Science with the Fermi Large Aera Telescope

12th Cosmic Ray International Seminar (CRIS 2022)

Naples 12 Sept 2022

D.Serini

on behalf of the Fermi-LAT Collaboration

davide.serini@ba.infn.it

Overview

- **General overview of the Fermi Mission**
  - The Fermi Large Area Telescope
  - Science with the LAT: source catalogs
  - Pulsars and gravitational waves
  - Magnetar Giant Flare

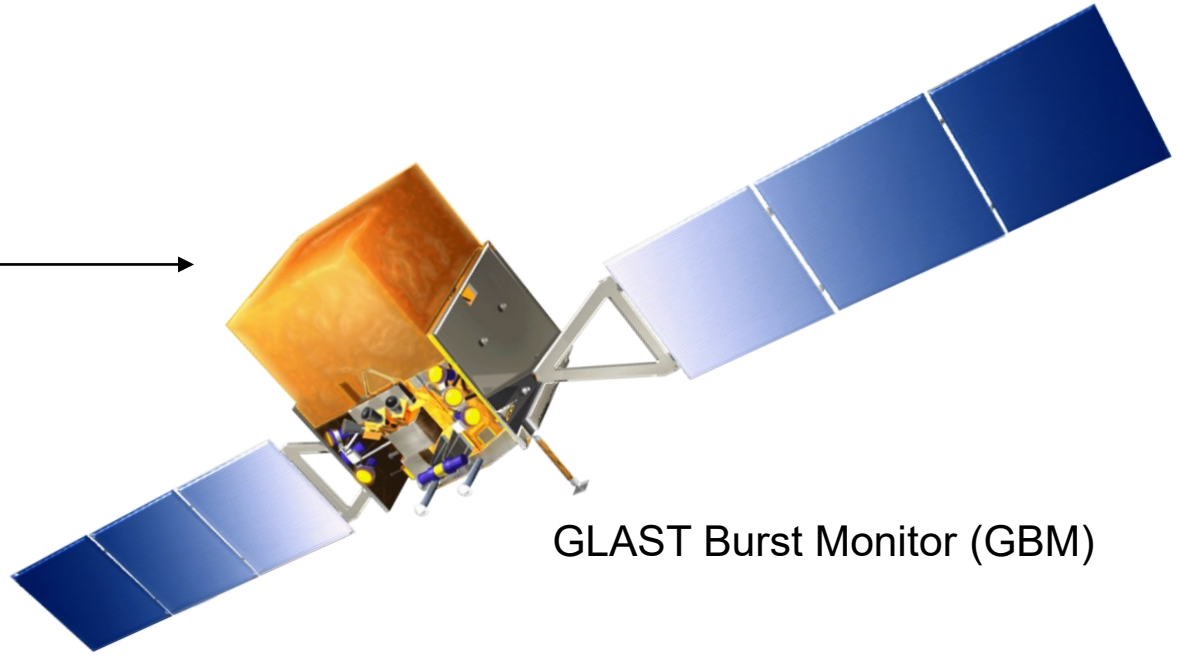
- **Indirect search of Dark Matter with the Fermi LAT**
  - Search for WIMPs
  - The Sun as target for indirect DM searches

- **Conclusions**

Fermi Mission

- **The Fermi Gamma-Ray Space Telescope is an International Science Mission exploring the gamma-ray sky by means of its two main instruments:**
  - GLAST Burst Monitor (GBM): 8 keV → 40 MeV
  - Large Area Telescope (LAT): 20 MeV → > 300 GeV

Large Area Telescope (LAT) →



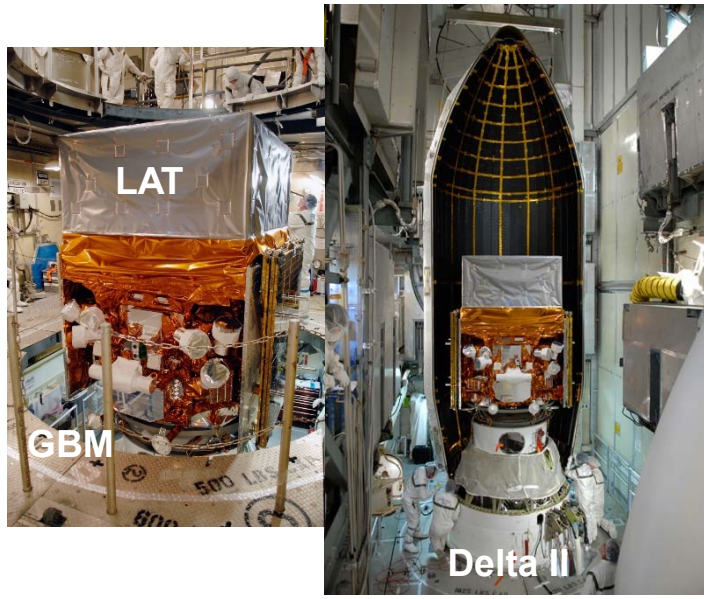
GLAST Burst Monitor (GBM)

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & ~400 Scientific Members

Fermi Launch

- **Launched 11 June 2008 from Cape Canaveral Kennedy Space Center – NASA with the Delta II Rocket**
  - Circular orbit, 565km altitude, 25.6 deg inclination
  - Science mission started on August 2008

- **Operations mode**
  - *Primary mode*: sky survey
    - scan entire sky every 3 hours
  - Autonomous Repoint Request
    - autonomously commanded pointed observations following detection of bright hard-spectrum GRB
  - Target of Opportunity
    - 1 day – few weeks in duration:
      - flaring AGN, Novae, Sun, Crab, Binary systems, etc.



Fermi Large Area Telescope (LAT)

More details in:
"Fermi Large Area Telescope Performance after 10 Years of Operation", The Astrophysical Journal Supplement Series 256 (2021), 1-12.

Precision Si-strip Tracker (TKR)

Measures incident γ-ray direction

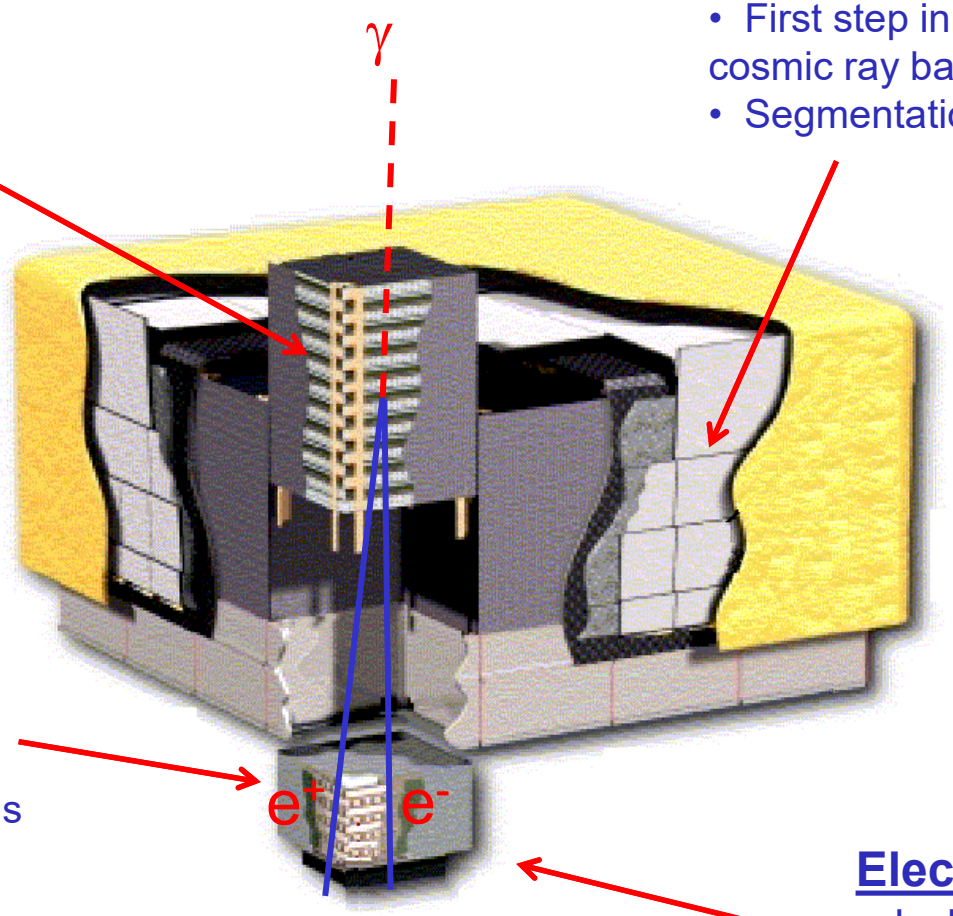
- Gamma conversion: $\gamma \rightarrow e^+e^-$
- 18 XY tracking planes: 228 μm strip pitch
- High efficiency. Good position resolution

FoV 2.4sr (~ 20% of the sky)
scans entire sky every ~3hrs

Anticoincidence Detector (ACD)

charged particle separation

- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy



Public Data Release:
All γ-ray data made public within 24 hours (http://fermi.gsfc.nasa.gov/ssc/) The science tools for data analysis are also provided

Hodoscopic CsI Calorimeter

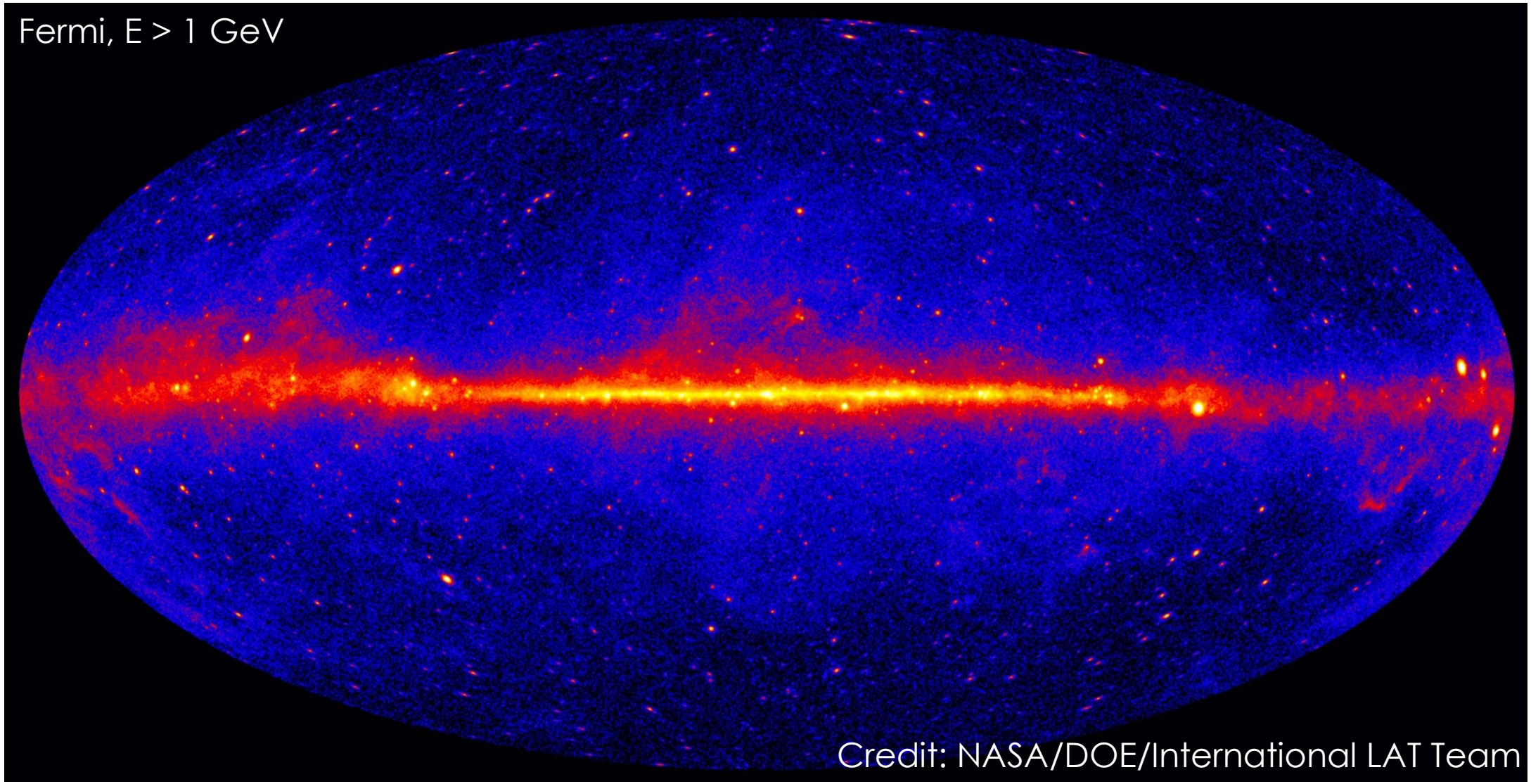
Measures the incident γ-ray energy

- Segmented array of 1536 CsI(Tl) crystals
- 8.6 X_0: shower max contained
  ~ 200 GeV normal (1.5X_0 from TKR included)
  ~ 1TeV @ 40° (CAL-only)

Electronics system

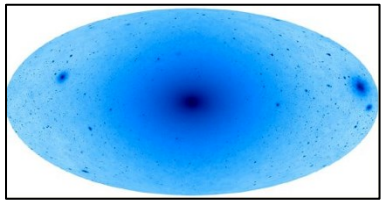
- Includes flexible, highly efficient, multi-level trigger (Reduce data rate from ~10kHz to 300-500 Hz)

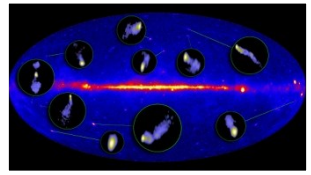
The gamma-ray sky seen by Fermi-LAT

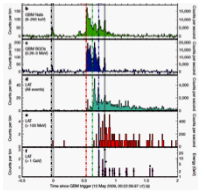


Science with Fermi LAT

Dark Matter searches

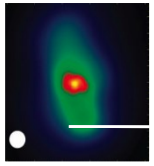




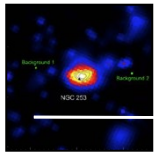


GRBs

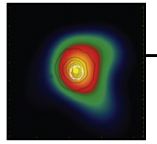
Blazars



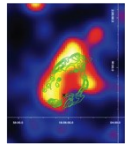
Radio Galaxies



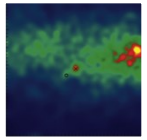
Starburst Galaxies



Globular Clusters



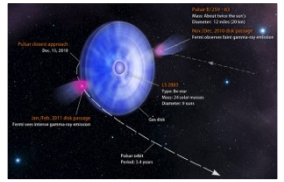
SNRs & PWN



Novae

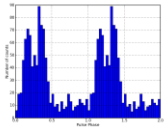
Extragalactic

Galactic



γ-ray Binaries

Pulsars: isolated, binaries, & MSPs



Moon

Earth

Limb

Local

Sun: flares & CR interactions

Terrestrial γ-ray Flashes

Unidentified Sources

The gamma-ray source catalogs

- **The catalogs drive the LAT science**
  - Classification of sources
  - Population studies
  - Possibility of finding new classes of sources
    - Every iteration of the catalog analysis is a deeper view of the gamma-ray sky
  - Both general and class-specific catalogs have been released
    - AGNs, Pulsars, GRBs, SNRs, transients…
  - Catalogs are usually the baselines for many analyses
    - They trigger deeper study of specific sources
    - Seed for multi-wavelength observation
    - Represent primary information to model any region of interest in the sky

Acronym	IRFs/Diffuse Model	Energy Range/Duration	Sources
1FGL	P6_V3_DIFFUSE gll_iem_v02	0.1–100 GeV 11 months	1451 (P)
2FGL	P7SOURCE_V6 gal_2yearp7v6_v0	0.1–100 GeV 2 yr	1873 (P)
3FGL	P7REP_SOURCE_V15 gll_iem_v06	0.1–300 GeV 4 yr	3033 (P)
FGES	P8R2_SOURCE_V6 gll_iem_v06	10 GeV–2 TeV 6 yr	46 (E)
3FHL	P8R2_SOURCE_V6 gll_iem_v06	10 GeV–2 TeV 7 yr	1556 (P)
FHES	P8R2_SOURCE_V6 gll_iem_v06	1 GeV–1 TeV 7.5 yr	24 (E)
4FGL	P8R3_SOURCE_V2 gll_iem_v07 (Section 2.4.1)	0.05 GeV–1 TeV 8 yr	5064 (P)

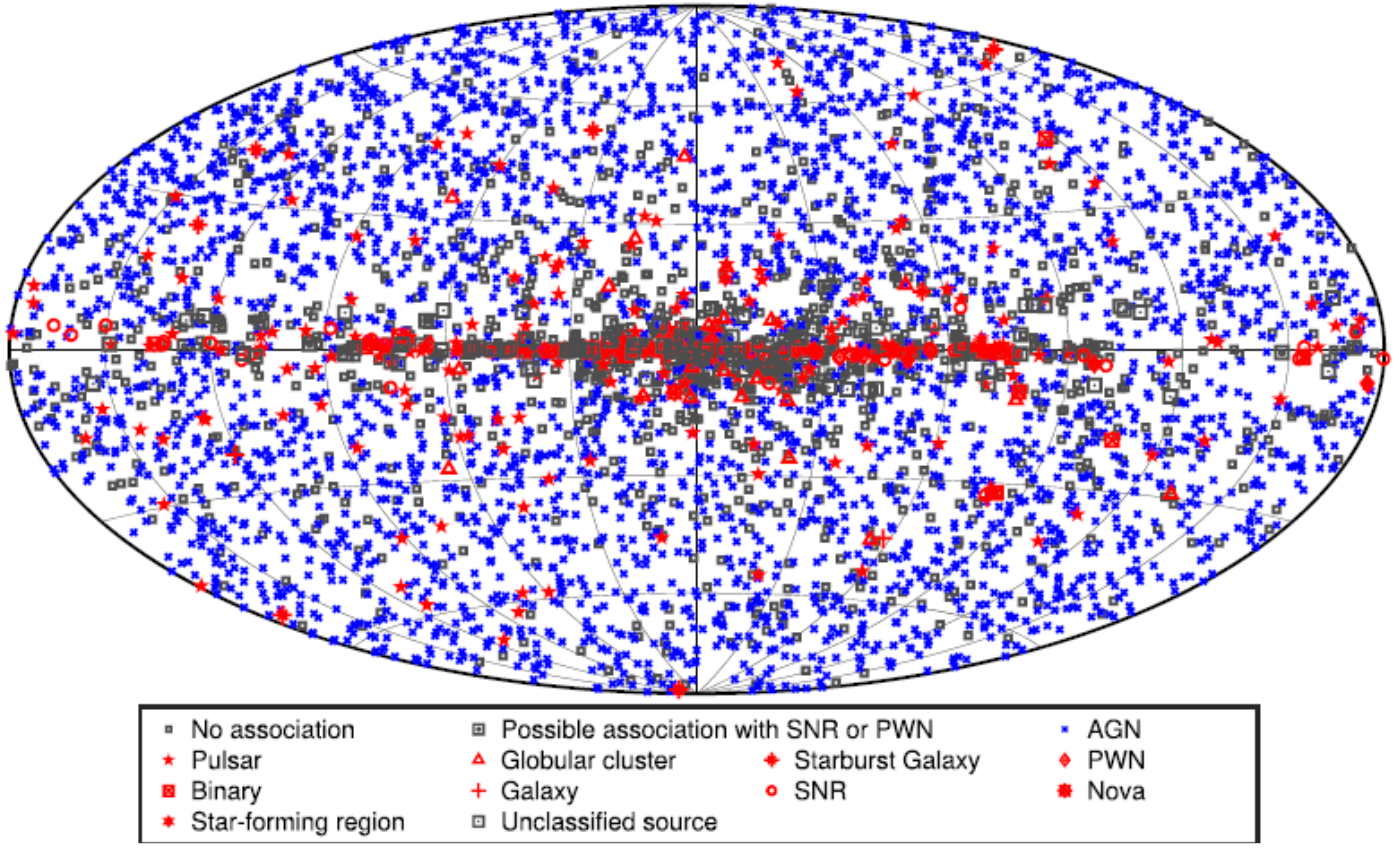
More details in:

- **"*Fermi Large Area Telescope Fourth Source Catalog*", Astrophys. J. Suppl. 247 (2020), 33.**
- **" *Incremental Fermi Large Area Telescope Fourth Source Catalog*", *arXiv:2201.11184* (2022).**

Currently on 4FGL_DR3 with 12 yrs of data

The 4th Fermi LAT Source Catalog (4FGL)

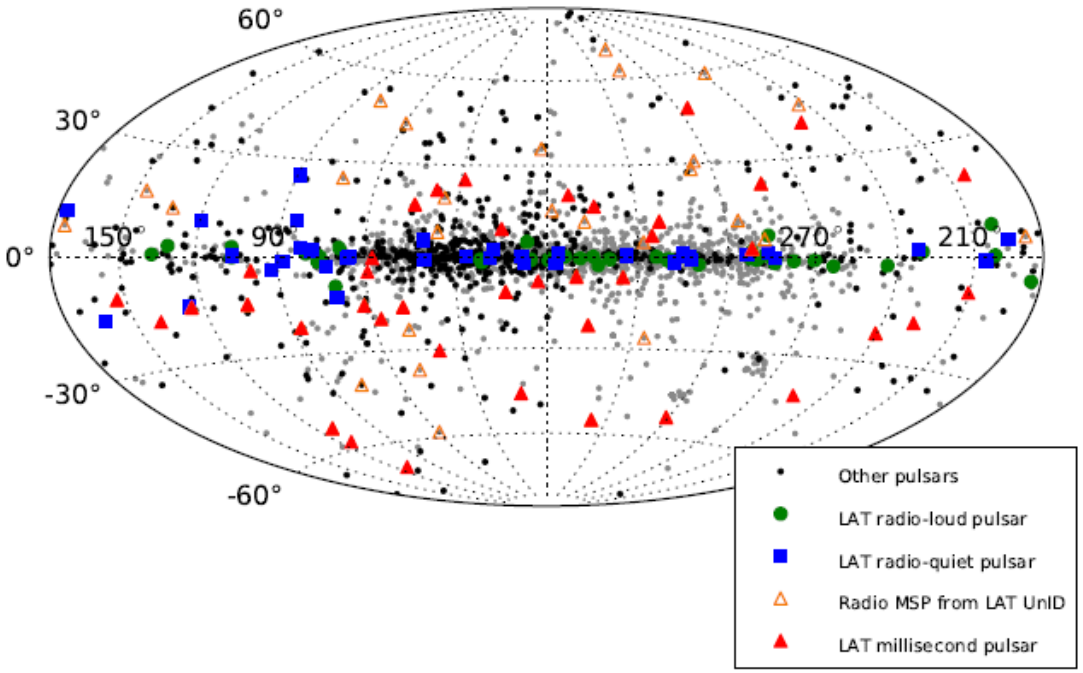
- The 4FGL catalog includes more than 6000 sources (4FGL_DR3 latest version) above 4σ significance:
  - Mostly blazar and pulsars:
    - More than 3000 of the identified or associated sources are active galaxies of the blazar class, and 276 are pulsars
  - 75 sources are modeled explicitly as spatially extended
  - Roughly 1/3 of the sources are unassociated



"*Fermi Large Area Telescope Fourth Source Catalog*", Astrophys. J. Suppl. 247 (2020), 33.

The Fermi LAT pulsars

- **At present the LAT has detected 276 gamma-ray pulsars**
  - Half of the gamma-ray pulsars were not known before Fermi
  - Pulsar science represents an example of successful cooperation between radio, X-ray and gamma-ray astronomers.
    - A Pulsar Search Consortium (PSC) undertook searches at radio and X-ray wavelengths at the positions of unidentified LAT gamma-ray sources.
  - For a complete list of the LAT pulsars see: https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

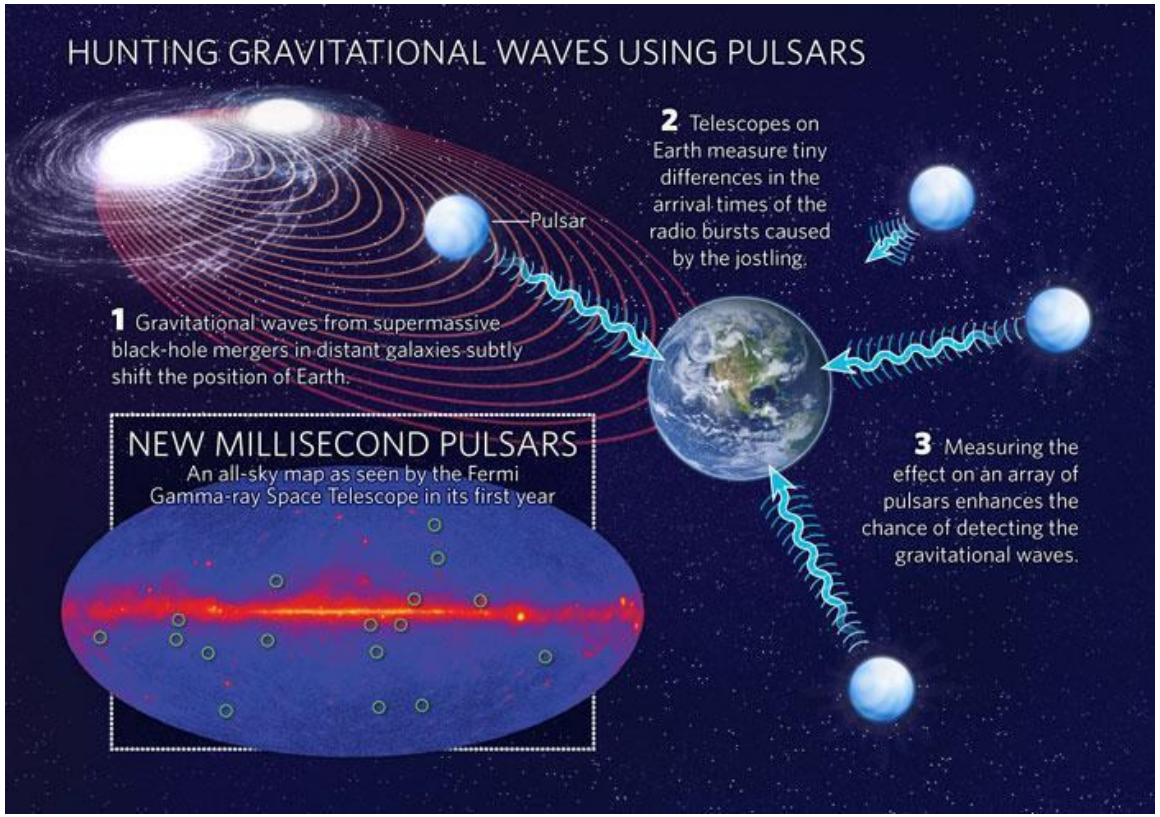


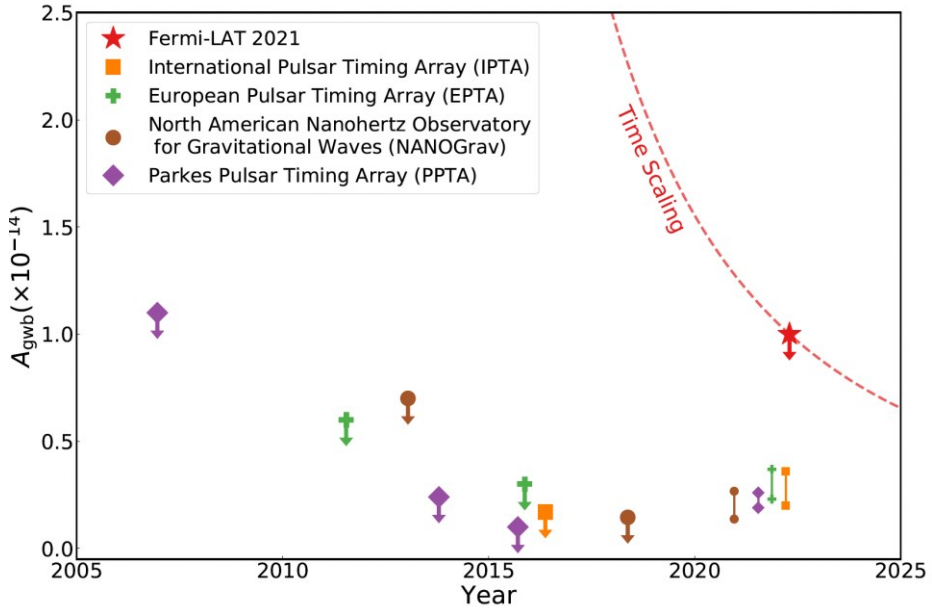
More details in:

- "*The Second Fermi Large Area Telescope Catalog of Gamma-ray Pulsars*", **Astrophys. J. Suppl. 208 (2013), 17**.

Pulsars and gravitational waves

- **Gravitational waves can be detected by monitoring the times of arrival of the steady pulses from each pulsar, which arrive earlier or later than expected due to the spacetime perturbations.**
  - After large galaxies merge, their central supermassive black holes (SMBH) are expected to form binary systems whose orbital motion generates a *gravitational wave background* (GWB) at nHz frequencies.
  - Using 12.5 years of LAT data to form a gamma-ray pulsar timing array (PTA) formed by 35 bright gamma-ray pulsars, it was possible to constrain the emission from the gravitational wave background (GWB).



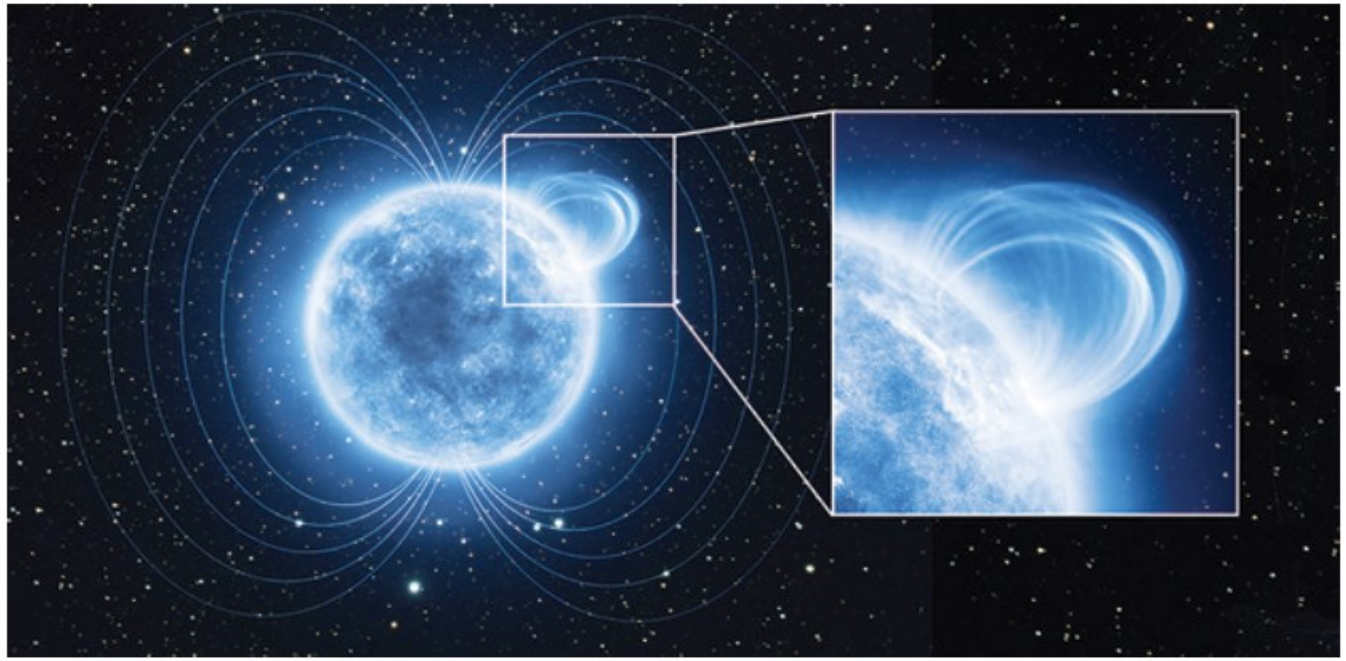


More details in:

- *"A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background"* **Science 376.6592 (2022): 521-523.**

High-energy emission from a magnetar giant flare in the Sculptor galaxy

- **Magnetars are the most highly magnetized neutron stars in the cosmos (magnetic field 10^{13}–10^{15} G).**
  - Magnetar Giant Flares (MGFs) from magnetars are rare, short-duration bursts of hard X-rays and soft γ rays
  - Origin of MGFs: Energy release by **crustal fractures induced by high magnetic fields**
    - ejects **hot plasma** into the inner magnetosphere
- **First discovery of GeV emission from a MGF associated to a Magnetar in the NGC 253 (Sculptor Galaxy) on 15 April 2020 by Fermi LAT**



More details in:

- "***High-energy emission from a magnetar giant flare in the Sculptor galaxy***", **Nature Astronomy, 2021, 5.4, 385-391.**

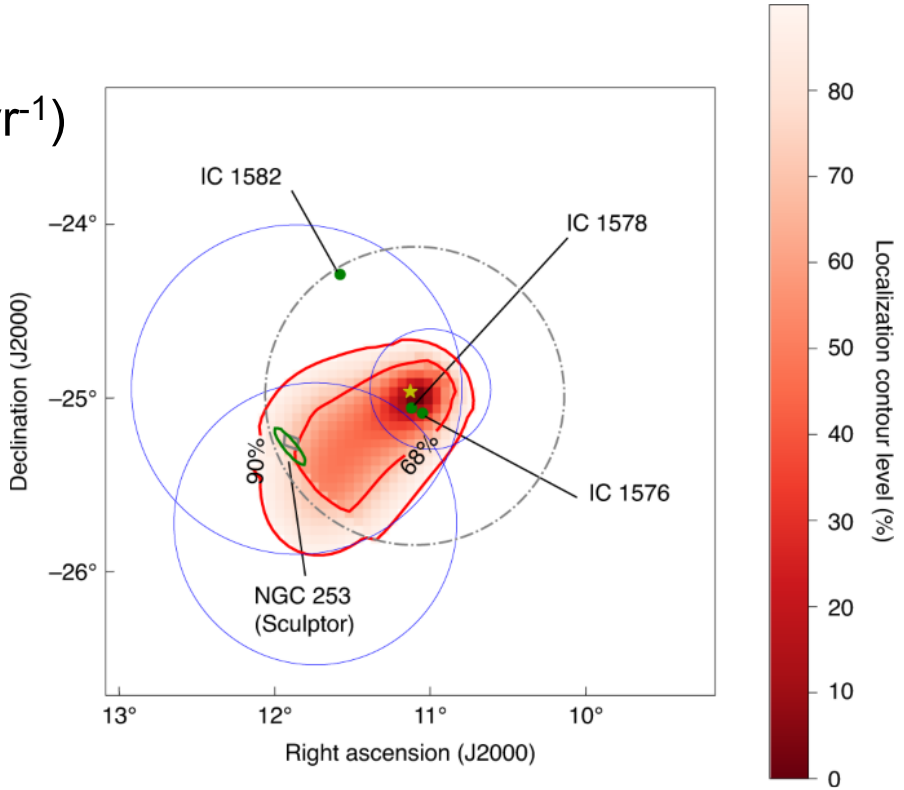
- **Bright transient triggered the Inter-Planetary Network (IPN) on April 15th, 2020**
  - *Fermi Gamma-ray Burst Monitor (GBM) Trigger* at 08:48:05.56 UTC (GRB 200415A)[1]

[1]Svinkin, D., Frederiks, D., Hurley, K. et al. «*A bright γ-ray flare interpreted as a giant magnetar flare in NGC 253*». Nature 589, 211–213 (2021).

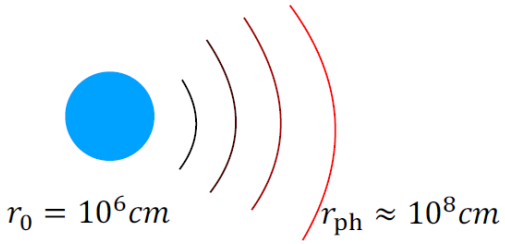
Magnetar Giant Flare

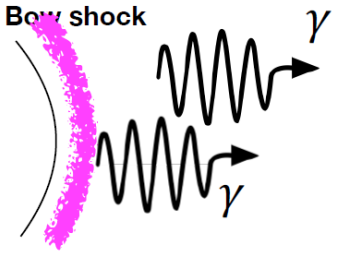
- **GRB Localization**
  - Burst localized with 20 square-arcmin precision through interplanetary Network of gamma-ray detectors most likely originated in the Sculptor Galaxy, DL ≈ 3.5 Mpc
- **LAT detected 3 photons**
  - Maximum test statistic TS=29
  - NGC 253 (Sculptur gal.) at 72% localization CL
  - Probability of chance coincidence: < 2.9 x 10^{-3} (FARs 5 x 10^{-4} yr^{-1})

Time since T0 (s)	*Energy* (MeV)	*Distance to NGC 253* (°)	*Assoc. probability*
19.18	480	0.3	0.990
180.22	1300	0.5	0.988
284.05	1700	0.9	0.999



LAT HE emission due to **synchrotron emission** of particle accelerated in the shock propagating into the ISM.





"*High-energy emission from a magnetar giant flare in the Sculptor galaxy*", **Nature Astronomy, 2021, 5.4, 385-391.**

Indirect searches of Dark Matter with the Fermi Large Area Telescope

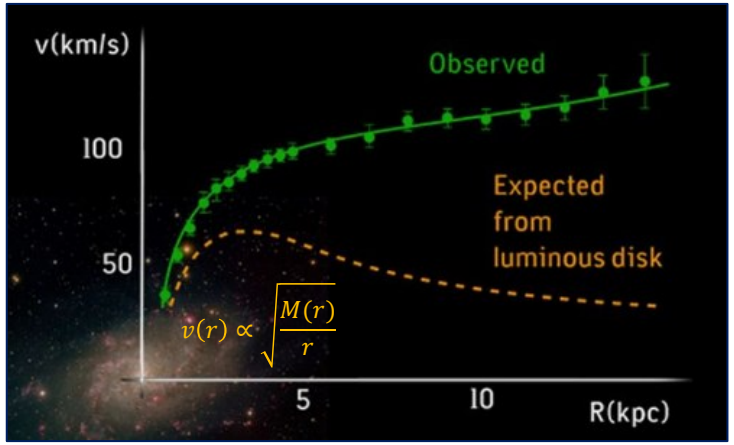
Dark Matter

- **Experimental evidences for Dark Matter:**
  - Galaxy rotation curves
  - Gravitational lensing
- **Observational evidence indicates:**
  - Non-baryonic
  - Neutral particles (do not interact electromagnetically)
  - Very stable particles with respect to the cosmological time scale
- **Possible theoretical candidate:**
  - Weakly interacting Massive Particles (WIMPs)
    - Neutralino χ

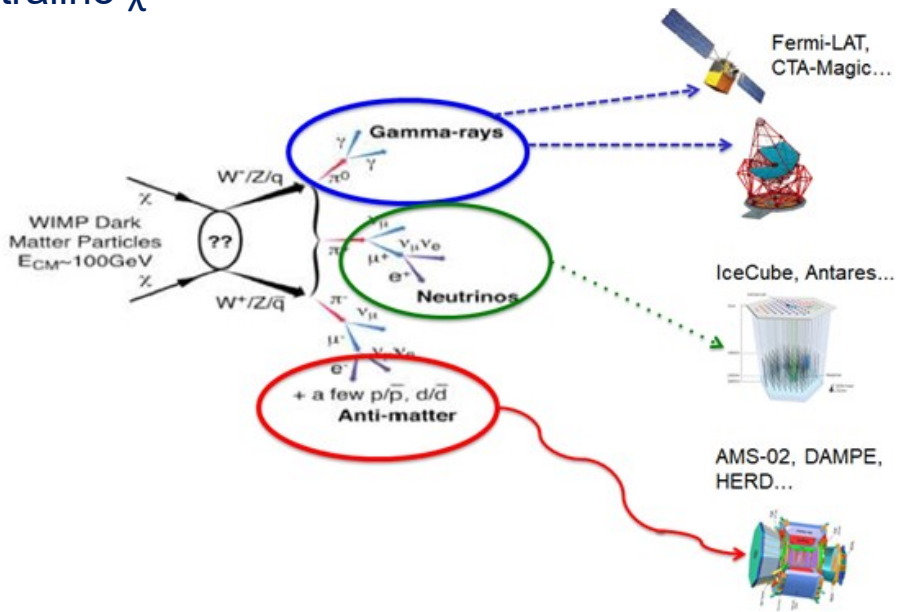
Ordinary matter inferred from known visible sources

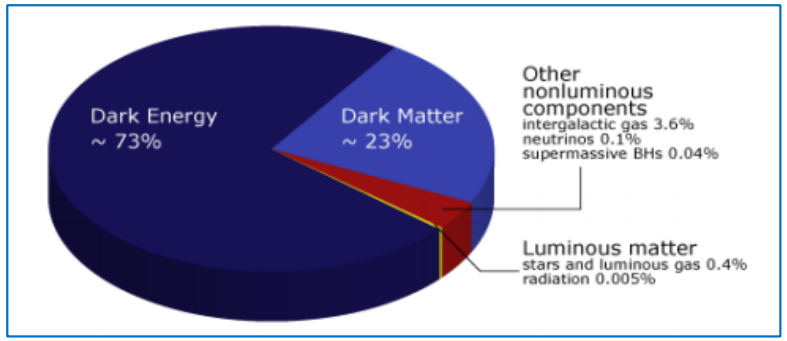
+

Missing Dark matter

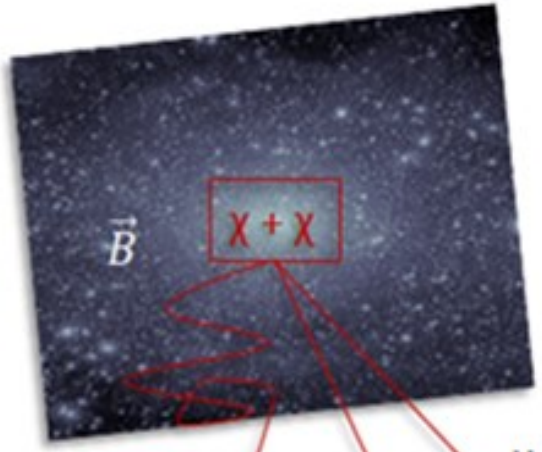


WIMPs "hunters"





Indirect searches for dark matter in the GeV gamma-ray sky



Annihilation:

Observed flux | Intrinsic Particle Properties | Astrophysics

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

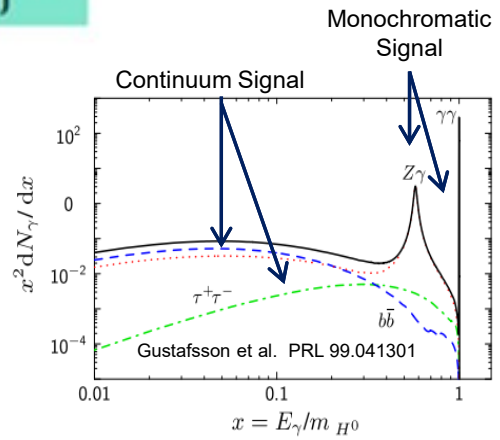
$\langle\sigma v\rangle_{ann} \sim 3\times10^{-26}\,cm^3/s$ for thermal relic

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

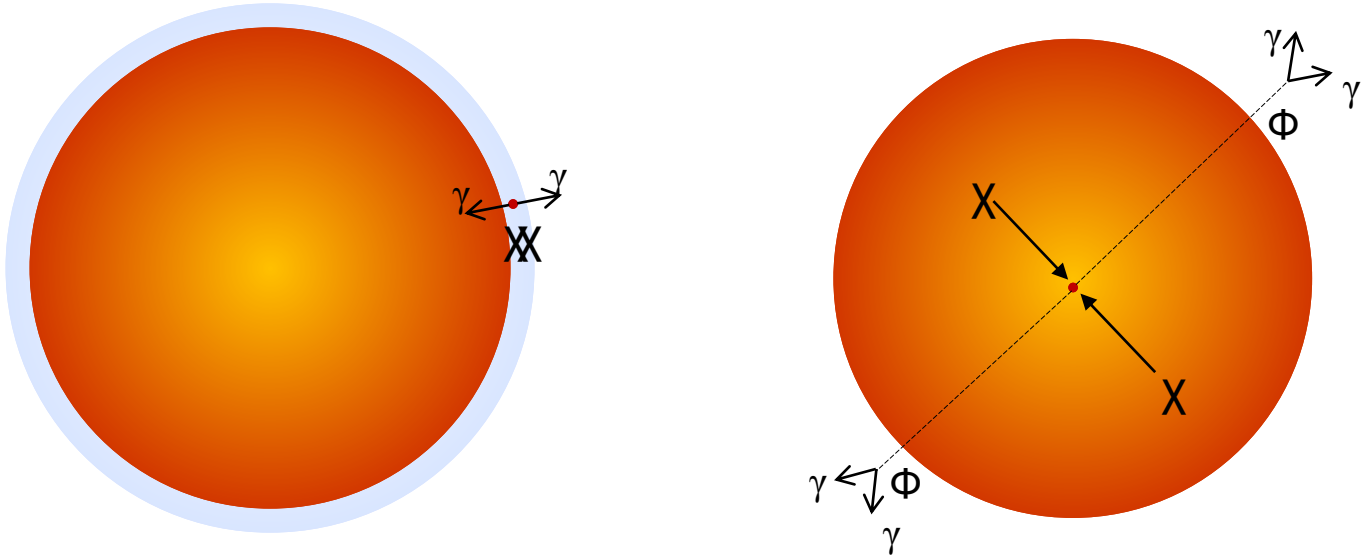


Optimal targets:

- Highest J-factors
- lowest astrophysical background

Searches for solar dark matter

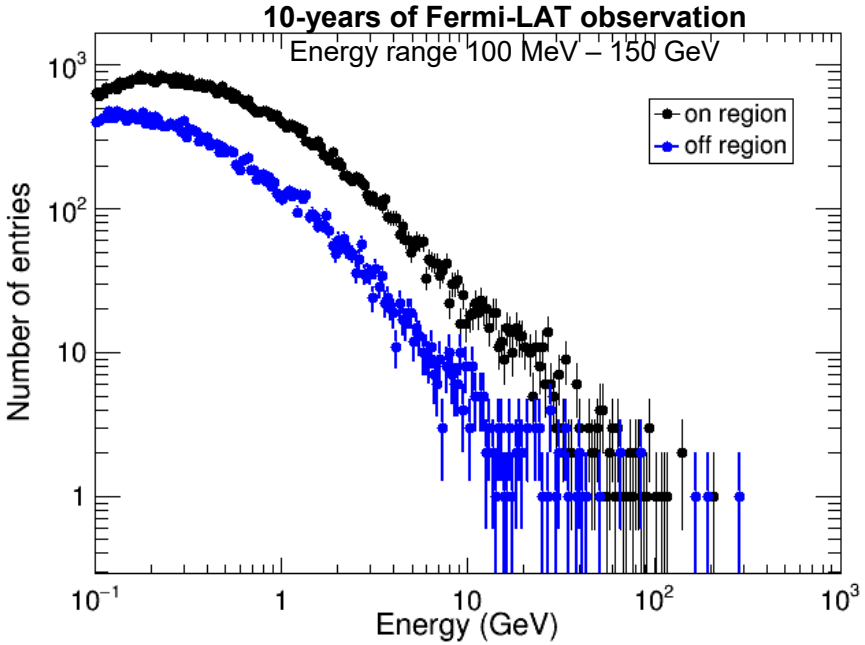
- **DM particles from the galactic halo can be gravitationally trapped by the Sun through scattering interactions with the nuclei in the solar environment**
  - The over-density of DM around the Sun or in its core can result in annihilations into SM particles

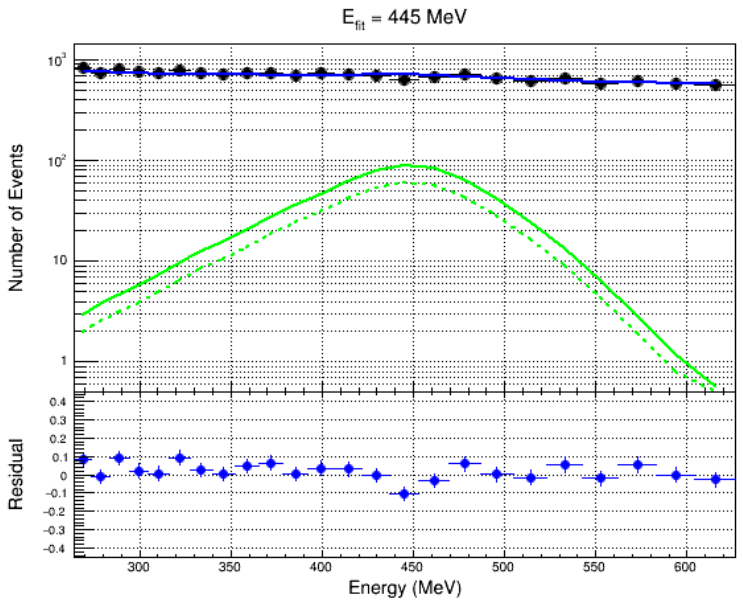


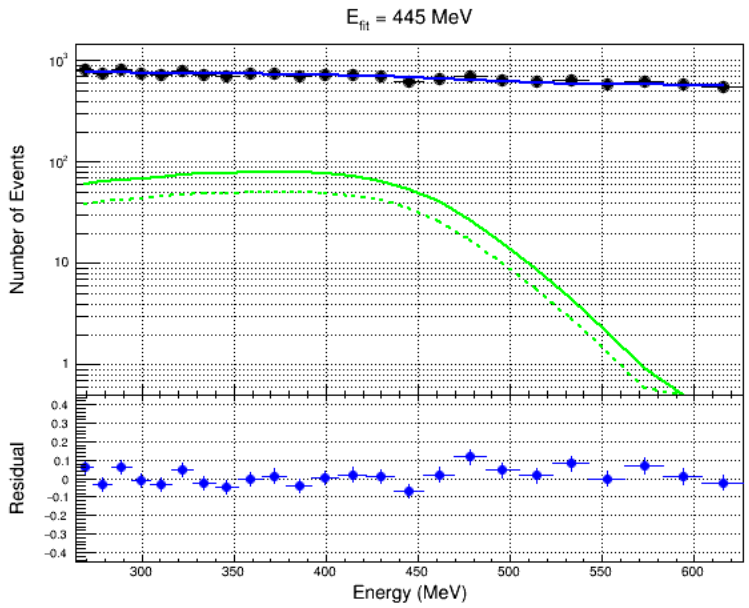
- **DM signals would appear as an excess on the top of the standard emission:**
  - WIMPs annihilating directly into γ pairs $(\chi\chi \rightarrow \gamma\gamma)$ → local ***line-like*** feature
  - WIMPs annihilating into light mediators $(\chi\chi \rightarrow \phi\phi)$:
    - Mediators decaying directly into gamma-ray pairs $(\phi \rightarrow \gamma\gamma)$ → ***box-shaped feature***
    - Mediators decaying with gamma rays in the final states (e.g. $\phi \rightarrow b\bar{b}$, $\tau^+\tau^-$,$\mu^+\mu^- \rightarrow \gamma\ldots$) → ***smooth spectrum***

Search for line-like and box-like features in the solar gamma-ray spectra

- **The Sun is a moving source**
  - ON/OFF technique analysis:
    - ON Region : centered on the Sun current position
    - OFF Region: centered on the 6 months time-offset position
      - The OFF region is used as control region to constrain the background
- **Analysis performed in sliding energy windows**
  - Search for possible local features and evaluation of their significance
    - *All possible features turn out to be statistically insignificant*





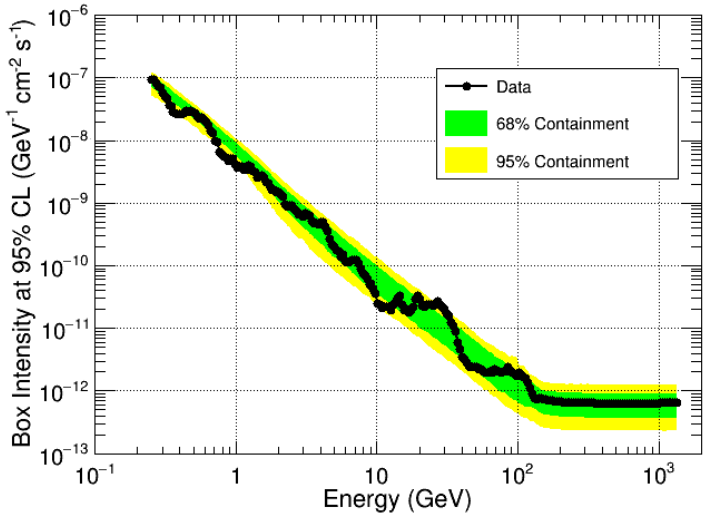


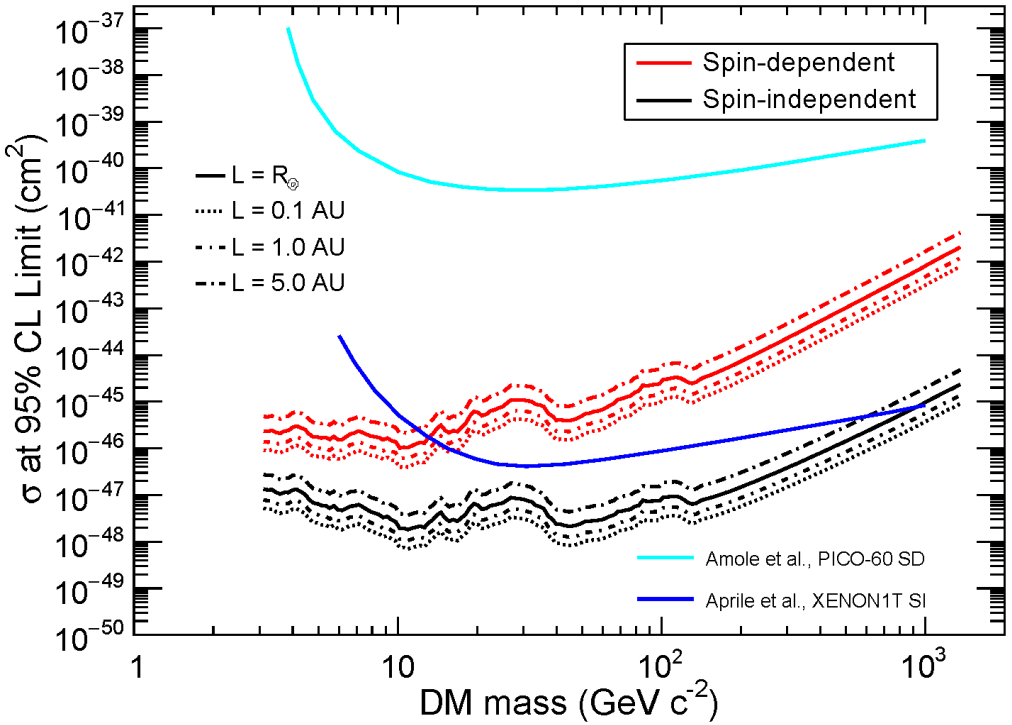
More details in:

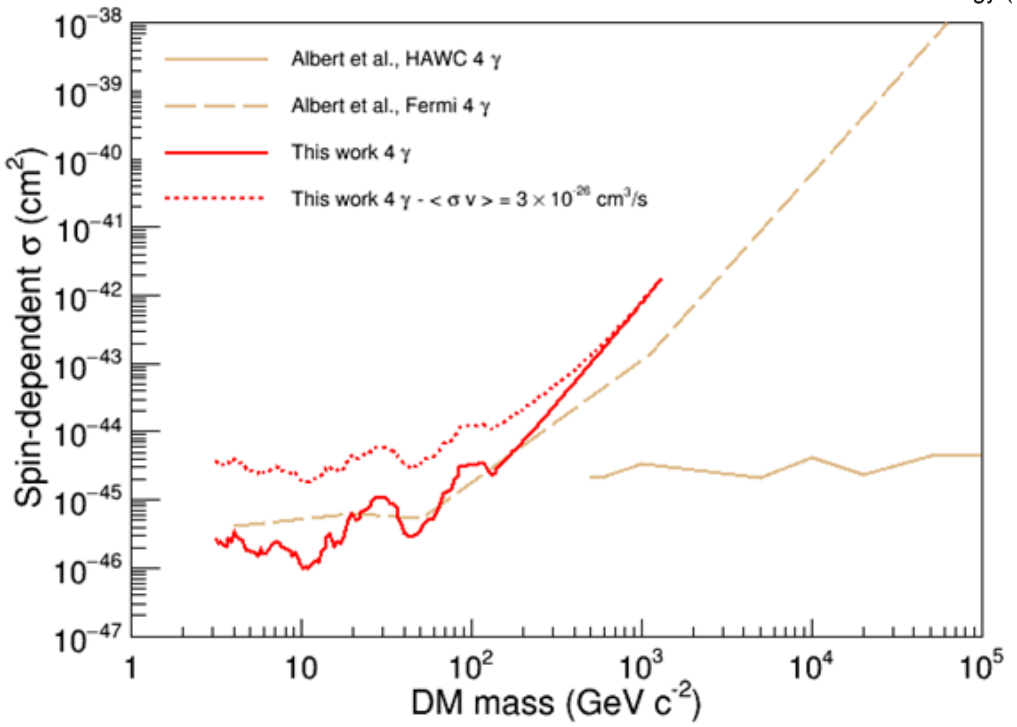
- "*Search for dark matter signatures in the gamma-ray emission towards the Sun with the Fermi Large Area Telescope*", **PRD, 102(2), 022003.**

DM - nucleon cross section limits (1)

- **The limits on the box feature intensities can be converted into limits on the DM-nucleon cross section by evaluating the capture rate ($\Gamma_{cap} \propto \sigma$)**
  - Results in agreement with other experiments
    - For further details see M. N. Mazziotta, F. Loparco, D. Serini et al., Physical Review D, 102(2), 022003

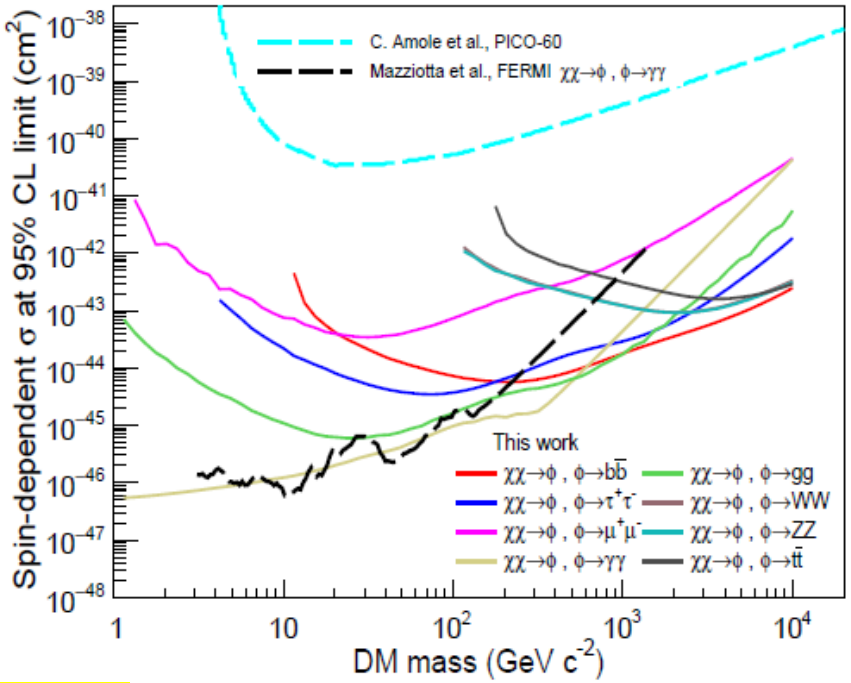


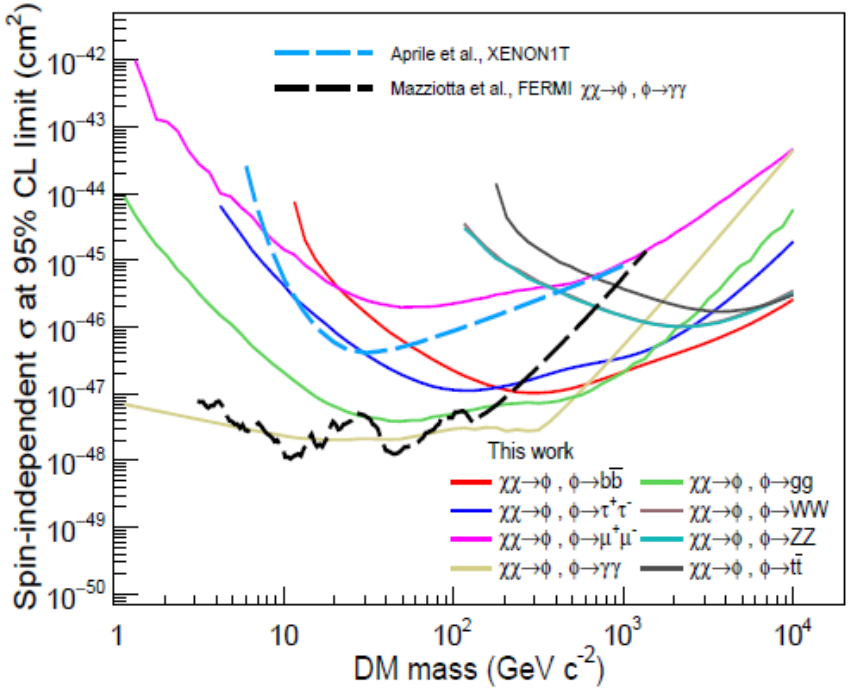




DM - nucleon cross section limits (2)

- **We have constrained a set of DM models predicting a gamma-ray signal from the Sun through the annihilation of solar WIMPs into long-lived mediators which can decay outside the Sun ($\chi\chi \to \phi\phi$, $\phi \to b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$...)**
  - These scenarios would yield a smooth γ-ray spectrum whose shape depends on m_ϕ and m_χ and on the mediator decay channel





Submitted to JCAP:
Arxiv arXiv:2208.13157

Conclusion

- **The LAT remains in excellent operating condition after 14 years in space.**
  - There are no consumables that will limit the lifetime of the LAT or Fermi.
    - In Fermi's 14th year in orbit, continued monitoring confirms the LAT's ongoing smooth operation.
- **Fermi has opened a window on the extreme high-energy Universe**
  - Exciting results in all fields of gamma-ray astrophysics
    - Many discoveries, many new source classes, many surprises
      - *Many results not shown here!*

- **Fermi-LAT is also an excellent probe of particle Dark Matter**
  - Indirect search is the technique used to investigate possible DM signals of astrophysical origin
  - The Sun is a promising target for indirect DM searches
    - We have searched for possible features in the solar gamma-ray spectrum as DM signatures
      - No evidence of DM signal found in any channel

        Upper limits on relevant physical quantities have been set