Search for lines in gamma rays as DM signatures: from *Fermi*-LAT to APT

ADAPT Collaboration Meeting

Bari, Dipartimento Interateneo di Fisica “M. Merlin”

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Outline

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- Fermi-LAT analysis:
  - ROIs and data selection
  - Analysis Method
    - Hypothesis test and fit procedure
    - Combined likelihood analysis
  - Results for line search (15.5-year *Fermi* LAT data)
    - Local significance
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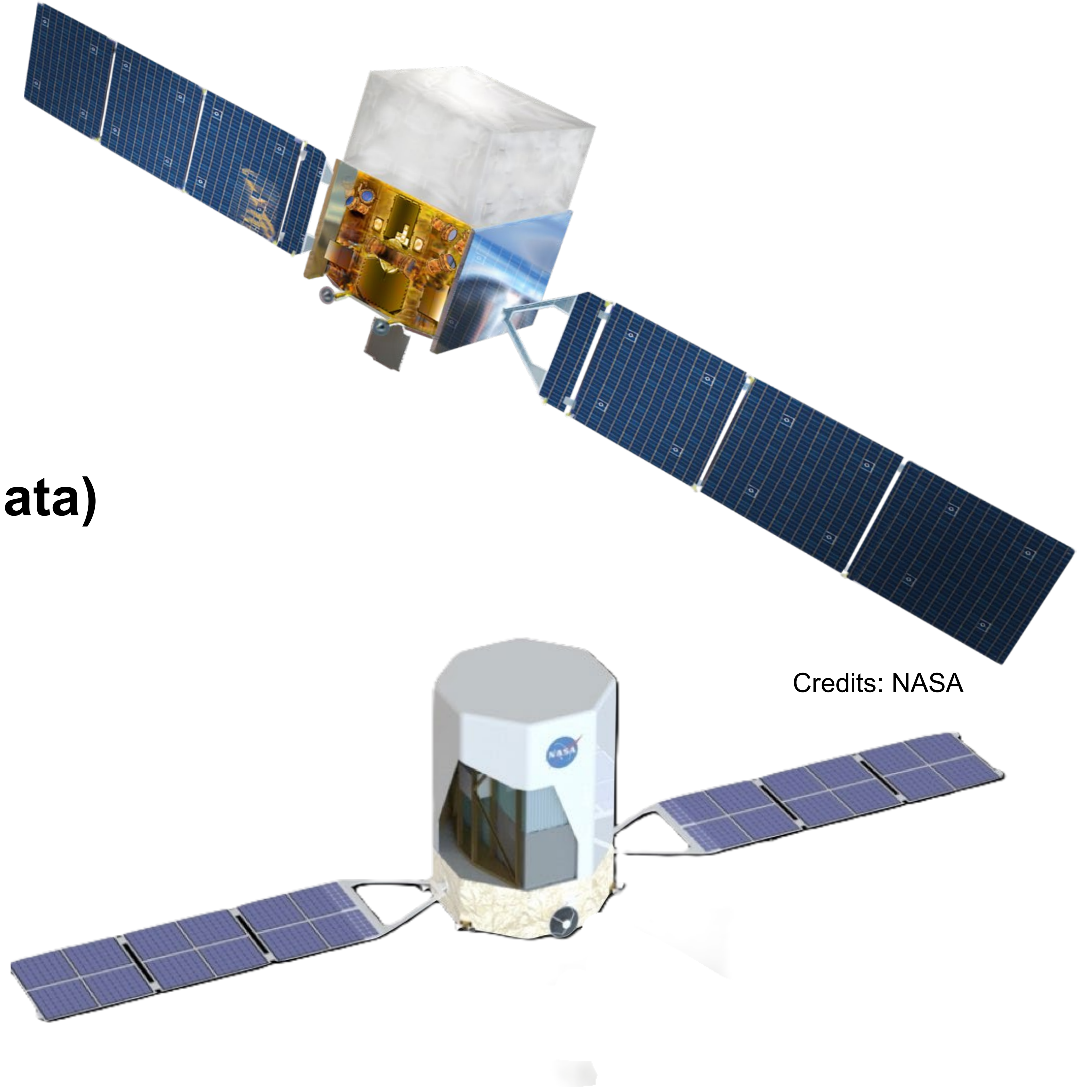
    - Constraints on $\langle \sigma v \rangle$ and τ
    - Global significance
- Perspectives for an APT-like detector
  - Simulated data sample
  - Fit results

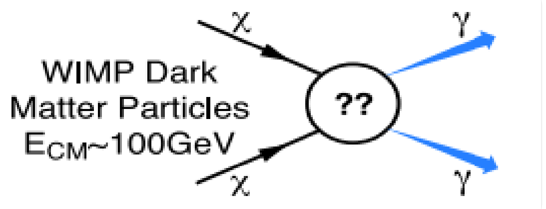


Credits: NASA

WIMP gamma-ray spectral lines

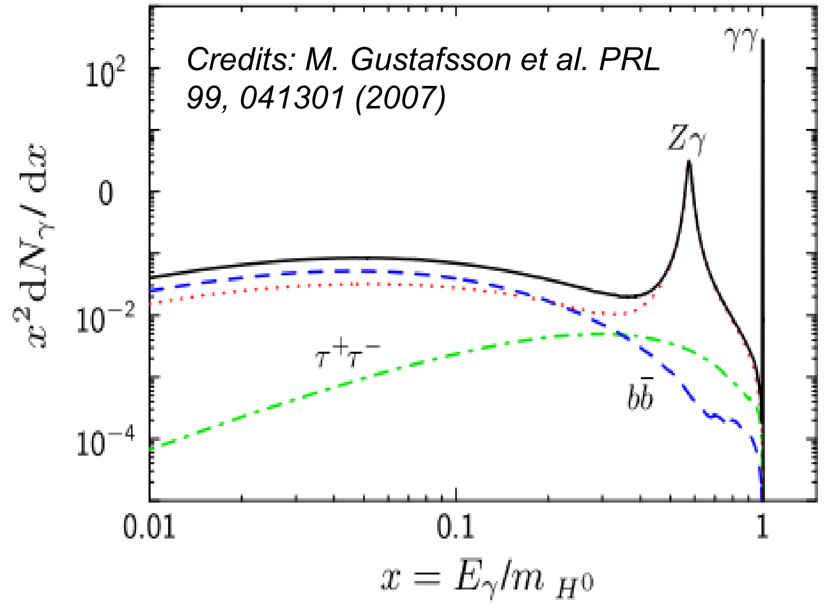
- **Self annihilation**: $\chi\chi \rightarrow \gamma\gamma$

$$\left(\frac{d\Phi}{dE}\right)_{ann} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\left(\frac{dN_\gamma}{dE}\right)_{ann} J_{ann}(\Delta\Omega)$$



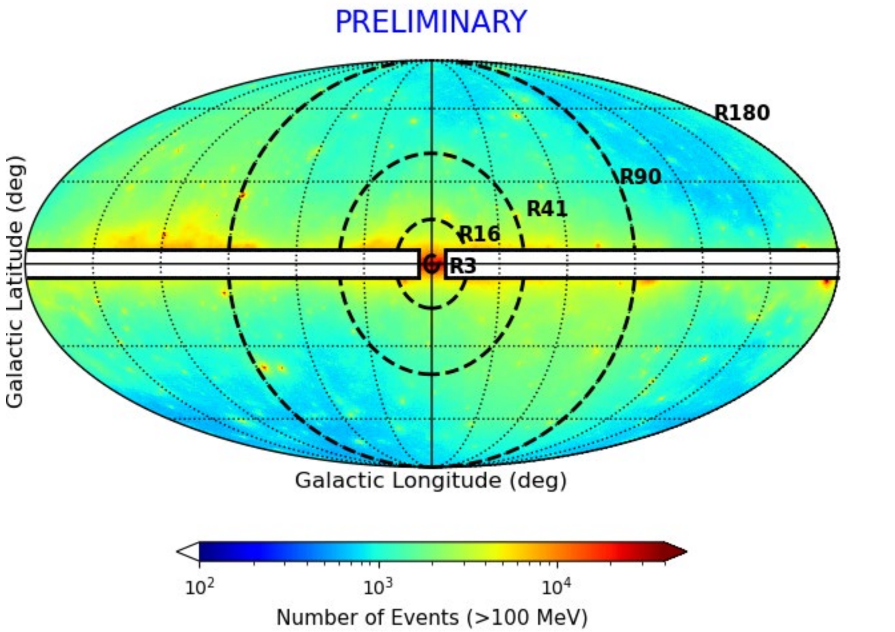
- **Decay**: $\chi \rightarrow \gamma\gamma$

$$\left(\frac{d\Phi}{dE}\right)_{decay} = \frac{1}{4\pi}\frac{1}{m_\chi \tau}\left(\frac{dN_\gamma}{dE}\right)_{decay} J_{decay}(\Delta\Omega)$$

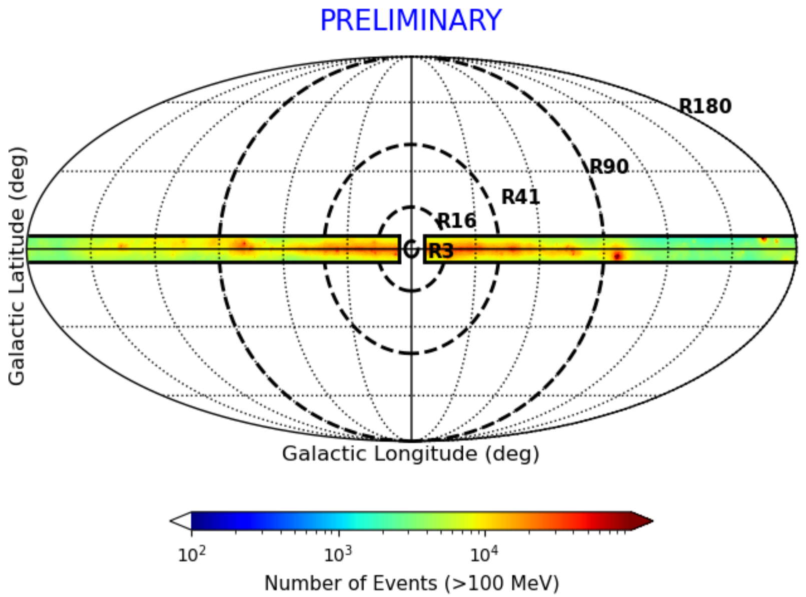


- $\frac{dN_\gamma}{dE} = \begin{cases} 2\delta(E - E_{line}) \, for\ annihilation \\ \delta(E - E_{line}) \ for\ decay \end{cases}$
- $E_{line} = \begin{cases} m_\chi \quad for\ annihilation \\ m_\chi/2 \quad for\ decay \end{cases}$

Fermi-LAT analysis: ROIs and data selection

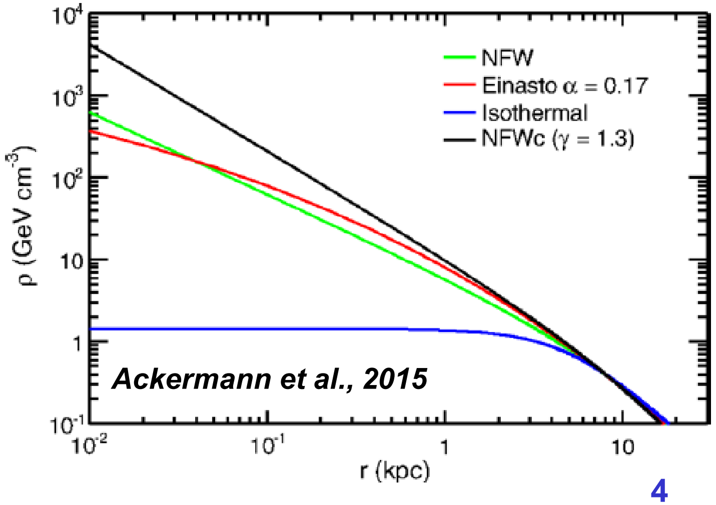


- Each ROI is a cone centered on the GC with different angular apertures
- **Galactic Plane used as a control region**
- RoIs optimized for some theoretically-motivated DM density profiles as in *PRD 91, 122002*



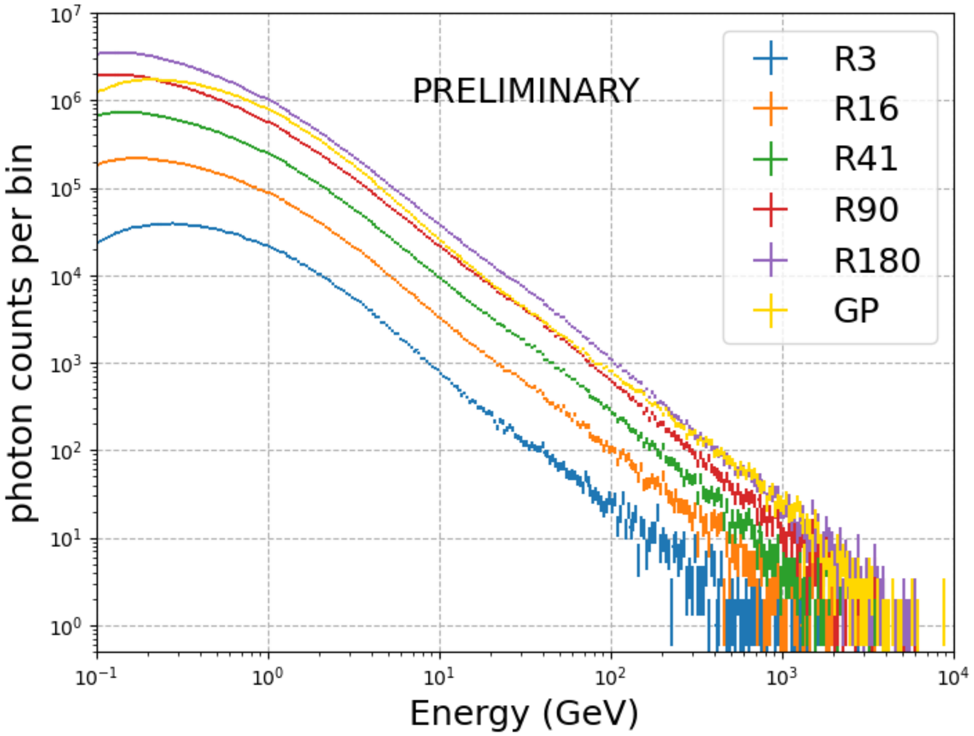
Observation time	August 2008 – December 2023
Energy Range	[10 MeV – 2 TeV]
Zenith angle θ_z	100°
Event class	256 (CLEAN)
Event Type	All EDISP event types
Data Quality	DATA_QUAL==1 LAT_CONFIG==1 IN_SAA!=T

- Individual analyses for each EDISP sample (EDISP0, EDISP1, EDISP2, EDISP3)
- Combined analysis of all EDISP samples



Analysis method: Hypothesis test and fit procedure

- **Photon flux from any ROI:**
  - $\mathbf{H1}: \boldsymbol{\Phi}_{RoI}(E) = \boldsymbol{\Phi}_{\mathbf{bkg}}(E) + \boldsymbol{\Phi}_{\mathbf{sig}}(E)$
  - $\mathbf{H0}: \boldsymbol{\Phi}_{RoI}(E) = \boldsymbol{\Phi}_{\mathbf{bkg}}(E)$
- **Signal flux :**
  - $\boldsymbol{\Phi}_{\mathbf{sig}}(E) = \mathbf{s}\boldsymbol{\delta}(E - \mathbf{E}_{\mathbf{line}})$
    - the parameter $s \geq 0$ represents the line intensity
- **Background flux:**
  - $\boldsymbol{\Phi}_{\mathbf{bkg}}(E) = \boldsymbol{\Phi}_{\mathbf{smooth}}(E) + \boldsymbol{\Phi}_{\mathbf{bkg,line}}(\mathbf{E_t})$
    - $\phi_{smooth}(E) = \begin{cases} k\left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log\left(\frac{E}{E_0}\right)} & if\ E_{fit} < 10GeV \\ k\left(\frac{E}{E_0}\right)^{-\Gamma} & if\ E_{fit} > 10GeV \end{cases}$
    - $\boldsymbol{\Phi}_{\mathbf{bkg,line}}(E) = \mathbf{b}\boldsymbol{\delta}(\mathbf{E} - \mathbf{E}_{\mathbf{line}})$
    - The parameter b can be either positive or negative



- Expected counts in each observed energy bin:
- $\boldsymbol{\mu_j} = \int \boldsymbol{dE_t \varepsilon_{RoI}(E_j|E_t)\,\Phi(E_t)}$
  - $\Phi(E_t)$ is the gamma-ray flux
  - $\boldsymbol{\varepsilon_{RoI}}$ is the exposure in each RoI
- **Maximum likelihood fit procedure implemented in sliding energy windows**

Combined likelihood analysis

- **Combined likelihood:**

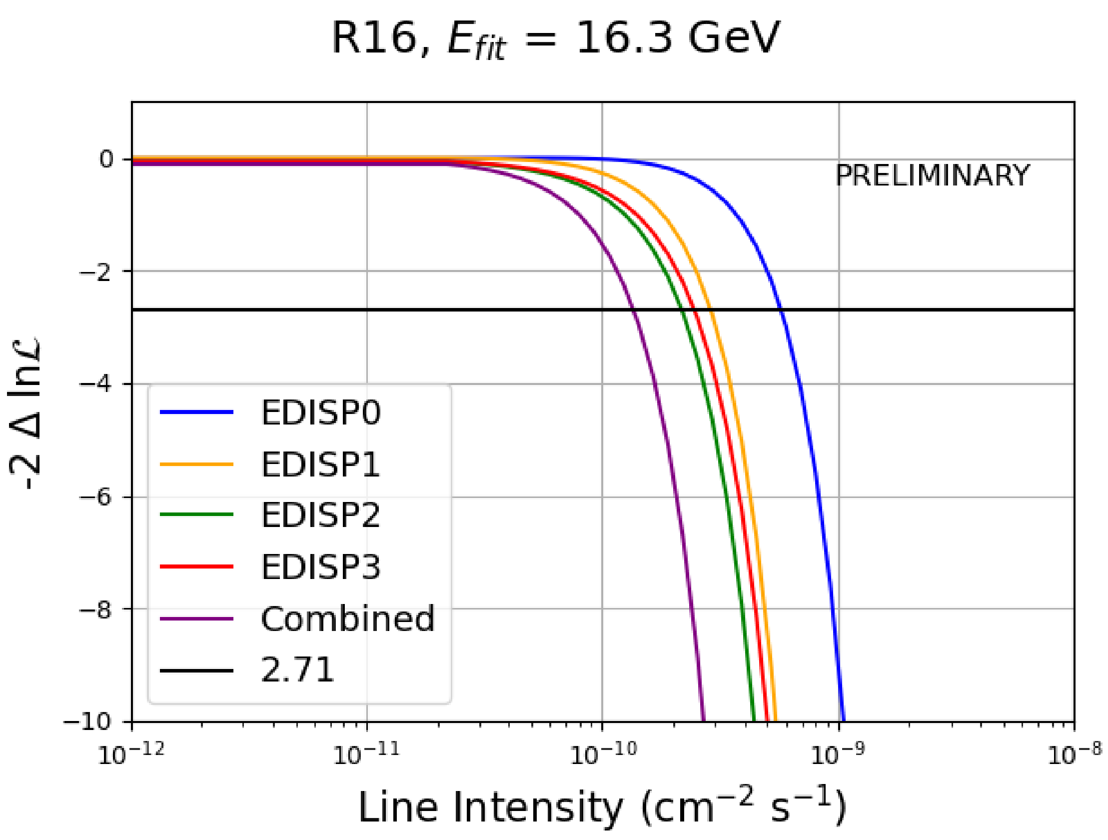
$$\mathcal{L}_{\mathbf{combined}}(\mathbf{s}) = \prod_{\mathbf{i}} \mathcal{L}_{\mathbf{i}}(\mathbf{s})$$

  - The index i runs over the different **EDISP types**
- We define the **Test Statistic *TS*:**

$$TS = 2[ln\mathcal{L}_{1,max} - ln\mathcal{L}_{0,max}]$$

- A feature is significantly detected if $TS > 25$
- If a signal is not significant, the UL on the line flux is evaluated from the $\log\mathcal{L}$ function:
  - UL at 95%CL:

$$\log\mathcal{L} = \log\mathcal{L}_{\mathrm{max}} - (2.71)/2$$



Results: Local significance of possible line features

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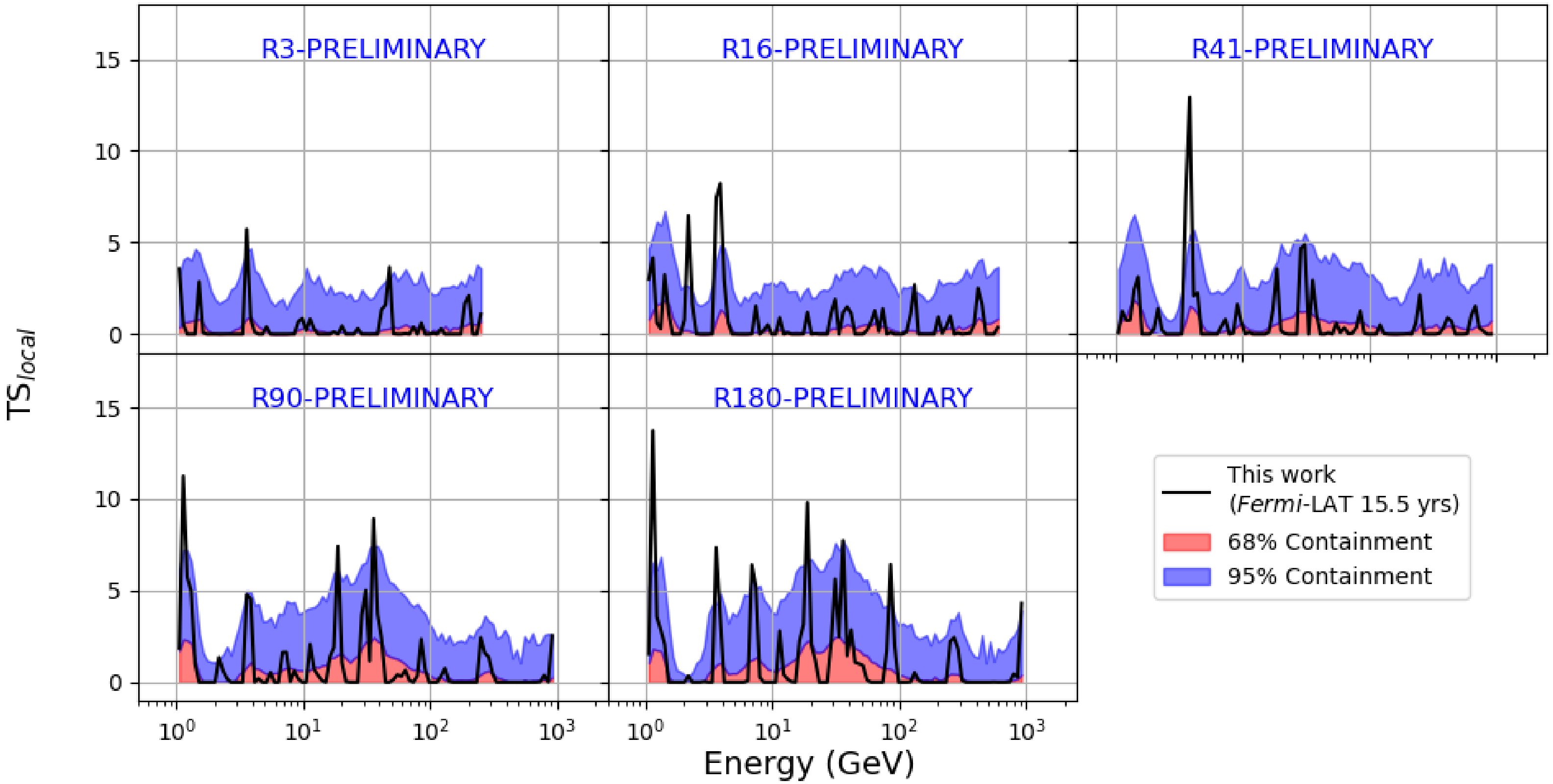

- **1000 background-only simulated pseudo-experiments:**
  - Counts in each energy bin extracted from a Poisson distribution with its average value taken from a template model (null hypothesis)
  - Same analysis chain as real data
  - ULs at 95% and TS distributions are evaluated
  - From the quantiles of the distributions 68% (red) and 95% (blue) containment bands are built

- **Expectation bands obtained from the 1000 pseudo-experiments**
- **Results consistent with expectations from the null hypothesis, with few outliers**

Results: ULs comparison with expectations from pseudo-experiments

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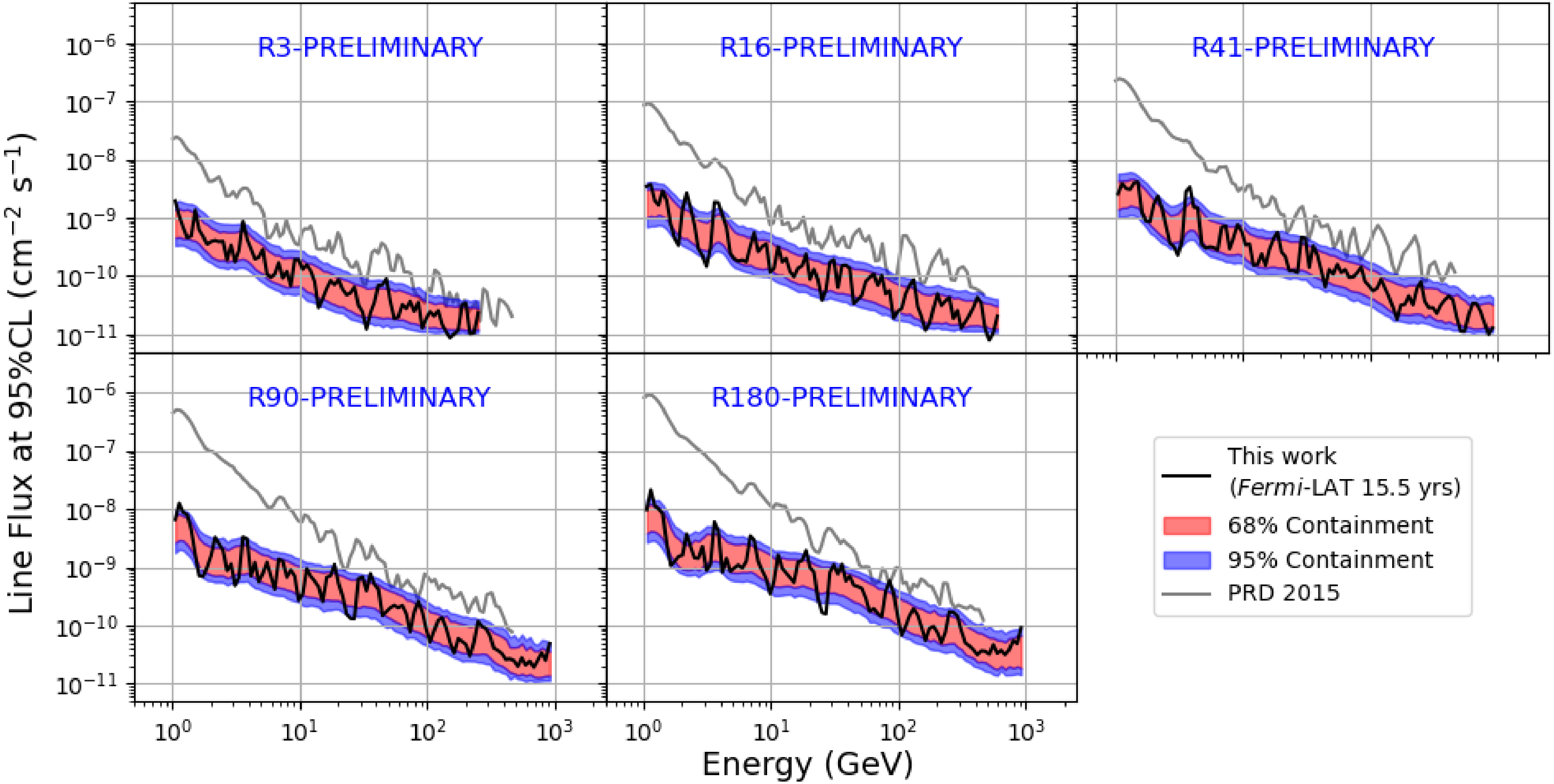
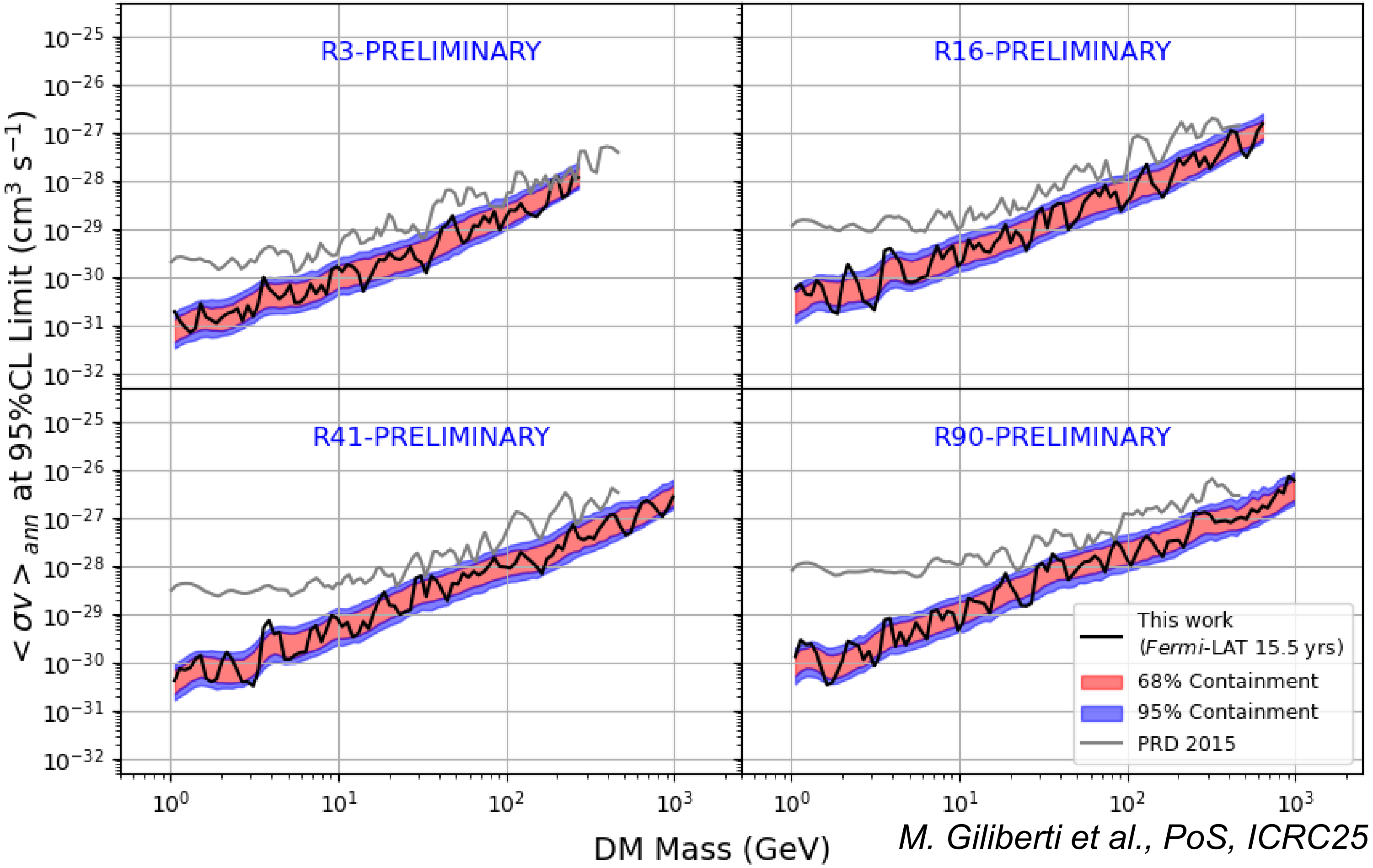


Measured limits lie within the containment bands, and are therefore consistent with the expectations for the null hypothesis

Constraints on $\langle \sigma v \rangle$ and τ from line search

- **Upper limits on signal strength converted into physical parameters of interest $\langle \sigma_{ann} v \rangle$ and $\tau_{\gamma\gamma}$**
  - **The upper limits on $\langle \sigma_{ann} v \rangle$ lie in the interval $10^{-30} - 10^{-26}\ cm^3 s^{-1}$**
  - **The lower limits on $\tau_{\gamma\gamma}$ are in the range $10^{30} - 10^{31}\ s$**



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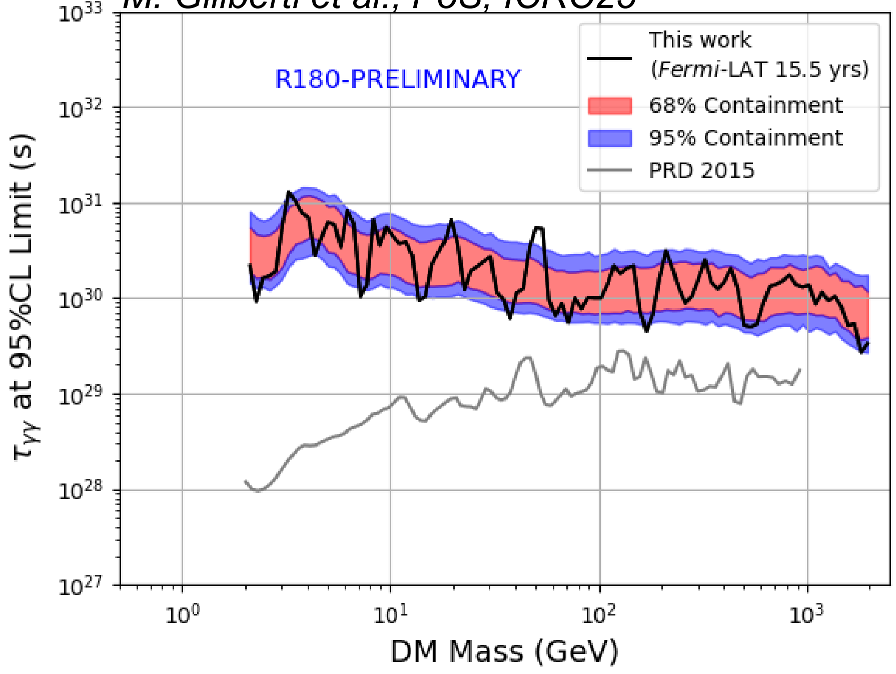

Global significance

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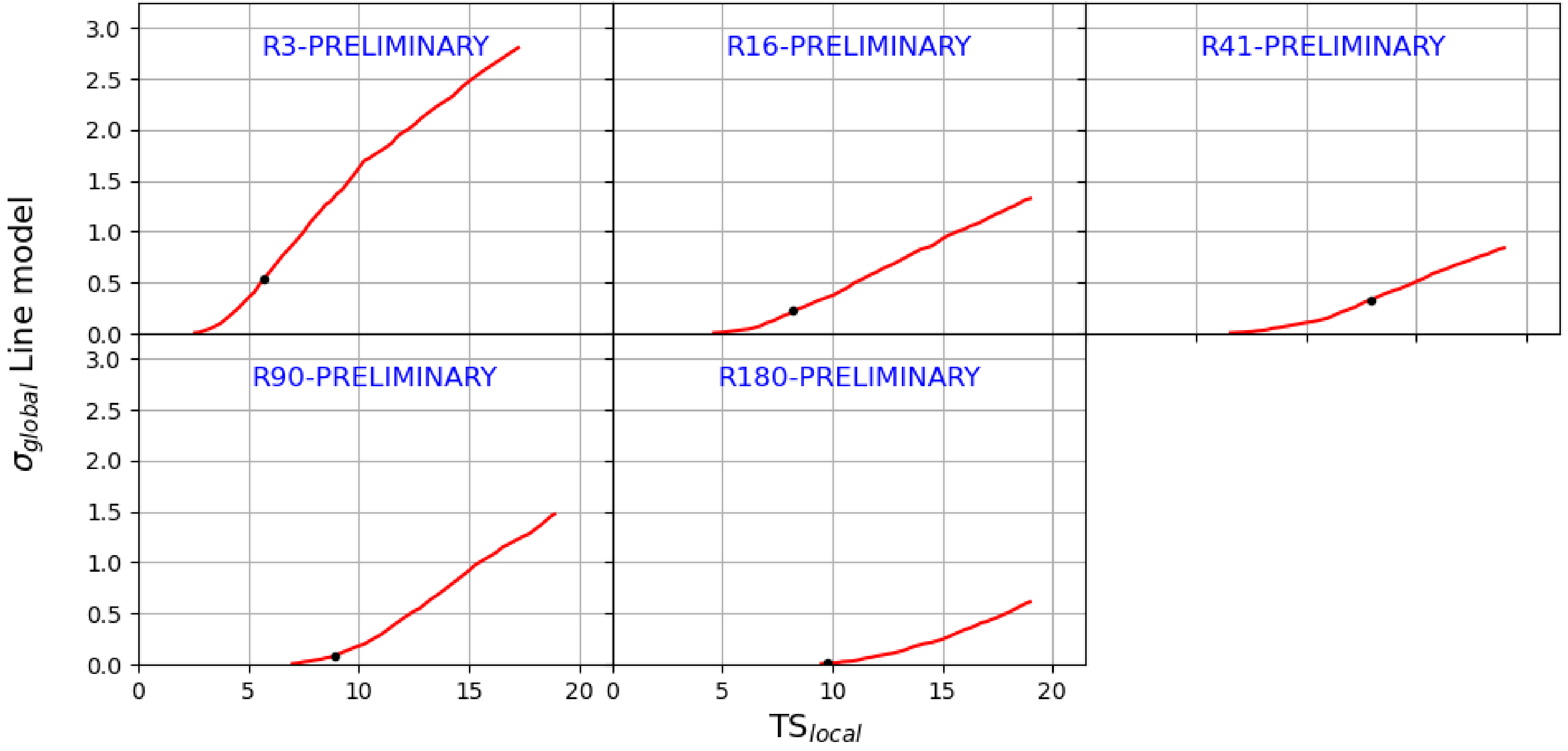
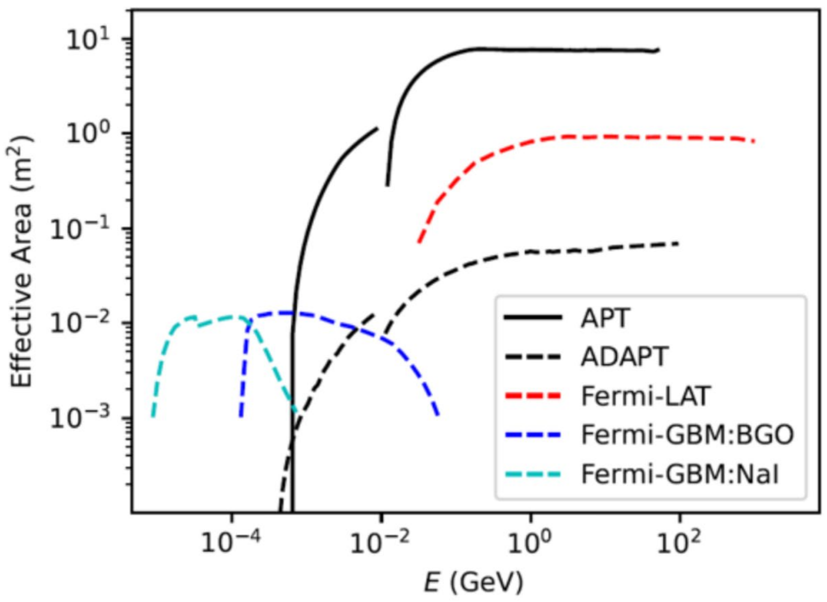


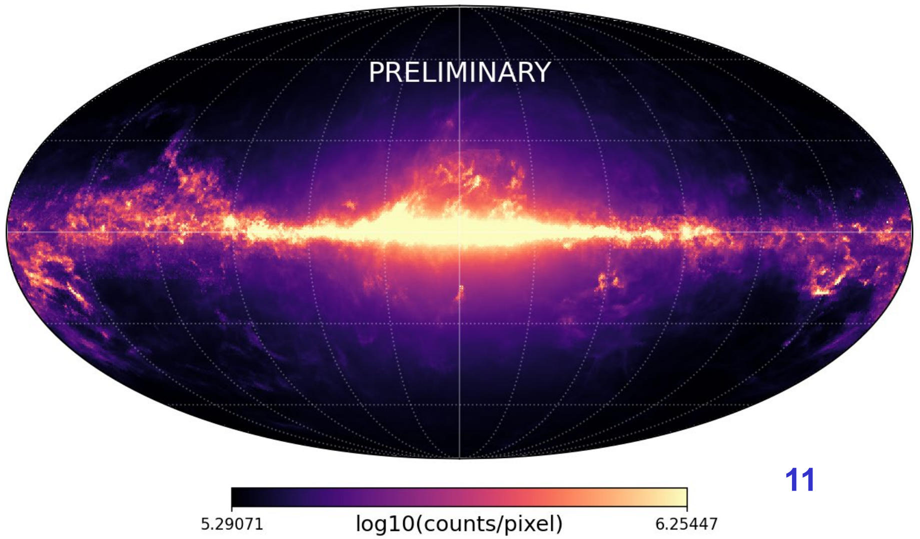
- For each ROI, we build the distribution of the maximum TS values obtained in the pseudo-experiments, and we evaluate its quantiles
- Assuming that the global significance obeys a half-normal distribution, we associate a global significance to each value of TS
  - The quantiles are converted in σ units
- **All features are globally insignificant**
  - In our data the potential feature with the highest global significance is found in R3, but its global significance is $\sim 0.55\sigma$

Perspectives for an APT-like detector: simulated data sample

- A simulation is performed assuming a total exposure of 50 m^2 yr
  - This corresponds ~ 12 years of APT in LEO orbit
    - APT on-axis effective area $\mathcal{A}_{APT} = 10\ m^2$
    - *Fermi*-LAT 15.5 years exposure : $\varepsilon_{LAT} \sim 6.35\ m^2 yr$
      - $\mathcal{A}_{LAT}$ of about 1 m^2 above 1 GeV
  - However, in the L2 position APT will operate without SAA and Earth occultation
    - Double exposure → half of time interval needed
- Gamma-ray sky model
  - Galactic diffuse emission evaluated with DRAGON code [1]
  - Isotropic gamma ray bagkround emission [2]
  - Energy dispersion of 10%



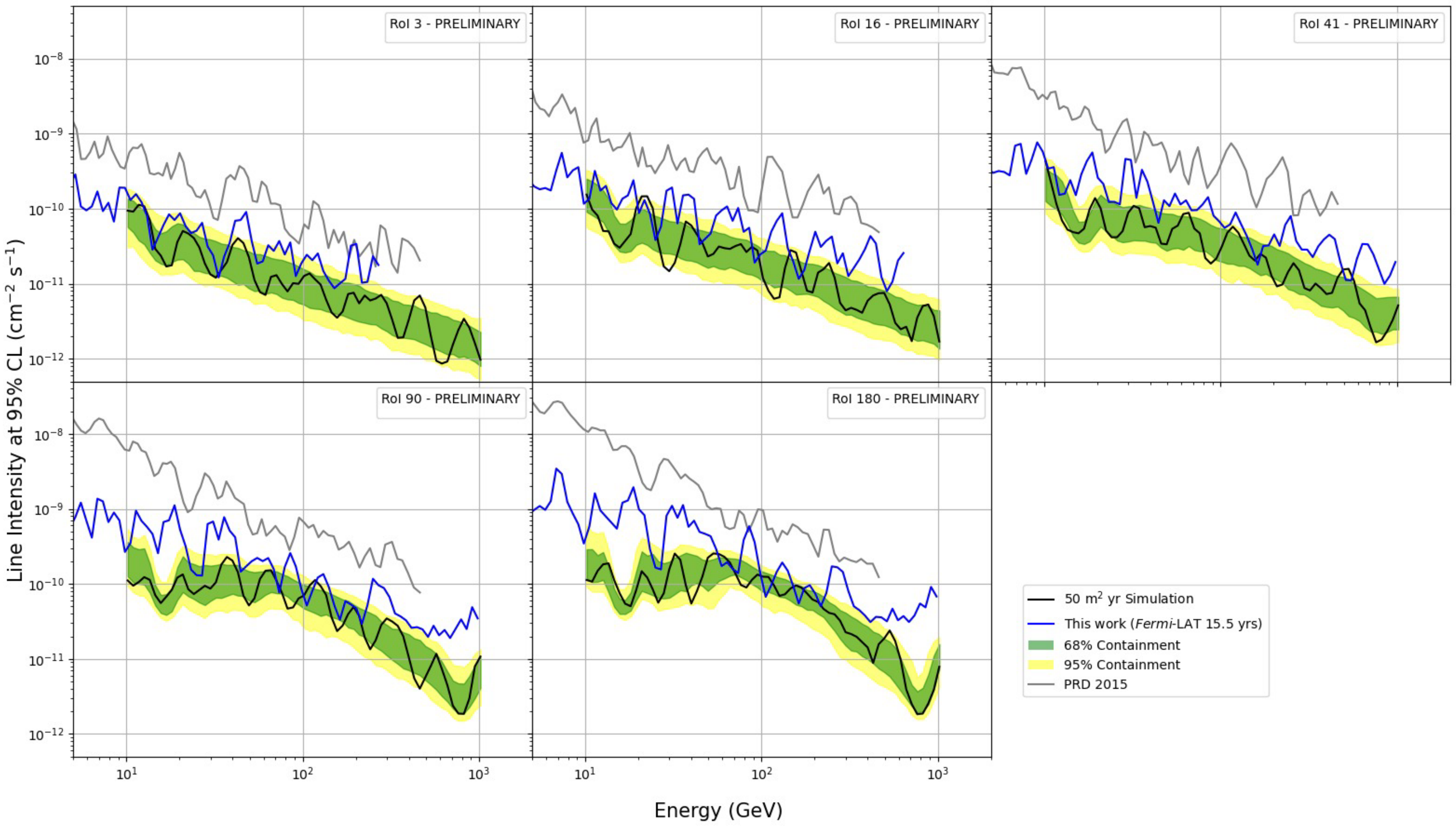
NSIDE=128, Energy from 10.00 MeV to 964661.62 MeV



[1] P. De La Torre Luque, M.N. Mazziotta, A. Ferrari, F. Loparco, P.R. Sala, and D. Serini. ***FLUKA cross sections for cosmic-ray interactions with the DRAGON2 code***. *Journal of Cosmology and Astroparticle Physics,2022(07):008, jul 2022*

[2] *M. Ackermann et al.* ***The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV***. *The Astrophysical Journal, 799(1):86, jan2015.*

Fit results



- **Same model as in LAT analysis**
- **No control region to account for possible systematic effects**
- **No EDISP subsamples, only 10% energy resolution**

- Observable improvement of upper limits thanks to increased exposure
- Poissonian pseudoexperiments by randomizing photon count spectra using template distributions for each ROI from simulated data

Conclusions

- We implemented a dedicated line-like feature search, obtaining competitive limits that are up to 2 orders of magnitude better than the previous *Fermi*-LAT line search in 2015
  - No candidate feature significantly observed
  - The improvement is due to:
    - Combined-likelihood analysis technique
    - More detailed modeling of the astrophysical background between 1 and 10 GeV
    - Larger data statistics
- We studied DM lines sensitivity of an APT-like detector
  - Simulated template of Galactic diffuse gamma-ray emission + Isotropic emission as test sample
  - A detector in L2 with higher effective area would improve the current limits