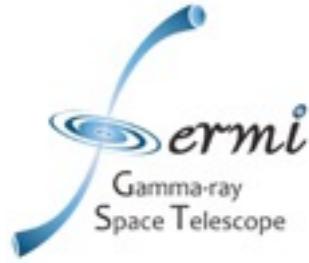


Fermi
Gamma-ray Space Telescope

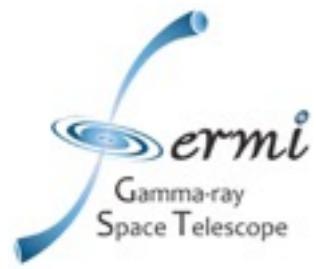


Recent Searches for Dark Matter with the Fermi-LAT

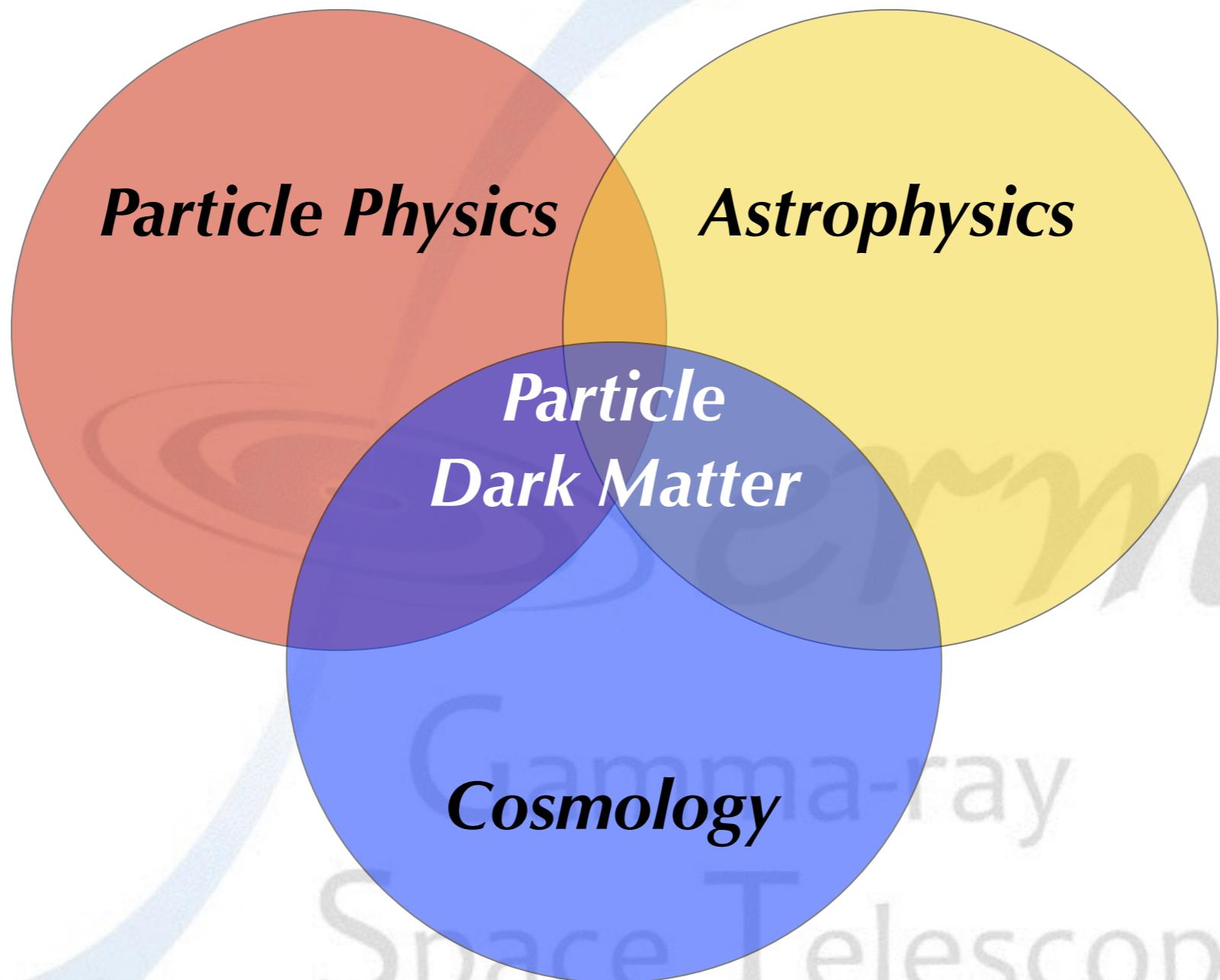
R. Caputo, UCSC
on behalf of the
Fermi-LAT Collaboration

ICHEP 2016
Chicago, IL



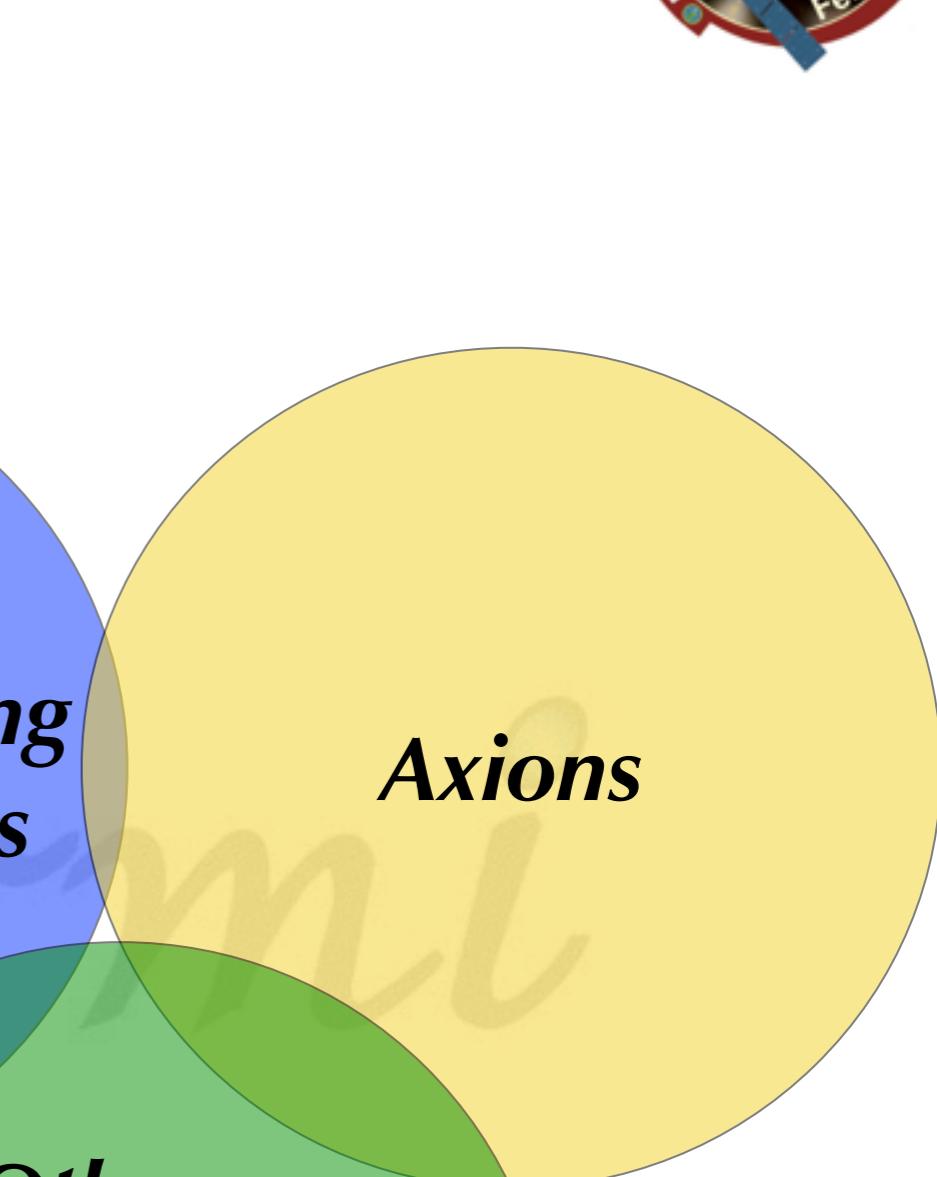
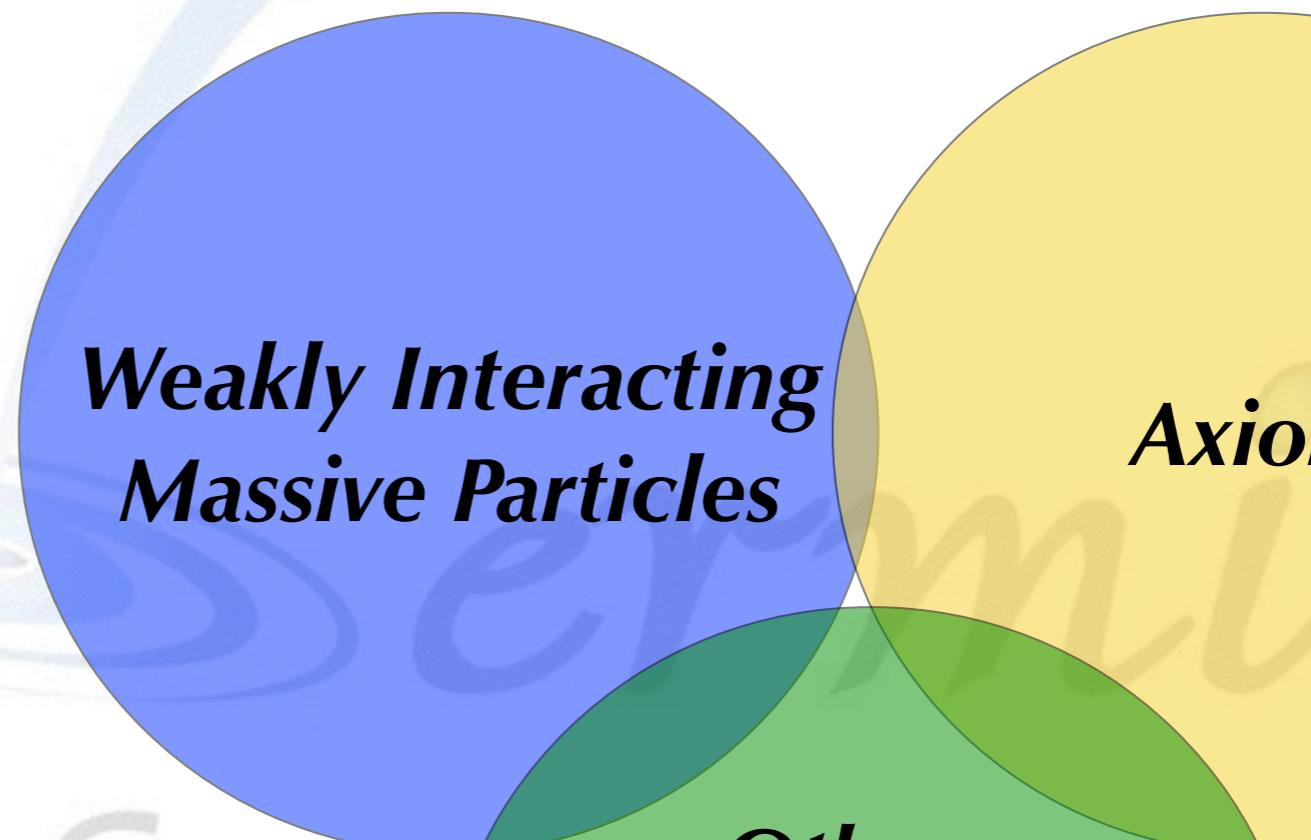


Joint Dark Matter, Particle Astrophysics and Cosmology



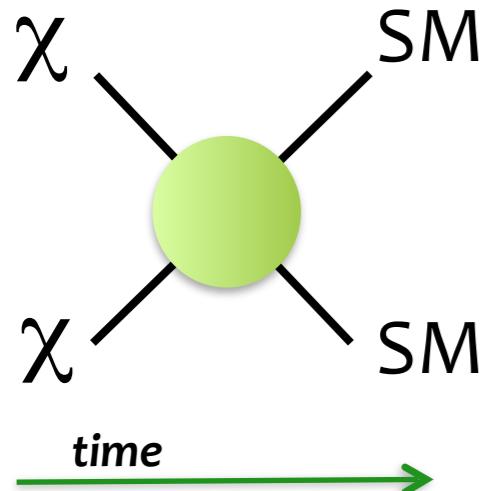


Potential Candidates



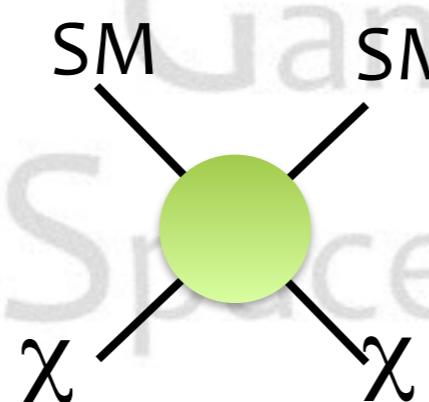


Detecting Particle Dark Matter

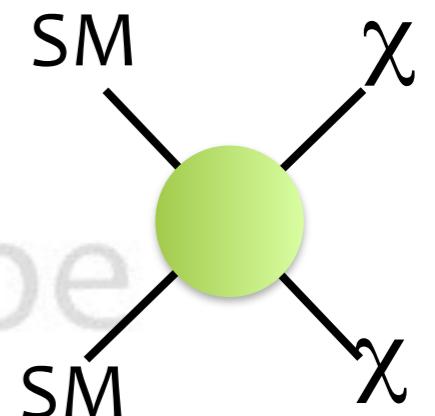


Indirect Detection

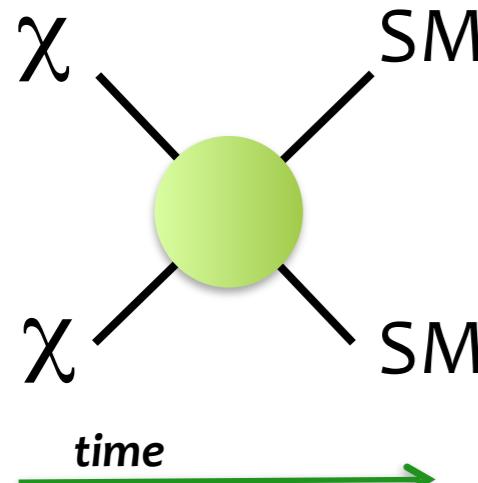
Direct Detection



Collider



Detecting Particle Dark Matter

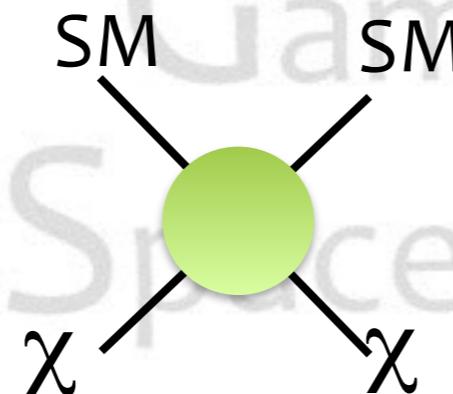


Indirect Detection

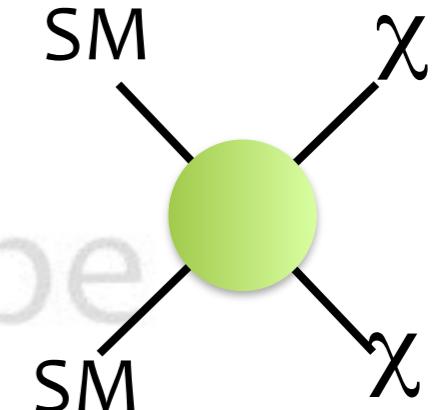
information about mass,
point back to source

| SM: | | | |
|--------------|-------------------------------|---------------------------------|----------------------------------|
| mass → | $\approx 2.3 \text{ MeV}/c^2$ | $\approx 1.275 \text{ GeV}/c^2$ | $\approx 173.07 \text{ GeV}/c^2$ |
| charge → | 2/3 | 2/3 | 2/3 |
| spin → | 1/2 | 1/2 | 1/2 |
| | u | c | t |
| | up | charm | top |
| QUARKS | d | s | b |
| | down | strange | bottom |
| | $\approx 4.8 \text{ MeV}/c^2$ | $\approx 95 \text{ MeV}/c^2$ | $\approx 4.18 \text{ GeV}/c^2$ |
| | -1/3 | -1/3 | -1/3 |
| | 1/2 | 1/2 | 1/2 |
| | e | μ | τ |
| | electron | muon | tau |
| LEPTONS | ν_e | ν_μ | ν_τ |
| | electron neutrino | muon neutrino | tau neutrino |
| | $0.511 \text{ MeV}/c^2$ | $105.7 \text{ MeV}/c^2$ | $1.777 \text{ GeV}/c^2$ |
| | -1 | -1 | -1 |
| | 1/2 | 1/2 | 1/2 |
| Gauge Bosons | Z | Z boson | W |
| | $91.2 \text{ GeV}/c^2$ | $80.4 \text{ GeV}/c^2$ | $80.4 \text{ GeV}/c^2$ |
| | 0 | 0 | +1 |
| | 1 | 1 | 1 |
| | γ | photon | W boson |

Direct Detection

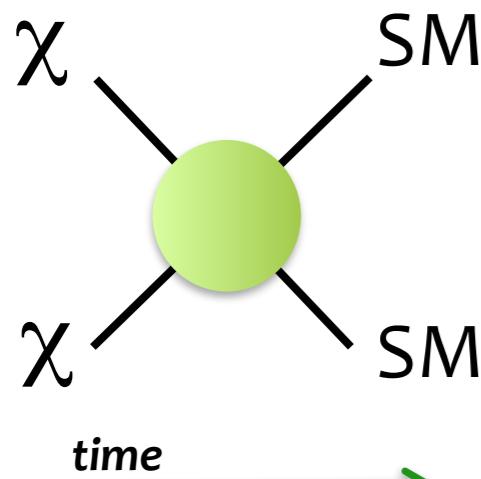


Collider



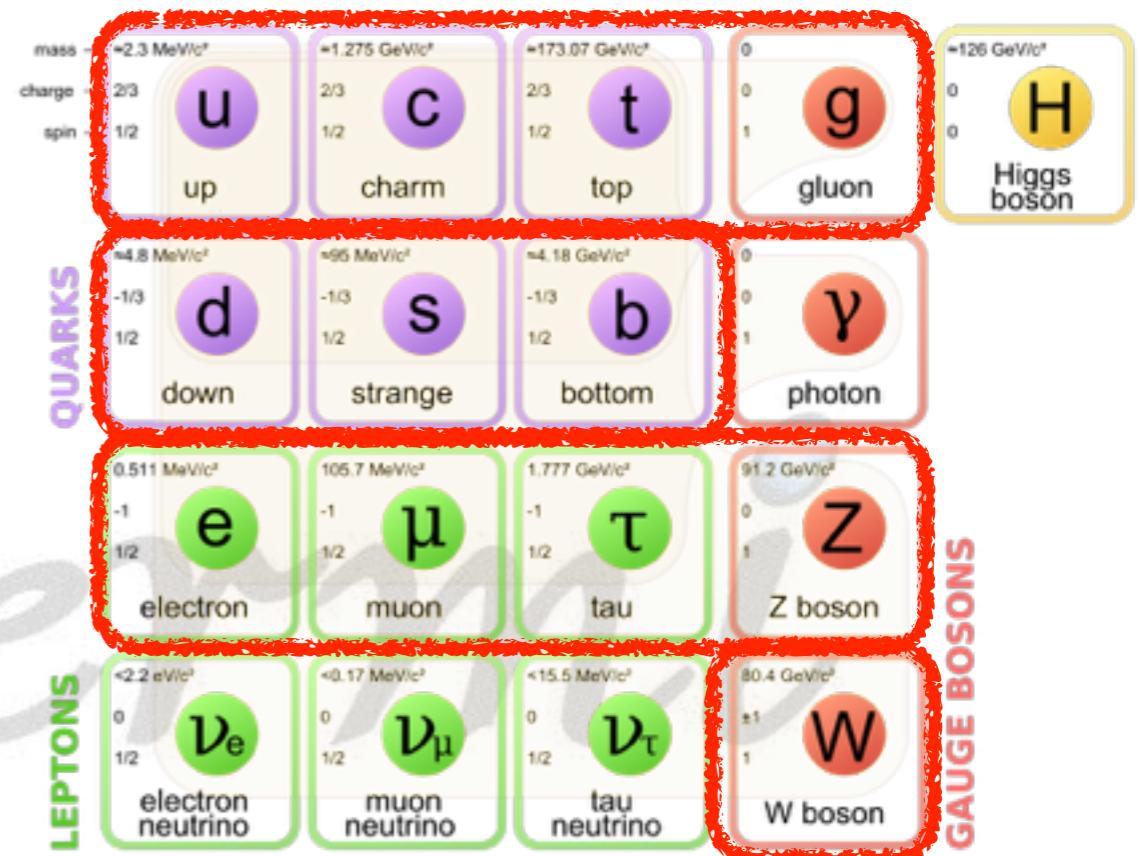


Detecting Particle Dark Matter

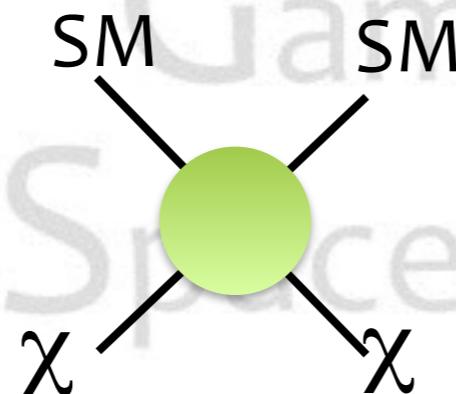


Indirect Detection

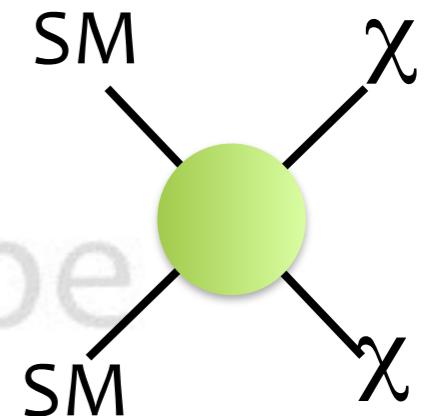
information about mass,
point back to source
eventually can get
to photons



Direct Detection

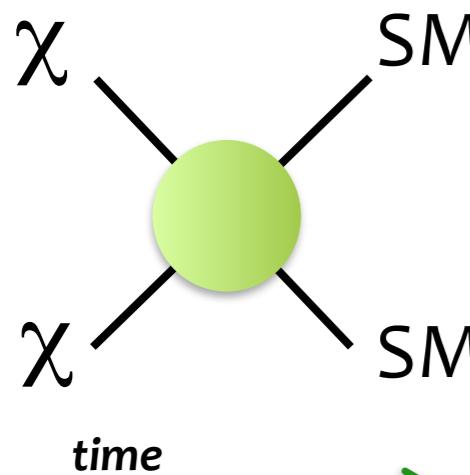


Collider



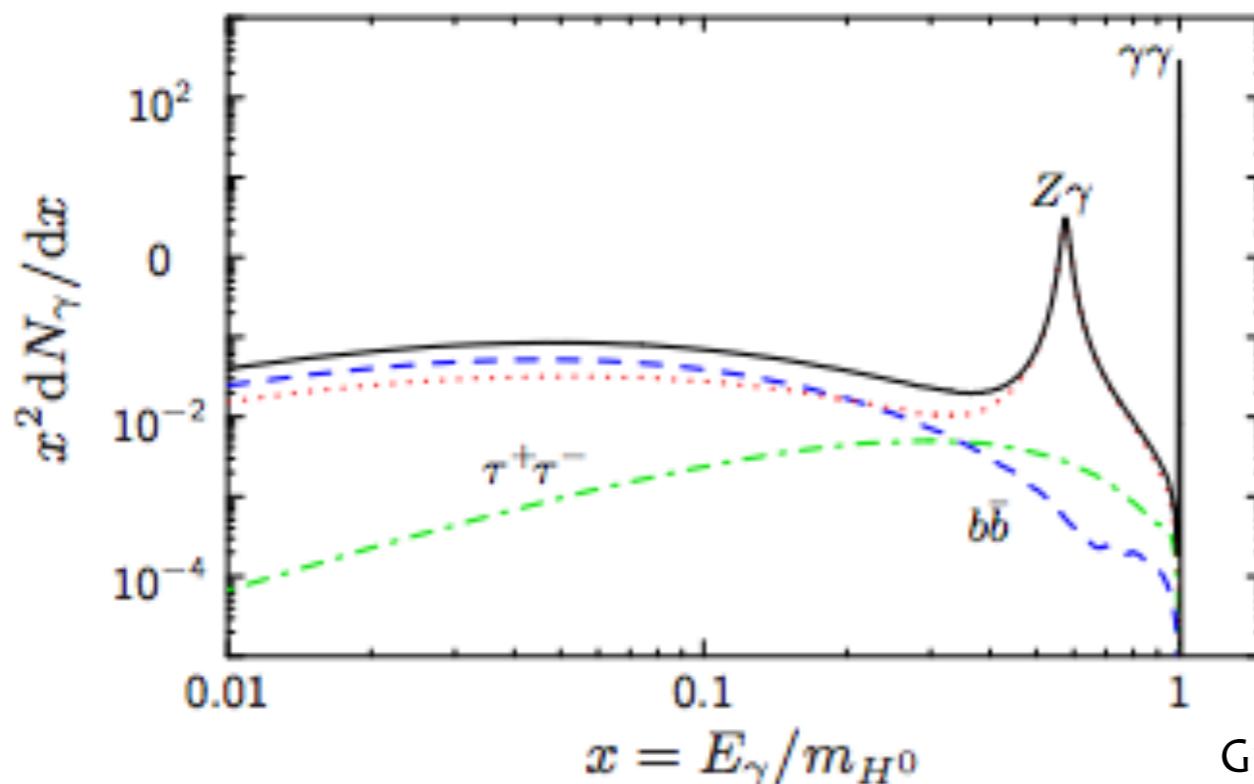


Detecting Particle Dark Matter



Indirect Detection

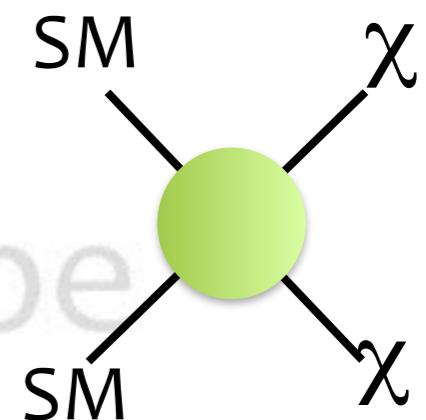
information about mass,
point back to source
eventually can get
to photons



SM:

| | | | | | |
|----------------|--|---|--|---|---|
| LEPTONS | mass - $\approx 2.3 \text{ MeV}/c^2$ charge - 2/3 spin - 1/2 up | mass - $\approx 1.275 \text{ GeV}/c^2$ charge - 2/3 spin - 1/2 charm | mass - $\approx 173.07 \text{ GeV}/c^2$ charge - 2/3 spin - 1/2 top | mass - 0 charge - 0 spin - 1 gluon | mass - $\approx 126 \text{ GeV}/c^2$ charge - 0 spin - 0 Higgs boson |
| QUARKS | mass - $\approx 4.8 \text{ MeV}/c^2$ charge - -1/3 spin - 1/2 down | mass - $\approx 95 \text{ MeV}/c^2$ charge - -1/3 spin - 1/2 strange | mass - $\approx 4,18 \text{ GeV}/c^2$ charge - -1/3 spin - 1/2 bottom | mass - 0 charge - 0 spin - 1 photon | |
| | mass - $0.511 \text{ MeV}/c^2$ charge - -1 spin - 1/2 electron | mass - $105.7 \text{ MeV}/c^2$ charge - -1 spin - 1/2 muon | mass - $1.777 \text{ GeV}/c^2$ charge - -1 spin - 1/2 tau | mass - $91.2 \text{ GeV}/c^2$ charge - 0 spin - 1 Z boson | |
| | mass - $< 2.2 \text{ eV}/c^2$ charge - 0 spin - 1/2 electron neutrino | mass - $< 0.17 \text{ MeV}/c^2$ charge - 0 spin - 1/2 muon neutrino | mass - $< 15.5 \text{ MeV}/c^2$ charge - 0 spin - 1/2 tau neutrino | mass - $80.4 \text{ GeV}/c^2$ charge - ±1 spin - 1 W boson | GAUGE BOSONS |

Collider



Gustafsson et al.
PRL 99.041301



Indirect Searches: γ -rays



Observed =



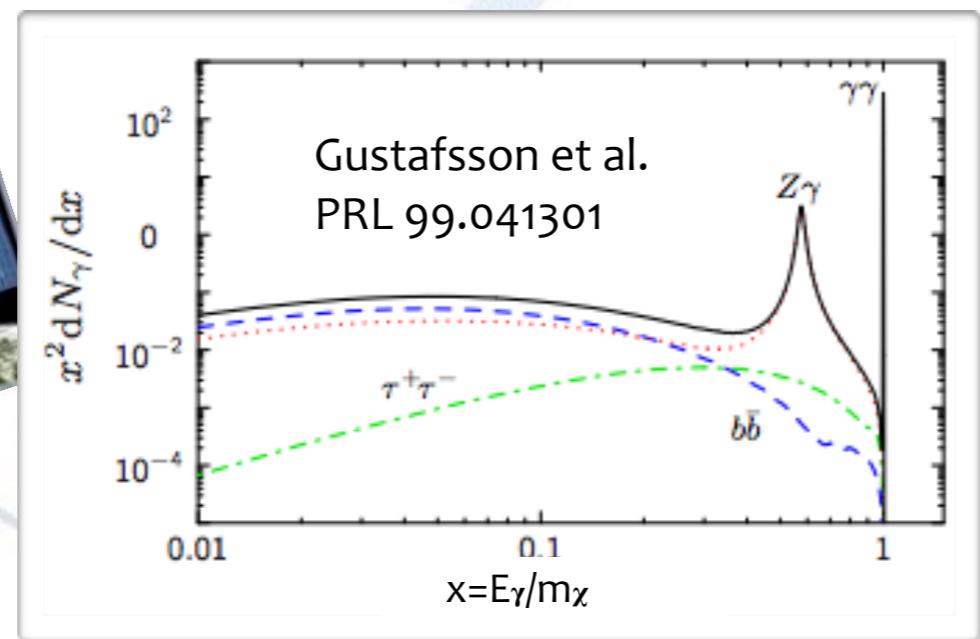
$$\Phi_\gamma(E, \psi) =$$

Gamma-ray
Space Telescope

Indirect Searches: γ -rays



Observed = Particle Properties \times



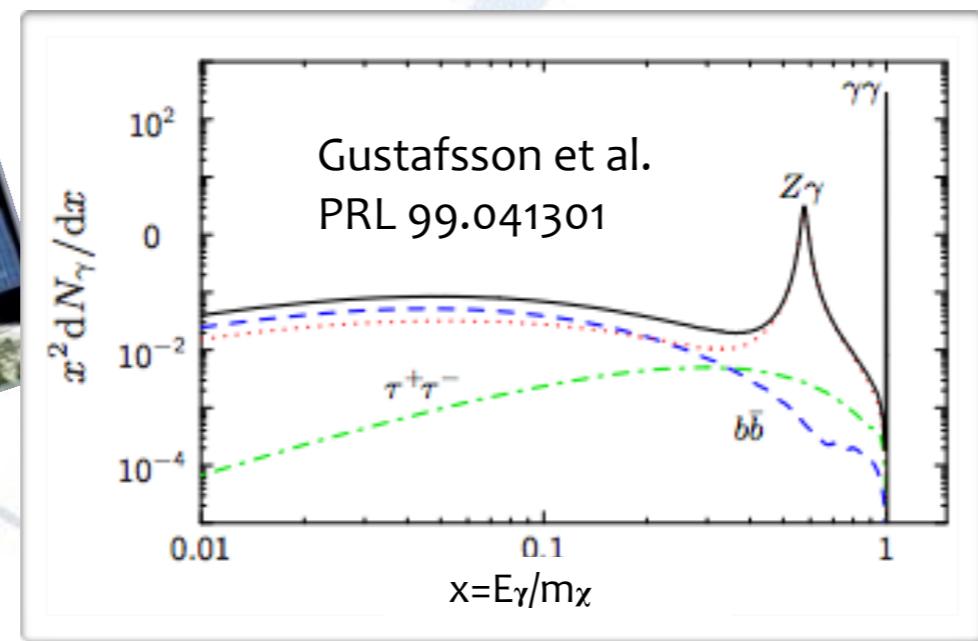
$$\Phi_\gamma(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_\chi v \rangle}{2m_\chi^2} N_\gamma(E)$$

Space Telescope

Indirect Searches: γ -rays



Observed = Particle Properties \times



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

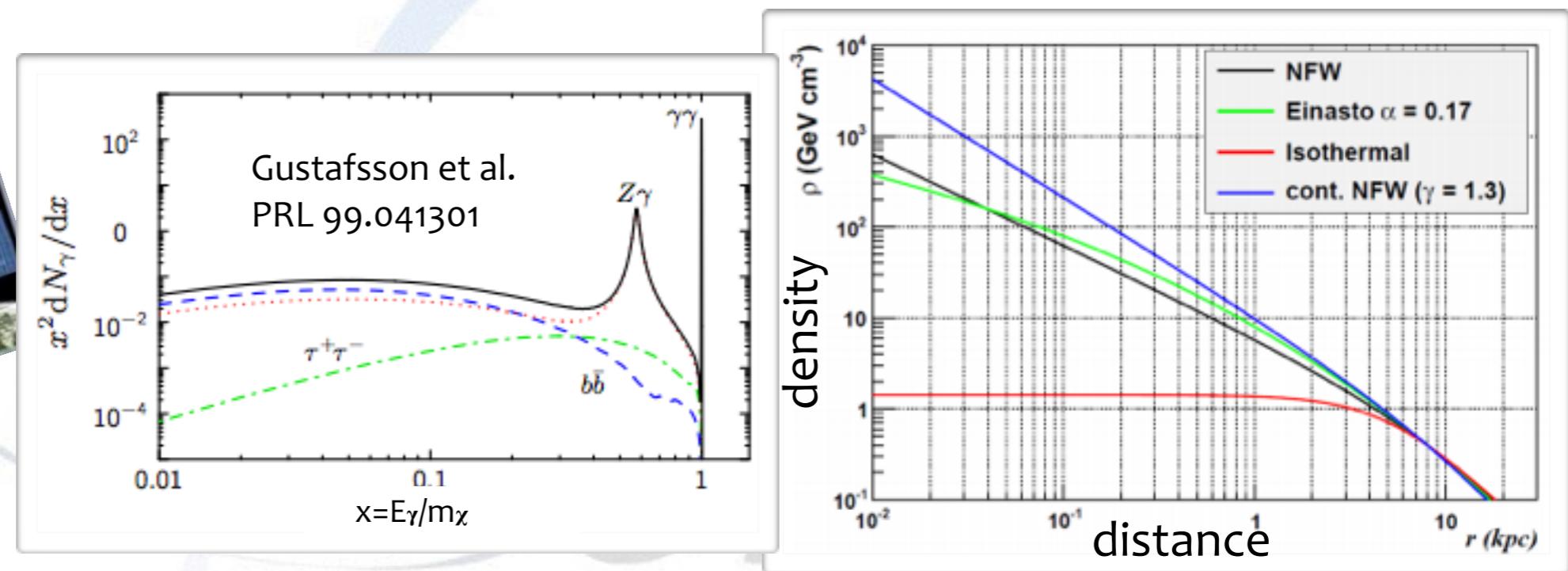
cross section
mass
photons



Indirect Searches: γ -rays



$$\text{Observed} = \text{Particle Properties} \times \text{Astrophysics Properties}$$



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

cross section

mass

photons

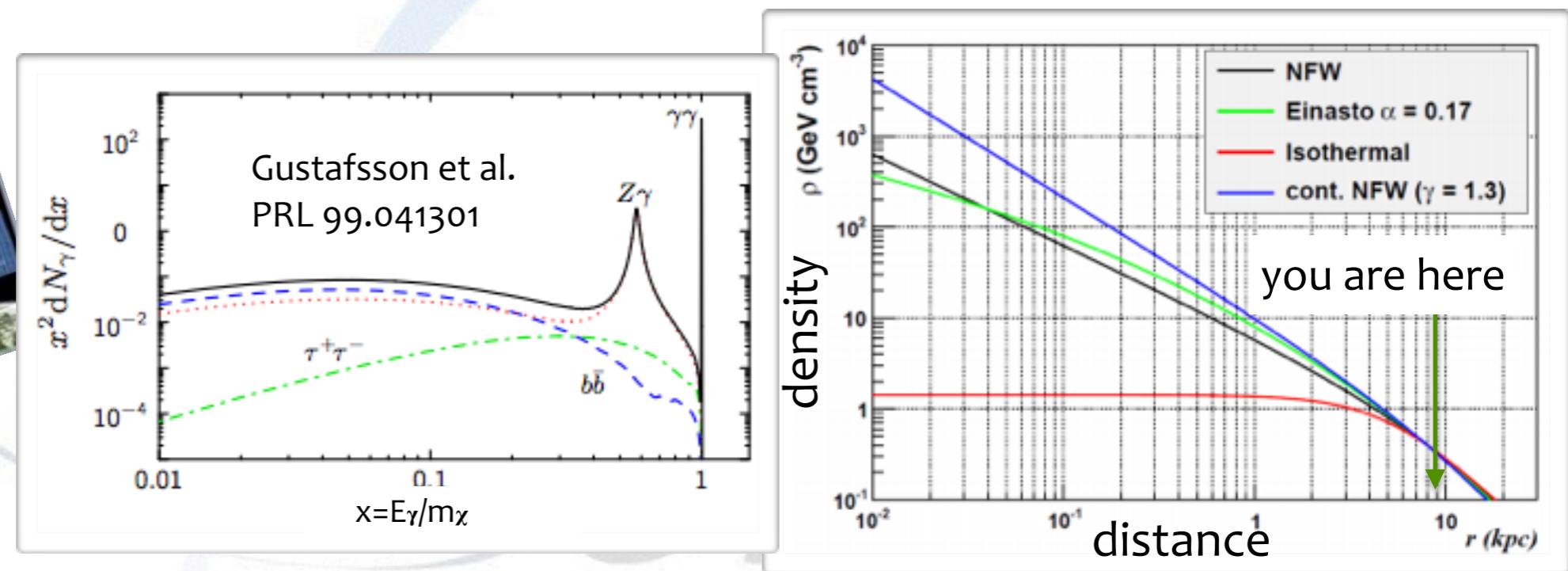
J-Factor: $\sim \int \rho^2$
(solid angle,
line of sight)



Indirect Searches: γ -rays



$$\text{Observed} = \text{Particle Properties} \times \text{Astrophysics Properties}$$



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

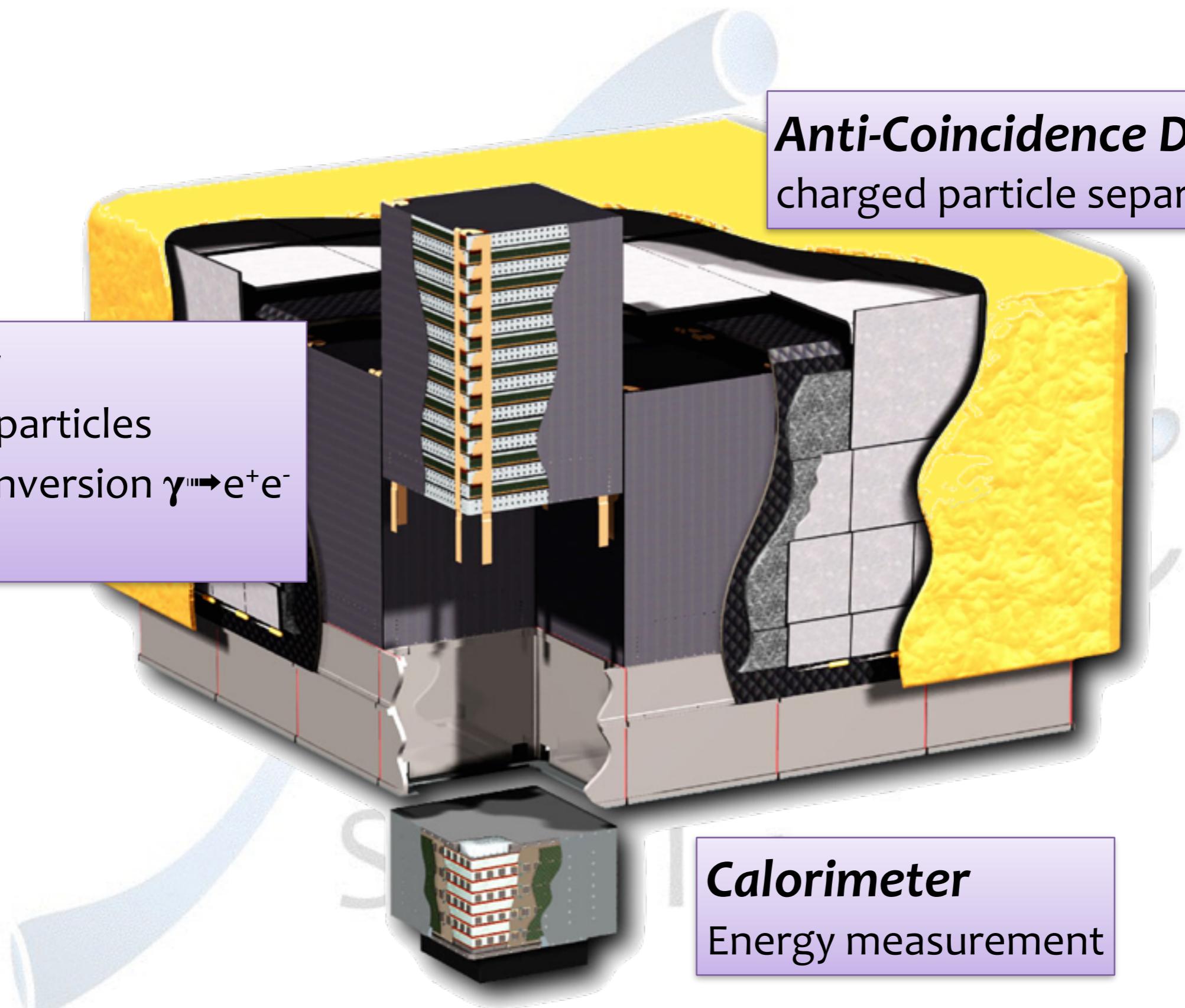
cross section

mass

photons

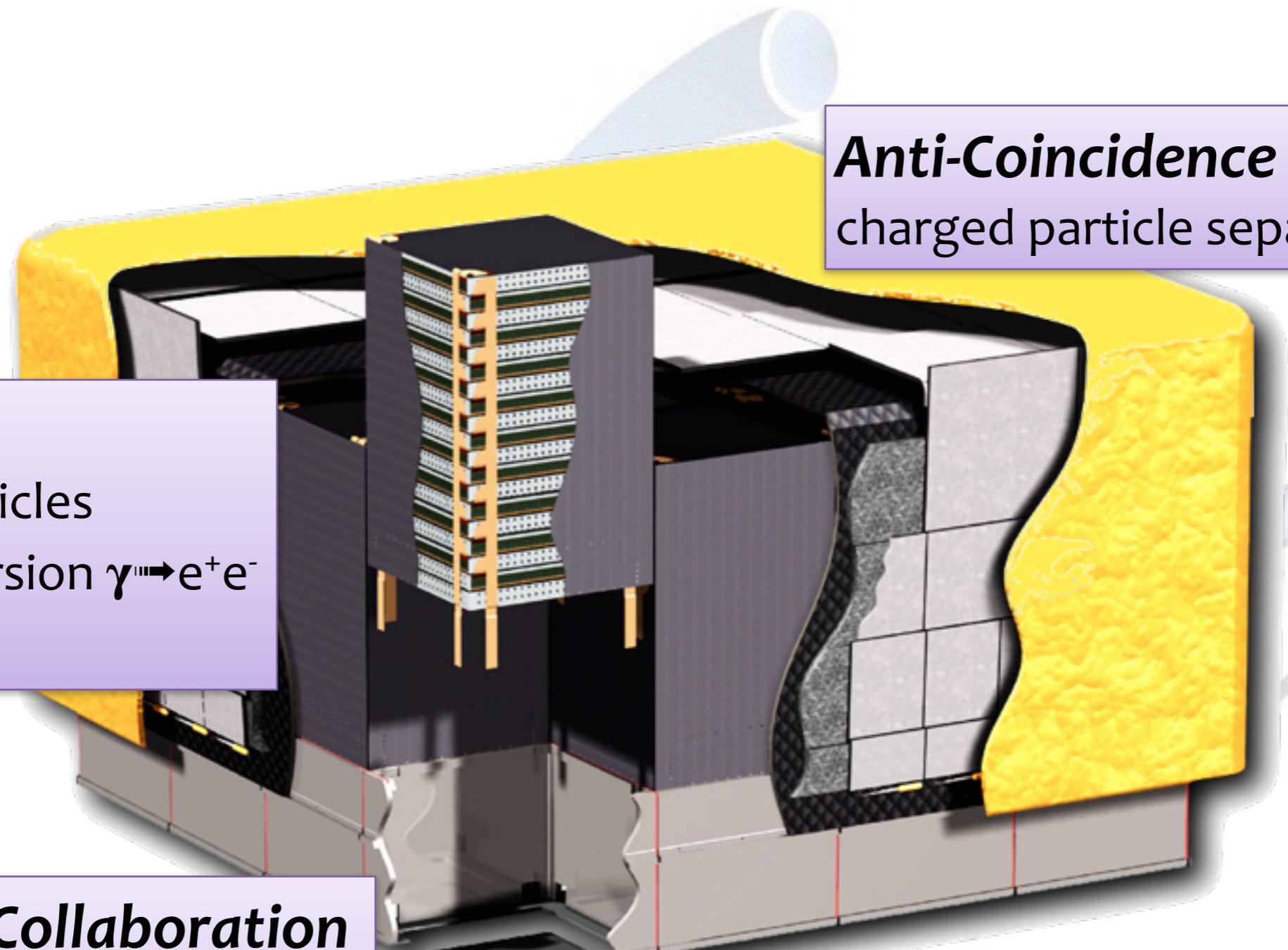
J-Factor: $\sim \int \rho^2$
(solid angle,
line of sight)

Fermi Gamma-Ray Space Telescope





Fermi Gamma-Ray Space Telescope



Tracker

charged particles

cause conversion $\gamma \rightarrow e^+e^-$

direction

Fermi LAT Collaboration

~400 Scientific Members

NASA/DOE & International

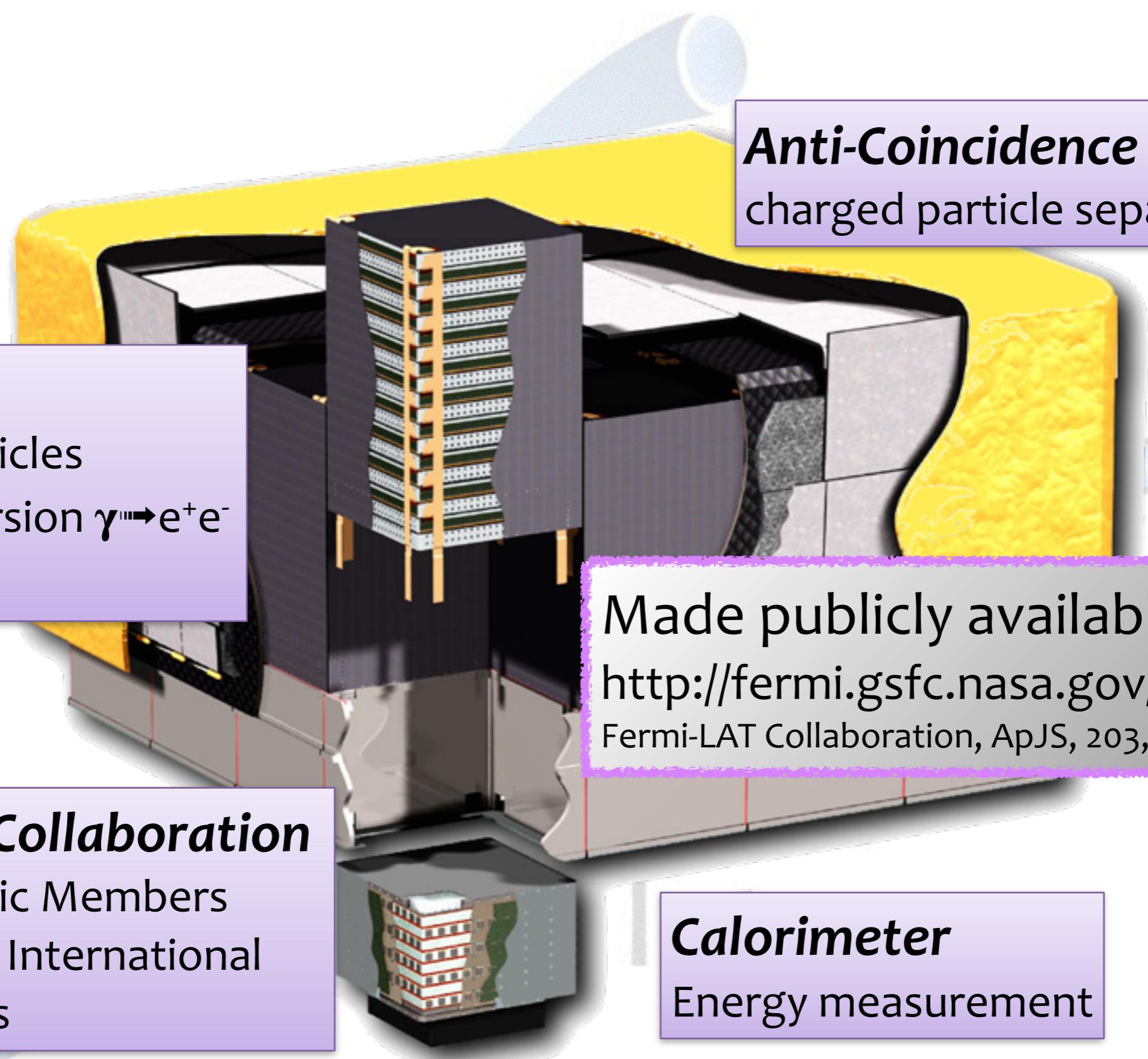
Contributions

Anti-Coincidence Detector
charged particle separation

Calorimeter
Energy measurement



Fermi Gamma-Ray Space Telescope



Tracker

charged particles

cause conversion $\gamma \rightarrow e^+e^-$

direction

Anti-Coincidence Detector
charged particle separation

Made publicly available ~24 h
<http://fermi.gsfc.nasa.gov/ssc/data/>
Fermi-LAT Collaboration, ApJS, 203, 4 (2012)

Fermi LAT Collaboration

~400 Scientific Members

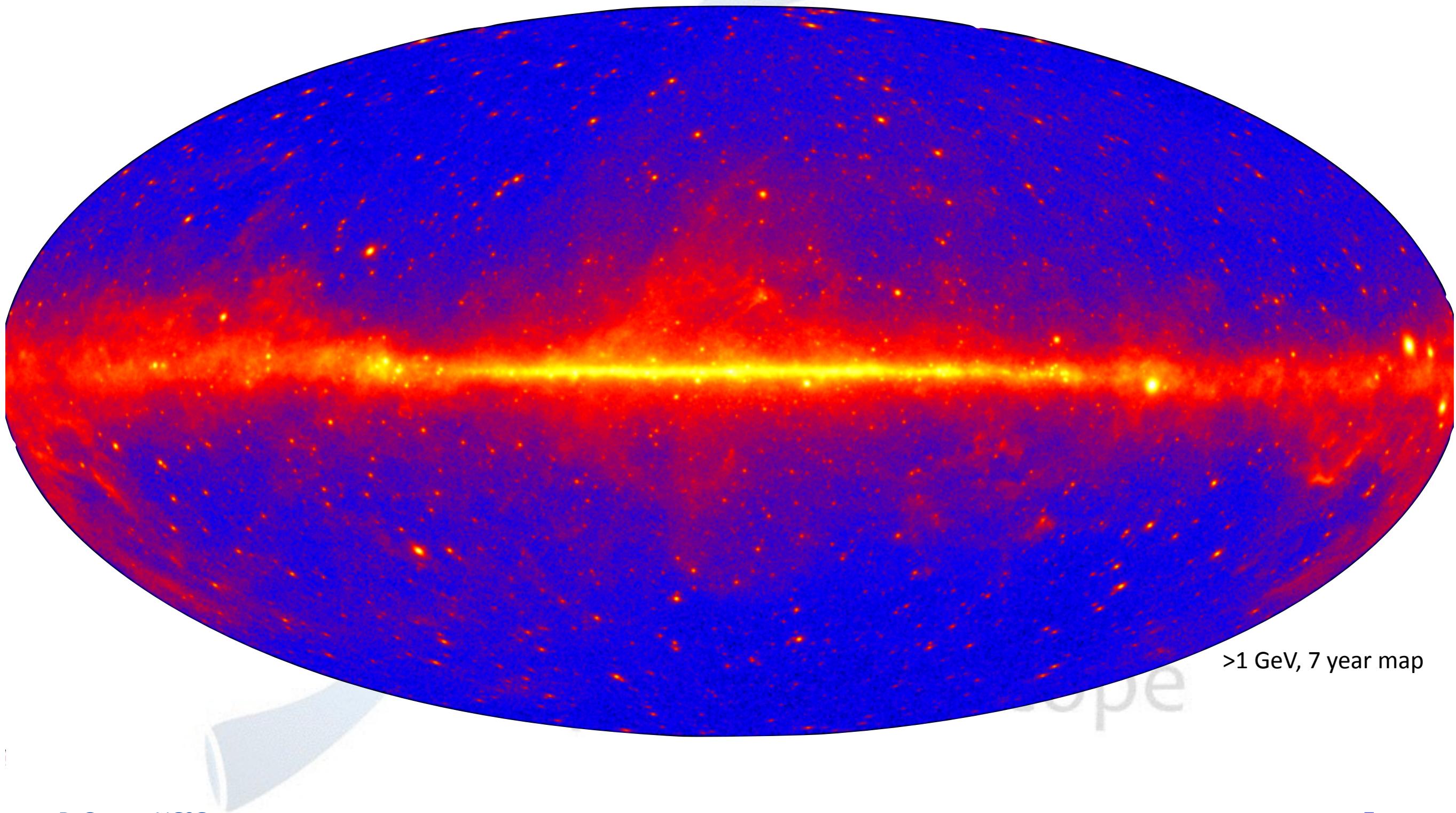
NASA/DOE & International

Contributions

Calorimeter
Energy measurement

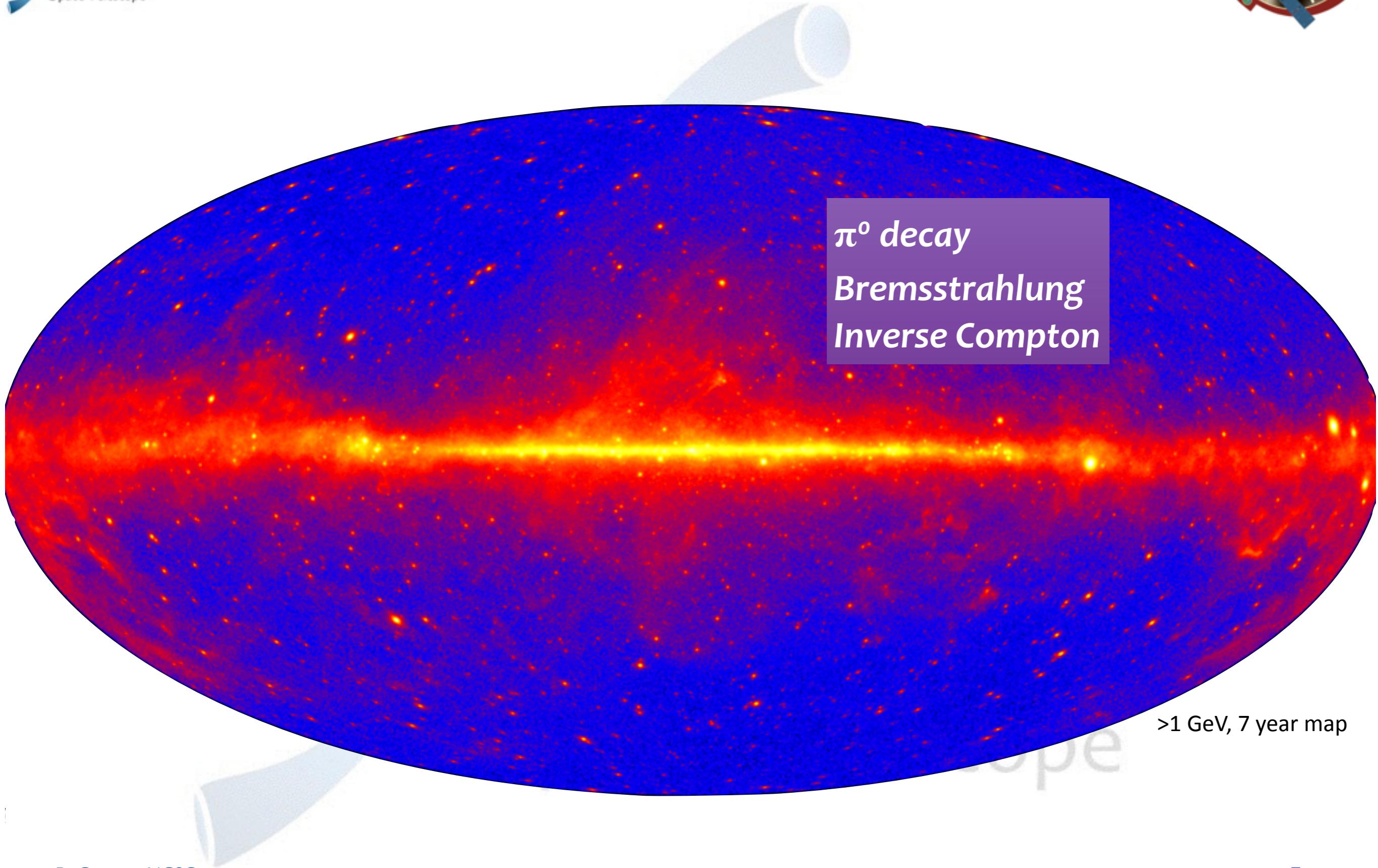


Fermi-LAT γ -ray sky

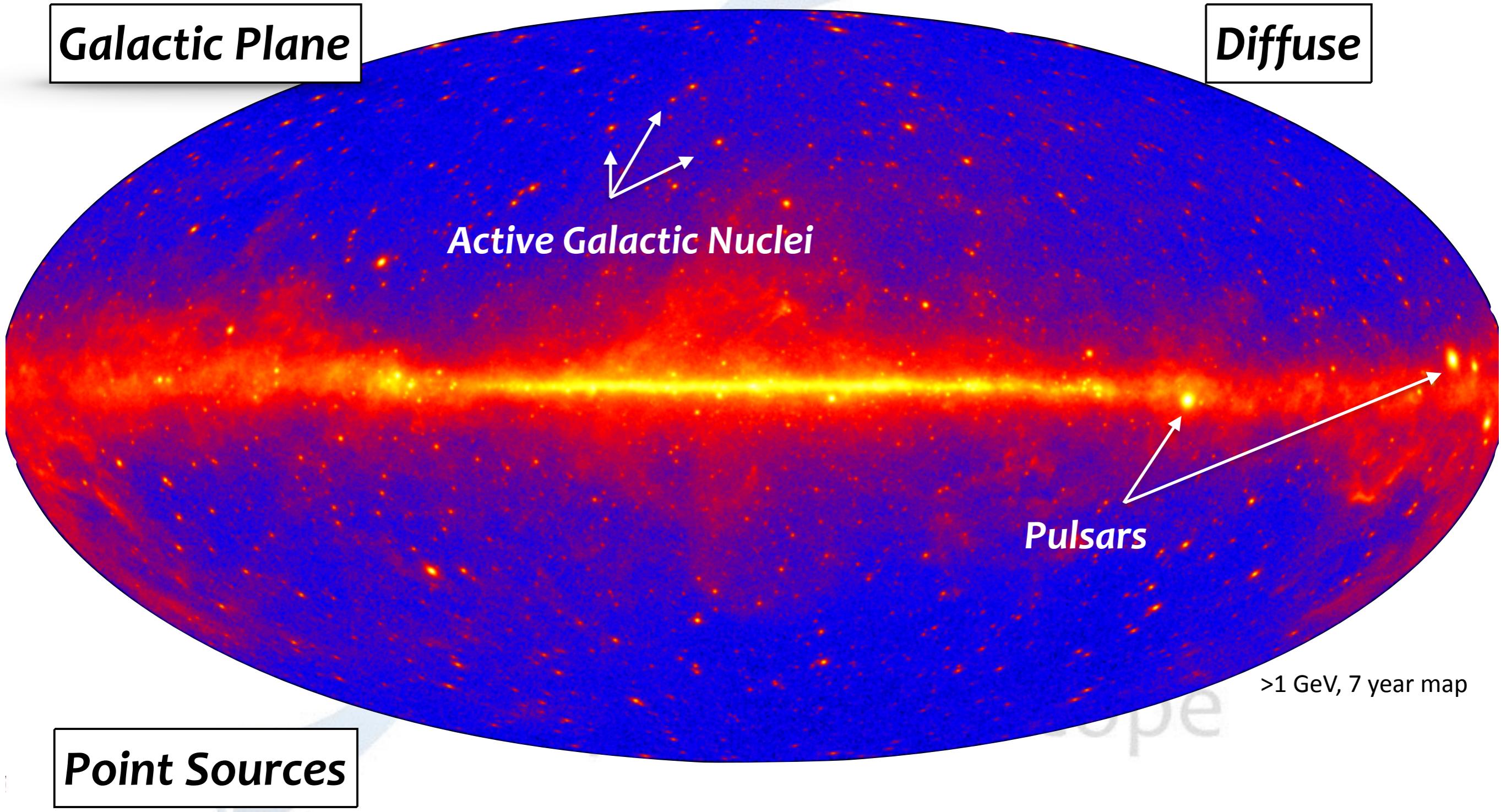




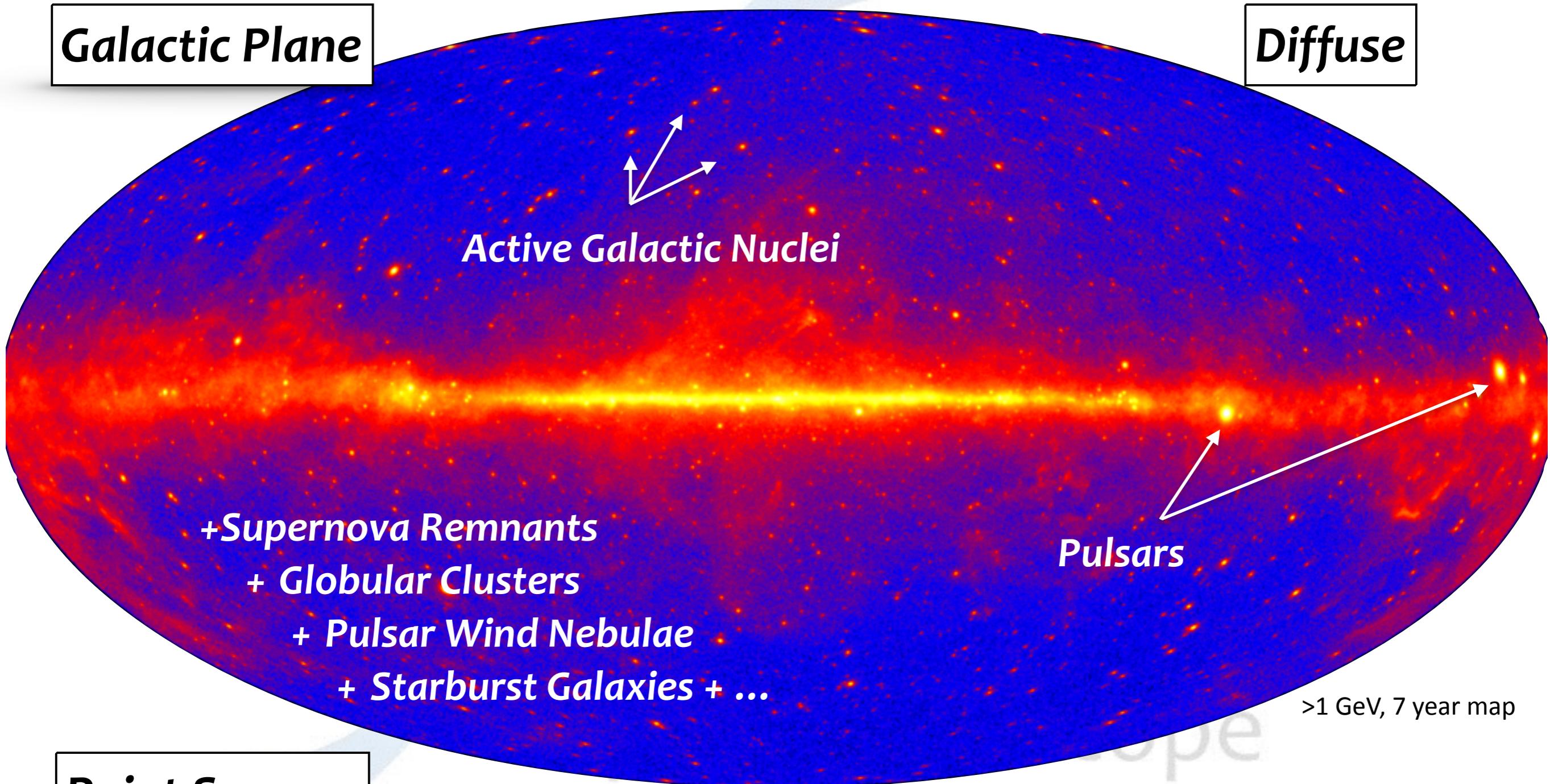
Fermi-LAT γ -ray sky



Fermi-LAT γ -ray sky

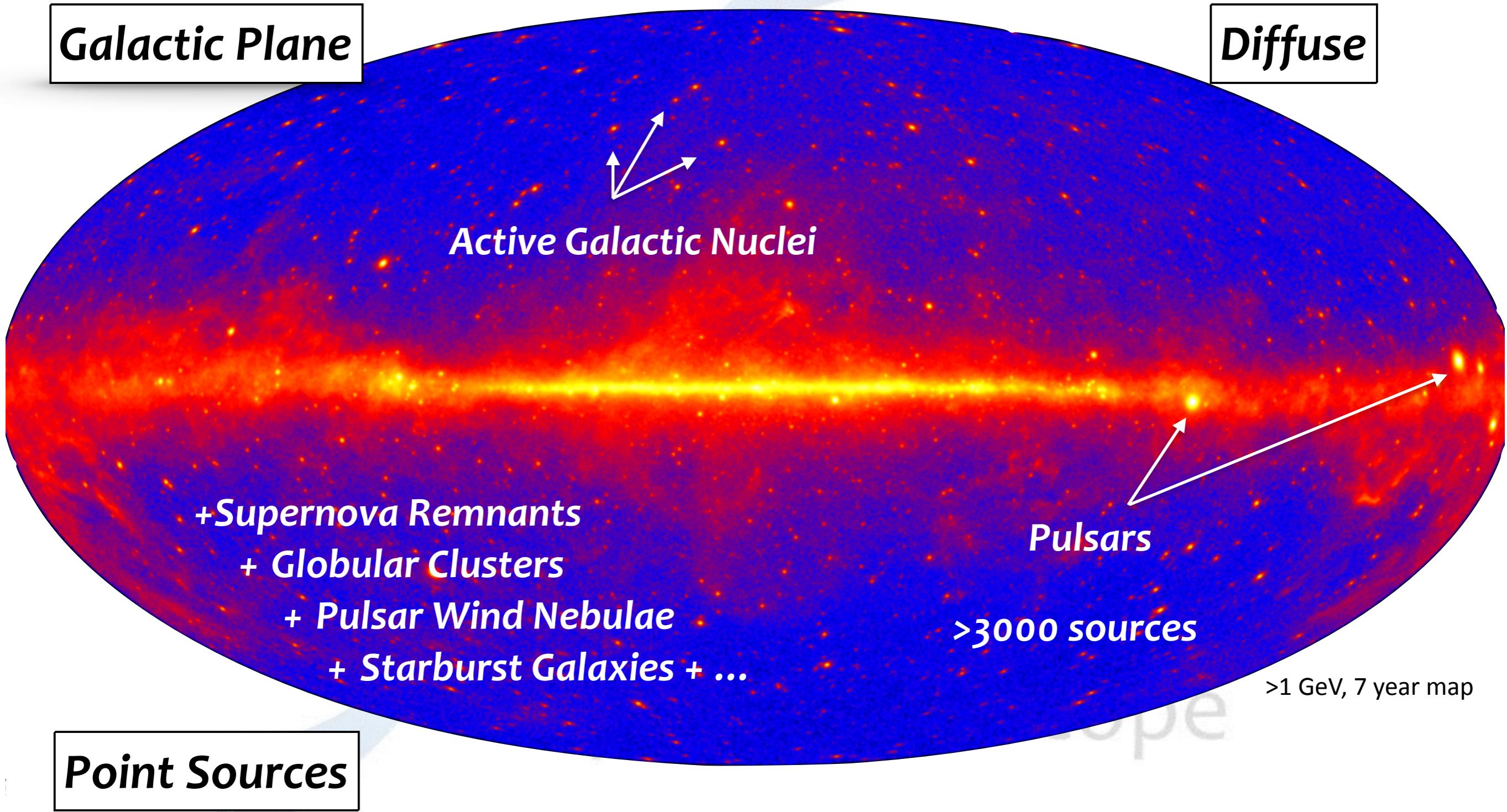


Fermi-LAT γ -ray sky

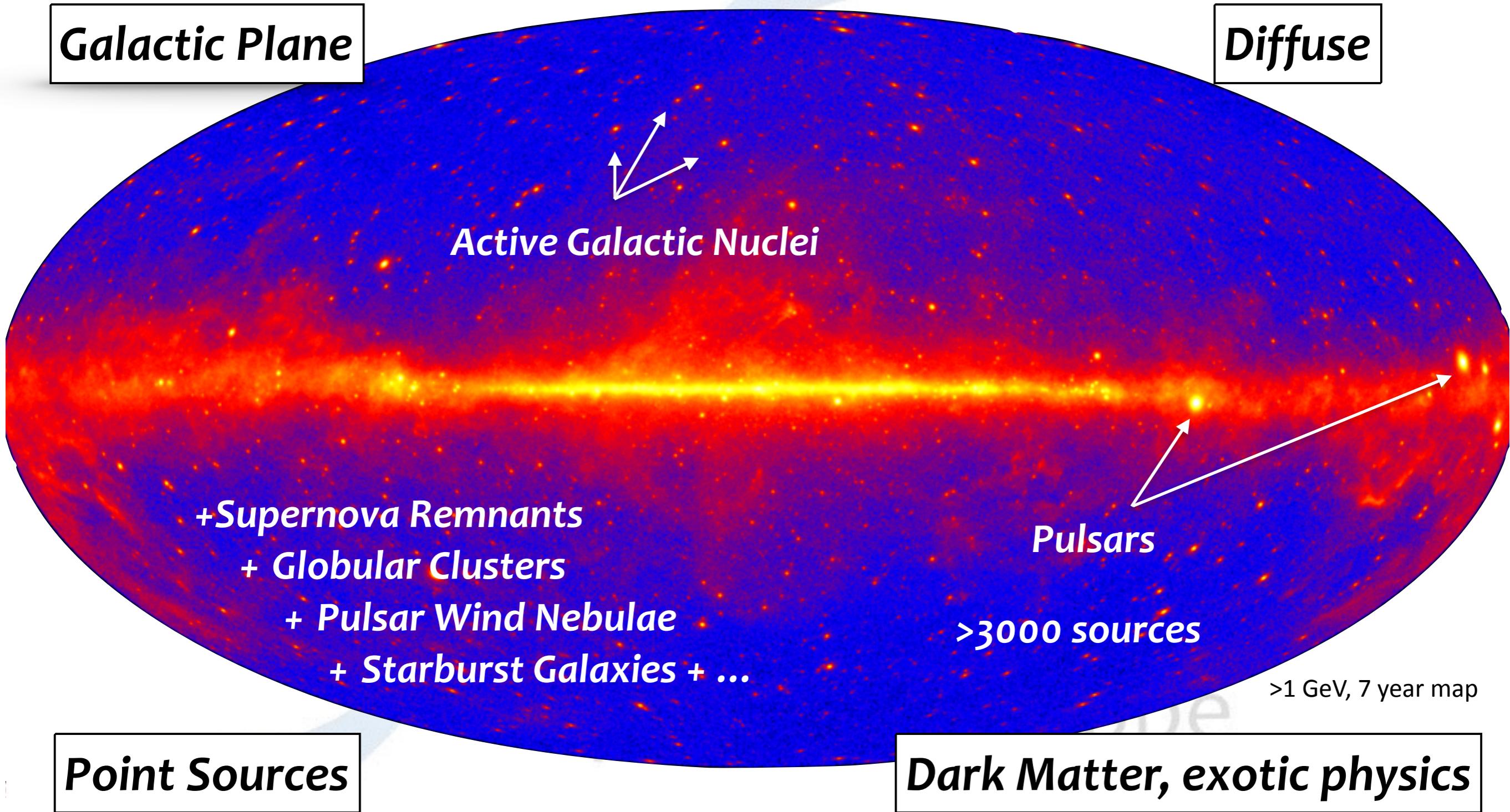


Point Sources

Fermi-LAT γ -ray sky



Fermi-LAT γ -ray sky

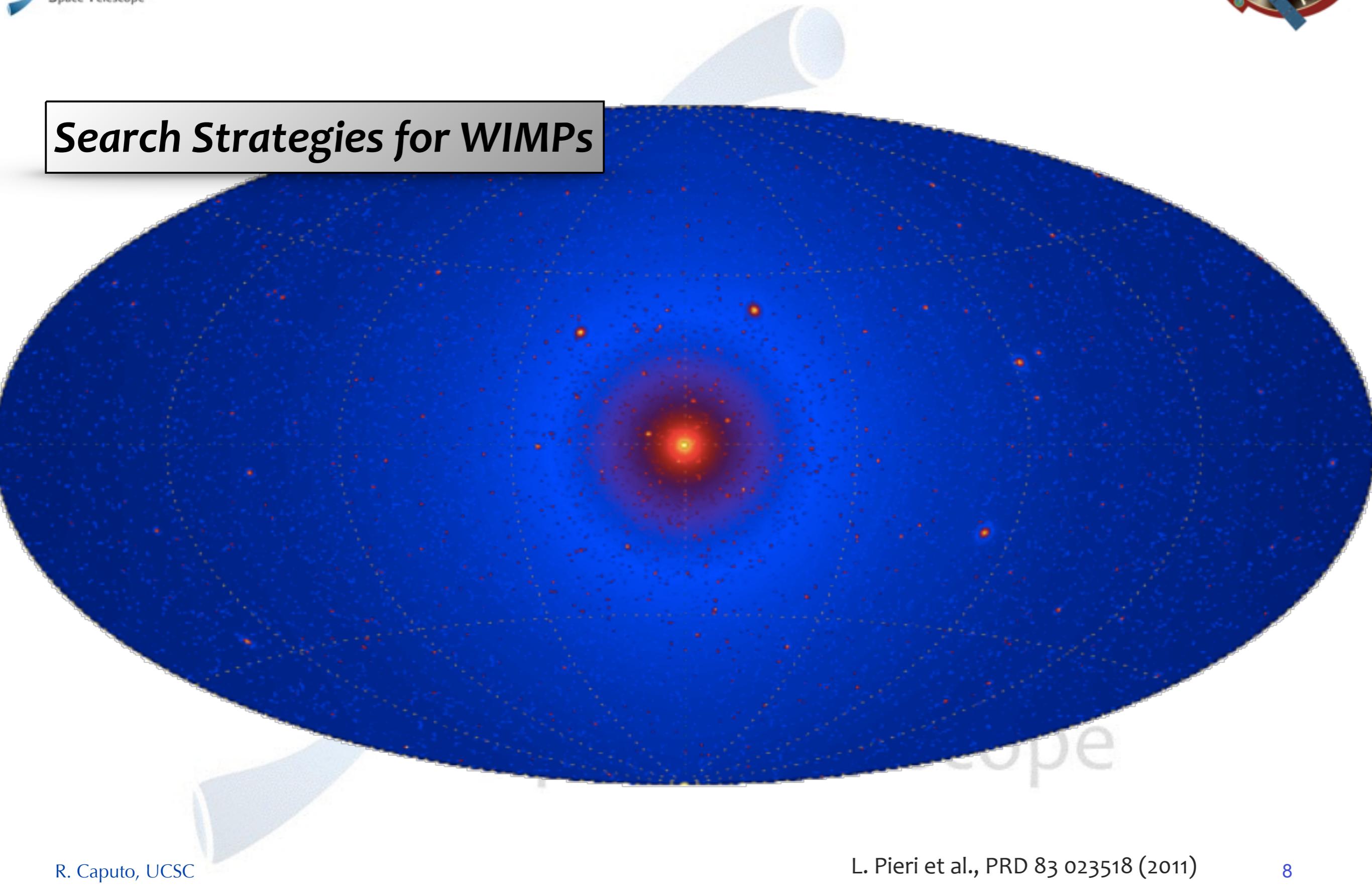




Dark Matter Distribution



Search Strategies for WIMPs



Dark Matter Distribution



Search Strategies for WIMPs

Dwarf Spheroidal
Satellite Galaxies

Milky Way Halo

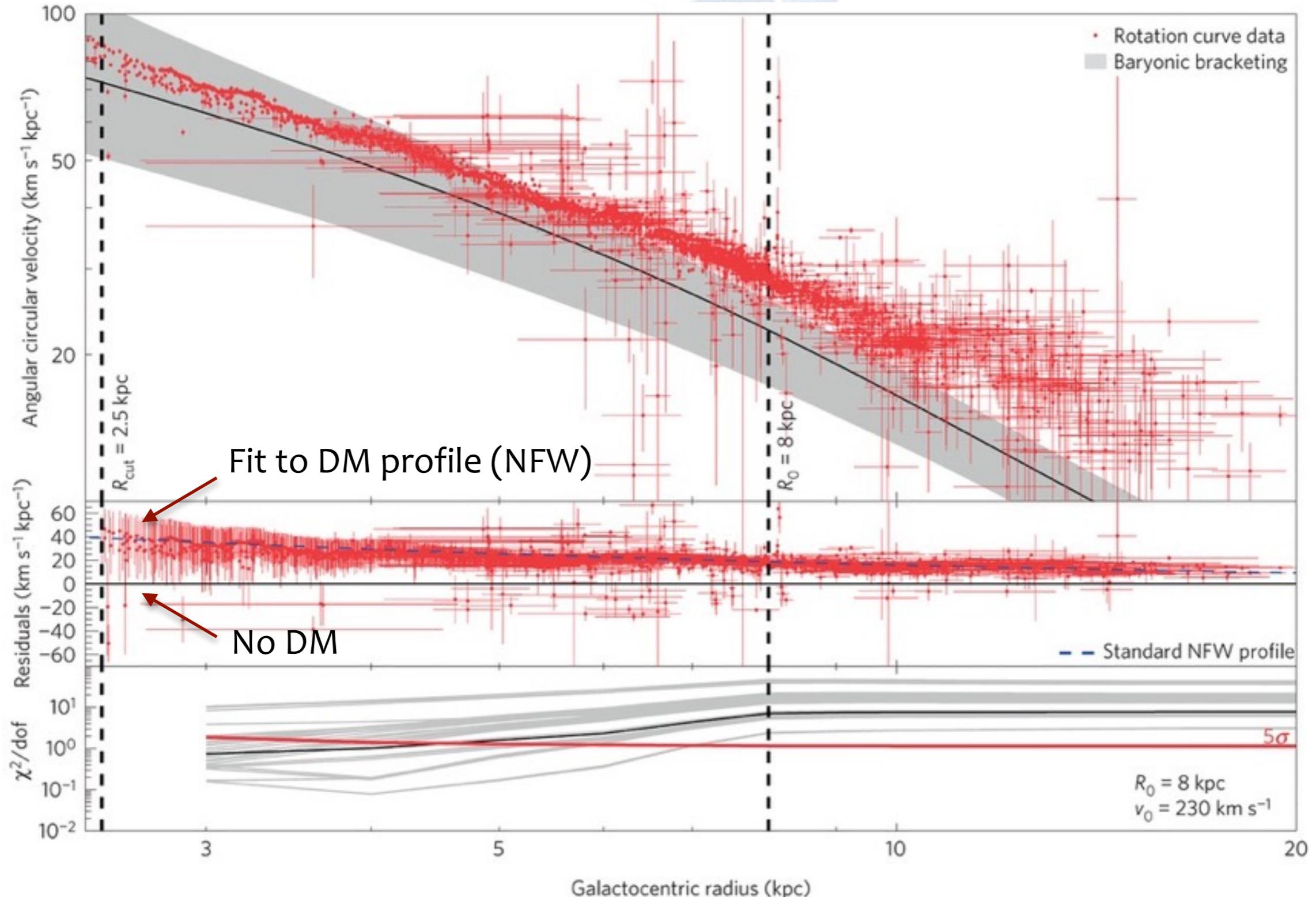
Spectral Lines

Galaxy Clusters

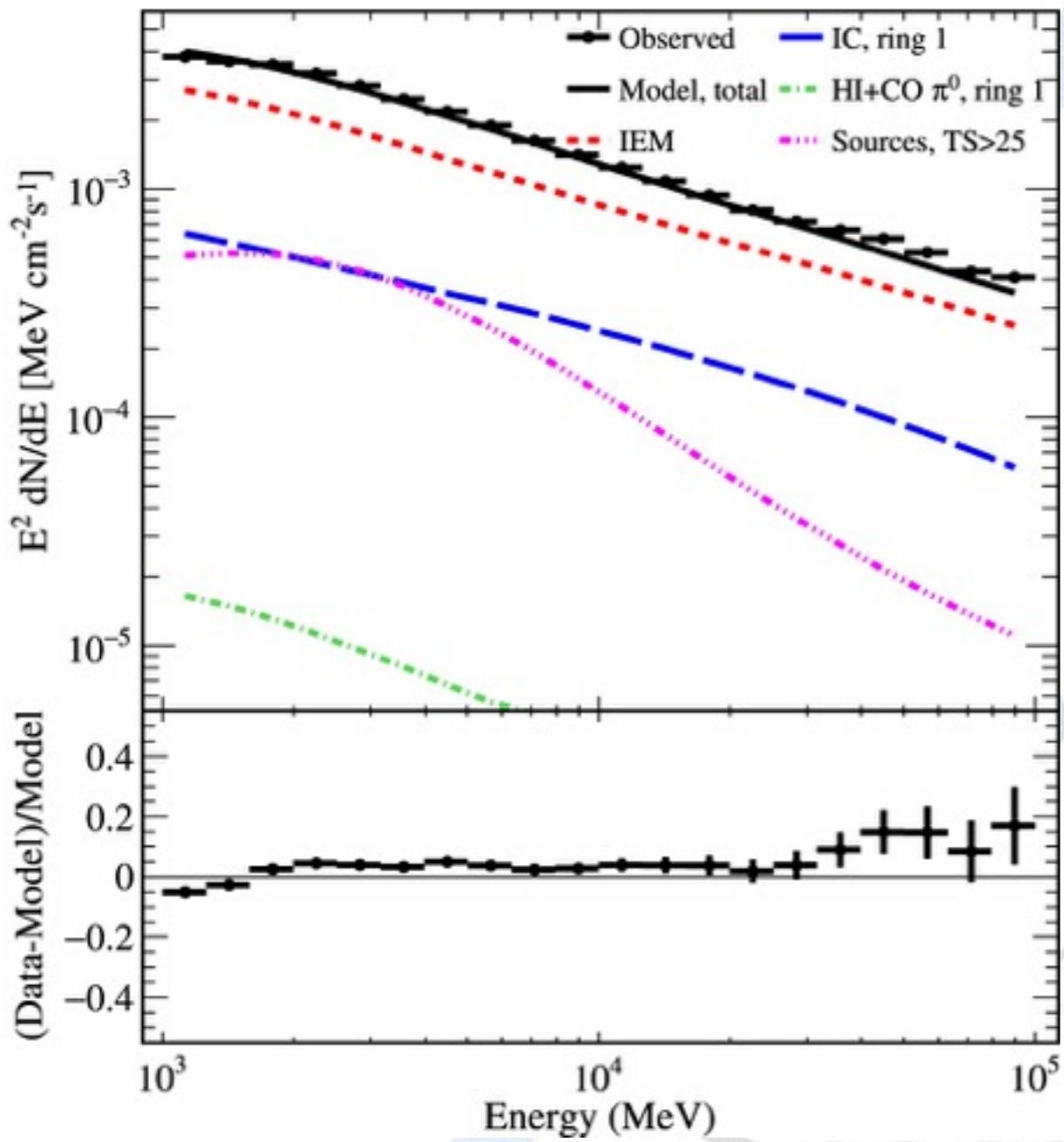
Galactic Center

Isotropic Background

Galactic Center

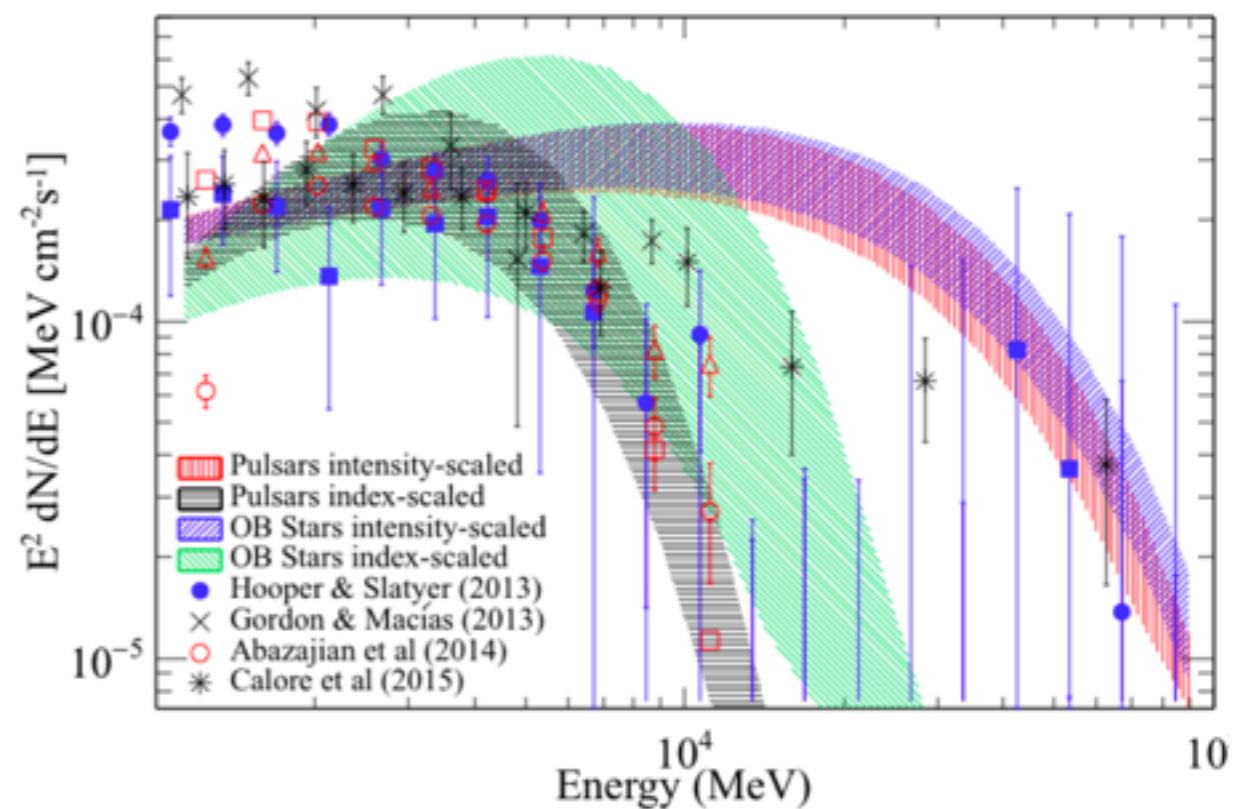


Dividing the Galaxy

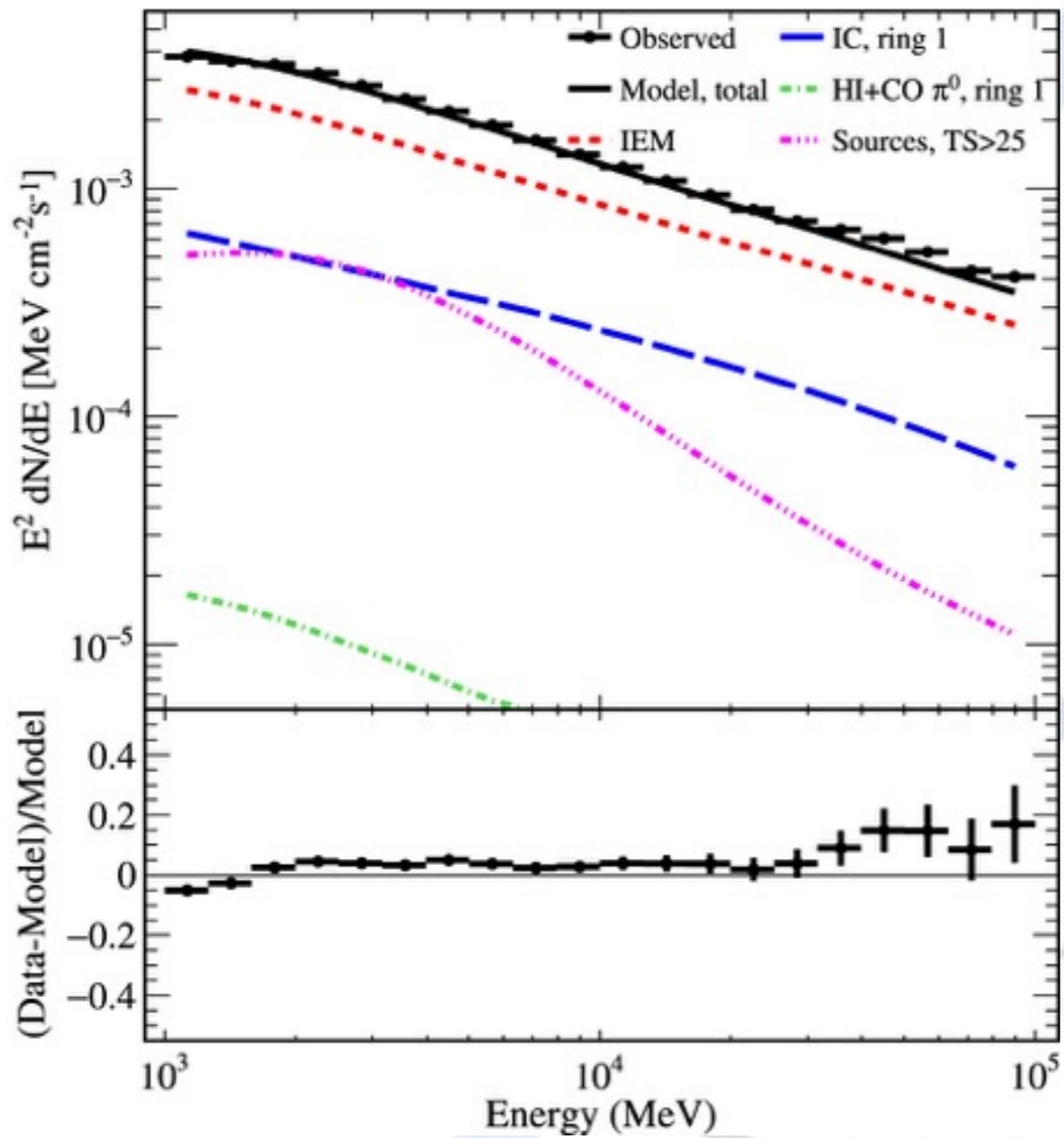


Not exhaustive:

- L. Goodenough, D. Hooper, arXiv:0910.2998
- D. Hooper, L. Goodenough, PLB, arXiv:1010.2752
- D. Hooper, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- D. Hooper, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S. Horiuchi, M. Kaplinghat, arXiv:1402.4090
- T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

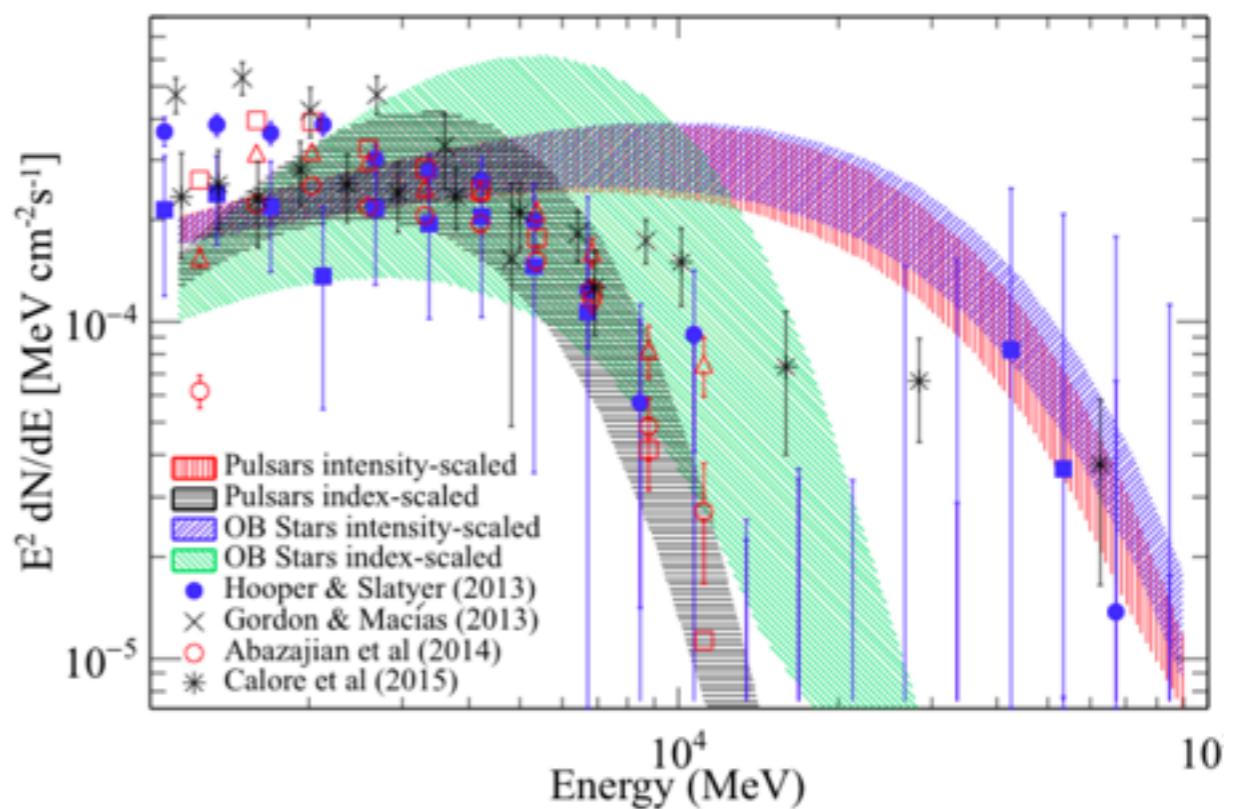


Dividing the Galaxy

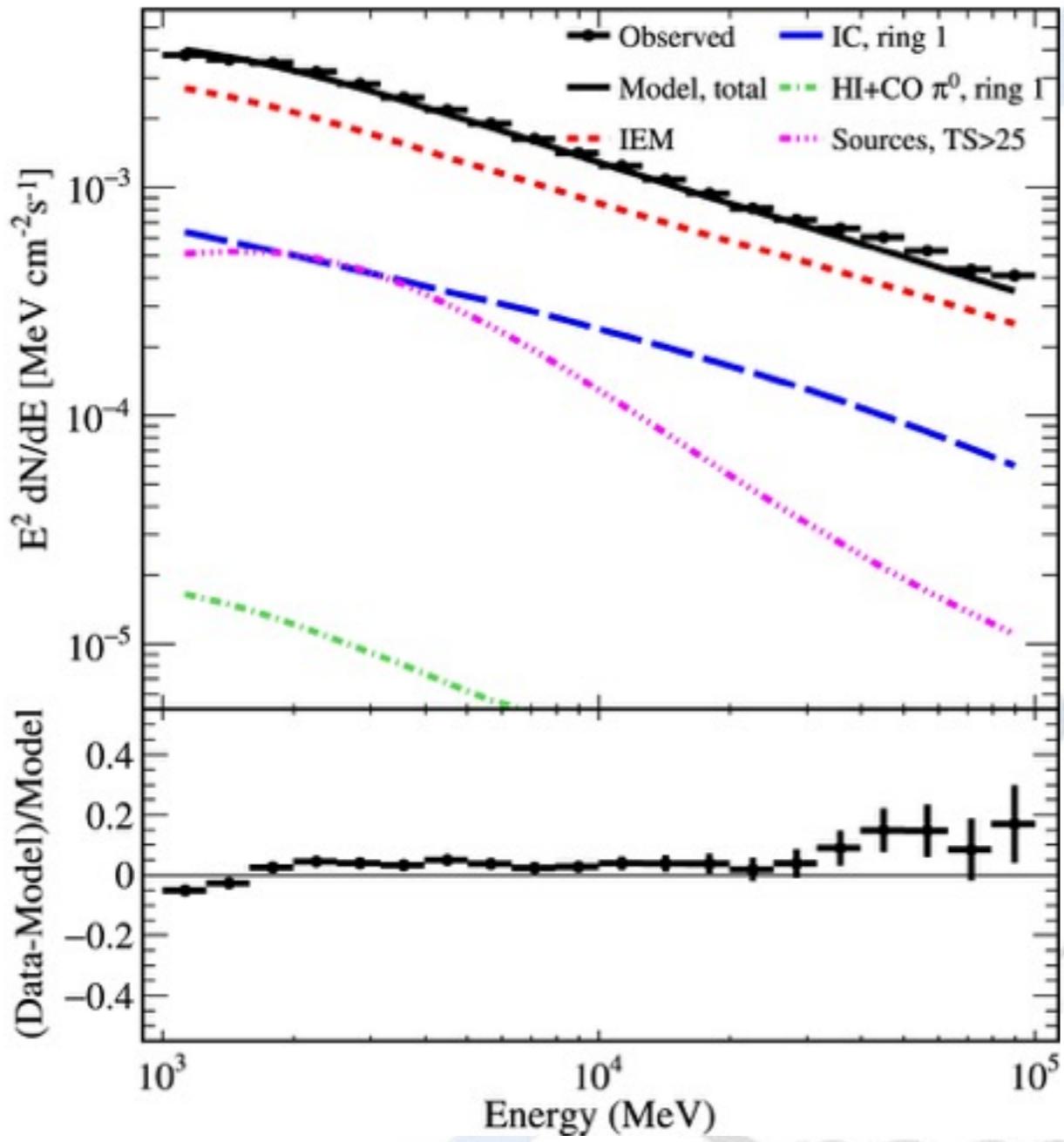


Constituents of the Model

Templates to define different background regions
 Gamma-ray sources (pulsars, OB stars)
 Intensity/Index scaled



Dividing the Galaxy

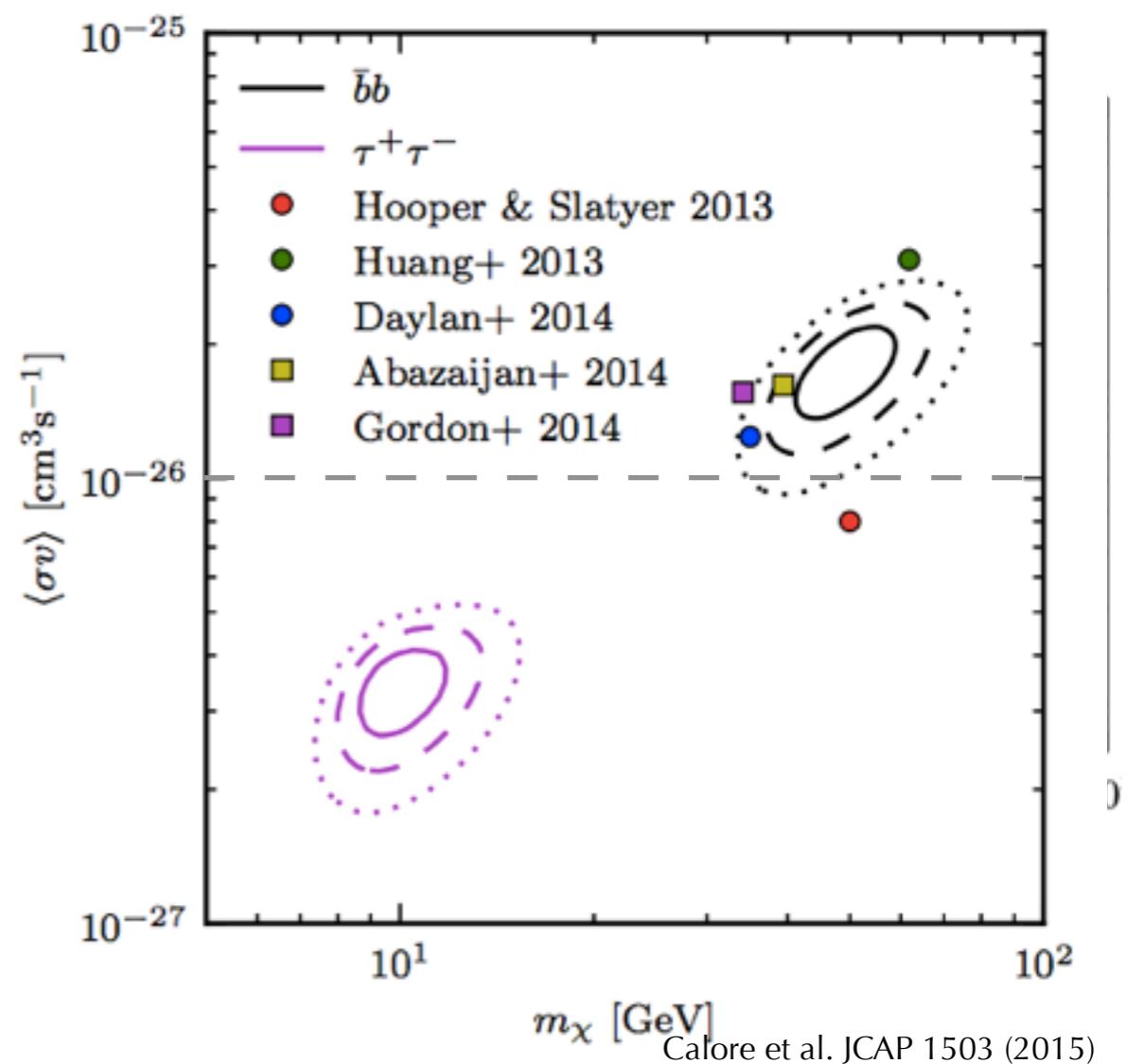


Constituents of the Model

Templates to define different background regions

Gamma-ray sources (pulsars, OB stars)

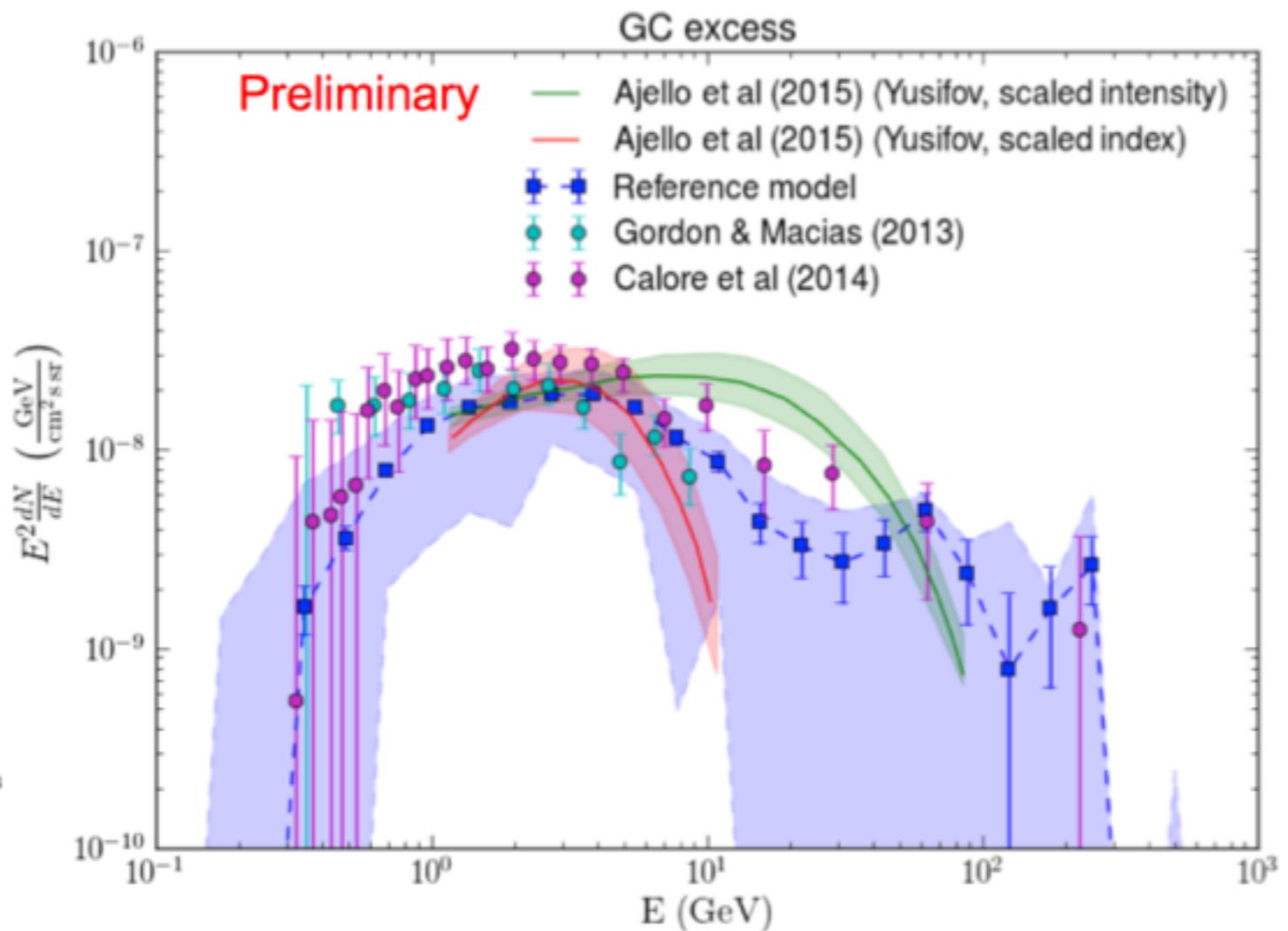
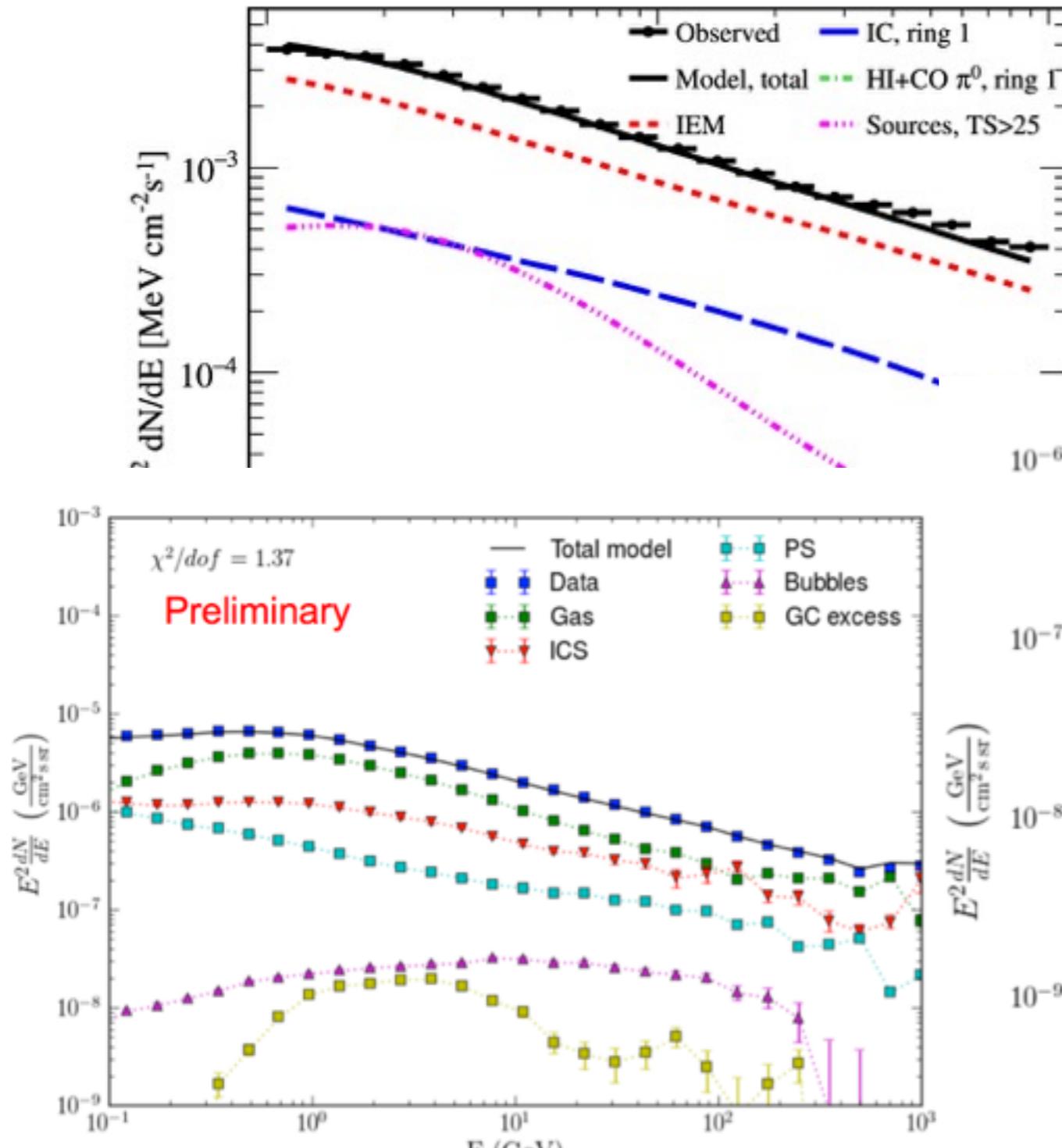
Intensity/Index scaled



Dividing the Galaxy



Variation of excess within modeling uncertainties studied using Pass 8 data...



Dark Matter Distribution



Search Strategies for WIMPs

Dwarf Spheroidal
Satellite Galaxies

See A. Drlica-Wagner's Talk next...

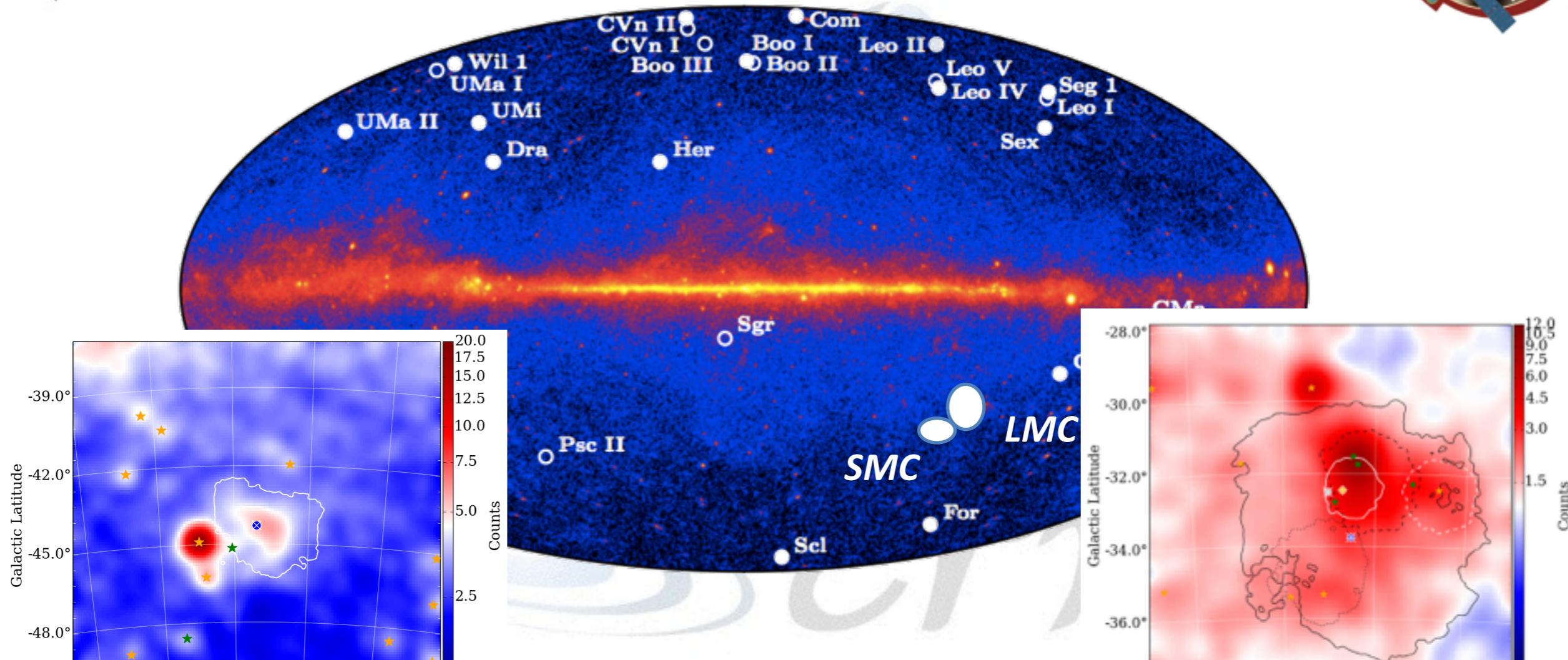
Milky Way Halo

Galactic Center

Spectral Lines

Isotropic Background

Large and Small Magellanic Clouds



J-factor: $\log_{10} J \sim 19.5$,
Distance: 60 kpc

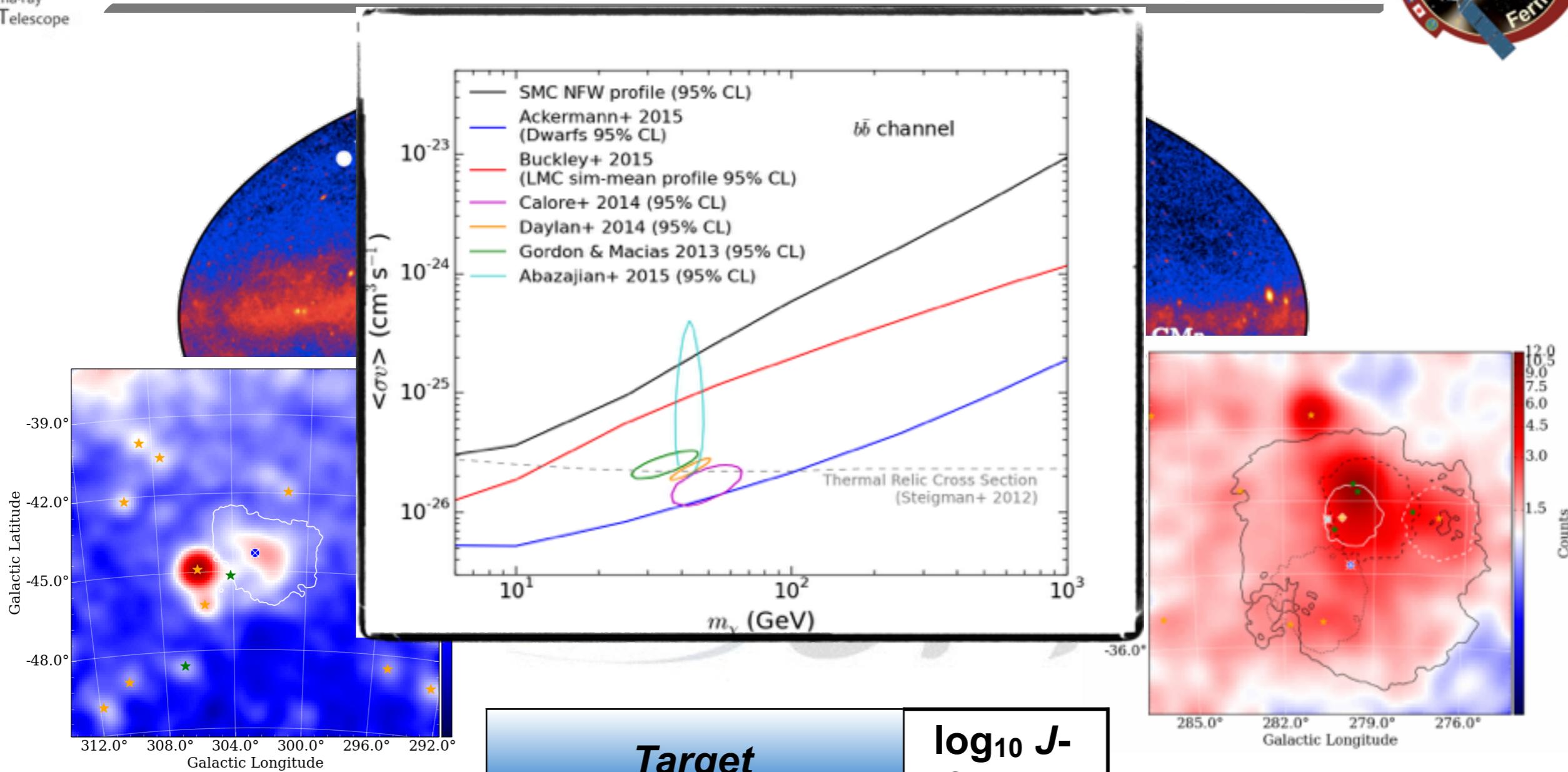
RC, et al.,
PRD 93.062004 (2016)

| Target | $\log_{10} J$ -factor |
|---------------------------|-----------------------|
| Galactic Center | 22-23 |
| Dwarf Spheroidal Galaxies | 17-19 |

J-factor: $\log_{10} J \sim 20$,
Distance: 50 kpc

M. Buckley, et al.,
PRD, 91.102001, (2015)

Large and Small Magellanic Clouds



J-factor: $\log_{10} J \sim 19.5$,
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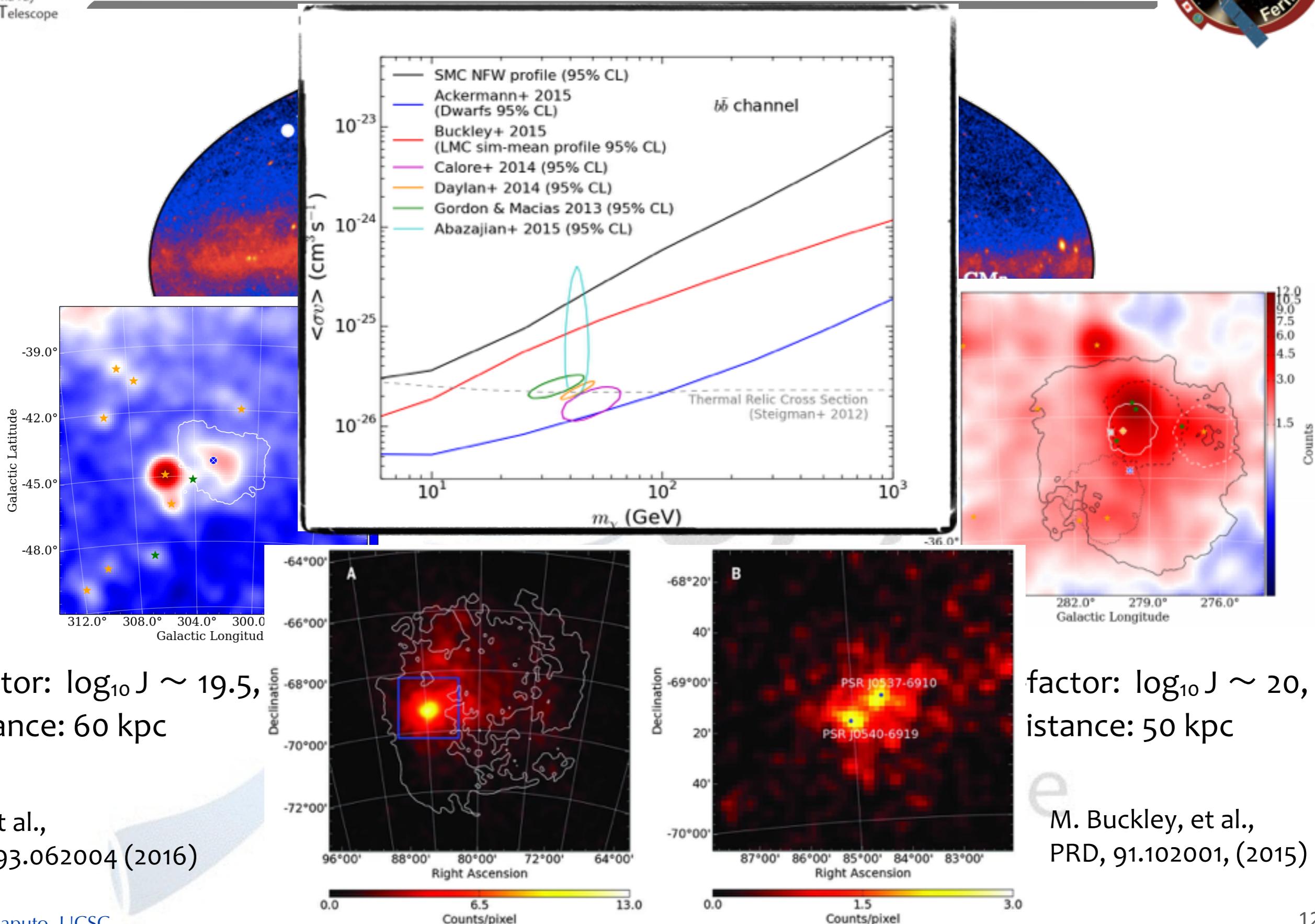
RC, et al.,
PRD 93.062004 (2016)

| Target | $\log_{10} J$ -factor |
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| Galactic Center | 22-23 |
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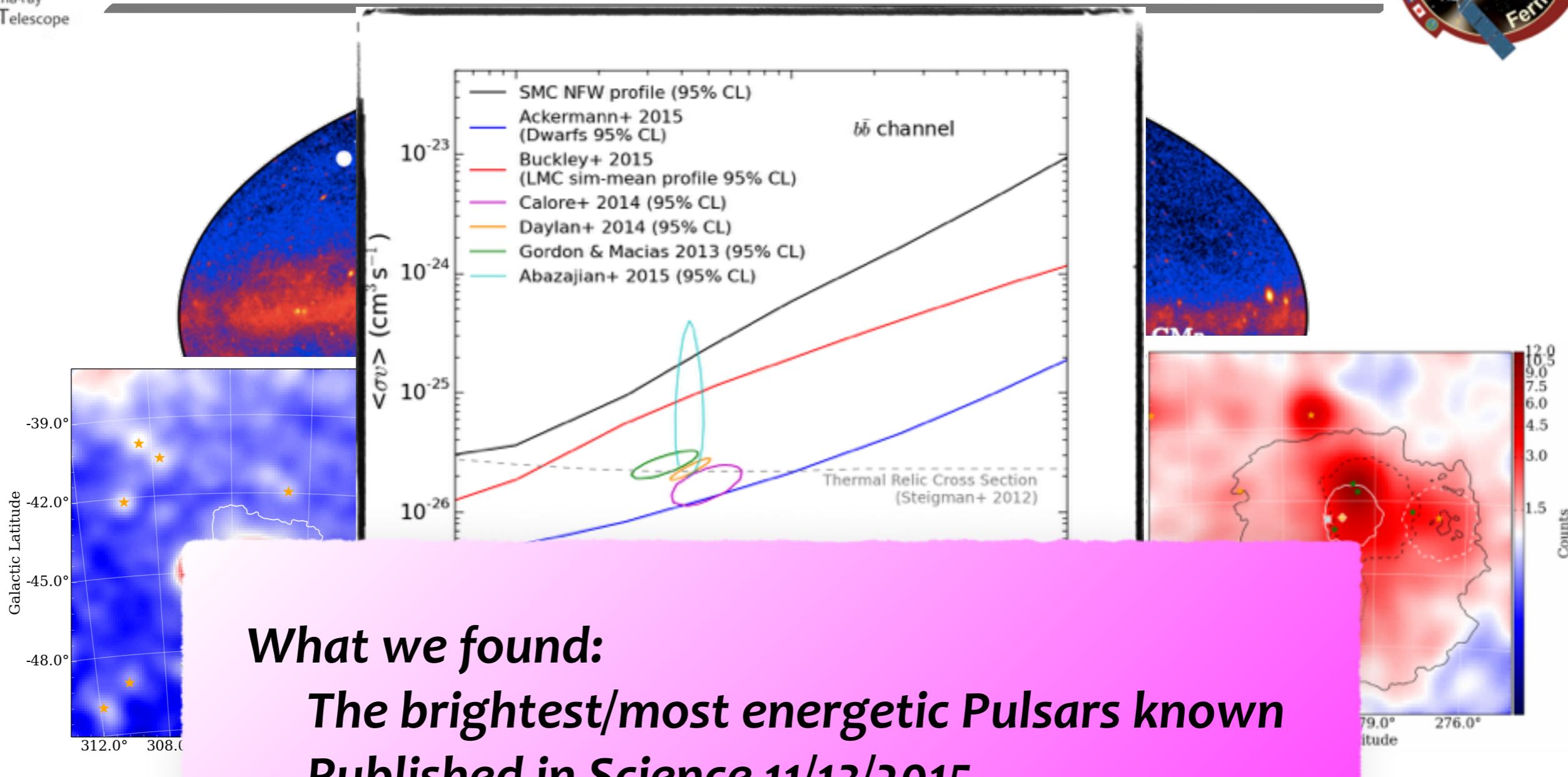
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M. Buckley, et al.,
PRD, 91.102001, (2015)

Large and Small Magellanic Clouds



Large and Small Magellanic Clouds



J-factor: $\log_{10} J$
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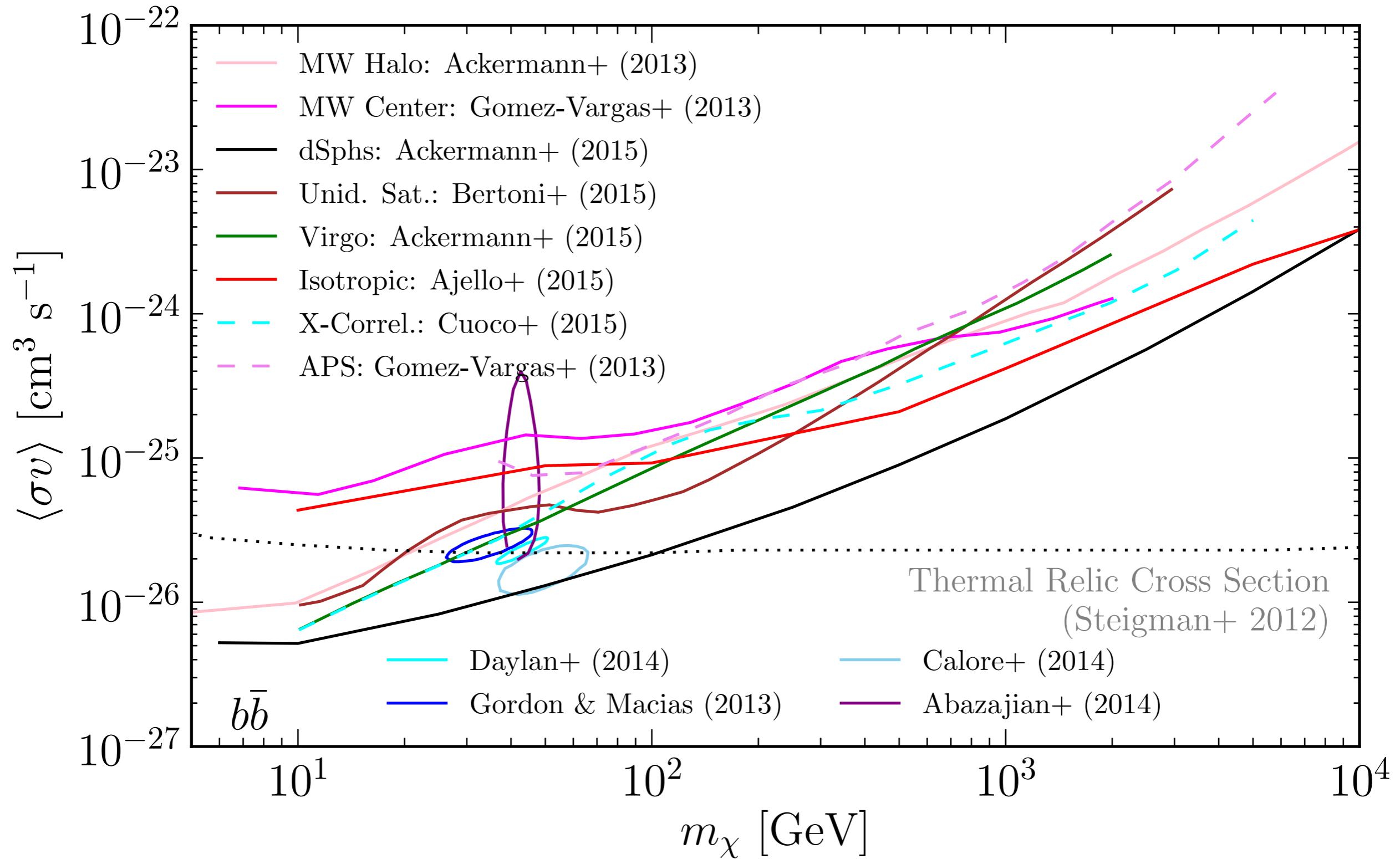
RC, et al.,
PRD 93.062004 (2016)

$\log_{10} J \sim 20$,
Distance: 50 kpc

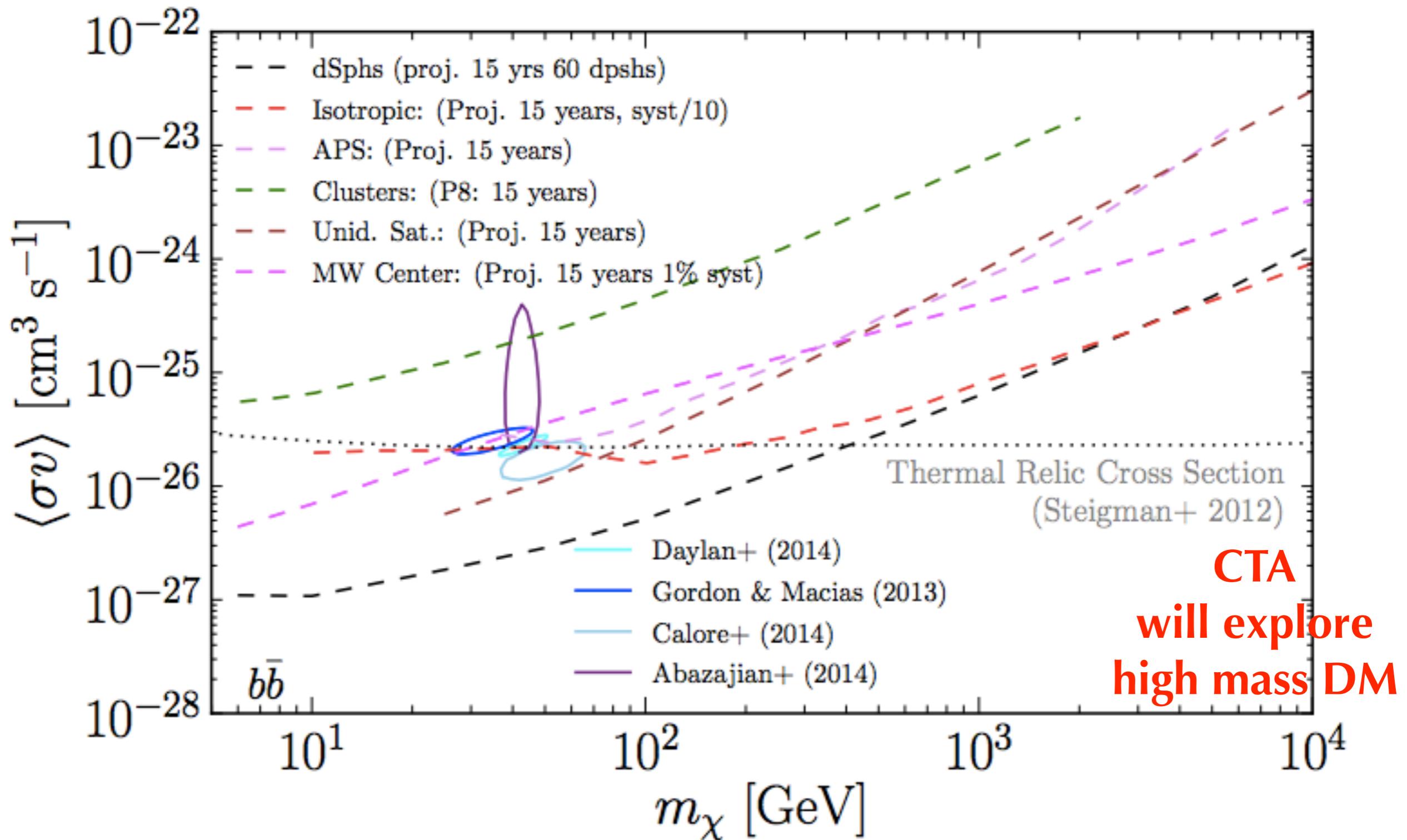
M. Buckley, et al.,
PRD, 91.102001, (2015)



Summary of Fermi-LAT WIMP Dark Matter Searches



Future WIMP Dark Matter Searches



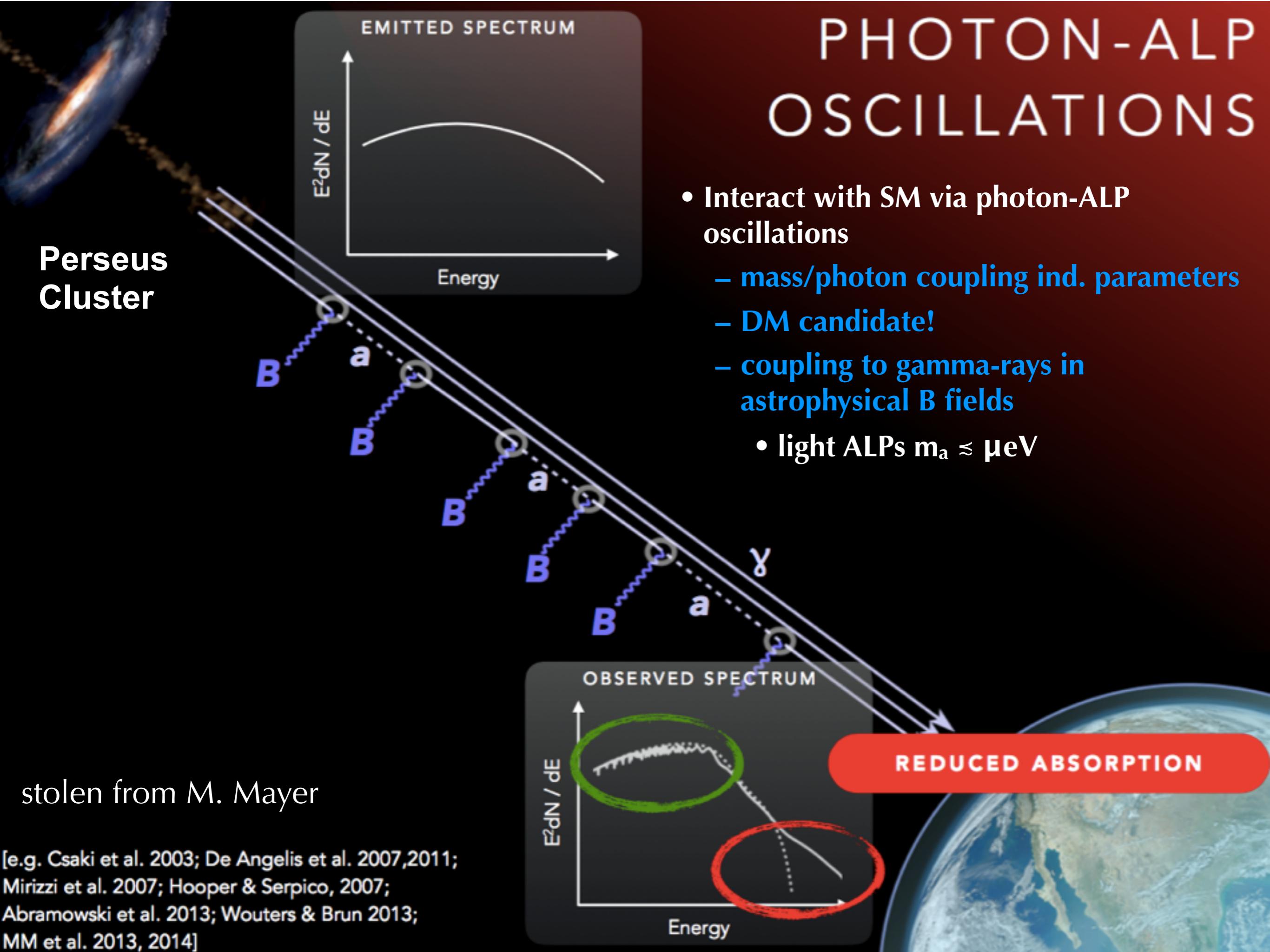


And now for something completely different...



A yellow circle containing the text "Axions and Axion-like particles" in a bold, black, serif font.

PHOTON-ALP OSCILLATIONS

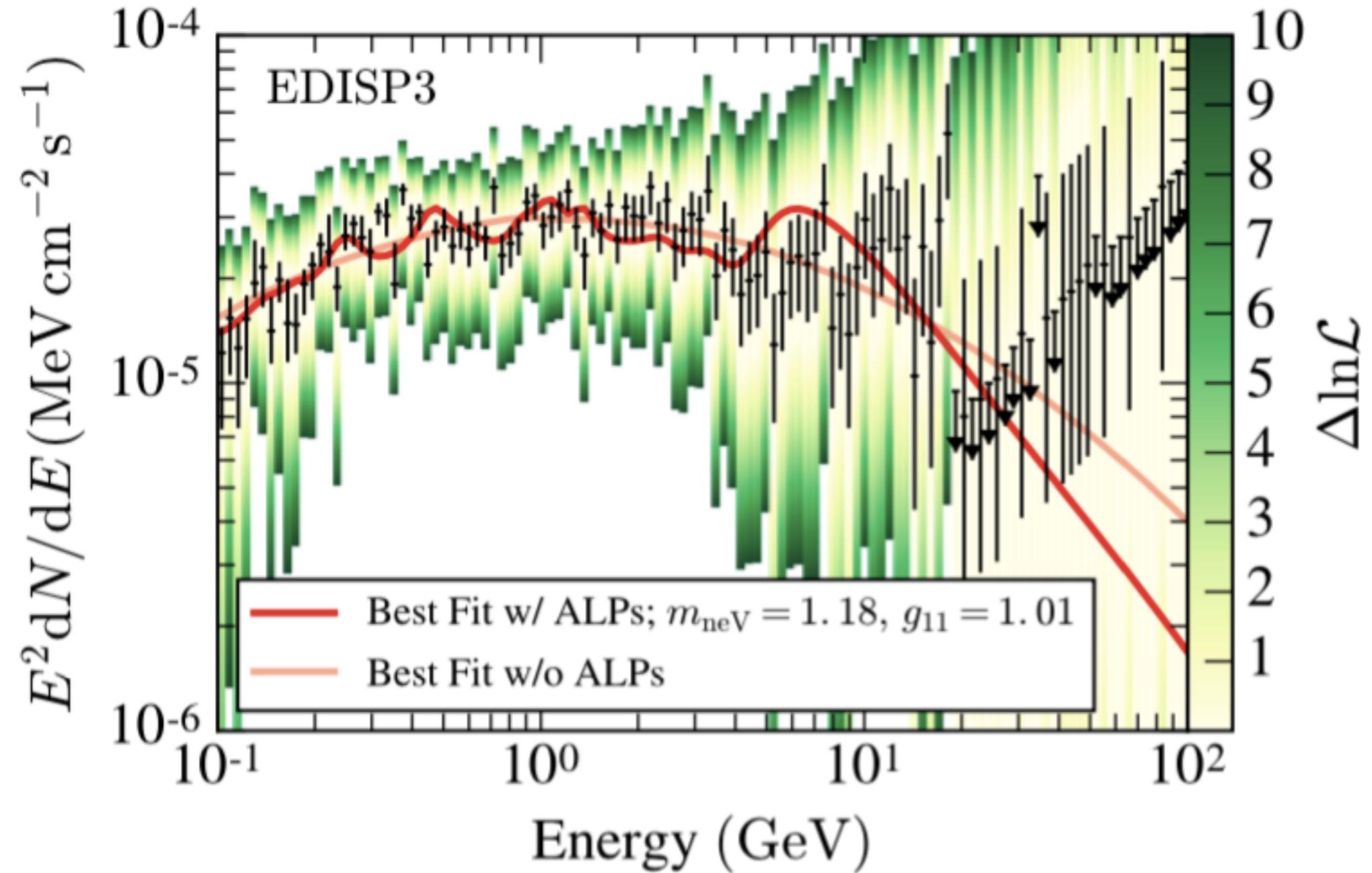


Perseus
Cluster

stolen from M. Mayer

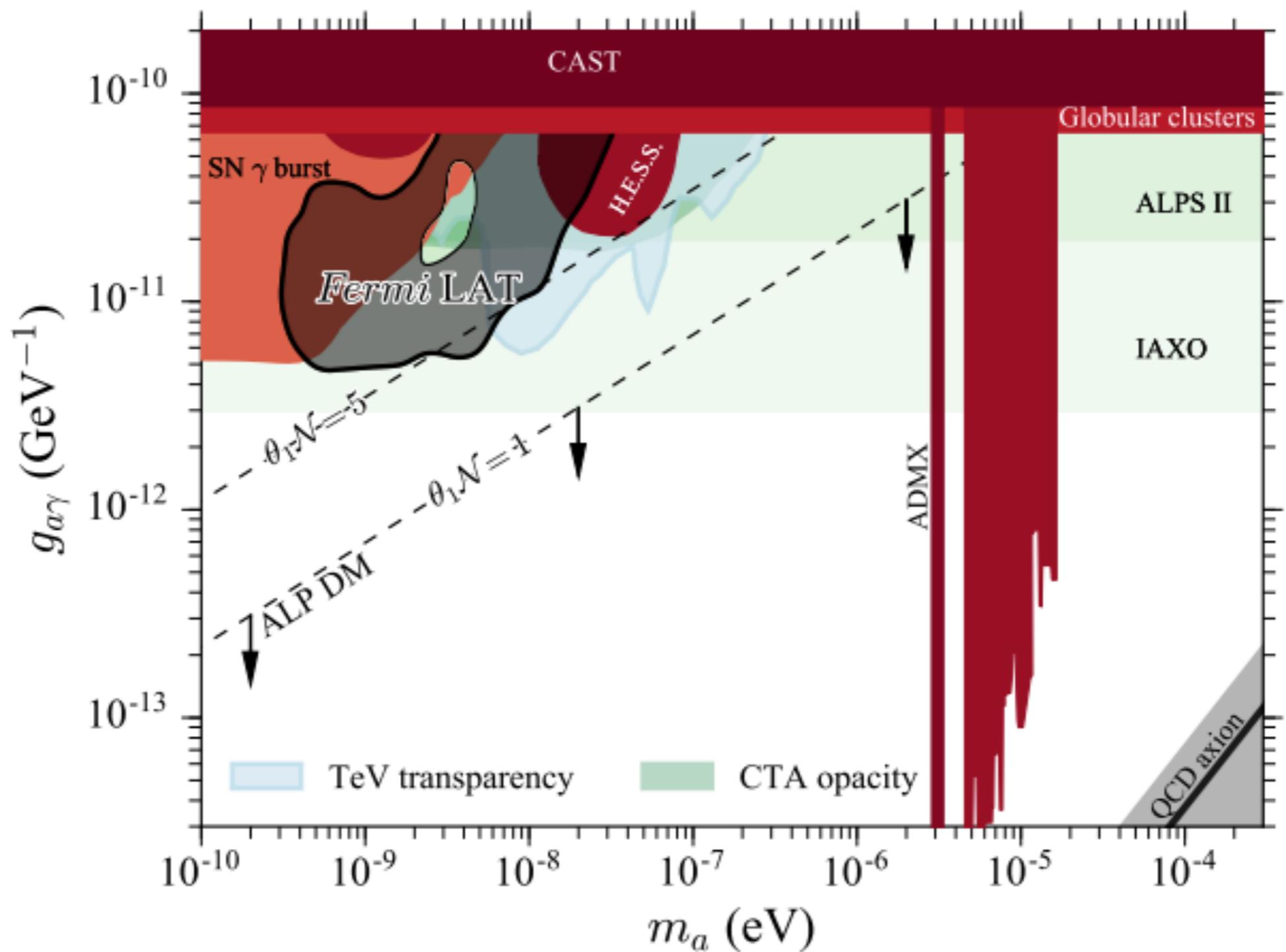
[e.g. Csaki et al. 2003; De Angelis et al. 2007,2011;
Mirizzi et al. 2007; Hooper & Serpico, 2007;
Abramowski et al. 2013; Wouters & Brun 2013;
MM et al. 2013, 2014]

Central Galaxy of the Perseus cluster: NGC 1275



M. Ajello et. al, Phys. Rev. Lett. 116, 161101 (2016) arXiv:1603.06978v1

Current Axion-like Particle Limits

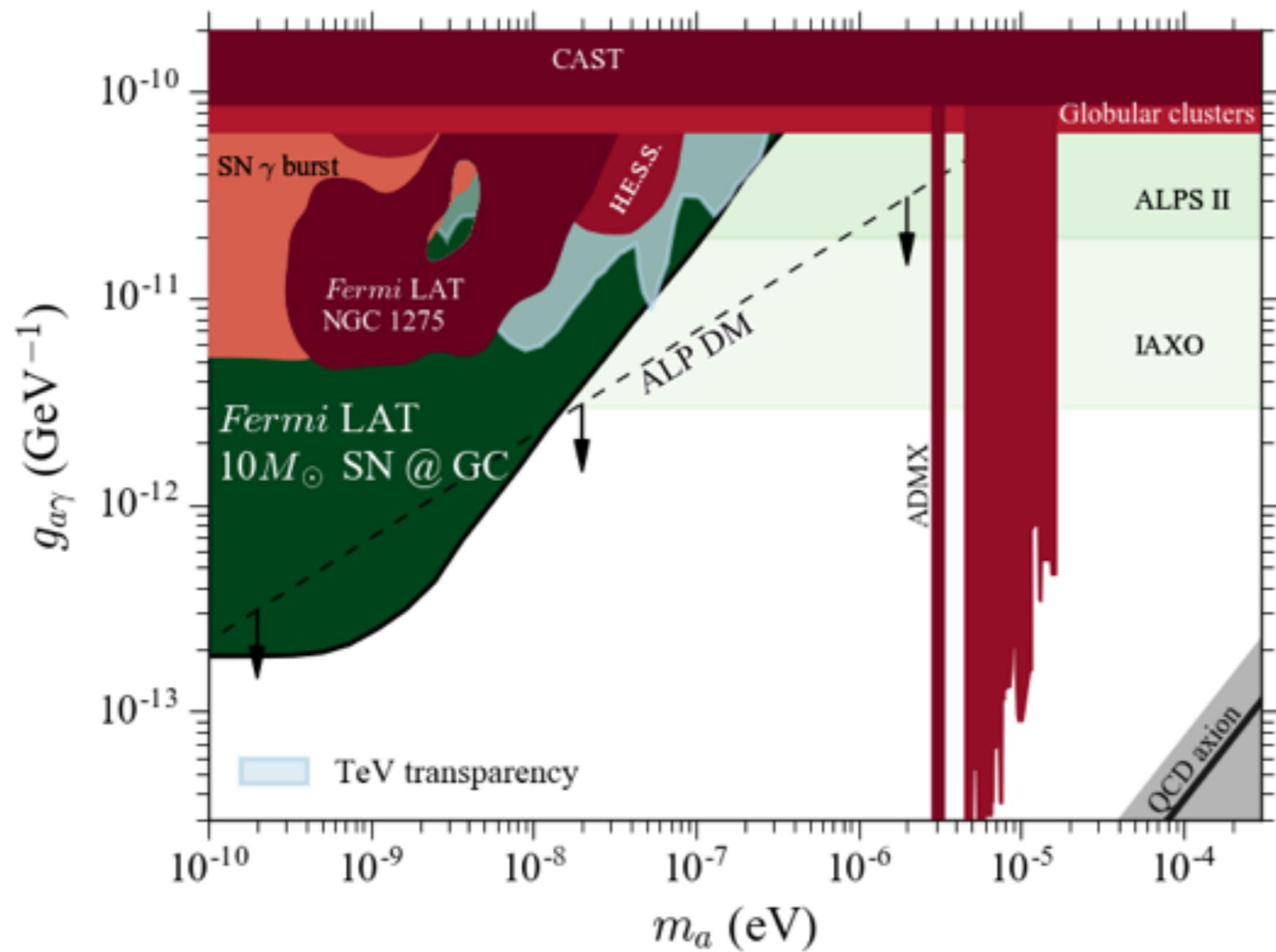


M. Ajello et. al, Phys. Rev. Lett. 116, 161101 (2016) arXiv:1603.06978v1

MeV Dark Matter: Axion-like Particles



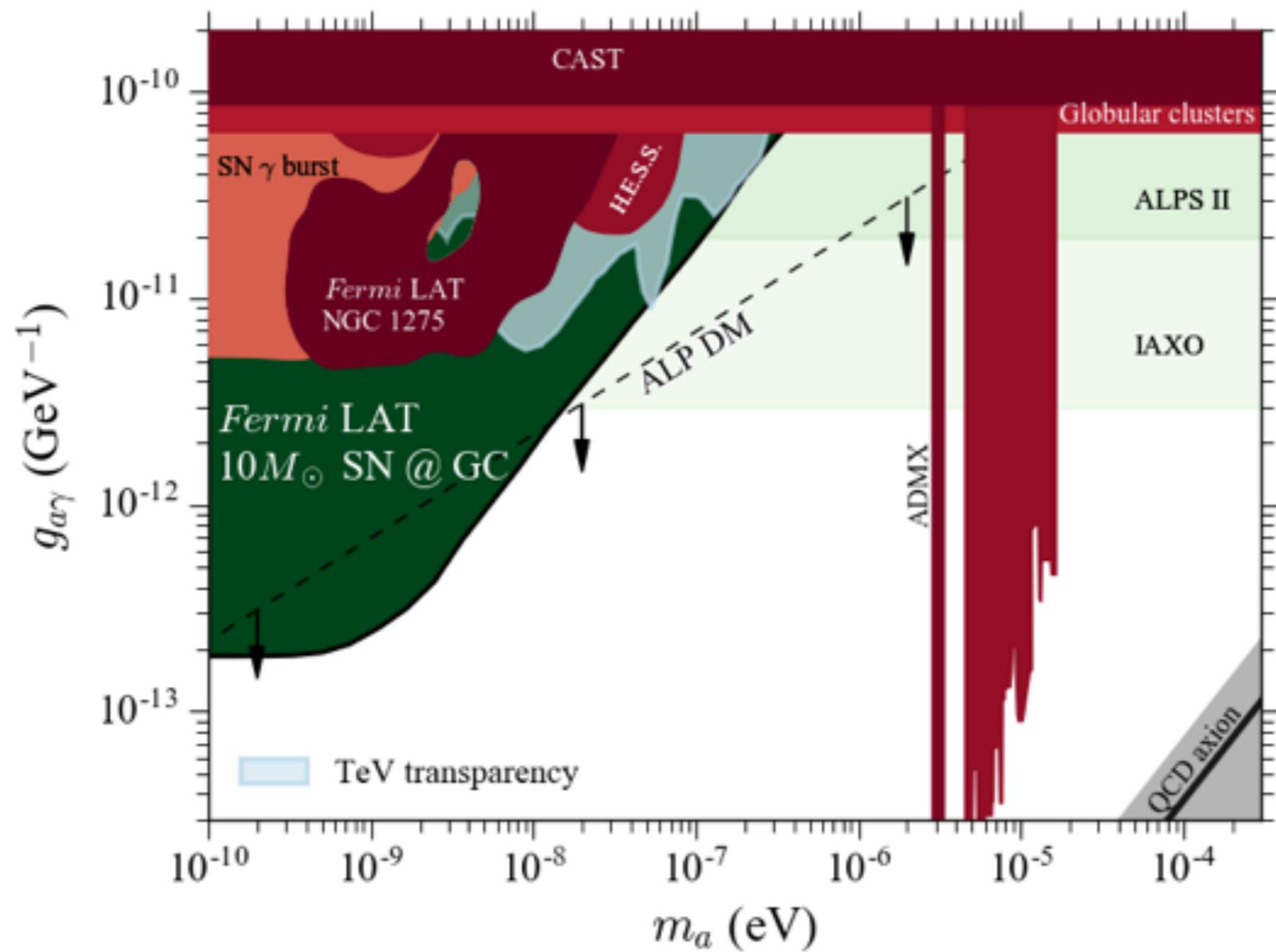
- Axions produced in supernovae
 - core collapse supernova (SN1987A)



MeV Dark Matter: Axion-like Particles



- Axions produced in supernovae
 - core collapse supernova (SN1987A)



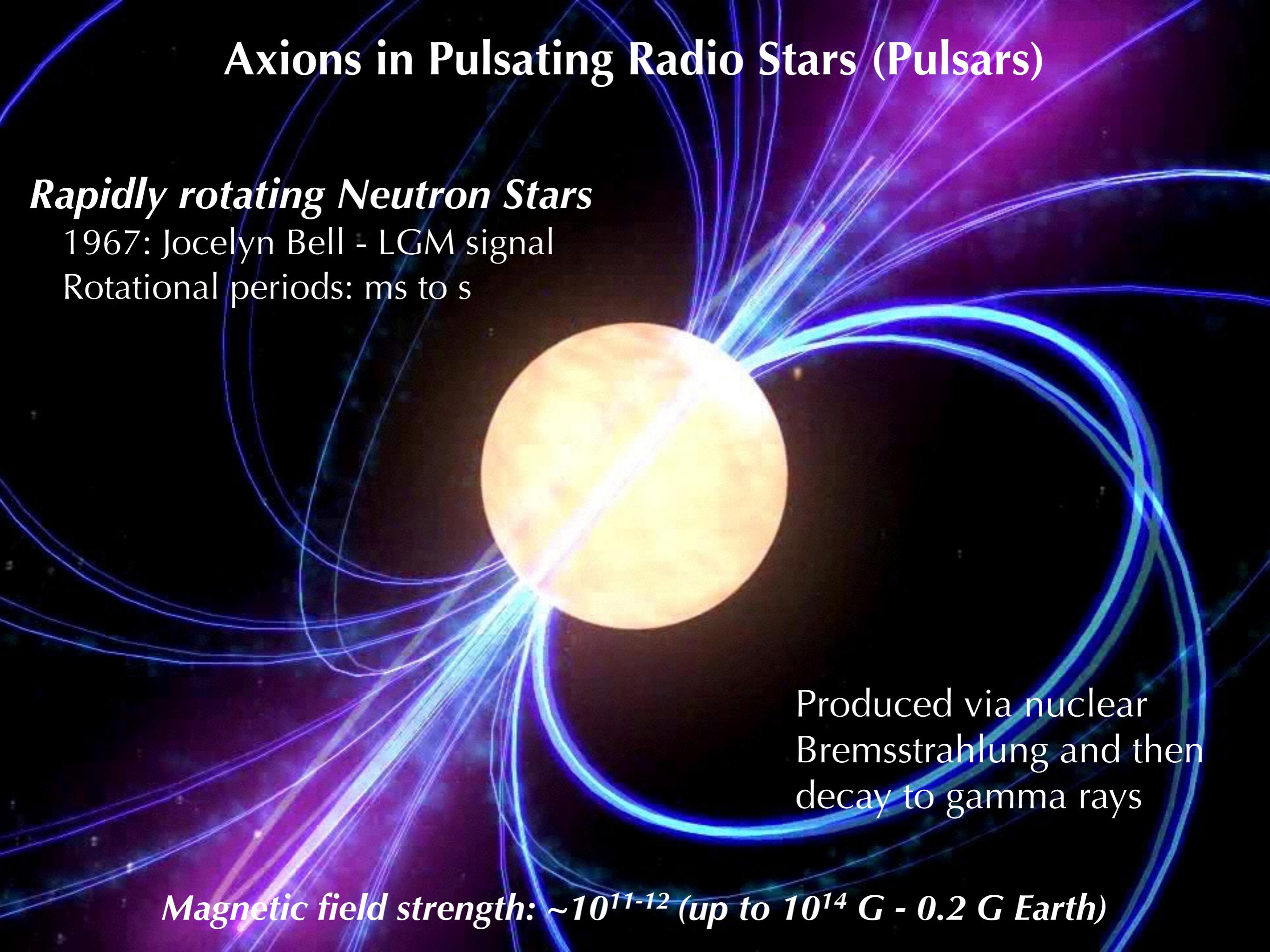
Limited by PSF
@<100 MeV

Axions in Pulsating Radio Stars (Pulsars)

Rapidly rotating Neutron Stars

1967: Jocelyn Bell - LGM signal

Rotational periods: ms to s



Produced via nuclear Bremsstrahlung and then decay to gamma rays

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

Axions in Pulsars

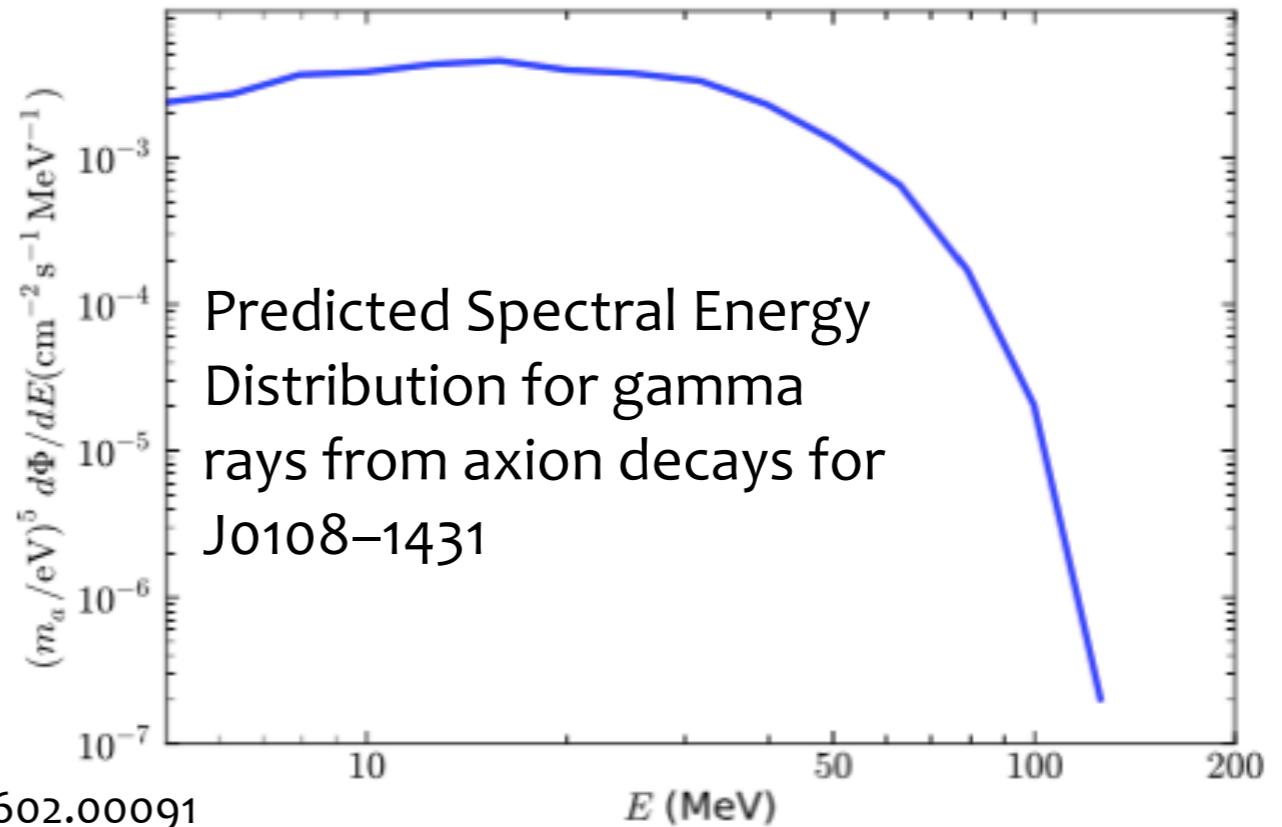


| Source Name | RA (°) | Dec.(°) | ℓ (°) | b (°) | d (kpc) | Age (Myr) | B_{surf} (G) |
|-------------|---------|---------|------------|---------|---------------------------|-----------|-----------------------|
| J0108-1431 | 17.035 | -14.351 | 140.93 | -76.82 | $0.240^{+0.124}_{-0.061}$ | 166 | 2.52×10^{11} |
| 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

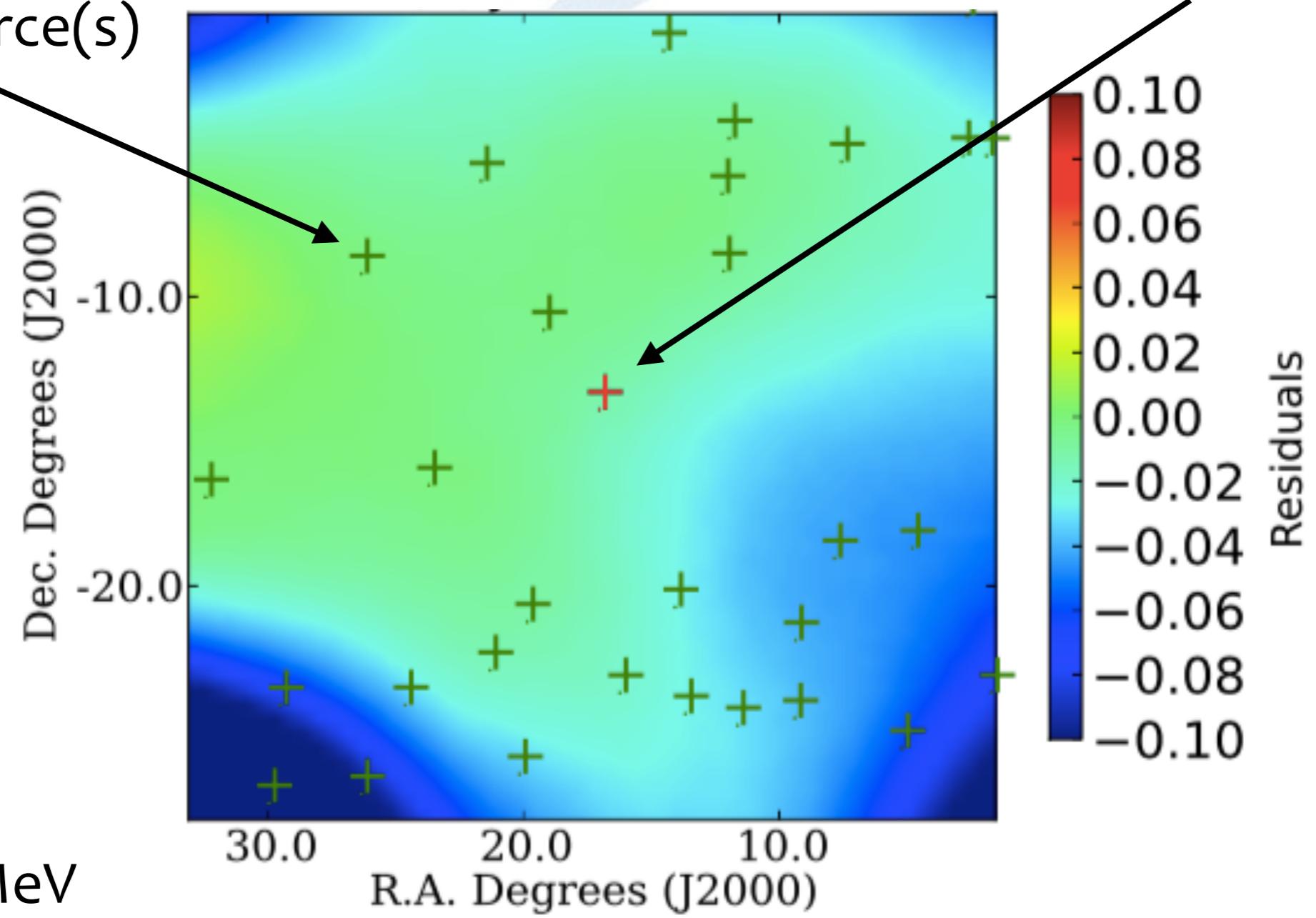
Measured
B-Field



Pulsar Target: J0108-1431



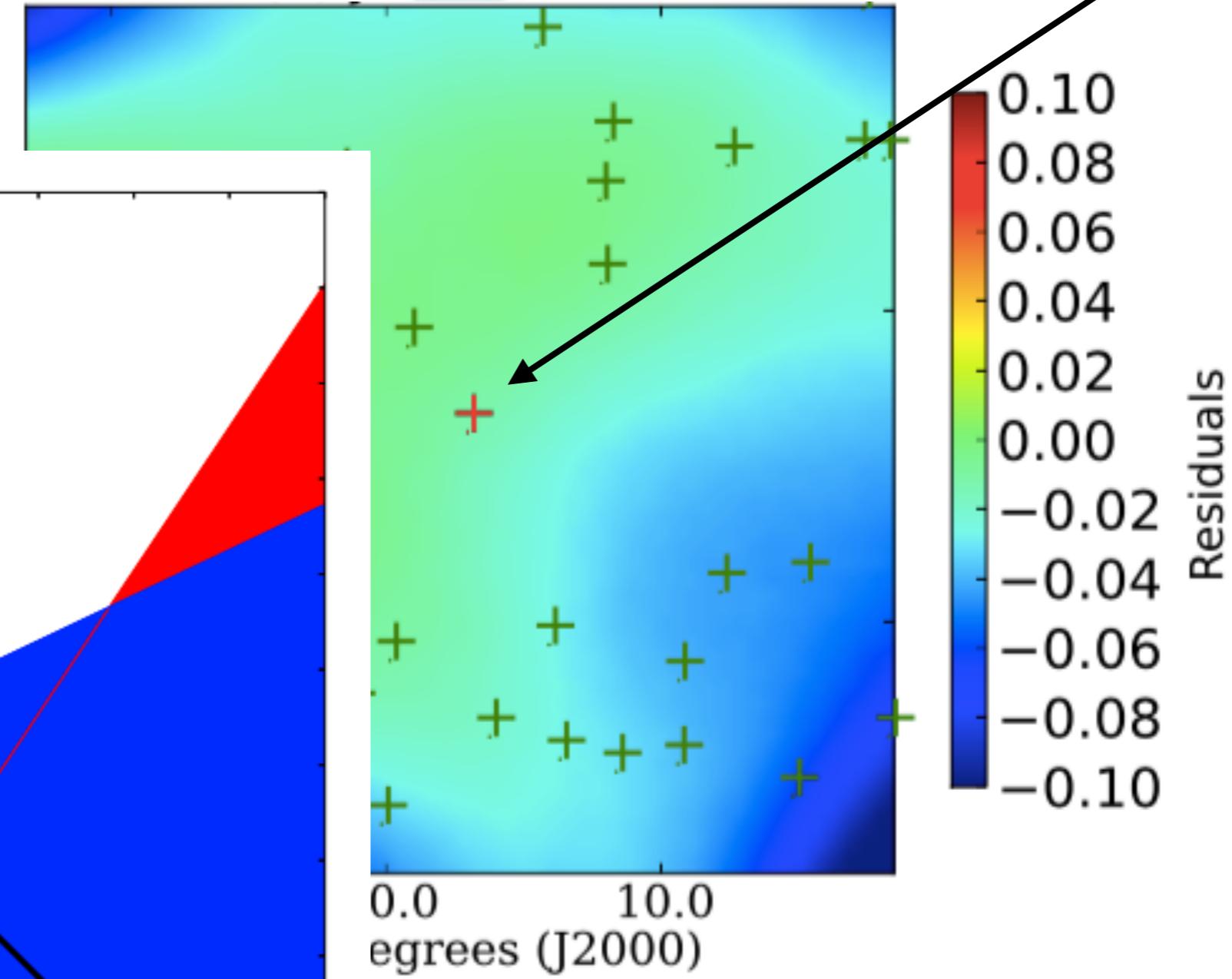
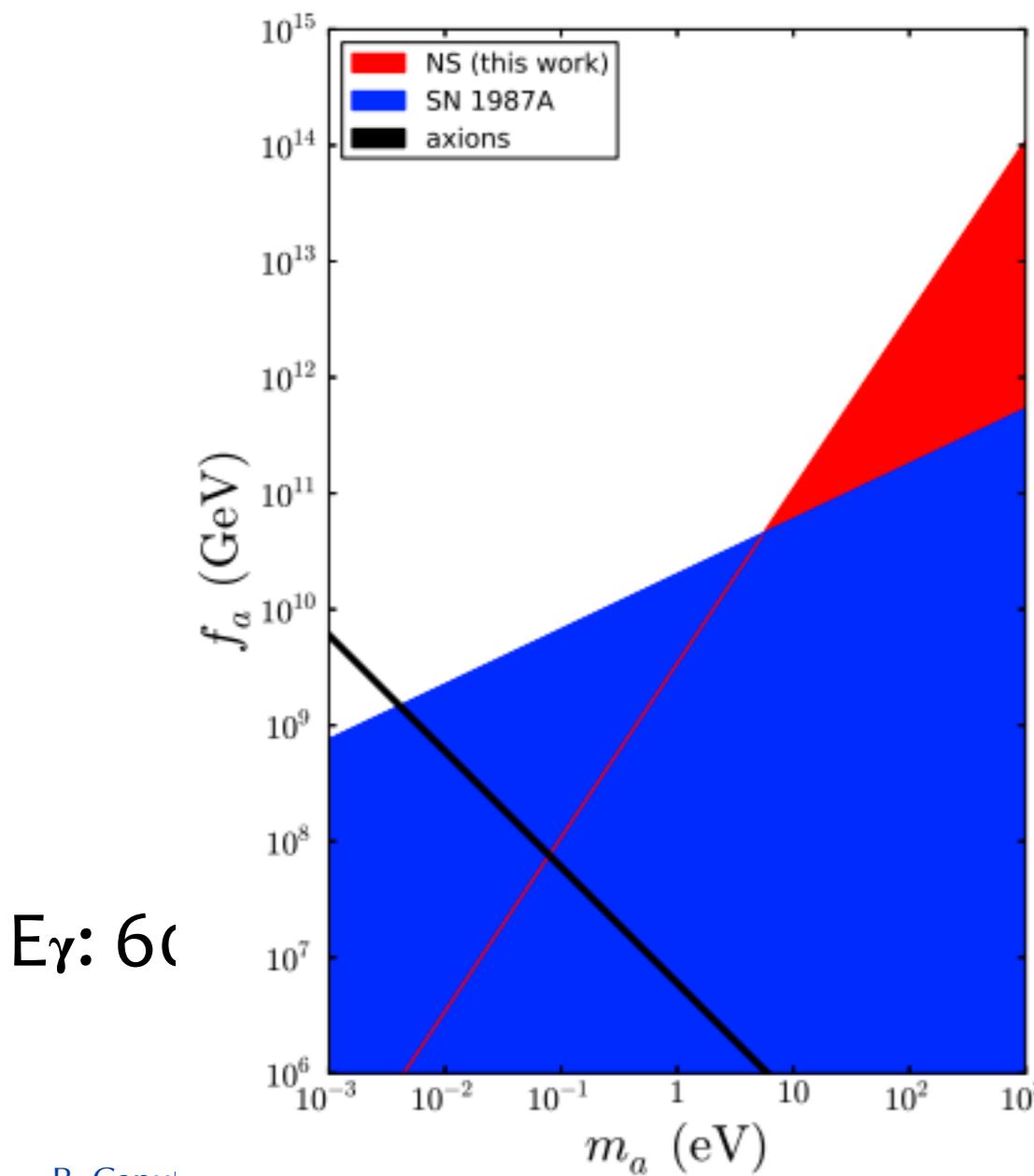
Known Source(s)



Pulsar Target: J0108-1431



Known Source(s)

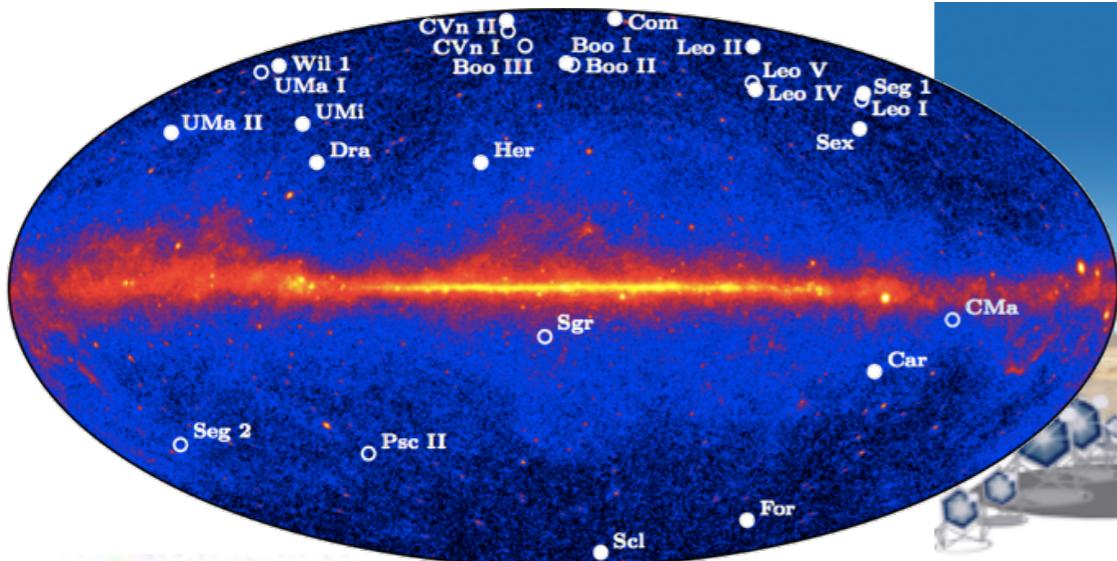


Our Pulsar

**No excess upper limit on QCD
axion mass: 7.9×10^{-2} eV**



The Future...



DARK ENERGY
SURVEY



ComPair
Funded for
prototype

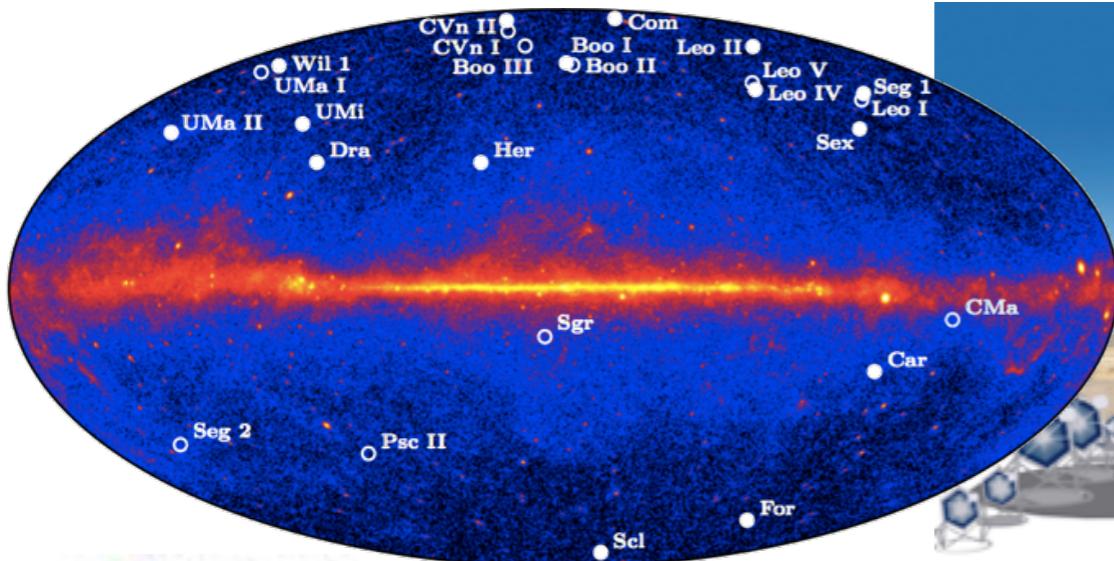
33% of
Fermi Sources
are unassociated



ermi
Gamma-ray
Telescope



The Future...



Astrophysics of Dark Matter (Special Dark)



DARK ENERGY SURVEY



ComPair
Funded for prototype

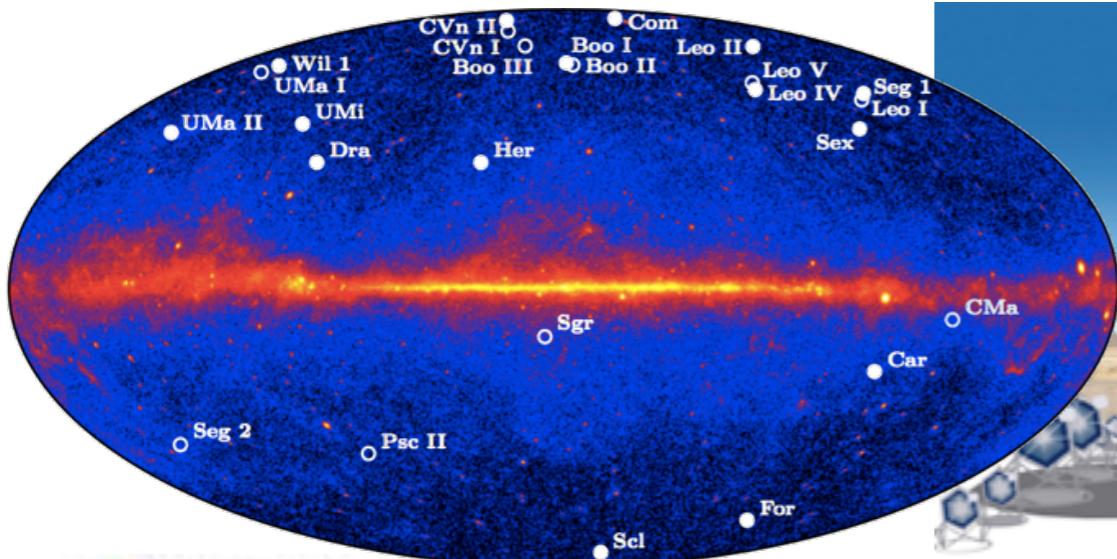
33% of
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ermi
Gamma-ray Telescope



The Future...



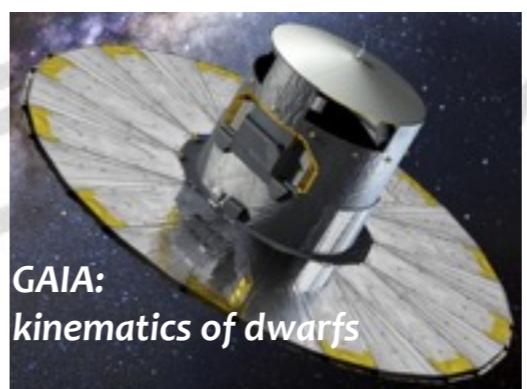
Astrophysics of Dark Matter (Special Dark)



DARK ENERGY SURVEY



33% of Fermi Sources are unassociated



GAIA:
kinematics of dwarfs



JWST:
gal. formation history



DESI:
more dwarfs



SKA:
Dark sub-halos and HI





- 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
 - The LAT has a suite of DM targets: Galactic Center, Galaxy Clusters, dwarf galaxies, the sun, etc...
 - More work to be done understanding the Galactic Center and other potential DM dominated targets
- Complementary searches between Direct Detection and Collider are necessary to understand the nature of a potential discovery
- Not finding dark matter in the obvious places
 - Explore dark matter beyond the standard WIMP paradigm



Thank you!

fermi
Gamma-ray
Space Telescope



Fermi Gamma-Ray Space Telescope



June 11, 2008



fermi
Gamma-ray
Space Telescope



Fermi Gamma-Ray Space Telescope



June 11, 2008



Large Area Telescope

20% sky at once
full sky 3 hours
20 MeV - 1 TeV

Gamma-ray
Space Telescope

Fermi Gamma-Ray Space Telescope

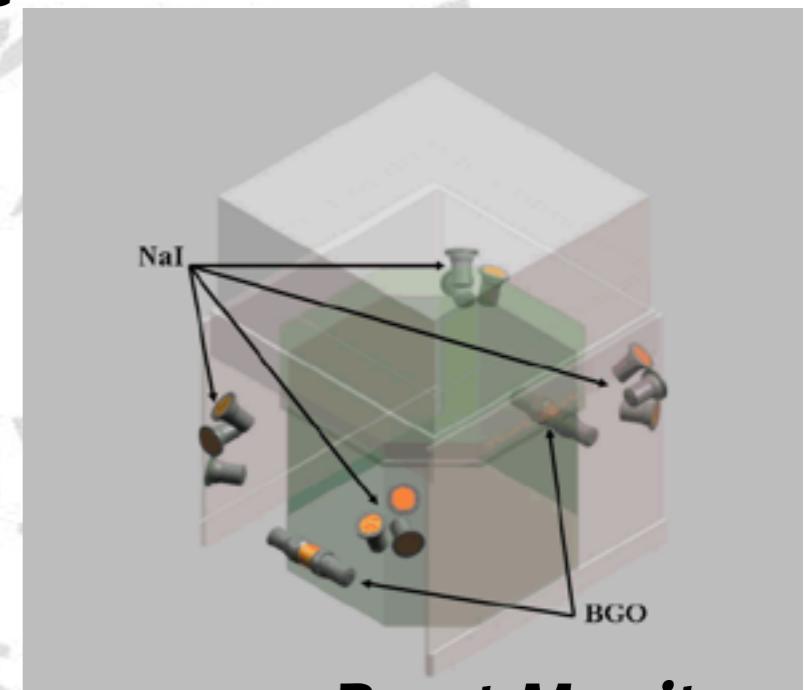


June 11, 2008



Large Area Telescope

20% sky at once
full sky 3 hours
20 MeV - 1 TeV



Gamma-ray Burst Monitor

full sky continuous
8 keV - 40 MeV



Galactic Center



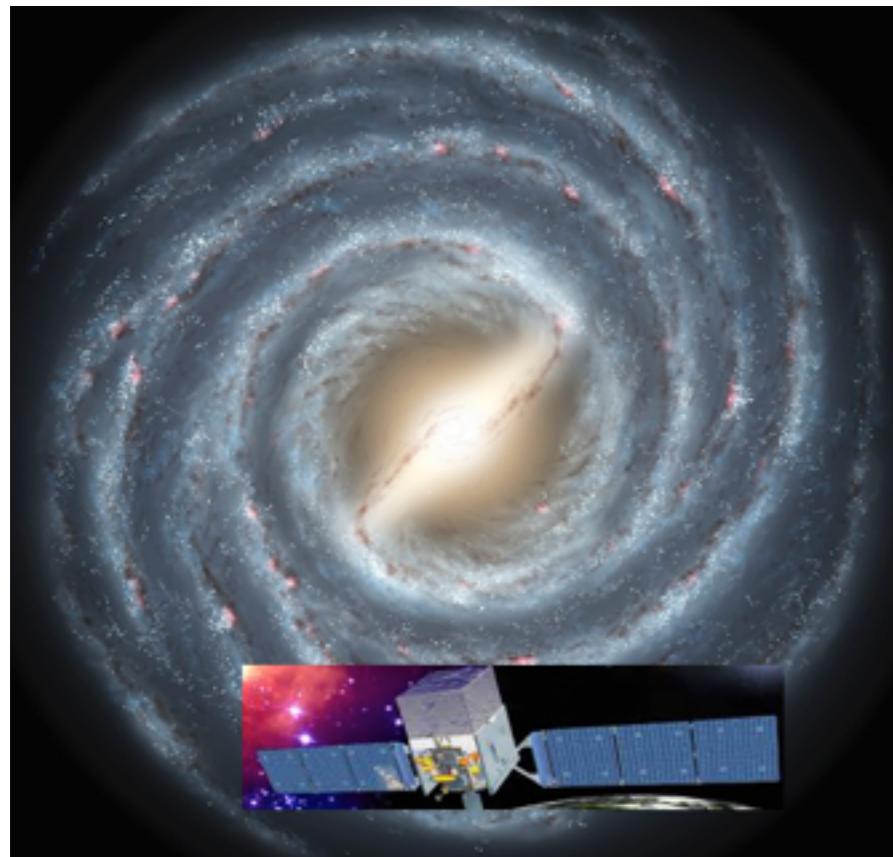
Challenges of observing the Galactic Center



Galactic Center



Challenges of observing the Galactic Center

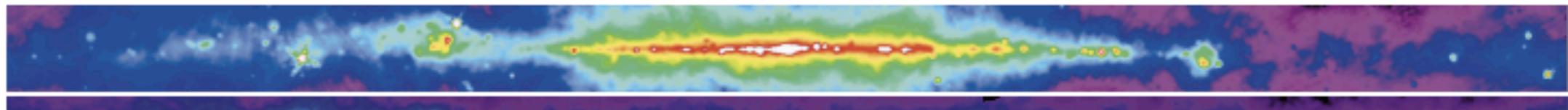


fermi
Gamma-ray
Space Telescope

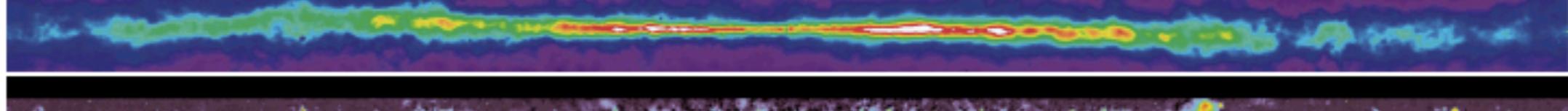


Challenges of observing the Galactic Center

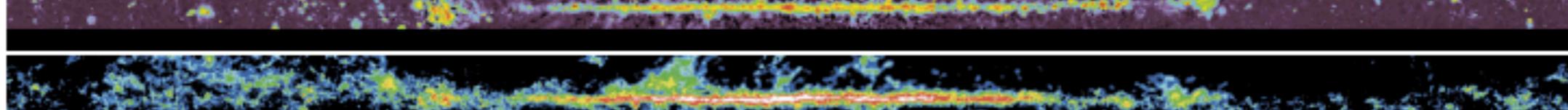
Radio (0.4 GHz)



Atomic Hydrogen



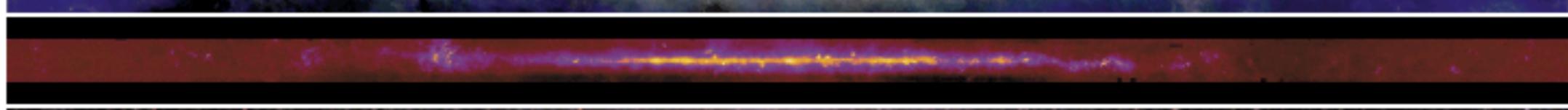
Radio (2.7 GHz)



Molecular Hydrogen



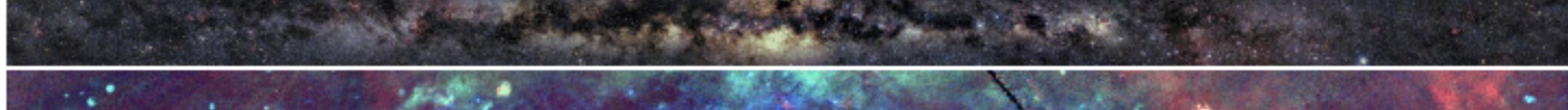
Infrared



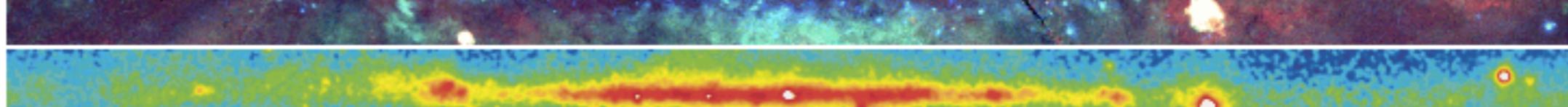
Mid Infrared



Near Infrared



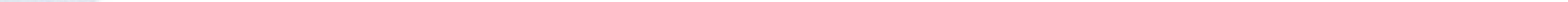
Optical



X-Ray



Gamma Ray



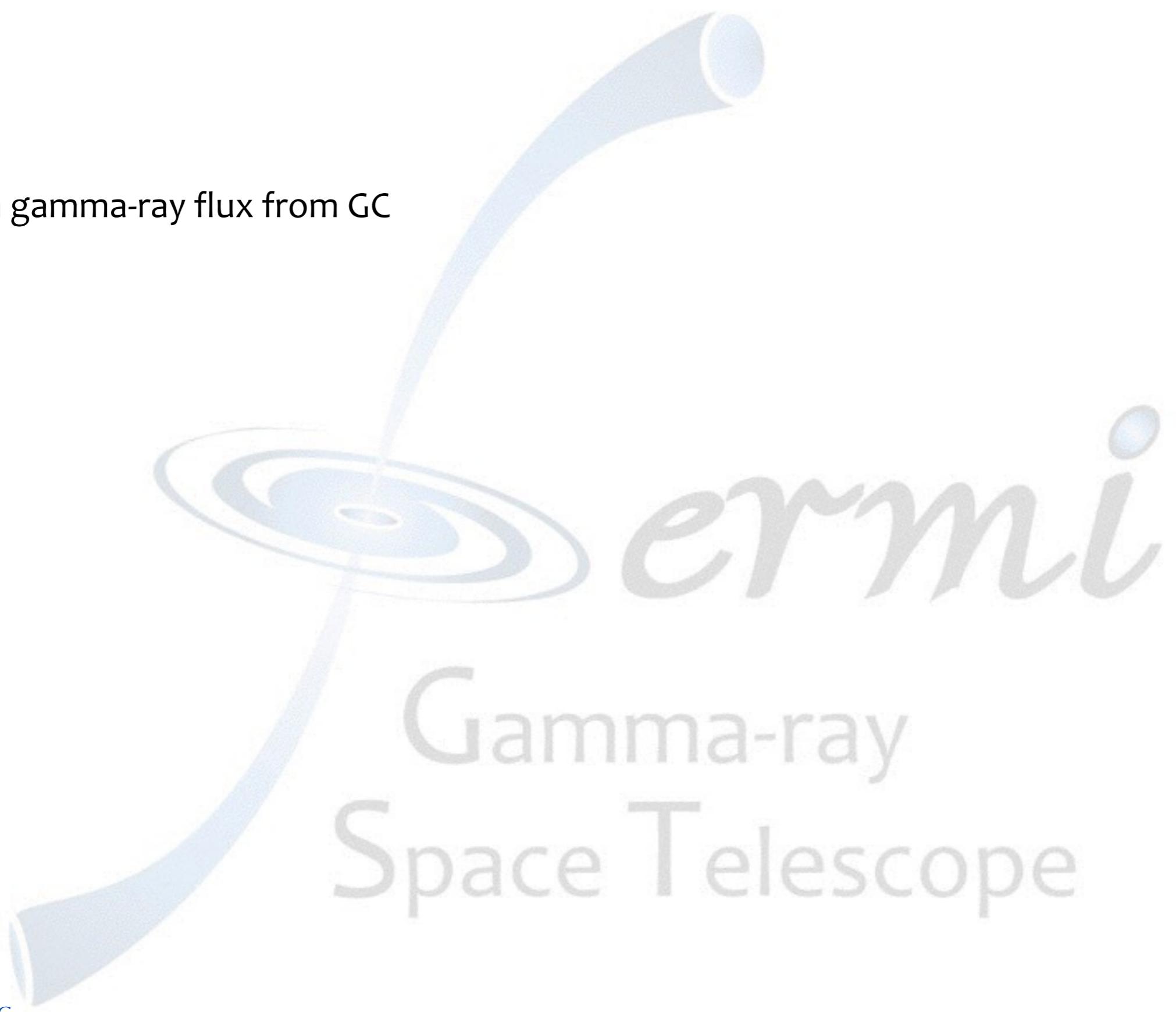


What's Going On in the Galactic Center?



2009

Excess in gamma-ray flux from GC





What's Going On in the Galactic Center?



2009

Excess in gamma-ray flux from GC

2009 — now

Many papers confirming the excess
Speculation as to its origin

Not exhaustive:

- L. Goodenough, D. Hooper, arXiv:0910.2998
- D. Hooper, L. Goodenough, PLB, arXiv:1010.2752
- D. Hooper, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- D. Hooper, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S. Horiuchi, M. Kaplinghat, arXiv:1402.4090
- T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

Dark Matter

Gamma-ray
Space Telescope



What's Going On in the Galactic Center?



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- T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

Unresolved populations**

Dark Matter

****Massive star formation (OB type stars)**

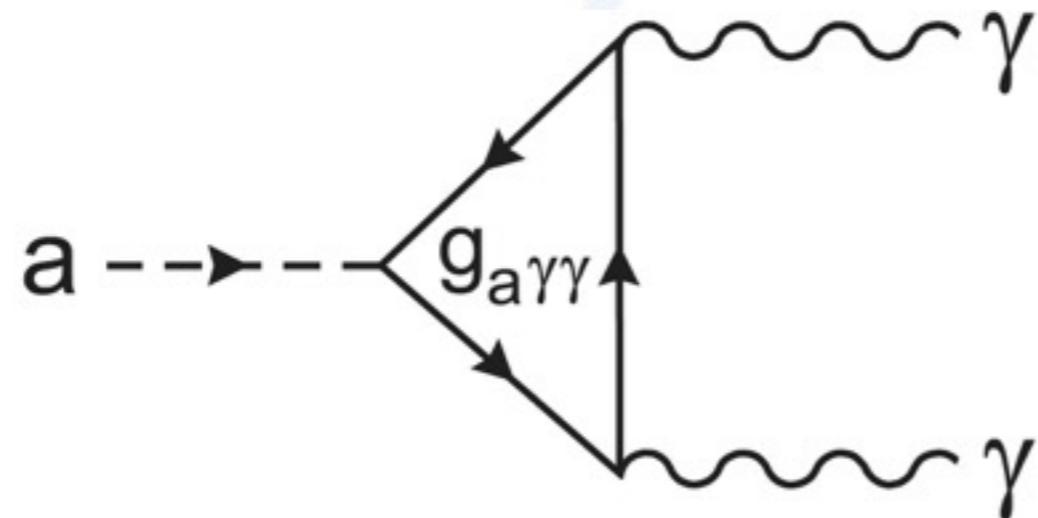
Unresolved point sources

Pulsars...

Axions and Axion-like Particles (ALPs)



- A solution to a different problem
 - Quantum chromodynamics (QCD)
 - Axions: 10^{-5} to 10^{-3} eV
 - Couple to photons in an external magnetic field
 - strong field = more coupling



Strong magnetic fields
in galaxy clusters...

- Axion-Like Particles (ALPs) ← this one
 - not restricted to those masses... but still light

M. Ajello et. al, Phys. Rev. Lett. 116, 161101 (2016) arXiv:1603.06978v1