



Fermi  
Gamma-ray Space Telescope



# Tools for Creating Analysis Pipelines for Diffuse Emission Modeling and Dark Matter Searches

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Symposium

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- Dark Matter Catalog (DMCat) Project
- Software tools
  - *dmsky*: bookkeeping and modeling of DM targets
  - *fermipy.jobs* & *dmpipe*: DM target analysis pipeline
  - *fermipy.diffuse*: All-sky analysis for diffuse emission modeling
- Summary

# DM Catalog Project



## DMcat project

See Mattia's Talk

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- **DMcat project:** perform a combined search for Dark Matter (DM) from multiple targets.
- We plan to release the results in a format that can be used by the community to perform their own DM searches.

**Milky Way Halo**  
Large statistics, but diffuse background

**Satellite galaxies**  
Low background and good source id, but low statistics

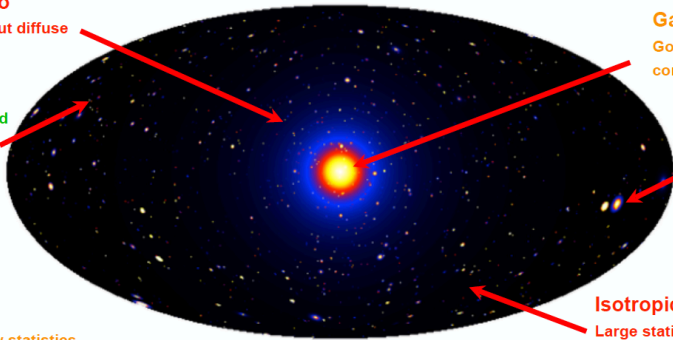
**Unassociated sources**

**Galaxy Clusters**  
Low background, but low statistics

**Targets already implemented**

**Targets will be considered in the future**

**Targets we will probably not consider**



**Galactic Center**  
Good statistics, but source confusion/diffuse background

**Nearby Galaxies**  
Good statistics, diffuse background

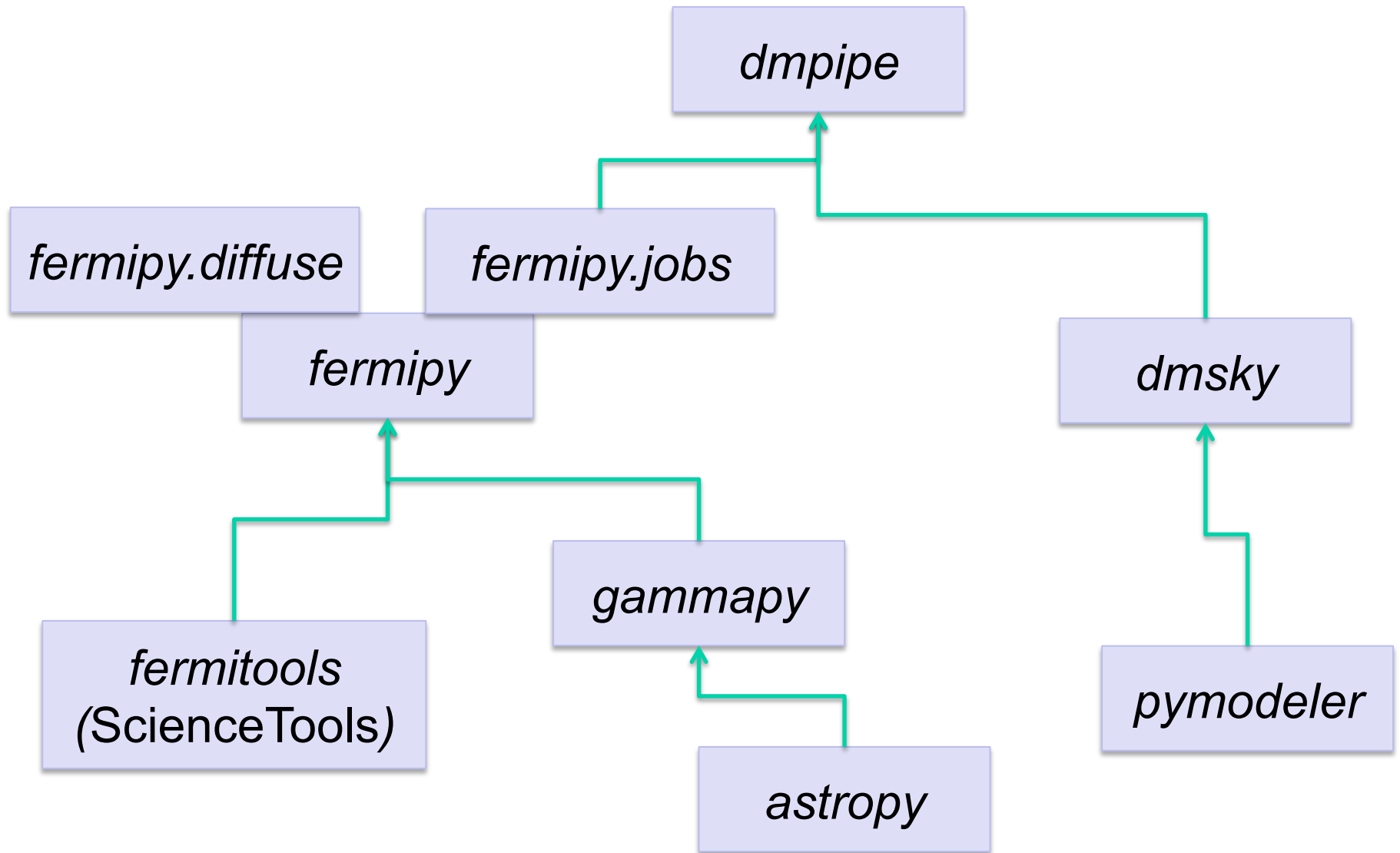
**Isotropic contributions**  
Large statistics, but astrophysics, Galactic diffuse background

**Spectral Lines**  
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

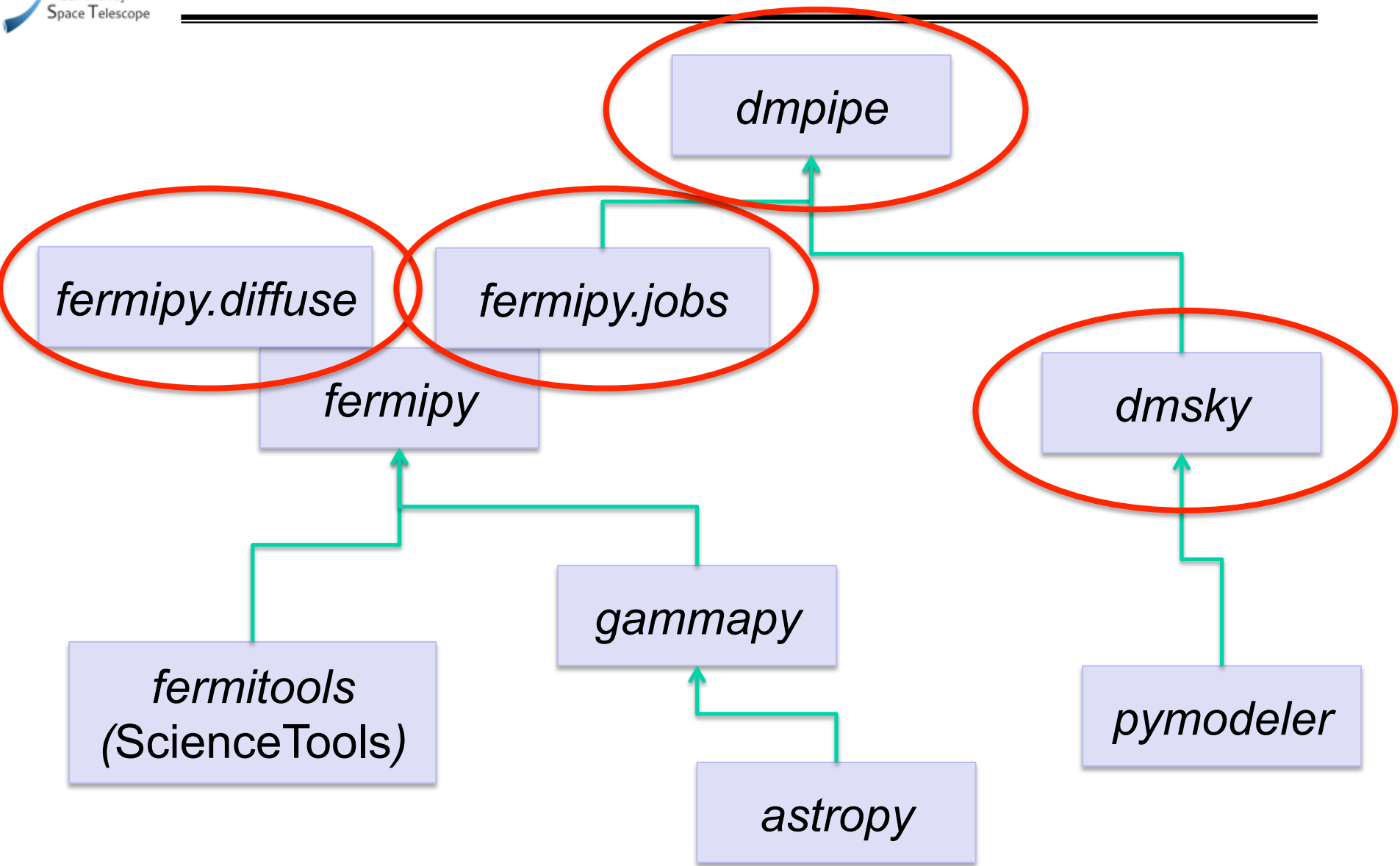
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- Mattia presented the DMcat project; this talk is about the underlying software.
- All of the software is publically available. We intend to release many of the intermediate data products as well.

# Software Tools (and dependencies)

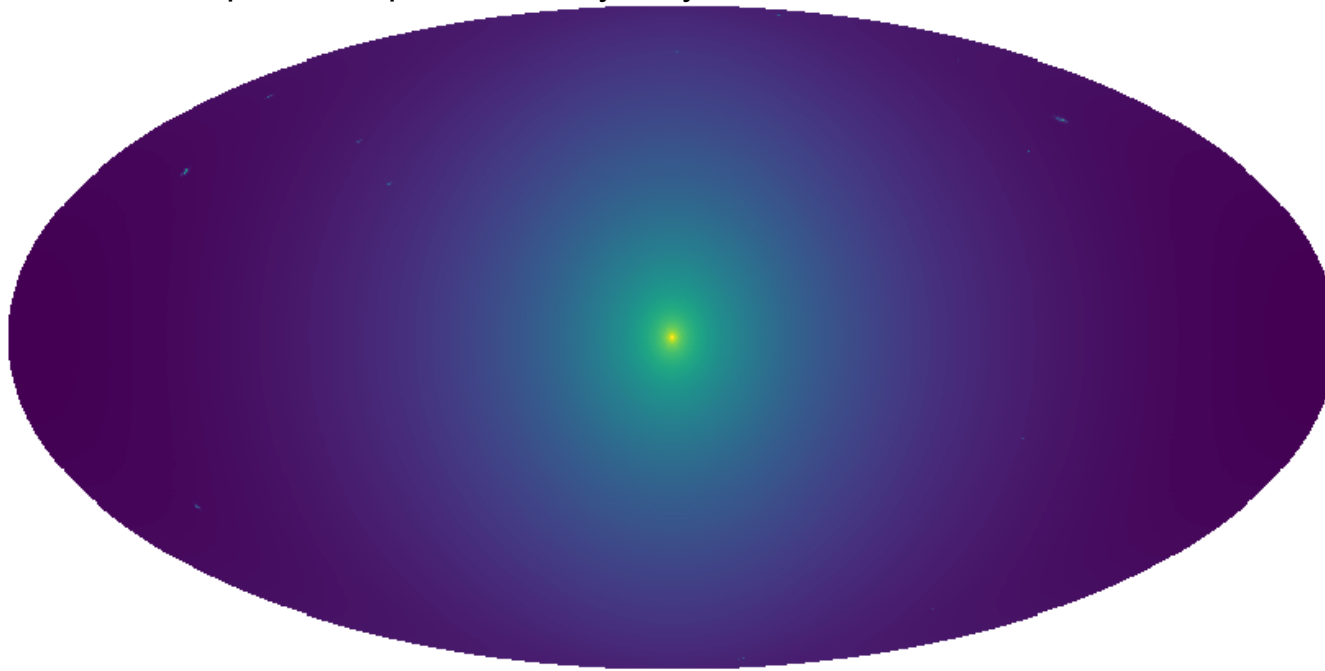


# Software Tools (and dependencies)



## *dmsky*: bookkeeping and modeling of DM targets

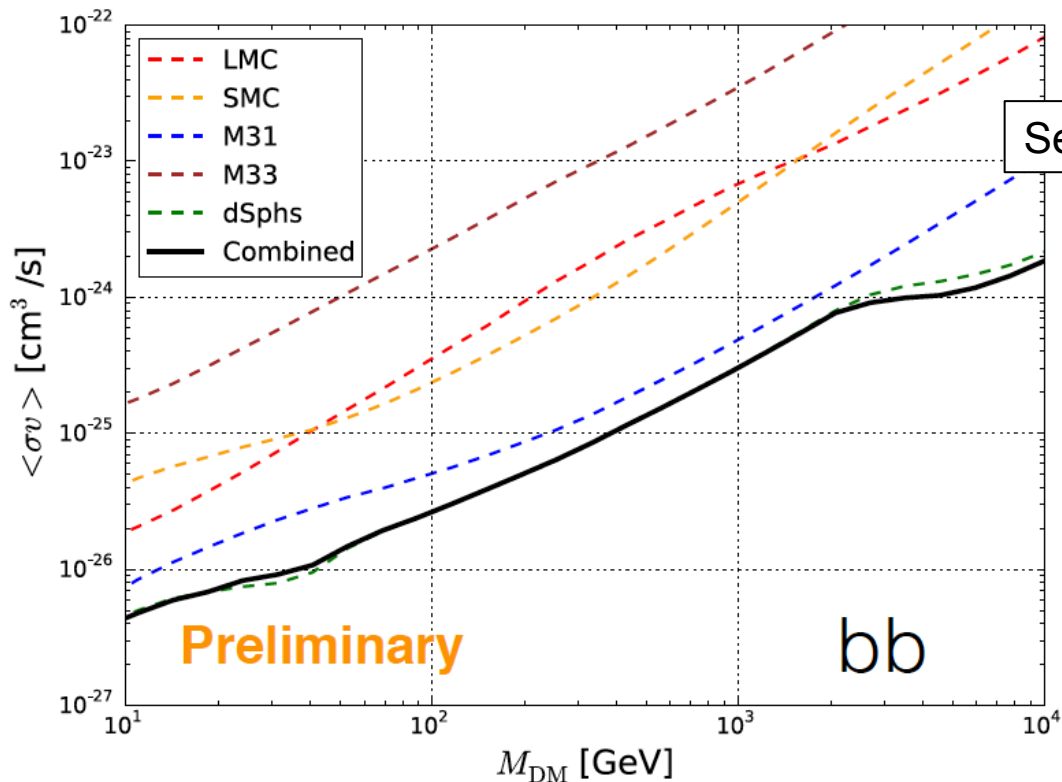
Combined J-factor Map from dSphs and Milky Way Halo: Galactic coordinates, Mollweide projection



- This all-sky J-factor map was generated using *dmsky*, and includes 24 Dwarf spheroidals (dSphs) and the Milky Way halo
- *dmsky* allow users to define DM density profile for many analysis targets
  - Performs line-of-sight integration to obtain astrophysical J-factors
- *dmsky* allows users to define “rosters” of targets for combined analyses

## *dmpipe*: DM analysis pipeline

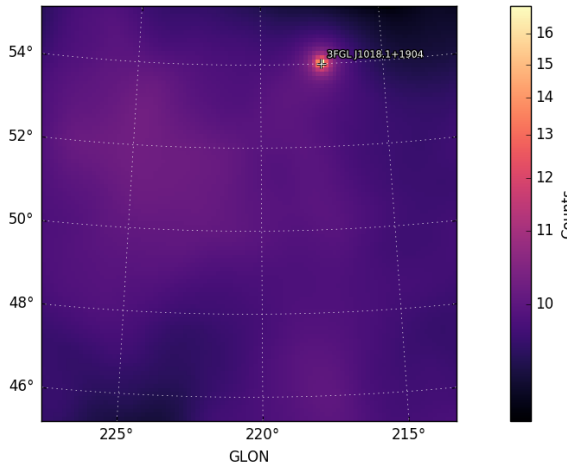
Combined DM  $\langle\sigma v\rangle$  Upper Limits from MW Satellites and Nearby Galaxies



- *dmpipe* was used to produce combined results from MW satellites (dSphs, LMC, SMC) & nearby Galaxies (M31, M33)
- Analysis pipeline chains together many standalone steps
  - Similar to the way that the *fermitools* work
  - *fermipy.jobs* provides a way to run the entire pipeline at once

# DM Analysis Pipeline Steps

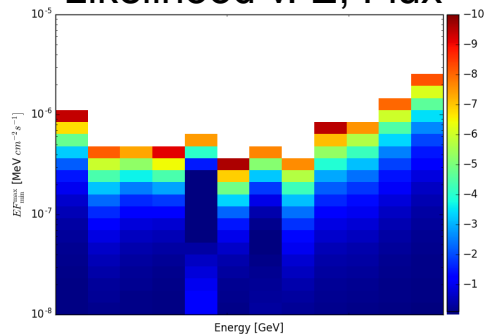
Single Target  
ROI Baseline Analysis



fermipy-analyze-sed



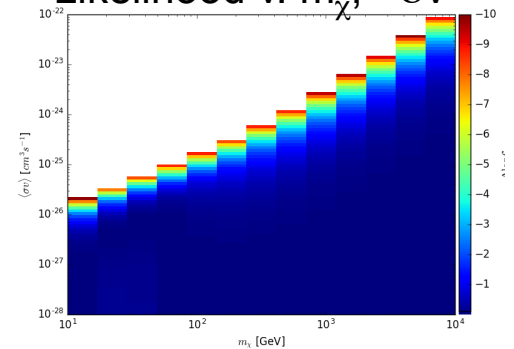
Target SED  
Likelihood v. E, Flux



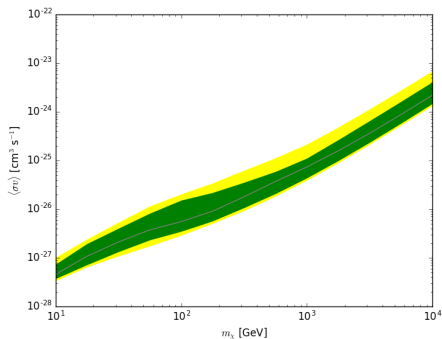
dmpipe-convert-castro



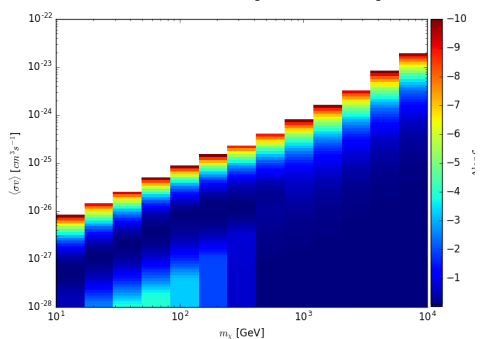
Target DM  
Likelihood v.  $m_\chi$ ,  $\langle\sigma v\rangle$



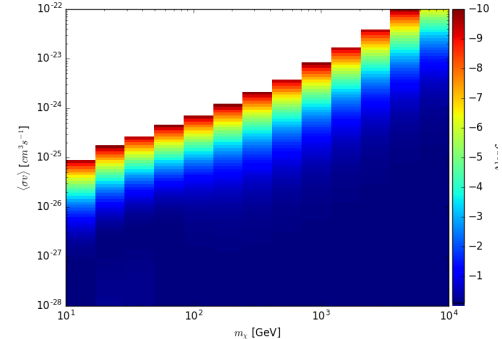
Expected upper limits  
from null-control simulations



Stacked DM Likelihood  
for all multiple dSphs



Target DM Likelihood  
w. J-factor uncertainties



dmpipe-collect-stacked-limits



dmpipe-stack-likelihood

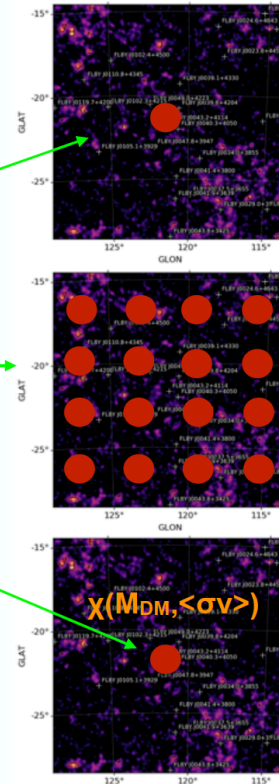




## Simulations

See Mattia's Talk

- It is also possible to perform simulations for the null signal or with an injected signal.
  - **sim\_null**: no sources at the location of the targets
  - **sim\_random**: searches for gamma-ray emission at different directions in the target ROIs.
  - **sim\_injected**: signal of DM emission with a given  $M_{DM}$  and  $\langle\sigma v\rangle$ .
- In the pipeline it is possible to chose different J profiles and priors to run the simulations with.

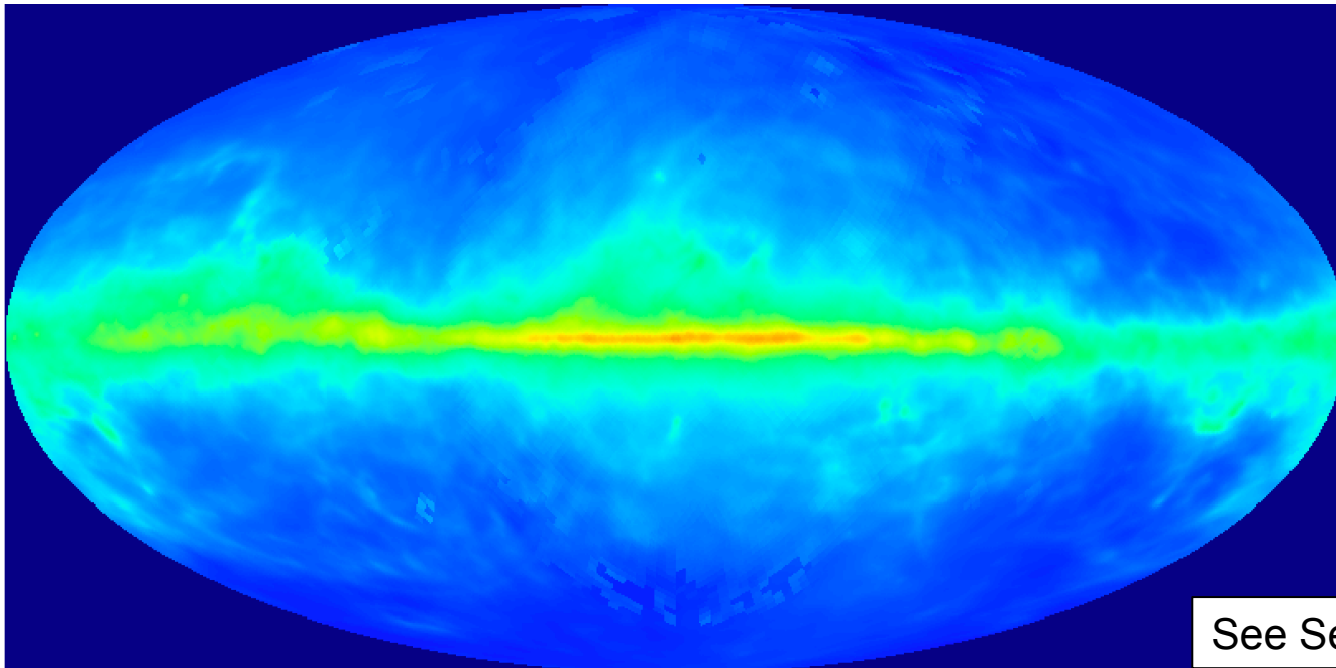


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- A significant (dominant?) part of DM analysis is performing standard control studies
- We have implemented standardized version of these in the *dmpipe* analysis pipeline

# *fermipy.diffuse*: All-sky Analysis for Diffuse Emission Modeling

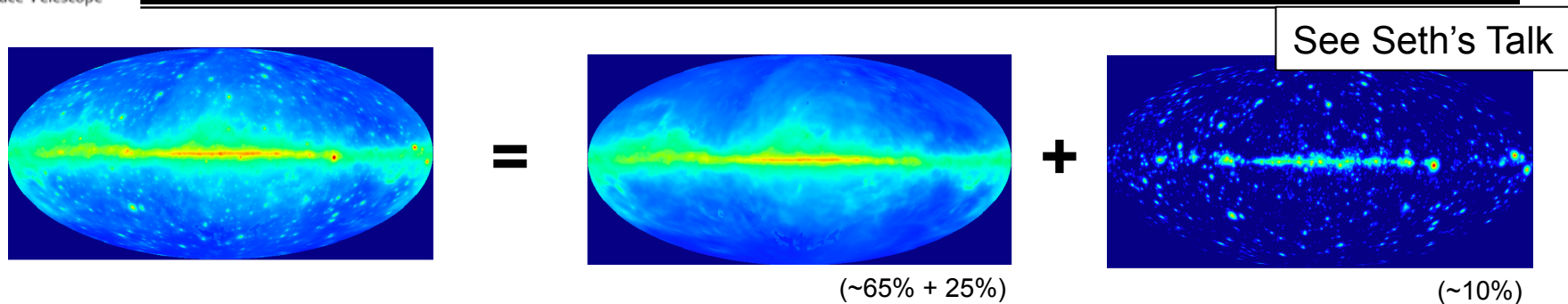
All-sky diffuse emission model, Galactic Coordinates, Aitoff Projection



See Seth's Talk

- Used to reproduce preliminary Pass 8 galactic diffuse emission model
- Official model will be produced with the custom GaRDIAN package
- This work allows us to reproduce and extend on that work in the *fermipy* and *fermitools* environment

# All-sky Diffuse Emission Modeling Pipeline



- The *fermitools* (formerly *Fermi-LAT ScienceTools*) did not originally support all-sky analysis
- All-sky Galactic diffuse emission models have been created using custom software
  - *GaDGET*, e.g., Ackermann, M. et al. 2015, ApJ, 799, 86A.
  - *GarDIAN*, e.g., Ackermann, M. et al. 2012, ApJ, 750, 3.
- As of *fermitools* version 1.0.0, specific tools do support all-sky analysis
  - However, it is not practical to analyze 5000+ FL8Y sources and 40+ diffuse emission components in a standard Fermi analysis
  - *fermipy.diffuse* analysis package parallelizes the data preparation

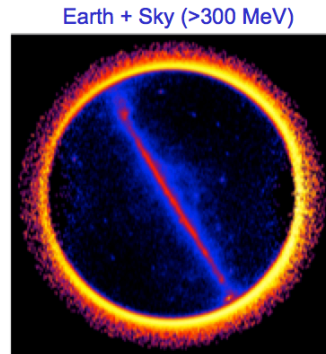
# All-Sky Diffuse Analysis Data Preparation

## LAT Data Set

fermipy-split-and-mktime-sg

- Joint analysis over 4  $\gamma$ -ray data sets
  - 8-year data set matching 4FGL selection
  - Different combinations of PSF event types and zenith angle limits, cutting more severely at lower energies, so that **residual Earth limb emission** does not need to be modeled.

Energy Range	Zen. max	Pass 8 Source PSF types
30–100 MeV	80°	3
100–300 MeV	90°	2, 3
300–1000 MeV	100°	1, 2, 3
1 GeV – 1 TeV	105°	0, 1, 2, 3



<https://aod.nasa.gov/aod/ap131206.html>

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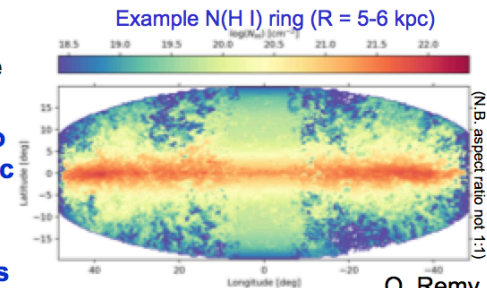
*fermipy.diffuse* data preparation tools to sub-select events, bin them in HEALPix maps, produce corresponding exposure maps

fermipy-sum-ring-gasmaps-sg

## Diffuse Emission Model Components

**Gas:** We use H I and CO spectral line surveys to trace (most of) the interstellar gas

- Doppler shifts are used to partition by Galactocentric distance (on kpc scales)
- Line profiles are used to estimate column densities
- Result is 'ring maps' for 10 ranges of Galactocentric distance
- These maps are taken to be the targets for cosmic-ray electrons and protons (Bremsstrahlung and  $\pi^0$  decay)
- 'Dark Gas' – neutral interstellar gas not traced properly in H I or CO
  - Using new Planck dust optical depth maps ( $\tau_{353}$ )
  - Improved angular resolution and dynamic range than SFD E(B-V), fewer artifacts around massive star-forming regions



Q. Remy

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*fermipy.diffuse* bookkeeping tools to combine templates from GALProp and other sources such as the sun, moon, Fermi bubbles, etc..

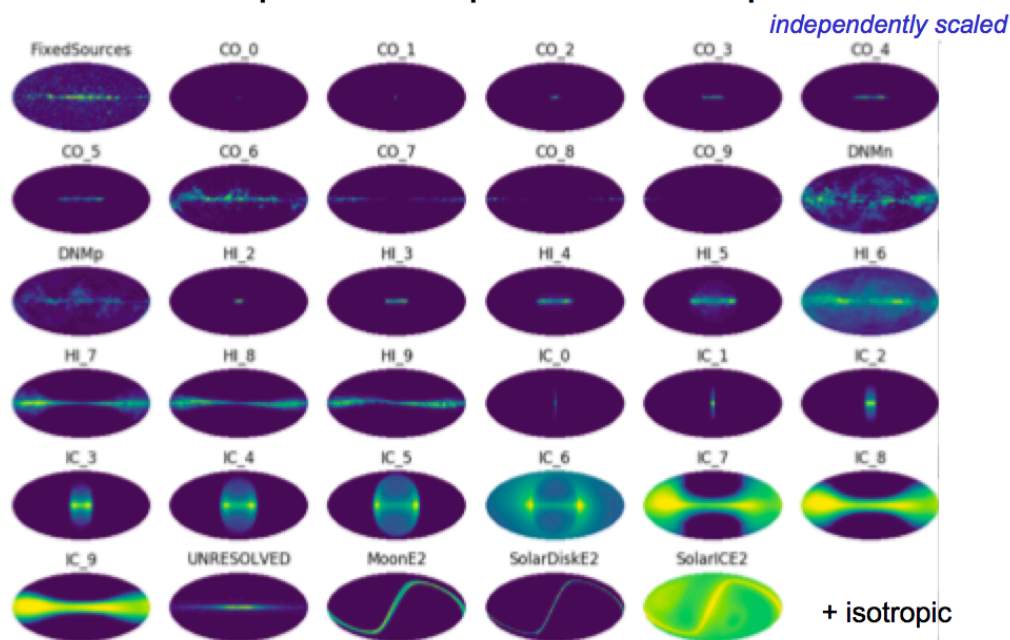
# All-Sky Predicted Counts Map Templates

fermipy-srcmap-diffuse-sg



## Example Templates (one energy band)

- These have been processed into predicted counts maps



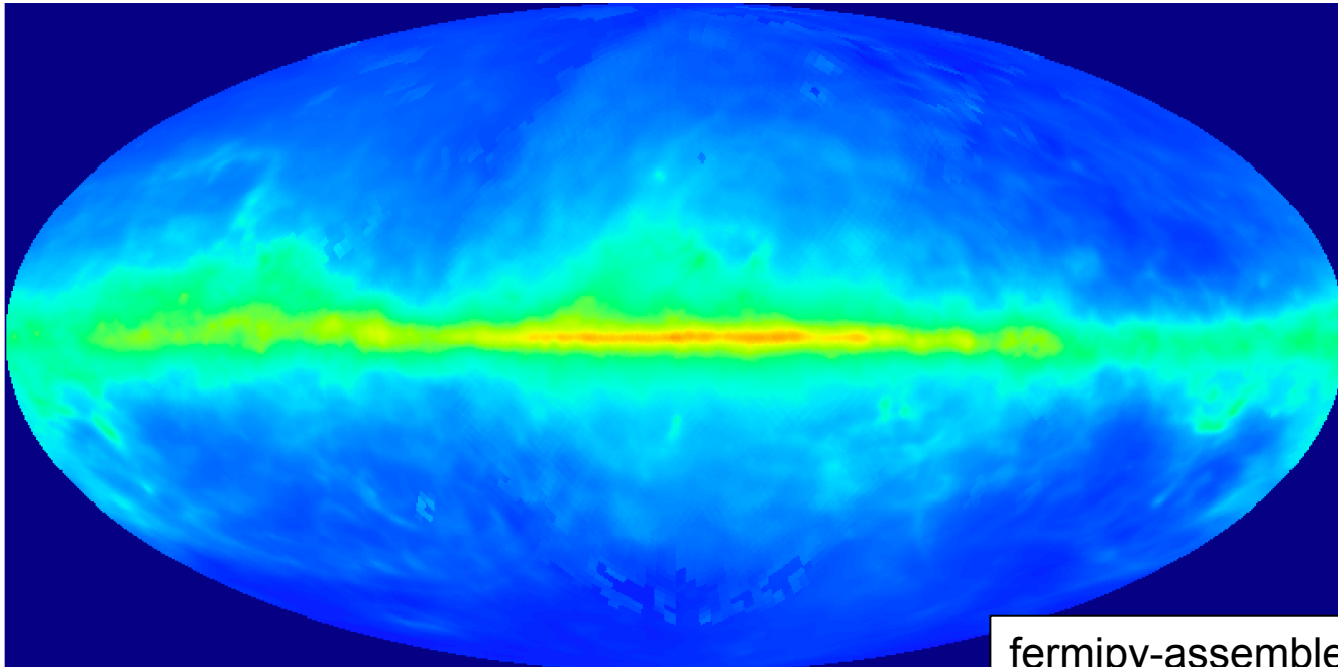
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- *fermipy.diffuse* tools to convolve component intensity maps with instrument response to produce predicted counts maps templates
- *fermipy.jobs* tools uses compute farm to run up to 500 cores simultaneously (total of ~8000 jobs for current model)

# Combining Templates into Emission Models

All-sky diffuse emission model, Galactic Coordinates, Aitoff Projection



fermipy-assemble-model

- *fermipy.diffuse* analysis pipeline produces a library of differential counts map templates sorted by emission component and energy range
- *fermipy.diffuse* package includes tools to combine these templates into diffuse emission models

## Summary

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- DM catalog project work includes providing software tools and intermediate results to allow people to combine and update results from different analysis targets
- The software exists in a combination of the *dmsky*, *fermipy* and *dmpipe* python packages (see additional slides for more details)
  - All of these packages are publically available via github and PyPI
  - Documentation and examples are available via readthedocs.io
- We plan to release intermediate data products along with our publications (see additional slides for more details)
  - Exact list of data products is still under discussion, and depends primarily on practicality and value to community

# MORE INFORMATION



## Package References

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- **astropy**: standard astronomical python library
  - <http://www.astropy.org/>
- **fermitools** (formerly ScienceTools): Fermi-LAT data analysis
  - <https://github.com/fermi-lat/Fermitools-conda>
- **gammapy**: gamma-ray data analysis libraries
  - <https://docs.gammapy.org/>
- **dmsky**: bookkeeping and modeling of DM targets
  - <https://dmsky.readthedocs.io/>
- **fermipy**: high level binned likelihood analysis of Fermi-LAT data
  - <https://fermipy.readthedocs.io/>
  - *fermipy.jobs*: tools to build analysis pipelines
  - *fermipy.diffuse*: tools for all-sky diffuse analysis
- **dmpipe**: DM analysis pipeline
  - <https://dmpipe.readthedocs.io/>

## dmsky package details

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- Installation:
  - `pip install dmsky`
- Documentation: <https://dmsky.readthedocs.io/>
- Code repo: <https://github.com/fermiPy/dmsky>
- Python Package Index: <https://pypi.org/project/dmsky/>
- Developers:
  - Alex Drlica-Wagner, Matthew Wood, Eric Charles
- Current version: dmsky 0.2.3
- Dependencies:
  - `numpy`, `healpy`, `astropy`, `pymodeler`

## *fermipy* package details:

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- Installation:
  - `pip install fermipy`
  - `conda install fermipy`
- Documentation: <https://fermipy.readthedocs.io/>
- Code repo: <https://github.com/fermiPy/fermipy>
- Python Package Index: <https://pypi.org/project/fermipy/>
- Developers:
  - Matthew Wood, Eric Charles, Mattia di Mauro, others...
- Current version: fermipy 0.17.3
- Dependencies:
  - `numpy`, `healpy`, `astropy`, `gammapy`, `fermitools`

## *dmpipe* package details:

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- Installation:
  - `pip install dmpipe`
- Documentation: <https://dmpipe.readthedocs.io/>
- Code repo: <https://github.com/fermiPy/dmpipe>
- Python Package Index: <https://pypi.org/project/dmpipe/>
- Developers:
  - Eric Charles, Mattia di Mauro
- Current version: dmpipe 0.1.2
- Dependencies:
  - `numpy`, `astropy`, `fermipy`, `dmsky`

## DM Pipeline Intermediate Data Products

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- Target J factor maps
- Pre-prepared events, spacecraft and livetime cube files
- Target ROI analysis inputs
  - Counts maps, exposure maps, “source map” templates
  - Model definitions
- Target ROI baseline analysis
  - *fermipy* Region of interest “snapshots”
- Target SED analysis
  - *fermipy* SED likelihood FITS files,  $L(E, F_E)$ 
    - <https://gamma-astro-data-formats.readthedocs.io/en/latest/spectra/>
- DM Likelihoods,  $L(m_\chi, \langle\sigma v\rangle)$ 
  - DM likelihood “castro” files, modified version of SED FITS files
- Simulation summary data
  - Expectation bands for limits and maximum likelihood estimate

## Diffuse Analysis Intermediate Data Products

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- Pre-prepared events, spacecraft and livetime cube files
- HEALPix Binned Counts maps
- HEALPix Exposure Maps
- GALProp predicted emission templates
- Merged GALProp predicted emission templates
  - E.g., combining Galacto-centric rings and correlated components
- “SourceMap” differential counts map templates
  - These are identical to the output of the *gtsrcmaps* tool
  - Produced in parallel for each diffuse emission component
  - Produced in batches for catalog sources

Caveat: all of these data products are specific to a given data selection, IRF set and binning

Caveat 2: there are **strong, longstanding** differences of opinion about the utility of releasing the intermediate data products