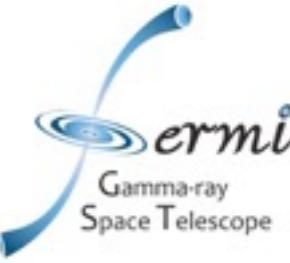


Fermi Gamma-ray Space Telescope



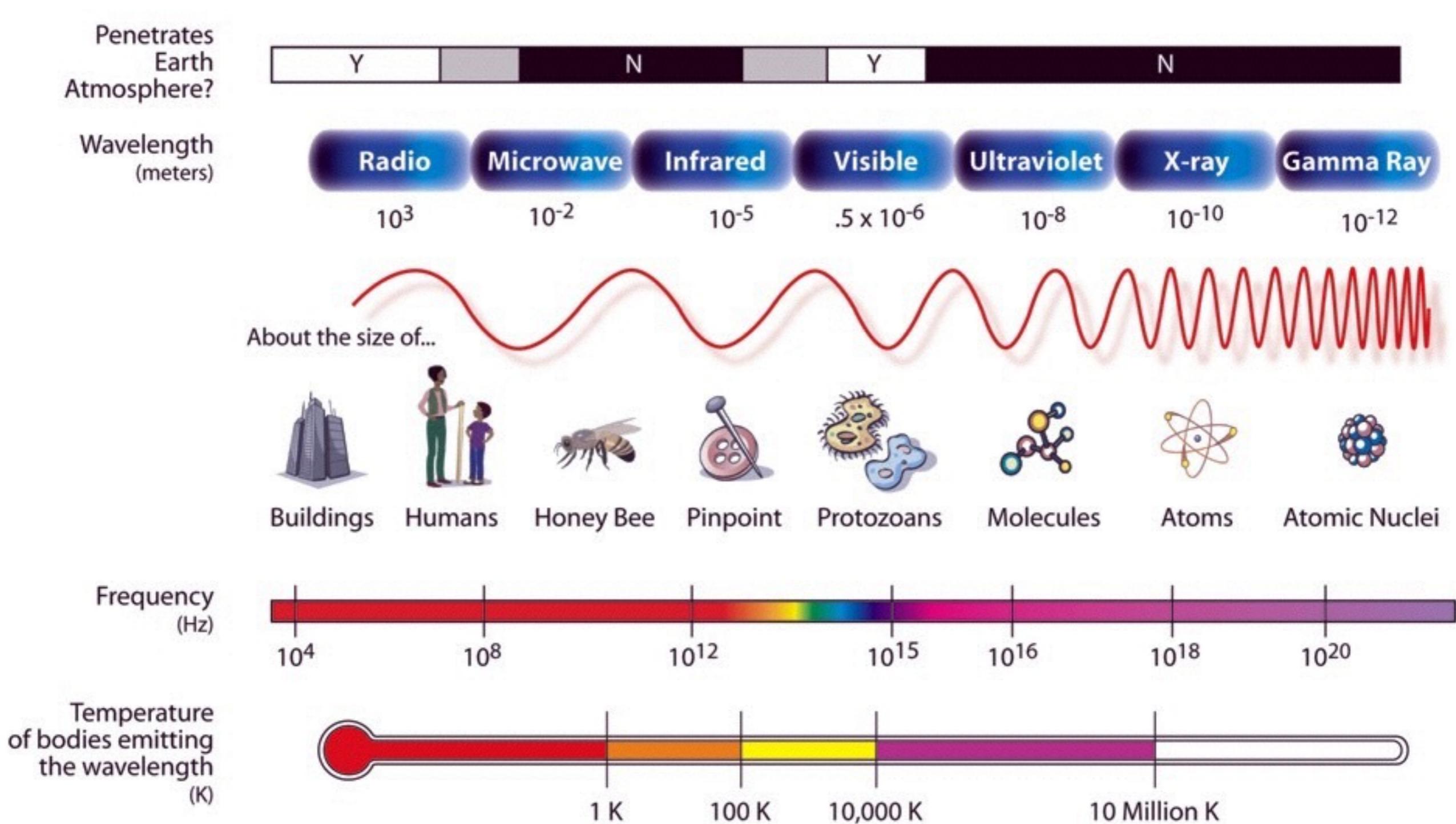
Latest Results with the *Fermi*-LAT

R. Caputo, UCSC
on behalf of the
Fermi-LAT Collaboration

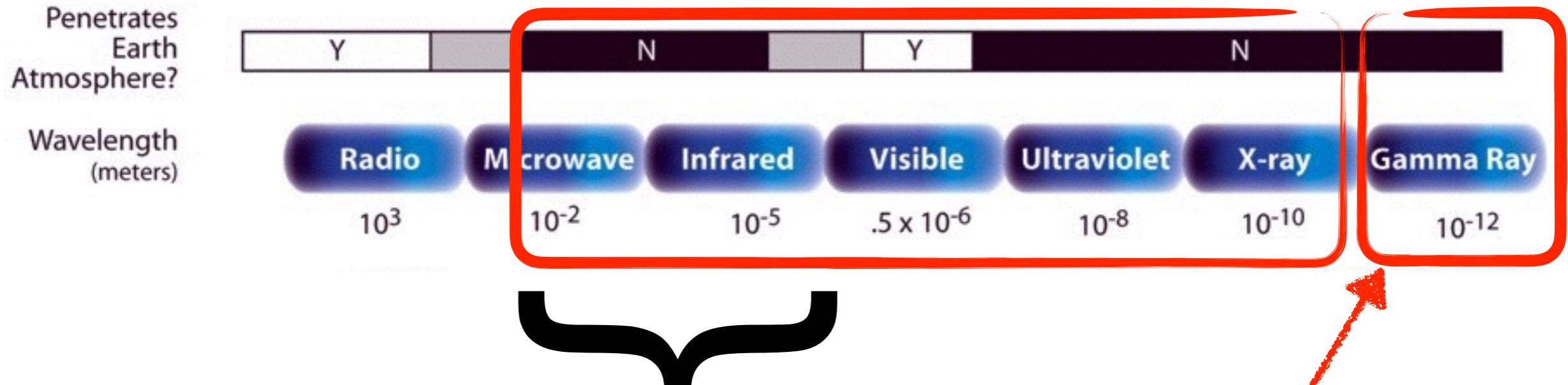
CosPA 2016
Sydney, Australia



Electromagnetic Spectrum



Electromagnetic Spectrum



Produced thermally
Stars, CMB, etc...

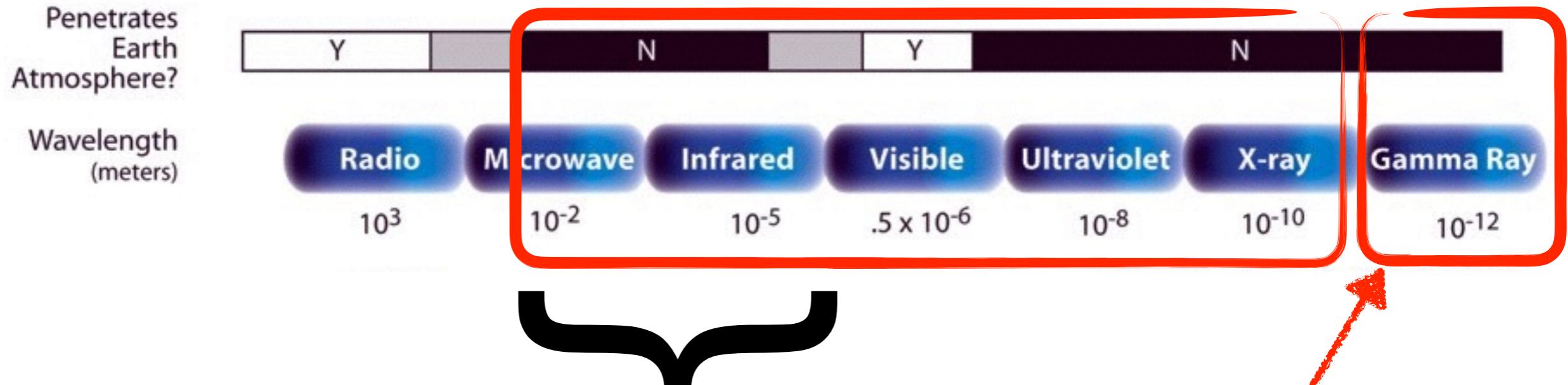
Energy Source + Acceleration Mechanism +

Gamma-ray Production Mechanism - Absorption/Propagation =

Gamma-ray Sky



Electromagnetic Spectrum

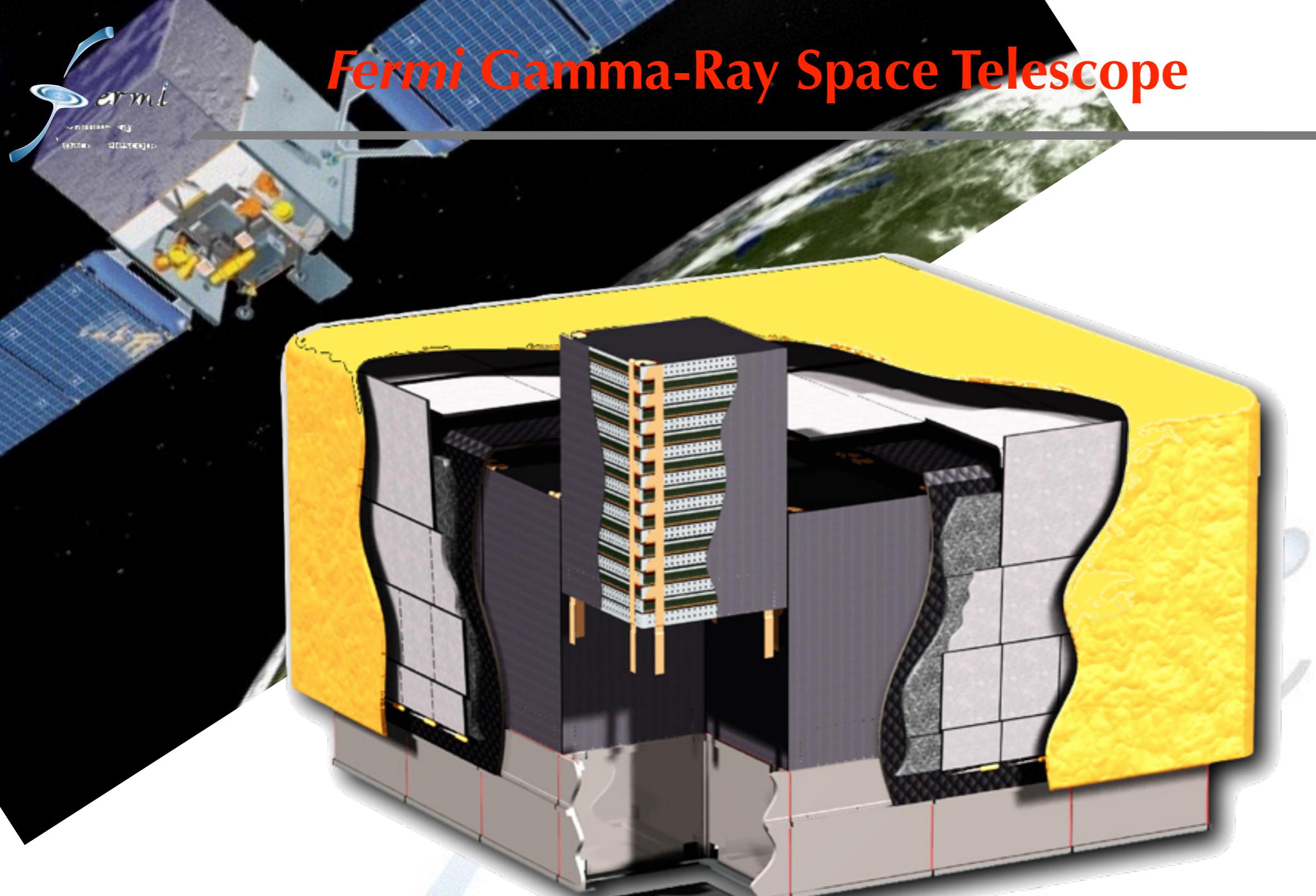


Produced thermally
Stars, CMB, etc...

Extreme Event + Extreme Fields +

Cosmic Rays and Targets - Foreground gas/dust =

Gamma-ray Sky





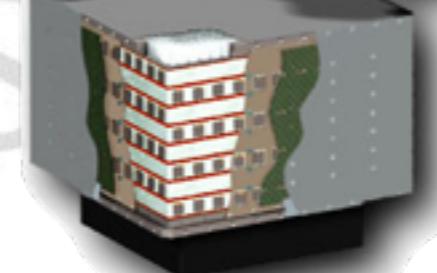
Fermi Gamma-Ray Space Telescope



Wide FOV: 20% sky at once
Full sky: 3 hours

Anti-Coincidence Detector
charged particle separation

Tracker
charged particles
cause conversion $\gamma \rightarrow e^+e^-$
direction



Calorimeter
Energy measurement



Fermi Gamma-Ray Space Telescope



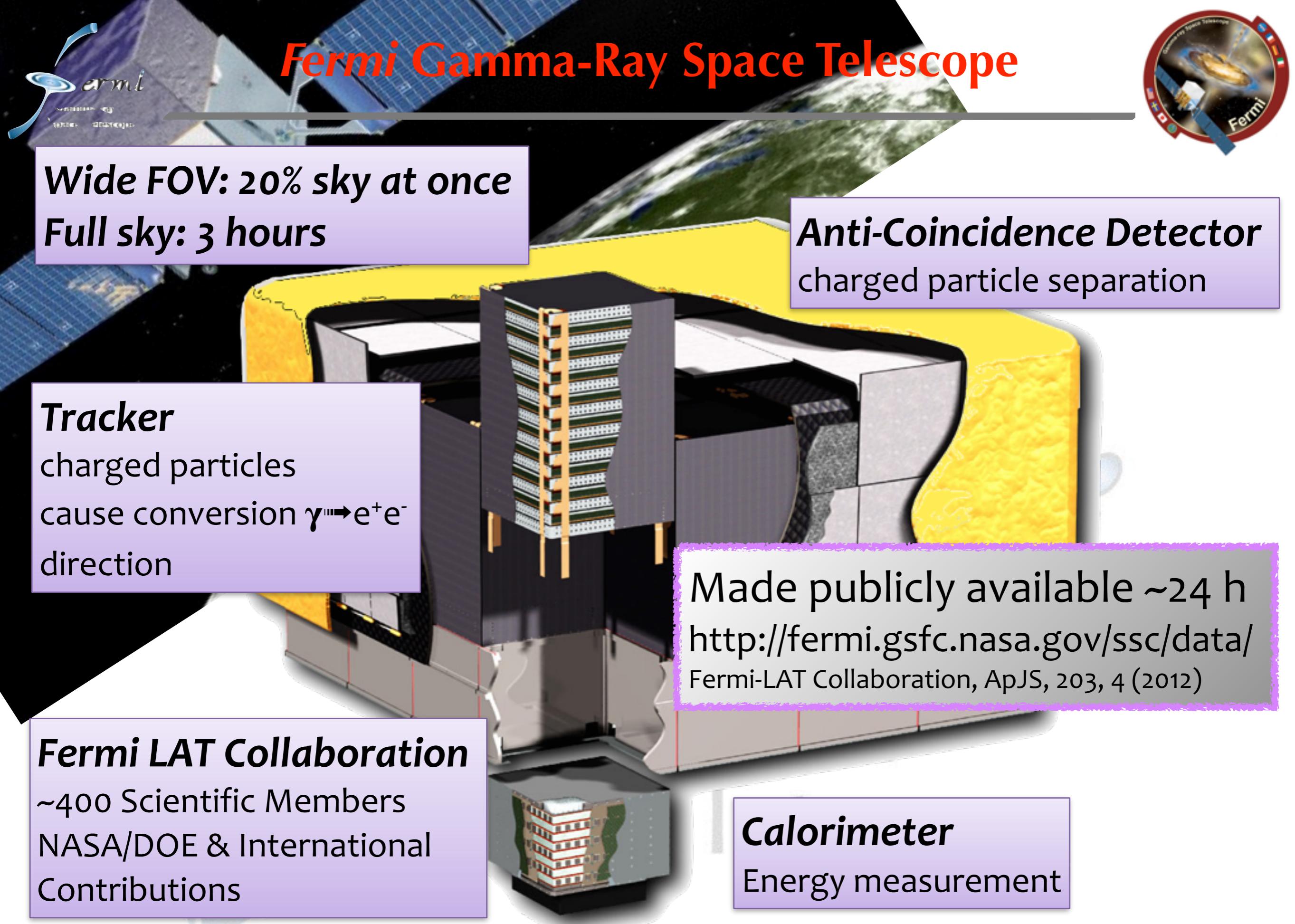
Wide FOV: 20% sky at once
Full sky: 3 hours

Anti-Coincidence Detector
charged particle separation

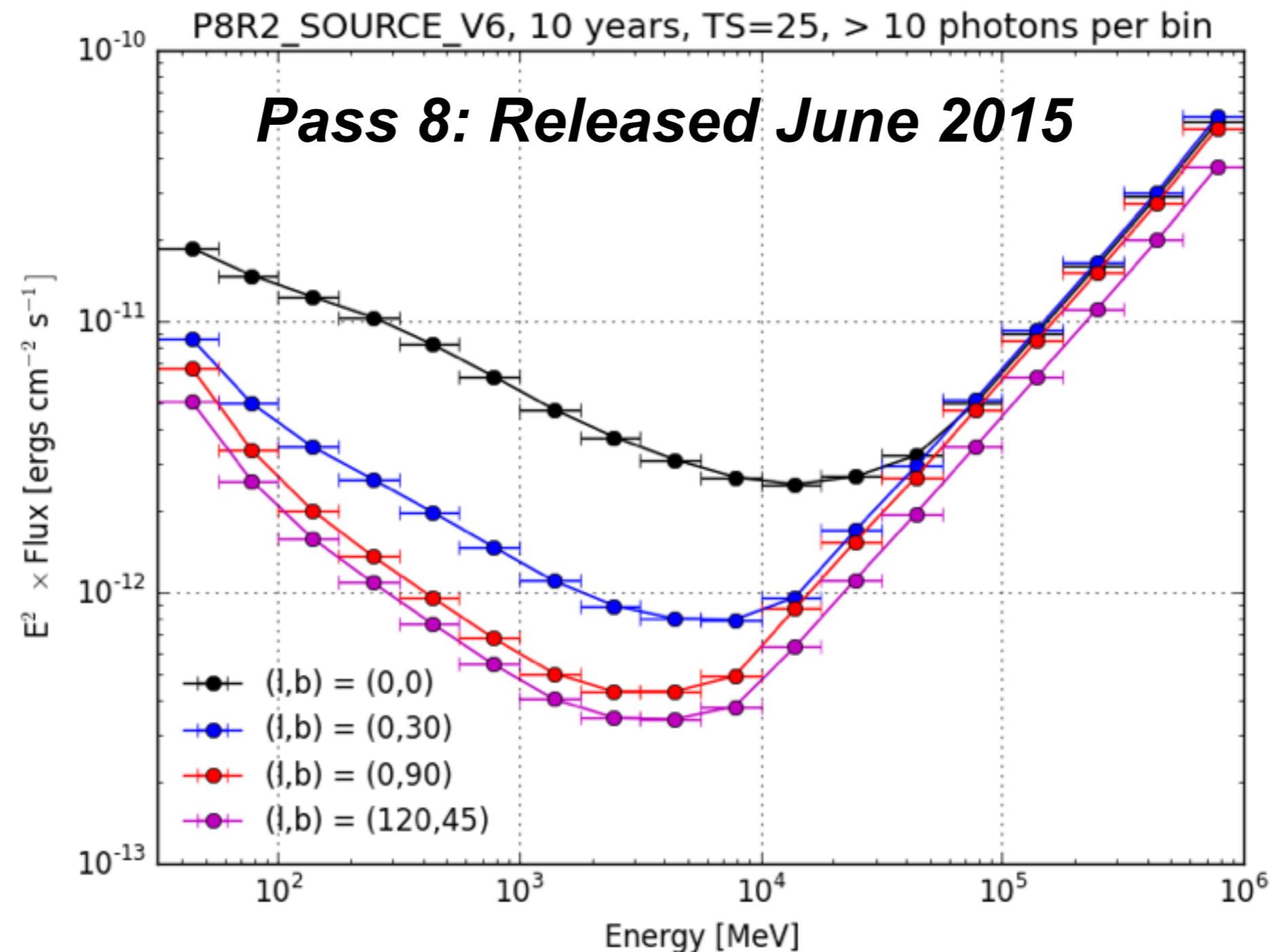
Tracker
charged particles
cause conversion $\gamma \rightarrow e^+e^-$
direction

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

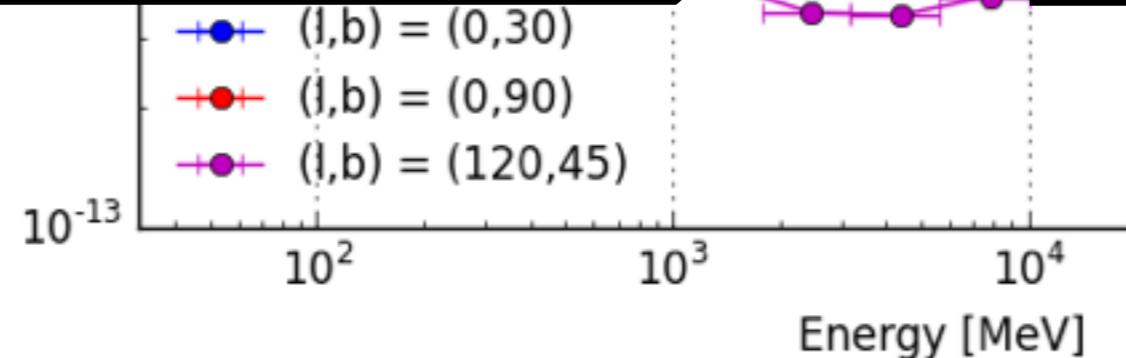
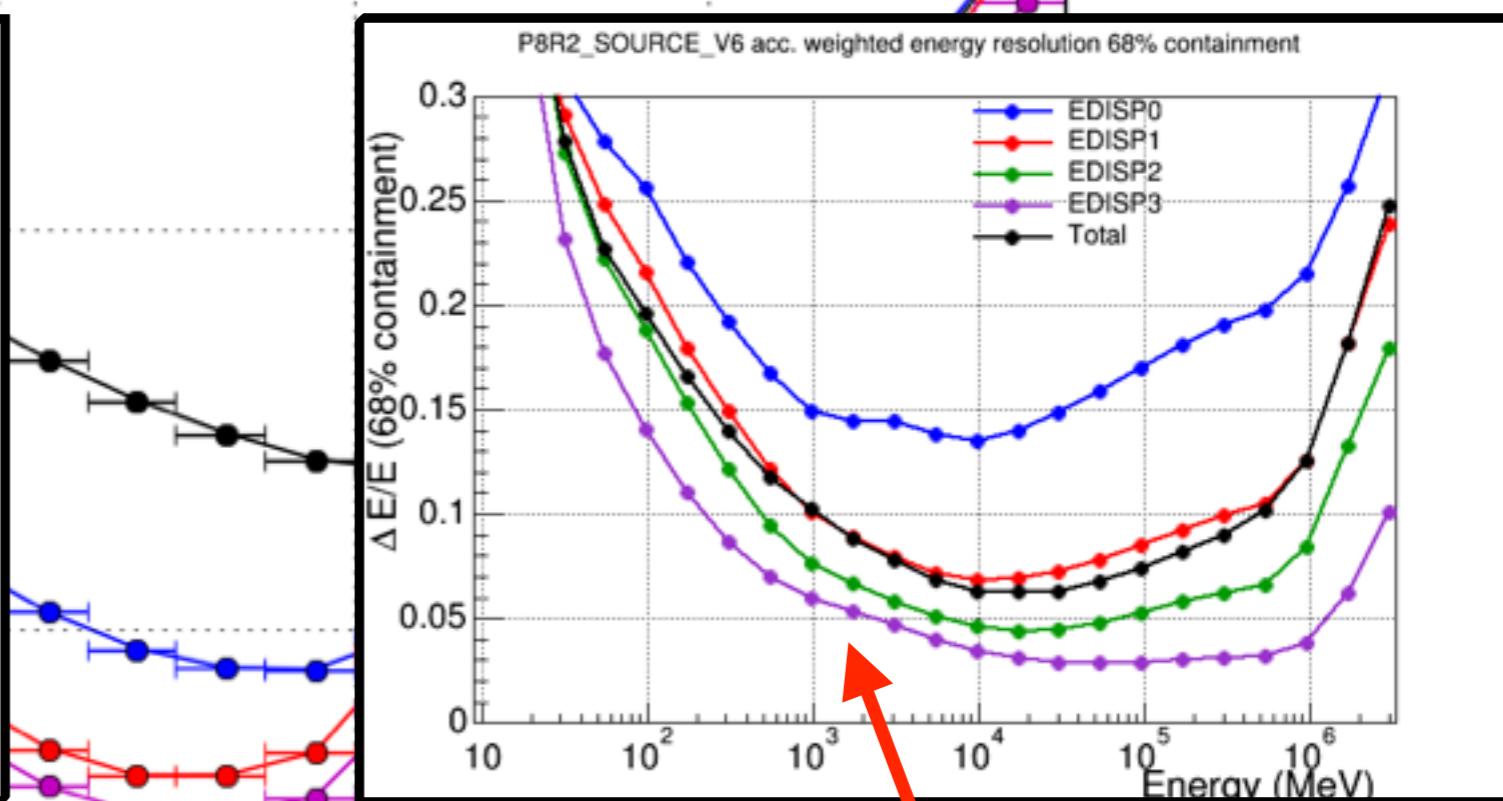
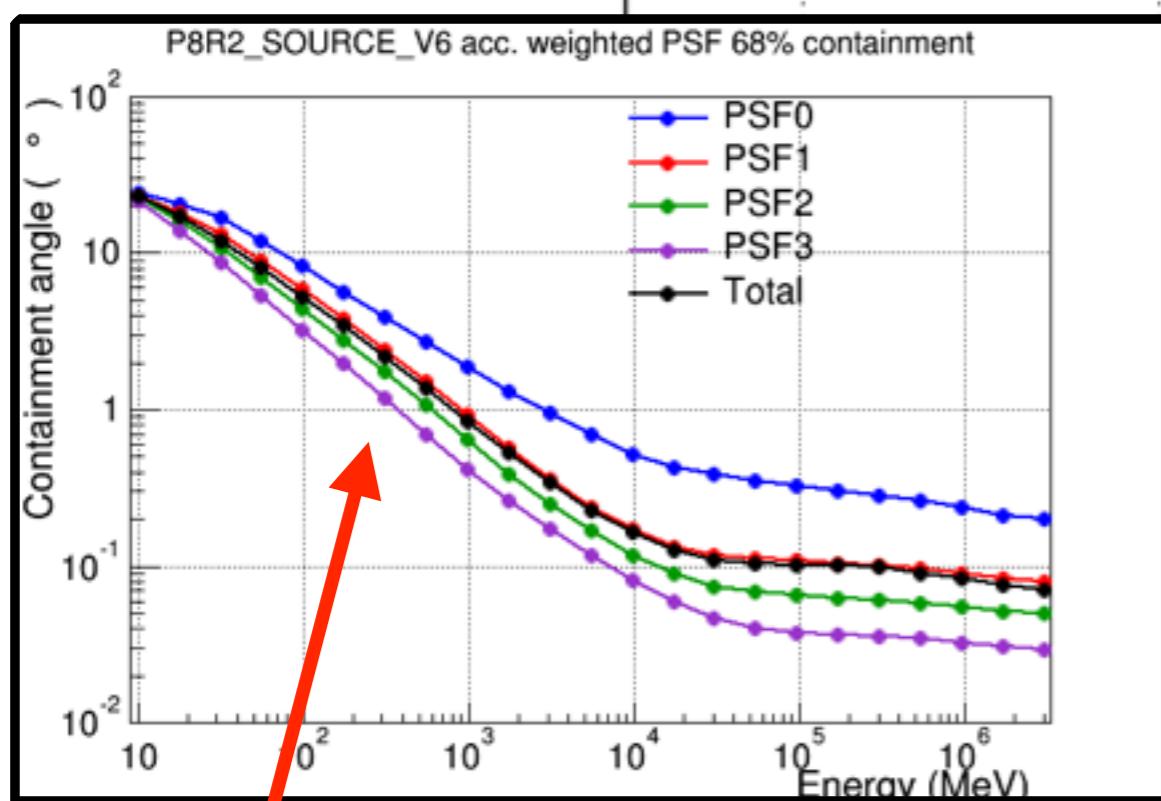
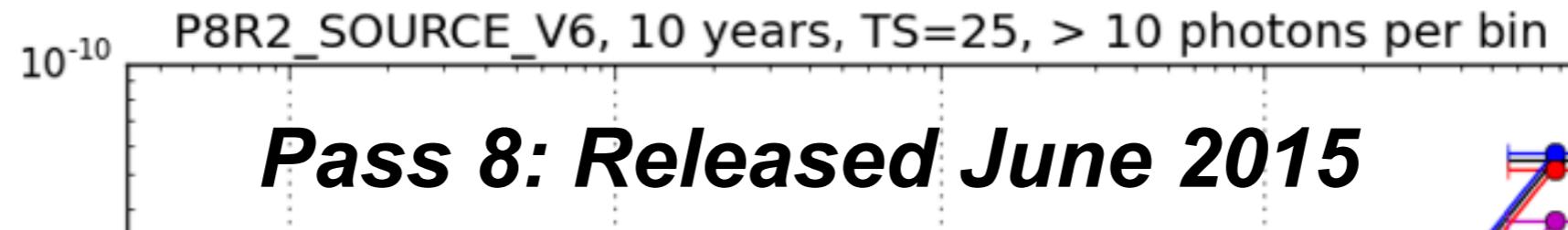
Calorimeter
Energy measurement



Fermi-LAT Performance



Fermi-LAT Performance



PSF Classes

EDISP Classes

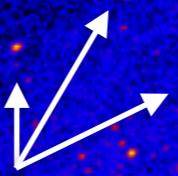
Fermi-LAT γ -ray sky



Extragalactic Sources

+ Supernova Remnants
+ Globular Clusters
+ Pulsar Wind Nebulae + ...

Active Galactic Nuclei
+ Gamma-ray Bursts
+ Starburst Galaxies...

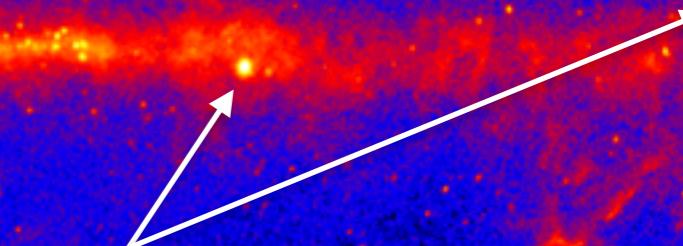


Local Sources

Solar Flares +
Terrestrial Gamma-ray Flashes

Pulsars

>3000 sources



>1 GeV, 8 year map

Galactic Sources

Exotic and Transient Astrophysics



Results from *Fermi-LAT*



Dark Matter

Indirect detection of Dark Matter

***Gamma-ray signatures
of Dark Matter***

***Recent Fermi-LAT Searches
for Dark Matter
WIMPs and Axions***

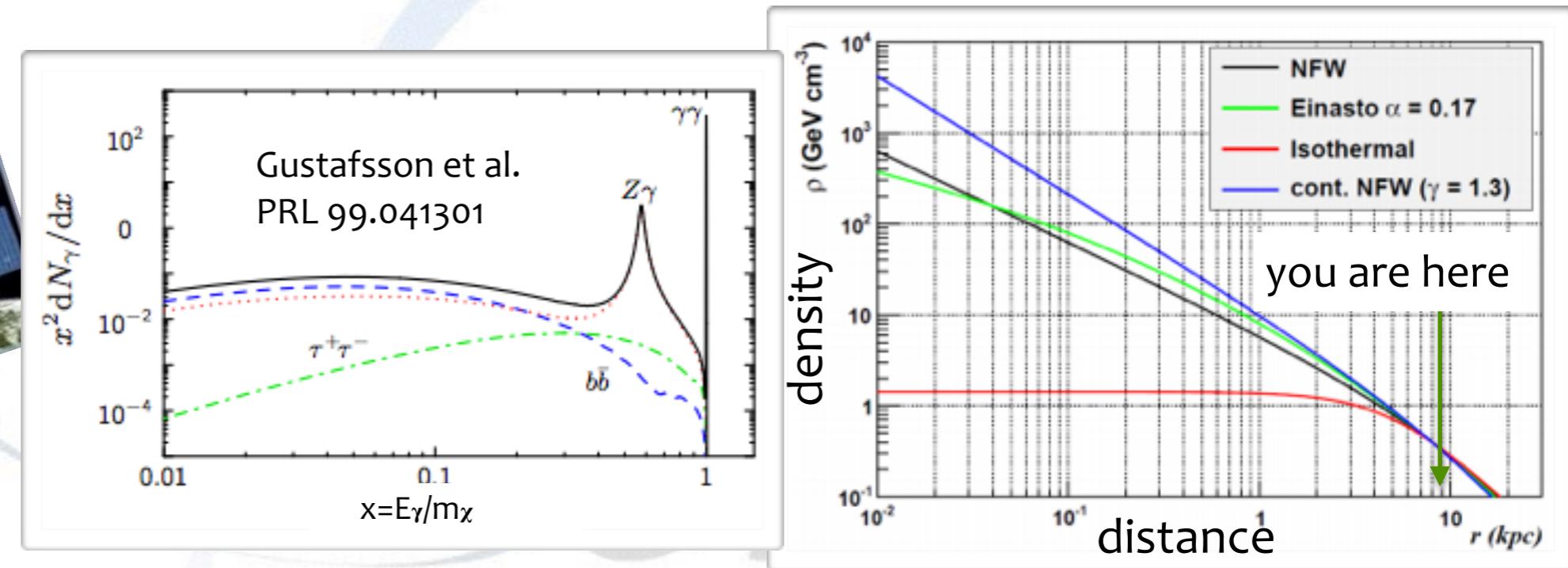
***Gamma-ray
Space Telescope***



Indirect Searches: WIMPs and gamma rays



Observed = Particle Properties x Astrophysics Properties



$$\Phi_\gamma(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_\chi v \rangle}{2m_\chi^2} N_\gamma(E) \times J(\psi)$$

cross section

mass

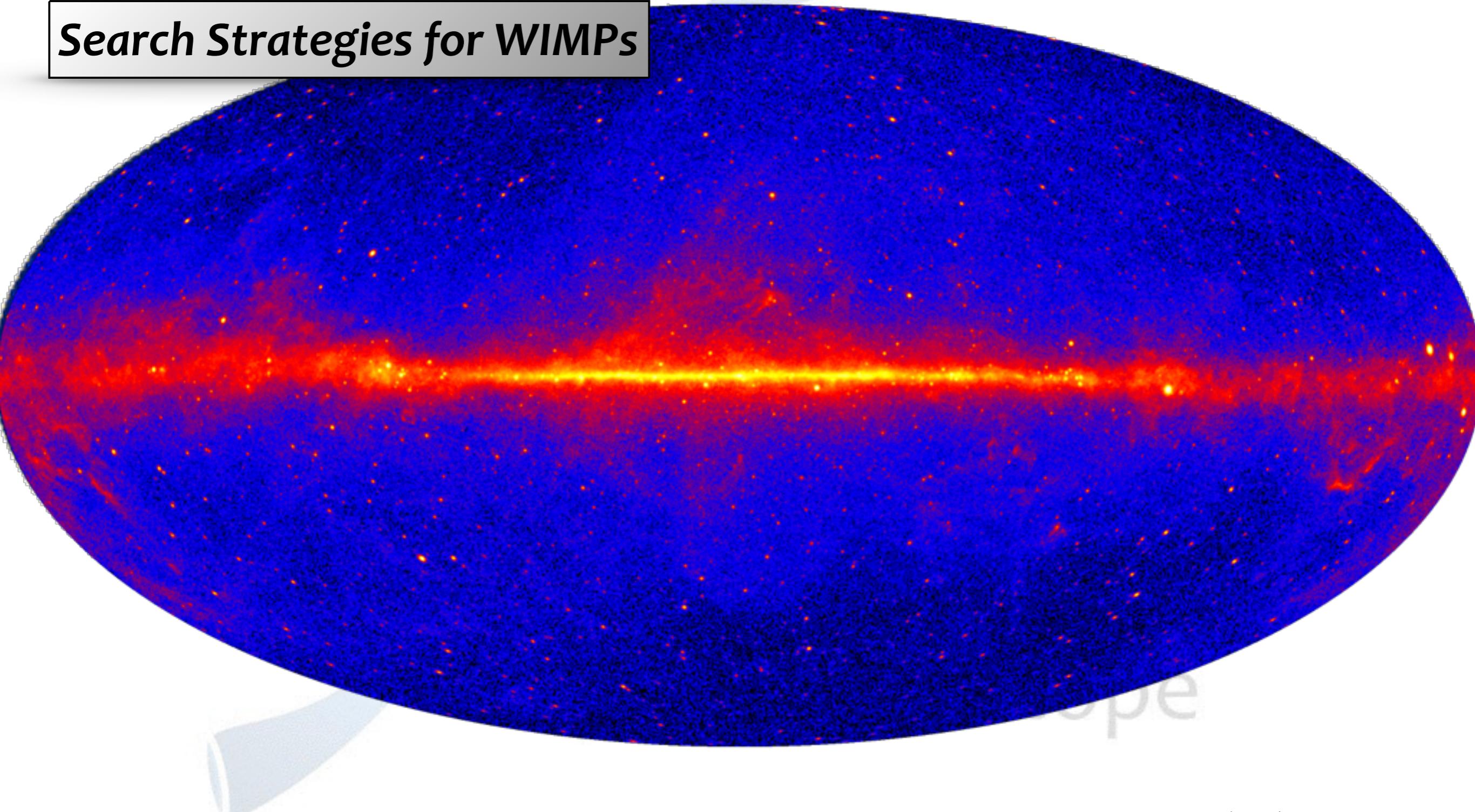
photons

J-Factor: $\sim \int \rho^2$
(solid angle,
line of sight)

Dark Matter Distribution



Search Strategies for WIMPs



Dark Matter Distribution



Search Strategies for WIMPs

Dwarf Spheroidal
Satellite Galaxies

Milky Way Halo

Spectral Lines

Galaxy Clusters

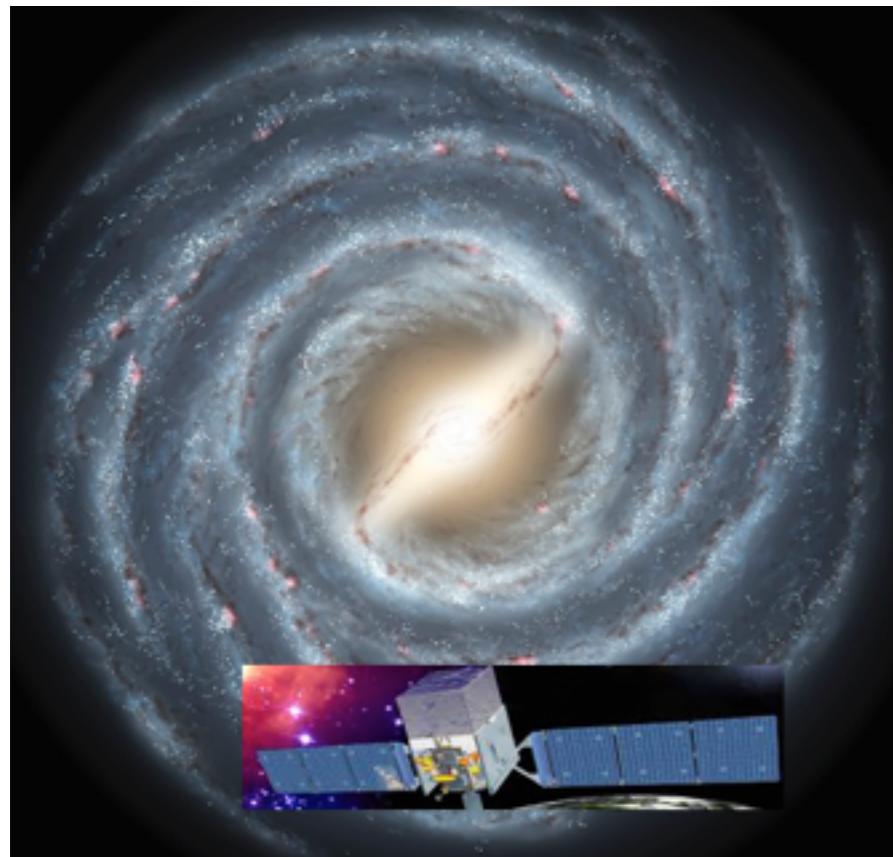
Galactic Center

Isotropic Background

The Galactic Center



Challenges of observing the Galactic Center



fermi
Gamma-ray
Space Telescope

The Galactic Center

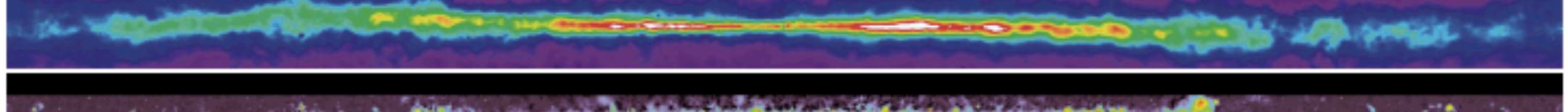


Challenges of observing the Galactic Center

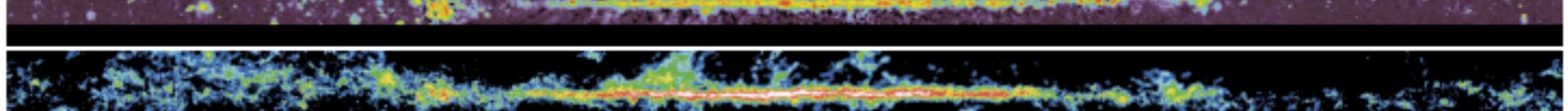
Radio (0.4 GHz)



Atomic Hydrogen



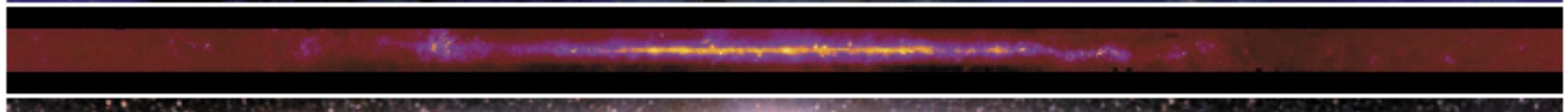
Radio (2.7 GHz)



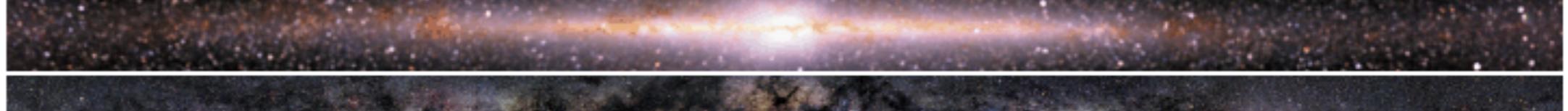
Molecular Hydrogen



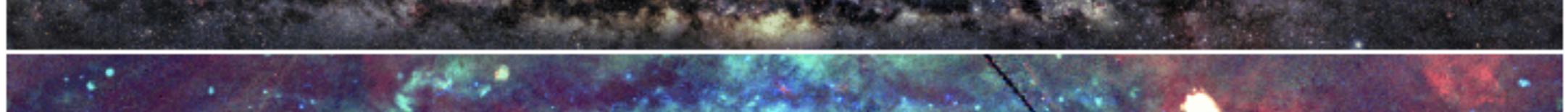
Infrared



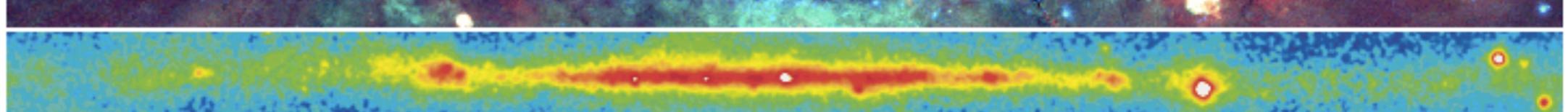
Mid Infrared



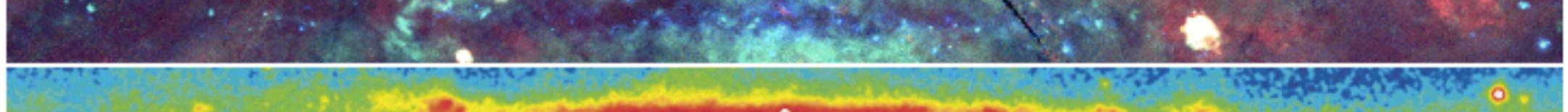
Near Infrared



Optical



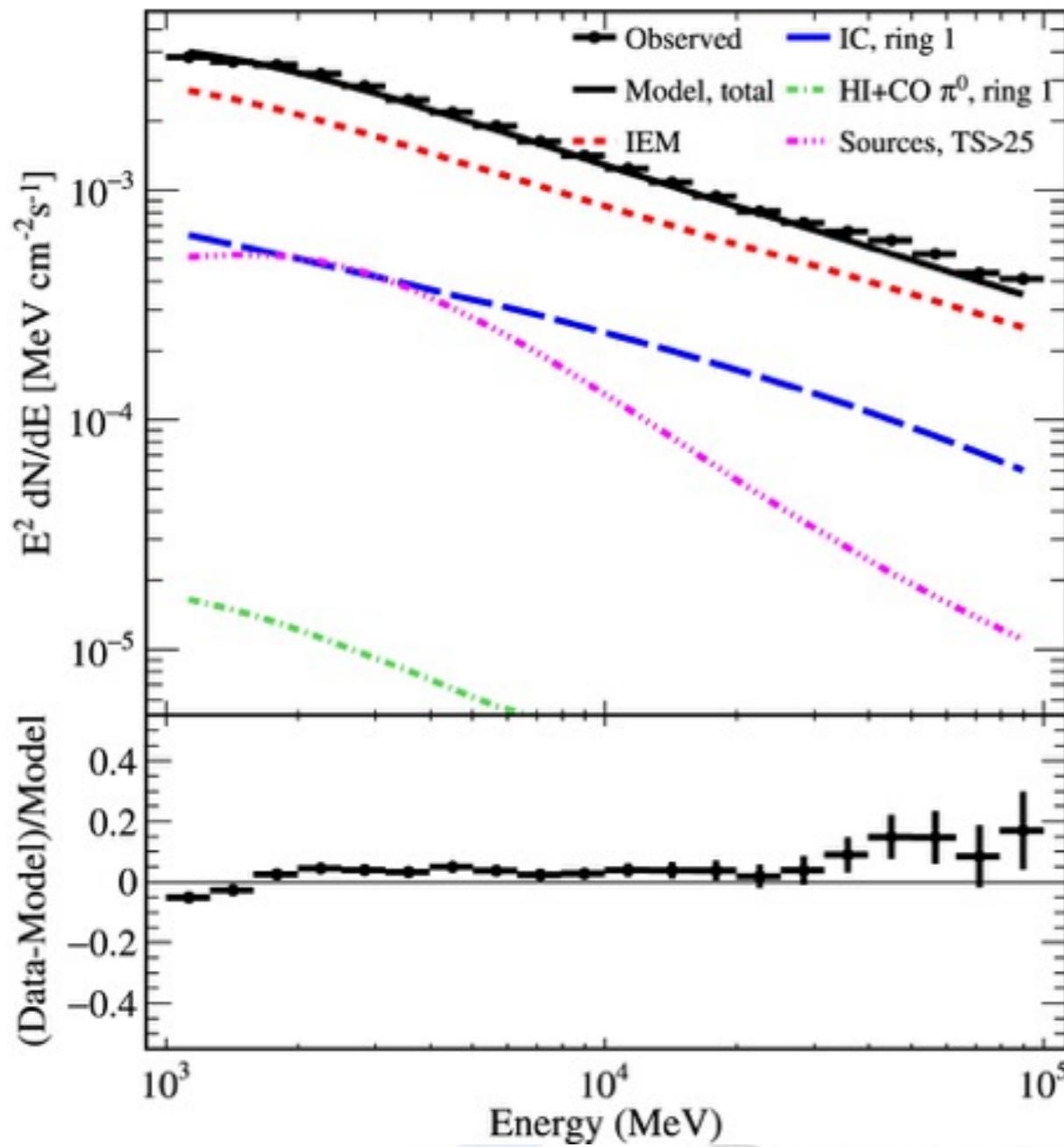
X-Ray



Gamma Ray



The Galactic Center



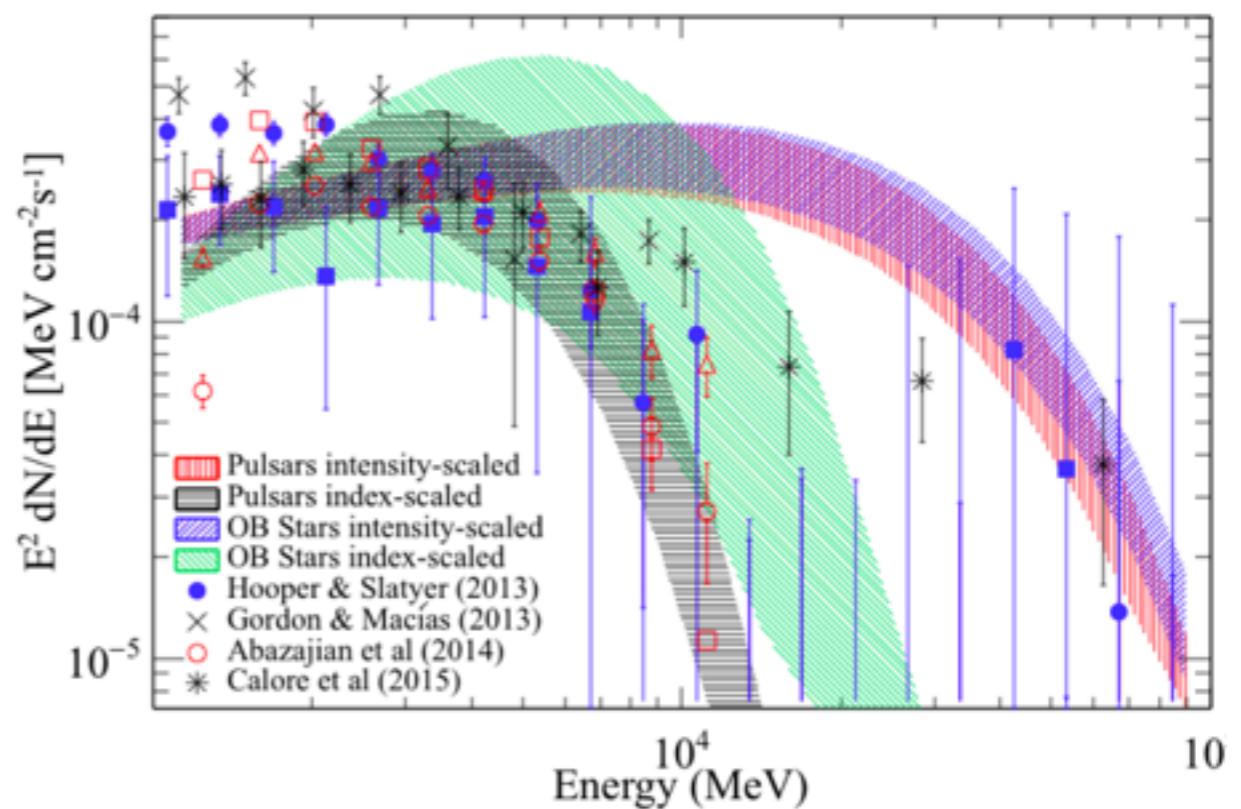
Constituents of the Model

Templates to define different background regions

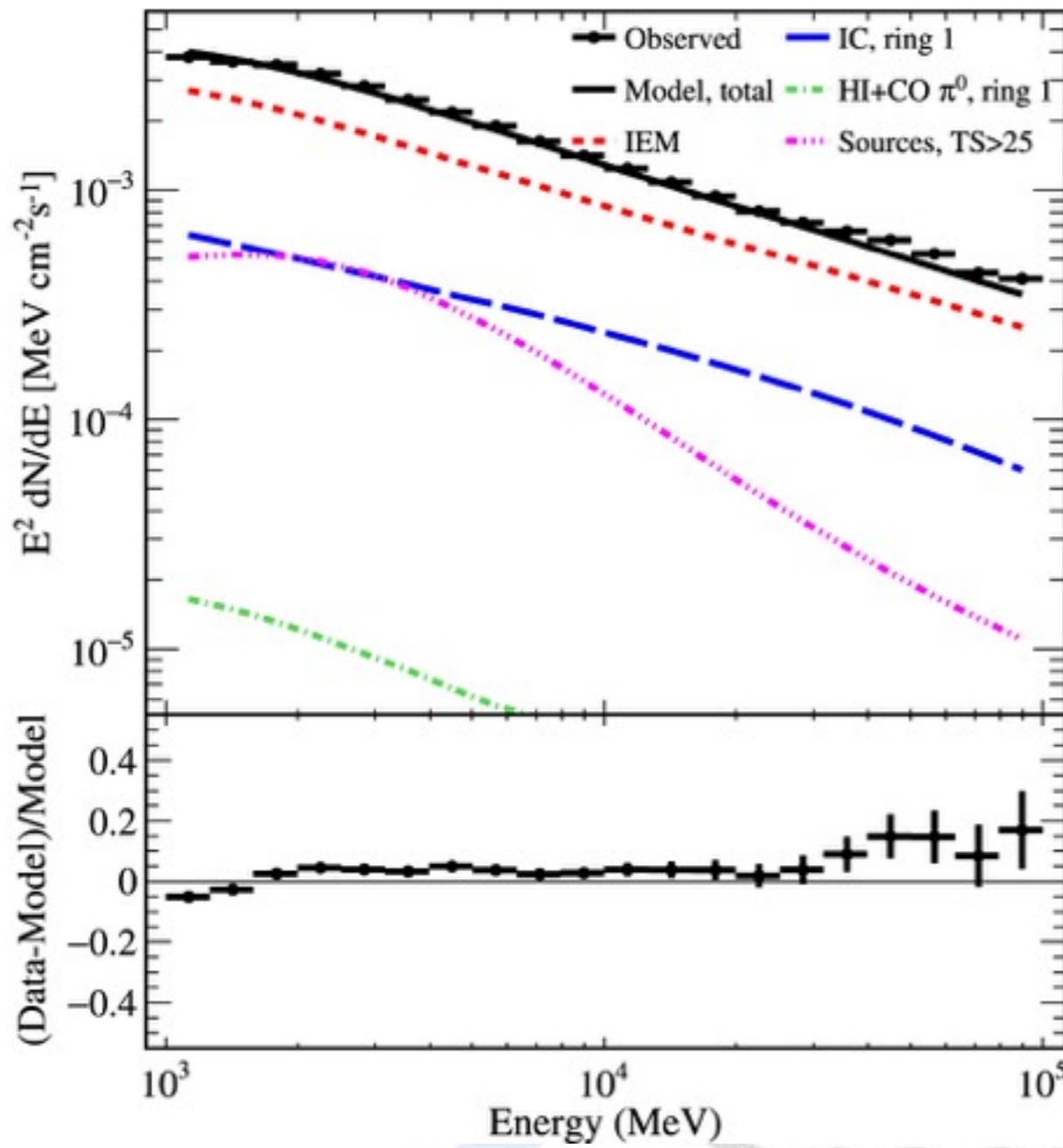
Gamma-ray sources (pulsars, OB stars)

Intensity/Index scaled

Only analysis to utilize these methods



The Galactic Center



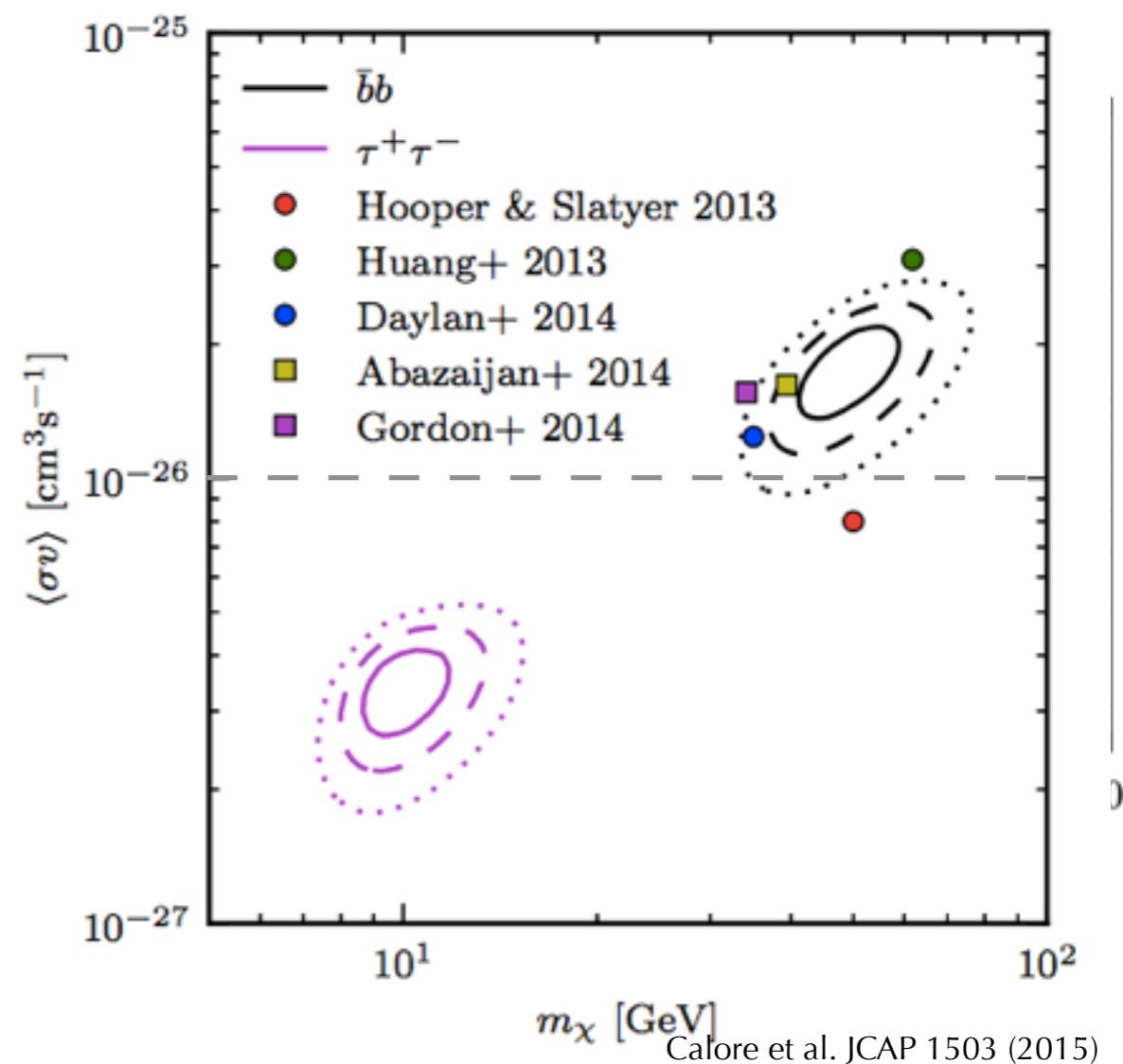
Constituents of the Model

Templates to define different background regions

Gamma-ray sources (pulsars, OB stars)

Intensity/Index scaled

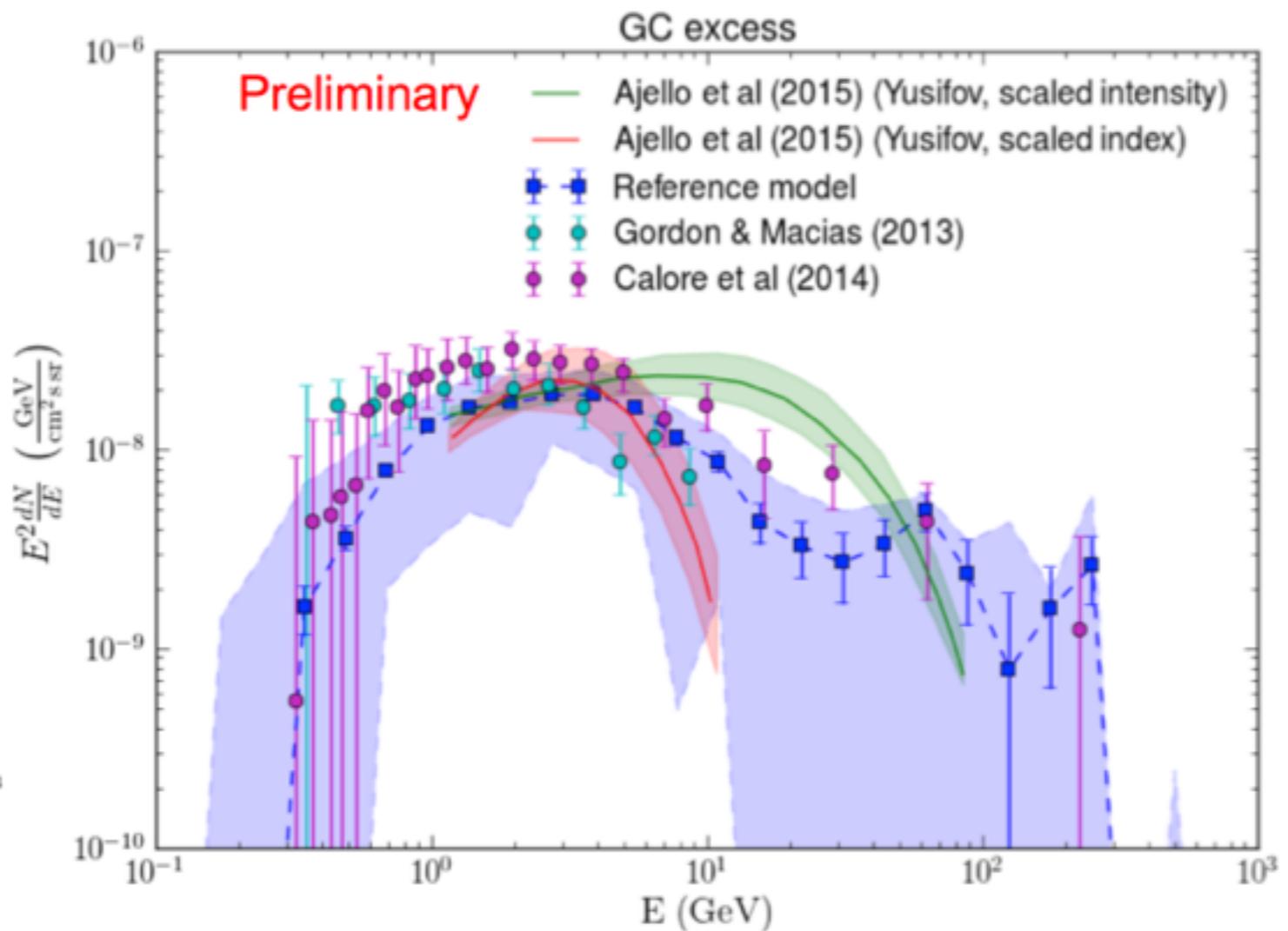
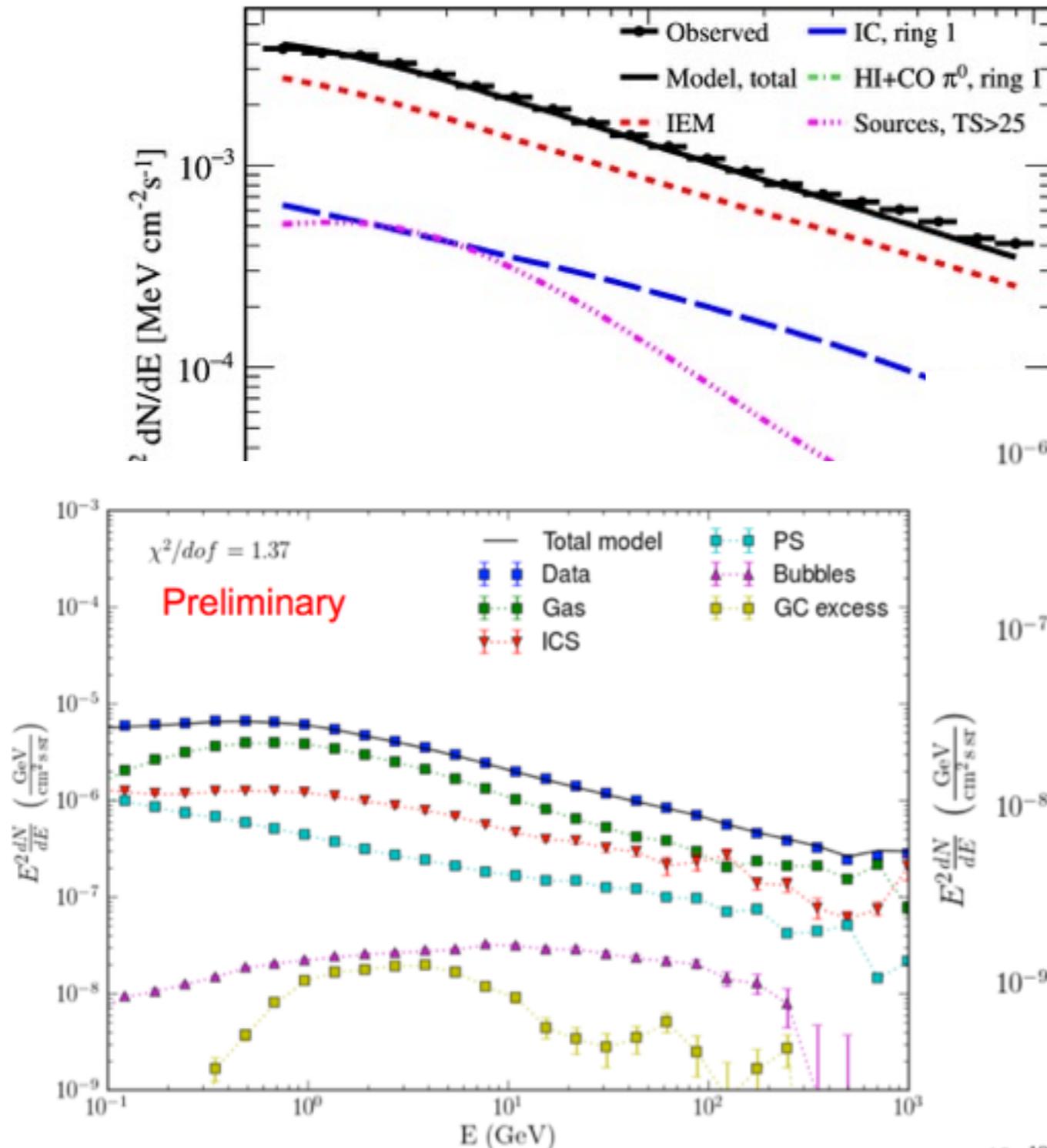
Only analysis to utilize these methods



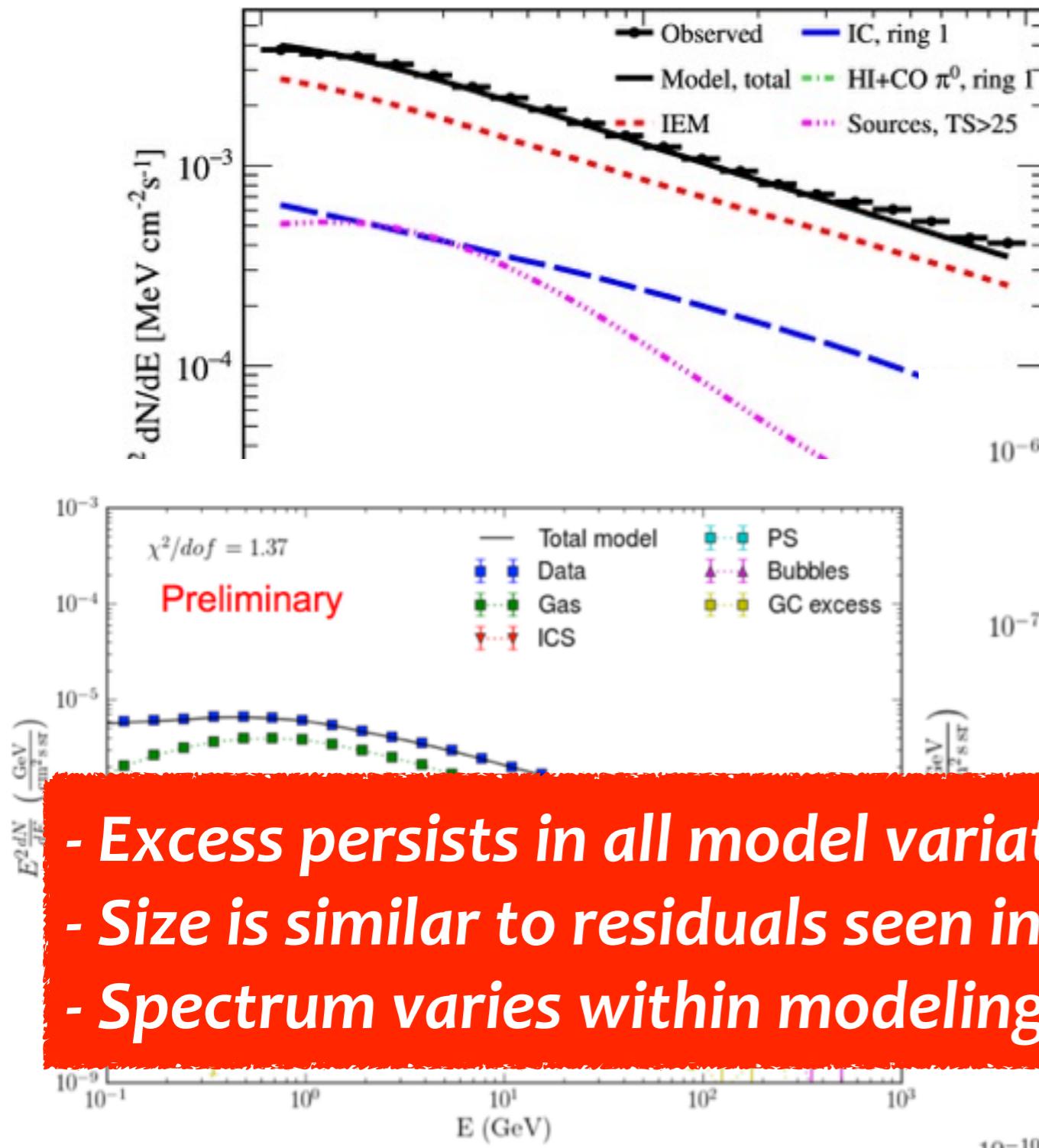
The Galactic Center



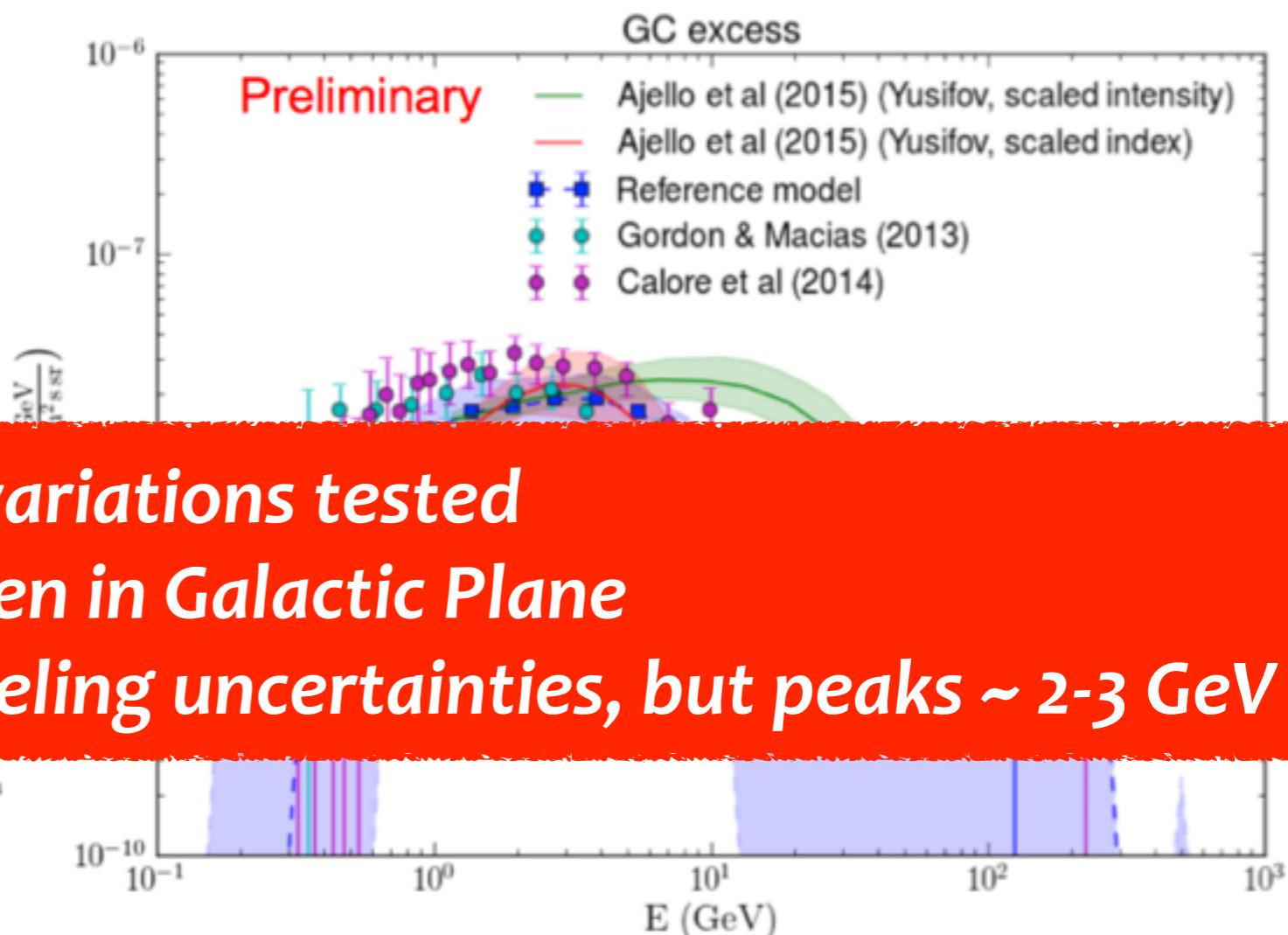
Variation of excess within modeling uncertainties studied using Pass 8 data



The Galactic Center



Variation of excess within modeling uncertainties studied using Pass 8 data



- Excess persists in all model variations tested
- Size is similar to residuals seen in Galactic Plane
- Spectrum varies within modeling uncertainties, but peaks ~ 2-3 GeV

Dwarf Spheroidal Galaxies

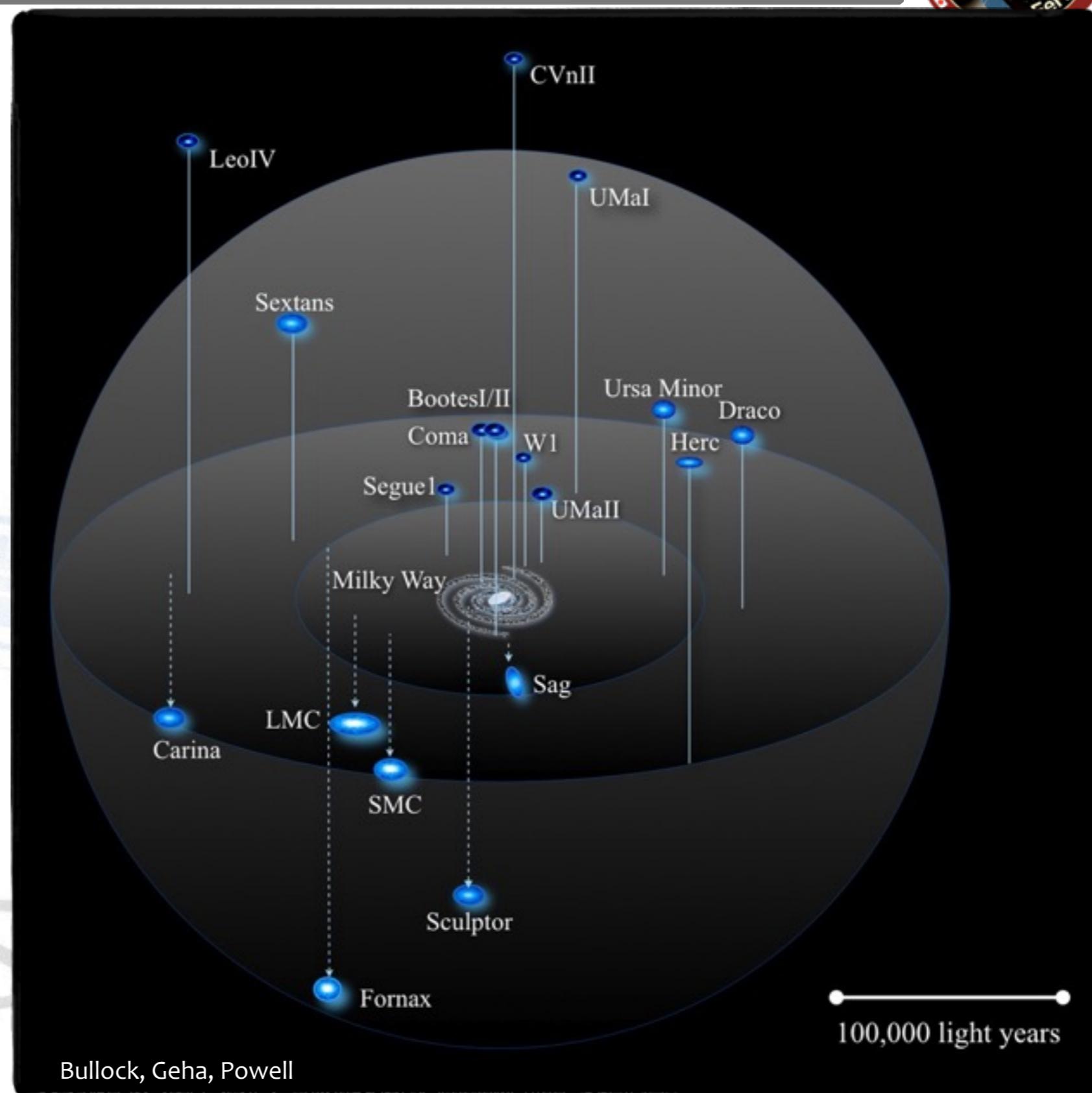


Companion galaxies
around Milky Way

Old, little star formation
Low Luminosity

High Mass-to-Light ratio

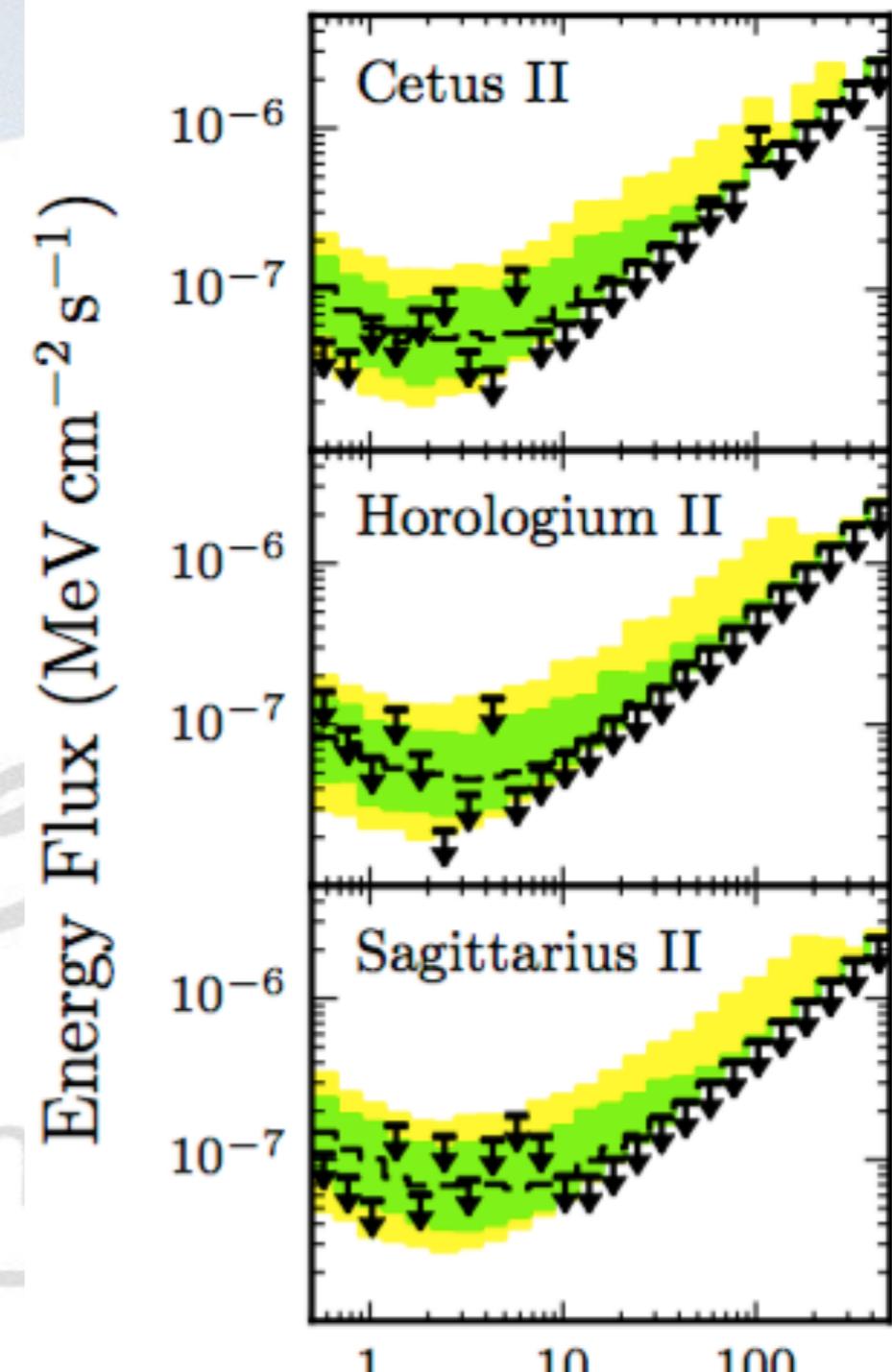
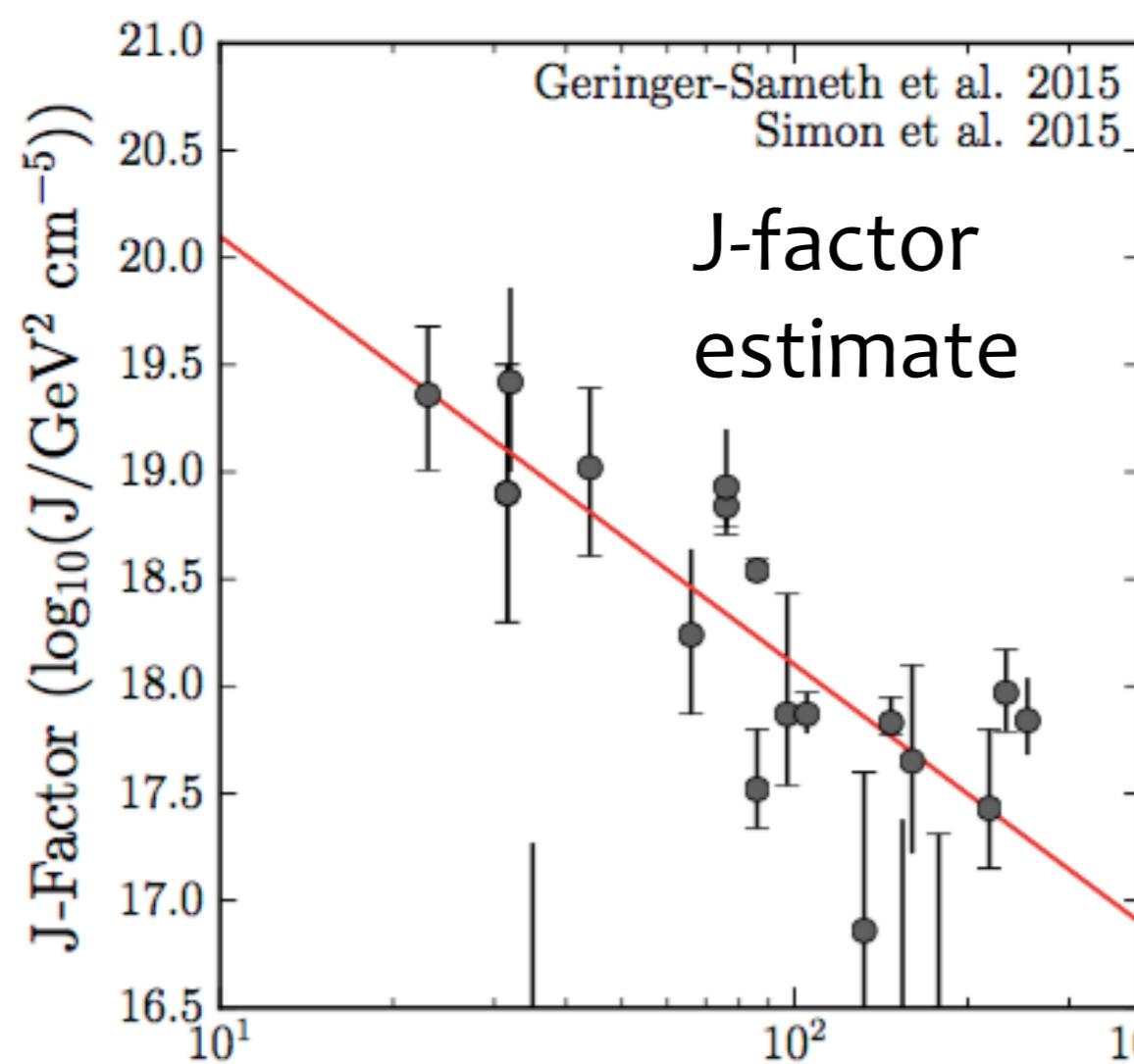
More nearby
with well constrained
J-factors



Joint LAT/DES results



Dark Energy Survey:
Finding new dwarf spheroidal galaxies



Fermi-LAT and DES Collaborations,
ApJ 809 L4 (2015), arXiv: 1503.02632

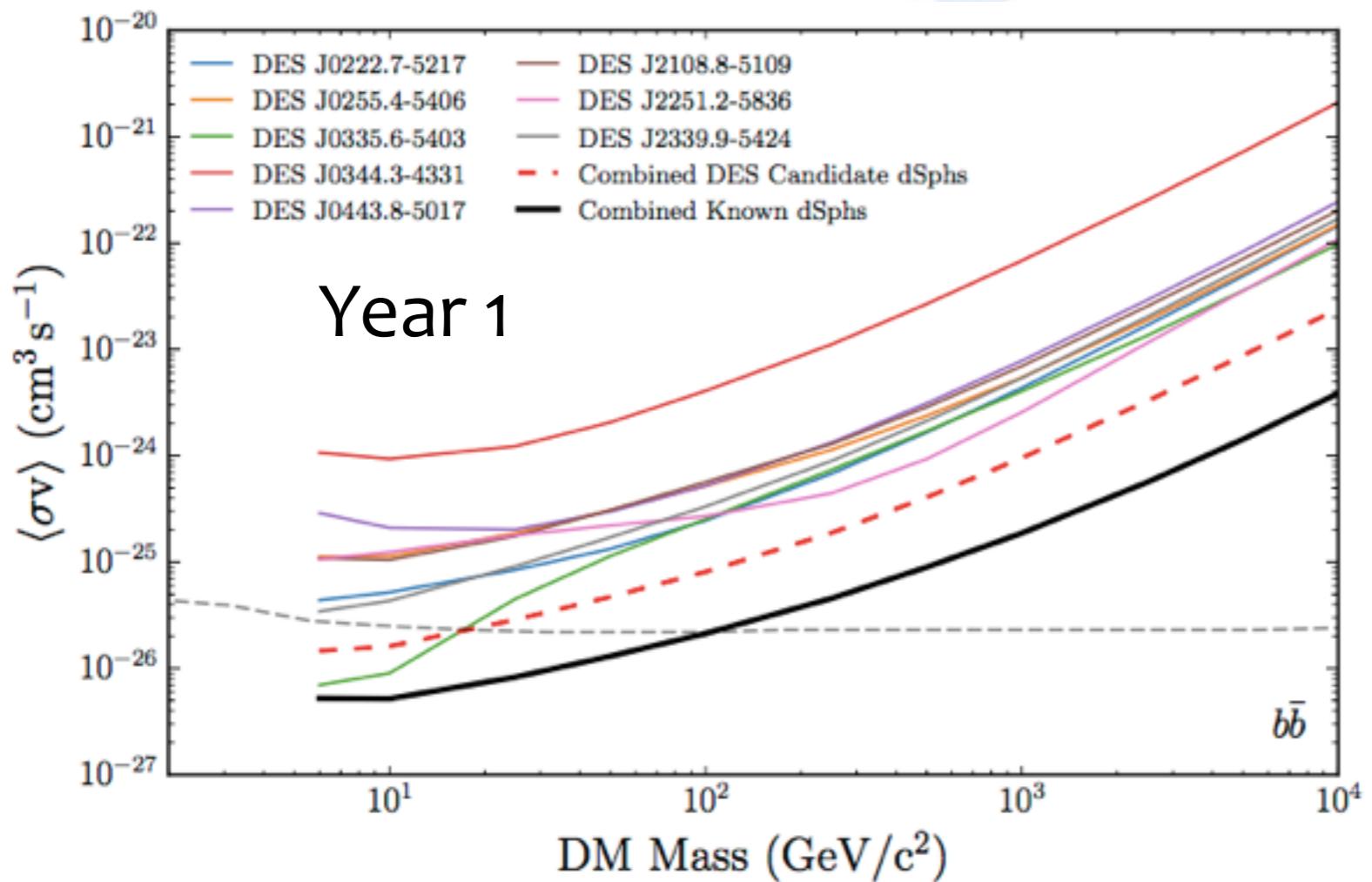
Fermi-LAT and DES Collaborations,
accepted ApJL arXiv: 1611.03184

R. Caputo, UCSC | CosPA 2016

Joint LAT/DES results



Dark Energy Survey:
Finding new dwarf spheroidal galaxies



Fermi-LAT and DES Collaborations,
ApJ 809 L4 (2015), arXiv: 1503.02632

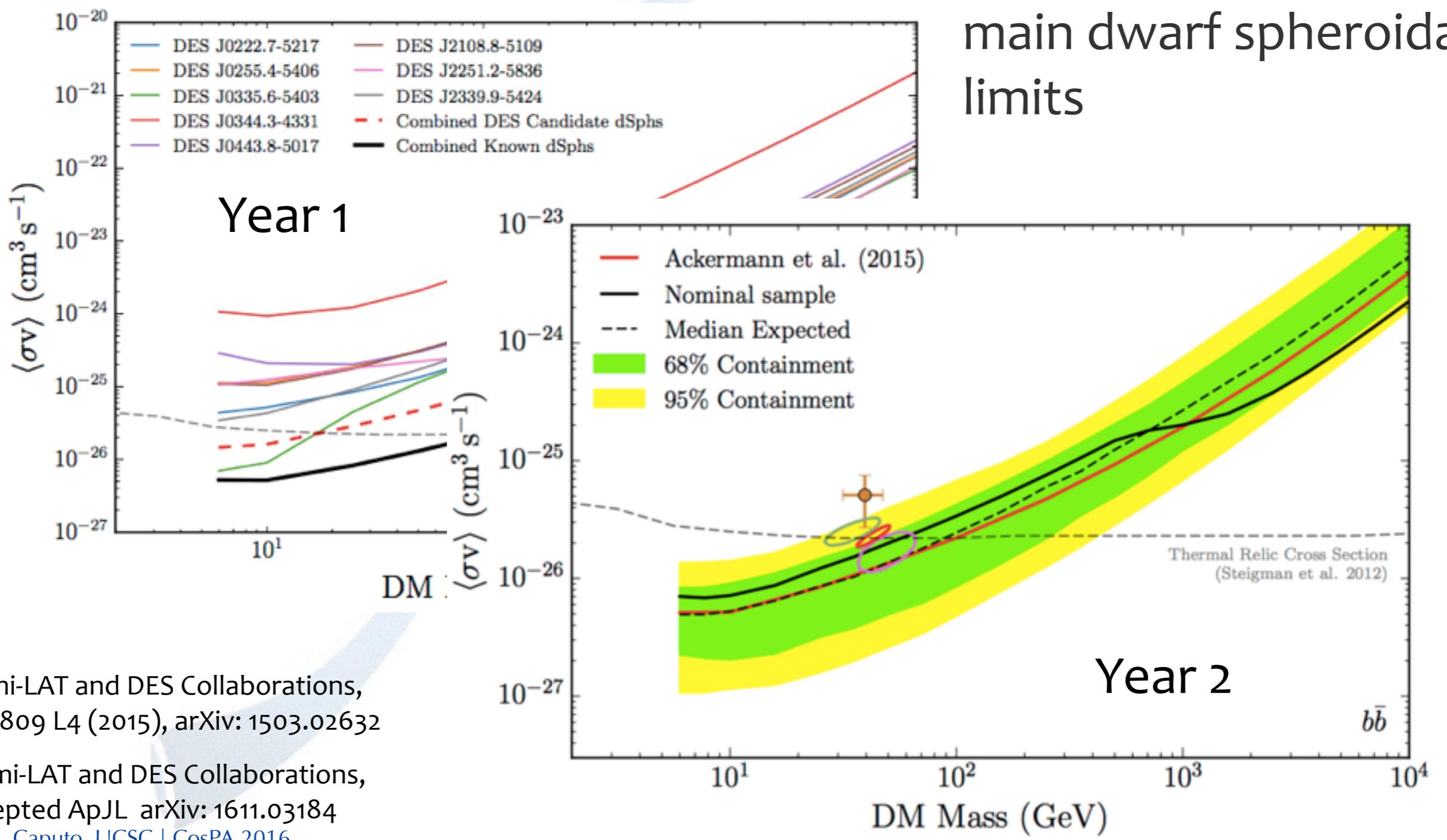
Fermi-LAT and DES Collaborations,
accepted ApJL arXiv: 1611.03184

R. Caputo, UCSC | CosPA 2016

Joint LAT/DES results



Dark Energy Survey:
Finding new dwarf spheroidal galaxies

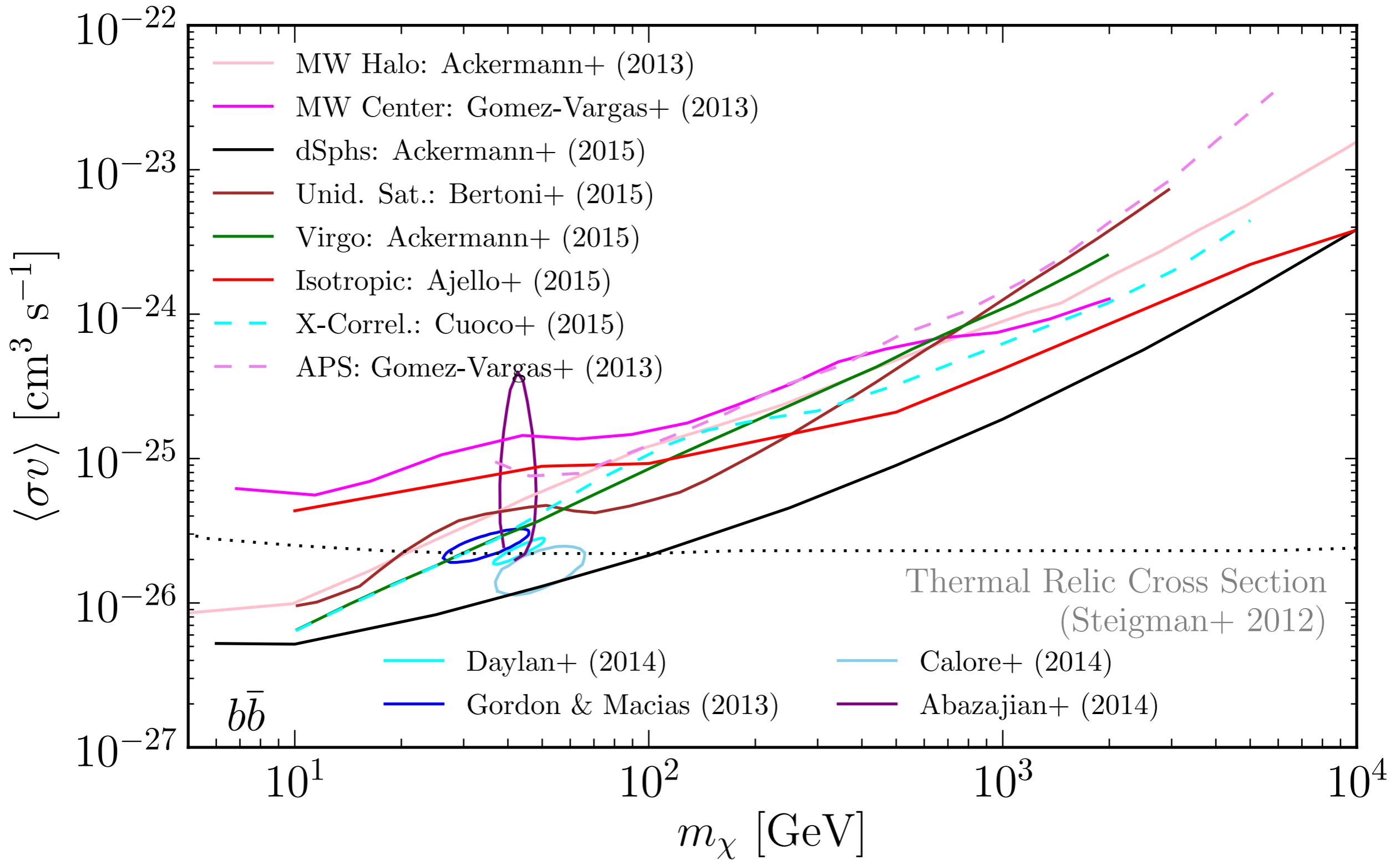


Fermi-LAT and DES Collaborations,
ApJ 809 L4 (2015), arXiv: 1503.02632

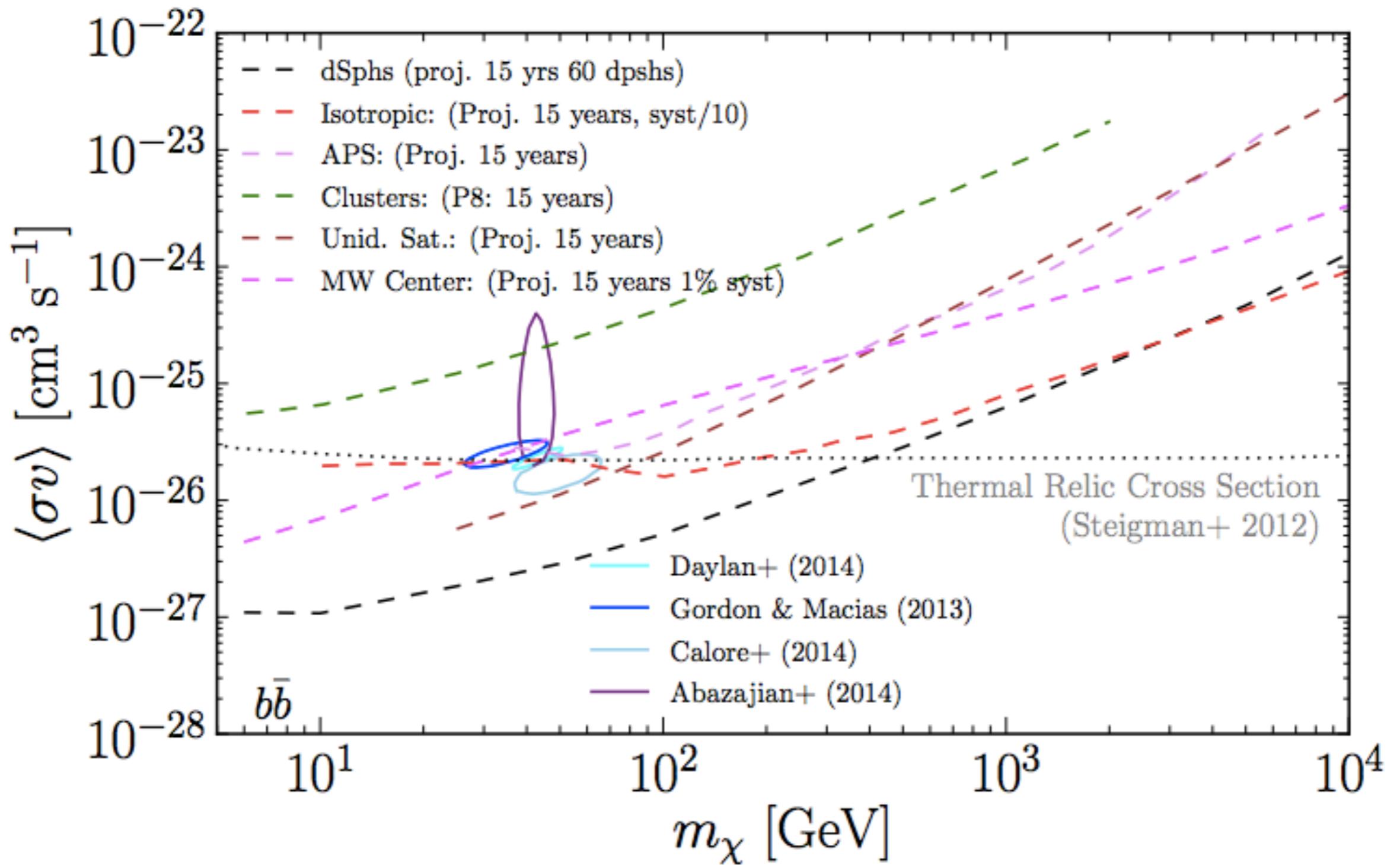
Fermi-LAT and DES Collaborations,
accepted ApJL arXiv: 1611.03184
R. Caputo, UCSC | CosPA 2016

Year 2 limits is that they
are consistent with the
main dwarf spheroidal
limits

Summary of WIMP Dark Matter Searches



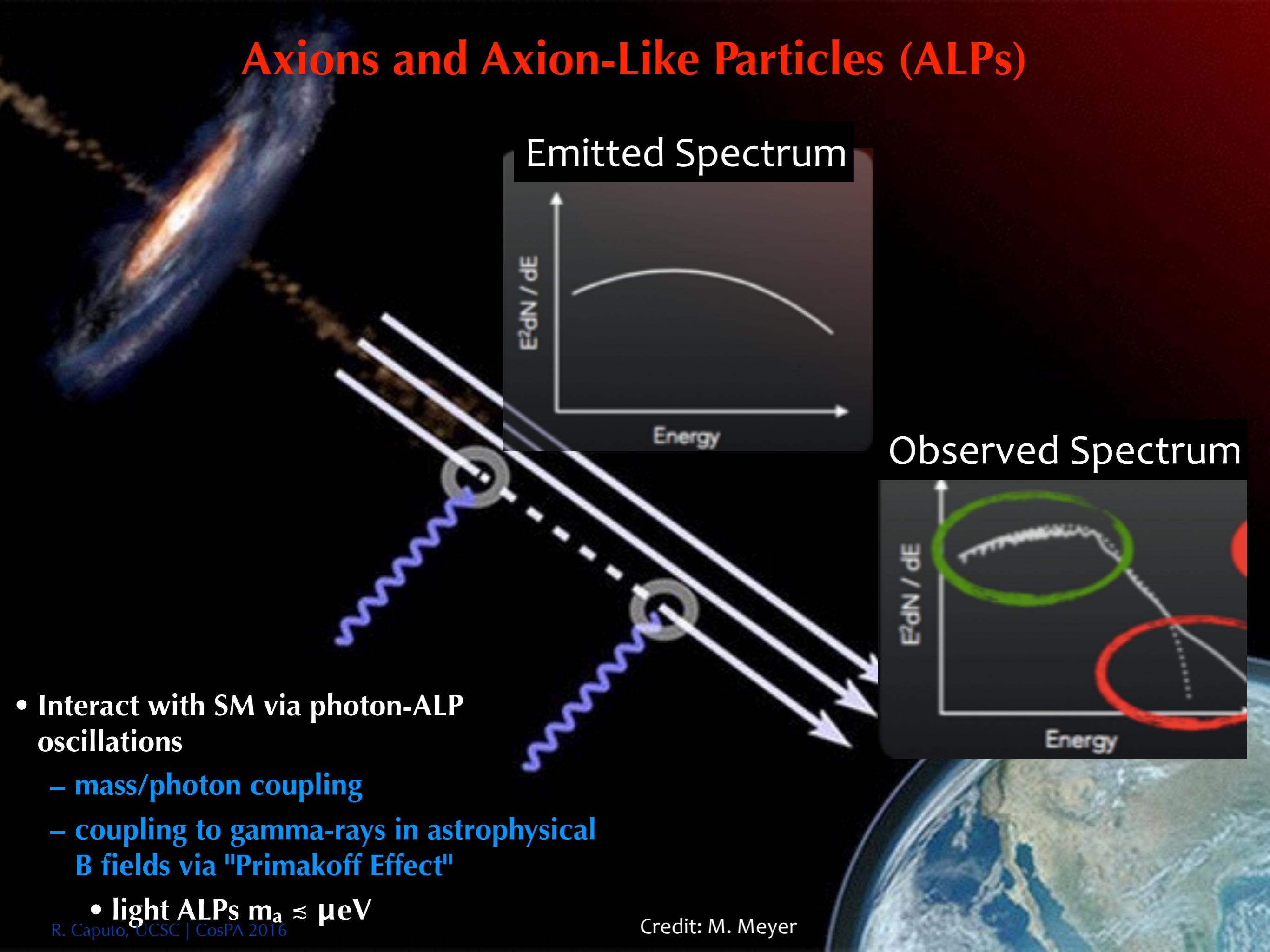
Future WIMP Dark Matter Searches



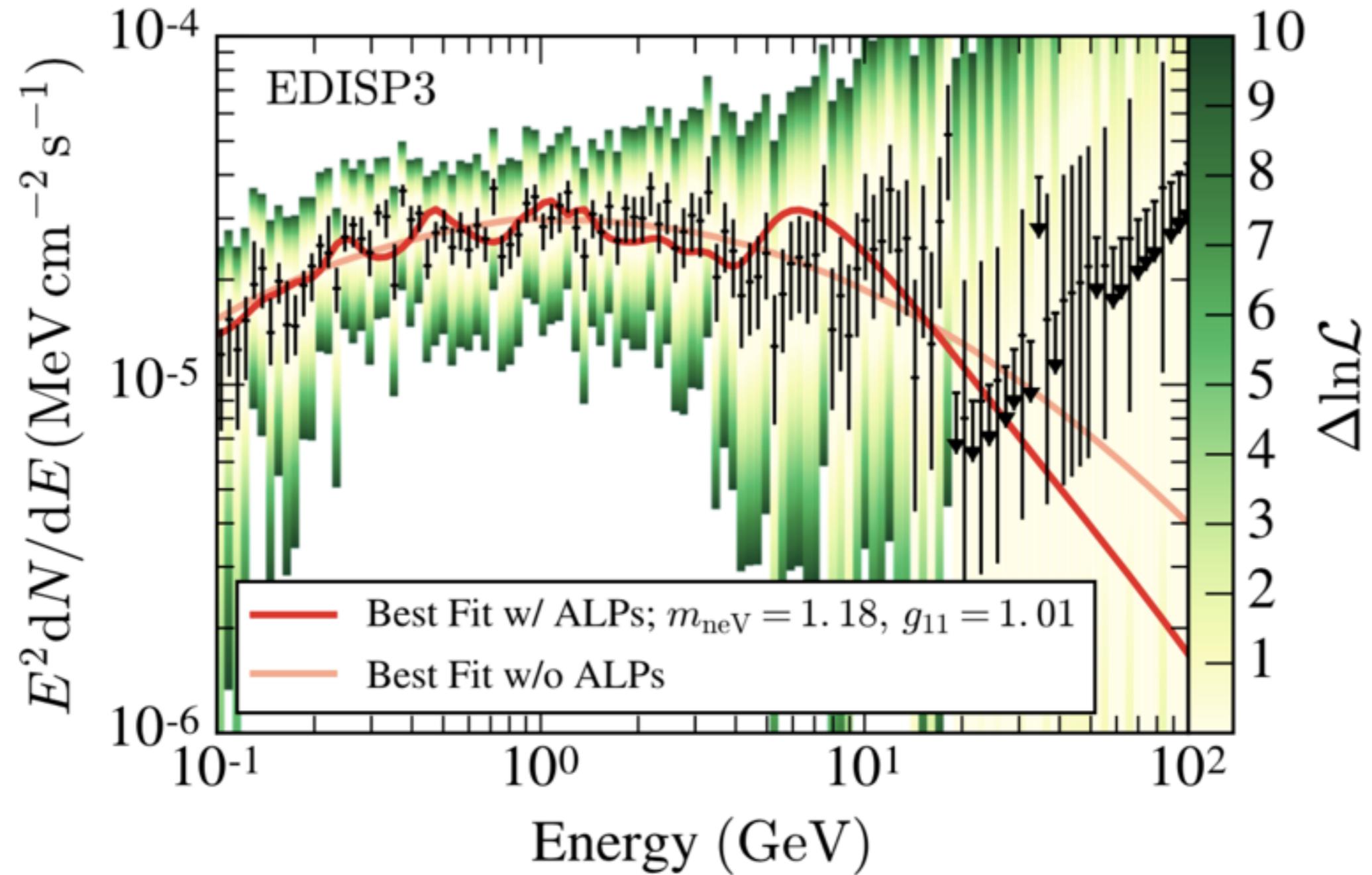
Other Dark Matter Candidates



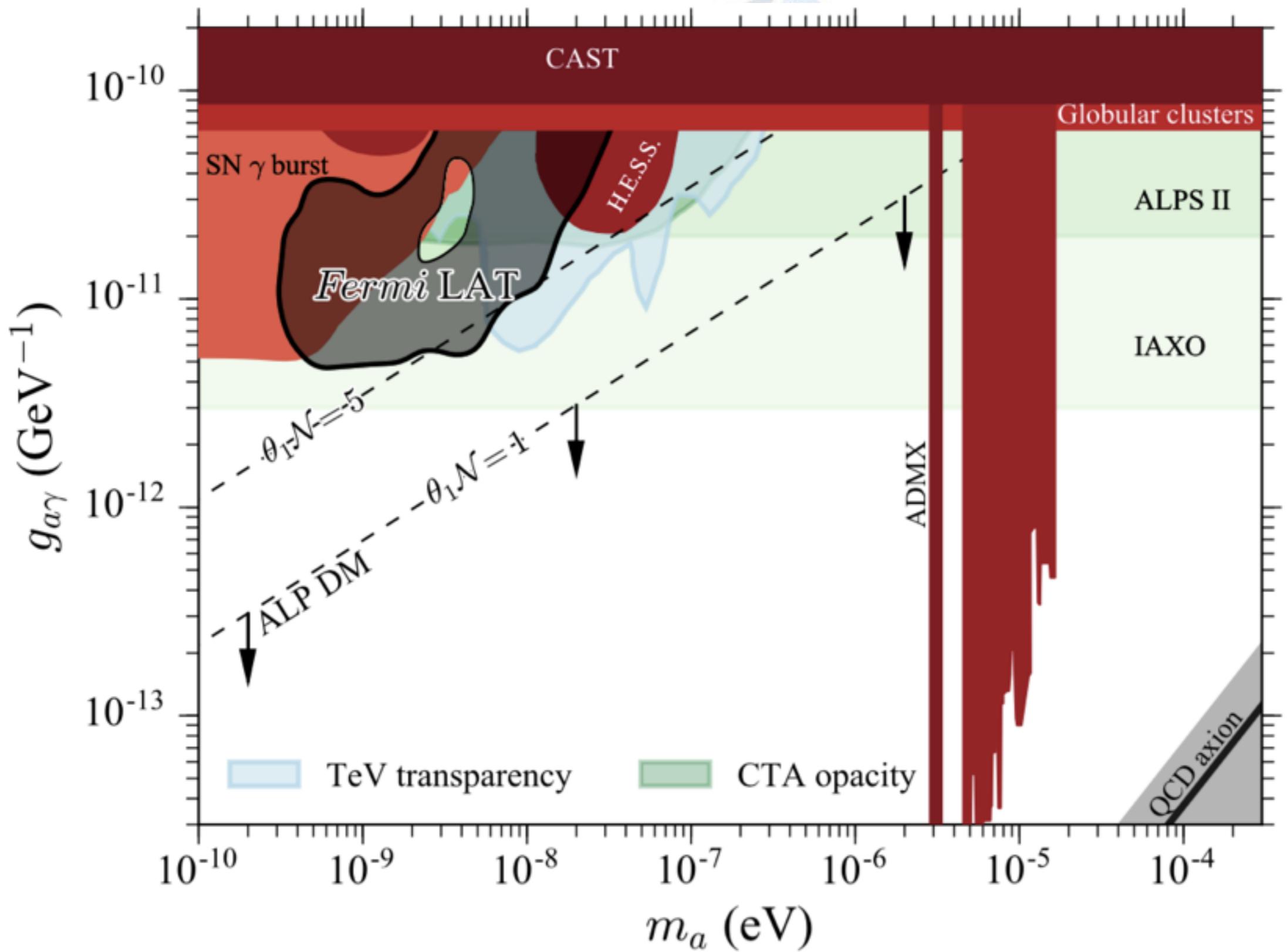
Axions and Axion-Like Particles (ALPs)



Central Galaxy of the Perseus cluster: NGC 1275



Central Galaxy of the Perseus cluster: NGC 1275



Axions in Pulsating Radio Stars (Pulsars)

Rapidly rotating Neutron Stars

1967: Jocelyn Bell - LGM signal

Rotational periods: ms to s

Produced in the neutron star
via nuclear Bremsstrahlung
then decay to gamma rays

Magnetic field strength: $\sim 10^{11-12}$ (up to 10^{14} G - 0.2 G Earth)

Axions in Pulsars

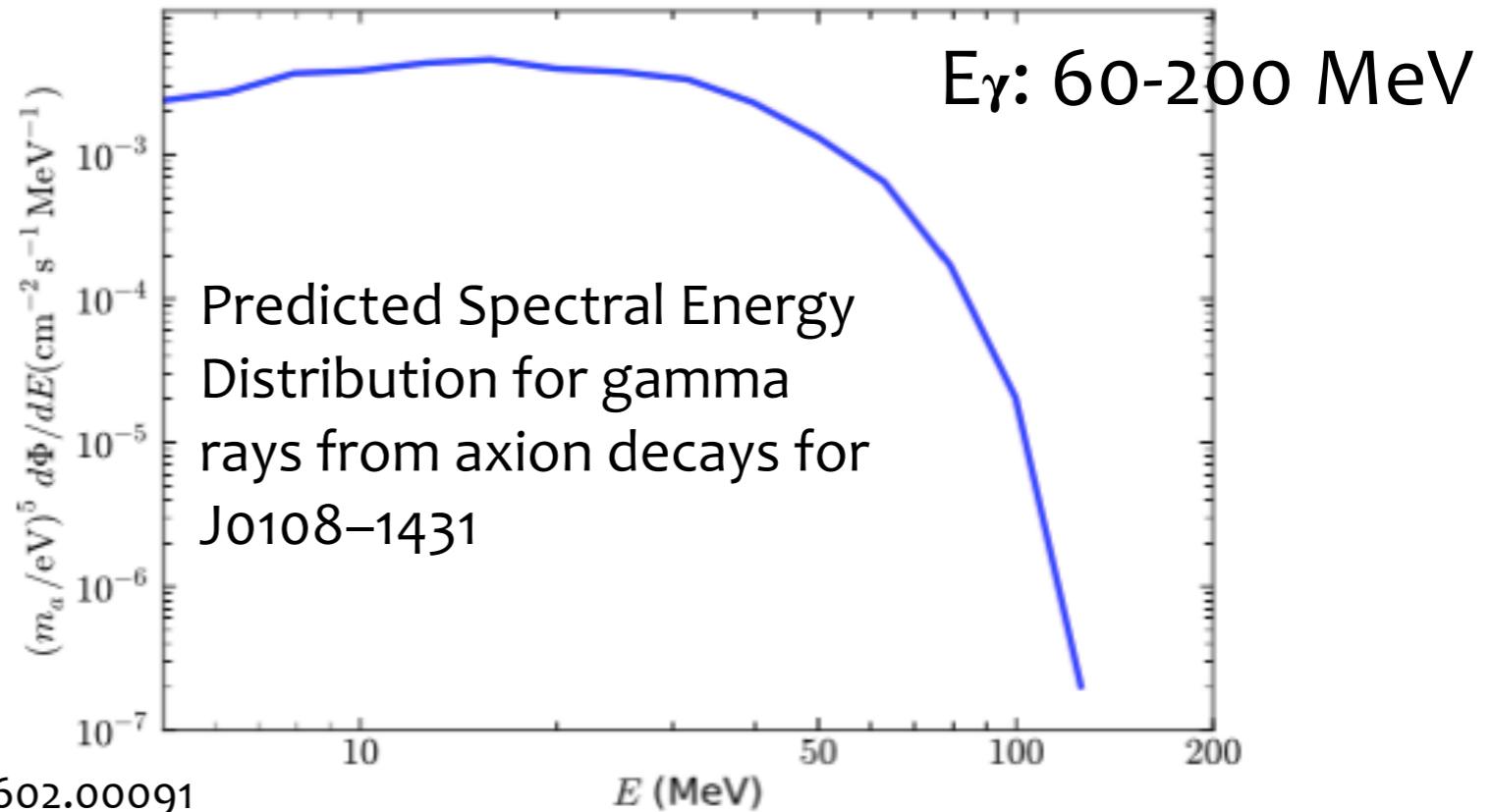


Source Name	RA (°)	Dec.(°)	ℓ (°)	b (°)	d (kpc)	Age (Myr)	B_{surf} (G)
J0108-1431	17.035	-14.351	140.93	-76.82	$0.240^{+0.124}_{-0.061}$	166	2.52×10^{11}
J0953+0755	148.289	7.927	228.91	43.7	$0.262^{+0.005}_{-0.005}$	17.5	2.44×10^{11}
J0630-2834	97.706	-28.579	236.95	-16.76	$0.332^{+0.052}_{-0.040}$	2.77	3.01×10^{12}
J1136+1551	174.014	15.851	241.90	69.20	$0.360^{+0.019}_{-0.019}$	5.04	2.13×10^{12}

*Away from
galactic plane*

Close

*Measured
B-Field*

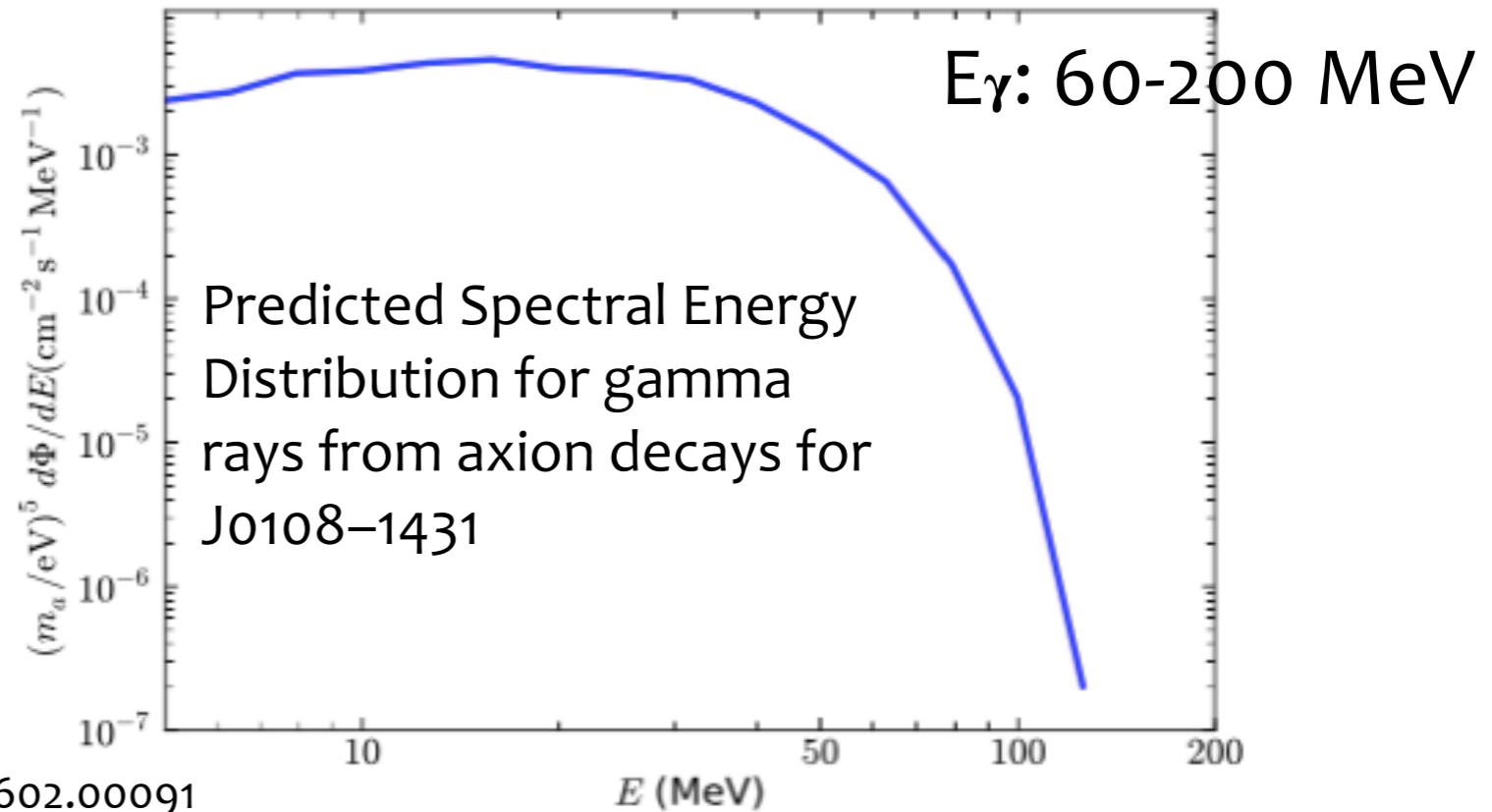


Axions in Pulsars



Source Name	RA (°)	Dec.(°)	ℓ (°)	b (°)	d (kpc)	Age (Myr)	B_{surf} (G)
J0108-1431	17.035	-14.351	140.93	-76.82	$0.240^{+0.124}_{-0.061}$	166	2.52×10^{11}
J0953+0755	148.289	7.927	228.91	43.7	$0.262^{+0.005}_{-0.005}$	17.5	2.44×10^{11}
J0630-2834	97.706	-28.579	236.95	-16.76	$0.332^{+0.052}_{-0.040}$	2.77	3.01×10^{12}
J1136+1551	174.014	15.851	241.90	69.20	$0.360^{+0.019}_{-0.019}$	5.04	2.13×10^{12}

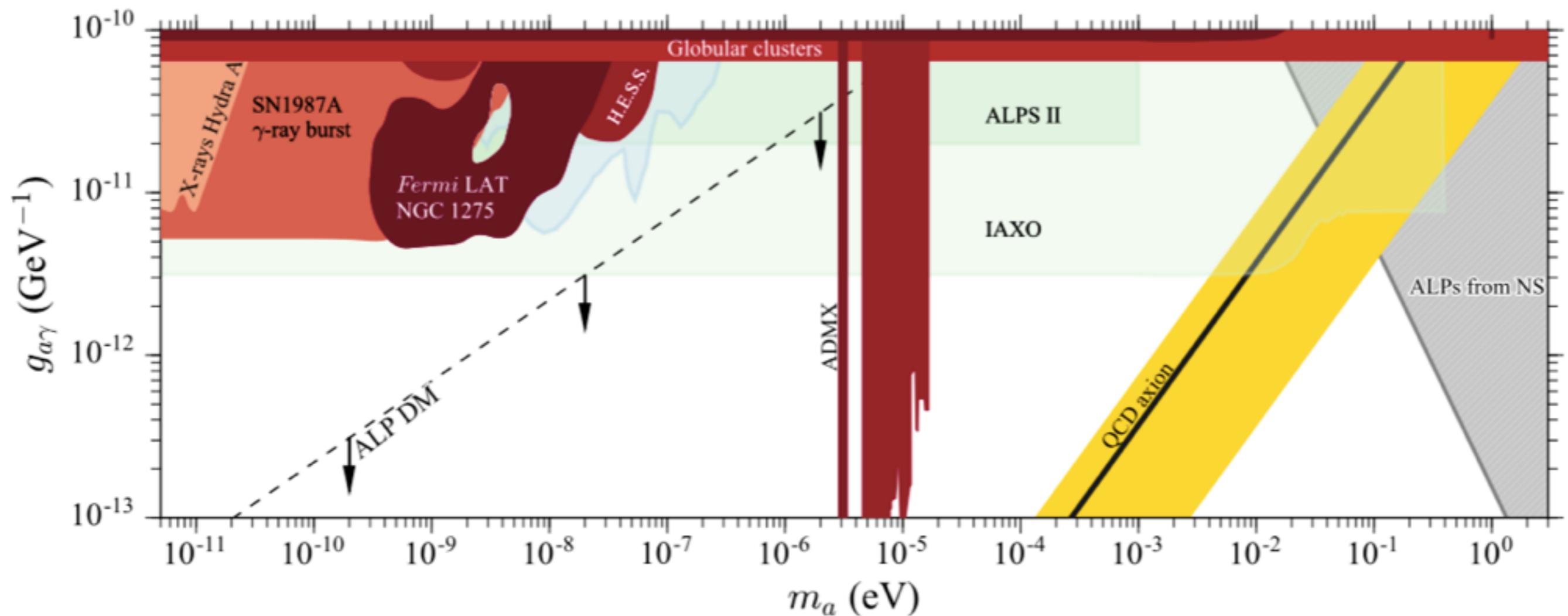
No excess upper limit on
QCD axion mass:
 $7.9 \times 10^{-2} \text{ eV}$



Axions in Pulsars

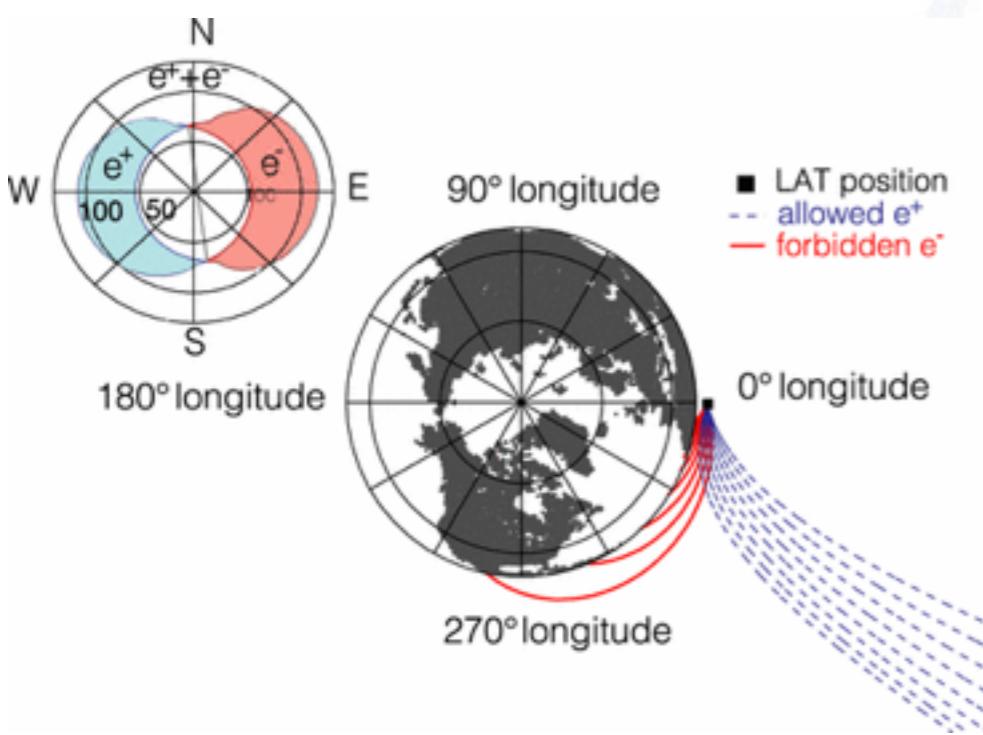


Source Name	RA (°)	Dec.(°)	ℓ (°)	b (°)	d (kpc)	Age (Myr)	B_{surf} (G)
J0108-1431	17.035	-14.351	140.93	-76.82	$0.240^{+0.124}_{-0.061}$	166	2.52×10^{11}
J0953+0755	148.289	7.927	228.91	43.7	$0.262^{+0.005}_{-0.005}$	17.5	2.44×10^{11}
J0630-2834	97.706	-28.579	236.95	-16.76	$0.332^{+0.052}_{-0.040}$	2.77	3.01×10^{12}





Ultra-high energy neutrinos



*Multi-messenger Astrophysics
high energy neutrinos*

*Fermi High Energy
Point source catalogs*

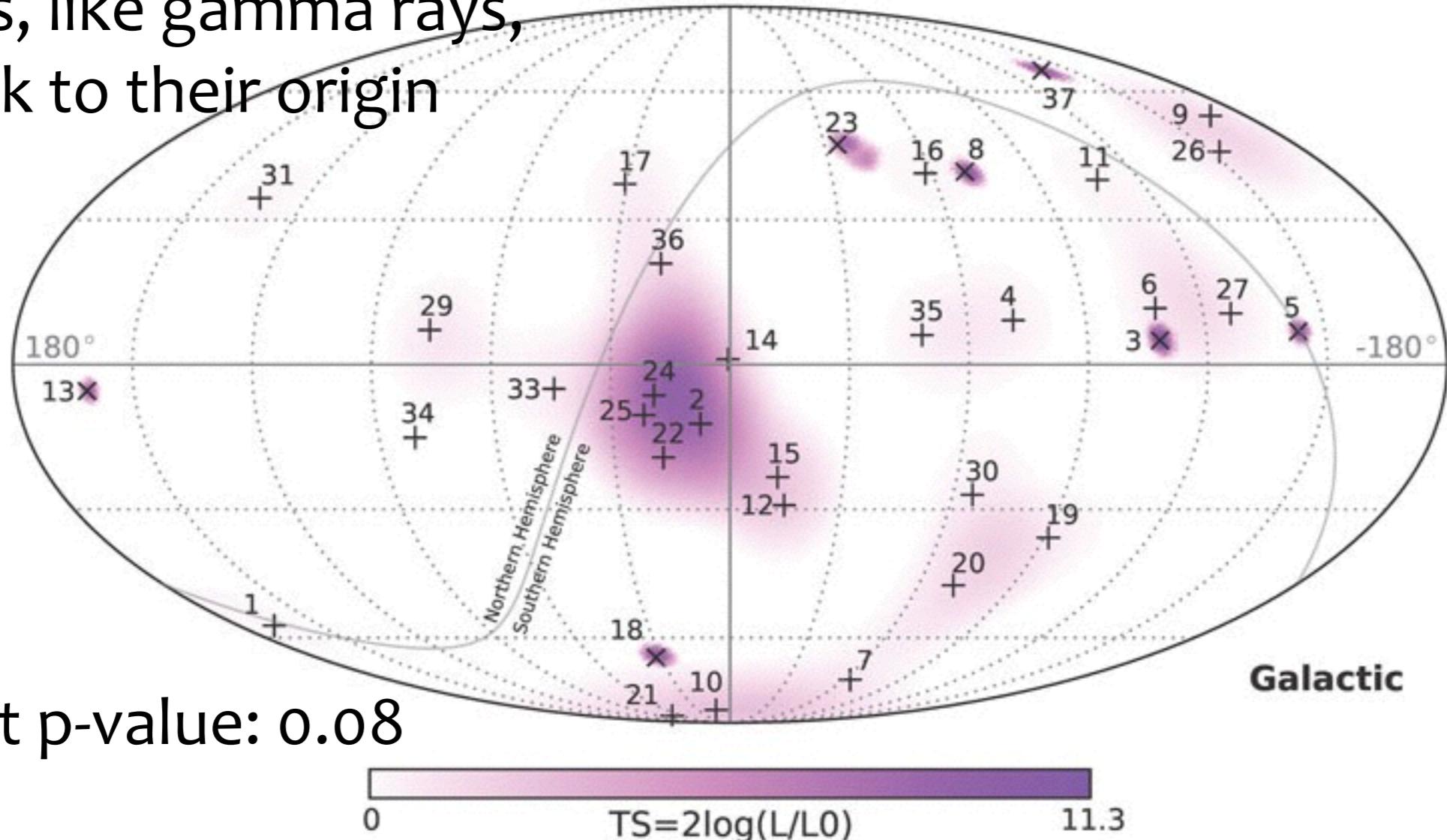
*Astrophysical Connections:
Blazars and Star Forming Galaxies*

*Note: Cosmic-ray electron and
 $e^{+/-}$ anisotropy papers coming soon*

The High Energy Neutrino Sky

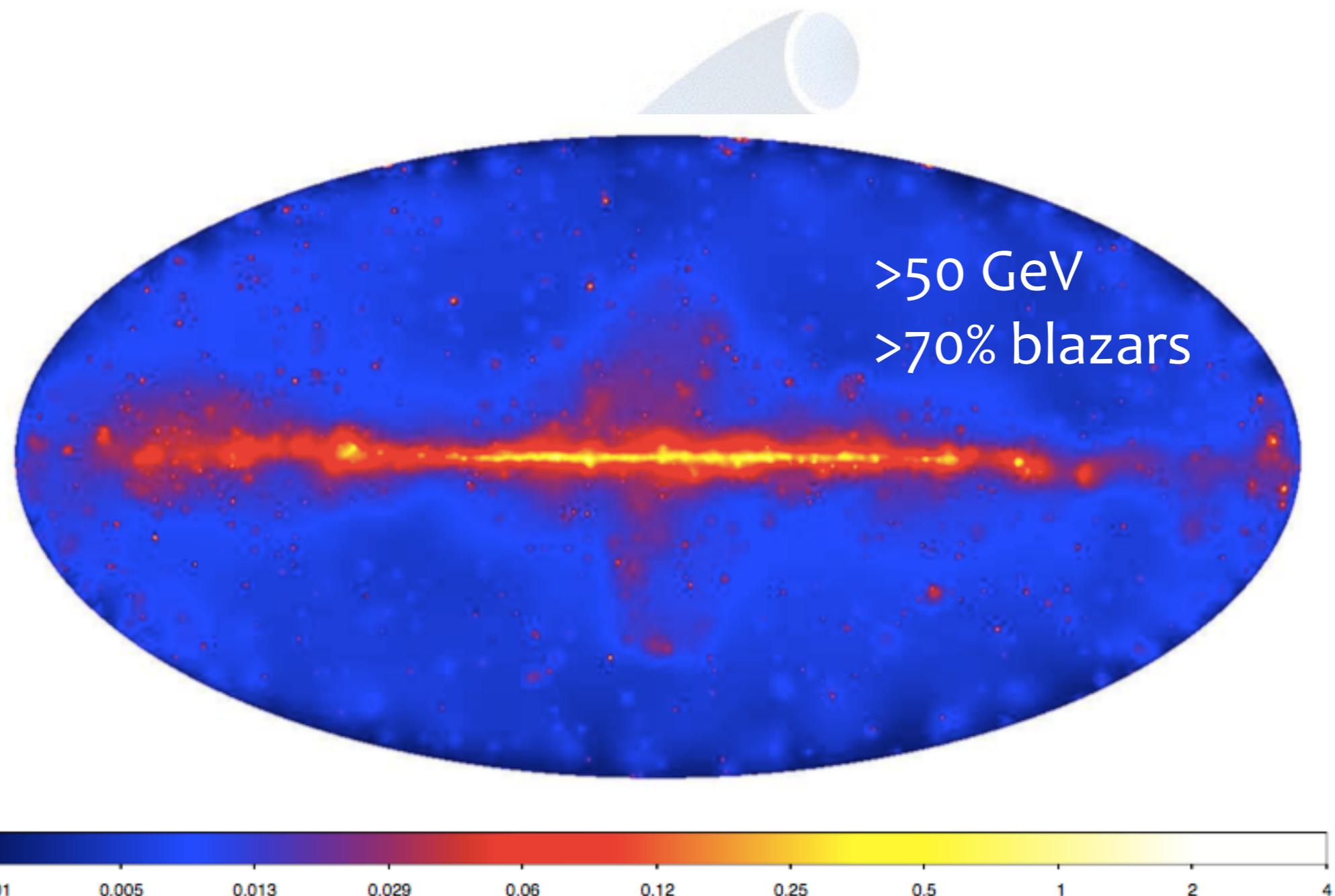


Neutrinos, like gamma rays,
point back to their origin



Connections between the Fermi-LAT 2FHL, UHE cosmic rays,
neutrinos and blazars

2FHL - HE Neutrino Connection



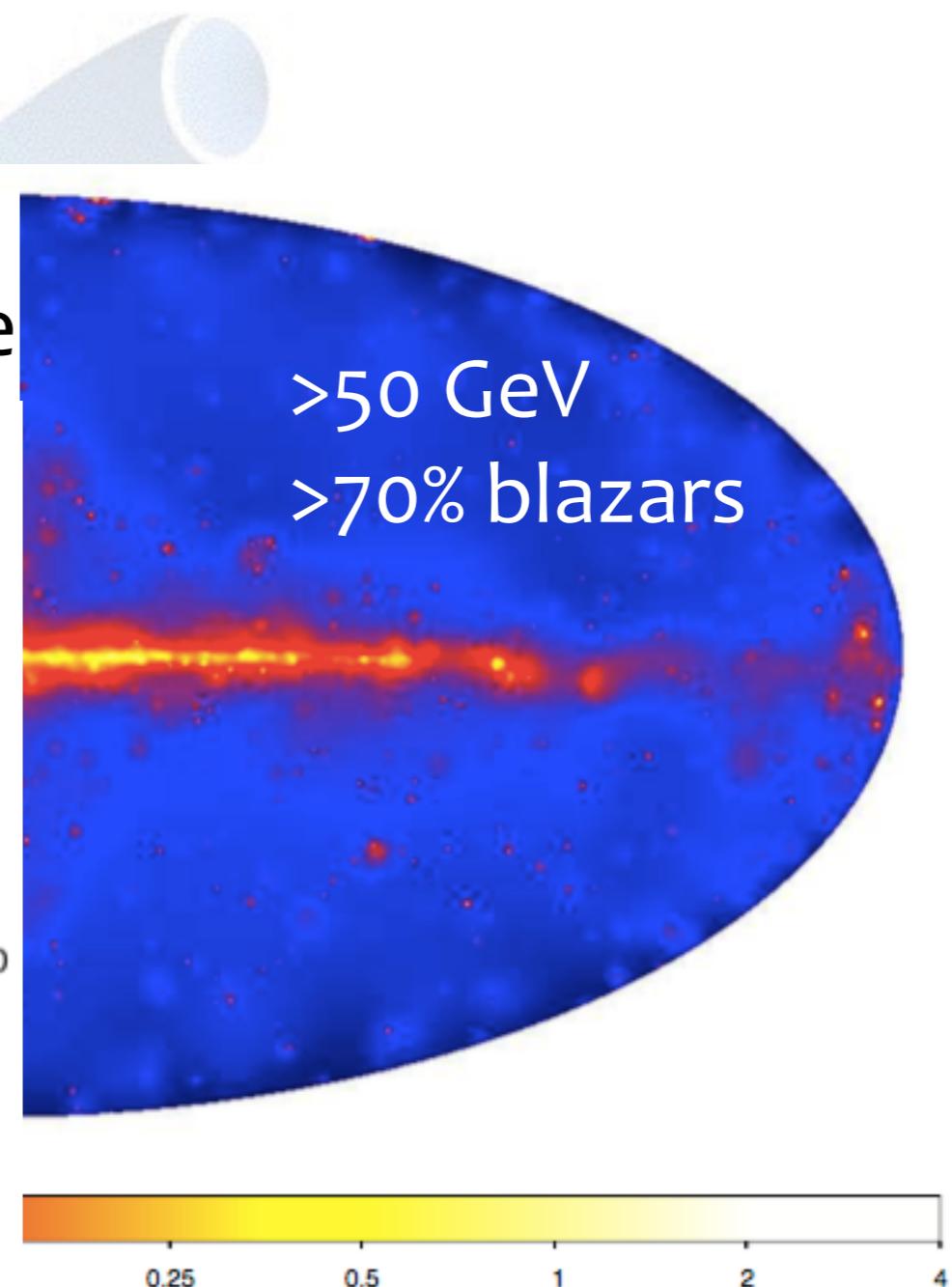
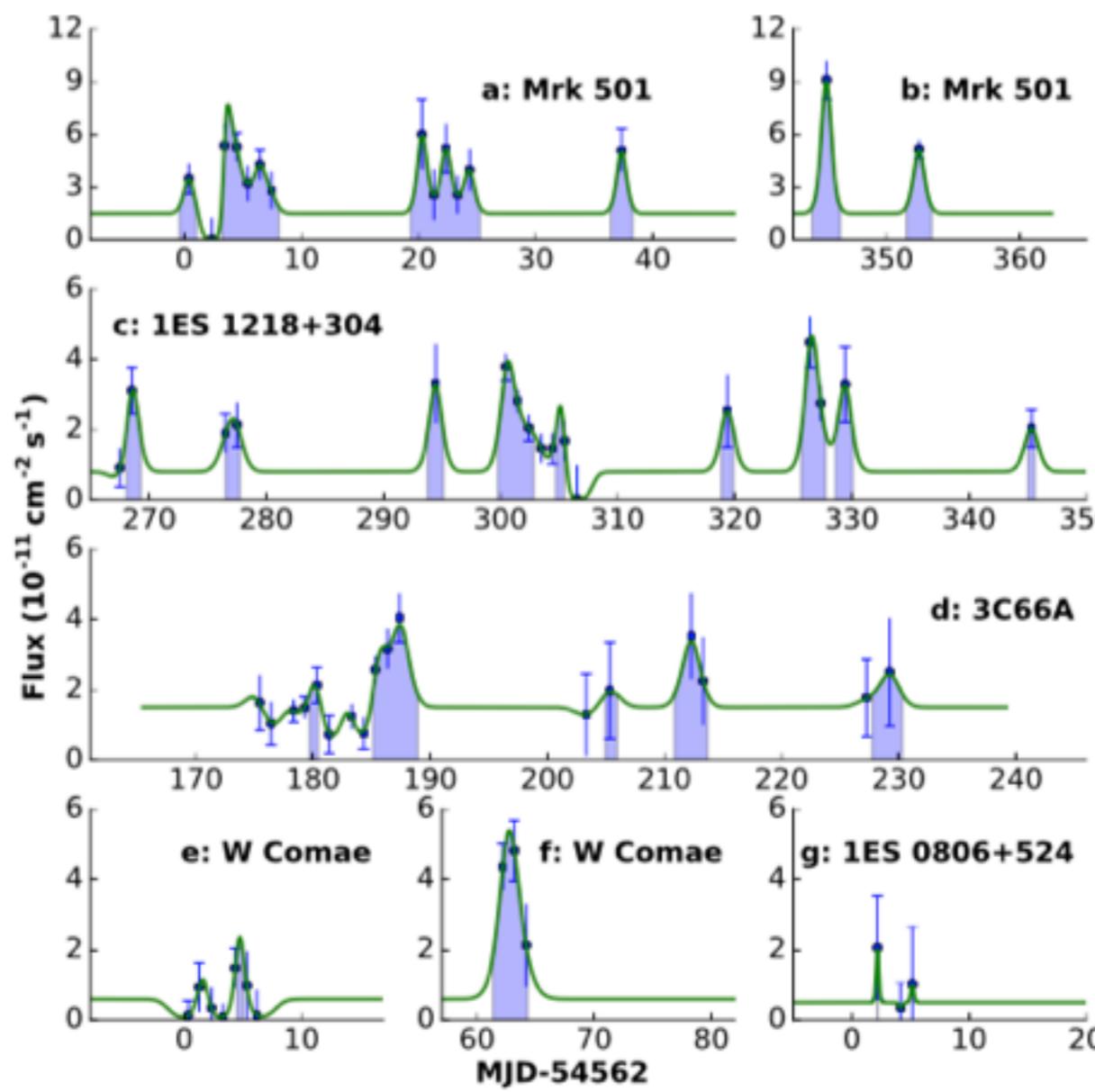
Space Telescope

2FHL - HE Neutrino Connection



Flaring blazars:

Mrk 421, Mrk 501, 1ES 0805+524,
1ES 1218+304, 3C66A, and W Comae



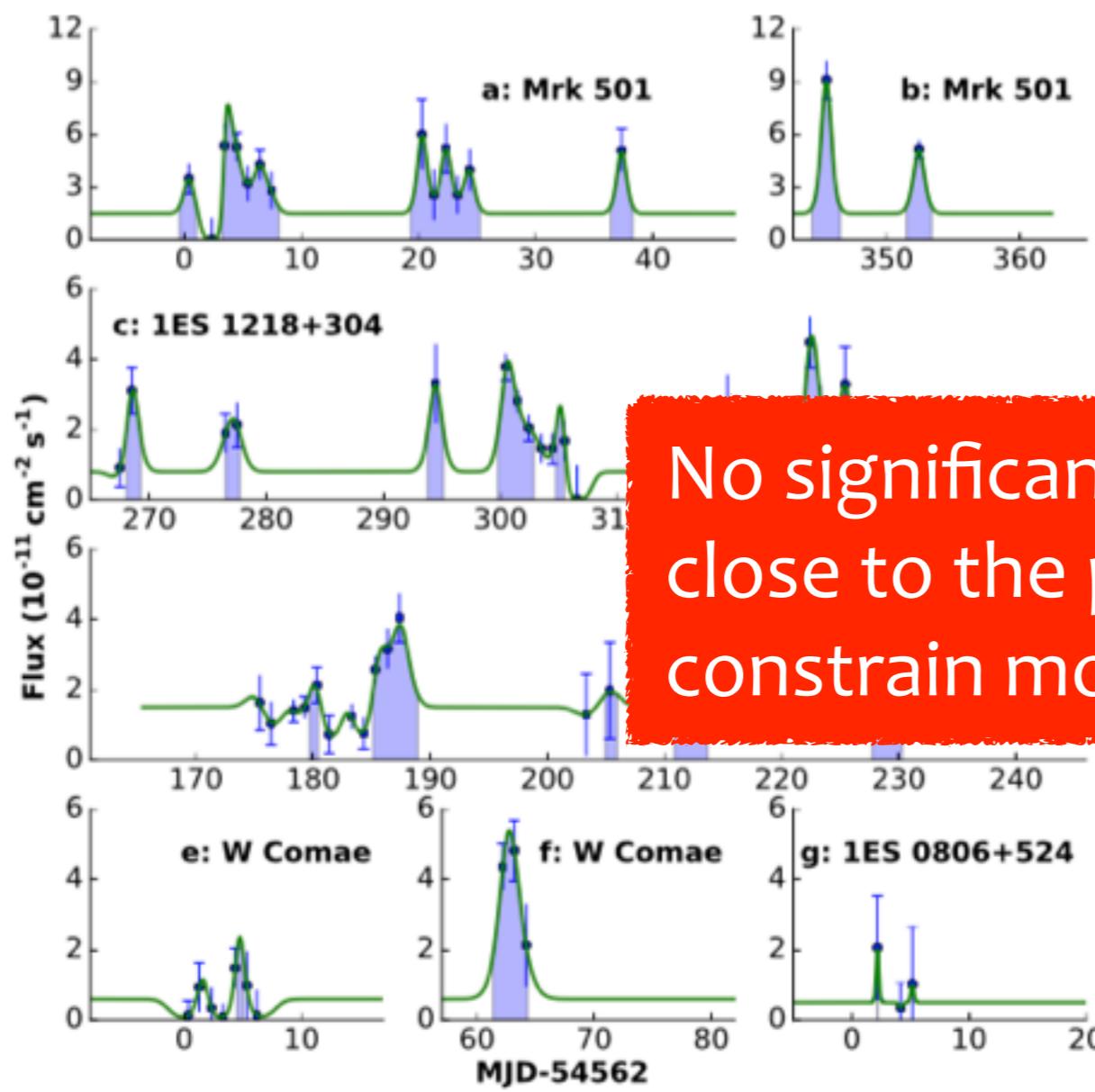
Telescope
+ACTs: VERITAS, MAGIC, HESS

2FHL - HE Neutrino Connection

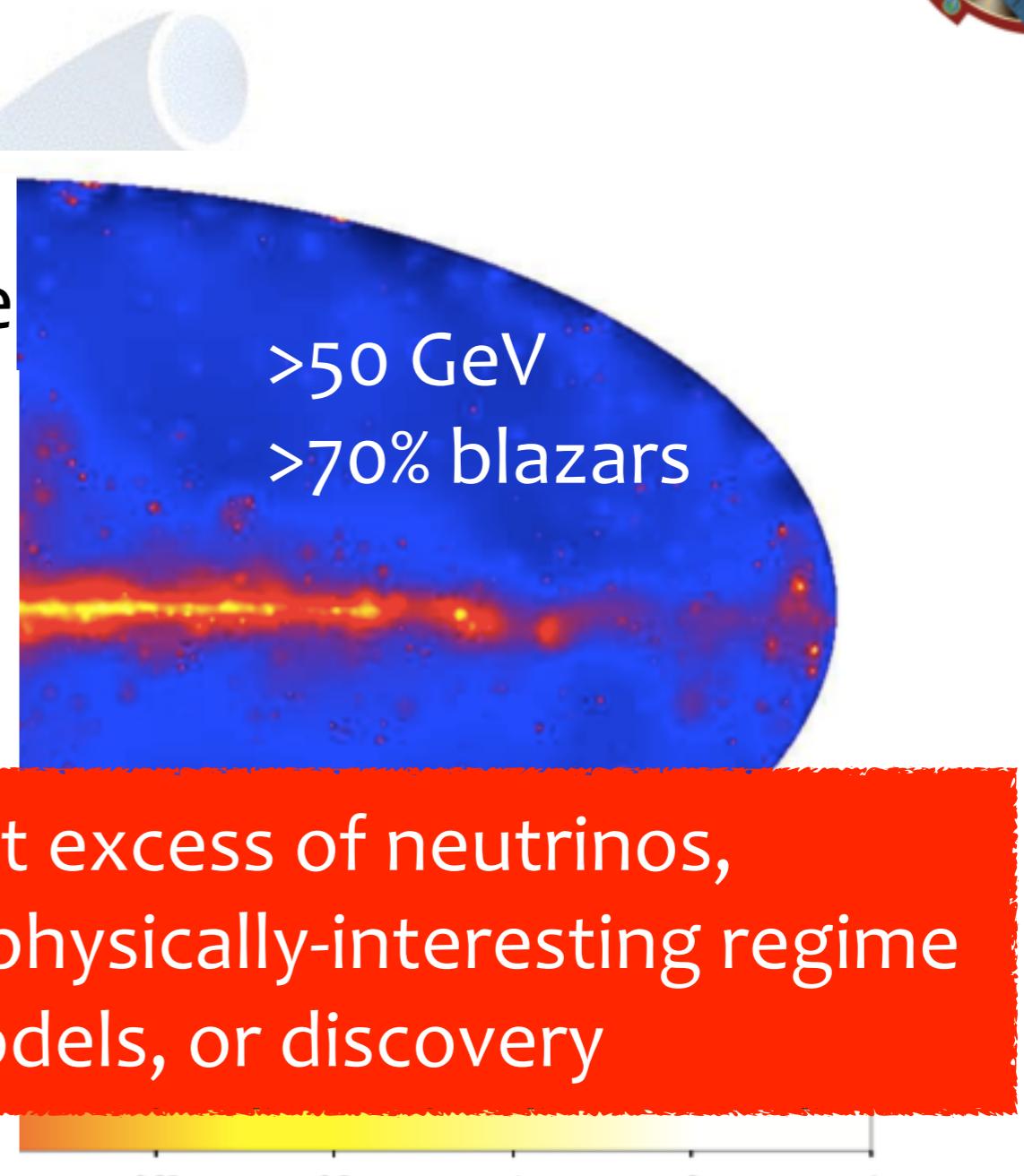


Flaring blazars:

**Mrk 421, Mrk 501, 1ES 0805+524,
1ES 1218+304, 3C66A, and W Comae**

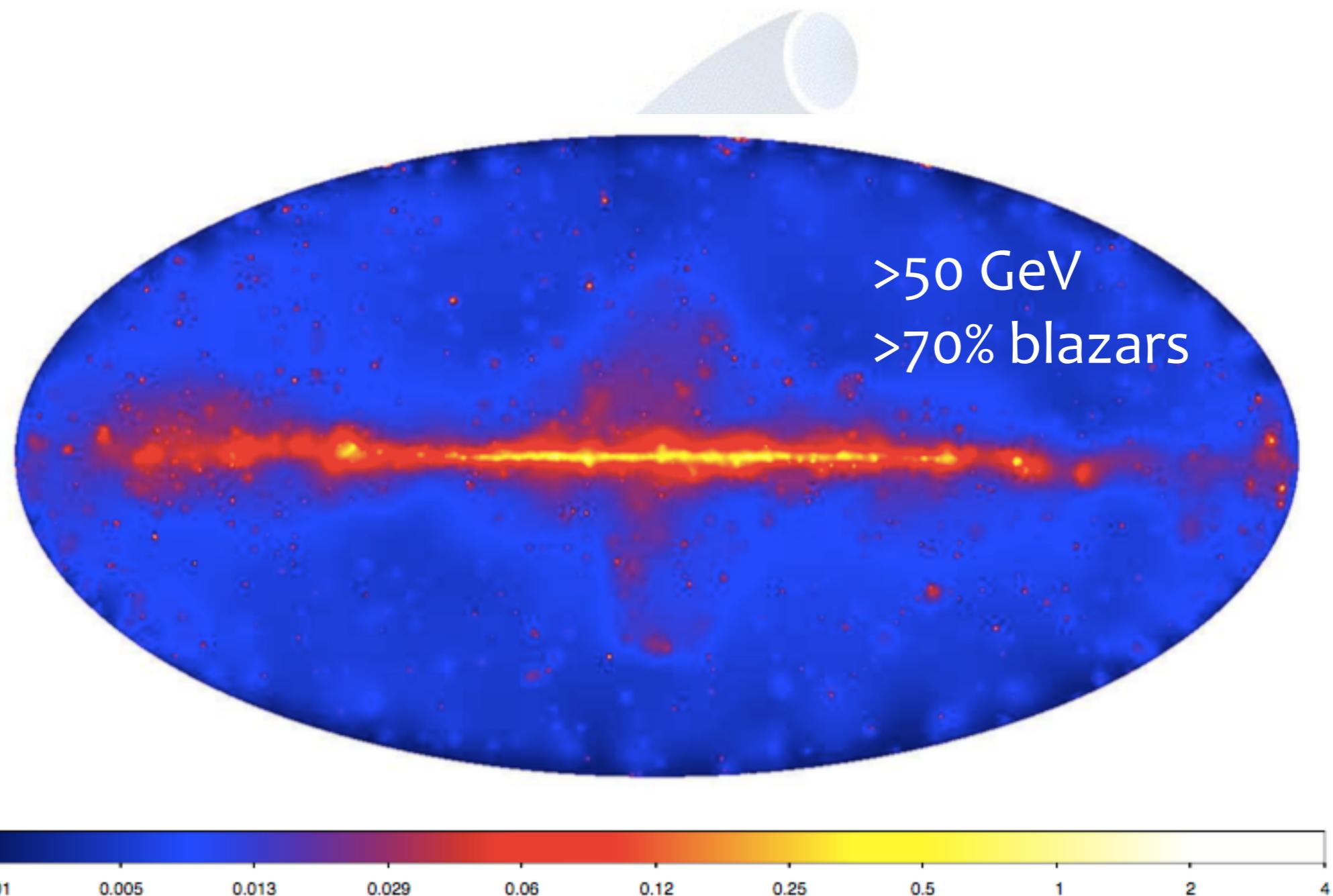


No significant excess of neutrinos,
close to the physically-interesting regime
constrain models, or discovery



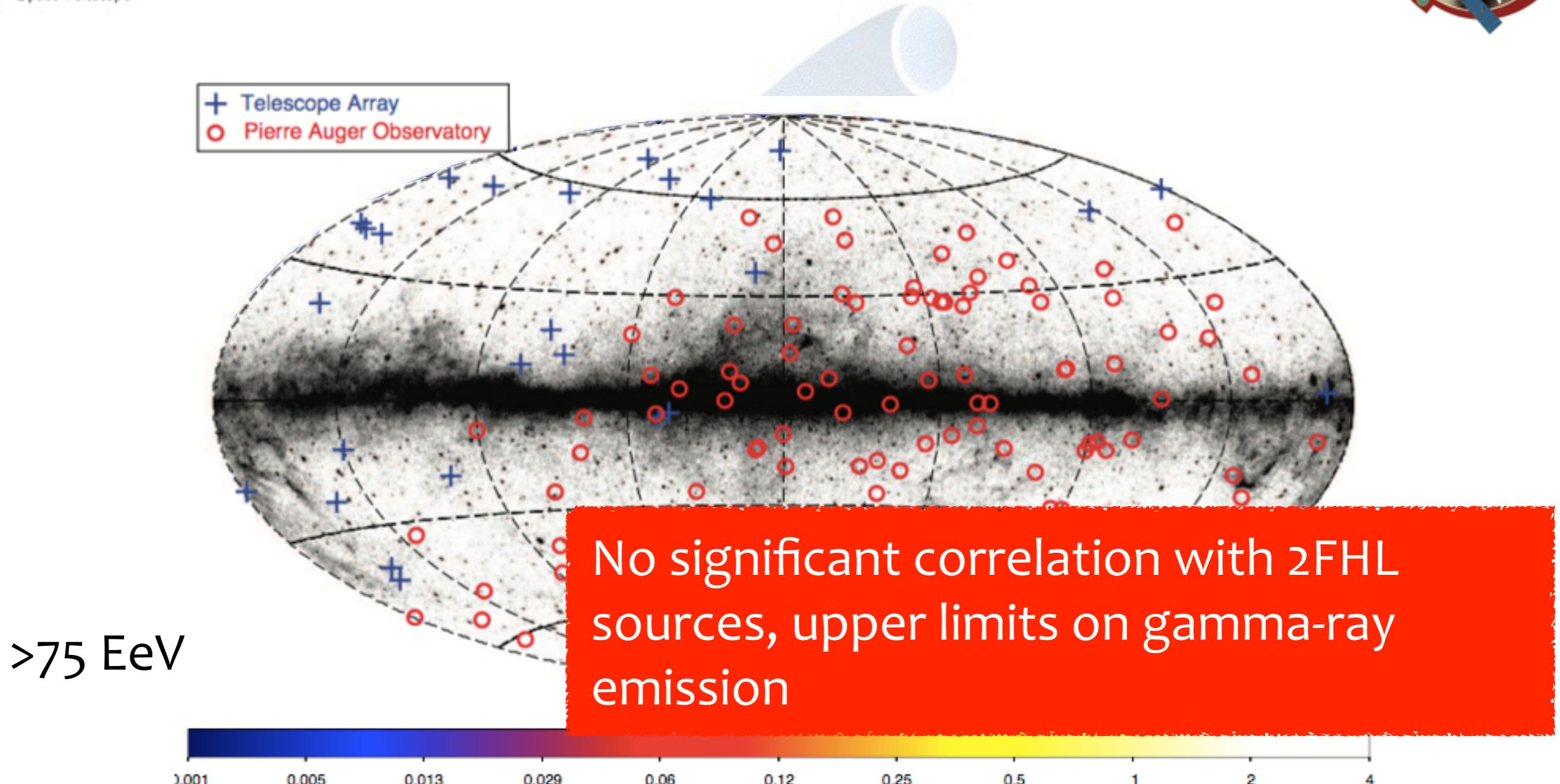
Telescope
+ACTs: VERITAS, MAGIC, HESS

2FHL - UHE Cosmic Ray Connection



Space Telescope

2FHL - UHE Cosmic Ray Connection



Space | telescope

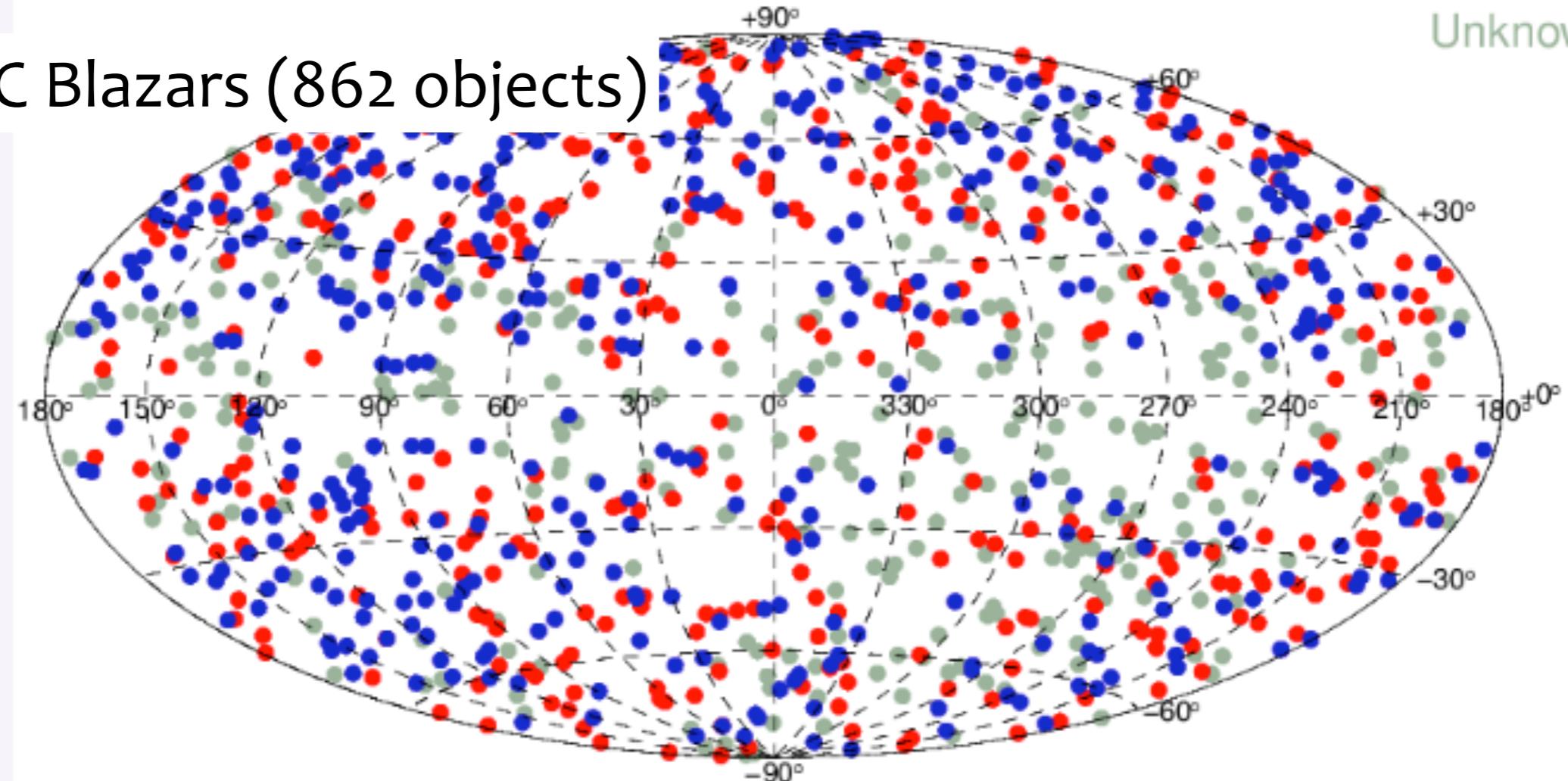
2LAC - HE Neutrino Connection



Second LAT Catalogue (2LAC)
TS>25, August 2008 – August 2010

FSRQ
BLLAC
Unknown

All 2LAC Blazars (862 objects)



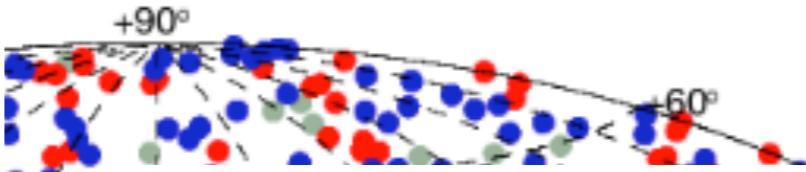
Space Telescope

2LAC - HE Neutrino Connection

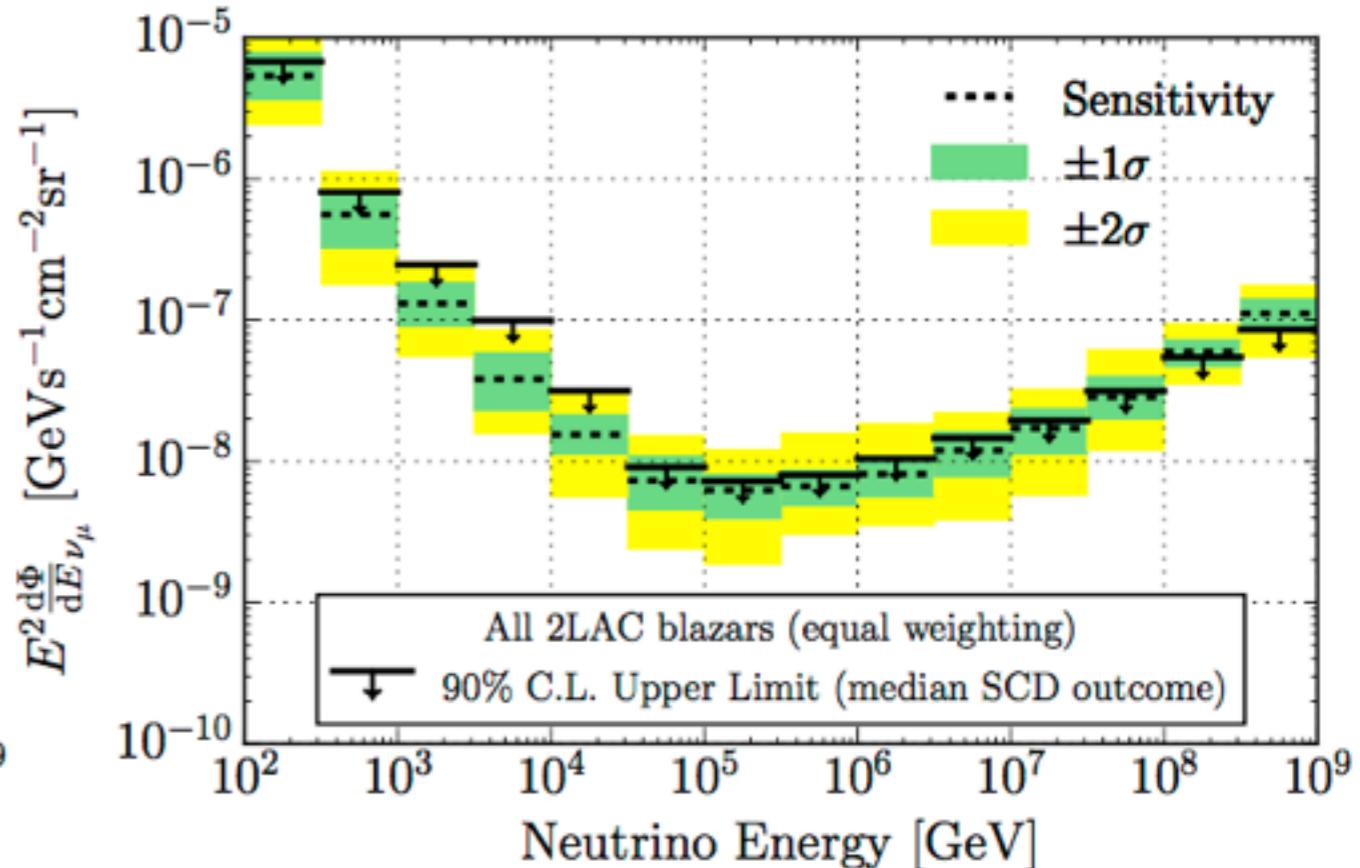
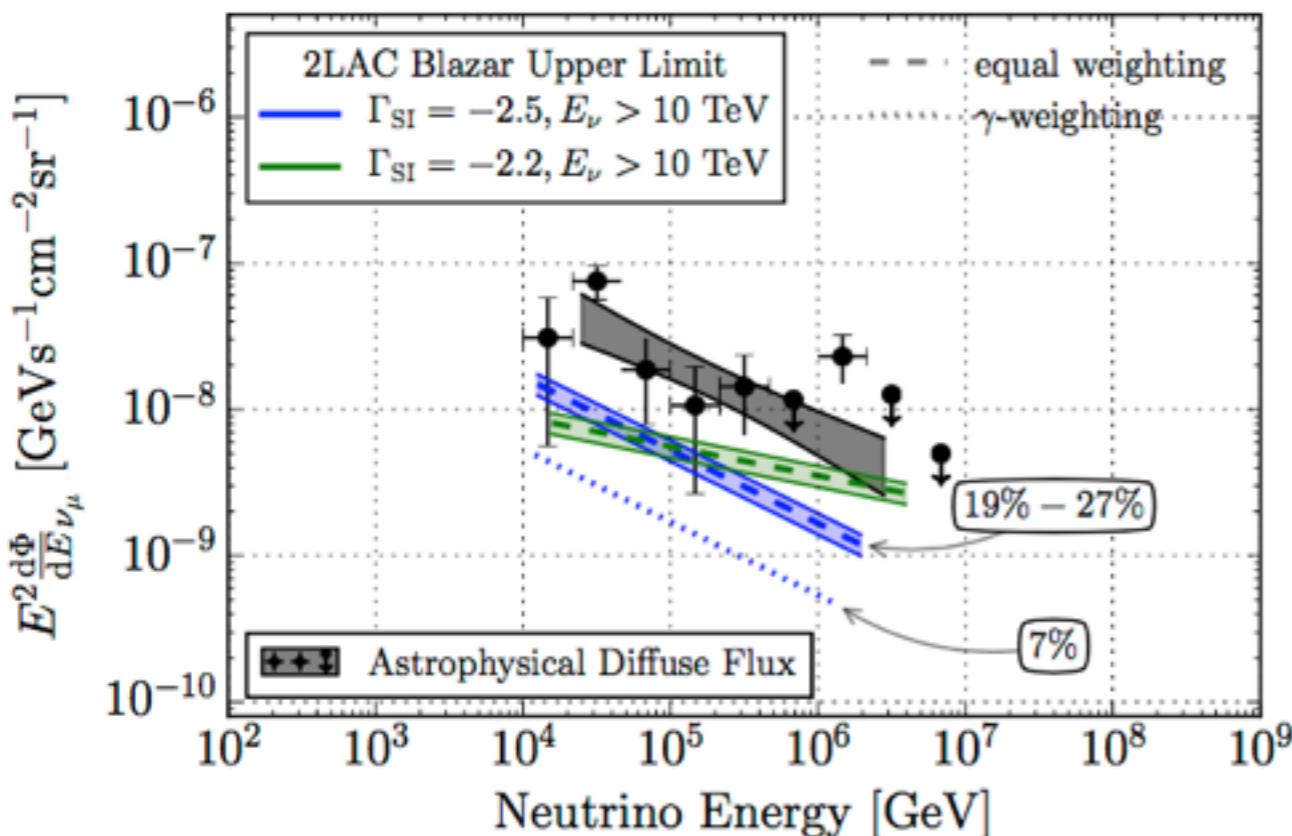


Second LAT Catalogue (2LAC) TS>25, August 2008 – August 2010

All 2LAC Blazars (862 objects)



FSRQ
BLLAC
Unknown



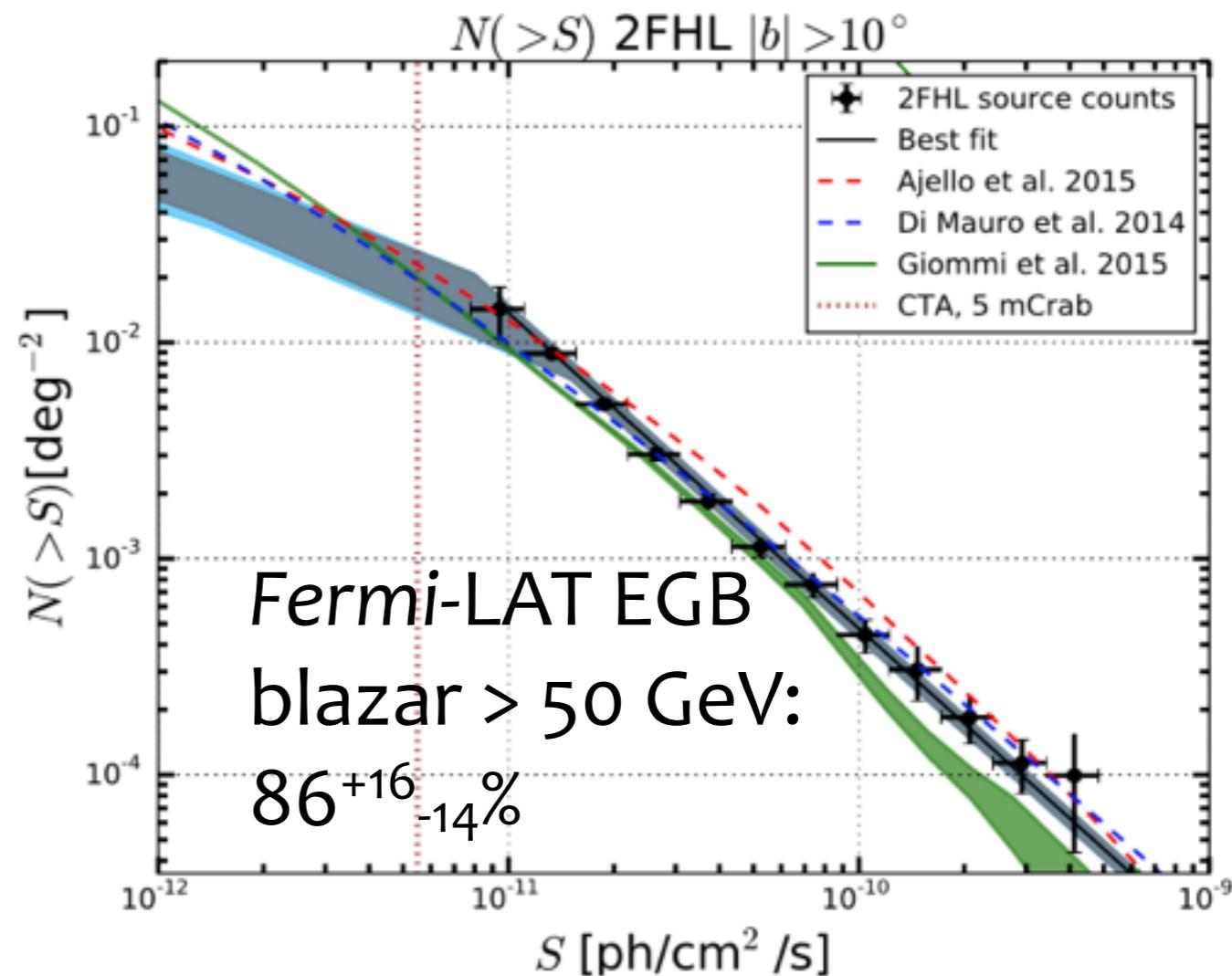
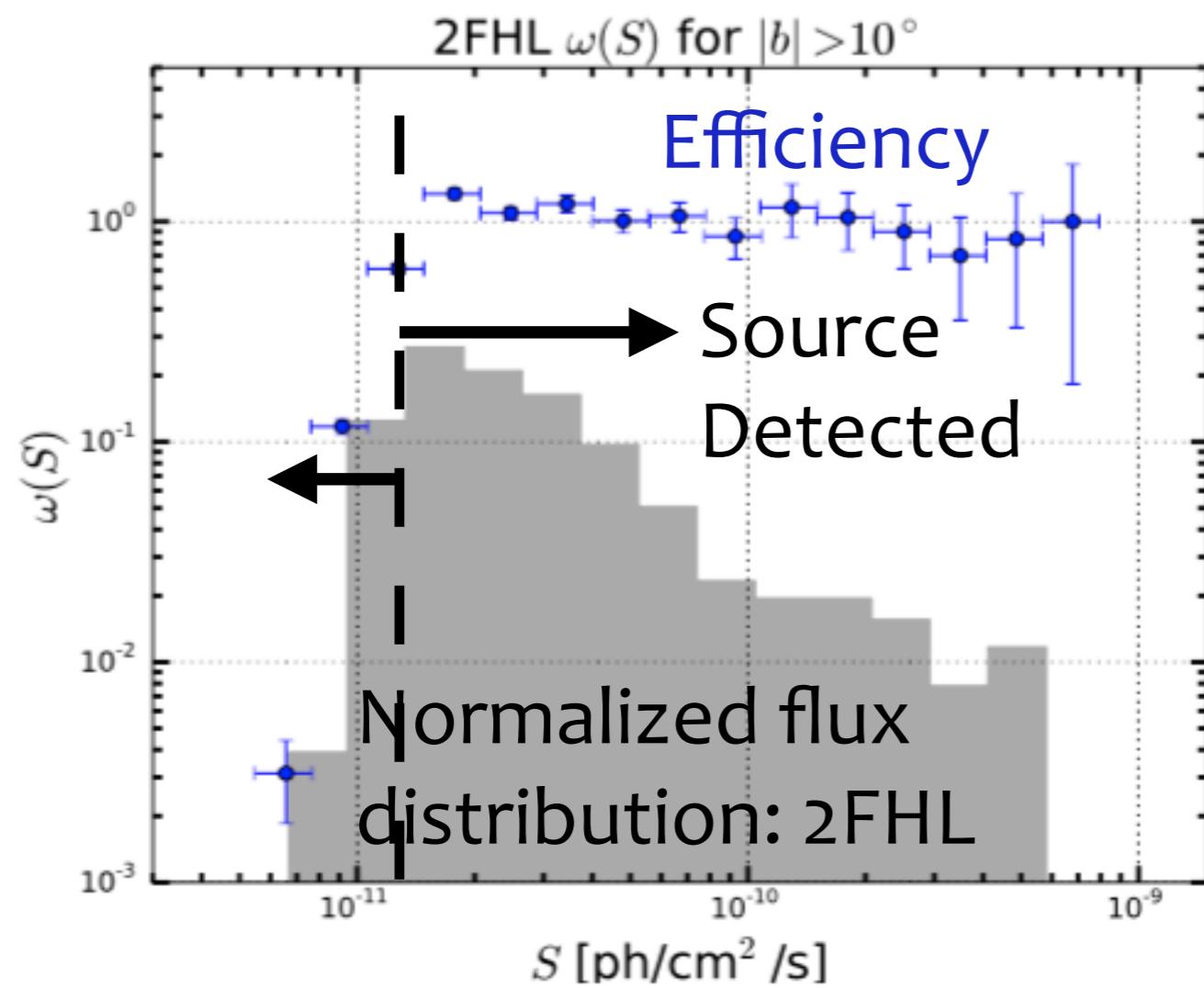
90% CL flux 2LAC objects vs.
Astrophysical neutrino flux

Differential 90% CL UL on
 $(\nu_\mu + \bar{\nu}_\mu)$ -flux

Extragalactic Gamma-ray Background - HE Neutrino Connection



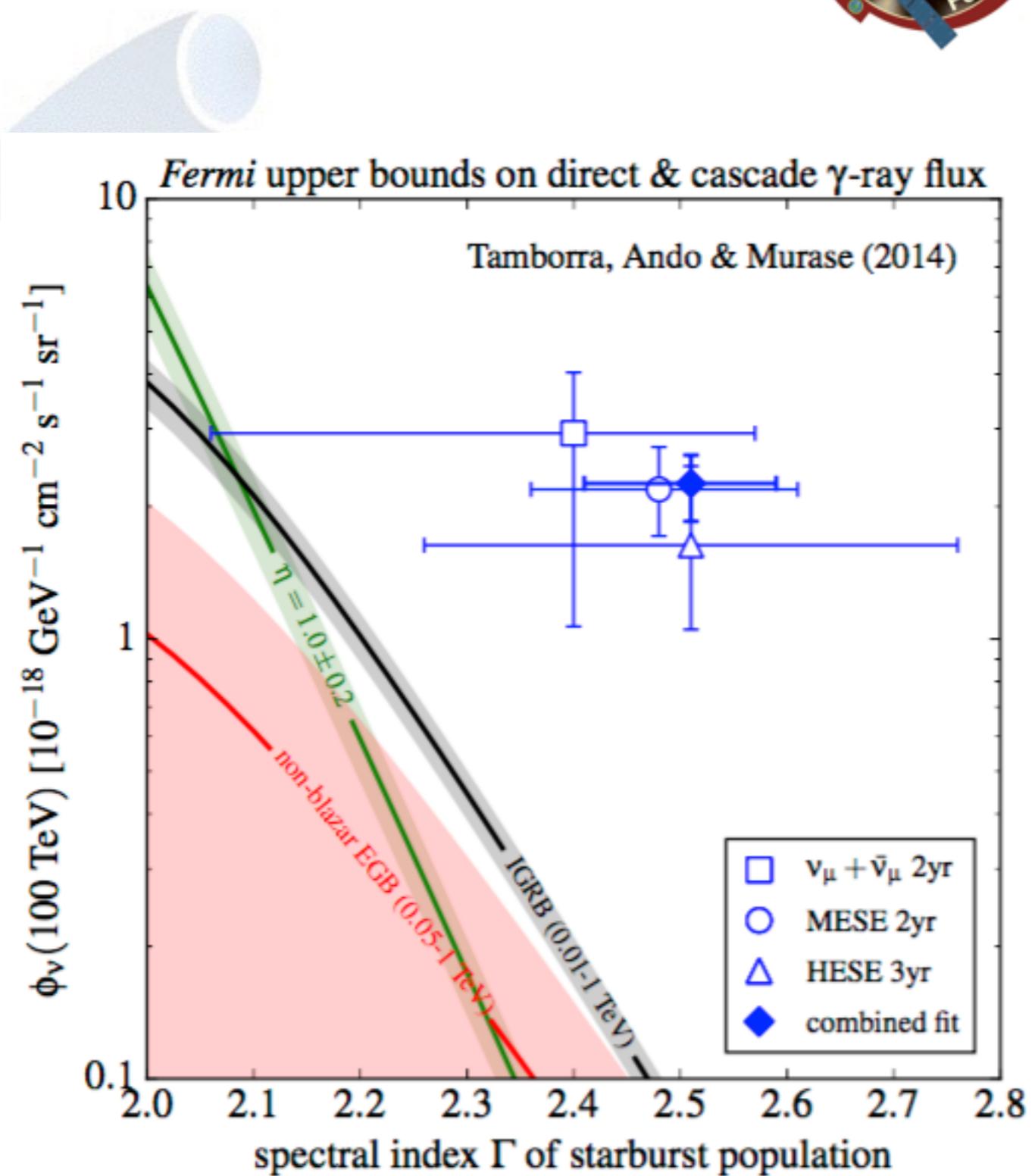
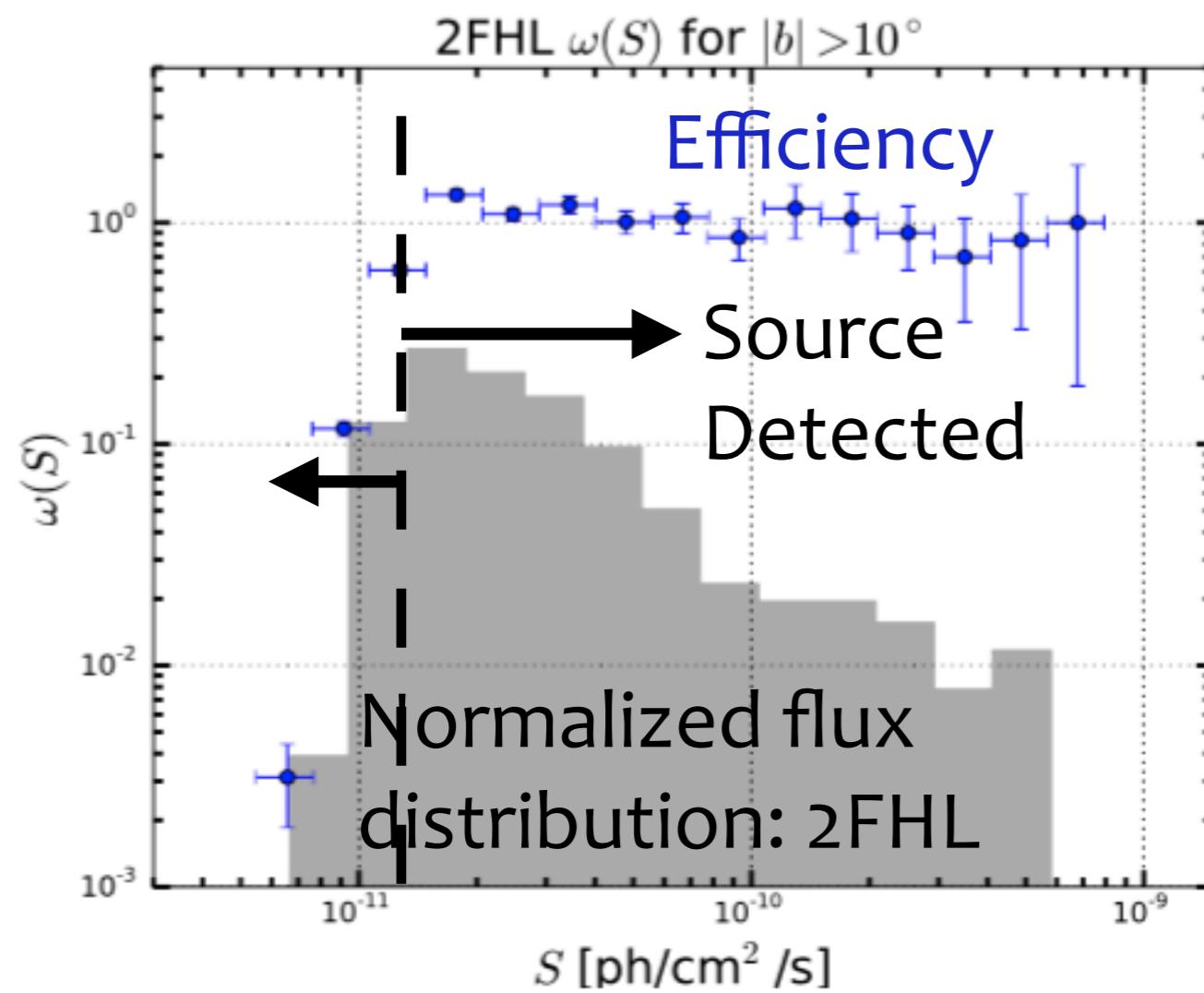
What Comprises the
Fermi-LAT EGB?



Extragalactic Gamma-ray Background - HE Neutrino Connection



Hadronic interactions in Star-Forming Galaxies





Results from *Fermi-LAT*



***Gravitational Wave
Astrophysics***

Detection of Gravitational Waves

***Electromagnetic
counterparts to GWs***

***Recent followup observations
of LIGO GW events***

***Gamma-ray
Space Telescope***

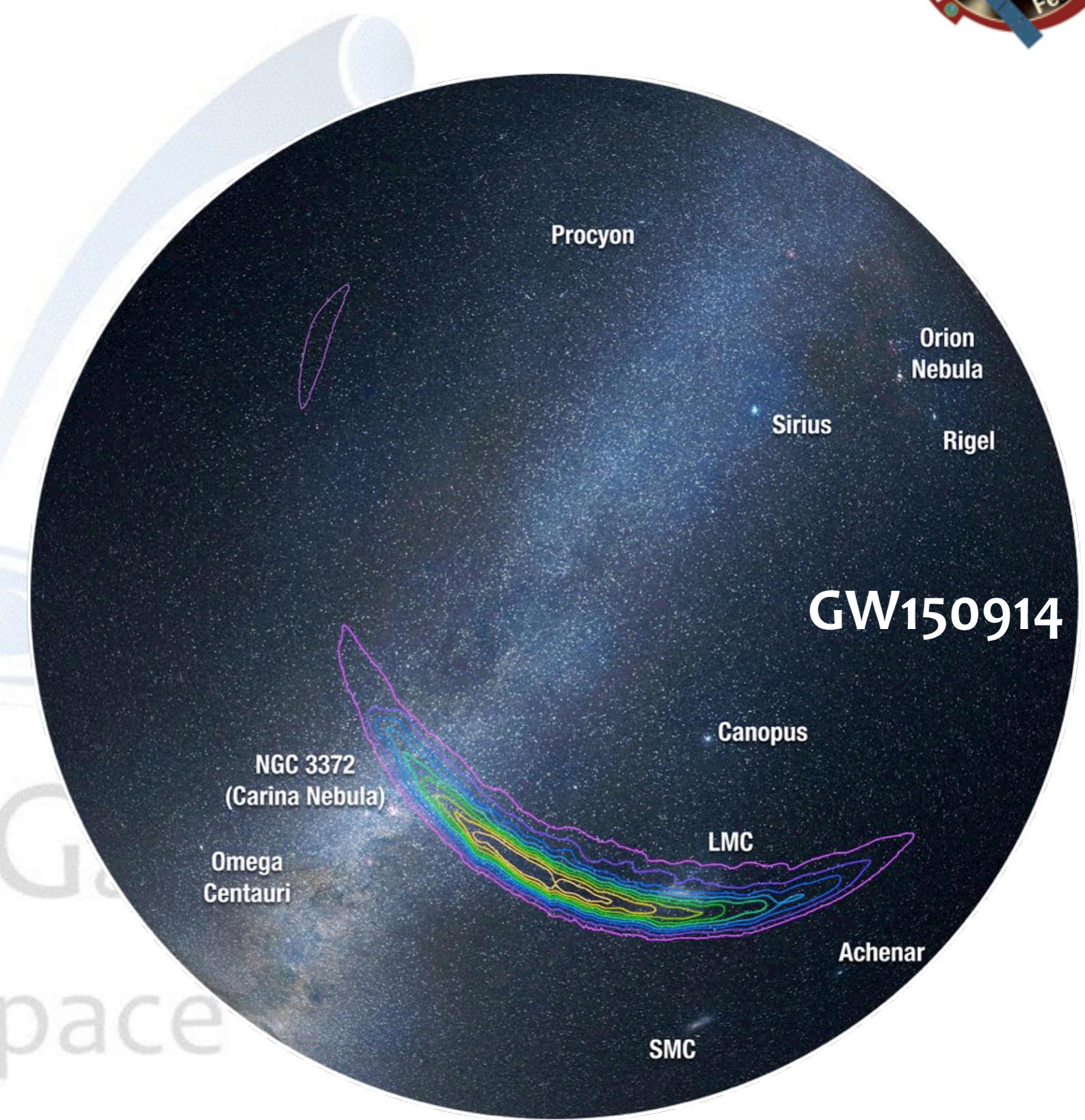
Era of Gravitational Wave Astrophysics



Fermi (GBM and LAT)
perfect instruments to
follow up transient
events

BBH mergers not
expected to produce
EM radiation

Short GRBs and NS-NS
mergers primary
candidate for GW
emission



Transient Pipelines Timescale



Transient Analyses with *Fermi-LAT*



Pipeline
Method
Timescale
Distribution
Status

GBM Untriggered Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

LAT Transient Factor (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered Operating + *Blind Search Coming Soon*

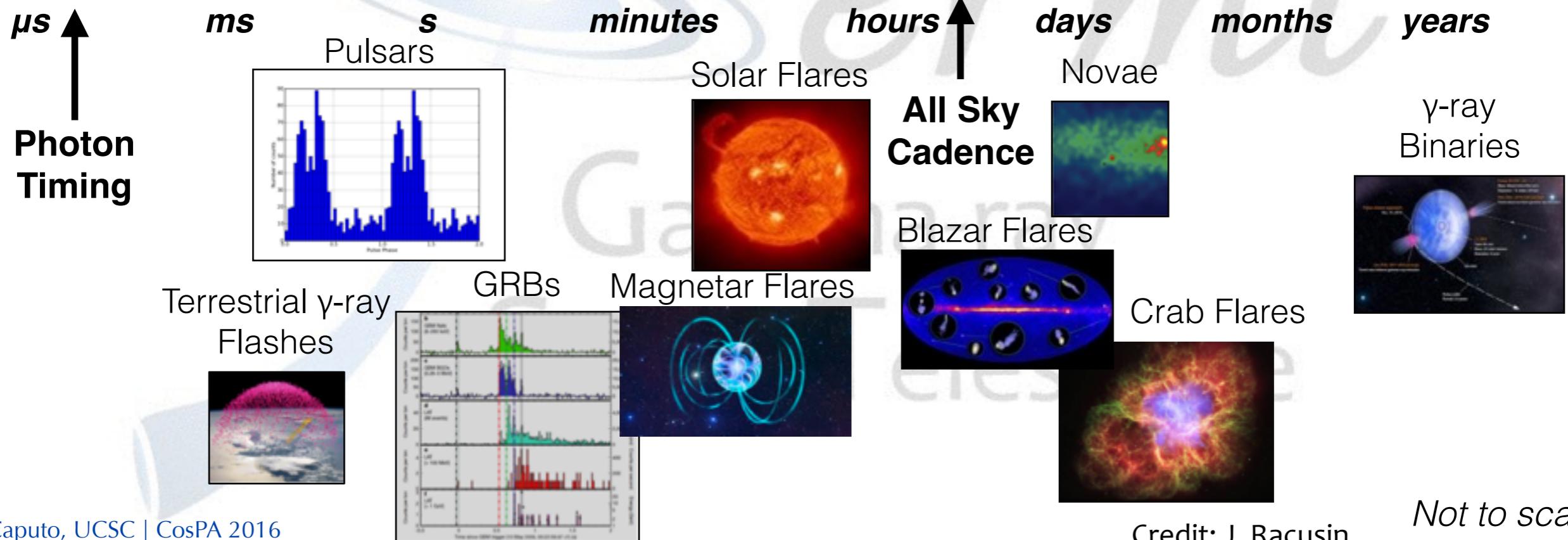
LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs
Operating

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating

LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating

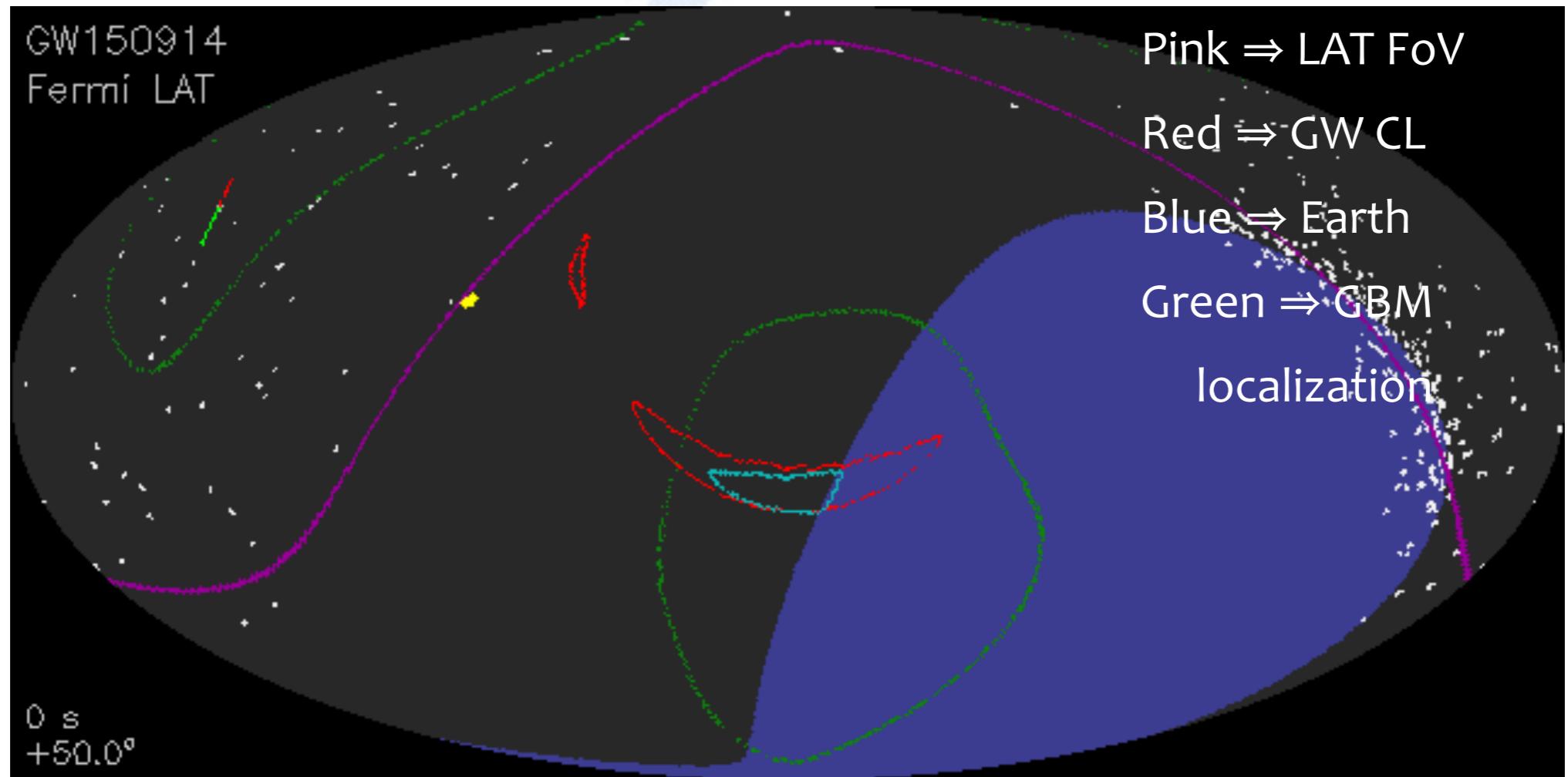
Fermi All-sky Variability Analysis (FAVA)
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
<http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/>

LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year
(1FGL), 2 years (2FGL), 4
years (3FGL)
[http://fermi.gsfc.nasa.gov/ssc/data/access/4FGL in progress](http://fermi.gsfc.nasa.gov/ssc/data/access/4FGL_in_progress)



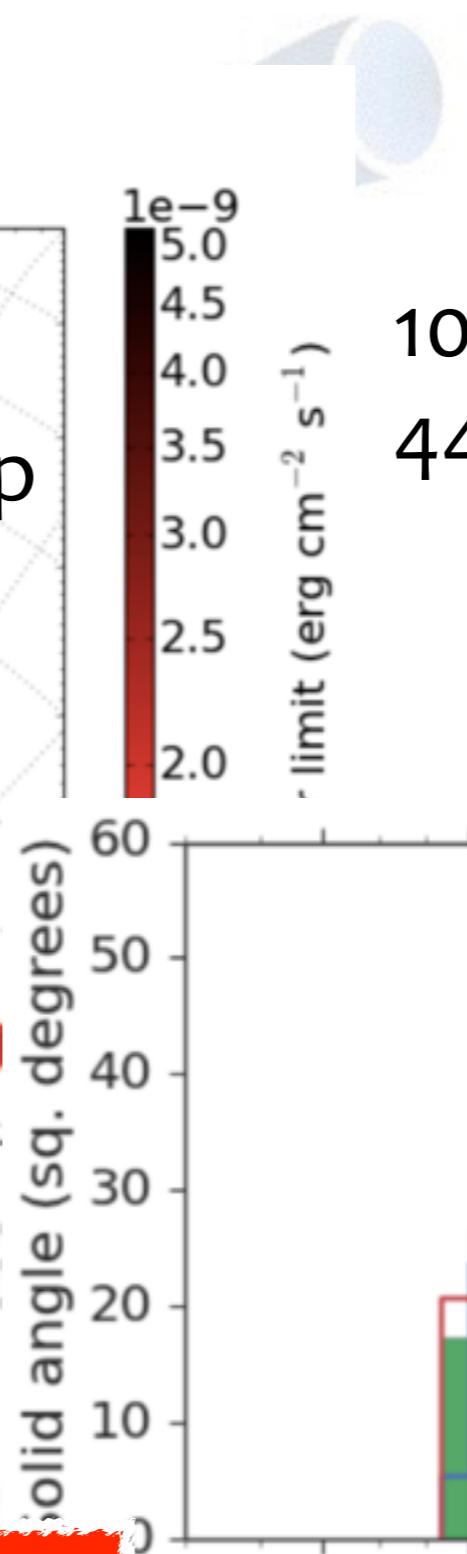
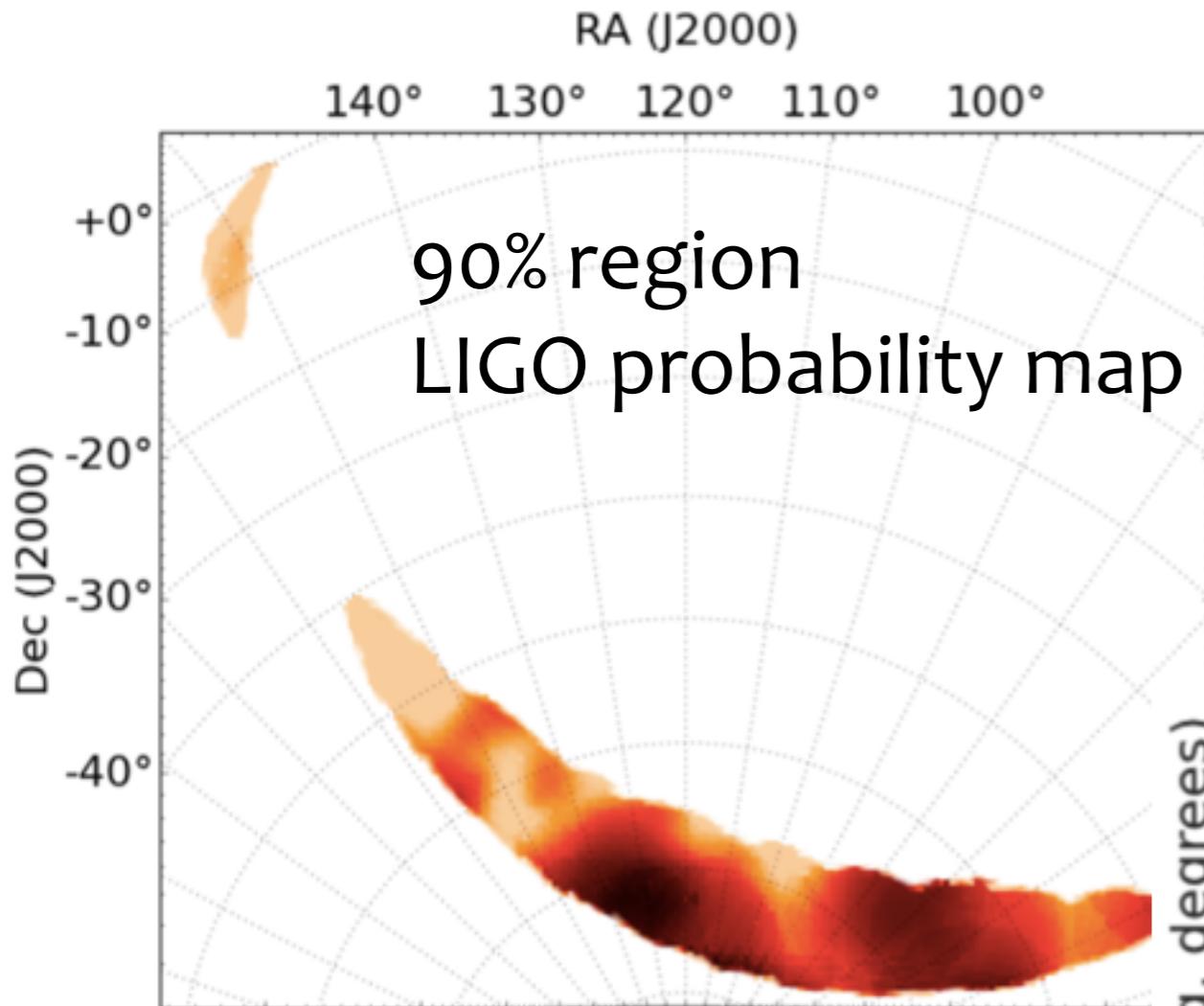


GW150914 and the LAT Field Of View



Light blue is the intersection between GBM+LIGO+excluding the Earth LAT “looking” in wrong direction upper limits were set on much later intervals.

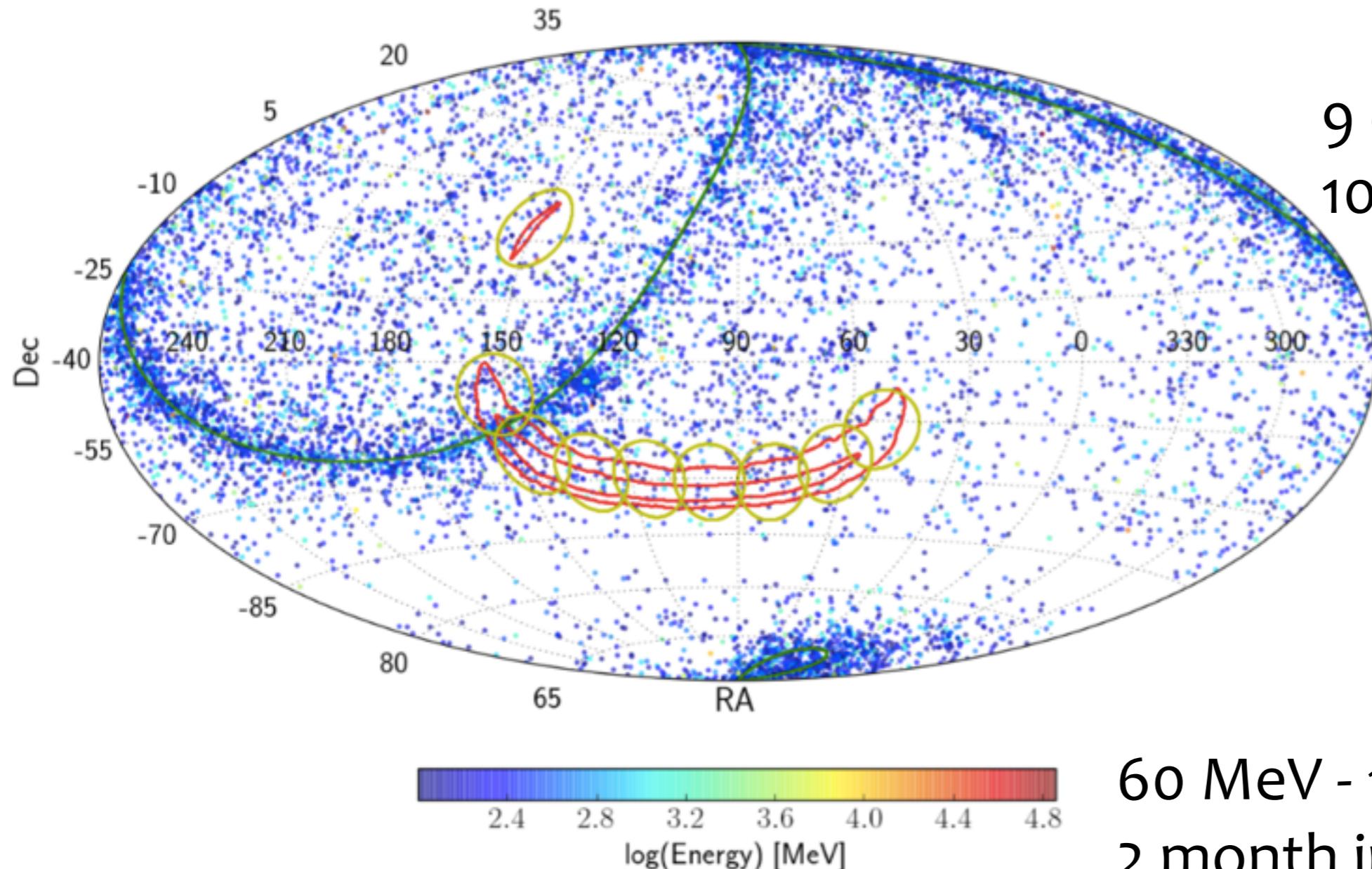
Short Baseline Search



No Significant Excess Found



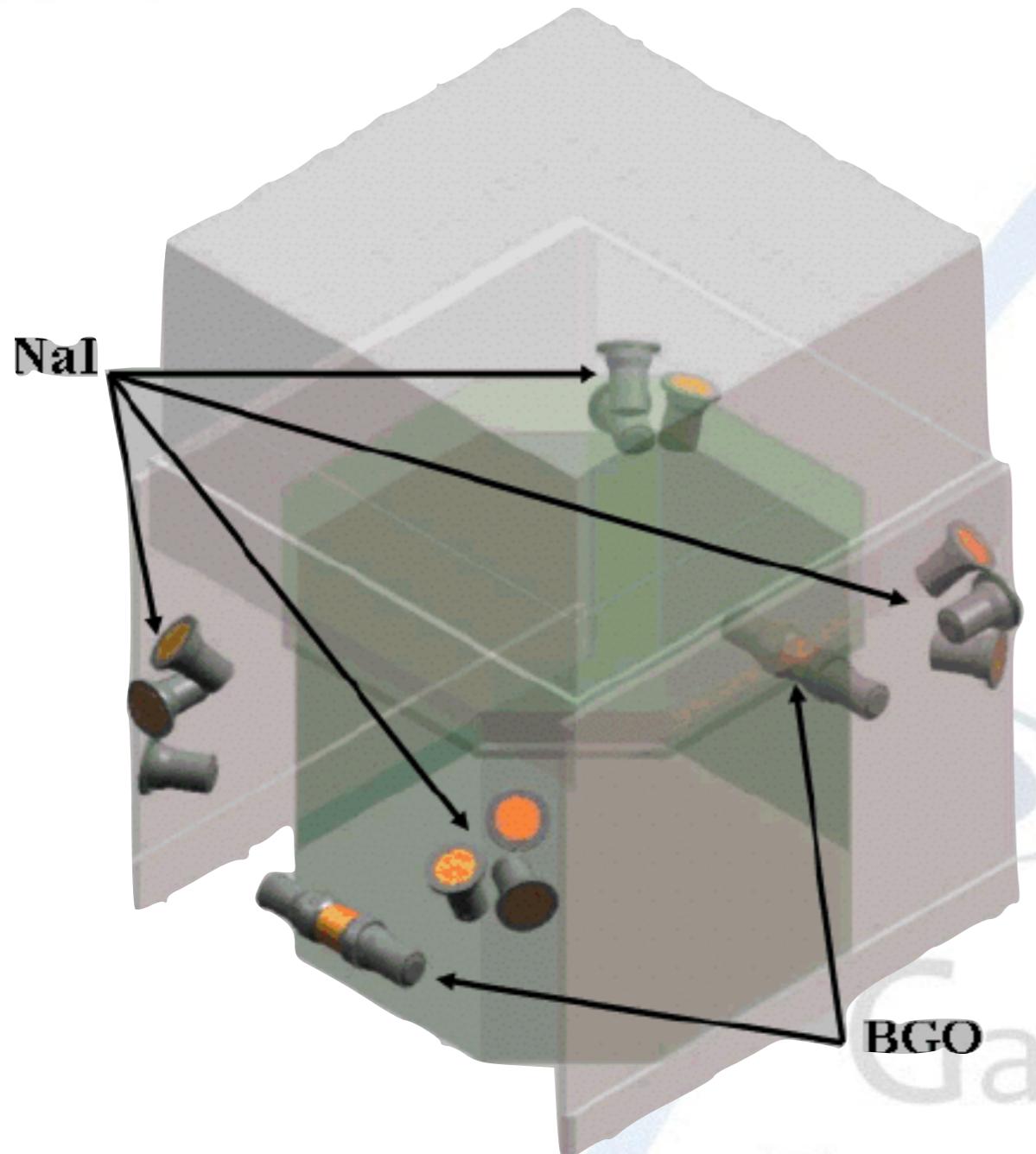
Long Baseline Search



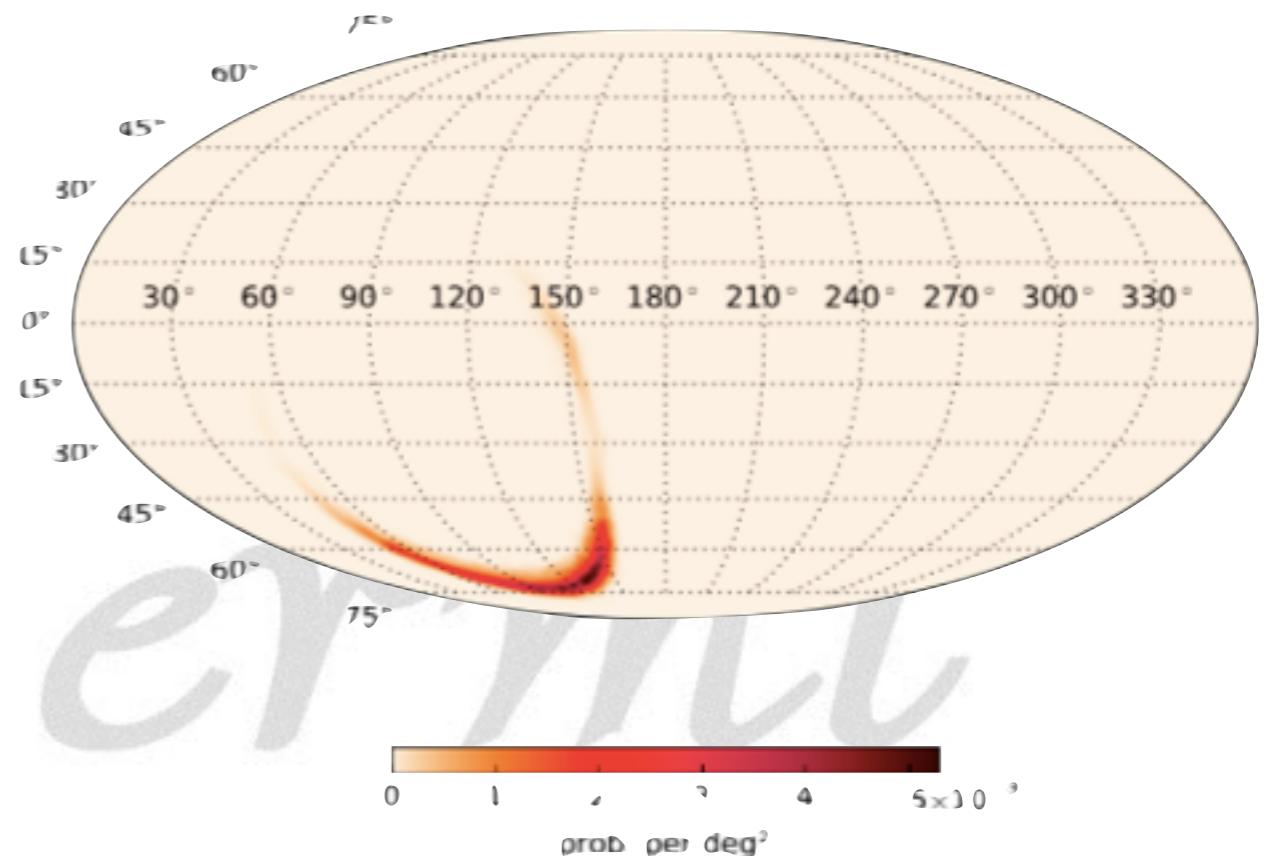
No Significant Excess Found

60 MeV - 100 GeV
2 month interval around t_{GW}
 TS_{\max} of a source probability
 >0.9 and associated with
candidate

A note on the *Fermi-GBM* detection

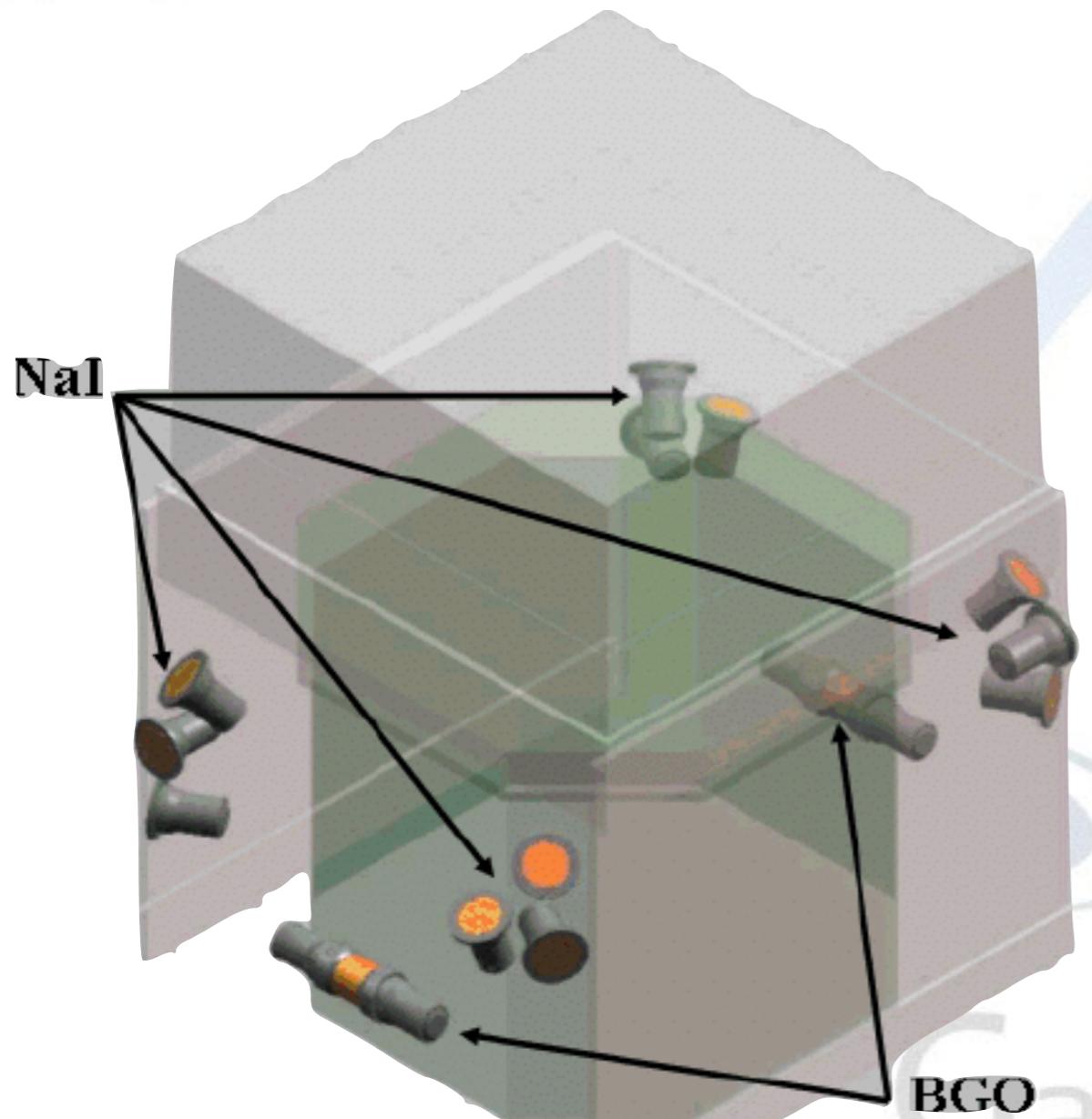


LIGO Localization

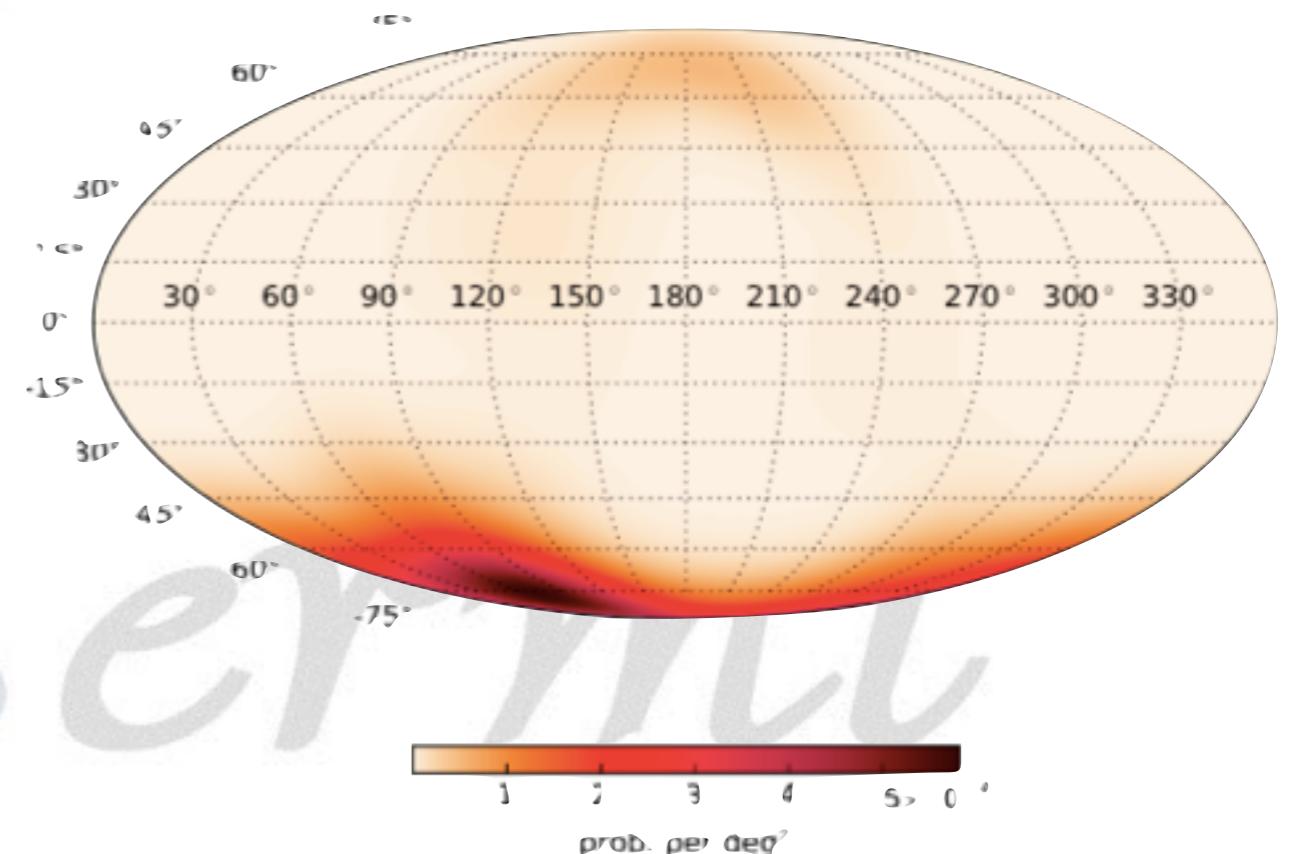


Gamma-ray
Space Telescope

A note on the *Fermi-GBM* detection

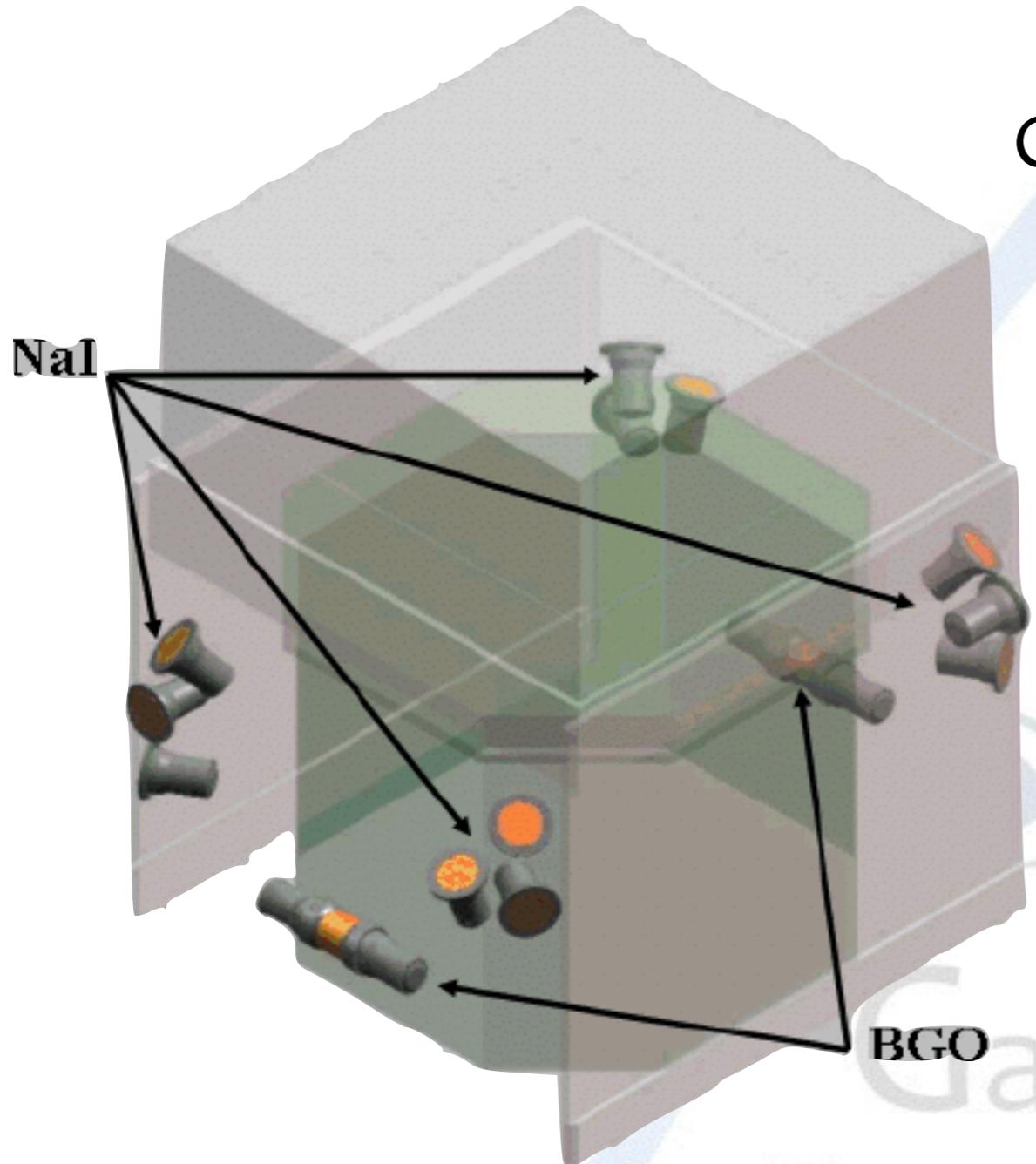


GBM Localization

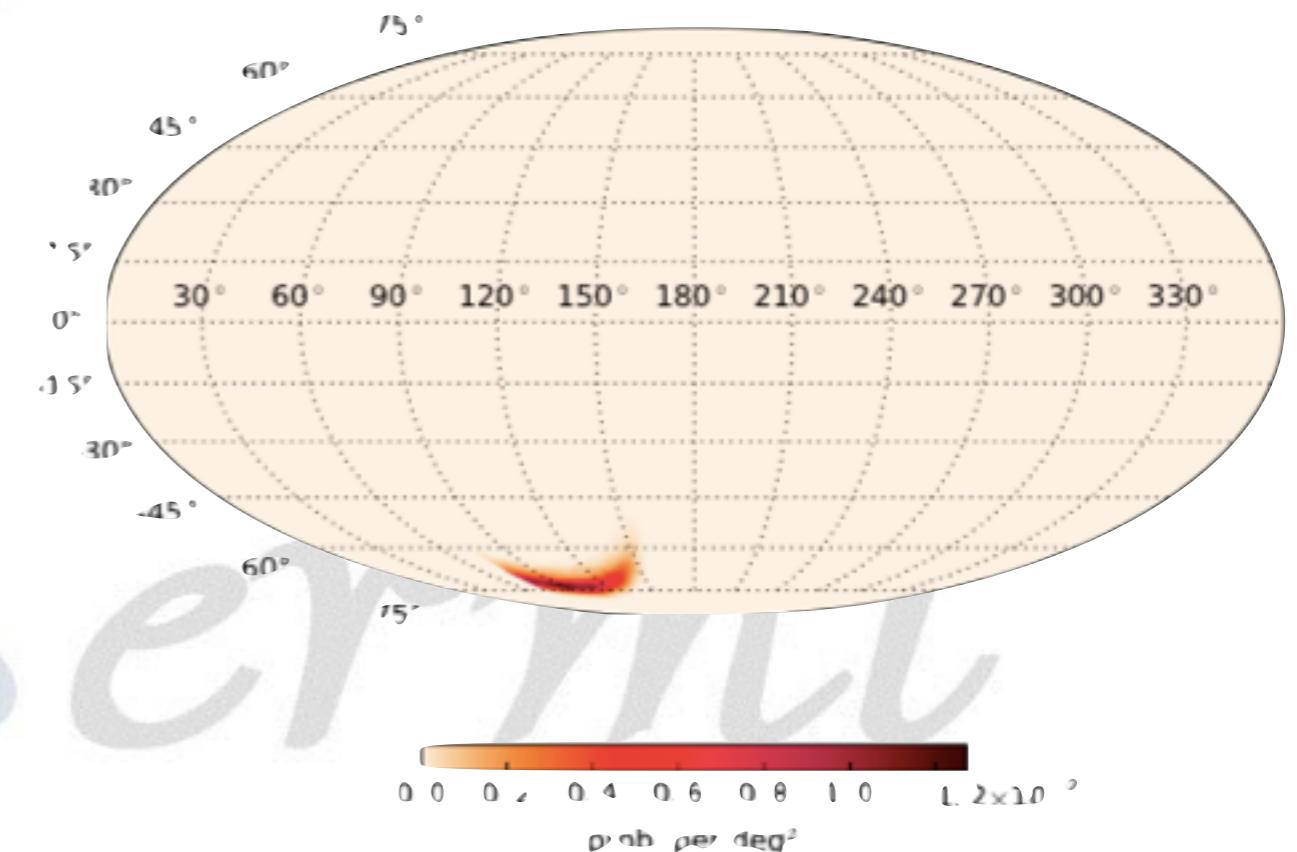


GBM localization from the bottom of the spacecraft,
shows up in all 14 detectors

A note on the *Fermi*-GBM detection



Combined Localization

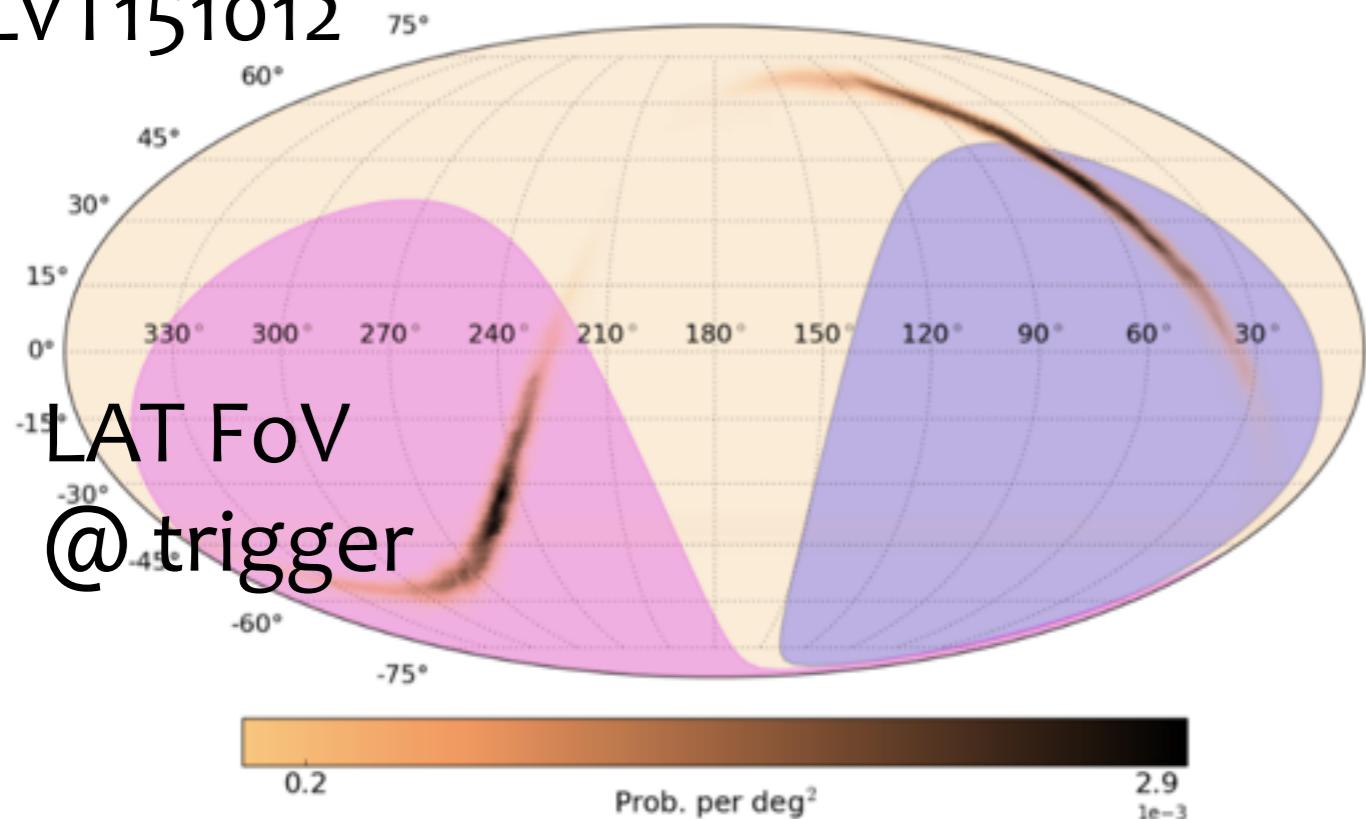


weak transient above 50 keV, 0.4 s after the GW event,
false alarm probability of 0.0022 (2.9 σ)

Fermi-LAT Observations

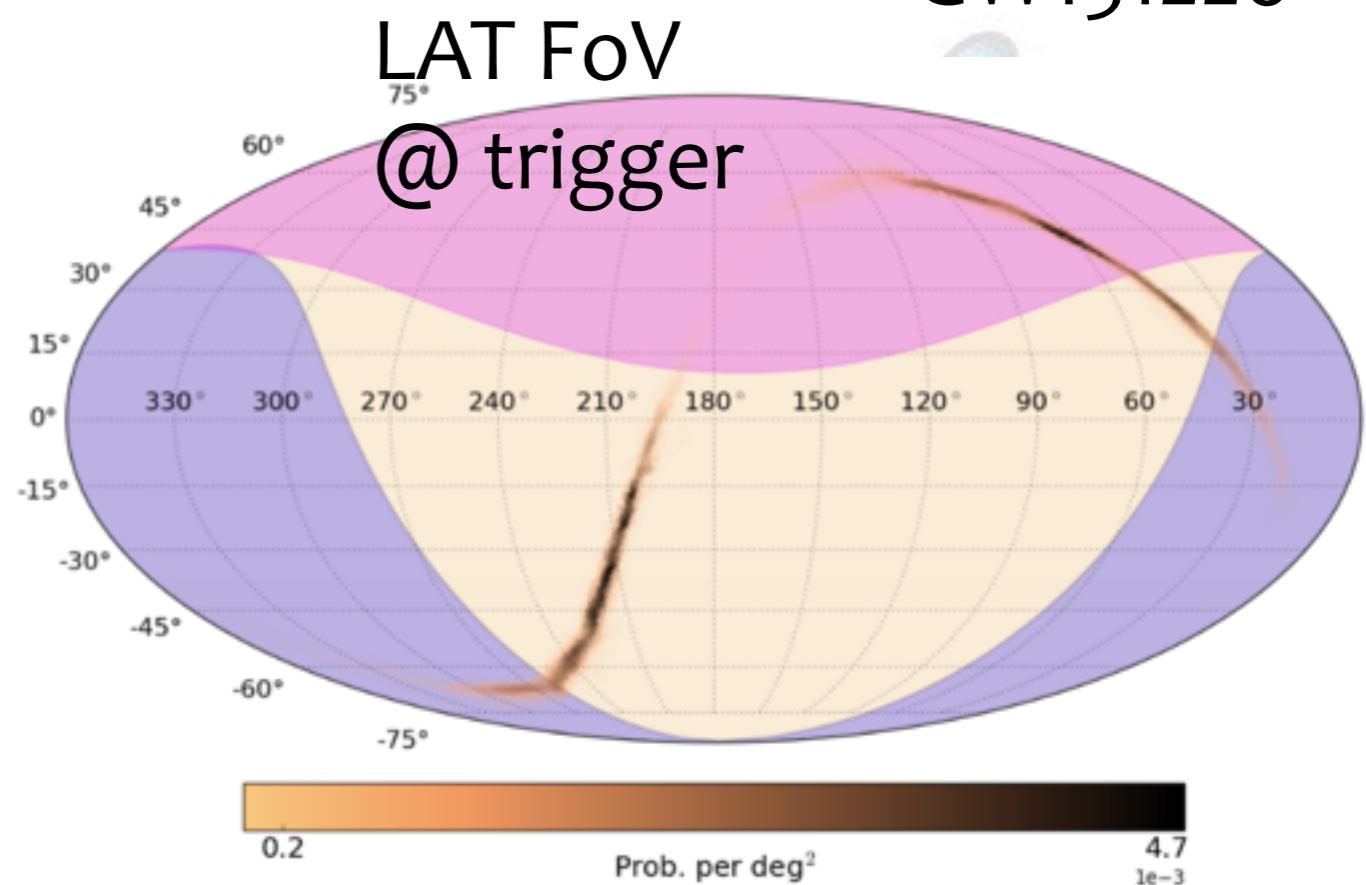


LVT151012



Gar
Spac

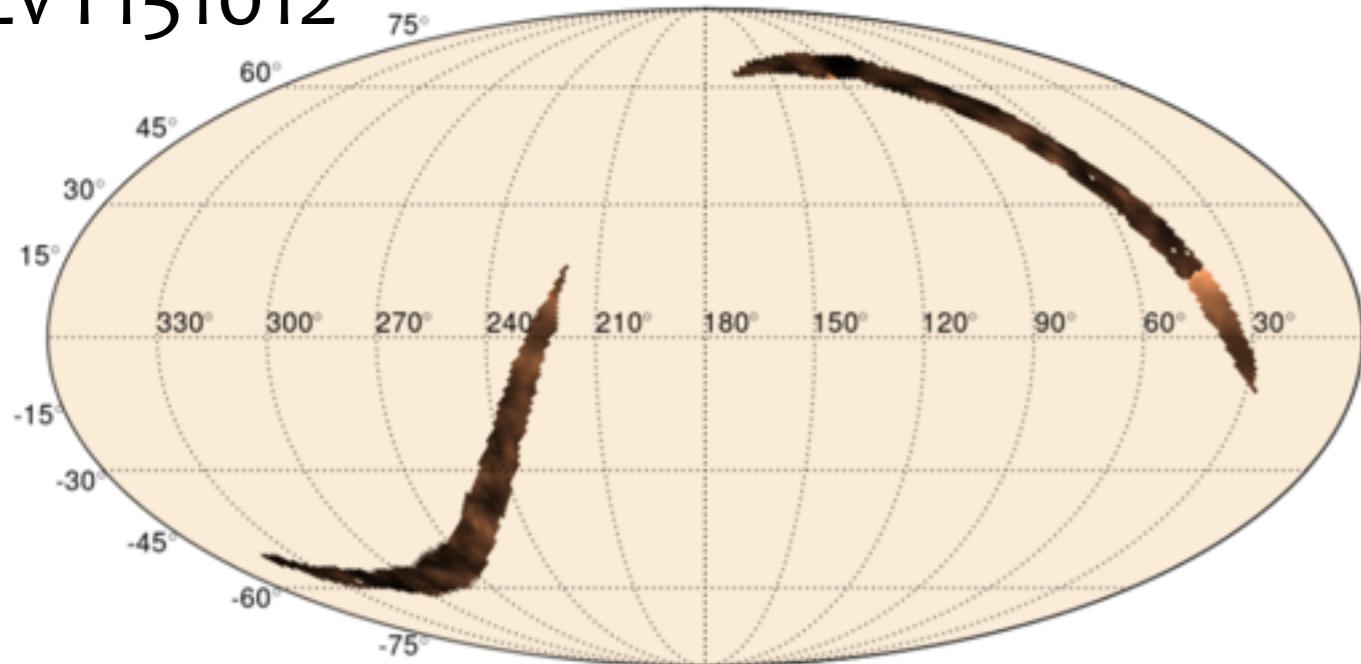
GW151226



Fermi-LAT Observations



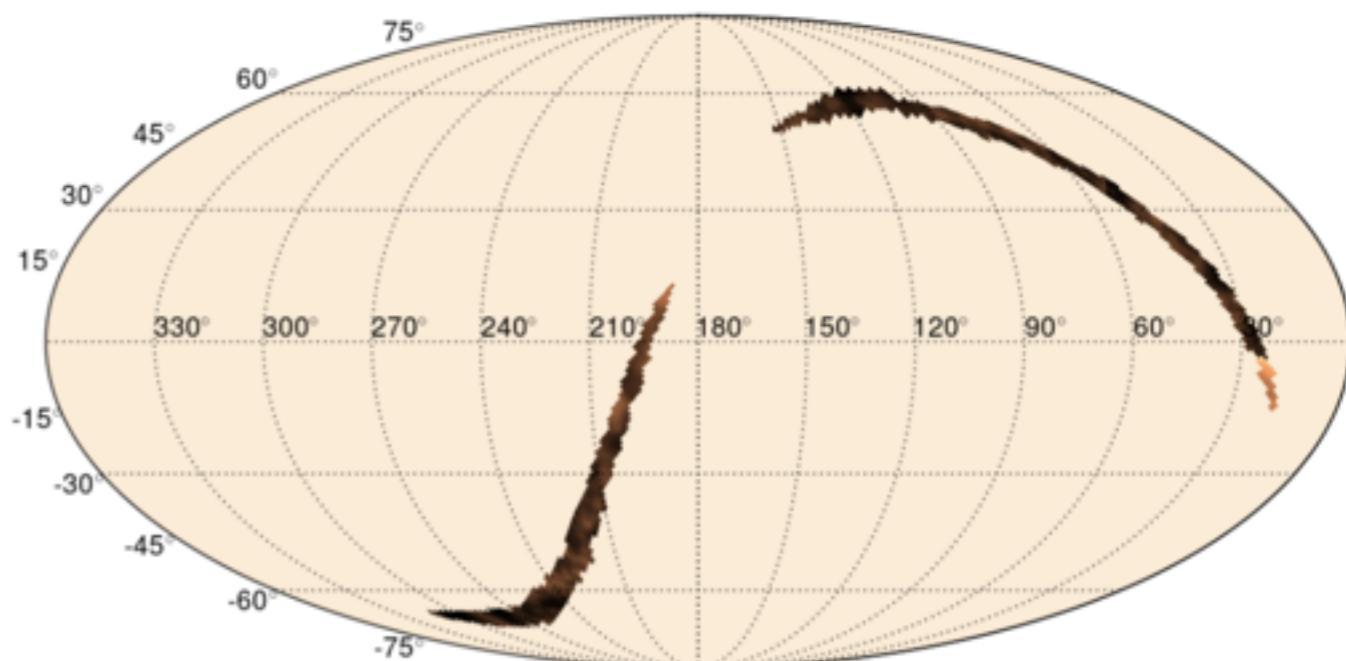
LVT151012



Upper limit (0.1-1 GeV) [10^{-10} erg cm $^{-2}$ s $^{-1}$]

2.1	119.2	236.3
-----	-------	-------

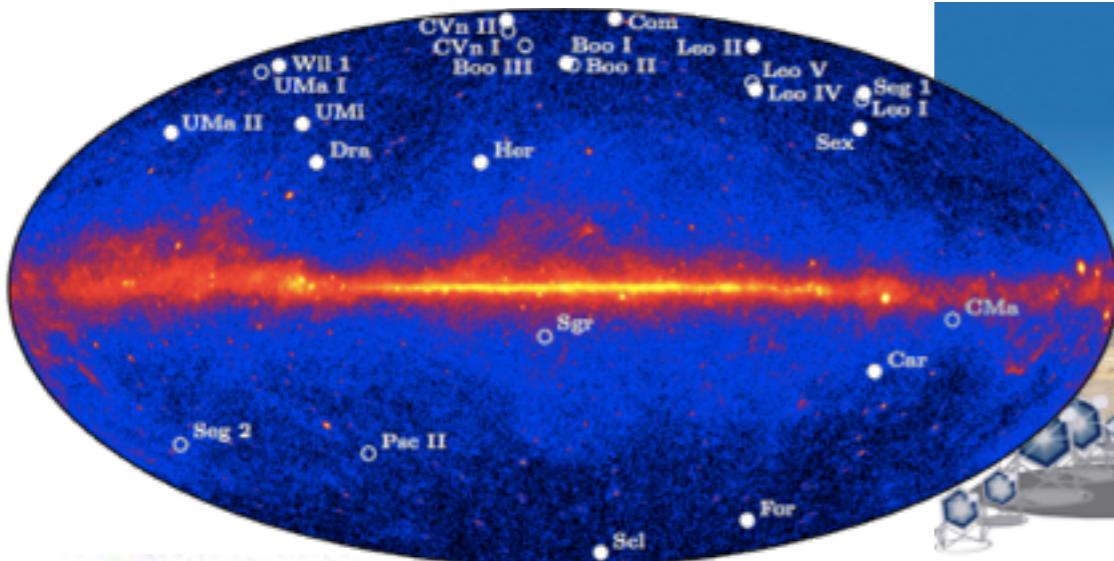
GW151226



No Significant Excess Found... Expectation for BH-BH mergers



The Future...



Astrophysics of Dark Matter (Special Dark)



DARK ENERGY SURVEY



33% of Fermi Sources are unassociated



GMT/TMT:
kinematics of dwarfs
J-factors



JWST:
gal. formation history



LSST:
more dwarfs

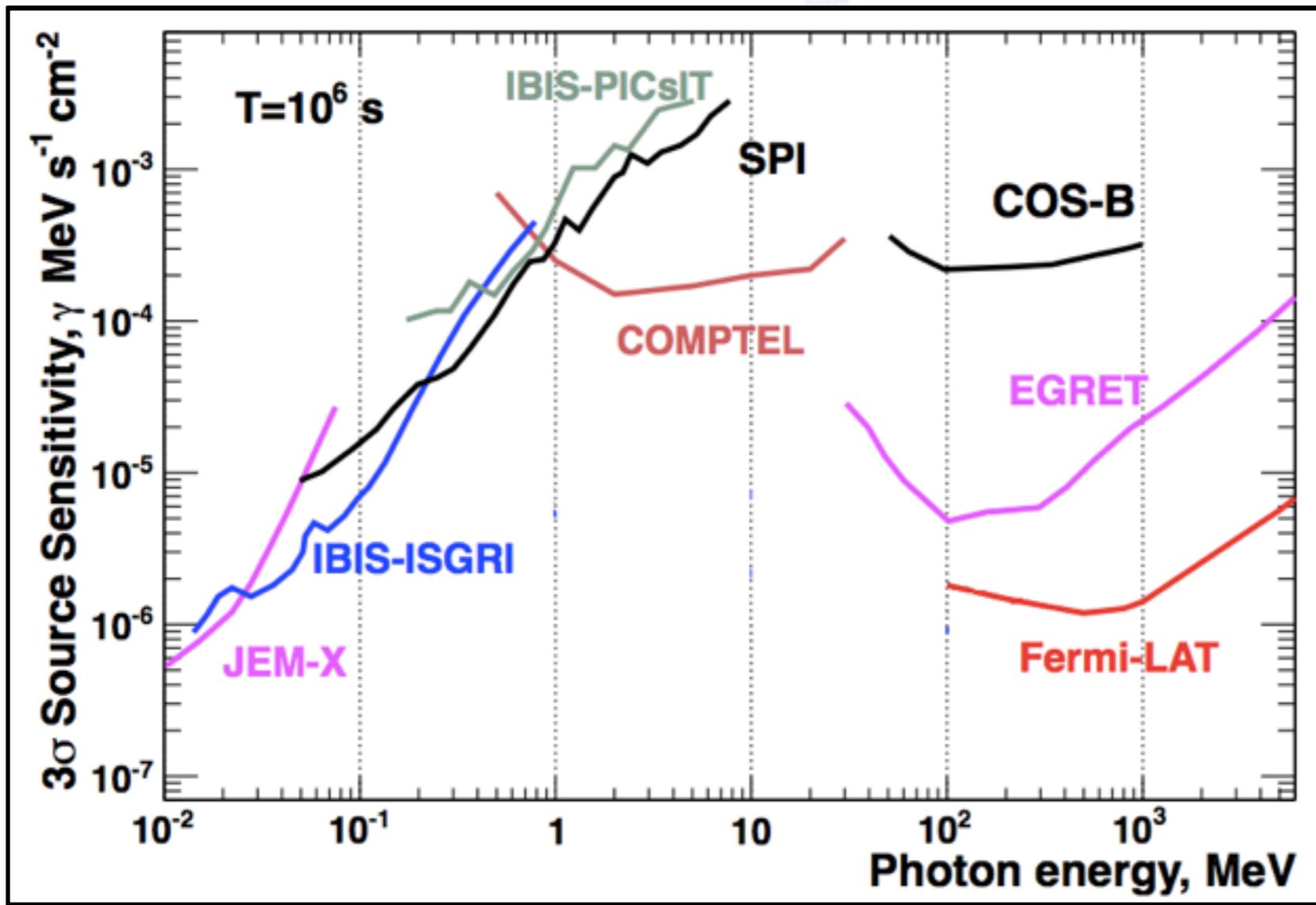


SKA:
Dark sub-halos
and HI





A Medium Energy Gamma-ray Observatory: AMEGO

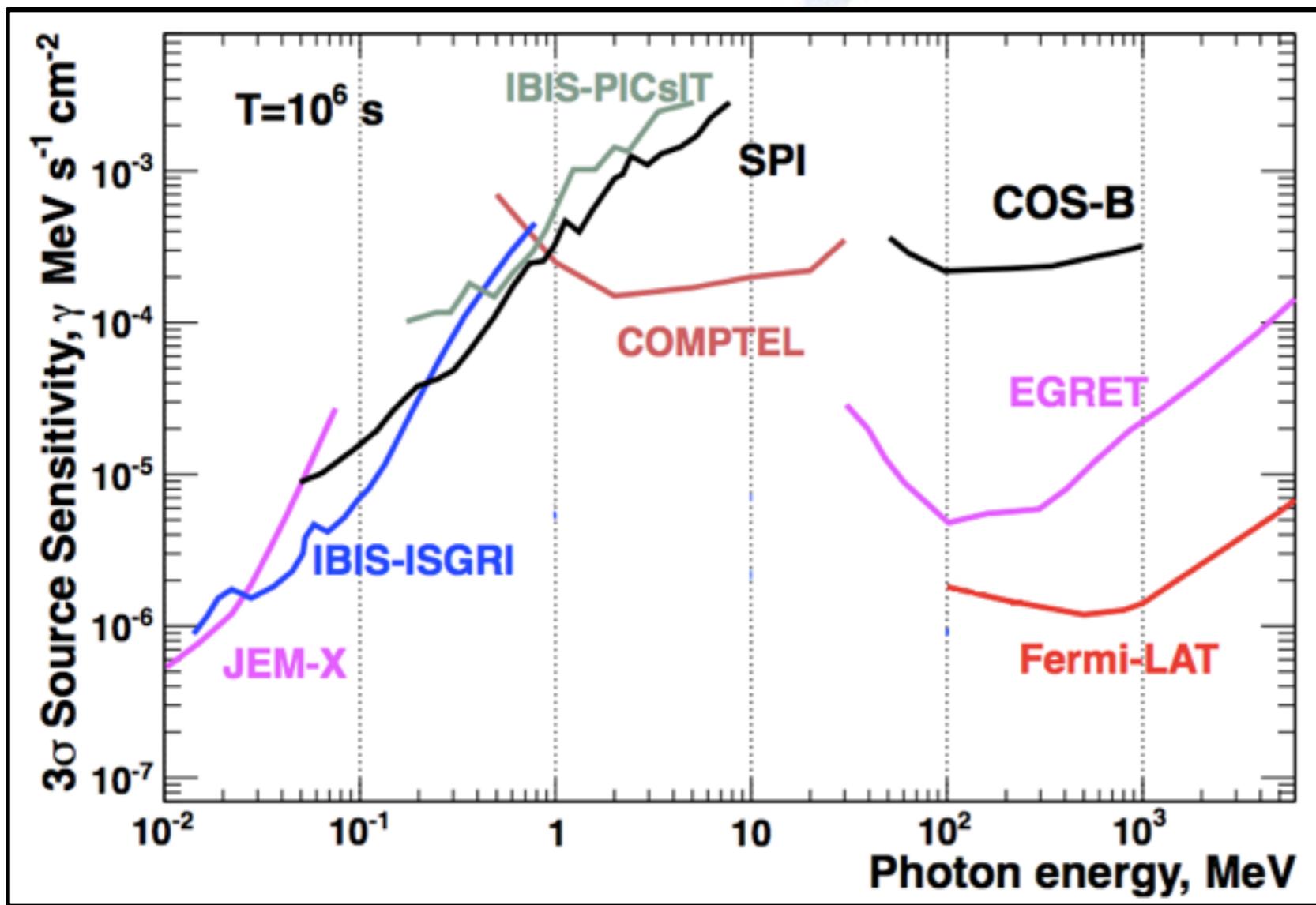


Intense Star formation at
GC necessitates
understanding of
the MeV rage

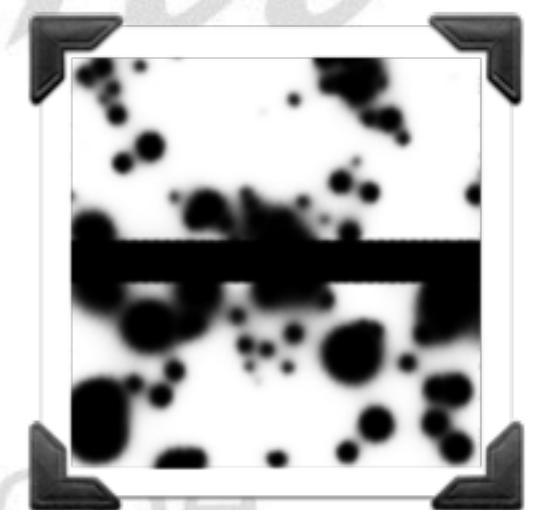
arXiv:1206.0772



A Medium Energy Gamma-ray Observatory: AMEGO



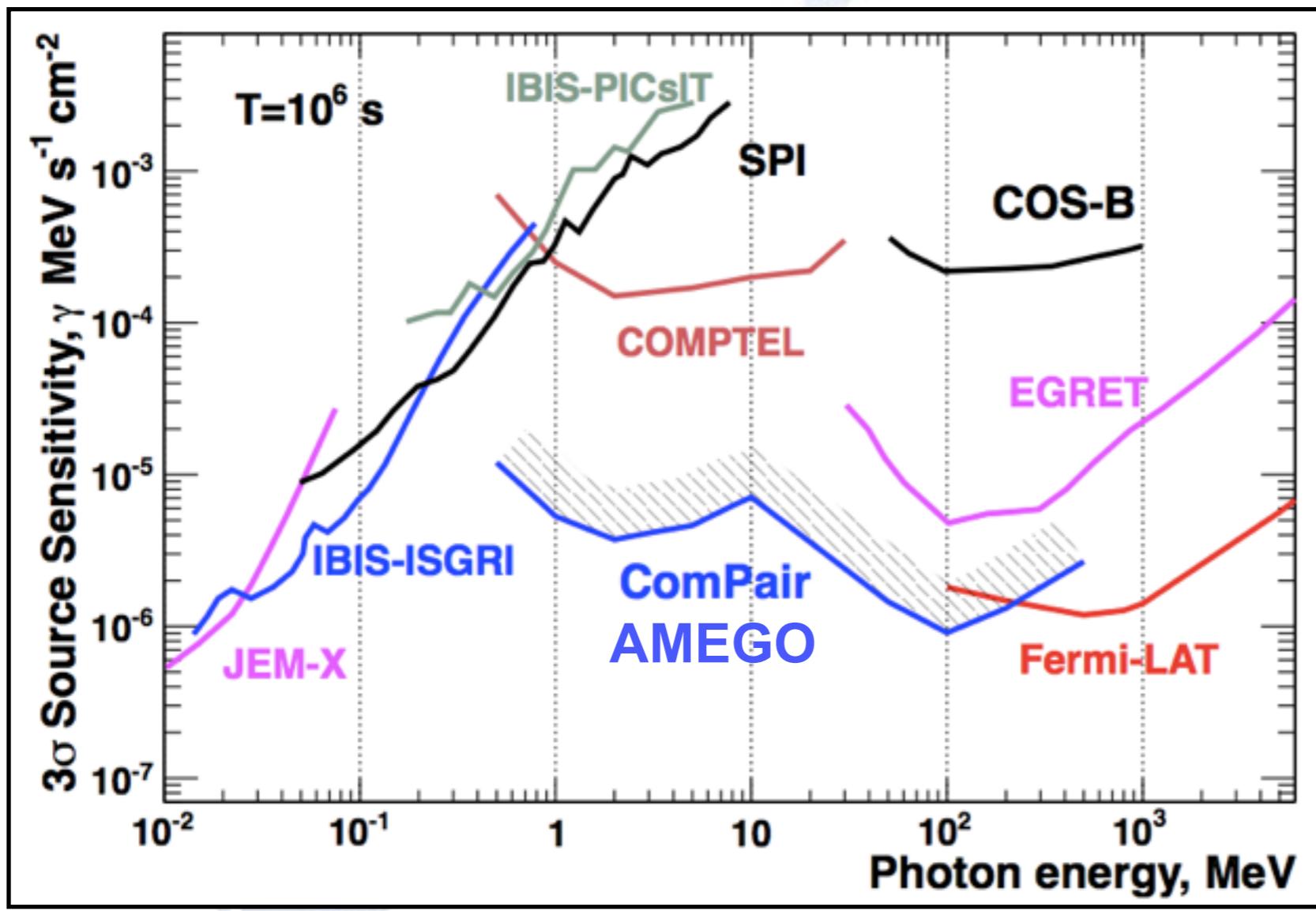
View of the
Galactic Plane



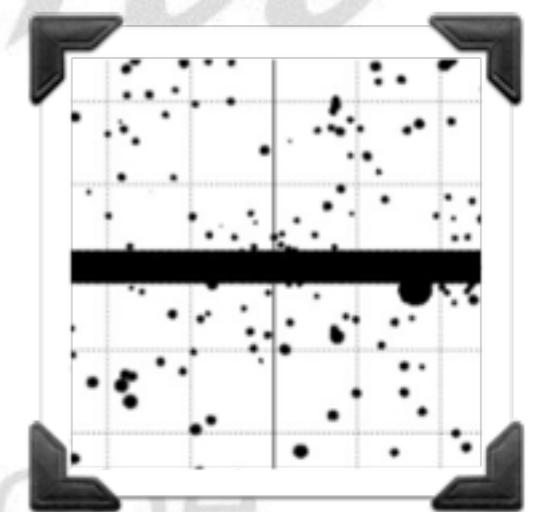
arXiv:1508.07349



A Medium Energy Gamma-ray Observatory: AMEGO



View of the
Galactic Plane



arXiv:1508.07349



- ***Fermi*-LAT is an excellent probe of particle Dark Matter**
 - Indirect detection is the only detection technique that searches for DM in astrophysical targets
 - The LAT provides the strongest constraints on thermal relic WIMPs and axions/ALPs
- ***Fermi*-LAT is an essential part of multi-messenger studies**
 - Astrophysical high energy neutrinos and cosmic rays
 - Catalogs provide a basis for connections
- **Gravitational Wave counterparts**
 - GBM the most prolific detector of sGRBs (~40 triggered per year, and 40-80 more in un-triggered ground sub-threshold searches)
 - LAT is the only instrument capable of detecting GRB afterglows over the entire sky during normal survey operations



Thank you!

Fermi
Gamma-ray
Space Telescope