AN OVERVIEW

EXPERIMENTAL SEARCHES FOR DARK MATTER

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1. Evidence for dark matter
2. Dark matter particle candidates
   i. WIMPs
   ii. Axions and ALPs
3. Dark matter searches

Disclaimer: won’t mention LHC, will focus on (some) activities in Sweden
EVIDENCE FOR DARK MATTER
ON SCALES OF GALAXIES: ROTATION CURVES

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]

Bergström 2000
EVIDENCE FOR DARK MATTER ON SCALES OF GALAXIES: ROTATION CURVES

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]

Bergström 2000

Knut Lundmark (1889-1954)
Professor for astronomy at Lund University

Lund Medd. No125 (1930), 1–10
EVIDENCE FOR DARK MATTER ON SCALES OF GALAXIES: ROTATION CURVES

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]

Vera Rubin (*1928)

M33 rotation curve

Bergström 2000
EVIDENCE FOR DARK MATTER

ROTATION CURVE OF THE MILKY WAY

Bertone, Iocco, Pato 2015
EVIDENCE FOR DARK MATTER

CLUSTER MERGERS

- Visible matter dominated by hot gas emitting X-rays
- Gravitational lensing shows that mass dominated by dark matter
EVIDENCE FOR DARK MATTER
COSMIC MICROWAVE BACKGROUND

- Temperature fluctuations at level $\Delta T / T \sim 10^{-5}$
- Spatial anisotropies require a non-relativistic non-interacting component (Dark matter!)

Planck / ESA
DARK MATTER PARTICLE CANDIDATES

- mSUGRA
- R-parity conserving
- pMSSM
- R-parity violating
- Gravitino DM
- MSSM
- NMSSM
- Extra Dimensions
- UED DM
- Warped Extra Dimensions
- Little Higgs
- T-odd DM

- Axion-like Particles
  - QCD Axions
  - Axion DM
  - Axion-like Particles
  - Dark Photon
- Sterile Neutrinos
- Light Force Carriers
- Warm DM
- Solitonic DM
- Q-balls
- Self-Interacting DM
- Dark Photon

- Supersymmetry
- Hidden Sector DM
- WIMPless DM
- Techni-
- Solitonic DM
- Quark Nuggets
- Techni-baryons
- Axion DM
- Axion-like Particles
- Todd DM
- Little Higgs
- Littlest Higgs

- Warm DM
- Littlest Higgs
- Solitonic DM
- UED DM
- Warped Extra Dimensions
- Little Higgs
- T-odd DM

[e.g. Snowmass 2013 CF3 report: arXiv:1310.8642]
DARK MATTER PARTICLE CANDIDATES

WIMPs

DARK MATTER PARTICLE CANDIDATES

WIMPs

ALPs

[NOTE: This image is a complex diagram illustrating various dark matter particle candidates. The diagram includes labels such as WIMPless DM, Self-Interacting DM, Dark Photon, Asymmetric DM, Warm DM, Axion DM, Axion-like Particles, and more. It connects these concepts with pathways labeled MSSM, NMSSM, Supersymmetry, Extra Dimensions, Little Higgs, and others.]

[e.g. Snowmass 2013 CF3 report: arXiv:1310.8642]
THE MIRACULOUS WEAKLY INTERACTING MASSIVE PARTICLE

• Expanding Universe leaves thermal relics if expansion faster than annihilation rate

• Coincidence?
  $m_{\text{WIMP}} = 100$ GeV with weak-scale interaction gives right relic abundance

\[ \langle \sigma v \rangle_{\text{weak}} \sim \frac{\alpha^2}{m_{\text{WIMP}}^2} \sim 10^{-25} \text{ cm}^3\text{s}^{-1} \]

\[ \Omega_{\text{DM}} \sim \frac{10^{-26} \text{ cm}^3\text{s}^{-1}}{\langle \sigma v \rangle} \sim 0.27 \]

Thermal production in early Universe

[Diagram showing thermal relic production and interaction rates]
WIMP DETECTION

indirect detection

production at colliders

direct detection

$\chi$ $\rightarrow$ $f$

$\chi$ $\rightarrow$ $\overline{f}$
WIMP DETECTION

Solar System
- Detect local dark matter halo (direct detection)
- WIMP capture in the Sun

Galaxy and Galactic Center
- Search for SM particles from dark matter annihilation
  - Cosmic rays
  - Gamma rays

Dwarf galaxies
- Search for gamma rays from dark matter annihilation
  - Low astrophysical background

indirect detection
production at colliders

distance
DIRECT DETECTION

• **Idea:** search for WIMP-nucleon scattering with low-background experiments

• WIMPs from **local DM halo**

• Sensitive to spin-(in)dependent **scattering cross sections**

• Necessitates modeling of WIMP-nucleon cross section

• Compare with indirect detection, colliders: **theoretical model necessary** (e.g. Effective Field Theories)
DIRECT DETECTION

- **Idea:** search for WIMP-nucleon scattering with low-background experiments

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Addressed in **Swedish Dark Matter Direct Detection Consortium** [SweD³] involving Stockholm University & Chalmers [Ricardo Catena, Christian Forssén]
DIRECT DETECTION
\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle \sum_f dN_x^f}{2m_X^2} \frac{dN_x^f}{dE_x} B_f
\]

**Expected flux:**

**Particle physics**

\[
\int \int_{\Delta \Omega} \rho_X^2(r) dl d\Omega
\]

**Astrophysics (J-factor)**

\[
x = \gamma, \nu
\]

and anti-matter (cosmic rays)
**Indirect Dark Matter Searches**

\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_X^2} \sum_f \frac{dN_{xf}}{dE_x} B_f \int \int \Delta \Omega \rho_X^2(r) dl d\Omega
\]

Expected flux:

- **Particle Physics**
- **Astrophysics (J-factor)**

\( x = \gamma, \nu \) and anti-matter (cosmic rays)

DM density from N-body (Millennium II) simulation

Expected flux: 0.5 Mpc / h
INDIRECT DARK MATTER SEARCHES

\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_X^2} \sum_f \frac{dN_x^f}{dE_x} B_f \int \int \rho_X^2(r) dl d\Omega
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Expected flux:

- Particle physics
- Astrophysics (J-factor)

DM density from N-body (Millennium II) simulation

Galactic center

\[ J \sim 10^{21} \text{ GeV}^2 \text{ cm}^{-5} \]

\[ x = \gamma, \nu \]

and anti-matter (cosmic rays)
\[ \frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m^2_X} \sum_f \frac{dN_f}{dE_x} B_f \]

Expected flux:

\[ \int \int \rho^2_X(r) dl \, d\Omega \]

\[ \Delta \Omega \quad \text{1.o.s.} \]

\[ x = \gamma, \nu \]

and anti-matter (cosmic rays)

**Particle physics**

**Astrophysics (J-factor)**

DM density from N-body (Millennium II) simulation

- **Dwarf galaxies**
  - \( J \sim 10^{19} \text{ GeV}^2 \text{ cm}^{-5} \)

- **Galactic center**
  - \( J \sim 10^{21} \text{ GeV}^2 \text{ cm}^{-5} \)

0.5 Mpc / h
\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m^2\chi} \sum_f \frac{dN_f}{dE_x} B_f \int_{\Delta\Omega} \int_{1.o.s.} \rho^2(r) dl d\Omega
\]

Expected flux:

**Particle Physics:**

DM density from N-body (Millennium II) simulation

**Astrophysics (J-factor):**

\[x = \gamma, \nu] \text{ and anti-matter (cosmic rays)}

Expected flux: \[0.5 \text{ Mpc} / h\]

\[\log(E^2 d\phi / dE_\gamma)\]

\[\log(E_\gamma)\]
\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_X^2} \sum_f \frac{dN_f}{dE_x} B_f \int \int \rho^2_X(r) dl d\Omega \quad \Delta \Omega \quad \text{1.o.s.}
\]

Expected flux:

\[ x = \gamma, \nu \]

and anti-matter (cosmic rays)

DM density from N-body (Millennium II) simulation

0.5 Mpc / h

log(\(E^2 \frac{d\phi}{dE_\gamma}\))

log(\(E_\gamma\))

astrophysical bkg

DM
\[ \frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m^2_\chi} \sum_f \frac{dN^f_x}{dE_x} B_f \] 

Expected flux:

\[ \int \int \rho^2(r) dl d\Omega \quad \Delta\Omega \quad \text{l.o.s.} \]

\( x = \gamma, \nu \)

and anti-matter

(cosmic rays)

DM density from N-body (Millennium II) simulation

Expected flux:

0.5 Mpc / h

log\( (E^2 \frac{d\phi}{dE_\gamma}) \)

log\( (E_\gamma) \)
**INDIRECT DARK MATTER SEARCHES**

\[
\frac{d\phi_x}{dE_x} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m^2_\chi} \sum_f \frac{dN^f_x}{dE_x} B_f
\]

Expected flux:

\[
\int \int_\Delta \Omega \rho^2_\chi(r) dl d\Omega
\]

1.o.s.

**particle physics**

**astrophysics (J-factor)**

\[x = \gamma, \nu\]

and anti-matter (cosmic rays)

---

DM density from N-body (Millennium II) simulation

Expected flux:

\[
\log(E^2 d\phi / dE_\gamma)
\]

astrophysical bkg

DM

log \(E_\gamma\)

log \(E_\gamma\)

0.5 Mpc / h
DETECTING GAMMA RAYS

- **Gamma rays**: light that is 1 million times more energetic than X rays

- **Fermi Large Area Telescope (LAT)**:
  - **Energy range**: 20 MeV — > 300 GeV
  - Observes **full sky** every three hours

- **Imaging Air Cherenkov Telescopes (IACTs)**:
  - **Energy range**: ~50 GeV - 100 TeV
  - Future **Cherenkov Telescope Array**: Factor 10 improvement in point source sensitivity; Northern & Southern array
INDIRECT GAMMA-RAY SEARCHES FROM GALACTIC CENTER
HIGHEST EXPECTED FLUX

- Several groups have found excess γ-ray emission in the galactic bulge in Fermi-LAT data

- Expected contributions:
  - star-forming regions
  - Fermi Bubbles
  - Millisecond pulsars (also suggested from wavelet transforms)
  - Dark matter?

Spherical symmetric emissivity

[Daylan et al. 2014]

Spectral residuals
1 - 3 GeV
7 x 7 deg²

[Calore et al. 2014]

[Calore et al. 2014]

Spectrum consistent with DM but also milli-second pulsars,...

[e.g. Goodenough & Hooper 2009; Vitale & Morselli 2009; Hooper & Linden 11;
Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13;
Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14;
Cholis+ 15; Bartels+ 15; Lee+ 15, Ajello+ 15]
**LINE SEARCHES FROM GALACTIC CENTER**

- Line signature easier to distinguish from astrophysical backgrounds ("smoking gun")

- **Evidence** for line found in Fermi-LAT data at ~130 GeV
  ~1 degree offset from GC
  [Weniger 2012; Su & Finkbeiner, 2012]
LINE SEARCHES FROM GALACTIC CENTER

- Line signature easier to distinguish from astrophysical backgrounds ("smoking gun")

- Evidence for line found in Fermi-LAT data at ~130 GeV ~1 degree offset from GC [Weniger 2012; Su & Finkbeiner, 2012]

- Not confirmed in updated Fermi-LAT analysis or H.E.S.S. II [Ackermann et al. 2015, Abdallah et al. 2016]
INDIRECT GAMMA-RAY SEARCHES FROM DWARF SPHEROIDAL GALAXIES
CLEANEST TARGETS

- **DM dominated** (1000:1)
- Often high latitude → low diffuse background emission
- **Negligible intrinsic astrophysical gamma-ray emission** [e.g. Winter et al. 2016]
- **Nearby** (<250 kpc)
- **Many** (50+) → Joint analysis!
INDIRECT GAMMA-RAY SEARCHES FROM DWARF SPHEROIDAL GALAXIES WITH FERMI LAT
CLEANEST TARGETS

- **Joint** analysis from Fermi-LAT Collaboration:
  - 15 targets
  - 60 months of data
  - excluded thermal cross section between 6 and 100 GeV

Recent papers:
- Geringer-Sameth et al. 2015
- Ackermann et al. 2015 (Fermi LAT)
- Drlica-Wagner et al. 2015 (Fermi LAT + DES)
- Ahnen et al. 2016 (Fermi LAT + MAGIC)
COMPILATION OF LIMITS ON ANNIHILATION CROSS SECTION

[Conrad & Reimer, in prep.]
FUTURE OBSERVATIONS

• **More dwarf galaxies** (will be) detected by DES (and LSST), follow up with Fermi LAT

• **CTA**: next generation Cherenkov telescope array with factor 10 improvement of point source sensitivity

• **Future space missions:**
  - DAMPE (launched)
  - Gamma-400
  - HERD
  - e-Astrogam / ComPair / Pangu

*DES footprint in gal. coordinates (~5000 deg²)*
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AXIONS AND AXIONLIKE PARTICLES

- Strong interactions (QCD): has CP violating term, leads to electric dipole moment of neutron, not measured

- Cured by introducing the axion

- Oscillations around potential minimum: act like cold dark matter

- Axionlike particles (ALPs):
  - Cold dark matter candidate but does not solve strong CP problem
  - plethora of ALPs predicted in string theory (axiverse) and other standard model extensions

[References: Peccei & Quinn 77; Wilczek 78; Weinberg 78; Preskill et al. 83; Abbott & Sikivie 83; Witten 84; e.g. Arvanitaki et al. 09; Cicoli et al. 12; Arias et al. 2012]
AXION AND ALP DETECTION WITH PHOTONS

PRIMAKOFF EFFECT

\[ a \rightarrow \gamma \]

DECAY

\[ a \rightarrow \gamma \]
AXION AND ALP DETECTION
WITH PHOTONS

QCD Axion: \[ m_a \approx 0.3 \text{ eV} \frac{g_{a\gamma}}{10^{-10} \text{ GeV}^{-1}} = 0.3 \text{ eV} g_{10} \]
**AXION HALOSCOPES**

- If axions are the dark matter: could **resonantly convert to photons in microwave cavity** [Sikivie 1982]

- Different axion masses probed by **tuning resonance frequency**

- Implemented in e.g. ADMX experiment, similar experiments under construction

[see e.g. Asztalos et al. 2010, Brubaker et al. 2016]
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Different axion masses probed by tuning resonance frequency

Implemented in e.g. ADMX experiment, similar experiments under construction

[see e.g. Asztalos et al. 2010, Brubaker et al. 2016]
SEARCHES FOR PHOTON-ALP MIXING AT GAMMA-RAY ENERGIES

[Credit: SLAC National Accelerator Laboratory/Chris Smith]

CONSTRAINTS & SENSITIVITIES

**Log$_{10}$ g [GeV$^{-1}$]**

**Log$_{10}$ $m_a$ [eV]**

- ALP CDM
- LSW (ALPS–I)
- Helioscopes (CAST)
- TeV Transparency
- ALPS–II
- IAXO
- ADMX–HF
- ADMX
- KSVZ axion
- SN $\gamma$-burst
- $e^+e^- \rightarrow \gamma + \text{inv.}$
- Beam Dump
- SWB
- EBL
- CMB
- BBN
- WD cooling hint
- AXion

**Constraints & Sensitivities**

- SN1987a
- Solar $\nu$
- HB
- X-Rays
**CONSTRAINTS & SENSITIVITIES**

- **Fermi-LAT limits** strongest to date between $0.5 \lesssim m_a \lesssim 20$ neV
- **Comparable** with sensitivity of future laboratory experiments in that mass range

[Ajello et al. 2016]
- ALPs could be produced in core-collapse supernova
- Would convert to $\gamma$ rays in Galactic magnetic field [see Payez et al. 2015]
- For progenitor of 10 solar masses at the position of the Galactic center, strong constraints would be possible

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, submitted. ArXiv:1609.02350]
SUMMARY AND CONCLUSION

• Dark matter paradigm well established through astrophysical observations

• Dark matter ~5 times more abundant than ordinary matter

• Plethora of theories that predict new particles that could constitute dark matter

• Searches for dark matter are conducted at colliders, with direct detection experiments, and indirect astrophysical observations

• All these fields benefit from contribution from Swedish institutes
BACK UP SLIDES
EVIDENCE FOR DARK MATTER

GALAXY VELOCITIES IN GALAXY CLUSTERS

Fritz Zwicky (1898-1974)

GALAXY VELOCITIES SUGGEST MASS-TO-LIGHT RATIO ~ 400
间接搜索：用宇宙射线反质子探测

- 背景：次级反质子CRs，来自 primary CR 的相互作用。
- 测量的流量与预期背景一致。
- 大的不确定性。
- 难以排除 astrophysical 来源的额外。

[e.g. Giesen et al. 2015, Evoli et al. 2015]
INDIRECT SEARCHES WITH COSMIC-RAY POSITRONS

• Background: secondary positrons

• Clear excess above secondaries observed

• All DM interpretation difficult to reconcile with γ-rays, anti-protons [e.g. Cirelli et al. 2010, Slayter et al. 2015]

• Nearby pulsars would give very similar signal [e.g. Pato et al. 2010]

• Strong limits on annihilation/decay into leptons possible for assumption that all positrons due to pulsars [Bergström et al. 2013]
WIMP CAPTURE IN THE SUN

- WIMPs could scatter elastically with nuclei in the Sun
- Get trapped in gravitational potential
- Annihilate into SM particles, only neutrinos escape (assume equilibrium)
- No neutrino flux observed with IceCube
WIMP CAPTURE IN THE SUN

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- Get trapped in gravitational potential
- Annihilate into SM particles, only neutrinos escape

No neutrino flux observed with IceCube

[Aartsen et al. 2015]
INDIRECT GAMMA-RAY SEARCHES FROM GALACTIC CENTER
HIGHEST EXPECTED FLUX

• No excess found at higher energies

• Cherenkov telescopes employ dedicated pointing schemes to estimate background

• Stringent limits from 10 years of H.E.S.S. observations [Abdallah et al. 2016]
**AXION AND ALPs FROM STARS**

- Axions and ALPs could be produced in stars and supernovae [Raffelt 1998]
- Would alter stellar lifetime
- Searched for with X-ray telescopes with magnets pointed at the sun [Andriamonje et al. 2008, Irastorza et al. 2013]
DETECTING GAMMA RAYS WITH THE FERMI LAT

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy range</strong></td>
<td>20 MeV - over 300 GeV</td>
</tr>
<tr>
<td><strong>Effective Area (E &gt; 1 GeV)</strong></td>
<td>~ 1 m²</td>
</tr>
<tr>
<td><strong>Point spread function (PSF)</strong></td>
<td>~ 0.8° @ 1 GeV</td>
</tr>
<tr>
<td><strong>Energy resolution ΔE/E</strong></td>
<td>5% - 15% @ 10 GeV</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>2.4 sr</td>
</tr>
<tr>
<td><strong>Orbital period</strong></td>
<td>91 minutes</td>
</tr>
<tr>
<td><strong>Altitude</strong></td>
<td>565 km</td>
</tr>
</tbody>
</table>

- **Survey mode**: observes **full sky every 3 hours**
- **Public data**: available within 12 hours
DETECTION OF GAMMA RAYS WITH IMAGING AIR CHERENKOV TELESCOPES (IACT)

• γ-rays initiate electromagnetic showers in Earth’s atmosphere

• e^+ and e^- in shower emit Cherenkov radiation, recorded with IACTs

• Energy range: 70 GeV ≤ E ≤ 100 TeV

• Energy resolution $\Delta E/E \sim 10 - 15\%$

• Angular resolution: $\sim 0.1^\circ$

• background (cosmic-ray) rejection with event images, time structure, arrival direction

[see, e.g., Aharonian et al., 2008; Rieger et al., 2013, for reviews; image from Hinton & Hofmann 2009]
Currently operating IACTs

- **VERITAS**
  - 4 telescopes
  - Mount Hopkins, Arizona, USA

- **MAGIC**
  - 2 telescopes
  - La Palma, Canary Islands

- **H.E.S.S.**
  - 4 + 1 telescopes
  - Khomas highlands, Namibia
- **Factor ~10 improvement of point source sensitivity** over currently operating Cherenkov telescopes

- Northern and southern array for **full-sky coverage**

- Southern array: multiple telescope designs, e.g.:
  - **4 large (23m) telescopes**, energy threshold ~30 GeV
  - **25 mid-sized (12m) telescopes + U.S. Schwarzschild-Couder telescopes**, 100 GeV - 10 TeV
  - **70 Small (4m) telescopes**, covering > 3km$^2$, large collection area for $E > 10$ TeV
**CTA Timeline**

**Project Phases**

- **Pre-Construction Phase**
  - Finish End of 2016

- **Pre-Production Phase**
  - 2017 - 2018

- **Production Phase**
  - 2019 - 2024

**Current Phase**

- **Pre-Construction Phase**

**Current Timeline**

- **Jul 2015**
- **Oct 2015**
- **Jan 2016**
- **Apr 2016**
- **Jul 2016**
- **Oct 2016**
- **Jan 2017**
- **Apr 2017**

- Site Negotiations Begin
- Instrument Contribution Expressions of Interest Received
- Initial Evaluation of Resources
- Initial Design Acceptance
- Headquarters Site Decision
- Work Begins On Site
- Financial Ability to Continue
- Call for Offers
- International Agreement
The claim

“(Millisecond) pulsars cannot account for the Inner Galaxy’s GeV Excess”

Hooper+ 2013

See also: Cholis+14; Linden 15; Petrovic+14; Abazajian+14

“They are not abundant enough in the Galactic bulge”

Who knows? Only MSPs at O(1 kpc) distances can be observed easily. Dynamical models actually suggest that MSPs are distributed similar to what the GeV excess suggests (Brandt & Kocsis ’15)

“Their progenitor systems (LMXB) are not abundantly observed in the bulge”

True, but the life-cycle of LMXBs are far from understood.

“Their observed gamma-ray spectrum is not compatible with the GeV excess”

Wrong. We demonstrated (Calore+13) that systematics are too large for this statement.

“Bulge MSPs should have been seen as individual sources, but they haven’t”

2x wrong. We showed (Bartels+15) that gamma-ray observations are not only compatible with the MSP hypothesis, but that they prefer it with high statistical significance.

“The wavelet fluctuation signal is just gas”

Almost certainly wrong. Masking problematic sky regions with strong gas contributions does not alter results significantly (Bartels+ in prep)

“The brightest bulge MSPs should have been seen in radio”

Wrong. We showed (Calore+15) that they are instead just around the corner.

BUSTED
SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

- Radio galaxy NGC 1275, bright Fermi source [e.g. Abdo et al. 2009]
- In the center of cool-core Perseus cluster
- Rotation measures: central B field $\sim 25\mu G$ [Taylor+ 2006]
- $B \gtrsim 2 \mu G$ from non-observation of $\gamma$ rays [Aleksic et al. 2012]
MODELING PHOTON-ALP CONVERSIONS IN PERSEUS CLUSTER

- Considered $B$ fields: Perseus cluster & Milky Way
- Conservative estimate of central $B$ field: $10 \, \mu G$ [Aleksić et al. 2012]
- Includes EBL absorption

$P_{\gamma\gamma}(E, m_a, g_{a\gamma}, B)$

[Ajello et al. 2016]
FERMI-LAT DATA ANALYSIS

• 6 years of Pass 8 Source data

• Split into analysis EDISP event types

• Method: log-likelihood ratio test for no-ALP and ALP hypothesis

• Use bin-by-bin likelihood curves, similar to dSph analysis [Ackermann et al. 2014, 2015]

• Hypothesis test calibrated with Monte-Carlo simulations

[Ajello et al. 2016]
NO ALP OBSERVED: CONSTRAINTS
FIT WITH ALPS NOT PREFERRED

[Diagram showing the relationship between $g_{\alpha\gamma}$ and $m_\alpha$ (neV) with different expected and observed regions highlighted.]

[Ajello et al. 2016]
THE STRONG CP PROBLEM

- In electroweak interactions: Parity (P) and time-reversal (T) symmetries commonly broken
- However: not observed in QCD — But should be there!

\[
\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu} a G^{\mu\nu}_a + \sum_q i \bar{q} \gamma^\mu D_\mu q - q m \bar{q} + \frac{\alpha_s}{8\pi} \theta G_{\mu\nu} a \tilde{G}^{\mu\nu}_a
\]

\[\theta \in \left(-\pi; \pi\right)\quad \text{Infinitely many versions of QCD — all violate P,T}\]
NEUTRON EDM

MOST IMPORTANT P, T VIOLATING OBSERVABLE

\[ \theta \sim \mathcal{O}(1) \]

\[ d_n \sim \theta \times \mathcal{O}(10^{-15}) \text{ e cm} \]

[Slide adopted from J. Redondo]
NEUTRON EDM

MOST IMPORTANT $P, T$ VIOLATING OBSERVABLE

$\theta \sim \mathcal{O}(1)$

$d_n \sim \theta \times \mathcal{O}(10^{-15}) \text{e cm}$

NOT OBSERVED — STRONG CP PROBLEM

$|\theta| < 10^{-10}$

[Slide adopted from J. Redondo]
SOLUTION: MAKE $\theta(t,x)$ A DYNAMICAL FIELD

- If $\theta(t,x)$ is dynamical field, relaxes to its minimum
- Solves strong CP problem [Peccei & Quinn 1977]

[Slide adopted from J.Redondo]
AXION-LIKE PARTICLES (ALPs)

- Phenomenology closely related to that of axions

- Predicted in several extensions of the standard model (Majoron, Familon, …)  
  [Chikashige et al. 78; Langacker et al. 86; Wilczek 82]

- Occur whenever additional symmetries are explicitly broken

- Do not solve the strong CP problem

- For instance: occur as Kaluza-Klein zero modes in compactifications in string theory — whole Axiverse predicted!  
  [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli et al. 12]
AXIONS/ALPs AS DARK MATTER
MISALIGNMENT MECHANISM

- Coherent oscillations = dark matter axions
- Oscillation frequency $\omega = m_a$
- Energy density: $\rho_{aDM} \sim \frac{1}{2}(75 \text{ MeV})^4 \theta_0^2$

[Slide adopted from J. Redondo]
[e.g. Arias et al. 2012]
SOLUTION: MAKE $\theta(t, x)$ A DYNAMICAL FIELD — AND A NEW PARTICLE IS BORN!

• If $\theta(t, x)$ is dynamical field, relaxes to its minimum

• Solves strong CP problem [Peccei & Quinn 1977]

• Field excitations around the vacuum are particles [Weinberg 1978, Wilczek 1978]
SOLUTION: MAKE $\theta(t, x)$ A DYNAMICAL FIELD — AND A NEW PARTICLE IS BORN!

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IRREGULARITIES MOVE OUT OF THE FERMI-LAT ENERGY RANGE

IRREGULARITIES MOVE INTO THE FERMI-LAT ENERGY RANGE

AMPLITUDE OF IRREGULARITIES BECOMES TOO SMALL

\[ g_{\gamma} \left(10^{-11} \text{ GeV}^{-1}\right) \]

\[ m_a \ (\text{neV}) \]

[Ajello et al. 2016]
UNDERSTANDING THE LIMITS

LAST OSCILLATION (BROAD) AT 1 GEV, BUT NOT AS PRONOUNCED ANYMORE, OVERALL SPREAD DECREASES.

"QUENCHING" AT HIGH COUPLINGS DUE TO GMF.

IRREGULARITIES OVER ENTIRE ENERGY RANGE.
UNDERSTANDING THE LIMITS

LAST OSCILLATION (BROAD) AT 1 GEV, BUT NOT AS PRONOUNCED ANYMORE,
OVERALL SPREAD DECREASES.

IRREGULARITIES OVER ENTIRE ENERGY RANGE

INCREASING COUPLING:
1. ENERGY RANGE OF IRREGULARITIES DECREASES
2. SPREAD BETWEEN B FIELD REALIZATION DECREASES (GAL FIELD)

[Ajello et al. 2016]
COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

BEST FIT — NOT PREFERRED

\[ m_{\text{neV}} = 44.61, \quad g_{11} = 4.76 \]

- Red line: Summed fit, \( \ln \mathcal{L} = -199.48 \)
- Blue line: Summed fit w/o ALP, \( \ln \mathcal{L} = -203.92 \)
- Max. \( \mathcal{L} \) per bin

[Ajello et al. 2016]
COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

EXCLUDED AT > 95% C.L.

$E^2 dN/dE \text{ (MeV cm}^{-2}\text{s}^{-1})$

$m_{\text{neV}} = 1.18$, $g_{11} = 1.01$

- Summed fit, $\ln \mathcal{L} = -261.65$
- Summed fit w/o ALP, $\ln \mathcal{L} = -203.92$
- max. $\mathcal{L}$ per bin

[Ajello et al. 2016]
COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

EXCLUDED AT 95% C.L.

$E^2 \frac{dN}{dE}$ (MeV cm$^{-2}$ s$^{-1}$)

$\mu$MeV = 3.96, $g_{11} = 1.01$

- Red line: Summed fit, ln$L$ = -214.43
- Blue line: Summed fit w/o ALP, ln$L$ = -203.92
- Max. $L$ per bin

[Ajello et al. 2016]
SYSTEMATIC UNCERTAINTIES

- **B-field modeling:**
  - Kolmogorov turbulence: Power-law index of turbulence \( q \)
  - Central magnetic field \( \sigma_B \)
  - Maximal spatial extent of \( B \) field \( r_{\text{max}} \)
  - Increasing \( \sigma_B \) increases excluded area of parameter space by 43%

- **Energy dispersion:**
  - Artificially broadened with 5%, 10%, 20%
  - Reduces excluded parameter space up to 25%

[Ajello et al. 2016]
ALPs would be **produced in a core-collapse SN explosion** via Primakoff process.

Could **convert into gamma-rays in Galactic magnetic field**.

Non-observation of signal from **SN1987A** with Gamma-Ray Spectrometer on Solar Maximum Mission satellite still **strongest bounds for ALPs with masses** $m_a \lesssim 1$ neV [Payez et al. 2015].
**EXPECTED ALP SIGNAL**

- ALPs produced in SN core within ~10 s after explosion and escape core ➔ short burst
- **Spectrum** has thermal-like shape, **peaks at ~50 MeV**
- Gamma rays would arrive co-incident with SN neutrinos (provides time tag)

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**ALP / γ-ray flux integrated over explosion time**

Better **gamma-ray sensitivity and large FoV** of Fermi LAT promise **unparalleled sensitivity** for ALPs in case of a Galactic core-collapse SN within Fermi-LAT lifetime and FoV

[Payez et al. 2015]
GC LIGHT CURVE OF ONE GTI WITHIN 68% PSF CONTAINMENT

- Use **Galactic Center** as target

- Estimate number of background counts from data:
  - From one exposure of the Galactic Center (~1500s)
  - Energy Range: **50-500 MeV**
  - Within **68% PSF (~ 11 degrees @ 50 MeV)**
  - Use **20s time bins** (full explosion time)

- Expected number of background counts: ~3.3

- Compare against number of **expected counts from SN explosion**

- Use **statistical test for low-count regime** [Feldman & Cousins 1998]

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**Energy range**: 50-500 MeV

**Event Class / IRF**: P8R2_TRANSIENT020_V6

**Zenith Angle**: < 80°

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; submitted; arXiv:1609:02350]
• Integrated over explosion time (~20s)

• Integrated over energy, 50-500 MeV

• Folded with Fermi-LAT instrumental response function

• Expected number of counts $\sim g_{a\gamma}^4$

• Little dependence on progenitor mass

Assuming 4 background counts in one 20s time bin:
**Exclude ALP models predicting more than 6.4 counts at 95% confidence**
TIME INTEGRATED EXPECTED ALP / $\gamma$-RAY FLUX

- Integrated over SN explosion time (20s for 18 solar masses, 10s for 10 solar mass progenitor)

\[
\frac{\mathrm{d}N_a}{\mathrm{d}E} = g_{a\gamma}^2 C \left( \frac{E}{E_0} \right)^\beta e^{-(\beta+1)E/E_0}
\]

Galactic center, $d = 8.5$ kpc, $g_{11} = 0.10$

[Collaboration with Giannotti & Mirizzi, see also Payez et al. 2015]
✓ Different progenitor masses

✓ Different Galactic magnetic field models (largest effect)

✓ Different sources (less background compared to GC)

✓ Different time intervals

✓ Analysis repeated with different time binning of 30 and 60s
CONSTRUCTING F&C CONFIDENCE INTERVAL

1. Step through expected counts $\mu$
2. For each value $\mu$: calculate log likelihood ratio (LLR) for a range of observed counts $N_{ON}$
3. Sum up poisson likelihoods for $N_{ON}$ sorted by LLR until you reach desired confidence level

$$TS = -2 \ln \left( \frac{L(\mu, \hat{b}(\mu); \alpha \mid N_{ON}, n)}{L(\hat{\mu}, \hat{b}; \alpha \mid N_{ON}, n)} \right)$$

Off counts:
$$n = \sum_i n_i$$

Exposure ratios:
$$\alpha = \left( \sum_i \epsilon_i \right)^{-1}$$

Maximum likelihood estimators:
$$\hat{b} = \alpha n$$
$$\hat{\mu} = N_{ON} - \alpha n$$

[Feldman & Cousins 1998; Rolke et al. 2005]
• Mixing in **coherent** component of B field

• **Position of SN** will determine $\gamma$-ray yield

• Two state-of-the-art models implemented

\[ g_{\alpha\gamma} = 5 \times 10^{-11} \text{ GeV}^{-1} \]

pure ALP beam propagating through entire Milky Way

[Jansson & Farrar 2012 model]