Ten years of dark matter searches with the Fermi-LAT

Francesca Calore
Laboratoire d’Annecy-le-Vieux de Physique Théorique
Dark matter constitutes about 85% of the matter content of the Universe.

We do not know what most of the Universe is made of!

Dark matter constitutes about 85% of the matter content of the Universe.

Planck 2015

Dark Energy 68%

Baryonic Matter

27% Dark Matter

4% 1%

~kpc

~Mpc

~Gpc

Cosmic microwave background

Large Scale structures

Galaxy clusters

Rotation curves

Dark matter gravitational evidence

We do not know what most of the Universe is made of!
The dark matter landscape

- Input from theory helps to better define the dark matter candidate of interest
- Identification strategies might be more or less model dependent
- The theoretical prejudice in dark matter searches is mostly set by what we can probe with available data

20 years of high-energy gamma rays

EGRET (1991-2000)  
30 MeV - 30 GeV

20 MeV - 500 GeV

Francesca Calore
CNRS, LAPTh
Dark matter candidates & Photon energy

FC, Storm & Weniger, In preparation

![Graph showing signal energy vs. center of mass energy for various dark matter candidates and photon energy regions.](image-url)
Dark matter candidates & Photon energy

Focus on searches for WIMP dark matter

DM annihilation/decay leads to production of observable fluxes of stable particles.
Dark matter candidates & Photon energy

Focus on searches for WIMP dark matter

DM annihilation/decay

Observable Fluxes
- Low-energy photons
- Medium-energy gamma rays
- High-energy gamma rays
- Neutrinos
- Antiprotons
- Protons
- Positrons
- Electrons

Decay process

Fluxes

Observations
What are we looking for?

Expected gamma-ray flux from **dark matter annihilation** in the smooth Galactic halo

\[ \Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2 \]
Dark matter signal predictions

\[ \Phi(E, \psi) = \frac{\sigma_{\text{A}} v}{8\pi m_{\chi}^2} \left( \frac{dN_{\gamma}}{dE} \right) \int d\ell \rho [r(\ell, \psi)]^2 \]

Spectral energy distribution (spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)

EM and EW corrections

Bringmann, FC+ JHEP'08;
Ciafaloni+ JCAP'11; Bringmann&FC PRL'14
Dark matter signal predictions

\[ \Phi(E, \psi) = \frac{\sigma_A \nu}{8\pi m^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2 \]

**Spectral energy distribution** (spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)

- **Emission from hadronic decays and cascades**
- **EM and EW corrections**
  - Bergström et al., JCAP'05
  - Ciafaloni+ JCAP'11; Bringmann&FC PRL'14

**Spatial distribution** in astrophysical targets (asymmetric density profiles, substructures boost factor, local DM density)

- Simulations w/ baryons
  - Schaller,FC+ MNRAS'16; FC+JCAP'15
- Rotation curve
  - Iocco+ Nature Phys.'15
- NFW Einasto Burkert

\[ [1.5 \text{ kpc} \approx 10^9] \]

- \[ \Delta E/E = 0.15 \]
- \[ \Delta E/E = 0.02 \]

- gamma-ray lines
  - Bergström et al., JCAP'05

\[ x = E / m_\chi \]

- \[ q q, Z Z, W W \]

\[ \rho_{\text{DM}}(R) \text{ [GeV/cm}^3\text{]} \]

- \[ \sim R^{-1} \]
- \[ \sim \text{constant} \]

Francesca Calore

CNRS, LAPTh
Dark matter searches with the Fermi-LAT: Current limits on WIMPs
Targets for dark matter gamma-ray searches

+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

Conrad & Reimer
Dwarf spheroidal galaxies

Target:
- **dSphs galaxies**: “clean” target for DM searches, high light-to-mass ratio and no astrophysical emission

Status:
- Exclude thermal cross section below 100 GeV (16 dSphs stacking, 6 yr of data)
- Syst unc **J-factor** determination for ultra-faint dSphs (tri-axiality, contamination, velocity anisotropy)
- Syst unc **background mis-modelling** are important (3x weaker limits)

Future:
- New data from Fermi-LAT (improvement by a factor of 2-5)
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019)
Dark matter subhaloes

Target:
- Gamma rays: look for subhalo candidates in Fermi-LAT unassociated sources

Status:
- The realistic estimation of the LAT sensitivity to the DM subhalo population from hydrodynamic simulations is crucial (th. unc) FC+ PRD’17

Future:
- CTA sensitivity in the extragalactic survey comparable to CTA dSPhs sensitivity Hütten+ JCAP’16
- **Follow-up observations** of point sources crucial to reduce the number of SH candidates; e.g. search for nearby dSPhs towards Fermi-LAT (unIDs & extended) sources with GAIA DR2 Ciucă, FC+ MNRAS’18
The high-latitude Milky Way halo

The high-latitude region provides very strong constraints on annihilating dark matter into hadronic final states.
Multi-target constraints

Status

- Current limits from other Galactic and extragalactic targets
- Powerful limits from galaxy group catalogs

Lisanti+ PRD’18, PRL’18

[Combined targets: see talk by Di Mauro (Thu)]

Future

- **Fermi-LAT** limits improvement depends on target (syst., bkg or signal limited)
- **HAWC** will improve limits from observations of dwarfs and Galactic centre; **CTA** will improve **HESS** limits by factor up to 10.
  Silverwood+ JCAP’15; Doro+ AP’13; Carr+ 2015; Lefranc+ PRD’15
- Great potential in the unexplored MeV/sub-GeV range (e.g. Amego; e-ASTROGAM)
  Bringmann+PRD’17; Bartels+2017

[CTA: see talk by Zaharijas (Thu)]
Beyond limits ... 
... Hints for dark matter signals?
Beyond limits ...

... Hints for dark matter signals?

aka: What anomalies in the gamma-ray sky?
Some gamma-ray anomalies in the GC region

Gamma-ray @ few GeV
Fermi-LAT
Fermi GeV excess

Gamma-ray @ 511 keV
INTEGRAL/SPI
Positron annihilation line
Purcell+’93,’97; Knödlseder+’03,’05

Gamma-ray @ hundreds GeV
Fermi-LAT
Fermi bubbles, and their radio/microwave counterparts

X-ray @ 20-40 keV
NuSTAR
hard diffuse excess emission

Excesses extended far well beyond central CMZ and nuclear bulge
The Galactic centre GeV excess

Signal:
• Well-established excess of Fermi-LAT GeV photons from the inner Galaxy
• Peculiar spectrum peaked at a few GeV
• Extended emission up to ~10 degrees (~1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:
• Diffuse emission from electrons/positrons at the Galactic centre (enhanced SF or activity GC)
  Gaggero+ JCAP’15; Carlson+PRD’15; Petrovic+ JCAP’14; Cholis,FC+JCAP’15
• Sub-threshold millisecond pulsar-like point sources
  Bartels+PRL’16; Lee+PRL’16; Ackermann+’17
• Dark matter annihilation: large freedom in channel/masses thanks to syst uncertainties
  Calore+ PRD’15; Agrawal+JCAP’15

**Some Refs. since 2009: Hooper&Goodenough ’09; Vitale&Morselli ’09; Abazajian&Kaplinghat PRD’12; de Boer+’16; Macias+’16; Hooper&Slatyer PDU’13; Huang+ JCAP’13; Zhou+ PRD’15; Daylan+ ’14; Calore+ JCAP’15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP ’15; Linden+PRD’16; Horiuchi+’16; Ackermann+ApJ’17; Ackermann+2017
Evidence for stellar bulge emission

Stellar bulge model (boxy + nuclear bulge) is preferred over (spherically symmetric) DM models with high statistical significance (16σ)

Morphology of the GCE is more oblate than what found before

Large enough ROI to discriminate foreground components (stable results)

[See also Macias+ Nature Astronomy’18]
Gamma-ray to stellar mass ratios

- Gamma-ray luminosity shows correlation with stellar mass in the Galactic bulge
- If from MSP: bulge and disk component consistent with each other
- Debate: In-situ formation of MSP (+ dynamical formation) or from disrupted globular clusters

The dark matter origin of the excess becomes less and less likely

- Degeneracy with Fermi bubbles hard emission, i.e. high-energy tail?
- Contribution of molecular clouds in the CMZ?
- Connection with TeV diffuse emission from the GC?
- Connection with 511 keV positron annihilation line?
Discovering radio MSPs in the inner Galaxy

Bulge population is just below sensitivity of Parkes HTRU mid-latitude survey.

• GBT targeted searches ~100h: ~3 bulge MSPs
• MeerKAT (and SKA) mid-lat survey ~300h: ~30 bulge MSPs

➡ With future dedicated observations we can discover this MSP bulge population.
➡ We need observation time (Fermi GI Proposals, TRAPUM MeerKAT legacy, etc.)

[Talks by Ray (Tue), Kerr (Wed), Sanpa-arsa (Wed)]
Beyond WIMPs with the Fermi-LAT
**ALPs: gamma-ray spectral distortions**

**Photon-ALPs oscillation** in external and Galactic magnetic fields, due to mixing between ALPs and photon polarization along field direction

1) Reduced absorption (EBL)
2) Oscillations below critical energy


Credit: M. Meyer
**ALPs: gamma-ray spectral distortions**

**Photon-ALPs oscillation** in external and Galactic magnetic fields, due to mixing between ALPs and photon polarization along field direction.

1) Reduced absorption (EBL)

2) Oscillations below critical energy

---

ALPs in Galactic sources

• At **Galactic scales** oscillations can be relevant at **GeV energies**
• Search for oscillation features in the disappearance channel from 6 bright Galactic pulsars
• Oscillations features enhanced for sources at large distance and in the l.o.s. with high transversal B-field (conversion in large-scale regular B-field component)

![Graph showing log(vf_0) vs log(E/MeV) for PSR J2021+3651 9yr Pass 8 with fits and intrinsic line.](Majumdar, FC, Horns JCAP'18)

- Significant fit improvement w/ ALPs: **4.6σ** significance for the combined fit
- 20%-40% spectral variation vs ~3% exper. syst. uncertainty (from Vela as control sample)
- Although, differences in mass and coupling for individual l.o.s. are not fully consistent
- Consistent results from SNR IC433

[Xia+PRD’18](#) [See also talk by Lloyd (Thu)](#)
ALPs-photon coupling constraints

- Excluded by CAST limits and SN1987A
  
  CAST Collab+Nature Phys’17; Payez+JCAP’14

- Excluded by latest limits from NCG1275
  
  Malyshev+1805.04388

- Consistent with TeV transparency lower-limit and CIBER contours
  
  Meyer+PRD’13; Kohri & Kodama PRD’17

How to relieve the tension?

✓ **Plasma/environment effects** can alleviate the tension with SN1987A/CAST limits
  
  Jaekel+PRD’07

✓ **Axion mediated dark-photon** mixing can also explain oscillations and the re-casted limits do not exclude the best-fit region
  
  Choi+1806.09508
Primordial black holes

• Extragalactic diffuse gamma-ray background can be used to constrain PBH which are evaporating at the present epoch ($10^{14} - 10^{17}$ g)
• Spectrum of emitted particles is centered at MeV - a few GeV energies


✓ Extragalactic diffuse background limits on the mean cosmological number density
✓ Galactic diffuse background constrains PBH clustered in the Galactic halo (EGRET)  
  Lehoucq+ A&A’09
✓ Looking for moving Fermi-LAT sources with hard gamma-ray spectra (evaporation phase) probes the local PBH density  
  Fermi-LAT Clb ApJ’18
✓ Strongest constraints from Voyager I data  
  Boudaud & Cirelli 1807.03075
The Fermi-LAT has truly made a **major leap forward in probing WIMP dark matter**, tantalising the thermal cross-section for few GeV - 100 GeV masses.

Fermi-LAT data can be successfully used to constrain non-WIMP dark matter models, e.g. ALPs, PBH.
Conclusions & Outlook

✓ Current searches can be improved by exploiting the complementarity with other wavelengths/messengers, e.g. antiproton constraints; radio, X-rays and optical follow up of unassociated/faint sources; identification of more dSPhs galaxies with optical surveys

✓ Synergy with future gamma-ray instruments from sub-GeV to TeV energies will be crucial in reducing the contamination from astrophysical sources/foregrounds

✓ Exciting anomalies do persist in the gamma-ray sky calling into question our standard frameworks for point-source and diffuse high-energy emission.

✓ Fermi-LAT can play a leading role for dark matter searches in the coming years if we exploit its great data e.g. to (a) reduce further theoretical model systematics; (b) improve the characterisation (and identification) of point sources
Backup slides
Status of decaying dark matter

- Light DM (10 MeV - GeV) constrained by: photon diffuse bkg [Essig+’13]; CMB [Slatyer&Wu’17]; Voyager [Boudaud+PRL’17]
- Heavy (> GeV) DM constrained by: dSPhs, MW halo, extragalactic photons [Cohen+PRL’17]

Decay lifetimes below $\sim 10^{27-28}$ s ruled out for most final states and keV-EeV DM masses;

for few-MeV DM decaying to e+e-, lifetimes can be as short as $10^{24-25}$ s
Status of line signal searches in gamma rays

Ackermann+ PRD’15

Abdalla+ PRL’18

254 h, DM DM → γγ
Einasto profile
Support for unresolved point sources

Local maxima of normalised wavelet transform

- No background modelling
- Evidence for MSP-like population in the bulge
- Constraints on luminosity function

Non-Poissonian template fitting

- The statistics of PS is non-Poissonian
- PS NPT NFW distribution absorbs the most of the excess
- A priori, it suffers more form contamination of background modelling

Caveat: Do we model the small scale gas correctly?