Searching for Dark Matter in Dwarf Galaxies

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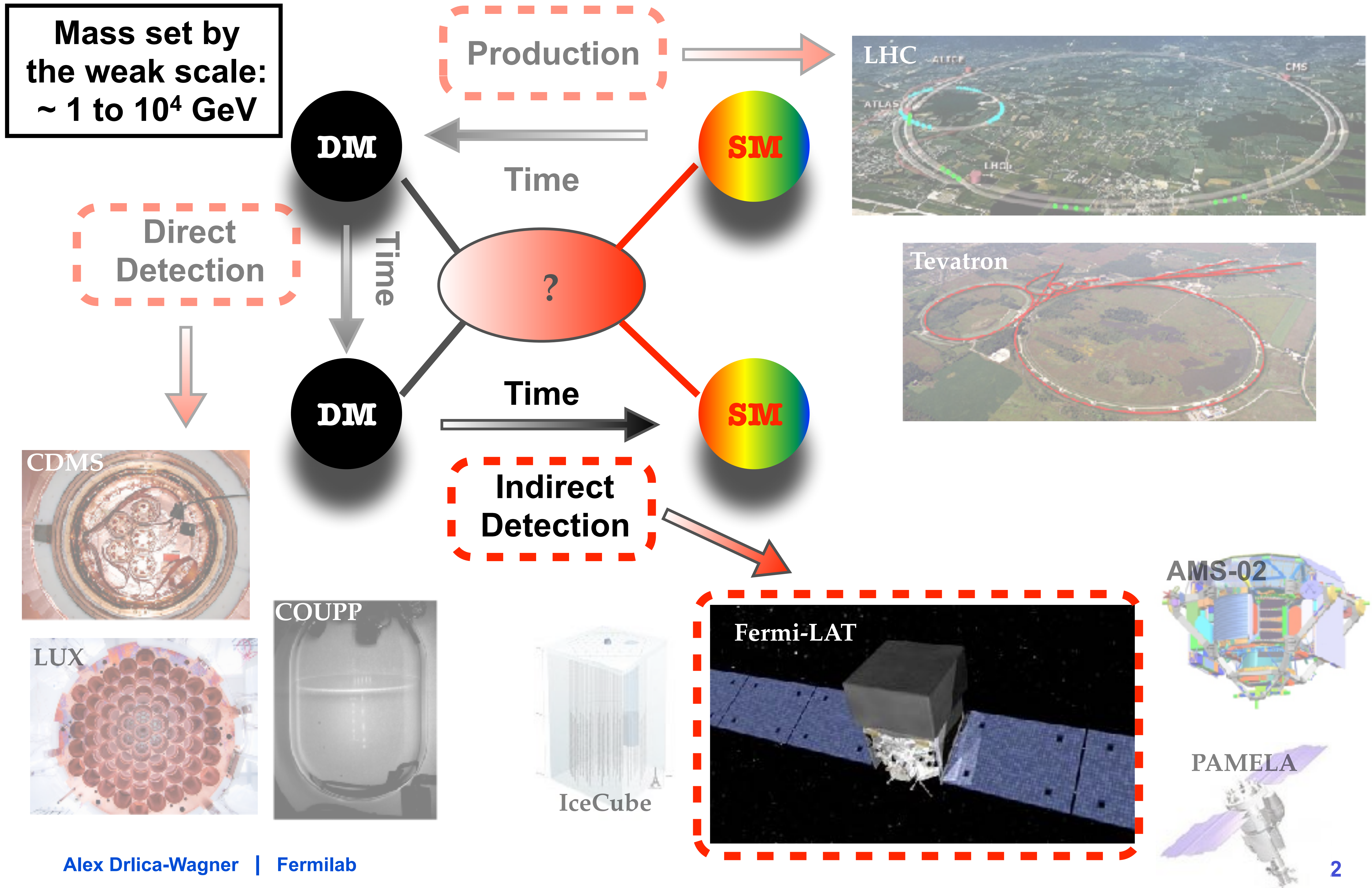
Fermilab

Aspen Winter Conference
March 20, 2017

Particle Dark Matter

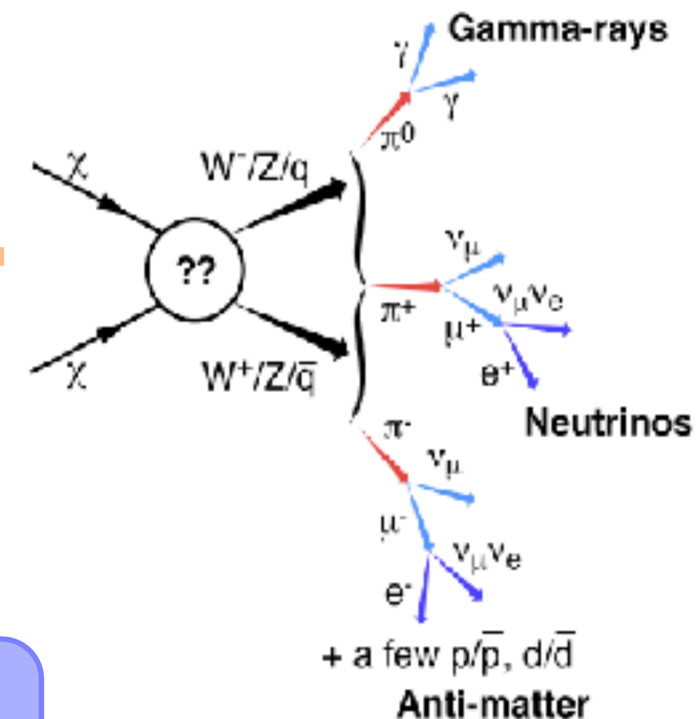


Indirect Detection

Gamma-ray Flux
(signal in data)

Particle Physics
(photons per annihilation)

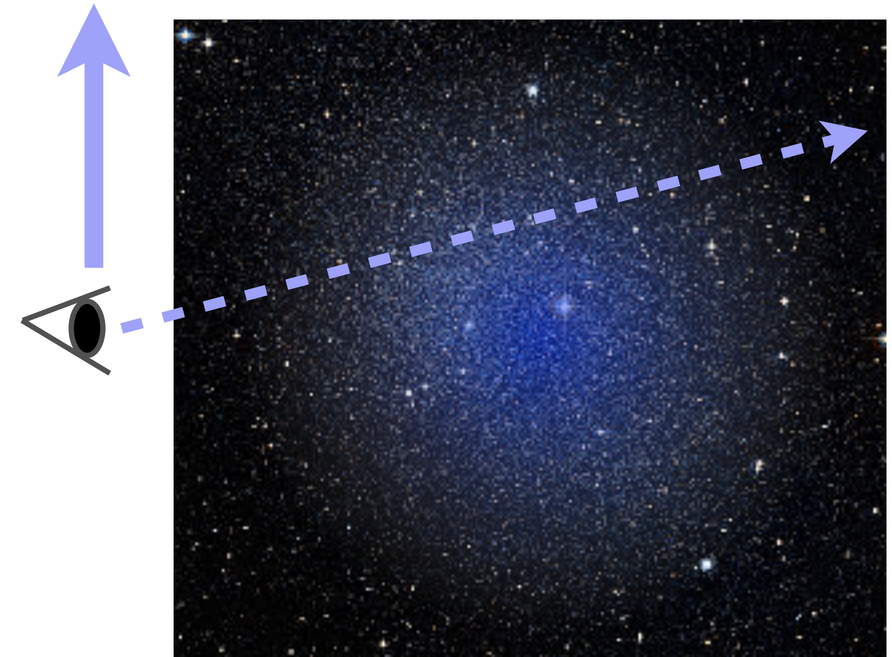
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$$



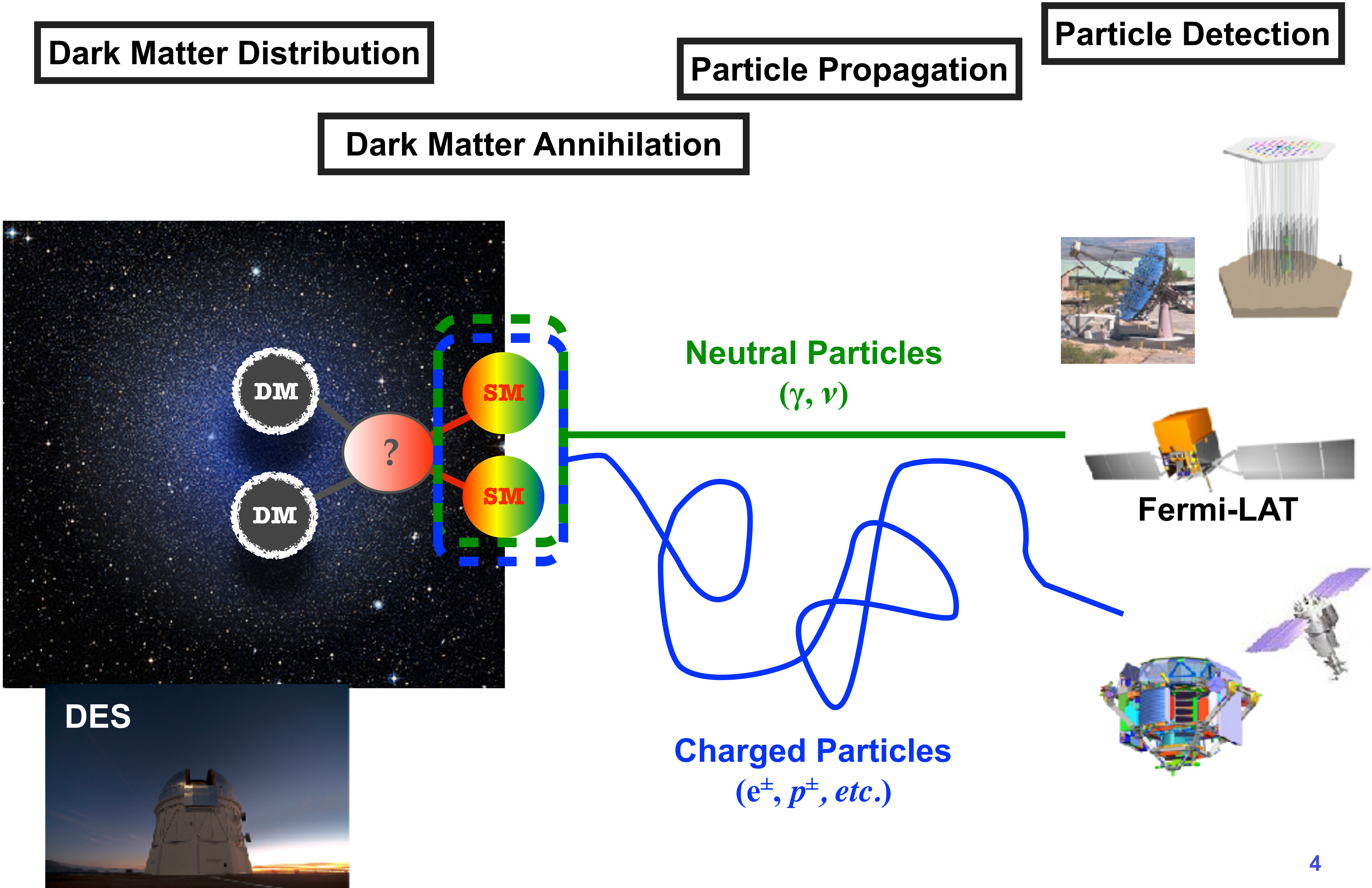
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Dark Matter Distribution
("J-factor")
(line-of-sight integral)



Indirect Detection

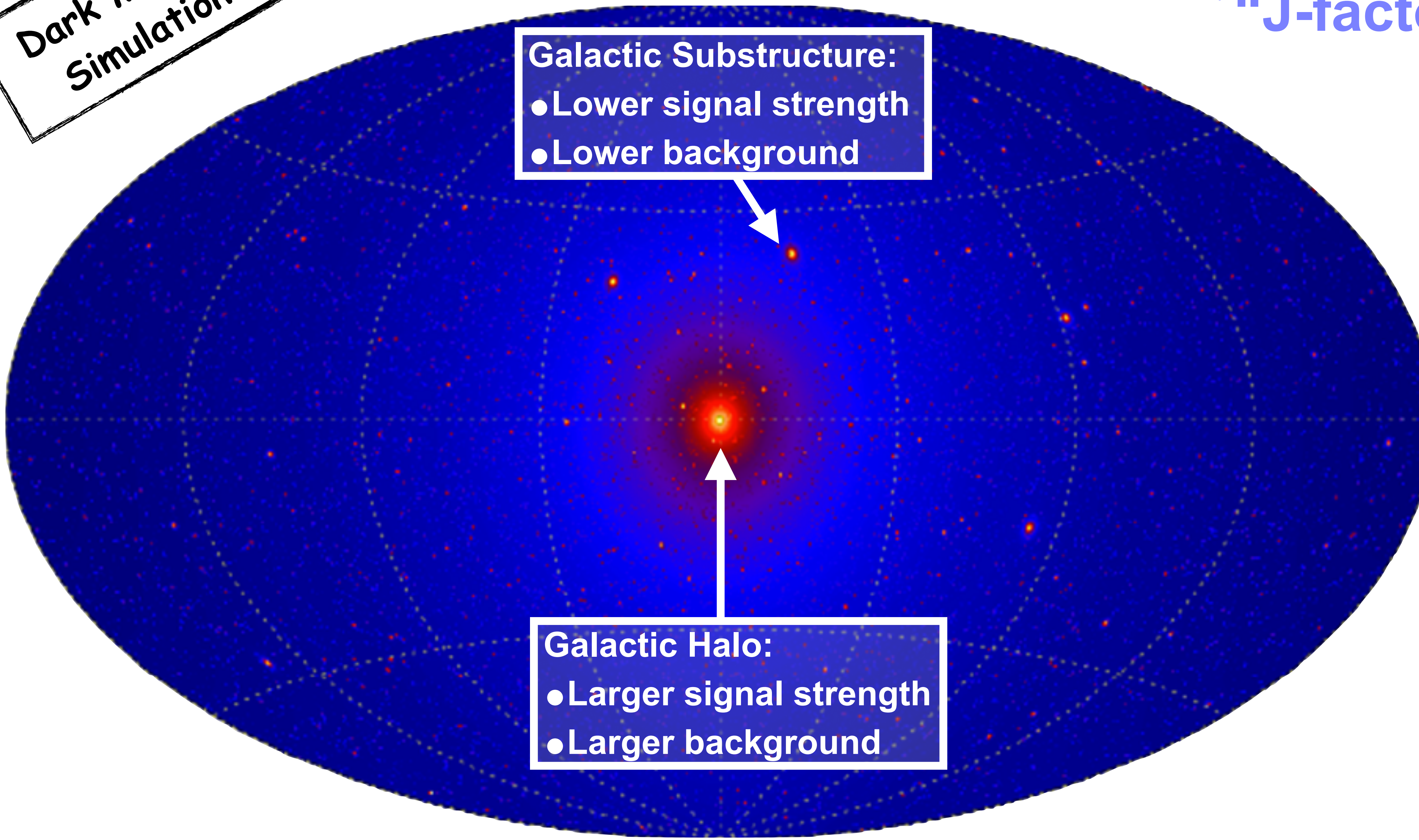


Dark Matter Distribution

Dark Matter Simulation

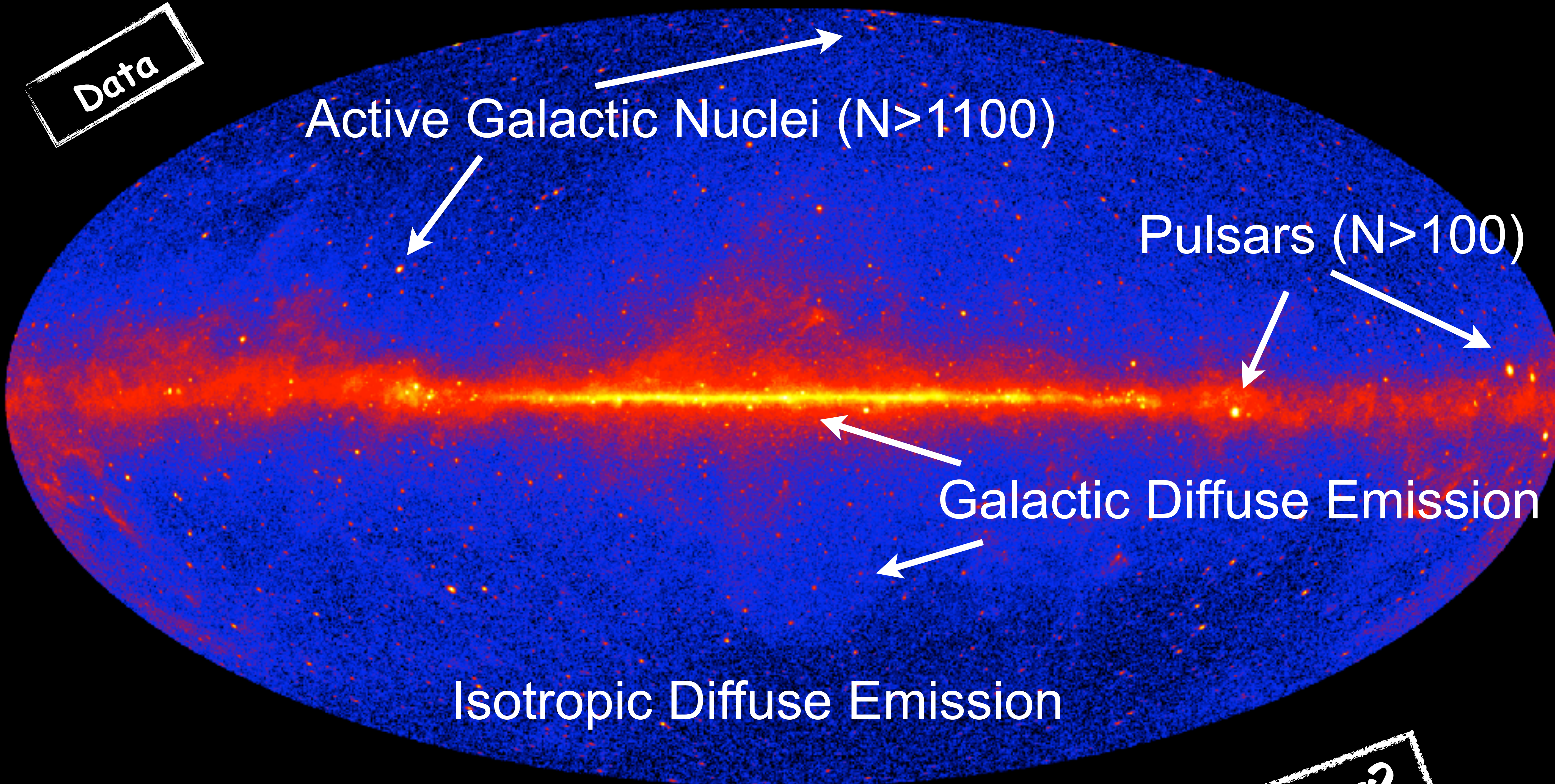
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

"J-factor"



Pieri et al. Phys Rev D83, 023518 (2011)

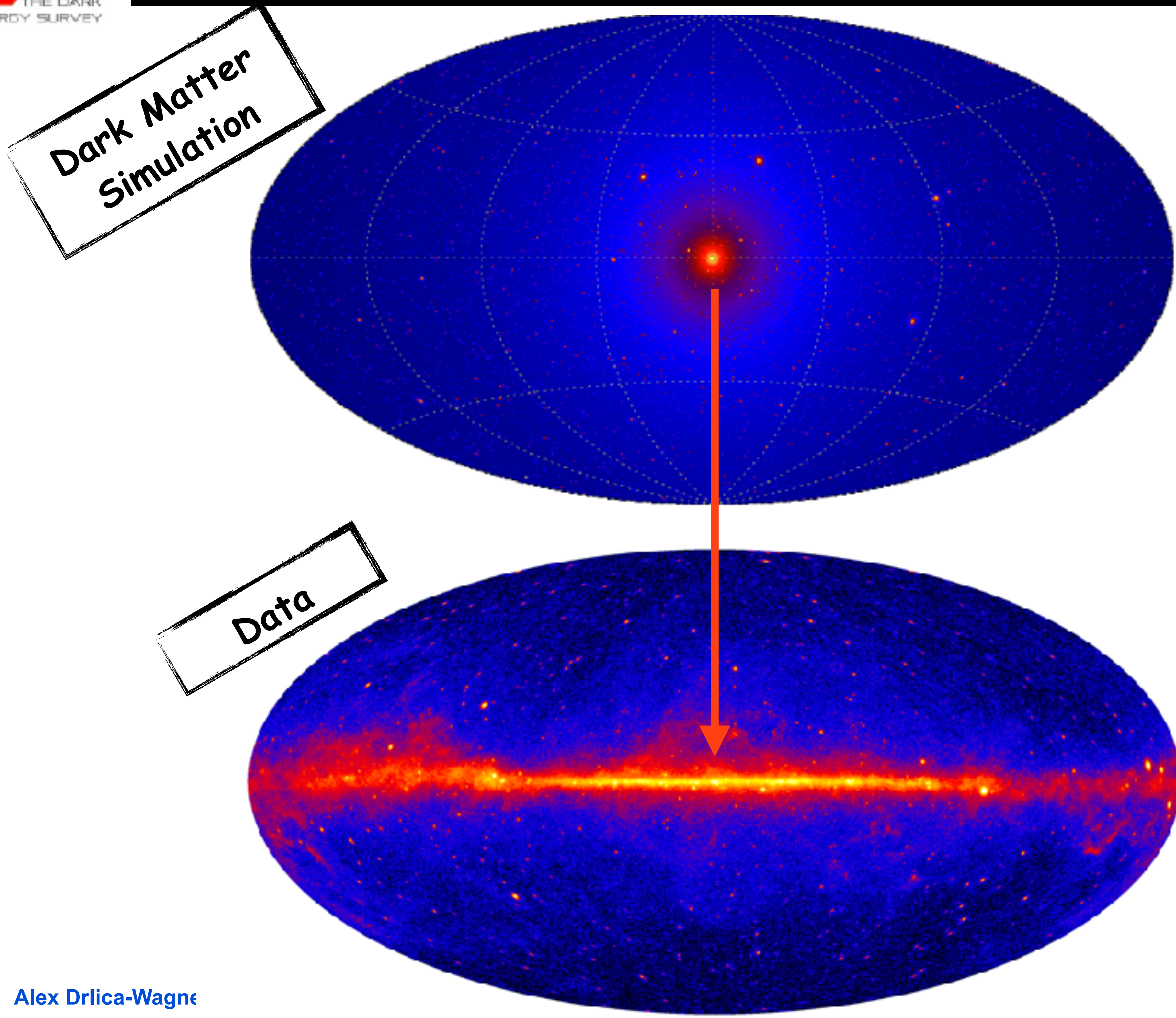
8-Year Gamma-Ray Data (Eγ > 1 GeV)



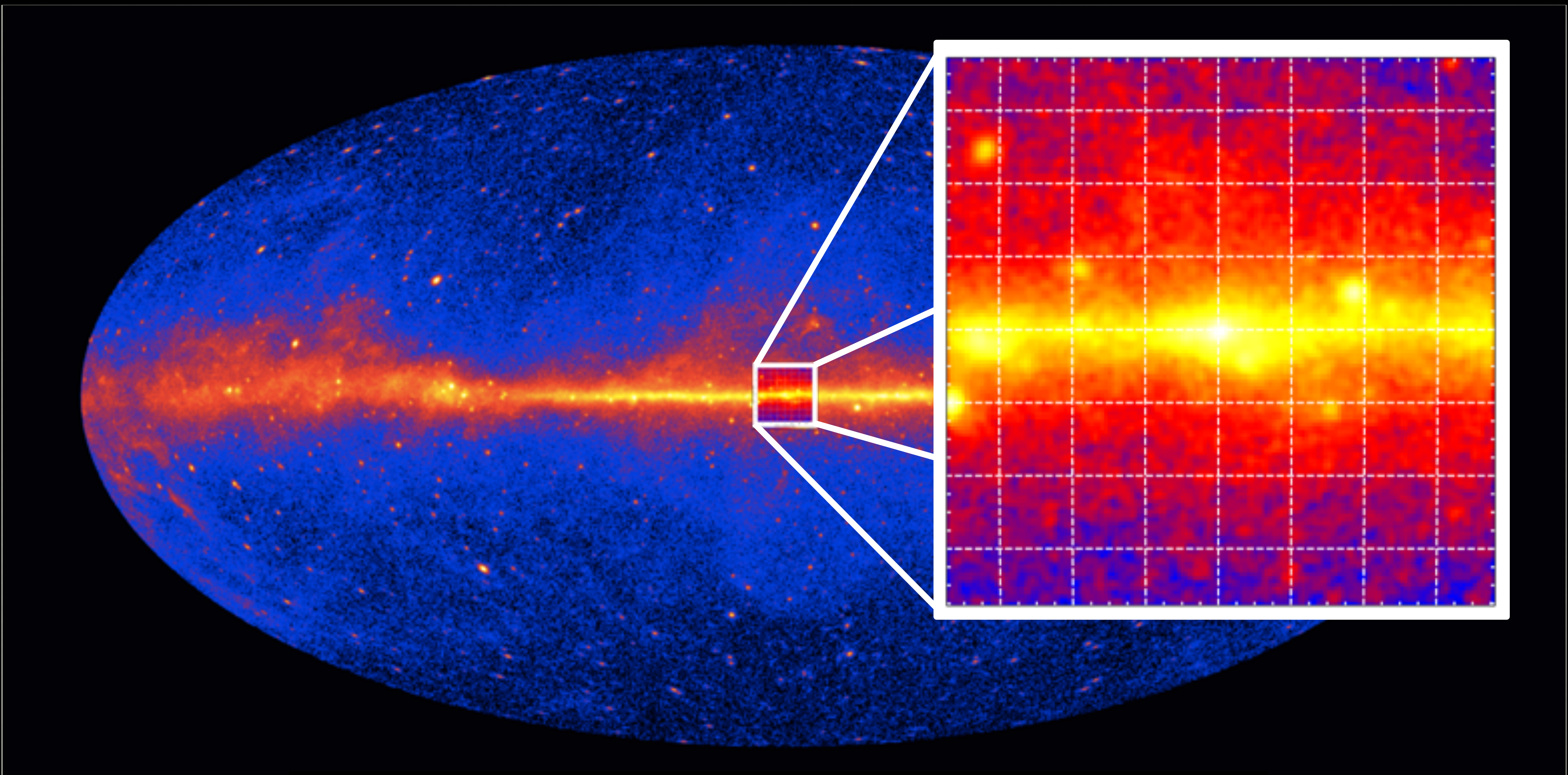
+ a lot of additional astrophysics …

+ Dark Matter?

The Galactic Center



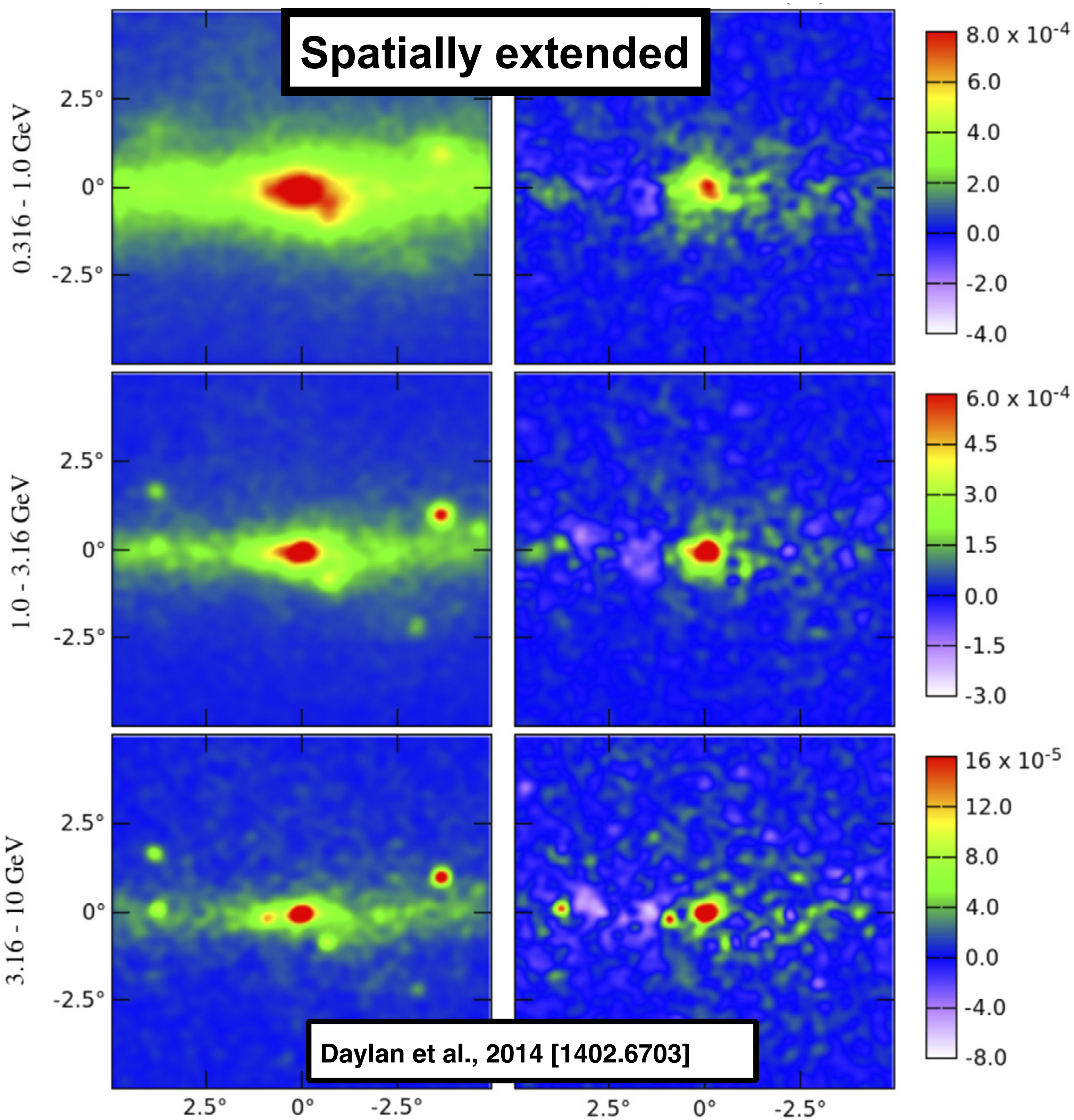
The Galactic Center



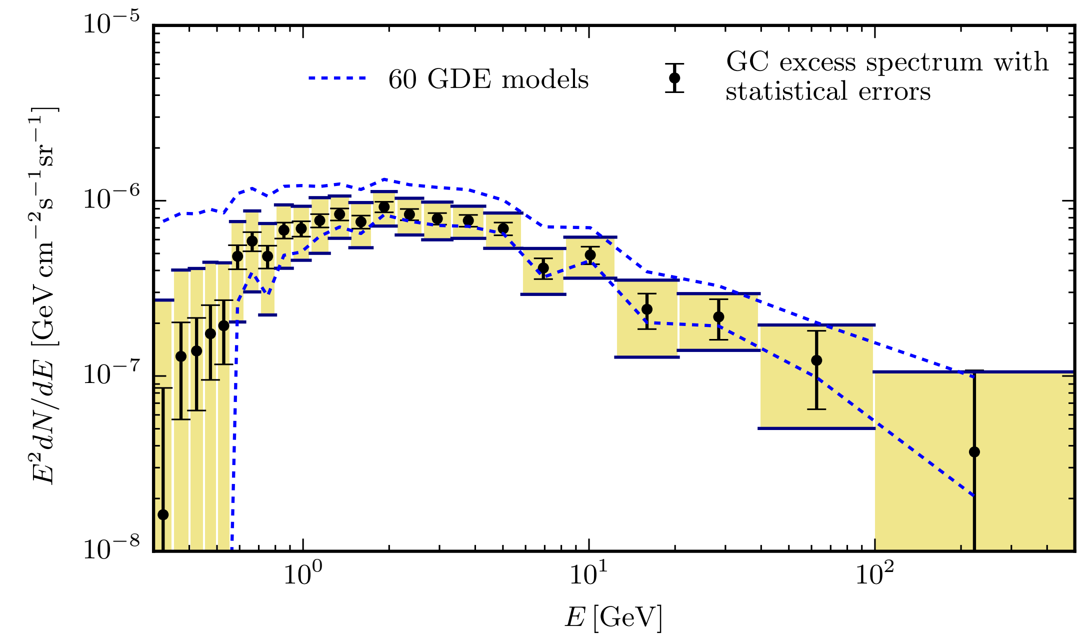
Fermi-LAT Gamma-ray Data ($E_\gamma > 1$ GeV)

The Galactic Center

Total Flux **Residual Flux**



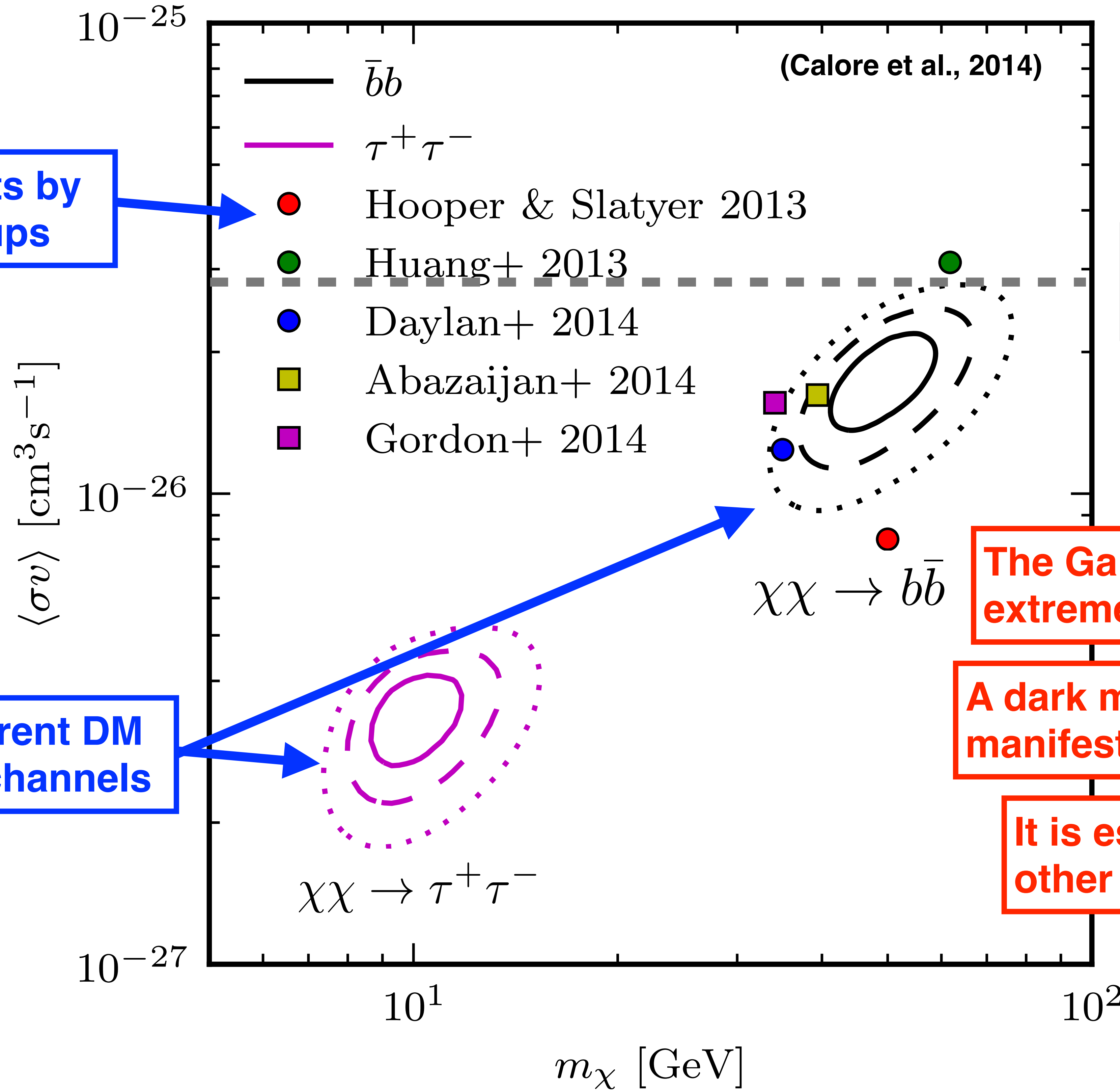
Energy spectrum peaks at a few GeV



Topic of much study!

Hooper & Goodenough (2009); Hooper & Linden (2011); Boyarski et al. (2011); Abazajian & Kaplinghat (2012); Gordon & Macias (2013); Huang et al. (2013); Abazajian et al. (2014); Daylan et al. (2014); Calore et al. (2014); Lee et al. (2015); Bartels et al. (2015) Ajello et al. (2015); etc.

The Galactic Center



Measurements by different groups

Assume different DM annihilation channels

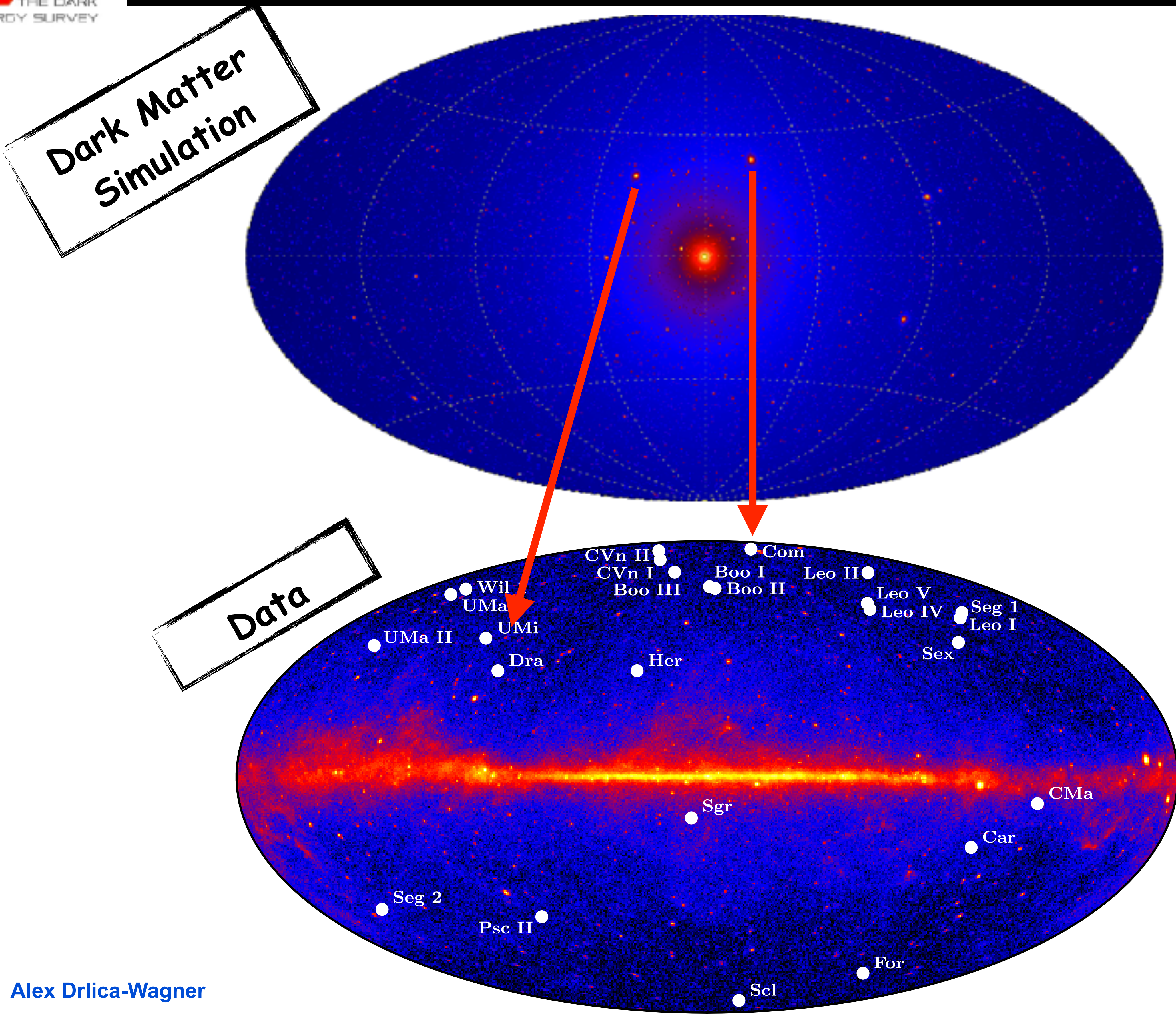
Thermal Relic Cross Section

The Galactic Center is an extremely complicated region

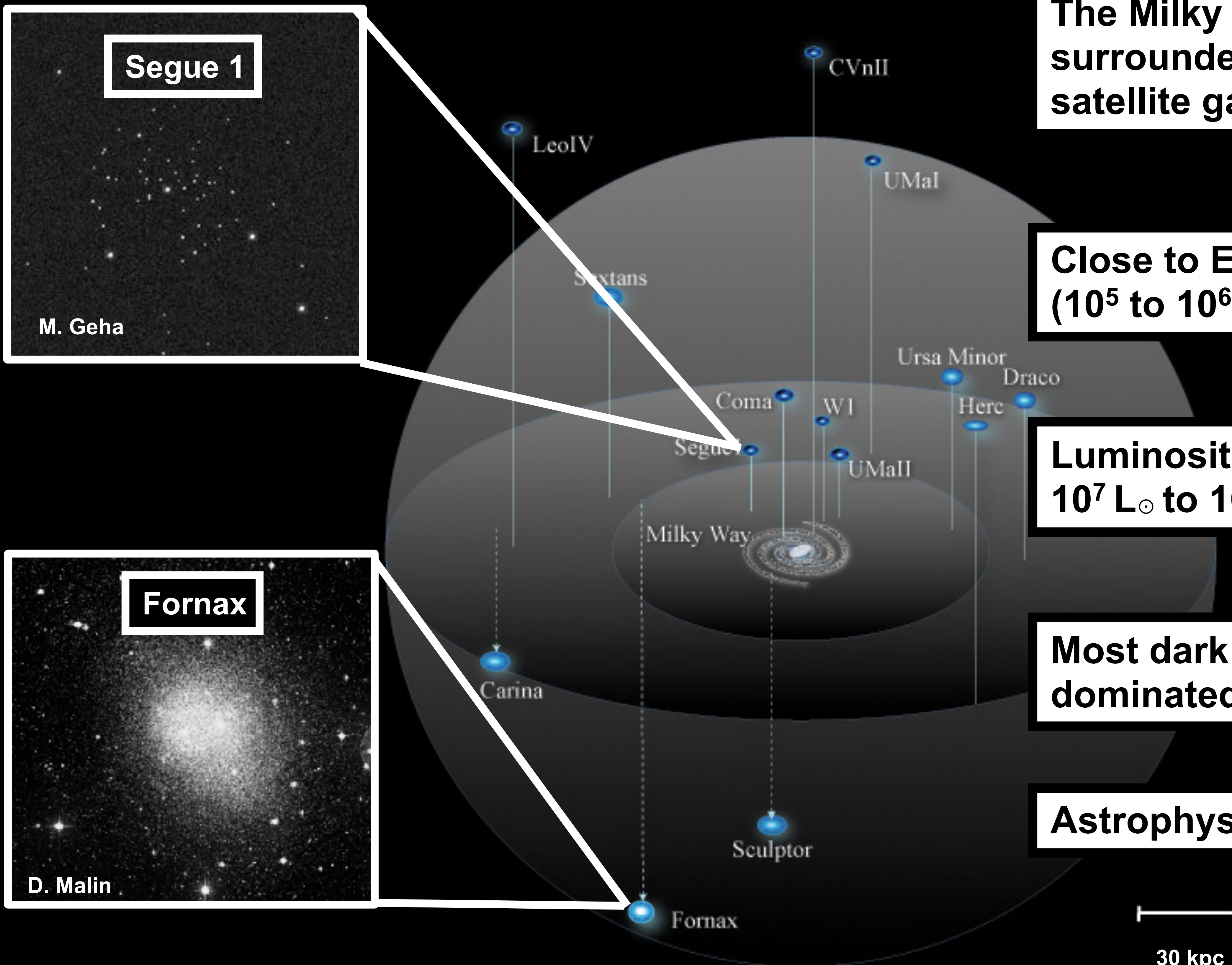
A dark matter signal should manifest itself in other regions

It is essential to investigate other dark matter targets

Milky Way Satellite Galaxies



Milky Way Satellite Galaxies

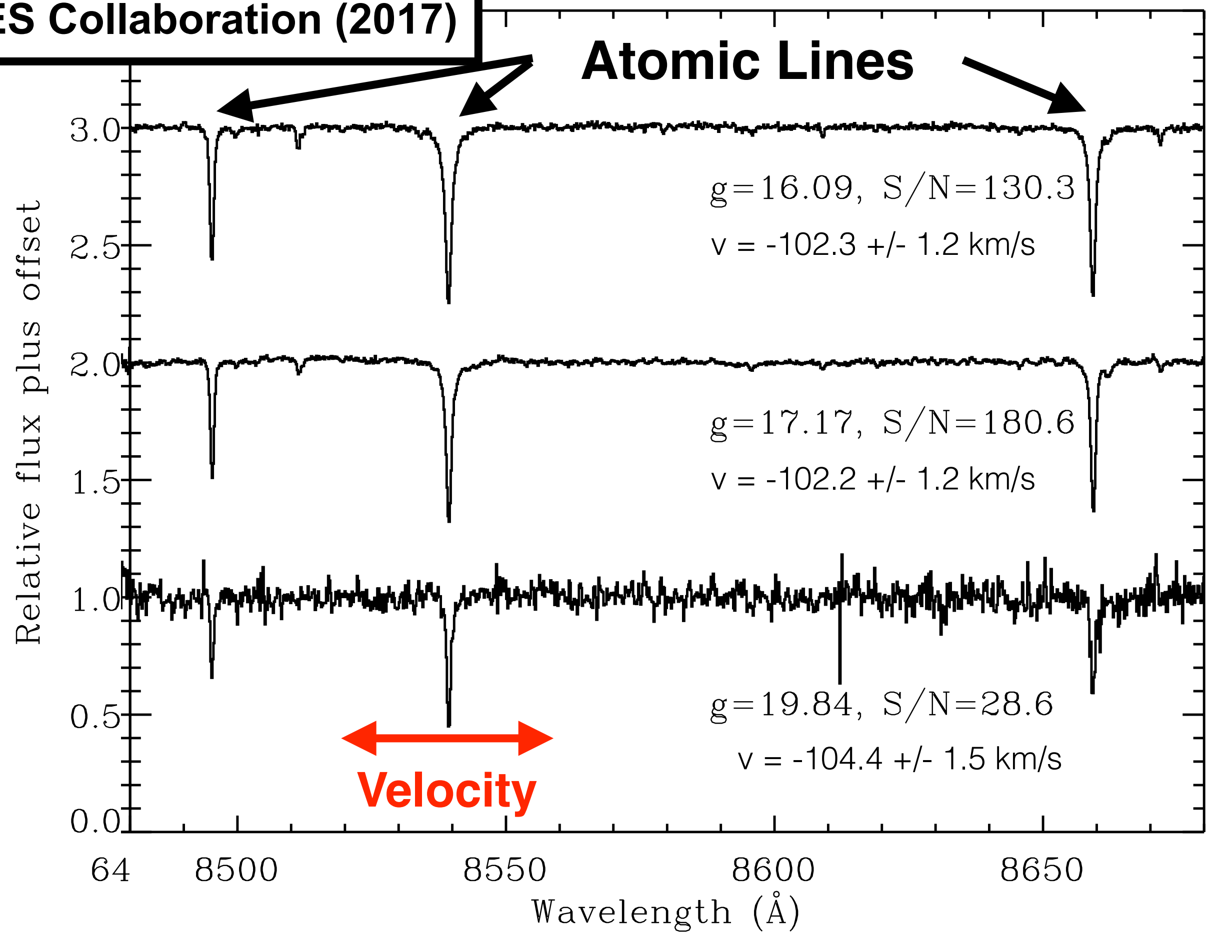


(Bullock, Geha, Powell)

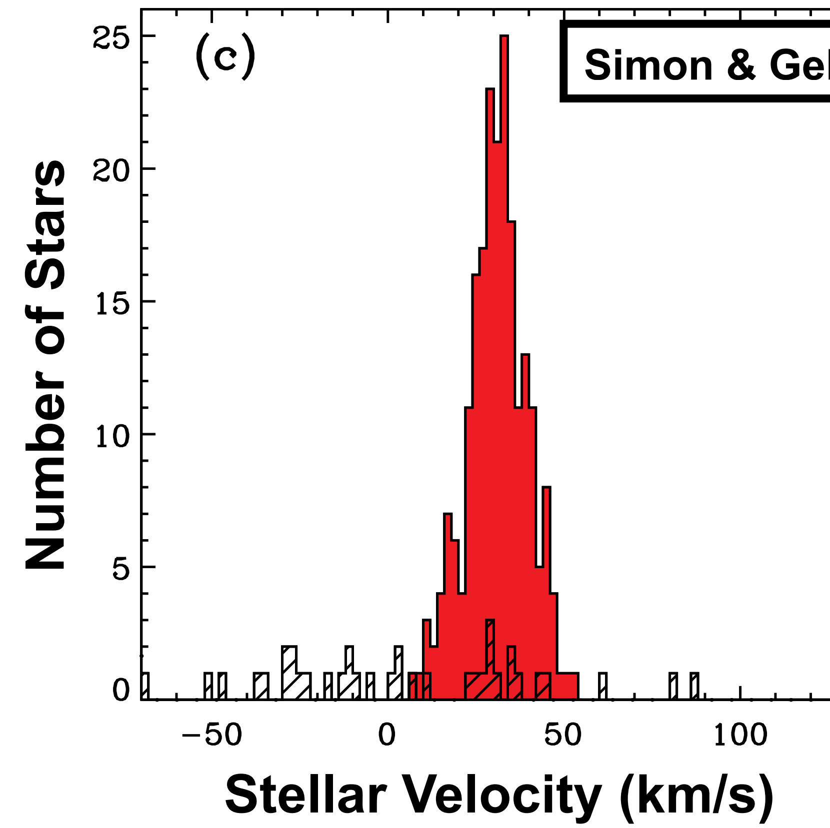
- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (10^5 to 10^6 ly)
- Luminosities range from $10^7\,L_\odot$ to $10^3\,L_\odot$
- Most dark matter dominated objects known
- Astrophysically simple

Dark Matter in Dwarf Galaxies

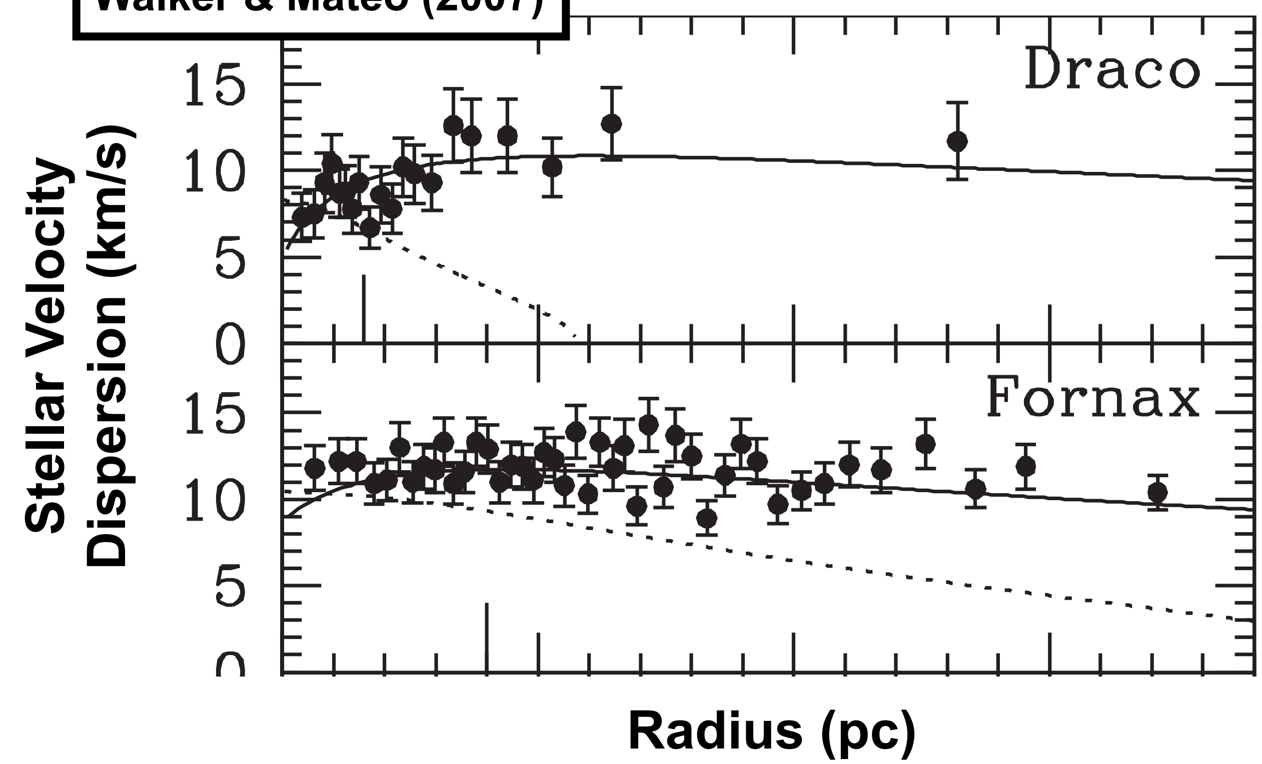
DES Collaboration (2017)



Simon & Geha (2007)



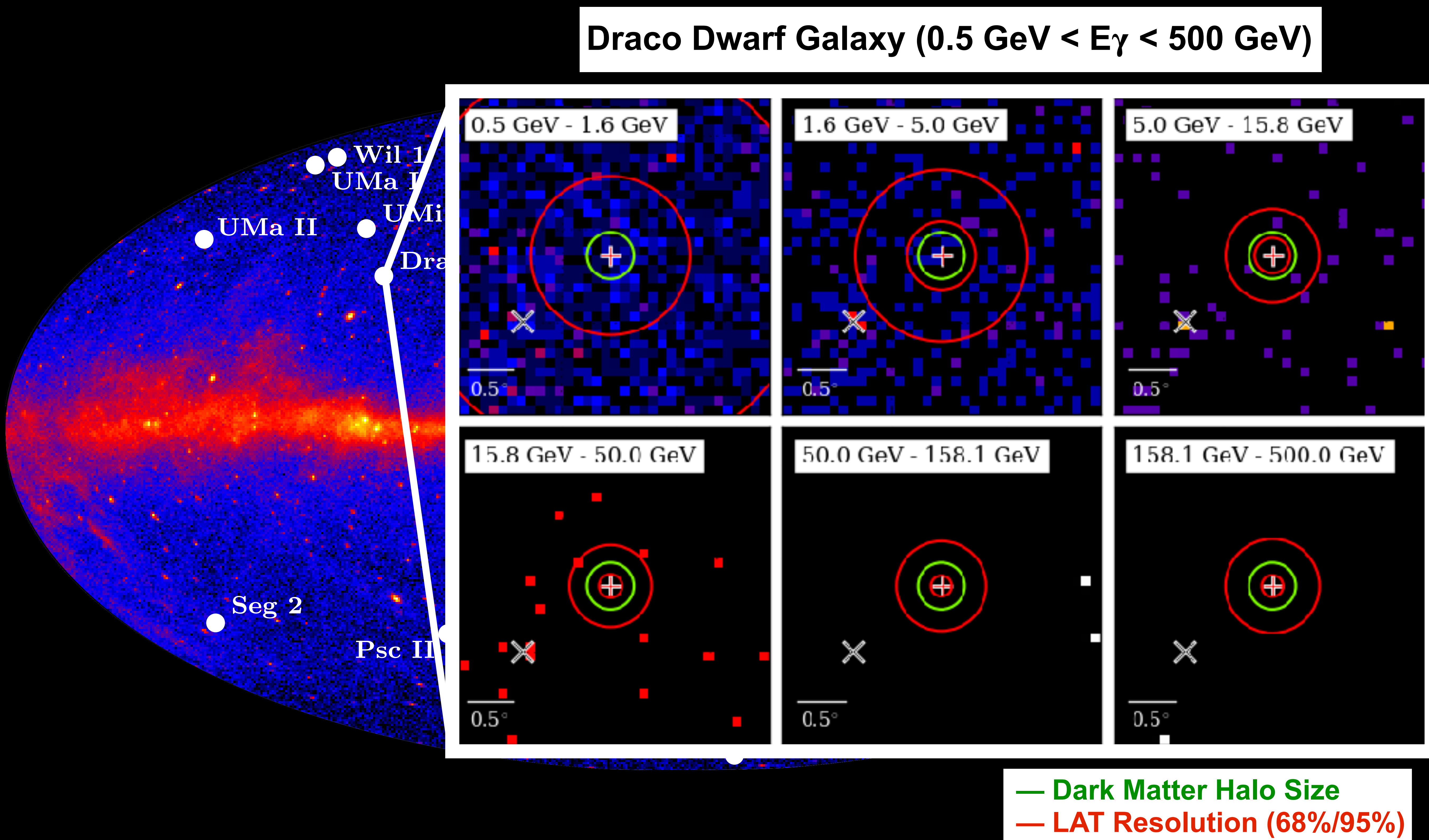
Walker & Mateo (2007)



Doppler shifts of atomic lines provide precise radial velocity measurements for stars

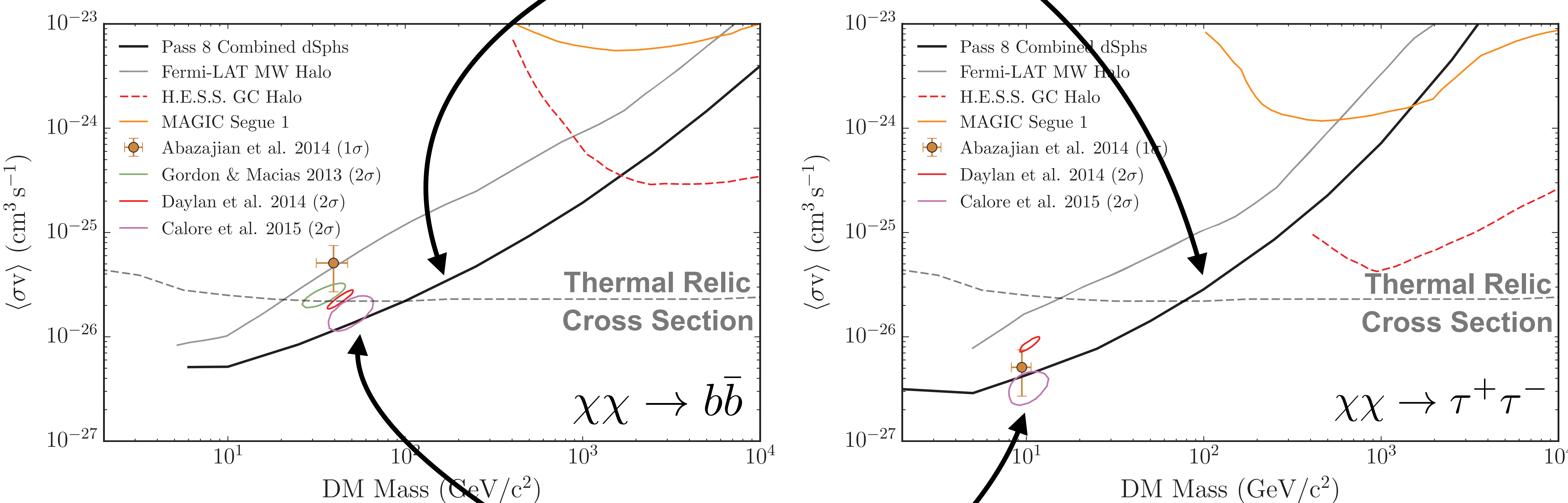
"Goldilocks" systems: enough stars to trace the gravitational potential, but not enough to alter it

Milky Way Satellite Galaxies



Dwarf Galaxy Constraints

95% CL upper limits from combined observation of 15 dwarf galaxies

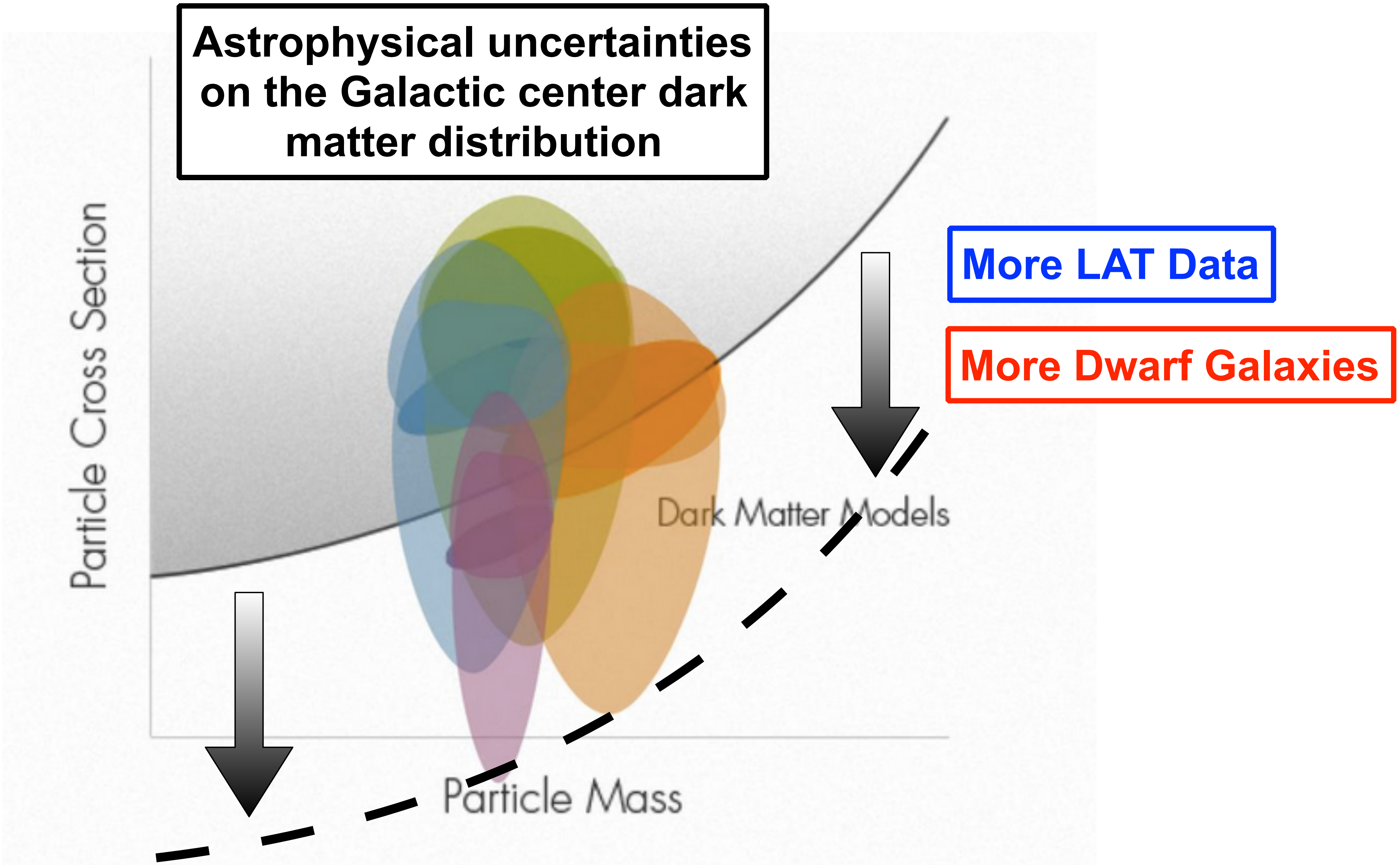


Dark matter interpretations of the Galactic Center excess

LAT Collaboration PRL 115, 231301 (2015)

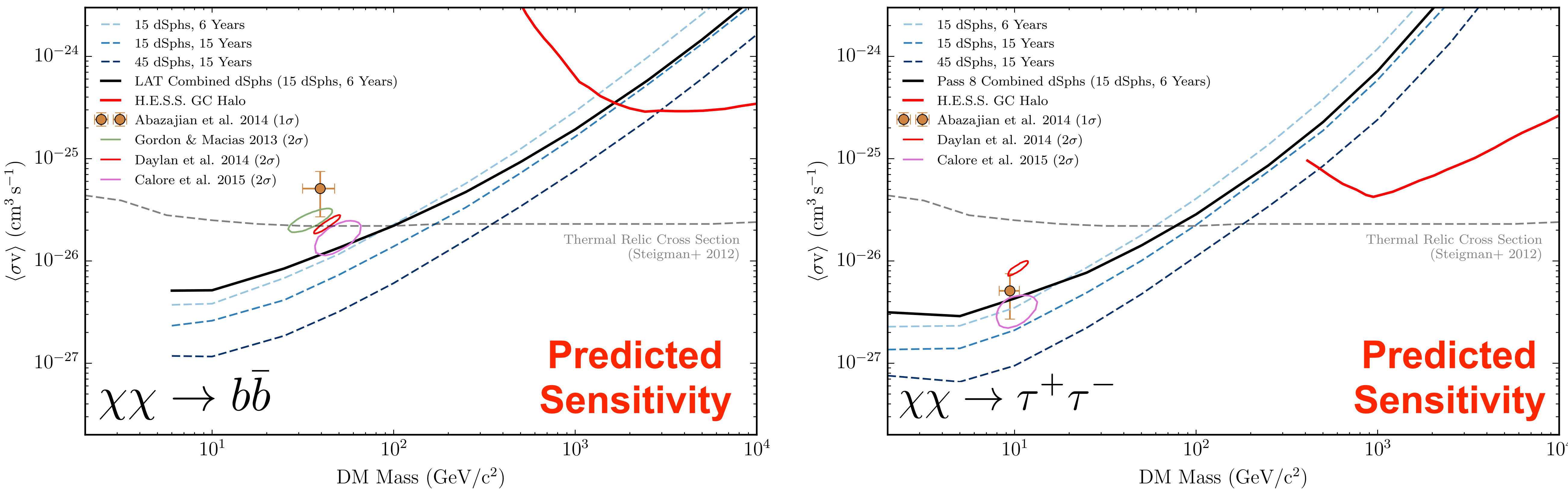
Galactic Center Comparison

CARTOON



Quanta Magazine & Kev Abazajian

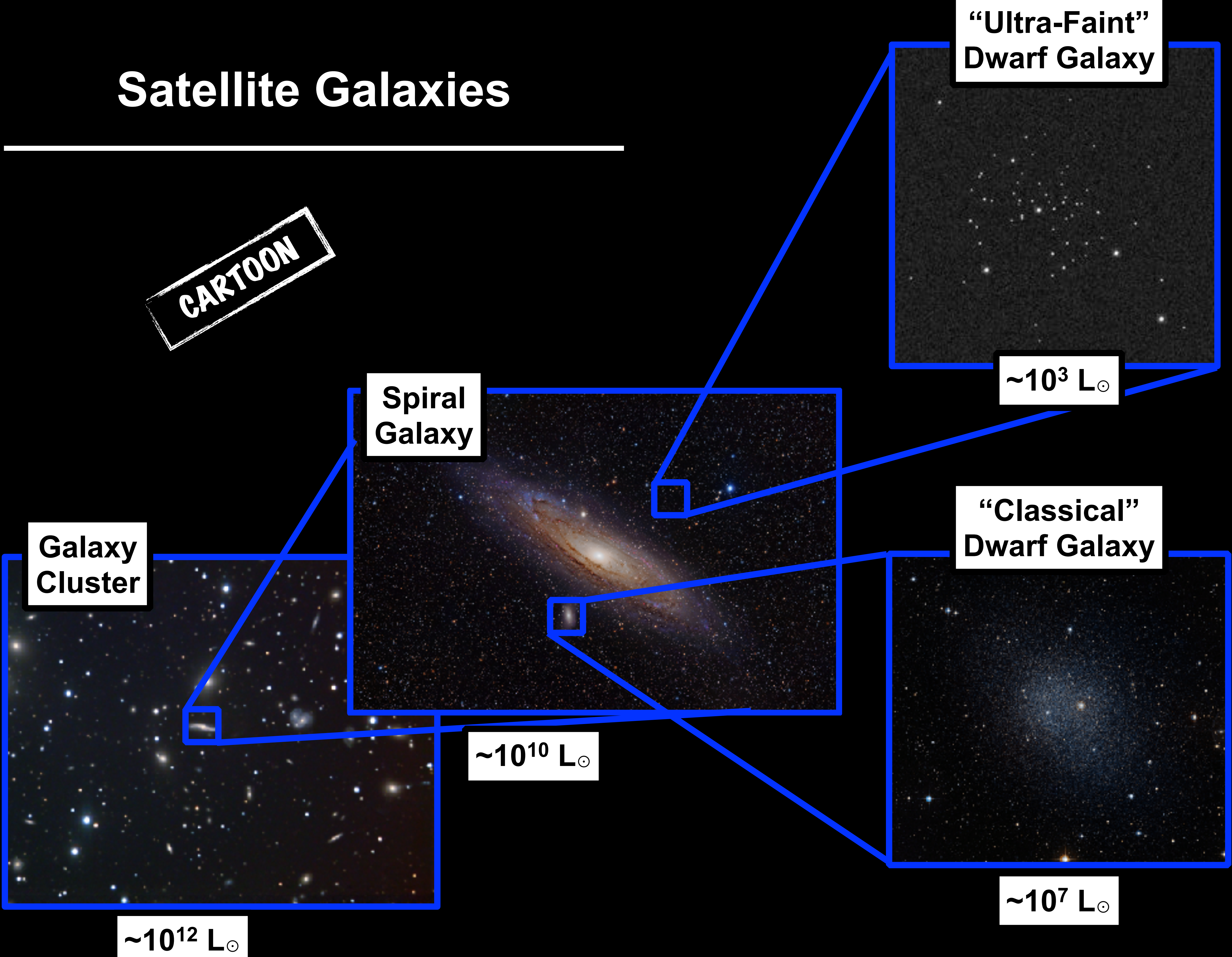
Looking Forward



LAT Collaboration, Phys. Rep. 636, 1 (2016)

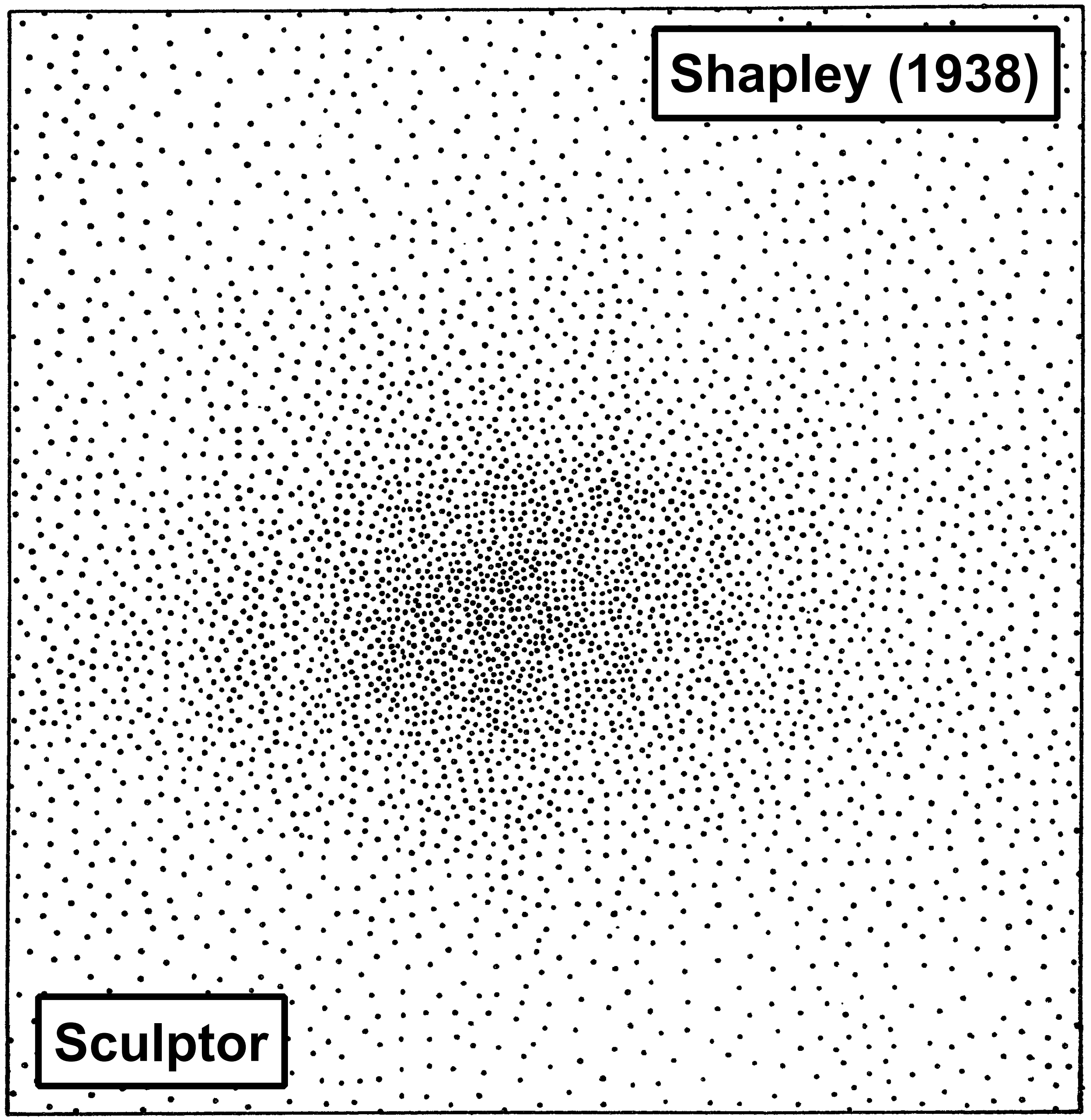

Finding Milky Way Satellite Galaxies
Detectors Drive Discoveries
Naked Eye

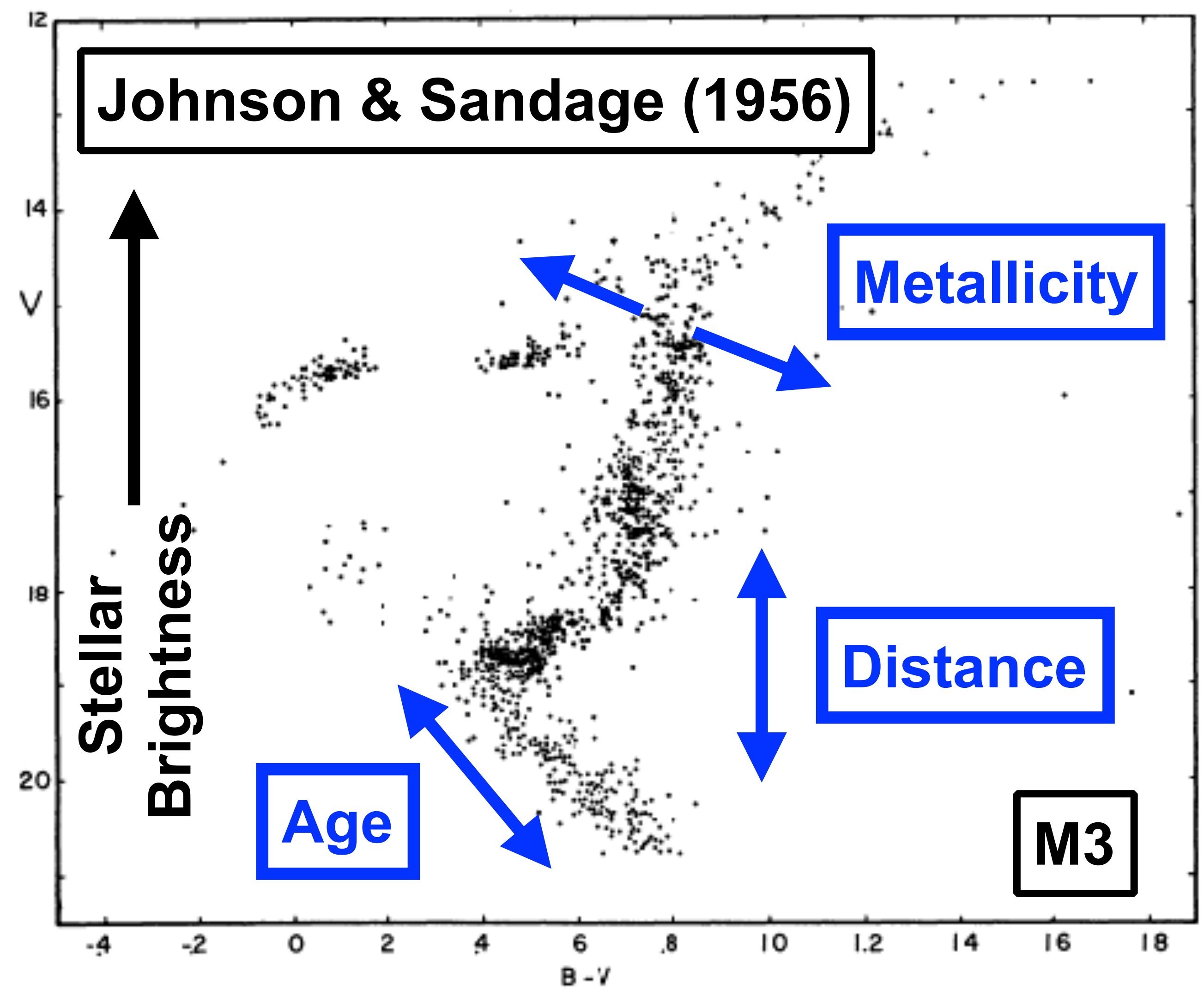
Satellite Galaxies



Visual Searches

- **First objects discovered by visual scans of photographic plates**

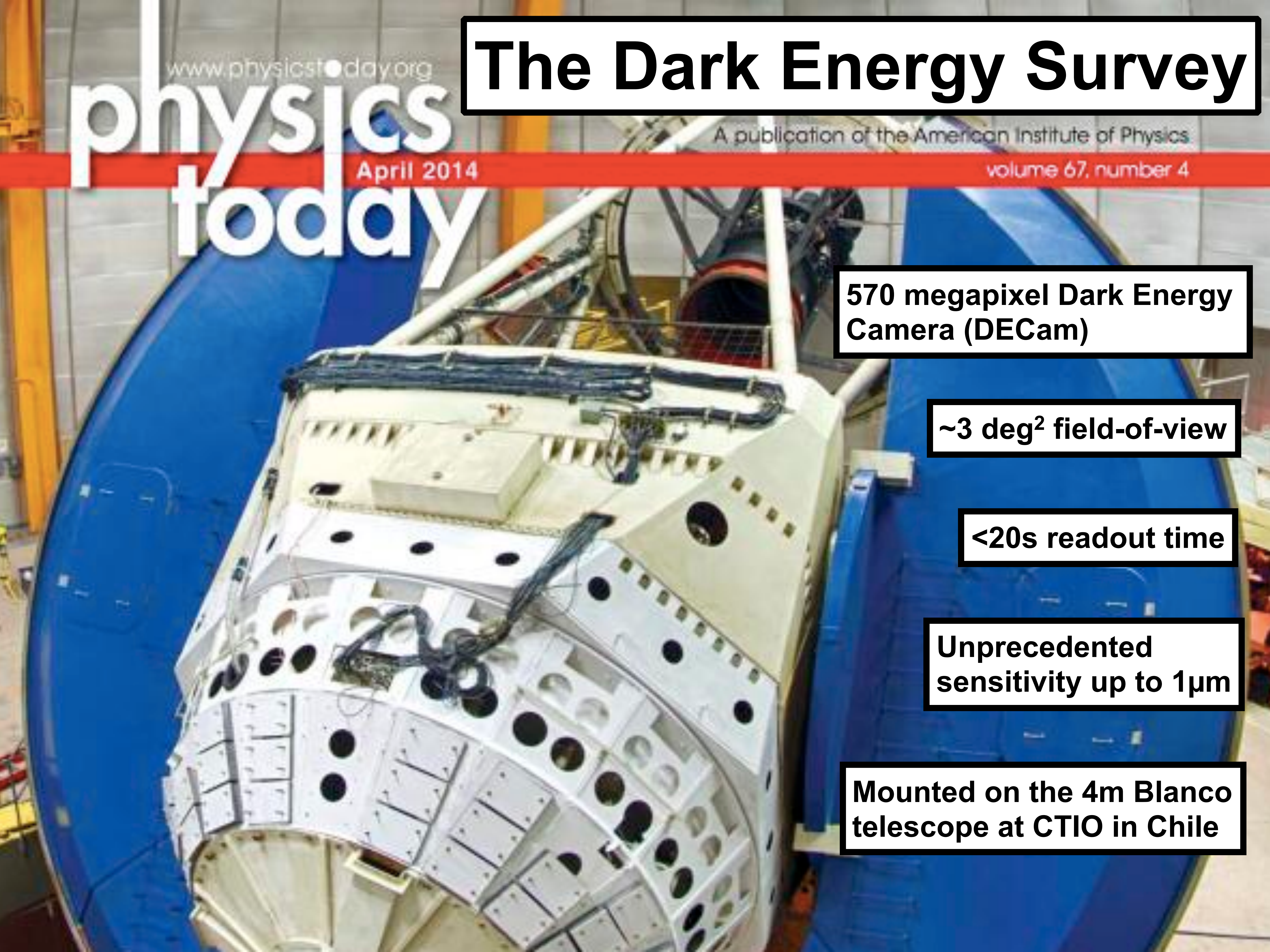




Blue ← **Stellar Color** → **Red**

24-inch Telescope Photographic Plates

The Dark Energy Survey



570 megapixel Dark Energy Camera (DECam)

~3 deg^2 field-of-view

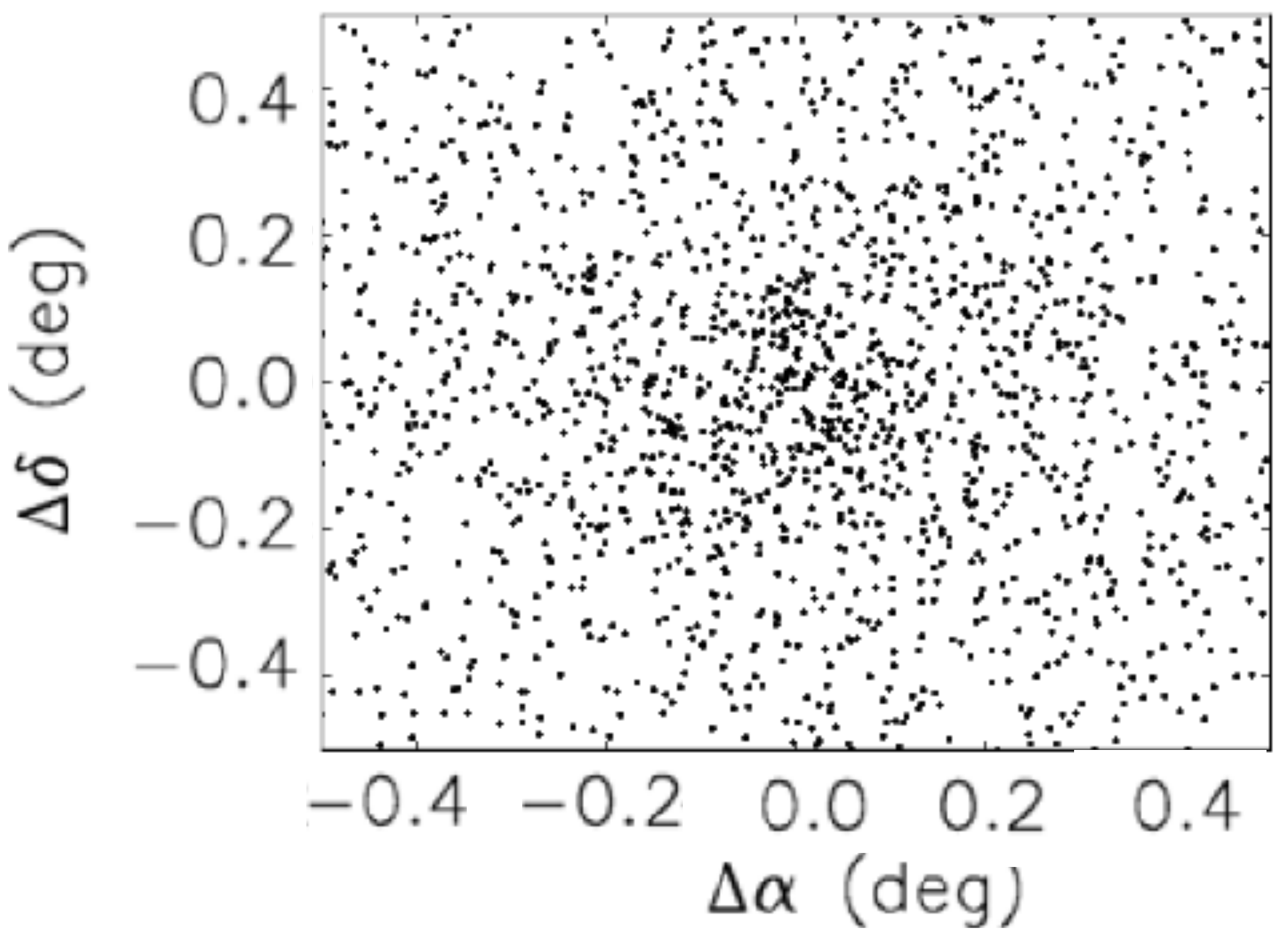
<20s readout time

Unprecedented sensitivity up to 1μm

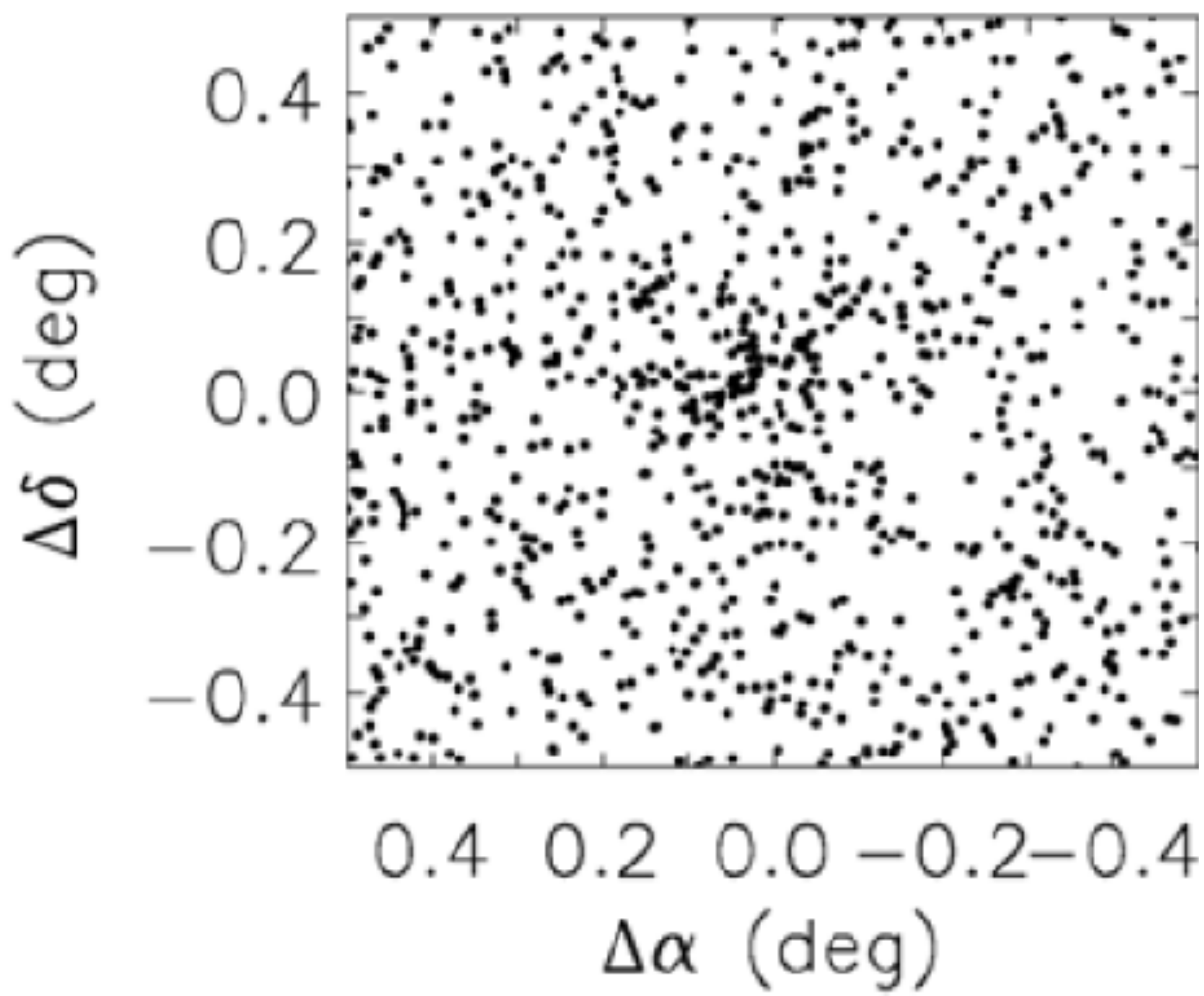
Mounted on the 4m Blanco telescope at CTIO in Chile

A Familiar Problem…

Gamma-ray Source (4C+21.35)

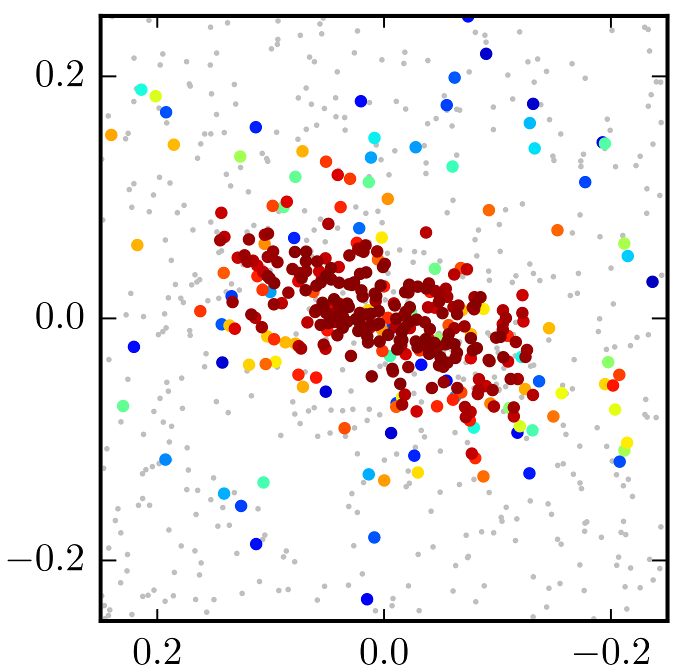


Dwarf Galaxy (Coma Berenices)

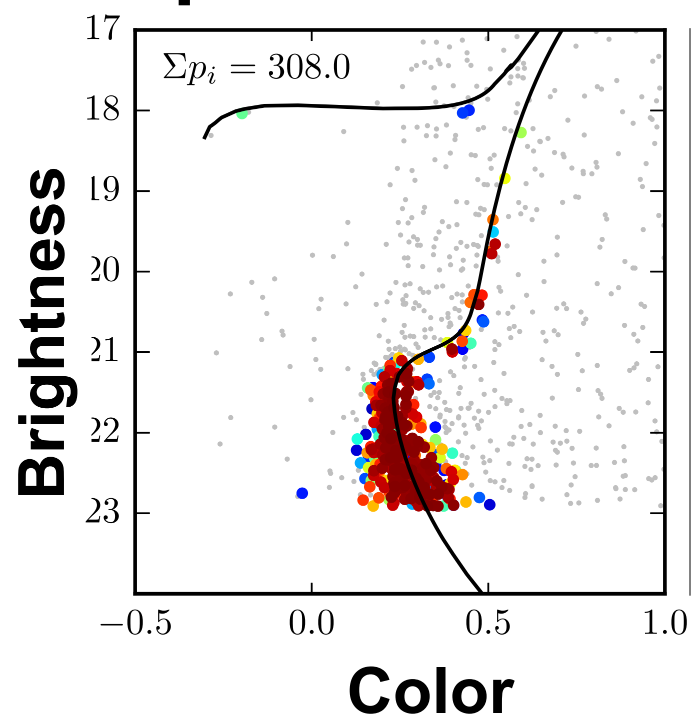


Maximum-Likelihood Searches

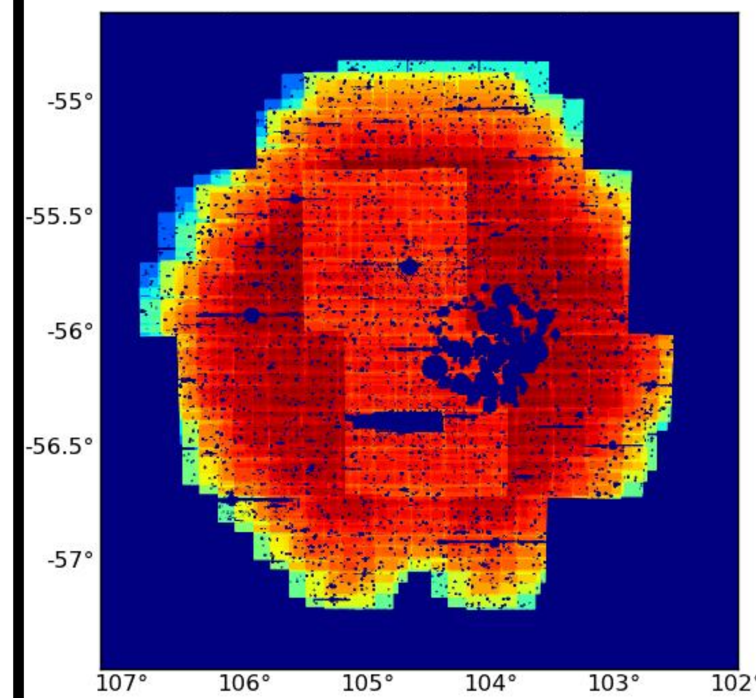
Spatial Model



Spectral Model



Survey Sensitivity



A likelihood analysis to simultaneously combine spatial and spectral information

$$p_i = \frac{\lambda u_i}{\lambda u_i + b_i}$$

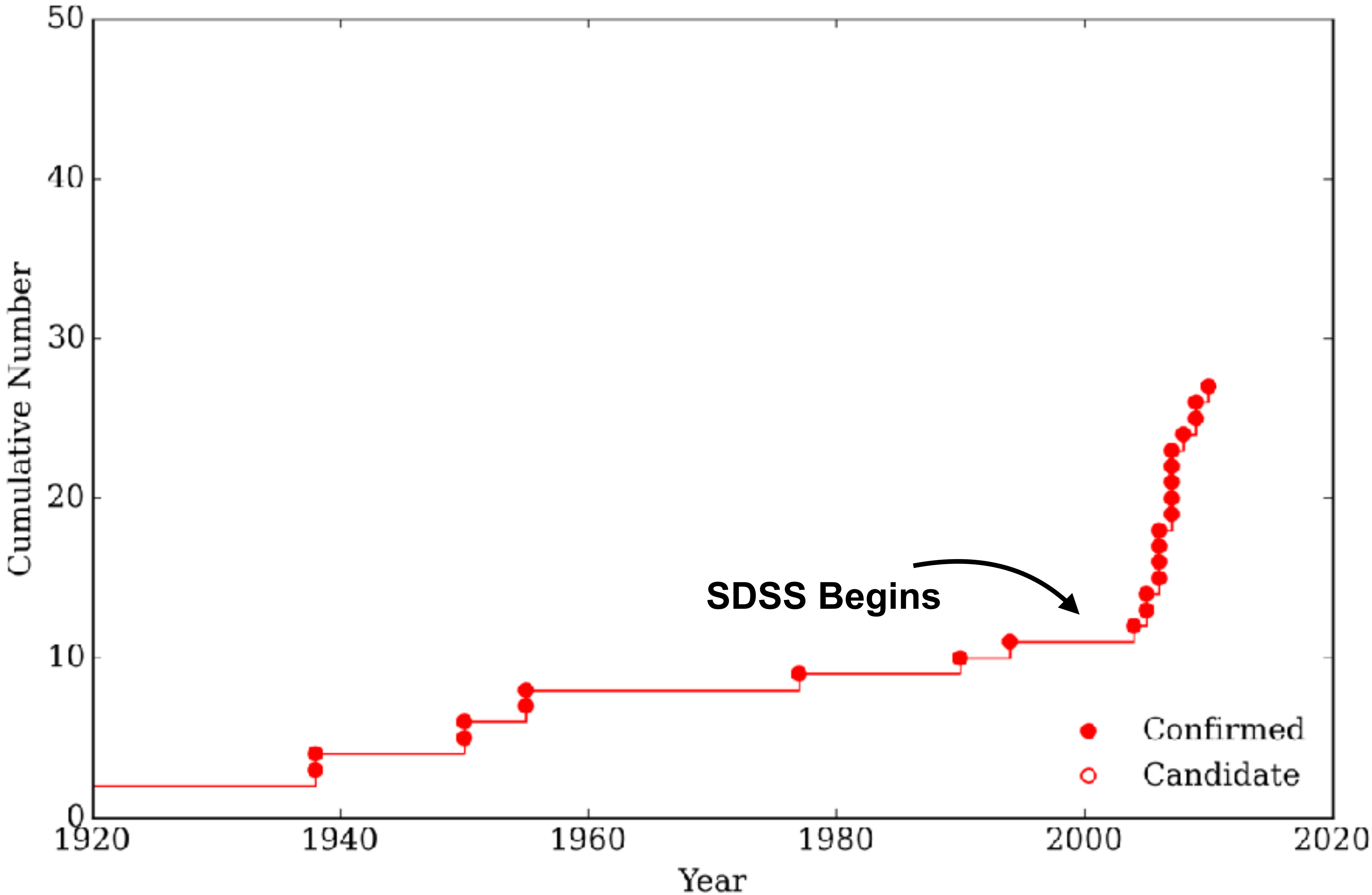
$$\lambda = \frac{1}{f} \sum_{i \in \mathrm{Stars}} p_i$$

$$\log L = -\sum_{i \in \mathrm{Stars}} \log(1 - p_i) - f\lambda$$

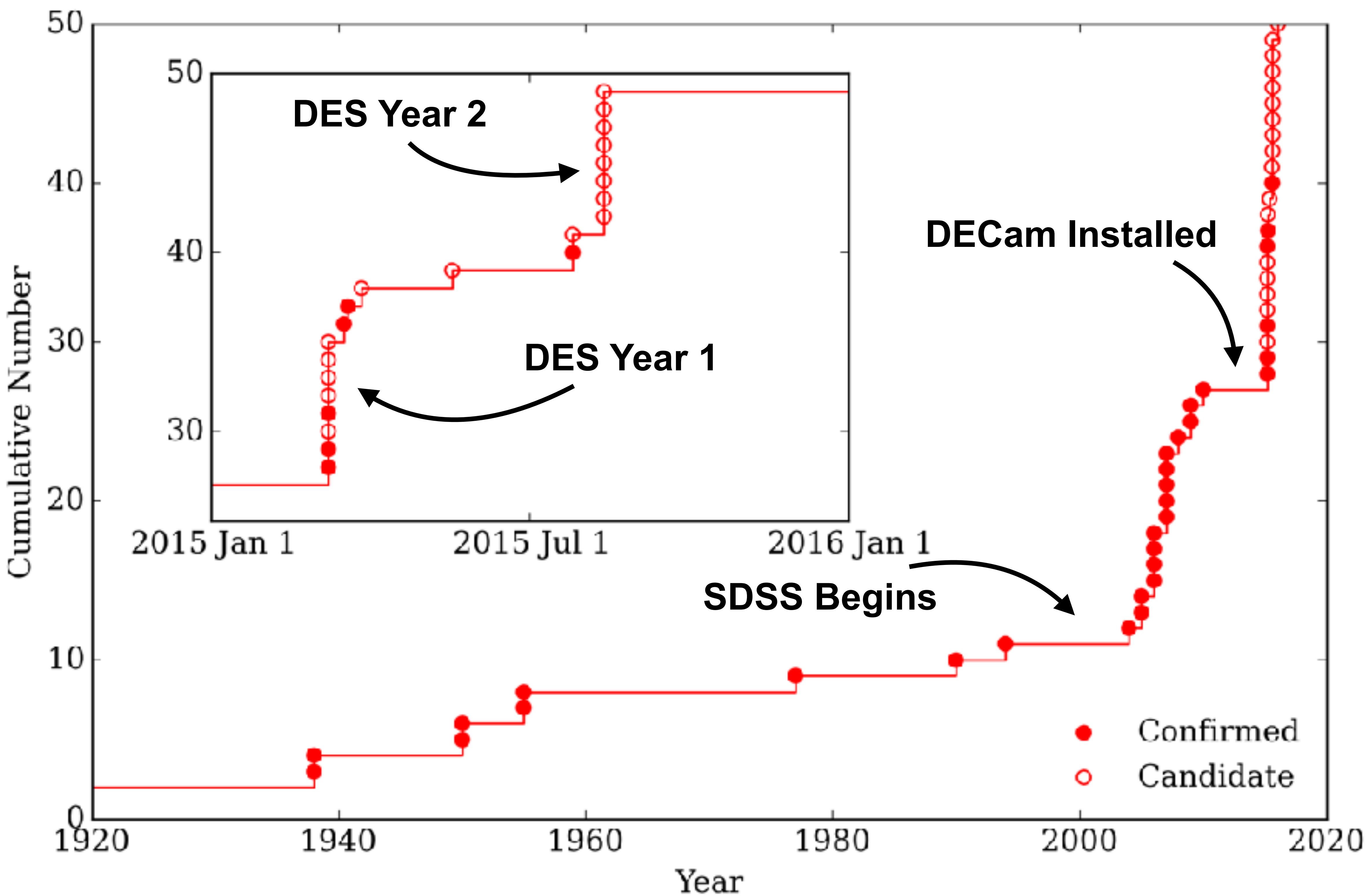
u_i = sig prob
b_i = bkg prob
λ = normalization = number of stars
f = observable fraction

This approach naturally yields a membership probability for each star; important for spectroscopy

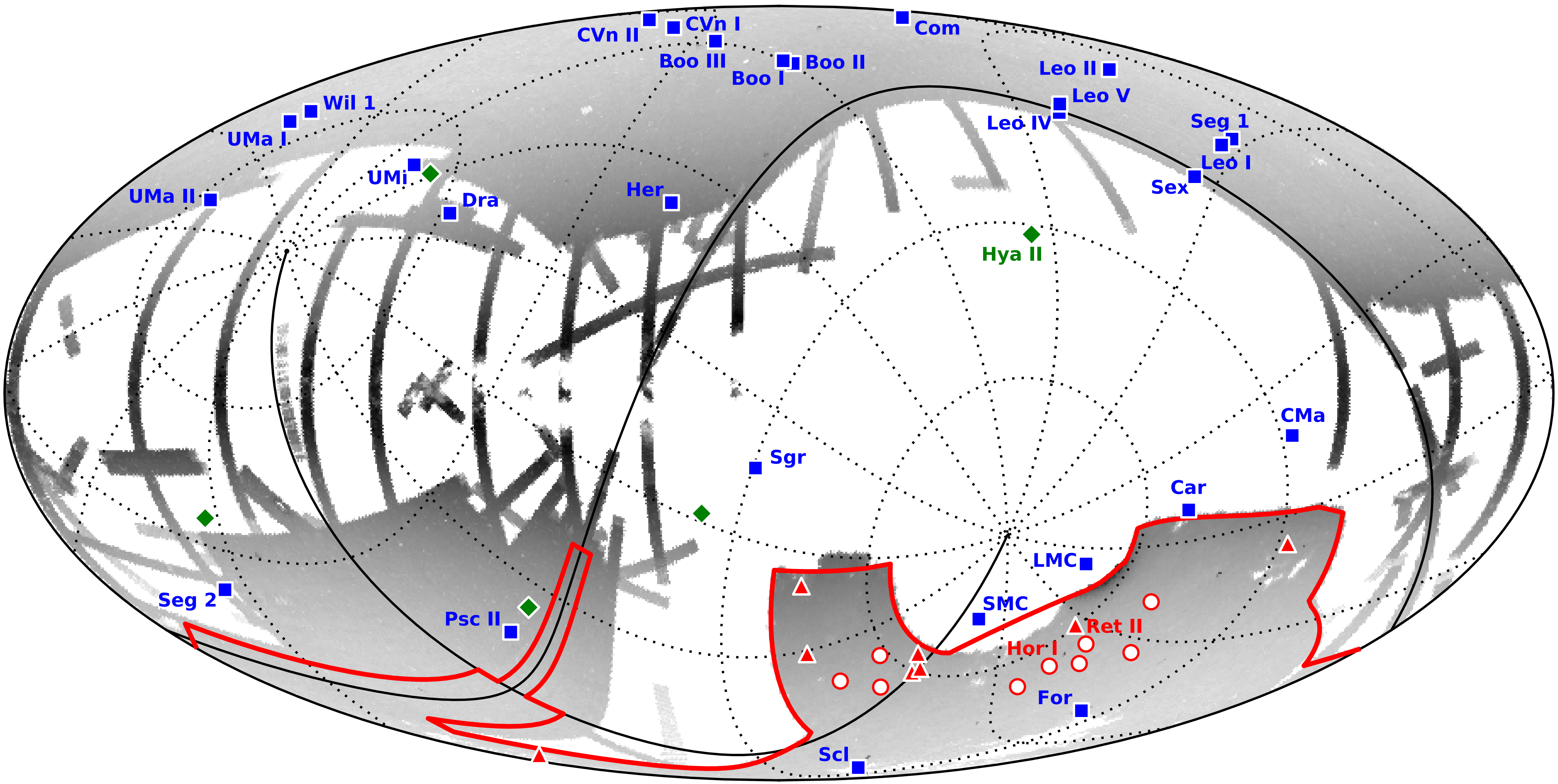
Discovery Timeline



Discovery Timeline



SDSS DR10 + DES Y2

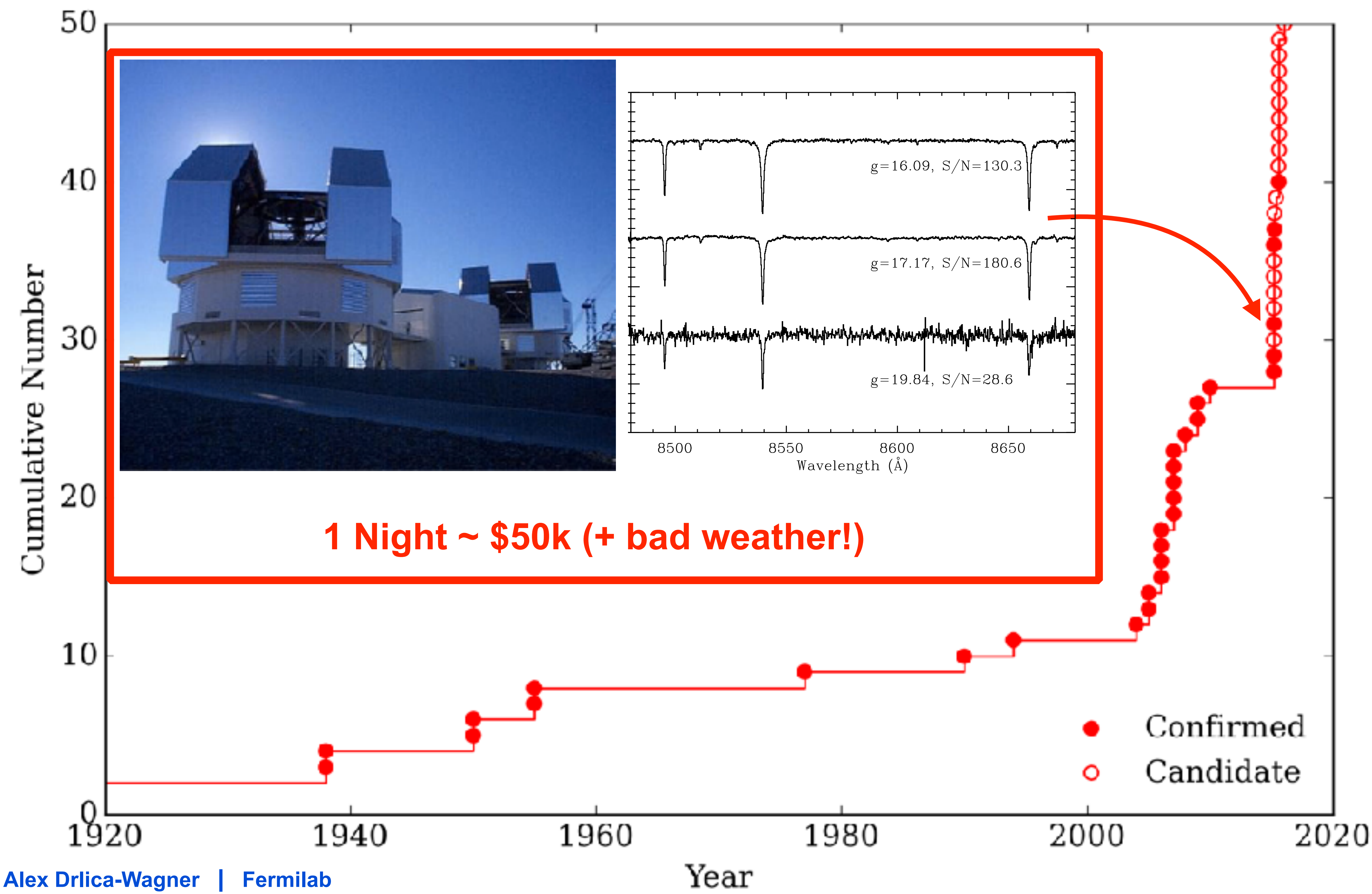


Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

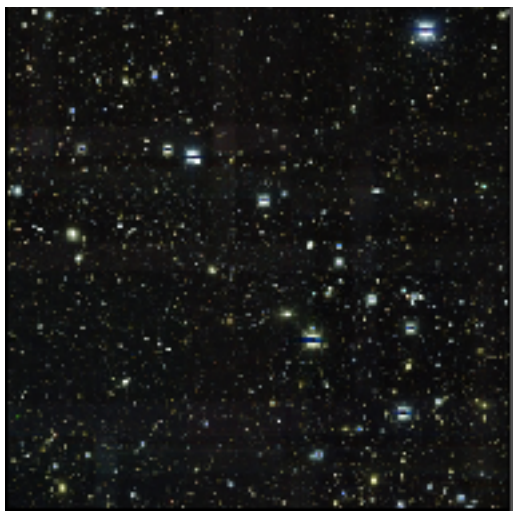
Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

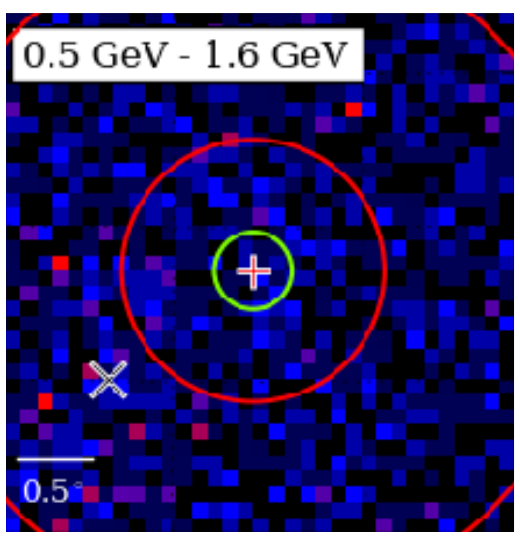
DES Collaboration, ApJ 813, 109 (2015)

Discovery Timeline

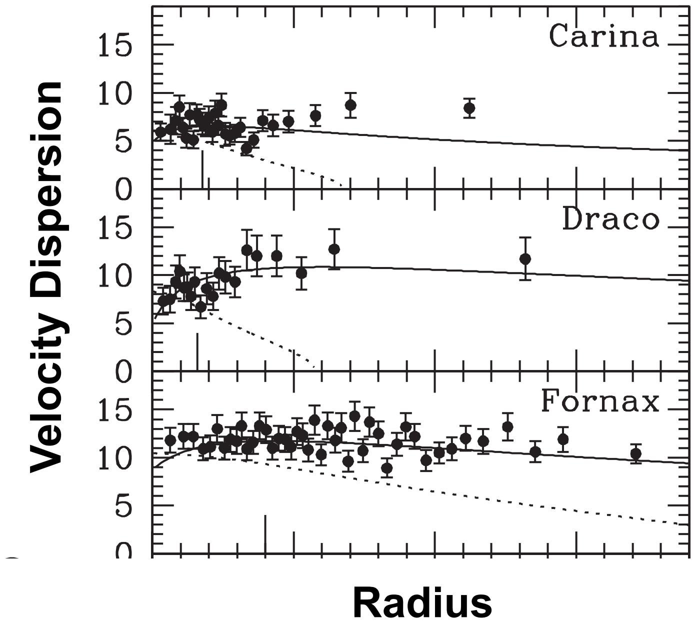


Search for Gamma Rays



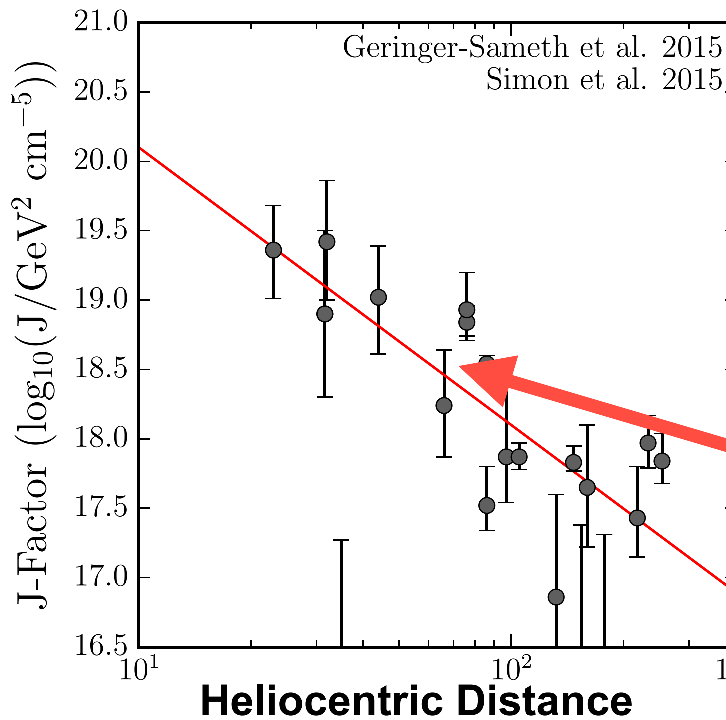


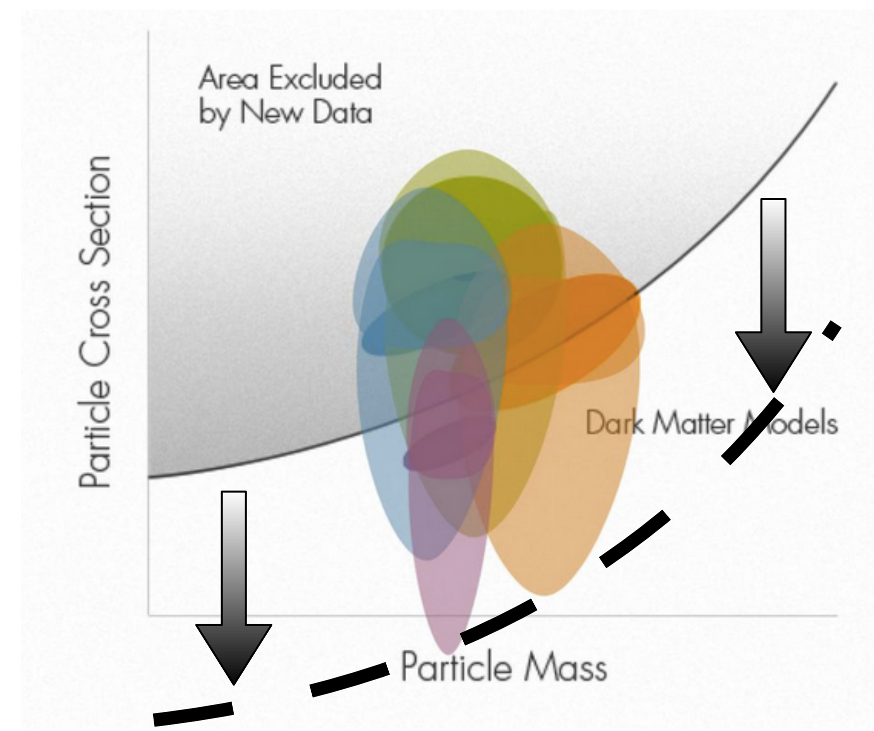
Walker et al. (2007)



What we want…

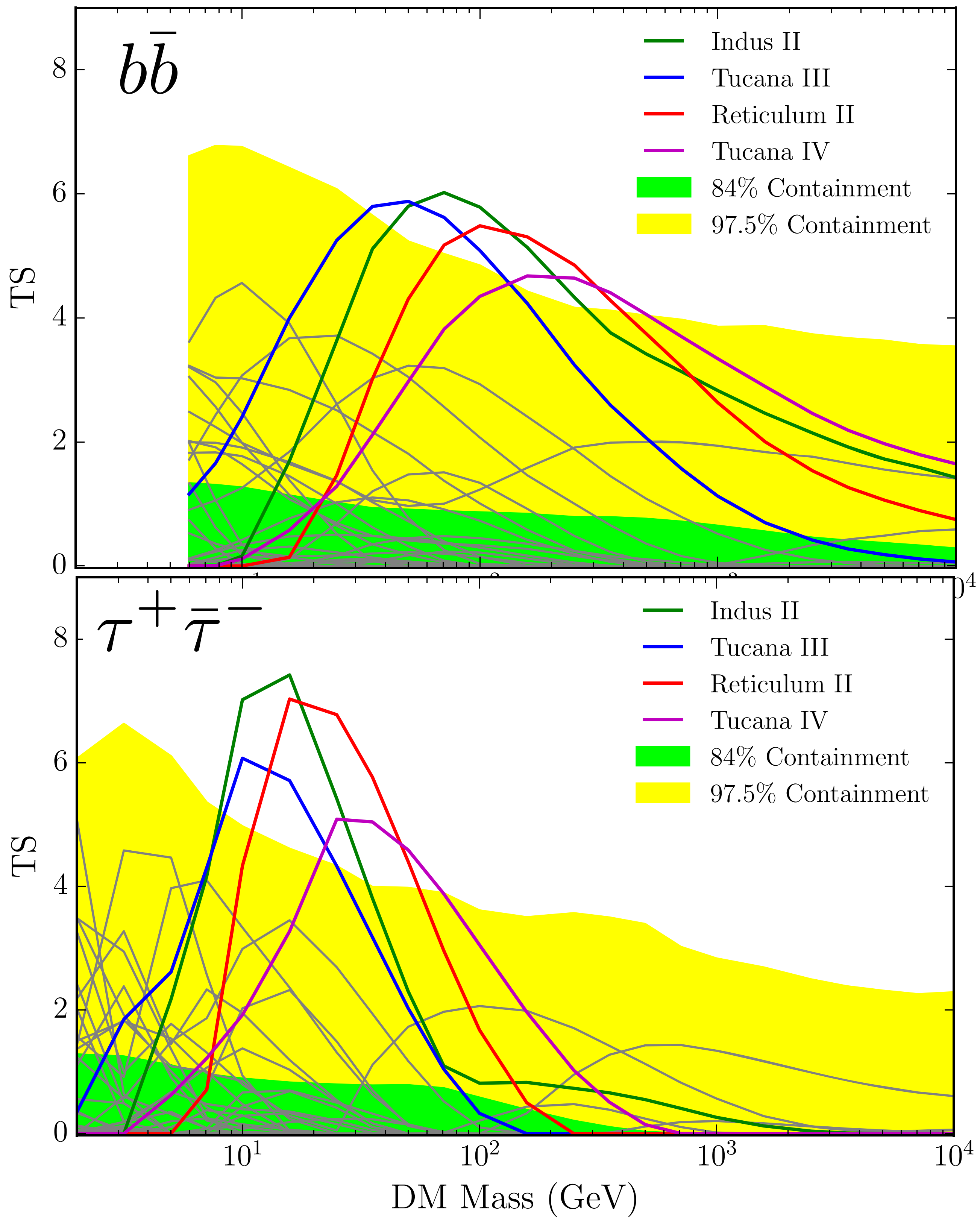
DM Content





What we have…

Gamma-ray Observations



Analyze 45 candidate and confirmed dwarf galaxies

Test for excess gamma-ray emission coincident with each individual target

Test Statistic:

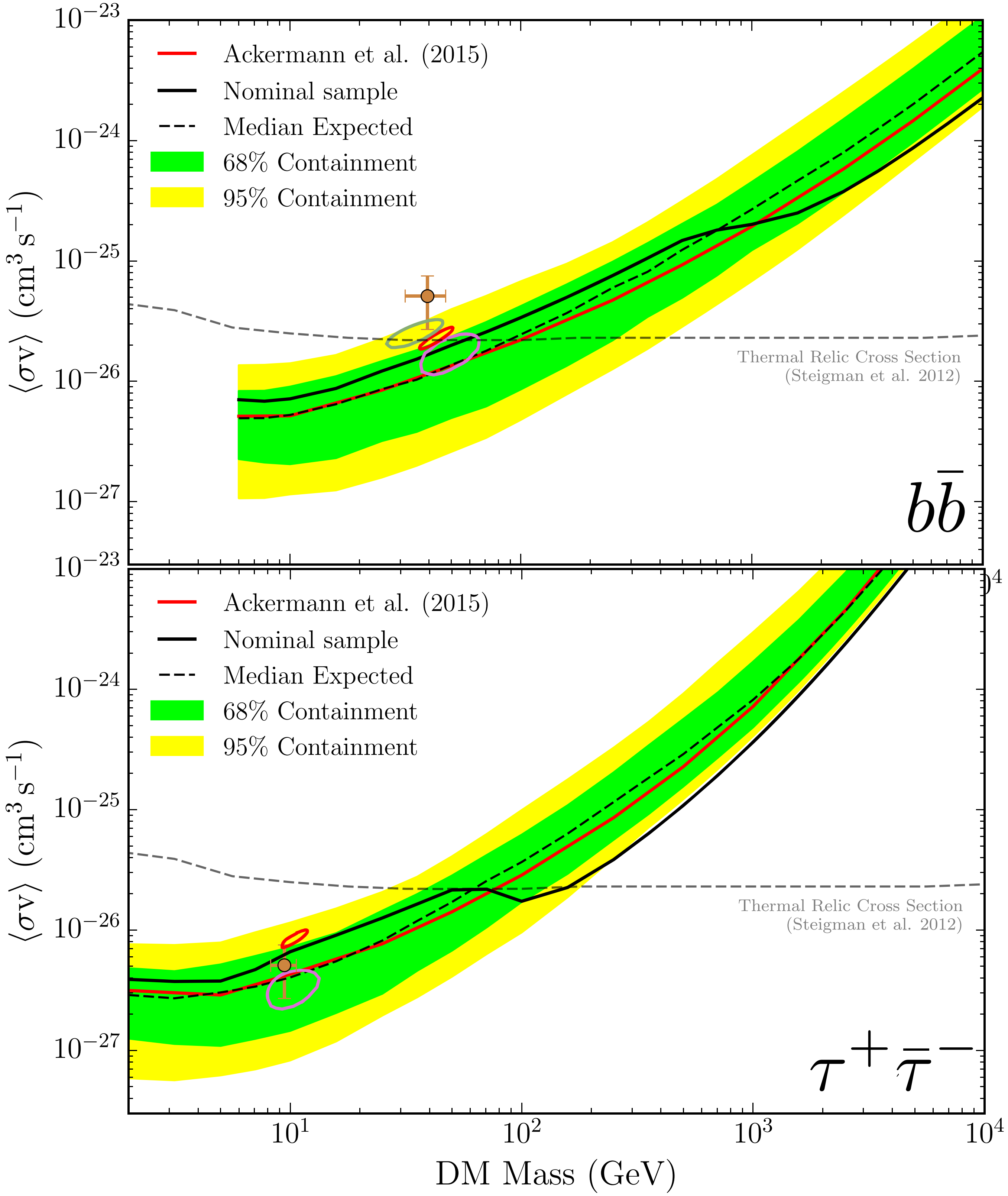
$$\mathrm{TS} = -2\Delta \log \mathcal{L}$$

- **Find 4 targets with ~2σ local significance excesses**
- **Significance drops to ~1.6σ with a trials factor for mass and channel**
- **<< 1σ after including a trials factor from searching 45 locations**

But dwarfs should not be weighted equally (i.e., different J-factors)…

LAT & DES Collaborations, ApJ 834, 110 (2017)

Gamma-ray Observations



Analyze 45 candidate and confirmed dwarf galaxies

Combine gamma-ray data weighted by expected/observed J-factor

Incorporate measurement uncertainty for targets with measured J-factors

Assume an uncertainty of 0.6 dex for targets without measured J-factors

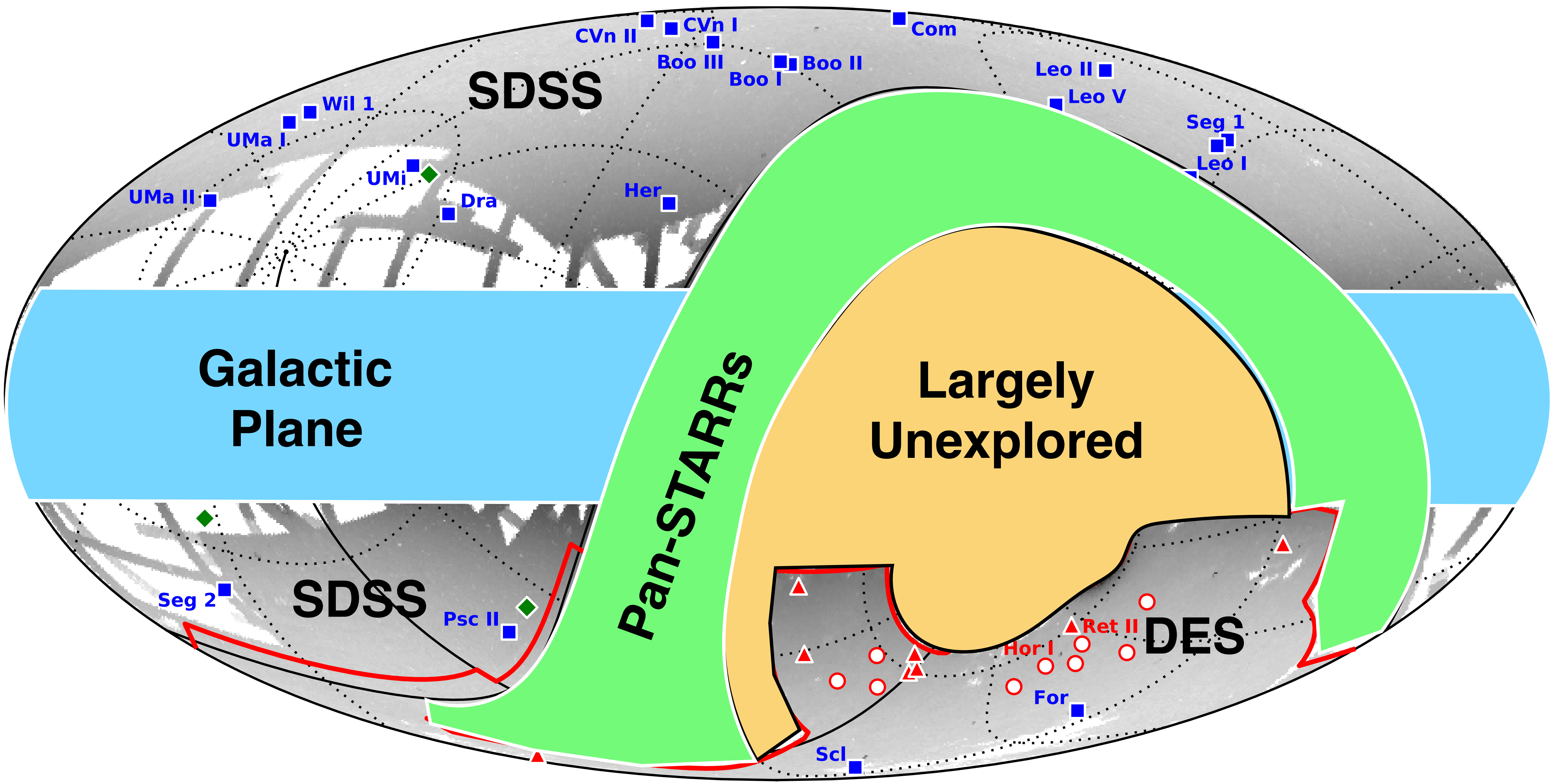
Global significance ~1σ, accounting for mass and channel

This result should be thought of as “an informed estimate” until we have measured J-factors for all targets

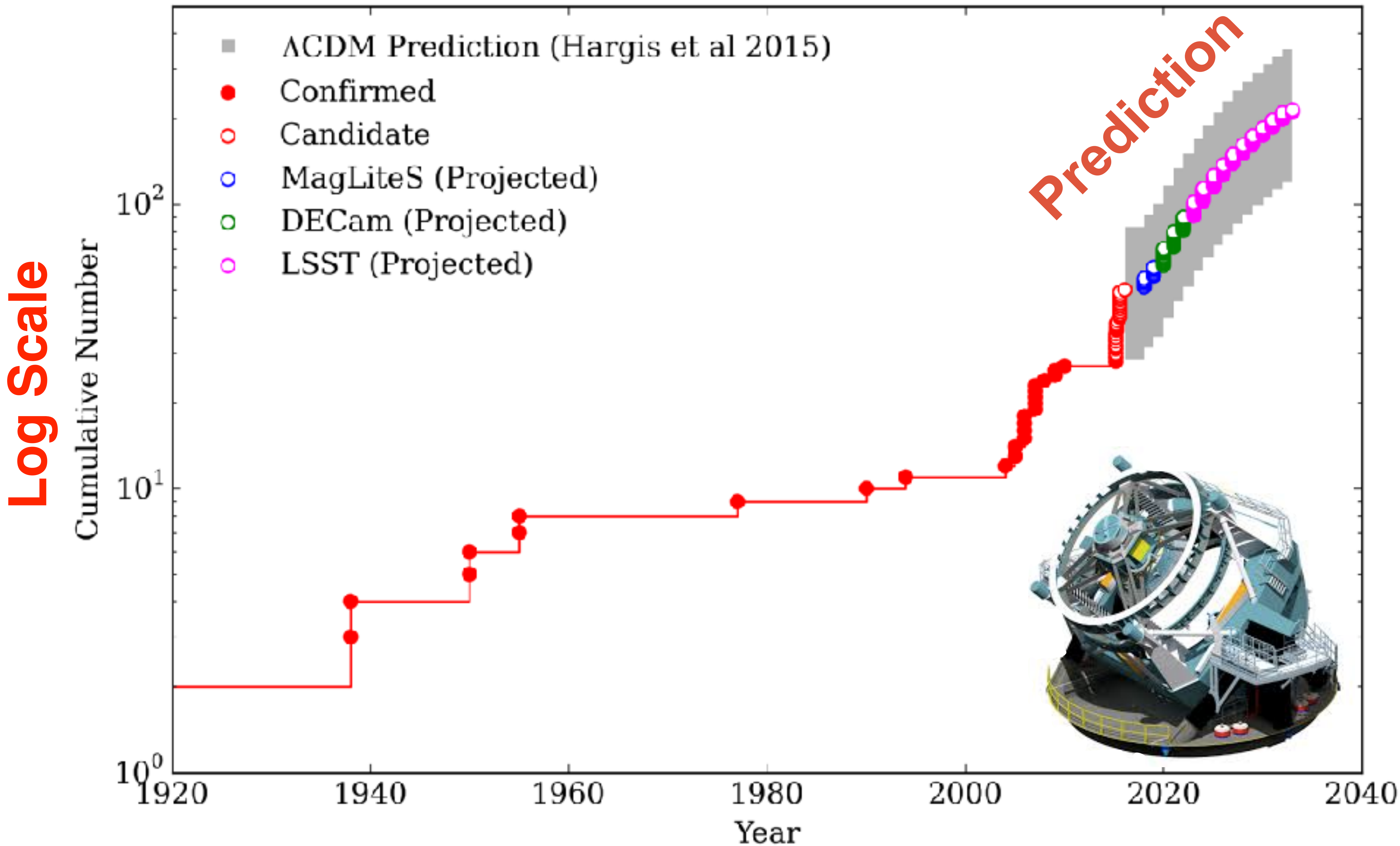
LAT & DES Collaborations, ApJ 834, 110 (2017)

A Lot of Sky to Cover!

DES (Milky Working Group Convener)
Magellanic Satellites Survey (Deputy PI)
Blanco Imaging of the Southern Sky (Co-PI)



LSST is Coming!

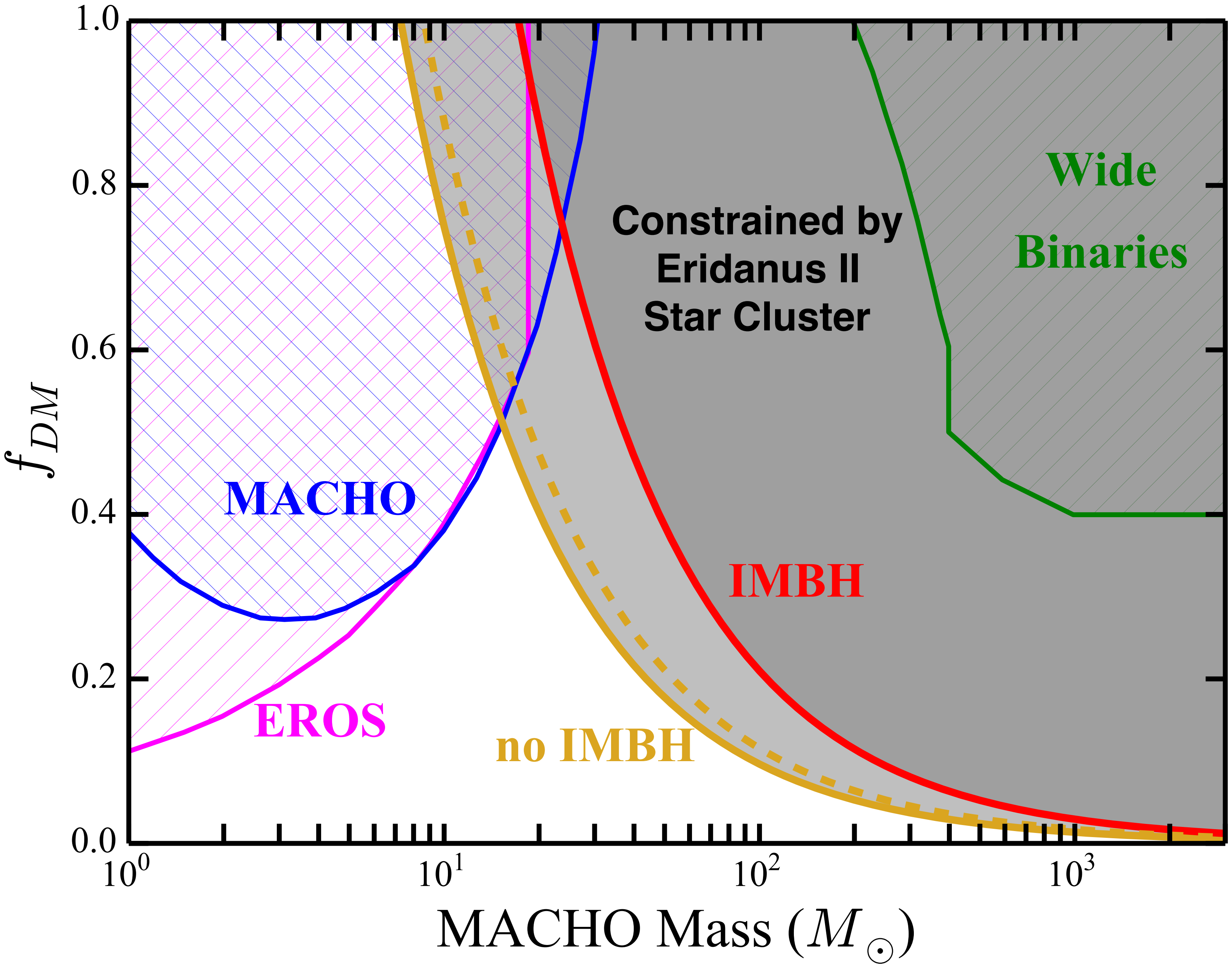


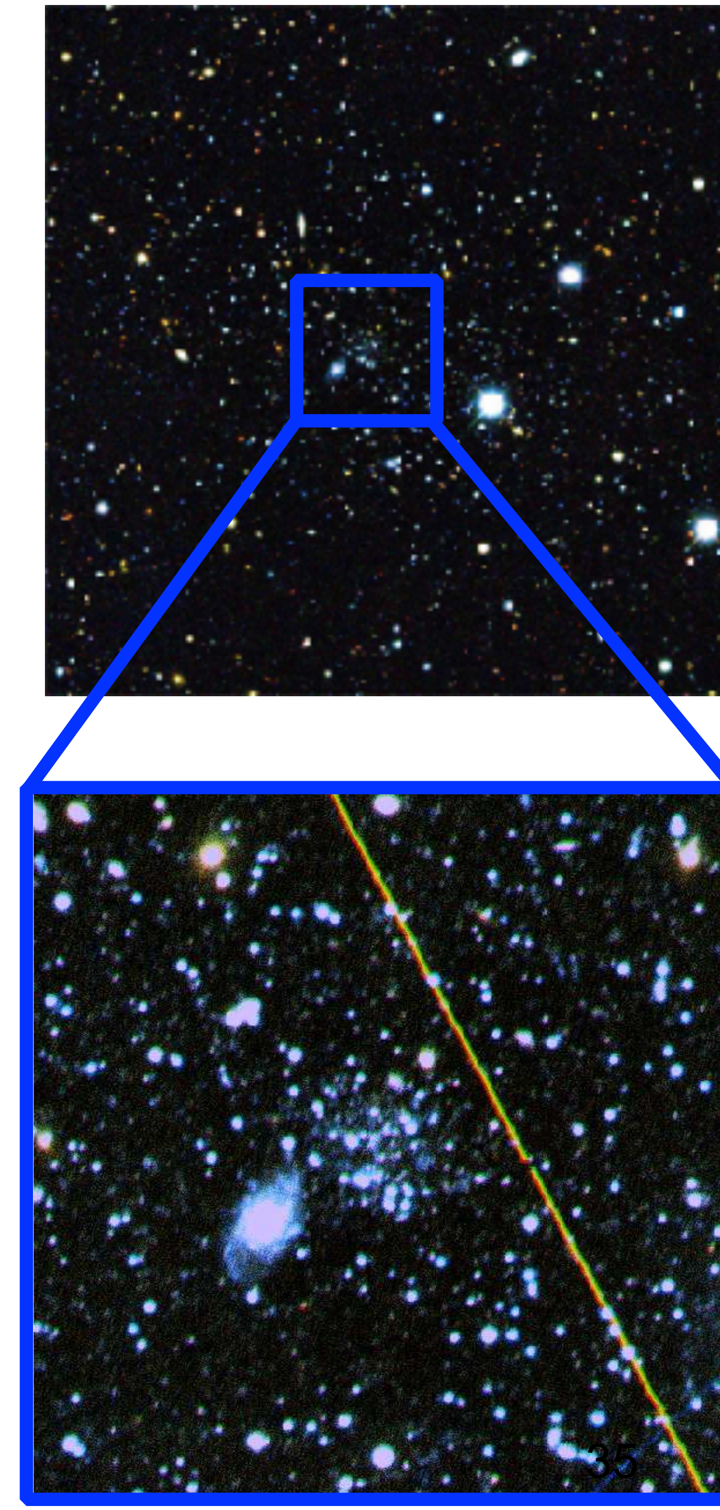
LSST is Coming!

Backup Slides

MACHO Dark Matter

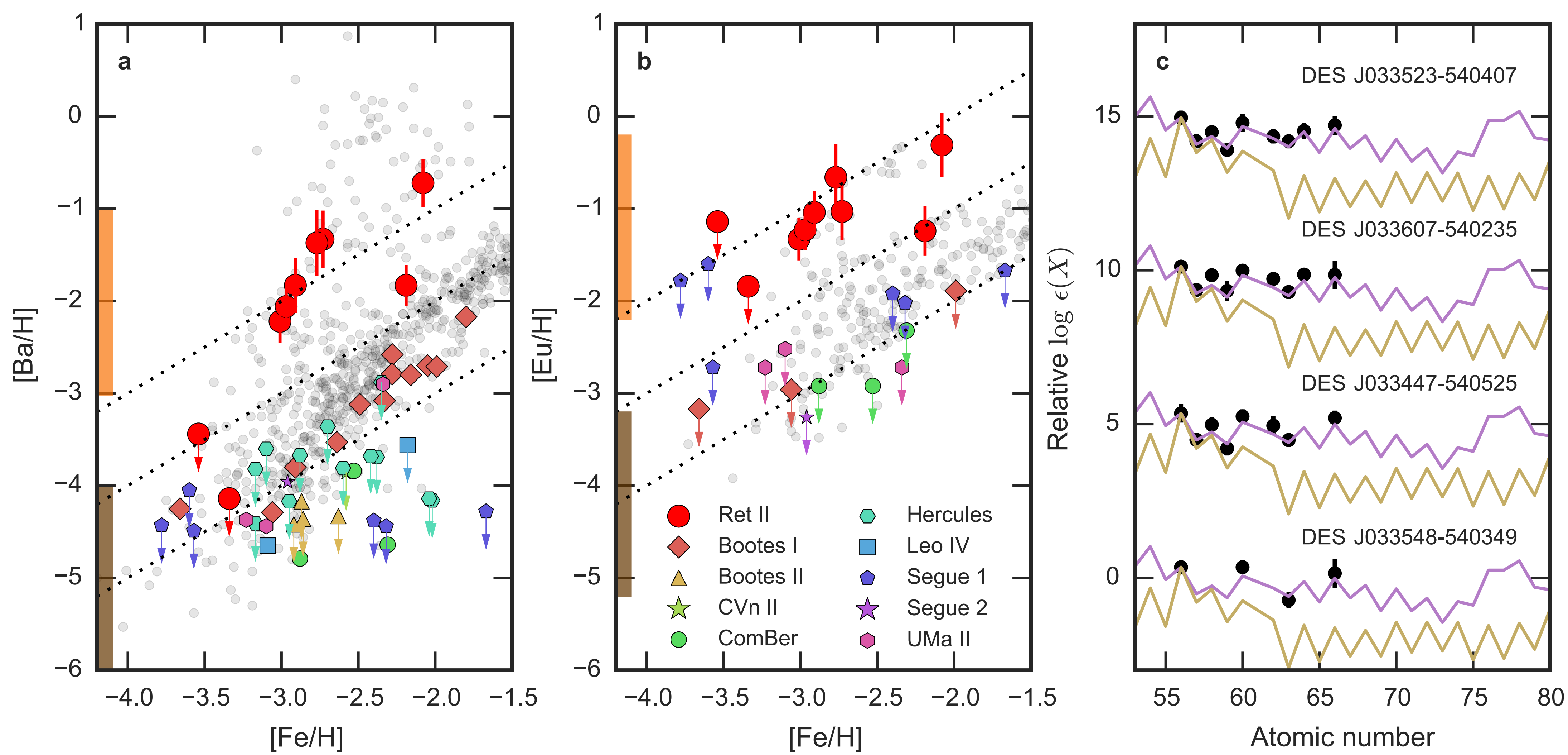
Massive, compact dark matter (i.e. 30 $M_\odot$ black holes) would disrupt the star cluster coincident with the center of Eridanus II





Formation of Heavy Elements

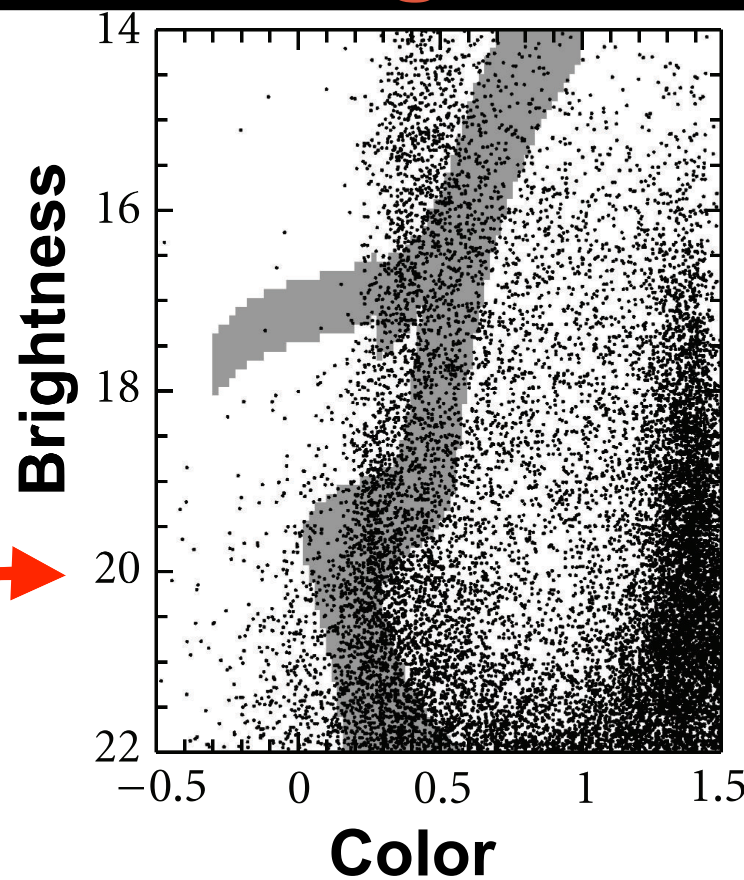
- **R-process enrichment in the Reticulum II dwarf galaxy appears more consistent with a single extreme event (e.g., neutron star merger) than a large number of common events (e.g. core-collapse supernovae).**



Matched-Filter Searches in the Sloan Digital Sky Survey (SDSS)

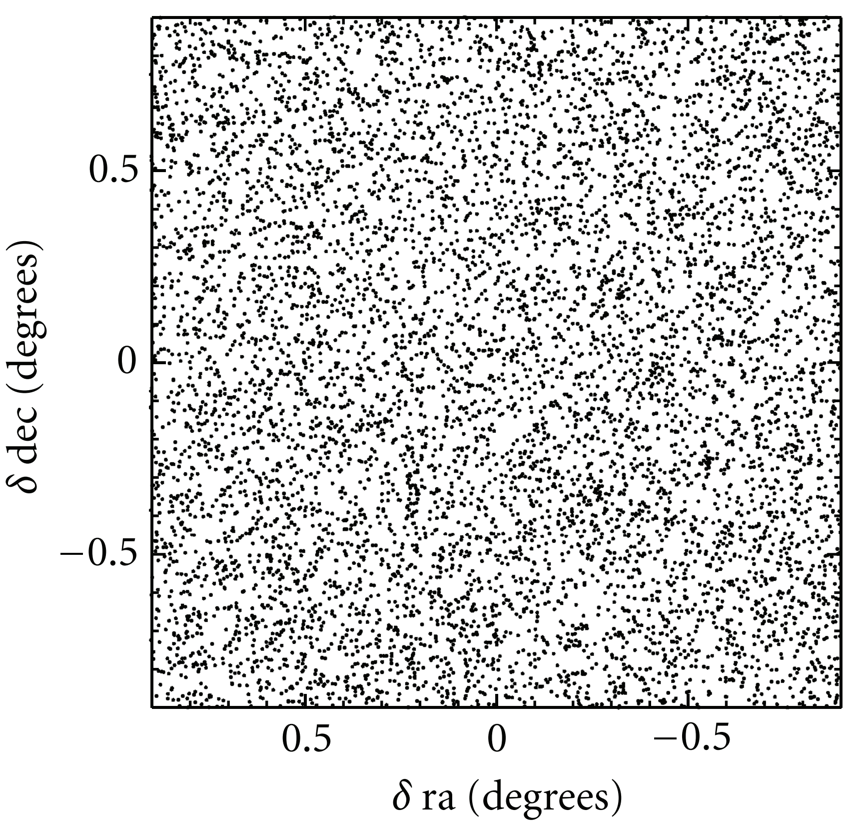
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

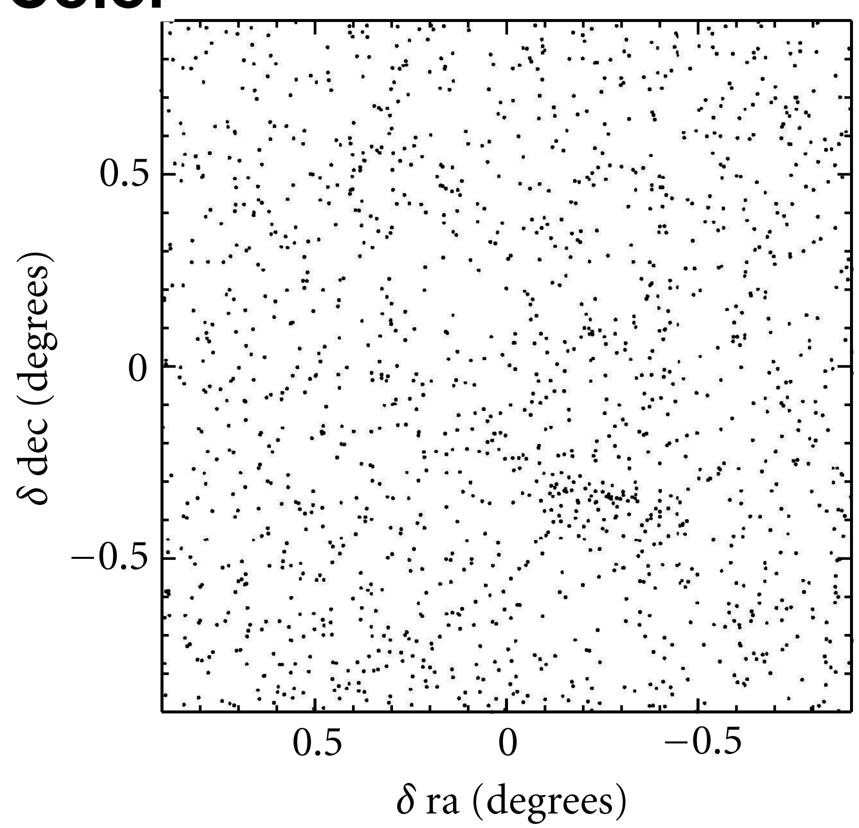
1) Start with a population of stars distributed on the sky

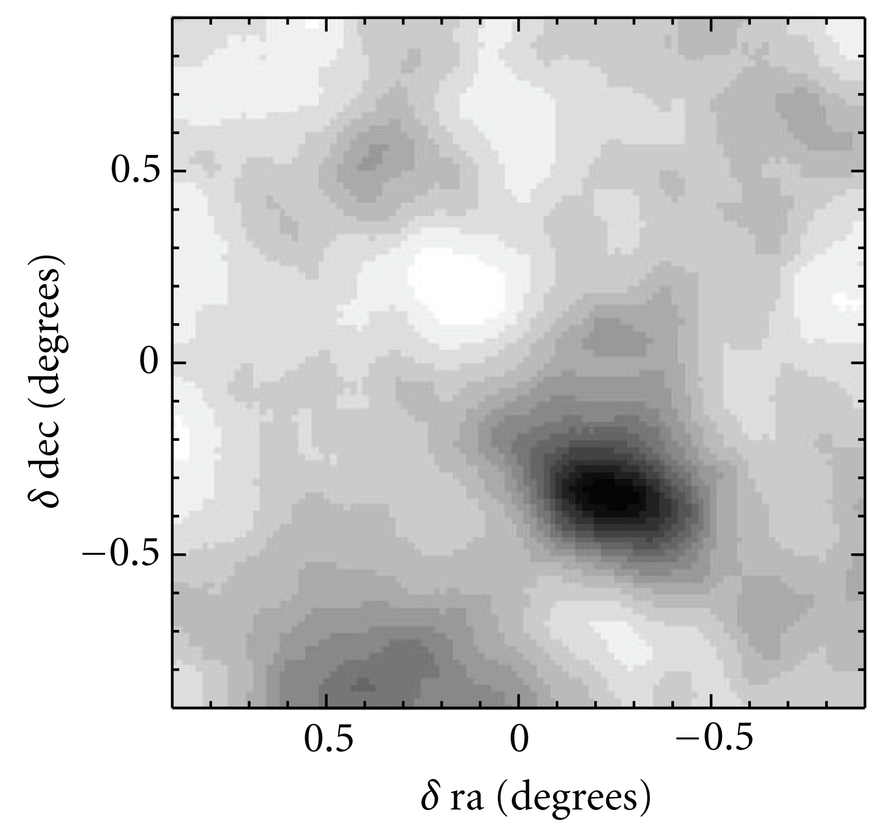


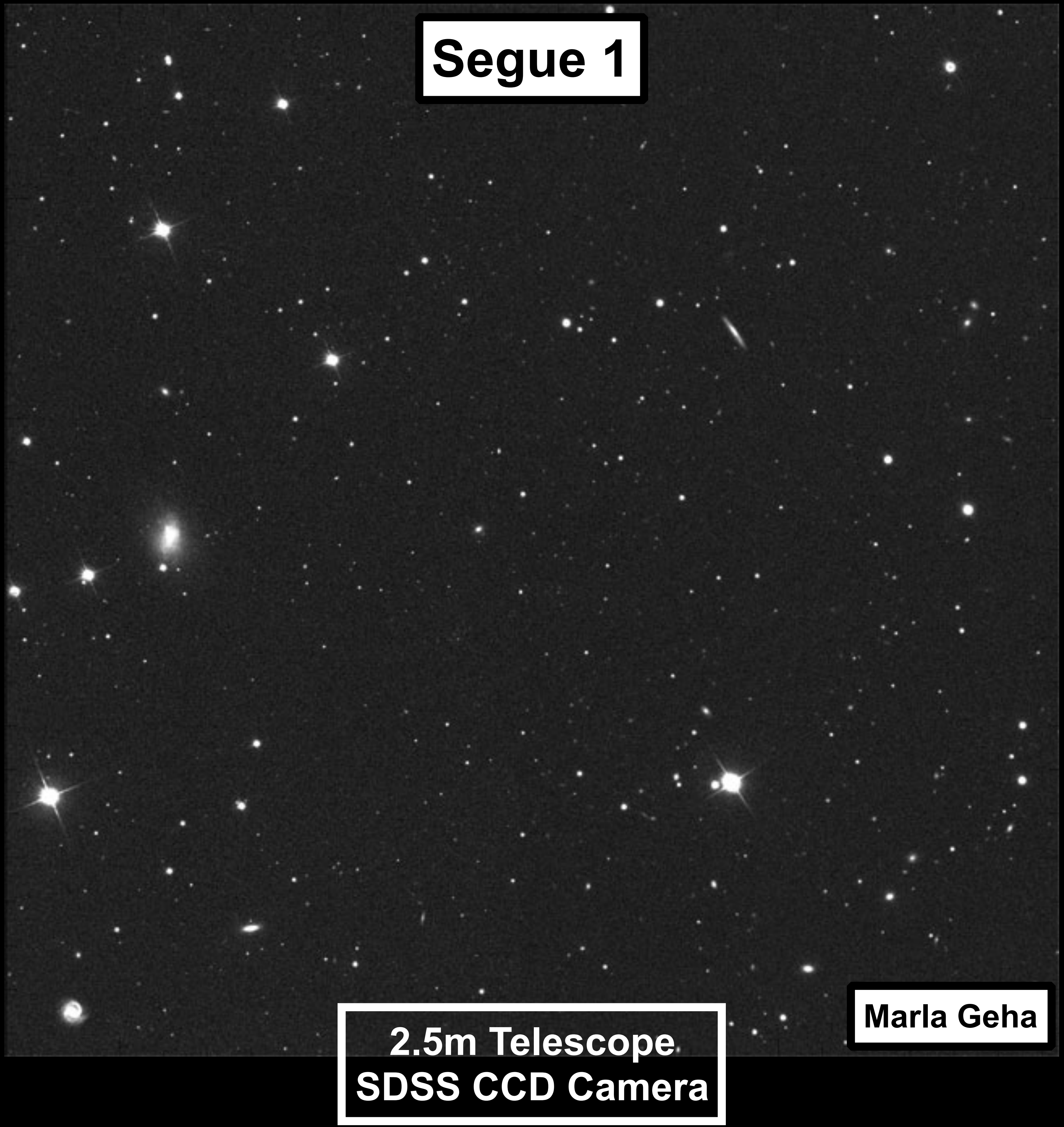
2) Apply a selection based on the isochrone in color-magnitude space

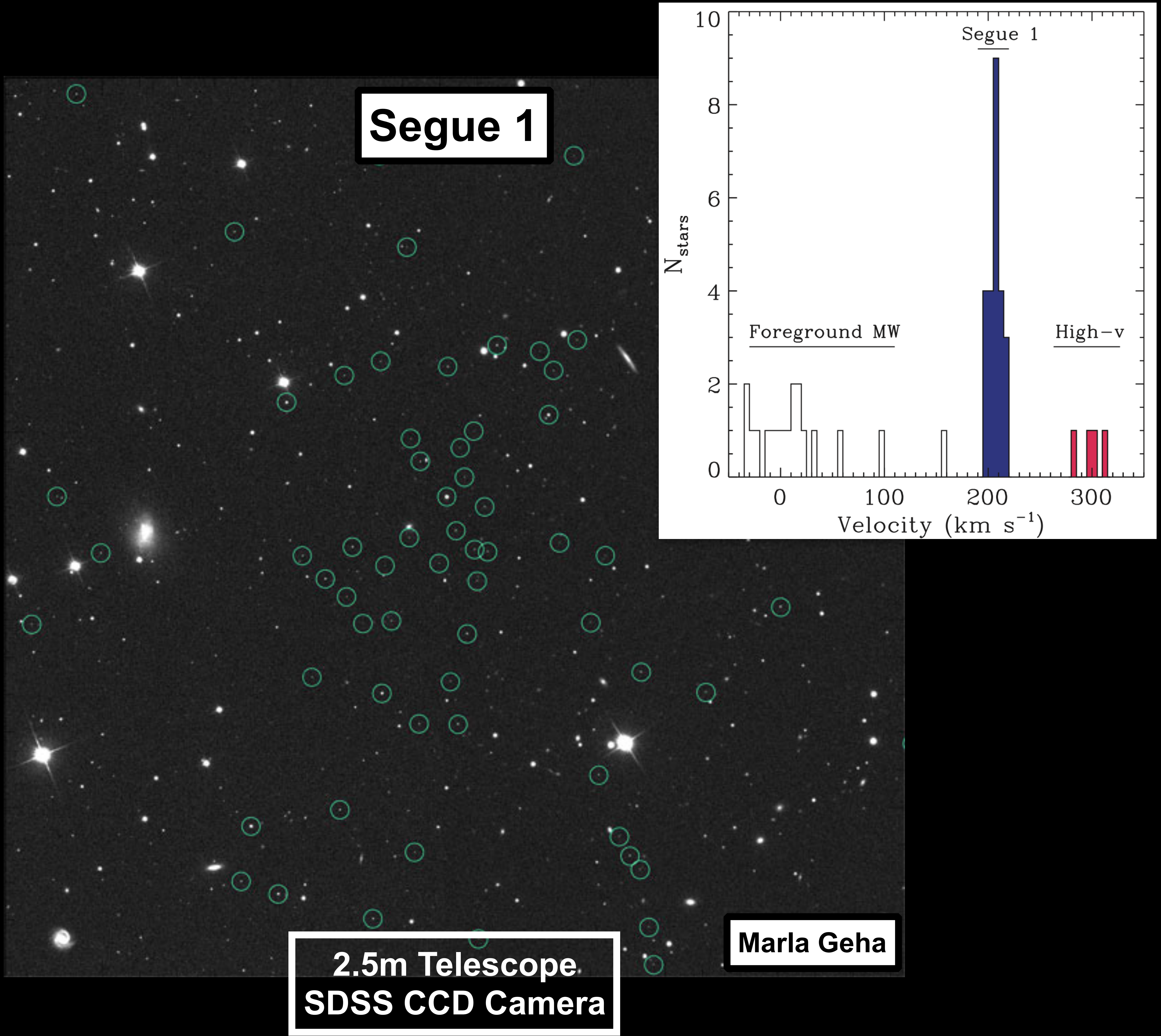
3) Convolve with a spatial kernel



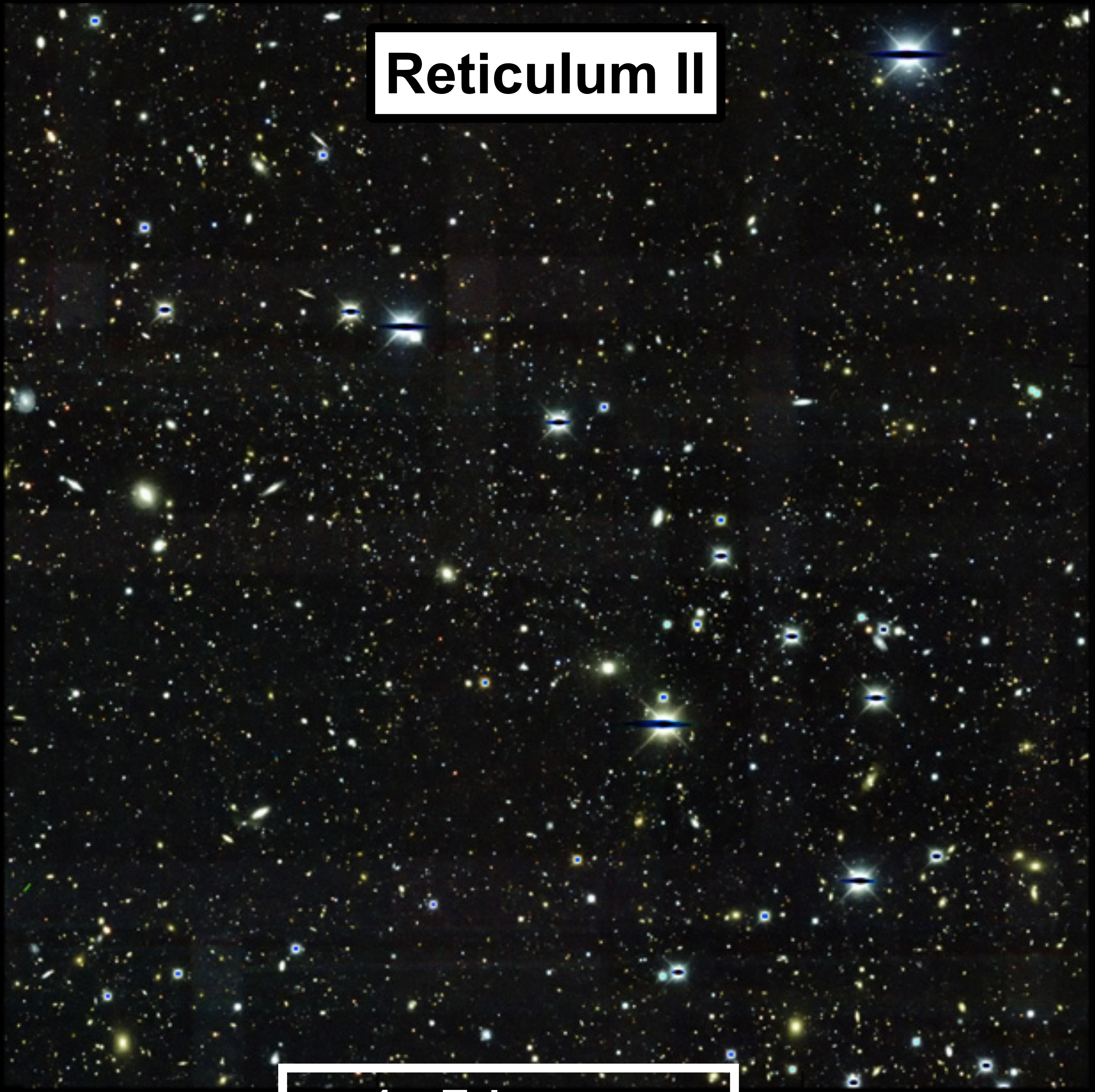





Segue 1
2.5m Telescope
SDSS CCD Camera
Marla Geha

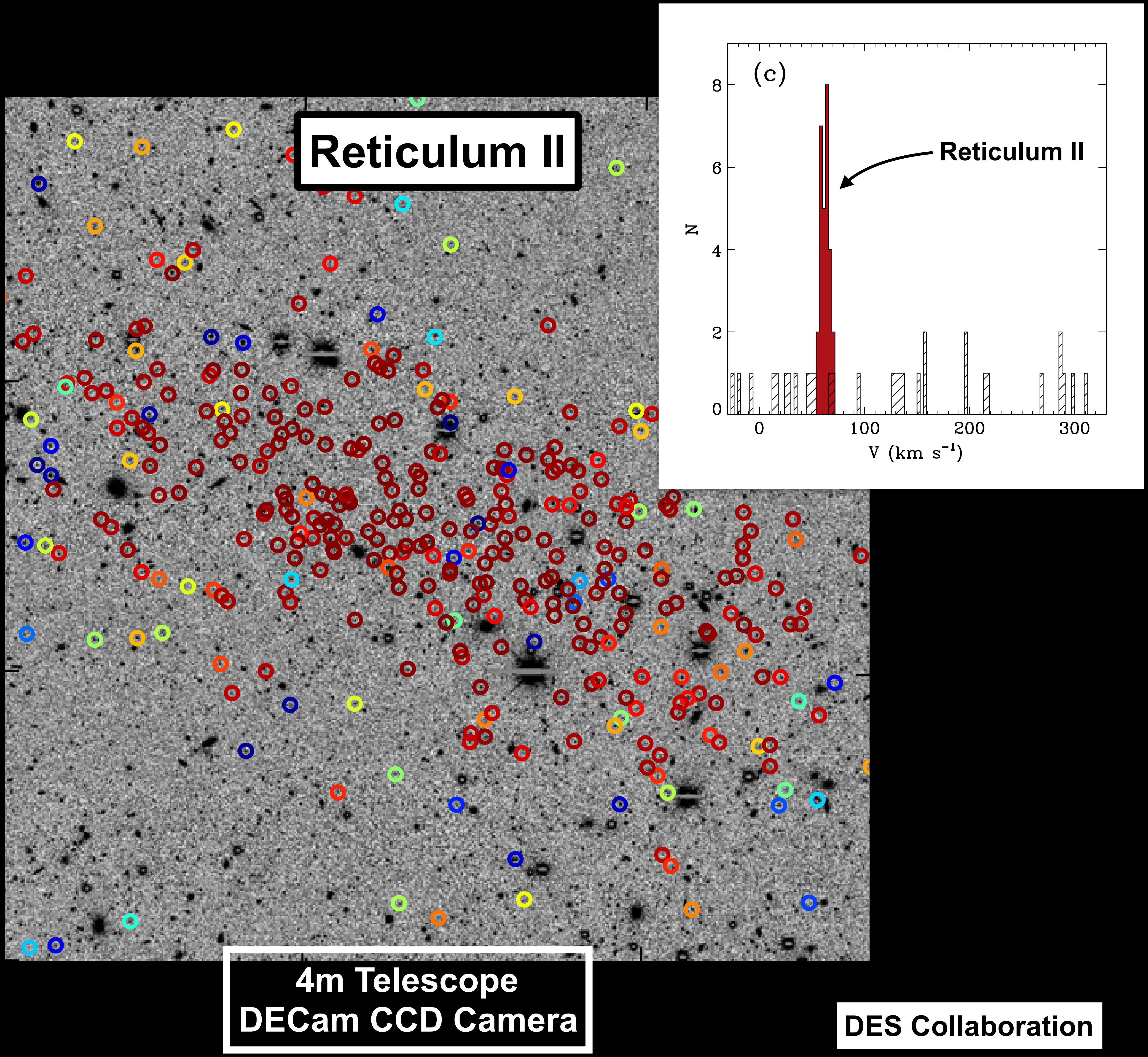


Segue 1
2.5m Telescope
SDSS CCD Camera
Marla Geha
Segue 1
Foreground MW
High−v
N_{stars}
Velocity ($km\ s^{-1}$)
0
100
200
300
10
8
6
4
2
0



4m Telescope
DECam CCD Camera

DES Collaboration



Reticulum II
(c)
Reticulum II
N
V (km s^{-1})
4m Telescope
DECam CCD Camera
DES Collaboration

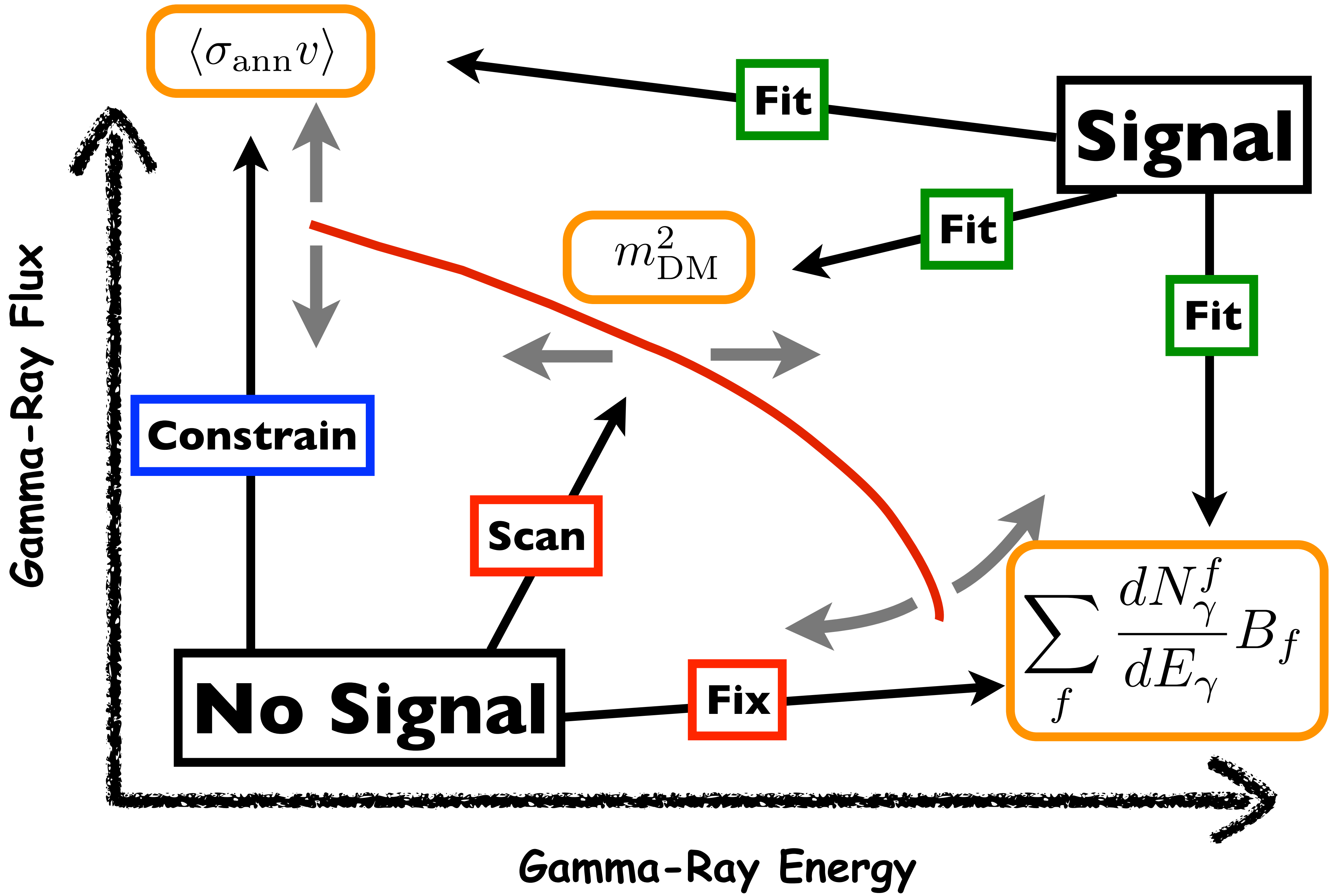
Gamma-ray Spectrum

Thermal Relic Cross Section

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$\frac{1}{4\pi} \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{2 m_{\mathrm{DM}}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

CARTOON

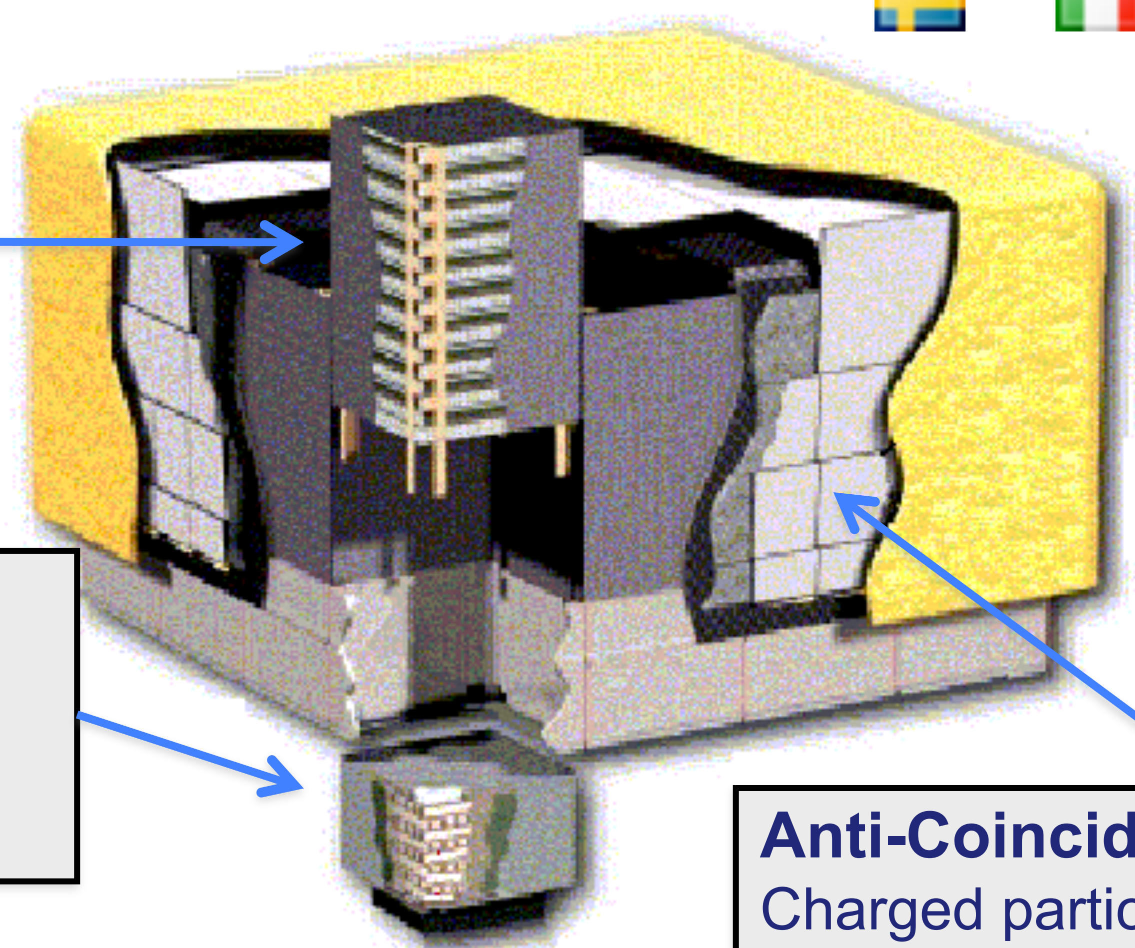


The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM vs. hadron separation



No Magnet

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

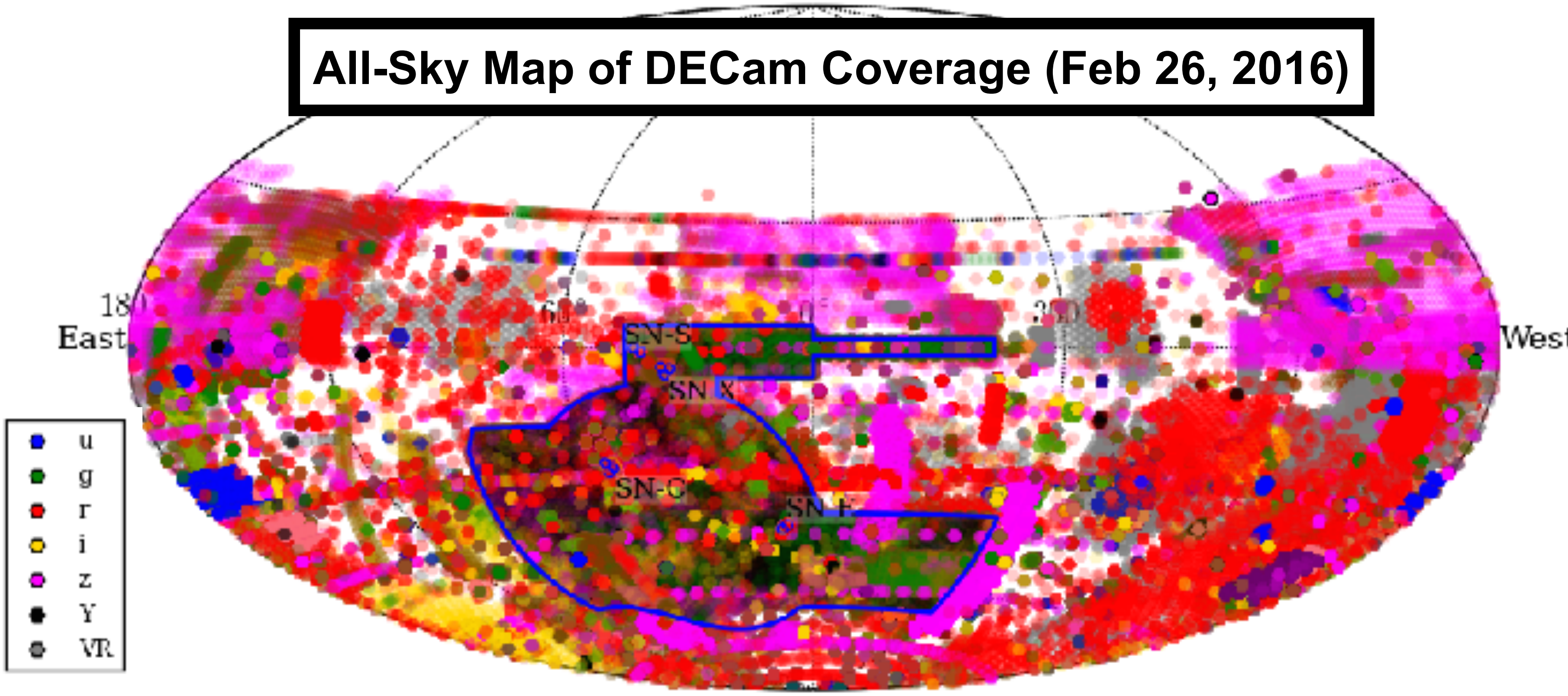
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
The LAT observes the whole sky every 3 hours (2.5 sr FOV)

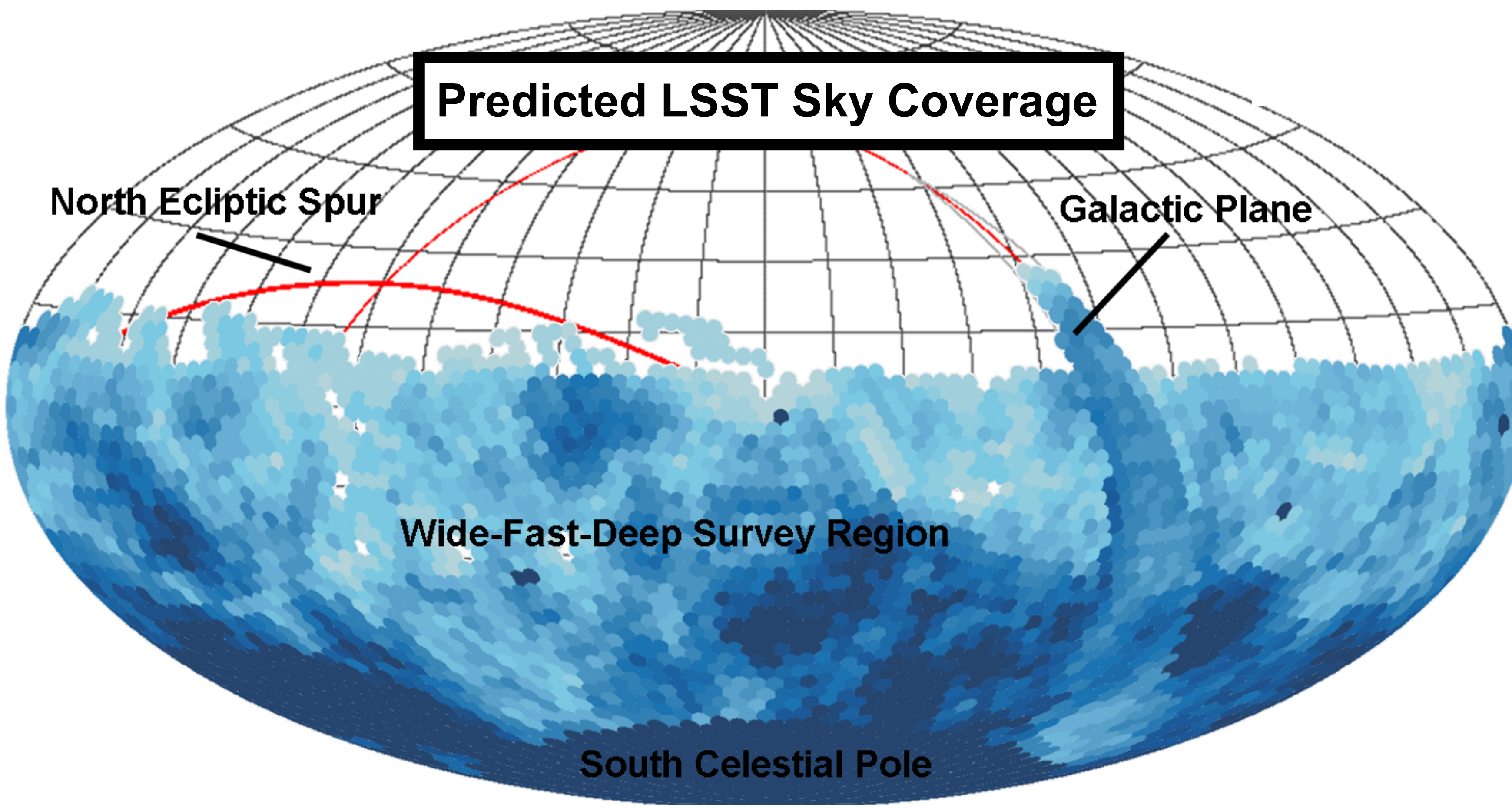
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Future Discoveries

All-Sky Map of DECam Coverage (Feb 26, 2016)



Predicted LSST Sky Coverage



DES only observes 1/6th of the sky accessible to DECam

Only 1/3 of the exposures taken with DECam are part of DES

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LSST will cover the entire southern sky and be a factor of 10 more sensitive

Milky Way Satellite Galaxies