Università degli Studi di Bari Aldo Moro

Dipartimento Interateneo di Fisica «M.Merlin»

Indirect searches of dark matter

Congresso della Sezione INFN e del Dipartimento di Fisica di Bari

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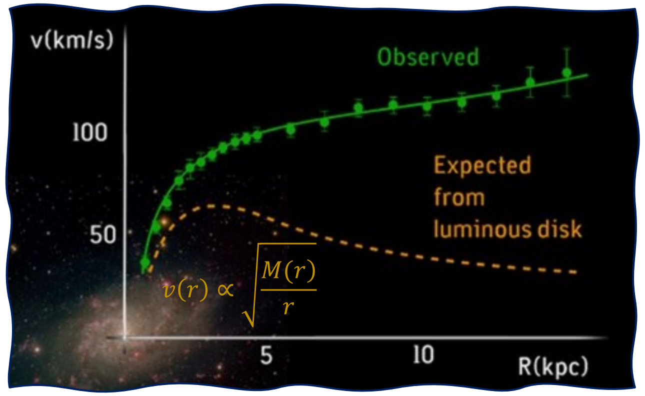
Outline

- Dark Matter
  - Properties and detection
- The Sun as a target for DM searches:
  - Solar DM models
  - Search for features in the solar gamma-ray and cosmic-ray electron and positron (CREs) energy spectra with the Fermi-LAT
    - Constraints on DM-nucleon scattering cross sections
- Search for features in the spectrum of galactic CREs
- Other targets explored with the Fermi-LAT
- Other DM searches activities in Bari
- Conclusions

Evidence for Dark Matter

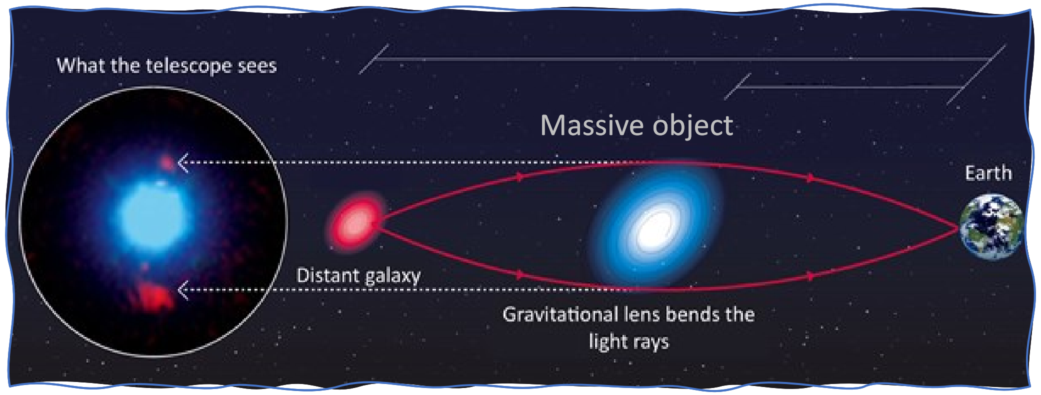
- Experimental evidences for Dark Matter:
  - Galaxy rotation curves
  - Gravitational lensing



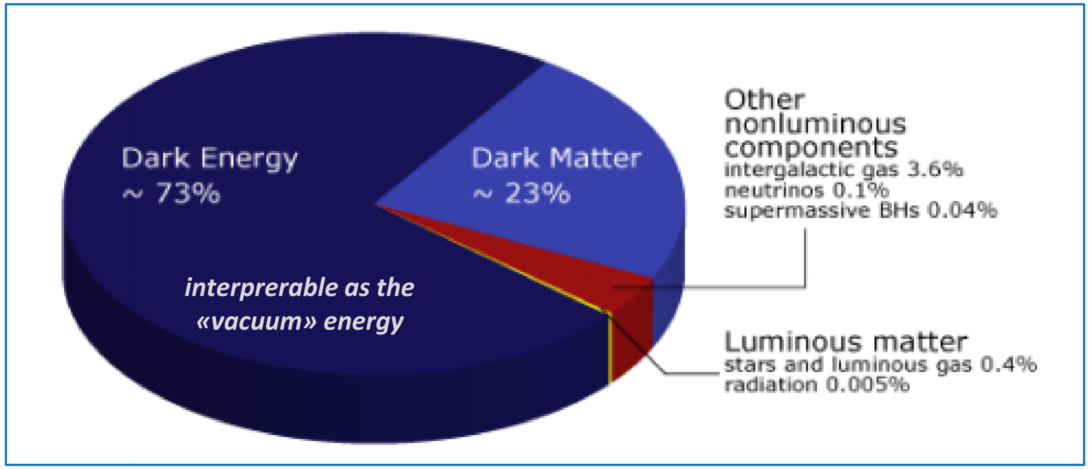
Ordinary matter inferred from known visible sources

+

Missing Dark matter



- The ΛCDM model is currently the most credited cosmological model, which explains the structure of the universe (isotropic and homogeneous on large scale) and its expansion
  - *Our Universe is composed only by a small fraction of visible baryonic matter (~ 4%), while the largest part consists of dark matter (~ 23%) and dark energy (~ 73%)*
    - $\Omega_b h^2 = 0.02237 \pm 0.00015$
    - $\Omega_{DM} h^2 = 0.1200 \pm 0.0012$



Dark Matter candidates

➢DM properties:

- Non-baryonic
- Cold
- Neutral particles (do not interact electromagnetically)
- DM should interact with ordinary matter, preferably only weakly
- DM self-interactions are weak
- Very stable particles with respect to the cosmological time scale

No Standard Model particle matches the known properties of DM

➢Possible theoretical candidate:

- Weakly interacting Massive Particles (WIMPs)
    - Neutralino χ

[1] Roszkowski, L., Sessolo, E. M., & Trojanowski, S. (2018). WIMP dark matter candidates and searches—Current status and future prospects. *Reports on Progress in Physics*, *81*(6), 066201.

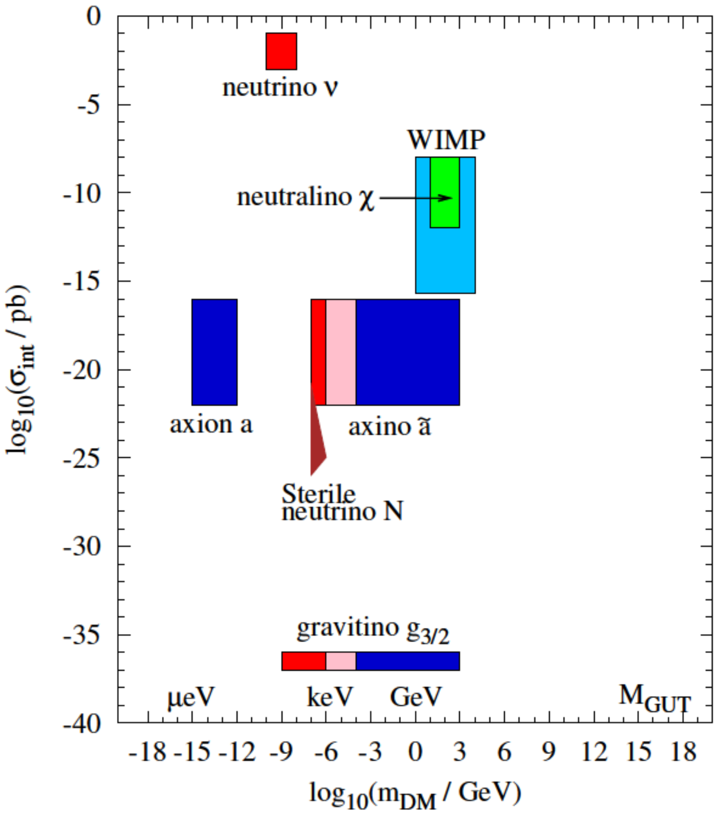
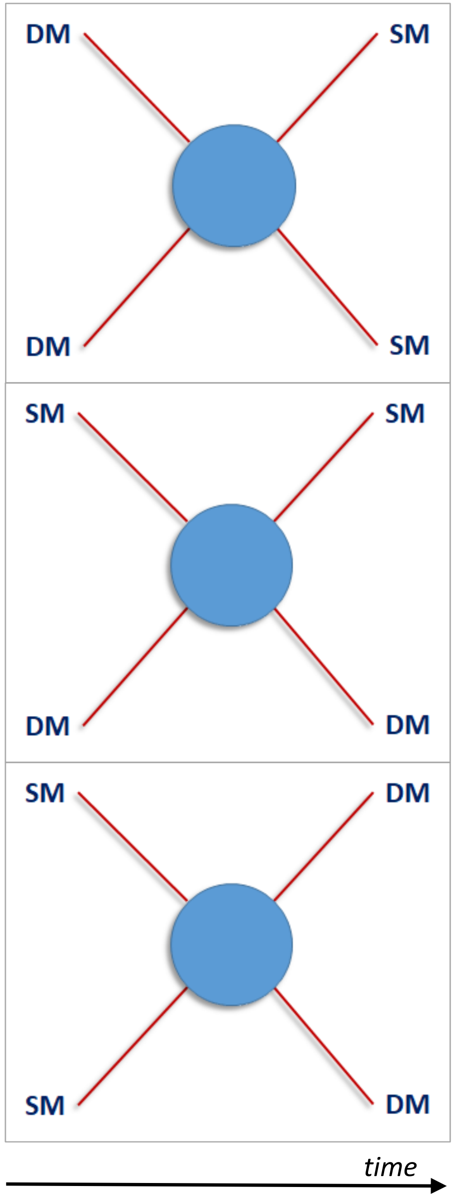


Fig. *Typical ranges of the cross section of DM interactions with ordinary matter vs DM mass for some of DM candidates.*

Searching for WIMPs

SM → ***S**tandard **M**odel particle*
DM →***D**ark **M**atter*



Indirect detection

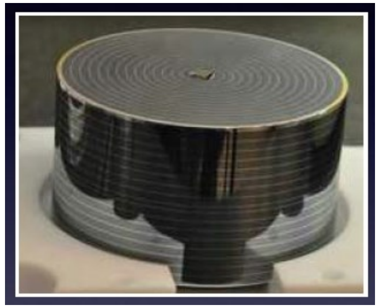
$$\chi + \chi \rightarrow SM + \mathrm{SM}$$

in space

Direct detection

$$\chi + \mathrm{SM} \rightarrow \chi + \mathrm{SM}$$

underground



Production

$$pp \rightarrow \chi\chi + X$$

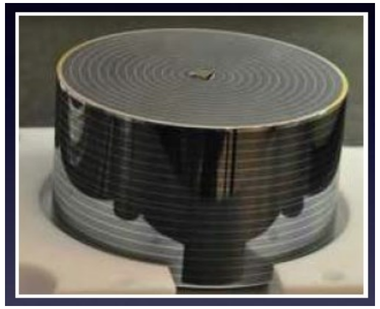
At accelerators

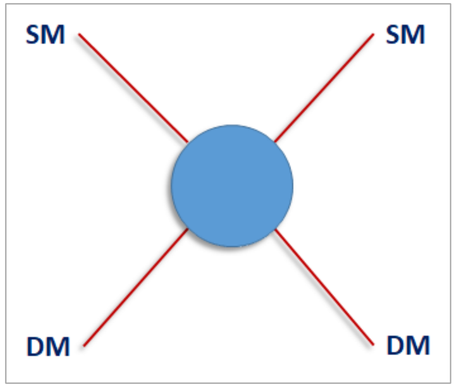
WIMP «Hunters»

➢ *Direct detection strategy*

- experiments are aimed to observe the small and rare signals induced by DM particle scattering in a detector
  - in the form of ionization, scintillation or lattice vibrations

underground



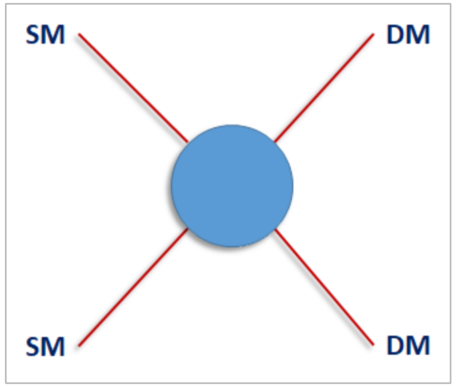


$\chi + \mathrm{SM} \rightarrow \chi + \mathrm{SM}$

➢ ***Particle colliders*** might produce DM in high energy particle collisions

- looking for a DM production signature by searching events with significant missing energy/momentum from the reconstructed jets produced in the reaction
  - It would be associated to the energy/momentum carried away by the DM particles escaping from the detector

At accelerators



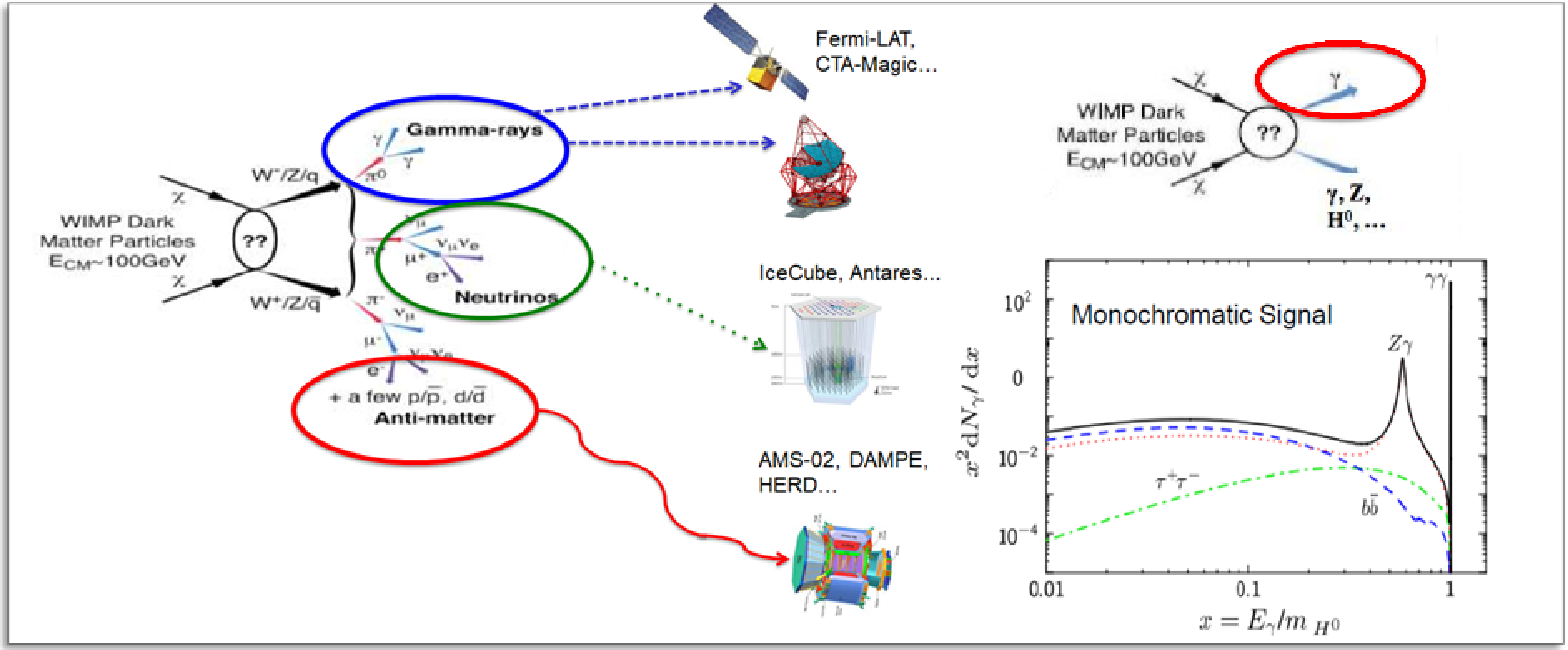
$pp \rightarrow \chi\chi + X$

*where X is whatever SM particles produced in the reaction

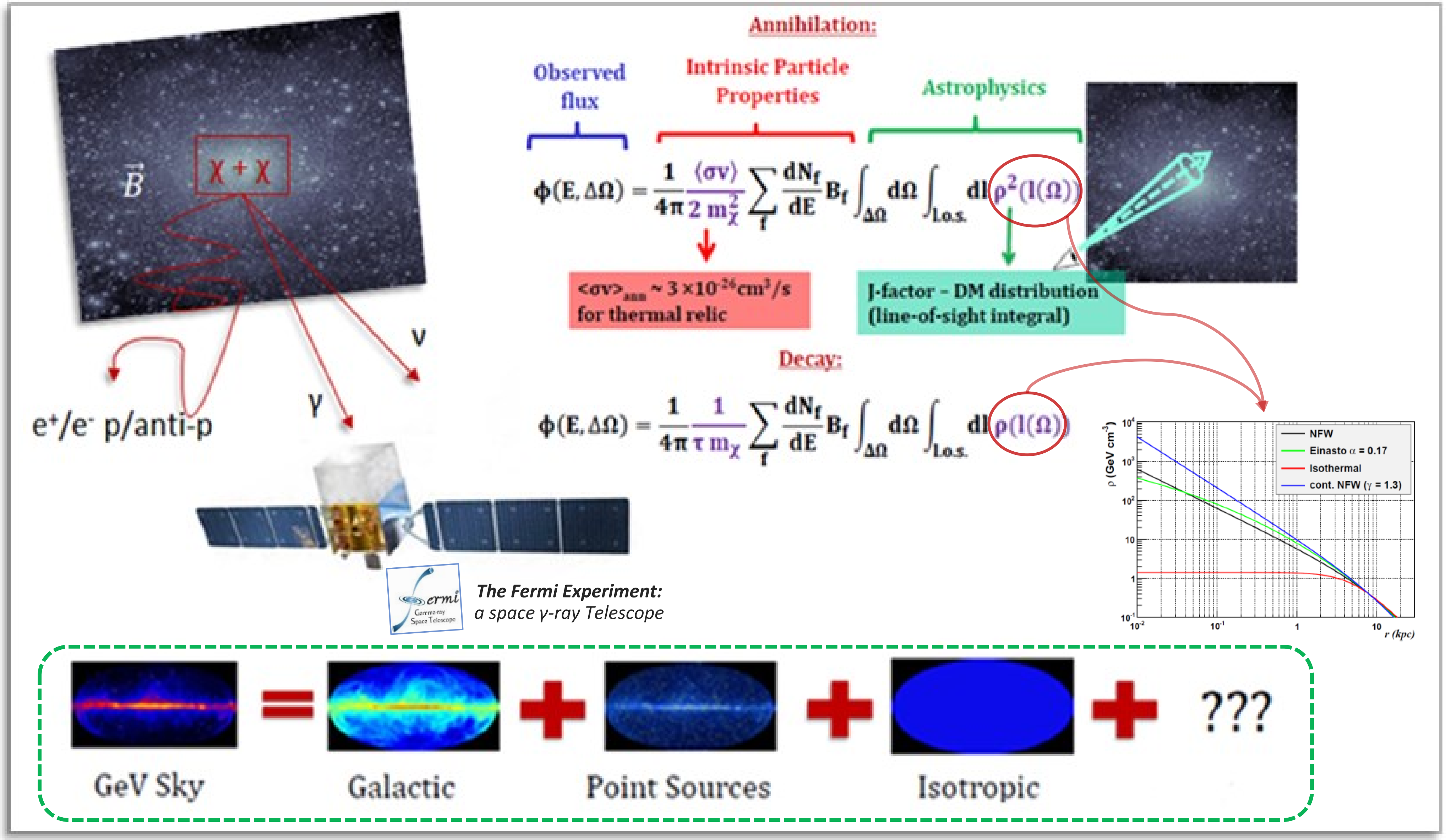
Indirect detection of DM

- **How can we detect DM?**
  - **direct search**
  - **production at colliders**
  - ***indirect search***
    - charged particles e$^+$/e$^-$, p
    - *neutral particles* γ,ν → ***Neutral messengers***→ *they are not deviated by magnetic fields* and therefore they point directly to the sources

- ***WIMPs annihilation***



Indirect detection of DM with γ rays: strategy



Annihilation:

$$\overbrace{\phi(E,\Delta\Omega)}^{\text{Observed flux}} = \frac{1}{4\pi}\overbrace{\frac{\langle\sigma v\rangle}{2\,m_\chi^2}\sum_f \frac{dN_f}{dE}B_f}^{\text{Intrinsic Particle Properties}}\overbrace{\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\,\rho^2(l(\Omega))}^{\text{Astrophysics}}$$

$<\sigma v>_{ann} \sim 3\times10^{-26}\,cm^3/s$ for thermal relic

J-factor – DM distribution (line-of-sight integral)

Decay:

$$\phi(E,\Delta\Omega) = \frac{1}{4\pi}\frac{1}{\tau\,m_\chi}\sum_f \frac{dN_f}{dE}B_f\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\,\rho(l(\Omega))$$

The Fermi Experiment:
a space γ-ray Telescope

Optimal targets:

- highest J-factors
- lowest astrophysical background

Gamma-ray signal from WIMPs

➢Gamma-ray flux produced by DM self-annihilation or decays from a given direction ψ in the sky, within a region covering a solid angle $\Delta\Omega$:

$$\Phi_{DM}(E,\Delta\Omega,\psi) = \Phi_{PP}(E) J(\Delta\Omega,\psi)$$

- Φ_{PP} (E) is the particle physics factor
  - depends on the physics of the processes involved
- $J(\Delta\Omega,\psi)$ is the astrophysical factor (J-factor)
  - depends on the DM density distribution along the line-of-sight

particle – physics factor

$$\Phi_{PP,ann}(E) = \frac{1}{4\pi}\frac{<\sigma_{ann}\,v>}{2m_\chi^2}\left(\frac{dN_\gamma}{dE}\right)_{ann}$$

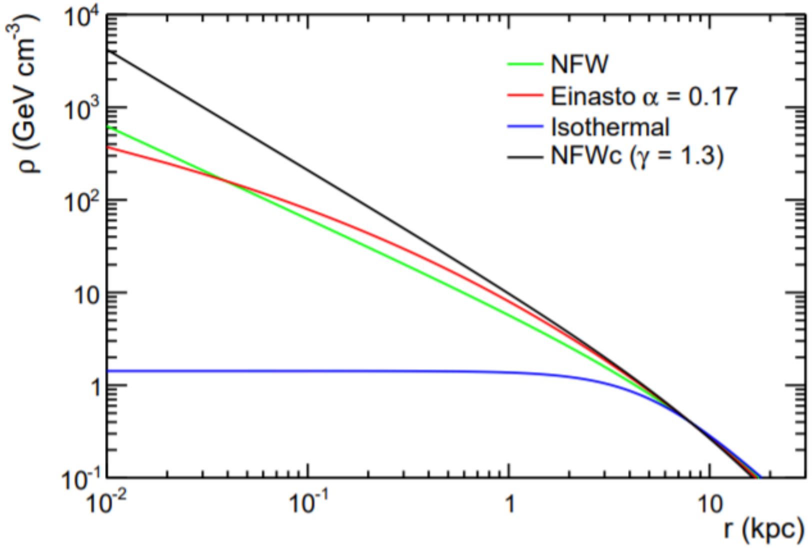
$$\Phi_{PP,ann}(E) = \frac{1}{4\pi}\frac{1}{m_\chi \tau}\left(\frac{dN_\gamma}{dE}\right)_{dec}$$

J-factor

$$J_{ann}(\Delta\Omega,\psi) = \int d\Omega \int_{l.o.s.} dl(\psi)\rho_{DM}^2(r)$$

$$J_{dec}(\Delta\Omega,\psi) = \int d\Omega \int_{l.o.s.} dl(\psi)\rho_{DM}\,(r)$$

Galactic DM density profiles.

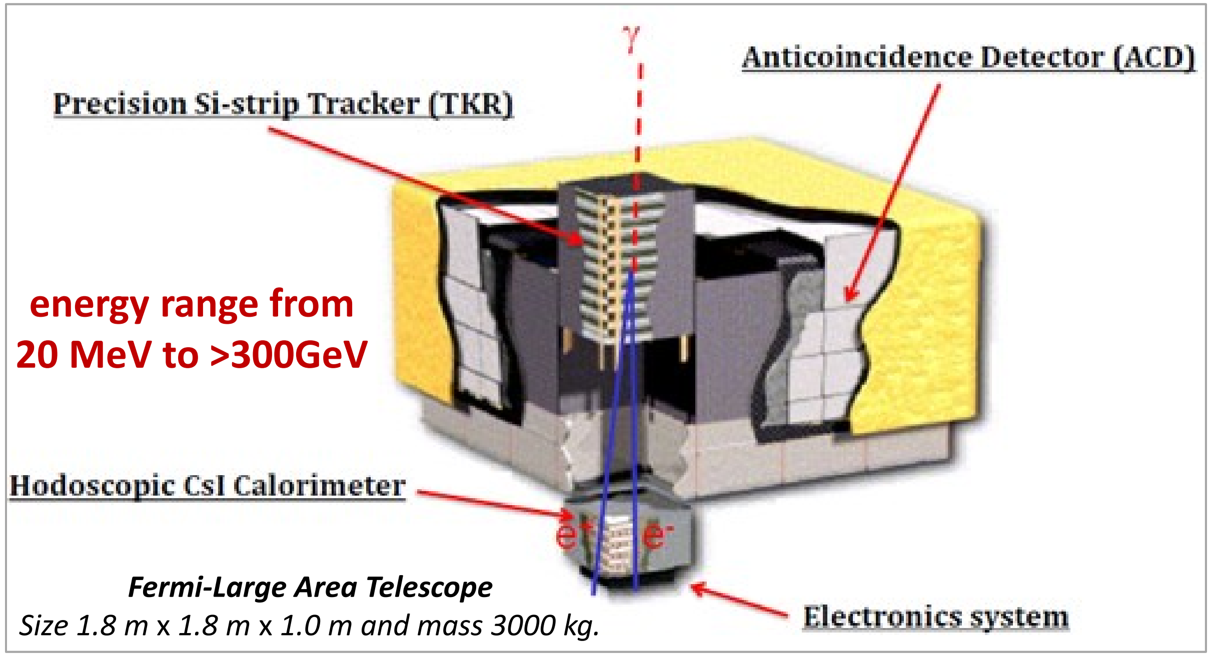


The Fermi LAT: a space γ -ray Telescope

- The Large Area Telescope (LAT) onboard the Fermi satellite
  - Converter-tracker system to track the electron-positron pairs generated by incident gamma rays + calorimeter to reconstruct energy
- 4x4 towers (37cm x 37cm x 85 cm)
  - tracker (TKR)
  - electromagnetic CsI(Tl) Calorimeter (CAL)
- Segmented Anti-Coincidence Detector (ACD)

The LAT can also work as a CRE detector

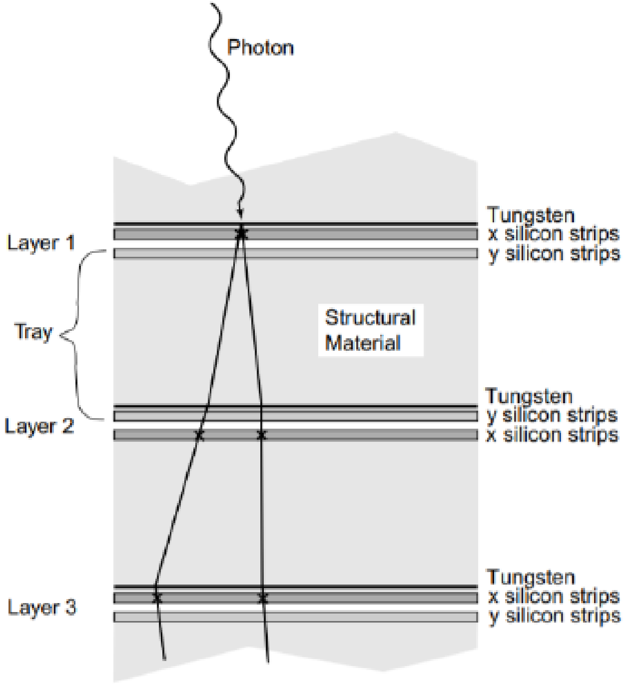
June 11th, 2008 Cape Canaveral (Florida)



energy range from 20 MeV to >300GeV

Fermi-Large Area Telescope

Size 1.8 m x 1.8 m x 1.0 m and mass 3000 kg.



The Sun as a target for DM searches

Signals from DM annihilations in the Sun

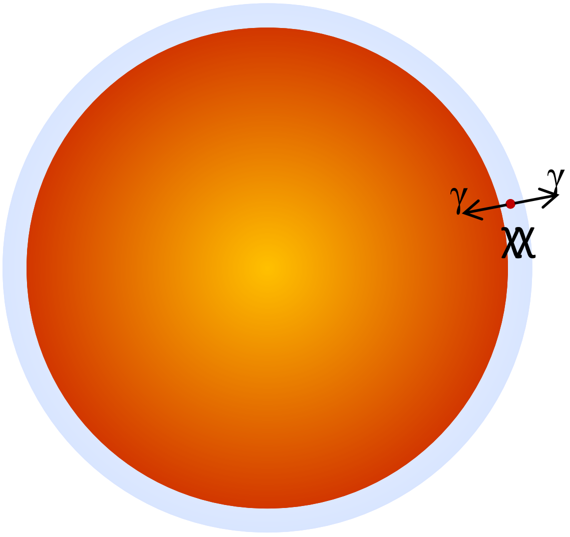
- DM particles from the galactic halo can be gravitationally trapped by the Sun through scattering interactions with the nuclei in the solar environment
  - DM particles can be captured by the Sun in external orbits (thus forming a halo around the Sun) and then annihilate outside the Sun producing gamma rays, electrons, or other SM particles:

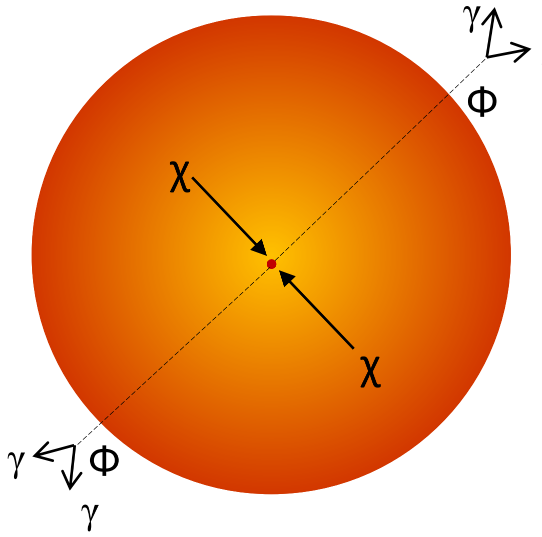
$$\chi\chi \to \gamma\gamma, \chi\chi \to e^+e^-, \ldots$$

  - DM particles can continue to lose energy through subsequent scatterings, reaching the thermal equilibrium at the Sun core
    - The over density of DM in the core can result in annihilations into SM particles
    - SM particles produced in the Sun (with the exception of neutrinos) are absorbed in the Sun interior
    - DM particles can annihilate into pairs of long-lived mediators that can escape and decay outside the Sun into gamma rays, electrons, or other SM particles:

$$\chi\chi \to \phi\phi, \phi \to \gamma\gamma, \phi \to e^+e^-, \ldots$$

- Both scenarios predict an enhancement of the gamma-ray (CRE) flux from the Sun
  - Line-like feature expected in case of direct annihilations in SM particles
  - Box-like feature expected in the mediator scenario (see next slide)

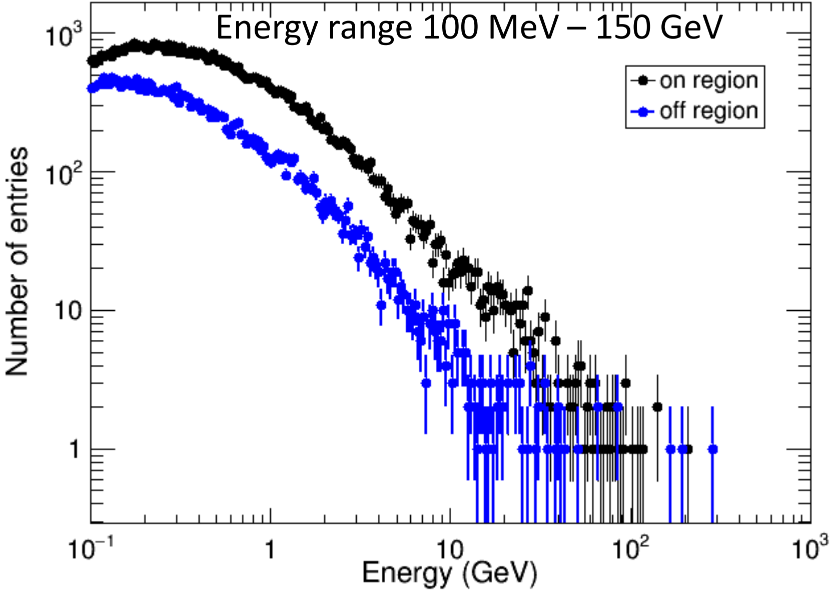


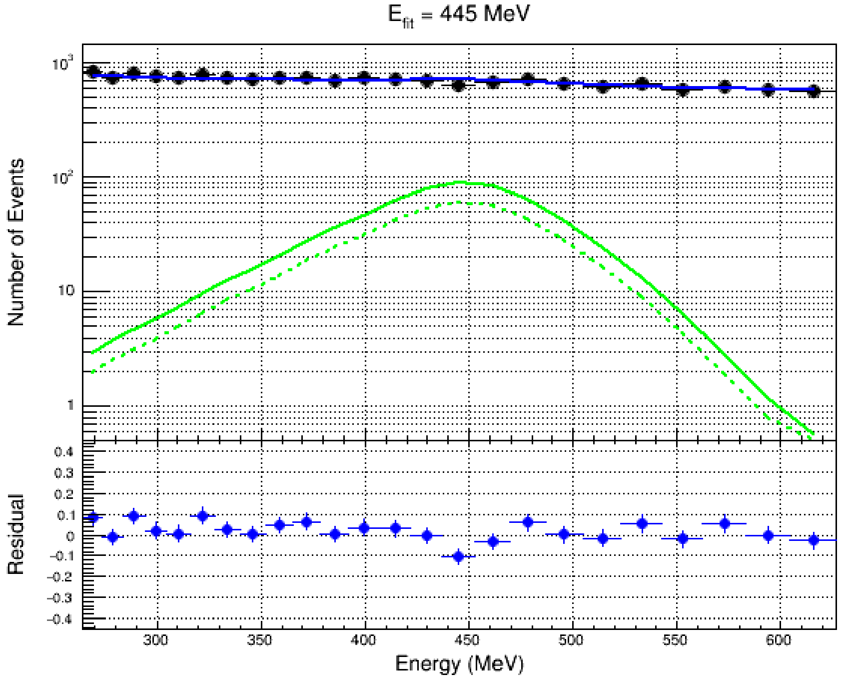


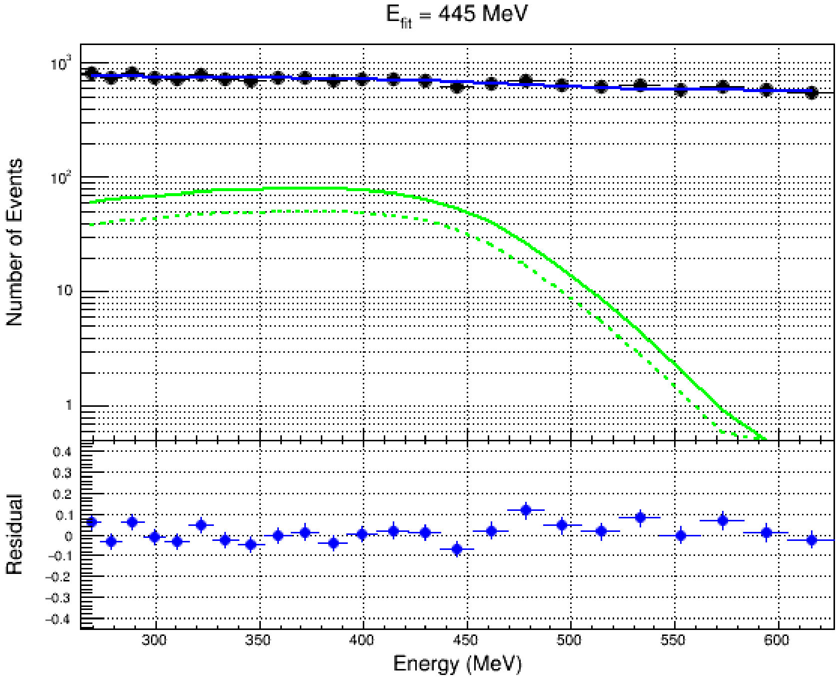
Fermi LAT data analysis: Search for line-like and box-like features

- ON/OFF technique analysis:
  - The Sun is a moving source
  - ON Region : RoI of 2° angular radius centered on the Sun current position
  - OFF Region: RoI of 2° angular radius centered on the 6 months time-offset position
    - The OFF region follows the same path in the sky of the Sun
    - Used as control region to constrain the background
- Analysis performed in sliding energy windows
  - Search for possible local features
  - Poisson maximum likelihood approach used to combine data from ON and OFF regions
- Significance of possible features evaluated
  - ***All possible features turn out to be statistically insignificant***

10-years of Fermi-LAT observation

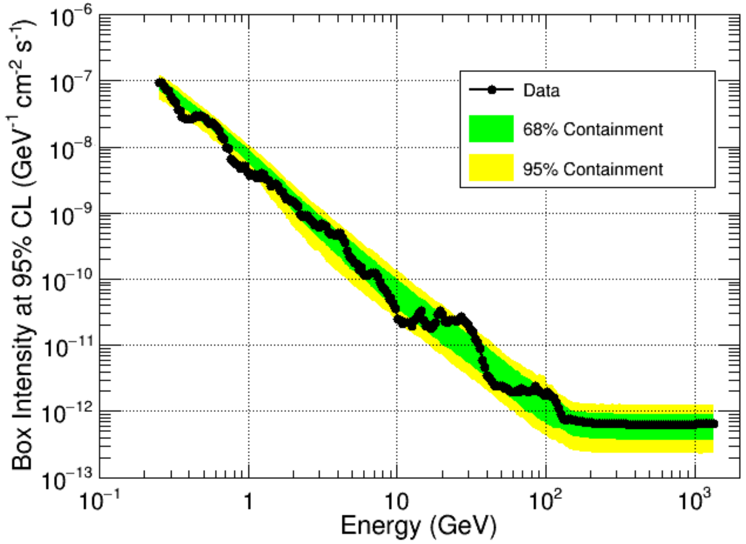


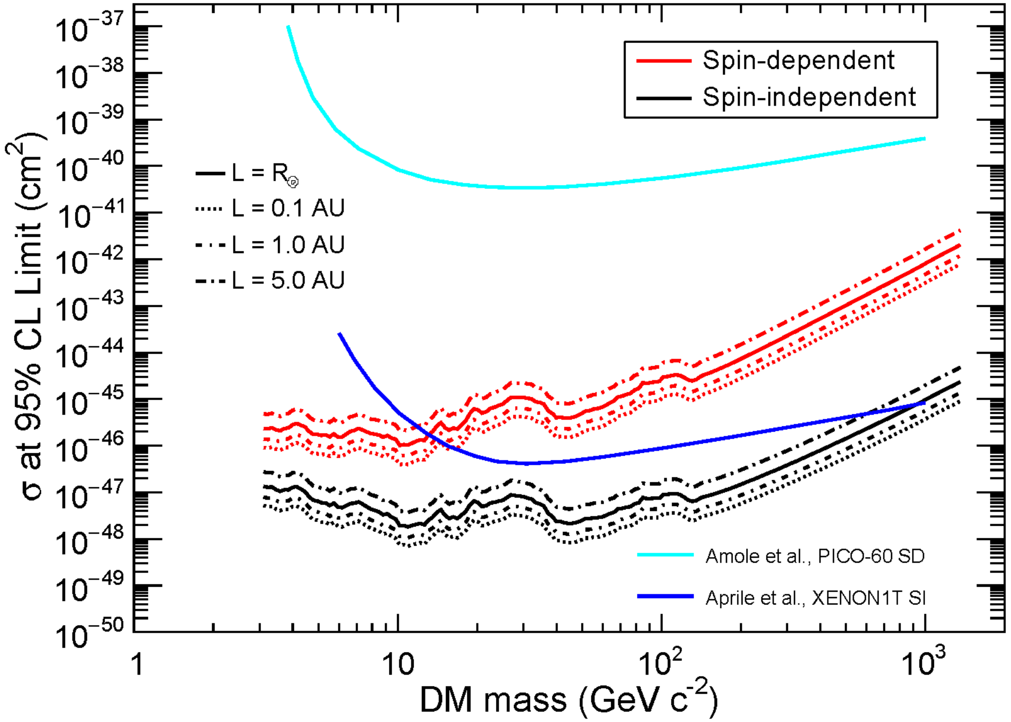


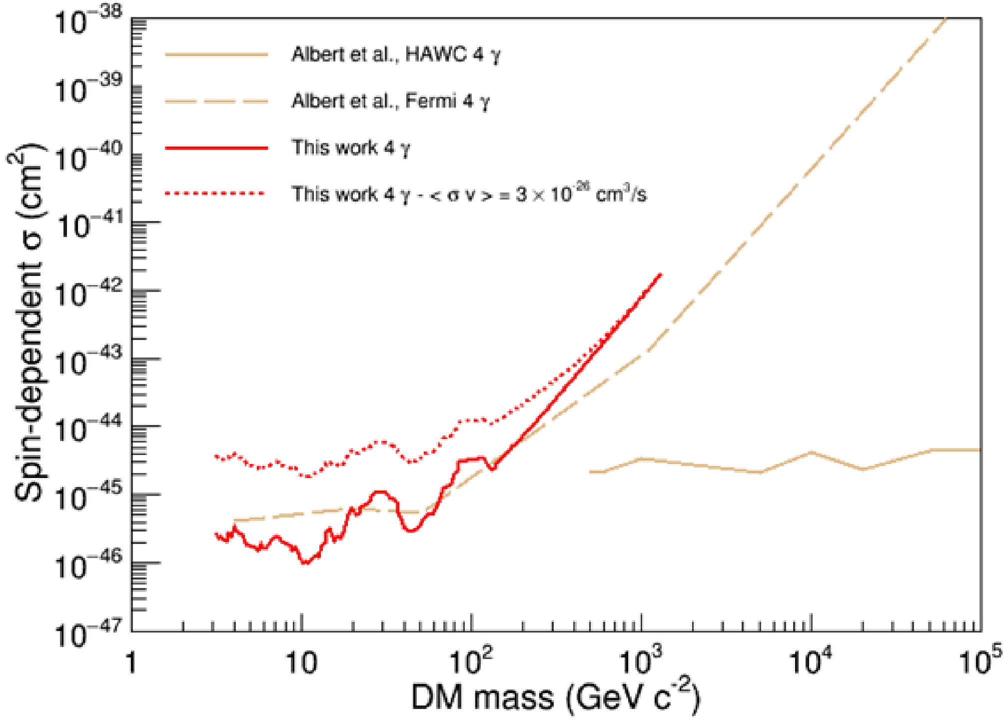


Summary of the fit results

- The limits on the box feature intensities can be converted into limits on the DM-nucleon cross section by means of the capture rate
- Results are in agreement with other experiments
  - For further details see M. N. Mazziotta, F. Loparco, D. Serini et al., Physical Review D, 102(2), 022003

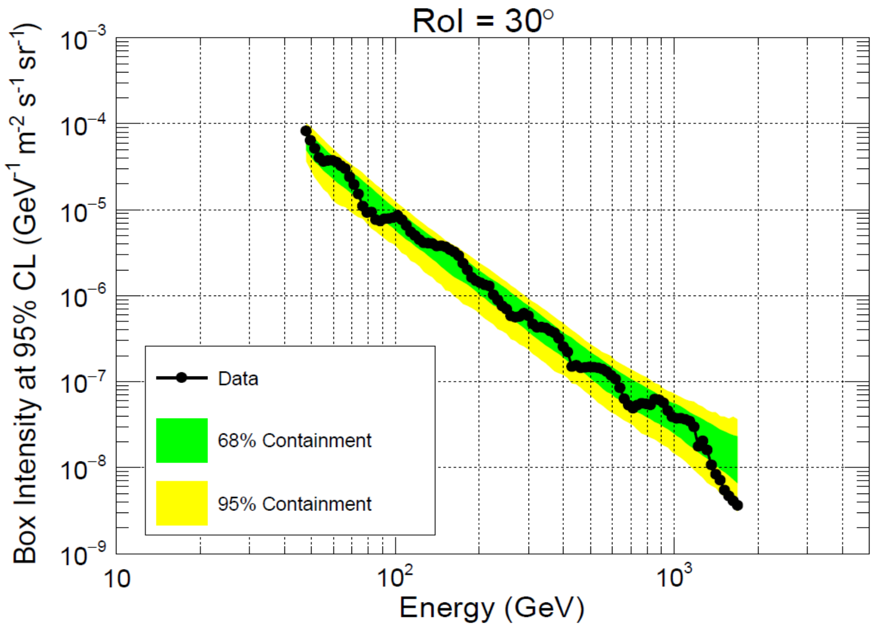


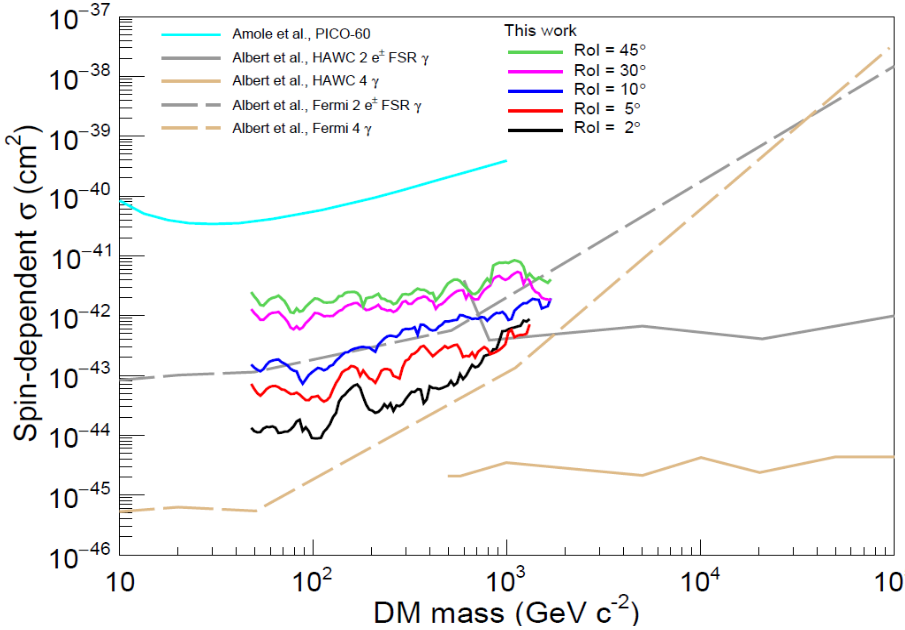




Search for features in the Solar CRE spectrum

- A search for box-like and line-like features has been performed also in the CRE spectrum
  - Analysis procedure similar to that used for gamma rays
  - Signal regions of different angular radii chosen to account for CREs being deflected by the Solar magnetic field
- No statistically significant features found
  - Upper limits on the DM-nucleon scattering cross sections derived from the upper limits on the box-like feature intensity
  - More details in A. Cuoco, P. De La Torre Luque, F. Gargano, M. Gustafsson, F. Loparco, M. N. Mazziotta and D. Serini, Physical Review D101 (2020), 022002





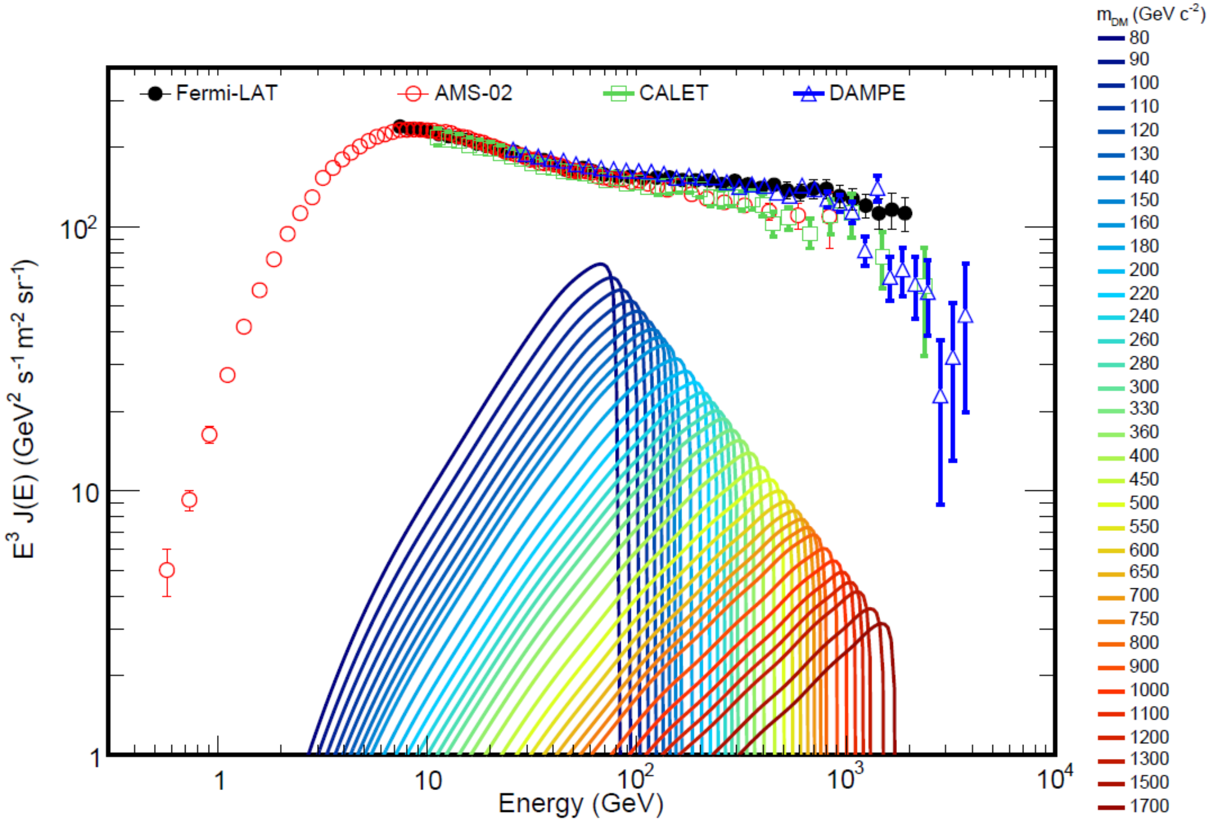
CREs from DM annihilations in the Milky Way

Analysis of Galactic CREs

- DM particles in the Milky Way halo can directly annihilate into electron-positron pairs in the process:

$$\chi\chi \rightarrow e^{+}e^{-}$$

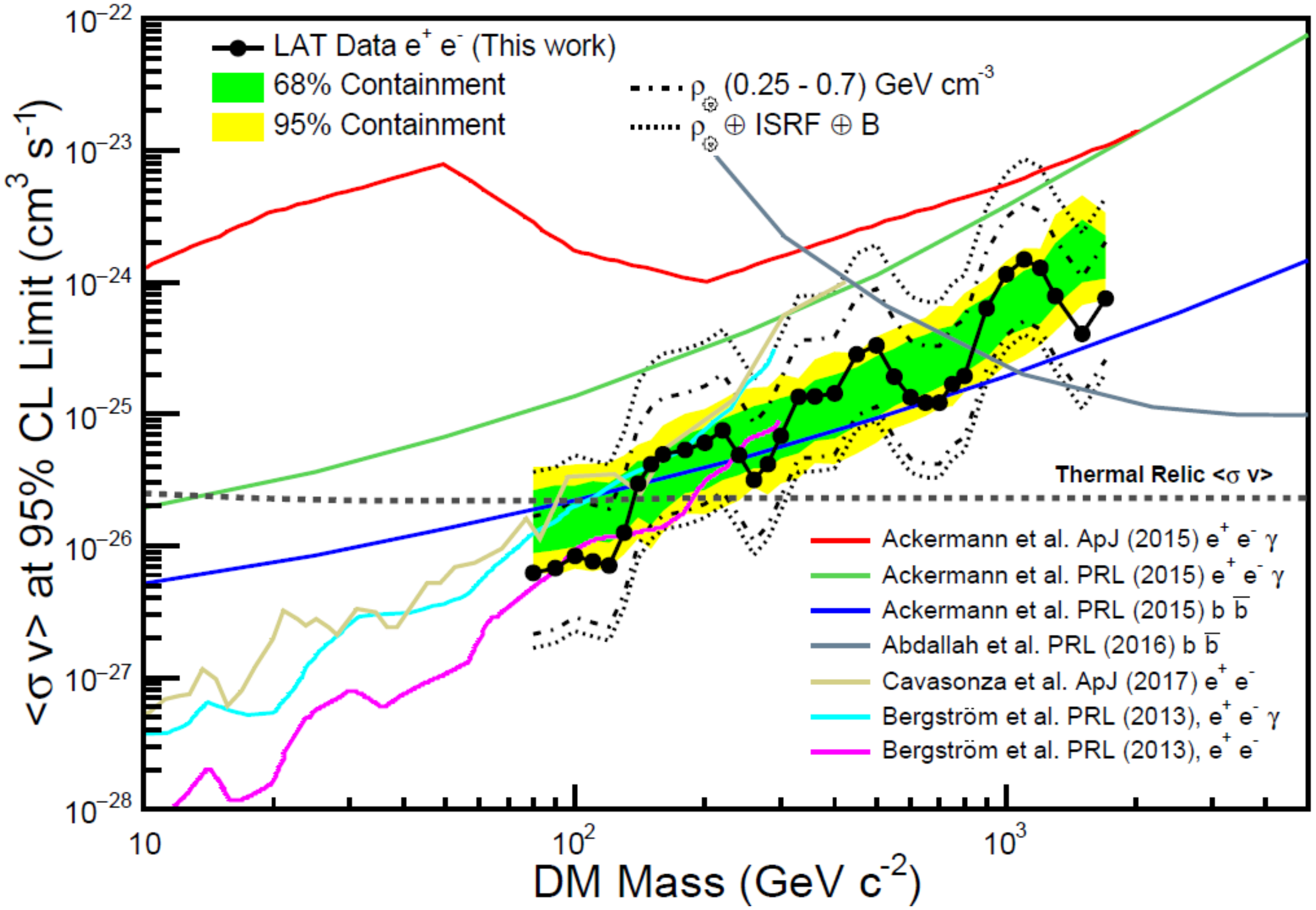
- The CRE energy spectra at Earth from DM annihilations depend on:
  - Dark matter mass m_χ and velocity-averaged DM annihilation cross section $\langle\sigma v\rangle$
  - DM density profile in the Galaxy
  - Propagation of CREs in the Galaxy
  - Propagation of CREs in the Solar system
- CRE spectra at Earth expected to exhibit an edge-like feature at $E = m_\chi$
  - Intensity of the feature proportional to $\langle\sigma v\rangle$
- The energy spectrum of Galactic CREs has been fitted in sliding energy windows to search for possible local edge-like features



- CRE spectra evaluated with $\langle\boldsymbol{\sigma v}\rangle = \mathbf{3 \times 10^{-25} cm^3 s^{-1}}$
- DM spectra are compared with the overall CRE spectra measured by different experiments

Analysis results

- Possible DM features are not significant
- Limits on the strength of the feature are converted into limits on $\langle \boldsymbol{\sigma v} \rangle$
  - Constraints in agreement with results from previous experiments
  - For further details see M. N. Mazziotta et al., Phys. Rev. D98 (2018), 022006



Other targets explored by the Fermi-LAT

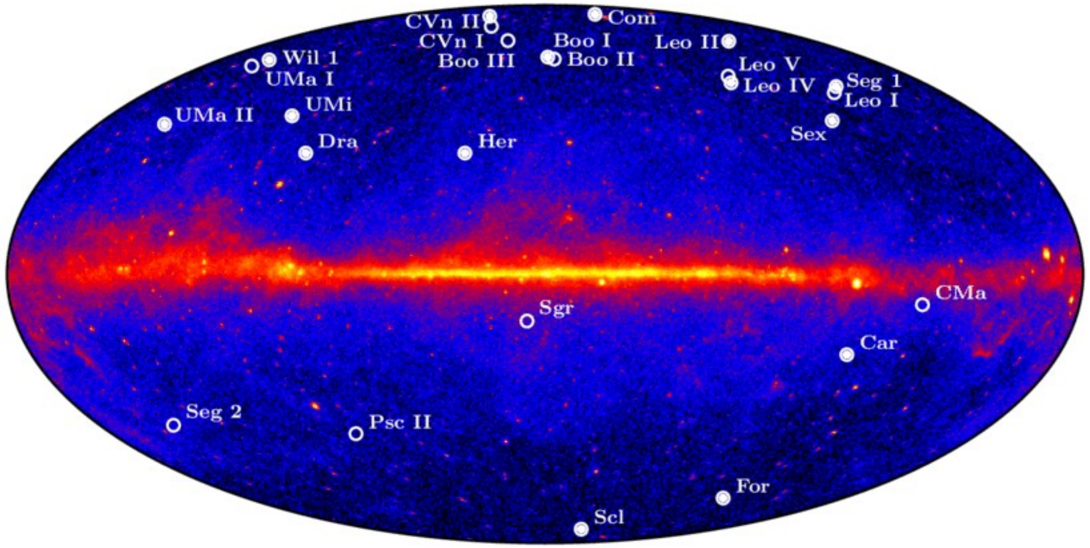
Gamma-ray signal from WIMPs

➢Galactic Center (GC)

- Largest J-factor (J ~ 10^{22} GeV^2/cm^5 within 1° solid angle), but high astrophysical backgrounds
- An excess of gamma rays with respect to the modeled diffuse emission in the GC region at a few GeV is well established
  - Possible DM interpretation

➢Milky Way Dwarf Spheroidal Galaxies (dSphs):

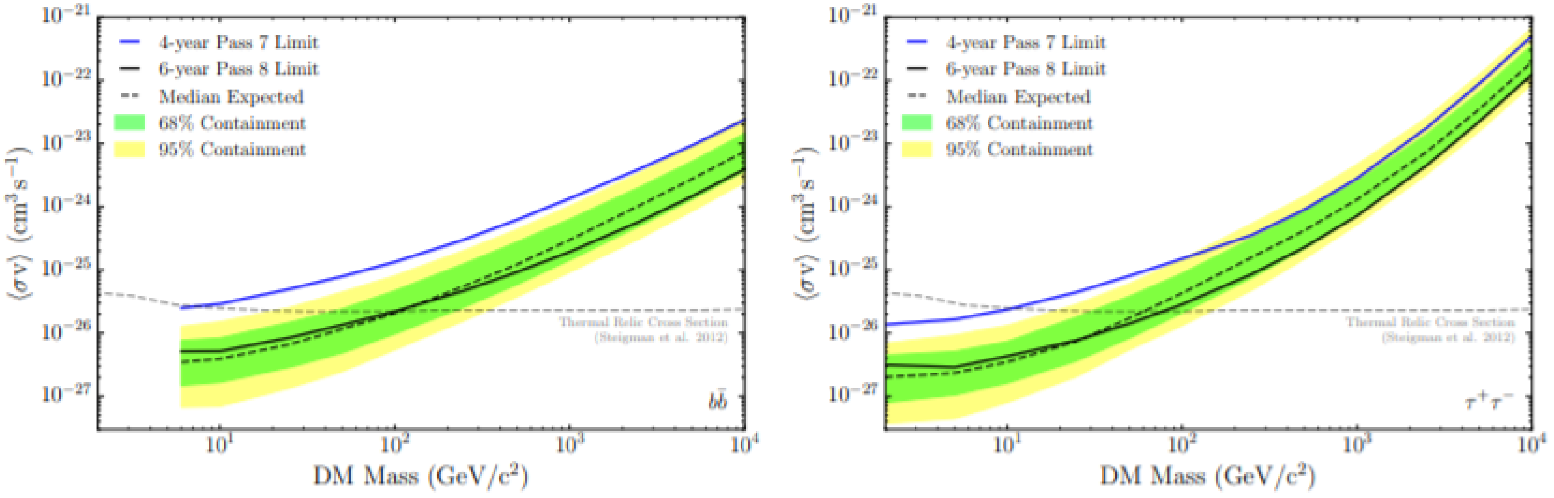
- Clean targets, but lower J-factors (J ~ 10^{18} - 10^{20} GeV^2/cm^5 with 1° solid angle)
  - Upper limits on the velocity-averaged DM annihilation cross sections



Name	l [deg]	b [deg]	D [kpc]	r_s/D [deg]	$\log_{10}(J_{\mathrm{obs}})$ [$\log_{10}(\mathrm{GeV}^2\mathrm{cm}^{-5})$]
Bootes I	358.08	69.62	66	0.23	18.8 ± 0.22
Canes Venatici II	113.58	82.70	160	0.071	17.9 ± 0.25
Carina	260.11	-22.22	105	0.093	18.1 ± 0.23
Coma Berenices	241.89	83.61	44	0.23	19.0 ± 0.25
Draco	86.37	34.72	76	0.26	18.8 ± 0.16
Fornax	237.10	-65.65	147	0.17	18.2 ± 0.21
Hercules	28.73	36.87	132	0.081	18.1 ± 0.25
Leo II	220.17	67.23	233	0.071	17.6 ± 0.18
Leo IV	265.44	56.51	154	0.072	17.9 ± 0.28
Sculptor	287.53	-83.16	86	0.25	18.6 ± 0.18
Segue 1	220.48	50.43	23	0.36	19.5 ± 0.29
Sextans	243.50	42.27	86	0.13	18.4 ± 0.27
Ursa Major II	152.46	37.44	32	0.32	19.3 ± 0.28
Ursa Minor	104.97	44.80	76	0.35	18.8 ± 0.19
Willman 1	158.58	56.78	38	0.25	19.1 ± 0.31

Table 1. DSphs used in the present analysis and their main properties: Name, Galactic longitude and latitude, distance to Earth, angular size of the DM halo scale radius, and J-factor (with statistical uncertainty) assuming an NFW density profile and integrated to a radius of 0.5° from the dSph center.

Gamma-ray signal from WIMPs (2)

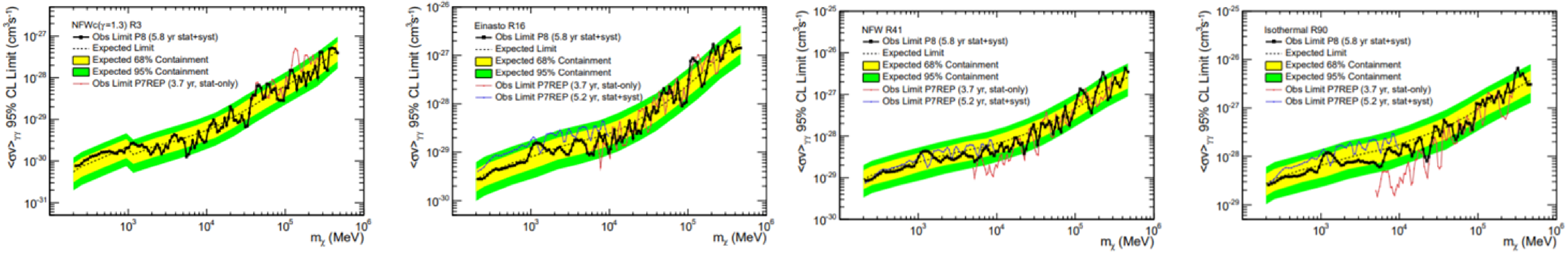


Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies

Phys. Rev. Lett. 115, 231301 (2015)
arXiv:1503.02641v2

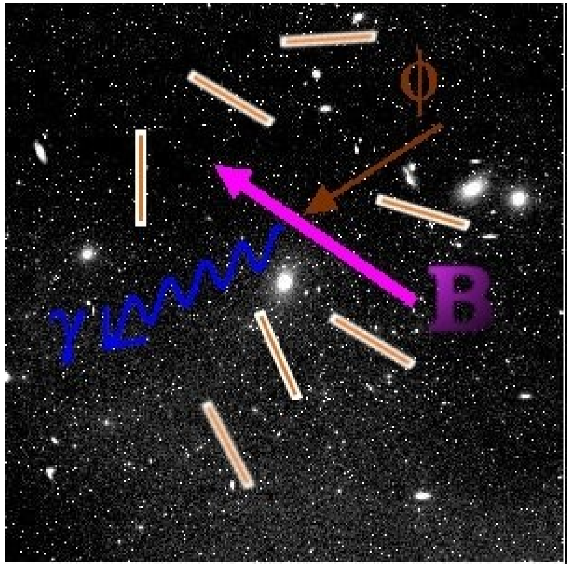
Search for lines in the Galactic gamma-ray emission

Phys. Rev. D91, 122002 (2015)
arXiv:1506.00013v1

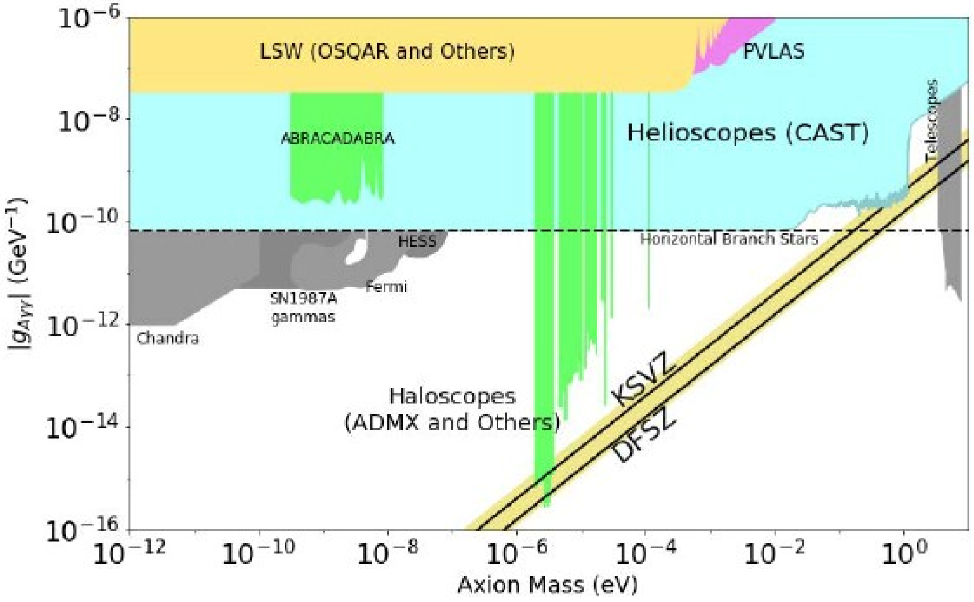


Other DM searches activities in Bari

AXION-LIKE PARTICLES (ALPs) FROM THE SKY



Referent:
Pierluca Carenza



Photons or ALPs from cosmic sources can mix each other in the large scale cosmic magnetic fields due to interaction term

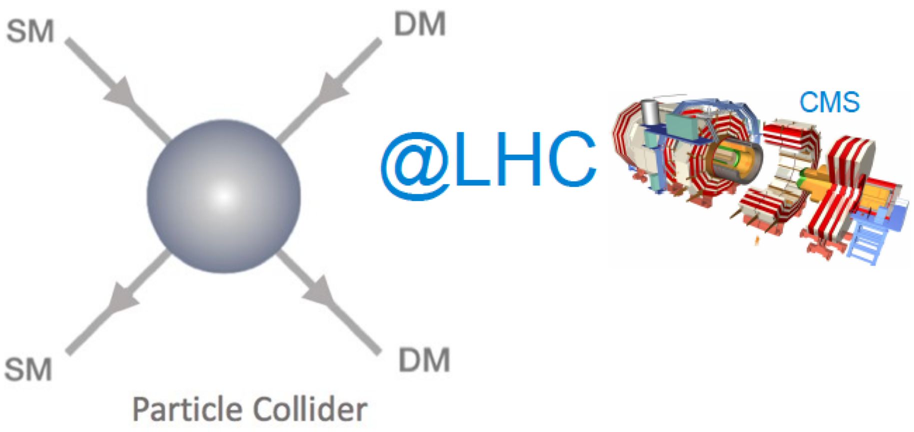
$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \widetilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

In the last recent years, different contraints and hints of ultralight ALP have emerged from various astrophysical observations.

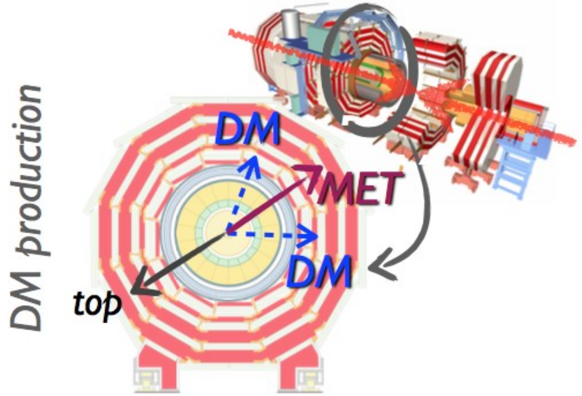
Dark Matter Search @ Collider

Referent: **Reham Aly**

- *DM could be produced at colliders*
  - no direct trace in the detector, but could create a *pT* imbalance (***MET***)
  - need *visible particle* to which DM particle recoils against
  - Mono-X searches (Where X = vector boson, jet, top, H or γ)



- *Search for dark matter produced in association with a Higgs boson*
  - Signature: Higgs + MET ➜ Higgs Particle used as a tag.
  - H → ZZ → 4 leptons decay channel considered.
  - Final States: (4e – 4μ – 2e2 μ) + MET
  - First analysis in the H → ZZ → 4l decay channel in CMS.



Conclusions

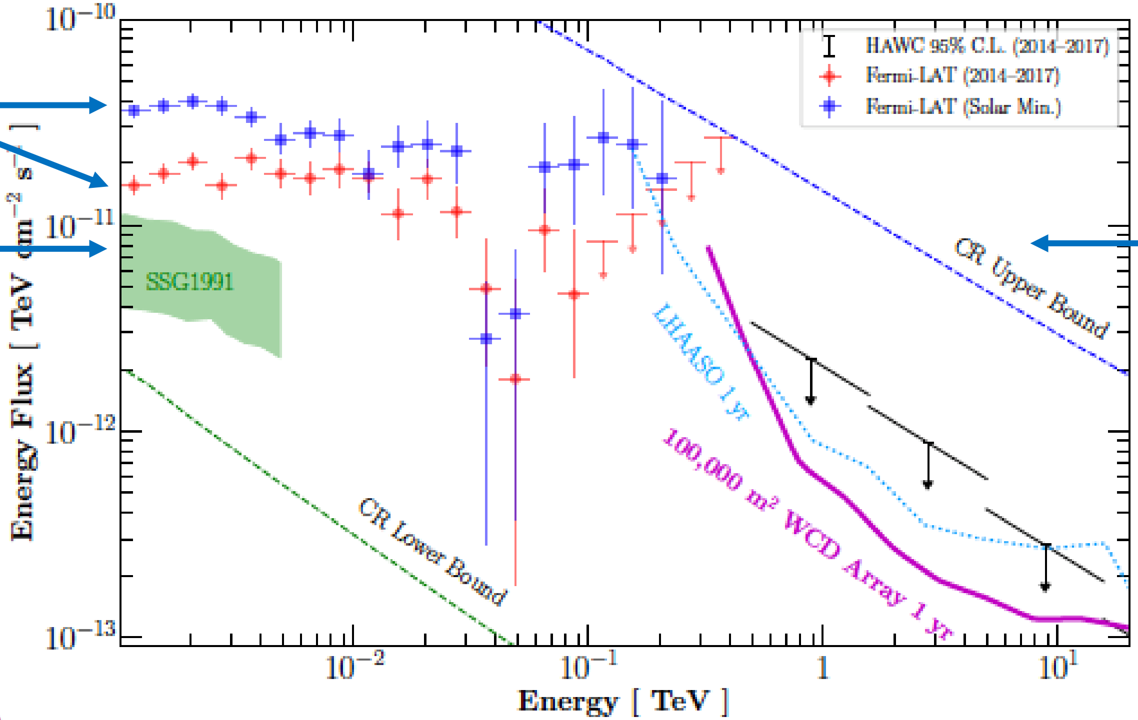
- ➢Indirect search is the technique used to investigate possible DM signals of astrophysical origin
- ➢The results of indirect DM searches with the Fermi LAT have been shown
  - Different probes:
    - Gamma rays
    - Cosmic-ray electrons
  - Different targets:
    - Sun
    - Galactic Halo
    - Galactic Center
    - Milky Way Dwarf spheroidal Galaxies
- ➢No evidence of DM signal found in any channel
  - Upper limits on relevant physical quantities have been set

Backup

ALPs

THE SUN AT GeV-TeV ENERGIES

[arXiv: 1903.06349]

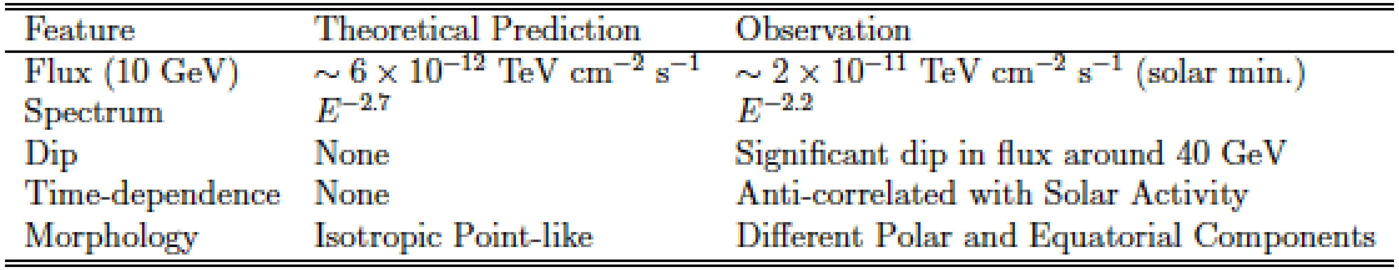


Observations

Theory

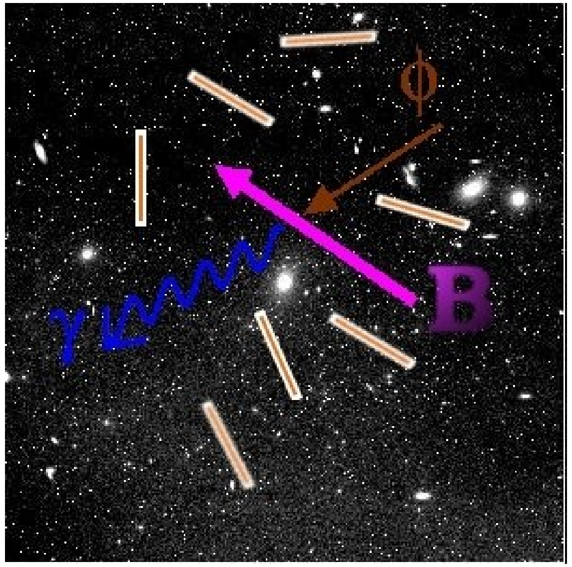
Max theoretical emission assuming 100 % efficiency

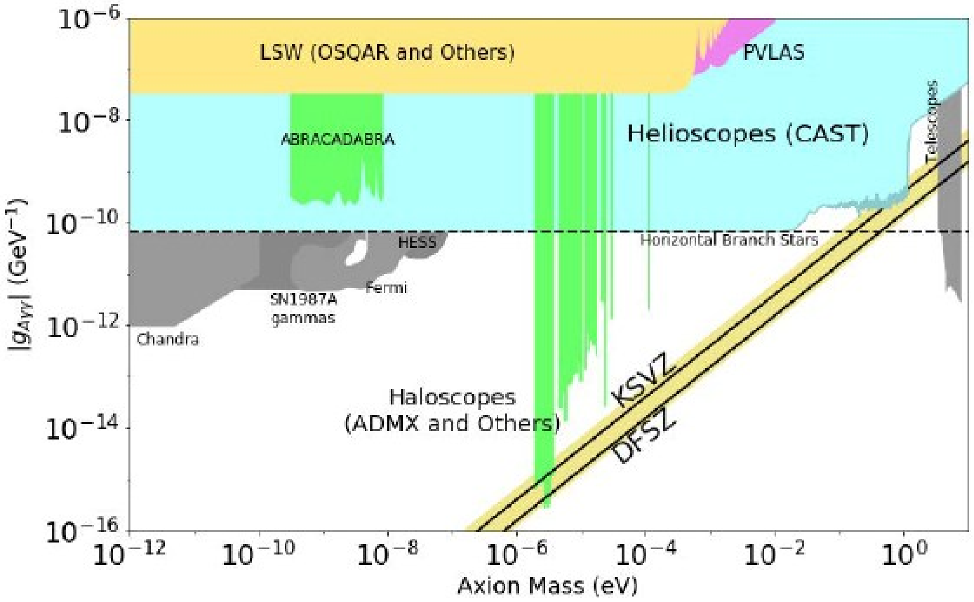
- **Solar Minimum flux is much harder and brighter!**
- **Unforeseen measurement in a physically interesting range. Mechanism?**
- **TeV prospects?**



Feature	Theoretical Prediction	Observation
Flux (10 GeV)	$\sim 6 \times 10^{-12}$ TeV cm^{-2} s^{-1}	$\sim 2 \times 10^{-11}$ TeV cm^{-2} s^{-1} (solar min.)
Spectrum	$E^{-2.7}$	$E^{-2.2}$
Dip	None	Significant dip in flux around 40 GeV
Time-dependence	None	Anti-correlated with Solar Activity
Morphology	Isotropic Point-like	Different Polar and Equatorial Components

AXION-LIKE PARTICLES (ALPs) FROM THE SKY





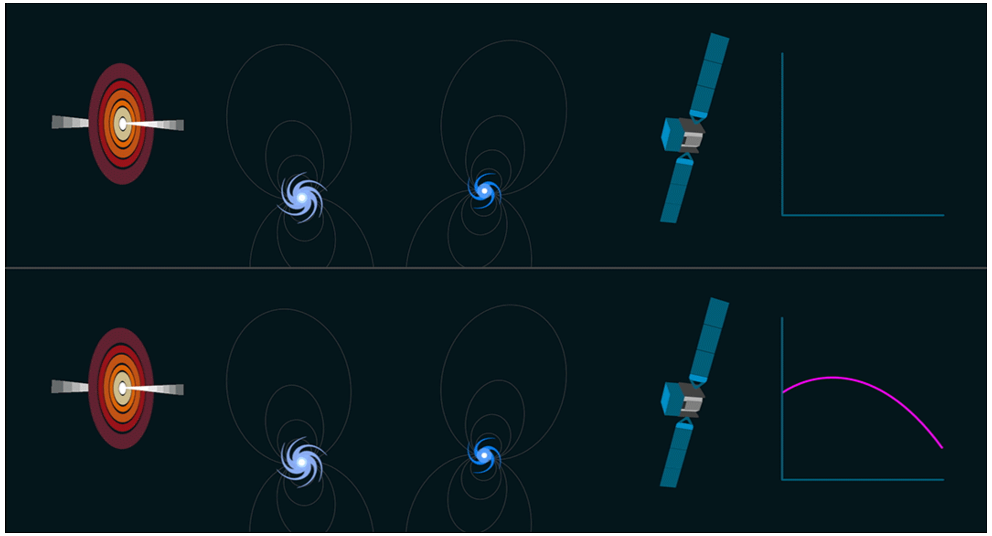
Photons or ALPs from cosmic sources can mix each other in the large scale cosmic magnetic fields due to interaction term

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \widetilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

In the last recent years, different contraints and hints of ultralight ALP have emerged from various astrophysical observations.

ALP BOUNDS FROM VHE GAMMA-RAYS

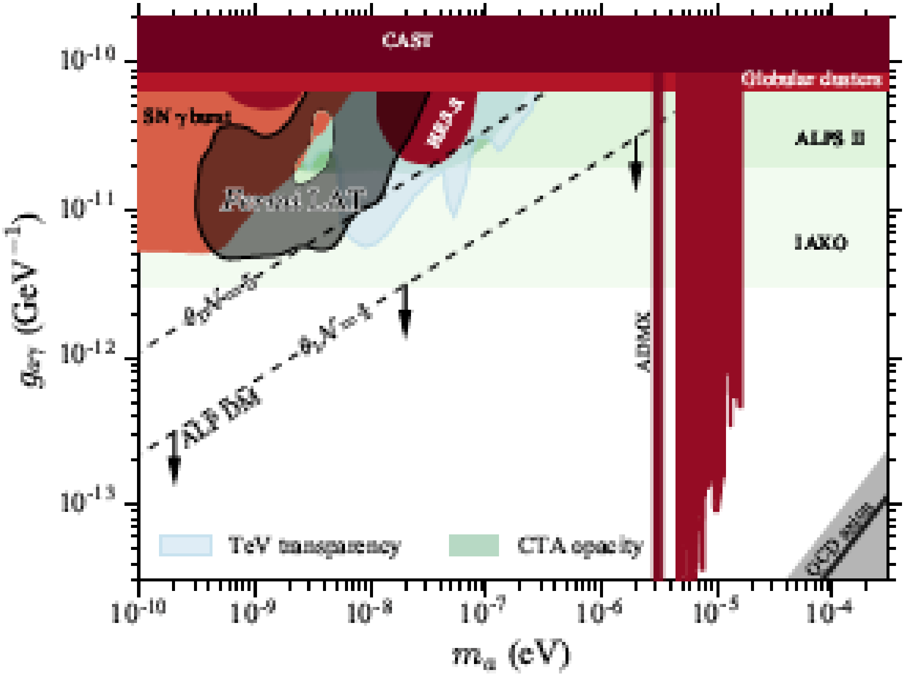
Bright source NGC 1275 in Perseus Cluster



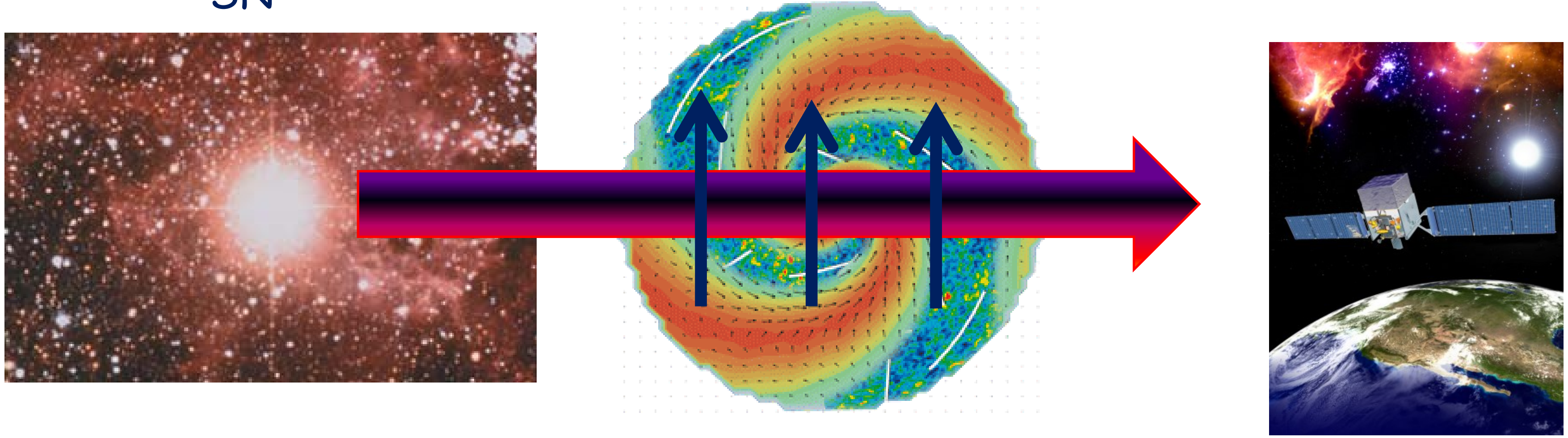
No ALPs

With ALPs

Fermi-LAT Collaboration [1603.06978]



ALPs FROM SUPERNOVAE



SN

Milky-Way

Gamma-ray satellite

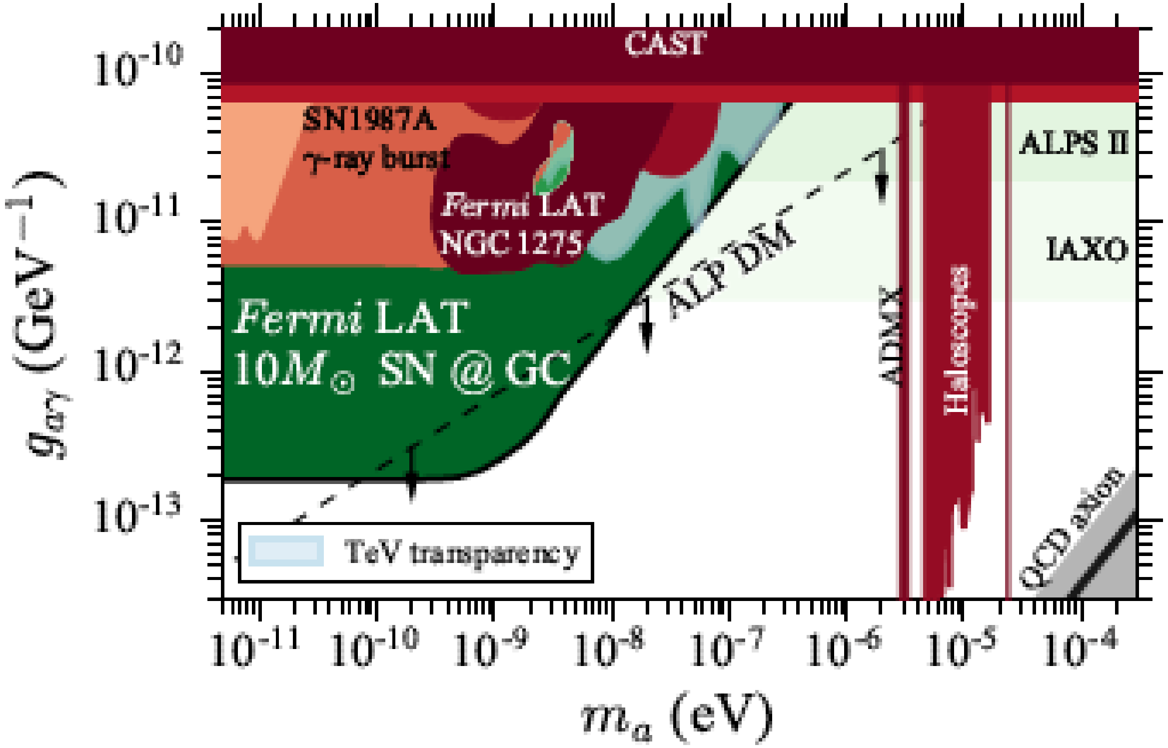
ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

Search excess gamma-rays in coincidence with a SN

Stringent bound from SN 1987A [Payez, Evoli, Fischer, Mirizzi, Ringwald, arXiv: 1410.3747]

FERMI-LAT SENSITIVITY TO ALPs FROM SUPERNOVAE



A Galactic SN explosion in the field of view of FERMI-LAT would allow us to improve the SN 1987A bound by more than one order of magnitude ...

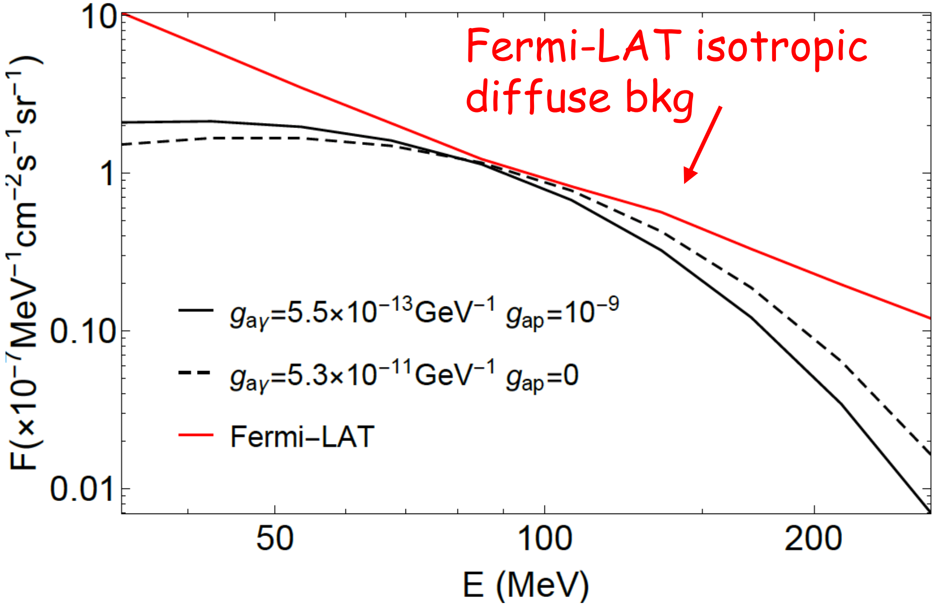
or even detect DM ALPs !

[Meyer, Giannotti, Mirizzi, Conrad, Sanchez-Conde, PRL 118 (2017) 1, 011103, arXiv: 1609.02350]

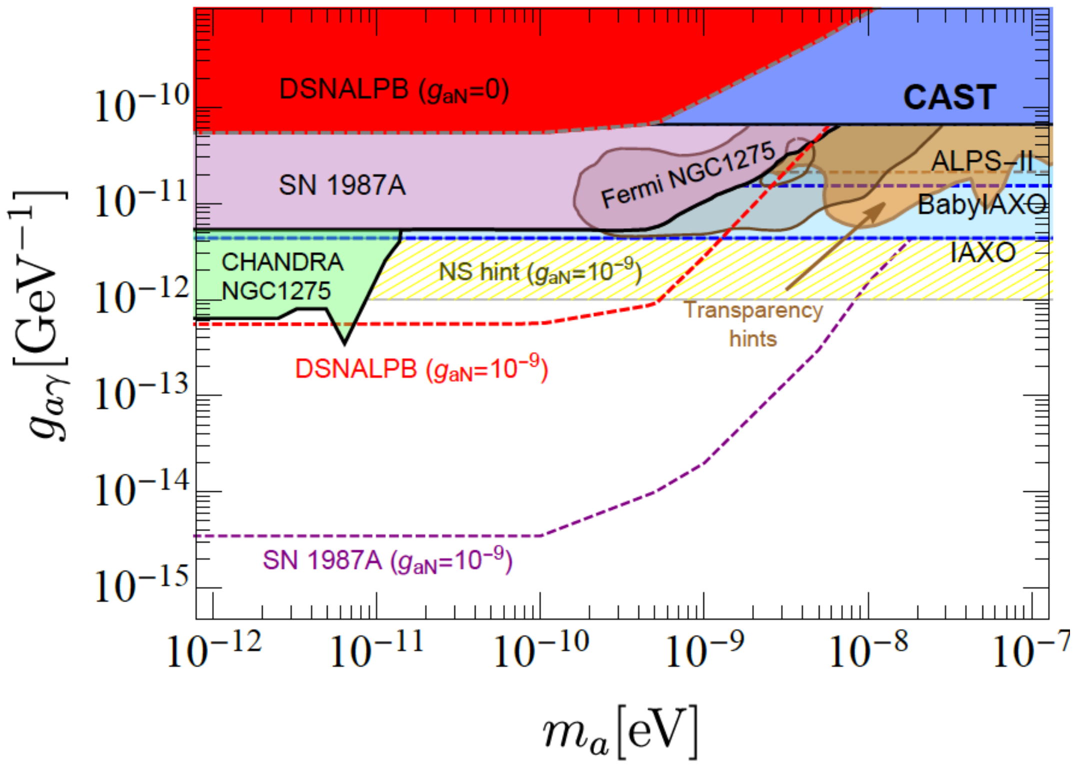
CONSTRAINTS FROM DIFFUSE SUPERNOVA ALP BACKGROUND

[Calore, Carenza, Giannotti, Jaeckel, A.Mirizzi, arXiv:2008.11741]

gamma-ray flux



Fermi-LAT isotropic diffuse bkg



Diffuse ALP flux from all core-collapse SNe in the Universe

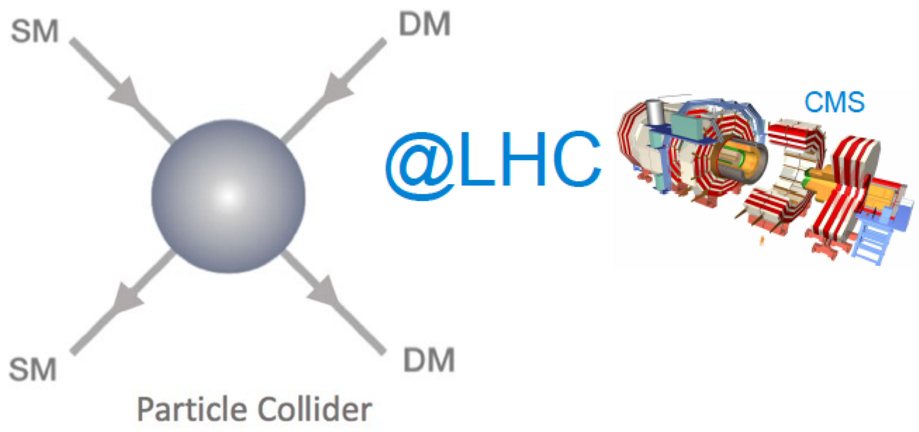
For g_{aN}=0 DNSALPB constraint

- ✓ Comparable with CAST
- ✓ Less stringent than SN 1987A

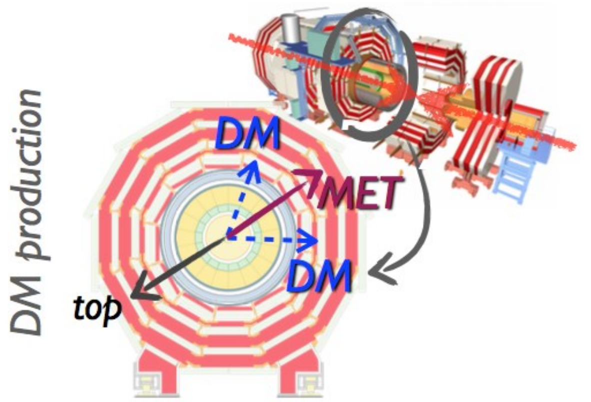
DM searches at LHC

Dark Matter Search @ Collider

- *DM could be produced at colliders*
  - no direct trace in the detector, but could create a *pT* imbalance ***(MET)***
  - need *visible particle* to which DM particle recoils against
  - Mono-X searches (Where X = vector boson, jet, top, H or γ)



- *Search for dark matter produced in association with a Higgs boson*
  - Signature: Higgs + MET ➜ Higgs Particle used as a tag.
  - H → ZZ → 4 leptons decay channel considered.
  - Final States: (4e – 4μ – 2e2 μ) + MET
  - First analysis in the H → ZZ → 4l decay channel in CMS.



Mono-Higgs (ZZ➤4l) search

- **Baseline selection**
- Reconstruction of SM Higgs boson from four charged leptons
- $|m_{4l}-125| \le 10$ GeV
- Number of leptons =4

- **Main Background**
- SM Higgs with five main production modes (mH=125 GeV)
- Non resonant ZZ , VVV, TTV (v= W,Z)
- Dedicated control regions for background estimation

JHEP, 03 (2020) 025.

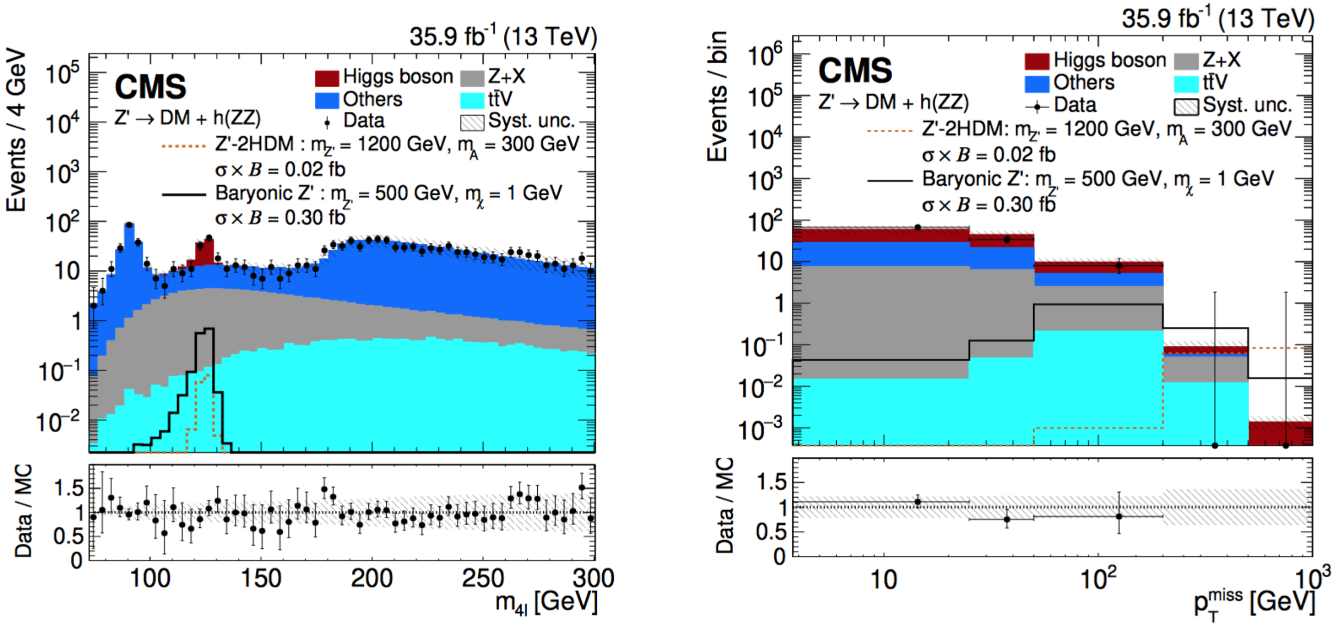
- **Model for interpretation**
- Z'- 2 Higgs doublet model
- Z' Baryonic model

2016 data

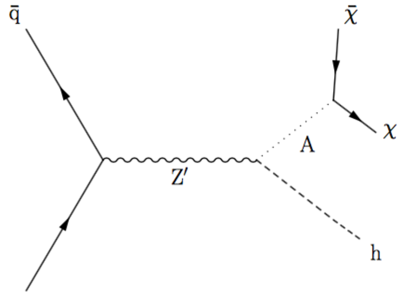
- Two Higgs doublet model + light pseudo-scalar "a" (2HDM+a) ➢ Full Run II data

AN-20-013

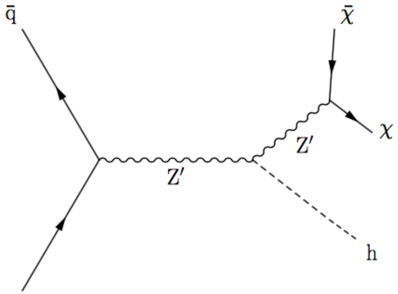
2016 CMS data



2016

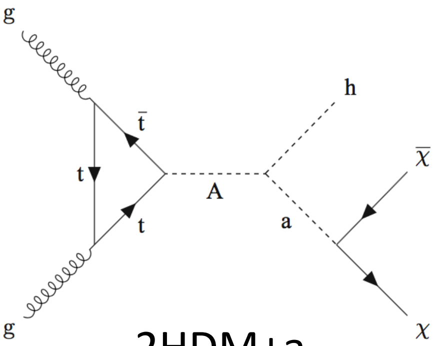


Z'-2HDM



Z'-Baryonic

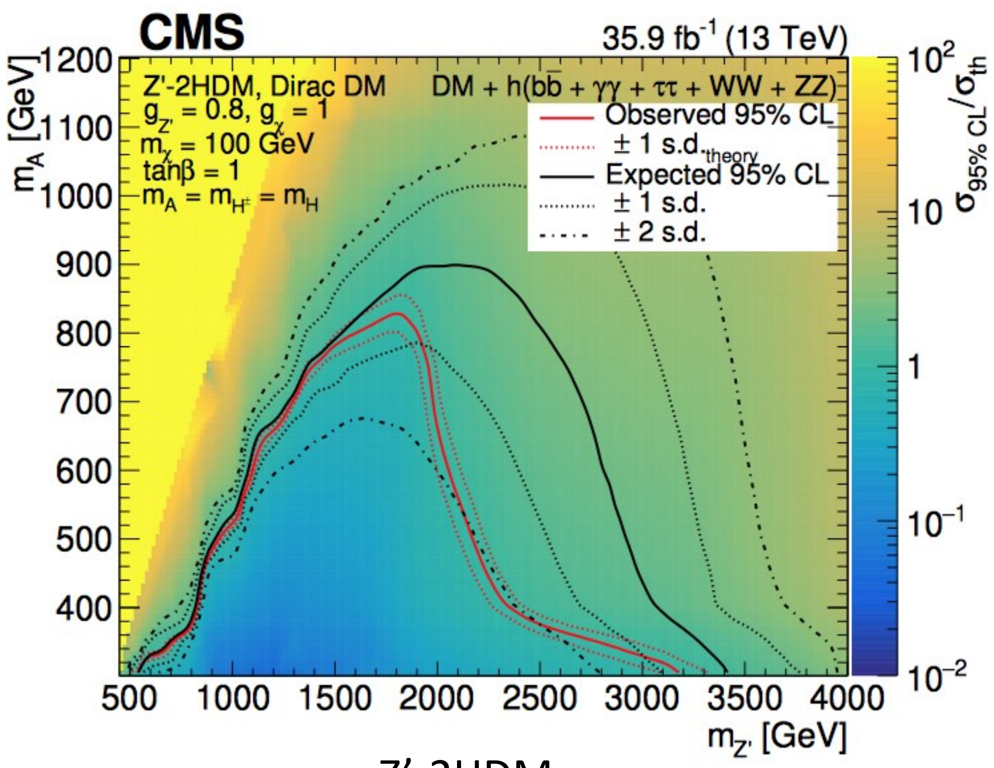
RunII



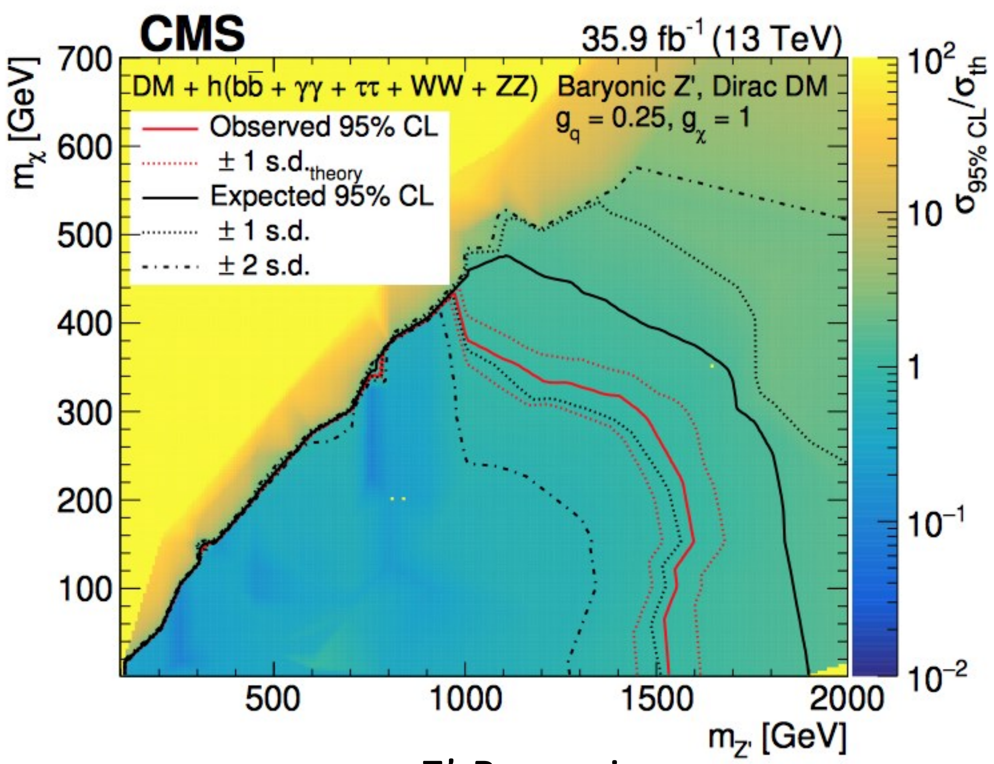
2HDM+a

Mono-Higgs (ZZ➛4l) search

- The results has been interpreted as an upper limit on the Dark Matter signal strength for the combination of five Higgs decay channels (ZZ, WW, bb, tt, $\gamma\gamma$)



Z'-2HDM



Z'-Baryonic

2016 CMS data

- In Z'-2HDM model: 500 GeV < $M_{Z'}$ < 3200 GeV and 300 GeV < m_{A0} < 800 GeV have been excluded
- In Baryonic Z' model: 100 GeV < $M_{Z'}$ < 1500 GeV and 1 GeV < M < 420 GeV have been excluded

Mono-Higgs (ZZ→4l) search

Run II CMS data

Analysis strategy

- Derived a sensitivity of Mono-Higgs analysis using:

- Cut Based Analysis
- Multivariate Analysis ⇨ Increase the analysis sensitivity by 20 – 40 %
- The results obtained are interpreted as an upper limit on the Dark Matter signal strength in term of 2HDM+a model
- Even if the analysis is limited by the low branching fraction of the Higgs decay, it is able to exclude point of the model parameter space
- **Plan:** Combination with other Mono-Higgs analysis
- Analysis not approved yet in CMS ⇨ in revision.

Fermi-LAT Analysis Backup

Balance equation for Solar DM

- Balance equation:

$$\frac{dN_\chi}{dt} = \Gamma_{cap} - C_{ann} N_\chi^2$$

  - Γ_{cap} = DM capture rate
  - C_{ann} = annihilation factor depending on the DM annihilation cross section

- Equilibrium hypothesis:

$$\frac{dN_\chi}{dt} = 0 \;\Rightarrow \Gamma_{ann} = \frac{1}{2} C_{ann} N_\chi^2 = \frac{1}{2}\Gamma_{cap}$$

  - Equilibrium is reached if $t_\odot \gg \tau$
    - $\tau = \left(\Gamma_{cap} C_{ann}\right)^{-1/2}$ is the time scale of the process and depends on $\langle\sigma_{ann} v\rangle$ and σ_{DM-n}

- Expected γ-ray flux in the mediator scenario:

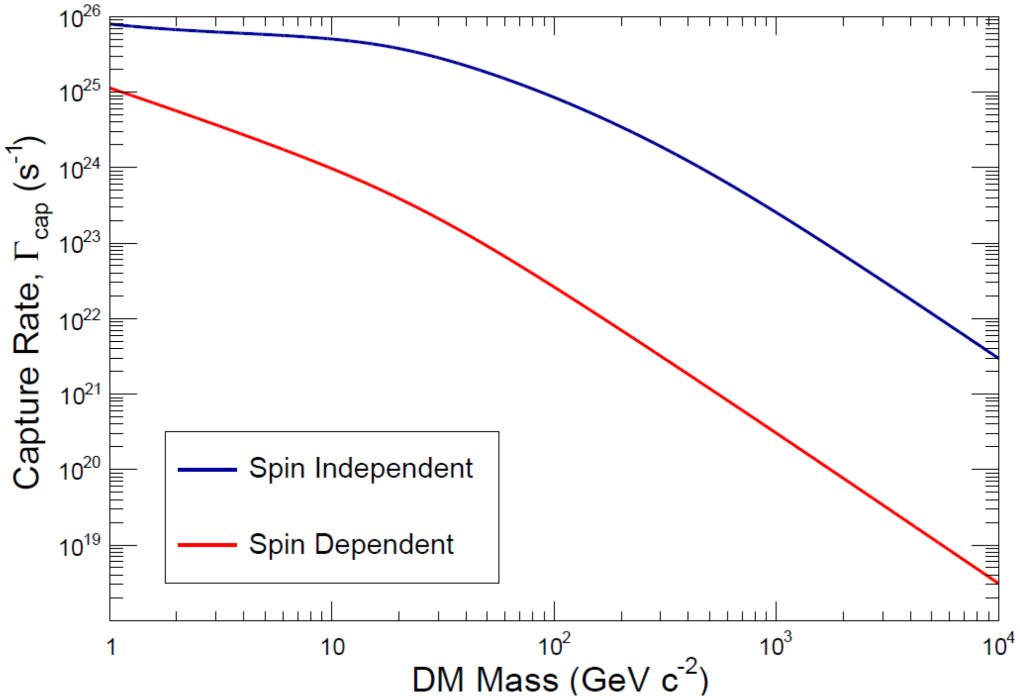
$$\Phi_{DM}(E;\; m_\chi, \sigma_{DM-N}, L, \ldots) = \Gamma_{cap}\,\frac{1}{4\pi D^2}\left(e^{-\frac{R_\odot}{L}} - e^{-\frac{D}{L}}\right) N_\gamma(E)$$

  - L = mediator decay length
  - N_γ (E) = DM γ-ray yield:
    - In case of light mediators and direct gamma-ray pair production $N_\gamma(E) = 2\frac{H(m_\chi - E)}{m_\chi}$

- The CRE flux can be evaluated in a similar way

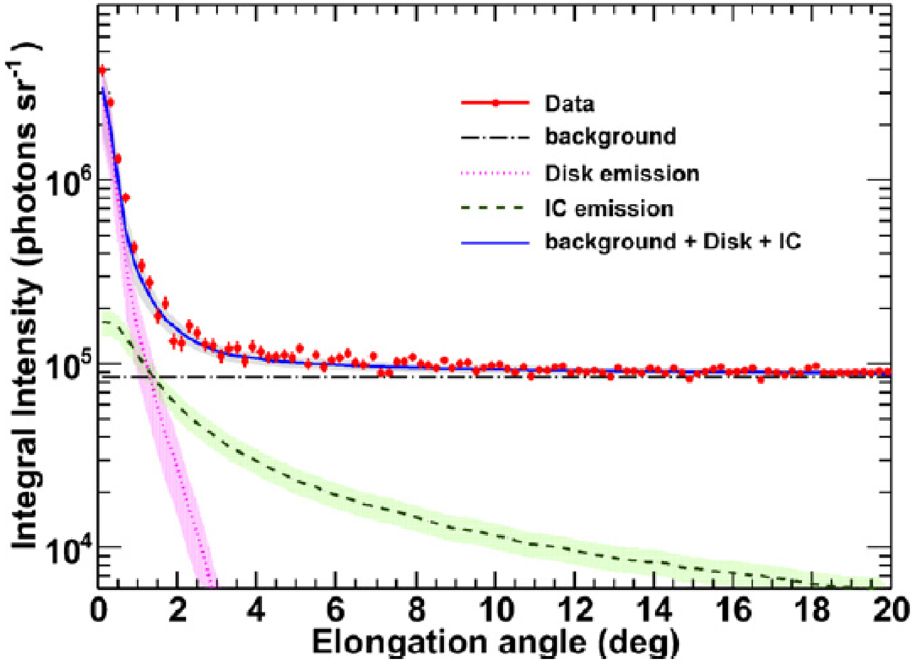
Solar DM capture rate

- The solar DM capture rate has been evaluated with DARKSUSY
  - Default settings:
    - local DM density $\rho_\odot$ = 0.3 GeV/cm^3
    - Maxwellian velocity distribution with <v> = 220 km/s and v_{rms} = 270 km/s
    - $\sigma_0 = 10^{-40}$cm^2
  - Calculations performed in both spin-dependent and spin-independent cases
  - The capture rate is proportional to the DM-nucleon scattering cross section



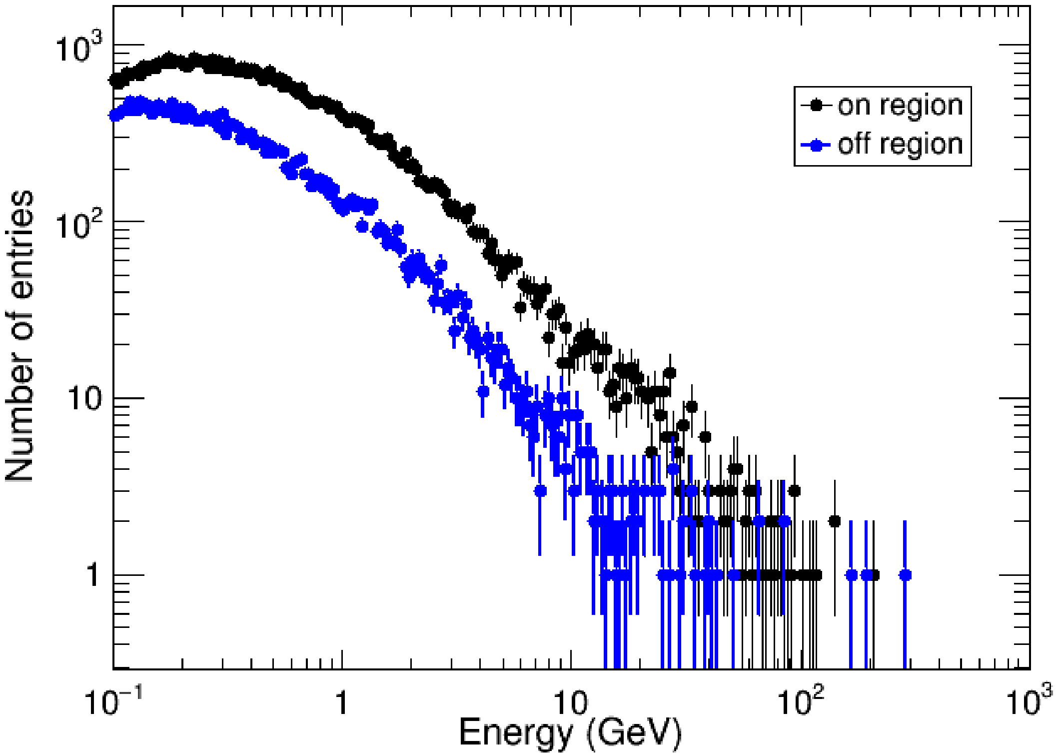
Search for features in the solar gamma-ray spectrum

- The Sun is visible in gamma rays due to the interactions of cosmic rays (CRs) with the solar environment
  - Disk emission due to the interactions of CR nuclei with the Sun atmosphere
  - Diffuse (extended) emission due to the inverse Compton scatterings of electrons with the optical solar photons in the heliosphere
  - Both emissions mechanisms yield a continuous gamma ray spectrum
  - A possible DM feature would appear on the top of the continuous emission spectrum



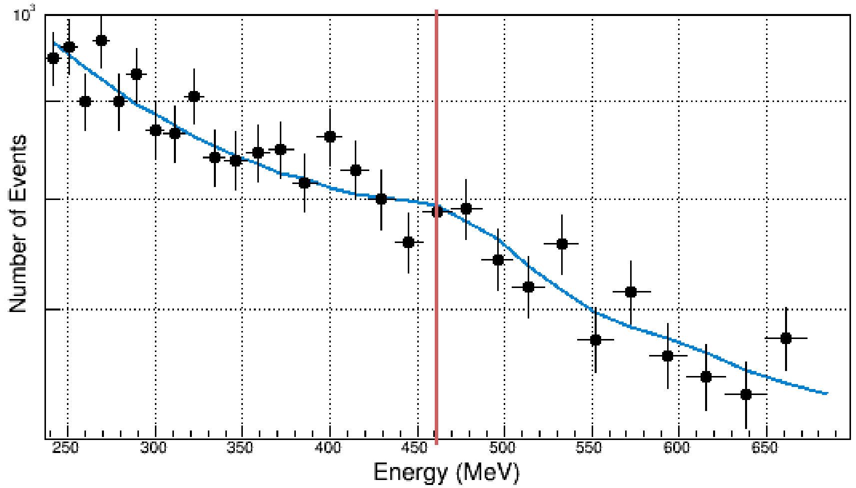
Fermi LAT data analysis

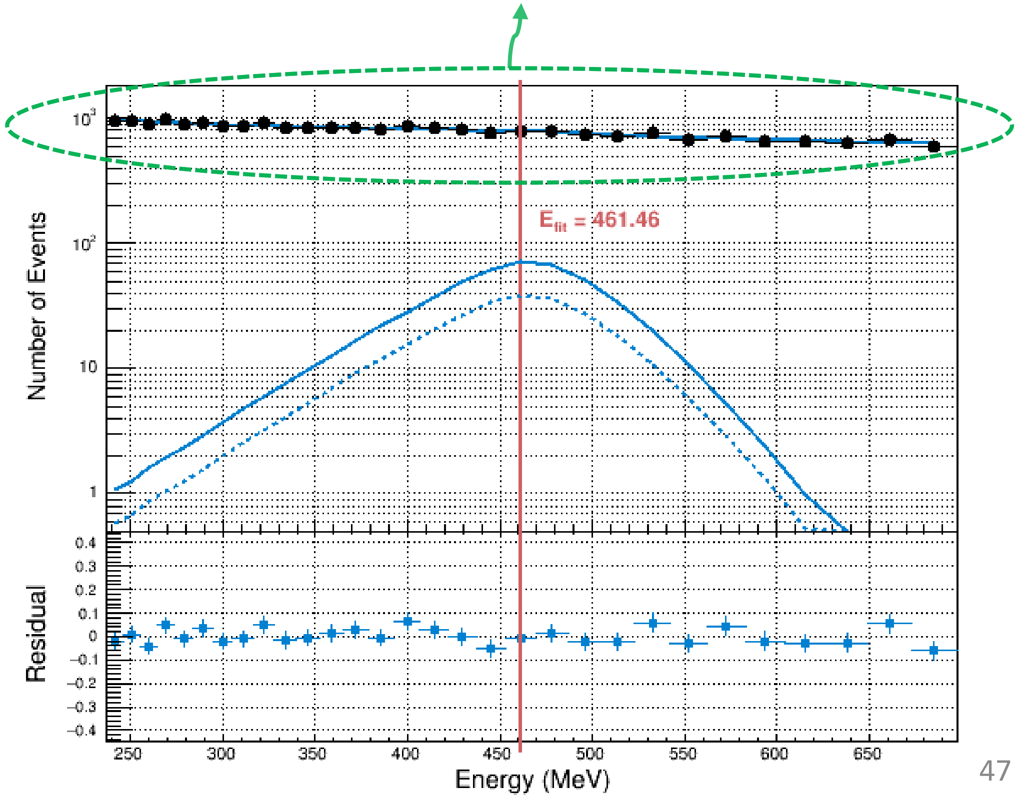
- ➢Dataset: 10-years of Fermi-LAT observation
  - Energy range 100 MeV – 150 GeV
- ➢ON/OFF technique analysis:
  - The Sun is a moving source
    - ON Region : RoI of 2° angular radius centered on the Sun current position
    - OFF Region: RoI of 2° angular radius centered on the 6 months time-offset position
    - The OFF region follows the same path in the sky of the Sun
      - *Used as control region to constrain the background*
- ➢Analysis performed in sliding energy windows
  - Search for possible local features
  - Poisson maximum likelihood approach used to combine data from ON and OFF regions
  - Significance of possible features evaluated



Search for line-like and box-like features

- Flux models:
  - $\Phi^{ON}(E) = \Phi_{smooth,bkg}(E) + \Phi_{feat}^{extra}(E) + \Phi_{smooth,sig}(E) + \Phi_{feat}^{ON}(E)$
  - $\Phi^{OFF}(E) = \Phi_{smooth,bkg}(E) + \Phi_{feat}^{extra}(E)$
    - $\Phi_{smooth,bkg}(E)$ is the continuous background spectrum, appearing in both regions
    - $\Phi_{smooth,sig}(E)$ is the continuous spectrum, appearing in the ON region
    - $\Phi_{feat}^{ON}(E)$ is the possible DM feature, appearing only in the ON region
      - *Line-like* feature: $\Phi_{feat}(E) = s\,\delta(E_w - E)$
      - *Box-like* feature: $\Phi_{feat}(E) = s\,H(E_w - E)$
    - $\Phi_{feat}^{extra}(E)$ is a possible feature originating from instrumental systematic effects
      - Could mimic a real feature
      - Should appear in both ON and OFF regions
      - Same shape as the expected feature
- Hypothesis testing:
  - Null hypothesis: $\Phi_{feat}^{ON}(E) = 0$
  - Alternative hypothesis: $\Phi_{feat}^{ON}(E) > 0$
  - Test statistics: $TS_{local} = -2\,(\log\mathcal{L}_{0,max} - \log\mathcal{L}_{1,max})$
- All possible features turn out to be statistically insignificant





Search for line-like and box-like features

Flux models:

- $\Phi^{ON}(E) \;=\Phi_{smooth,bkg}(E)+\Phi_{feat}^{extra}(E)+\Phi_{smooth,sig}(E)+\Phi_{feat}^{ON}(E)$
- $\Phi^{OFF}(E)=\Phi_{smooth,bkg}(E)+\Phi_{feat}^{extra}(E)$

Flux contributions:

- $\Phi_{smooth,bkg}(E)$ modeled with a power law
- $\Phi_{smooth,sig}(E)$ corresponds to the standard solar emission, modeled with a power law
- $\Phi_{feat}^{ON}(E)$ corresponds to the feature
  - line like feature $\Phi_{feat}(E)=s\,\delta(E_w-E)$
  - box-like feature $\Phi_{feat}(E)=s\,H(E_w-E)$
- $\Phi_{feat}^{extra}(E)$ corresponds to a possible instrumental systematic effect

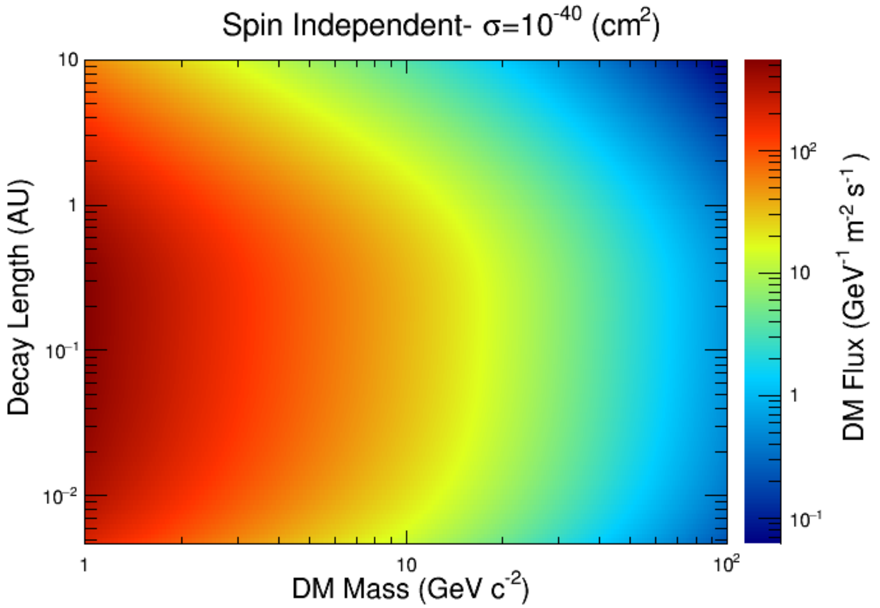
Expected counts in a bin of observed energy E_j:

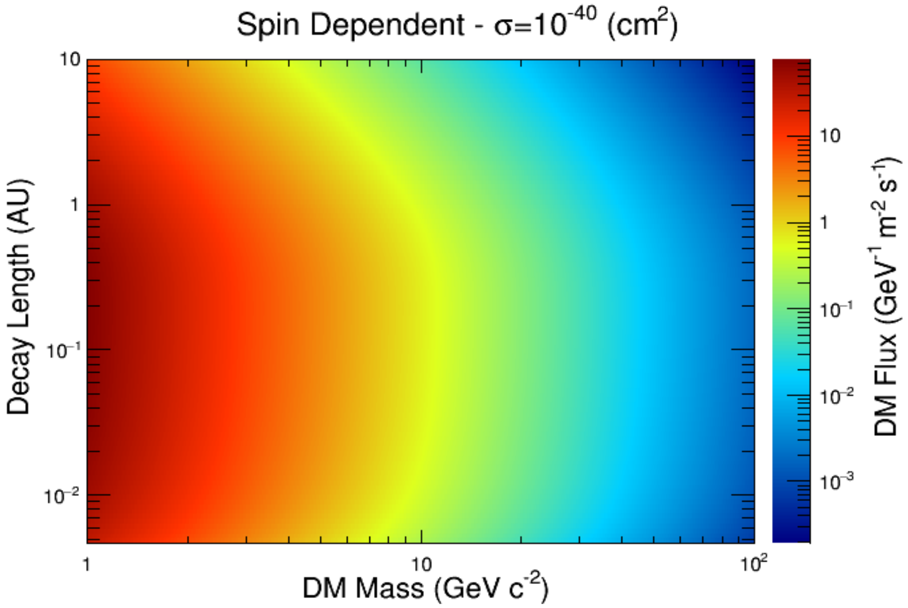
- $\mu^{ON/OFF}(E_j)=\int\,\mathcal{E}^{ON/OFF}(E_j|E)\,\Phi^{ON/OFF}(E)dE$

DM - Nucleon cross section limits

- The limits on the box feature intensities can be converted into limits on the DM-nucleon cross section by means of the capture rate evaluated at a reference σ and assuming a linear scaling ($\Gamma_{cap} \propto \sigma$)
  - The capture rate has been calculated with the DARKSUSY code in case of spin-dependent and spin-independent cross sections assuming the default settings:
    - local DM density $\rho_{\odot} = 0.3$ GeV/cm^3
    - Maxwellian velocity distribution with <v> = 220 km/s and $v_{rms} = 270$ km/s
    - $\sigma_0 = 10^{-40}$cm^2
- Using the evaluation of Γ_{cap} it is possible to evaluate the expected DM gamma-ray flux at Earth Φ_{DM}

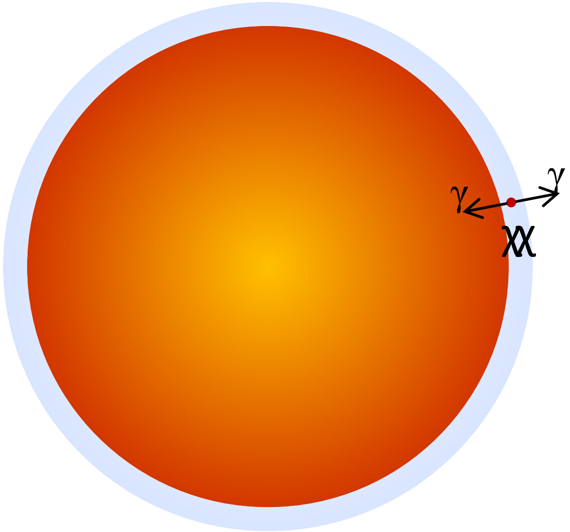
$$\sigma_{UL} = \frac{\Phi_{UL}(E = m_\chi)}{\Phi_{DM}(E = m_\chi)} \times 10^{-40} cm^2$$

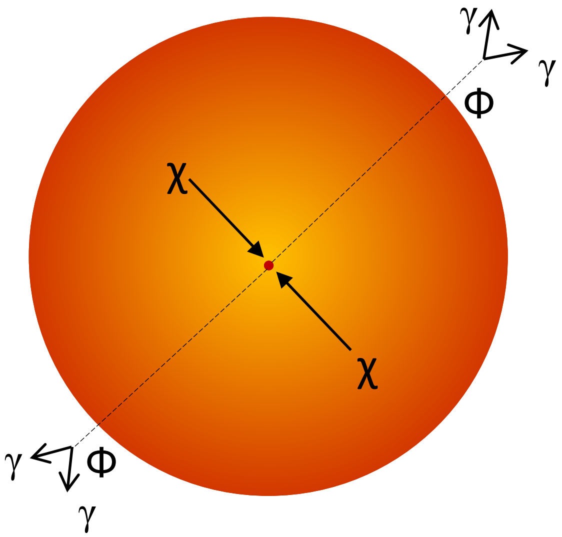




Signals from DM annihilation

- DM particles from the galactic halo can be gravitationally trapped by the Sun through scattering interactions with the nuclei in the solar environment





The Sun is visible in gamma rays due to the interactions of cosmic rays (CRs) with the solar environment

- Disk emission due to the interactions of CR nuclei with the Sun atmosphere
- Diffuse (extended) emission due to the inverse Compton scatterings of electrons with the optical solar photons in the heliosphere

Both emissions mechanisms yield a continuous gamma ray spectrum

- DM signals would appear as an excess on the top of the standard emission:

$\chi\chi \rightarrow \gamma\gamma$ → local ***line-like*** feature

$\chi\chi \rightarrow \phi\phi$:

- $\phi \rightarrow \gamma\gamma$ ➔ ***box-shaped feature***
- $\phi \rightarrow b\bar{b}, \tau^+\tau^- \rightarrow \gamma$… ➔ ***smooth spectrum***

Solar DM capture

- Balance equation for solar DM:

$$\frac{dN_\chi}{dt} = \Gamma_{cap} - C_{ann} N_\chi^2$$

  - Γ_{cap} is the capture rate
  - C_{ann} is the annihilation factor, which depends on the DM annihilation cross section

- Equilibrium assumption:

$$\frac{dN_\chi}{dt} = 0 \Rightarrow \Gamma_{ann} = \frac{1}{2} C_{ann} N_\chi^2 = \frac{1}{2}\Gamma_{cap}$$

- Expected γ ray flux in the mediator scenario:

$$\Phi_{DM}(E;\ m_\chi, \sigma_{DM-N}, L, \ldots) = \Gamma_{cap}\ \frac{1}{4\pi D^2}\left(e^{-\frac{R_\odot}{L}} - e^{-\frac{D}{L}}\right) N_\gamma(E)$$

  - L is the mediator decay length
  - N_γ (E) is the DM γ-ray yield:
    - In case of light mediators and direct gamma-ray pair production $N_\gamma(E) = 2\frac{H(m_\chi - E)}{m_\chi}$

Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies

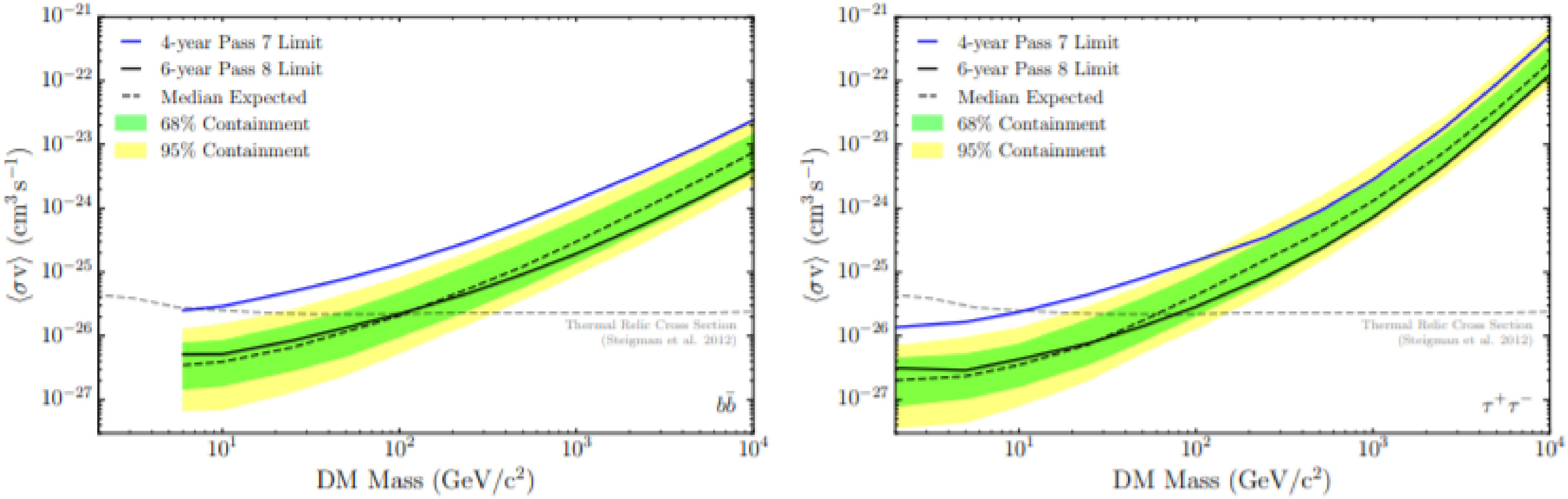
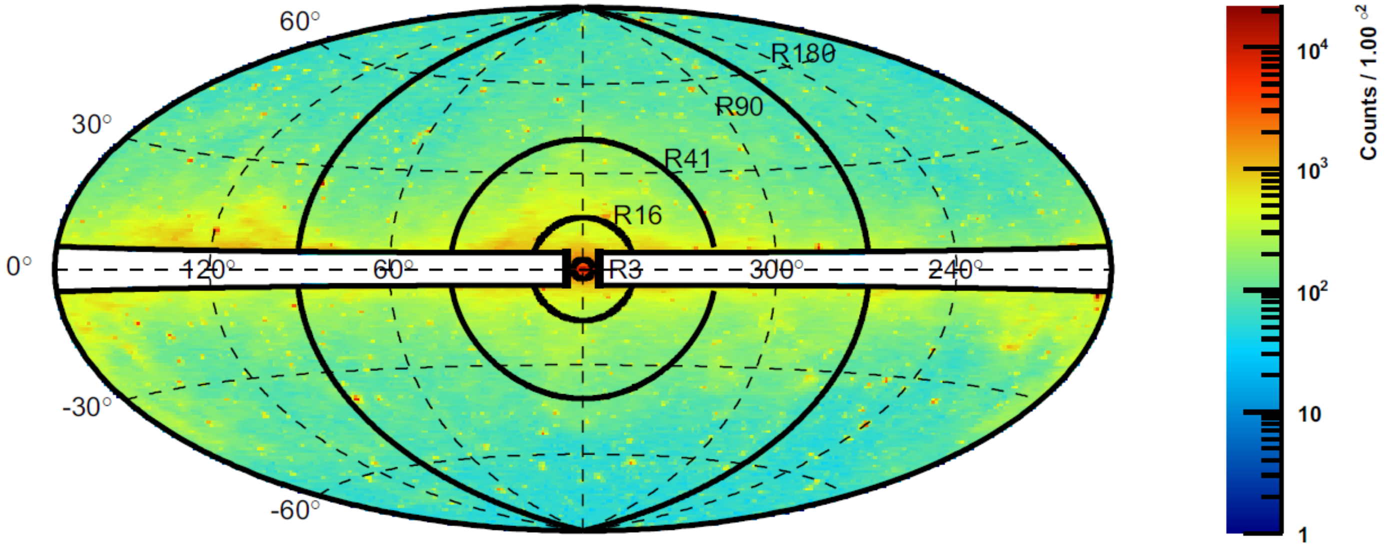


FIG. 1. Constraints on the DM annihilation cross section at 95% CL for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J-factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of `Pass 7 Reprocessed` data and the same sample of 15 dSphs [13]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman *et al.* [5].

Phys. Rev. Lett. 115, 231301 (2015)
arXiv:1503.02641v2

Search for lines in the Galactic gamma-ray emission (1)

- WIMP annihilations in the Galaxy may produce gamma rays detectable by the LAT
  - $\chi\chi \rightarrow \gamma\gamma$, γZ^0, γH^0 would produce a narrow feature
  - Sharp, distinct spectral feature (“smoking gun”)
    - Likely a small branching fraction (~10^{-2} to 10^{-4})
    - Signal predicted to be small
- Most recent line search from the LAT Collaboration:
  - 5.8 years Pass 8 data sample
  - ROIs for line search optimized for different DM profiles:
    - R3 (GC), R16 (Einasto), R41 (NFW), R90 (isothermal), R180 (decay)
  - Control regions:
    - 31 boxes 10°× 10° along the GP
  - See Phys. Rev. D91, 122002 (2015)



Search for lines in the Galactic gamma-ray emission (2)

No evidence of spectral lines found!

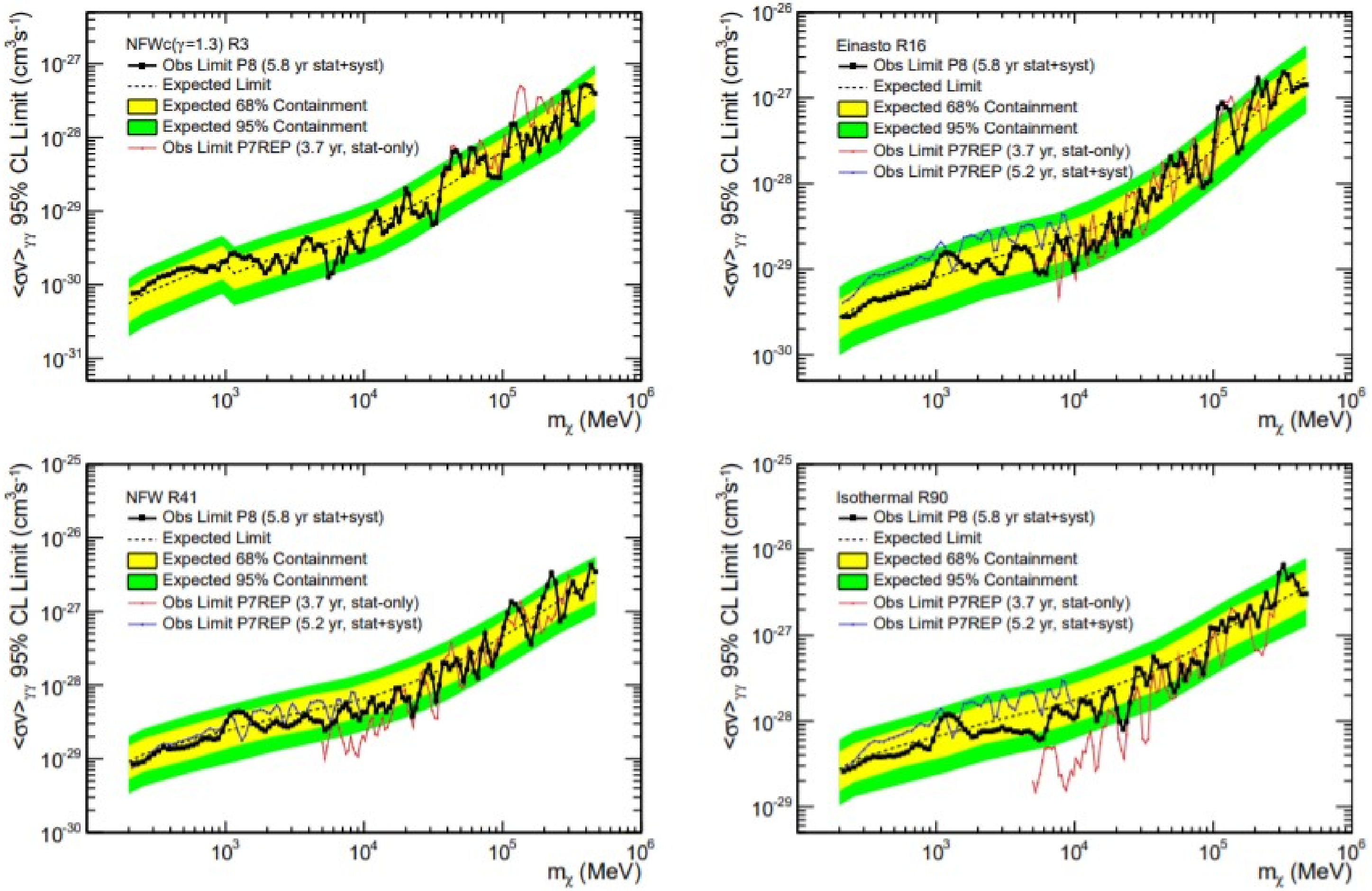


FIG. 8. 95% CL $\langle \sigma v \rangle_{\gamma\gamma}$ upper limits for each DM profile considered in the corresponding optimized ROI. The upper left panel is for the NFWc (γ=1.3) DM profile in the R3 ROI. The discontinuity in the expected and observed limit in this ROI around 1 GeV is the result of using only PSF3 type events. See Sec. III for more information. The upper right panel is for the Einasto profile in the R16 ROI. The lower left panel is the NFW DM profile in the R41 ROI, and finally the lower right panel is the Isothermal DM profile in the R90 ROI. Yellow (green) bands show the 68% (95%) expected containments derived from 1000 no-DM MC simulations (see Sec. V B). The black dashed lines show the median expected limits from those simulations. Also shown are the limits obtained in our 3.7-year line search [19] and our 5.2-year line search [22] when the assumed DM profiles were the same.

Phys. Rev. D91, 122002 (2015)
arXiv:1506.00013v1