Searching for Dark Matter in Distant Galaxies

Nick Rodd

To appear (very soon!) w/ Mariangela Lisanti, Siddharth Mishra-Sharma, and Ben Safdi

TeVPA
9 August 2017
OUTLINE

Galaxy groups (this work)
- 95% containment
- 68% containment
Galaxy groups, no boost
Fermi dwarfs (2016)

Preliminary
Fermi Galaxy Groups
Tully Catalogs, $\bar{b}$

Thermal relic cross section

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1. GCE and Dwarf limit

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$\langle \sigma v \rangle$ [cm$^3$ s$^{-1}$]

$m_\chi$ [GeV]
1. GCE and Dwarf limit

2. How to set limits w/ galaxy catalogs

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1. GCE and Dwarf limit

2. How to set limits w/ galaxy catalogs

3. Our catalog limits - in Sid’s talk next!

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$m_\chi$ [GeV]

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Where should we look?

\[ \Phi_{DM} \propto J \sim \int ds \, \rho^2 \]
WHERE SHOULD WE LOOK?

Galactic Center

- Bright but significant backgrounds
- An excess in the data!

NR et al (1402.6703)
See also NR et al (1604.01026) and many more!

\[ \Phi_{DM} \propto J \sim \int ds \rho^2 \]
WHERE SHOULD WE LOOK?

**Galactic Center**
- Bright but significant backgrounds
- An excess in the data!

NR et al (1402.6703)
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**Milky Way Dwarfs**
- Dim but low backgrounds
- Many discovered recently!

Fornax
Sextans

See Fermi-LAT Collaboration: 1310.0828, 1503.02641, 1611.03184

\[ \Phi_{DM} \propto J \sim \int ds \rho^2 \]
WHERE SHOULD WE LOOK?

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Where should we look?

**Galaxies and Clusters**

- Even dimmer than Dwarfs
- But there are many more!

\[ \Phi_{DM} \propto J \sim \int ds \rho^2 \]

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Building a Map Of Extragalactic DM

- **Starting point:** a catalog of galaxies, e.g. 2MASS

![Map of Extragalactic DM](image)

Huchra et al 1108.0669

- **Basic problem:** How do we go from galaxies to DM?
**Building a Map Of Extragalactic DM**

\[ J = (1 + b_{sh}) \int \rho^2 (s, \Omega) \, ds \, d\Omega \]

\[ \rho_{NFW}(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2} , \quad c_{\text{vir}} \equiv r_{\text{vir}}/r_s \]

\[ \Rightarrow J \sim (1 + b_{sh}) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d_A^2 [z]} \]

- Need all 4 for every galaxy
- \( z \) often well known, others less so

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\[ \Rightarrow J \sim (1 + b_{sh}) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d_A^2[z]} \]

DarkSky N-body Simulation

4096^3 \text{ particles}; 400 \text{ Mpc/h box}; m \sim 7.6 \times 10^7 M_\odot

Skillman et al 1407.2600; darksky.slac.stanford.edu

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\[ J \sim (1 + b_{\text{sh}}) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d_A^2 [z]} \]

Luminosity-mass relation
DarkSky-400 simulation

Inferred vs true mass
DarkSky-400 simulation

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$$\Rightarrow J \sim \left(1 + b_{sh}\right) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d_A^2 [z]}$$

Concentration-mass relations

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\[ J \sim (1 + b_{sh}) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d_A^2 [z]} \]

Boost model we use (1507.08656)

Much larger boosts now disfavoured (1107.1916)
Building a Map Of Extragalactic DM

- Can now build up a full map of extragalactic DM
Building a Map Of Extragalactic DM

- Use these to perform a stacked template fit analysis:
Conclusion

- Clusters are a powerful probe of DM annihilation
- I’ve shown how to go from galaxies, to a DM map, to a limit
- Sid will take over and show our application to the Fermi data
Backup Slides
**J-factor Scaling**

- For extragalactic halos an excellent approximation is:

\[
J_{\text{NFW}} = (1 + b_{sh}[M_{\text{vir}}]) \int dsd\Omega \rho_{\text{NFW}}^2(s, \Omega)
\]

\[
\approx (1 + b_{sh}[M_{\text{vir}}]) \frac{1}{d_A^2(z)} \int_V dV' \rho_{\text{NFW}}^2(r')
\]

\[
= (1 + b_{sh}[M_{\text{vir}}]) \frac{M_{\text{vir}}c_{\text{vir}}^3 \rho_c \Delta_c(z)}{9d_A^2(z)}
\]

\[
\times \left[1 - \frac{1}{(1 + c_{\text{vir}})^3}\right] \left[\ln(1 + c_{\text{vir}}) - \frac{c_{\text{vir}}}{1 + c_{\text{vir}}}\right]^{-2}
\]

\[
\sim (1 + b_{sh}) \frac{M_{\text{vir}}c_{\text{vir}}^3}{d_A^2(z)}
\]

Same scaling holds for Burkert profile
Injected Signal

$m_\chi = 10$ GeV

$m_\chi = 100$ GeV

$m_\chi = 10$ TeV

(\sigma v)_{\text{inj}} / \text{cm}^3 \text{s}^{-1}

(\sigma v)_{\text{rec}} / \text{cm}^3 \text{s}^{-1}

Location 1

Location 2

\( m_\chi \) = 10 GeV

\( m_\chi \) = 100 GeV

\( m_\chi \) = 10 TeV

(\sigma v)_{\text{rec}} / \text{cm}^3 \text{s}^{-1}

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Elephants

$m_\chi = 10 \text{ GeV}$

$m_\chi = 100 \text{ GeV}$

$m_\chi = 10 \text{ TeV}$

Location 1

Location 2

Location 3

Location 4

$N_h$
Impact of Systematic Modeling

Preliminary
**Template Fitting**

DM Annihilation

p7v6 Diffuse Model

Fermi Bubbles

Isotropc Emission

Fix a value

Scan to find best fit values in each energy bin

Simulated Fermi data

Fit implemented with NPTFit:
github.com/bsafdi/NPTFit/

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**Template Fitting**

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**Template Fitting**

- DM Annihilation
- p7v6 Diffuse Model
- Fermi Bubbles
- Isotropc Emission

**Example Output**

Simulated Fermi data
Fit implemented with NPTFit: Rodd et al, Astron. J. 153 (2017) 253; github.com/bsafdi/NPTFit/

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Searching for Extragalactic DM

DM Annihilation

Fermi Bubbles

Isotropic Emission

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Scan to find best fit values in each energy bin

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Searching for Extragalactic DM

- Limit set in DarkSky + Fermi Monte Carlo on 100 GeV DM to $bs$

- Limit is dominated by the top ~ 100 halos when all added
Building a Map Of Extragalactic DM

\[ J \approx (1 + b_{sh}) \frac{M_{\text{vir}} c_{\text{vir}}^3}{d(z)^2} \]

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Dark Matter at Fermi: Profile Likelihood

- Bin the data in energy (i) and spatial pixels (p): \( \{l, b, E\} \Rightarrow n^p_i \)
- Describe with model parameters: \( \theta = \{\psi_{\text{DM}}, \lambda_{\text{nuisance}}\} \)
- Construct the Poisson likelihood in each energy bin \( i \)
  \[
  p_i(d_i|\theta_i) = \prod_p \frac{\mu^p_i(\theta_i)^n^p_i e^{-\mu^p_i(\theta_i)}}{n^p_i!}
  \]
- Eliminate the nuisance parameters by profile likelihood
  \[
  \log p_i(d_i|\psi_i) = \max_{\lambda_i} \log p_i(d_i|\theta_i)
  \]
- Likelihood of a model depends on the injected galactic and extragalactic flux
  \[
  \log p(d|M, \{\langle\sigma v\rangle, m_{\text{DM}}\}) = \sum_{i=0}^{39} \log p_i(d_i|I^i_{\text{cat}})
  \]
- From this define a TS, from which limits can be set
- Implement analysis using NPTFit (1612.03173)
Fermi Data Details

Simulated Monte Carlo base on: 423 weeks of Fermi-LAT data
40 log spaced energy bins, from 200 MeV - 2 TeV
UltracleanVeto BestPSF
Background Mismodelling

- Models of the gamma ray sky do not explain the data to the level of Poisson noise, e.g. below for GCE from NR et al 1604.01026

- These issues are much more pronounced for larger ROIs

- As modelling of the sky improves, will be able to safely use larger ROIs and thereby more data

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**Wimp Miracle**

- We know the amount of DM
- If it was once in thermal EQ with SM, then:

\[
\text{Amount of DM} \propto \frac{1}{\langle \sigma v \rangle}
\]

- Putting in numbers find:

\[
m_\chi \sim \text{EW} \ (\approx \text{TeV})
\]

\[
\langle \sigma v \rangle \sim 10^{-26} \ \text{cm}^3/\text{s}
\]

- Suggestive, provides a benchmark!
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**Wimp Miracle**

- We know the amount of DM
- If it was once in thermal EQ with SM, then:

  \[ \text{Amount of DM} \propto \frac{1}{\langle \sigma v \rangle} \]

- Putting in numbers find:

  \[ m_\chi \sim \text{EW} \ (\approx \text{TeV}) \]
  \[ \langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3 / \text{s} \]

- Suggestive, provides a benchmark!
WHERE SHOULD WE LOOK?

\[ \Phi(l, b) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE} \, dE \times \int_{\text{los}} \rho_{\text{DM}}^2(r) \, ds \]

\[ \langle \sigma v \rangle \]

\[ \frac{dN_\gamma}{dE} \]

\[ \rho_{\text{DM}}^2(r) \]

\[ \text{“Particle Physics Factor”} \]

\[ \text{“J-Factor”} \]

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**Where should we look?**

\[
\Phi(l, b) = \frac{\langle \sigma v \rangle}{8\pi m^2_\chi} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE} dE \times \int_{\text{los}} \rho_{\text{DM}}^2(r) ds
\]

\[
\langle \sigma v \rangle = 10^{-26} \text{ cm}^3/\text{s}
\]

\[
m_\chi = 100 \text{ GeV}
\]

\[
dN_\gamma/dE = 2\delta(E - m_\chi) \ (\chi\chi \rightarrow \gamma\gamma)
\]

\[
\Rightarrow \text{PP} \approx 10^{-31} \text{ cm}^3/\text{s}/\text{GeV}^2
\]
Where should we look?

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\]

\[
\frac{\gamma}{\text{cm}^2/\text{s}}
\]

“Particle Physics Factor”

“J – Factor”

\[
\langle \sigma v \rangle = 10^{-26} \text{ cm}^3/\text{s}
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m_{\chi} = 100 \text{ GeV}
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\]

\[
\Rightarrow \text{PP} \approx 10^{-31} \text{ cm}^3/\text{s}/\text{GeV}^2
\]

E.g. Segue 1:

\[
J \approx 10^{20} \text{ GeV}^2/\text{cm}^5
\]
WHERE SHOULD WE LOOK?

\[ \Phi(l, b) = \frac{\langle \sigma v \rangle}{8\pi m_{\chi}^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE} dE \times \int_{\text{los}} \rho_{DM}^2(r) ds \]

\[ \langle \sigma v \rangle = 10^{-26} \text{ cm}^3/\text{s} \]
\[ m_{\chi} = 100 \text{ GeV} \]
\[ dN_\gamma/dE = 2\delta(E - m_{\chi}) (\chi\chi \rightarrow \gamma\gamma) \]
\[ \Rightarrow PP \approx 10^{-31} \text{ cm}^3/\text{s/GeV}^2 \]

\[ J \approx 10^{20} \text{ GeV}^2/\text{cm}^5 \]
\[ \Rightarrow \Phi \approx 10^{-11} \gamma/\text{cm}^2/\text{s} \]
Where should we look?

\[ \Phi(l, b) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE} dE \times \int_{\text{los}} \rho_{\text{DM}}^2(r) ds \]

\[ \langle \sigma v \rangle = 10^{-26} \text{ cm}^3/\text{s} \]
\[ m_\chi = 100 \text{ GeV} \]
\[ \frac{dN_\gamma}{dE} = 2\delta(E - m_\chi) \ (\chi\chi \to \gamma\gamma) \]
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\[ J \approx 10^{20} \text{ GeV}^2/\text{cm}^5 \]
\[ \Rightarrow \Phi \approx 10^{-11} \gamma/\text{cm}^2/\text{s} \]

If we had a 1 m$^2$ space based telescope operate for 10 years:

\[ (10^{-11} \gamma/\text{cm}^2/\text{s}) \times (10^4 \text{ cm}^2) \times (10 \times \pi \times 10^7 \text{ s}) \approx 30 \gamma \]
Where should we look?

- Fermi Large Area Telescope (LAT): pair-conversion telescope consisting of layers of tungsten and silicon on top of a calorimeter
- Launched June 2008, still running
- Narrowly avoided hitting a Soviet spy satellite in mid 2013
- Sensitive to EW scale thermal DM!
- Rest of talk: where should we point?