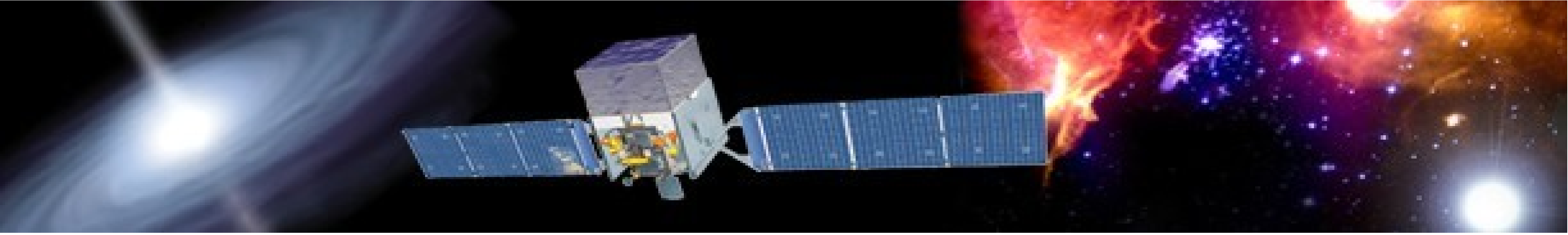

Dark Matter Searches in the Inner Galaxy with the *Fermi*-LAT

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Universidad Autónoma de Madrid - IFT UAM/CSIC

INFN Roma Tor Vergata

On behalf of the LAT team

ICTP – Trieste

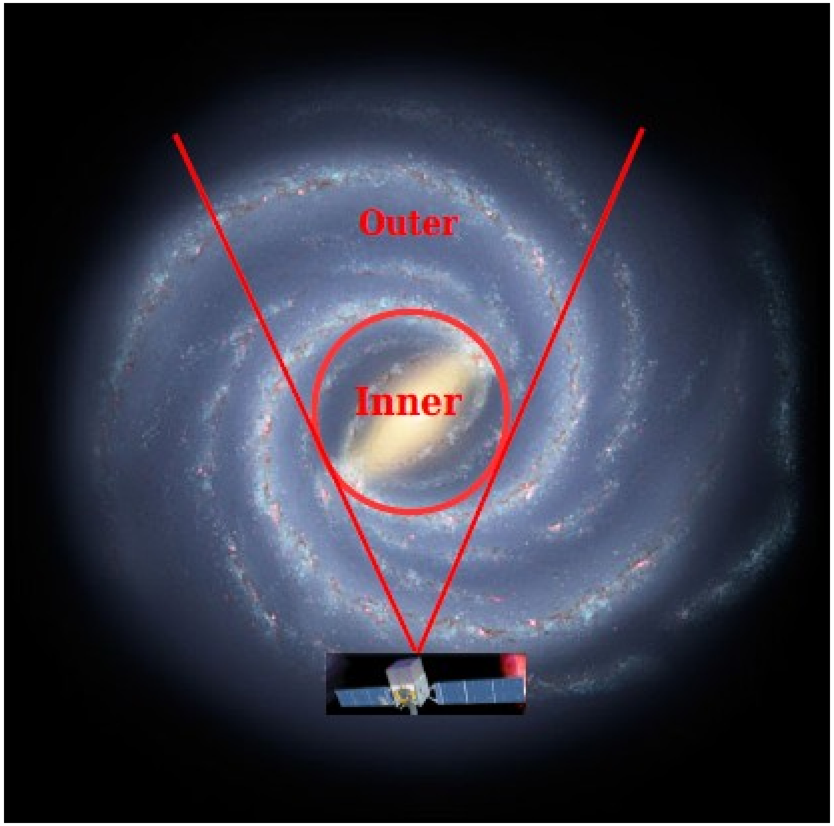
Oct. 8, 2013

MultiDark
Multimessenger Approach for Dark Matter Detection

Indirect DM Searches

- **DM-induced SM** particles would appear as **exotic contributions** in astrophysical observations, they can **affect fluxes and spatial distribution of CR**, i.e. protons, antiprotons, electrons, positrons, gamma-rays and neutrinos **measured at the Earth.**
- We need to **measure those fluxes and understand** the non-exotic contributions, i.e. **the background.**
- To set **conservative constraints** we don't need to understand the background, we can **simply require that the expected DM signal does not exceed the measurement**.

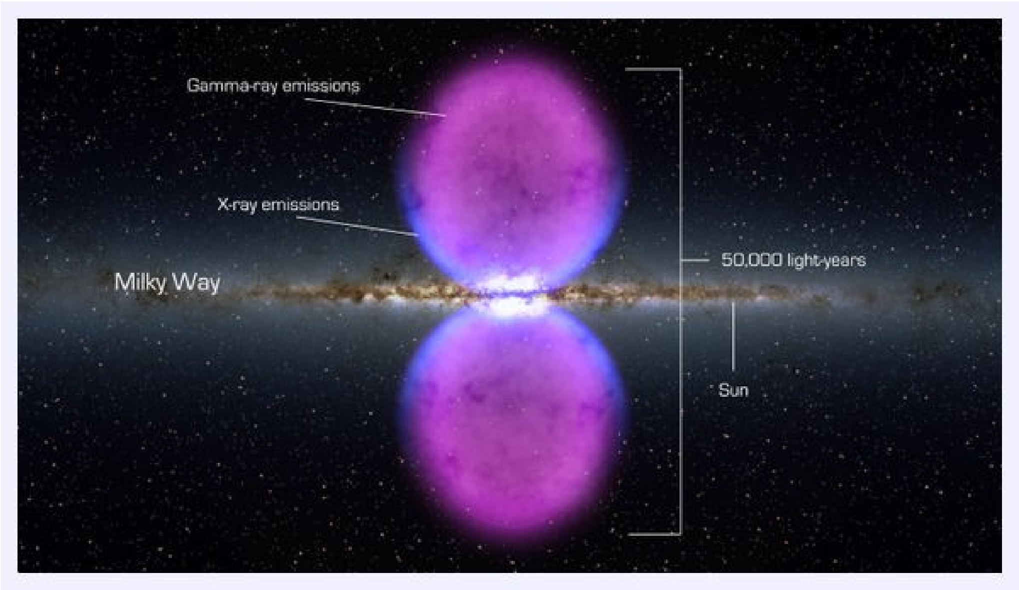
Inner Galaxy



Emission from the inner Galaxy is made of:

- Outer Galaxy
- True inner Galaxy
- Unresolved sources
- Point or small extended sources
- Extragalactic emission
- Possible DM contribution
- CR instrumental background

Inner Galaxy



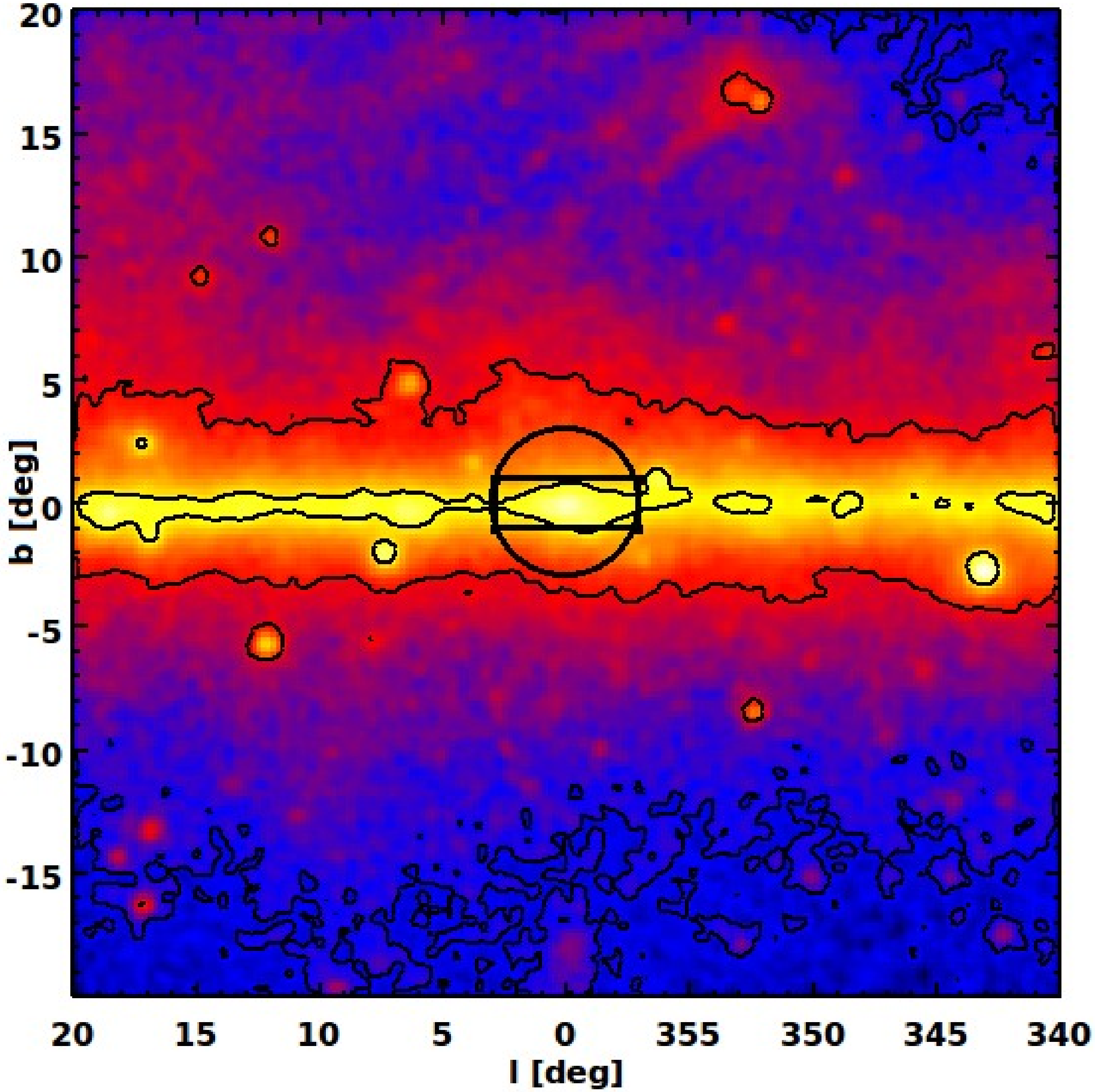
Emission from the inner Galaxy is made of:

- Outer Galaxy
- True inner Galaxy
- Fermi bubbles
- Unresolved sources
- Point or small extended sources
- Extragalactic emission
- Possible DM contribution
- CR instrumental background

Fermi-LAT view of the inner Galaxy

Gamma-ray flux 1-100 GeV

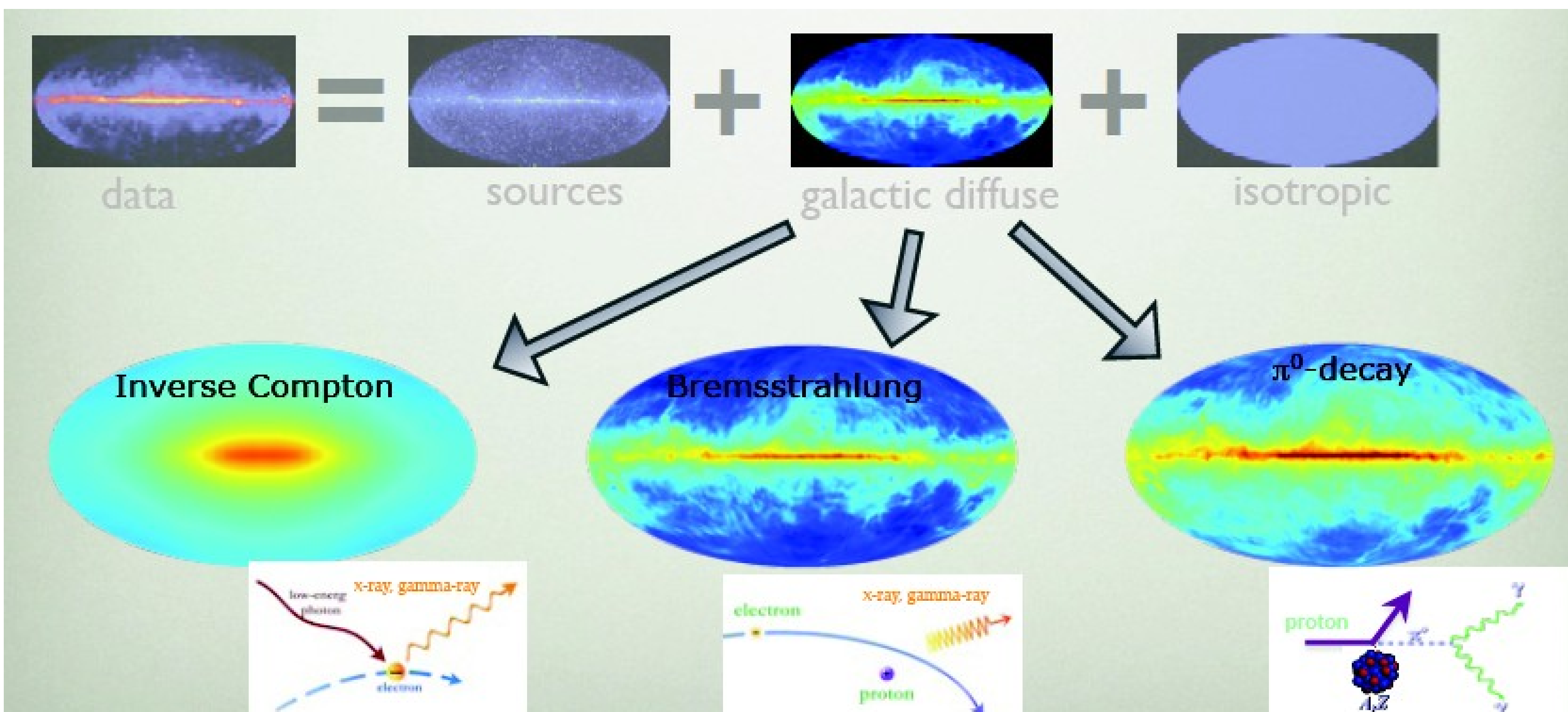
G. G-V et al. 2013. ArXiv:1308.3515



More on diffuse emission at Elena Orlando's talk on Friday

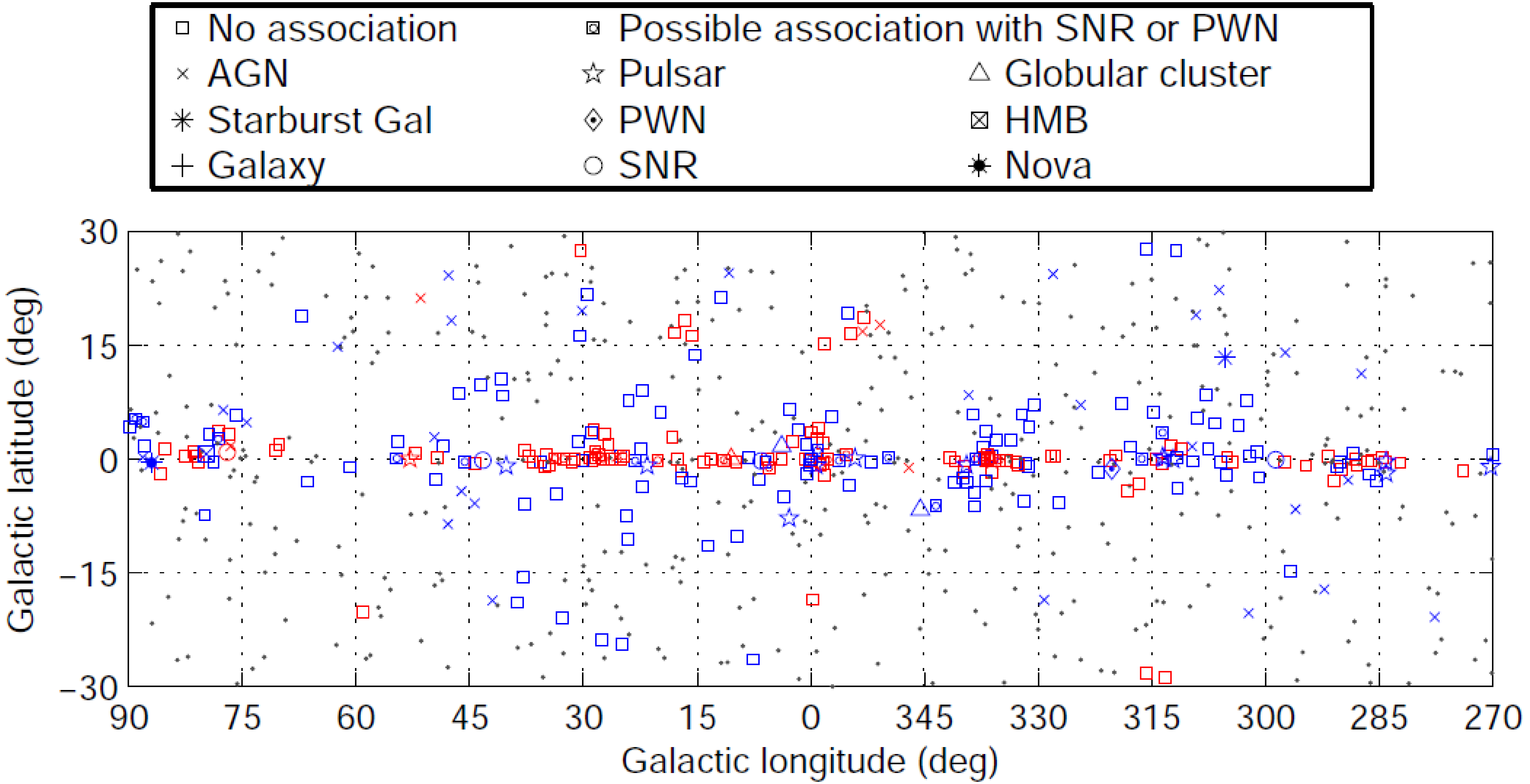
Astro zoo in gamma-ray

- **Diffuse emission.**
  - Unresolved/undetected point sources
  - **Interaction** between **CR** and interstellar **gas** (pion decay and bremsstrahlung), and **radiation fields** (ICS).



Astro zoo in gamma-ray

- **Point sources 2FGL** (Fermi Coll. Astrophys.J.Suppl. 199 (2012) 31)

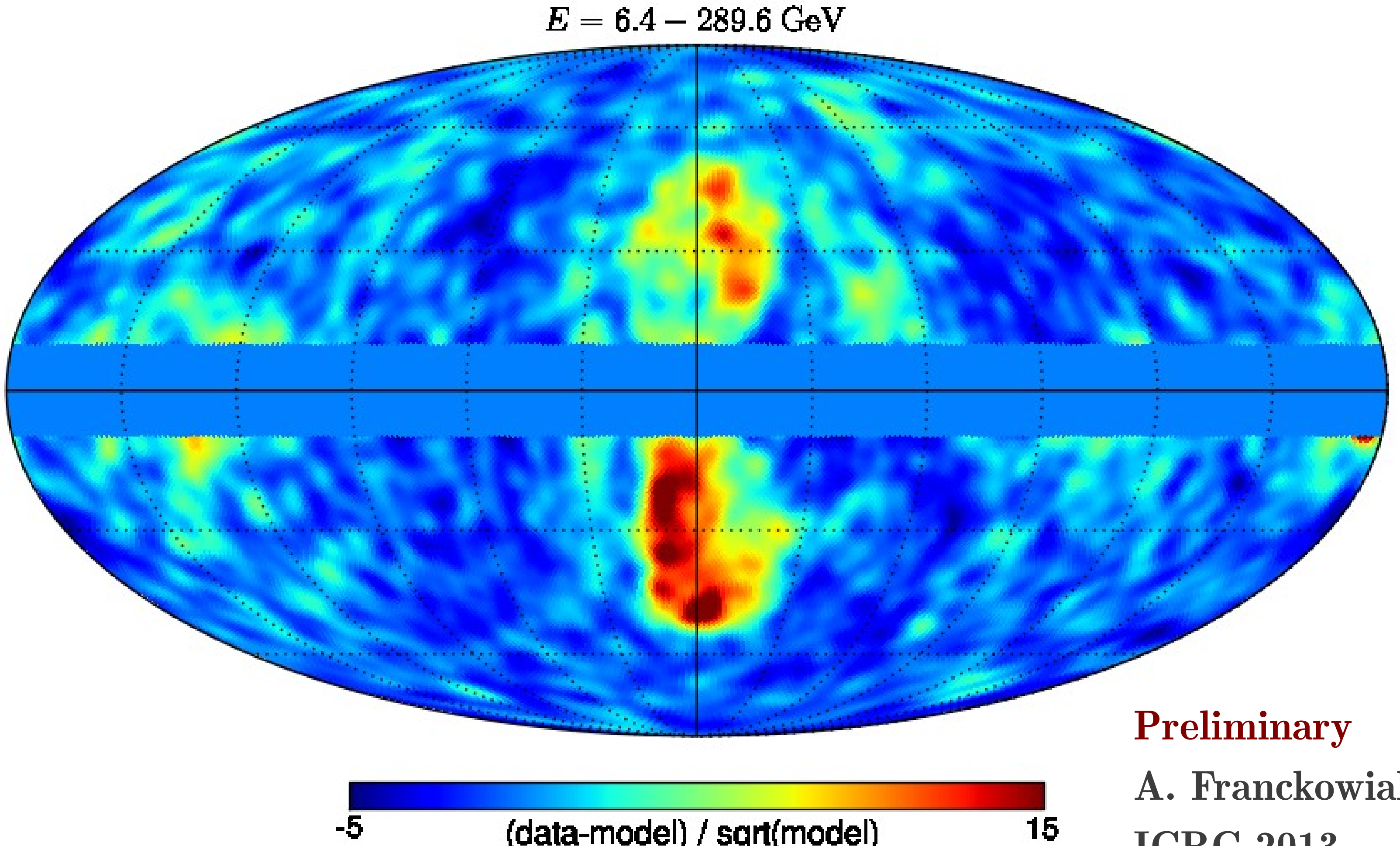


Astro zoo in gamma-ray

- **Point sources 2FGL**
- **Caveats:**
  - **Point sources** characteristics **depend on the diffuse model** used in their extraction
  - Some diffuse emission regions (like in gas cloud regions) could be confused with point sources
  - Concentration of sources **in the inner Galaxy** creates confusion. Therefore it is **difficult to distinguish between point sources and diffuse emission**

Astro zoo in gamma-ray

- **Fermi bubbles**



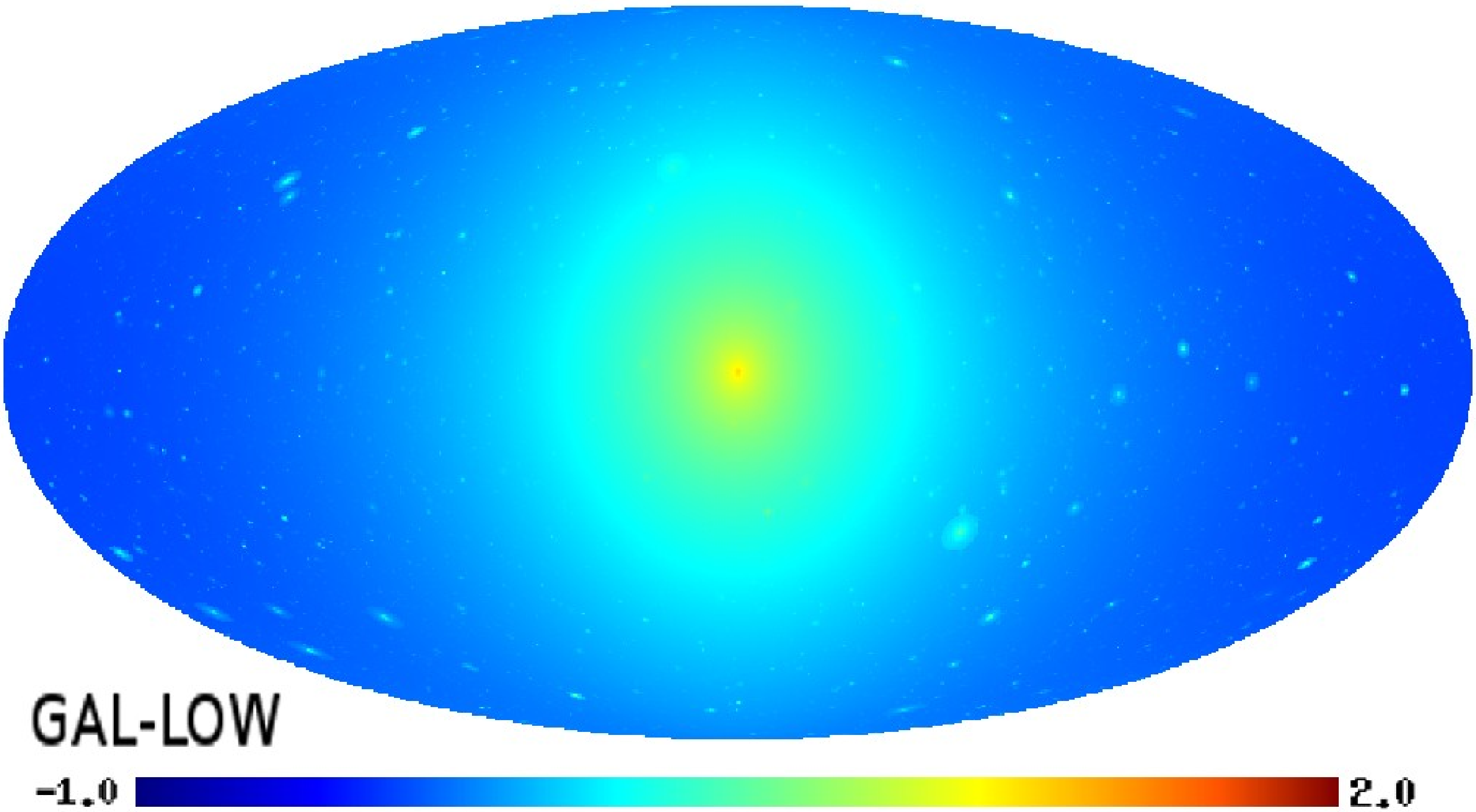
Preliminary

A. Franckowiak, ICRC 2013

Astro zoo in gamma-ray

- **Dark matter?**

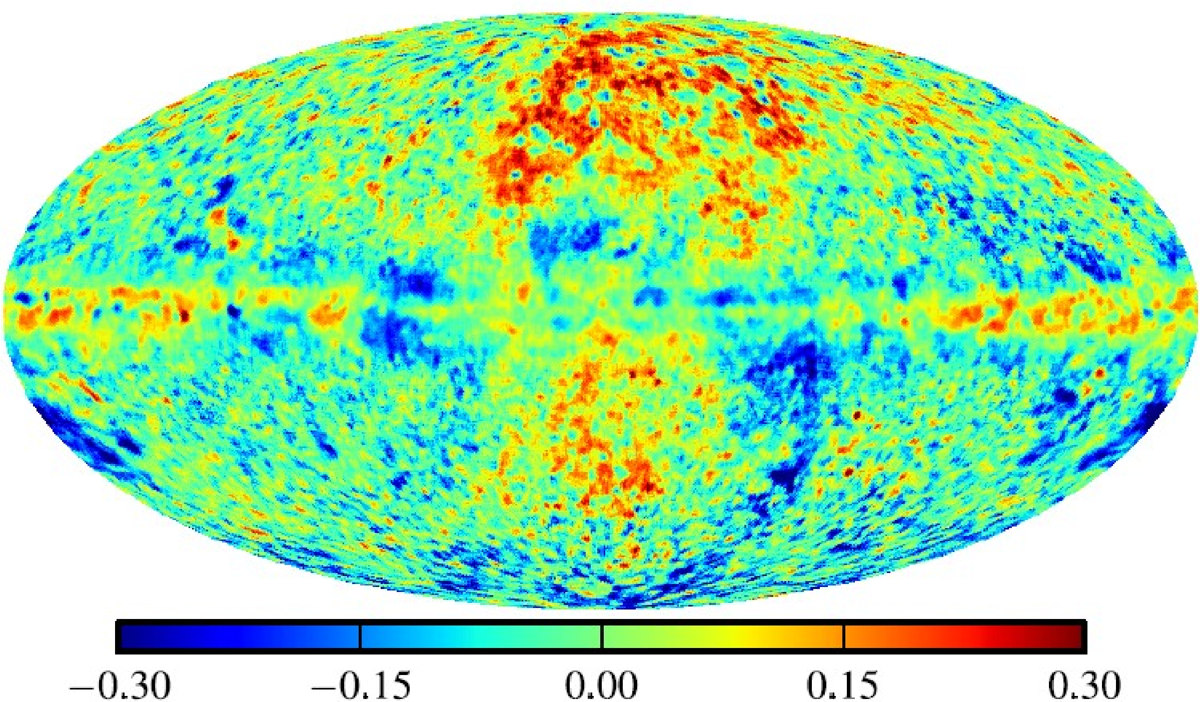
Fornasa et al, 2013, mnras, 429, 1529

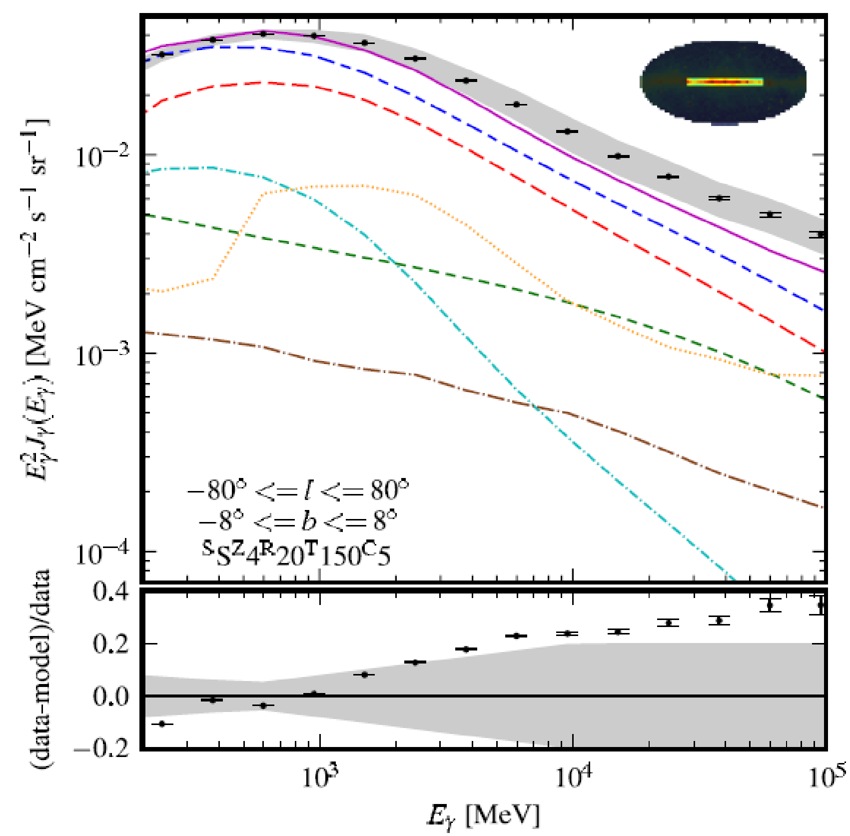


N-body simulations predict the Galactic Center as the brightest DM-induced gamma-ray source.

All sky modeling

- **CR origin, propagation, and properties of the interstellar medium** can be constrained by **comparing the data to predictions.**
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare with Fermi-LAT data (21 months, 200 MeV to 100 GeV, P6 DATACLEAN)
- **On a large scale the agreement between data and prediction is overall good, however some extended excesses stand out.**



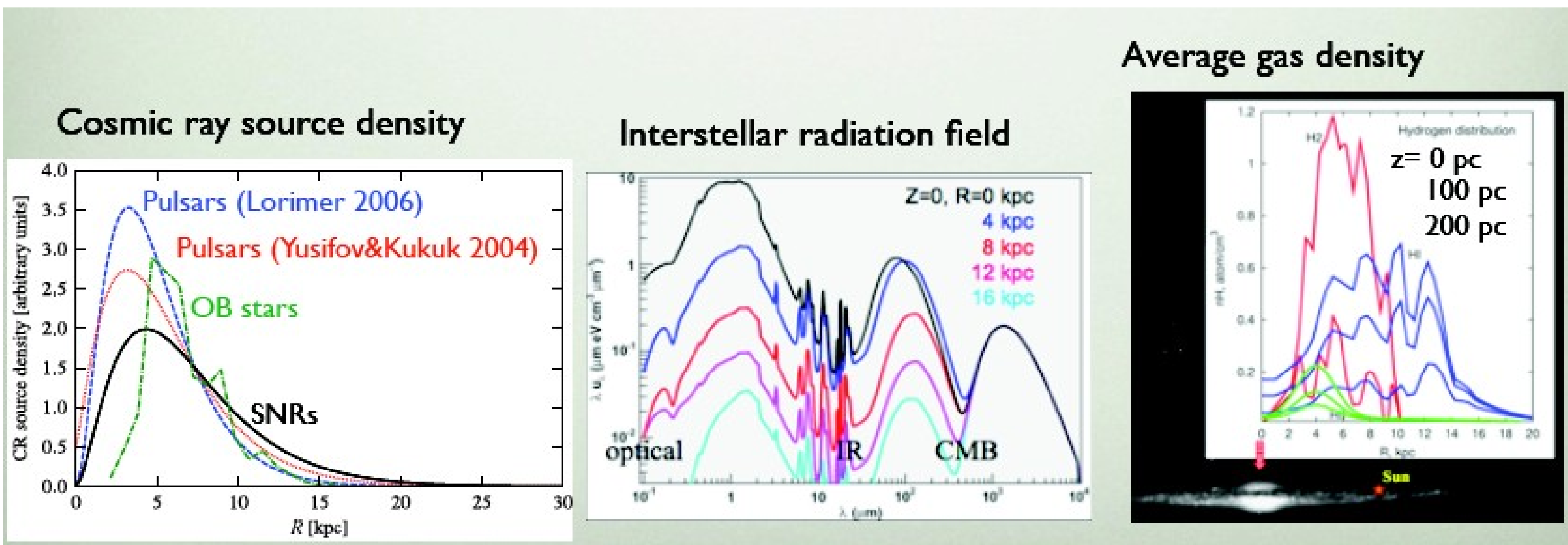


Fractional residual maps, (model − data)/data, in the energy range 200 MeV–100 GeV.

(Fermi-LAT Coll. The Ast. Journal, 750:3 (35pp), 2012)

Galactic Center region

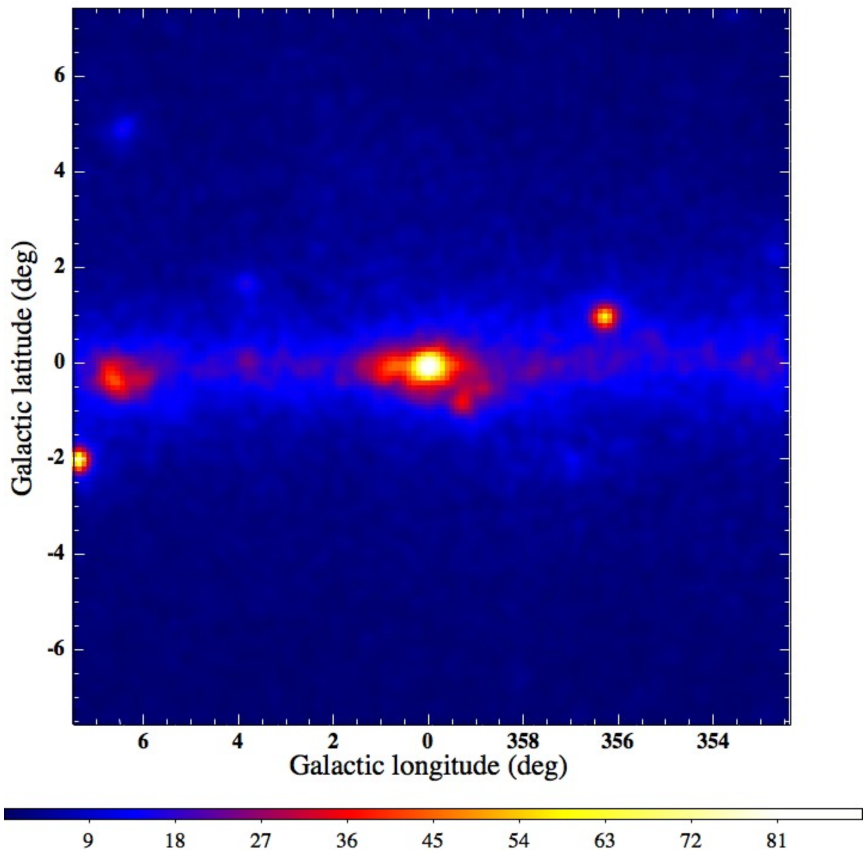
- Steep DM profiles predicted by CDM => Large DM annihilation/decay signal from GC!
- Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky:
  - **Source confusion:** many energetic sources near to or in the l.o.s. of the GC
  - **Diffuse emission modeling:** large uncertainties due to overlap of structures along the l.o.s. difficult to model



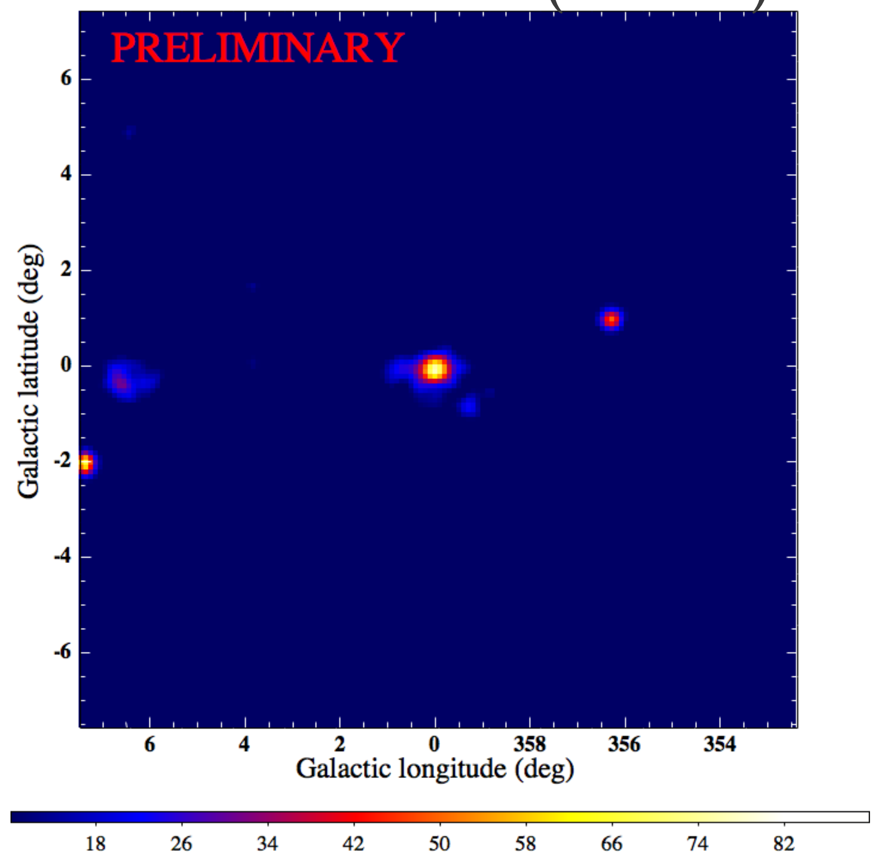
Fermi's View of the Inner Galaxy (15°x15° region)

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):

Data



Data – Model (diffuse)



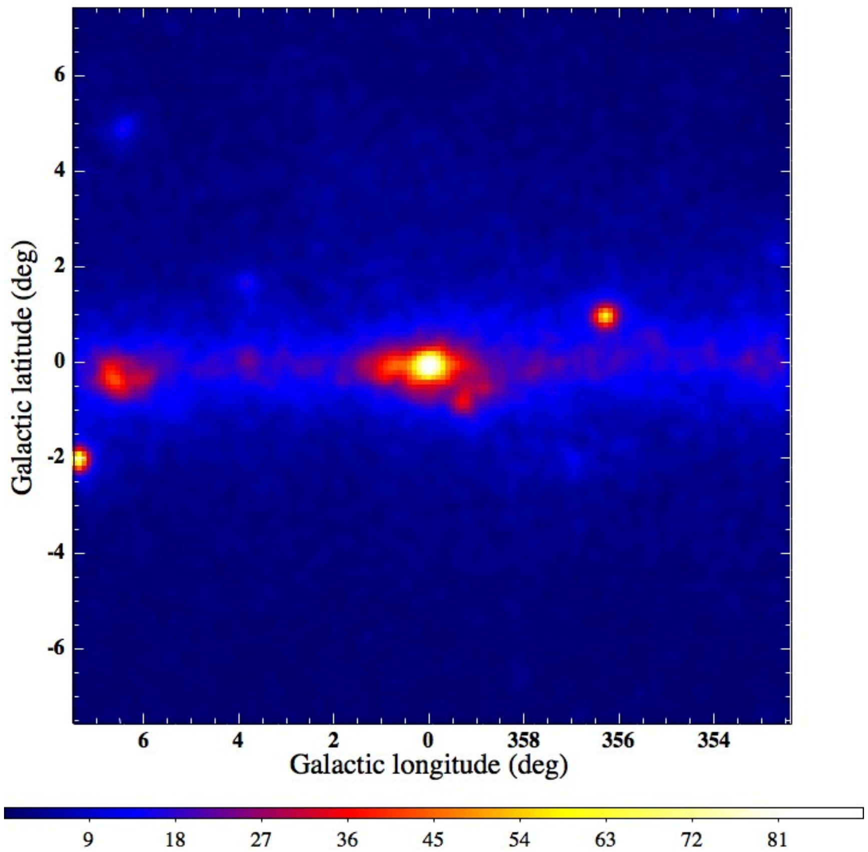
Galactic diffuse emission model: all sky GALPROP model tuned to the inner galaxy

Bright excesses after subtracting diffuse emission model are consistent with known sources.

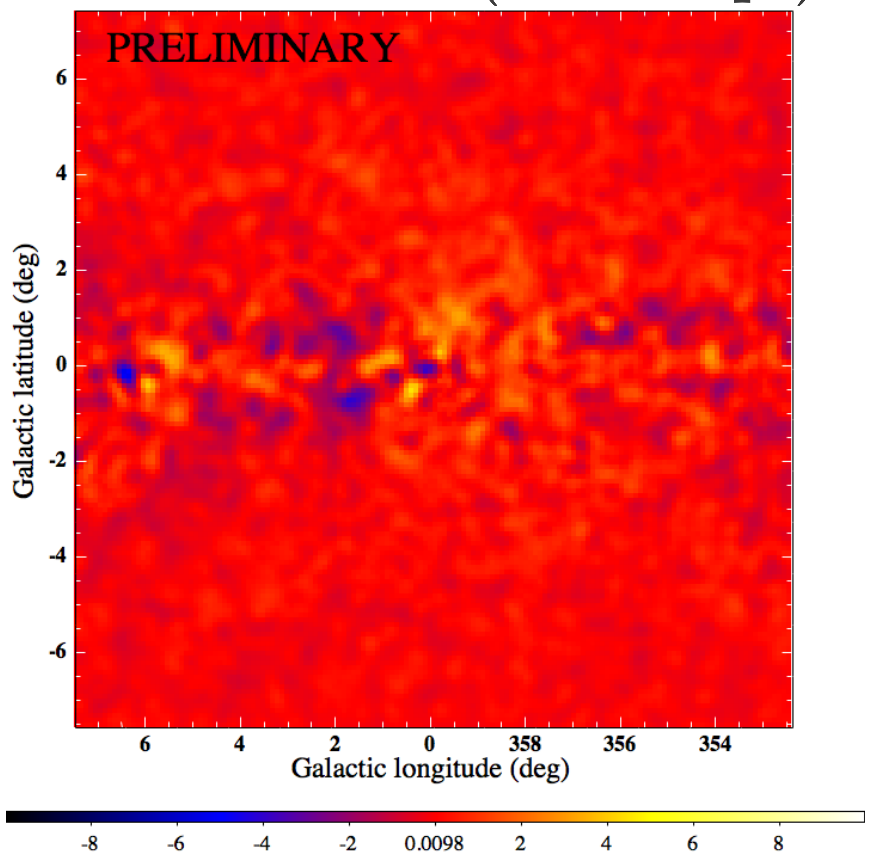
Fermi's View of the Inner Galaxy (15^{o}x15^o region)

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):

Data



Data – Model (diffuse+ps)



Diffuse emission and point sources account for most of the emission observed in the region.

Fermi's View of the Inner Galaxy (15^ox15^o region)

- **DM** would appear as an **exotic contribution** to the **conventional gamma-ray emitters.**
- **However**, our knowledge of **astrophysical background is uncertain**. This is currently a **big limitation** for the search of DM in the GC with gamma rays, which otherwise has a huge potential for discovery.
- **Nevertheless**, we can set **conservative constraints** on DM simply requiring that the **expected DM signal does not exceed the measurement** (*G. G-V et al. 2013. ArXiv:1308.3515 to appear in JCAP soon).*

DM-Induced Gamma rays. Aka, expected DM signal

The **gamma-ray flux from DM annihilation** has two main contributions: **prompt** photons and photons **induced via ICS**. The former are produced indirectly through **hadronization, fragmentation and decay of the DM annihilation products or by internal bremsstrahlung, or directly through one-loop processes.** The second contribution is originated from **electrons and positrons produced in the DM annihilations, via ICS off the ambient photon background.**

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{prompt} = \boxed{\sum_i \frac{dN_\gamma^i}{dE_\gamma} \frac{\langle\sigma_i v\rangle}{8\pi m_{DM}^2}} \boxed{\bar{J}(\Delta\Omega)\Delta\Omega}$$

Gamma-ray Flux

Particle Physics
Spectral information

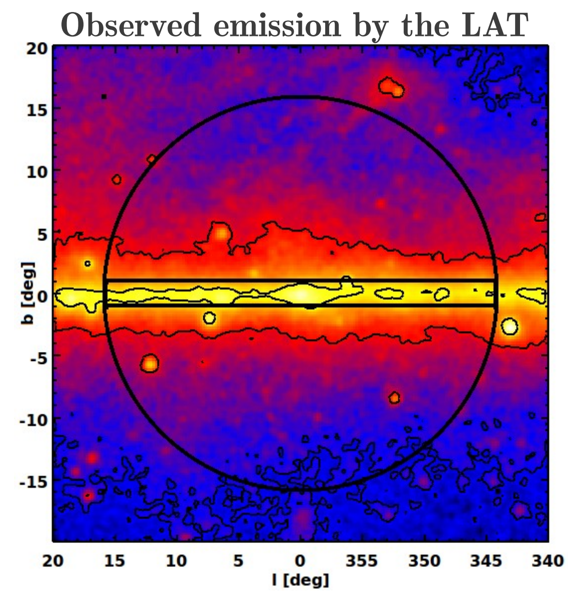
DM Distribution
(J-Factor)
Spatial information

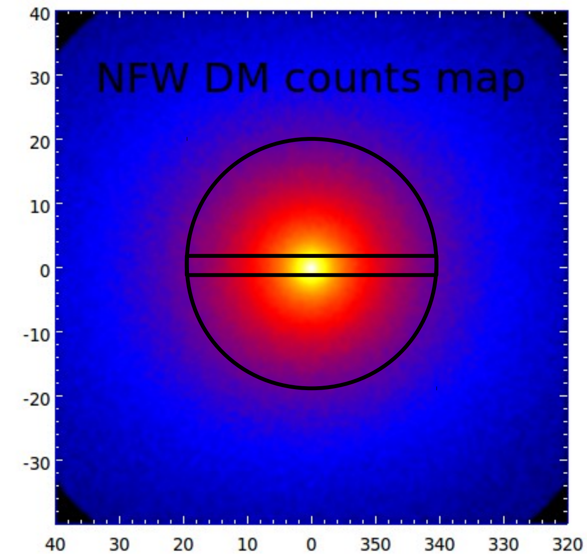
$$\bar{J}(\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\, dl$$

Methodology

- Our analysis is **conservative** since it simply requires that the **expected dark matter signal does not exceed the emission observed by the LAT** in an optimized region around the GC.

- Since **N-body simulations are not able to predict the DM distribution towards the GC**, we use four well motivated DM profiles tunned to observables of the Milky Way.





G. G-V et al. 2013. ArXiv:1308.3515

DM density profiles

We use realistic DM density profiles directly derived from MW observational data:

- NFW (Prada+04)

- Einasto (Catena&Ullio10).

- Burkert (inspired on Catena&Ullio10).

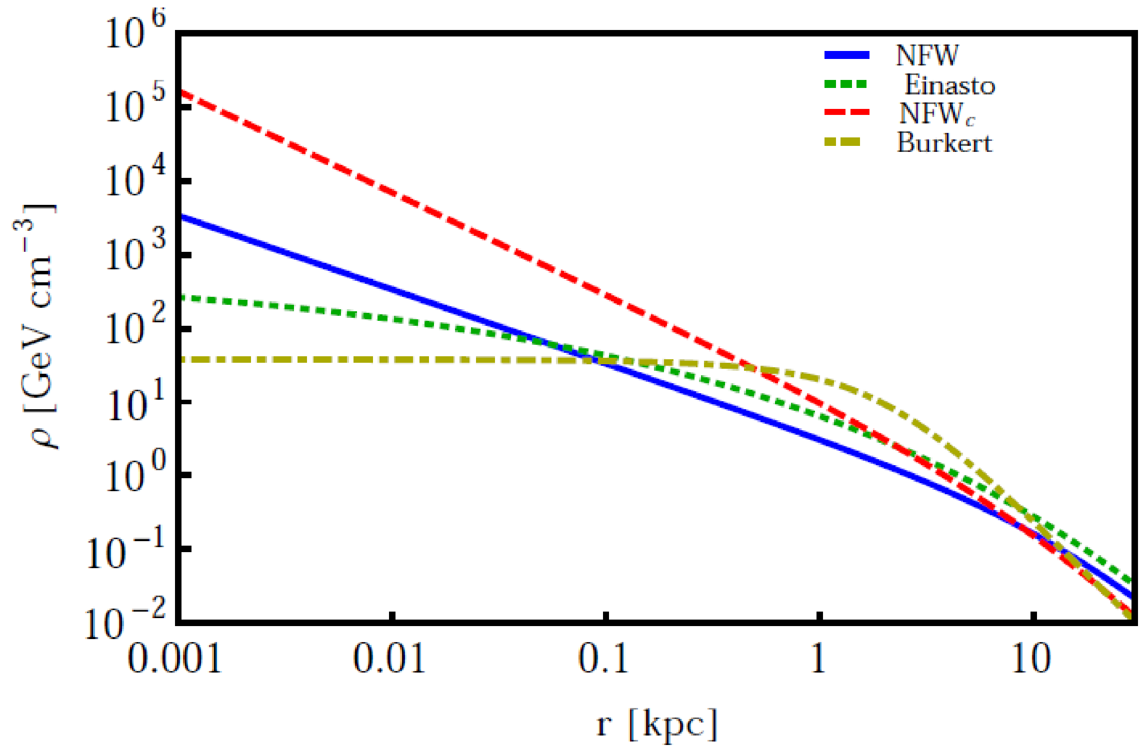
- Adiabatically compressed NFW (Prada+04).

Profile	α	β	γ	ρ_s [GeV cm^{-3}]	r_s [kpc]
Burkert	$--$	$--$	$--$	37.76	2
Einasto	0.22	$--$	$--$	0.08	19.7
NFW	1	3	1	0.14	23.8
NFW$_c$	0.76	3.3	1.37	0.23	18.5

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

$$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\rho_{\rm Burkert}(r) = \frac{\rho_s\ r_s^3}{(r+r_s)\ (r^2+r_s^2)}$$



G. G-V et al. 2013. ArXiv:1308.3515

Compressed profiles

- **DM-only simulations predict NFW or Einasto**, but ordinary matter (**baryons**) dominates the **central region of our Galaxy**. Thus, baryons may significantly **affect the DM distribution.**
- As **baryons collapse** and move to the center they **increase the gravitational potential,** which in turn forces the **DM** to contract and **increase its density**.
- The ***adiabatic compression*** is **confirmed by high-resolution hydrodynamic simulations** that self-consistently include complex baryonic physics (gas dissipation, star formation, supernova feedback…) [Gustafsson+06, Colin+06, Tissera+10, Gnedin+11]
- **Caution:** other baryonic effects may **flatten the DM cusp:**

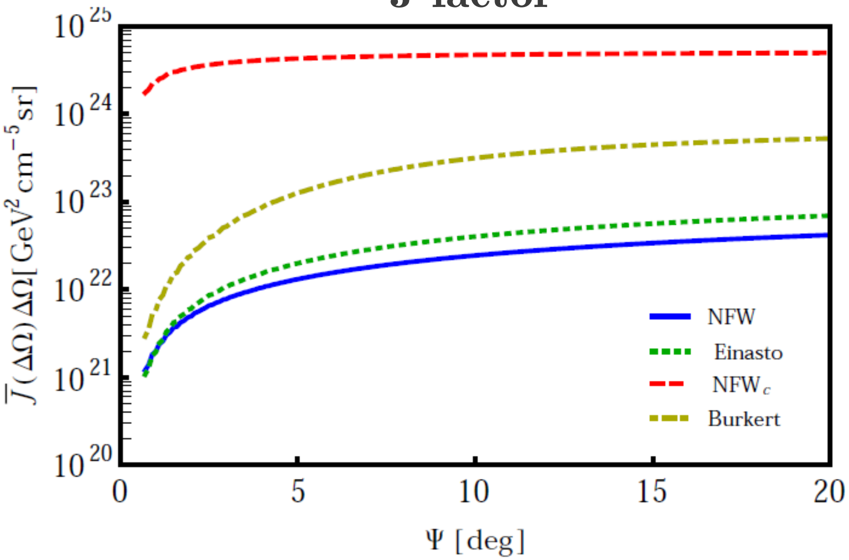
1. Strong bursts of star formation with a series of multiple explosions
2. inner material expelled, causing a DM density decrease

[Mashchenko+06, Mashchenko+08, Governato+10, Pontzen+12]

G. G-V et al. 2013. ArXiv:1308.3515

Baryons as seen by Spitzer in IR

J-factor



Particle physics models

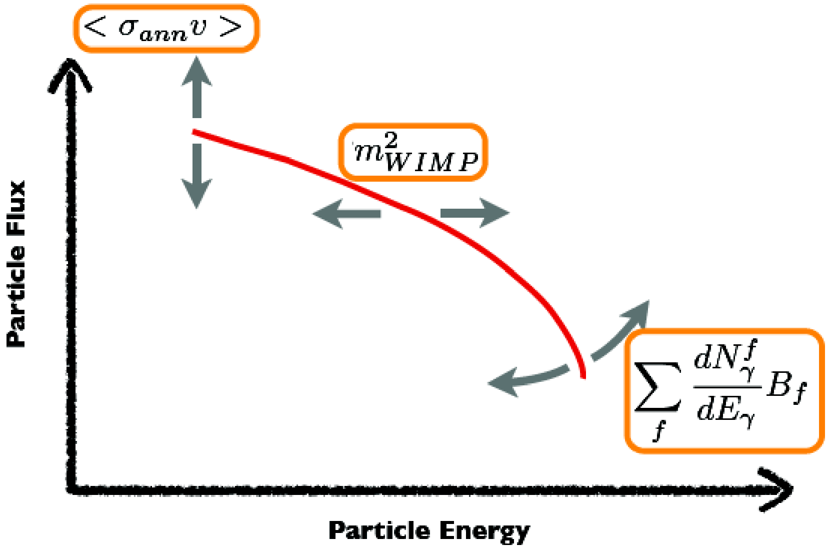
Particle physics factor:

Vanilla-like DM: ***Prompt, FSR, and ICS processes.***

PPPC 4 DM ID tables: **used for prompt and FSR.**

DM mass range: **5 GeV – 3 TeV**

Channels: **bb, $\tau^+\tau^-$, $\mu^+\mu^-$, W^+W^-**



Inverse Compton Scattering calculation:

For heavy DM it can be dominant over prompt in the *Fermi*-LAT energy range used.

Numerical calculation of galactic CR diffusion-loss equation.

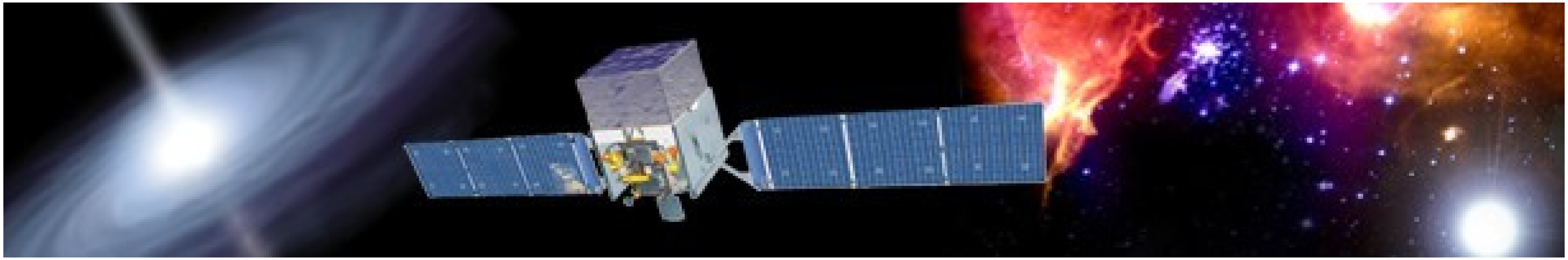
MIN, MED, MAX model + b(E) suitable for GC region.

MIN and MAX models do not imply minimal or maximal expected gamma-ray signal, respectively.

ICS is more significant for leptonic channels

G. G-V et al. 2013. ArXiv:1308.3515

Fermi-LAT data analysis



- Ferm-LAT: **2008 Aug. 4 – 2012 June 15.**
- Energy range: **1-100 GeV.**
- Class events: **Pass 7 V6 Ultraclean front conversion**. This choice reduces the cosmic-ray background contamination and takes advantage of a narrower PSF w.r.t. back-converting events
- Science tools: **V9r28**
- Region of analysis: **30 deg around the GC**
- We build a set of 0.2 deg/pixel resolution flux maps ***f(E,l,b)*** at different energies.

G. G-V et al. 2013. ArXiv:1308.3515

Fermi-LAT data analysis

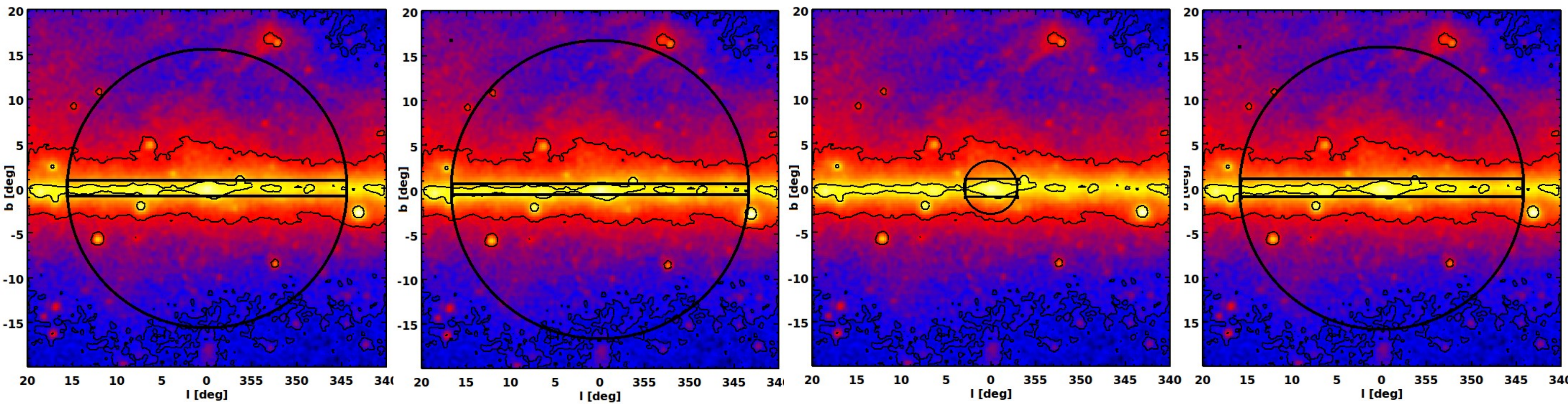
We choose the region of interes driven by a S/N optimization:

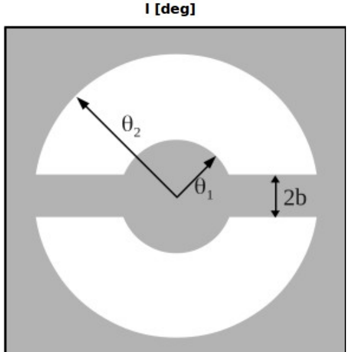
- *Signal*: J-factor maps for every DM density profile.

- *Noise*: Square root of the photon flux map.

ROI's optimal parameters are those that make the S/N the largest for every profile

Einasto **NFW** **NFW-compressed** **Burkert**

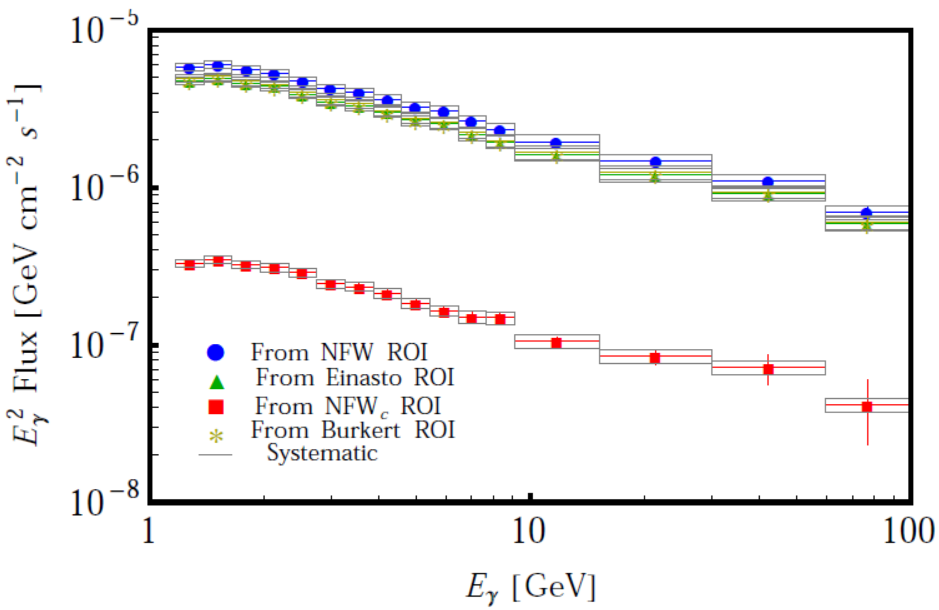




Profile	θ_1 [°]	θ_2 [°]	$\lvert b \rvert$ [°]	$\Delta\Omega$ [sr]	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]	Flux $(1-100$ GeV) [$\times 10^{-7}$ cm^{-2}s^{-1}]
Burkert	0.8	15.9	0.8	0.225	41.9	32.1 ± 0.3
Einasto	0.7	15.6	0.7	0.217	5.1	31.4 ± 0.3
NFW	0.6	16.7	0.6	0.253	3.3	38.0 ± 0.3
NFW$_c$	1.0	3.0	1.0	0.005	86.8	2.2 ± 0.1

G. G-V et al. 2013. ArXiv:1308.3515

Setting up constraints



Profile	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]
Einasto	5.1
NFW	3.3
NFW$_c$	86.8
Burkert	41.9

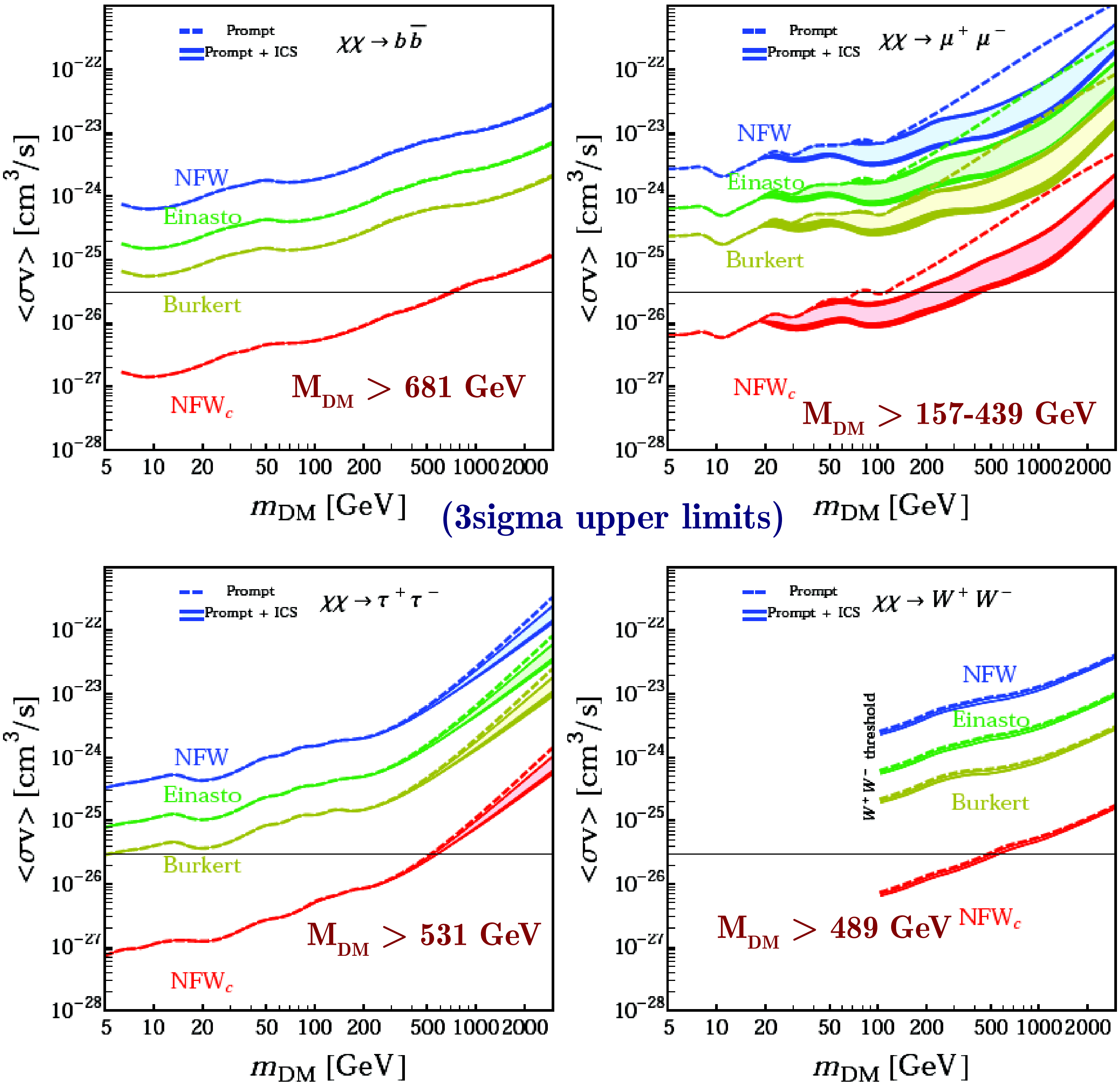
Energy spectrum as directly obtained from the data **VS.** **J-factors**

By comparing the inclusive energy spectrum extracted from the data for every ROI and the J-factors for every profile, we set DM constraints only requesting that the DM-induced gamma-ray emission *does not overshoot* the flux measurement at *3sigma* level.

G. G-V et al. 2013. ArXiv:1308.3515

Results:

G. G-V et al. 2013. ArXiv:1308.3515



DM Astro-Particle Future

- In the adiabatically contracted model, gas cools towards the center of halos and forms stars, pulling dark matter inward and increasing the central density.
- However, it has also long been known that simply including gas cooling within a cold dark matter universe may lead to catastrophic overcooling (White & Rees 1978)
- Some form of feedback energy is required to offset cooling so that the transformation of gas to stars is inefficient. Indeed, models of galaxy formation consistently show that significant outflows are necessary to match a wide range of galaxy properties.
- Such outflows may reverse the effects of adiabatic contraction, and expand the inner dark matter distribution.
- Realistic outflows need to be included in SPH simulations in order better understand the effect of baryons in the dark matter density profile.
- More and better Fermi-LAT data, Pass8 and new obs. estrategies (Luca Latronico's talk on Friday)

G. G-V et al. 2013. ArXiv:1308.3515

DM Astro-Particle Future

- We have analyzed **four annihilation channels** but **in general** the **final state will be a combination of them** e.g., in SUSY, the neutralino annihilation modes are **70% bb - 30% tau+tau-** for a Bino DM, and 100% W+W- for a Wino DM.
- Also, the value of **<σv> in the Galactic halo** might be **smaller than 3×10^{-26} cm^3 s^{-1}**, e.g., in SUSY, in the early Universe coannihilation channels can also contribute to <σv>. Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of sigmav in the Galactic halo, where the DM velocity is much smaller, and can escape this constraint.
- **Specific DM candidate signatures** in the gamma-ray sky must be **contrasted** with **observations** in order to get more **accurate model constraints.**

Conclusions

Several astrophysical processes at work in the crowded GC region and their uncertain make it extremely difficult to disentangle a DM signal from conventional emissions.

We derived constraints on the parameter space of generic candidates using Fermi-LAT inner Galaxy measurements.

We considered well motivated DM density profiles which are perfectly compatible with current observational data of the Milky Way.

A compressed DM profile allows to place much stringent u.l. then thermal <sigmav> excluded up to few hundreds GeV depending on channel

A large region of the vanilla WIMP parameter space models and contracted DM profiles are incompatible given the Fermi data.

Back up slides

Diffuse Emission Uncertainties

Use galprop cosmic ray propagation/diffuse emission code

http://galprop.stanford.edu/index.php

- The code calculates the propagation of cosmic-rays, and computes diffuse γ-rays emission in the same framework. Each run of the code is governed by a configuration file. Thus, each run of the code corresponds to a potentially different “MODEL”.

Diffuse Emission Uncertainties

- The GALPROP code uses realistic astrophysical inputs together with theoretical models. Each run needs a specific set of those parameters.

- The gas-related γ-ray intensities calculated from the emissivities using the column densities of HI LAB survey and composite CO survey for Galactocentric rings.

- The inverse Compton scattering is treated using the formalism for an anisotropic radiation field developed by Moskalenko & Strong (2000a) and uses a model for ISRF.

- Other parameters for a given GALPROP model are the CR primary injection spectra, the spatial distribution of CR sources, the size of the propagation region, the spatial and momentum diffusion coefficients and the Galactic magnetic field model.

- **All this parameters have uncertainties associated.**

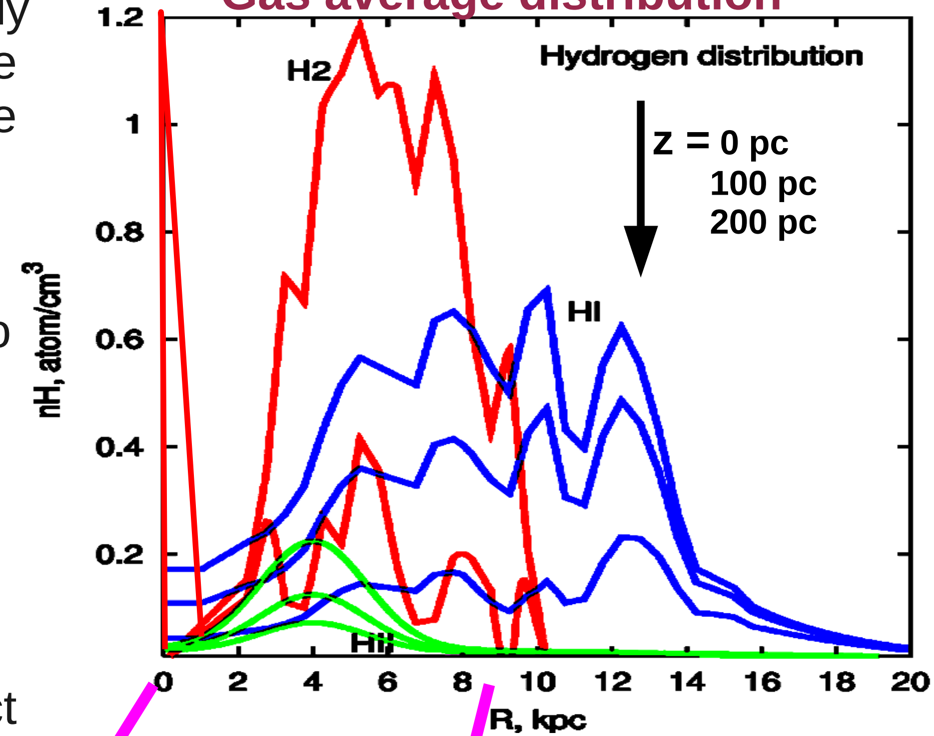
Diffuse Emission Uncertainties

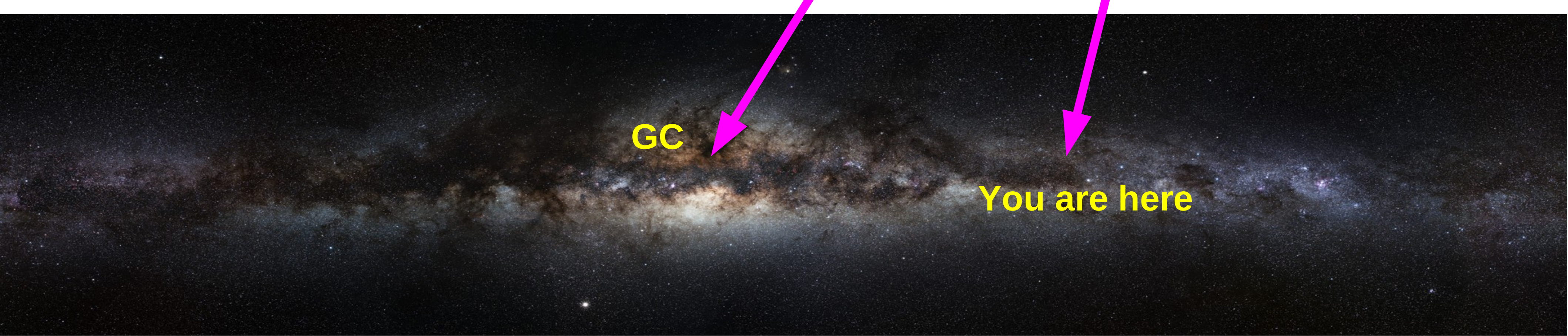
- Molecular Hydrogen H2. Concentrated mostly in the plane. The main tracer is CO. Distance information from velocity and a rotation curve is used to assign the gas to galactocentric rings.

- The standard method of assigning velocity to distance breaks down toward the galactic center. More details in next slides.

- The Xco factor to convert CO to H2 column density is believed to vary as a function of the galactocentric radius. However, the exact form of the variation is not well know.

Gas average distribution





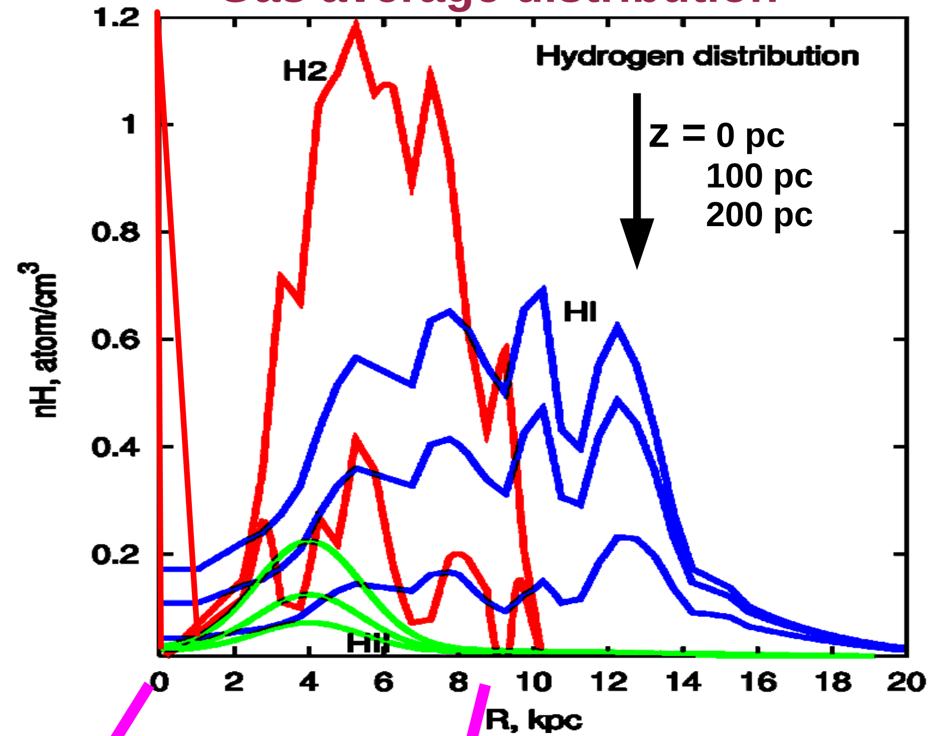
Diffuse Emission Uncertainties

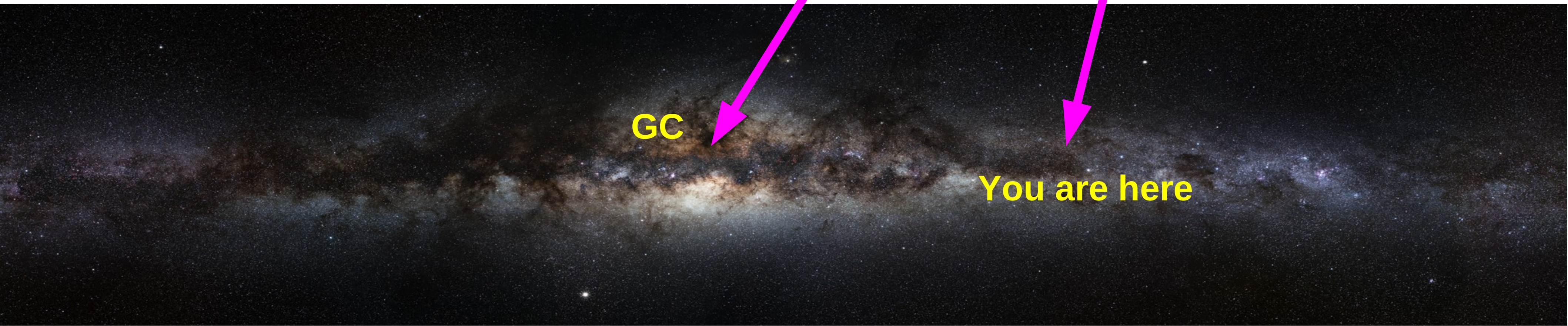
- Atomic Hydrogen HI. The 21 cm line HI used is from Kalberla et. al. (2005). As for H2 distance information from velocity and a rotation curve is used to assign the gas to galactocentric rings.

- The main uncertainty come from the spin temperature Ts. We adopt a single Ts.

- HI is a mixure of various phases, observations of Ts show it to vary from 10s of K up to 1000s of K, so that the adoption of a single Ts is in any case an approximation.

Gas average distribution

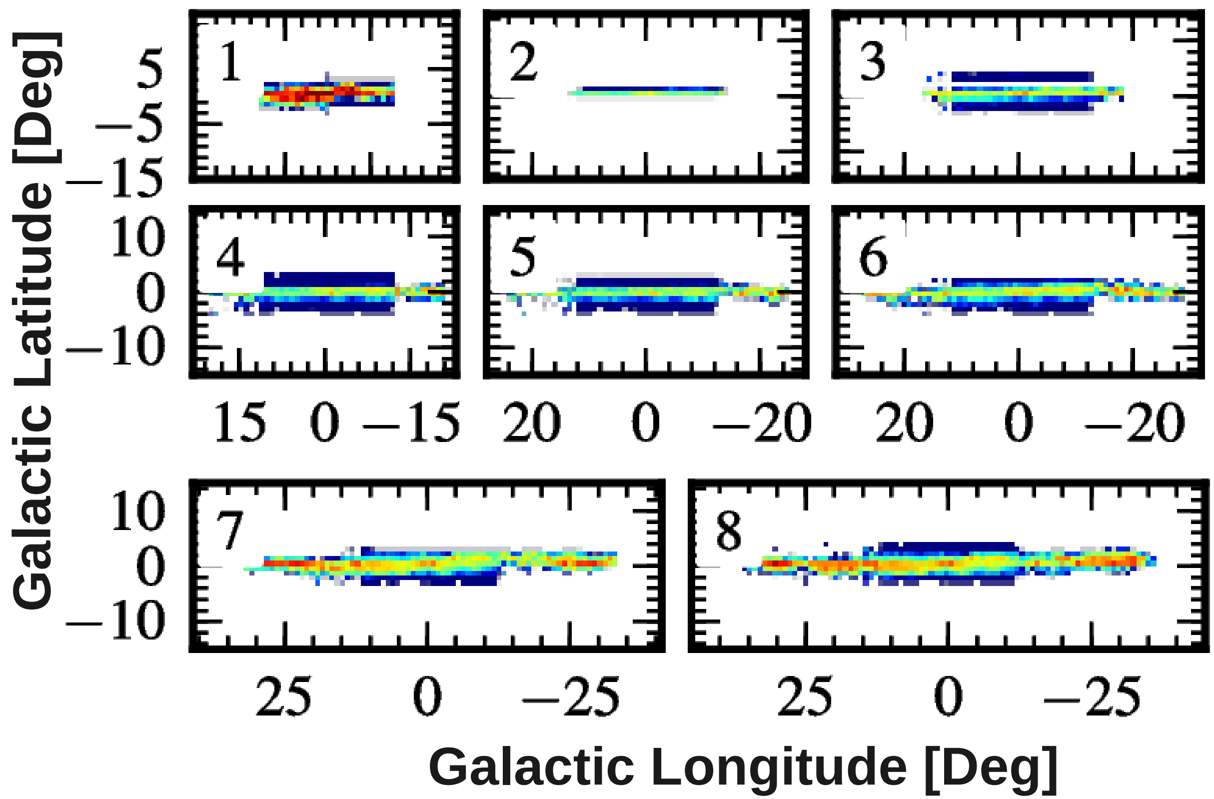




Diffuse Emission Uncertainties

- Galactocentric rings toward the galactic center. The kinematic resolution of the method used to relate velocity and distance vanishes for directions near the Galactic center.
- We linearly interpolate each annulus independently across the range |l|<10 to get an estimate of the radial profile of the gas.
- The innermost annulus is entirely enclosed within the interpolated region, necessitating an different method to estimate its column density.

CO(J=1→0) galactocentric rings



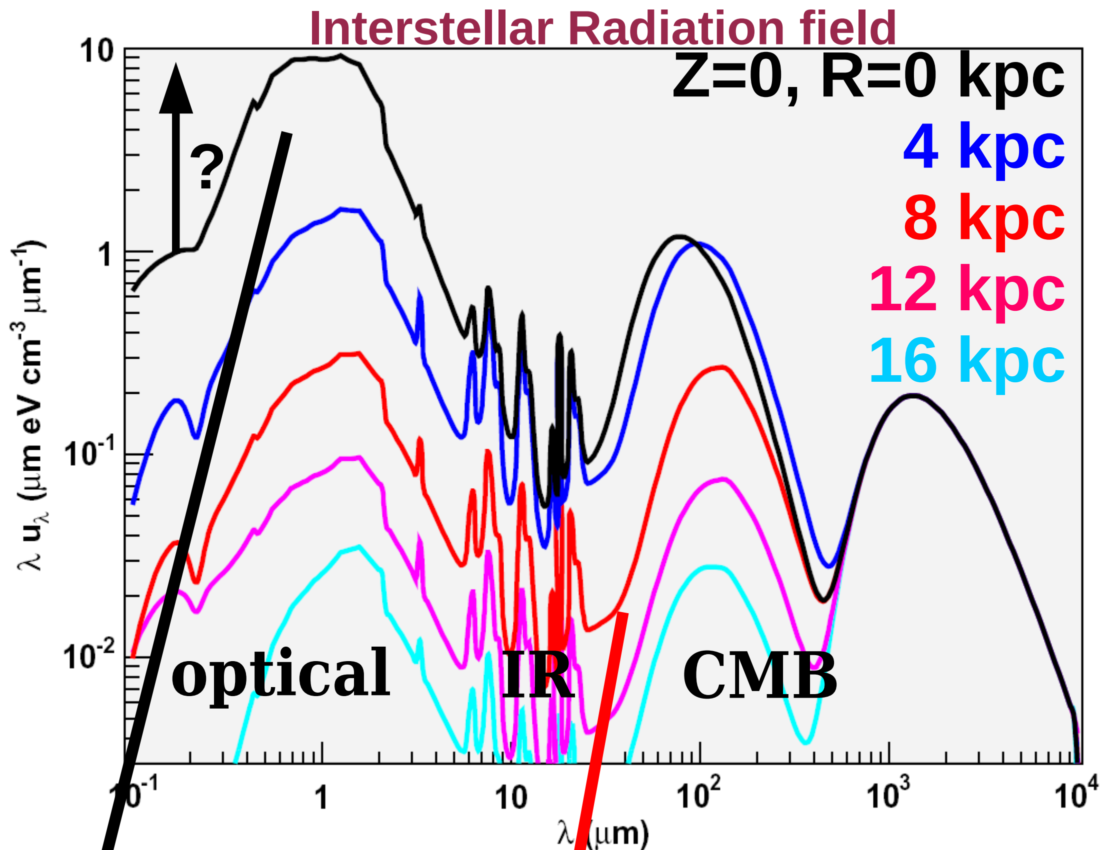
- For H I the innermost annulus contains 60% more gas than its neighbouring annulus. This is a conservative number
- For CO, we assign all high velocity emission in the innermost annulus.

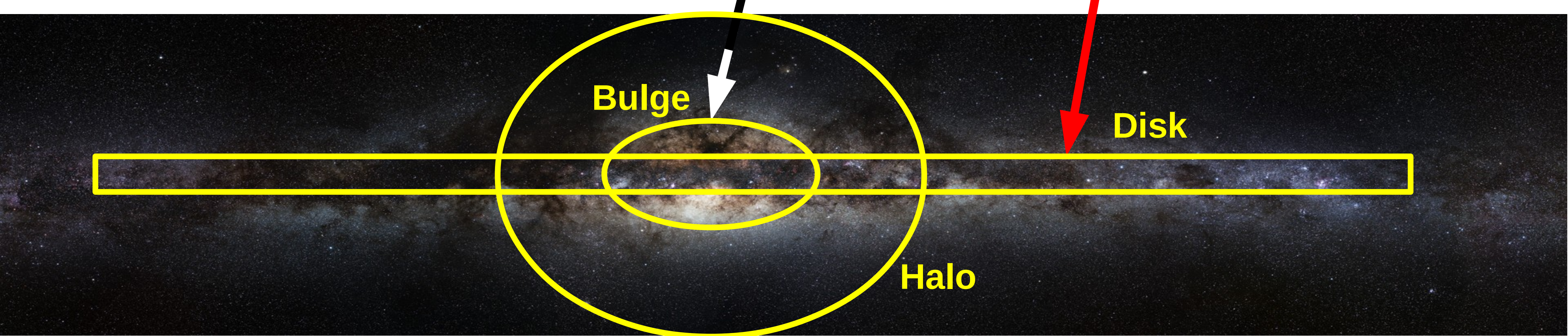
Diffuse Emission Uncertainties

- ISRF Interstellar radiation field. Emission from stars, and the scattering, absorption, and re-emission of absorbed starlight by dust in the ISM.

- The FRaNKIE radiation transport code (Porter et. al. 2008) is used to model the distribution of optical and infrared (IR) photons throughout the Galaxy.

- The main uncertainty is the overall input stellar luminosity and how it is distributed amongst the components of the model (bulge, thin and thick disk, and halo)



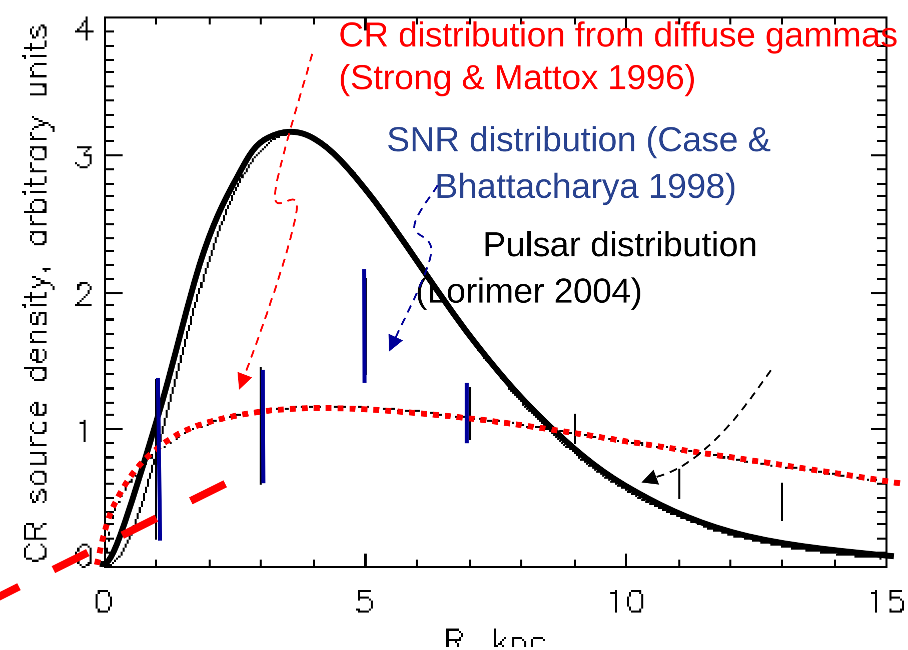


Diffuse Emission Uncertainties

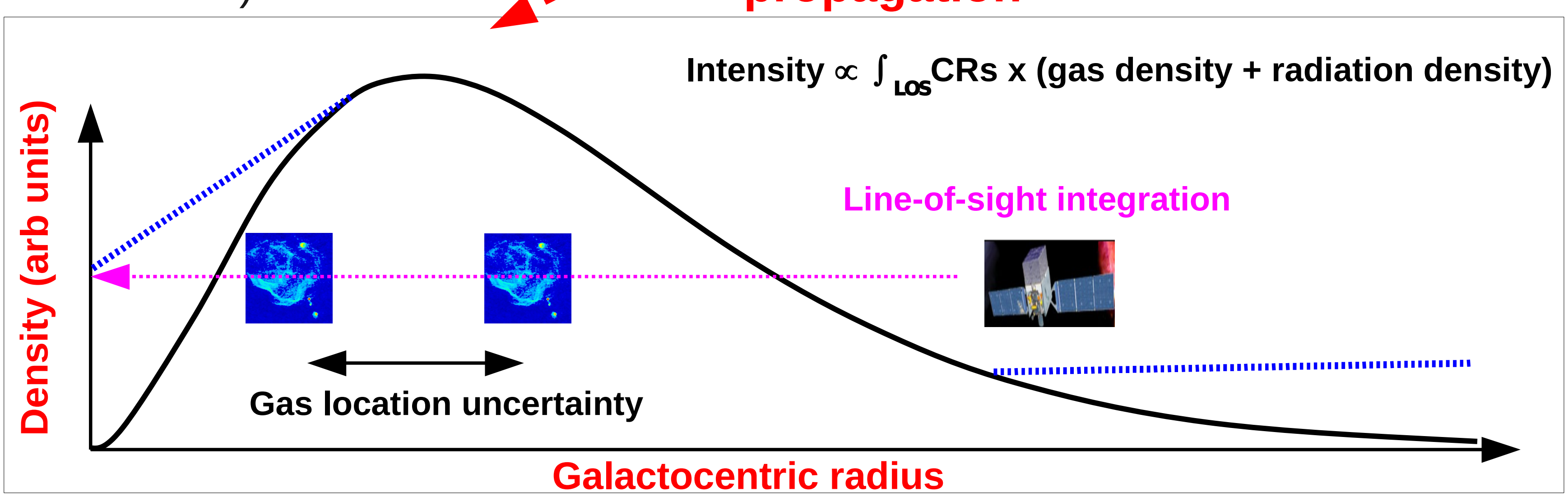
- Cosmic-Ray injection and propagation. SNRs are widely accepted as the main sources of CRs. However, their distribution is not well determined.

- Pulsars are SN explosion end state and its distribution is better determined than SNRs, but still, it suffers from observational bias.

- CR propagation is not well known and its uncertainties involve spectra injection, transport parameters, halo size, etc. (see Dr. Johannesson talk at TeVPA 2011)



'propagation'



Previous Galactic center analysis

- In Vitale & Morselli (2009) arXiv:0912.3828v1 a different analysis of the GC region was presented.
- This analysis is for 11 months, the region of interest is 7x7deg @ GC, pass 6 selection was used
- This analysis is for 11 months, the region of interest is 7x7deg with centre in Sgr A*. P6_v3 IRFs were used, only diffuse class events.
- All the point sources in the area have been fitted individually.
- The model contained a Galactic Diffuse gamma-ray model from GALPROP code and an Isotropic component.
- A residual gamma-ray emission was left, not accounted for by the above models