ARE WE SEEING DARK MATTER WITH THE FERMI-LAT IN A REGION AROUND THE MILKY WAY CENTER?

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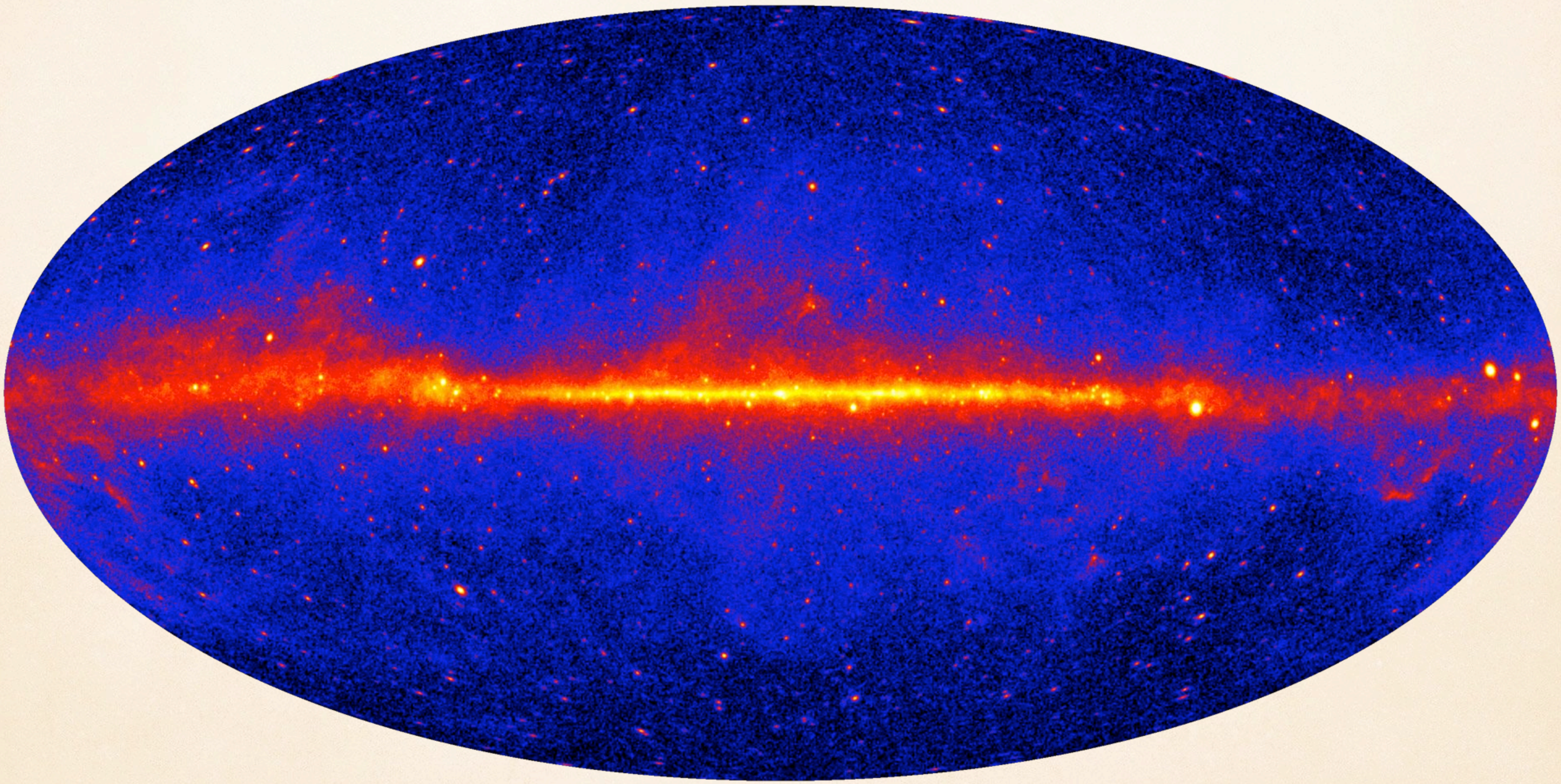
OUTLINE

- The diffuse γ-ray sky
- Dark matter-induced γ-ray emission
- Fermi view of the Galactic Center
- Disentangling a dark matter signal from the Galactic Center
- Cooking a model for the Galactic interstellar emission
    - Ingredients
    - Recipe I: cosmic-ray propagation codes
    - Recipe 2: templates
- Take home message

THE GAMMA-RAY SKY

Fermi-LAT, 4 years, energies > 1 GeV



THE GAMMA-RAY SKY

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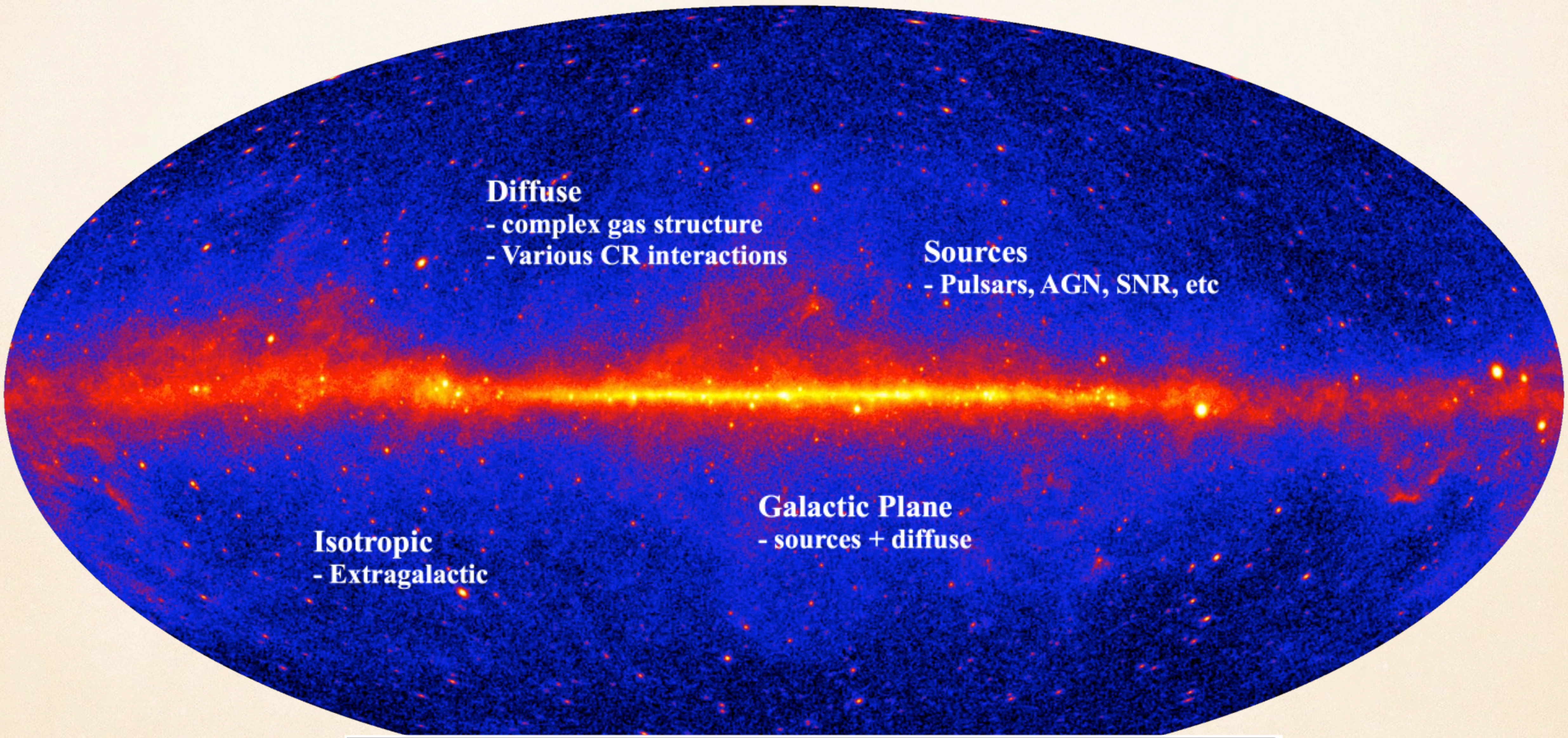
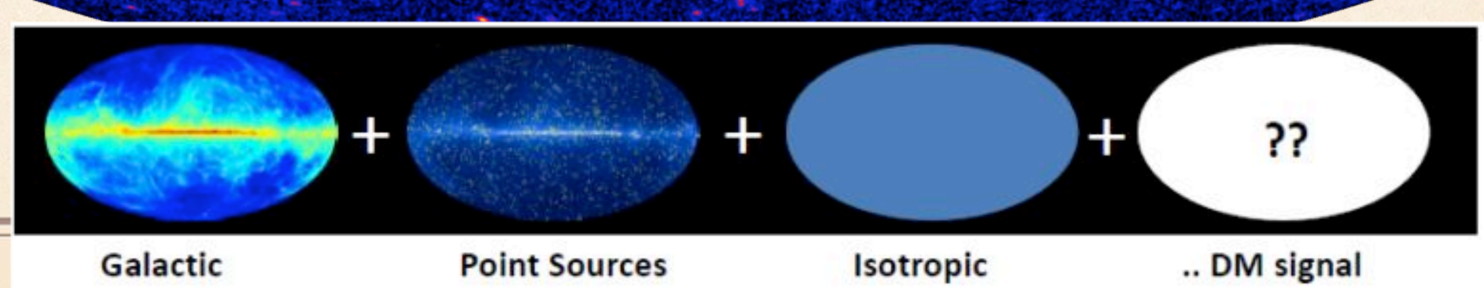
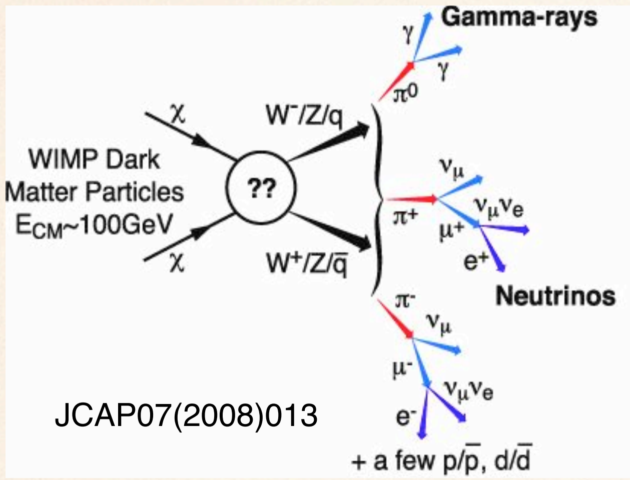
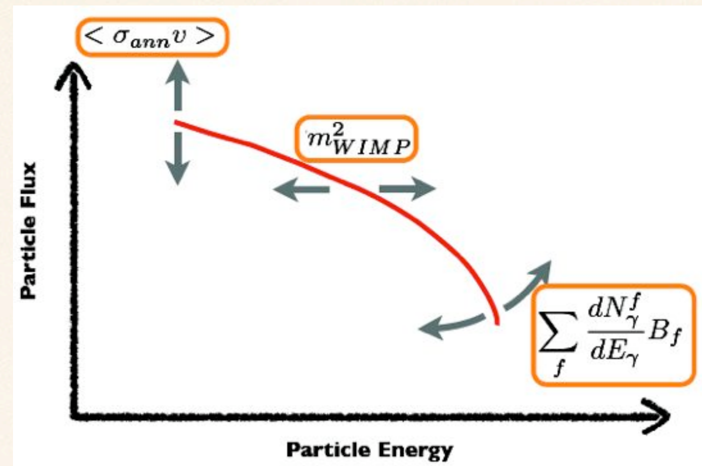
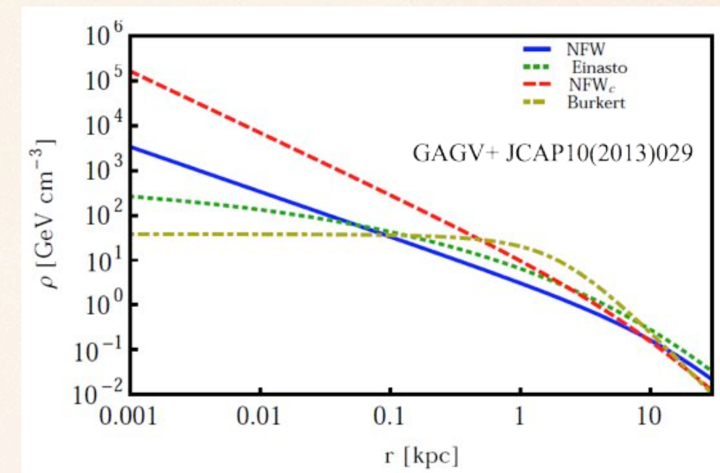




DM-INDUCED GAMMA RAYS







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

Particle Physics
Spectral information

DM Distribution
(J-Factor)
Spatial information

WIMP = Weakly Interacting Massive Particle

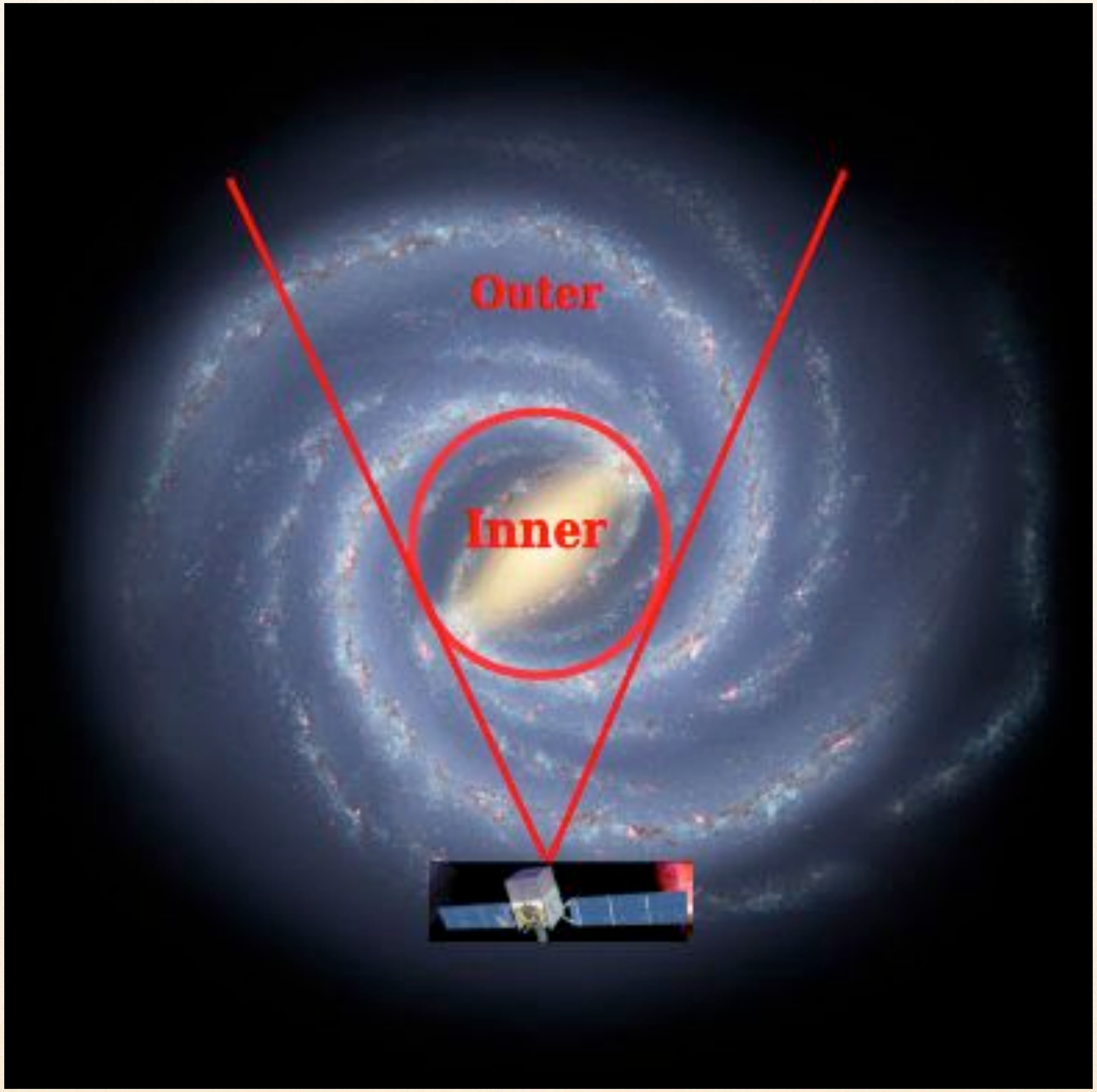
– DM candidate (e.g. neutralino)

– Believe the Milky Way sits in a large spherical "halo" or cloud of DM

- Non-relativistic (cold) DM

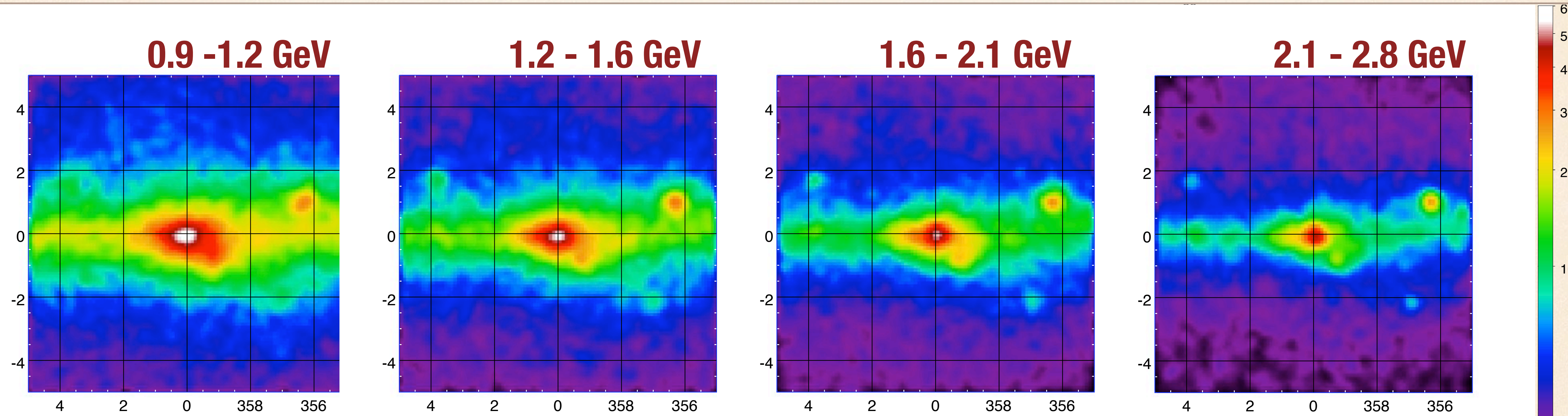
$$\bar{J}(\Delta\Omega) \equiv \frac{1}{\Delta\Omega} \int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\, dl$$

FERMI-LAT VIEW OF THE GALACTIC CENTER

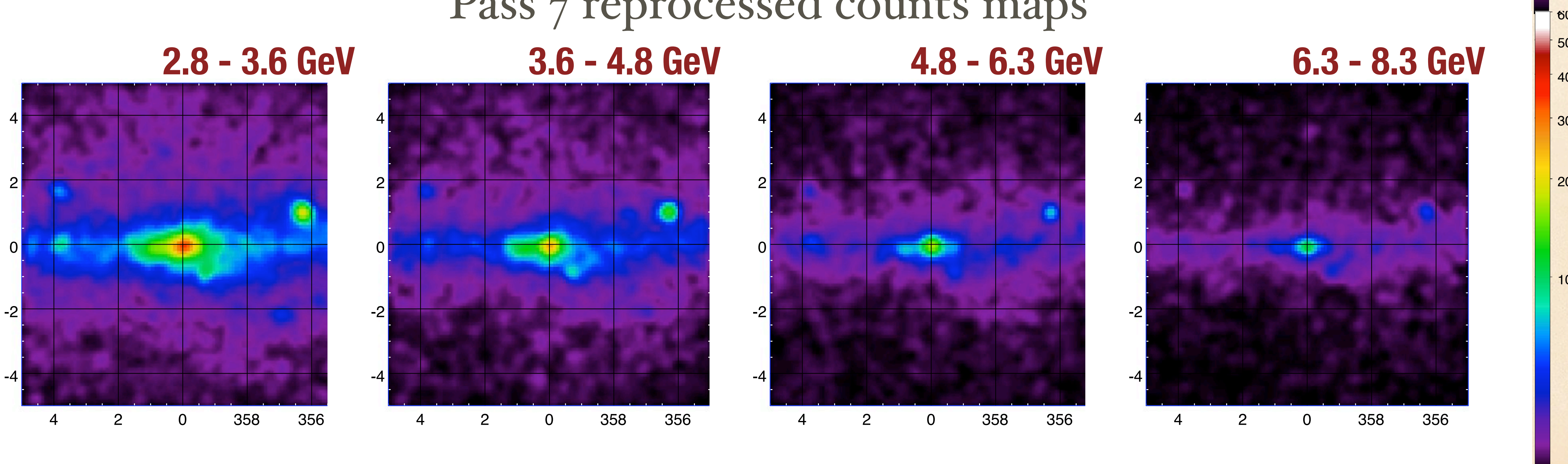


FERMI-LAT VIEW OF THE GALACTIC CENTER

Fermi-LAT, 5.5 years, energies > 1 GeV



Pass 7 reprocessed counts maps



DISENTANGLING A DM SIGNAL FROM THE GALACTIC CENTER

You are here

Trying to figure out what is here

DISENTANGLING A DM SIGNAL FROM THE GALACTIC CENTER

- DM-induced γ rays would appear as an exotic contribution in Fermi-LAT data of the Galactic Center
- We need to understand the non-exotic contributions, i.e. the background, in order to disentangle the possible DM-induced γ rays
- To set conservative constraints we don't need to understand the background, we can simply requiere that the expected DM signal does not exceed the measurement (GAGV+ JCAP 10(2013)029)

DISENTANGLING A DM SIGNAL FROM THE GALACTIC CENTER

Many independent groups have reported an extended source in the very Galactic Center

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope
Vincenzo Vitale, Aldo Morselli, for the Fermi/LAT Collaboration
Proceedings of the 2009 Fermi Symposium, 6 pages, eConf Proceedings C091122
arXiv:0912.3828

Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope
Dan Hooper (Fermilab & Chicago U., Astron. Astrophys. Ctr.), Lisa Goodenough (New York U.). Oct 2010. 21 pp.
Published in **Phys.Lett. B697 (2011) 412-428**

On The Origin Of The Gamma Rays From The Galactic Center
Dan Hooper (Fermilab & Chicago U., Astron. Astrophys. Ctr.), Tim Linden (UC, Santa Cruz & Fermilab). Oct 2011. 13 pp.
Published in **Phys.Rev. D84 (2011) 123005**

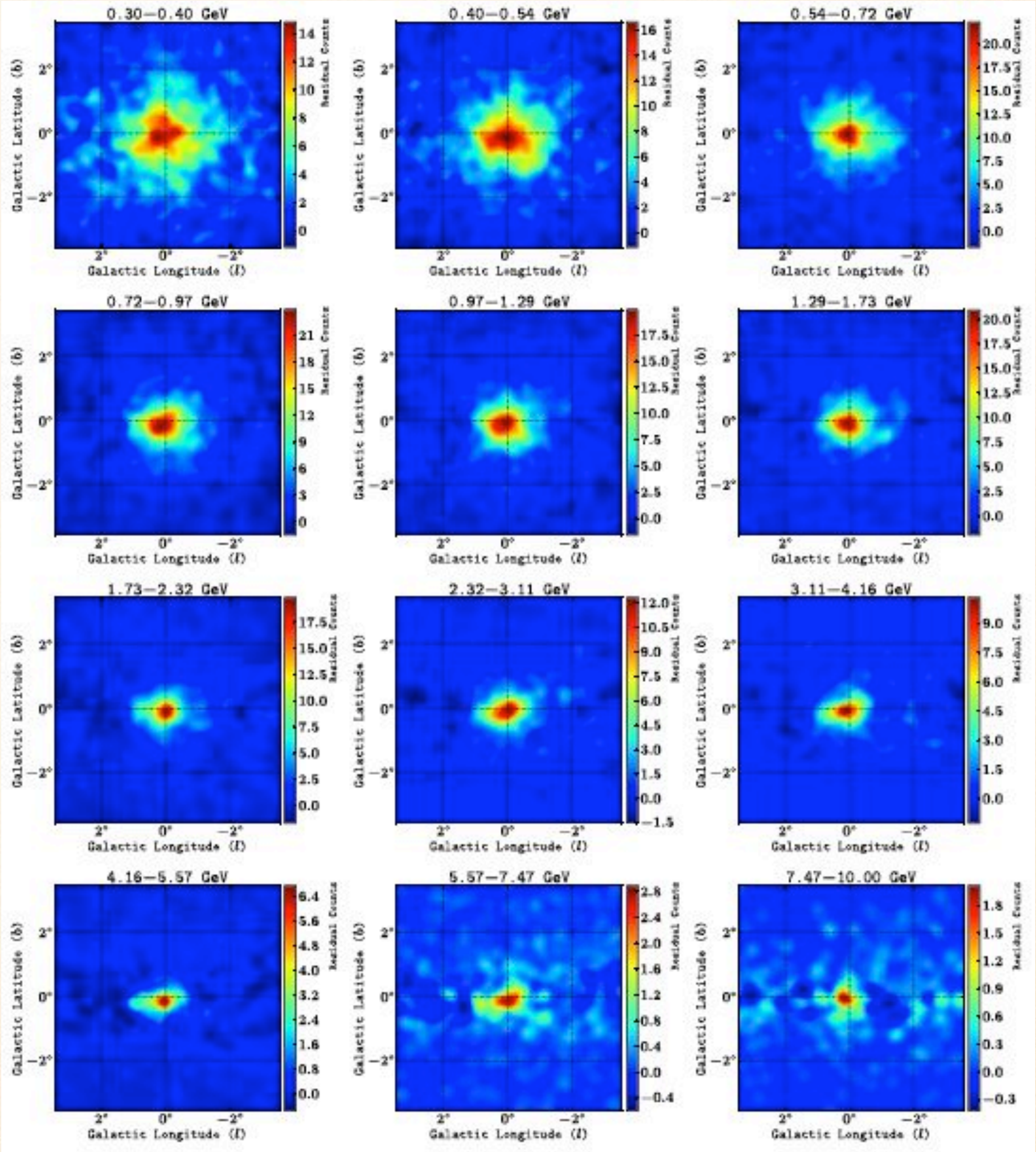
Detection of a Gamma-Ray Source in the Galactic Center Consistent with Extended Emission from Dark Matter Annihilation and Concentrated Astrophysical Emission
Kevork N. Abazajian, Manoj Kaplinghat (UC, Irvine). Jul 2012. 13 pp.
Published in **Phys.Rev. D86 (2012) 083511**

Dark Matter and Pulsar Model Constraints from Galactic Center Fermi-LAT Gamma Ray Observations
Chris Gordon, Oscar Macías (Canterbury U.). Jun 24, 2013. 20 pp.
Published in **Phys.Rev. D88 (2013) 083521**

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter
Tansu Daylan (Harvard U., Phys. Dept.), Douglas P. Finkbeiner (Harvard U., Phys. Dept. & Harvard-Smithsonian Ctr. Astrophys.), Dan Hooper (Fermilab & Chicago U., Astron. Astrophys. Ctr.), Tim Linden (Chicago U., KICP), Stephen K. N. Portillo (Harvard-Smithsonian Ctr. Astrophys.), Nicholas L. Rodd (MIT, Cambridge, CTP), Tracy R. Slatyer (MIT, Cambridge, CTP & Princeton, Inst. Advanced Study). Feb 26, 2014. 26 pp.
e-Print: **arXiv:1402.6703** [astro-ph.HE] | **PDF**

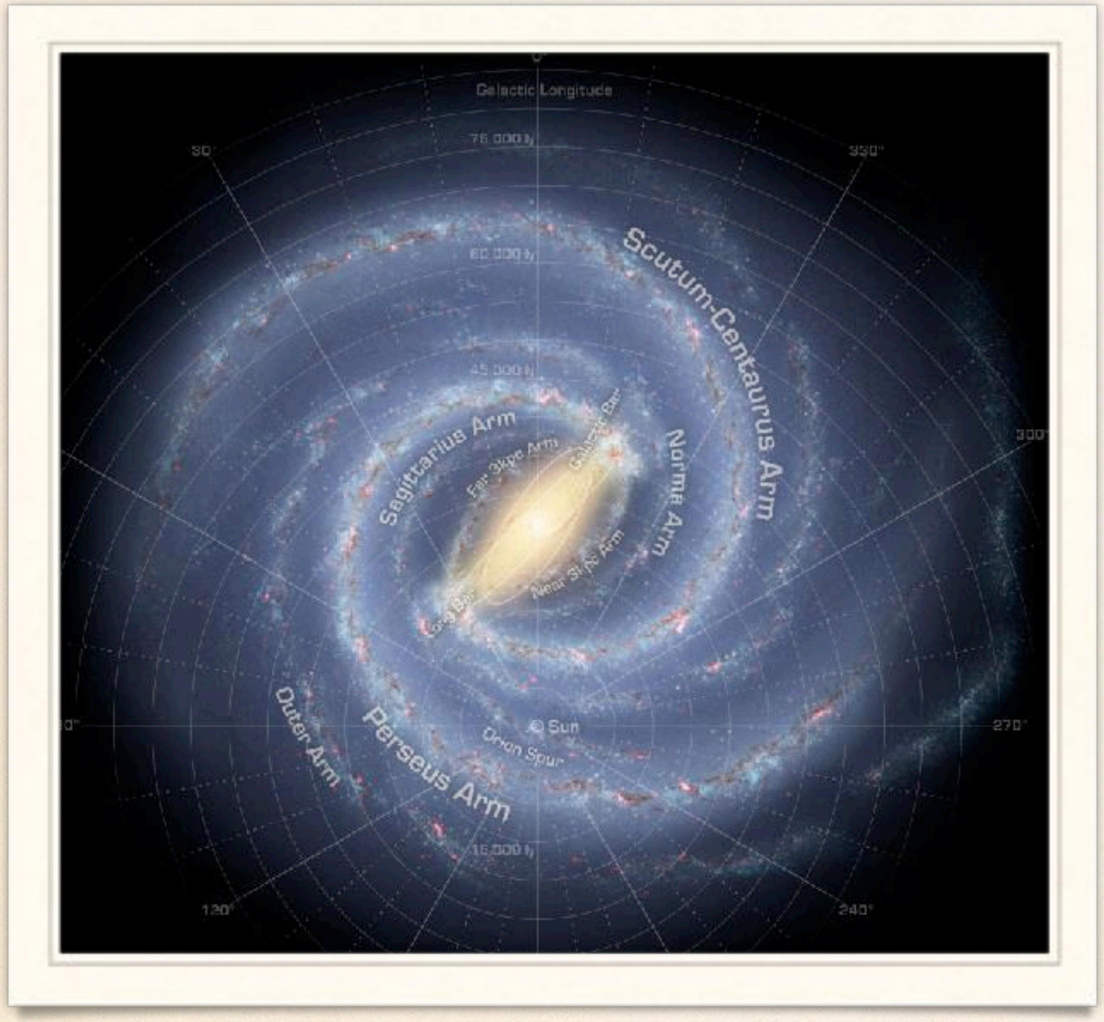
DISENTANGLING A DM SIGNAL FROM THE GALACTIC CENTER

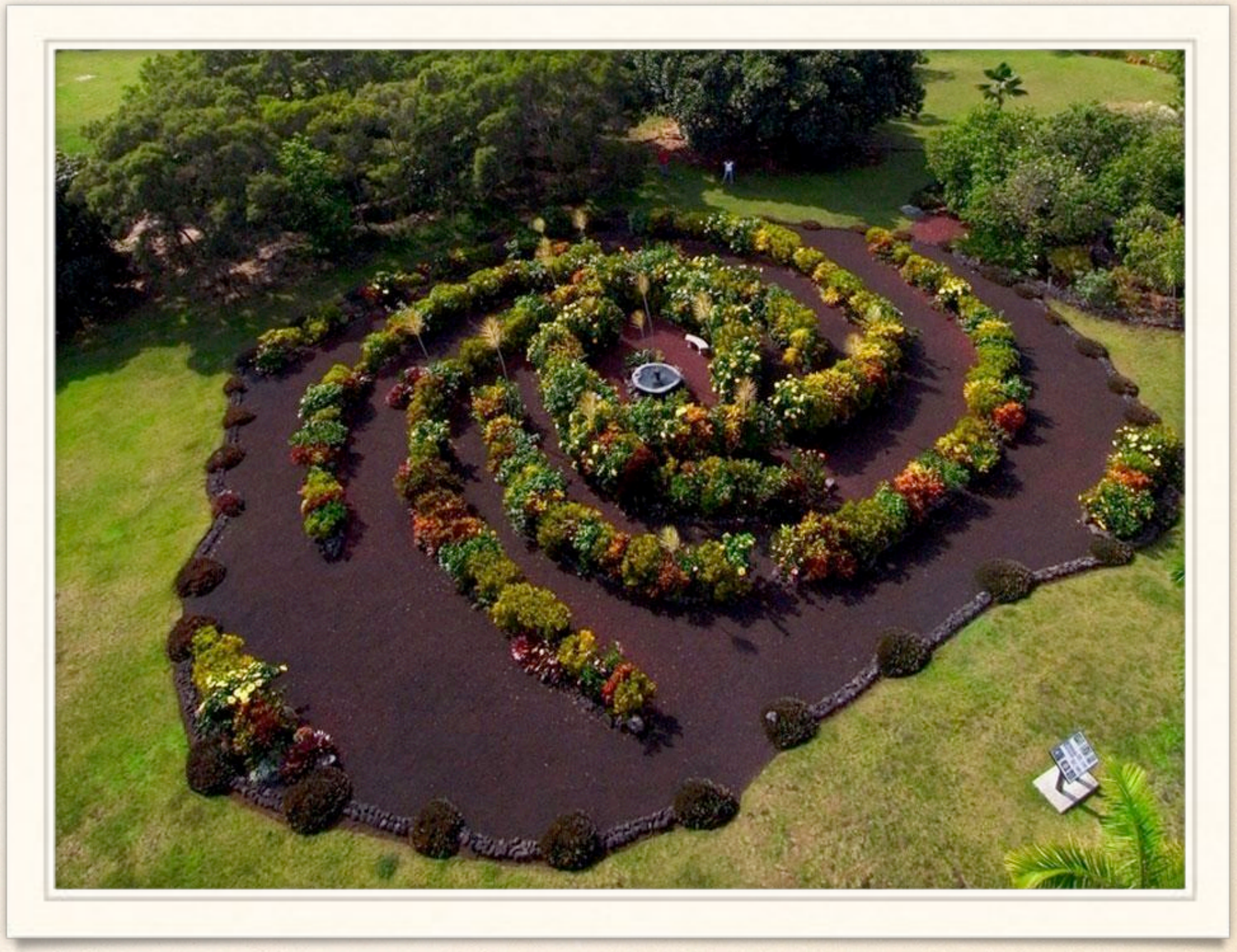
- This source may be due to DM particles annihilating, but other plausible phenomena may be responsible of this.
- First we need to establish the reality of the source, then its energy spectra and spatial distribution in order to understand its nature.
- All these analysis are based on the remotion of background models, diffuse interstellar emission and point sources (2FGL catalog P. L. Nolan *et al.* 2012 ApJS **199** 31), from the data.
- The diffuse models used are the ones recommended and provided by the Fermi-LAT collaboration http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
- In particular the latest model is explicitly not recommended for study extended emission in the Galactic Center region http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/FSSC_model_diffus_reprocessed_v12.pdf



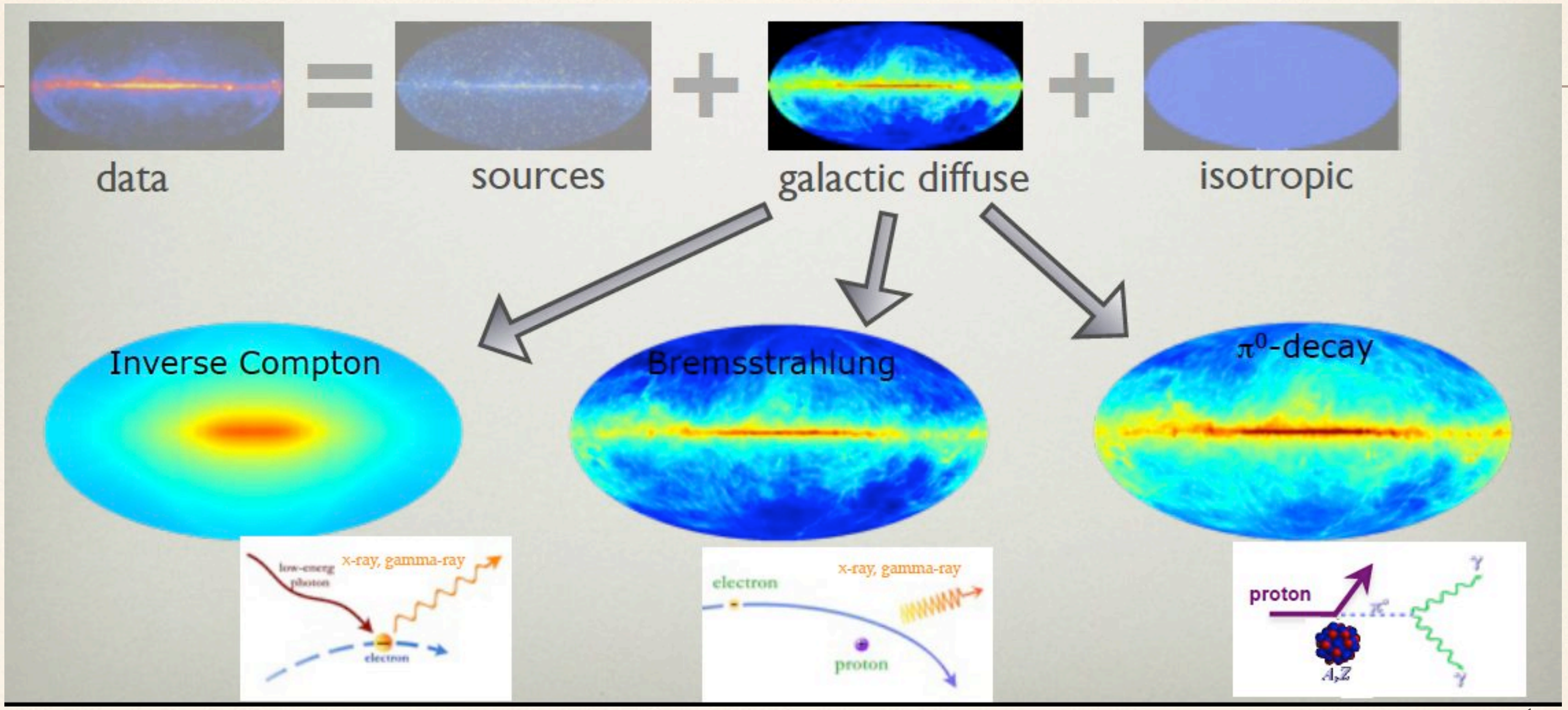
Macias & Gordon Phys.Rev. D89 (2014) 063515 arXiv:1312.6671

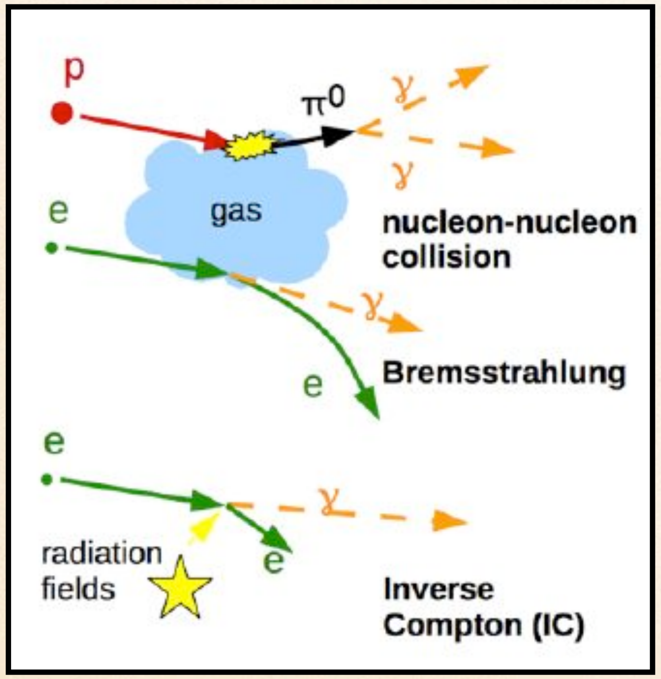
AS THE GARDEN, THE BACKGROUND IS ALSO A MODEL OF THE MILKY WAY





HOW TO COOK A GALACTIC INTERSTELLAR GAMMA-RAY EMISSION?

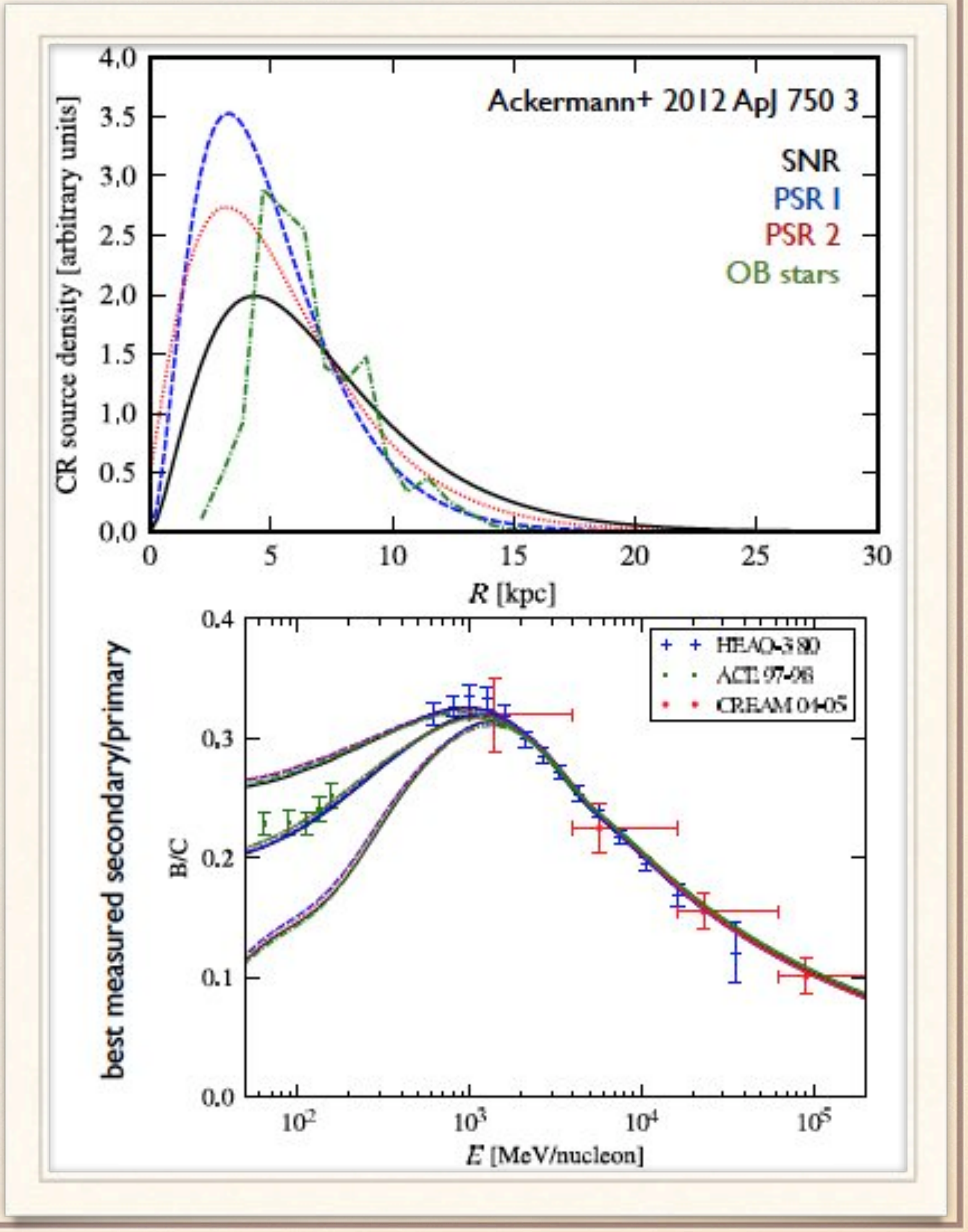




- Interaction between cosmic rays and interstellar gas (pion decay and Bremm.), and radiation fields (IC), and magnetic fields (synchrotron)
- Intensity $\propto \int_{LOS}$CRs × (gas density + radiation density)
- Point source characteristics depend on the diffuse model used in their extraction
- Some diffuse emission regions could be confused with point sources
- their understanding is the key to search for dark matter

INGREDIENTS: CR SOURCES AND TRANSPORT

- CR source distribution
  - supernova remnants, pulsars, massive stars ...
  - spiral arm structure?
- CR injection spectrum at sources
- transport mechanism(s)
  - diffusion coefficient
  - role of convection, reacceleration?
- size of propagation volume

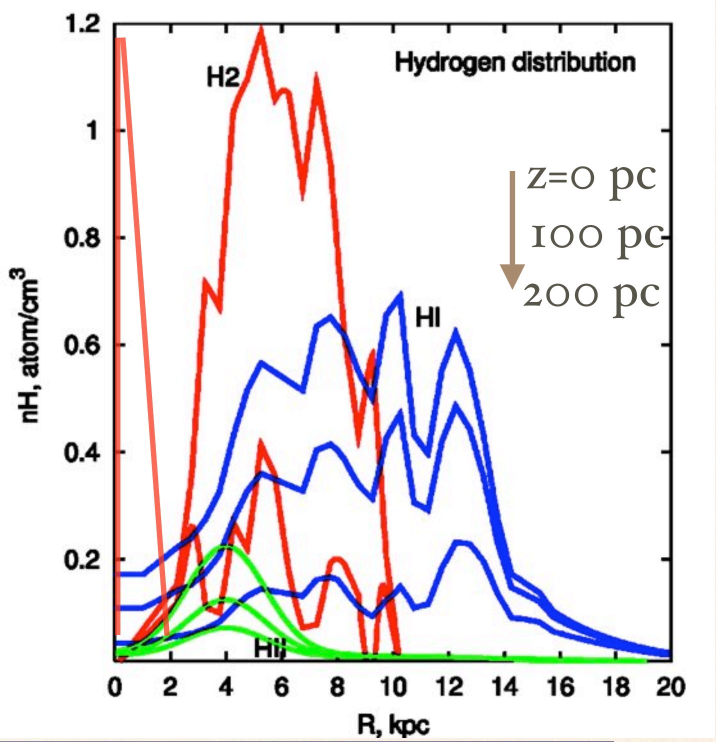


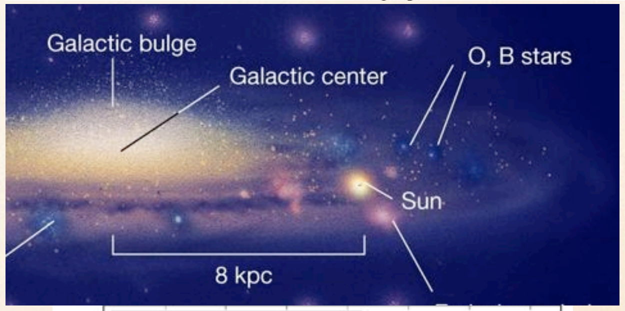
INGREDIENTS: TARGETS

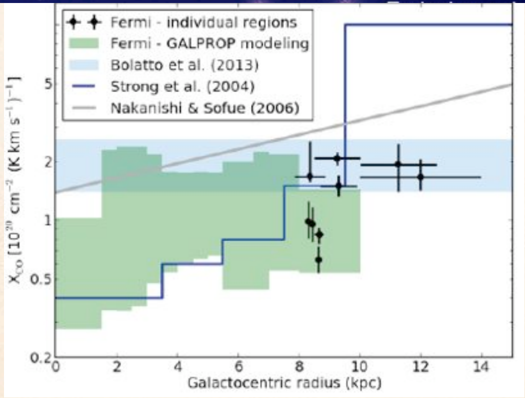
- **Molecular hydrogen H2:**
  Concentrated mostly in the plane. The main tracer is CO (from the 115 GHz composite survey of Dame et al. 2001). Distance information from velocity and a rotation curve (Clemens 1985) is used to distribute gas in galactocentric rings.

- The standard method to relate velocity with distance breaks down toward the Galactic Center

- The Xco factor to convert CO to H2 column density varies as a function of the galactocentric radius. However the exact form of the variation is not known.

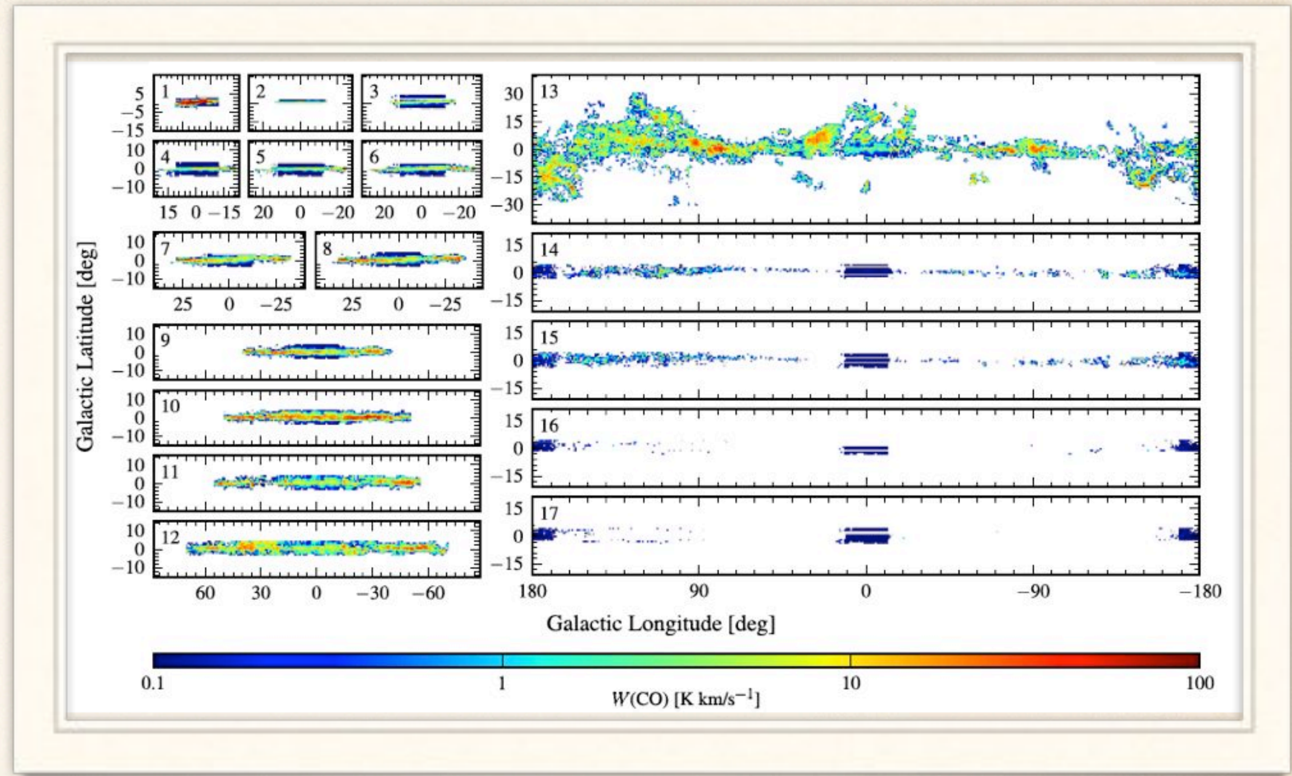






INGREDIENTS: TARGETS

- **Molecular hydrogen H2:**
  - Integrated line intensity of CO as function of Galactocentric radius
  - The innermost annulus is entirely enclosed in a region where kinematic resolution of the method vanishes, then to estimate its column density all high-velocity emission is assigned to this region

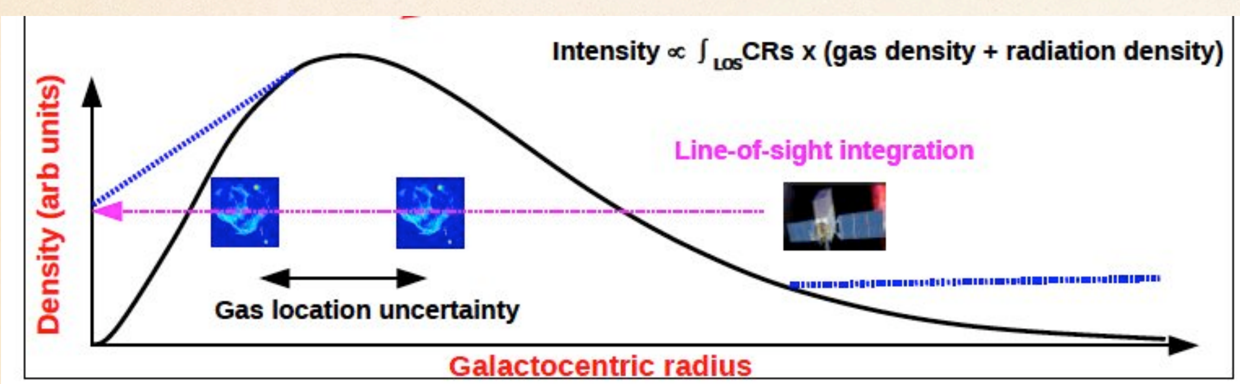


CO traces molecular hydrogen

$$X_{CO} = \frac{N(H_2)}{W_{CO}}$$

Boundaries of Galactocentric Annuli Used in Gas Maps

Annulus No.	R_{min} (kpc)	R_{max} (kpc)
1	0	1.5
2	1.5	2.0
3	2.0	2.5
4	2.5	3.0
5	3.0	3.5
6	3.5	4.0
7	4.0	4.5
8	4.5	5.0
9	5.0	5.5
10	5.5	6.5
11	6.5	7.0
12	7.0	8.0
13	8.0	10.0
14	10.0	11.5
15	11.5	16.5
16	16.5	19.0
17	19.0	50.0



From Galactic rotation curves

$$v_{LSR} = R_{\odot}\left(\frac{V(R)}{R} - \frac{V_{\odot}}{R_{\odot}}\right)\sin(l)\cos(b).$$

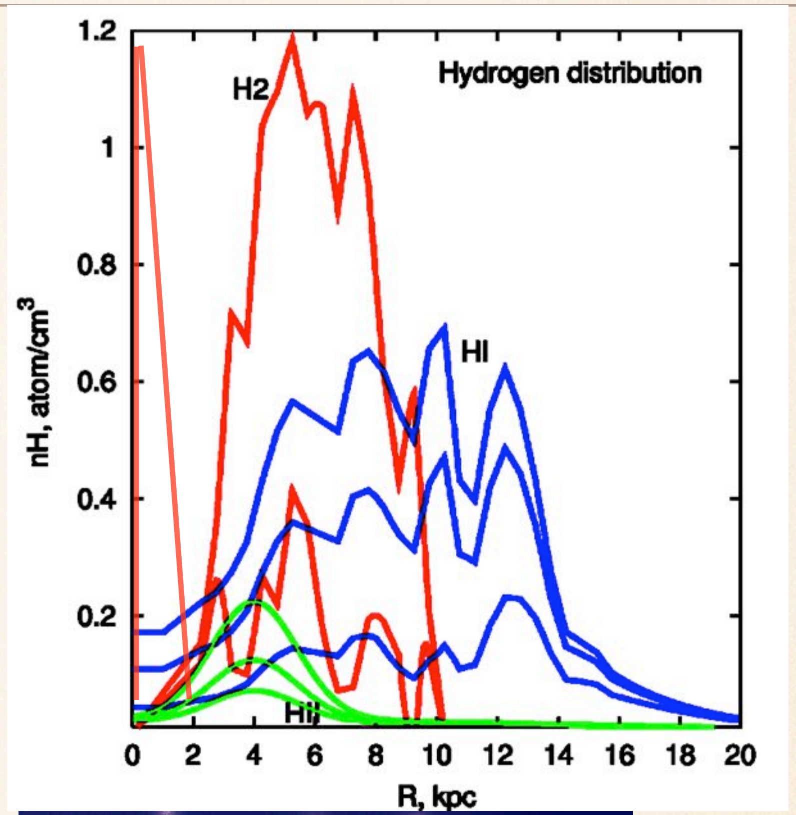
From gas survey

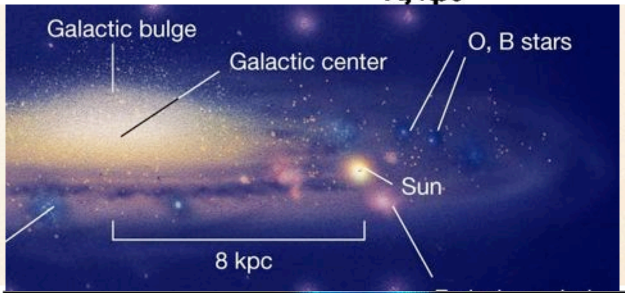
INGREDIENTS: TARGETS

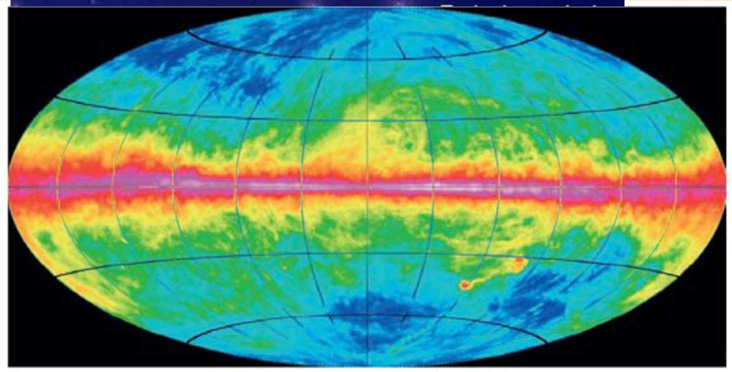
- **Atomic hydrogen HI:** 21-cm brightness temperature maps from the composite LAB survey (Kalberla et al. 2005). As for H2 distance information is quite unknown in the Galactic Center direction.

- The primary uncertainty in the conversion from brightness temperature to column density comes from the assumed spin temperature, Ts, used to correct for the opacity of the 21-cm line. We adopt a constant Ts value.

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



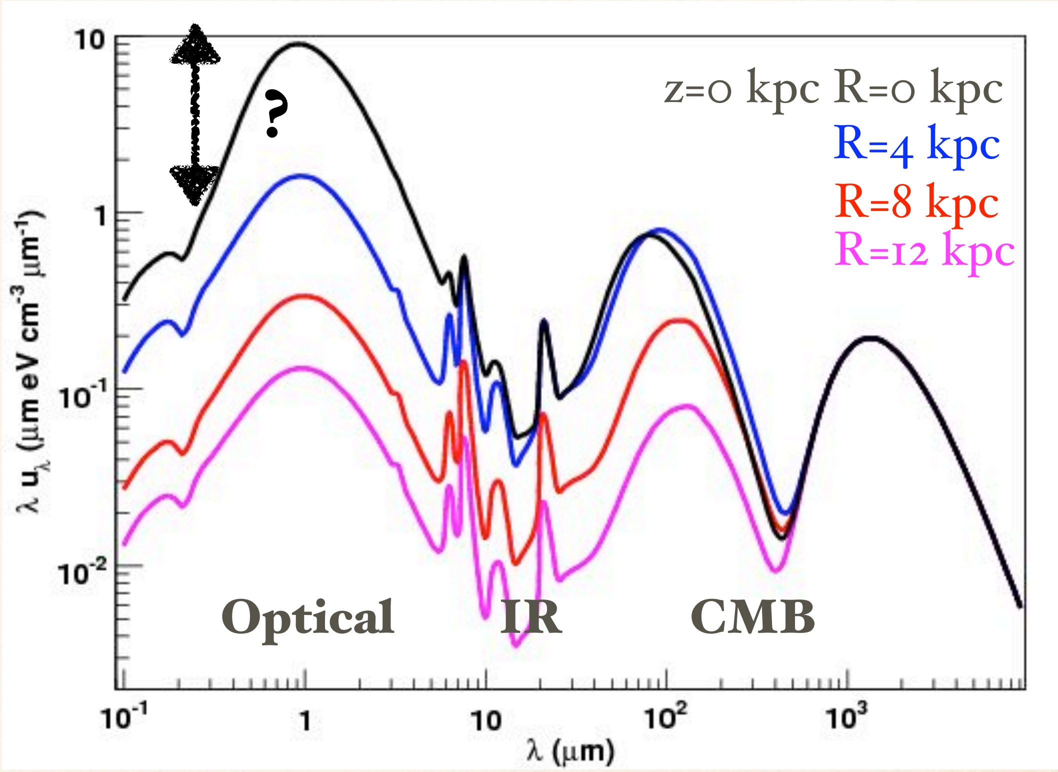


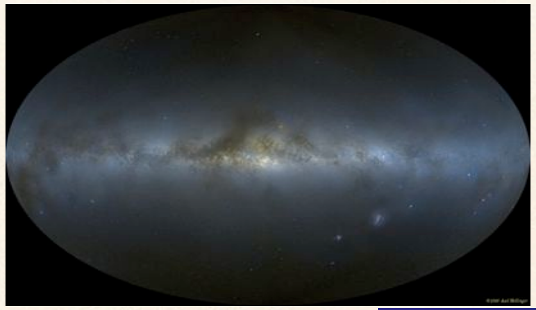


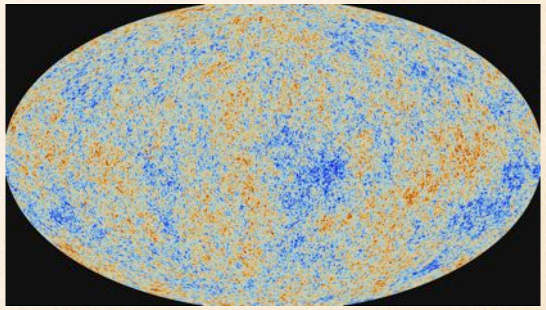
HI gas from LAB survey

INGREDIENTS: TARGETS

- **Interstellar radiation field:** ISRF is the resulting emission by stars, and the scattering, absorption, and re-emission of absorbed starlight by dust in the ISM.
- optical photons are the principal target for high energy electrons to produce Inverse Compton emission in the energy range ~50 MeV -100 GeV.
- 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)

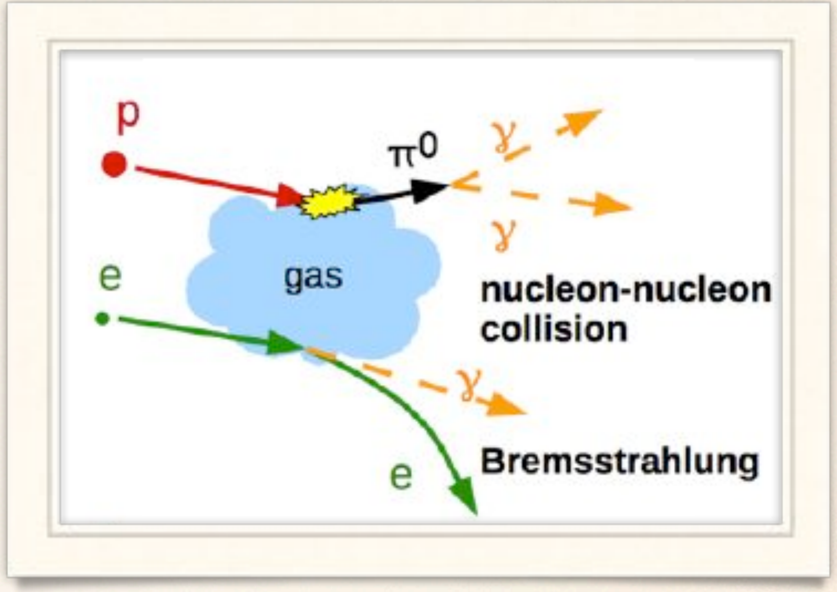


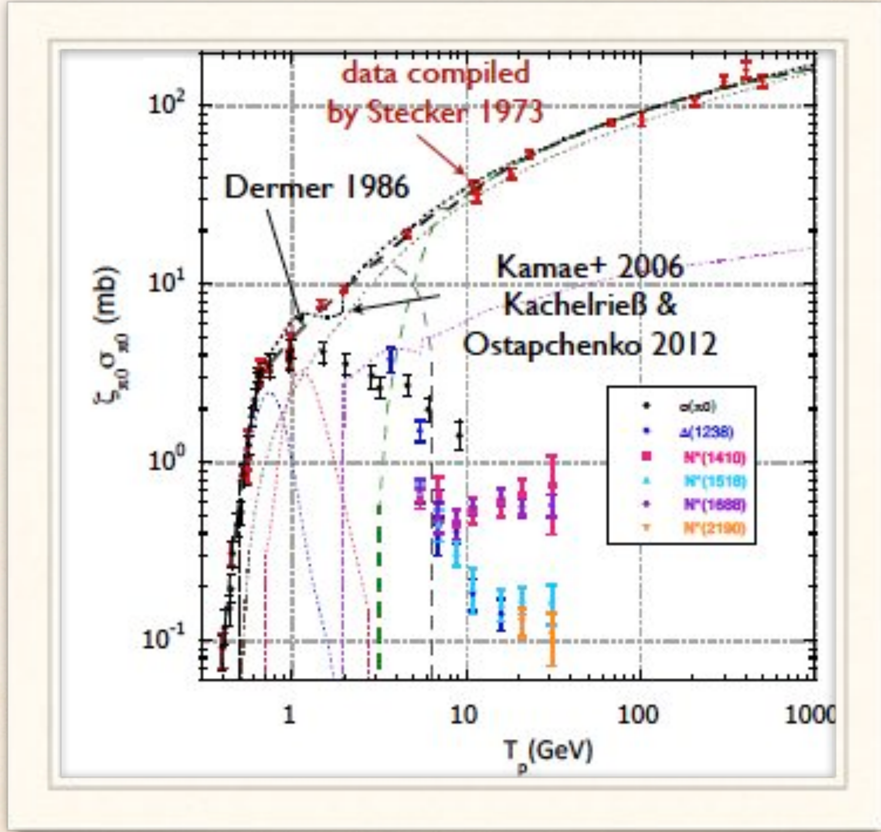




INGREDIENTS: INTERACTION MODELS

- Data and theory from particle physics
  - bridged by theoretical framework(s)
- For nuclear interactions
  - Limited measurements (bullet energies, bullet/target species, angular distribution)
  - 5-15% uncertainties at proton kinetic energy Tp < 10 GeV

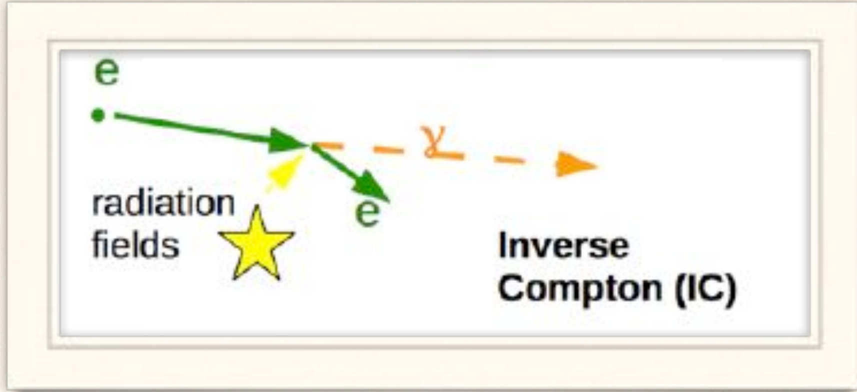


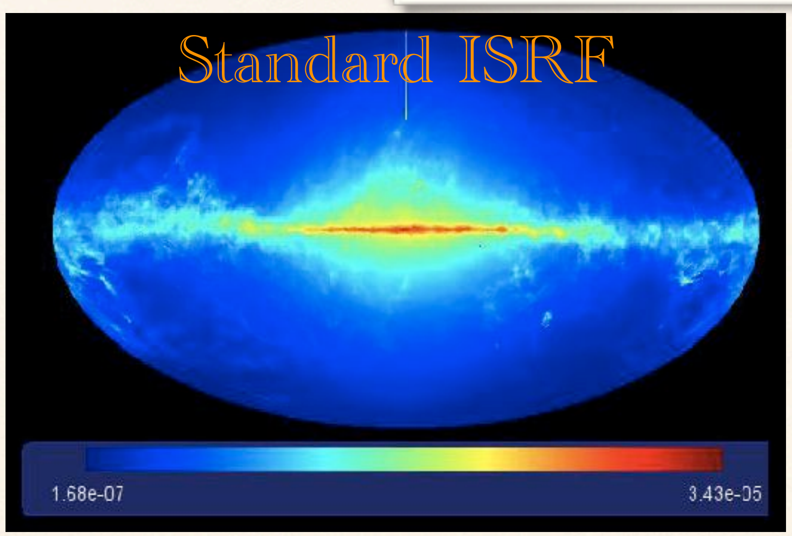


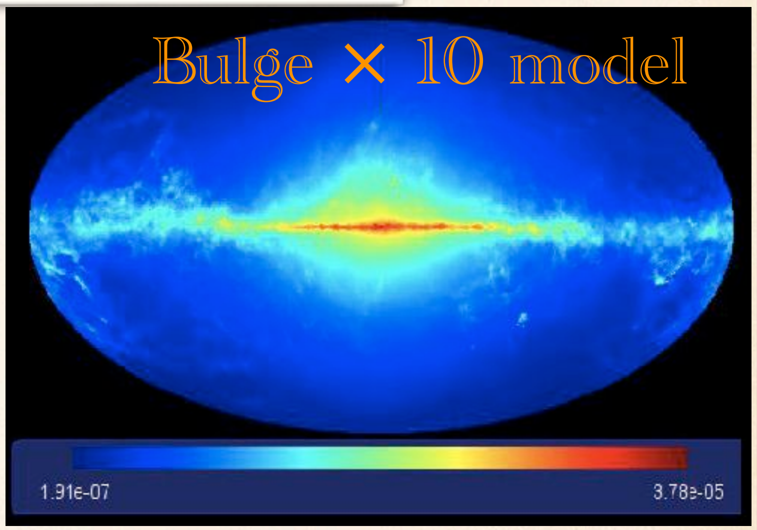
INGREDIENTS: IC TEMPLATE

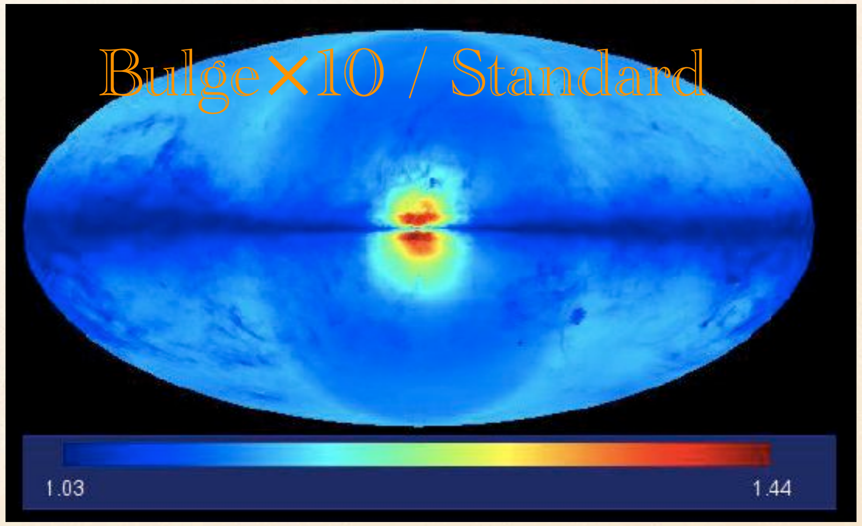
- The IC template is brightest in the direction of the inner Galaxy, and while it should be smooth because of the physics of radiation in the Galaxy, there are most likely fluctuations in that component that are not modeled with GALPROP.

- We need a dedicated study of the ISRF and the CR source distribution in the direction of the inner Galaxy to be able to estimate this contribution.



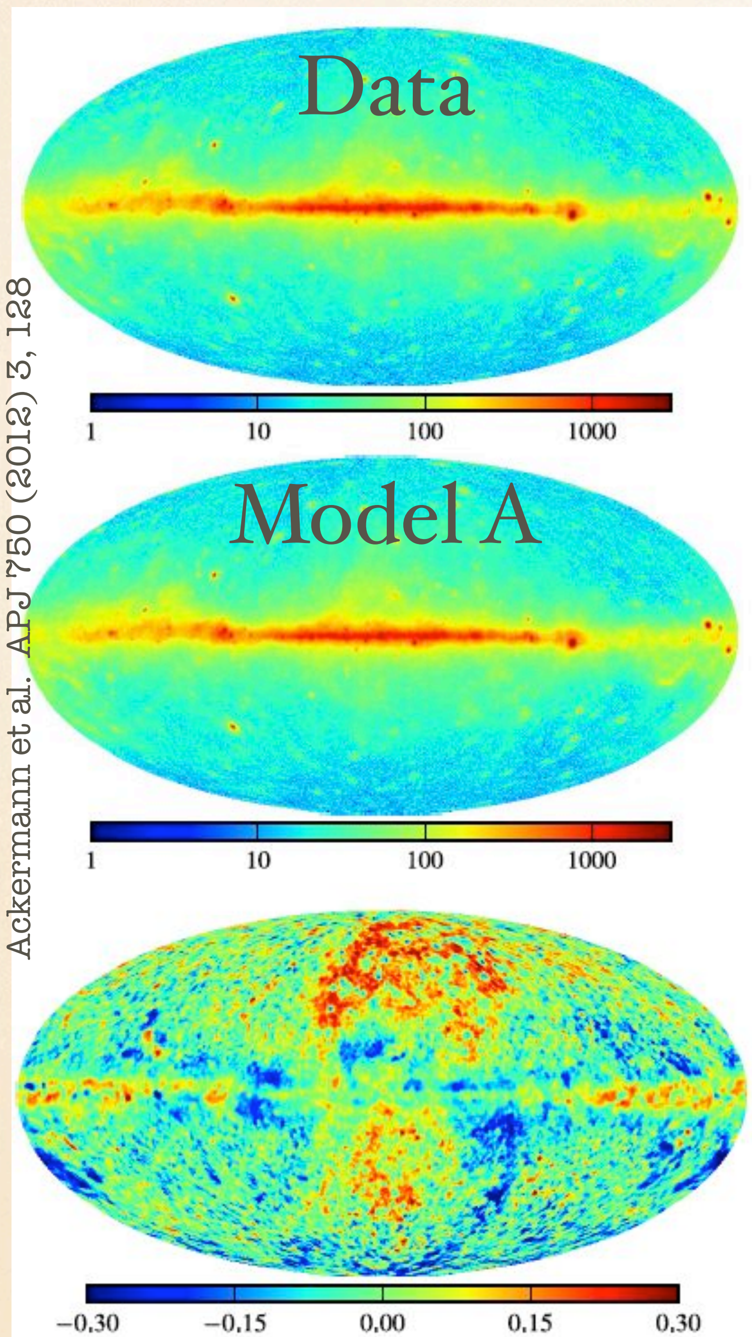






RECIPE I: CR PROPAGATION CODES

http://galprop.stanford.edu



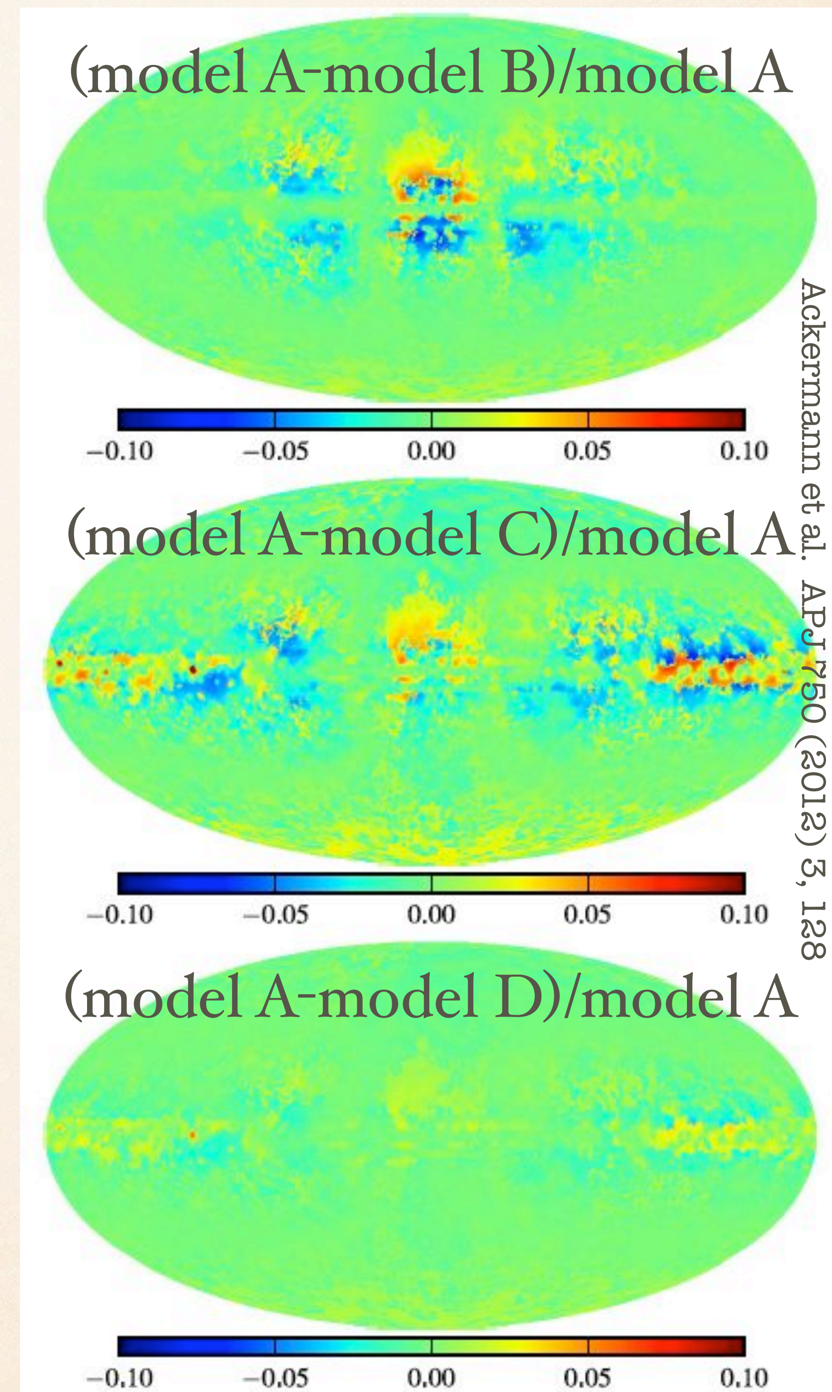
(data-model A)/model A

Ackermann et al. APJ 750 (2012) 3, 128

The GALPROP code can be used to model the diffuse Galactic γ-ray emission from processes such as inelastic hadronic collisions, bremsstrahlung, and ICS.

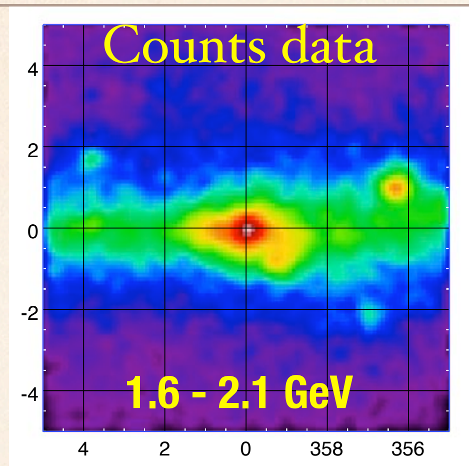
It uses realistic astrophysical inputs together with theoretical models. Varying these inputs within their limits many models can be created.

In Ackermann et al. APJ 750 (2012) 3, 128 different GALPROP models were compared with data, finding that all of them are in good (~20%) agreement with all sky data

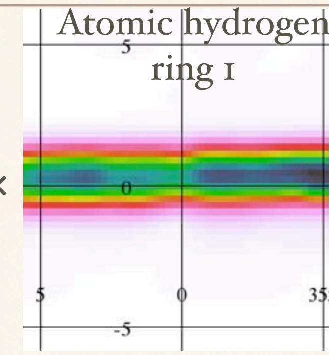


Ackermann et al. APJ 750 (2012) 3, 128

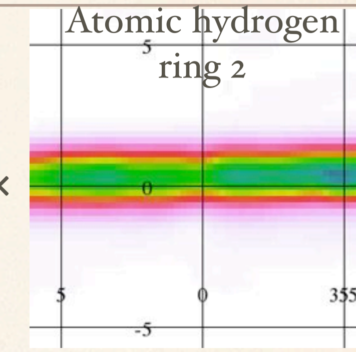
RECIPE 2: TEMPLATES



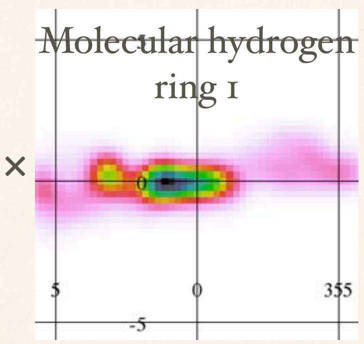
= psf ⊕ exposure × [q(HI)1×



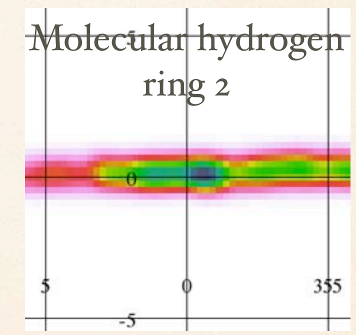
+ q(HI)2×



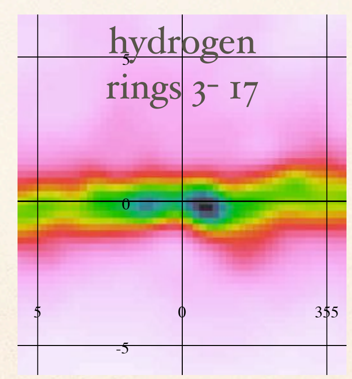
+ q(H2)1×



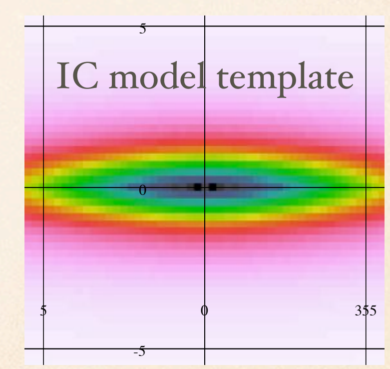
+ q(H2)2×



+ q×



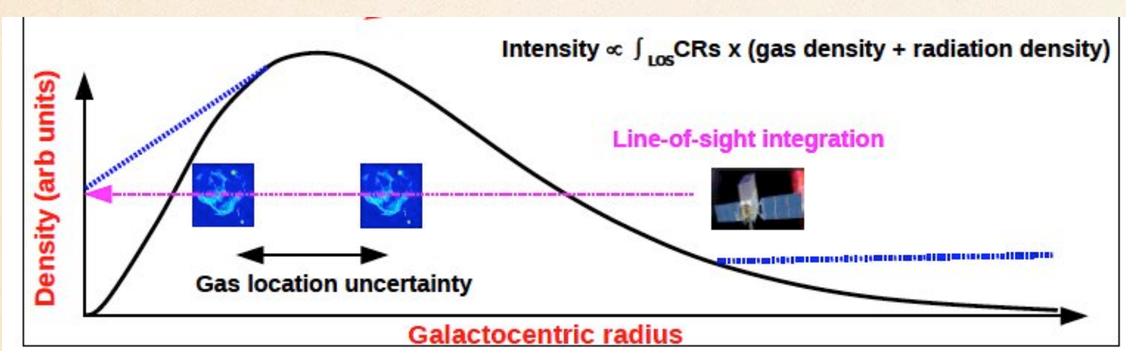
+ α_{IC}×



+ Isotropic + Bubbles + LoopI

+ Point sources + unmodeled emission]

At some particular energy the gamma-ray intensity is modeled as a linear combination of gas column-density map template, a predicted IC intensity map and a residual intensity of unmodeled emission



ISSUES WITH INTERSTELLAR DIFFUSE MODELS

- All the template-based models provided by the Fermi-LAT collaboration are fitted to the whole-sky with the purpose of serving as background models for analysis of pointlike or small sources, and as such tried to pick up as much extended emission as possible. The double fit (original one plus GC fit) introduces complications in the interpretation of the results which are not trivial to understand.

- Any model based on the gas maps created for full sky analysis will not be very good in the inner Galaxy by design. The linear interpolation used for the distance estimator is really 0^{th} order approximation and can not really be used to estimate the diffuse emission in that region. One would need to do a very dedicated study on the gas templates to understand the region.

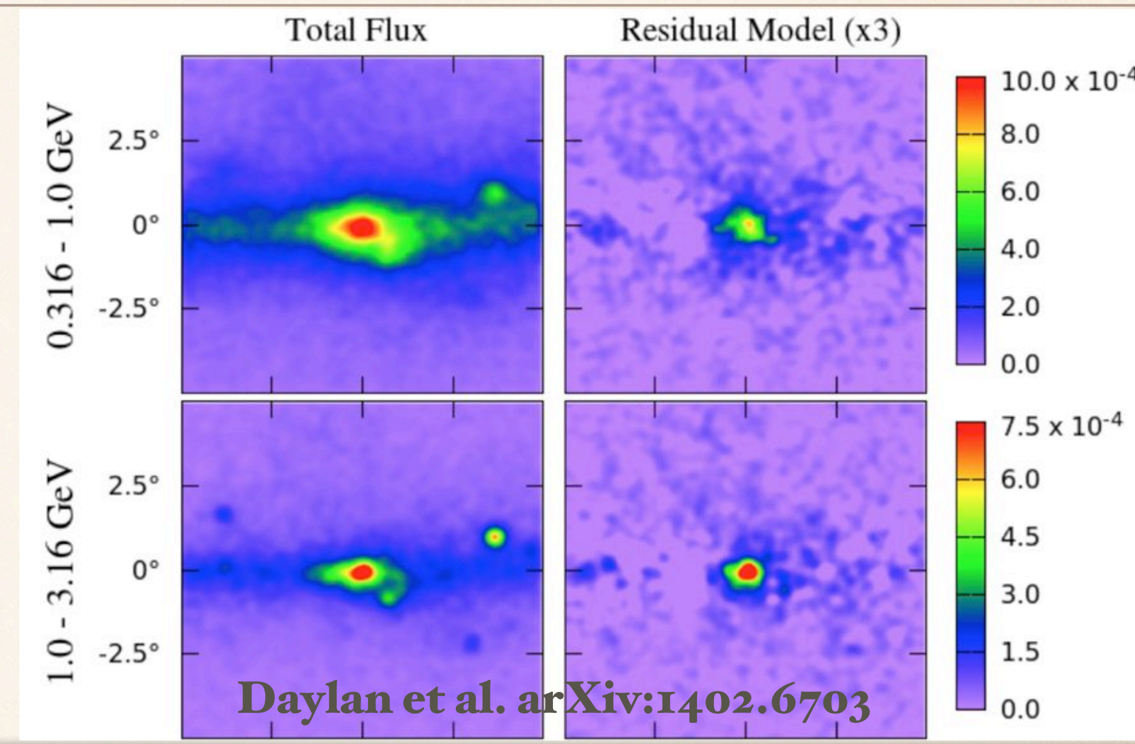
- The IC template is brightest in the direction of the inner Galaxy, and while it should be smooth because of the physics of radiation in the Galaxy, there are most likely fluctuations in that component that are not modeled with GALPROP. Again we need a dedicated study of the ISRF and the CR source distribution in the direction of the inner Galaxy to be able to estimate this contribution.

- The most important message is that if you want to study extended emission around the Galactic center there is no ready-made solution in terms of a diffuse background model to use. None of the models we have are adequately describing γ-ray emission from that region.

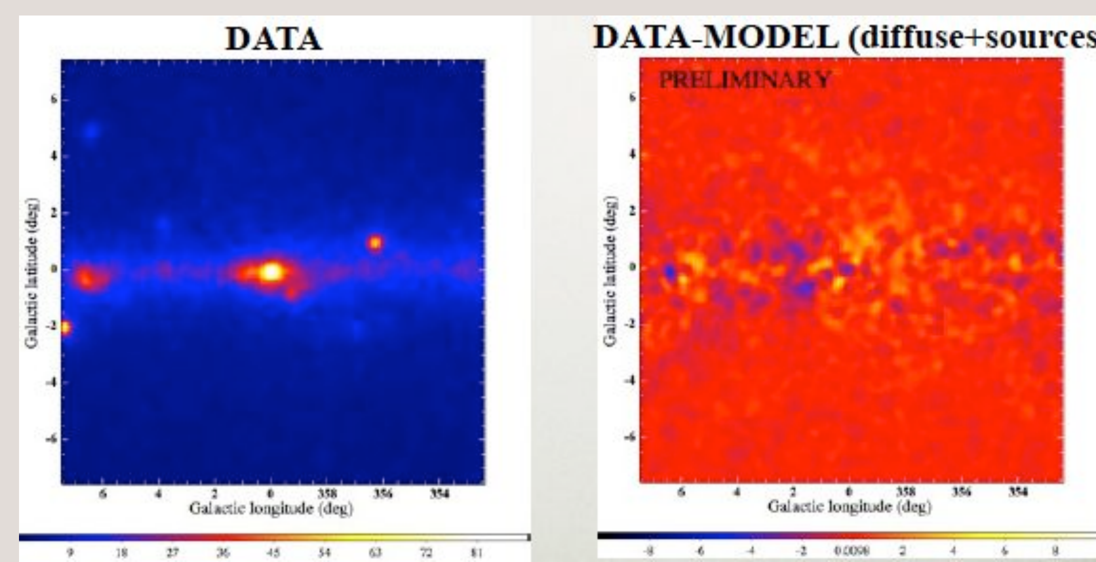
ARE WE SEEING DARK MATTER WITH THE FERMI-LAT IN A REGION AROUND THE MILKY WAY CENTER?

Maybe yes, but we can't be sure as far as we don't understand the background at the level needed for disentangle a DM-induced γ-ray flux in this interesting region.

New molecular and atomic gas, CR and γ-ray data is around the corner, keep tune!

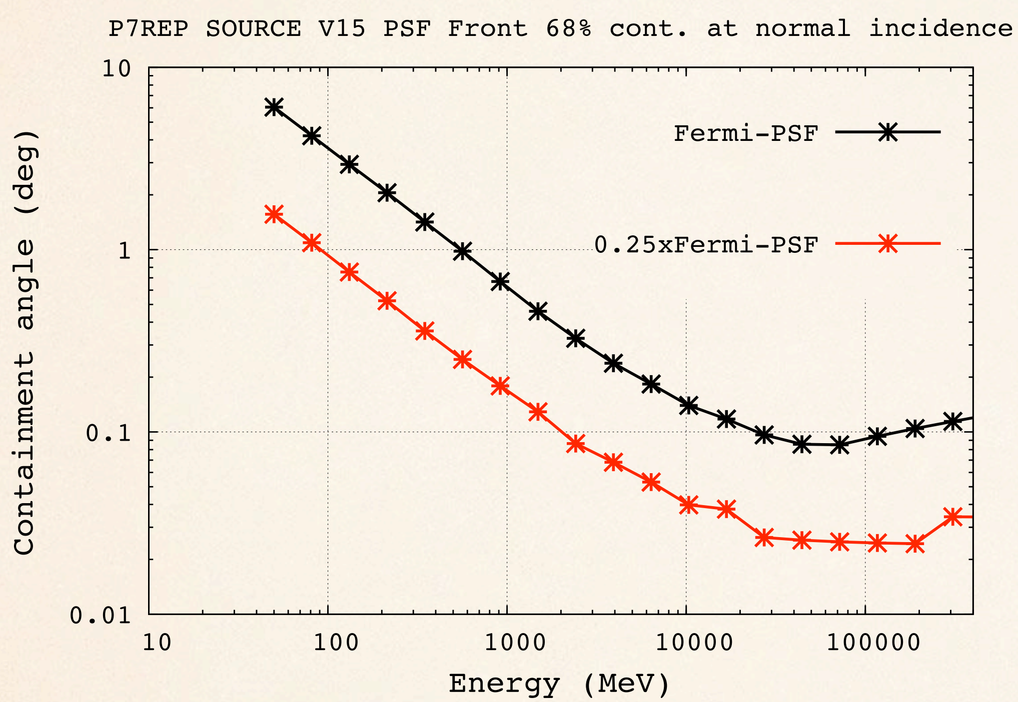


Daylan et al. arXiv:1402.6703

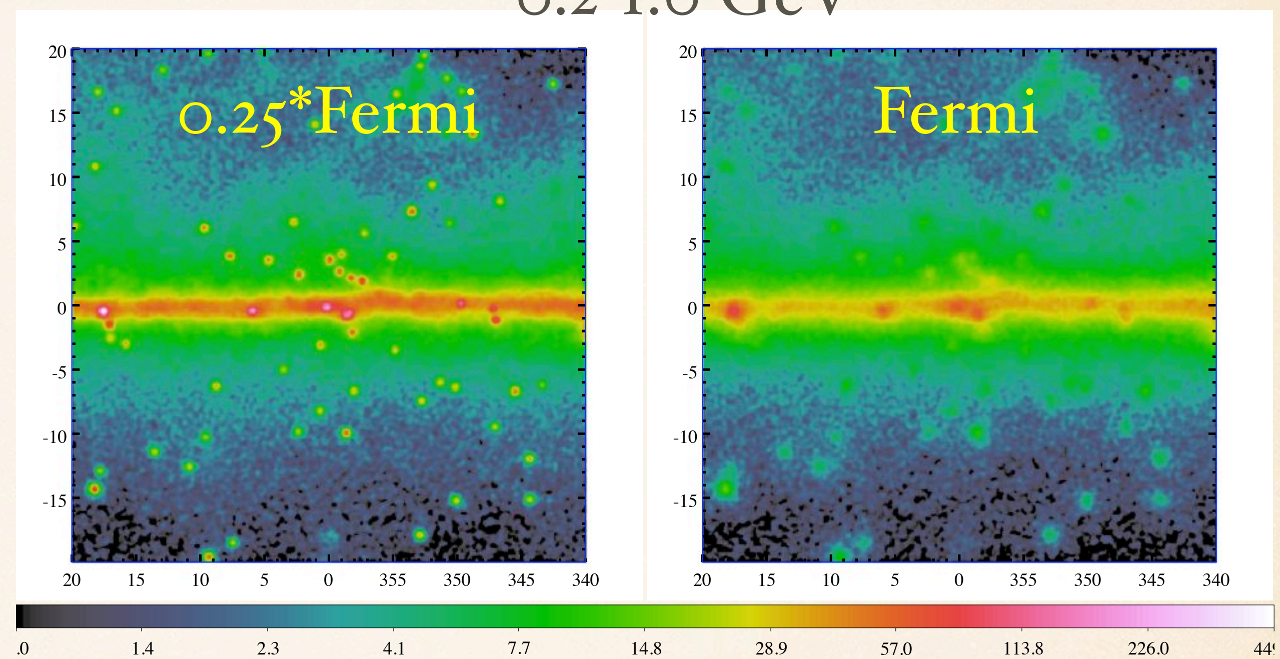


Fermi-LAT preliminary result

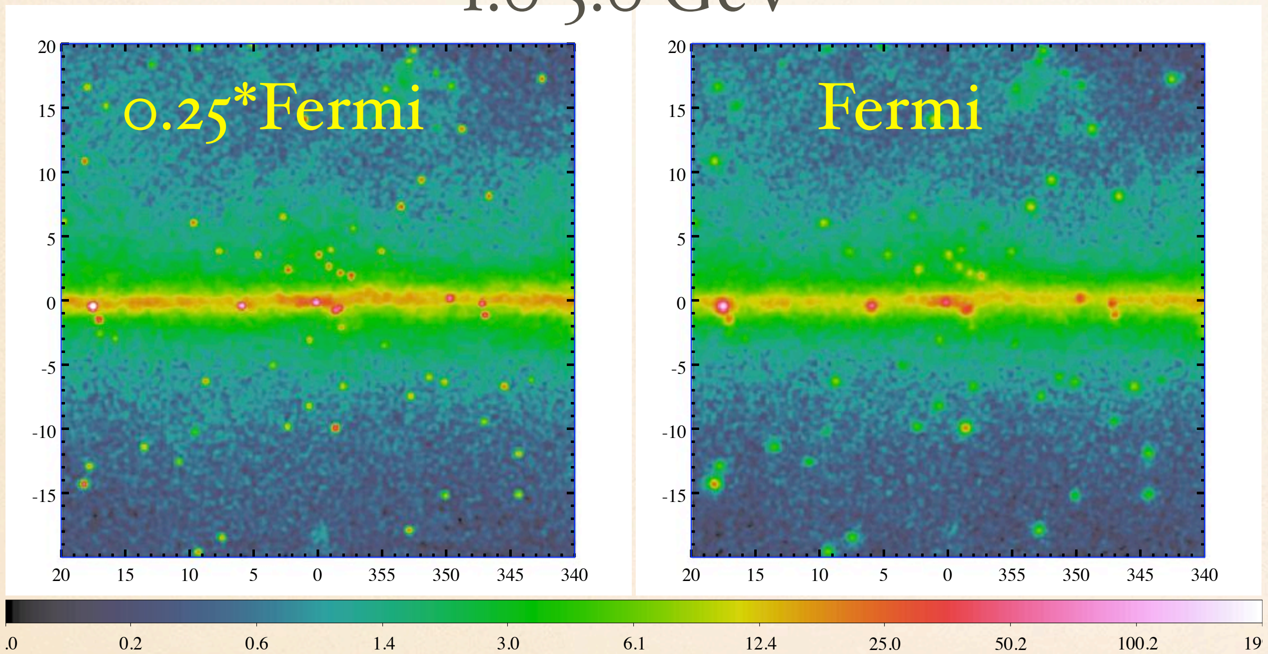
FUTURE BETTER PSF



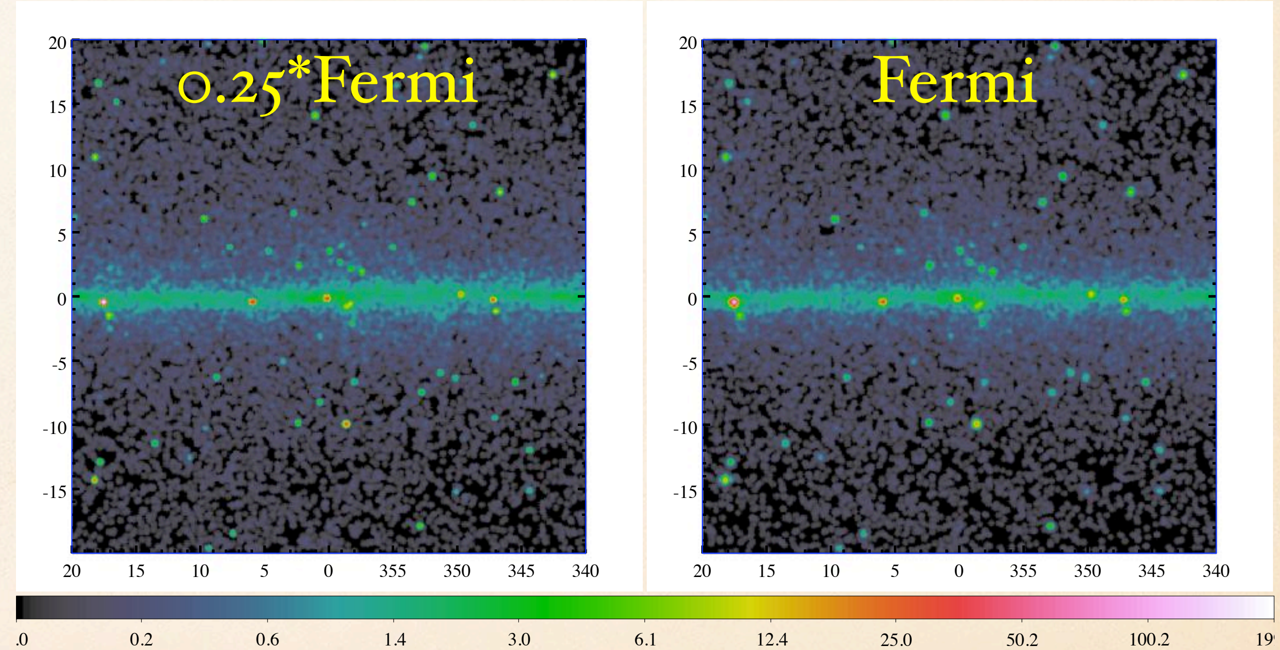
0.2-1.0 GeV



1.0-5.0 GeV



5.0-10.0 GeV



GRAZIE!!

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BACKUP

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:12 (23pp), 2012 March doi:10.1088/0067-0049/199/1/12

New HI data

THE AUSTRALIA TELESCOPE COMPACT ARRAY H I SURVEY OF THE GALACTIC CENTER

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New dark gas data

A&A 536, A19 (2011)
DOI: 10.1051/0004-6361/201116479

Planck early results

Astronomy & Astrophysics
Special feature

Planck early results. XIX. All-sky temperature and dust optical depth from *Planck* and IRAS. Constraints on the "dark gas" in our Galaxy*

Mapping the Milky Way bulge at high resolution: the 3D dust extinction, CO, and X factor maps

M. Schultheis[1], B.Q. Chen[2,3], B.W. Jiang[3], O.A. Gonzalez[4], R. Enokiya[5], Y. Fukui[5], K. Torii[5], M. Rejkuba[6], and D. Minniti[7,8,9]

Mapping the Milky Way bulge at high resolution: the 3D dust extinction, CO, and X factor maps

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arXiv:1405.05.3

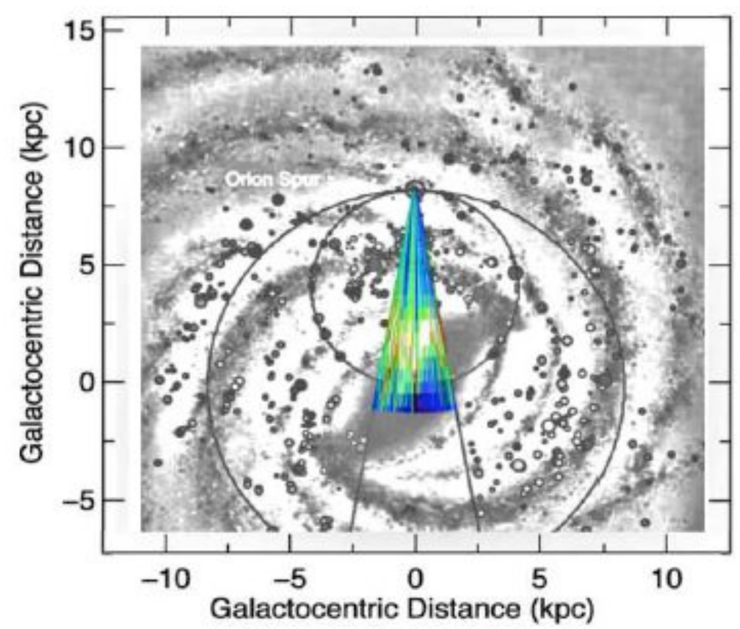
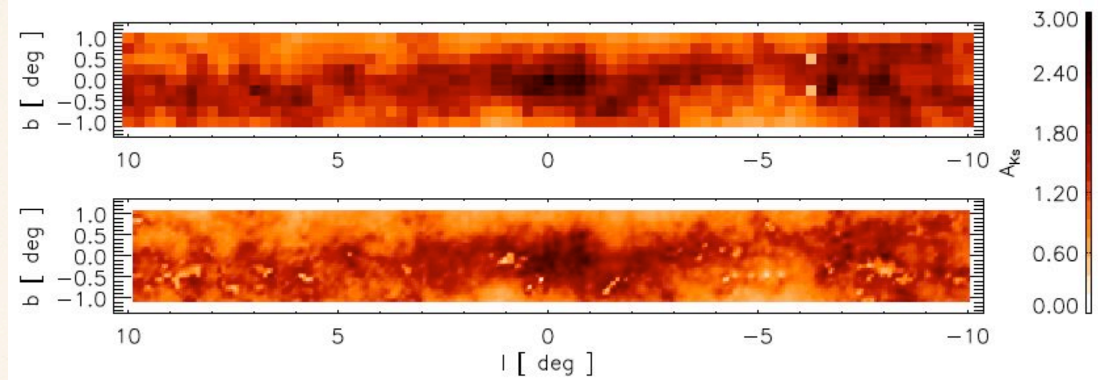


Fig. 10. Face-on view of the differential dust extinction shown overplotted on the illustration of the Milky Way produced by Robert Hurt and positions of HII+ MYSOs sources detected in the Galactic disk from Fig. 6 of Urquhart et al. (2014).



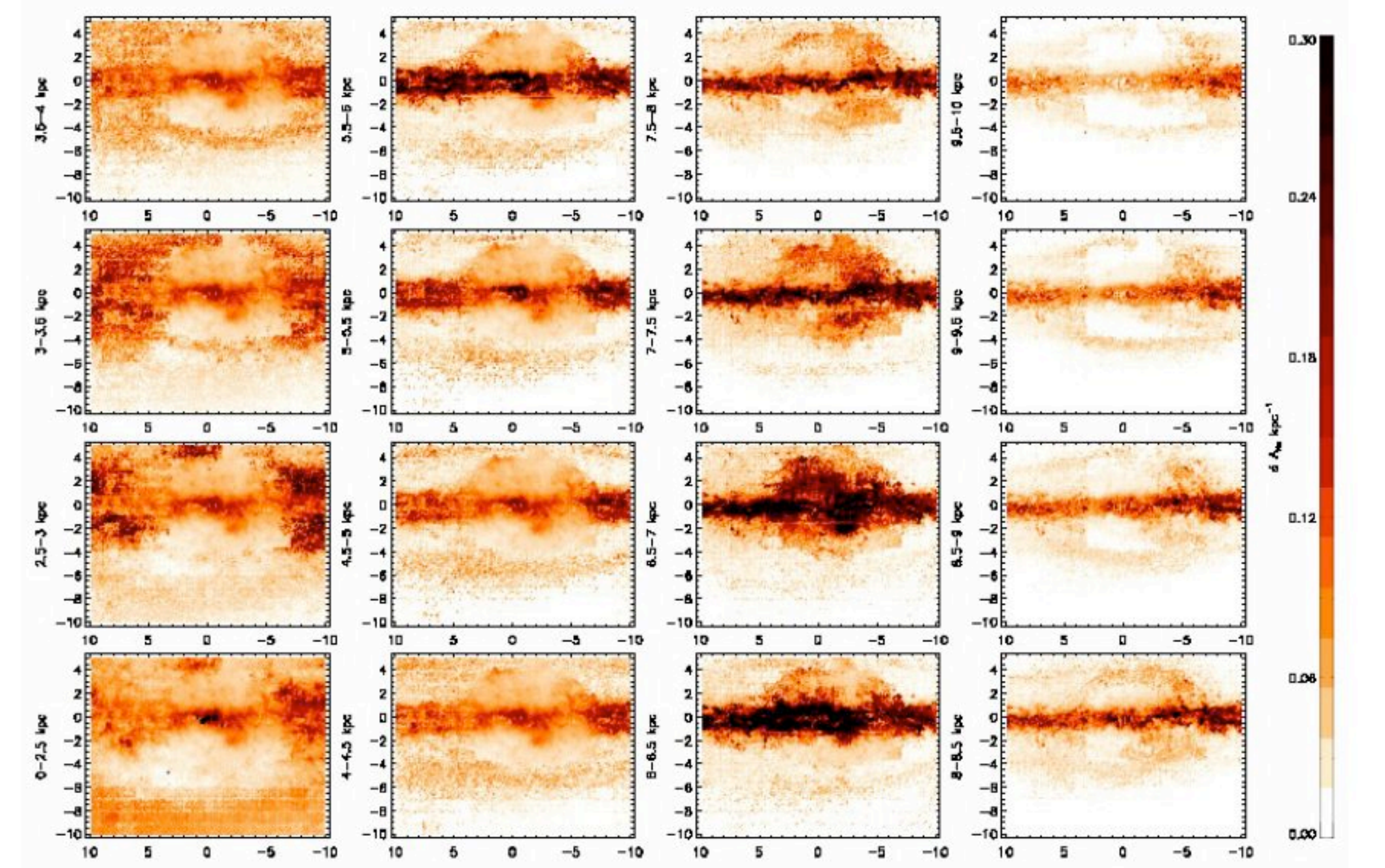


Fig. 7. Differential 3D extinction A_{Ks}. The x-axis denotes the Galactic longitude, the y-axis the Galactic latitude. The units are δA_{Ks} kpc^{-1}. The distances are given with respect to the sun.

PHYSICAL REVIEW D **89**, 063515 (2014)

Contribution of cosmic rays interacting with molecular clouds to the Galactic Center gamma-ray excess

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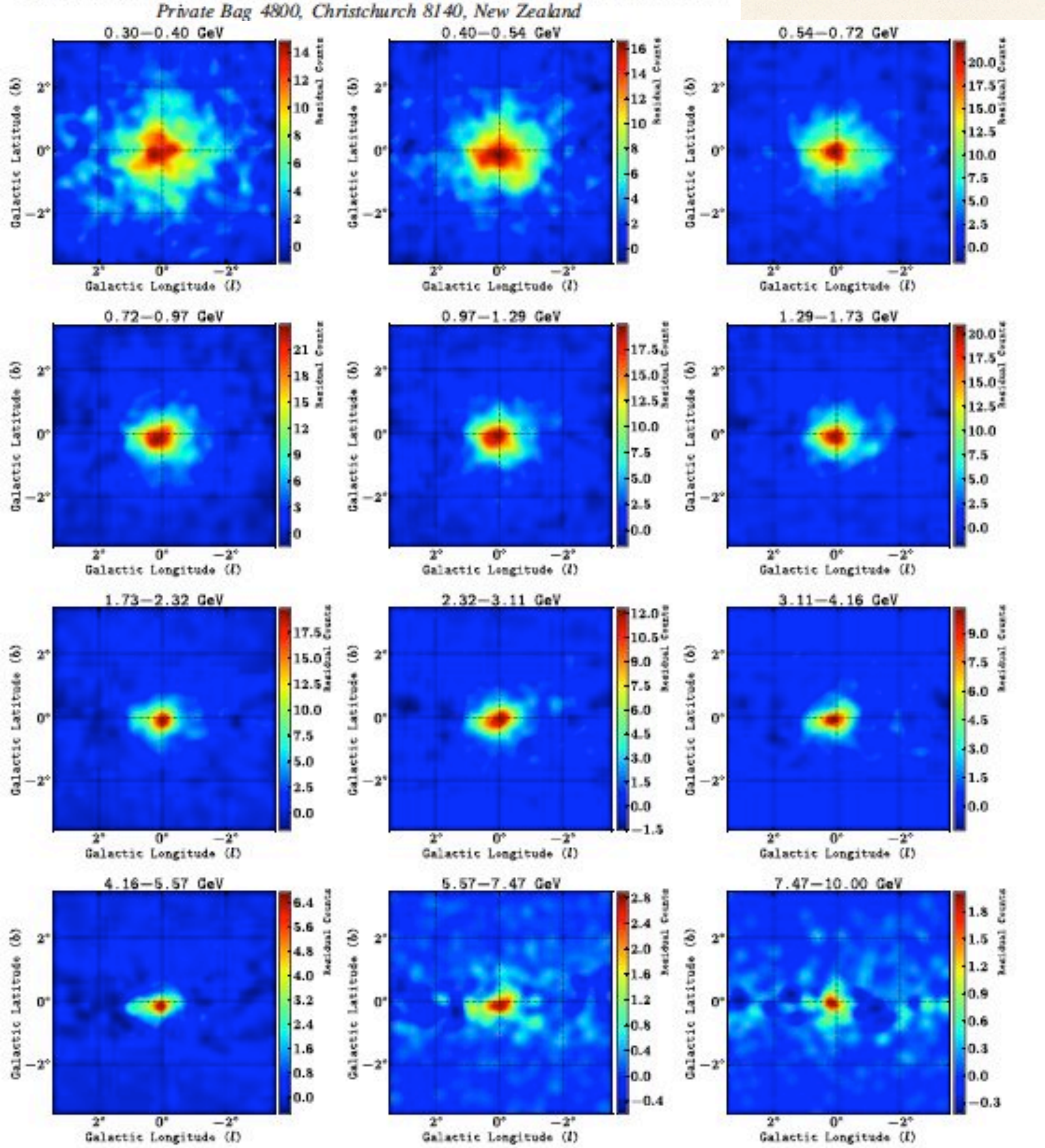
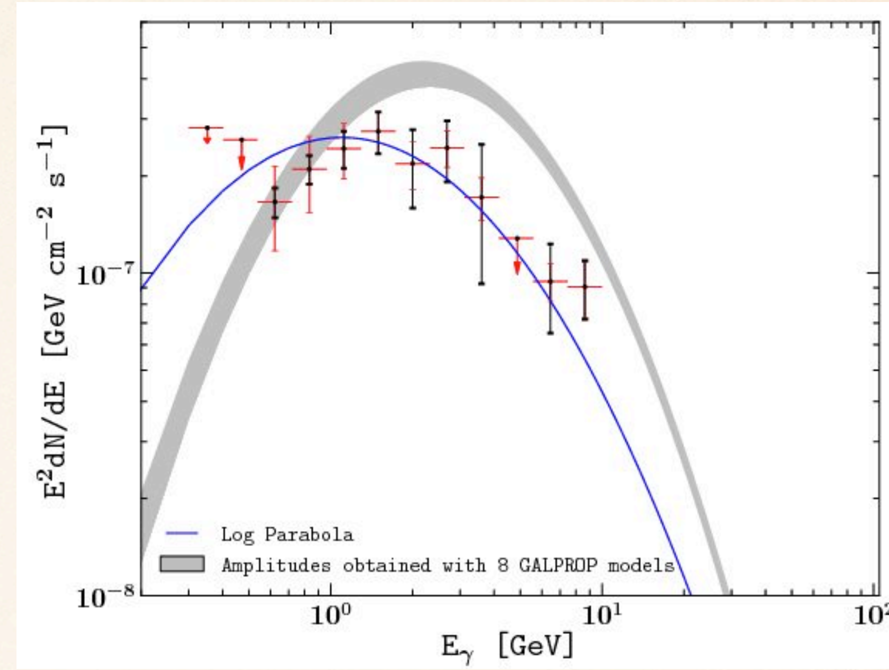
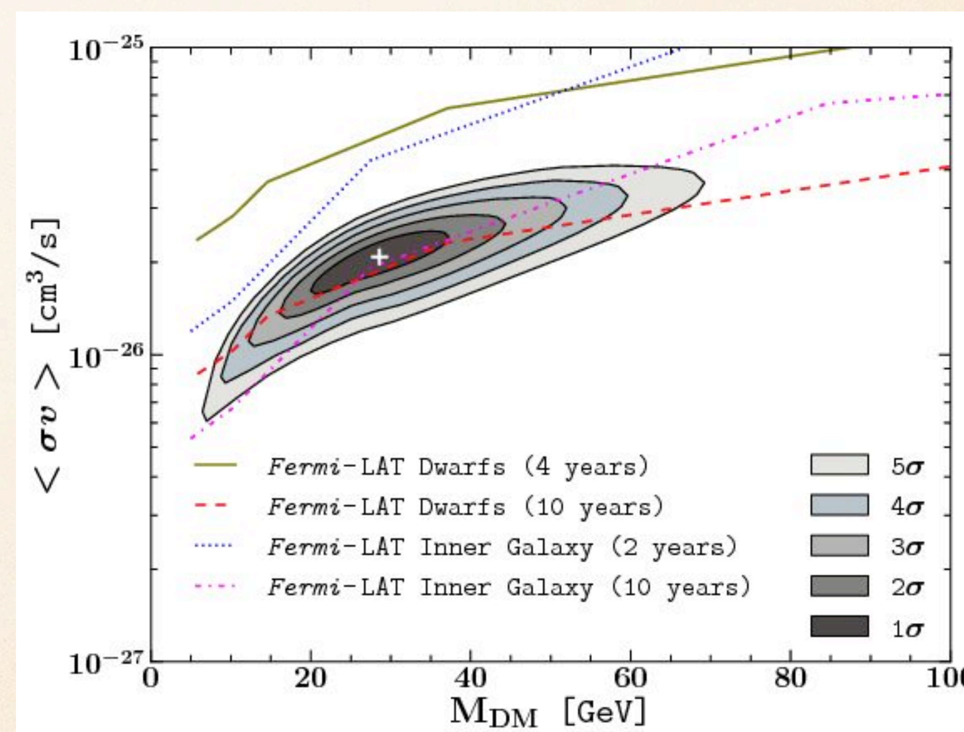


regions like the Galactic Center. Unless otherwise stated, the models included all sources suggested in the 2FGL [25] catalog plus the LAT standard DGB and extragalactic background models GAL_2YEARP7V6_V0.FITS and ISO _P7V6SOURCE.TXT, respectively.



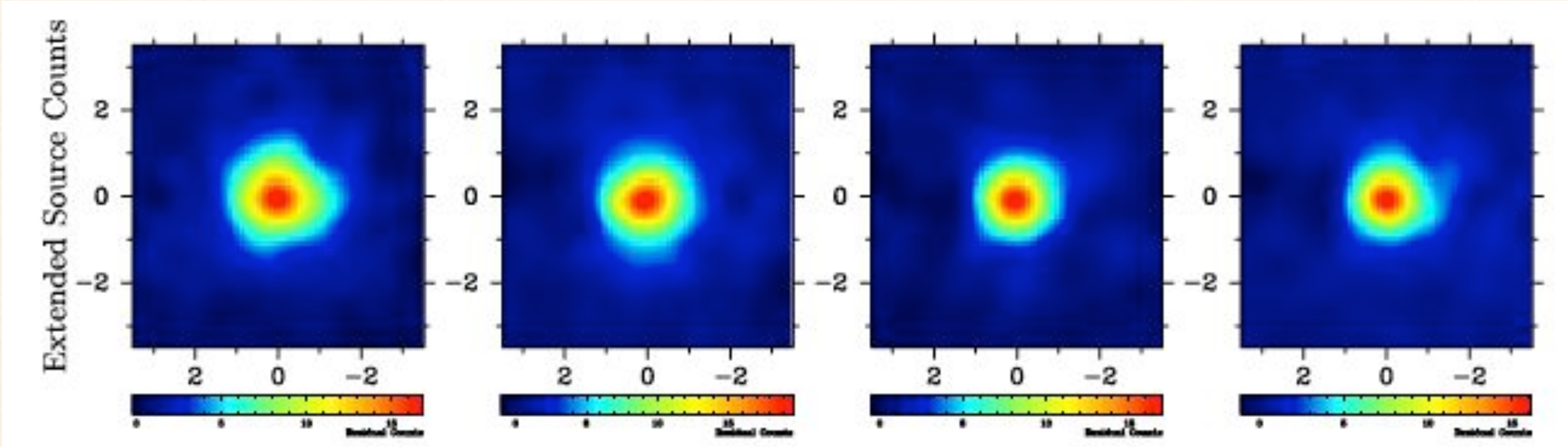


PHYSICAL REVIEW D **86,** 083511 (2012)

Detection of a gamma-ray source in the Galactic Center consistent with extended emission from dark matter annihilation and concentrated astrophysical emission

Kevork N. Abazajian* and Manoj Kaplinghat†

In this paper, we present the analysis of 3.8 years of data from the Fermi-LAT in the inner $7° \times 7°$ toward the Milky Way Galactic Center using the current second-year Fermi-LAT point source catalog (2FGL), the second-year Fermi-LAT diffuse Galactic map, isotropic emission model, and new models for any extended emission coming from the GC. We find that due to the required fitting of the



The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

arXiv:1402.6703v1 [astro-ph.HE] 26 Feb 2014