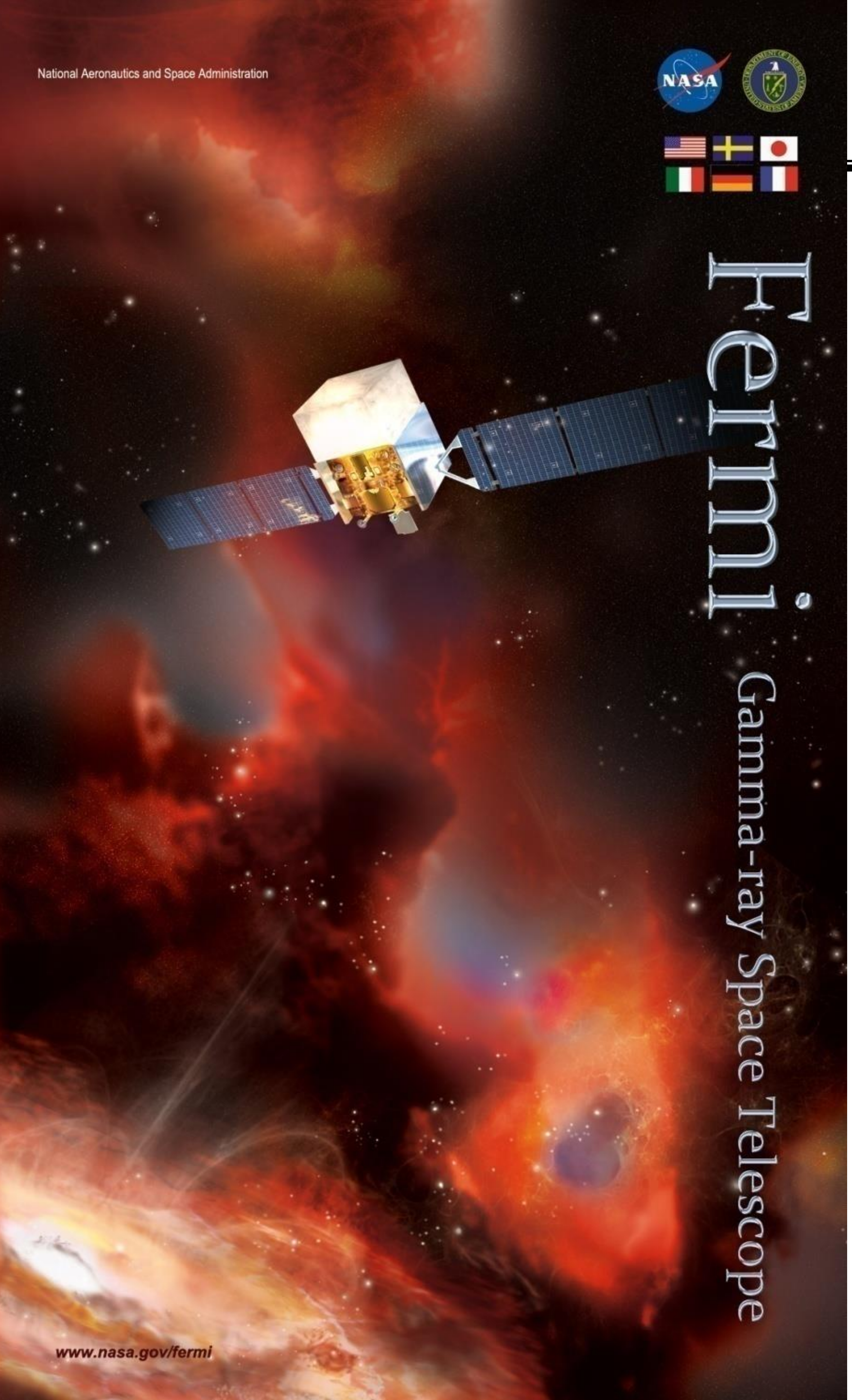

Science with the Fermi Large Area Telescope

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On behalf of the Fermi-LAT Collaboration

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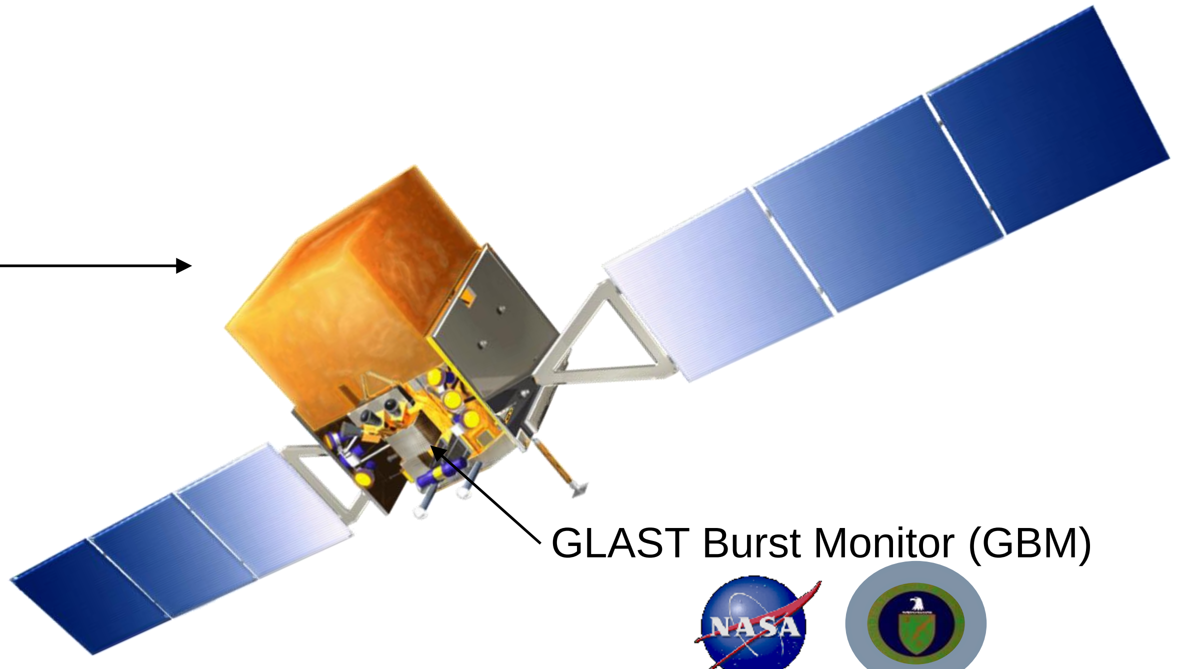
The Fermi mission

- Launched by NASA on 2008 June 11, from Cape Canaveral, Florida
  - Almost circular orbit, at 565 km altitude and 25.6° inclination
- Science mission started in August 2008
- Mission extended until 2025 after the NASA Senior Review in 2022

The Fermi satellite



- **The Fermi Gamma-Ray Space Telescope is an international Science Mission exploring the gamma-ray sky by means of its two instruments:**
  - **Gamma-ray Burst Monitor (GBM): 8 keV → 40 MeV**
  - **Large Area Telescope (LAT): 20 MeV → > 300 GeV**
- **Huge energy range: including a total of >7 energy decades!**

Fermi observation strategy

- Mostly uniform sky survey
  - Dec 2013 – Dec 2014, transitioned to Galactic-Center biased survey for 1 year
- Target of opportunity (ToO) observations
  - flaring AGNs, novae, Sun, Crab, binary systems, etc.
  - generally between 1 day and a few weeks in duration
- Autonomous repoint requests (ARR):
  - 2.5-hour autonomously commanded pointed observations following detection of bright hard-spectrum gamma-ray bursts (GRBs)
  - This operation mode was available until 2018
    - Failure of a solar array drive motor in March 2018
- The wide field of view and survey mode operation allows Fermi to explore the high-energy gamma-ray sky on timescales from milliseconds to years

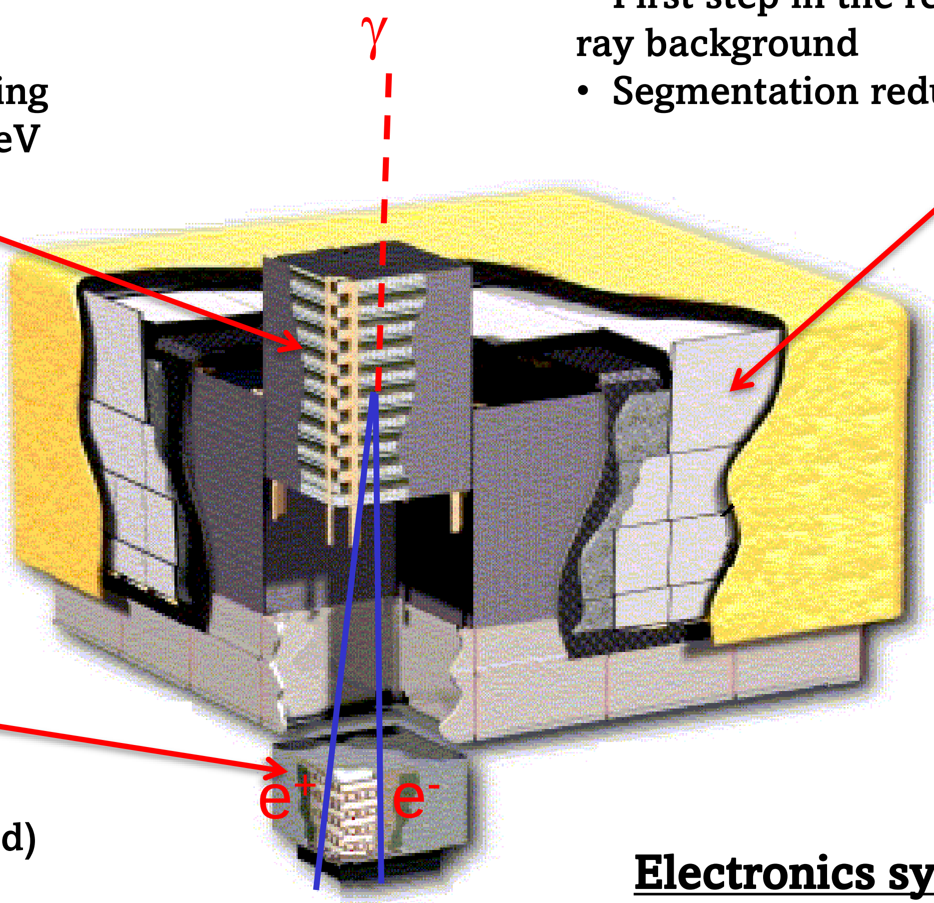
The Large Area Telescope

Precision Si-strip Tracker (TKR)

- Measures incident γ-ray direction
- 18 XY tracking planes: 228 µm strip pitch
- High efficiency. Good position resolution
- 12x 0.03 X_0 front end → reduce multiple scattering
- 4x 0.18X_0 back-end → increase sensitivity >1 GeV

Anticoincidence Detector (ACD)

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



Full details in Atwood et al., ApJ 697, 1071 (2009)

Hodoscopic CsI Calorimeter

- 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)
- Measures the incident γ-ray energy
- Rejects cosmic-ray (CR) background

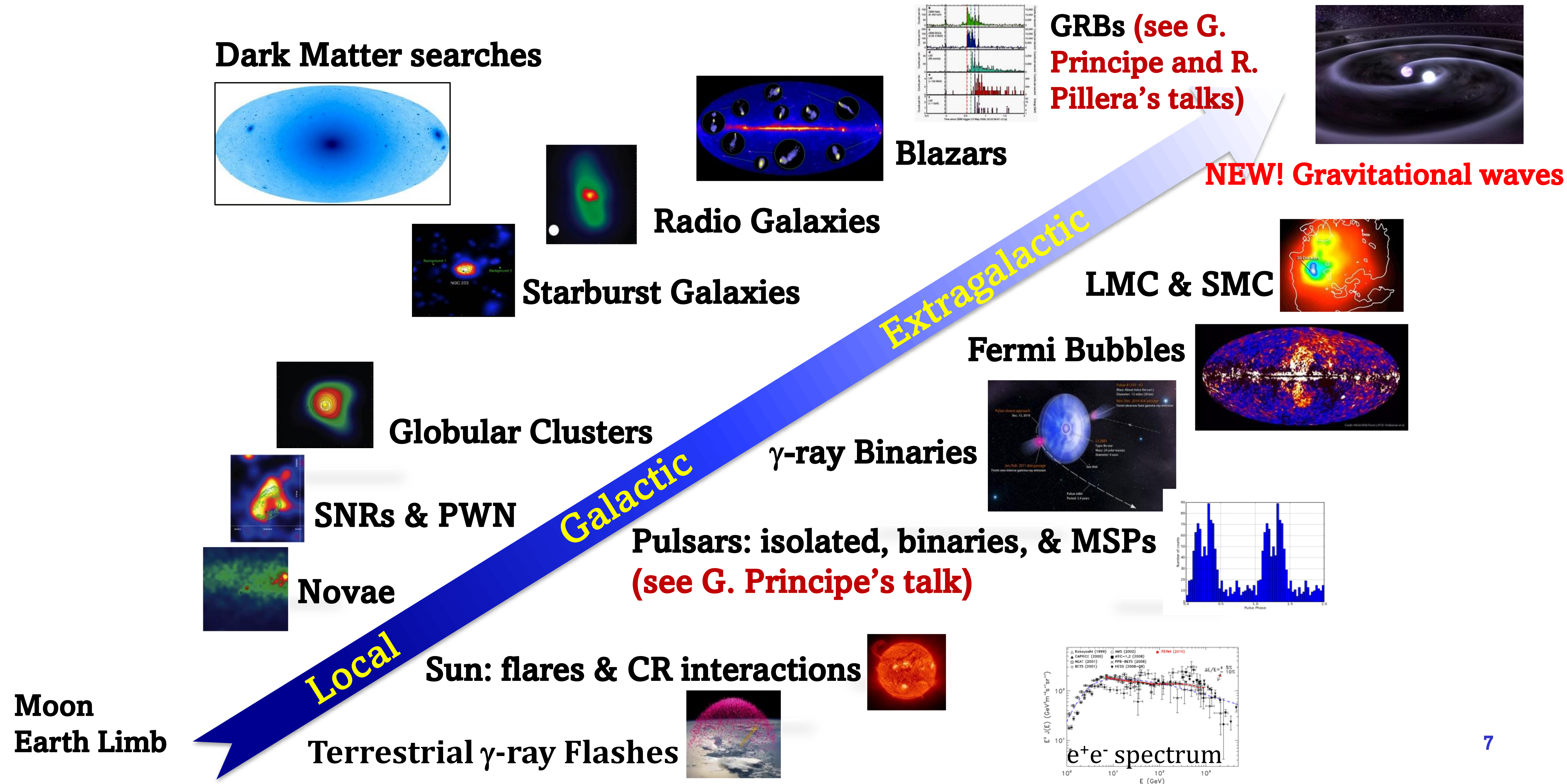
Electronics system

- Includes flexible, highly efficient, multi-level trigger

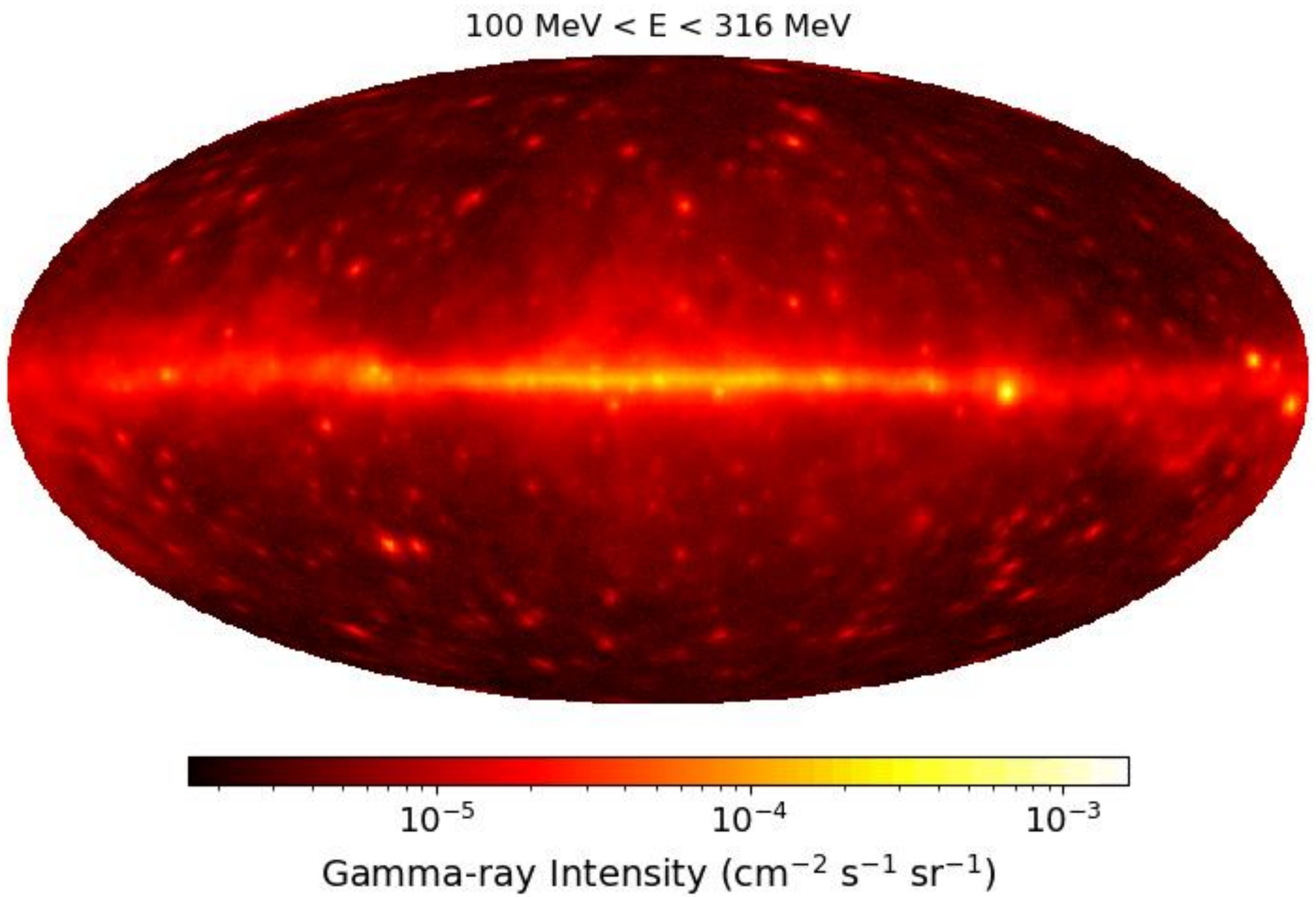
The LAT data

- The LAT observes about 20% of the sky at any time
  - The whole sky is observed every 3 hours
- Uptime fraction ~ 99%
- About 880 billion triggers from launch @March 2023
  - 176 billion events downlinked (20%)
  - 4.25 billion events available at the FSSC (2.4%)
  - 1.61 billion source photon events (38%)
- Different gamma-ray event classes:
  - Triggered events are dominated by CR background events
    - Need to define additional cuts to get γ-ray rich dataset
  - Several event reconstruction and classification algorithms have been developed during the mission
    - Starting from July 2015, the LAT data are processed with the newest "Pass 8" classification algorithms
  - Nested "event classes", optimized for the analysis of different types of γ-ray sources
- Data are public and can be downloaded from the FSSC website (http://fermi.gsfc.nasa.gov/ssc/)
  - Data are made public after 24 hours (or less)
  - The science tools for data analysis are also provided
    - https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

Science with the Fermi-LAT



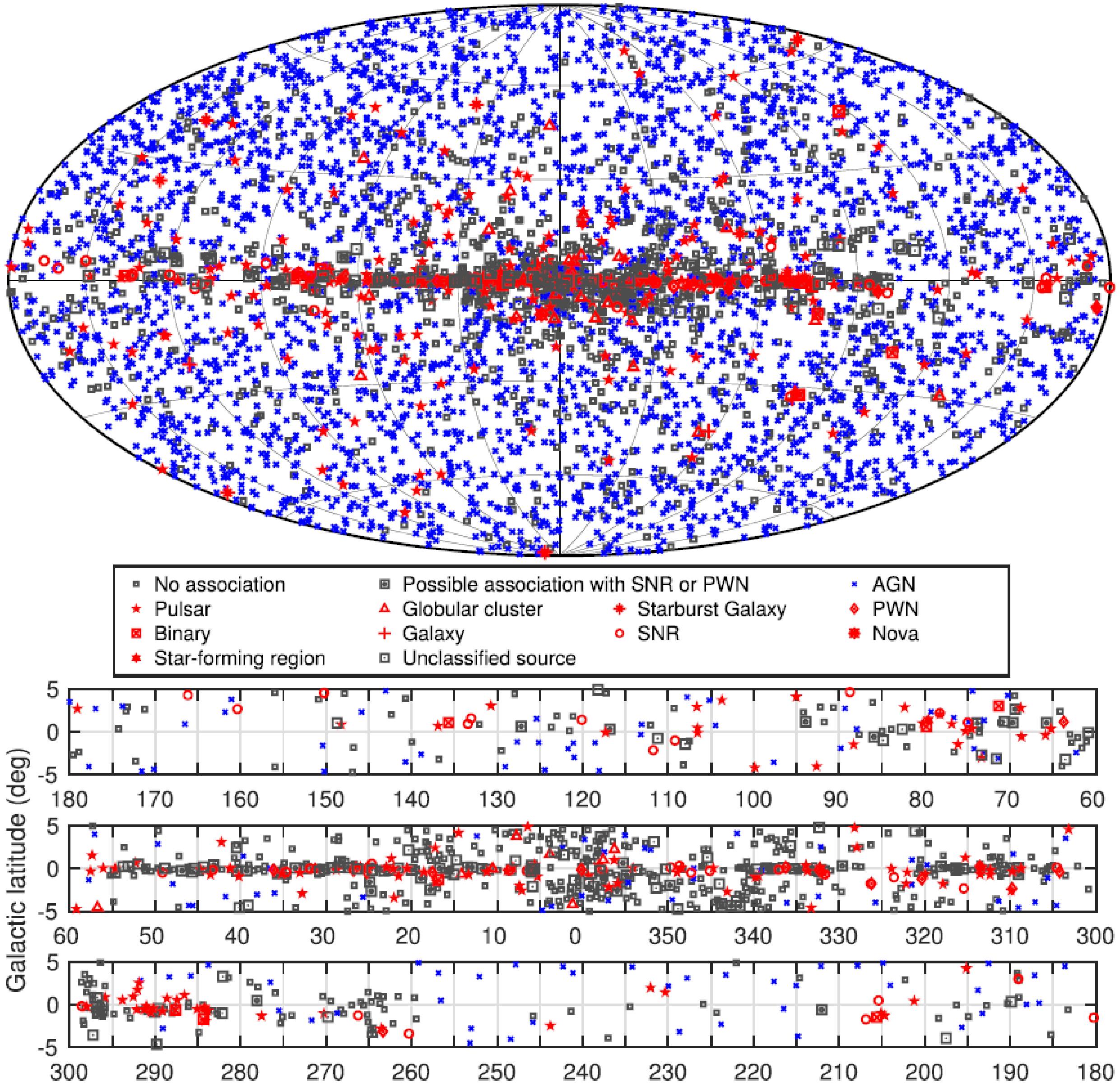
The gamma-ray sky seen by the LAT in different energy windows



The Fermi-LAT 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

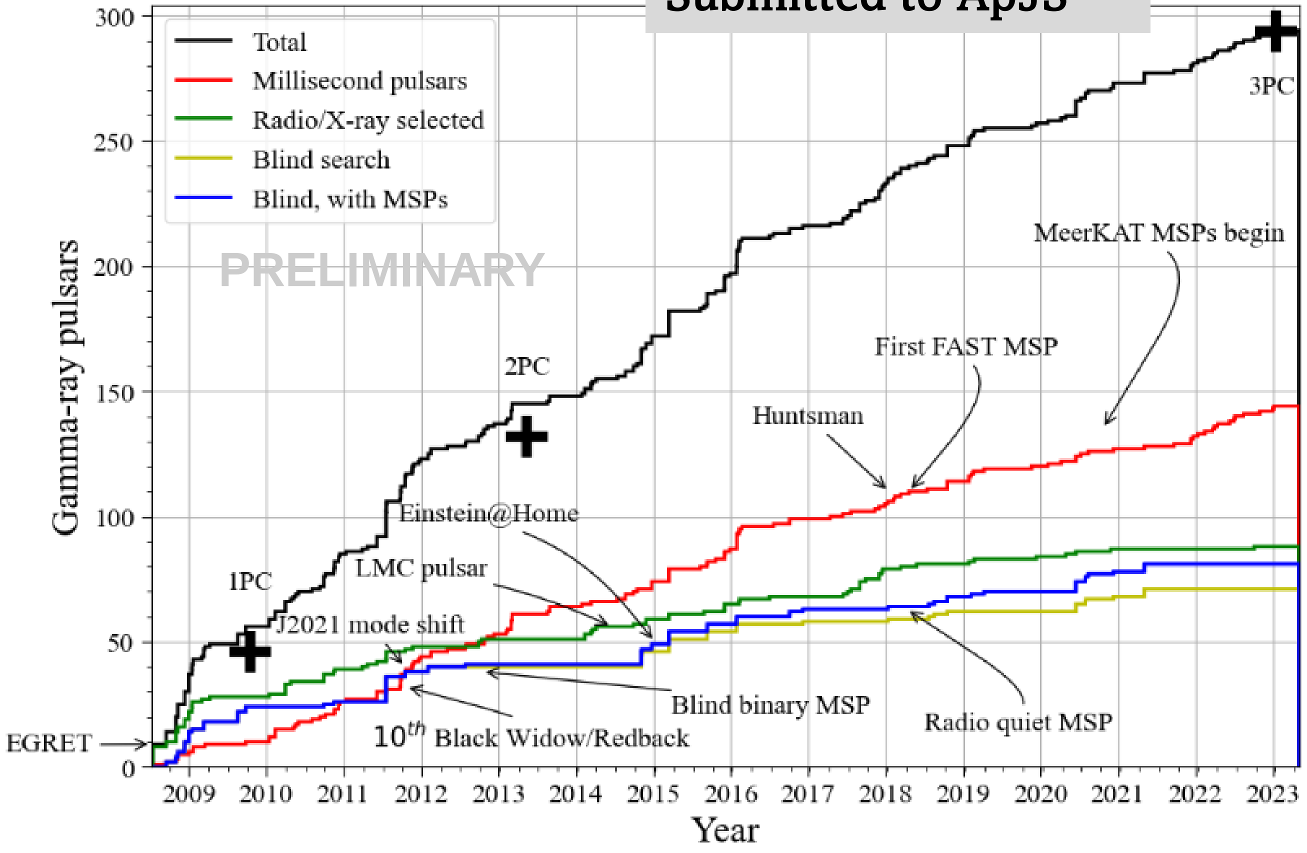
The Fermi-LAT fourth source catalog (4FGL)



- The 4FGL-DR3 catalog includes 6658 sources detected in the energy range 50 MeV – 1 TeV
  - Catalog built with a 12-years dataset (Aug 2008 - Aug 2020)
  - Roughly 1/3 unassociated sources
  - Pulsars are the main class of galactic sources (292)
  - Blazars are the main class of extragalactic sources (3743)
- Further details:
  - 4FGL-DR3 in Abdollahi et al., ApJS 260, 53 (2022)
  - 4FGL in Abdollahi et al., ApJS 247, 33 (2020)
- DR4 coming very soon

The LAT pulsars

Credit: D. Smith et al.
Submitted to ApJS

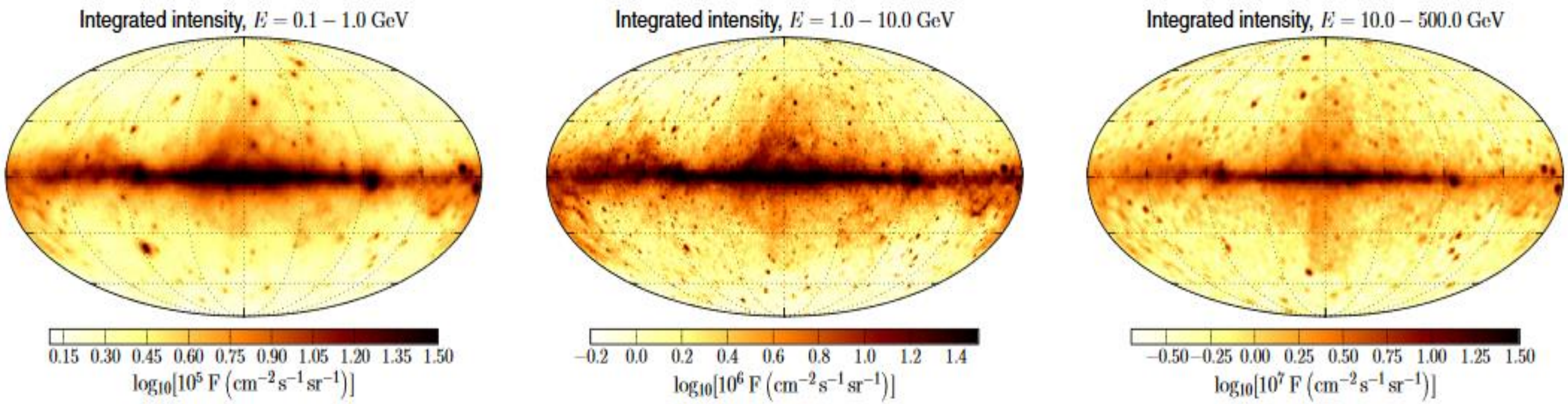


- At present, the LAT has detected 294 gamma-ray pulsars
  - Half of the gamma-ray pulsars were not known before Fermi!
  - Before Fermi only 7 gamma-ray pulsars were detected
  - Emission region location: outer-gap model preferred with respect to the polar-gap
  - Discovery of gamma-ray millisecond pulsars (MSPs)
  - Pulsars, considered stable sources, were discovered to be variable!
- Public list of the LAT pulsars:
  - https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
- More details on pulsar science in the talk by G. Principe
- Fermi 3PC coming very soon

The Fermi bubbles

- Excess in the diffuse emission detected between 1 GeV up to 50GeV
  - The bubbles extend for ~55° above and below the Galactic plane
  - See Ackermann et al., ApJ 793, 64 (2014)
- The Fermi bubbles have the same morphology as the WMAP microwave haze with a magnetic field between 5 and 20 μG ➔ common origin
- The Fermi bubble structures were likely created by some large energy injection in the Galactic Center, such as a past accretion event onto the central black hole SgrA in the last ~10 My
  - See Su et al., Astrophys. J., 724, 1044 (2010)

Plot taken from ApJ 793, 64 (2014)

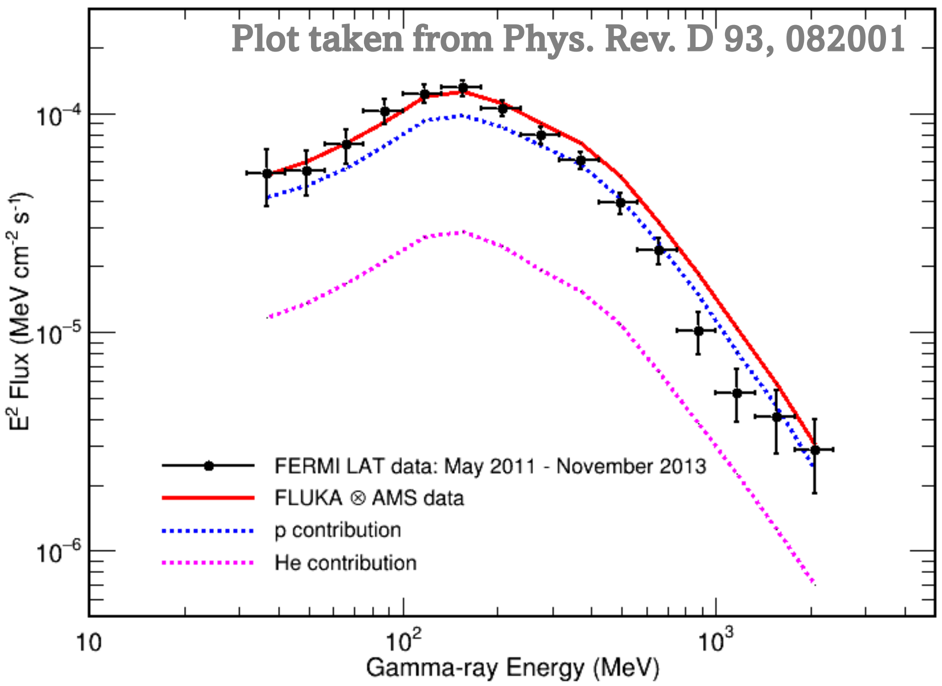


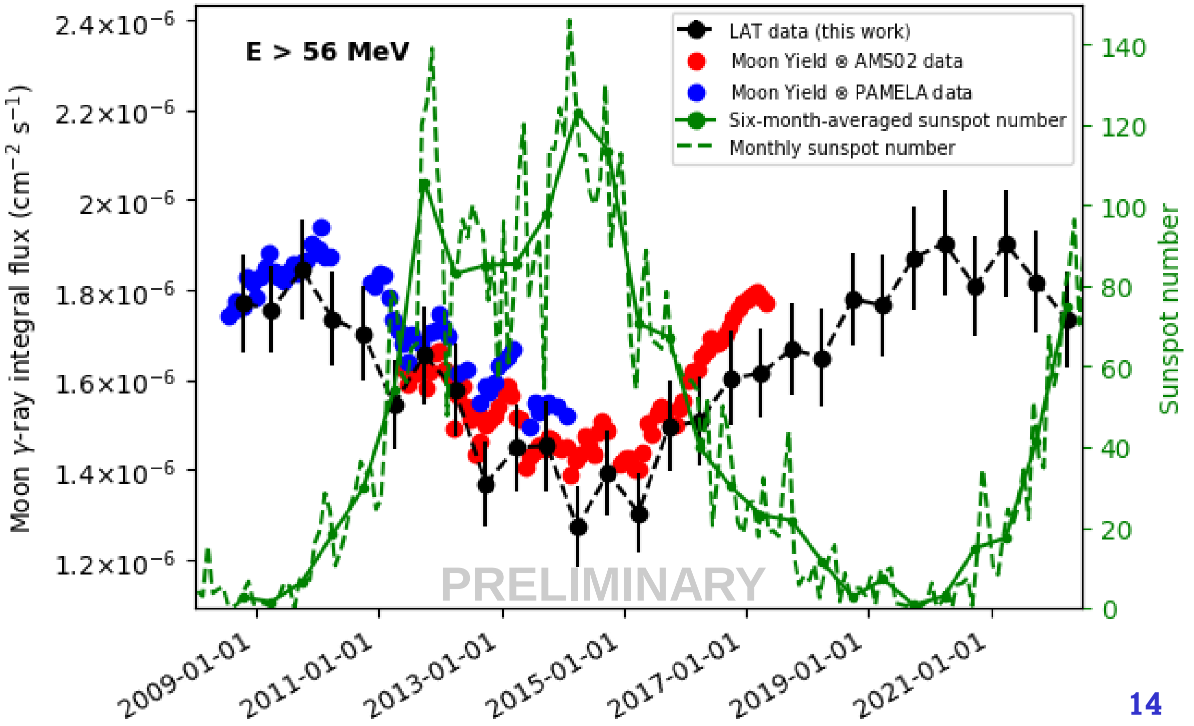
Gamma-ray sources in the Solar System

- The Sun
  - Steady emission
    - Interactions of charged CRs with the Solar atmosphere
    - Inverse Compton emission due to CR electrons scattering off Solar photons in the heliosphere
  - Solar flares
    - Radiation emitted across the whole electromagnetic spectrum
  - Protons, electrons, ions accelerated in the Solar atmosphere
- The Earth
  - Interactions of charged CRs with the atmosphere ➔ Earth's Limb
  - Terrestrial Gamma-ray Flashes (TGFs)
    - Associated with storms
- The Moon
  - Interactions of charged CRs with the lunar surface
  - Gamma-ray emission studies are a probe for CR fluxes in the Solar System

Gamma rays from the Moon

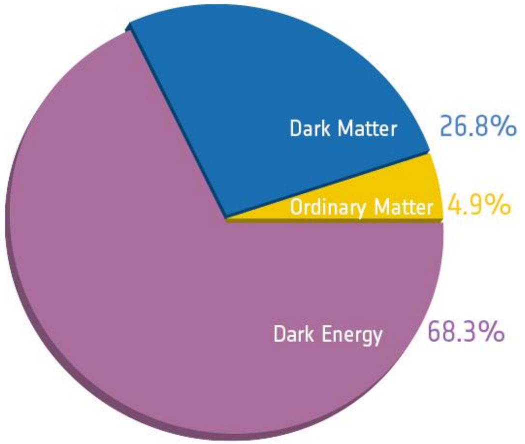
- The lunar gamma-ray flux depends on the cosmic-ray (mainly p and He) fluxes
- We have developed a full MC simulation of CR interactions with the Moon based on FLUKA
    - validated with p and He data collected by AMS-02 in 2011-13
  - LIS model which reproduces experimental observations
  - force field approximation to describe solar modulation on charged CRs
  - More details in Ackermann et al., Phys. Rev. D 93, 082001 (2016)
- The gamma-ray flux from the Moon is correlated with the Solar activity



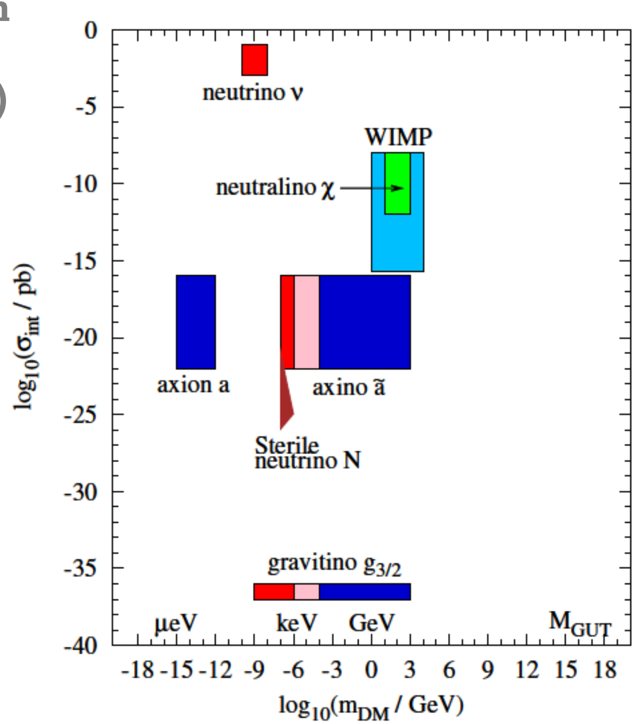


Dark matter (DM)

- **Astrophysical evidence for missing mass**
  - Galaxy rotation curves
  - Dynamics of galaxy clusters
  - Cosmological probes
- **Observational evidence indicates:**
  - DM is non-baryonic
  - DM (almost totally) neutral
  - DM (almost totally) stable
  - DM (almost totally) collisionless
- **Theoretical candidates:**
  - Axions, sterile neutrinos, etc.
  - Modifications to gravity
  - Weakly Interacting Massive Particles (WIMPS)

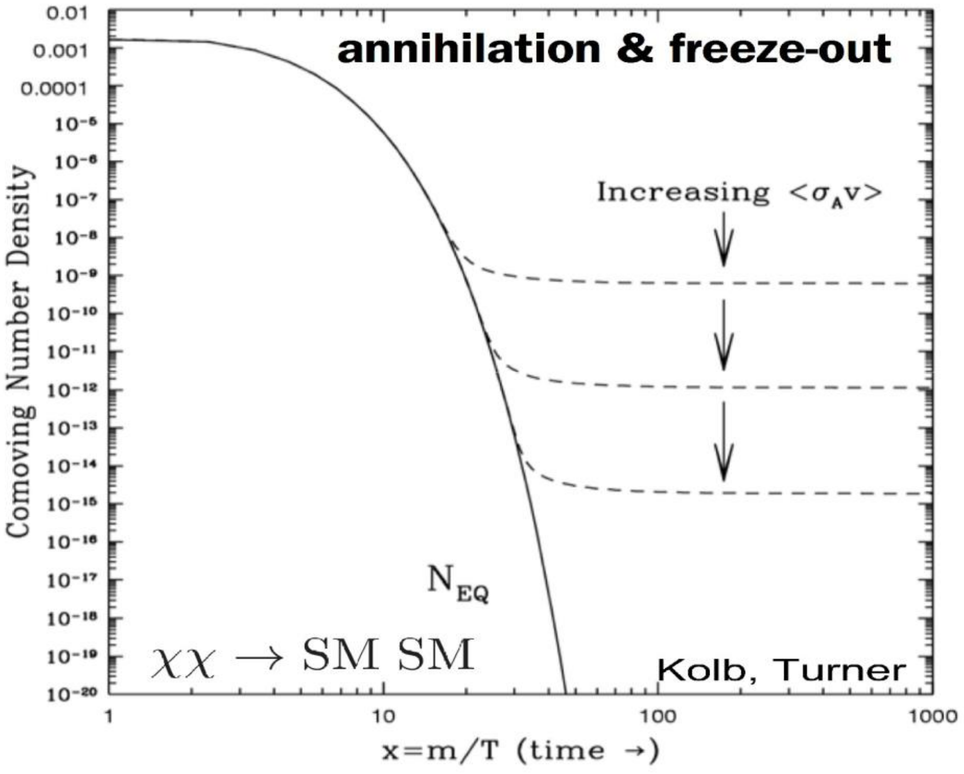


Plot adapted from Baer et al., Phys. Rep. 555, 1 (2015)



WIMPs as DM candidates

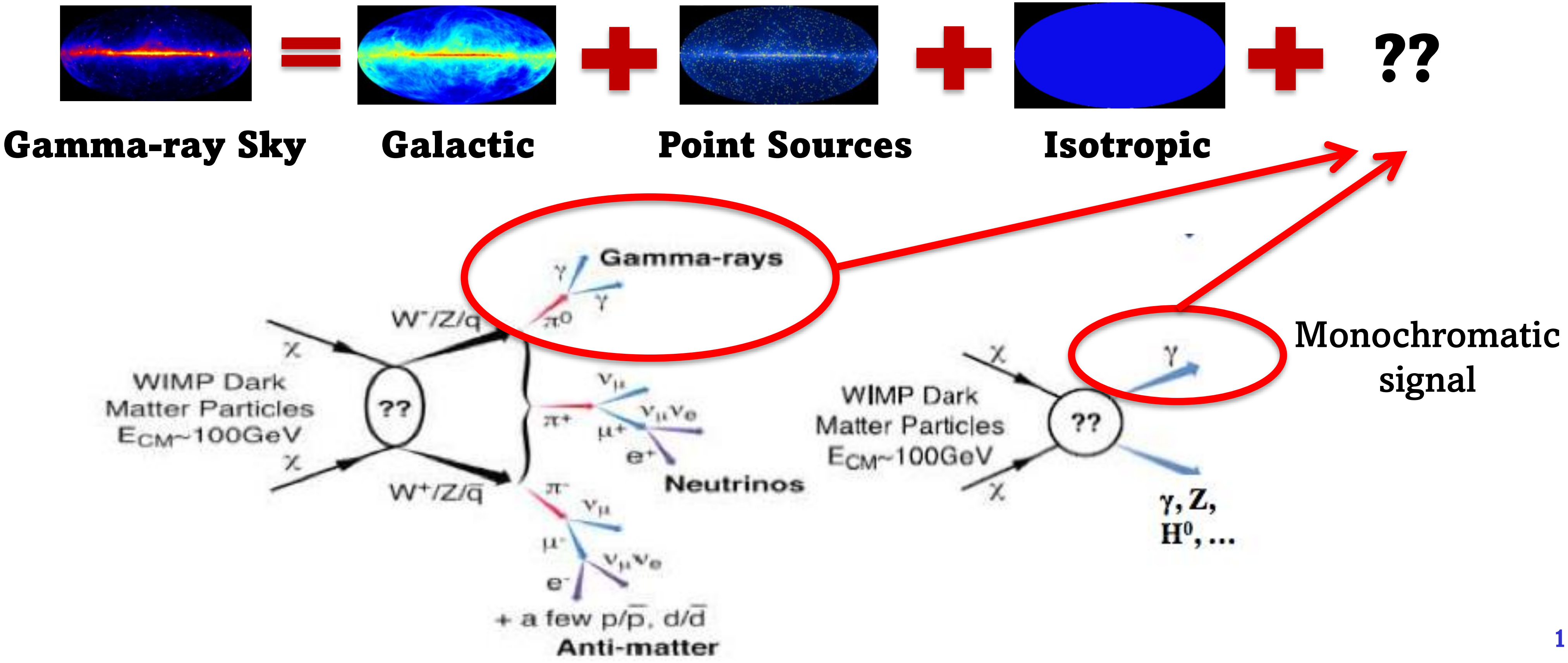
- A WIMP in equilibrium in the early Universe naturally has the right density to be Cold Dark Matter
  - At early times, WIMPs are produced in l^+l^-, … collisions in the hot primordial soup (thermal production)
  - WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate (freeze-out)
  - After freeze-out, the number of WIMPs per photon is constant
- Standard relic density calculation yields for nonrelativistic relics:
  - $\Omega_{dm} h^2 \approx \frac{3\times10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle} \approx 0.1$
- Electroweak cross-sections are in correct range:
  - $< \sigma v > \sim 10^{-26} cm^3 s^{-1}$



Plot adapted from Kolb and Turner, The early Universe (1990)

Indirect DM searches with gamma rays

- Indirect detection (i.e., astrophysical) searches for DM in the astrophysical targets where it is known to exist
  - The LAT is the only instrument that is sensitive to DM annihilation at the present-day thermal relic cross section



Gamma-ray flux from DM annihilations/decays

See Bergstrom, Ullio and Buckley, Astrop. Phys. 9, 137 (1998)

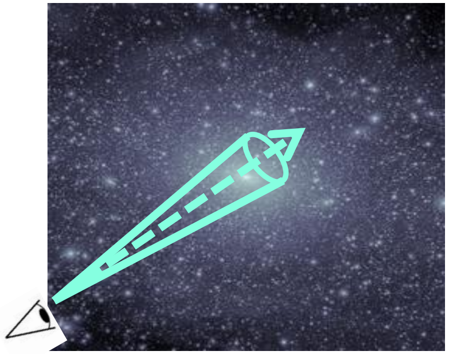
Observed flux | Intrinsic Particle Properties | Astrophysics

Annihilation:

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

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

J-factor: originates from the DM distribution (line-of-sight integral)



Decay:

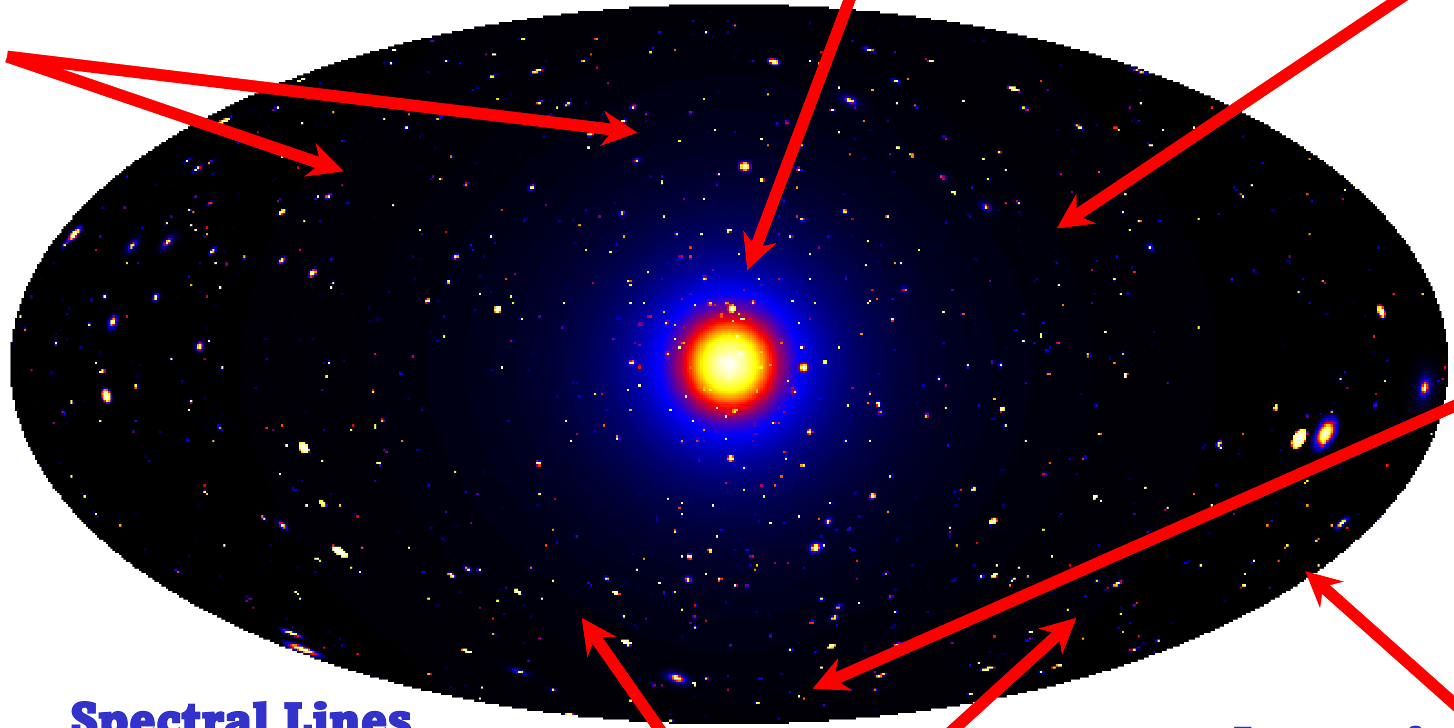
$$\phi(E,\Delta\Omega) = \frac{1}{4\pi}\frac{1}{\tau\,m_\chi}\sum_f \frac{dN_f}{dE}B_f\int_{\Delta\Omega}d\Omega\int_{l.o.s.}dl\,\rho(l(\Omega))$$

DM search targets

Satellites
Low background but low statistics

Galactic Center
Good Statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background



Dwarf Galaxies
Known location and DM content
Low statistics

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters
Low statistics, some astrophysical background

Isotropic contributions
Large statistics, but astrophysics, galactic diffuse background

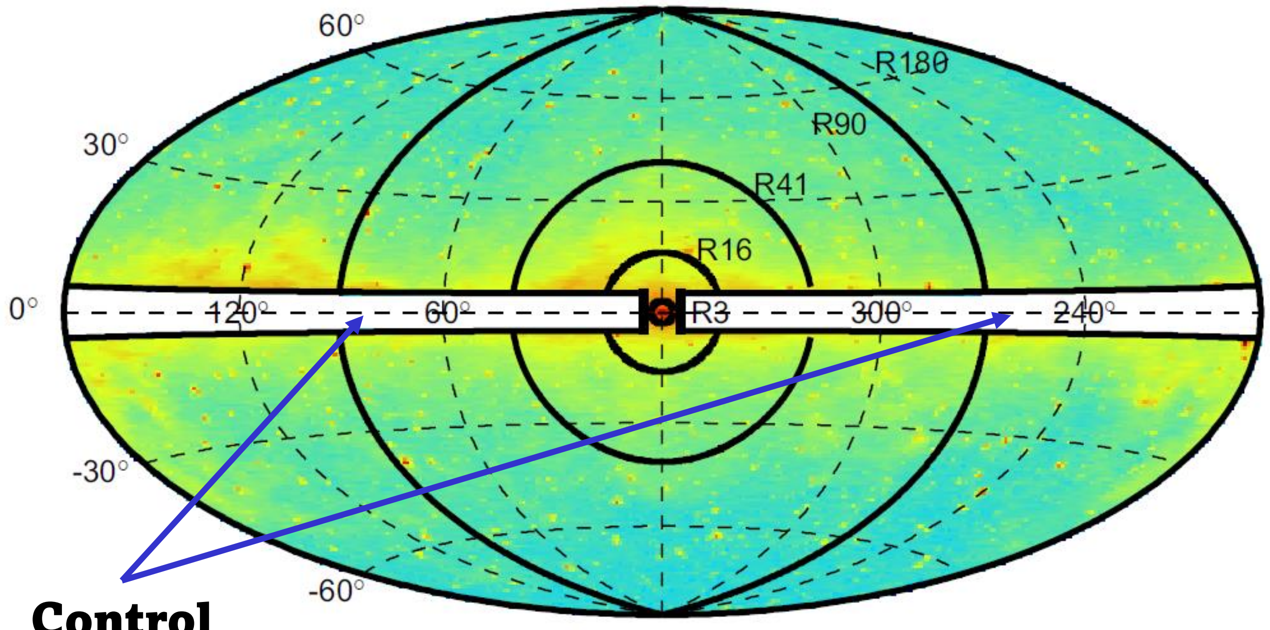
Search for gamma-ray lines

- WIMP annihilations or decays can yield monochromatic gamma rays
  - In the process $\chi + \chi \rightarrow \gamma + X$ the gamma-ray is produced with energy

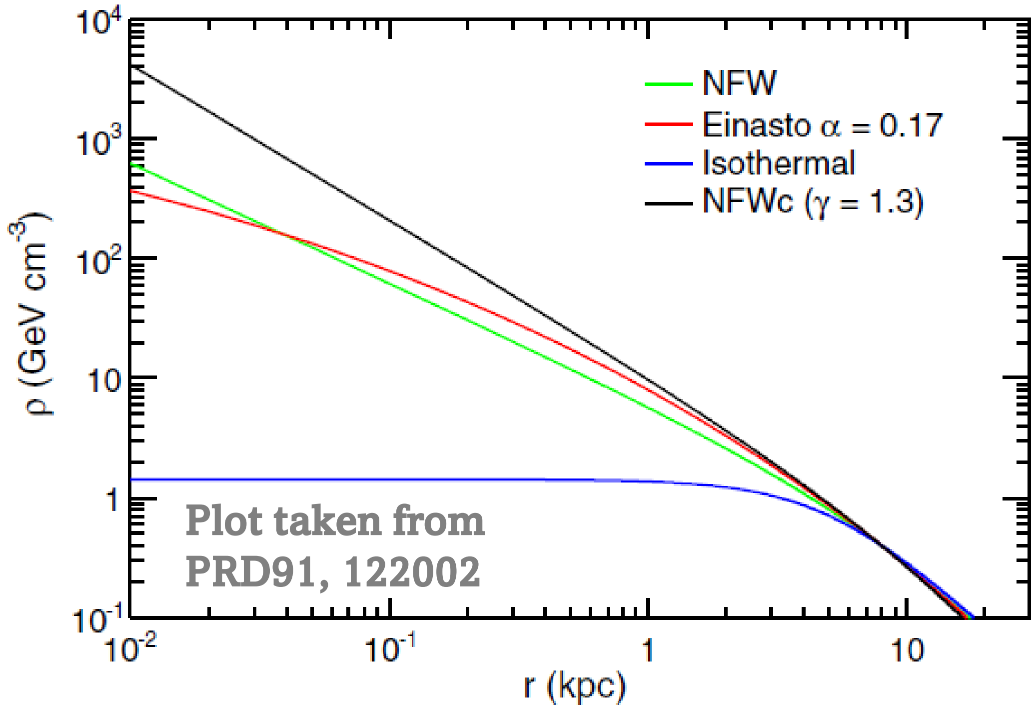
$$E_\gamma = m_\chi - \frac{m_X^2}{4m_\chi}$$

    - If the X is another photon, then $E_\gamma = m_\chi$
  - In case of decay $\chi \rightarrow \gamma + X$ the photon energy is obtained with $m_\chi \rightarrow m_\chi/2$
- WIMP annihilations in the Galactic Halo 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 ($\sim 10^{-2}$ to 10^{-4})
    - Signal predicted to be small
- The Fermi LAT Collaboration has performed several line searches
  - No evidence of spectral lines found
  - Constraints have been set on the velocity-averaged DM annihilation cross sections and on the DM decay times
  - More details in Ackermann et al., PRD91, 122002 (2015); Ackermann et al., PRD88, 082002 (2013); Ackermann et al., PRD86, 022002 (2012); Abdo et al., PRL 104, 091302 (2010)

Analysis strategy: choice of the ROI



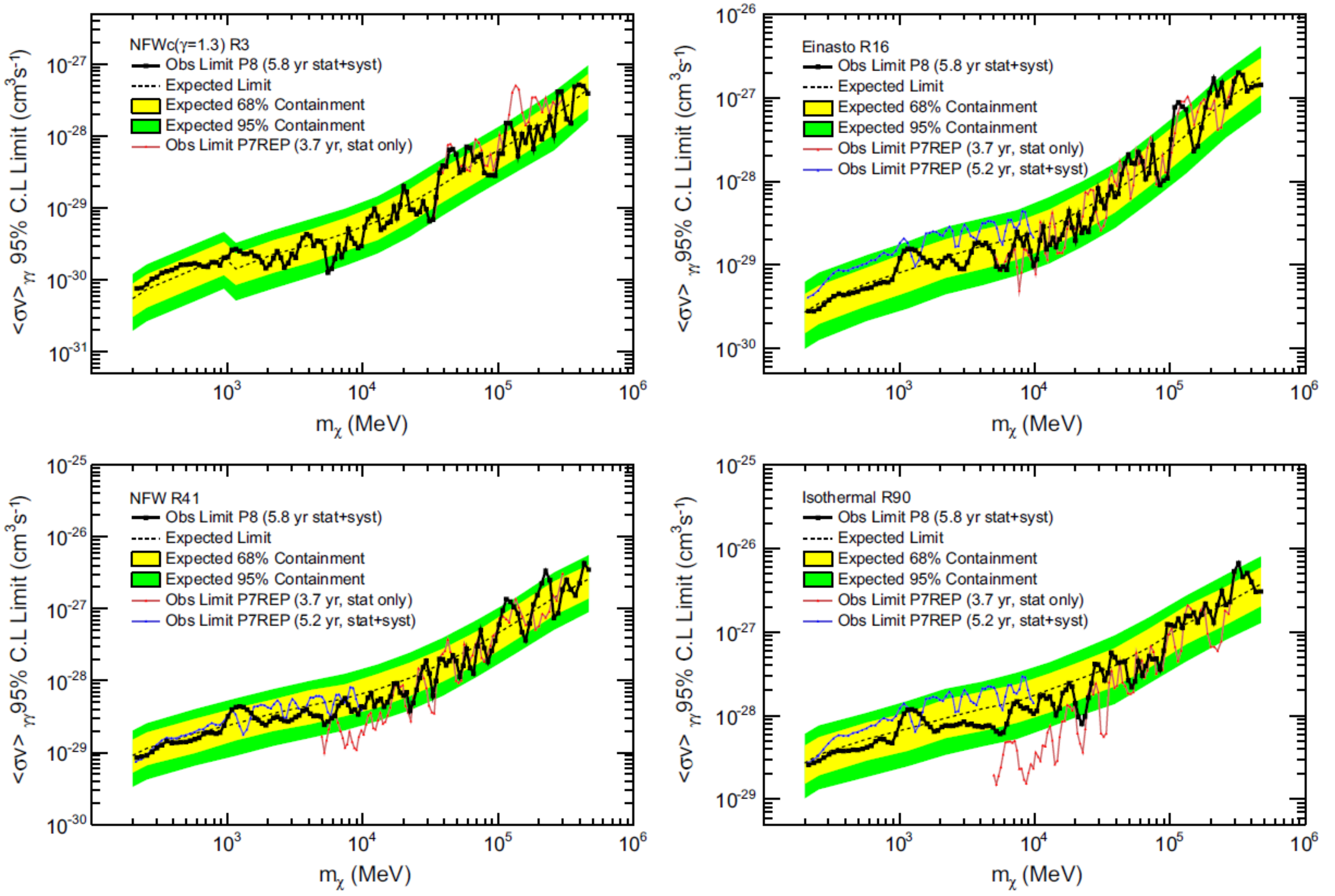
Plot taken from PRD88, 082002



- Each Region of Interest (ROI) is defined as a circular region centered on the Galactic Center (GC)
  - ROIs optimized for the different DM density profiles:
    - R3 (NFWc optimized), R16 (Einasto), R41 (NFW), R90 (isothermal), R180 (decay searches)
- Control regions:
  - 31 boxes 10°× 10° along the Galactic plane (GP)
  - Same line search algorithms as in signal ROIs
  - Allow to evaluate possible systematics

Upper limits on ⟨σv⟩ from line searches

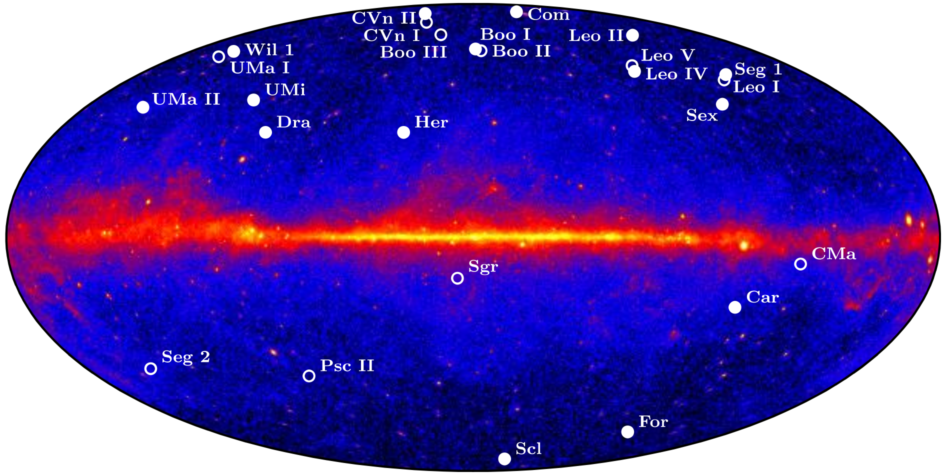
- **In all ROIs a Poisson maximum likelihood fitting procedure in sliding energy windows has been implemented**
  - **The signal hypothesis (line in the gamma-ray spectrum) is tested against the null hypothesis**
- **No evidence of line is found**
  - **The limits on the signal strength are converted into constraints on $\langle \sigma v \rangle$**
  - **Results are in agreement with expectations from pseudo-experiments**

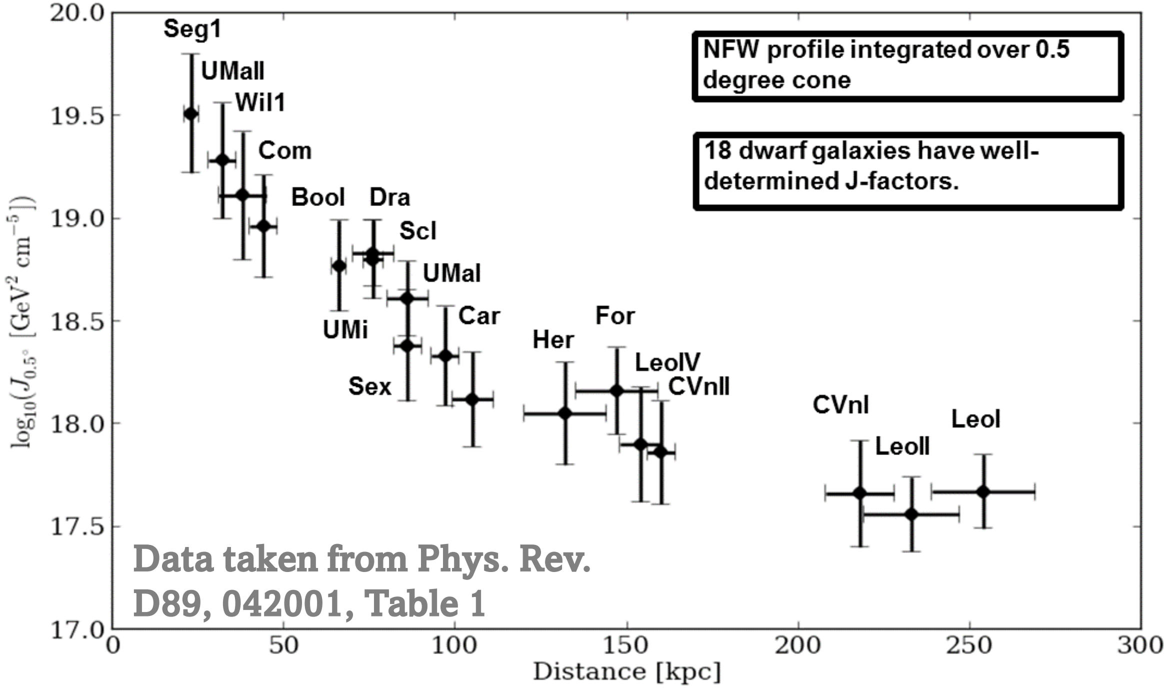


Plots taken from Phys. Rev. D 91, 122002

Searches for DM in dSph Galaxies

Plot taken from Phys. Rev. D89, 042001



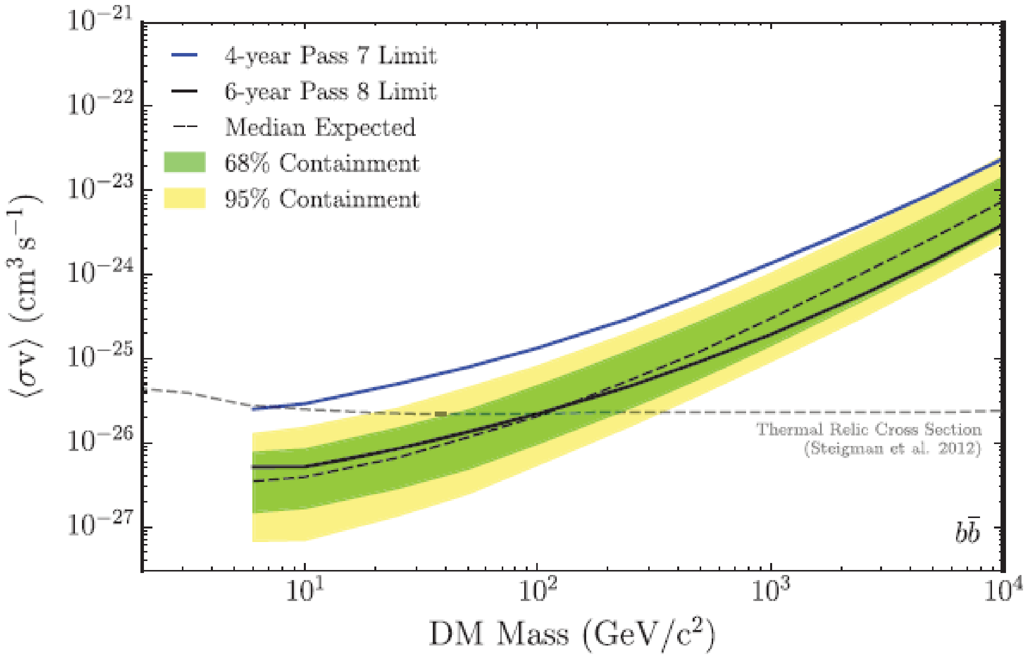


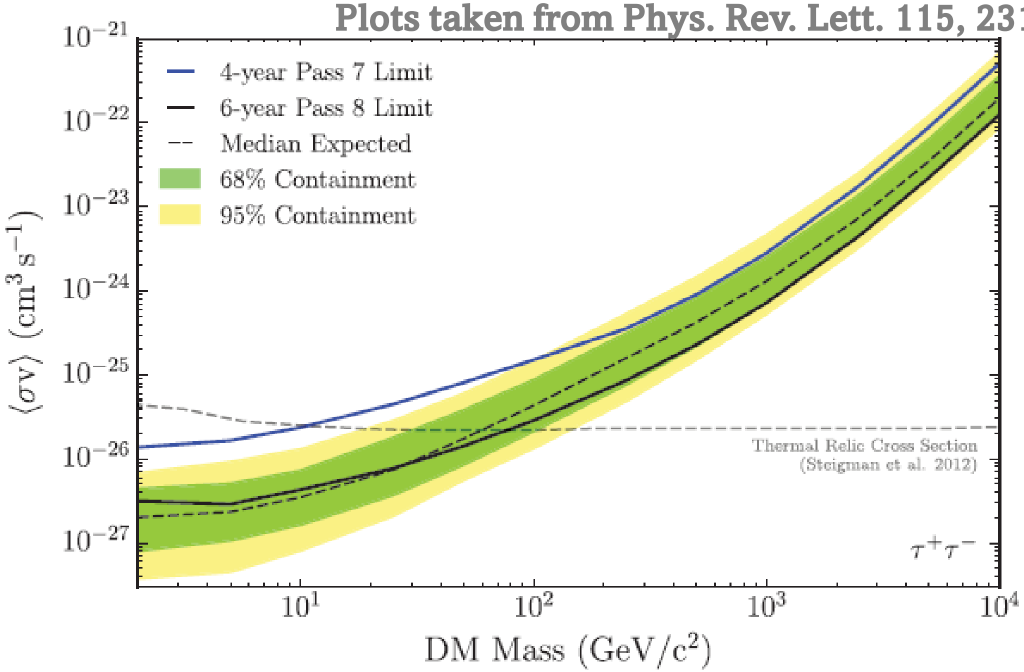
- **Dwarf Spheroidal (dSph) Galaxies are the cleanest target for DM searches**
  - DM-dominated (mass-to-light ratios ~1000 in some cases)
  - 10s to 1000s of stars
    - Mostly old stars
    - Few gamma-ray emitters (pulsars, SNRs)
    - Little gas content
  - often high latitude
    - low diffuse background
  - nearby (<250 kpc)
  - many! (50+)
    - allows for joint analyses

Data analysis and results

- Analysis of individual dSphs and combined analysis of 15 dSphs
  - Uncertainties on the J-factors are included
- A hypothesis testing is implemented:
  - Null hypothesis: absence of a DM signal
  - Alternative hypothesis: presence of a DM signal
- No evidence of any DM signal found
- Constraints on the velocity-averaged DM annihilation cross section are derived
  - Limits are below the thermal relic cross section for DM masses up to ~100 GeV
  - See Ackermann et al., Phys. Rev. Lett. 115, 231301 (2015); Ackrmann et al., Phys. Rev. D89, 042001 (2014); Abdo et al., ApJ 712, 147 (2010)

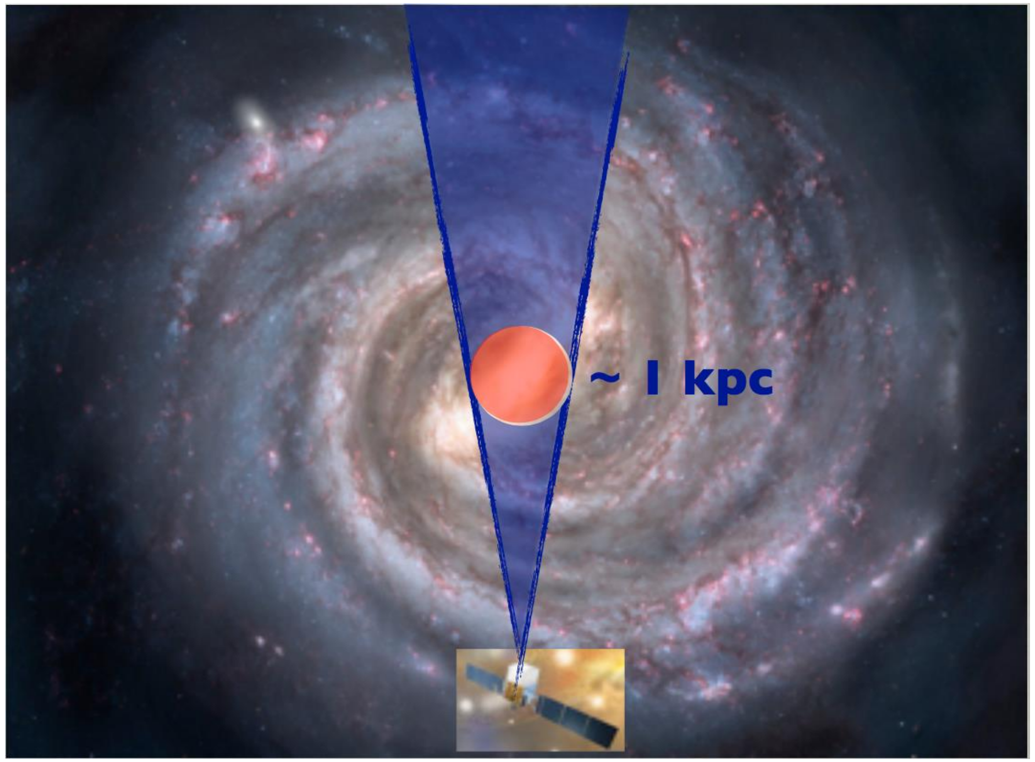
Plots taken from Phys. Rev. Lett. 115, 231301





The Galactic Center

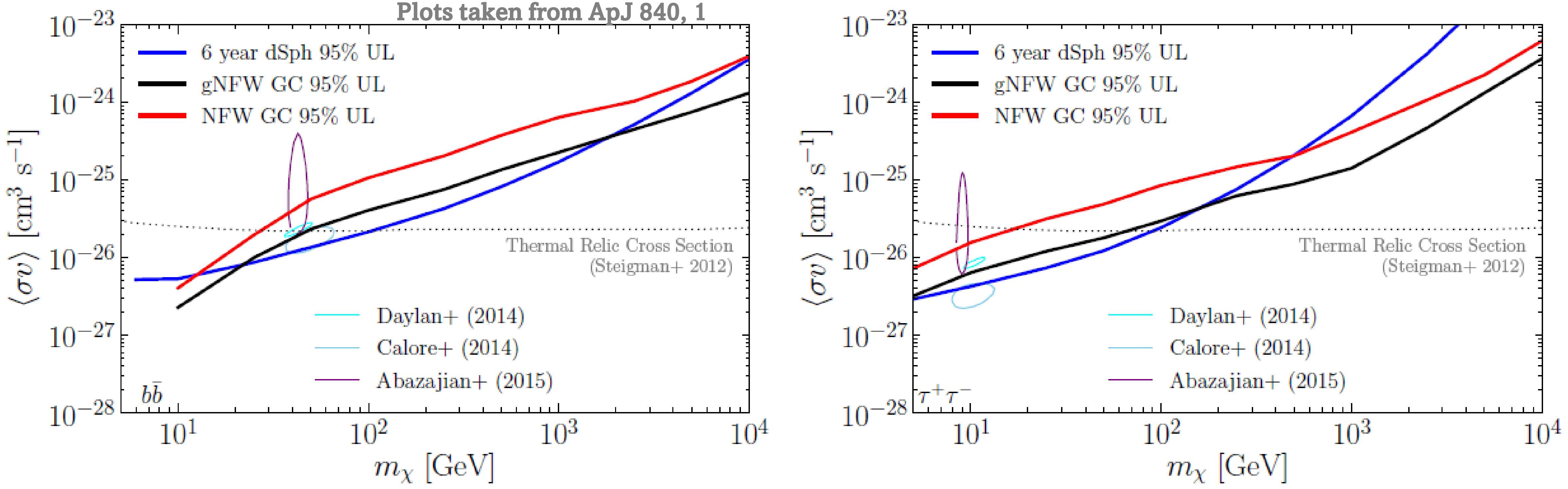
- The center of the Galactic DM halo is likely the brightest DM source in the gamma-ray sky
  - Deep gravitational potential
  - Relatively nearby
- However, it is extremely complicated
  - Diffuse emission from cosmic-ray interactions with Galactic gas and dust
  - Densely populated by astrophysical sources (e.g., pulsars, SNR)
- Several independent studies find GeV excesses above the expected diffuse background
  - The excess and its spatial extension are robust
  - The spectrum of the excess depends strongly on the emission model
- For more details see:
  - Ackermann et al., Astrophys. J. 840, 1 (2017); Ajello et al., Astrophys. J. 819, 1 (2016)



Constraints on ⟨σv⟩ from the GC analysis

- **The GC excess is compatible with DM, both spectrally and morphologically**
- **Other astrophysics explanations are possible**
  - **MSPs are possible candidates to explain the GC excess**
    - **Not yet observed at any wavelength!**
  - **A similar fractional excesses are found along the Galactic plane, where no DM signal is expected**
- **Limits on the DM velocity-averaged annihilation cross section $\langle \sigma v \rangle$ can be obtained by requiring that the DM signal does not exceed the GC excess upper bounds in any energy bin**
  - **See ApJ 840,1 (2017); ApJ 819,1 (2016); APJ 761, 91 (2012)**

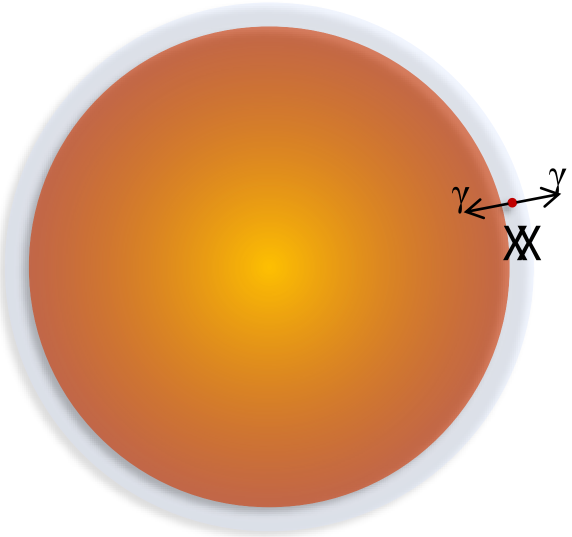
Plots taken from ApJ 840, 1

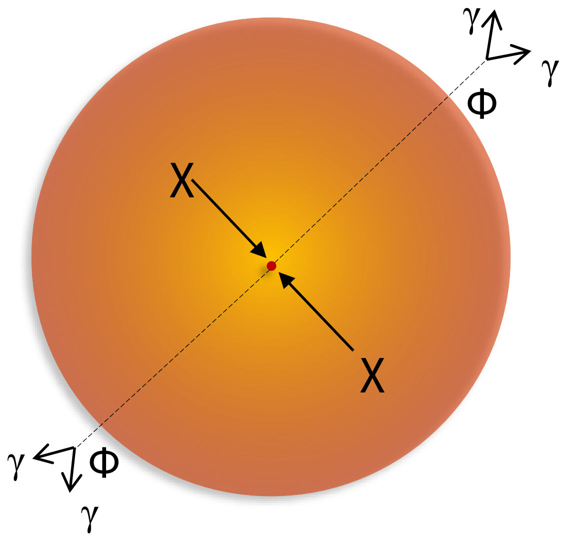


Search for gamma rays from Solar DM

- 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 are captured by the Sun in external orbits
  - A DM halo is formed around the Sun and DM particles annihilate outside the Sun producing SM particles: $\chi\chi \rightarrow \gamma\gamma, e^{+}e^{-} \dots$
- DM particles keep losing energy through subsequent scatterings, reaching the thermal equilibrium at the Sun core
  - The excess 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 SM particles: $\chi\chi \rightarrow \phi\phi, \phi \rightarrow \gamma\gamma, e^{+}e^{-}, \dots$
- Both scenarios predict an enhancement of the DM photon flux close to Sun
  - DM signals would appear as an excess on the top of the standard emission

Possible gamma-ray signals from solar DM



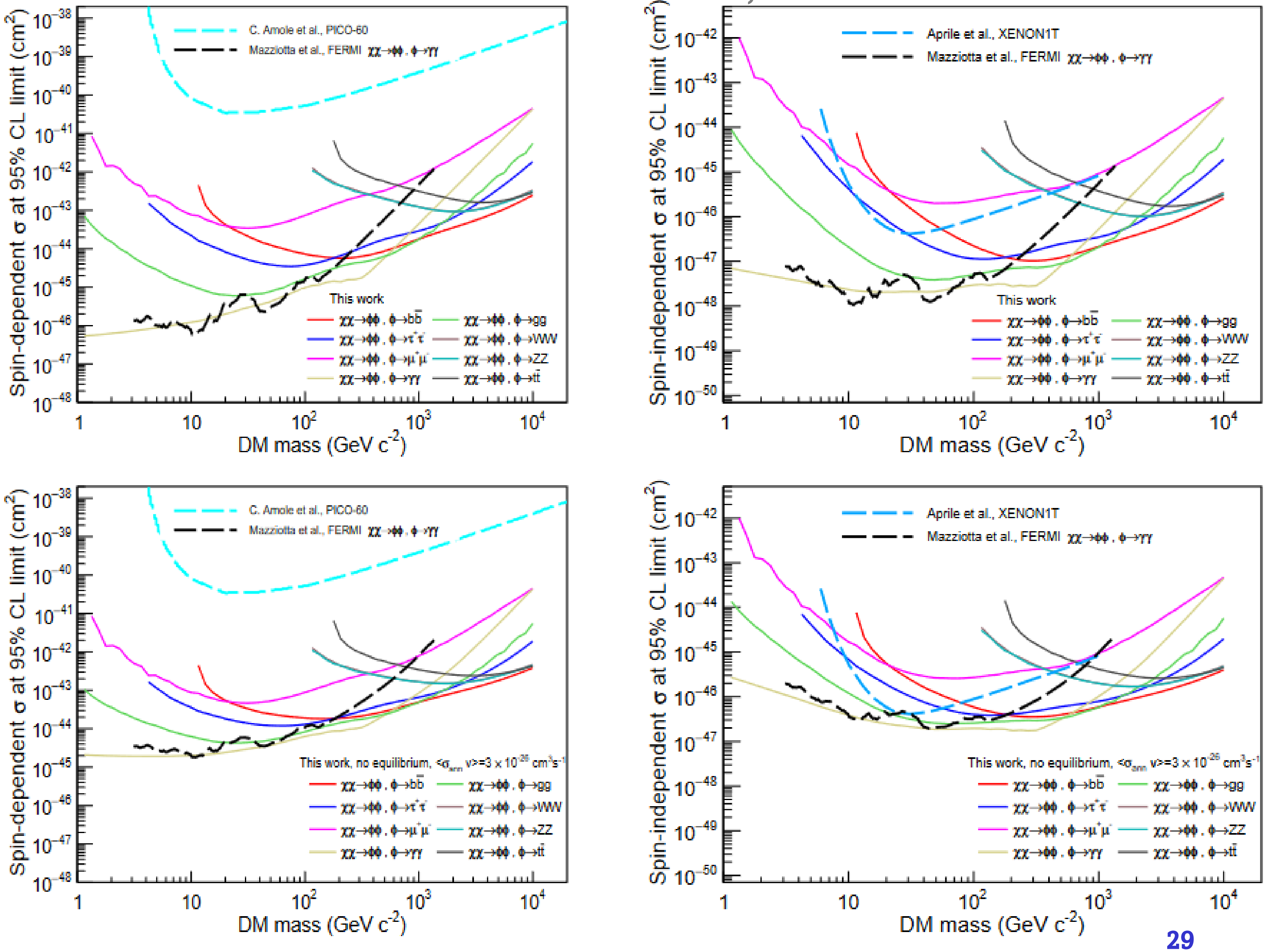


- **WIMPs annihilating into gamma rays**
  - The energy spectrum of gamma rays is a line centered at $E_\gamma = m_\chi$
- **WIMPs annihilating into long-lived mediators decaying into gamma rays**
  - Continuous gamma-ray spectrum
    - For light mediators ($m_\phi \ll m_\chi$) a box-shaped spectrum is expected with upper edge at $E_\gamma = m_\chi$

Constraints on the DM-nucleon cross section

- **ON/OFF analysis technique**
  - ON Region: cone of 2° angular radius centered on the Sun current position
  - OFF Region: cone of 2° angular radius centered on the 6 months time-offset position
    - The OFF region follows the same path in the sky as the Sun
    - It is used as a 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
- **No significant features found**
- **Constraints on the DM-nucleon scattering cross section are derived**
  - See Serini et al., JCAP 02 (2023), 025 and Mazziotta et al., PRD 102 (2020), 022003

Plots taken from JCAP 02, 025



Conclusions

- Fermi has opened a window on the extreme high-energy Universe
- The LAT is an instrument with unprecedented capabilities that has been exploring the gamma-ray sky since 2008
  - The LAT has been monitoring the gamma-ray sky for 15 years and is still in good health
- Outstanding results in all fields of gamma-ray astrophysics
  - Shed light on CR origin, particle acceleration and propagation
  - The LAT is an invaluable resource for indirect DM searches
    - New DM searches from transient sources
      - Search of signals from axion-like particles (ALPs)
      - See M. Crnogorcevic et al., Phys. Rev. D104, 103001 (2021)
- Fermi observations will keep playing a key role in multi-messenger astrophysics
  - Exciting perspectives in the search for EM counterparts to GW

Backup slides

Adding new dSph Galaxies to the sample…

- New Milky Way satellites discovered by the Dark Energy Survey (DES)
  - Photometric characteristics consistent with being dSph Galaxies
- Total sample:
  - 28 confirmed dSphs + 13 likely dSphs (nominal sample of 41 dSphs) + 4 ambiguous systems
    - new stellar systems are assumed to occupy similar DM halos to the population of known dSphs
    - J-factors of the new systems evaluated from their distances
- Analysis of individual targets and combined analysis
  - Improved limits on $\langle \sigma v \rangle$ at high DM masses
  - See Drlica Wagner et al. Astrophys. J. Lett. 809, L4 (2015), Albert et al., Astrophys. J. 834, 110 (2017)