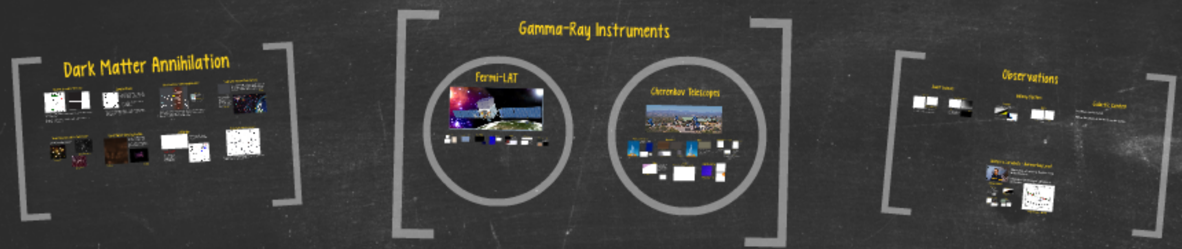
The Indirect Detection of Dark Matter with Gamma-Rays



Tim Linden

Lecture 7

Fall 2014 Compton Lectures

Next Week

Doubly indirect searches for dark matter annihilation

Question: What happens if the annihilation produces something like electrons and protons, can we see those too?

The Indirect Detection of Dark Matter with Gamma-Rays

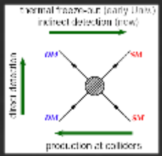
Tim Linden

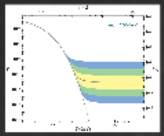
Lecture 7

Fall 2014 Compton Lectures

Dark Matter Annihilation

Dark Matter Indirect Detection

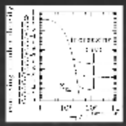




Dark Matter annihilation in the early universe should still continue today (at a reduced rate)

Unlike accelerator and direct detection seaches, we know the cross-section we are looking for!

Complications

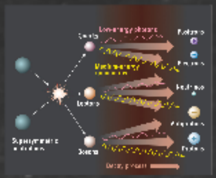


The perfect correspondence between the WIMP cross-section in the early universe can be spoiled by a few different features:

- Velocity Dependent Cross-section
- Resonances
- Coannihilations

However, many models predict some portion of the interaction is simple - leading to a cross-section today that is relatively close to the magic 3×10^{-26} cm^3 s^{-1}

What Does Dark Matter Annihilate Into?



If dark matter is it's own antiparticle (or if a dark matter particle and antiparticle collide), then it can annihilate into any set of standard model particles and antiparticles

Looking for Standard Model Particles

Uncharged particles (photons, neutrinos) leage the site of the dark matter annihilation event, and travel straight to our detectors on earth

this week!

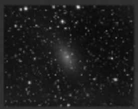
Charged particles don't move in straight lines, the get bounced around before they reach earth

next week!

Where Should We Look for Dark Matter?

Lots of possible targets!

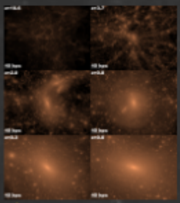
Galaxy Clusters



Dwarf Spheroidal Galaxies

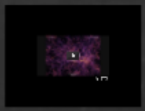
Galactic Center

Dark Matter Density Profiles



Simulations tell us where the dark matter density is high

The square of the dark matter density tells us the annihilation rate



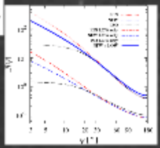
Via Lactea

Aquarius

J-Factor

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m^2_{DM}}\int_{E_{min}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma}_{\Phi_{PP}} \times \underbrace{\int_{\Delta\Omega}\left\{\int_{l.o.s.}\rho^2(r)dl\right\}d\Omega'}_{J\text{-factor}}$$

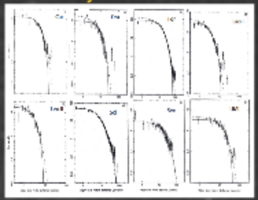
Number of annihilations expected from astrophysics



Three Key Targets:

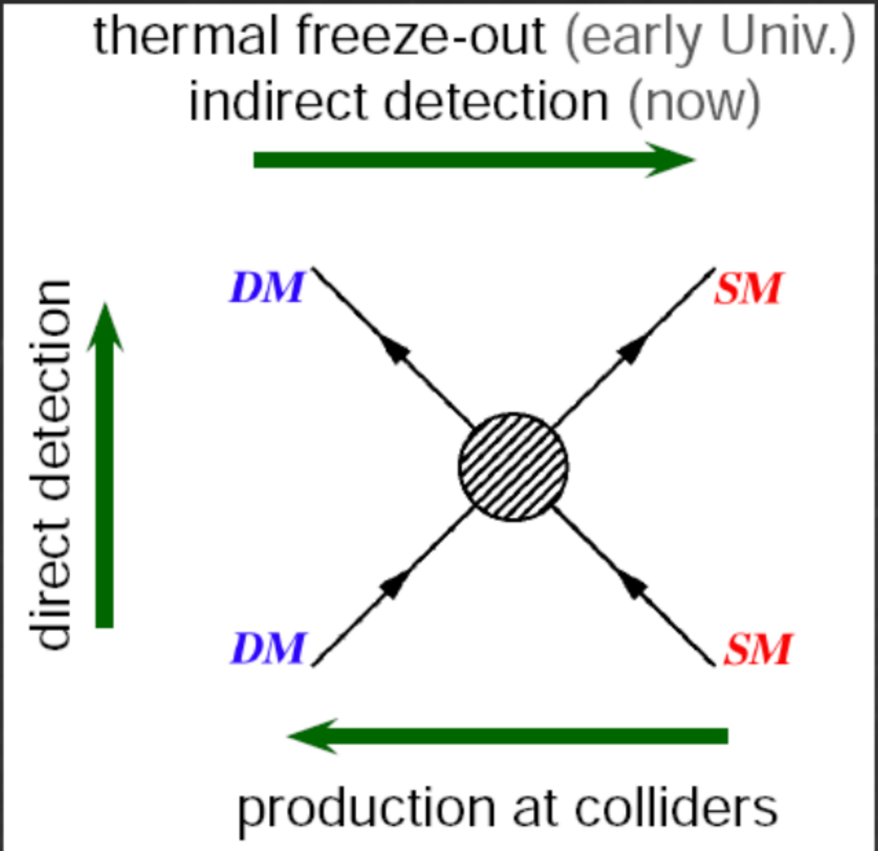
1.) Galactic Center
2.) Dwarf Galaxies
3.) Galaxy Clusters
4.) Galactic Halo

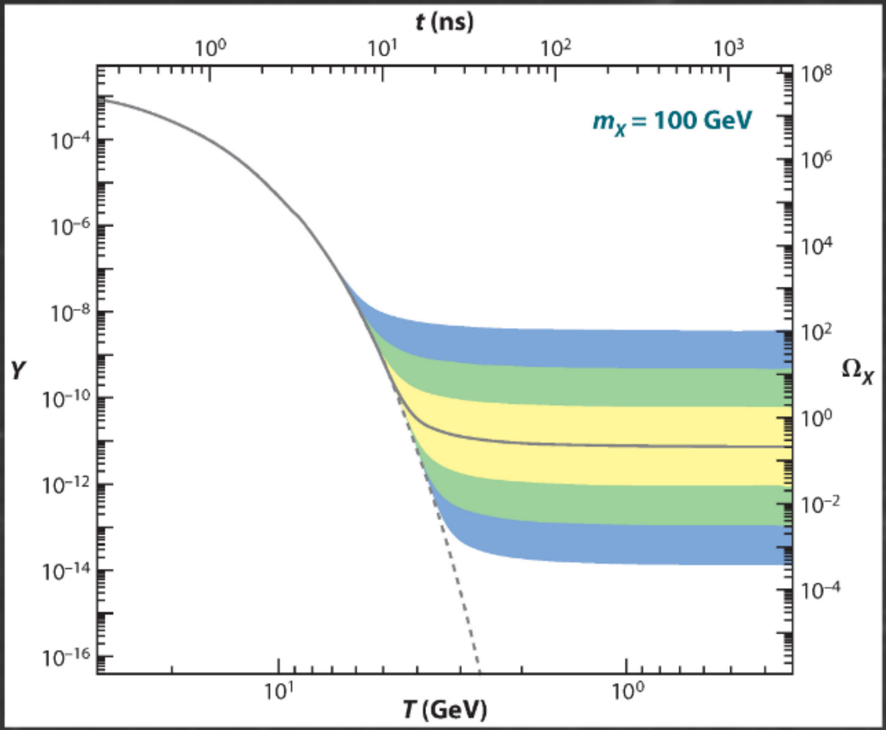
Measuring Dark Matter in Dwarfs



Can actually measure the velocity of each star - calculate the gravitational force from dark matter!

Dark Matter Indirect Detection





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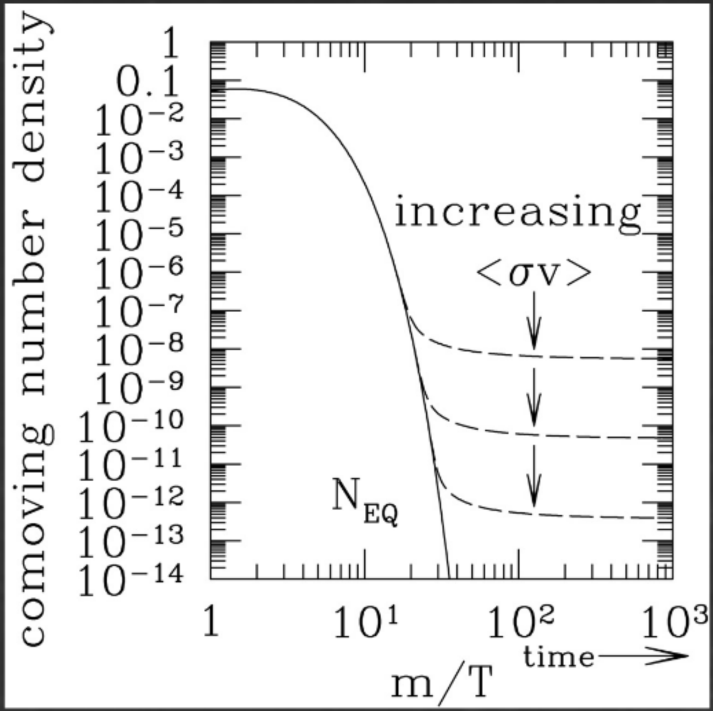

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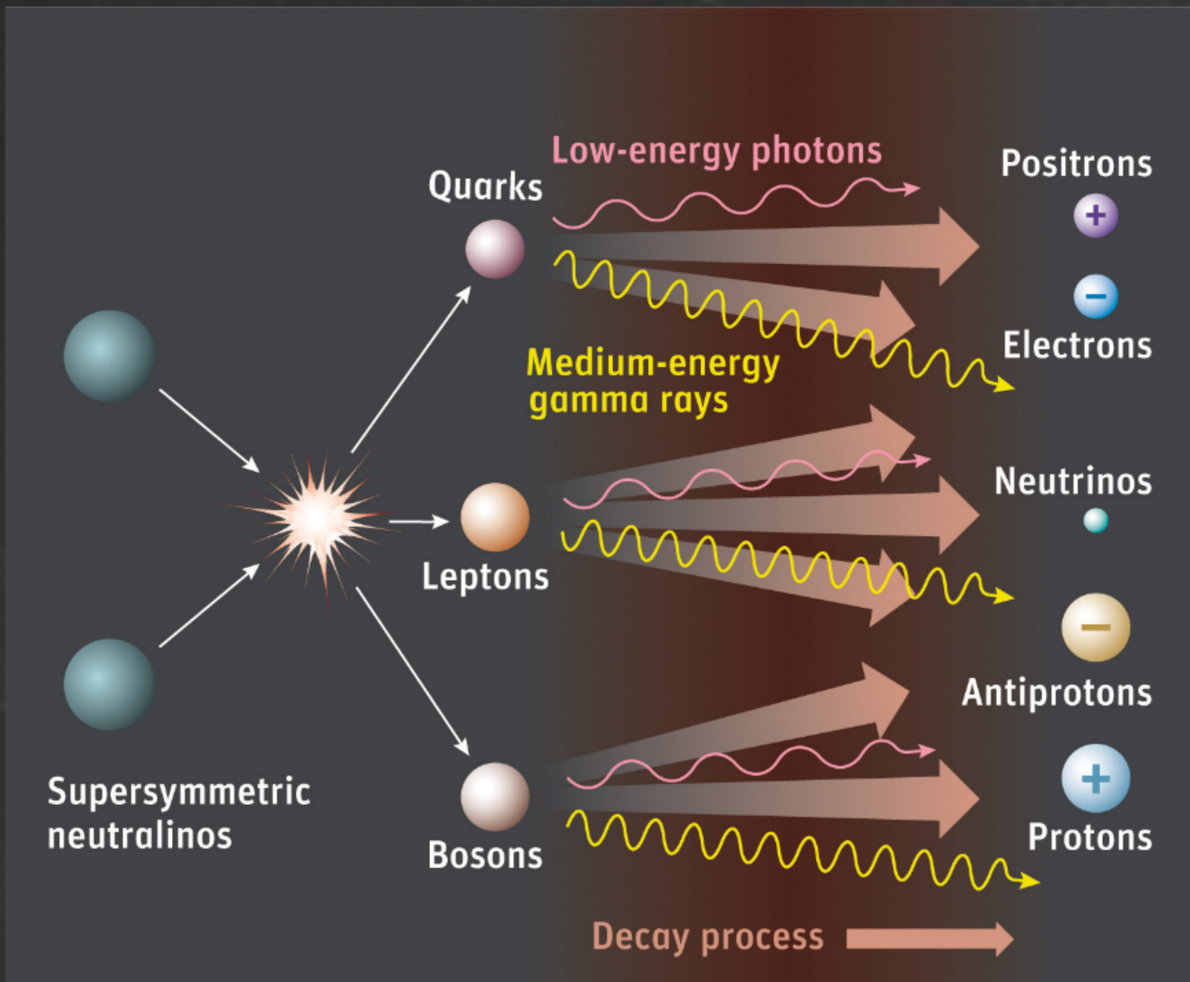

Why Gamma-Rays?

Remember, the WIMP miracle says that the particle that interacts via a weak force, and has a mass on the weak scale (~100 GeV) can produce the dark matter

When these particles annihilate, a fraction of that energy goes into light immediate

So this light tends to have an energy of <~100 GeV (usually the photon energy peaks at about 1/20th of the dark matter mass)

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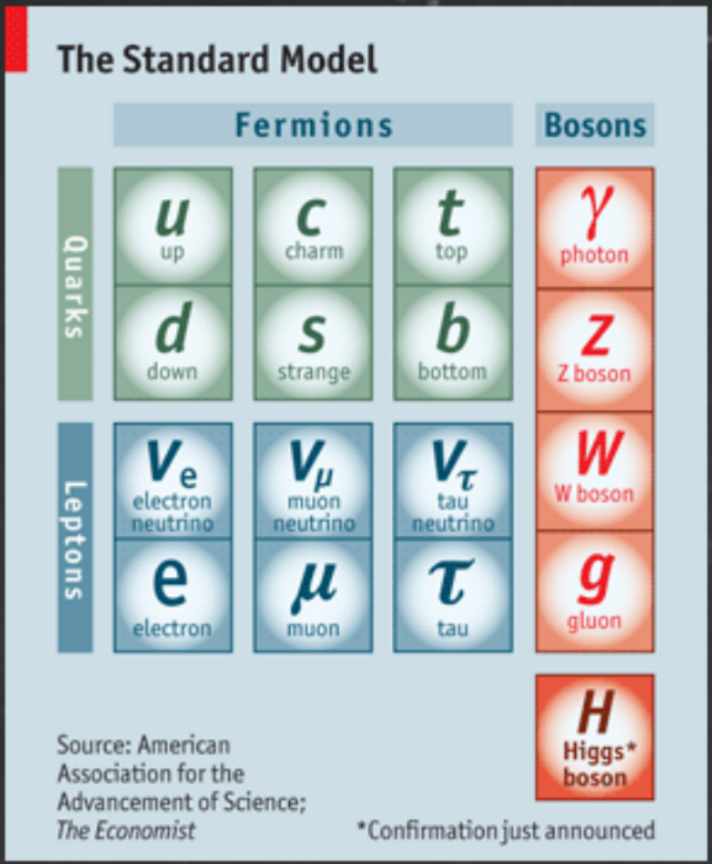

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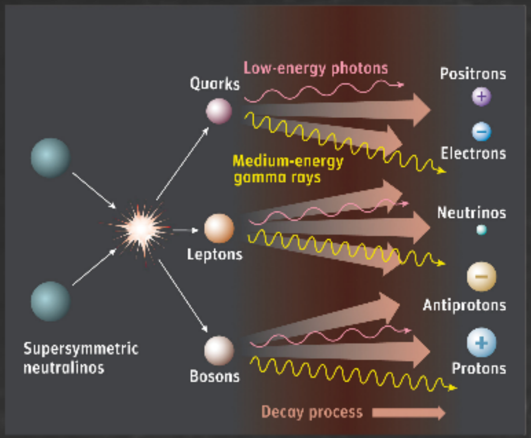

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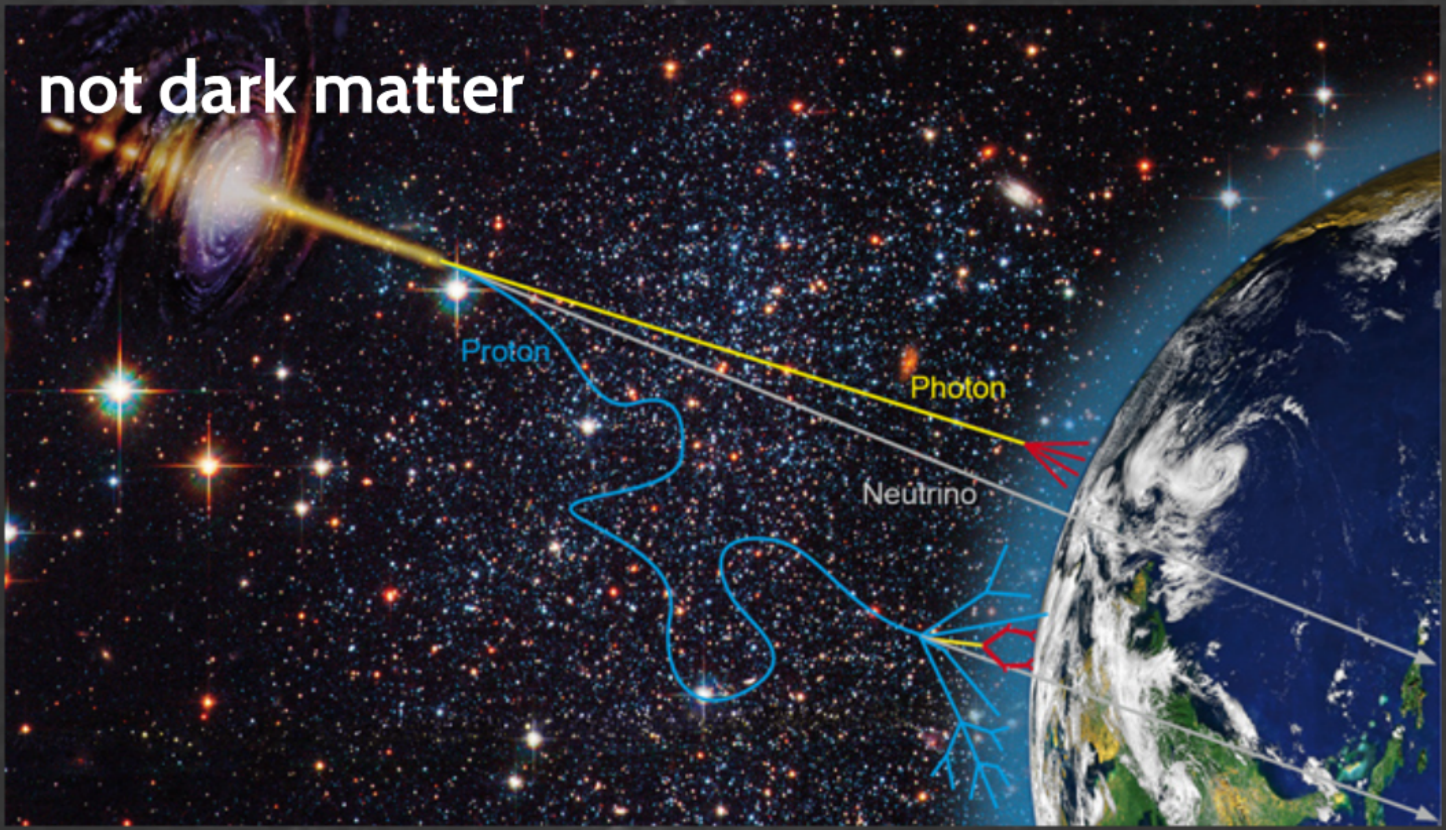

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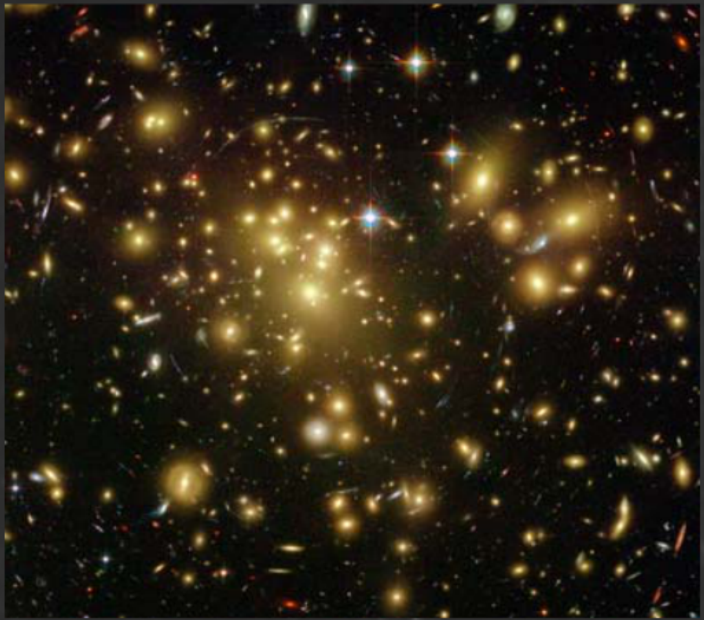

Galaxy Clusters

Dwarf Spheroidal Galaxies

Galactic Center

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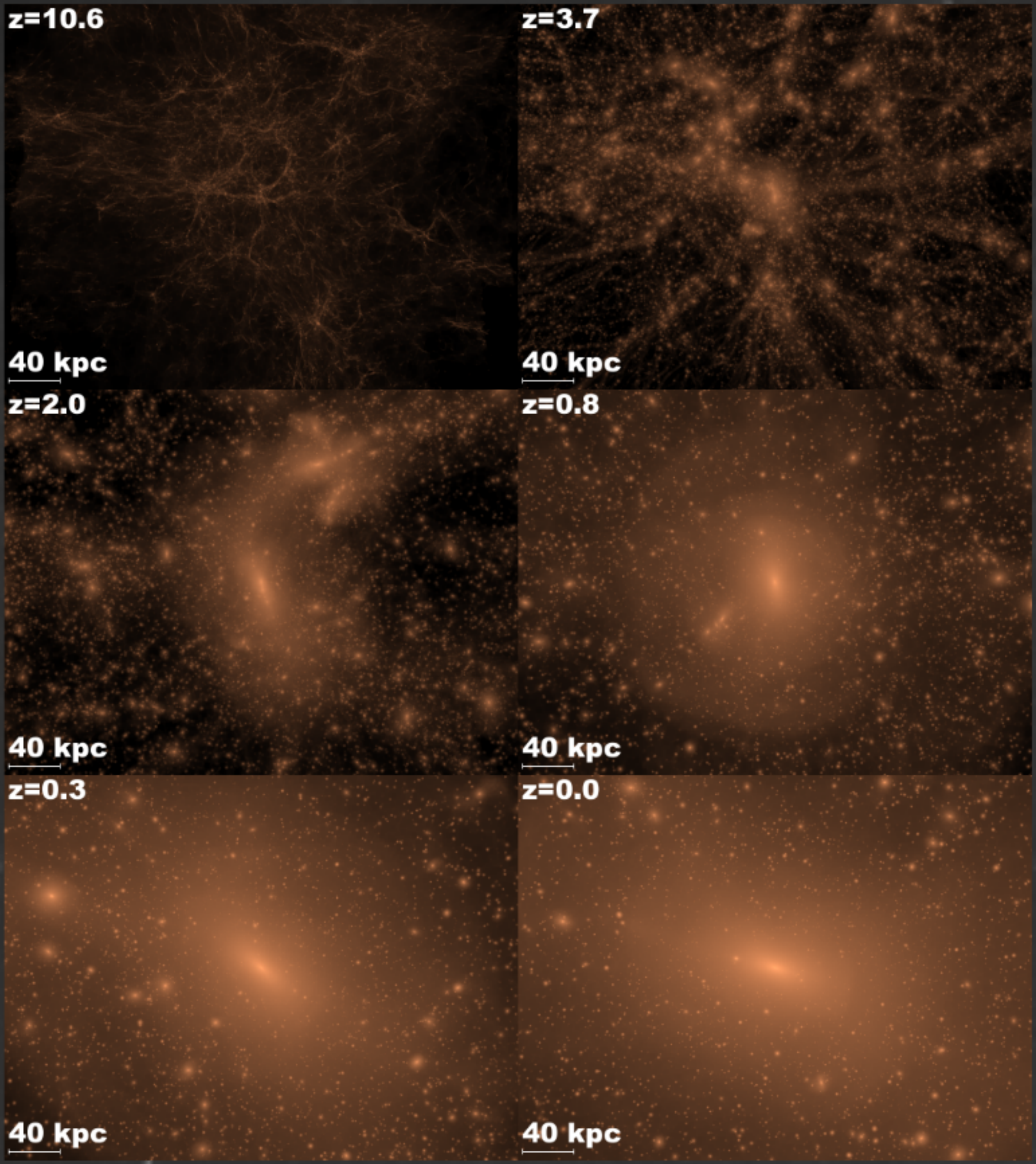

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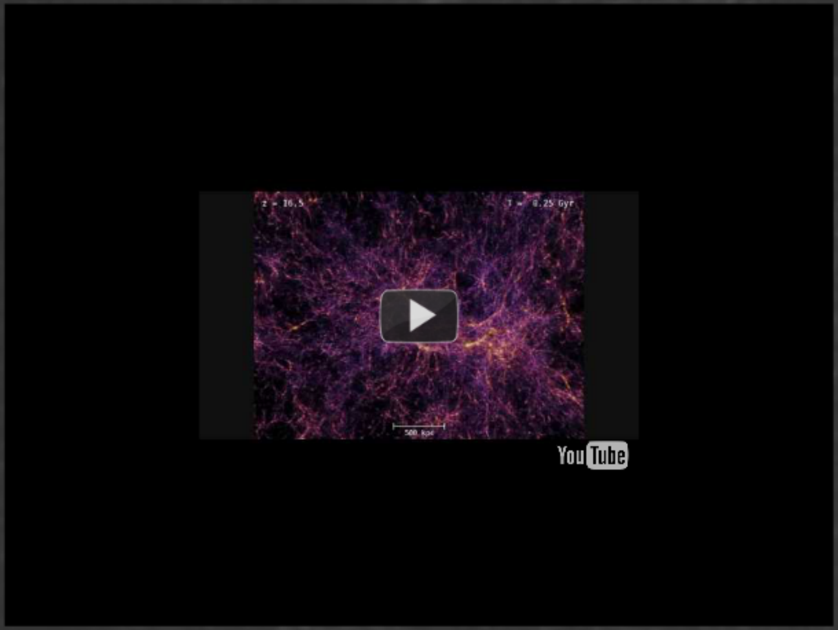

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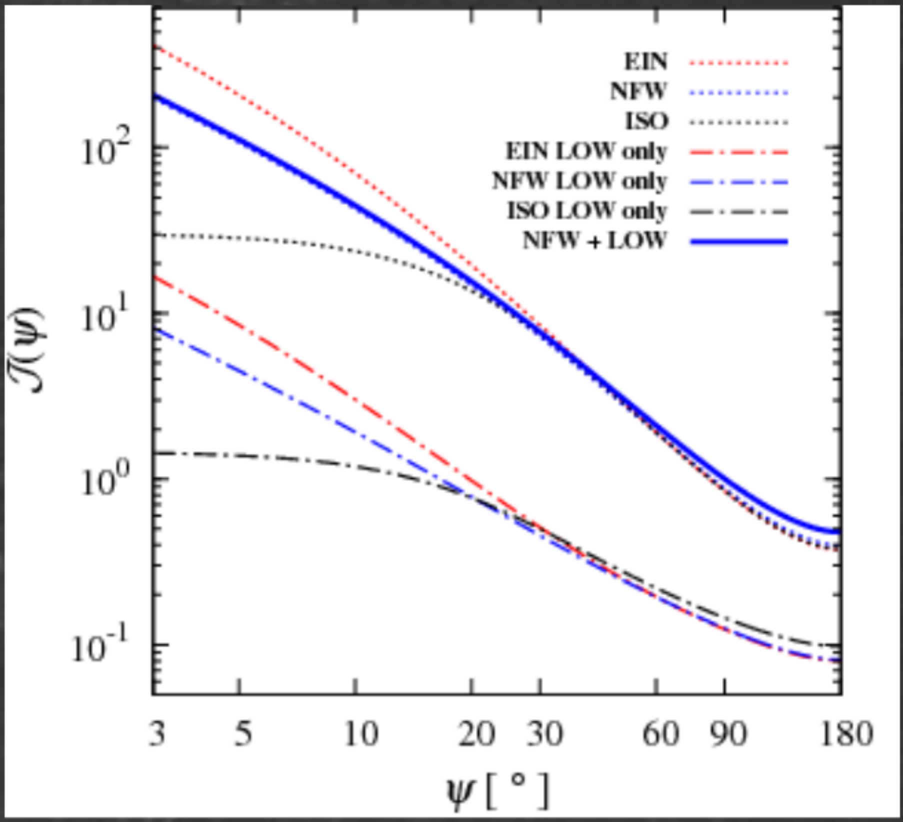

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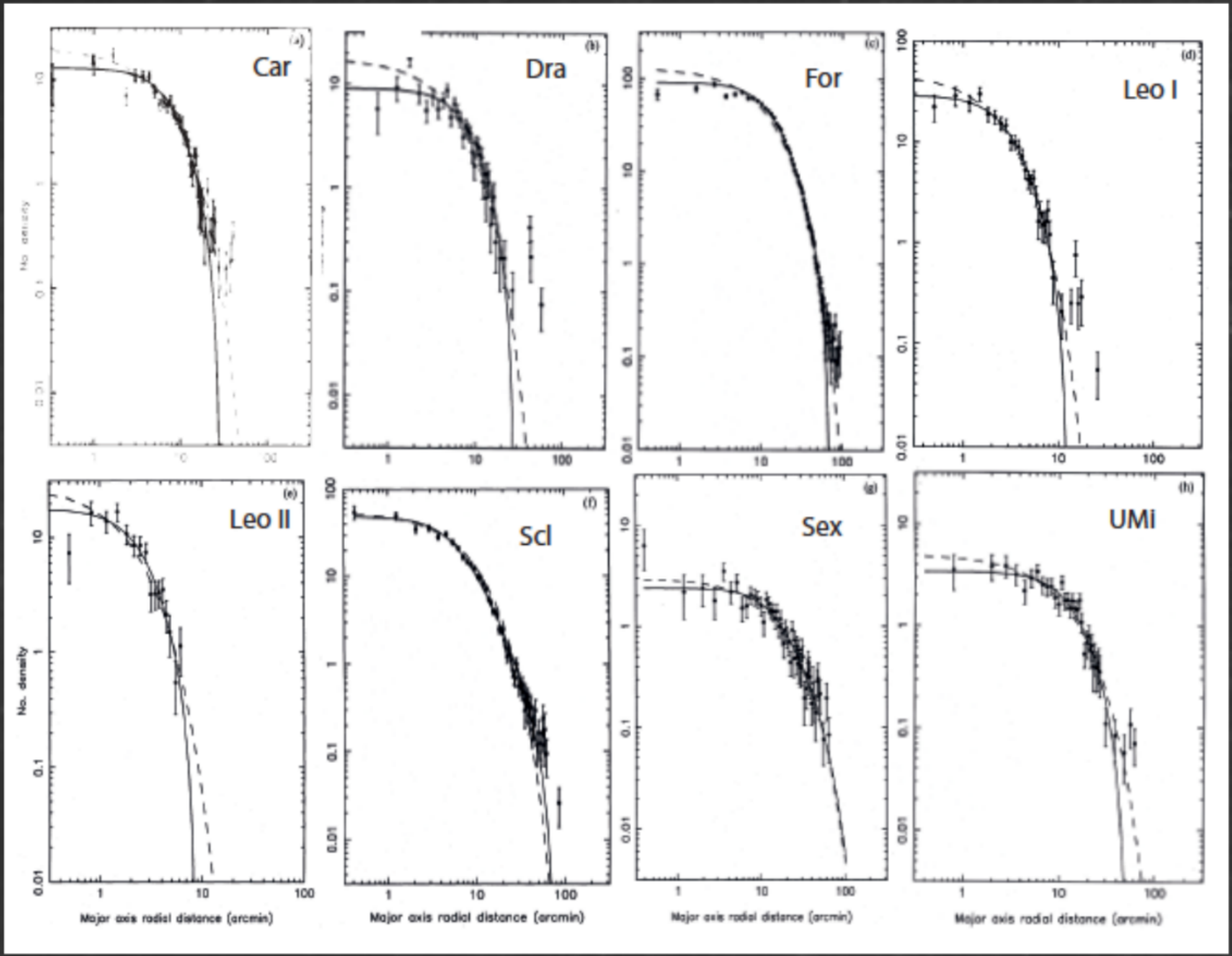

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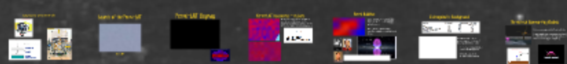
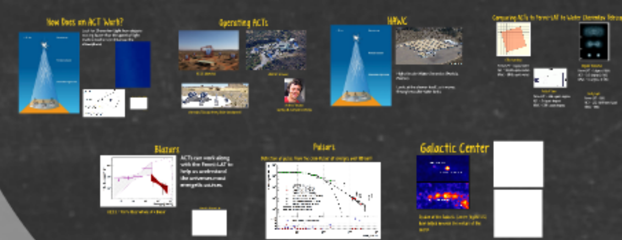
Gamma-Ray Instruments

Fermi-LAT



Cherenkov Telescopes



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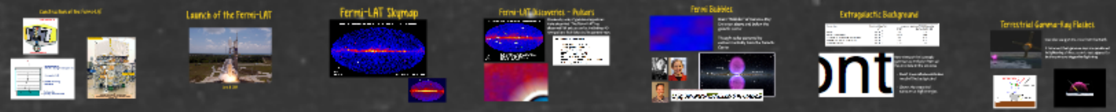
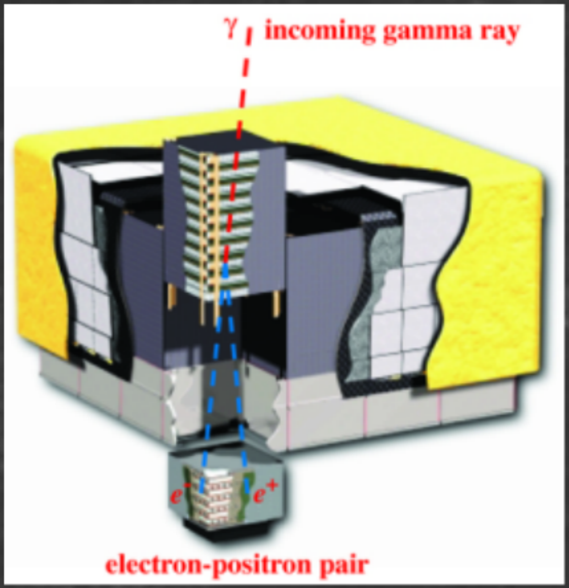
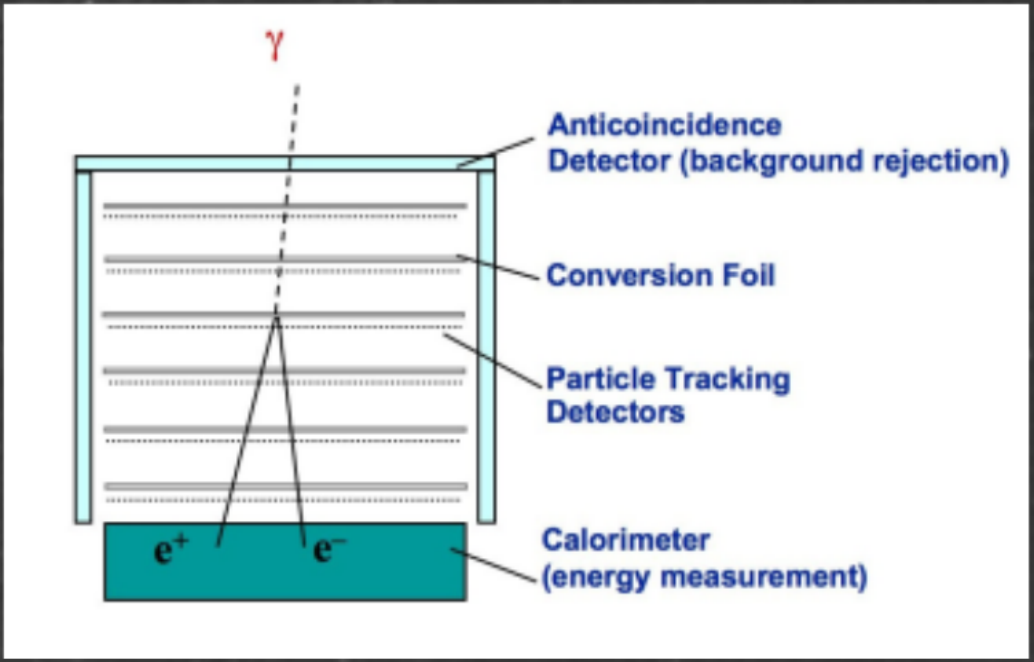

Launch of the Fermi-LAT
Fermi-LAT Skymap
Fermi-LAT Discoveries - Pulsars
Fermi Bubbles
Extragalactic Background
Terrestrial Gamma-Ray Flashes

Construction of the Fermi-LAT

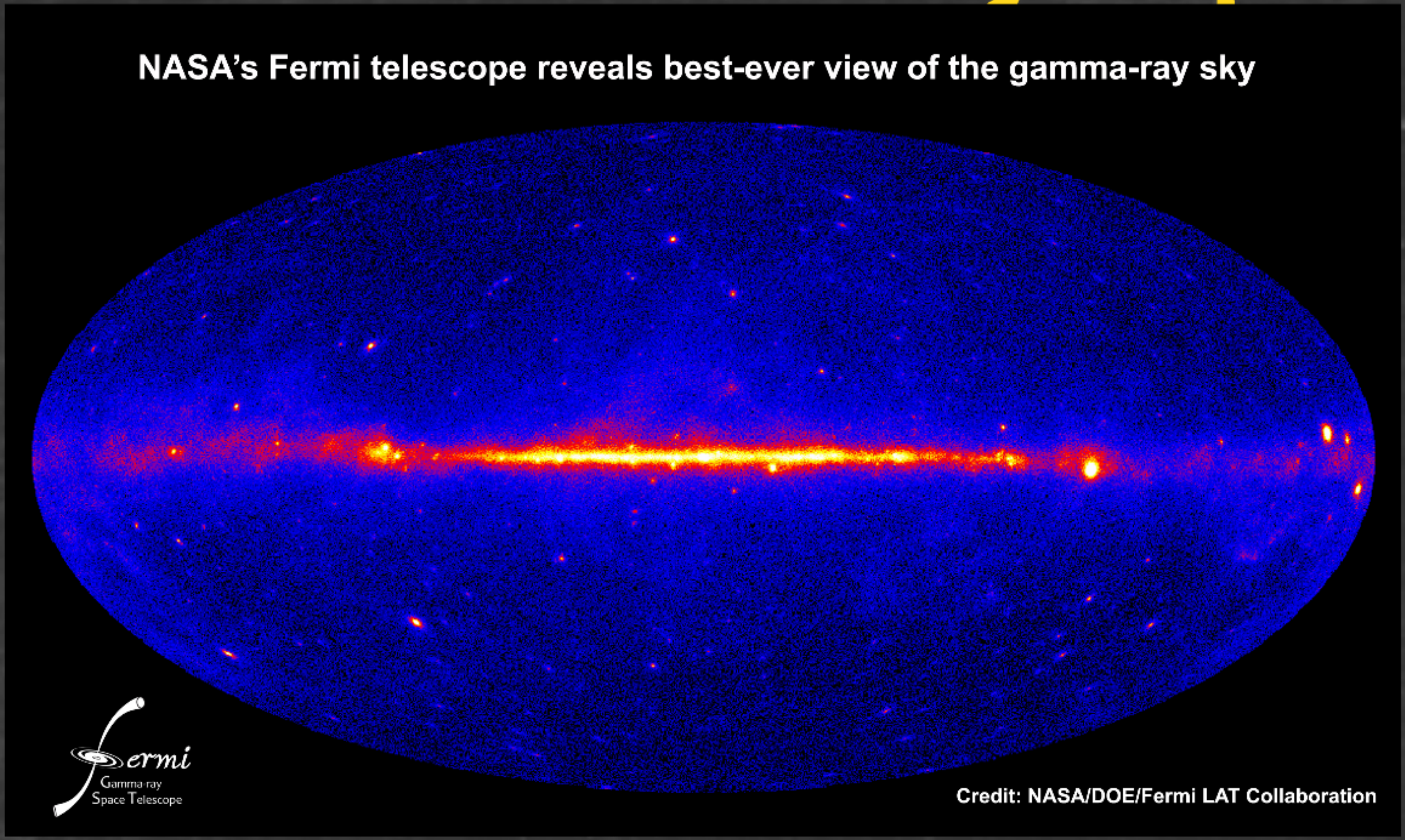


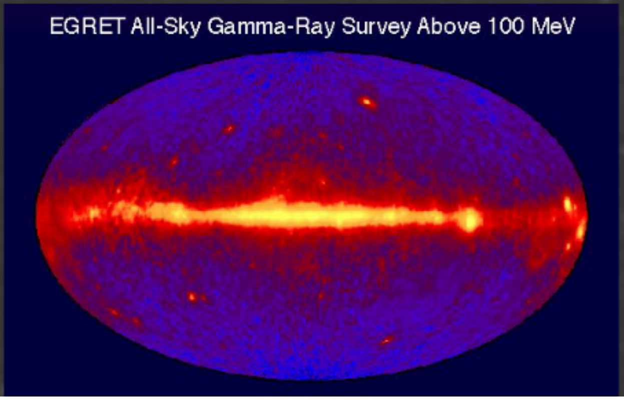


Launch of the Fermi-LAT

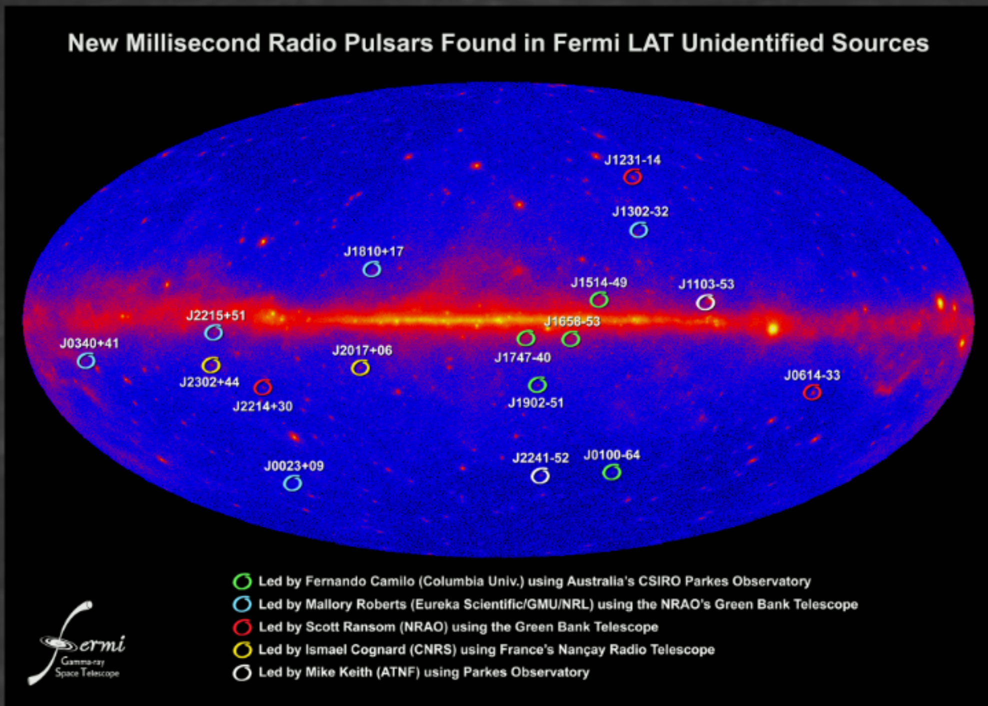
June 11, 2008

Fermi-LAT Skymap





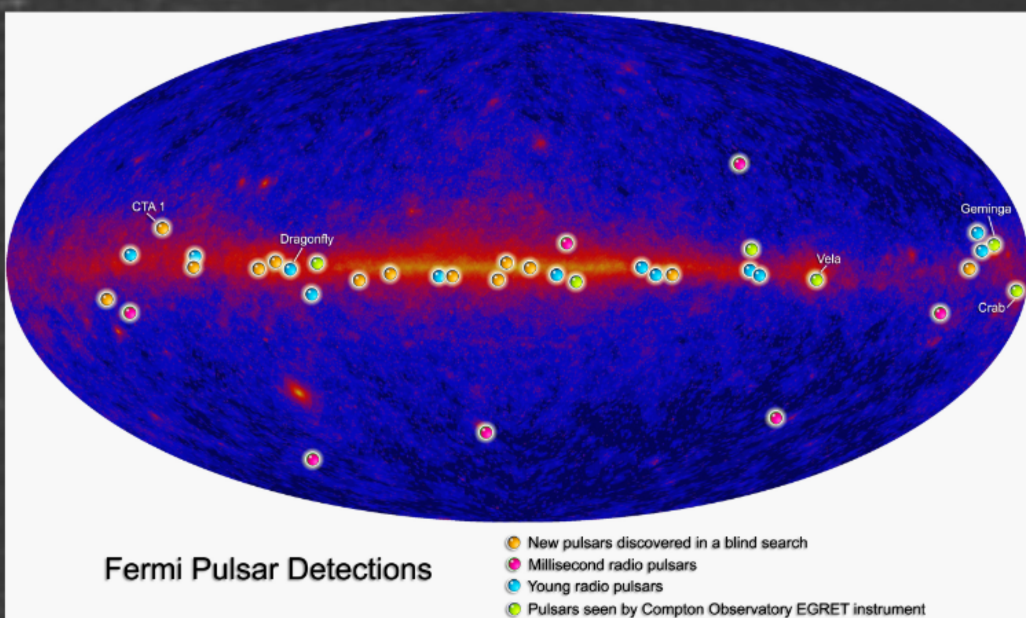
Fermi-LAT Discoveries - Pulsars



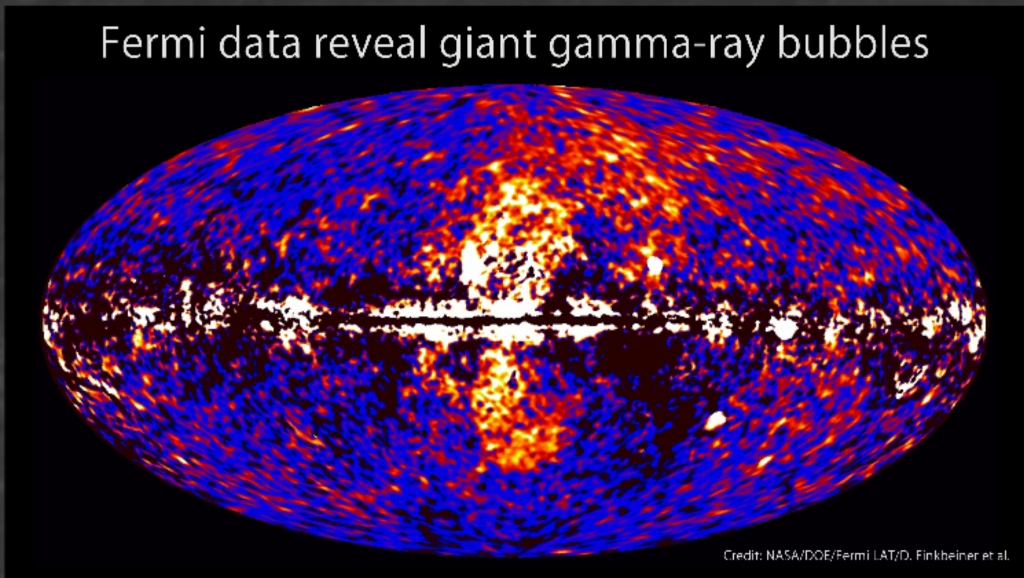
Previously, only 7 gamma-ray pulsars were observed. The Fermi-LAT has observed 161 pulsars so far, including 40 new pulsars first detected in gamma-rays.

Total number of pulsars: 161

- Young, radio selected: 46
- Young, gamma selected: 40
- Young, X-ray selected: 4
- MSP, radio selected : 70
- MSP, gamma selected : 1
- Found in radio searches of LAT sources : 38
- EGRET/COMPTEL pulsars: 7

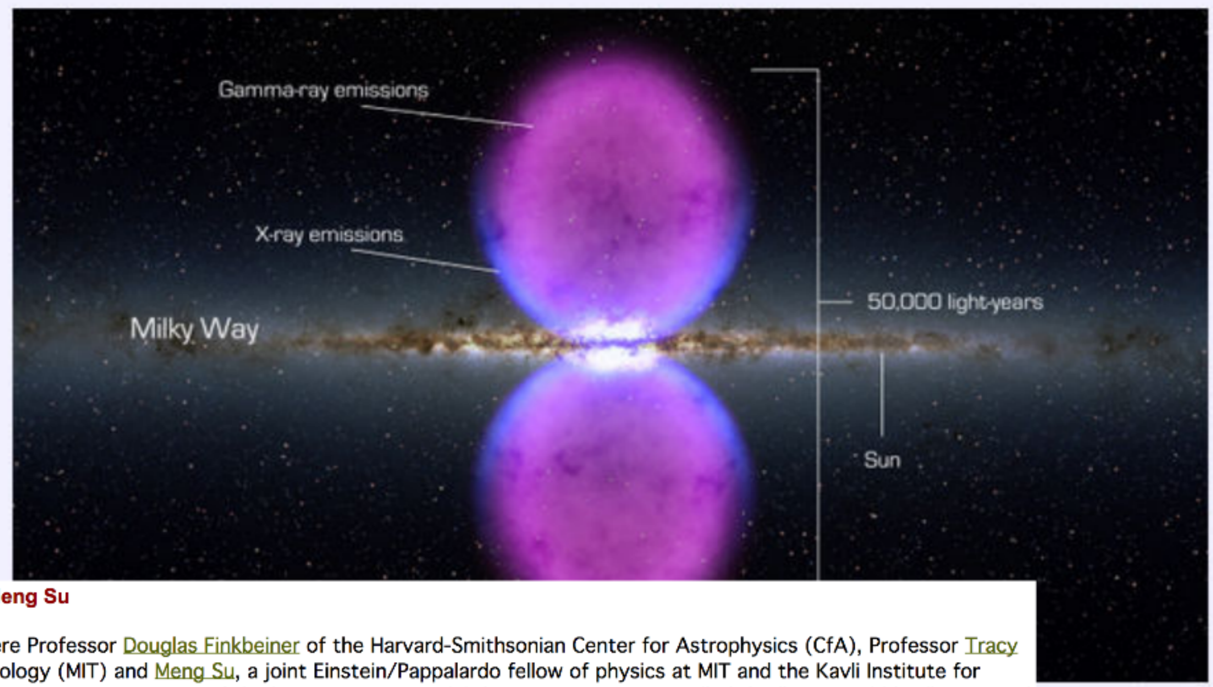


Fermi Bubbles



Giant "Bubbles" of Gamma-Ray Emission above and below the galactic center

Thought to be powered by outburst activity from the Galactic Center

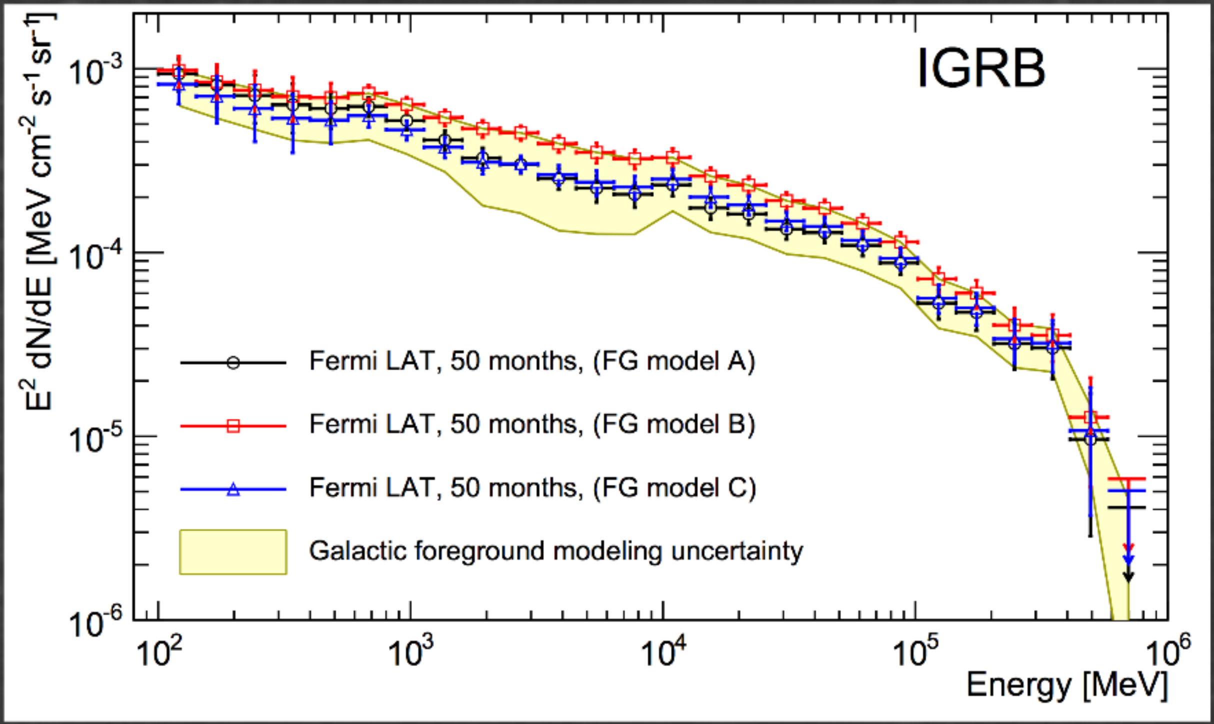


2014 Douglas Finkbeiner, Tracy Slatyer, and Meng Su

The scientists awarded the 2014 Rossi Prize were Professor Douglas Finkbeiner of the Harvard-Smithsonian Center for Astrophysics (CfA), Professor Tracy Slatyer of the Massachusetts Institute of Technology (MIT) and Meng Su, a joint Einstein/Pappalardo fellow of physics at MIT and the Kavli Institute for Astrophysics and Space Research for their discovery, in gamma rays, of the large unanticipated Galactic structure now called the "Fermi Bubbles." From end to end, Fermi bubbles extend 50,000 light years, or roughly half of the Milky Way's diameter. These structures may be the remnant of an eruption from a supersized black hole at the center of our Galaxy.

Extragalactic Background

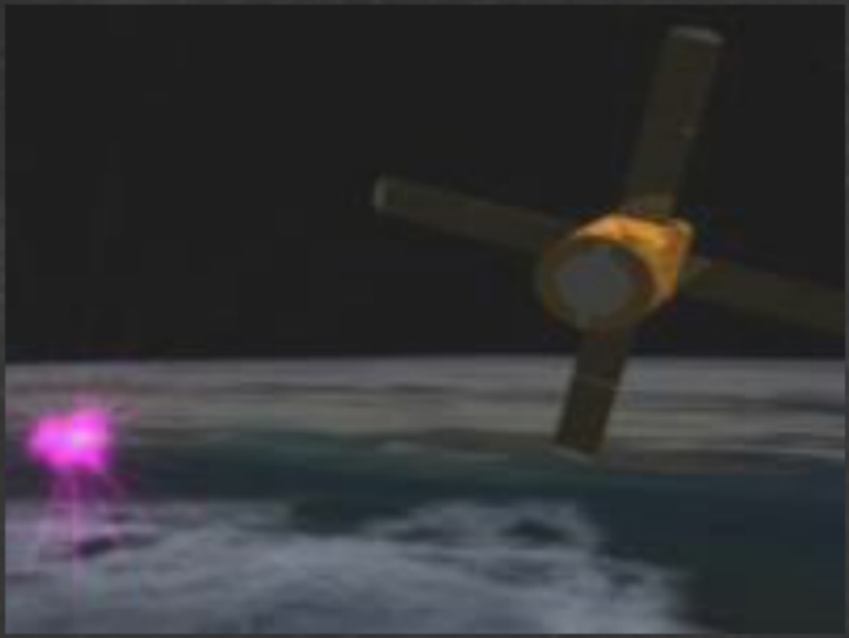
Source class	Predicted $C_{100}/\langle I \rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%



New views of the isotropic gamma-ray emission from all the structure in the universe

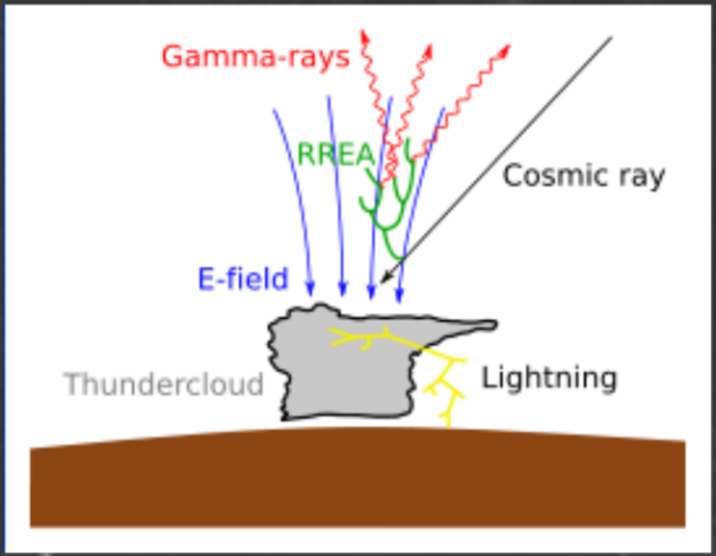
- Don't know what contributes most of the background
- Shows the expected turnover at high energies

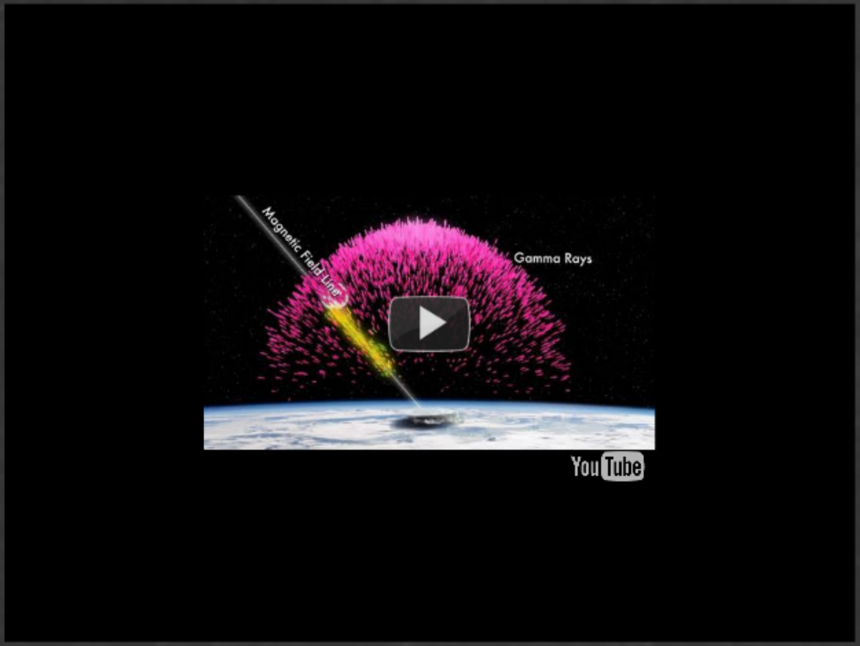
Terrestrial Gamma-Ray Flashes

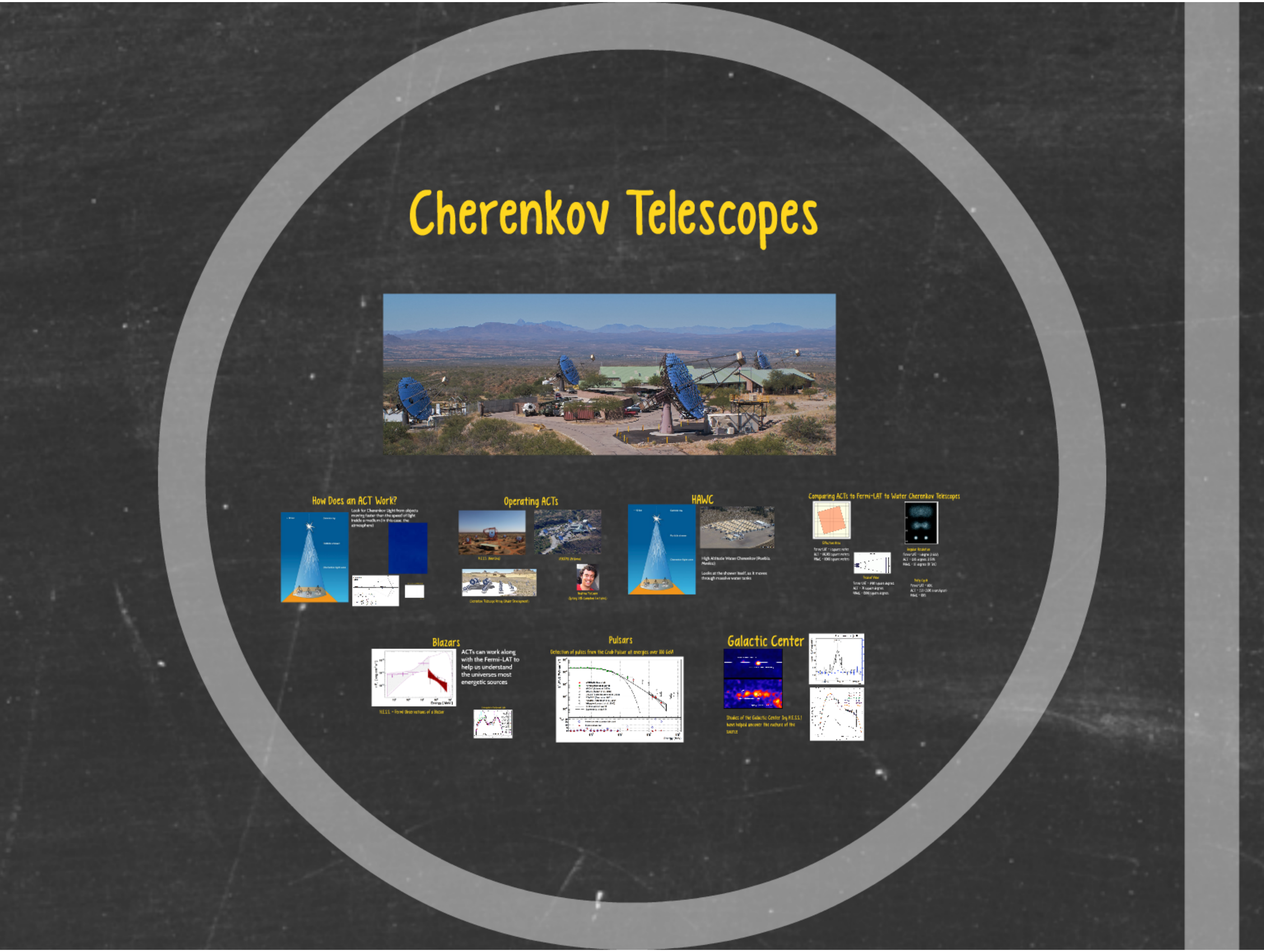


Can also see gamma-rays from the Earth.

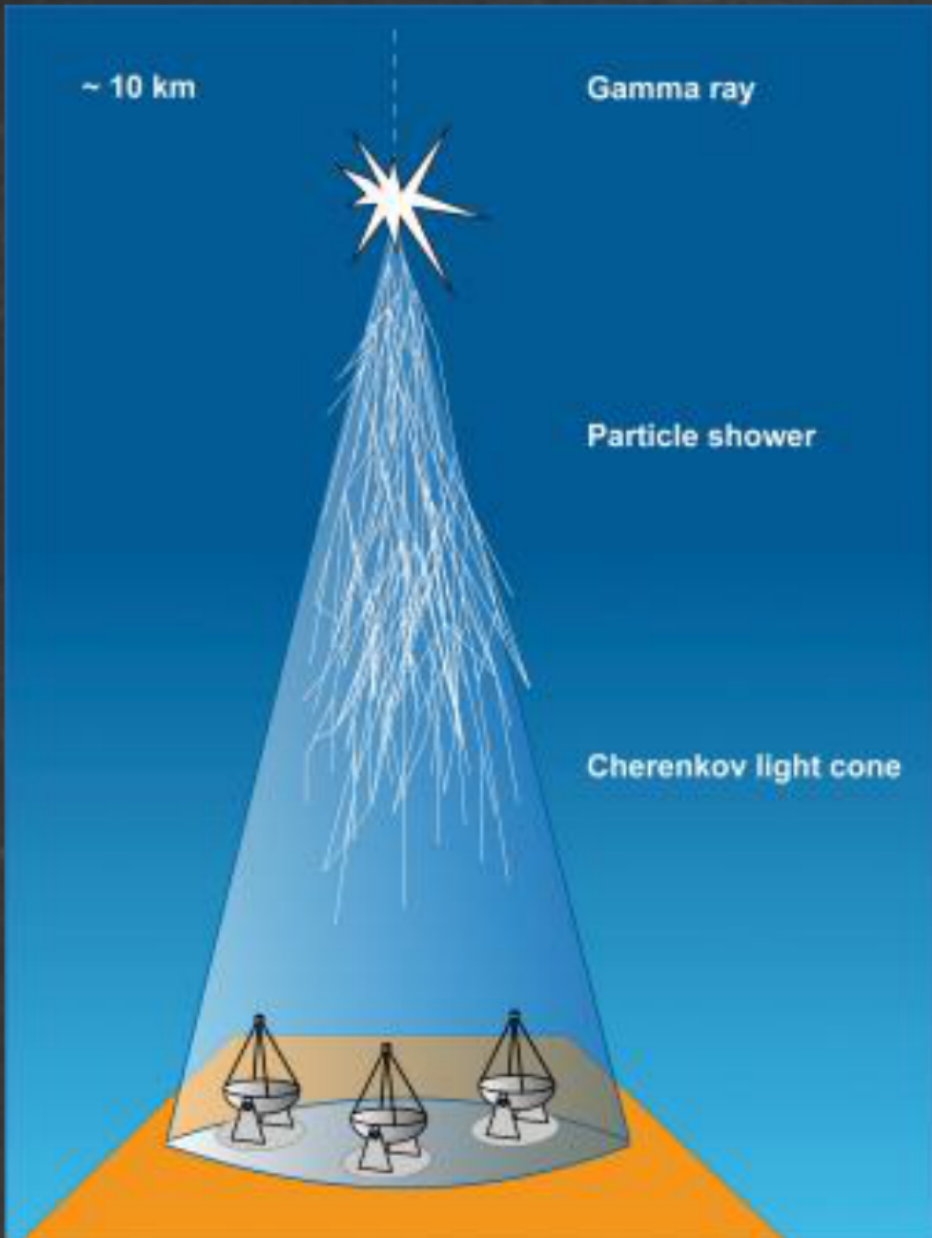
It turns out that gamma-rays are produced in lightening strikes, cosmic-rays appear to be the primary trigger for lightning






Cherenkov Telescopes
How Does an ACT Work?
Look for Cherenkov Light from objects moving faster than the speed of light inside a medium (in this case, the atmosphere)
Operating ACTs
HAWC
High Altitude Water Cherenkov (Puebla, Mexico)
Looks at the shower itself, as it moves through massive water tanks
Comparing ACTs to Fermi-LAT to Water Cherenkov Telescopes
Blazars
ACTs can work along with the Fermi-LAT to help us understand the universes most energetic sources
H.E.S.S. + Fermi Observations of a Blazar
Pulsars
Detection of pulses from the Crab Pulsar at energies over 100 GeV!
Galactic Center
Studies of the Galactic Center (by H.E.S.S.) have helped uncover the nature of the source

How Does an ACT Work?



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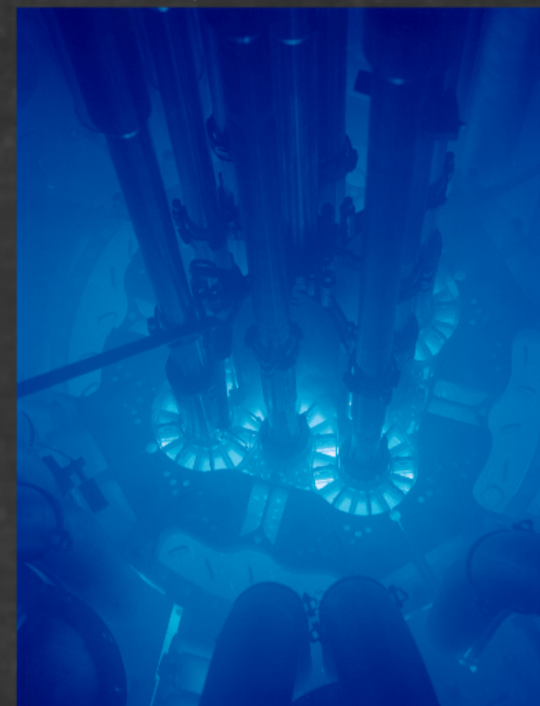
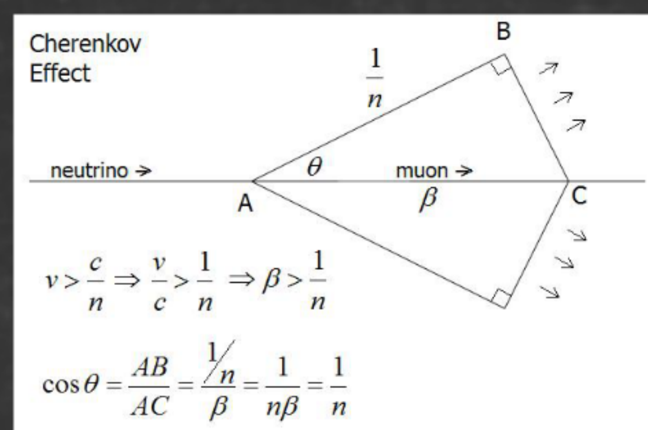
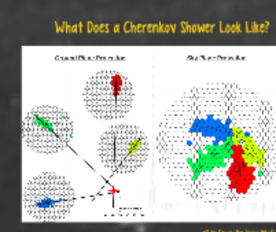
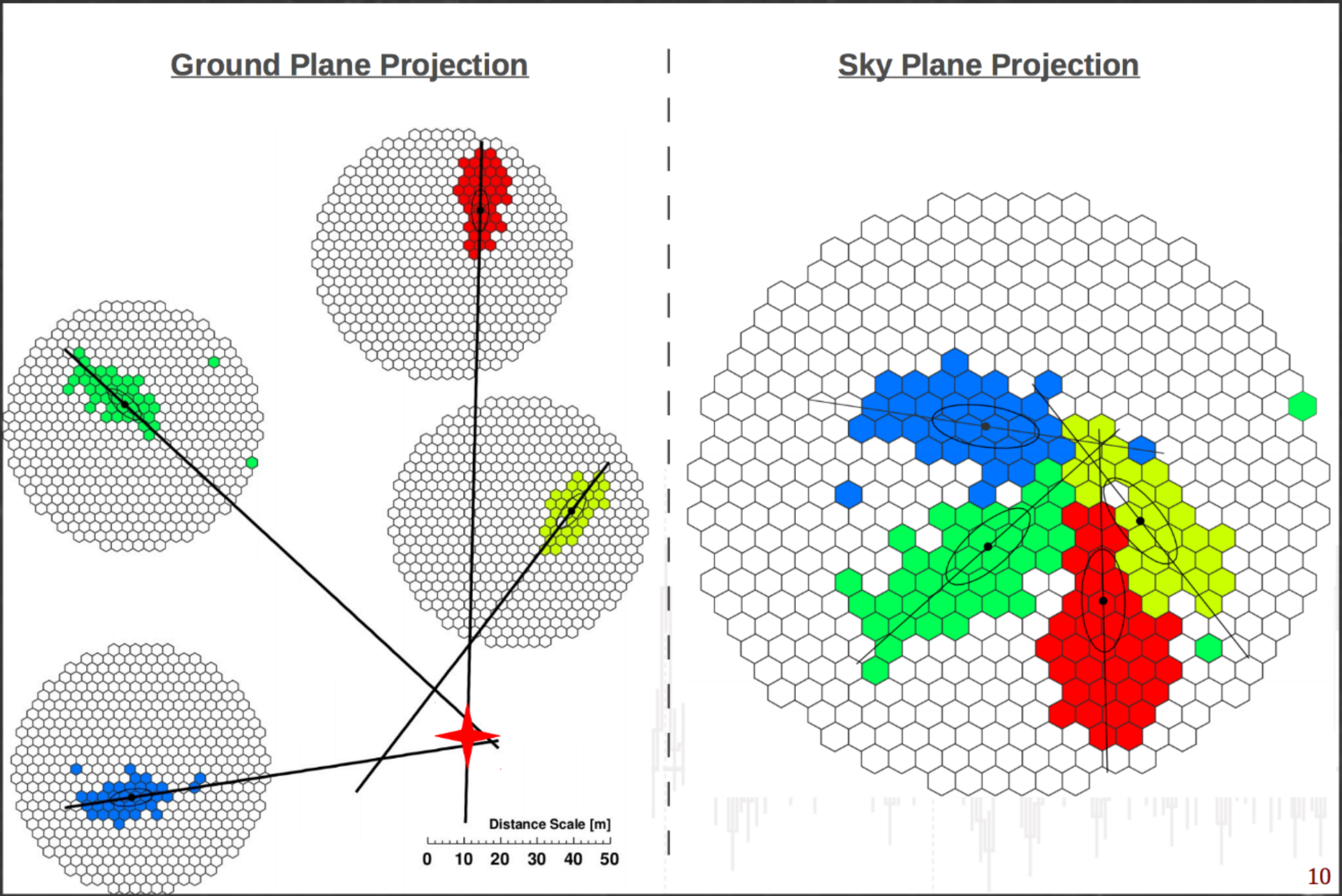






What Does a Cherenkov Shower Look Like?

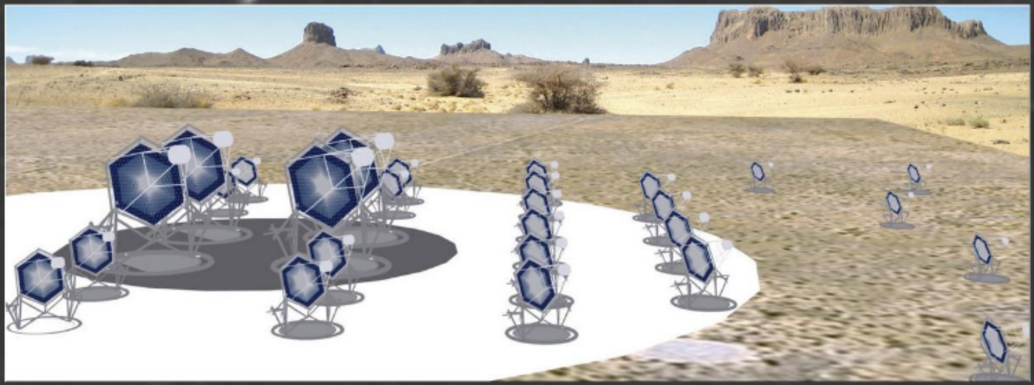


slide from Andrew McCann

Operating ACTs

H.E.S.S. (Namibia)

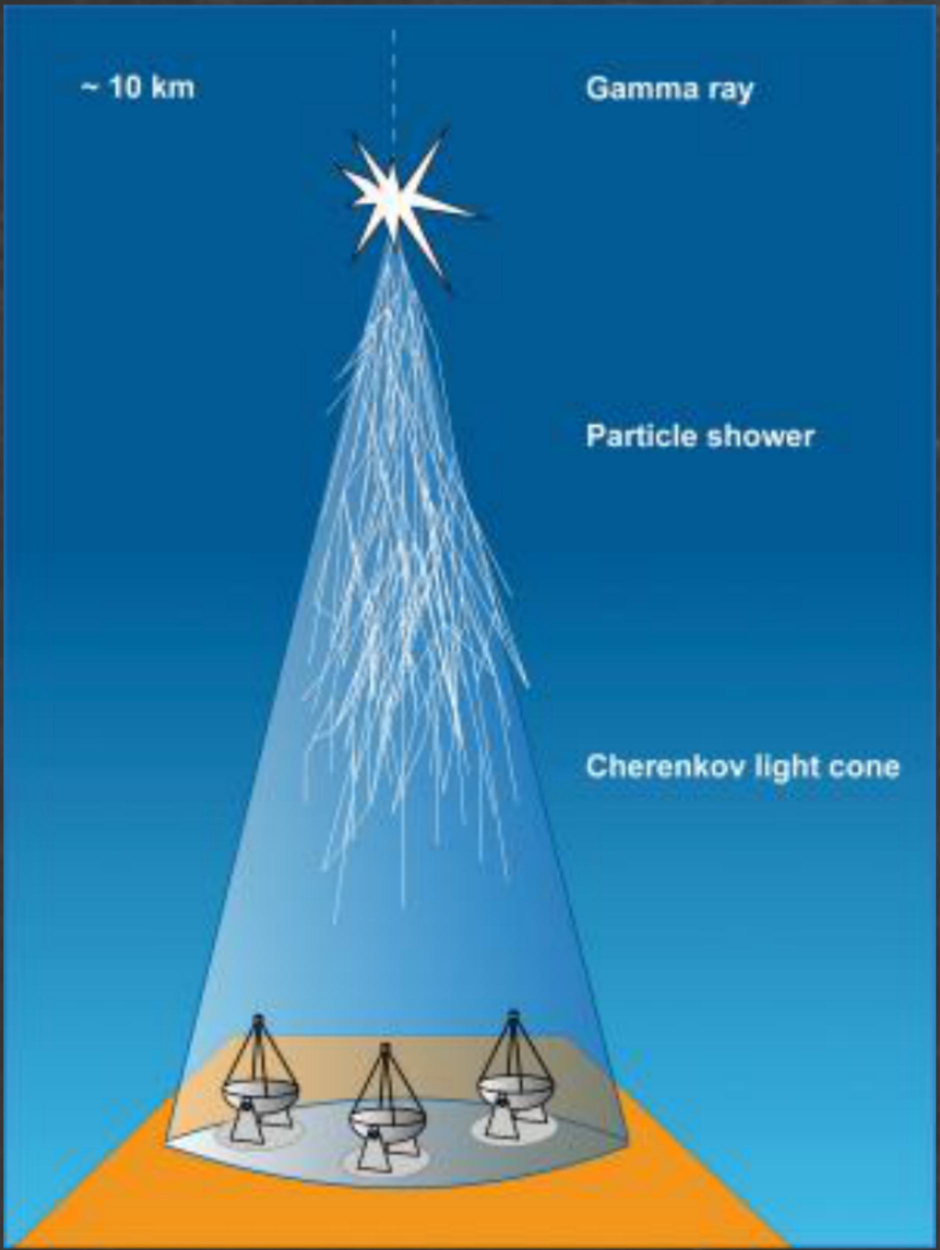
VERITAS (Arizona)



Cherenkov Telescope Array (Under Development)

Andrew McCann
(Spring 2015 Compton Lectures)

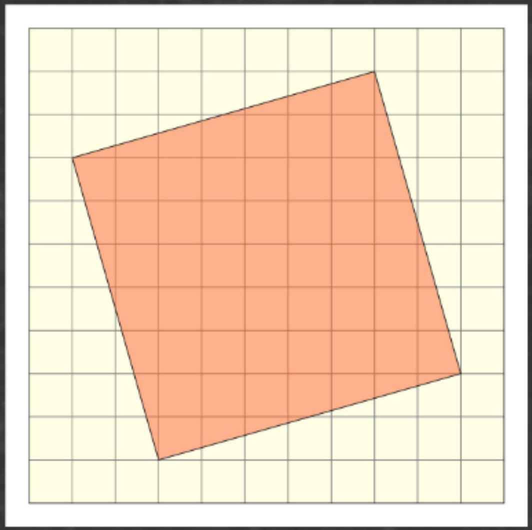
HAWC



High Altitude Water Cherenkov (Puebla, Mexico)

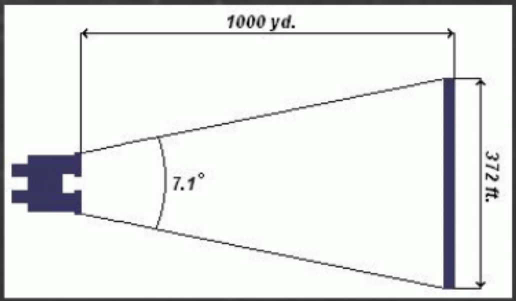
Looks at the shower itself, as it moves through massive water tanks

Comparing ACTs to Fermi-LAT to Water Cherenkov Telescopes



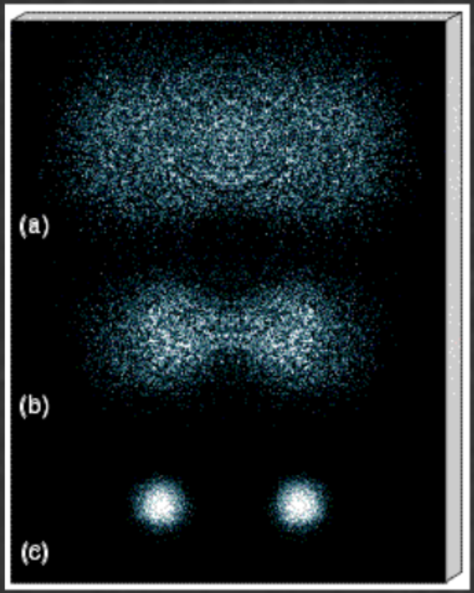
Effective Area

Fermi-LAT – 1 square meter
ACT – 100,000 square meters
HAWC – 10000 square meters



Field of View

Fermi-LAT – 6400 square degrees
ACT – 70 square degrees
HAWC – 15000 square degrees



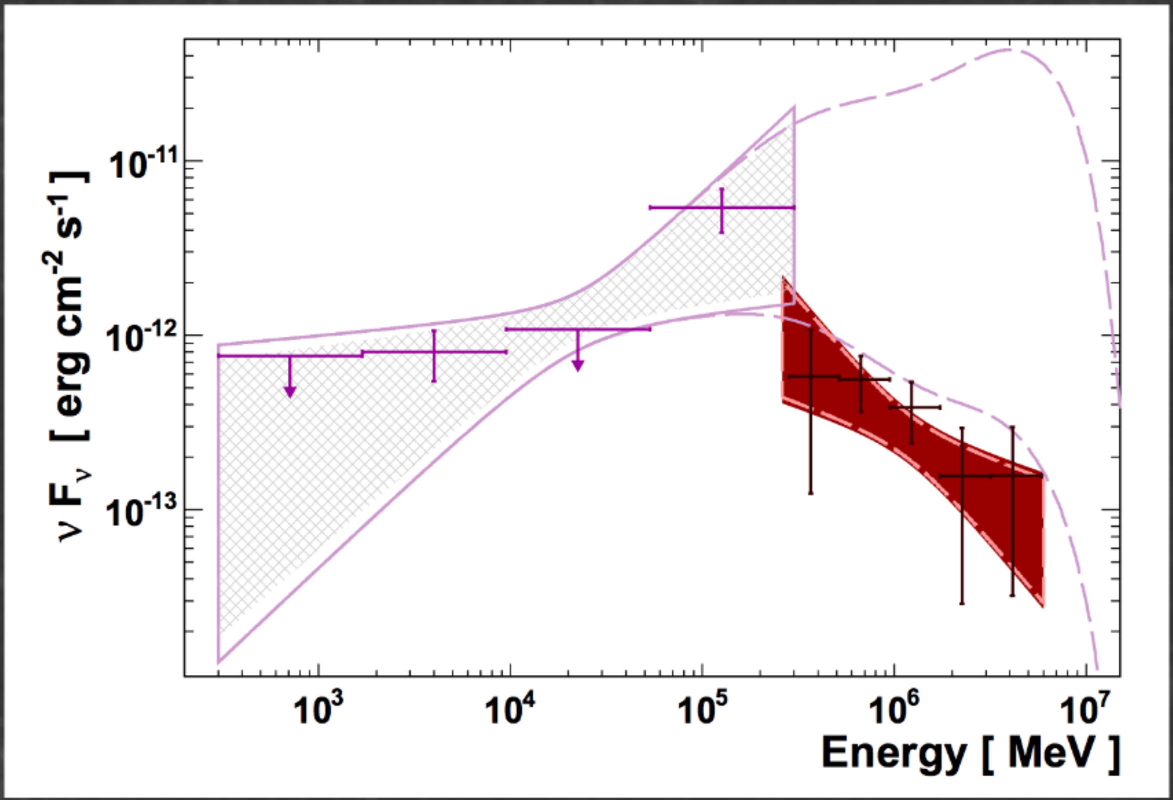
Angular Resolution

Fermi-LAT – 1 degree (1 GeV)
ACT – 0.03 degrees (1 TeV)
HAWC – 0.1 degrees (10 TeV)

Duty Cycle

Fermi-LAT – 100%
ACT – 25% (2000 hours/year)
HAWC – 100%

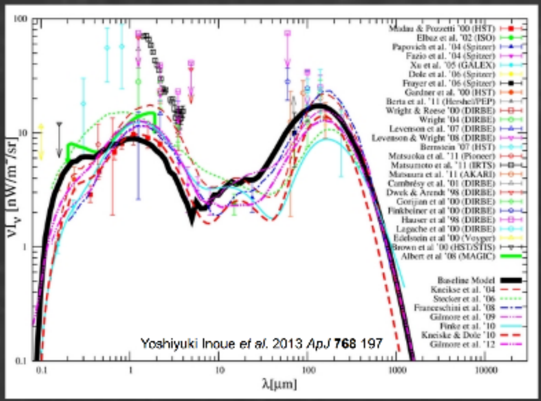
Blazars



ACTs can work along with the Fermi-LAT to help us understand the universes most energetic sources

H.E.S.S. + Fermi Observations of a Blazar

Extragalactic Background Light



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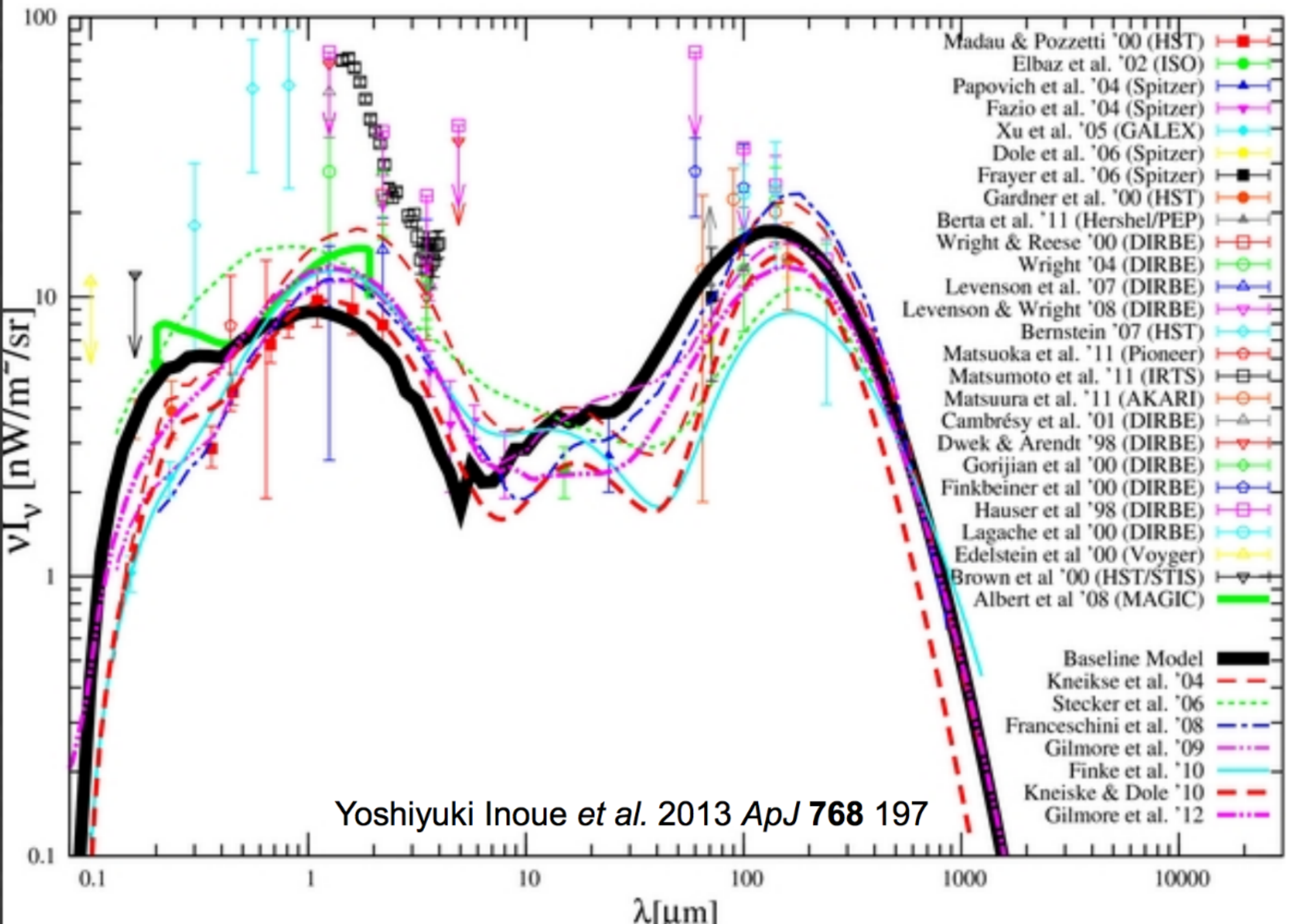
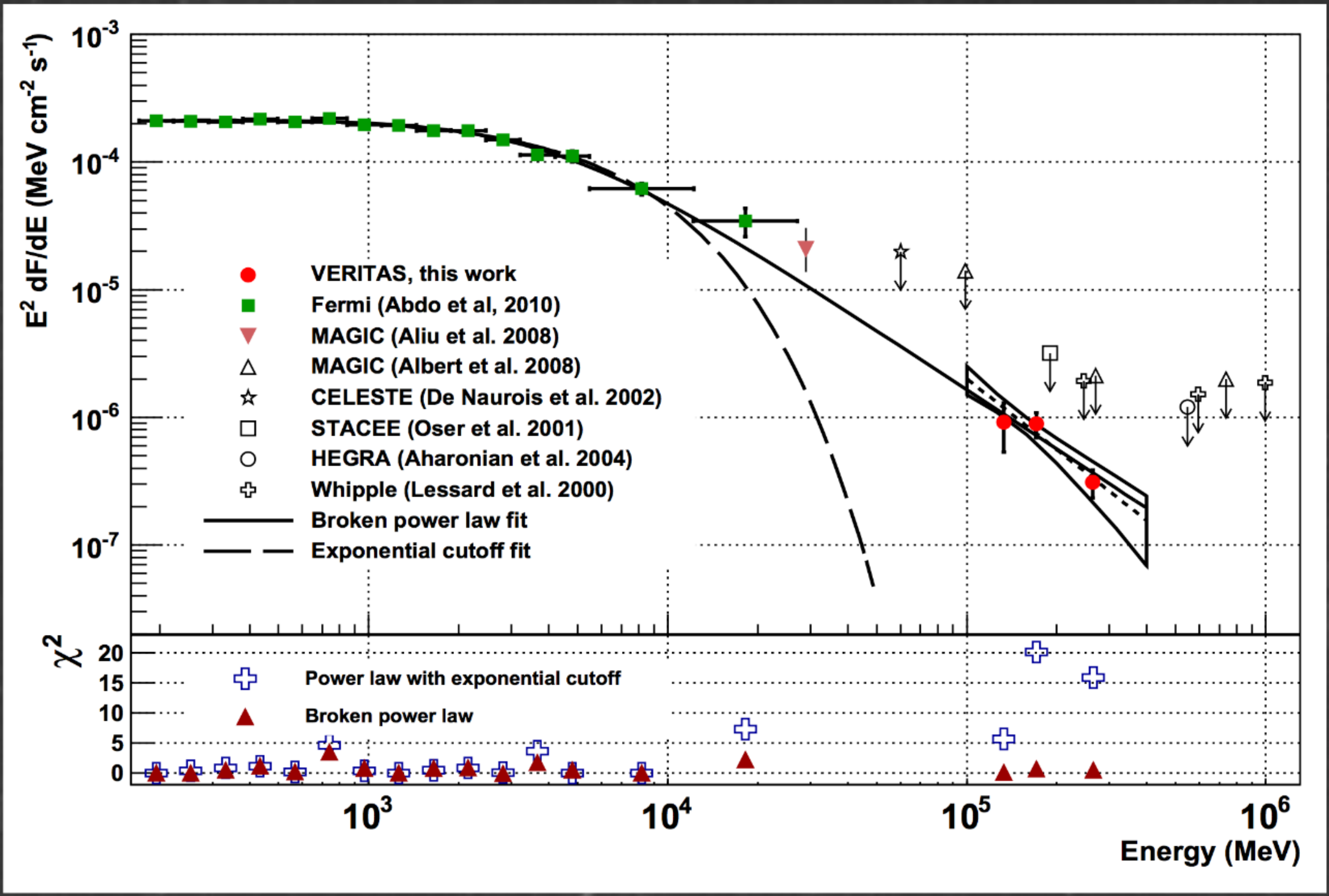


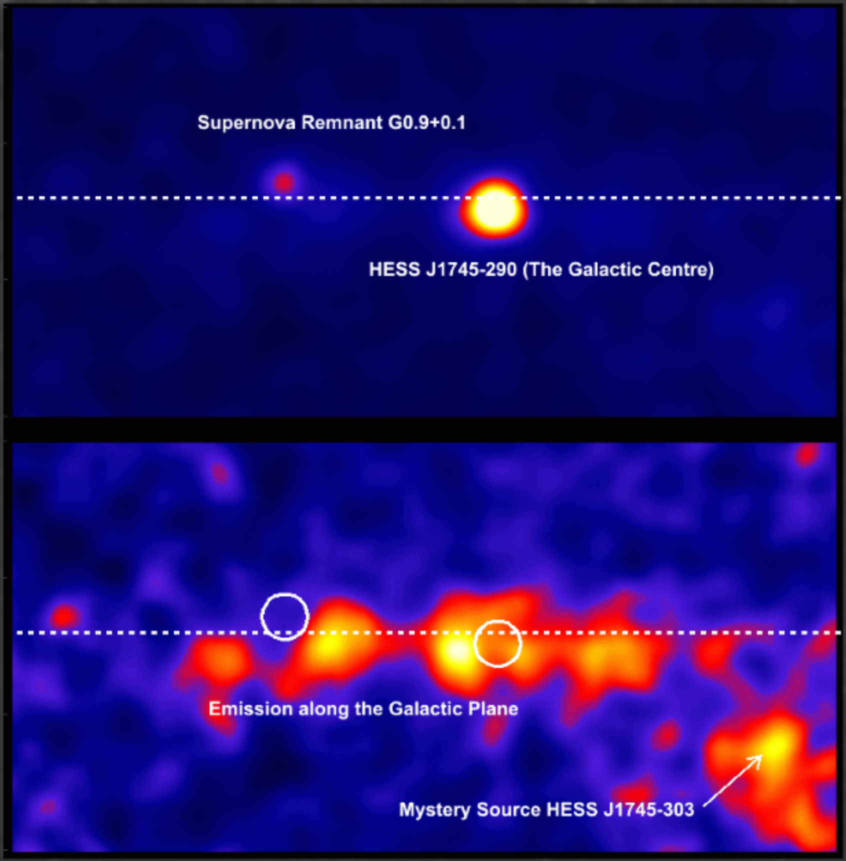
Yoshiyuki Inoue *et al.* 2013 *ApJ* **768** 197

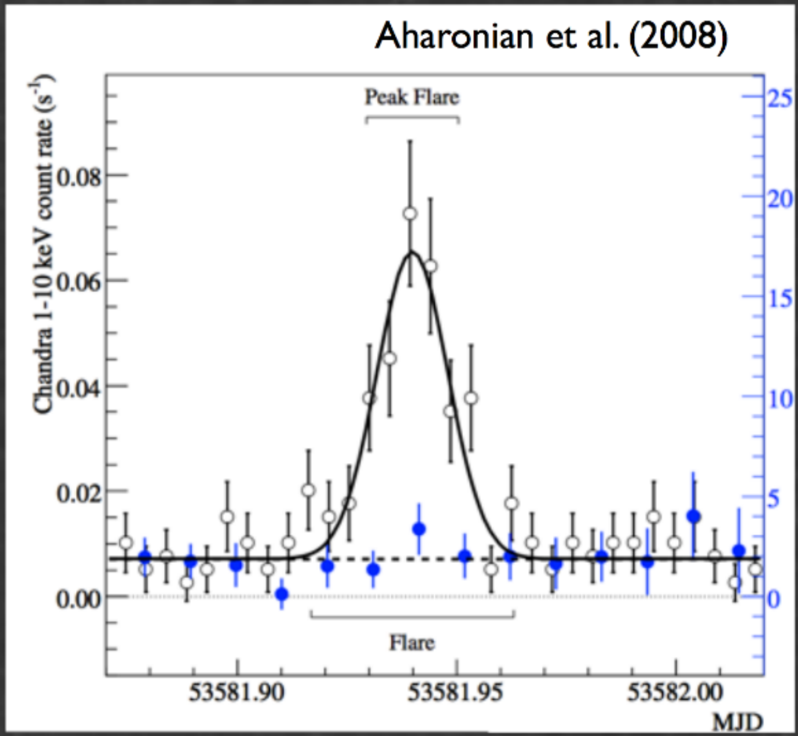
Pulsars

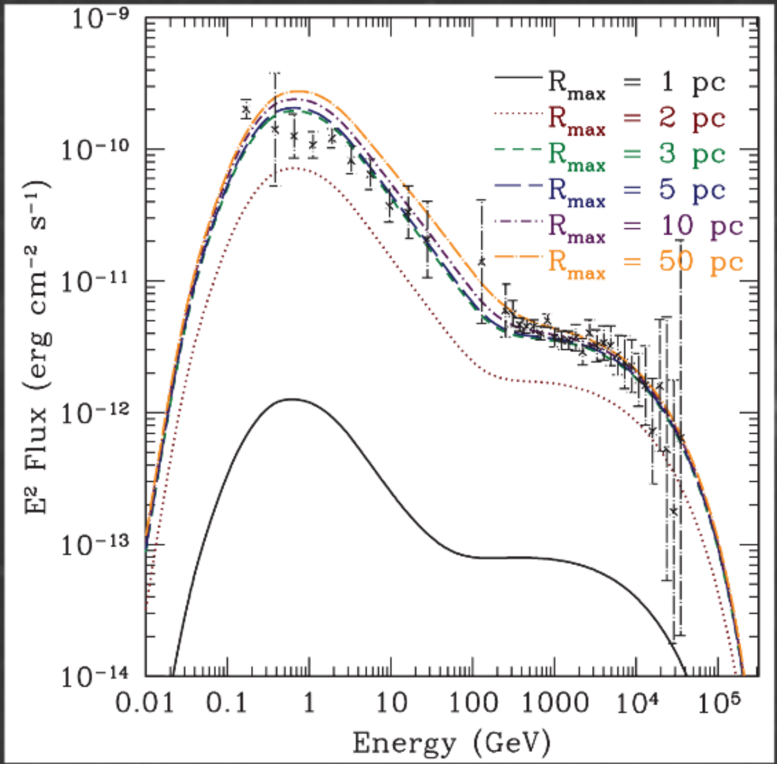
Detection of pulses from the Crab Pulsar at energies over 100 GeV!



Galactic Center





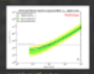


Studies of the Galactic Center (by H.E.S.S.) have helped uncover the nature of the source

Observations

Dwarf Galaxies

Fermi-LAT



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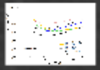

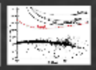

H.E.S.S.

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Veritas

Galaxy Clusters

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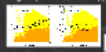

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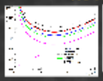

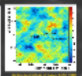

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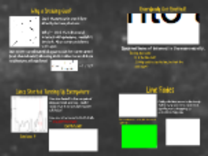

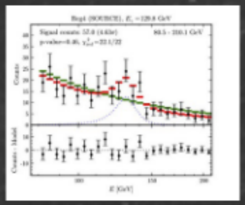

Extra Photons at 130 GeV!

Dwarf Galaxies

Fermi-LAT

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}[J^{NFW}]}^a$ ($\log_{10}$[GeV^2 cm^{-5} sr])
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	-65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Leo V	261.9	58.5	178	–
Pisces II	79.2	-47.1	182	–
Sagittarius	5.6	-14.2	26	–
Sculptor	287.5	-83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Segue 2	149.4	-38.1	35	–
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major I	159.4	54.4	97	18.3 ± 0.24
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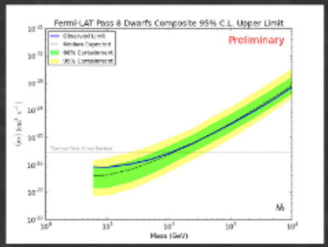
The Fermi-LAT Collaboration (2013)



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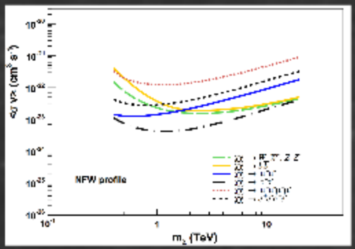

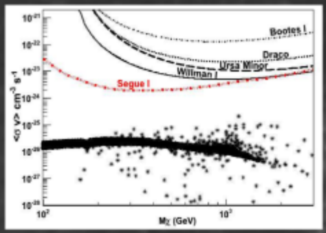

H.E.S.S.

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Veritas

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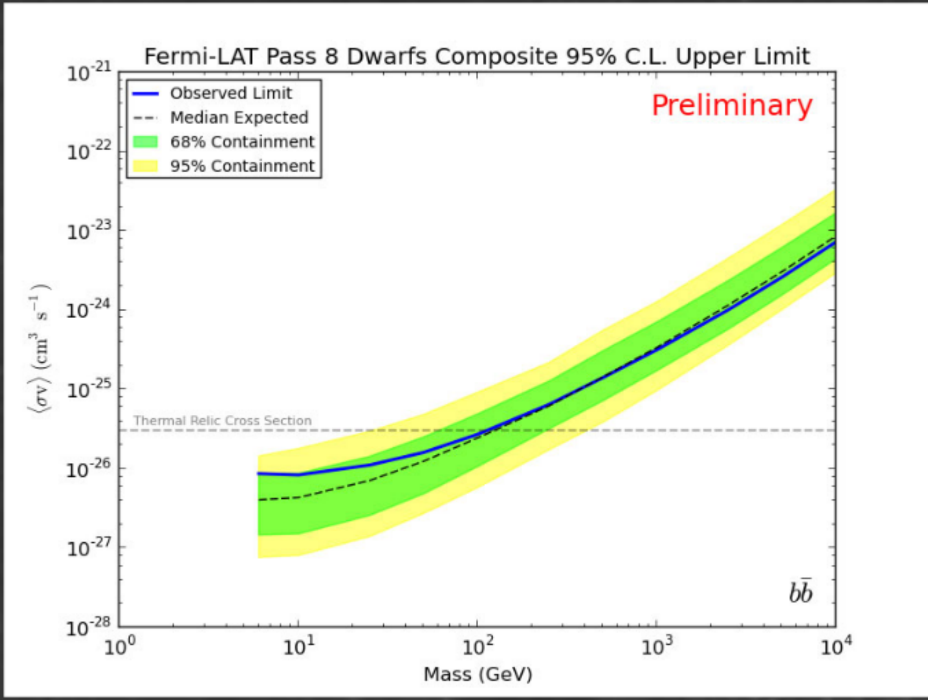

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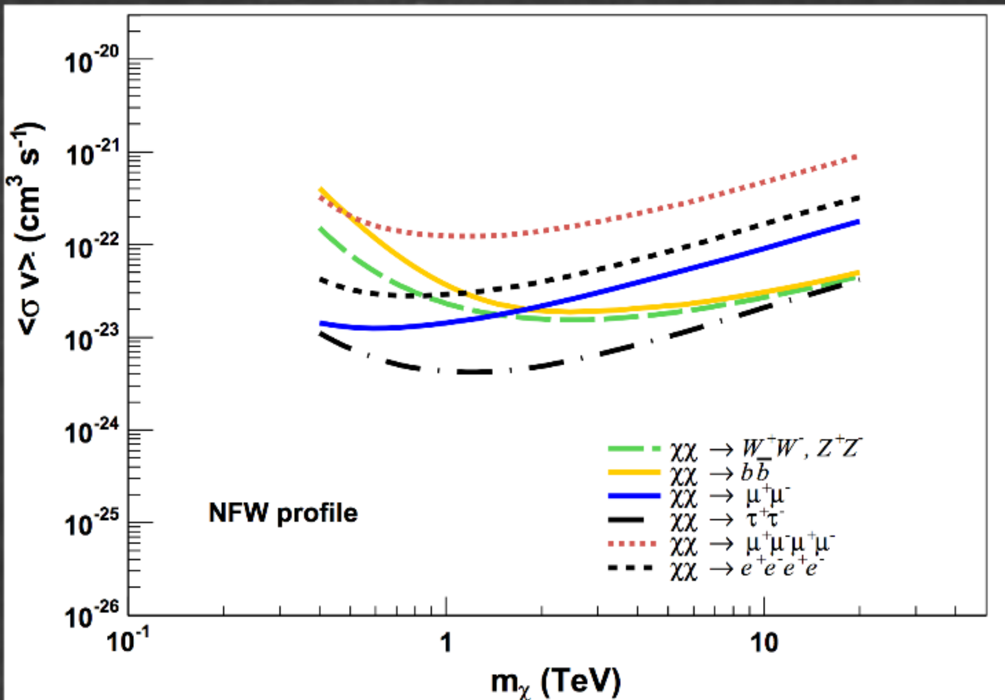

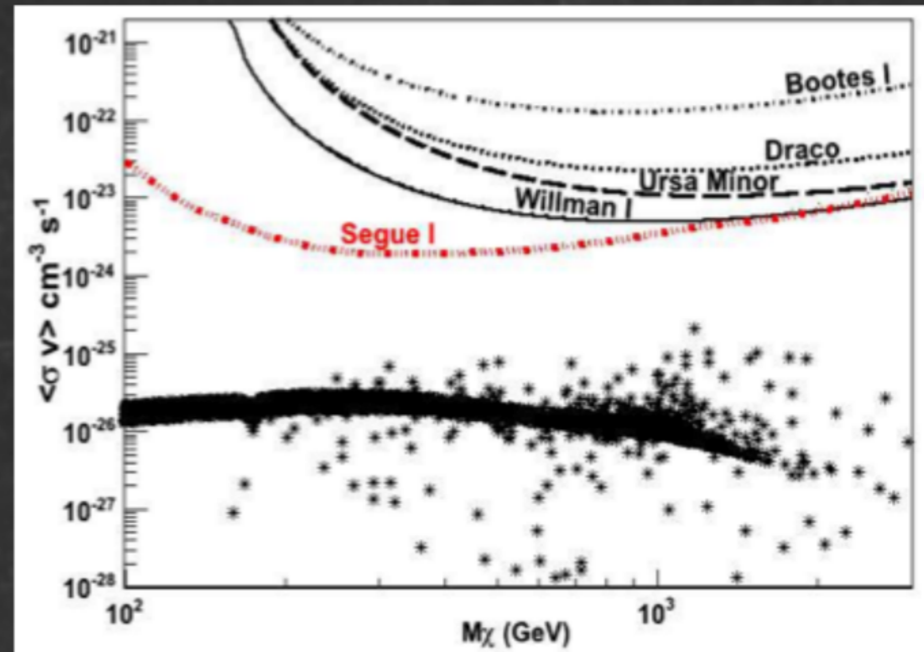

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Galaxy Clusters

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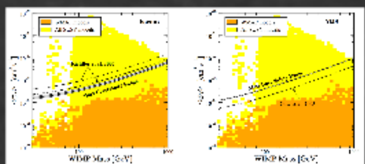

Fermi-LAT Collaboration (2010)

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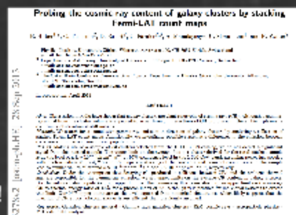
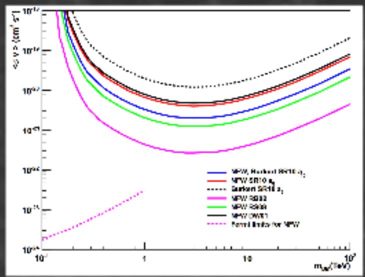
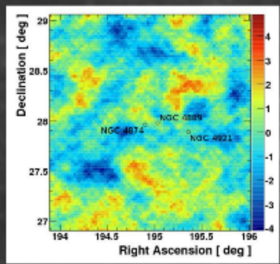

Probing the cosmic-ray content of galaxy clusters by stacking Fermi-LAT count maps

ACTs



H.E.S.S. limits from the Fornax Dwarf



Veritas observations of Coma Cluster (2008)

Nada!

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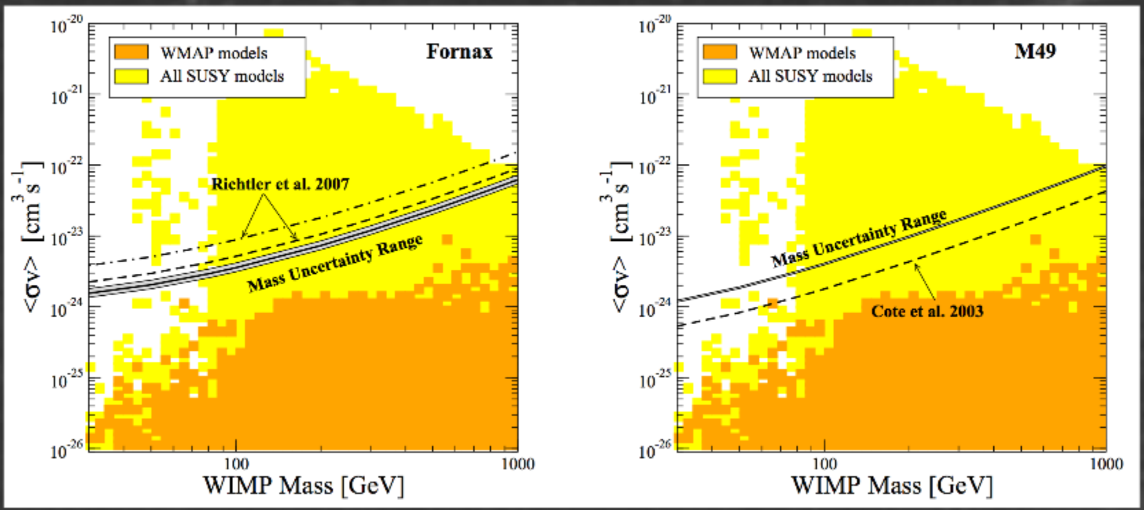

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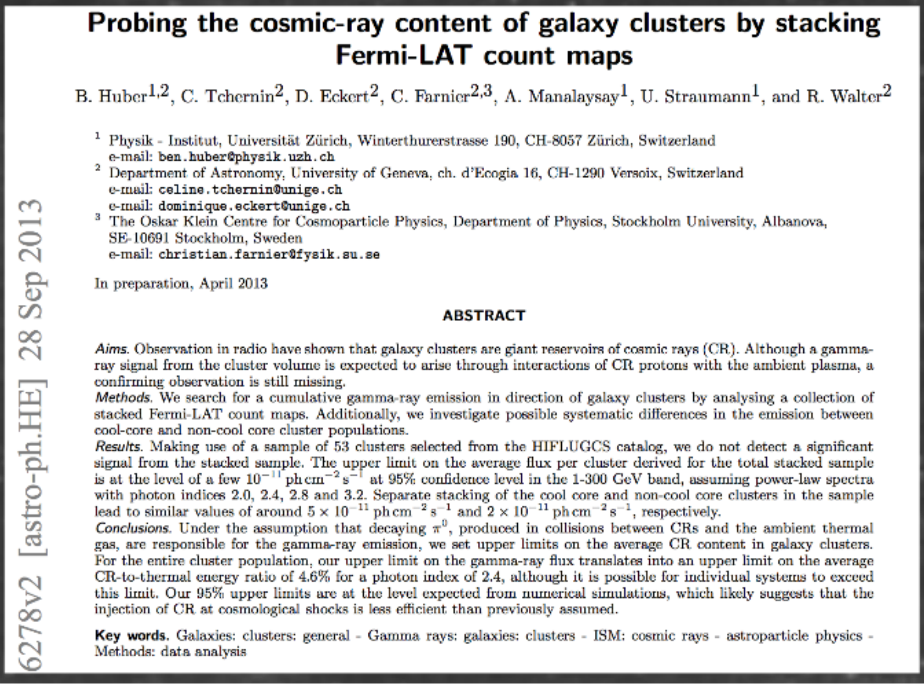

6278v2 [astro-ph.HE] 28 Sep 2013

Probing the cosmic-ray content of galaxy clusters by stacking Fermi-LAT count maps

B. Huber[1,2], C. Tchernin[2], D. Eckert[2], C. Farnier[2,3], A. Manalaysay[1], U. Straumann[1], and R. Walter[2]

[1] Physik - Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
e-mail: ben.huber@physik.uzh.ch
[2] Department of Astronomy, University of Geneva, ch. d'Ecogia 16, CH-1290 Versoix, Switzerland
e-mail: celine.tchernin@unige.ch
e-mail: dominique.eckert@unige.ch
[3] The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, Albanova, SE-10691 Stockholm, Sweden
e-mail: christian.farnier@fysik.su.se

In preparation, April 2013

ABSTRACT

Aims. Observation in radio have shown that galaxy clusters are giant reservoirs of cosmic rays (CR). Although a gamma-ray signal from the cluster volume is expected to arise through interactions of CR protons with the ambient plasma, a confirming observation is still missing.
Methods. We search for a cumulative gamma-ray emission in direction of galaxy clusters by analysing a collection of stacked Fermi-LAT count maps. Additionally, we investigate possible systematic differences in the emission between cool-core and non-cool core cluster populations.
Results. Making use of a sample of 53 clusters selected from the HIFLUGCS catalog, we do not detect a significant signal from the stacked sample. The upper limit on the average flux per cluster derived for the total stacked sample is at the level of a few 10^{-11} ph cm^{-2} s^{-1} at 95% confidence level in the 1-300 GeV band, assuming power-law spectra with photon indices 2.0, 2.4, 2.8 and 3.2. Separate stacking of the cool core and non-cool core clusters in the sample lead to similar values of around 5×10^{-11} ph cm^{-2} s^{-1} and 2×10^{-11} ph cm^{-2} s^{-1}, respectively.
Conclusions. Under the assumption that decaying π^0, produced in collisions between CRs and the ambient thermal gas, are responsible for the gamma-ray emission, we set upper limits on the average CR content in galaxy clusters. For the entire cluster population, our upper limit on the gamma-ray flux translates into an upper limit on the average CR-to-thermal energy ratio of 4.6% for a photon index of 2.4, although it is possible for individual systems to exceed this limit. Our 95% upper limits are at the level expected from numerical simulations, which likely suggests that the injection of CR at cosmological shocks is less efficient than previously assumed.

Key words. Galaxies: clusters: general - Gamma rays: galaxies: clusters - ISM: cosmic rays - astroparticle physics - Methods: data analysis

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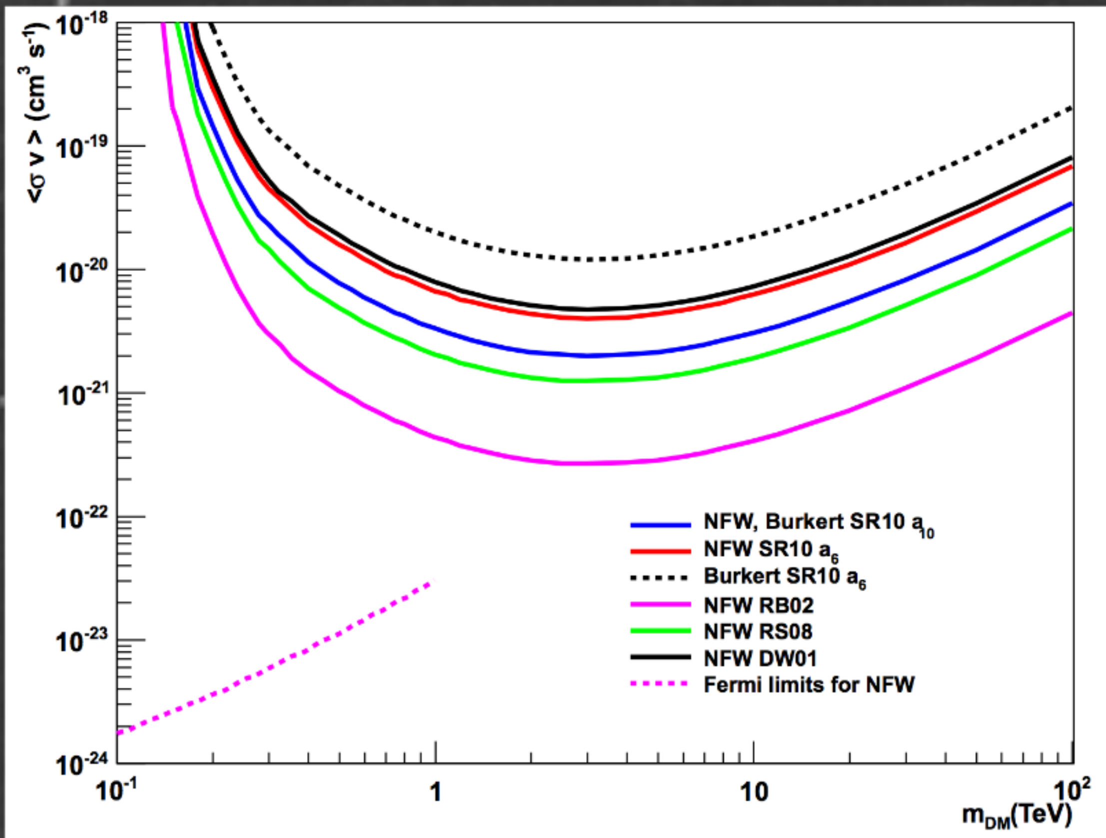
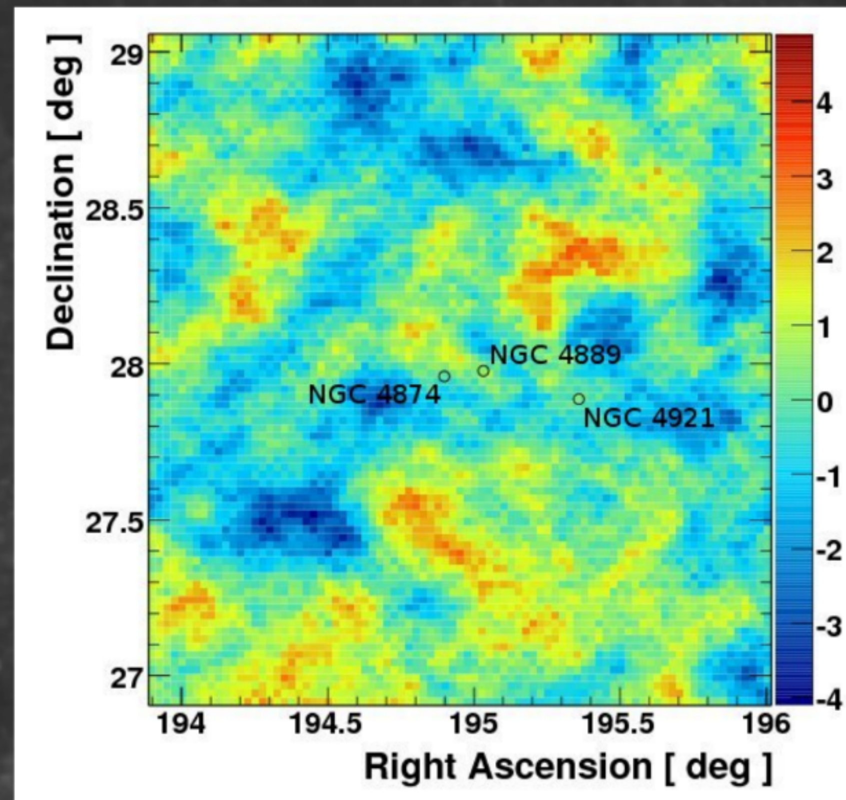
ACTs





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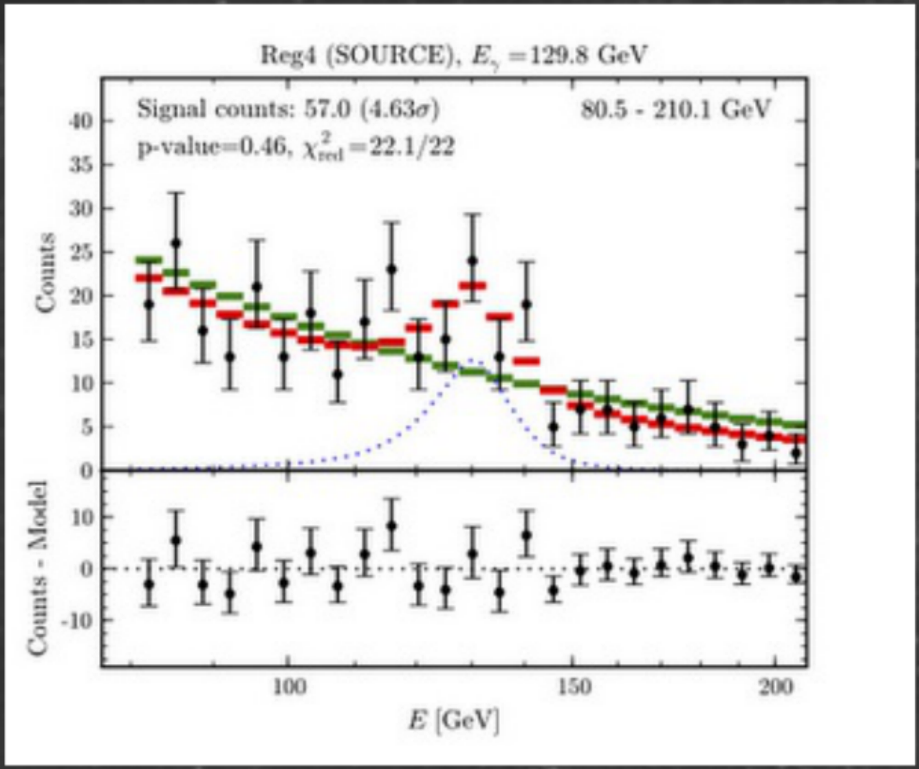
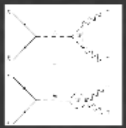


Extra Photons at 130 GeV!

Why a Smoking Gun?



Dark Matter can't annihilate directly to two photons

Why? - Well then it would interact with photons, wouldn't be dark. Also some problems with spin

But more complicated diagrams can be constructed (and should exist) allowing dark matter to annihilate to photons at loop level $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c}$ = 1 / 137

Everybody Get Excited!

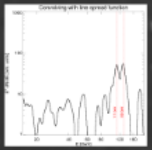
Spurred tons of interest in the community.

Two key questions:

1.) Is the line real?

2.) Why could we see the line, but not the continuum?

Lines Started Turning Up Everywhere



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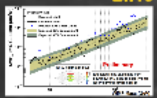
Line was found in the sample of unassociated sources - could mean that they are dark matter subhalos!

Line was also found in Earth limb -- shouldn't be there

Earth Limb?

Line Fades



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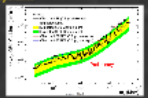
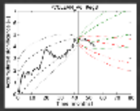
Fermi Analysis sees the line, but at a reduced significance





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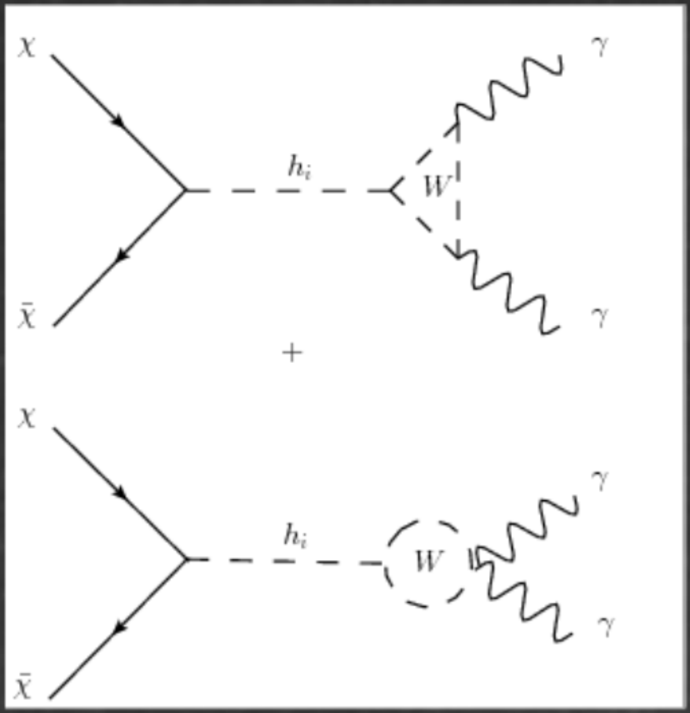

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Information | References (74) | Citations (280) | Files | Plots

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

Christoph Weniger (Munich, Max Planck Inst.)

Apr 2012 - 21 pages

JCAP 1208 (2012) 007
DOI: 10.1088/1475-7516/2012/08/007
MPP-2012-73
e-Print: arXiv:1204.2797 [hep-ph] | PDF

Abstract (arXiv)
The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6 sigma indication for a gamma-ray line at 130 GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2 sigma. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of 129.8\pm2.4^{+7}_{-13} GeV and a partial annihilation cross-section of <\sigma v> = 1.27\pm0.32^{+0.18}_{-0.28} x 10^-27 cm^3 s^-1 when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons/ it will take a few years of additional data to clarify its existence.

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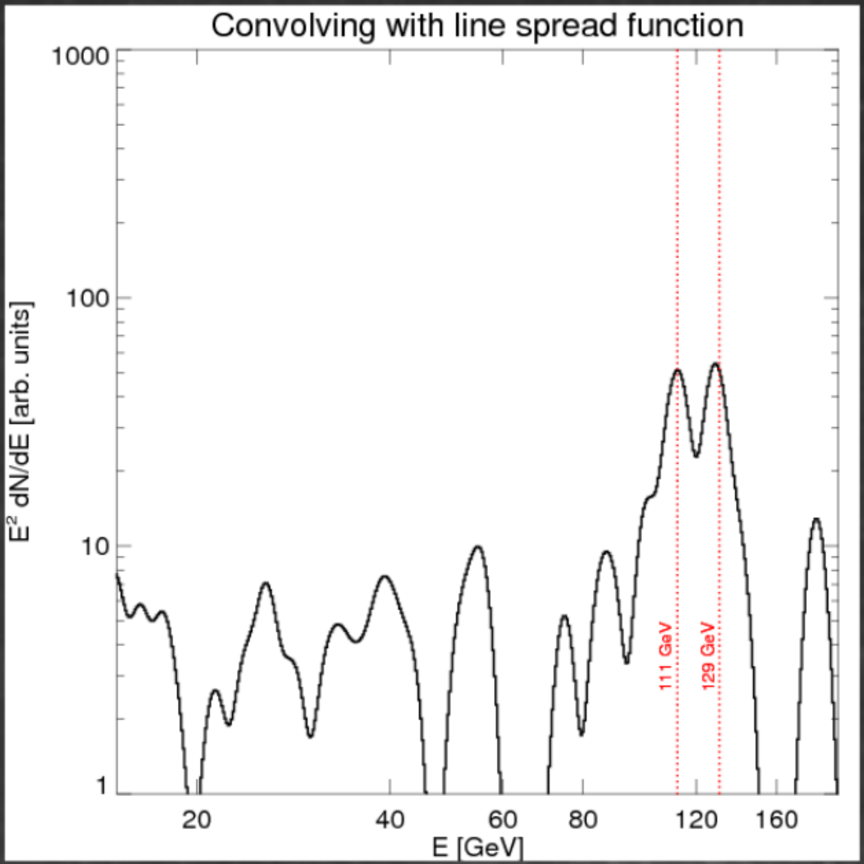

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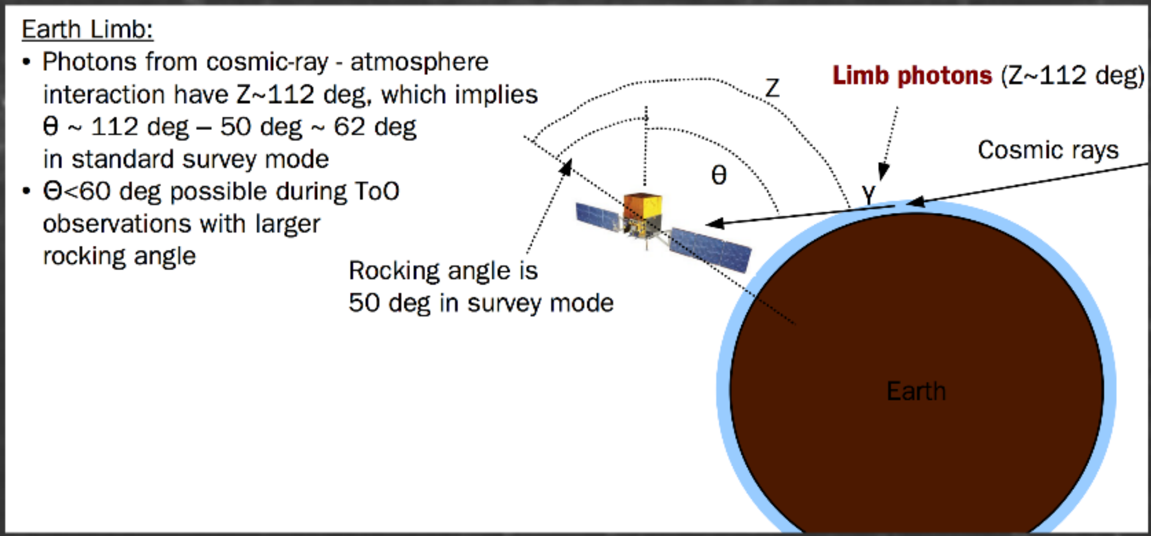

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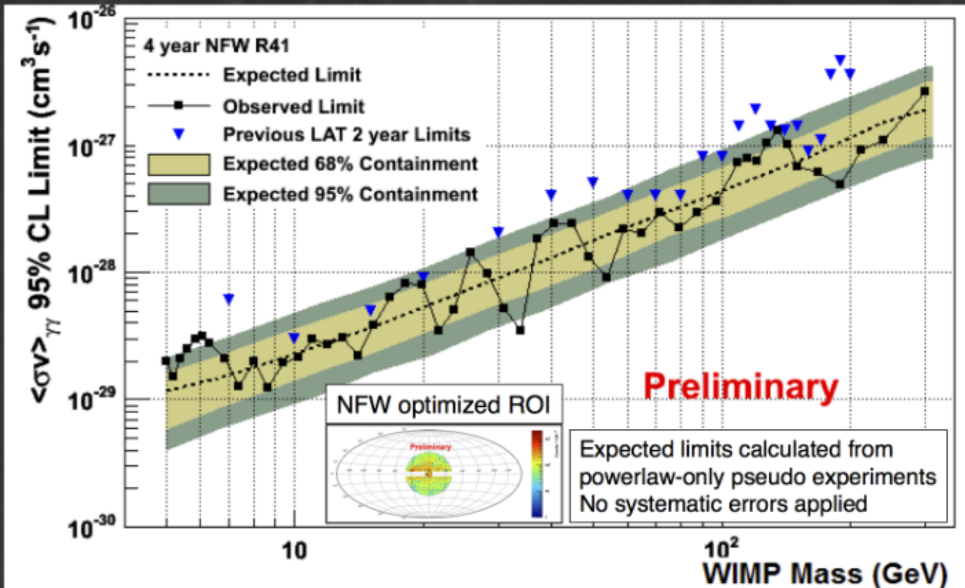

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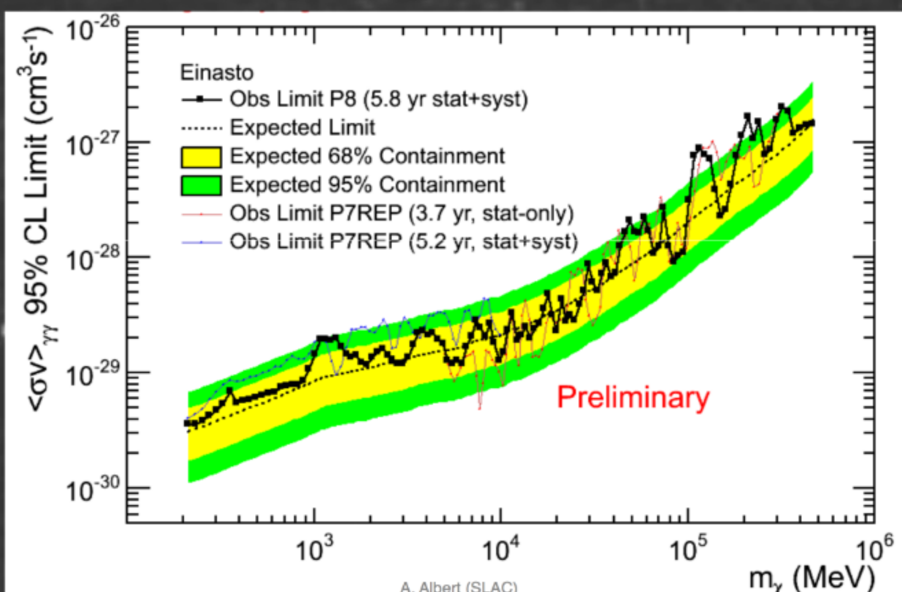
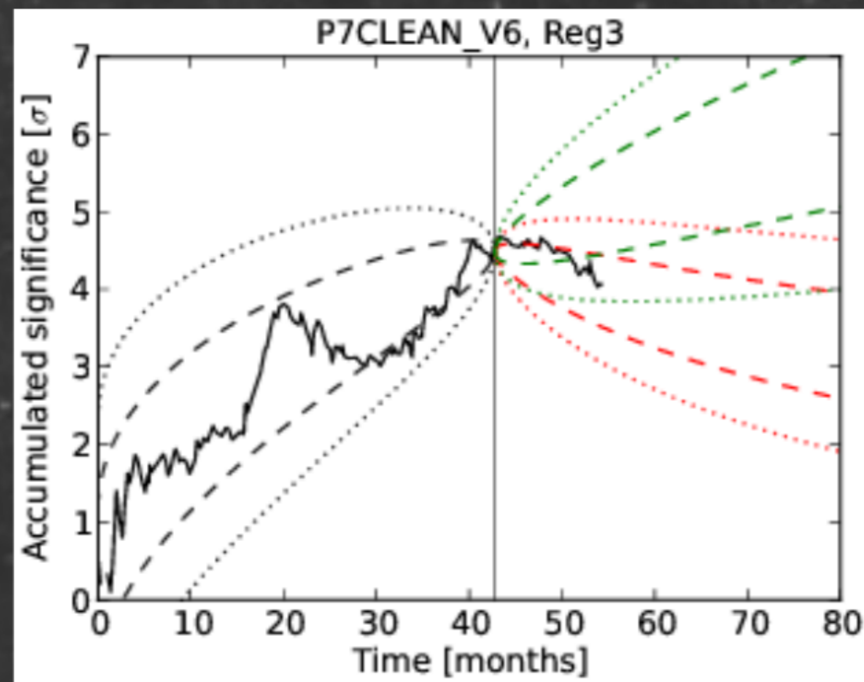


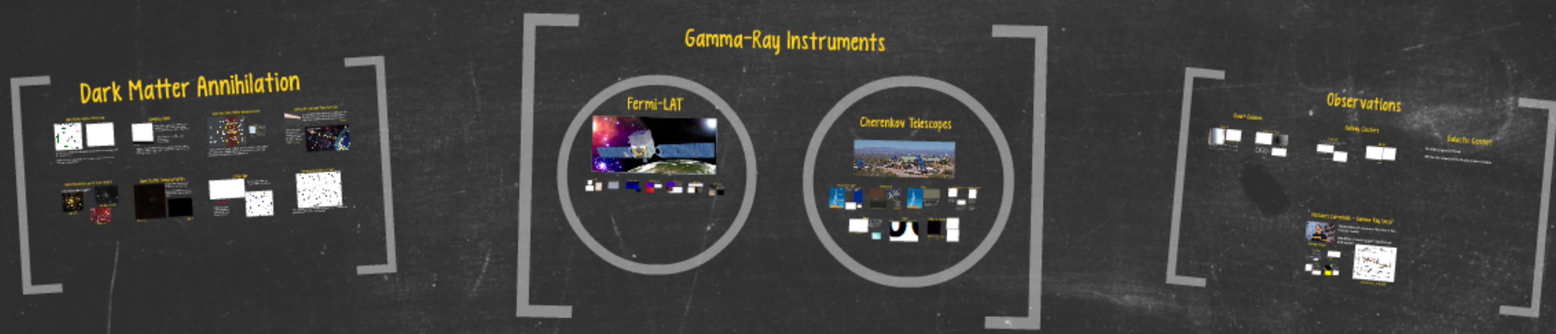


Next Week

Doubly indirect searches for dark matter annihilation

Question: What happens if the annihilation produces something like electrons and protons, can we see those too?

The Indirect Detection of Dark Matter with Gamma-Rays



Tim Linden

Lecture 7

Fall 2014 Compton Lectures