Understand all sources of gamma rays

\[\Rightarrow\] Subtracting the known sources yields the following inset picture
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Astrophysics goal: Understand all sources of gamma rays

Subtracting the known sources yields the following picture

NASA press release 2014:
The inset is a map of the galactic center with known sources removed, which reveals the gamma-ray excess (red, green and blue) found there. This excess emission is consistent with annihilations from some hypothesized forms of dark matter. Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden (Univ. of Chicago)
What can it be?

- Unknown pulsars ?
- Dark Matter annihilation ?
- Something else ?
DM searches in the inner Galactic region with Fermi LAT

Fermi LAT; $> 1\,\text{GeV}$

Subtract
1) Known point sources
2) Diffuse foregrounds

Do residuals look like this?

By Ch. Weniger (UvA)
Fermi GC excess: First appearance in 2009

First clear statements about properties of excess emission (morphology, spectrum etc., subject to some changes in later analyses):

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough¹ and Dan Hooper²,³
¹Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003
²Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510
³Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm$^3$/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an extra...

First very cautious comments by the LAT team, without any detailed characterization of the residual:

2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

...improved version of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.
Follow-up studies

At the Galactic center (roughly 7deg x 7deg)

Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+ 2014

In the inner Galaxy (roughly |b|>1 deg to tens of deg)

Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014
We adopt here the results from Calore, Cholis, Weniger where the excess emission was studied at latitudes above 2 degree. This region is very sensitive to a dark matter signal, but avoids the much more complicated Galactic center region.

Phenomenological tasks

Astronomy:
¬ Can it be explained by unknown pulsars or other astrophysics source?

Particle Physics:
¬ Is it possible that this is really DM annihilation?
DM Signal Modelling

\[ \chi_1^0 \rightarrow q \tau \gamma \]

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\[ \Pi^0 \rightarrow \gamma \gamma \]

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Model building

• It (early days) it seemed to be that the signal could be described by $\text{DM DM} \Rightarrow \text{bb or tautau}$ with a DM mass of 20-40 GeV
  => Pythia spectrum nicely in agreement with data
• Such process are not possible within ‘minimal SUSY models due to limits on staus and sbottoms (need to be in nMSSM etc., such DM particles hard to test at LHC since they need to be mixed such that they have escaped detection e.g. at LEP)
• It seems to be that such processes have also difficulties from recent dwarf limits on DM => gamma rays
• Actually more parameter space seems to be allowed…
• No MSSM solution… somehow difficult to for model building…

also; P. Agrawal, B. Batell, P. J. Fox, and R. Harnik, WIMPs at the Galactic Center, arXiv:1411.2592.
Fermi-LAT detector

- Formerly known as GLAST
- Particle physics detector
- Photon Conversion
  ⇒ Silicon Tracker for pointing resolution
  ⇒ Calorimeter for energy measurement
- Anticoincidence Detector to remove unwanted charged cosmics
Fermi-LAT detector

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Energy Calibration

- 9% shift measured in test beams not yet understood
- 2-5% shift measured in range 6-13 GeV with

Fermi-LAT conclusion:
"Based on the full body of information currently available we conclude that the energy scale for the LAT is correct to +20-50% of the energy resolution of the LAT at a given energy. This corresponds to an uncertainty of 2-5% on energy scale over the range 10-100 GeV, and increases to 4-10% below 100 MeV and above 300 GeV."

So assuming 5% for the unmeasured region at 3-4 GeV seems reasonable.

We derived effect on energy spectrum, shape changes by up to 20%

Shape uncertainty 3-10%
DM Signal Modelling

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Signal Modelling

Tunes from here:

http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html

Minimal modelling again uncertainty 5-10%!
• Variation of Pythia8 tunes seems to **underestimate** true uncertainty (pi0 production, charge distribution)
Signal Modelling

Adding both effects (MC modelling and energy scale) in squares yields a minimal modelling uncertainty (outside Astronomical uncertainties) of 8-15%.

Changing e.g. only the shape from nominal $E$ to $-5\% \times E$ changes $p$-value for fit from 0.035 to 0.09.
Signal normalization

\[
\frac{d\Phi\gamma(E\gamma)}{dE\gamma d\Omega} = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \frac{dN\gamma}{dE} \int ds \rho_{DM}^2(r(s, \theta))
\]

2 sigma up from nominal

DM density^2 has large uncertainties..

Need to be taken into account

About 1 sigma up
Is there really no minimal Supersymmetry solution?
The Minimal SUSY SM

Remember: This is for almost everybody the most general version you know (126 parameters)....

We are just assuming this:

The MSSM is still the most promising framework for WIMP dark matter.

It is the first to study in my mind.
In this scheme, one assumes that: (i) All the soft SUSY-breaking parameters are real, therefore the only source of CP-violation is the CKM matrix.
(ii) The matrices of the sfermion masses and the trilinear couplings are diagonal, in order to avoid FCNCs at the tree-level.
(iii) First and second sfermion generation universality to avoid severe constraints, for instance, from $K^0$ mixing.

126 parameters can be reduced to 19 which are phenomelogically relevant for DM and direct searches at LHC
The Minimal SUSY SM

126 parameters can be reduced to 19 which are phenomenologically relevant for DM and direct searches at LHC

The 19 remaining parameters are 10 sfermion masses,\(^1\) 3 gaugino masses \(M_{1,2,3}\), the ratio of the Higgs vacuum expectation values \(\tan \beta\), the Higgsino mixing parameter \(\mu\), the mass \(m_A\) of the CP-odd Higgs-boson \(A^0\) and 3 trilinear scalar couplings \(A_{b,t,\tau}\).

\(^1\) \(\tilde{Q}_1, \tilde{Q}_3, \tilde{L}_1, \tilde{L}_3, \tilde{u}_1, \tilde{d}_1, \tilde{u}_3, \tilde{d}_3, \tilde{e}_1\) and \(\tilde{\tau}_3\).
Scanning ? How?

• How to search for a solution?

• => Try random sampling

• Found no solution...

• Idea: Try something more sophisticated...
Iterative Particle Filtering

A filter algorithm (you know the Kalman filter)
Usually used for e.g. “tracking objects” (your new car or drone)

*Idea: importance sampling*

⇒ *Generate recursively more points in interesting regions*

Set of particles
(parameter points)
to represent the
posterior density.
⇒ Particles sampled in regions of higher likelihood...

⇒ Have a look at the MSSM solutions to see how good this actually works...
Our particle filter is implemented in new code to automatically generate layout of photobooks... see www.resnap.com

CREATE A FREE PHOTO BOOK IN 1 MINUTE → Start

www.resnap.com
What do we exactly do?

• Use full machinery of SUSY codes, i.e. Suspect, MicroMegas, DarkSUSY, etc.

• Lightest Neutralino is required to be DM candidate

• LEP limits on the mass of the lightest chargino

• $122 \text{ GeV} < \text{mass(Higgs)} < 128 \text{ GeV}$
  (allowing for SUSY code uncertainty of 3 GeV)

  - Upper limits from the LUX experiment on the spin-independent cross section.

  - Upper limits from the IceCube experiment with the 79 string configuration on the spin-dependent cross section , assuming that neutralinos annihilate exclusively to $W^+W^-$ pairs.
We train the particle filter **only** with the chi2 which compares the GC data with the generated GC spectrum.

\[
\chi^2 = \sum_{i,j} (d_i - m_i)(\Sigma_{ij})^{-1}(d_j - m_j)
\]

**\(\Sigma_{ij}\)** is the covariance matrix with statistical and systematic uncertainties.

Includes the “highly correlated” Astro uncertainties + **10% additional uncertainty** for modelling the spectrum (see before).

**After finding first good fits we constrain the parameter space further to the relevant parameters:**

\[M_1, M_2, \mu, \tan \beta, M_A, \tilde{d}_3, \tilde{Q}_3, A_t.\]
24 degrees of freedom
Signal Modelling

\[
\begin{align*}
\chi_1^0 & \rightarrow W^- \\
\chi_1^+ & \rightarrow W^+ \\
\chi_1^0 & \rightarrow W^+ \\
\chi_1^- & \rightarrow W^-
\end{align*}
\]
Signal Modelling

Shown are only Astronomy uncertainties which are highly correlated.

➔ P-value of this fit : **0.3-0.4**
3 solutions

A) Maximum P-value = 0.35: A Bino-Higgsino neutralino with mass 84-92 GeV as DM annihilating into W+W-

B) Maximum P-value ≈ 0.13: A Bino-Wino-Higgsino neutralino with mass 85-100 GeV as DM annihilating into W+W-

C) Maximum P-value ≈ 0.05: A (mainly) Bino neutralino with mass about 170-200 GeV as DM annihilating into top pairs
OK, they must have been excluded already by LHC searches?
No !!!

Carefully checked
All 3 solutions!

None of them is excluded by LHC

Solutions also consistent with all precision measurements
OK, let’s look at more properties
Dwarf galaxies...

Our solutions are not excluded...
Relic Density MSSM

Figure 2: Dark Matter relic density $\Omega_c h^2$ obtained from the 19 parameter pMSSM models compared with the accepted region. The number of models is shown as a function of $\Omega_c h^2$. 
Relic Density best fit points

.... My legs became a bit shaky to be honest...we did not include this in the fit!
Impressive to find such located solutions... constrained by Higgs mass...
Particle Filter locates regions which are $10^{-20}$ of phase space
What can we do now?

LUX?

Xenon1T?
What can we do now?

Best WW Solution will be tested with Icecube upgrade
What can we do now?

- All 3 solutions give extremely precise forecasts for LHC

Monojets

Higgs+DM
Monojets

• Bino Higgsino
  ➔ Should be testable with 50fb-1 at 14 TeV
• Bino Wino Higgsino
  ➔ Difficult... but almost only chance, need to check
• Stop pairs...?

  ➔ Better new dedicated search dedicated to small (but not too small) compression, e.g. soft leptons + Monojet?
Higgs + DM

• Both WW solutions have very constrained neutralino/chargino parameters...

Heavy neutralino 3 and 4 will be 400-600 GeV and decay via $Z$, Higgs or $W + DM$

→ Strengthen Higgs + DM searches

Higgs, di-Higgs and tri-Higgs production via SUSY processes at the LHC with 14 TeV

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Summary:

Is this all by pure chance?

LHC can tell us... if we try...

Need manpower
For massless quarks, the longitudinal component of the energy carried by a hadron formed in the string-breaking process string → hadron + string' is governed by the Lund symmetric fragmentation function:

\[ f(z) \propto \frac{z^{(a_i-a_j)}(1-z)^{a_j}}{z} \exp \left( \frac{-bm_\perp^2}{z} \right), \tag{3} \]

where \( z \) is the energy carried by the newly formed \((ij)\) hadron, expressed as a fraction of the (light-cone) energy of the quark (or antiquark) endpoint, \( i \), of the fragmenting string. (The remaining energy fraction, \((1-z)\), goes to the new string' system, from which another hadron can be split off in the same manner, etc., until all the energy is used up.) The transverse mass of the produced \((ij)\) hadron is defined by \( m_\perp^2 = m_{\text{had}}^2 + p_{\perp,\text{had}}^2 \), hence heavier hadrons have harder spectra. The proportionality sign in eq. (3) indicates that the function is to be normalized to unity.
New gamma projects in space

- **AstroGam**: 300 KeV- GeV (Proposal to ESA for M4)

- **Gamma-light**: (Proposed to ESA but not approved)
  [Link](http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267)

- **Gamma-400**: launch foreseen by 2020
  100 MeV - 3 TeV, an approved Russian γ-ray satellite. Energy resolution (100 GeV) ~ 1 %, Effective area ~ 0.4 m². Angular resolution (100 GeV) ~ 0.01°.
  [Science with Gamma-400 Workshop](http://cdsagenda5.ictp.it/full_display.php?ida=a1311)

- **DAMPE**: Satellite of similar performance as Gamma-400.

- **HERD**: Instrument on the planned Chinese Space Station.
  Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m². Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

- **PANGU**: suggested as a candidate for the joint small mission between the European Space Agency (ESA) and the Chinese Academy of Science (CAS)
  [arXiv:1407.0710](http://arxiv.org/abs/1407.0710) (performances similar to Gamma-Light)