Towards a map of the 6-D radiation field and 3-D ISM map.

Douglas Finkbeiner

25 June, 2014

TeVPA/IDM 2014

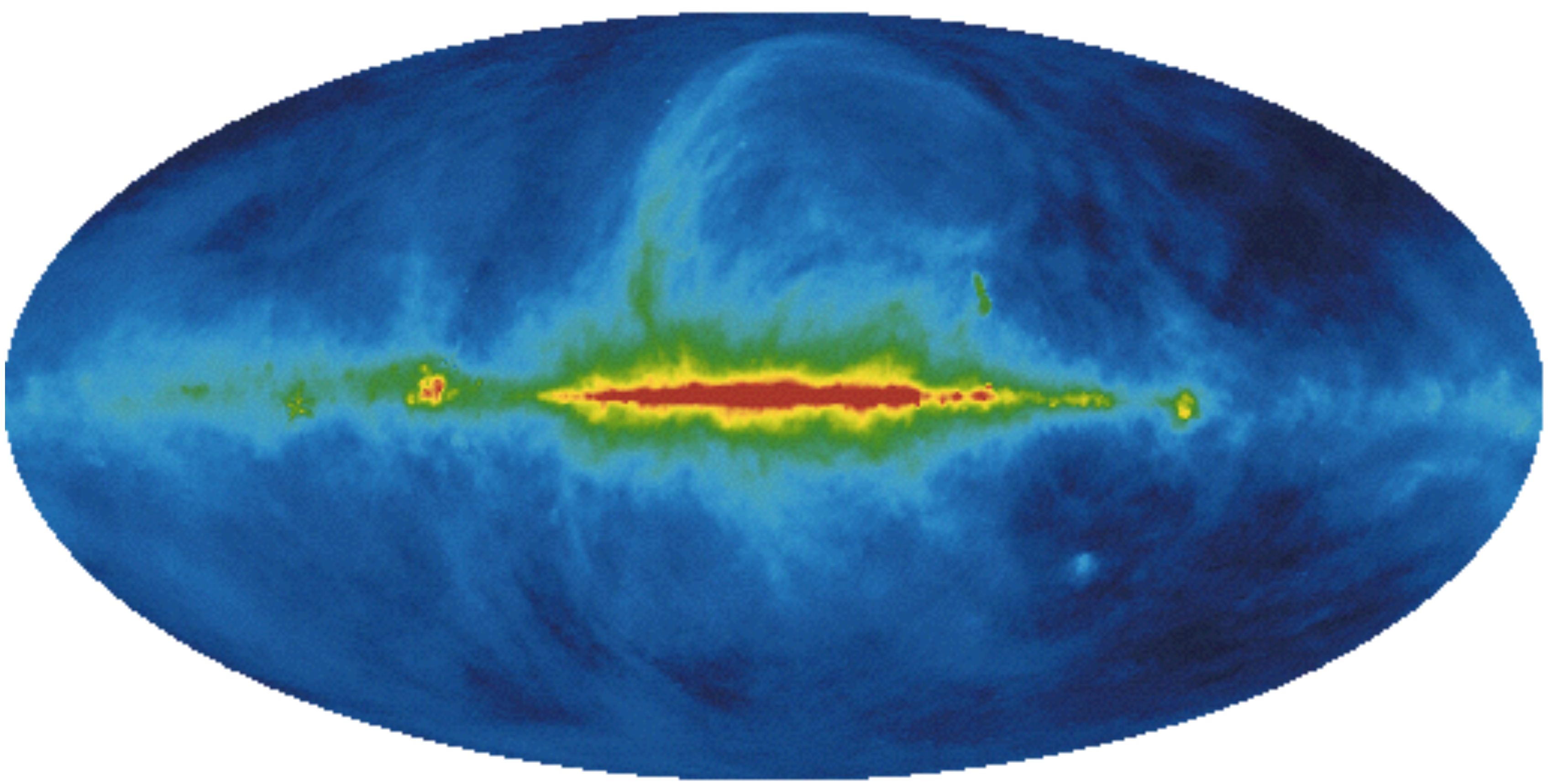
There are many reasons to want a

- 3-D map of gas and dust
- 6-D map of the interstellar radiation field

(one of them is to search for dark matter annihilation / decay)

The Milky Way as a dark matter detector

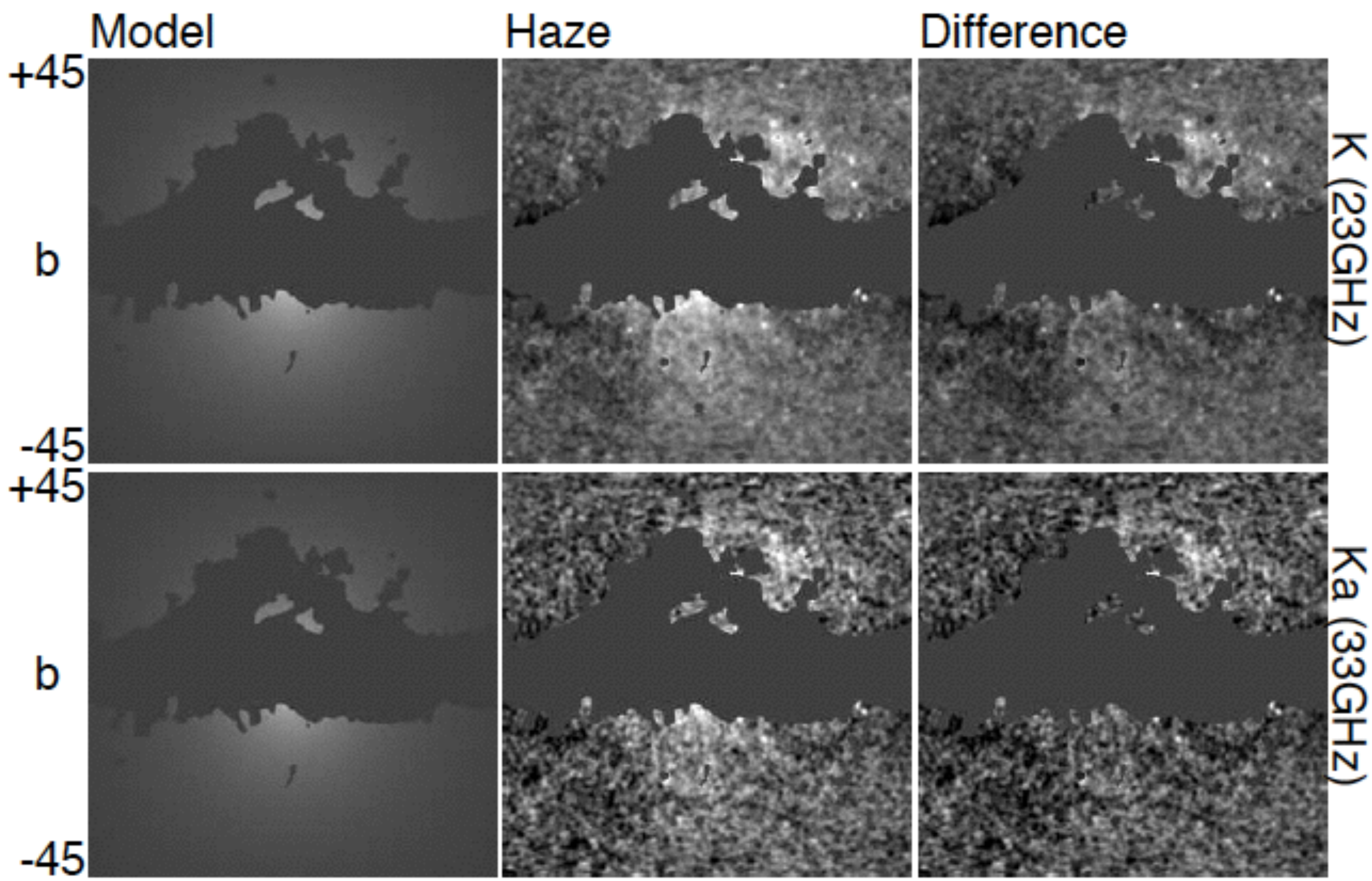
The Galaxy is both source and calorimeter
(at least for e+e- via IC and synchrotron)



Haslam+ (1982)

The microwave haze (2004)

My interest was motivated by the so-called WMAP haze.
Could this be a signal of WIMP annihilation?



Finkbeiner (2004)

Much of (most of?) the WMAP haze turned out to be associated with the *Fermi Bubbles*.

But there is still a curious gamma-ray signal in the Inner Galaxy: the ~ GeV-scale excess.

(See special session on the GeV excess tomorrow)

arXiv:1010.2752

Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope
Dan Hooper, Lisa Goodenough

arXiv:1110.0006

On The Origin Of The Gamma Rays From The Galactic Center
Dan Hooper, Tim Linden

arXiv:1402.6703

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter
Tansu Daylan, Douglas P. Finkbeiner, Dan Hooper, Tim Linden, Stephen K. N. Portillo, Nicholas L. Rodd, Tracy R. Slatyer

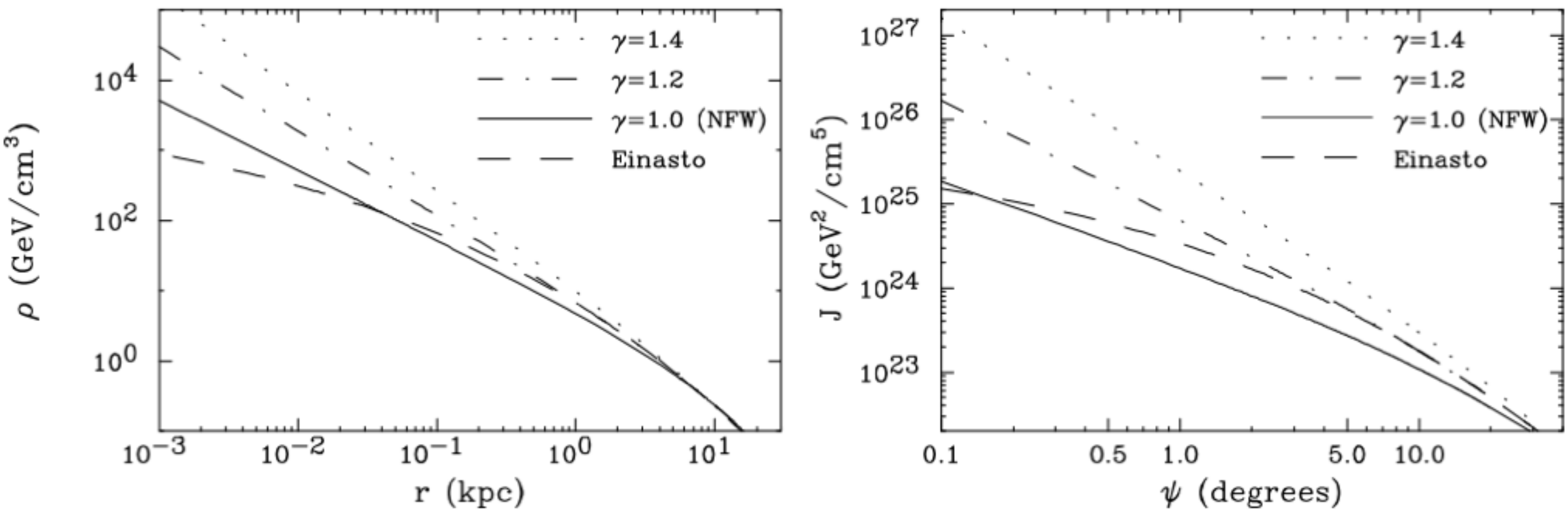
arXiv:1404.0022

Simplified Dark Matter Models for the Galactic Center Gamma-Ray Excess
Asher Berlin, Dan Hooper, Samuel D. McDermott

arXiv:1404.1373

Flavored Dark Matter and the Galactic Center Gamma-Ray Excess
Prateek Agrawal, Brian Batell, Dan Hooper, Tongyan Lin

Dark matter profiles



$$\Phi(E_\gamma, \psi) = \frac{\sigma v}{8\pi m_X^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \int_{\mathrm{los}} \rho^2(r)\, \mathrm{d}l,$$

Daylan+ 2014

Assume the observed gamma-ray map at each energy is a linear combination of template maps:

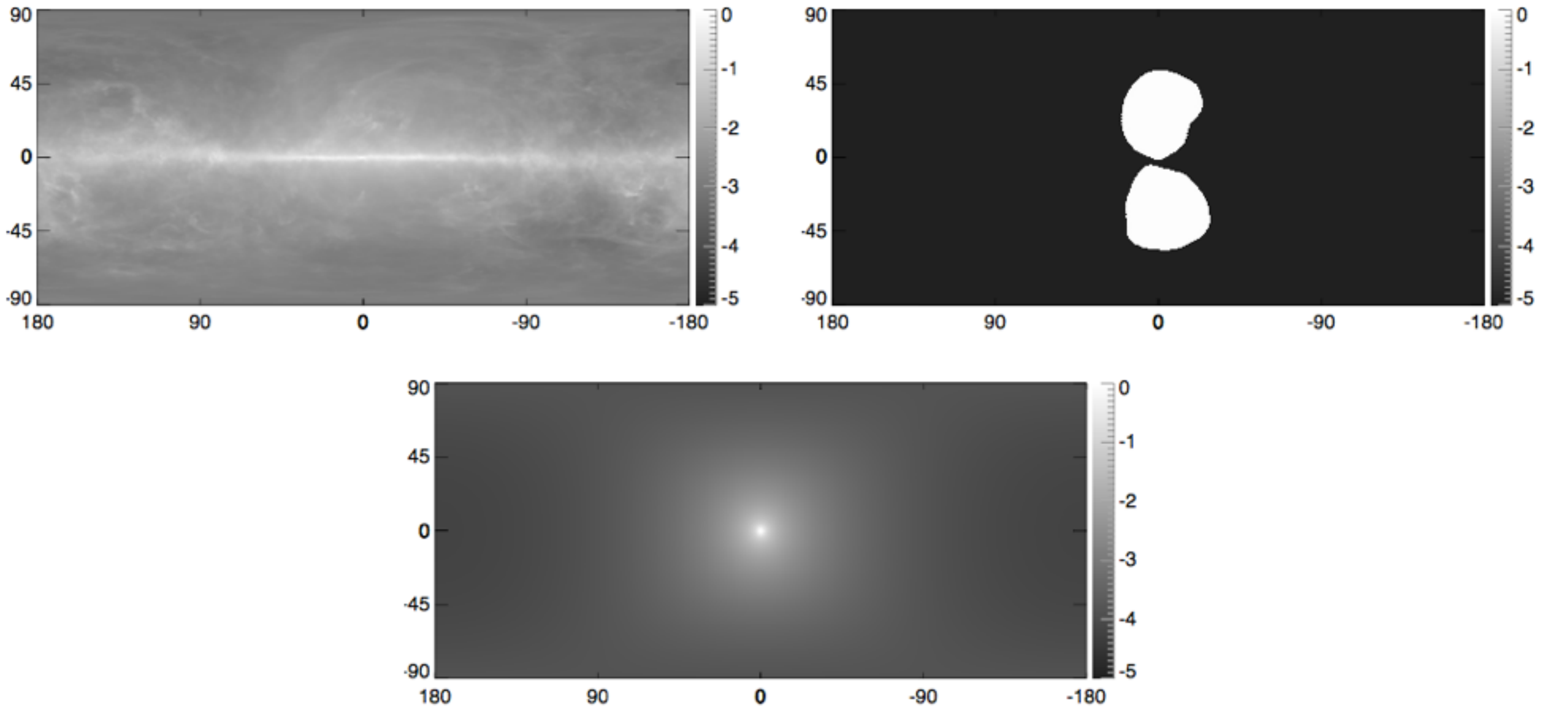
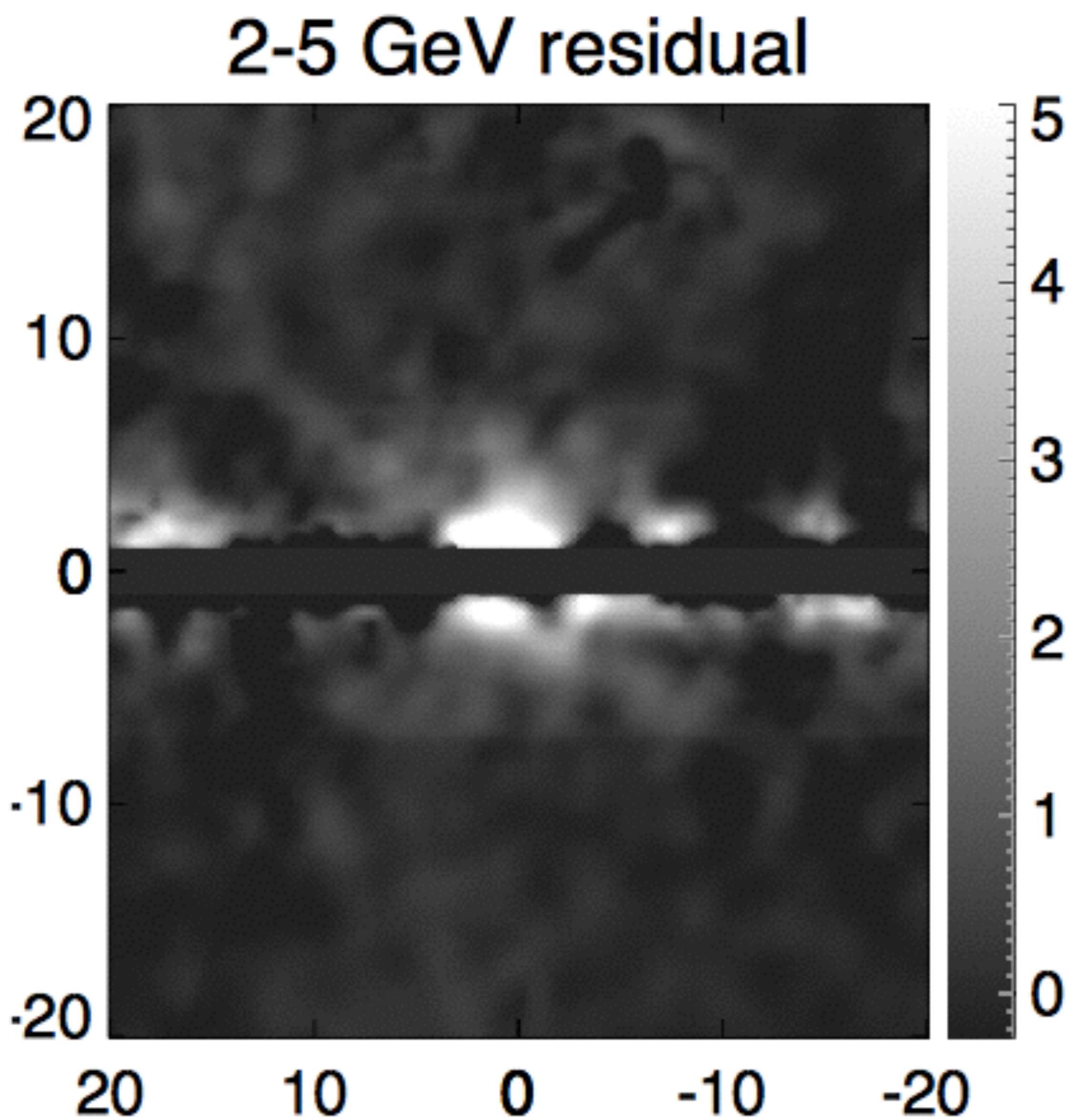


FIG. 4: The spatial templates (in galactic coordinates) for the Galactic diffuse model (upper left), the *Fermi* bubbles (upper right), and dark matter annihilation products (lower), as used in our Inner Galaxy analysis. The scale is logarithmic (base 10), normalized to the brightest point in each map. The diffuse model template is shown as evaluated at 2 GeV, and the dark matter template corresponds to a generalized NFW profile with an inner slope of $\gamma = 1.3$.

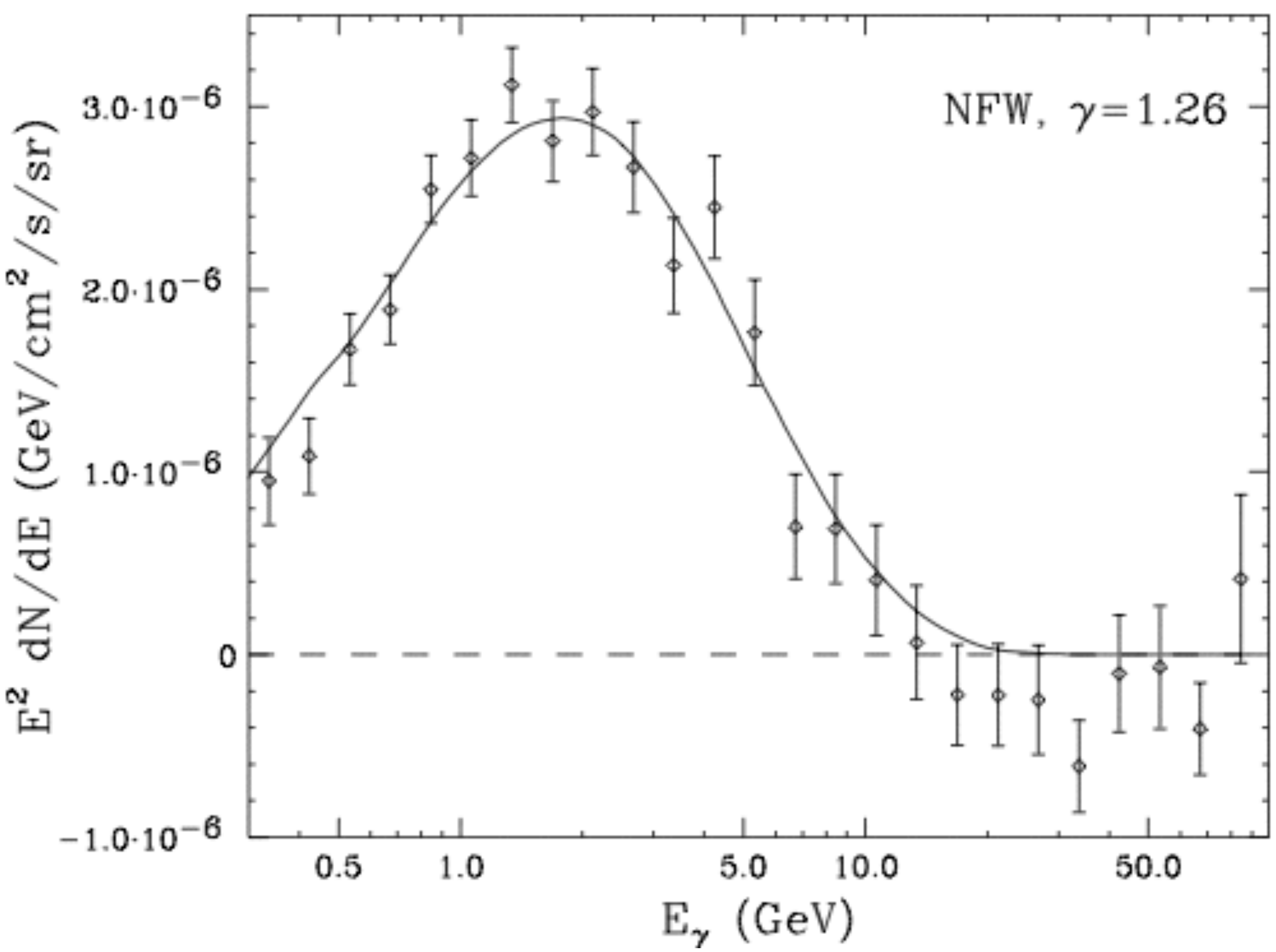
Daylan+ 2014

The residual if we do not include the “NFW” template looks like this:



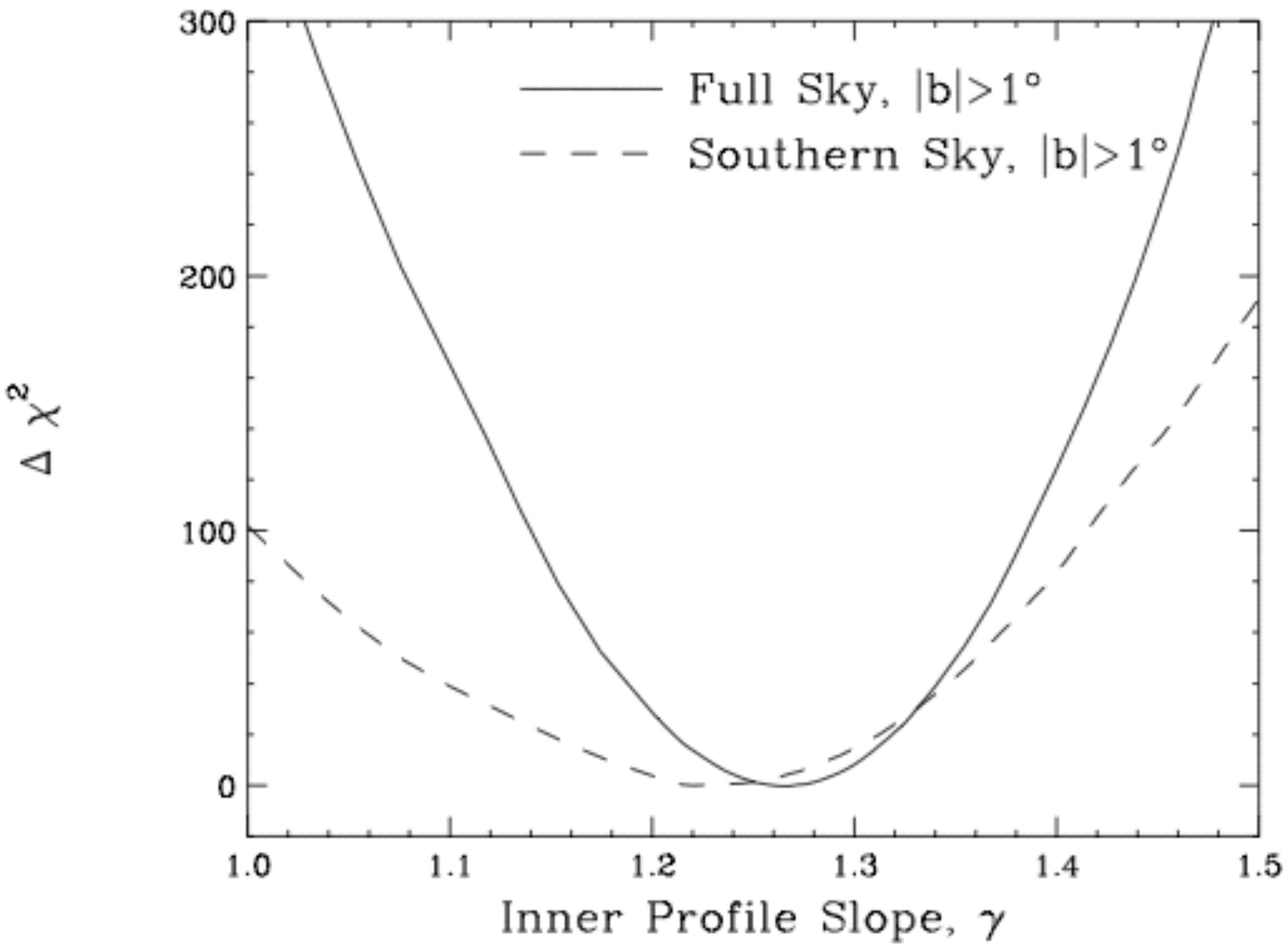
Daylan+ 2014

If we do include it, the spectrum is:



Daylan+ 2014

We can even constrain the slope of the profile



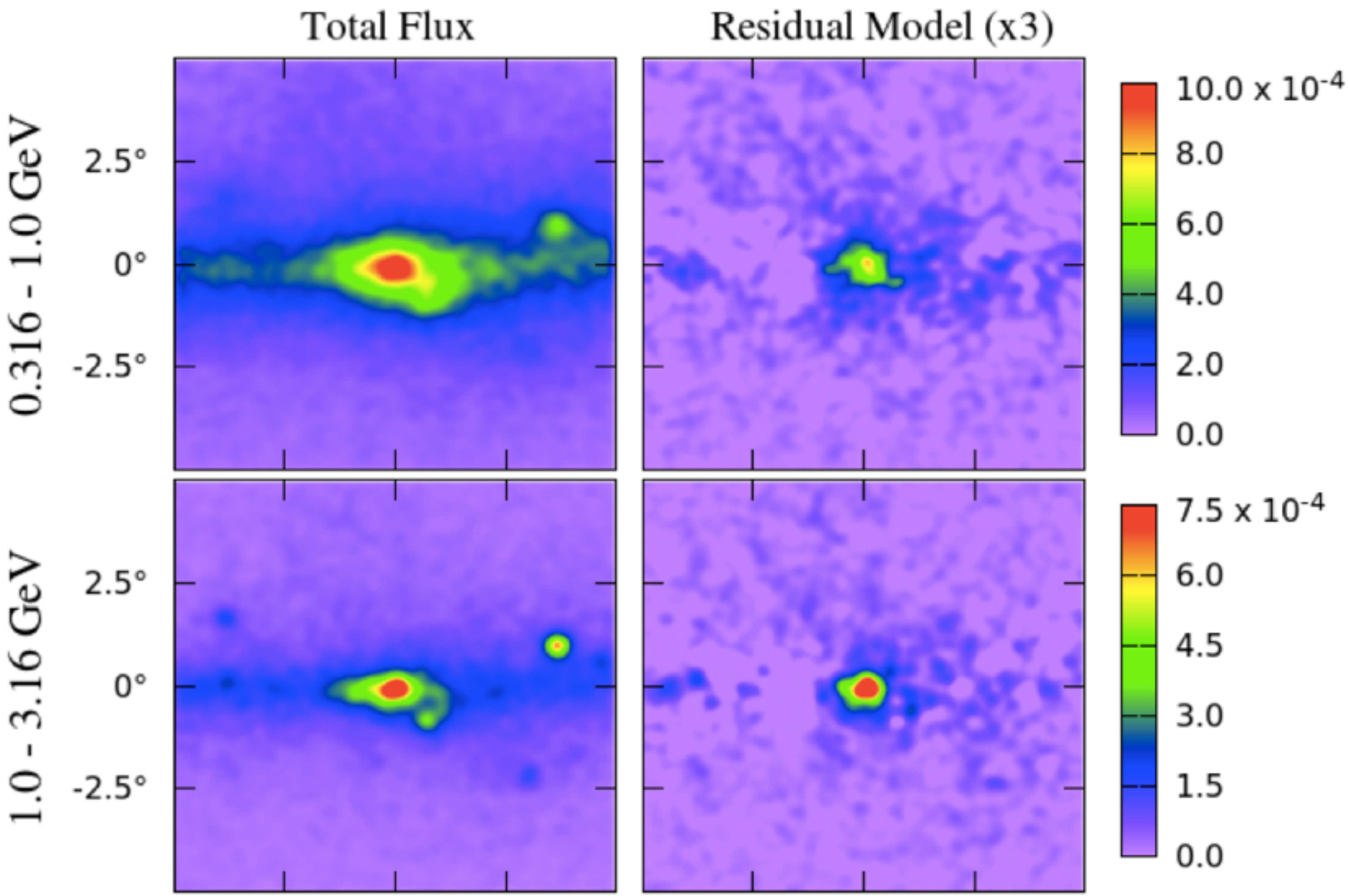
Daylan+ 2014

Now, the Galactic center ($|b| < 1$ degree)

model point sources explicitly, including GC source, look for excess

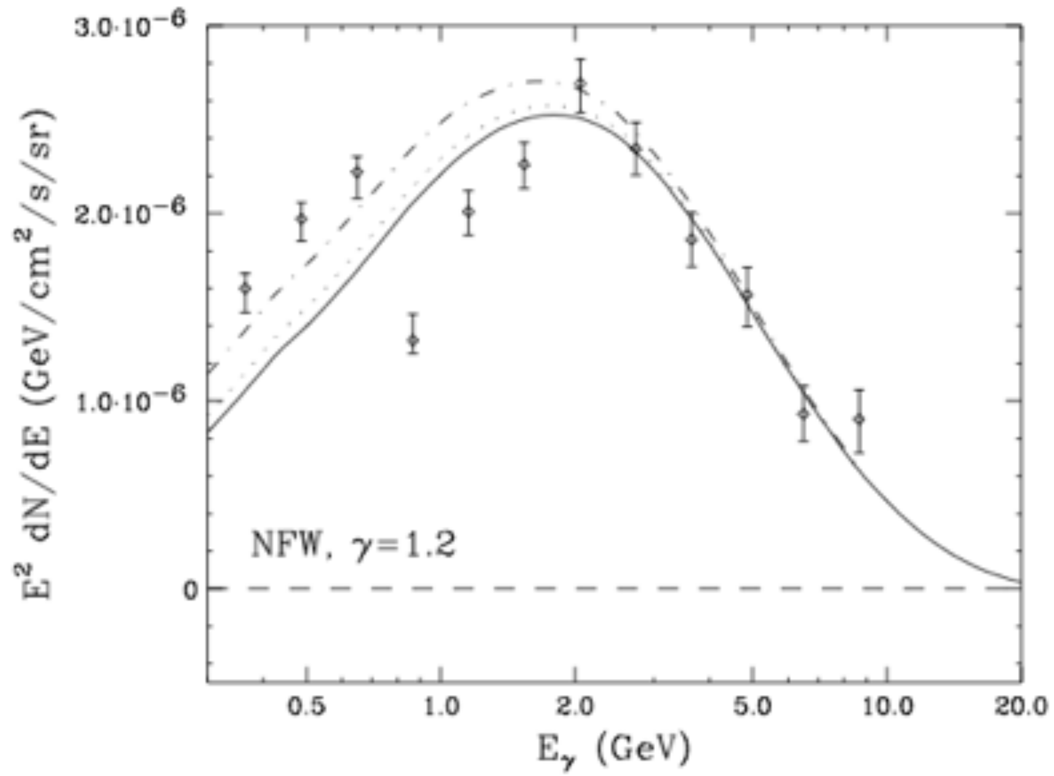
Daylan+ 2014

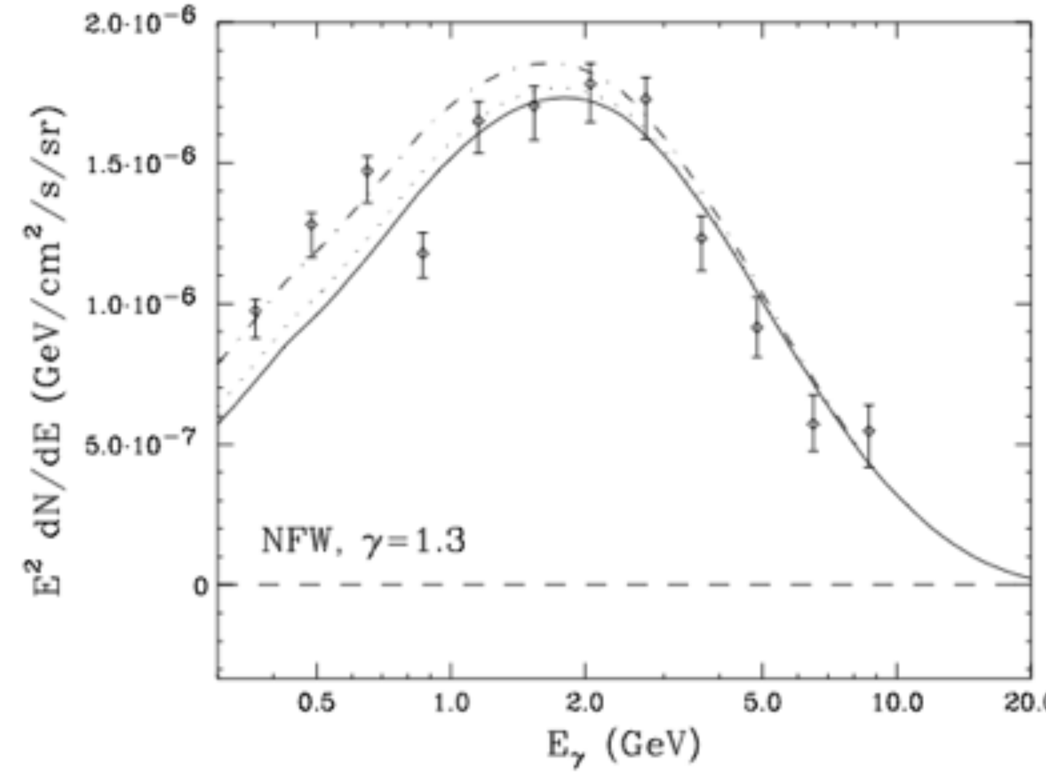
Now, the Galactic center (|b| < 1 degree)

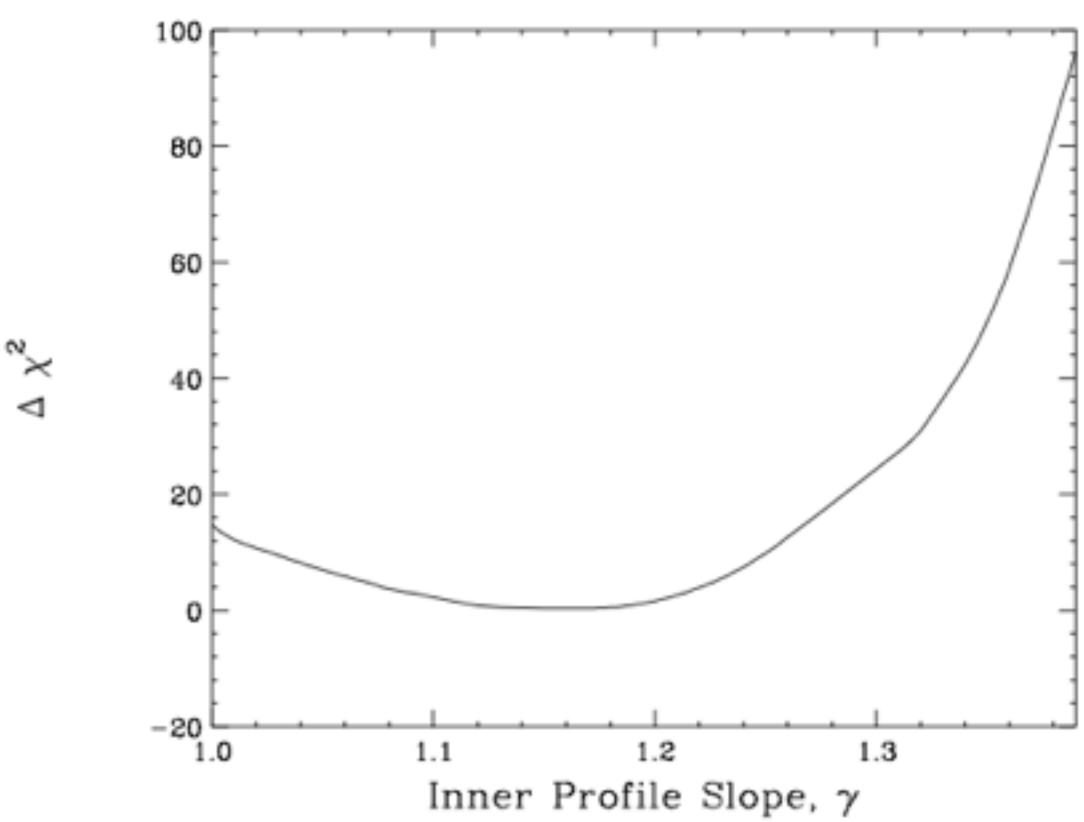


Daylan+ 2014

The spectrum is similar, and show is the implied DM profile







Daylan+ 2014

But we have *forced* it to have an NFW-like shape.
Now let's fix the energy spectrum and let the radial profile float:

Daylan+ 2014

But we have *forced* it to have an NFW-like shape.
Now let's fix the energy spectrum and let the radial profile float:

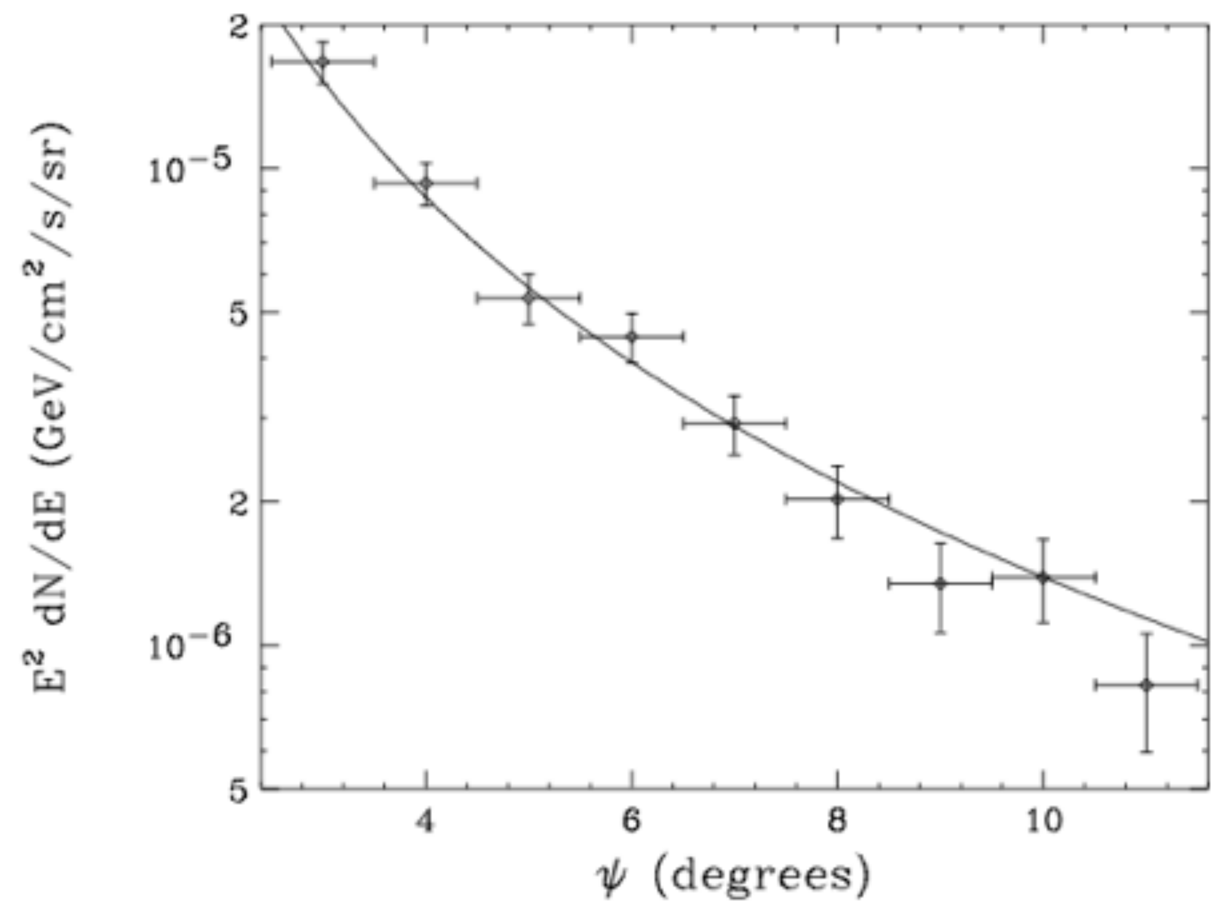


FIG. 13: To constrain the degree to which the gamma-ray excess is spatially extended, we have repeated our Inner Galaxy analysis, replacing the dark matter template with a series of concentric ring templates centered around the Galactic Center. The dark-matter-like emission is clearly and consistently present in each ring template out to $\sim 12^\circ$, beyond which systematic and statistical limitations make such determinations difficult. For comparison, we also show the predictions for a generalized NFW profile with $\gamma = 1.4$.

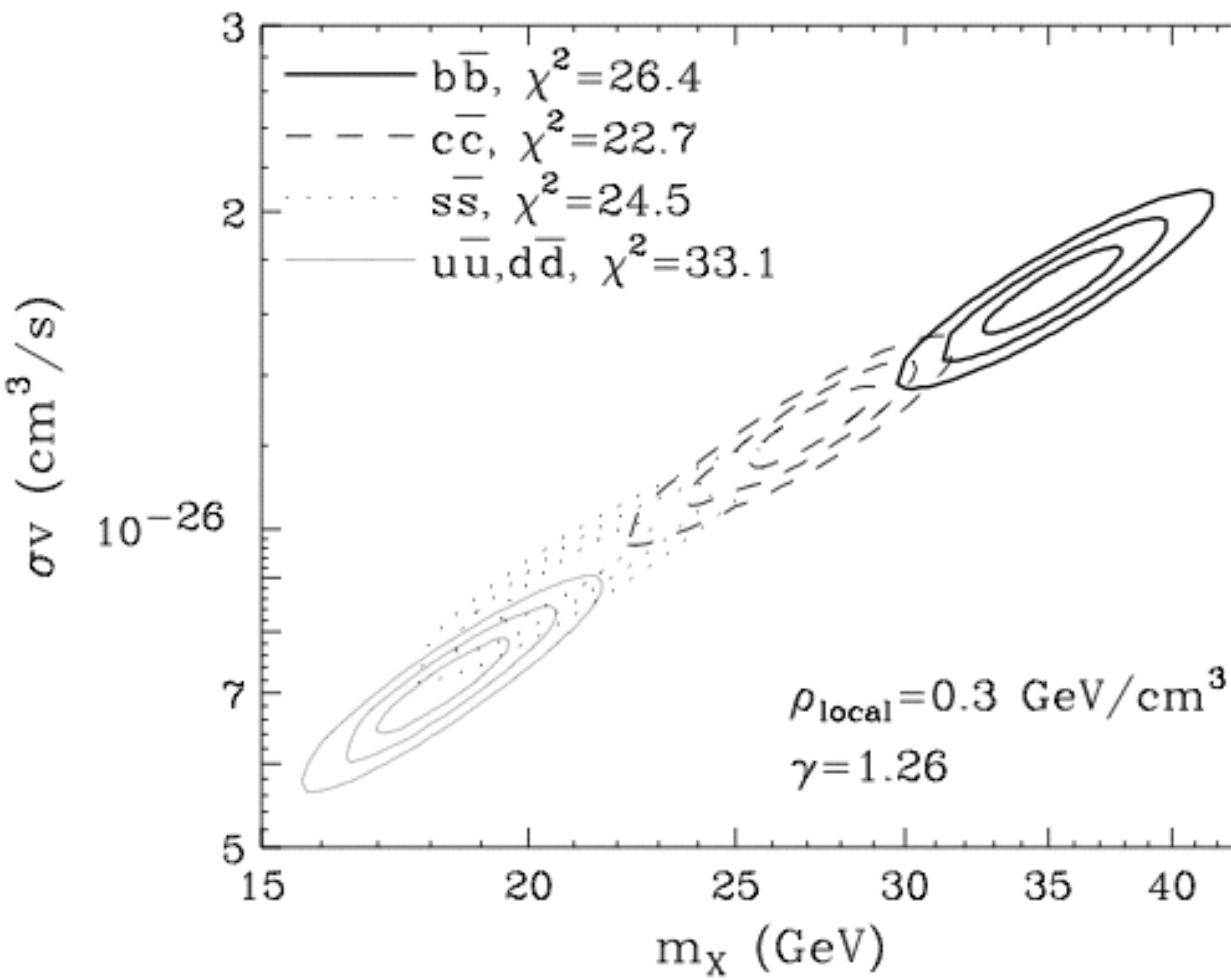
Daylan+ 2014

OK, so there is some signal there that is not in the Fermi diffuse model.
What if it is DM?

Daylan+ 2014

OK, so there is some signal there that is not in the Fermi diffuse model.
What if it is DM?

The implied mass is 20-40 GeV and cross section is just below thermal relic(!)



Daylan+ 2014

There will much more on this tomorrow…

Fermi Diffuse Model

This gamma-ray excess may be a dark matter annihilation signal, but this interpretation depends on a model of the “ordinary” diffuse emission (from π^0, inverse Compton, and bremsstrahlung).

Indeed, the diffuse model will be an essential part of any claim of astrophysical DM detection. (Even if we find it in the dwarf galaxies, we want confirmation from the inner Galaxy).

We need a better diffuse model.

(c.f. earlier talk by L. Tibaldo)

Dreams of future data:

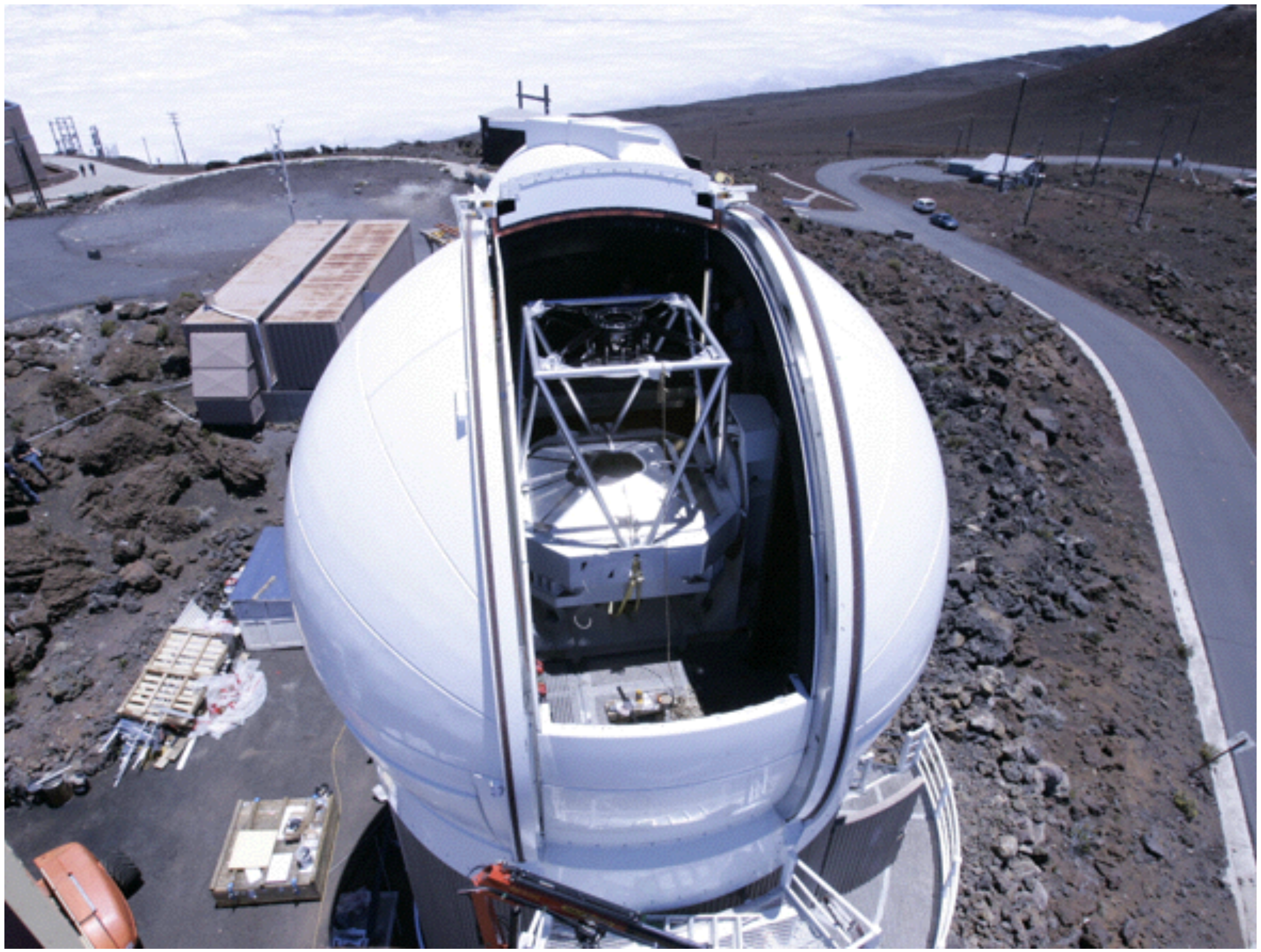
Suppose we knew the location, luminosity, and metallicity of *every star* in the MW, and the amount of dust and gas in every volume element. With a model of cosmic ray density, we could compute

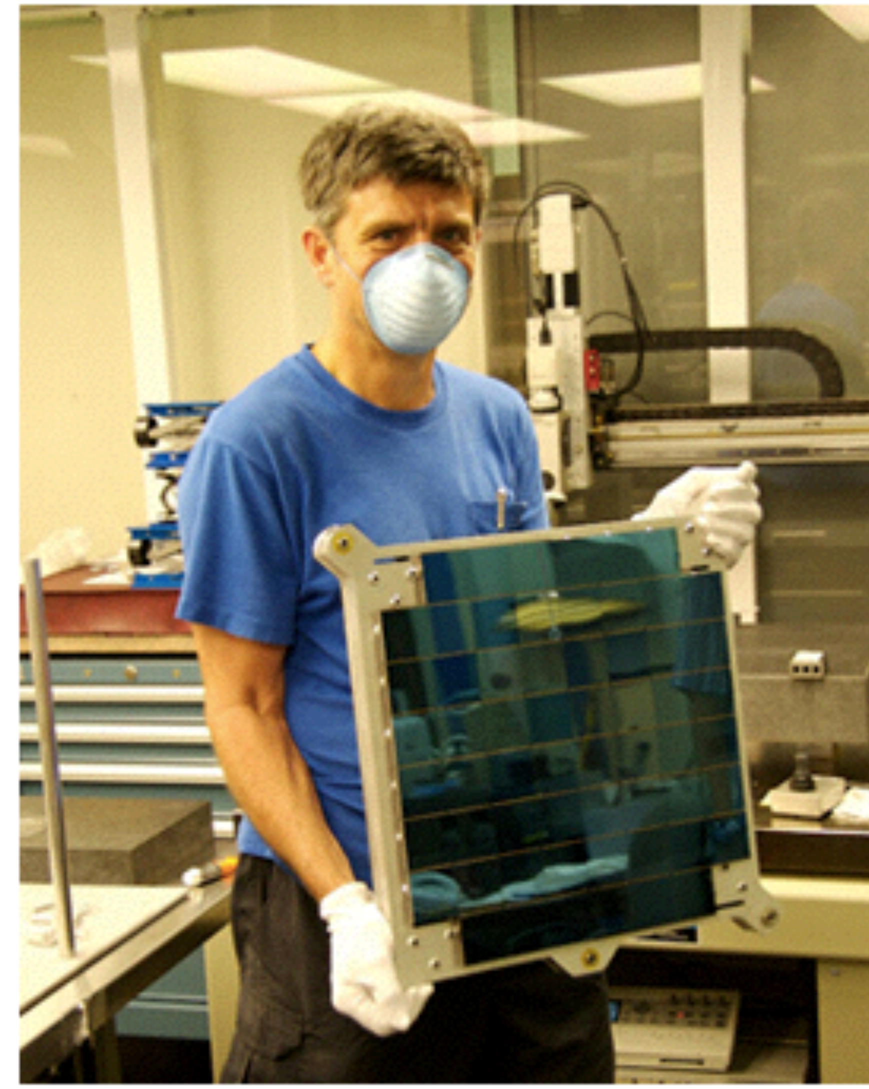
- The full 6D radiation field of the Galaxy
- The inverse Compton from electrons scattering the radiation
- π^0 emission from protons hitting the gas/dust
- bremsstrahlung from electrons hitting the gas/dust

So, how do we make these maps?

Pan-STARRS

(The Panoramic Survey Telescope and Rapid Response System)





John Tonry of the Institute for Astronomy holds an entire array of 60 chips; an array of 60 OTAs will be installed in the focal plane of each of the four telescopes in the Pan-STARRS facility.

1.4 billion pixel camera

1.8m telescope on Haleakala

3π sr coverage in 5 bands (g,r,i,z,y)

Eugine Magnier (UH IfA), Peter Draper & Nigel Metcalfe (Durham University), ©PS1 Consortium

3-D dust with Pan-STARRS

What can we learn about dust using g,r,i,z,y photometry of 500,000,000 stars?

- Distance to specific dust clouds
- Combine with HI, CO maps to identify distances to velocity components
- 3-D stellar map
- “Virgo overdensity,” tidal streams, dwarf galaxies...
- Prelude to GAIA

3-D dust with Pan-STARRS

Greg Green

Bayesian pundit,
MCMC connoisseur

Eddie Schlafly

Calibrator in chief

Mario Jurić

Database guru

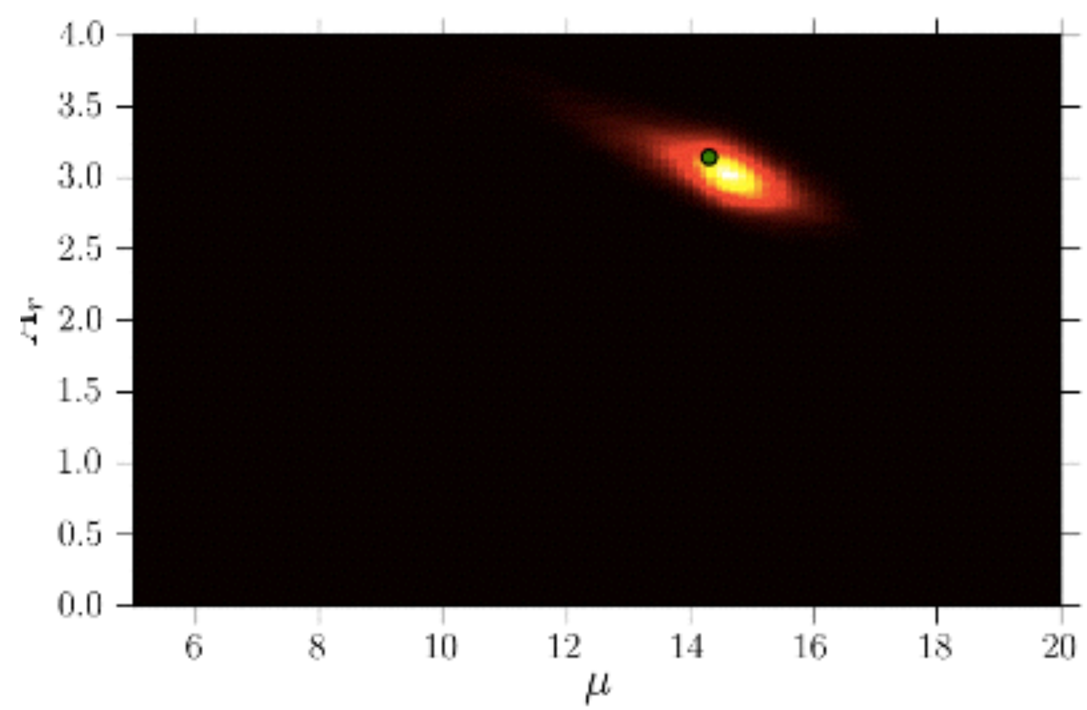
3-D dust with Pan-STARRS

- Pan-STARRS has collected photometry on $\sim 5 \times 10^8$ stars.
- Group stars into sufficiently small pixels.
- Calculate photometric parallax and reddening for each star.
- Find reddening profile as a function of distance which is consistent with all stars in pixel.

3-D dust with Pan-STARRS

For each star our goal is to compare a stellar template library with observed apparent stellar magnitudes in order to determine the joint posterior $p(\mu, A_r \,|\, \vec{m}_{\rm obs})$. Here,

$$\mu = \text{Distance Modulus}\,,$$
$$A_r = \text{Extinction in } r \text{ band}\,,$$
$$\vec{m}_{\rm obs} = \text{Observed } grizy \text{ apparent magnitudes}\,.$$



3-D dust with Pan-STARRS

Two intrinsic parameters used to describe star:

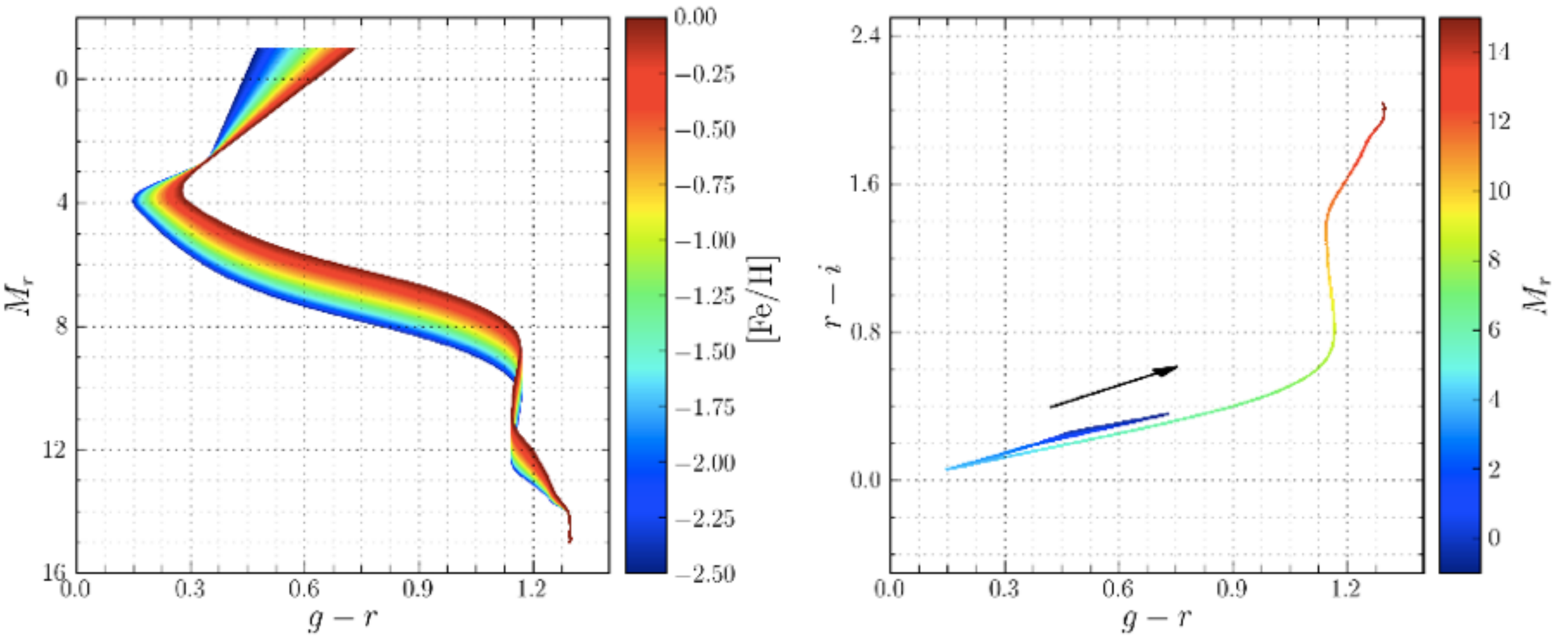
- M_r
- $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right]$

Two extrinsic parameters per star:

- μ = distance modulus
- A_r = extinction in r-band

3-D dust with Pan-STARRS

- Colors are queried in a stellar template library indexed by M_r and $[^{Fe}/_{H}]$.
- $R_V = 3.1$ is assumed, fixing reddening vector.



3-D dust with Pan-STARRS

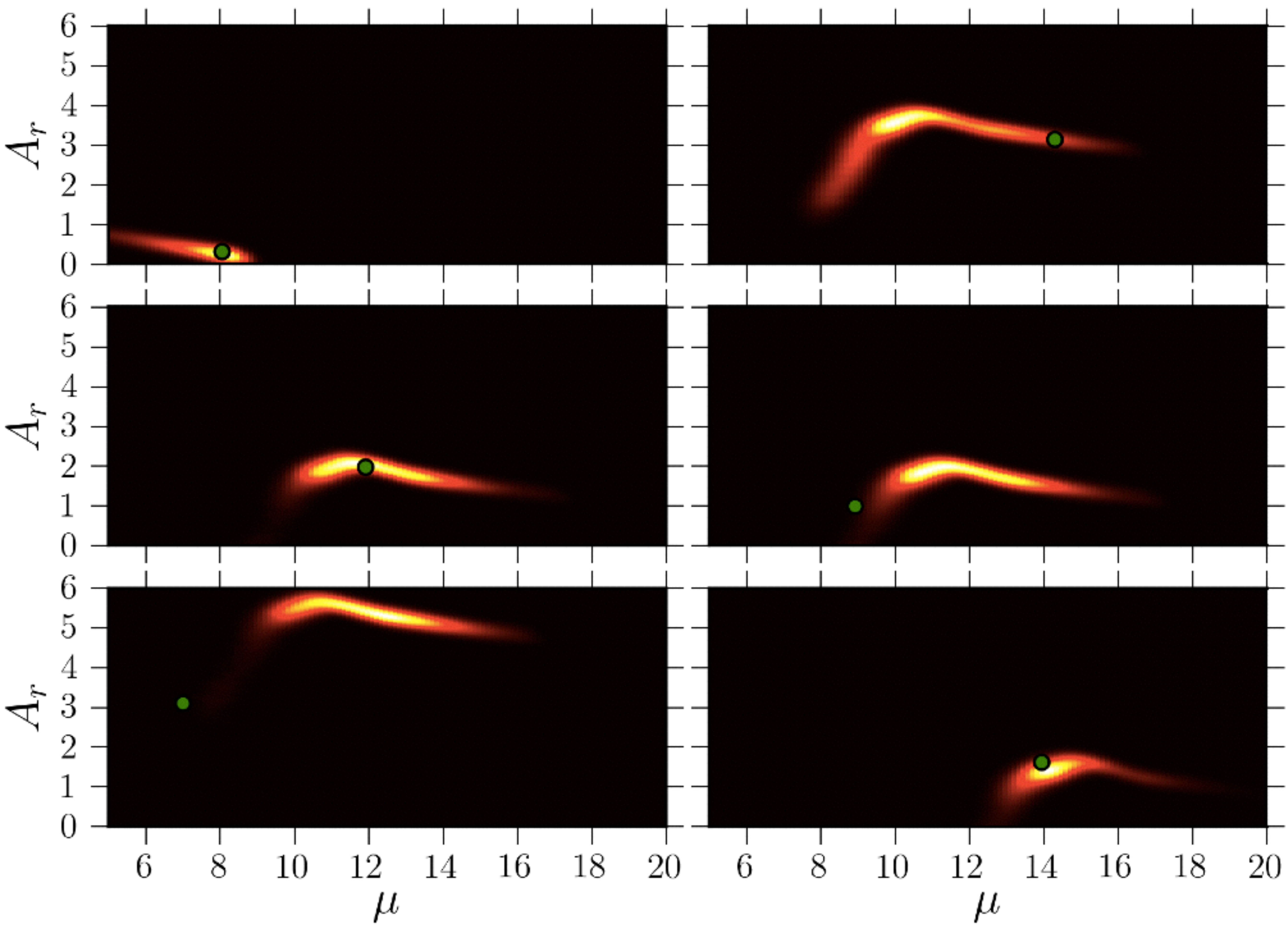
- Given M_r, $[^{Fe}/_{H}]$, μ and A_r, we generate apparent magnitudes:

$$\vec{m} = \vec{M}(M_r, [^{\mathrm{Fe}}/_{\mathrm{H}}]) + \vec{A}(A_r) + \mu \, .$$

- We can calculate the likelihood of the observed magnitudes, given a set of model parameters:

$$p\left(\vec{m}_{\mathrm{obs}} \,|\, \mu, A_r, M_r, [^{Fe}/_{H}]\right) = \mathcal{N}\left(\vec{m}_{\mathrm{obs}} - \vec{m}, \vec{\sigma}\right) \, .$$

- Use Markov-Chain Monte Carlo technique to sample from posterior.
    - Multimodality of posterior.
    - Population-based MCMC – “affine sampler” [Goodman & Weare, 2010].

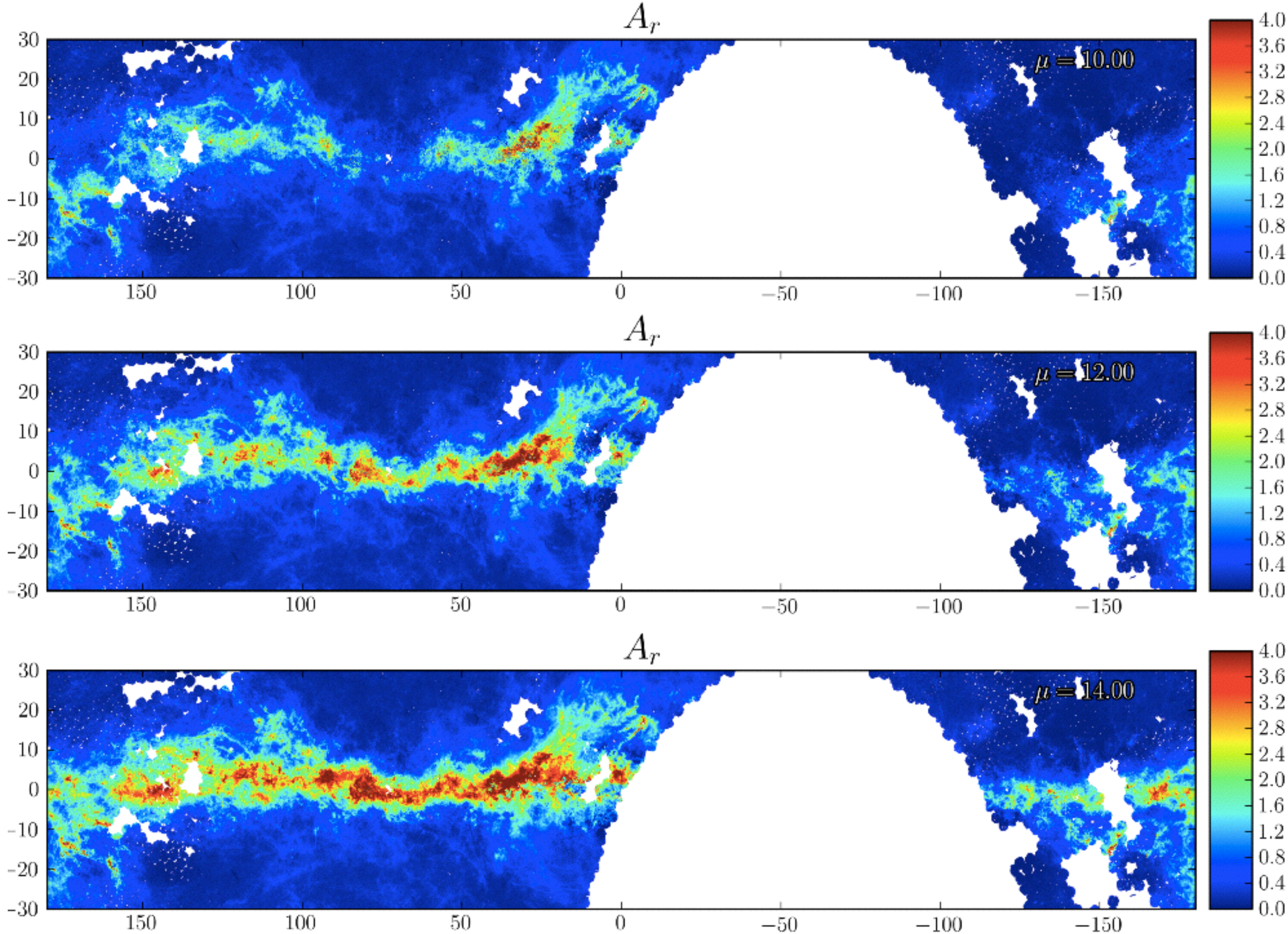


A_r
μ
0 1 2 3 4 5 6
6 8 10 12 14 16 18 20

Do this for many stars.

Combine 100-1000 stars per pixel to obtain estimate of dust along each line of sight.

Do this for millions of pixels.



A_r
$\mu = 10.00$
A_r
$\mu = 12.00$
A_r
$\mu = 14.00$
30
20
10
0
−10
−20
−30
150
100
50
0
−50
−100
−150
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

1. arXiv:1405.2922 [pdf, ps, other]

A Map of Dust Reddening to 4.5 kpc from Pan-STARRS1

E. F. Schlafly, G. Green, D. P. Finkbeiner, M. Juric, H.-W. Rix, N. F. Martin, W. S. Burgett, K. C. Chambers, P. W. Draper, K. W. Hodapp, N. Kaiser, R.-P. Kudritzki, E. A. Magnier, N. Metcalfe, J. S. Morgan, P. A. Price, C. W. Stubbs, J. L. Tonry, R. J. Wainscoat, C. Waters

Comments: 10 pages, 7 figures, accepted for publication in ApJ

Subjects: **Astrophysics of Galaxies (astro-ph.GA)**

2. arXiv:1403.3393 [pdf, ps, other]

A Large Catalog of Accurate Distances to Molecular Clouds from PS1 Photometry

E. F. Schlafly, G. Green, D. P. Finkbeiner, H.-W. Rix, E. F. Bell, W. S. Burgett, K. C. Chambers, P. W. Draper, K. W. Hodapp, N. Kaiser, E. A. Magnier, N. F. Martin, N. Metcalfe, P. A. Price, J. L. Tonry

Comments: 16 pages, 4 figures

Subjects: **Astrophysics of Galaxies (astro-ph.GA)**

3. arXiv:1401.1508 [pdf, ps, other]

Measuring Distances and Reddenings for a Billion Stars: Towards A 3D Dust Map from Pan-STARRS 1

Gregory Maurice Green, Edward F. Schlafly, Douglas P. Finkbeiner, Mario Jurić, Hans Walter Rix, Will Burgett, Kenneth C. Chambers, Peter W. Draper, Heather Flewelling, Rolf Peter Kudritzki, Eugene Magnier, Nicolas Martin, Nigel Metcalfe, John Tonry, Richard Wainscoat, Christopher Waters

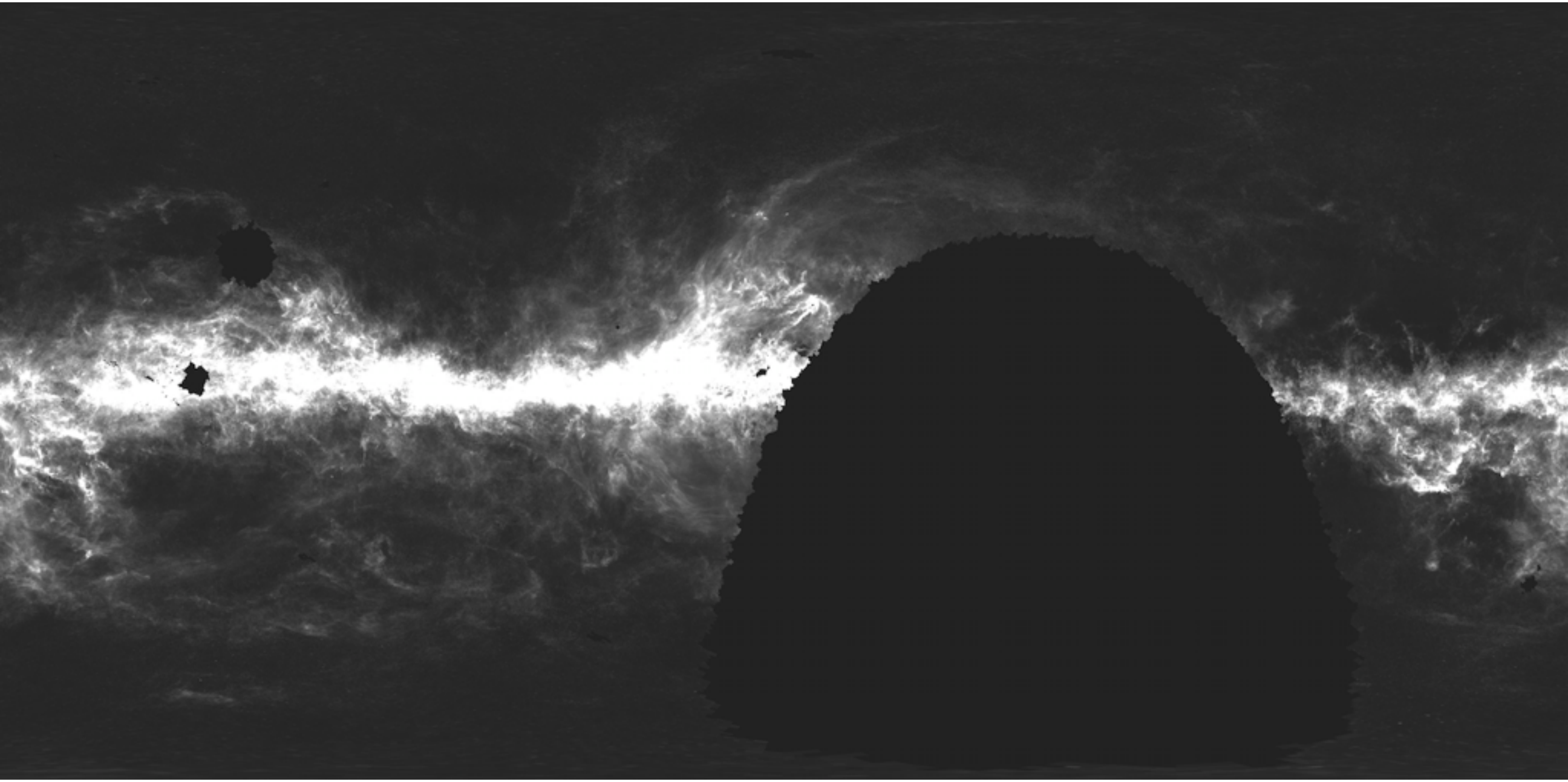
Comments: 18 pages, 12 figures

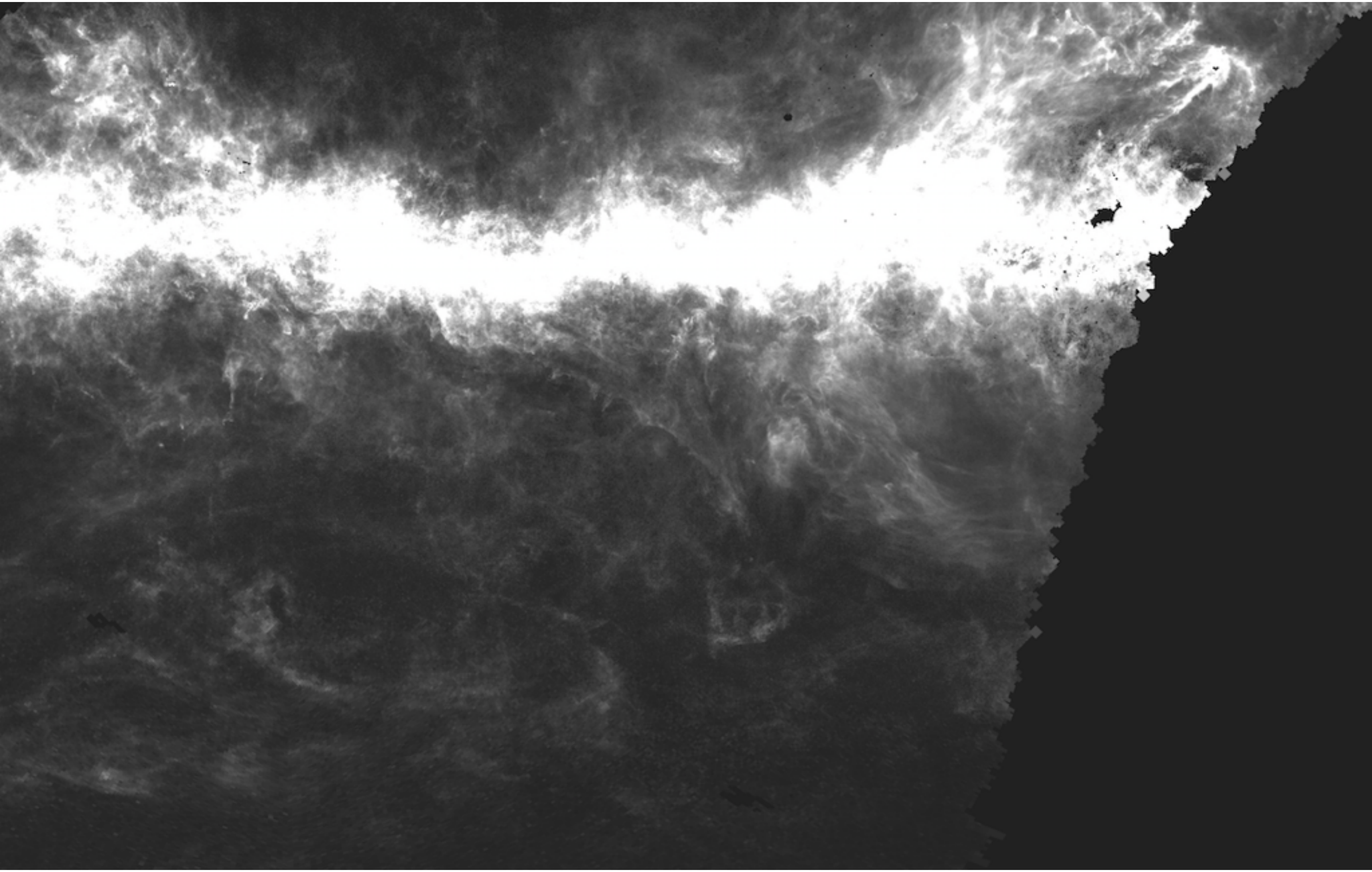
Subjects: **Astrophysics of Galaxies (astro-ph.GA)**

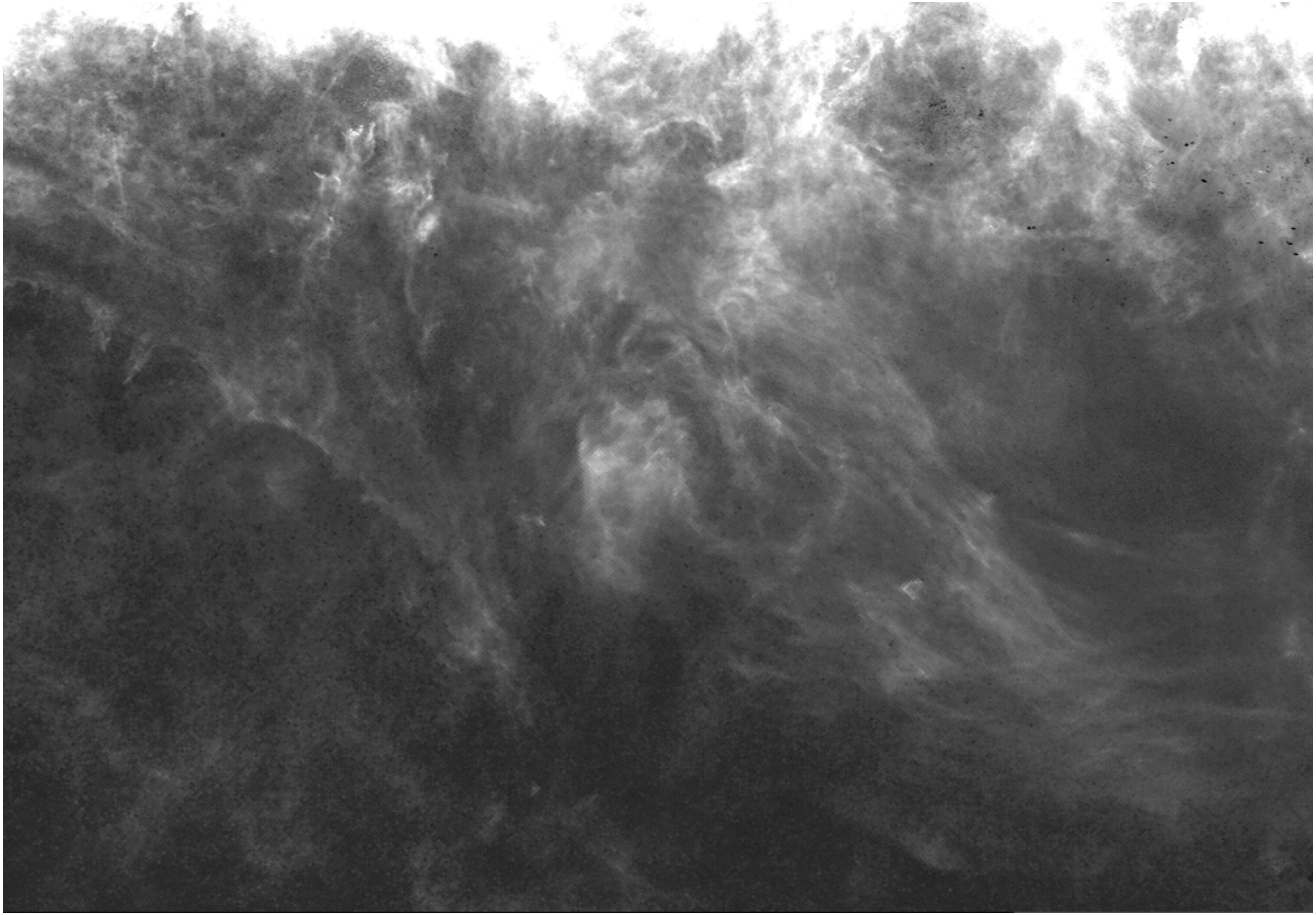
We are already making maps over 3/4 of the sky. DECam will fill in the rest (eventually).

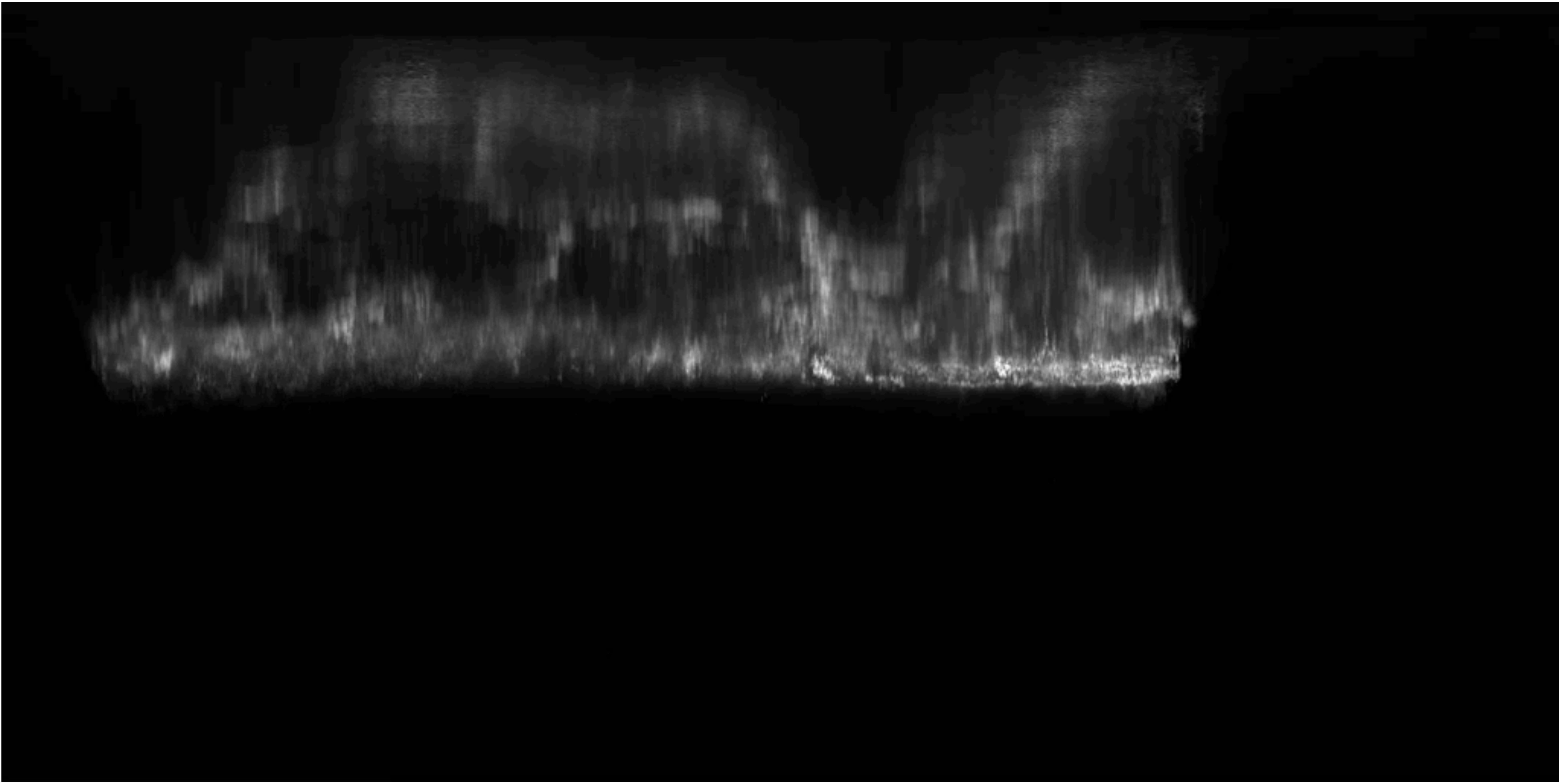
GAIA and LSST will be a big help.

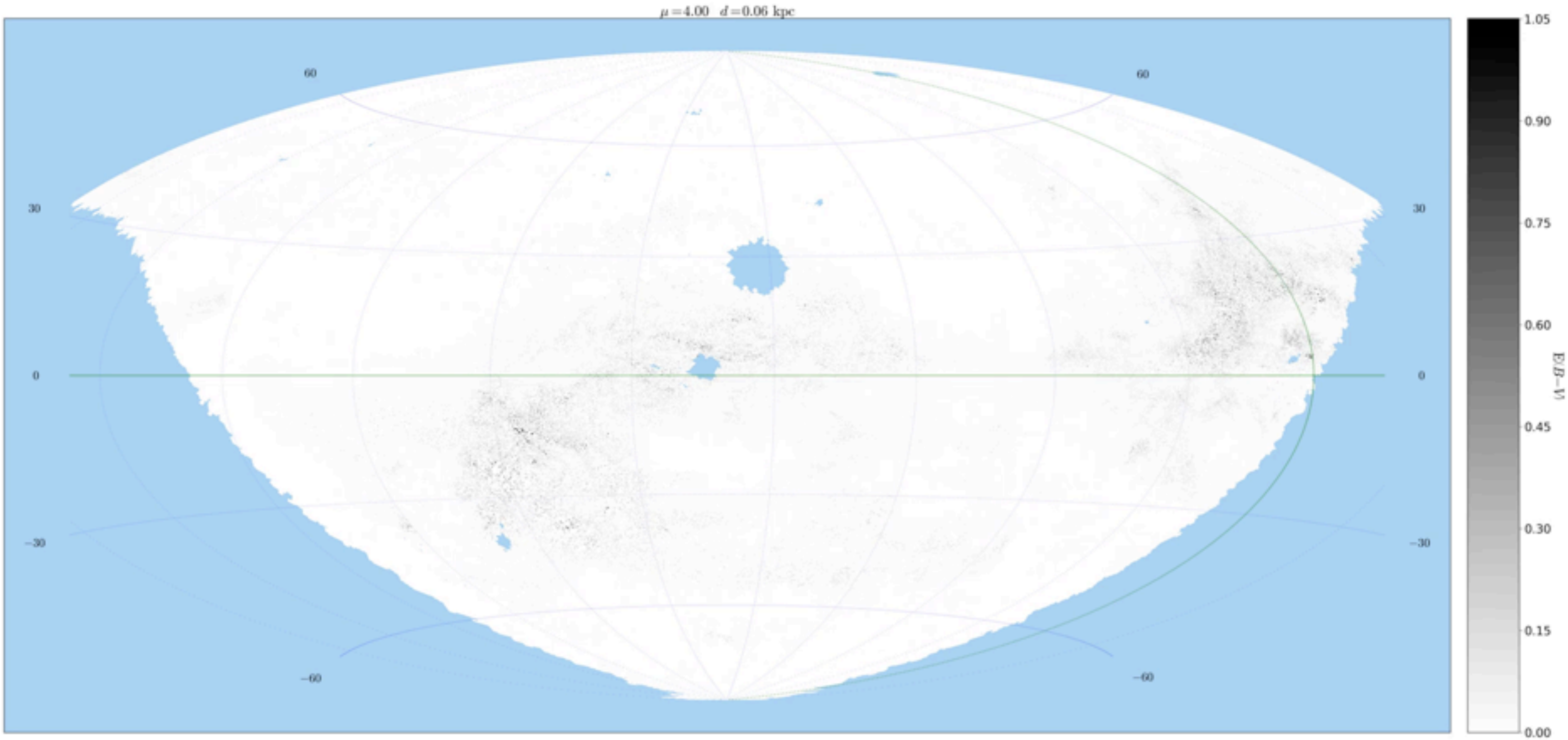
Dust integrated to 10 kpc, over 3/4 of the sky:











Conclusions:

- The quest to understand dark matter is far from over.
- There have been many hints in recent years. Some fizzle, some we just stop talking about.
- The "Hooper" excess remains, is statistically robust, and is ~ simple to explain theoretically.
- We need confirmation from dwarfs, direct detection, etc.
- We need a better model of Galactic gamma-ray emission
- Using PS1, DECam, GAIA, LSST… we can make progress towards a better understanding of the MW, and lay the groundwork for an actual *discovery* of dark matter emission.