UNIVERSITÀ
DEGLI STUDI
DI TORINO

Physics Torino
Department of Excellence

INFN
Istituto Nazionale di Fisica Nucleare

Constraining Galactic dark matter in the Fermi-LAT sky with photon counts statistics

Dark Side of the Universe 2018

Annecy-le-Vieux, France

Silvia Manconi

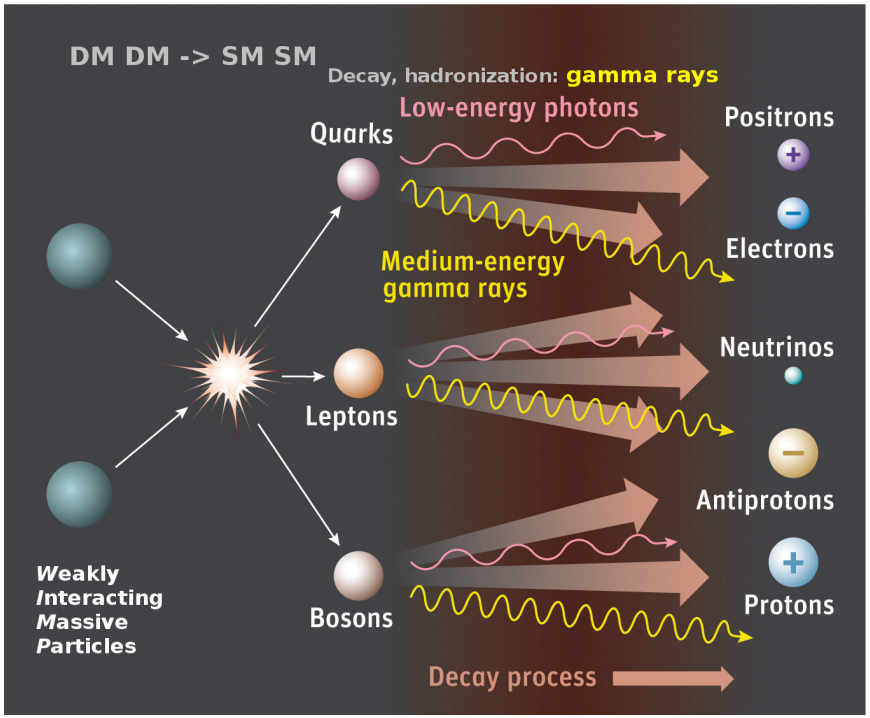
(University of Turin & INFN)

June 26, 2018

In collaboration with: Hannes Zechlin, Fiorenza Donato

Outline

Indirect dark matter (DM) detection with γ-rays



Prompt γ-rays emission:

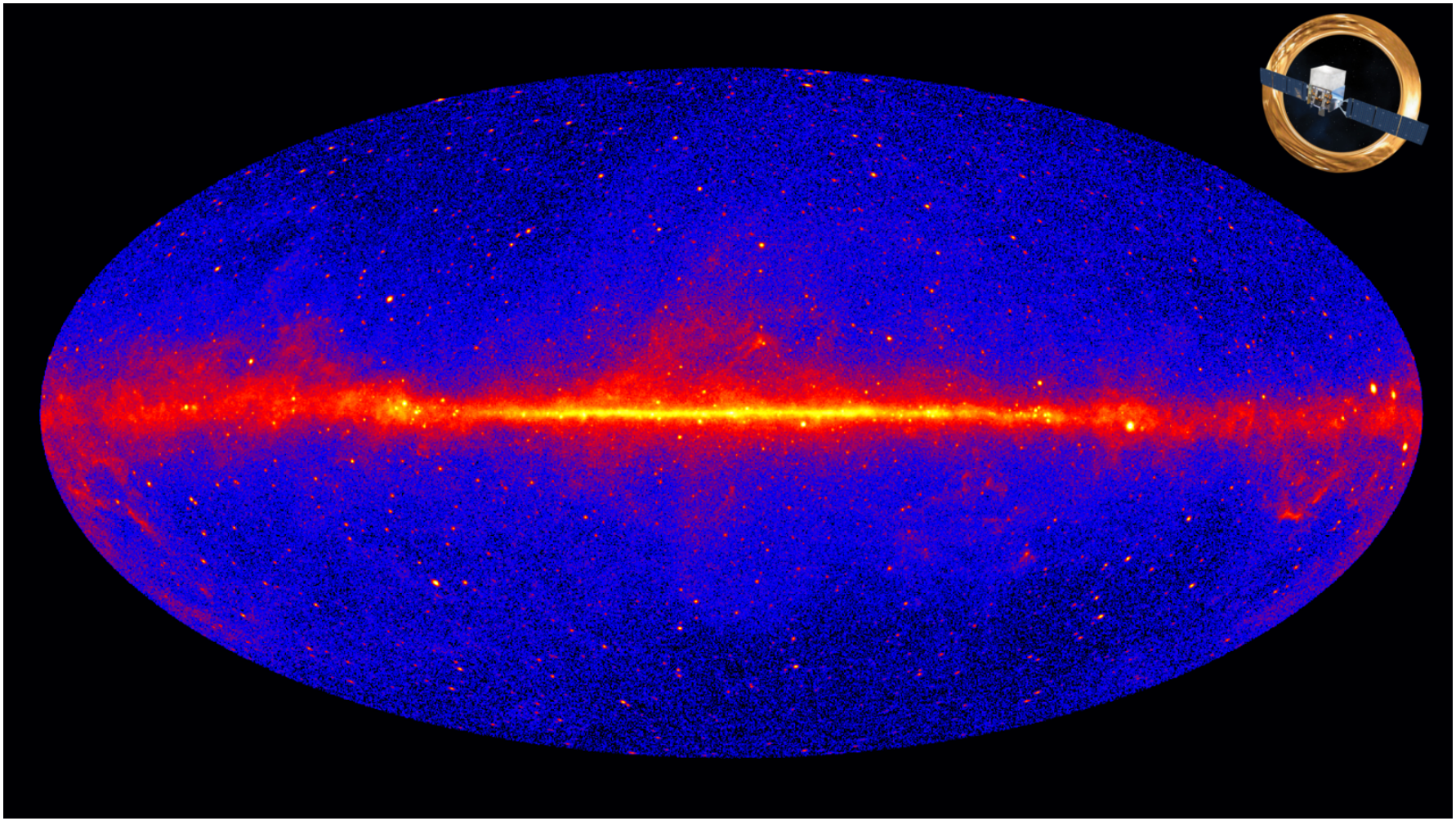
- Production, decay of π^0
- Hadronization
- Internal bremsstrahlung
- Monocromatic lines

Focus on **Weakly Interacting Massive Particles**, benchmark

other candidates:
axions, ALPs, ..

The γ-ray sky seen from Fermi-LAT

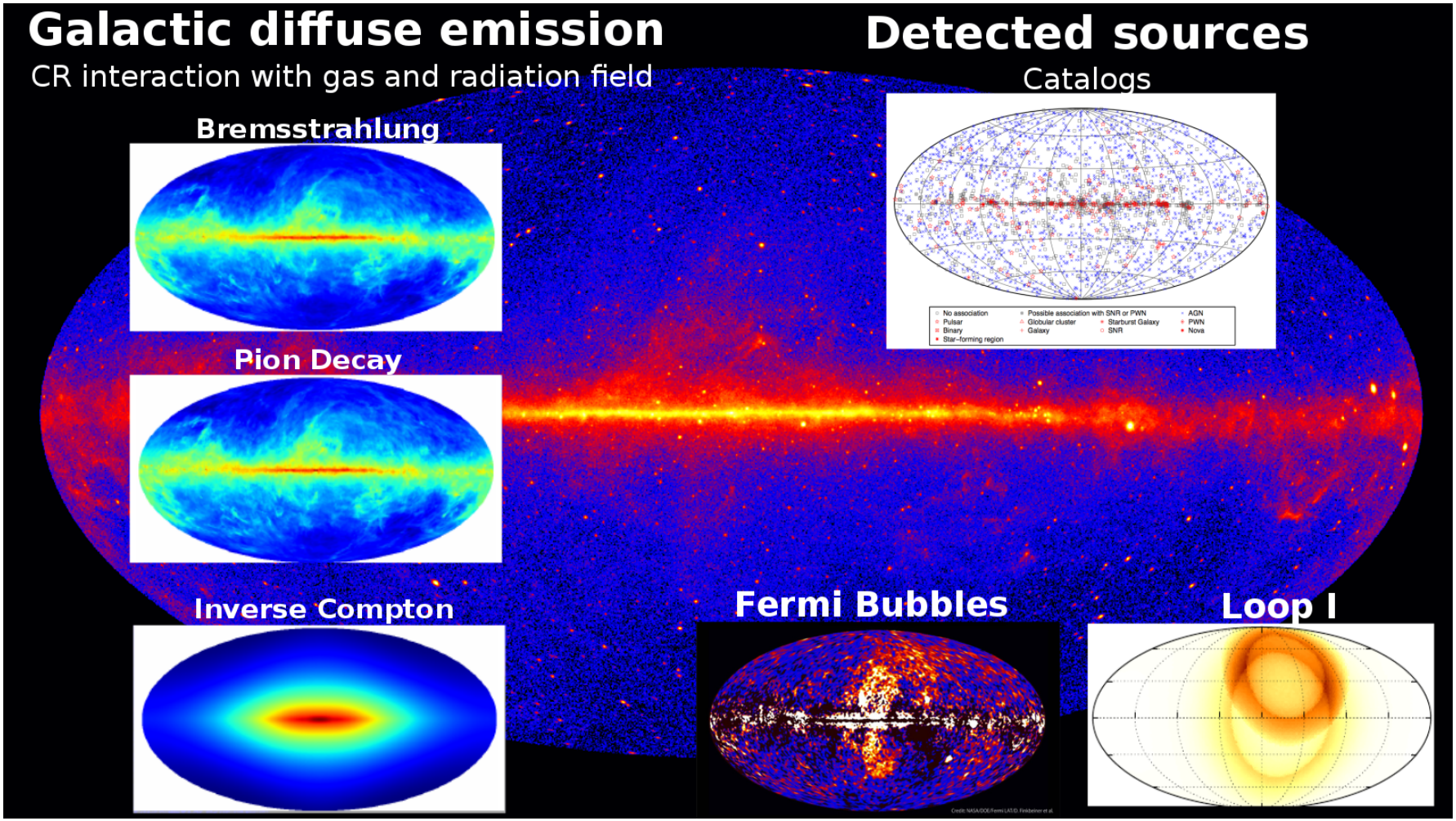
[Fermi-LAT 5 years, energy $>$ 1 GeV]



Fermi-**L**arge **A**rea **T**elescope: high-energy gamma-ray telescope,
data from $E = 20$ MeV to more than 300 GeV, 10 years of operation

The γ-ray sky seen from Fermi-LAT

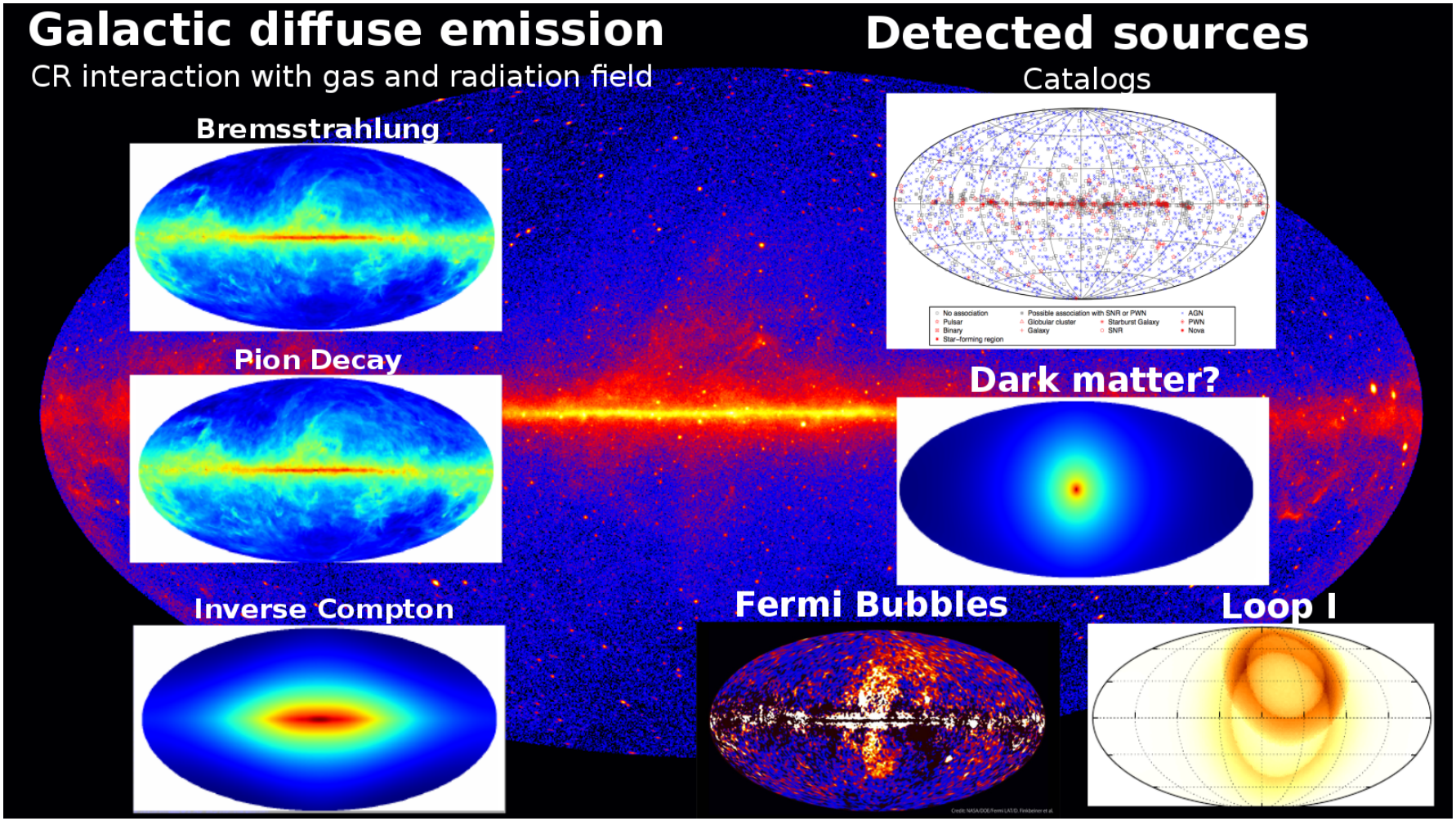
[Fermi-LAT 5 years, energy $>$ 1 GeV]



+ **isotropic emission** from unresolved sources and truly diffuse processes

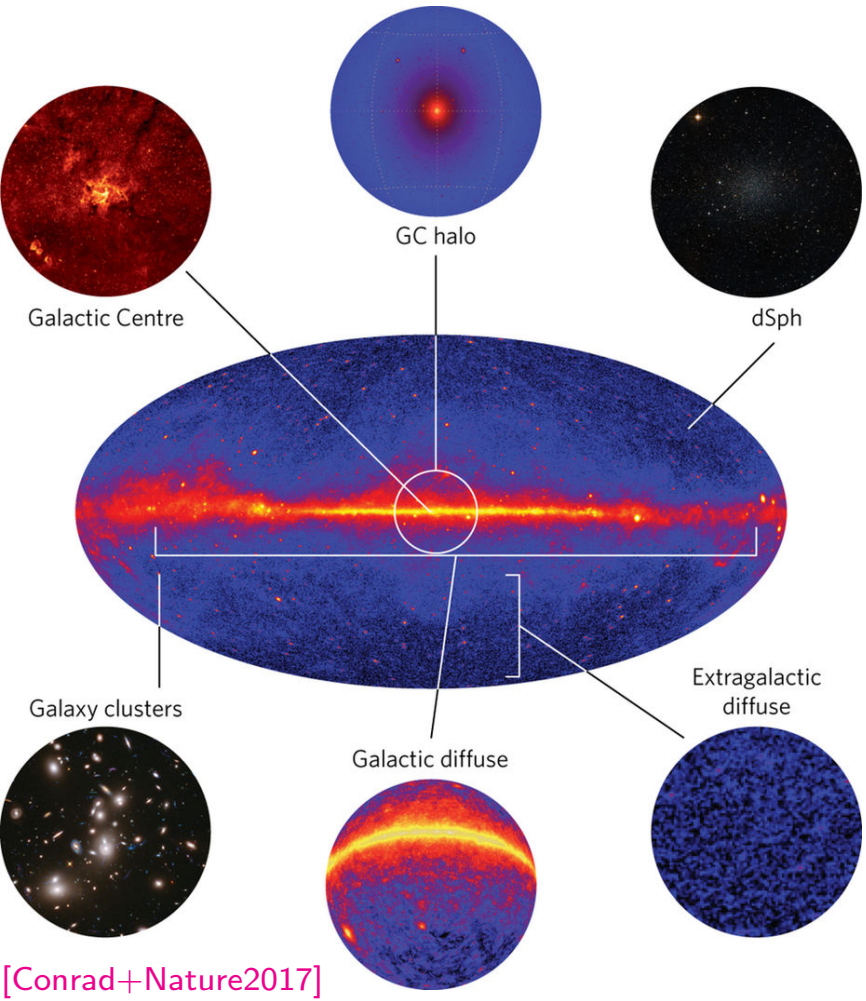
The γ-ray sky seen from Fermi-LAT

[Fermi-LAT 5 years, energy $>$ 1 GeV]

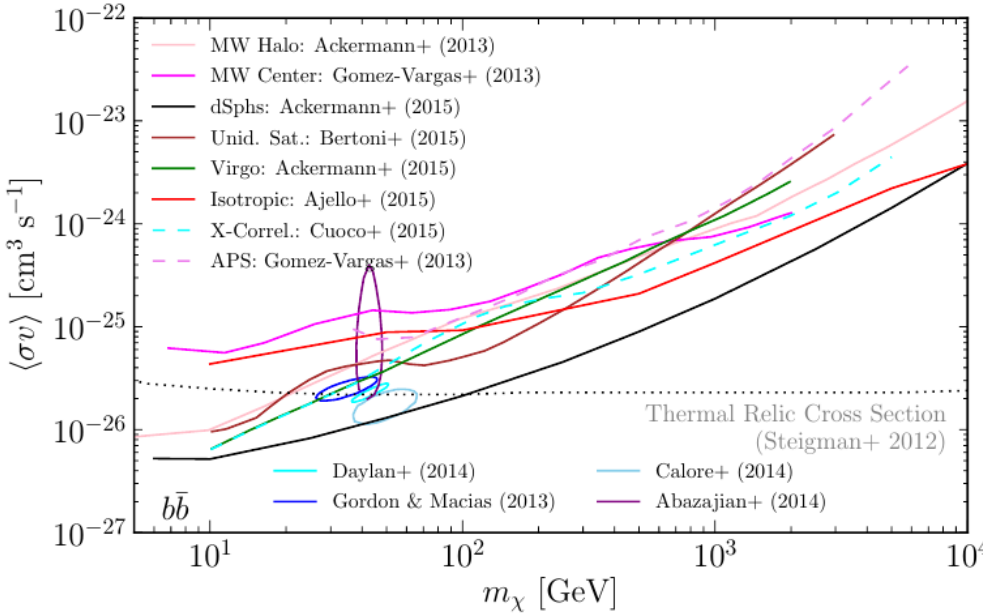


+ **isotropic emission** from unresolved sources and truly diffuse processes... DM?

Targets for dark matter searches



[Conrad+Nature2017]



Constraints from different targets, see [Charles+PhysRep2016]

This talk:

Galactic DM halo, high latitudes

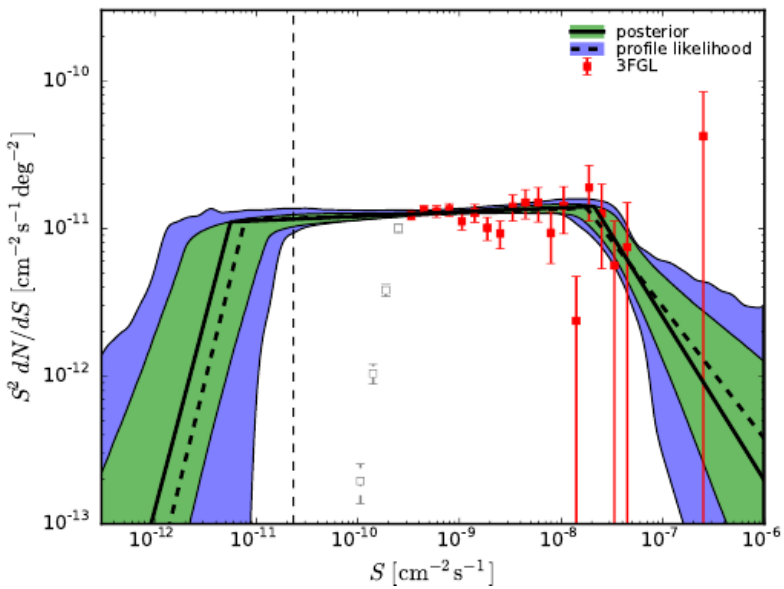
Decomposing the γ-ray sky

γ-ray sky = Galactic diffuse + **E**xtragalactic γ-ray **B**ackground (**EGB**) emissions.

EGB= point sources* + isotropic diffuse background

Source count distribution dN/dS: # of sources N per $d\Omega$ with integral flux in $(S, S+dS)$.

Catalog (3FGL) $\rightarrow$
Detection efficiency < 1
Statistical analysis results



[Zechlin+ApjS2016, 1-10 GeV]

- fundamental to understand composition of EGB
  ($\Rightarrow$ origin of IceCUBE ν, UHECR, DM [Ahlers+ApJ2017,Taylor+PRD15,DiMauro+PRD15])
- **extrapolations** below detection threshold lead to **significant uncertainties**
- Statistical methods **increase sensitivity** for resolving faint point sources!

*AGN, mAGN, star-forming galaxies,...

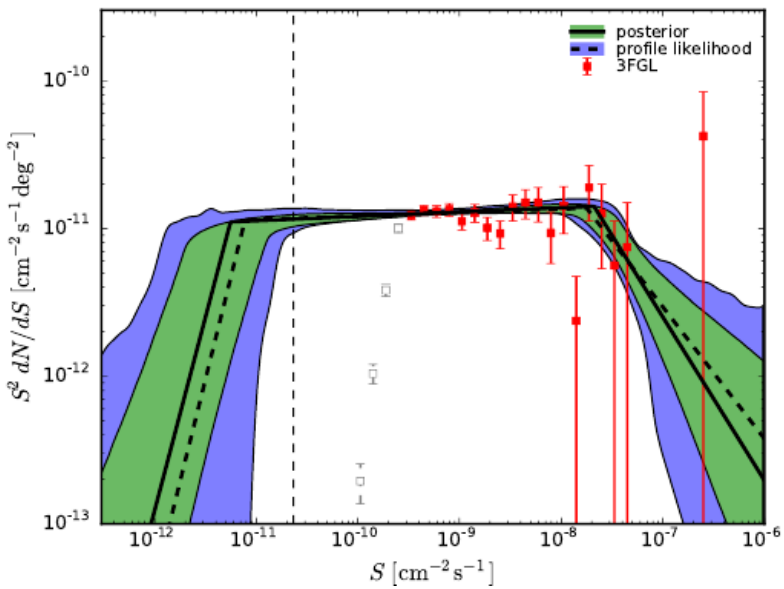
Decomposing the γ-ray sky

γ-ray sky = Galactic diffuse + **E**xtragalactic γ-ray **B**ackground (**EGB**) emissions.

EGB= point sources* + isotropic diffuse background

Source count distribution dN/dS: # of sources N per $d\Omega$ with integral flux in $(S, S+dS)$.

Catalog (3FGL) $\rightarrow$
Detection efficiency < 1
Statistical analysis results



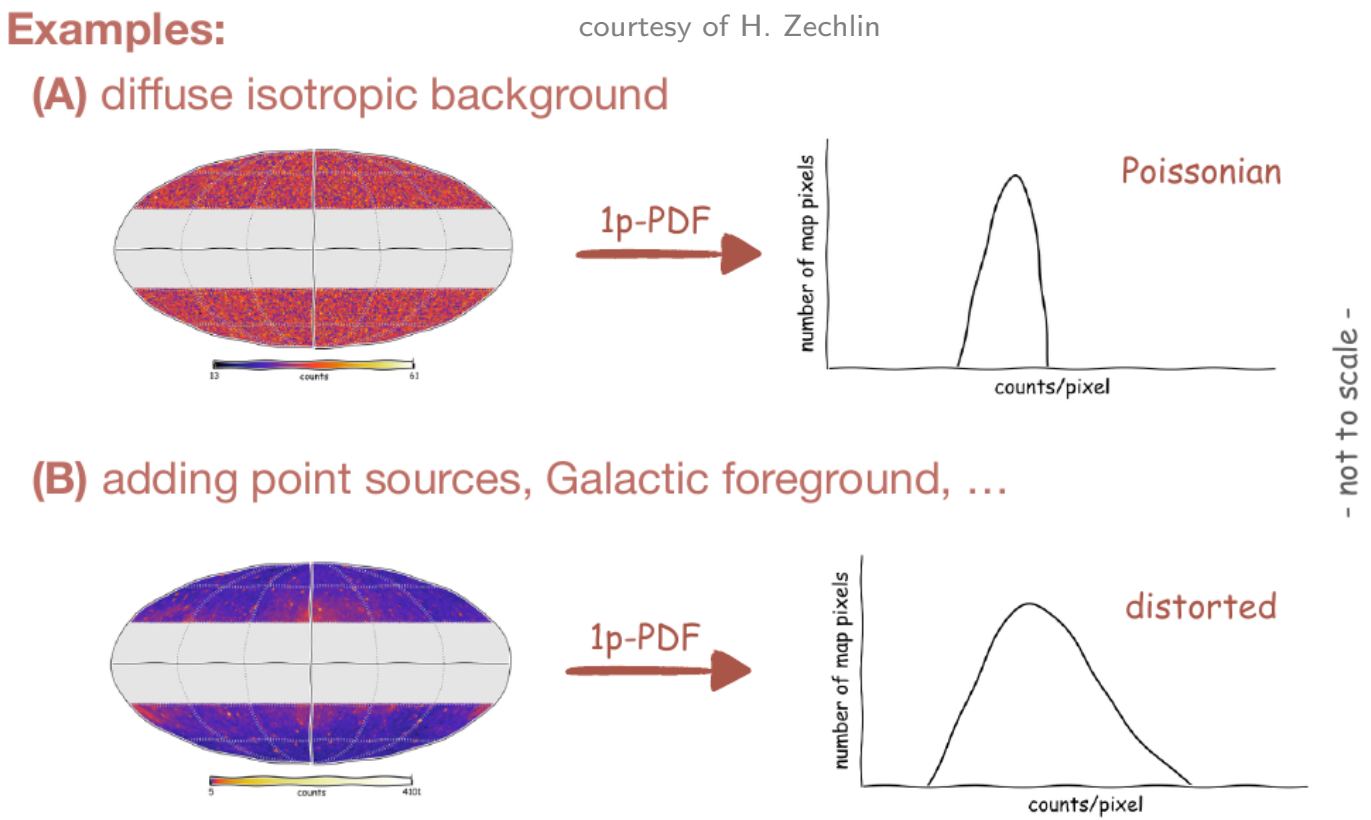
[Zechlin+ApjS2016, 1-10 GeV]

- fundamental to understand composition of EGB
  ($\Rightarrow$ origin of IceCUBE ν, UHECR, DM [Ahlers+ApJ2017,Taylor+PRD15,DiMauro+PRD15])
- **extrapolations** below detection threshold lead to **significant uncertainties**
- Statistical methods **increase sensitivity** for resolving faint point sources!

*AGN, mAGN, star-forming galaxies,...

Pixel count statistics with the 1-point Probability Distribution Function (1pPDF)

Statistical analysis of intensity to decompose the γ-ray sky



Details in [Malyshev+ApJ2011], [Zechlin+ApjS2016].
Similar methods used also in radio [Vernstrom+MNRAS2015] and X-ray [Soltan+A&A2011]

The **1pPDF** analysis

Separate sources based on statistical properties of their photon counts

Modeling: *probability generating functions* $\mathcal{P}^{(p)}(t)$:

$$p_k^{(p)} = \frac{1}{k!} \left. \frac{\mathrm{d}^k \mathcal{P}^{(p)}(t)}{\mathrm{d}t^k} \right|_{t=0}$$

$p_k^{(p)}$ = probability to find k photons in pixel (p)

OBSERVED
Probability distribution of photon counts in pixels $p_k^{(p)}$

$\Longleftrightarrow$

WANTED
Decompose γ-ray sky in:
-Point sources dN/dS
-Diffuse contributions

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k = \exp\left(\sum_{m=1}^{\infty} x_m^{(p)} (t^m - 1) \right)$$

$x_m^{(p)}$ = **expected number of sources contributing m photons per pixel p:**

- point sources (dN/dS)
- Galactic diffuse emission
- Diffuse isotropic background
- **Dark matter ?**

The **1pPDF** analysis

Separate sources based on statistical properties of their photon counts

Modeling: *probability generating functions* $\mathcal{P}^{(p)}(t)$:

$$p_k^{(p)} = \frac{1}{k!} \left. \frac{\mathrm{d}^k \mathcal{P}^{(p)}(t)}{\mathrm{d}t^k} \right|_{t=0}$$

$p_k^{(p)}$ = probability to find k photons in pixel (p)

OBSERVED
Probability distribution of photon counts in pixels $p_k^{(p)}$

$\Longleftrightarrow$

WANTED
Decompose γ-ray sky in:
-Point sources dN/dS
-Diffuse contributions

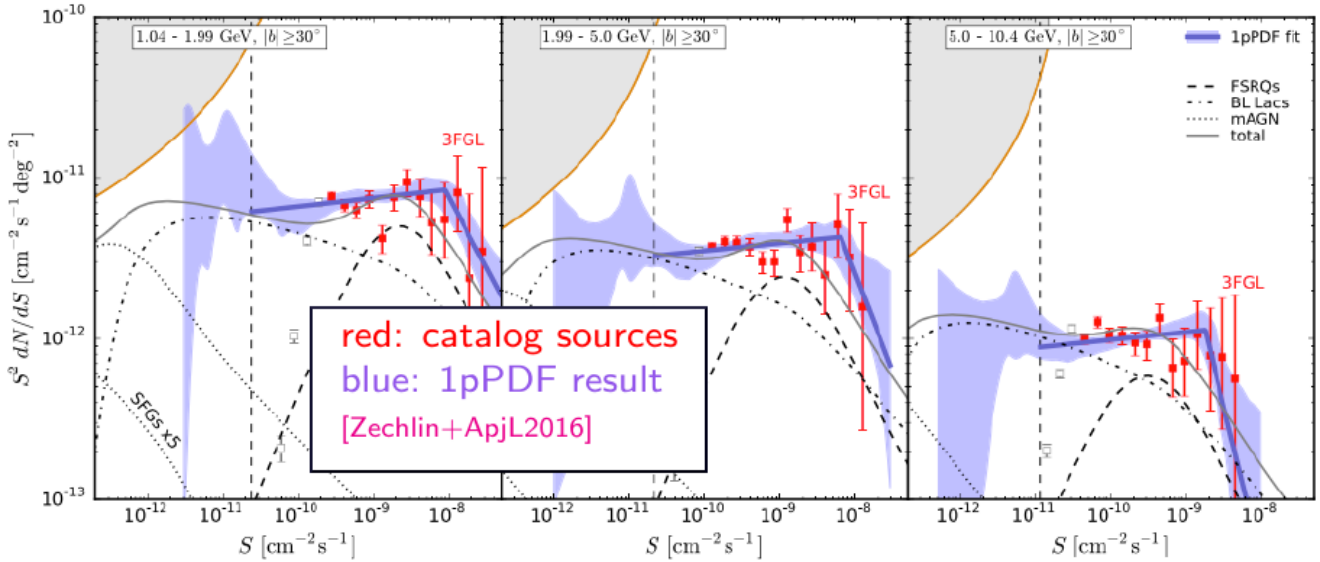
$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k = \exp\left(\sum_{m=1}^{\infty} x_m^{(p)} (t^m - 1) \right)$$

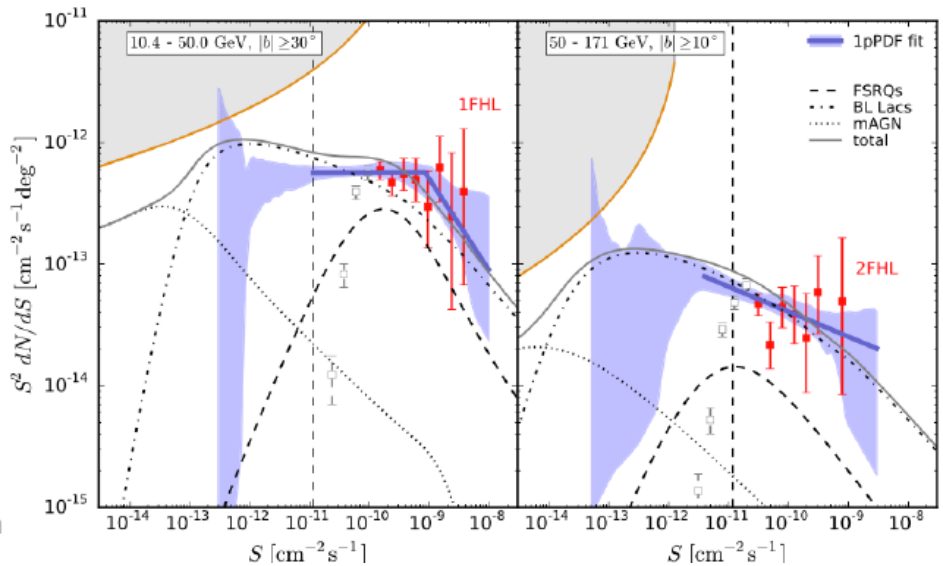
$x_m^{(p)}$ = **expected number of sources contributing m photons per pixel p:**

- point sources (dN/dS)
- Galactic diffuse emission
- Diffuse isotropic background
- **Dark matter ?**

1pPDF results: source count distribution dN/dS

Successfully applied in [Zechlin+ApjS2016, ApjL2016], [DiMauro+Apj2018], [Lisanti+Apj2016] (dN/dS of high latitude sources), [Lee+PRL2015] (Galactic Center)





⇒ **Point sources resolved below catalog detection threshold**

⇒ **γ-ray sky decomposed** (ex. [1,2] GeV)

- Point sources: $0.27^{+0.002}_{-0.04}$
- Galactic diffuse: $0.74^{+0.003}_{-0.05}$
- Isotropic: $0.02^{+0.004}_{-0.01}$

1pPDF applied to **Galactic DM searches**

see arXiv:1710.01506

Investigate sensitivity reach of 1-point statistics for constraining a diffuse DM component at *high latitudes*

$\Rightarrow$ Unresolved point sources: *subdominant BUT comparable* to DM component

$\Rightarrow$ 1pPDF is *indipendent* from source catalogs

$\Rightarrow$ First time 1pPDF is tested for constraining Milky Way DM halo

Similar analysis at high latitudes, standard template fitting: [Chang et al, arXiv:1804.04132]

1pPDF applied to **Galactic DM searches**

see arXiv:1710.01506

Investigate sensitivity reach of 1-point statistics for constraining a diffuse DM component at *high latitudes*

$\Rightarrow$ Unresolved point sources: *subdominant BUT comparable* to DM component

$\Rightarrow$ 1pPDF is *indipendent* from source catalogs

$\Rightarrow$ First time 1pPDF is tested for constraining Milky Way DM halo

Similar analysis at high latitudes, standard template fitting: [Chang et al, arXiv:1804.04132]

1pPDF applied to Galactic DM searches

Analysis overview:

1. **Data**: Fermi-LAT 8yrs, 3 energy bins from 1 GeV to 10 GeV
2. **DM profile**:* Einasto, $\rho_\odot = 0.4$ GeV cm^{-3} [Catena+JCAP2010]
3. **DM spectra**: dN_f/dE from [Cirelli+JCAP2010], $b\bar{b}$, $\tau^+\tau^-$ final states
4. **Main systematics**: Galactic diffuse emission
   - $\Rightarrow$ high latitudes $|b| > 30$ deg
   - $\Rightarrow$ different benchmarck templates
   - $\Rightarrow$ ROI optimization
5. **Simulations***: to validate analysis framework

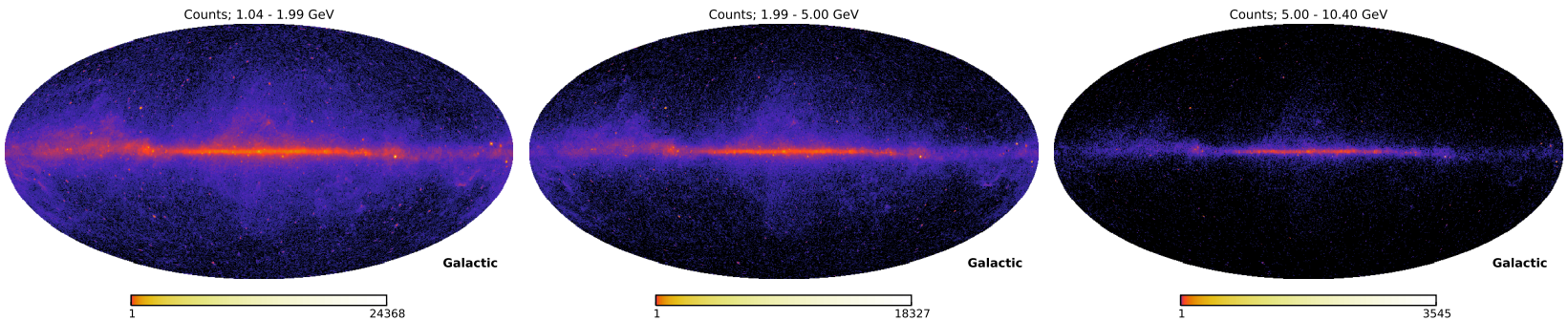


figure: Counts maps for 8 years of real-sky data and the different energy bins

* see backup slides

Main systematics: Galactic Diffuse Emission

Complex modeling, e.g. possible degeneracy Inverse Compton $\Longleftrightarrow$ DM halo

Different benchmark templates:

1. *Official* released with pass8 Fermi-LAT data
2. *models A,B,C* from [Ackermann+ApJ2015]

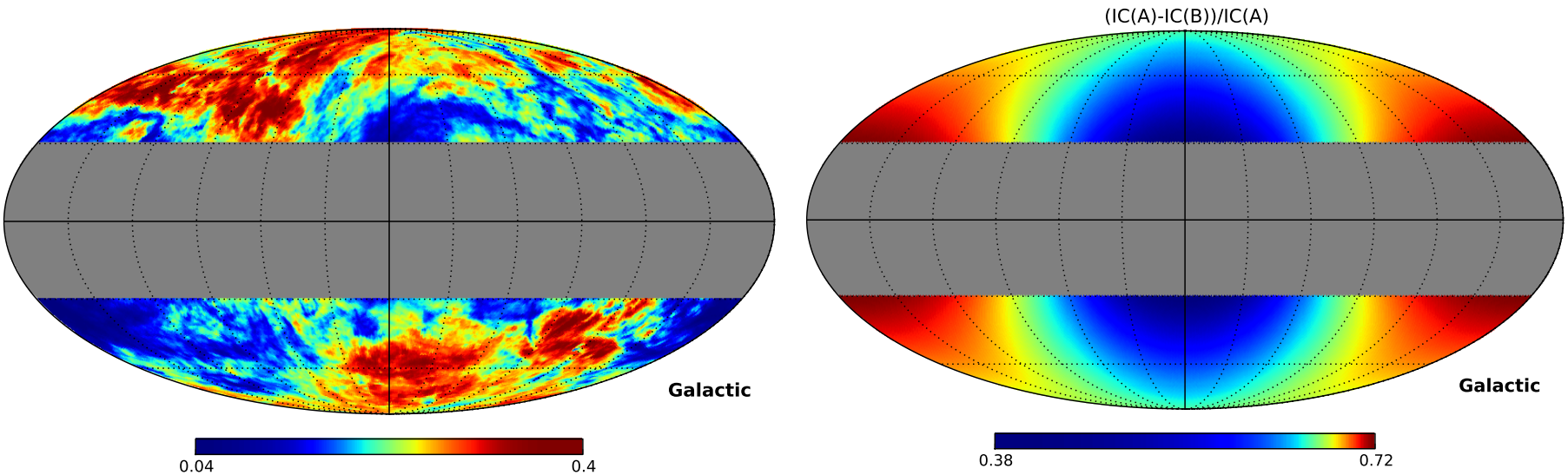


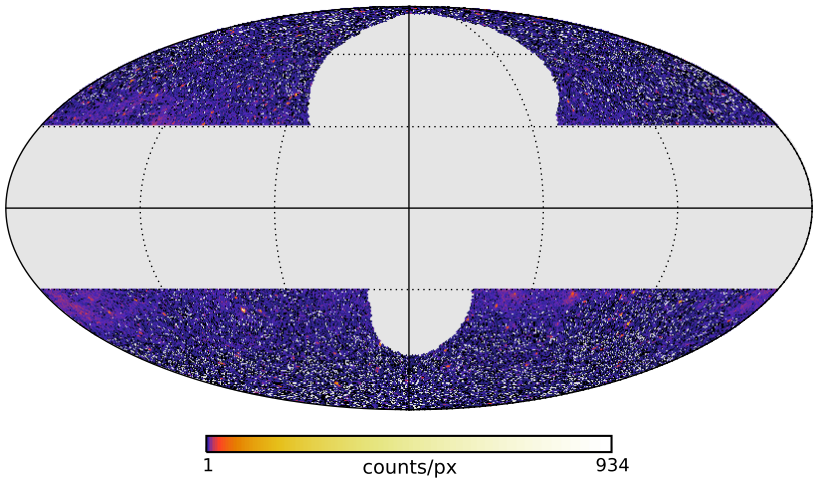
figure: Relative difference between Galactic diffuse emission (left) and Inverse Compton components only (right) from **mod A** and **mod B** **integrated in the energy bin [2,5] GeV** for $|b| > 30$ **deg**

$\Rightarrow$ **Region of interest search depends from the galactic diffuse emission**

Better modeling: ongoing effort, e.g. SkyFact [Storm+17], [Porter+17,Gaggero+15, Selig+15]

Region Of Interest (ROI) optimization

- Mask galactic plane: $|b| > 30 - 40$ deg
- Mask stuctures: Fermi Bubbles, Loop I
- Small ROI: over-subtraction of background
- Simulations w/o DM, expected sensitivity



$\Rightarrow$ DM_ROI at high latitudes where real sky results consistent with simulations in all bins:

95% CL from simulations
Real sky $\searrow$

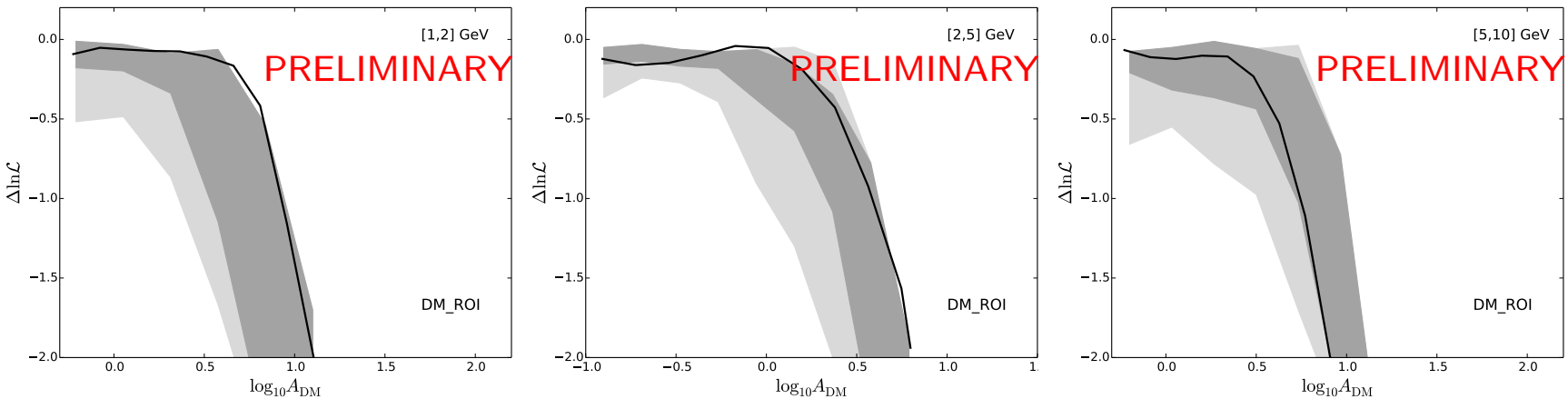
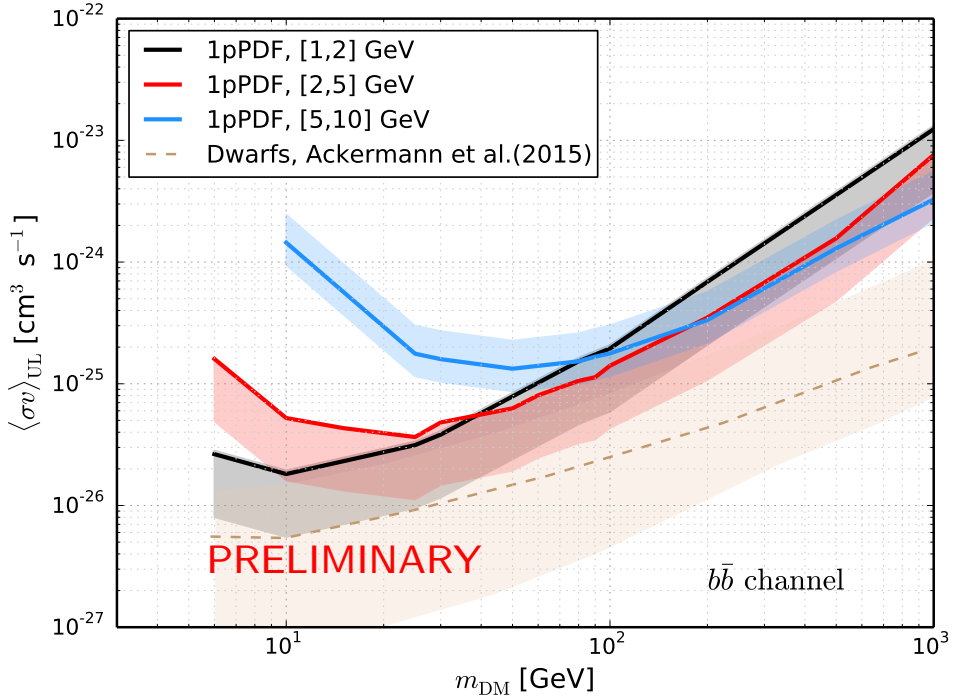
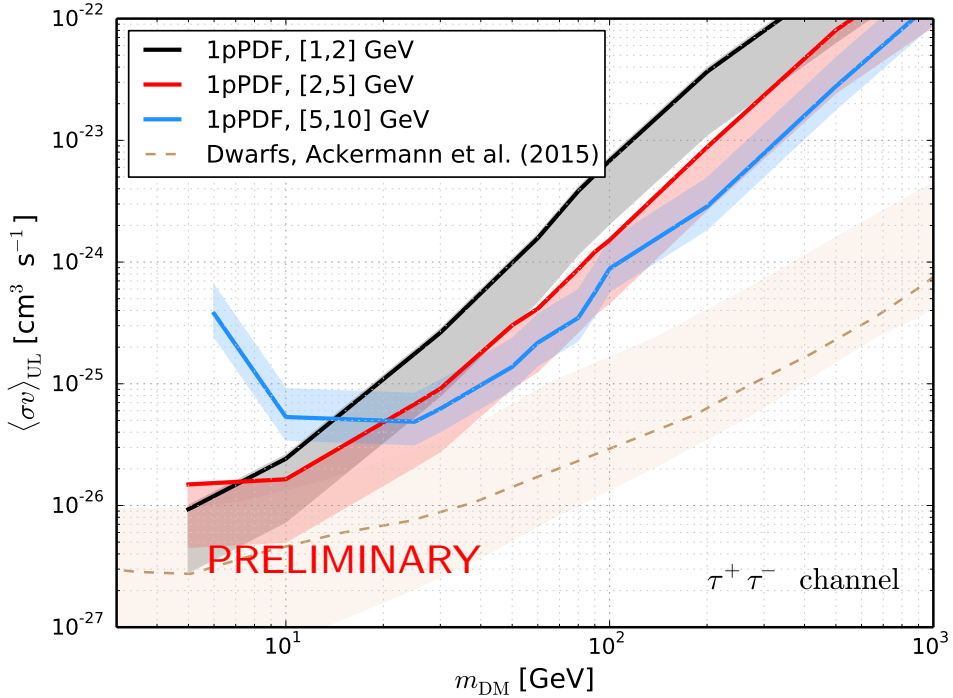


figure: Profile likelihood for $A_{\rm dm}$, rescaling parameter for $\langle \sigma v \rangle_0 = 10^{-26}$ cm^3 s^{-1} for $m_{\rm dm} = 15$ GeV

Results: upper limits on $\langle \sigma v \rangle$

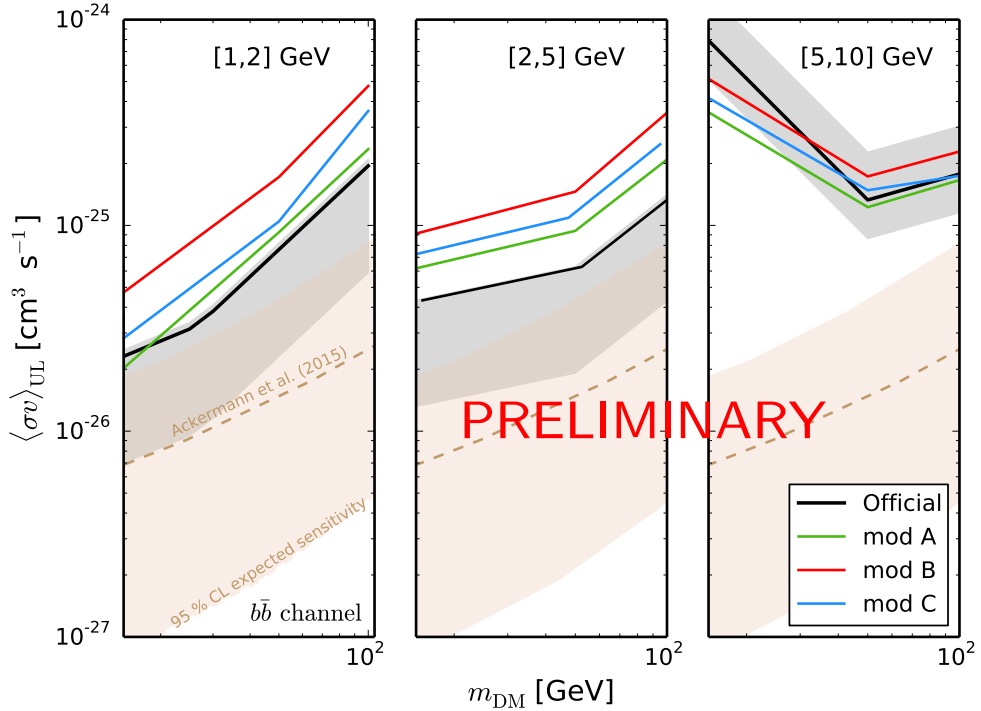




Sensitivity of 1pPDF for DM searches at high latitudes is comparable with other methods and targets

Systematics on Galactic Diffuse Emission

upper limits on $\langle \sigma v \rangle$



$\Rightarrow$ **Scatter between models: factor** $\sim 2-5$ in $\langle \sigma v \rangle$

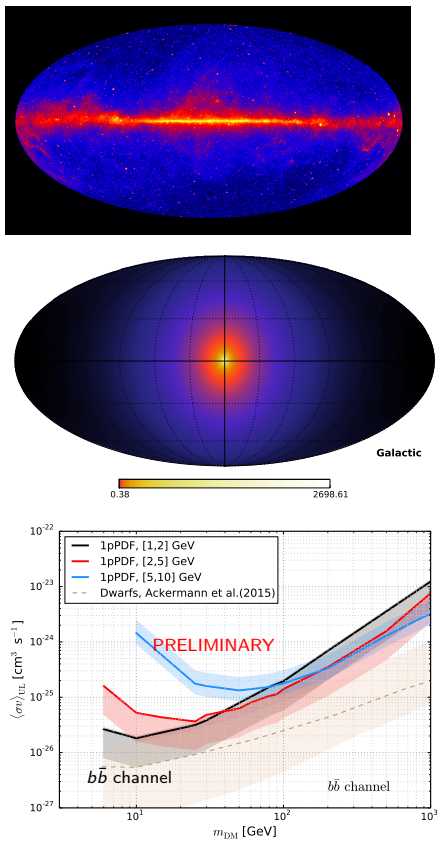
model B has lower inverse Compton for $|b| > 30$ deg, so more room for DM

Galactic DM with photon counts statistics at high latitudes- *Summary*

- The **1**-**p**oint **P**robability **D**istribution **F**unction is a **powerful statistical method** to:
  - ⋆ resolve faint point sources
  - ⋆ dissect γ-ray sky components
- **1pPDF sensitivity for Galactic DM halo signals at high latitudes was explored in simulated and real data**
  (8 yrs Fermi-LAT, [1,10] GeV)

Results:

1. **Sensitivity is comparable** with other searches and methods
2. Limited by systematics from background Galactic emission modeling



Constraining Galactic dark matter with gamma-ray pixel counts statistics
H.Zechlin, S.M., F.Donato
arXiv:1710.01506

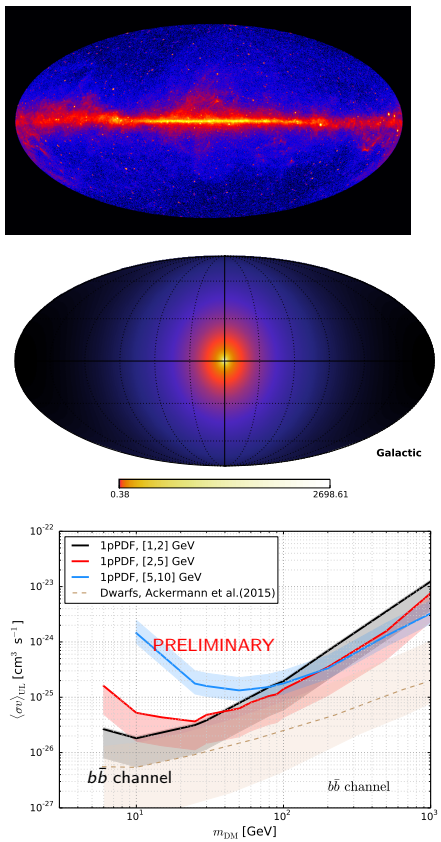
Thank you for your attention!

Galactic DM with photon counts statistics at high latitudes- *Summary*

- The **1**-**p**oint **P**robability **D**istribution **F**unction is a **powerful statistical method** to:
  - ⋆ resolve faint point sources
  - ⋆ dissect γ-ray sky components
- **1pPDF sensitivity for Galactic DM halo signals at high latitudes was explored in simulated and real data**
  (8 yrs Fermi-LAT, [1,10] GeV)

Results:

1. **Sensitivity is comparable** with other searches and methods
2. Limited by systematics from background Galactic emission modeling



Constraining Galactic dark matter with gamma-ray pixel counts statistics
H.Zechlin, S.M., F.Donato
arXiv:1710.01506

Thank you for your attention!

Backup

Simulations of the Fermi-LAT sky

Components simulated with Fermi Science Tool *gtobbsim*:

1. **Point sources** following same dNdS of real sky
2. **Galactic diffuse** background (gll_iem_v06)
3. **Isotropic** background (iso_P8R2_ULTRACLEANVETO_V6_PSF3_v06)

Each simulation contains a list of point sources from a different Monte Carlo realization of the dN/dS:

- Power law, $\Gamma_{\rm mean} = 2.4$, $\sigma_\Gamma = 0.4$
- $S_{\rm min} = 10^{-12}{\rm cm}^{-2}{\rm s}^{-1}$
- random positions across the sky

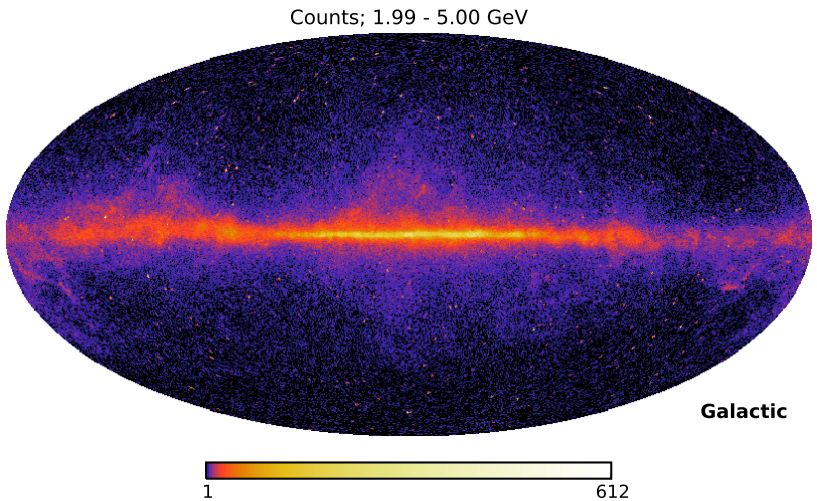
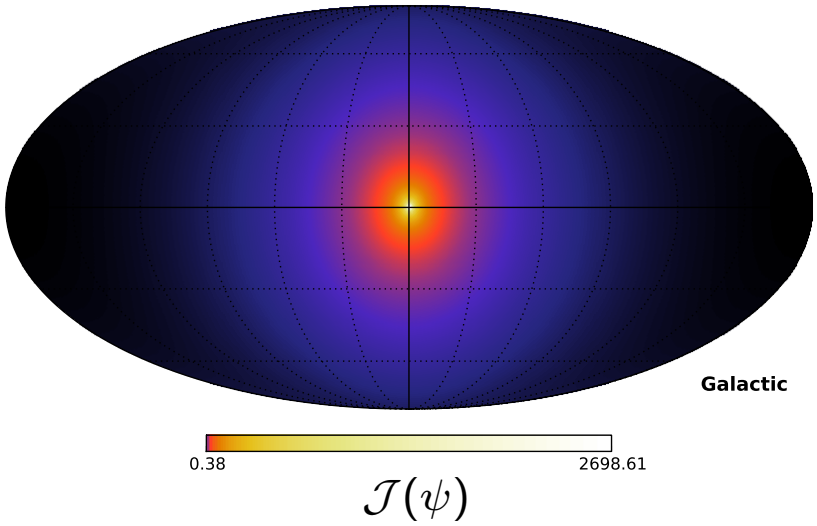


figure: Counts map for a simulation w/o DM, [2,5] GeV

Galactic DM halo modeling

Flux per unit energy and solid angle:

$$\frac{\mathrm{d}\phi_{\mathrm{DM}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2} r_\odot \frac{\rho_\odot^2}{m_{\mathrm{DM}}^2} \sum_f \left(\frac{\mathrm{d}N_f}{\mathrm{d}E} B_f\right) \mathcal{J}(\psi)\,.$$

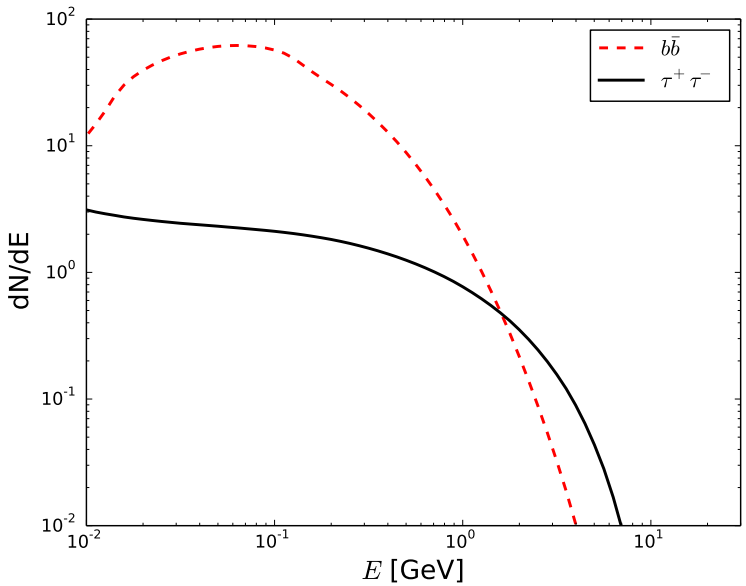


Spatial :

- Smooth DM halo: Einasto, $\rho_\odot = 0.4$ GeV cm^{-3} [Catena+JCAP2010]
- Extragalactic: subdominant
- possible DM suhalos absorbed by dN/dS

Energy:

- WIMP self-annihilations into pure $b\bar{b}$, $\tau^+\tau^-$ final states
- dN_f/dE from [Cirelli+JCAP2010]



Fermi-LAT Data selection

- 8 years of Pass8 data [239557417, 492018220] s MET
- `DATA_QUAL==1` and `LAT_CONFIG==1`
- evclass=ULTRACLEANVETO, evtype=PSF3
- Energy bins: [1, 2] GeV, [2,5] GeV, [5,10] GeV as in [Zechlin+ApjS2016, ApjL2016]
- Derived PSF widths: 0.31 deg, 0.18 deg, 0.10 deg
- HEALPix order 7

The 1-point Probability Distribution Function analysis

- **Pixel-dependent likelihood**:

$$\mathcal{L}(\boldsymbol{\Theta}) = \prod_{p=1}^{N_{\rm pix}} P(k_p)$$

- **Parameter estimation**:
  profile likelihood from Bayesian posterior, MCMC sampling (MultiNest)

Details in [Zechlin+ApjS2016].