Astrophysics with TeV particles

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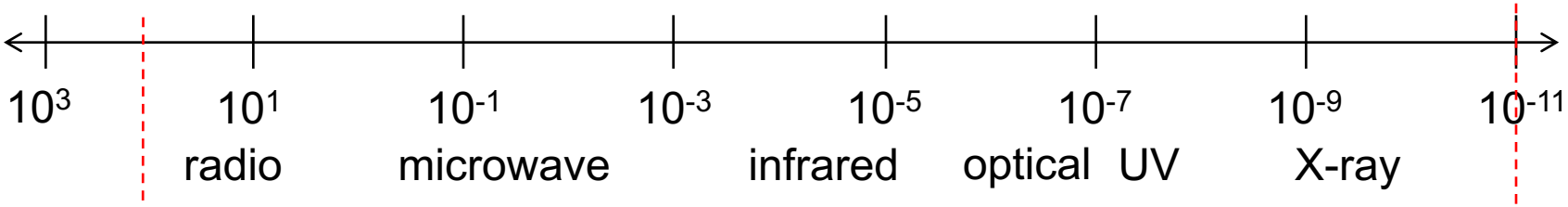
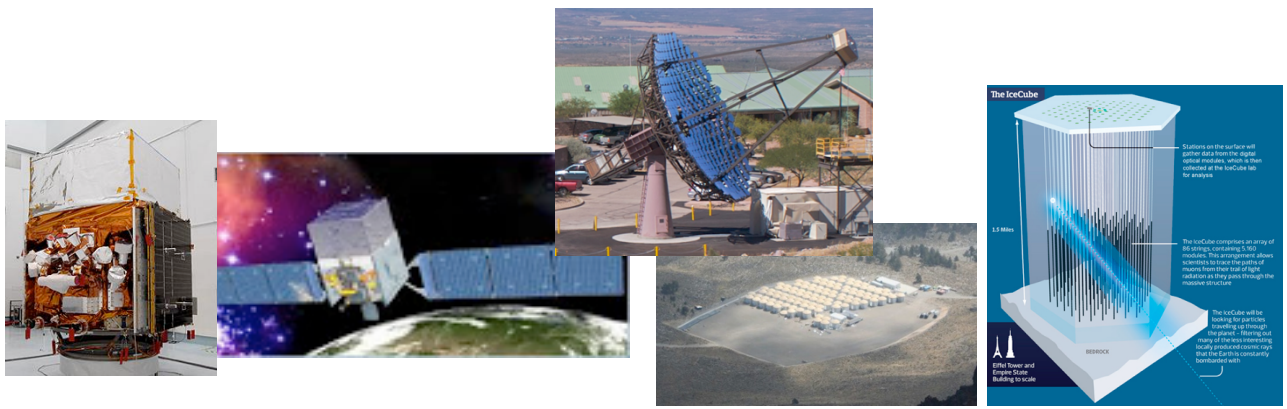
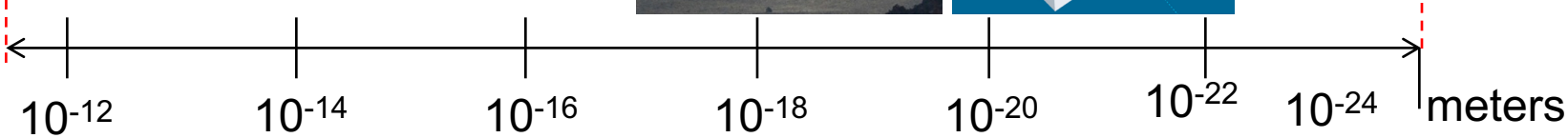
Physics 301: Physics Today, University of Wisconsin
March 7, 2017

(1) TeV gamma-ray astronomy: motivation

Astro-particle physics over 13 orders of magnitude



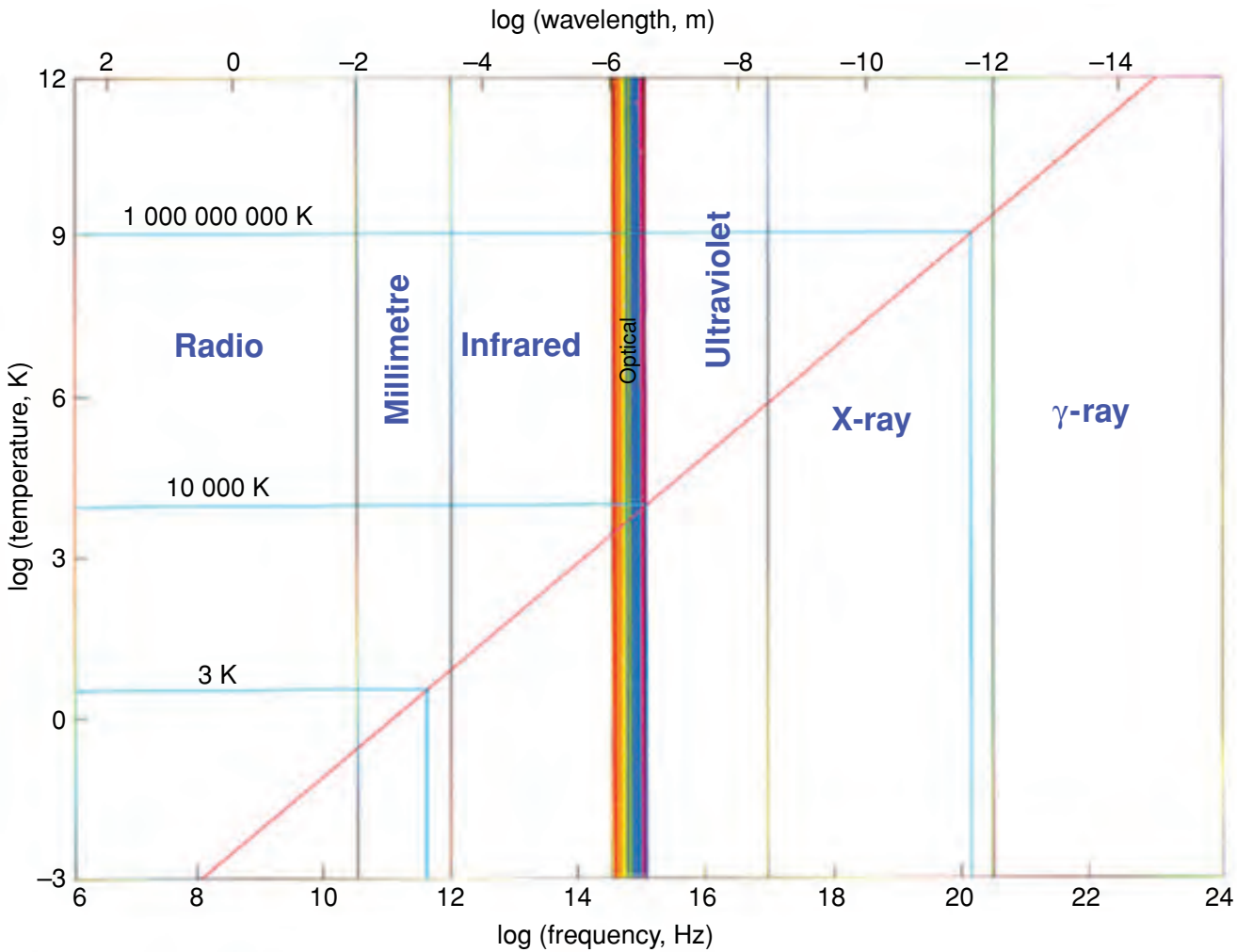




Gamma rays over 9 orders of magnitude

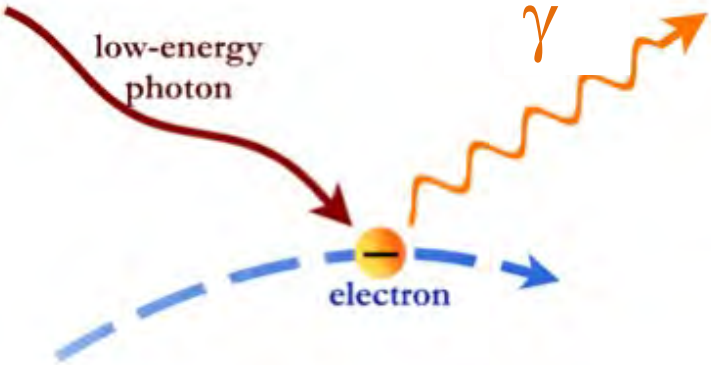
The non-thermal universe

- CTA

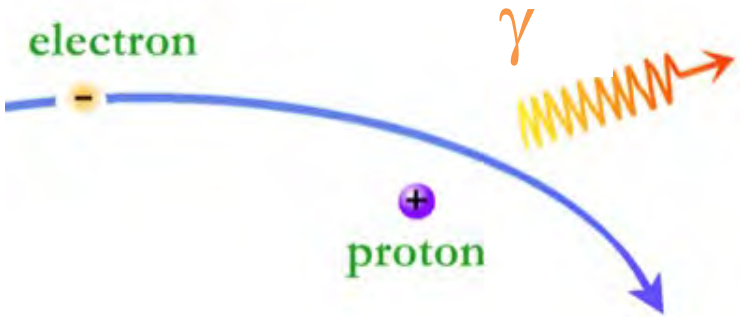


Non-thermal mechanisms of gamma-ray production

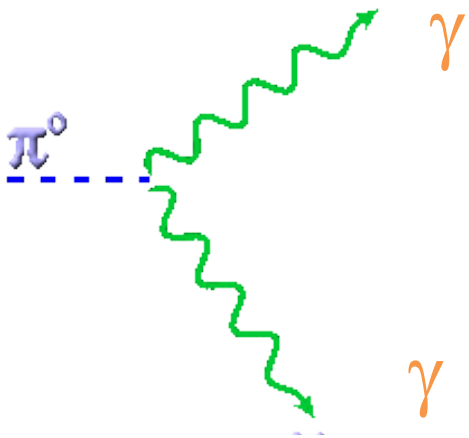
(1) Synchrotron (electromagnetic)



(2) Inverse Compton (electromagnetic)

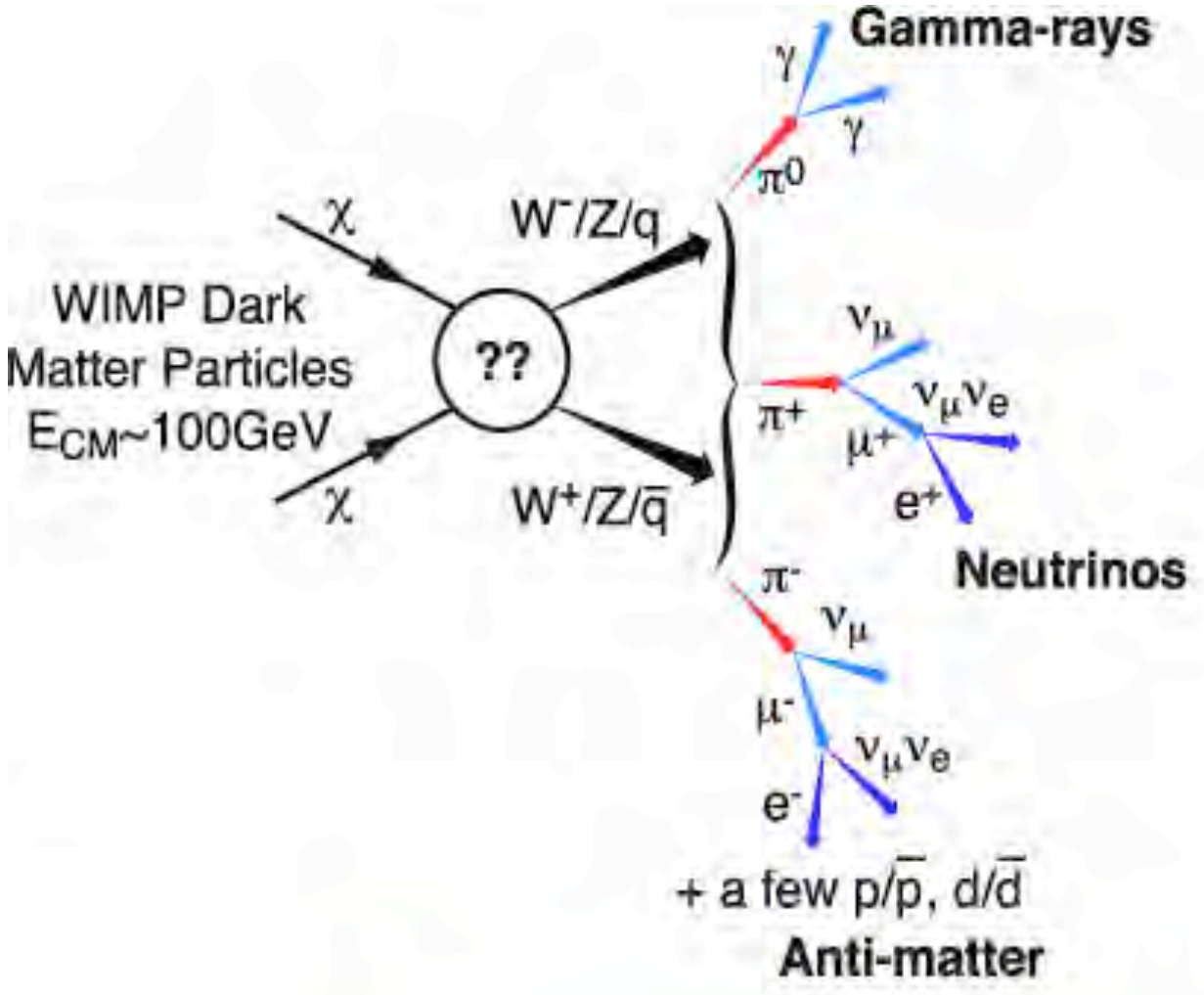


(3) Bremsstrahlung (electromagnetic)

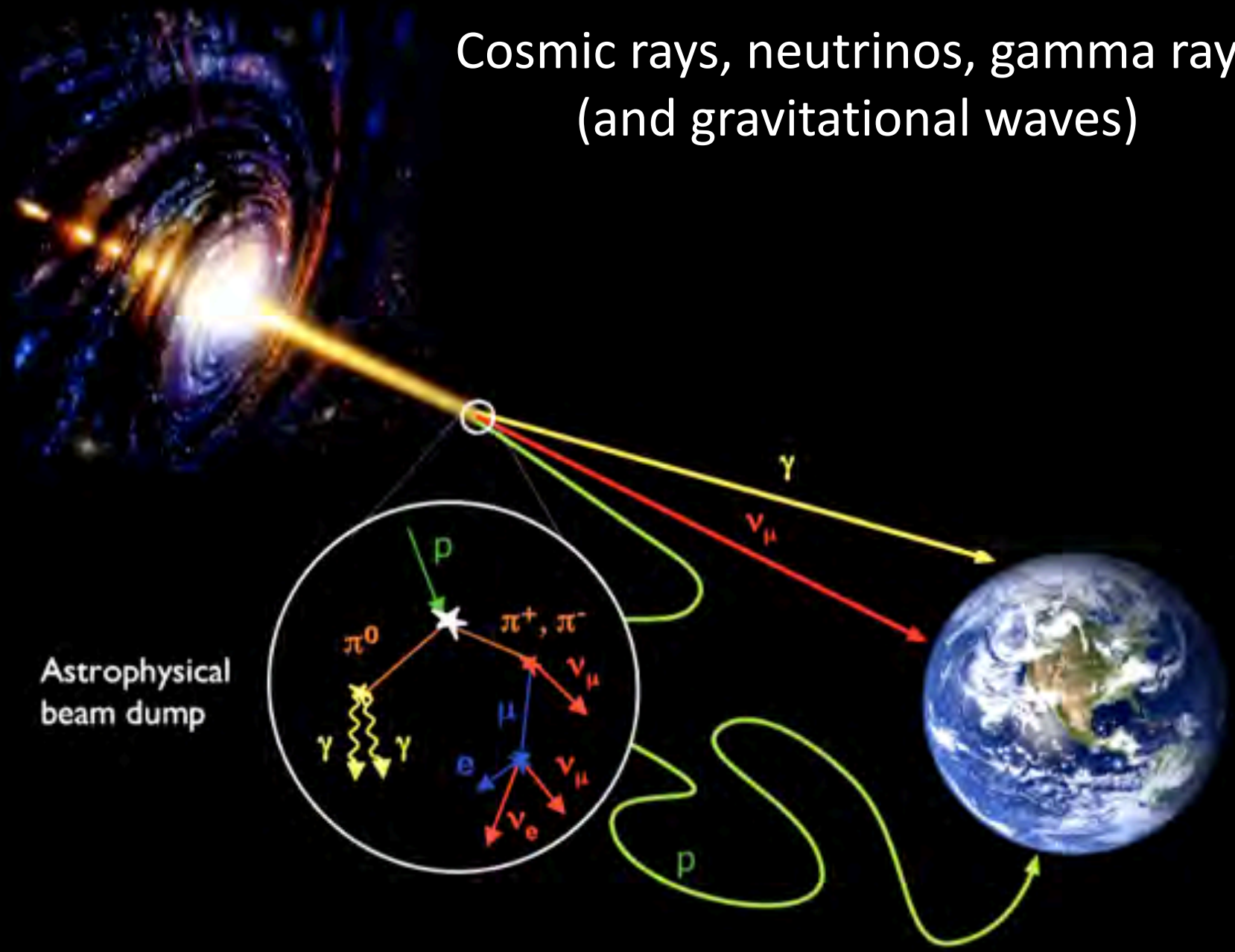


(4) Pion decay (hadronic)

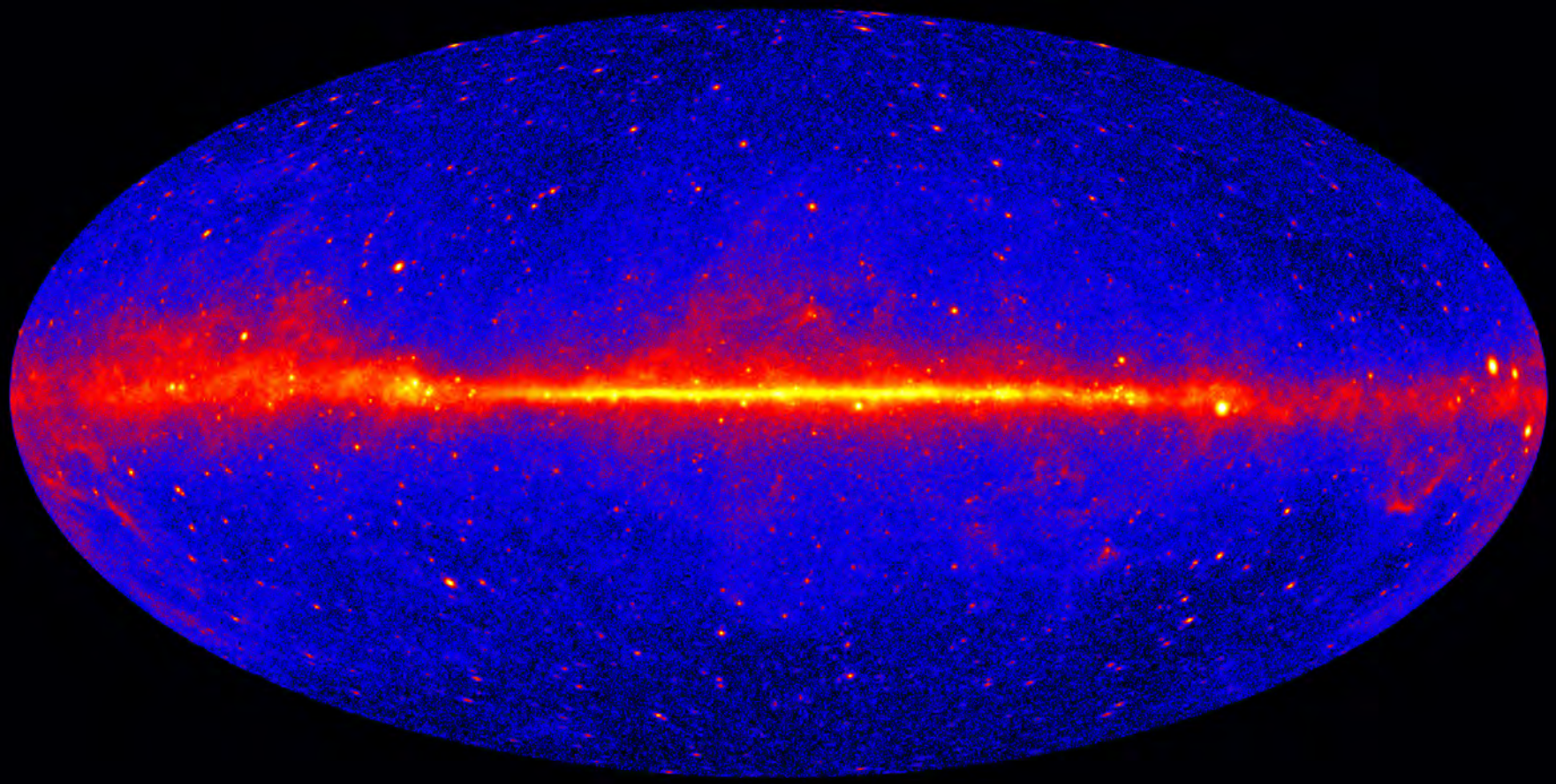
A fifth mechanism to produce gamma rays: exotic particle (e.g. dark matter) rest mass



Cosmic rays, neutrinos, gamma rays (and gravitational waves)

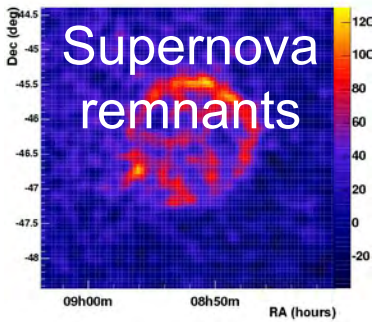


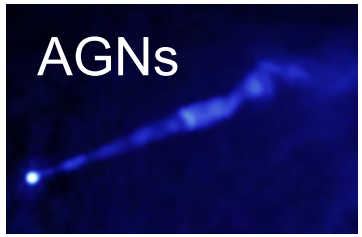
The universe viewed in >1 GeV photons

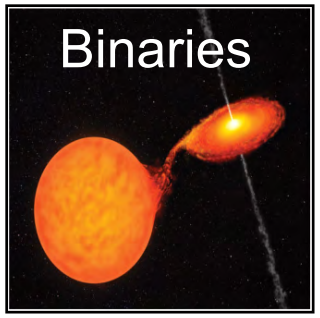


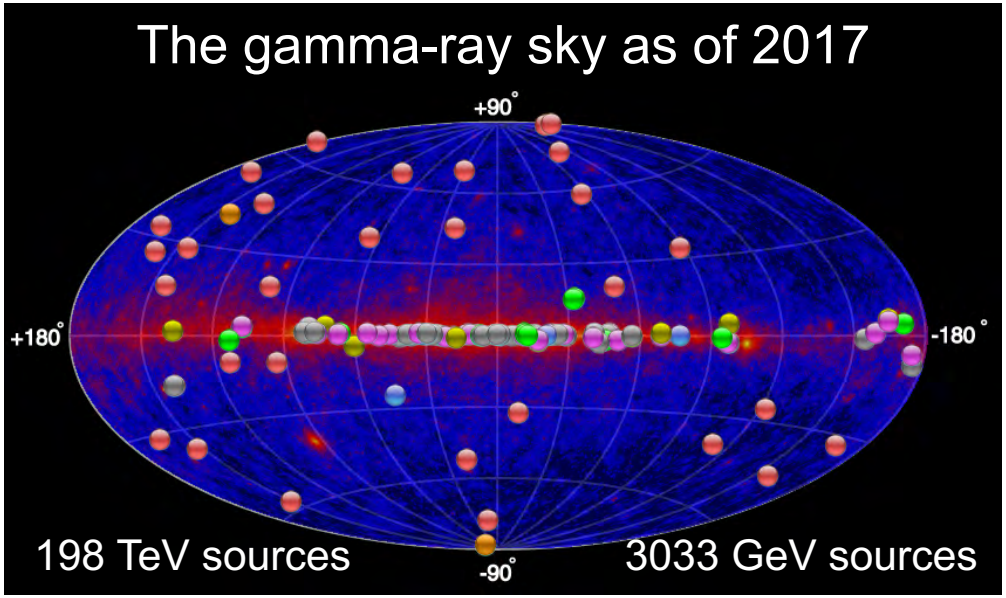
5 years of data from the Fermi Large Area Telescope

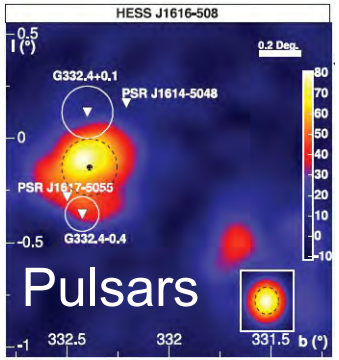
Physics with TeV gamma-ray telescopes



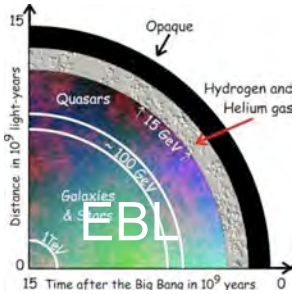






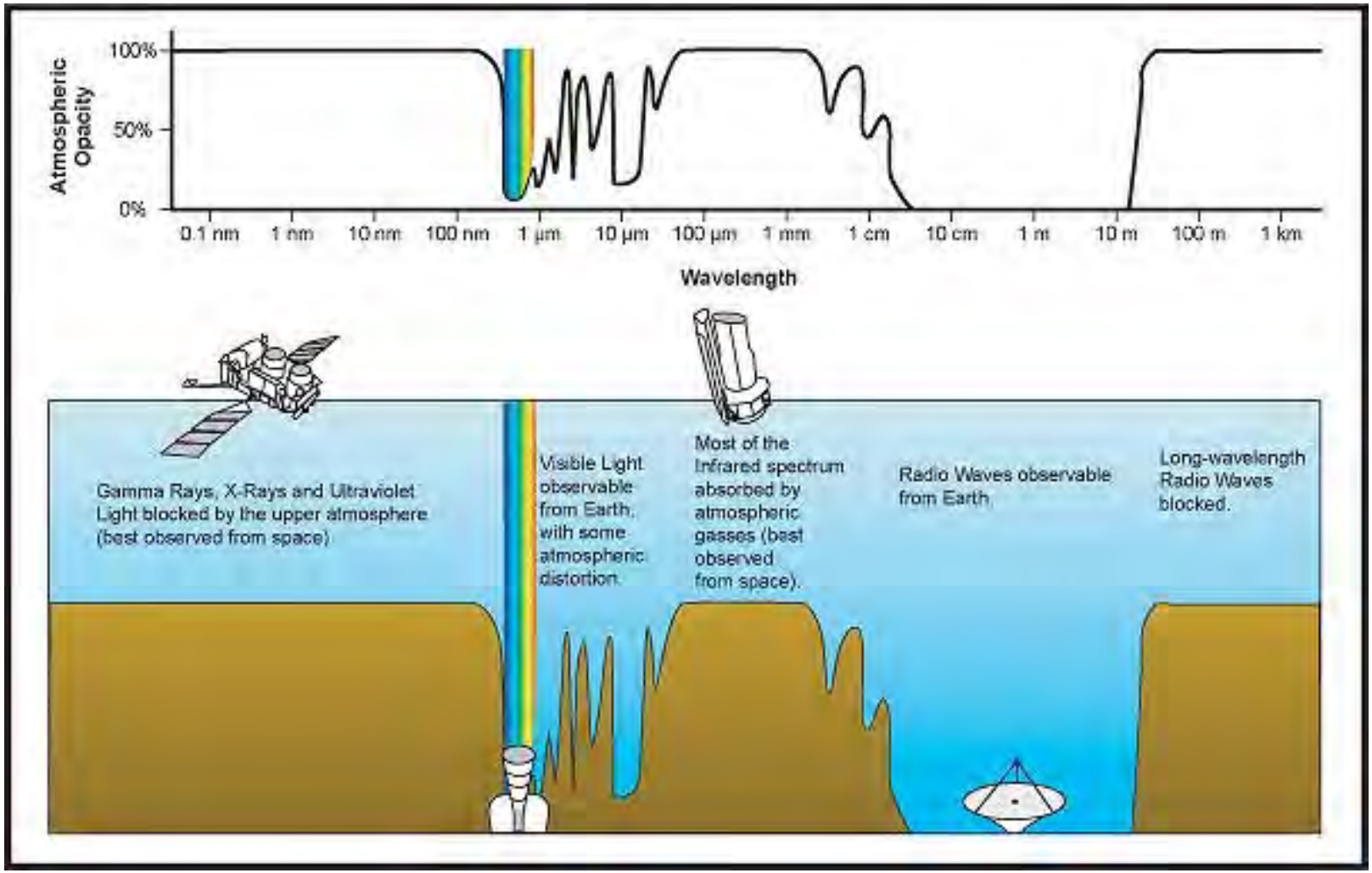


Axions, …

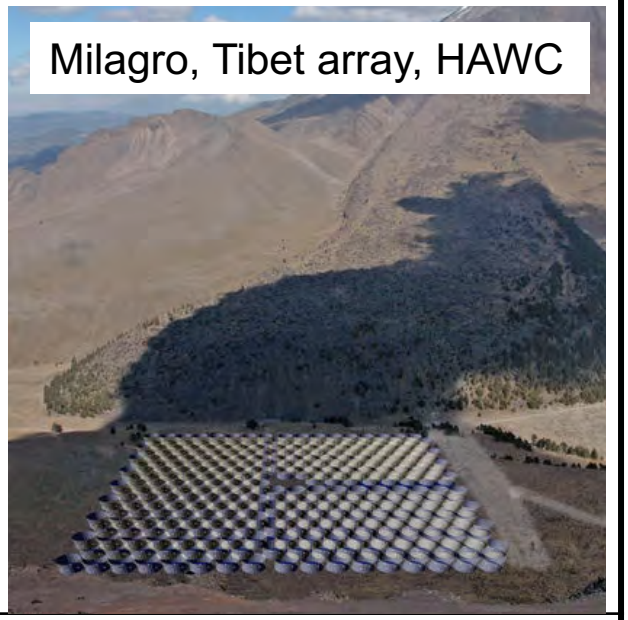


(2) Techniques for TeV gamma-ray astronomy

The atmosphere is opaque to gamma rays



- Which process will a TeV gamma-ray undergo when it hits the atmosphere?

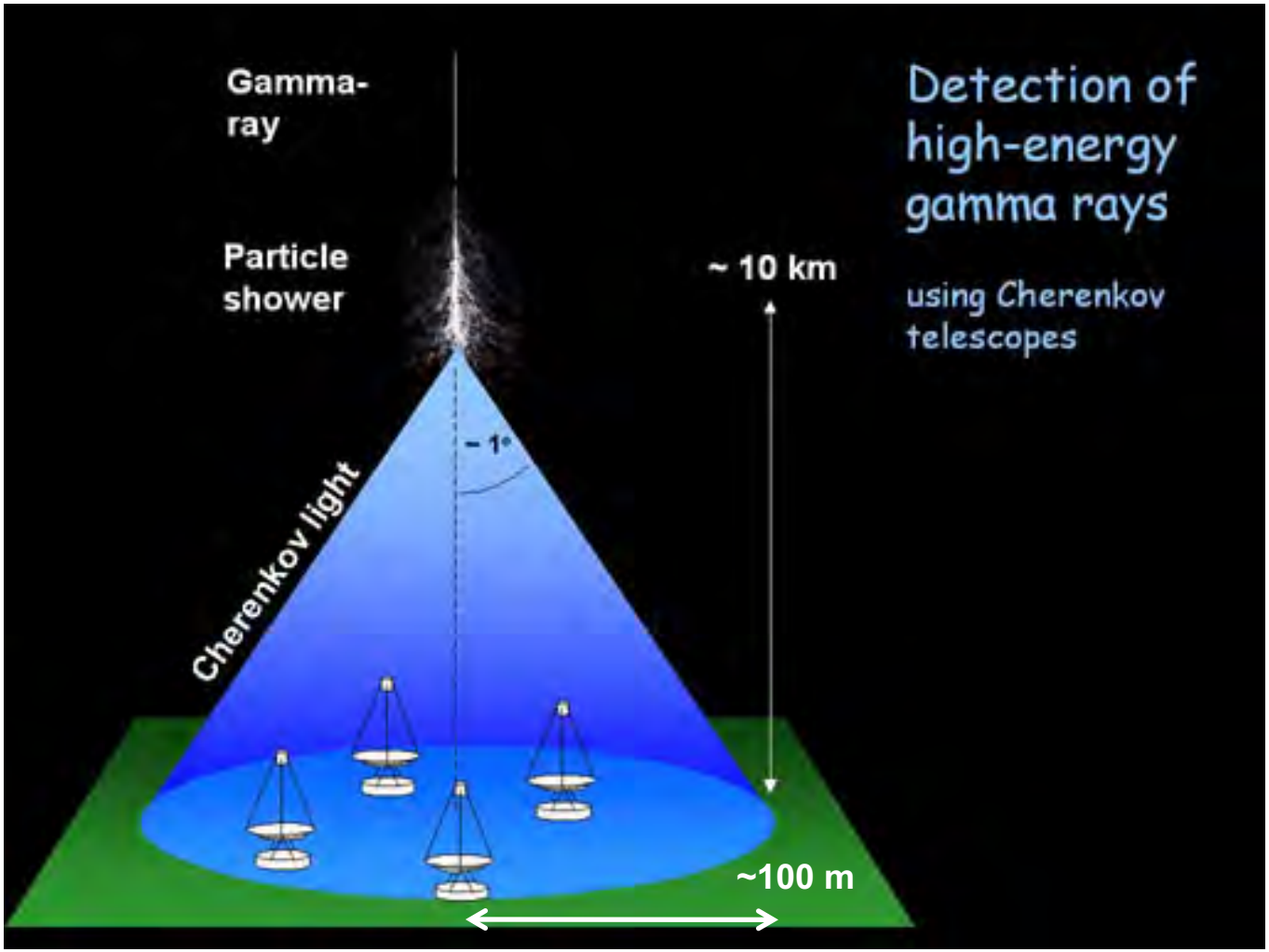
Pair production telescopes	Atmospheric Cherenkov tels.	Particle detector arrays
 EGRET, Fermi	 MAGIC, HESS, VERITAS, CTA	 Milagro, Tibet array, HAWC
0.1 - 100 GeV	30 GeV - 70 TeV	100 GeV - 100 TeV
Space borne: limited in area	Large effective area	Large effective area
Nearly background free	Excellent background rejection	Very good background rejection
Large field of view / high duty cycle	Small field of view / low duty cycle	Large field of view / high duty cycle
All-sky survey and monitoring Extragalactic (AGNs, GRBs), PSRs, MQSO Dark matter	Study of known sources Deep survey of limited regions Morphology of TeV emitters (SNRs, PWN) High resolution spec. to 30 TeV	Partial (2/3) sky survey and monitoring Extended sources Transients (GRBs) > 30 GeV Spectra up to 100 TeV

The atmosphere as a detector

- Optical frequency (blue) light
- Very short (few ns) exposure to limit night sky background
- Cherenkov cone very narrow, ~1° :

$$\theta = \cos^{-1}\frac{1}{n\beta}$$

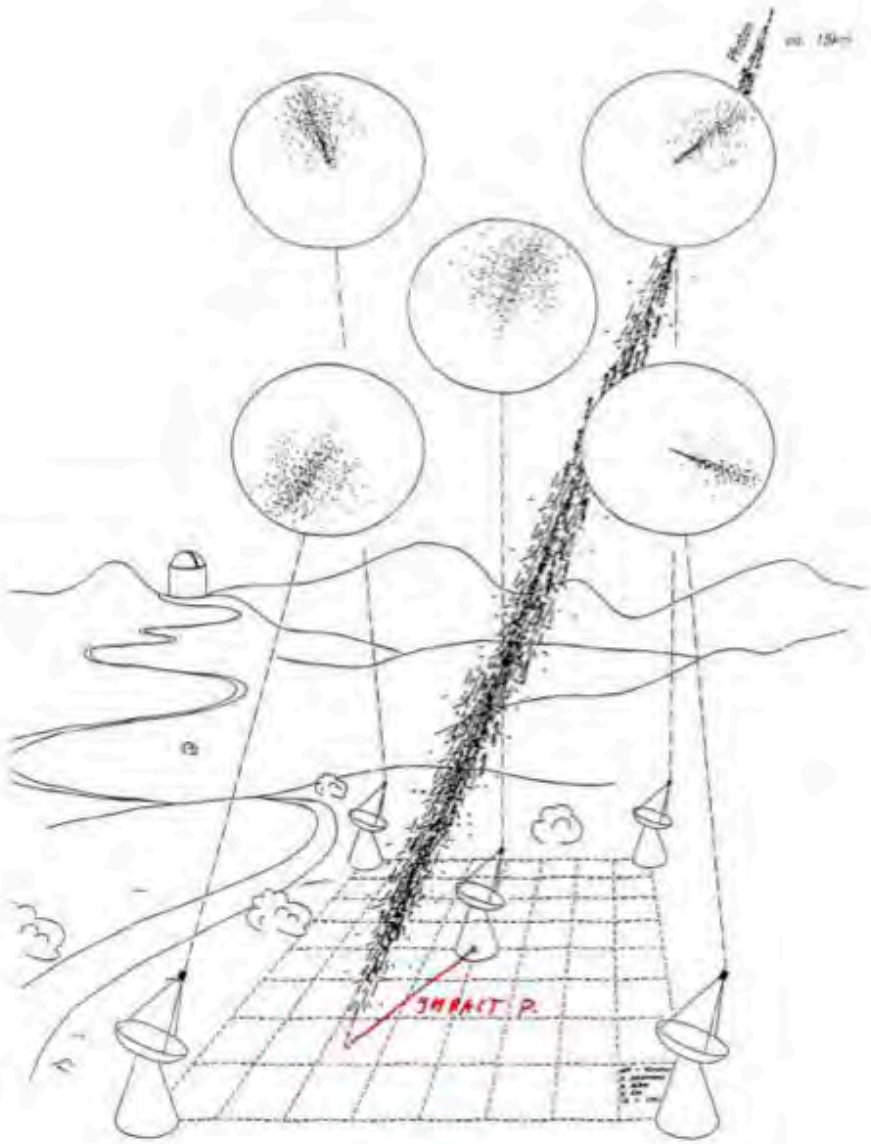
- 1000-1500 hours per year (dark, good weather)



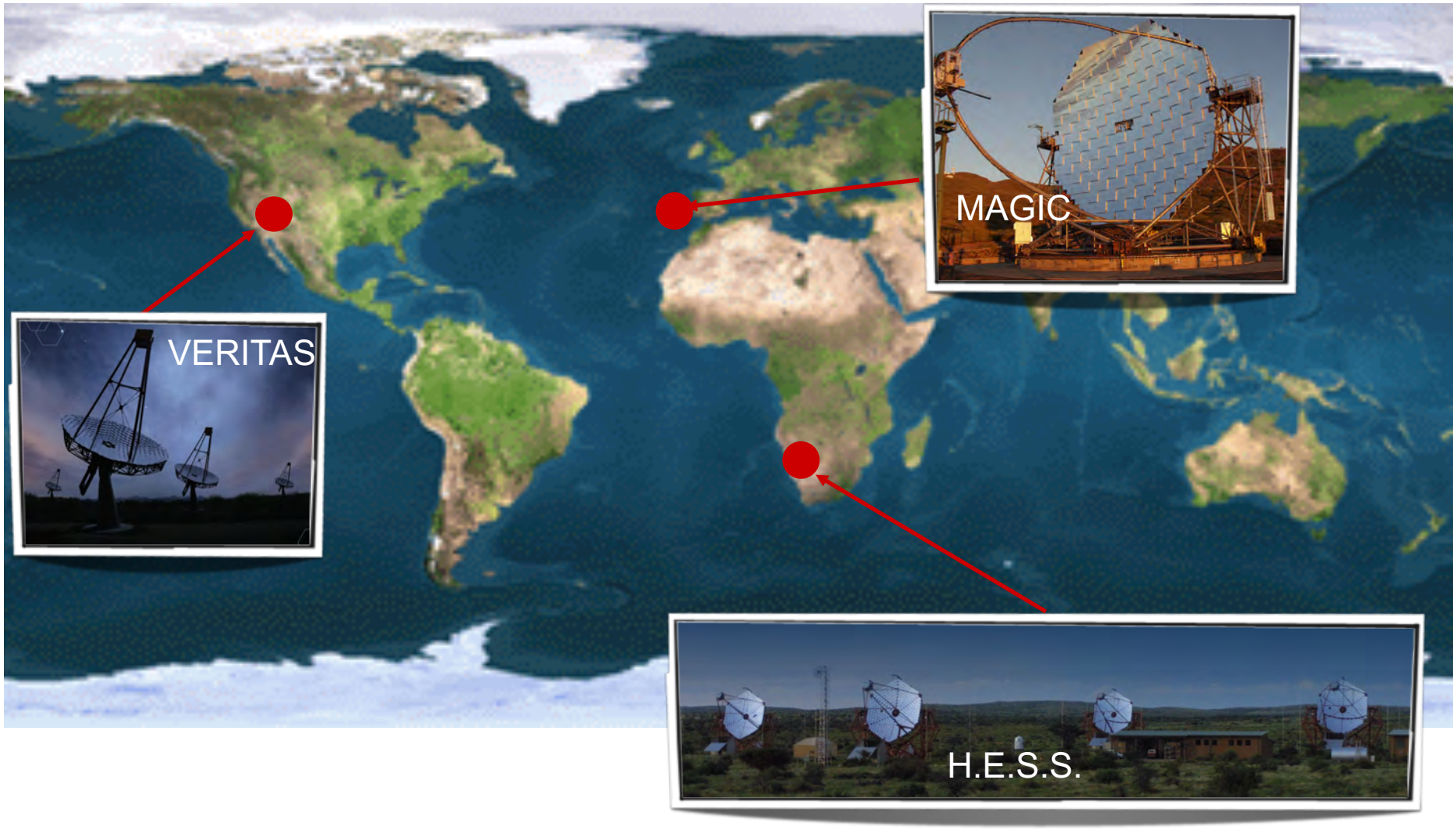
The Whipple 10 m telescope on Mt Hopkins, Arizona

- Pioneer imaging atmospheric Cherenkov telescope
- Discovered the first very-high energy (TeV) astronomical sources
  - Crab Nebula: 1989
  - Markarian 421 (1992): a nearby blazar
  - Markarian 501 (1997): another nearby blazar

The next leap forward: stereo observation



Current generation of (stereo) imaging atmospheric Cherenkov telescopes



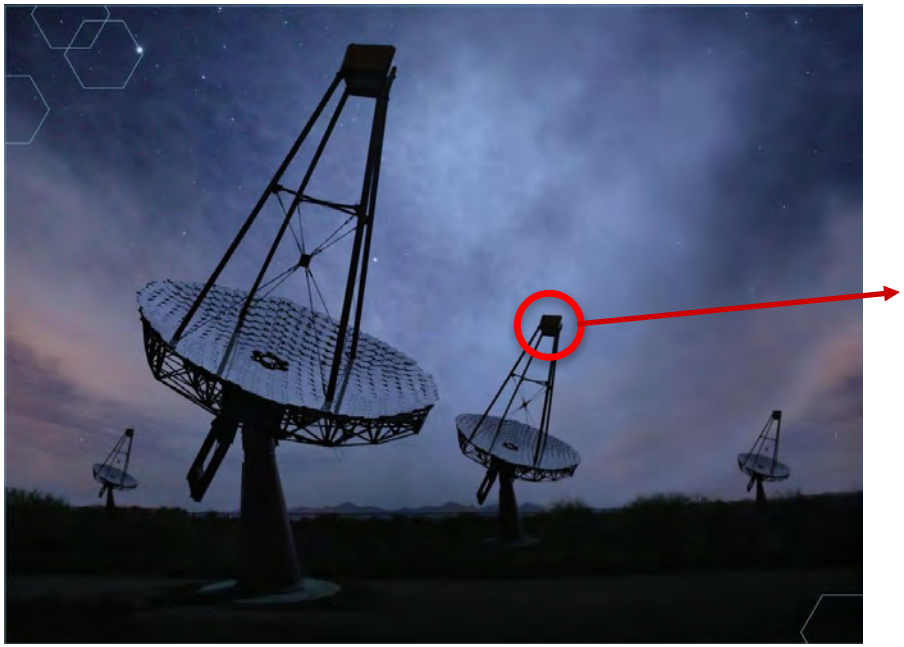

View from MAGIC


H.E.S.S.


VERITAS

Example Cherenkov telescope (looks like astronomy) and “camera” (looks like particle physics)

Telescope:



Camera:

Segmented mirrors , like optical telescopes, and detect optical light, but do not need as good angular resolution

Camera like a particle physics detector:

- Photo-detectors to detect individual photons
- Fast electronics to discriminate the few-nanosecond Cherenkov pulse from the steady night sky

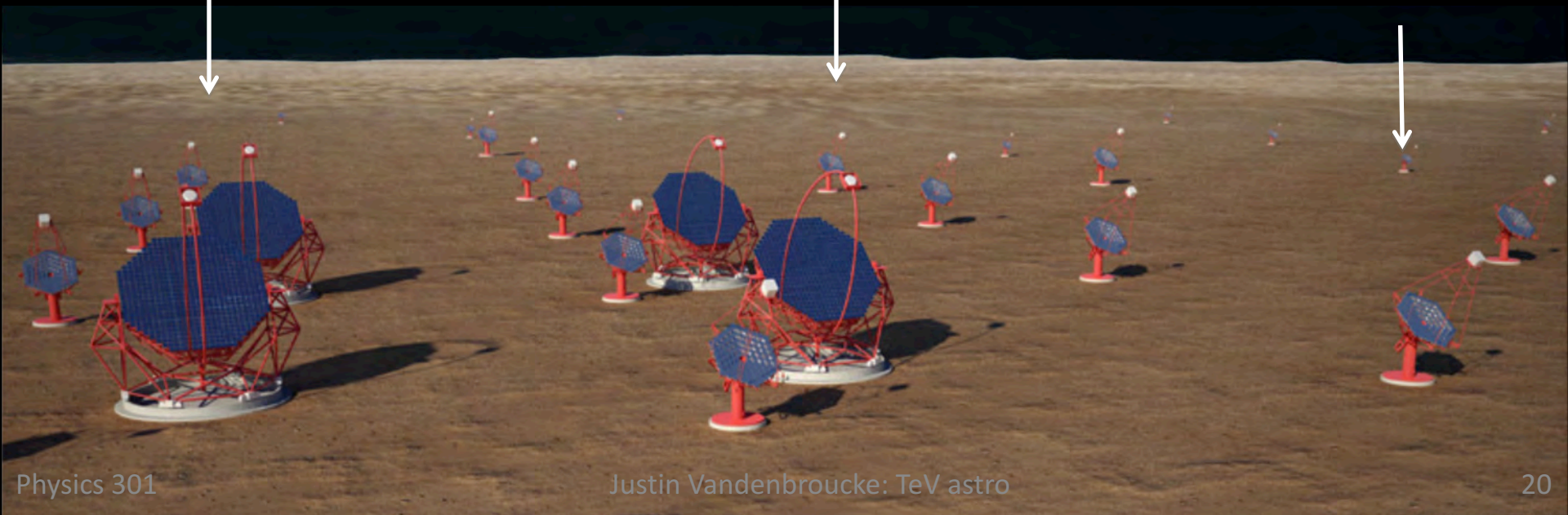
(3) Design and performance

The Cherenkov Telescope Array

Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes (South)
4 telescopes (North)

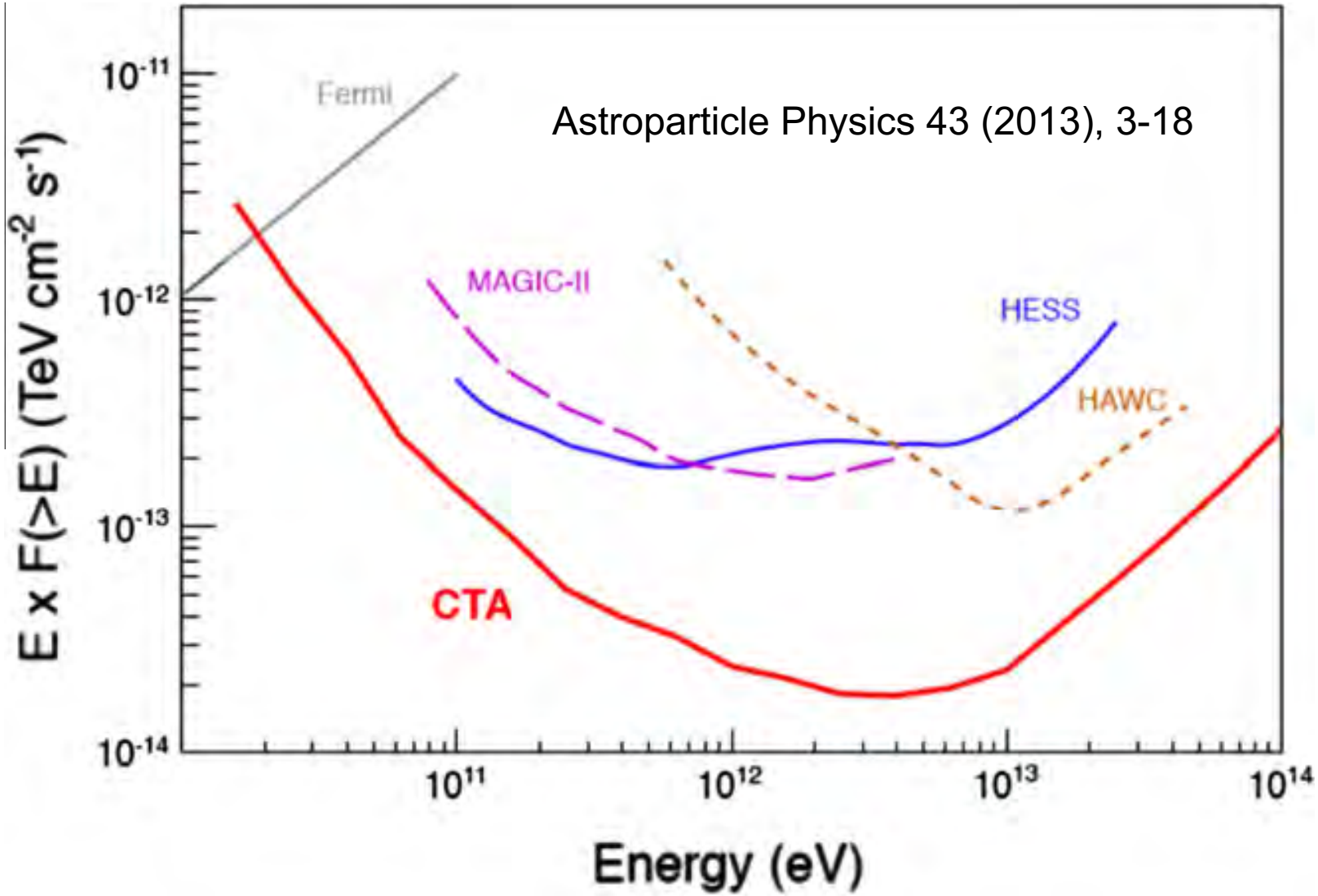
Medium energies
100 GeV – 10 TeV
9.5 to 12 m diameter
25 medium-size telescopes (S)
15 medium-size telescopes (N)

High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 small-size telescopes (S only)




Spain
La Palma
Mexico
San Pedro
Martir
northern hemisphere
southern hemisphere
Chile
Paranal
Namibia
Aar
Under Negotiation
Back-up Sites

Point source sensitivity

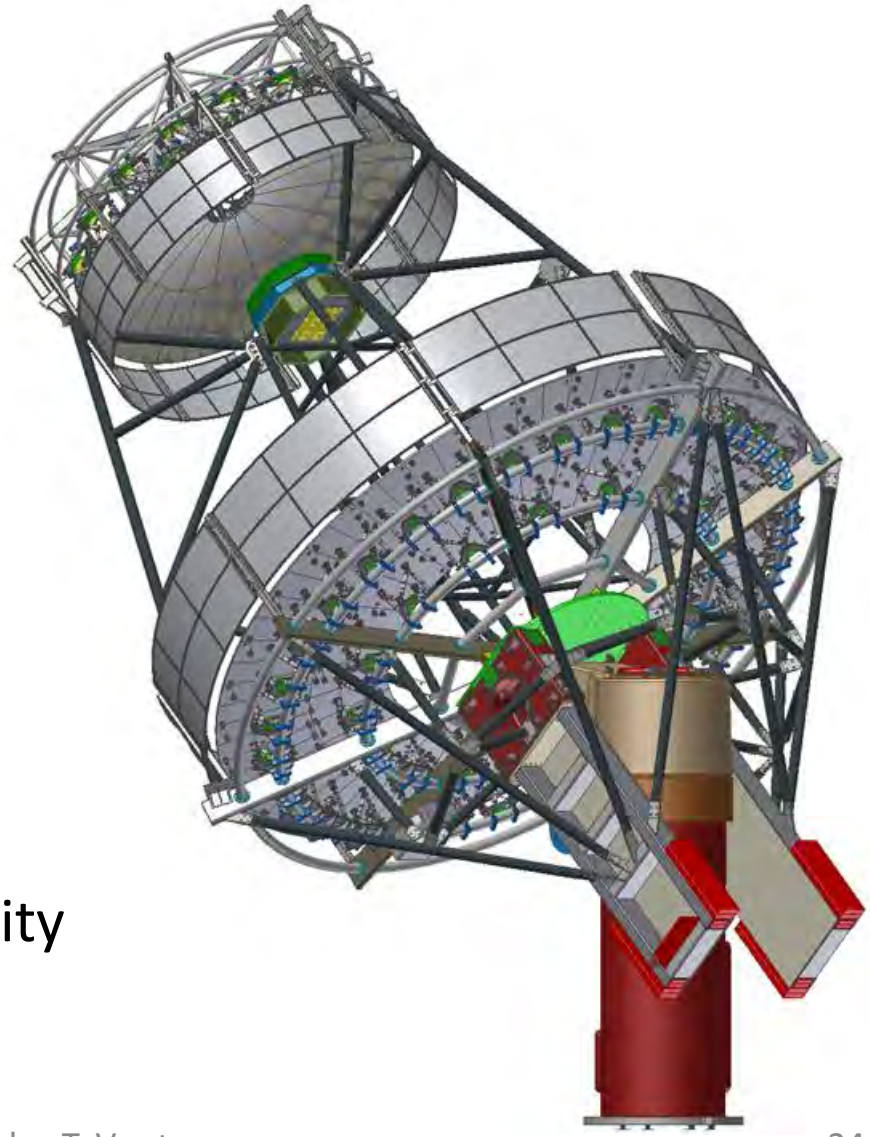


Atmospheric Cherenkov telescopes: 50 hrs
Wide field instruments (Fermi, HAWC): 1 year

(4) Prototype telescope construction

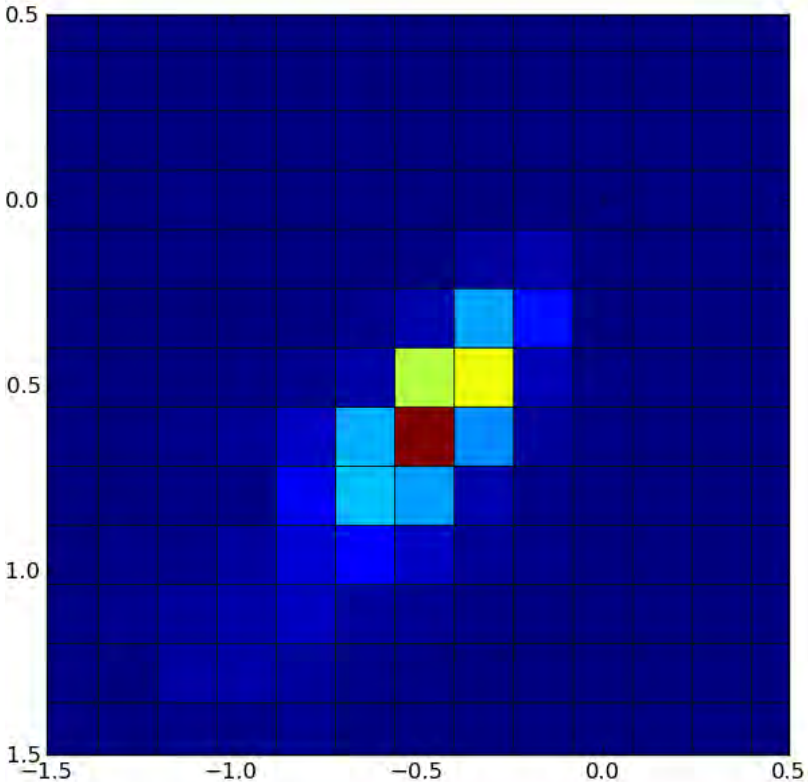
New technologies for high performance: dual mirror optics, silicon photomultipliers, multi-channel waveform digitizers

- Allows (1) better optical angular resolution over wide (8° diameter) field of view (2) small camera
- Small focal plane well suited for modern dense, highly integrated photo-detectors (silicon photomultipliers) and electronics (application-specific integrated circuits)
- Improved gamma-ray angular resolution and background rejection allow qualitatively improved sensitivity

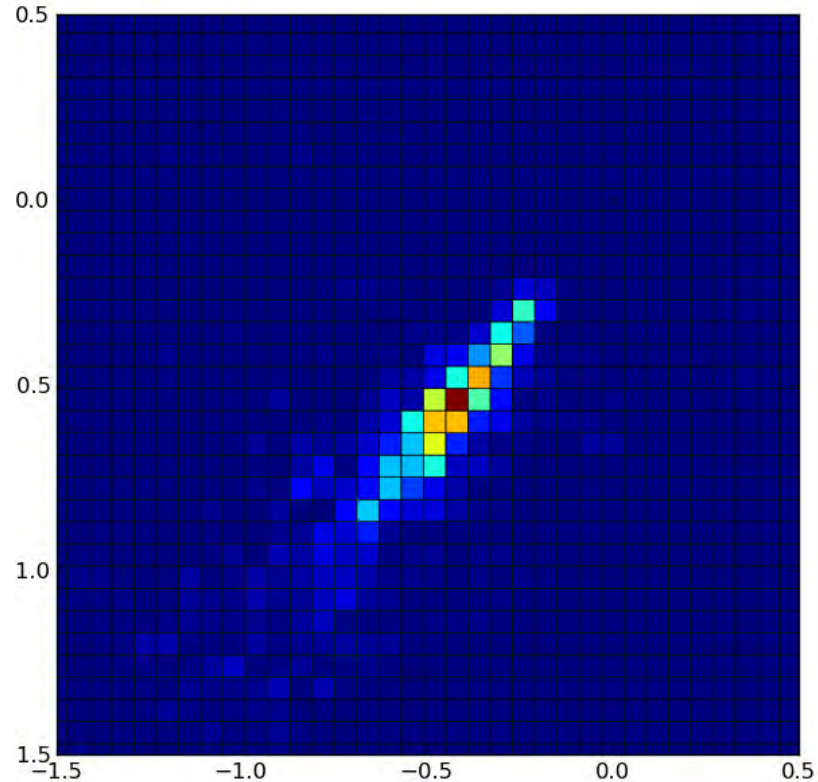


Simulated shower images for two-mirror vs. one-mirror telescope design

Example 1 TeV gamma-ray shower as seen by one-mirror or two-mirror telescope



DC telescope (~2k 0.16° pixels)

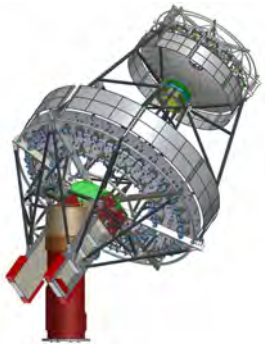


SC telescope (~10k 0.06° pixels)

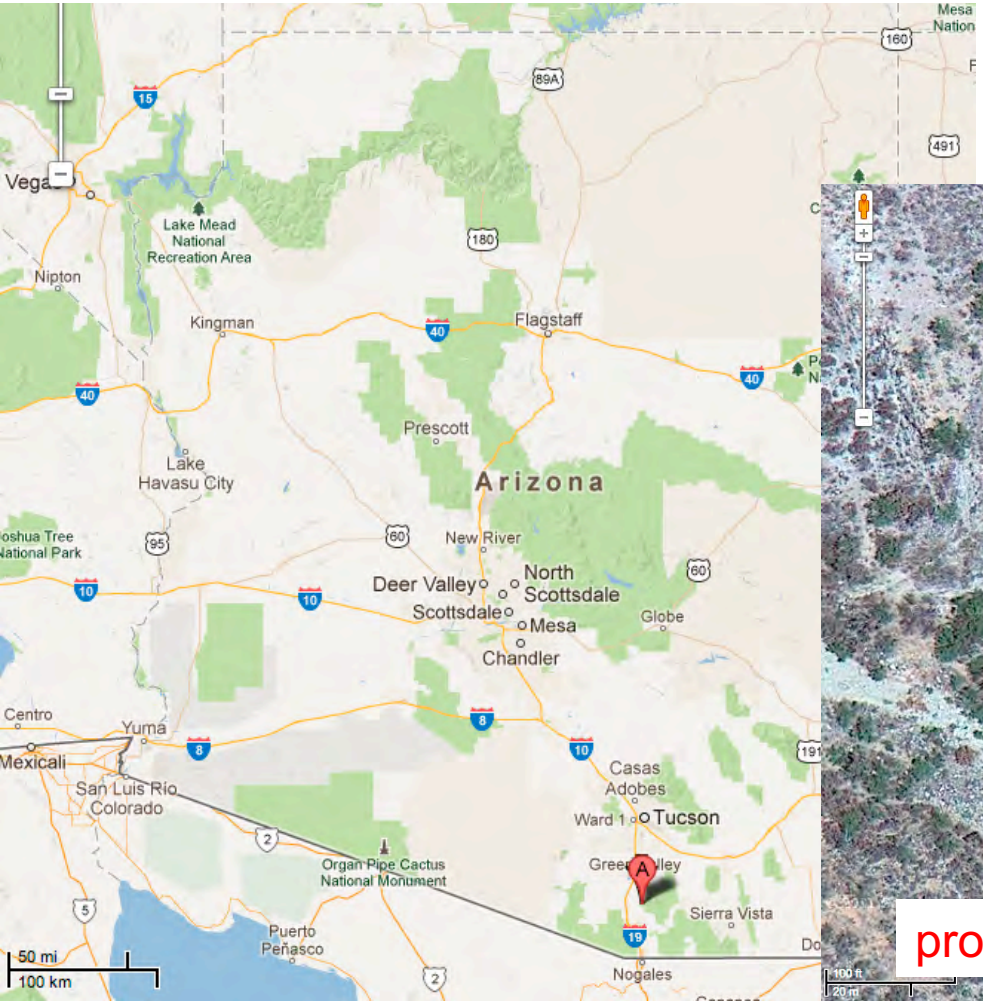
Both images zoomed in (2° across, compared to 8° field of view)

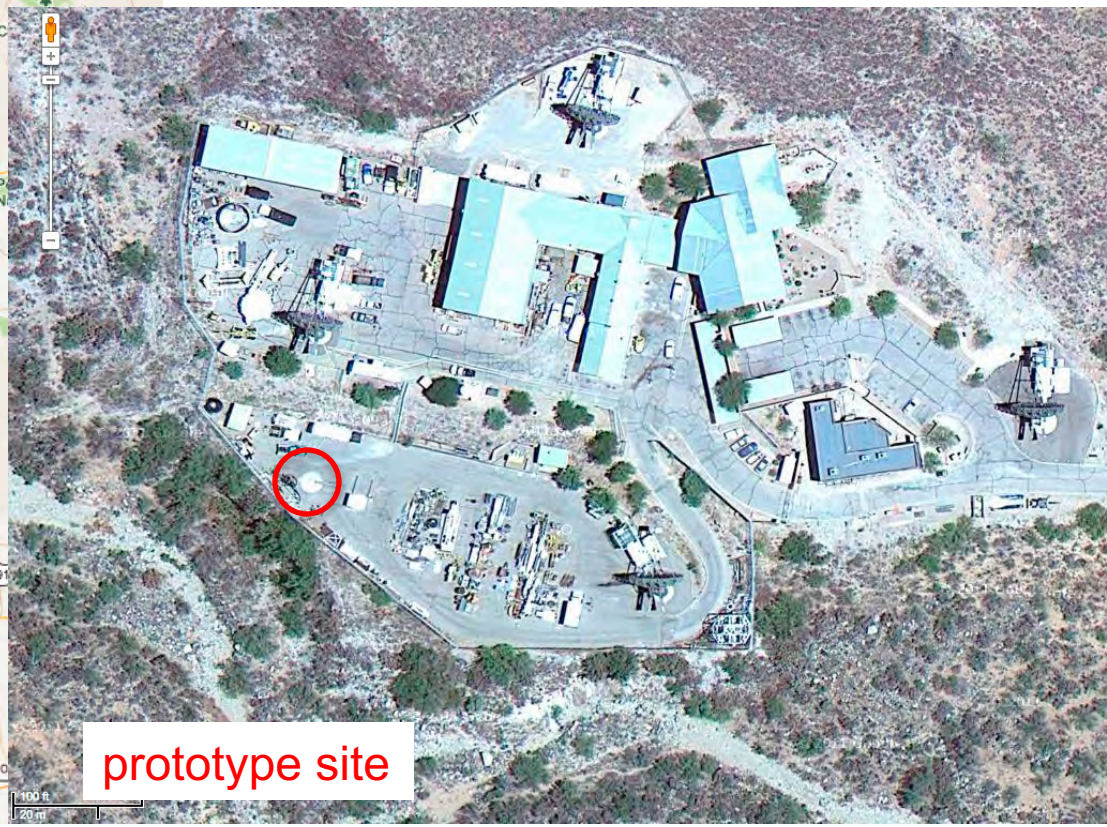
Schwarzschild-Couder (dual-mirror) Telescope prototype construction underway

- NSF-funded prototype at VERITAS site in Arizona
- Full primary mirror, full mechanics, full secondary mirror, partial camera
- Silicon photomultipliers and readout electronics for one full sub-field (25 modules)
- Sub-system production and testing underway now
- Prototype commissioning in 2017



VERITAS site
at 4,200 ft altitude on Mount Hopkins in Arizona





Prototype construction in Arizona

http://cta-psct.physics.ucla.edu

live web cam

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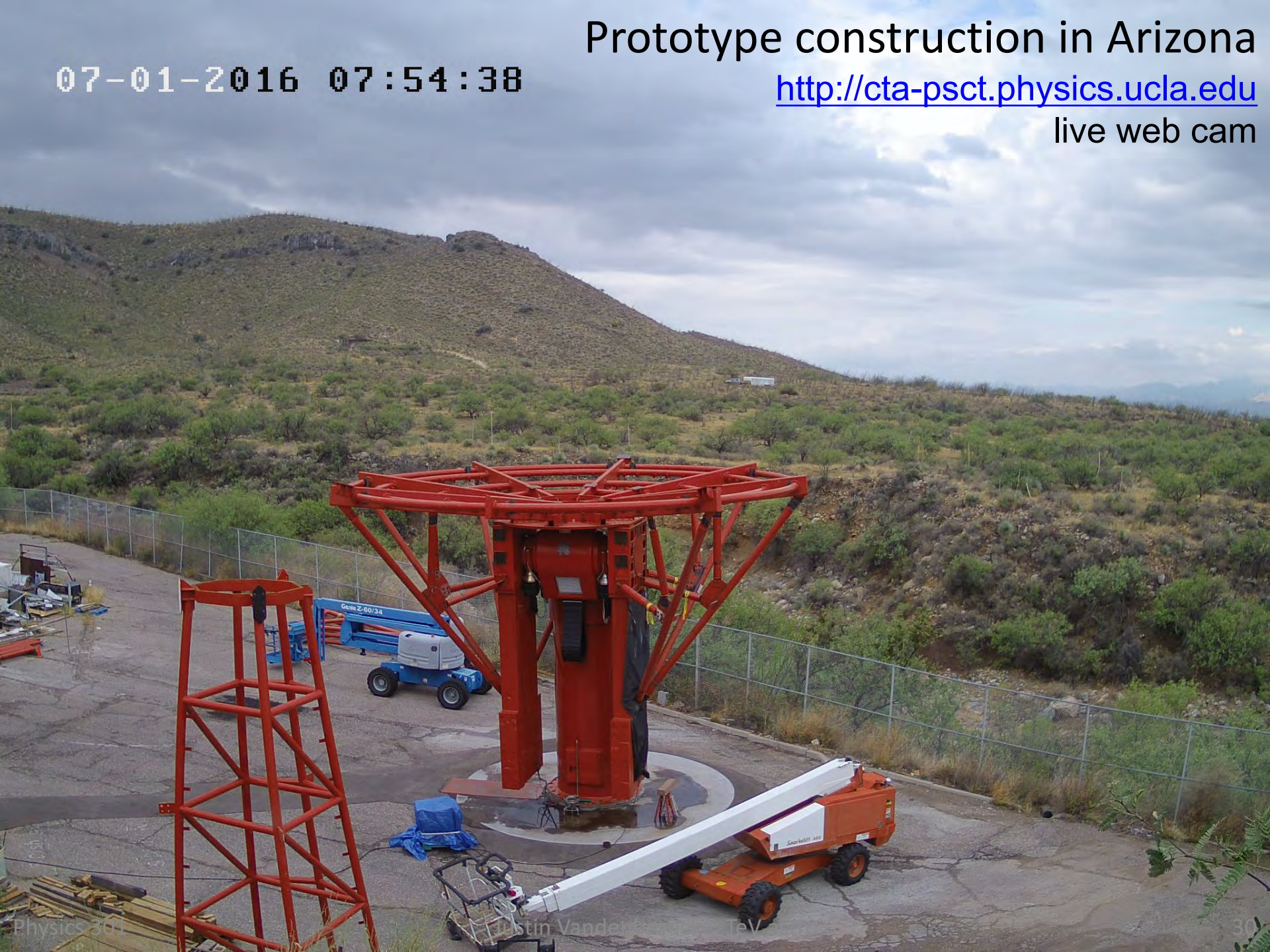

Prototype construction in Arizona

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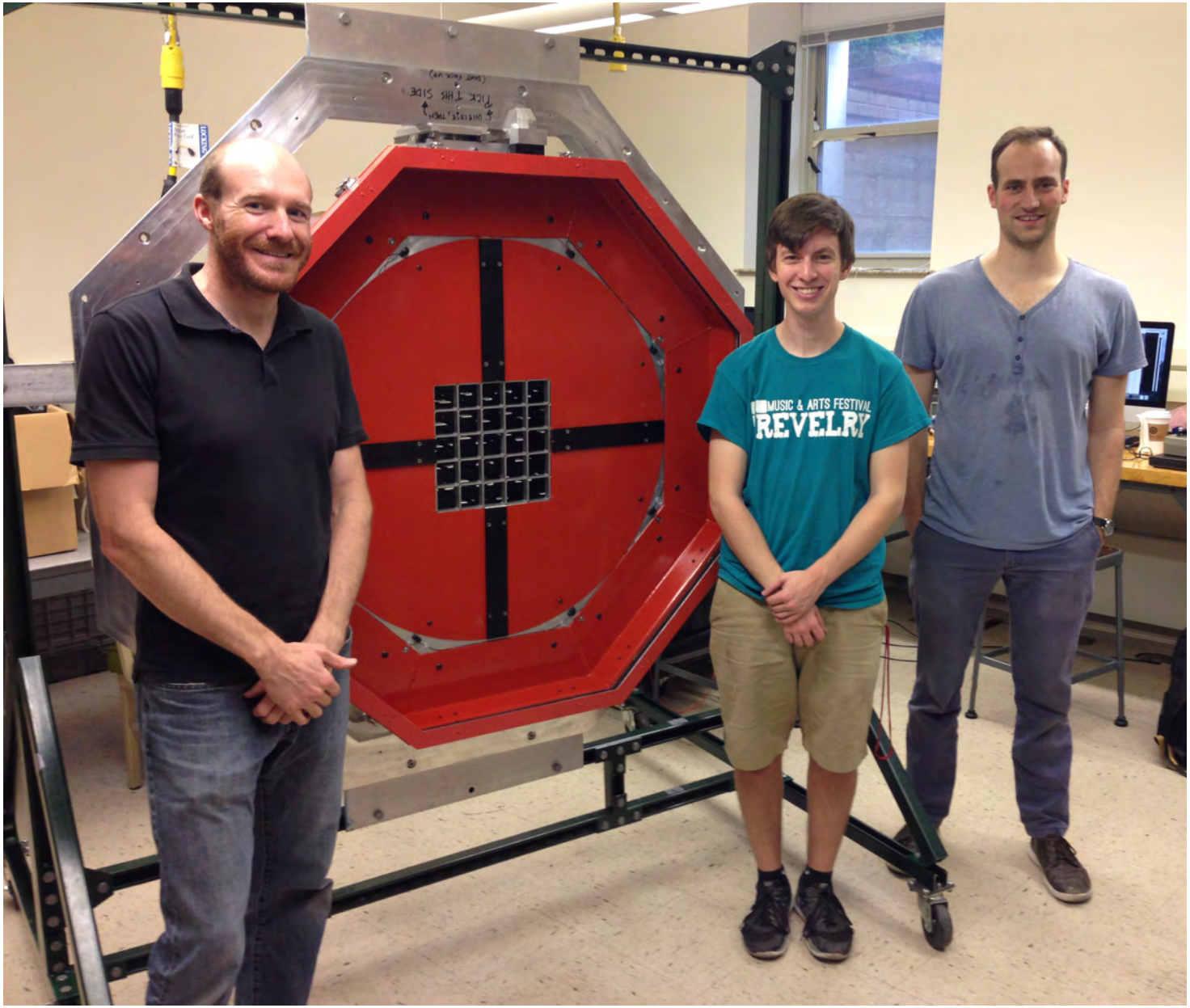
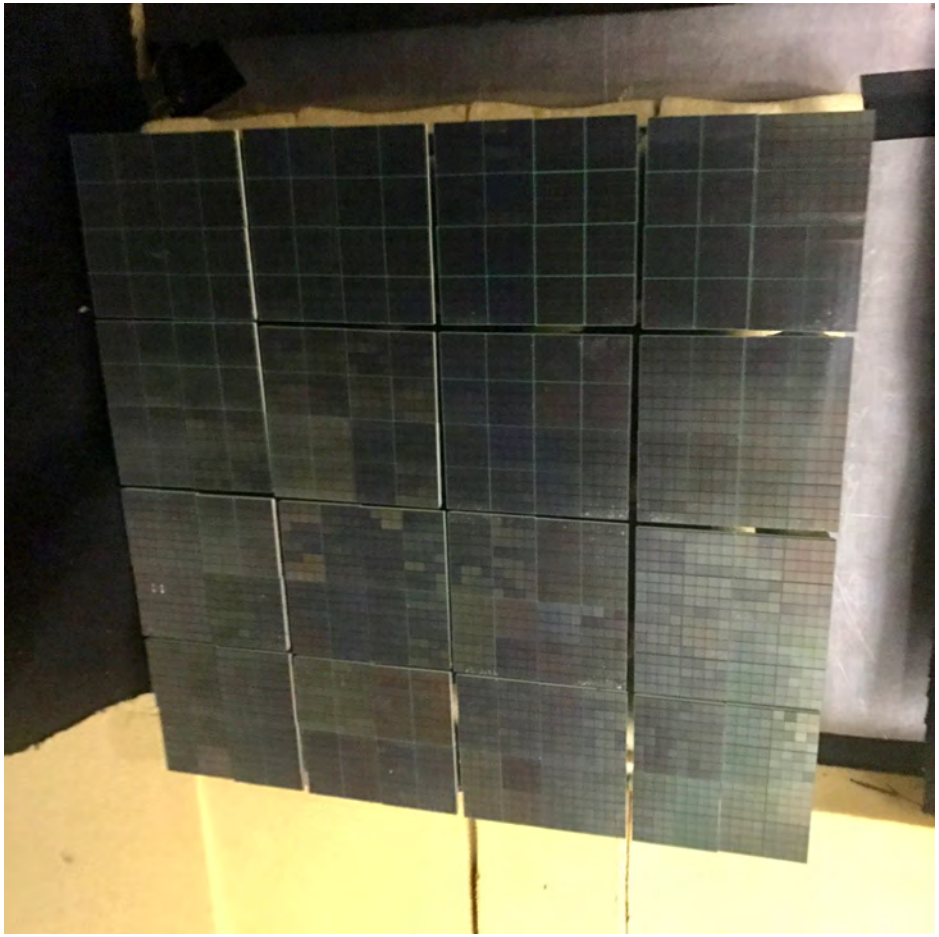
live web cam

Camera integration and testing in Chamberlin (first floor lab)



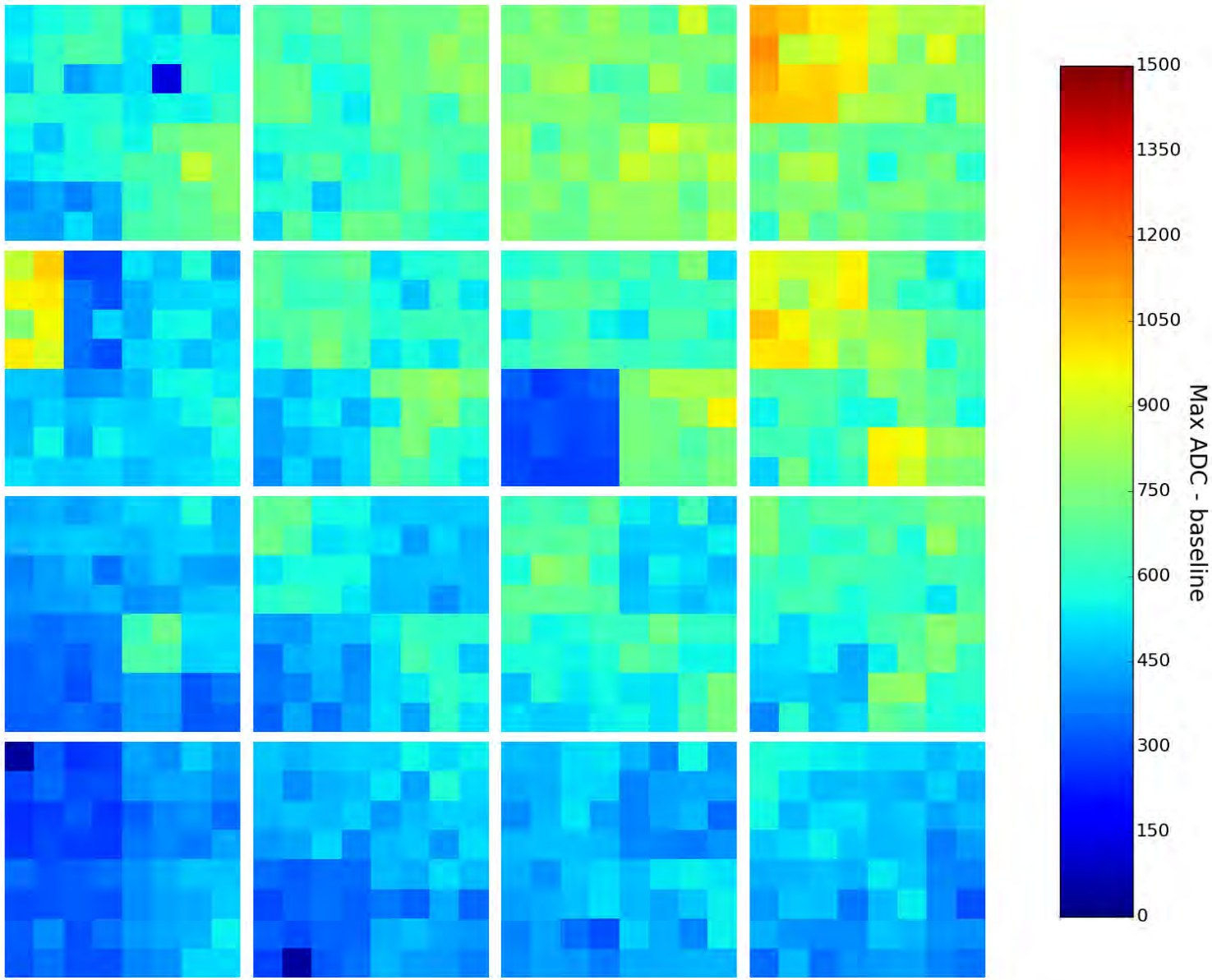
Camera integration and testing in Chamberlin (first floor lab)

integrated camera



focal plane sensors

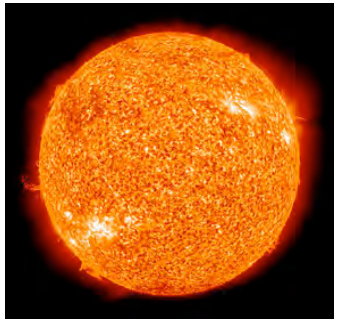
SCT camera in Chamberlin hall:
first recording of light with full camera last week!



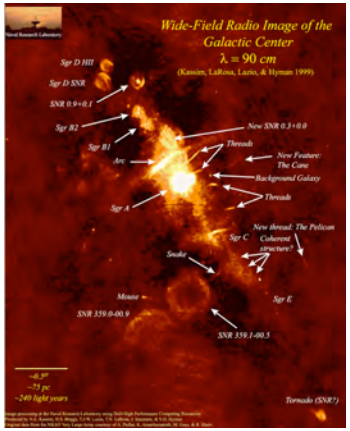
(5) Scientific prospects: highlights

Where does dark matter accumulate in the Universe? Search for neutrinos and/or gamma rays from these

Center of Earth



Center of Sun



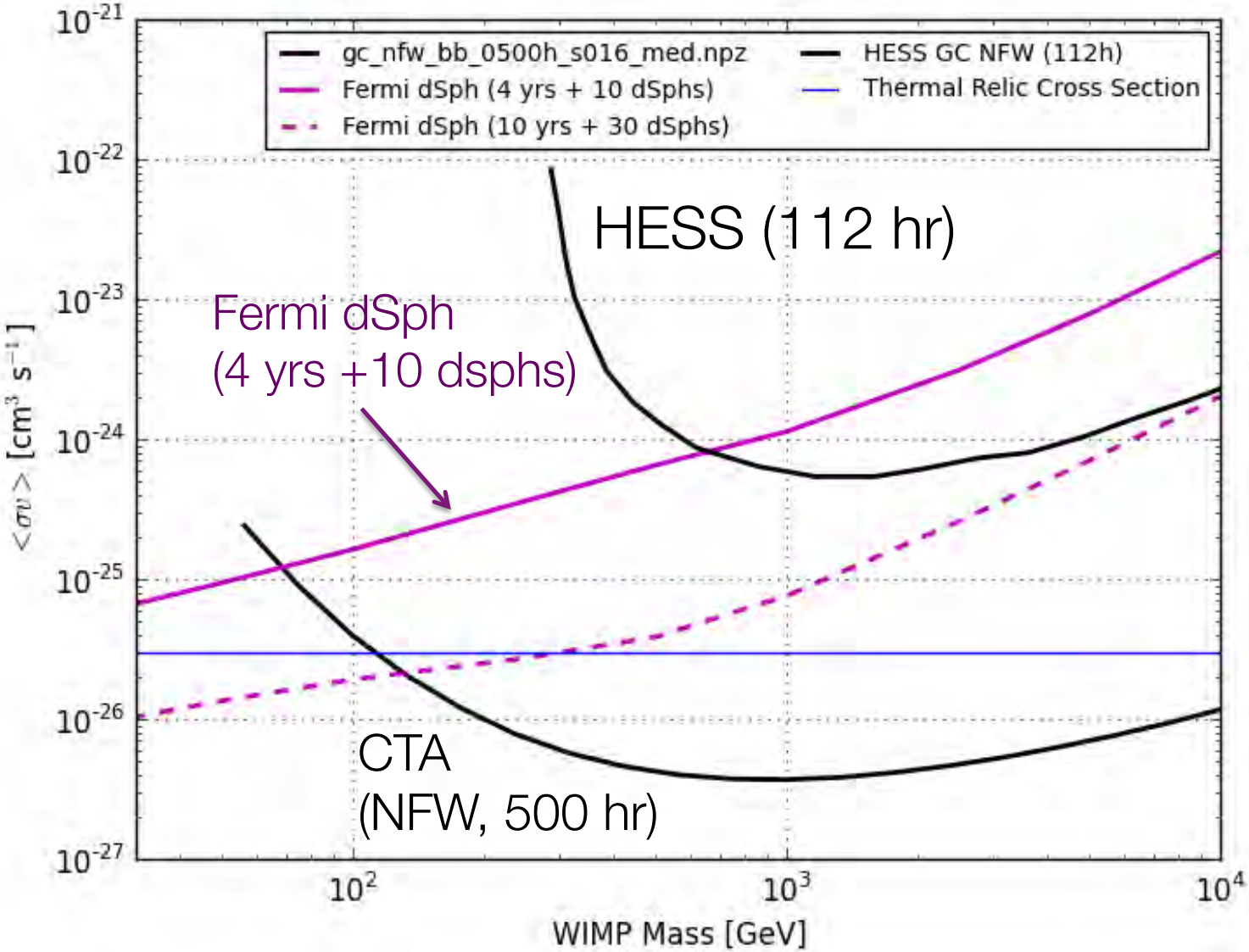
Center of Galaxy

Galactic halo

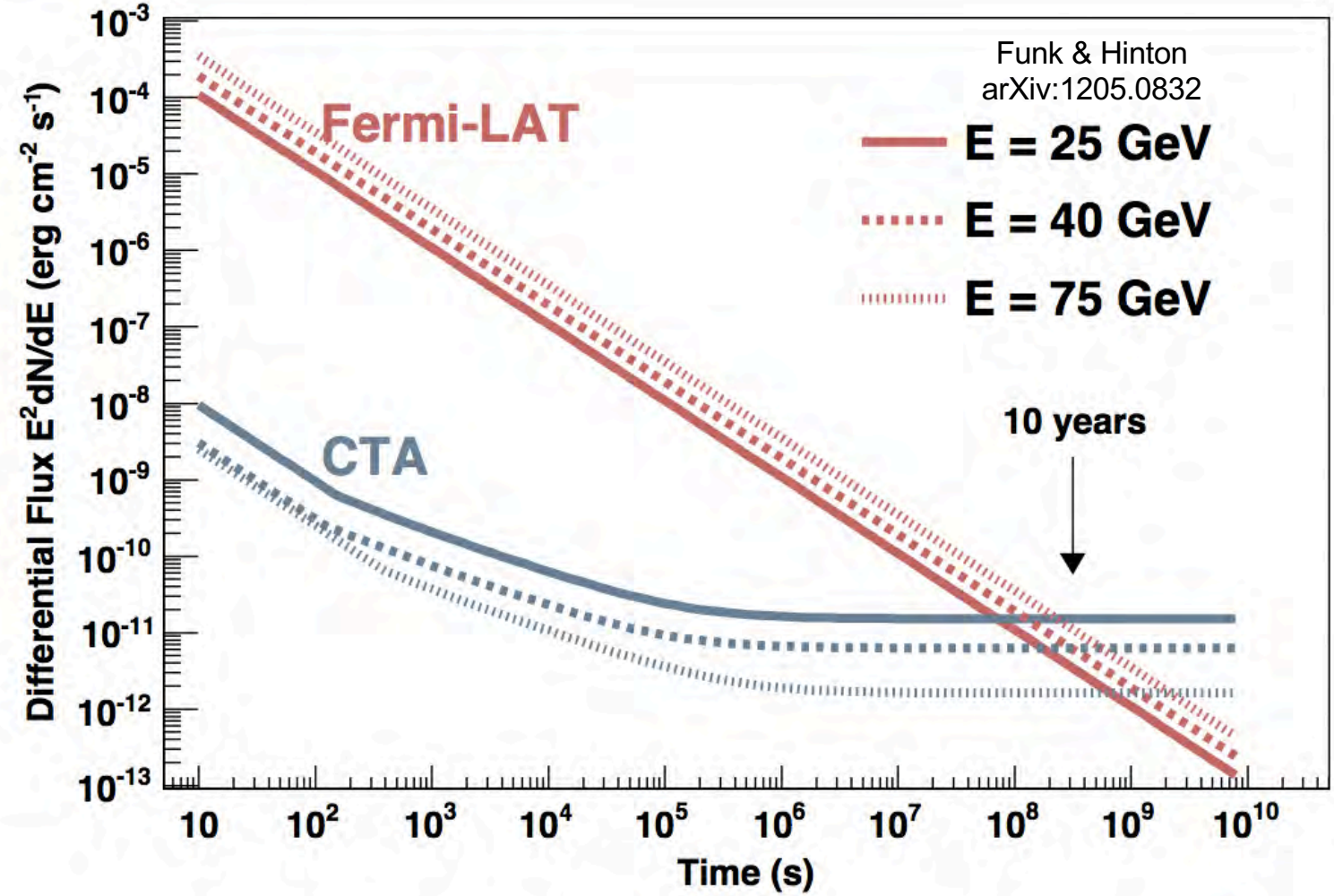
Dwarf galaxies

Galaxy clusters

Fermi dwarfs & CTA Galactic center will cover entire mass range down to thermal cross section

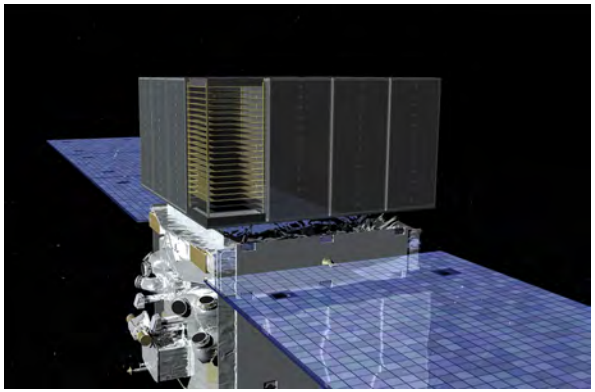


Opening up the time domain



Field of view, duty cycle also matter

Multi-messenger astronomy



Fermi

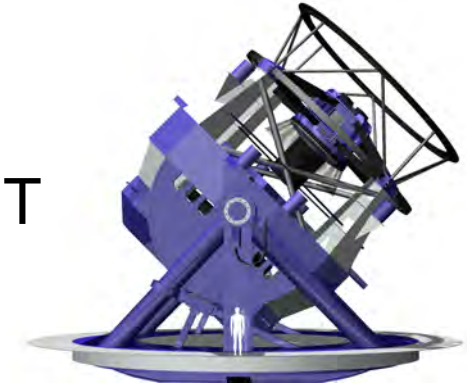
SKA

LIGO

HAWC

IceCube

LSST

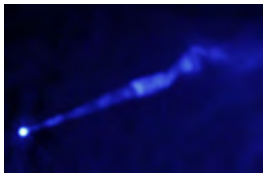
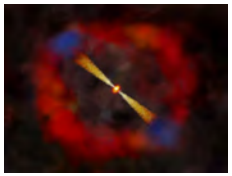
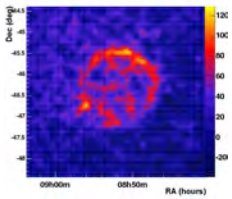


Conclusion and outlook

- The Cherenkov Telescope Array will study astrophysics and particle physics with the highest energy photons ever detected
- CTA will provide important discoveries and constraints concerning dark matter, astrophysical particle accelerators, transient bursts, electrons and positrons, and Lorentz invariance
- Simultaneous operation with Fermi, HAWC, LIGO, IceCube, SKA, LSST and other wide-field observatories will enable discovery through multiple messengers and transients
- See also Distributed Electronic Cosmic-ray Observatory, DECO (use your smart phone to detect particles) https://wipac.wisc.edu/deco
- **Undergraduate research opportunities available: justin.vandenbroucke@wisc.edu**



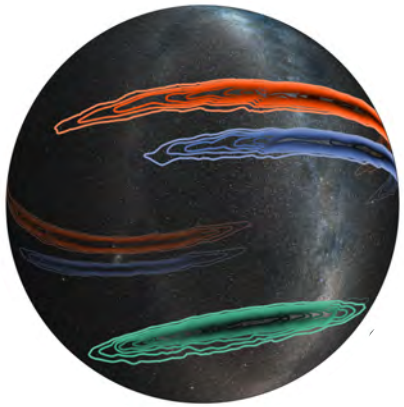


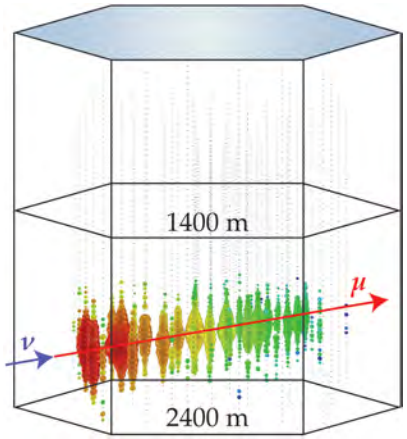





Extra slides

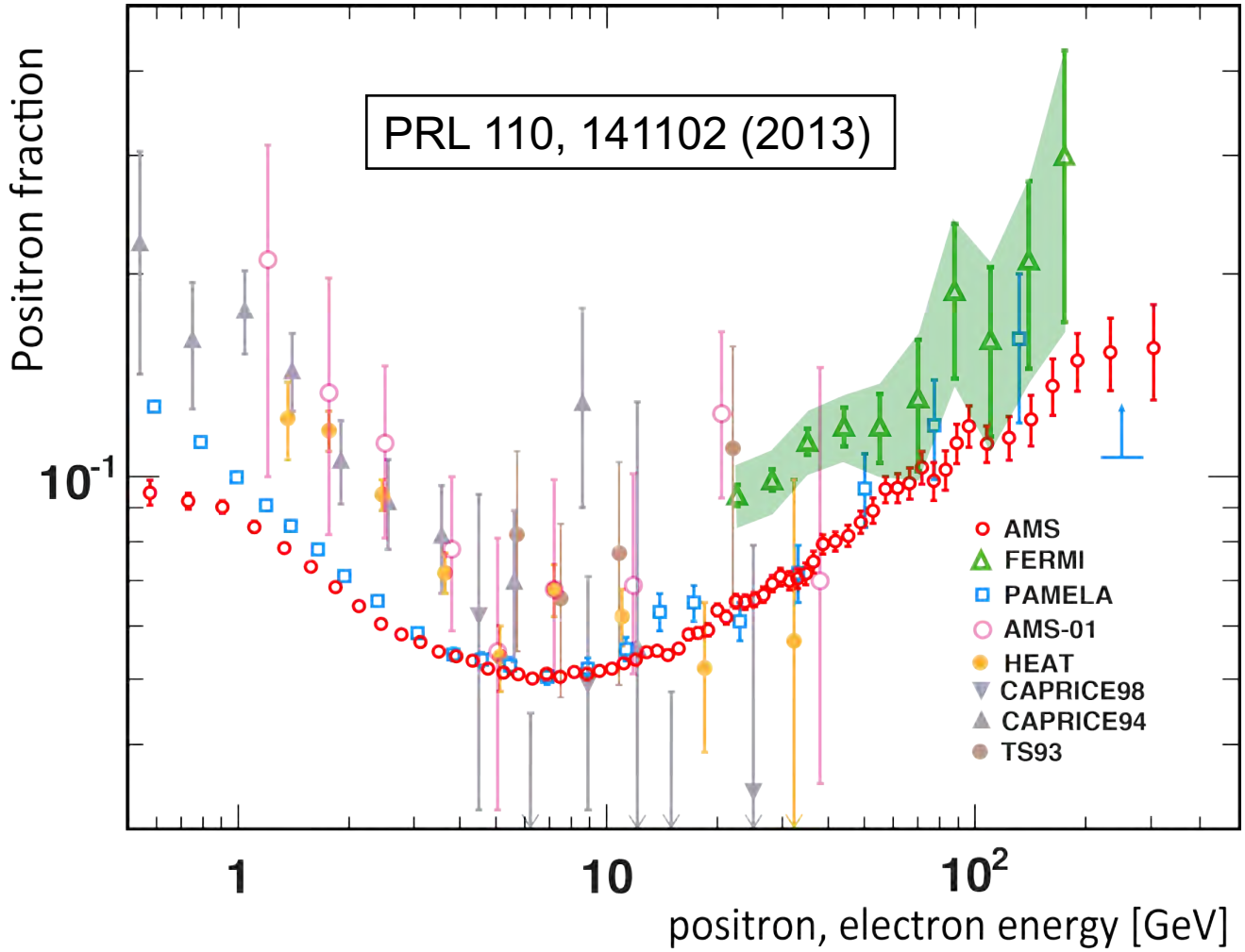
Rapid follow up of transients: receiving and issuing multi-messenger alerts

- Telescopes can slew in <30 seconds
- Astrophysical neutrinos: search for electromagnetic counterpart, to identify neutrino (and cosmic ray) origins
- Gravitational waves: TeV emission from black hole or neutron star mergers (including those producing gamma-ray bursts)
- Gamma-ray burst light curves and spectra with high statistics per burst
- Triggers from optical/IR/radio transient factories: tidal disruption events, fast radio bursts, supernova shock breakout, …
- Galactic transients inc. novae, Crab nebula flares (up to 100 TeV)
- Real-time analysis (<30 sec) for serendipitous transient detection and alerting other observatories
- 8° field of view per telescope, can cover larger areas with tiling or divergent pointing



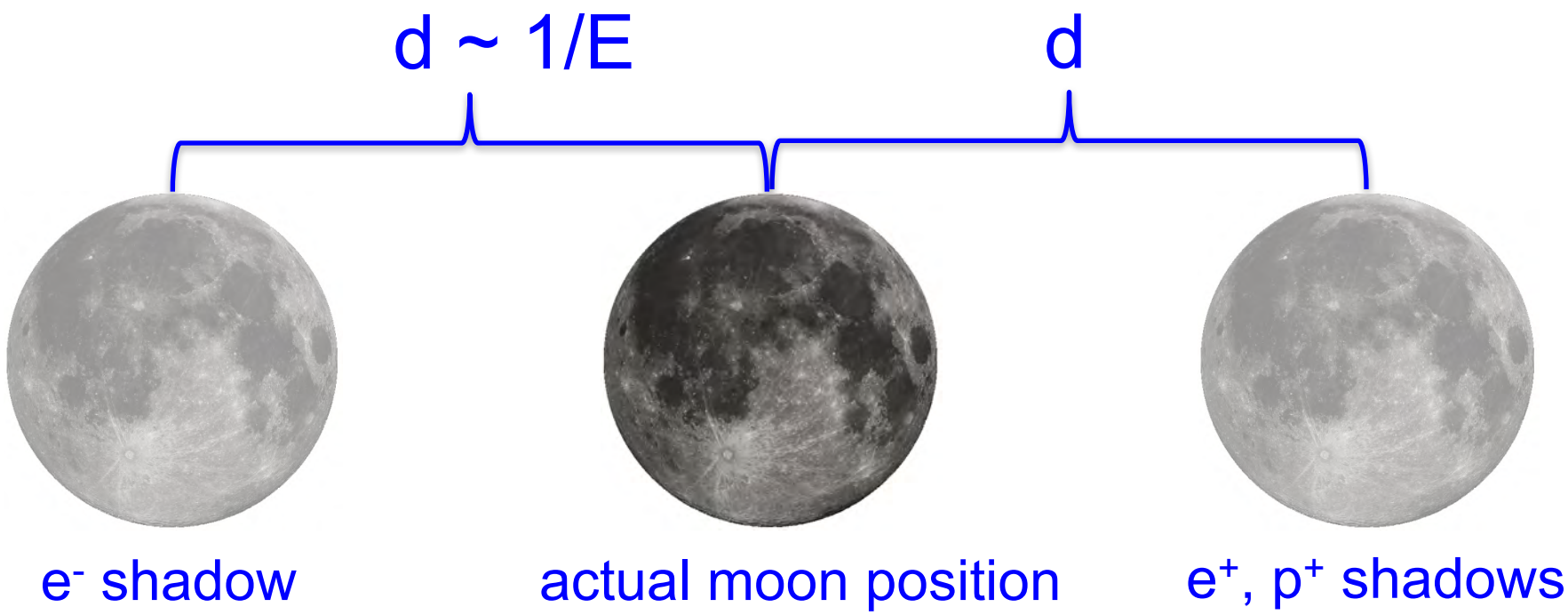


AMS measurement of positron fraction and constraints on its anisotropy



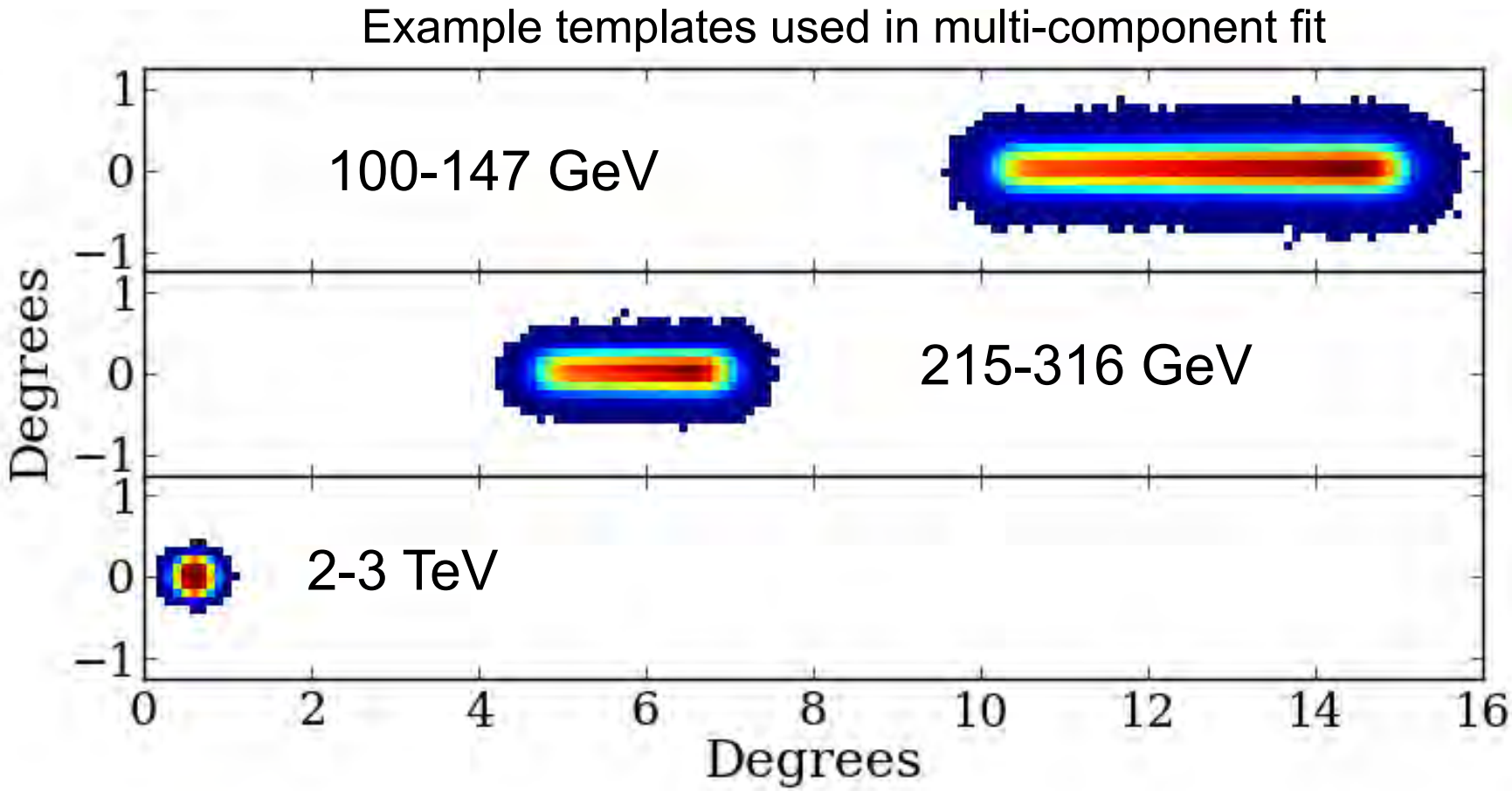
- Positron fraction (integrated from 16 to 350 GeV) shows no anisotropy
- Dipole anisotropy < 0.036 (95% confidence)

The Moon spectrometer



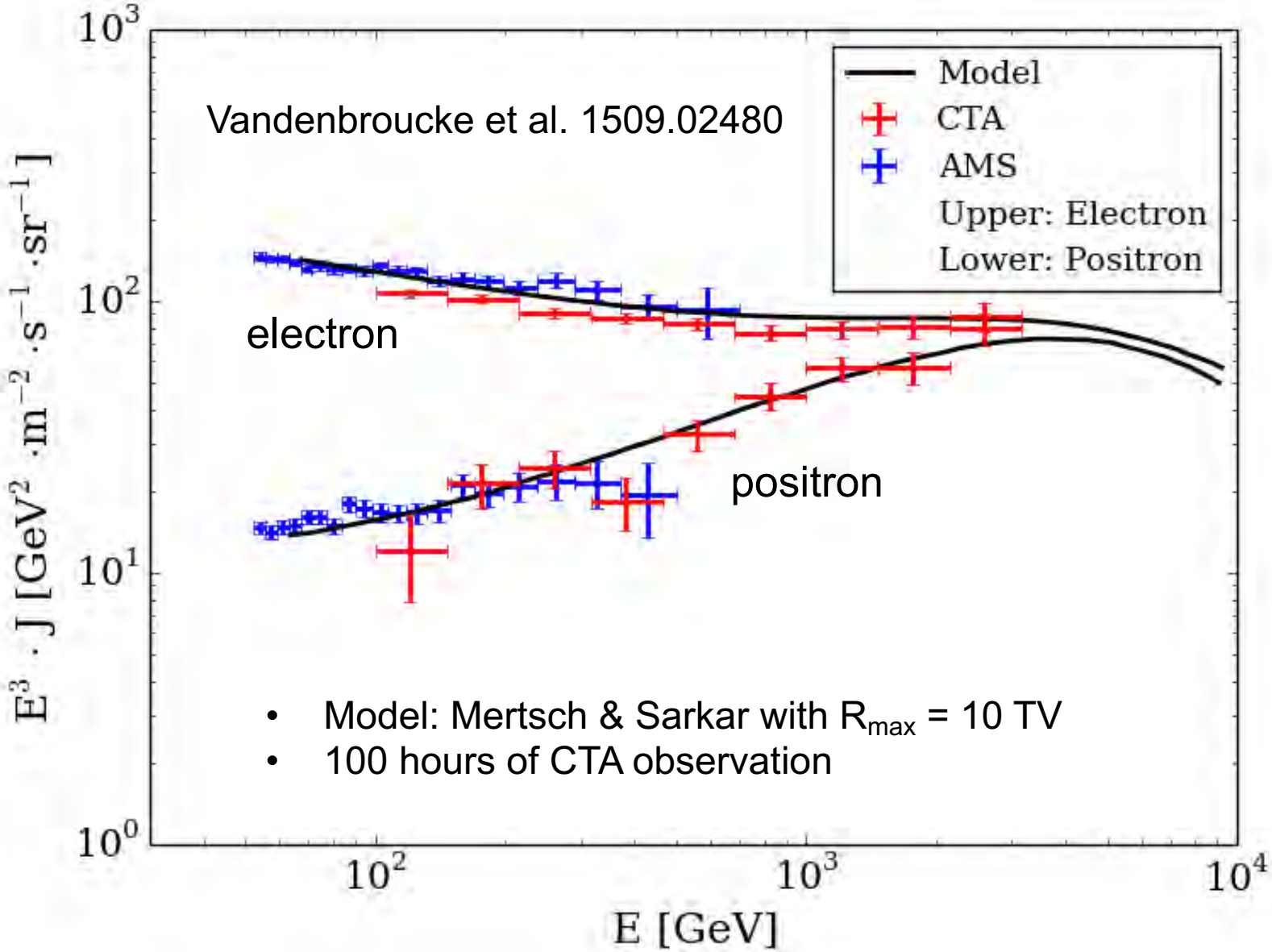
- Magnetic deflection in Earth's field along trajectory from Moon is ~1.5° at 1 TeV (depending on viewing direction and location on Earth)
- Electron, positron shadows are displaced in opposite directions
- In our ultra-relativistic regime (>100 GeV), protons and positrons deflect same amount
- Measured proton, positron shadows have different size and position due to different pointing resolution and energy reconstruction

Simulated CTA positron Moon shadow in various energy bins



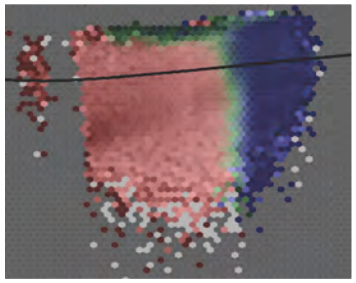
- Above ~3 TeV: deflected Moon shadow starts to overlap true Moon position
- Below ~0.3 TeV: dim shower difficult to detect above background moonlight; large deflection requires separate telescope pointing

Simulated CTA positron spectrum measurement

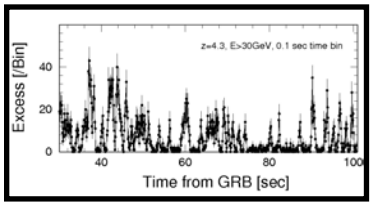


- Model: Mertsch & Sarkar with R_{max} = 10 TV
- 100 hours of CTA observation

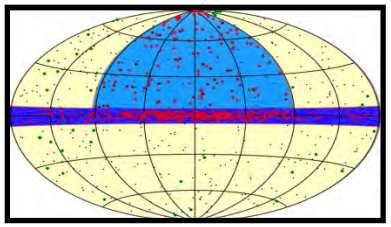
Key Science Projects (KSPs)



Dark Matter Programme

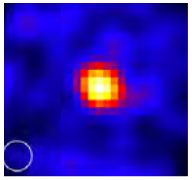


Transients



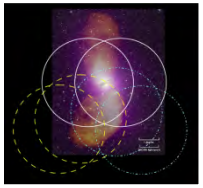
ExGal Survey

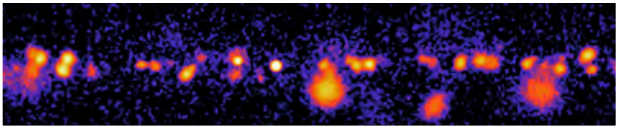
Galaxy Clusters



Star Forming Systems

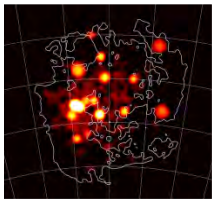
AGN



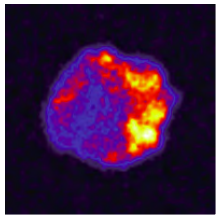


Galactic Plane Survey

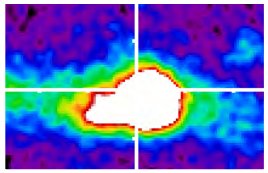
LMC Survey



PeVatrons



Galactic Centre



Extragalactic

Galactic

cta cherenkov telescope array

Gamma rays from dark matter annihilation in the cosmos

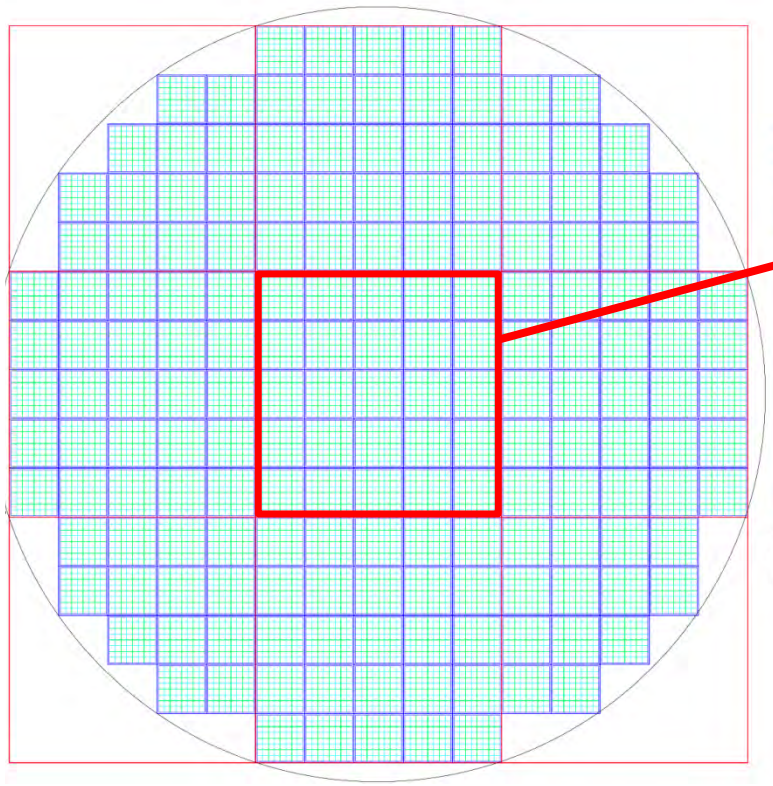
- **Galactic center halo**
  - Large expected signal (J factor)
  - Large astrophysical backgrounds, but they can be distinguished from smooth halo shape
  - Large uncertainty on dark matter density (squared)
  - Probably the best target
- **Dwarf spheroidal galaxies**
  - Much more mass (DM) than light (stars)
  - Little/no astrophysical background from cosmic rays
  - Smaller J factor than halo
  - Smaller uncertainty on dark matter distribution
- **Galaxy clusters**
- **Milky Way subhalos**
- Prioritization among dark matter targets is underway (while maintaining flexibility for new targets such as dwarf spheroidals)

Modular, hierarchical camera design

(1) Full camera: 9 sub-fields

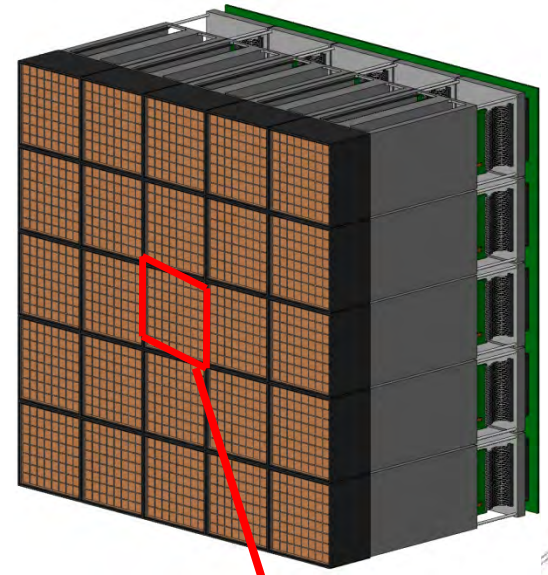
8° (0.81 m) diameter for 11,328 pixels

(24 telescopes will have 272k channels)



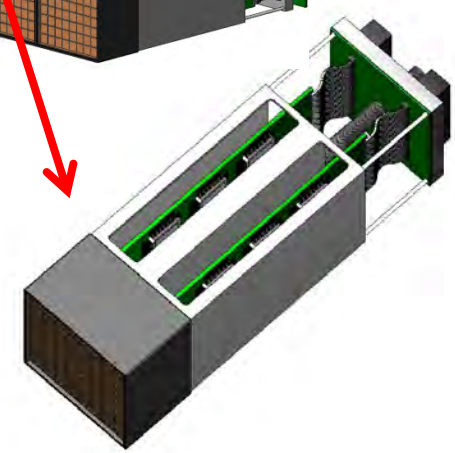
Astroparticle Physics 36 (2012) 156-165

(2) Sub-field: 25 modules



(3) Camera module:

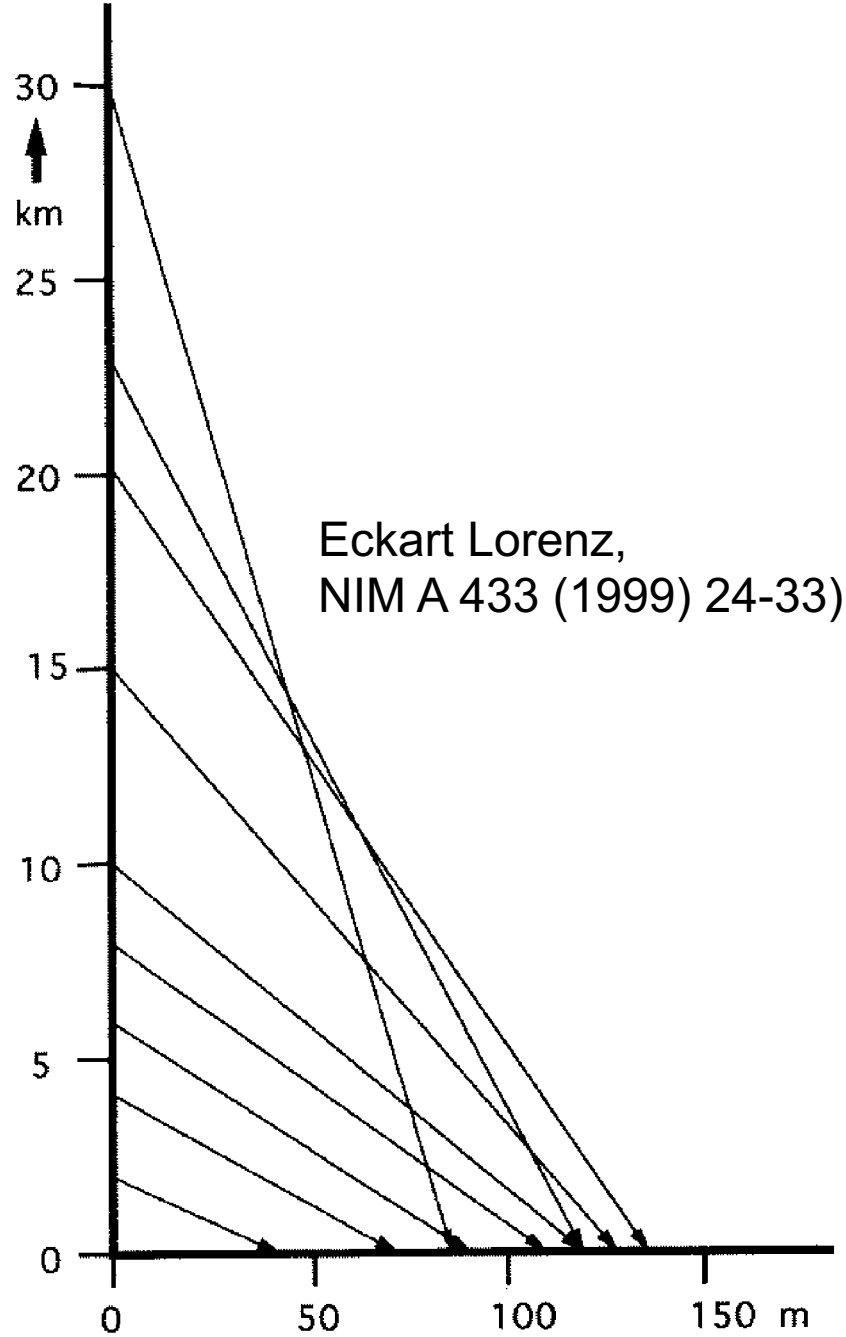
- 16 SiPM tiles
- 64 image pixels
- 16 trigger pixels
- 4 TARGET chips
- Each pixel is 0.067° (6 mm) square



Each telescope has more pixels than VERITAS, MAGIC, and H.E.S.S. combined

Simple calculation: Cherenkov light pool from infinite vertical shower

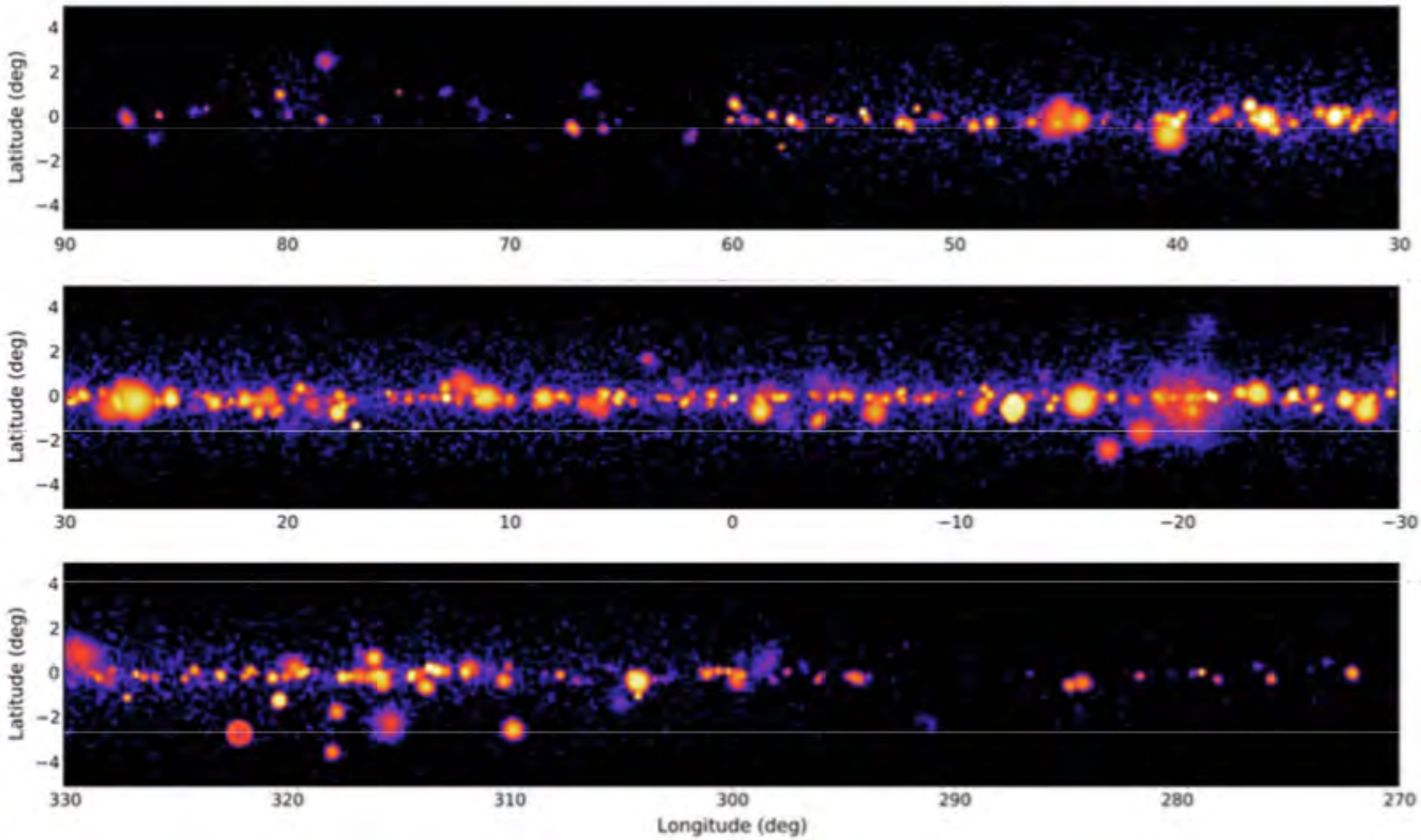
- At high altitude, density is small, index of refraction is close to 1, and Cherenkov angle is small
- Towards ground level, each of these increases
- Light pool of radius ~120-140 m on ground



Eckart Lorenz,
NIM A 433 (1999) 24-33)

Galactic plane survey

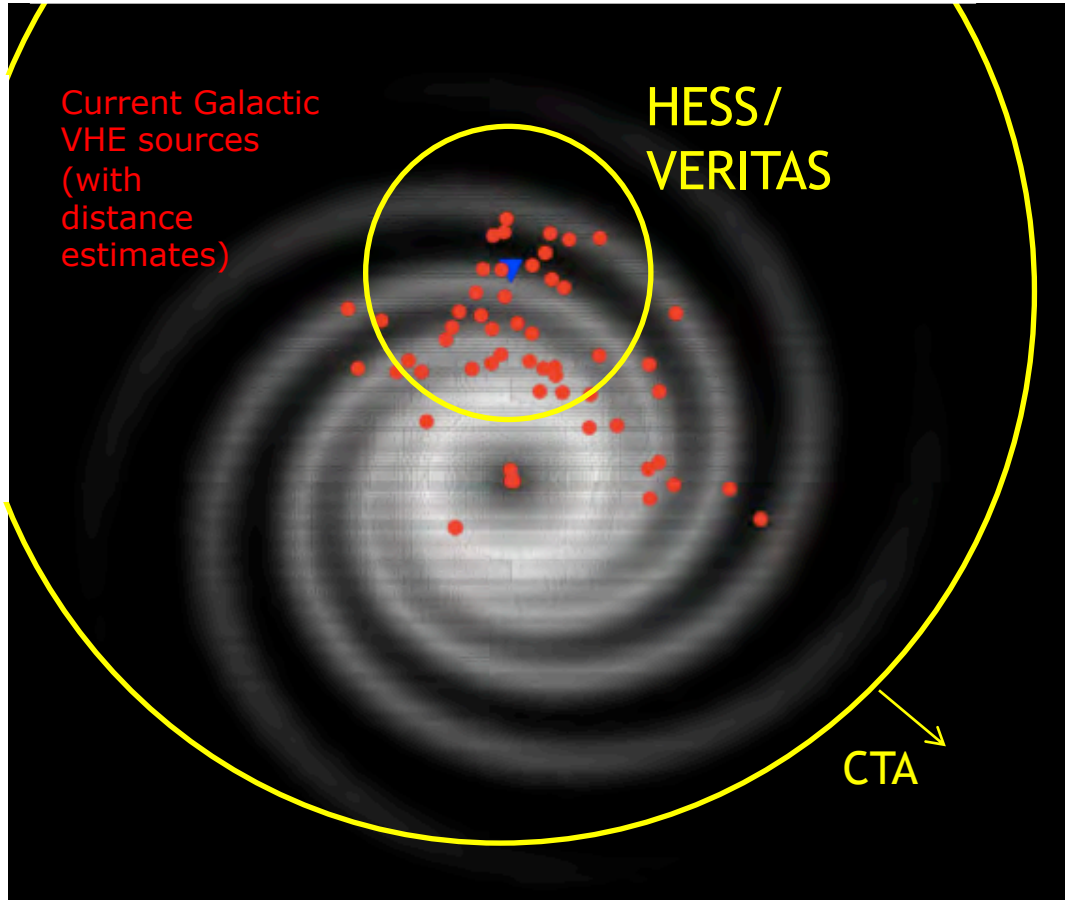
Entire plane surveyed to < 3.8 mCrab - several 100's of sources

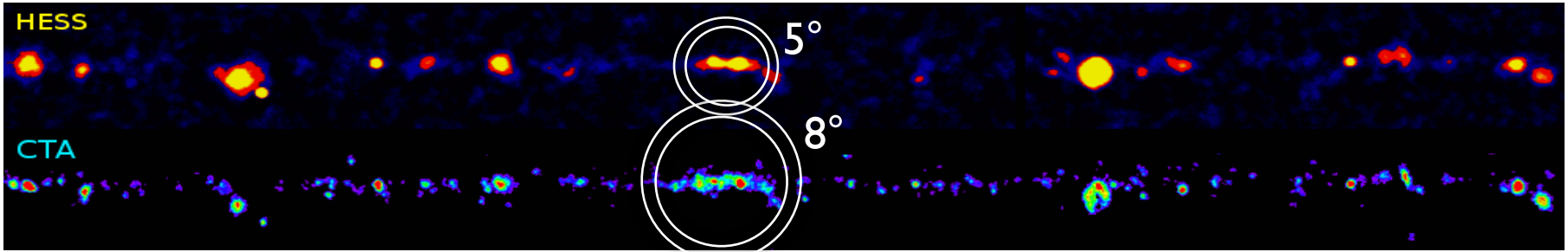


Galactic particle accelerators

Surveys of:

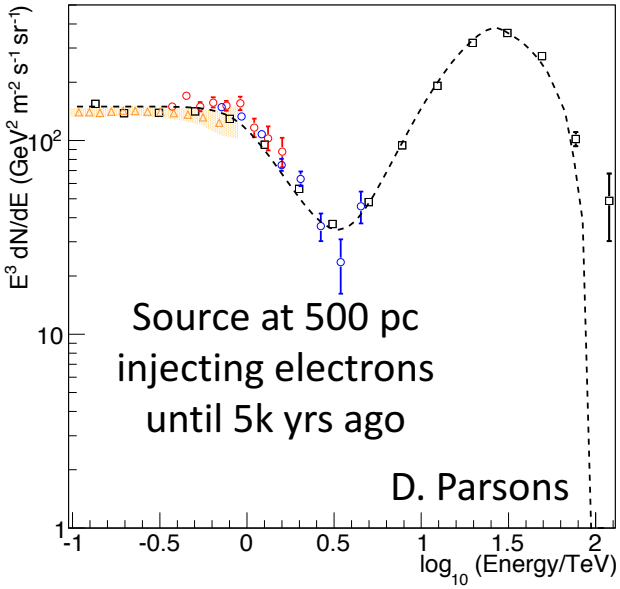
- Galactic center
- Galactic plane
- LMC

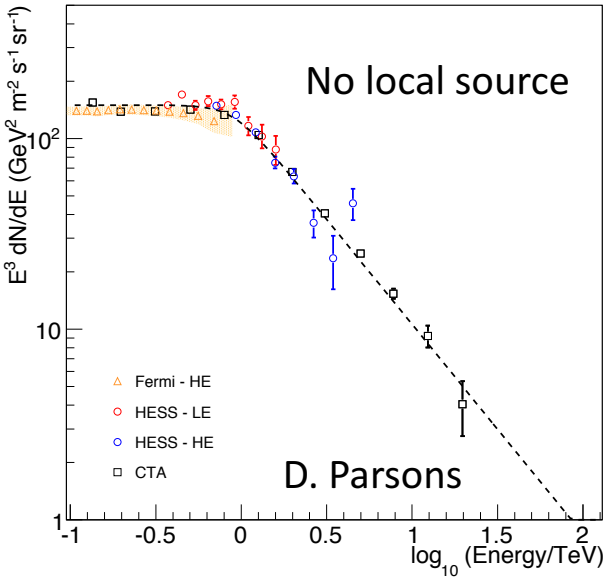




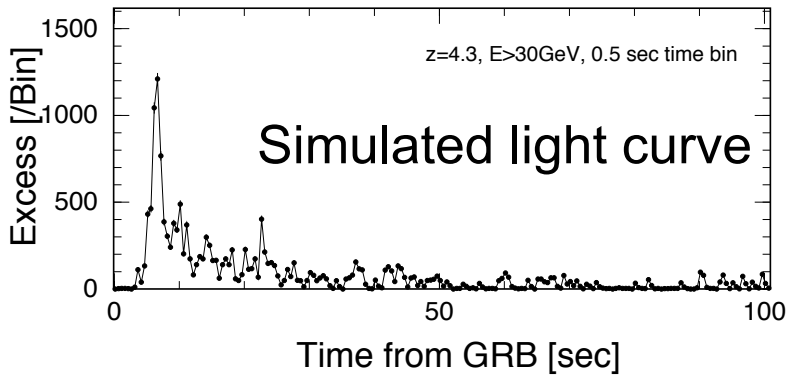
CTA will precisely measure the total electron + positron spectrum

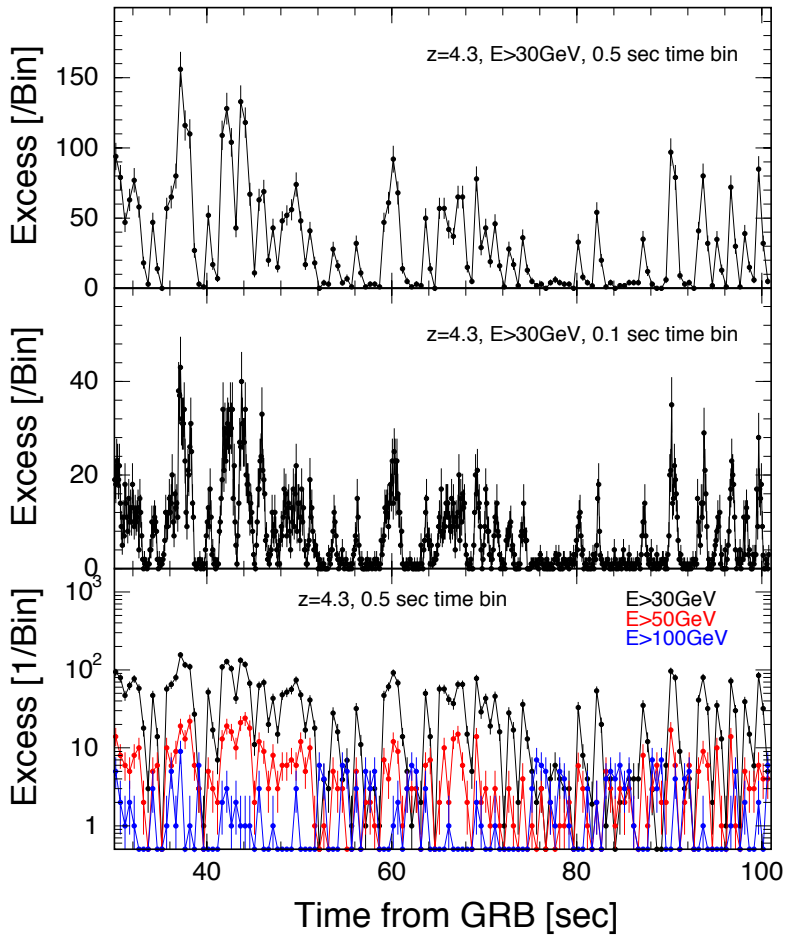
- Cosmic ray electrons and positrons provide important constraints on cosmic ray production and propagation and on dark matter
- CTA will measure total electron + positron spectrum up to 30-100 TeV (depending on its shape)
- CTA will also measure anisotropy by comparing different sky directions



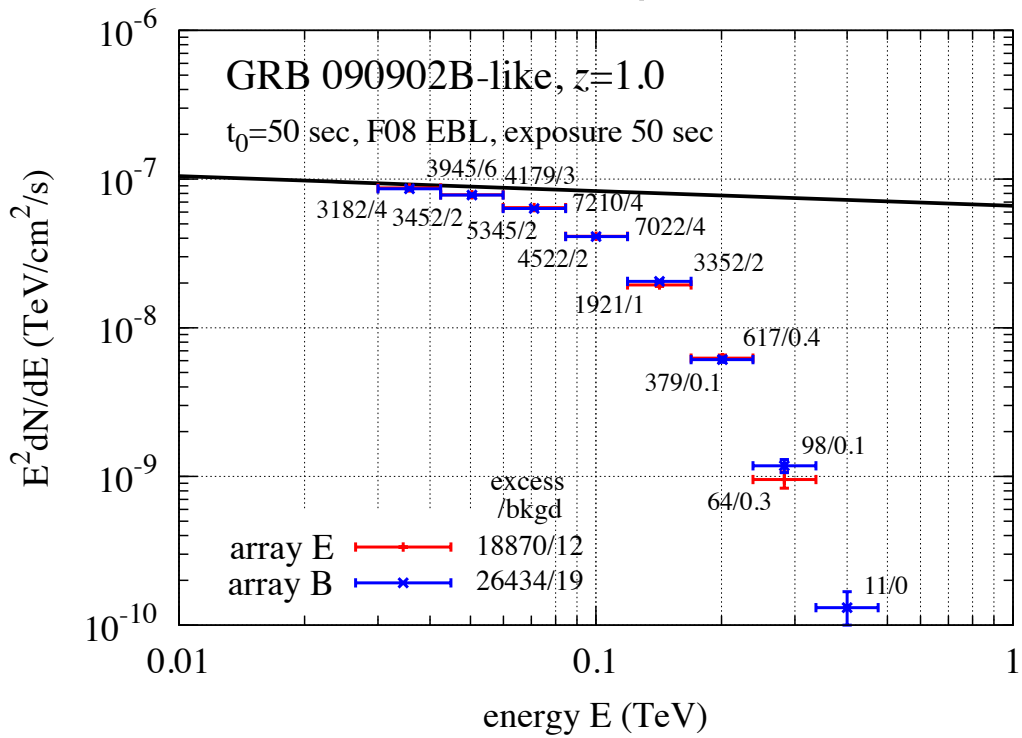


Gamma-ray bursts at very-high energy





Simulated spectrum



S. Inoue et al. for CTA, Astroparticle Physics 43 (2013) 252-275

VHE GALACTIC SURVEYS

- Previous Surveys

Experiment	Hemisphere	Galactic Plane Coverage	Energy (GeV)	Sensitivity (mCrab)
H.E.S.S.-I	S	$-70° < l < 60°$, $\|b\| < 2°$	$>\sim 300$	10 – 30
VERITAS	N	$67° < l < 83°$, $-1° < b < 4°$	$>\sim 300$	20 – 30
ARGO-YBJ	N	Northern Sky	> 300	240 – 1000
HEGRA	N	$-2° < l < 85°$, $\|b\| < 1°$	> 600	150 – 250
Milagro	N	Northern Sky	$> 10,000$	300 – 500

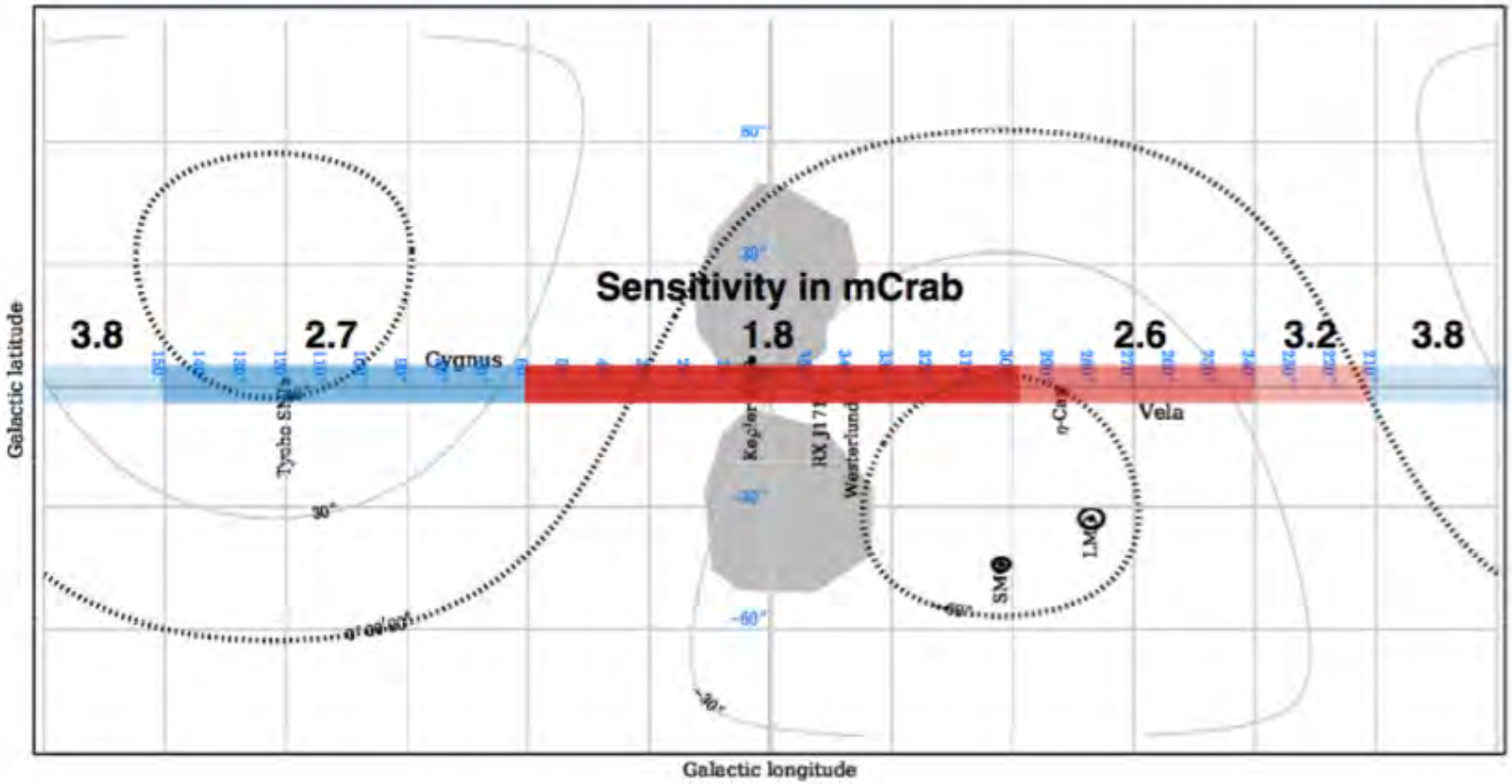
- Present/future Surveys

Observatory	Hemisphere	Energy Threshold	Angular Resolution	Pt. Source Sensitivity
CTA	N, S	125 GeV	$\sim 0.10°$ at 300 GeV	2 – 4 mCrab
HAWC	N	2 TeV	0.30°	20 mCrab

CTA GPS: **Full-plane survey with graded exposure**
Wide energy range and unprecedented angular resolution
Order of magnitude improvement in sensitivity

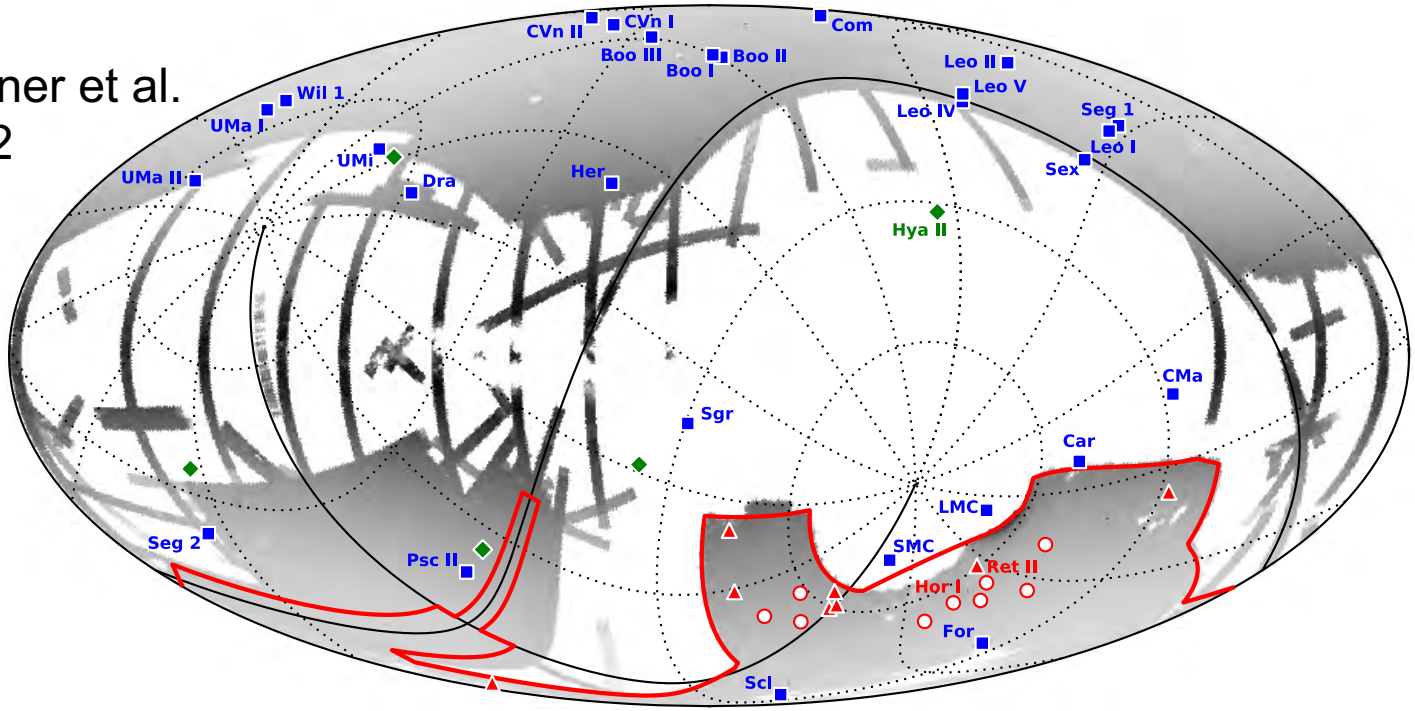
GPS SENSITIVITY

Entire plane surveyed to < 3.8 mCrab - several 100's of sources



New dwarf galaxies continue to be discovered, particularly in Southern hemisphere

Drlica-Wagner et al.
1508.03622



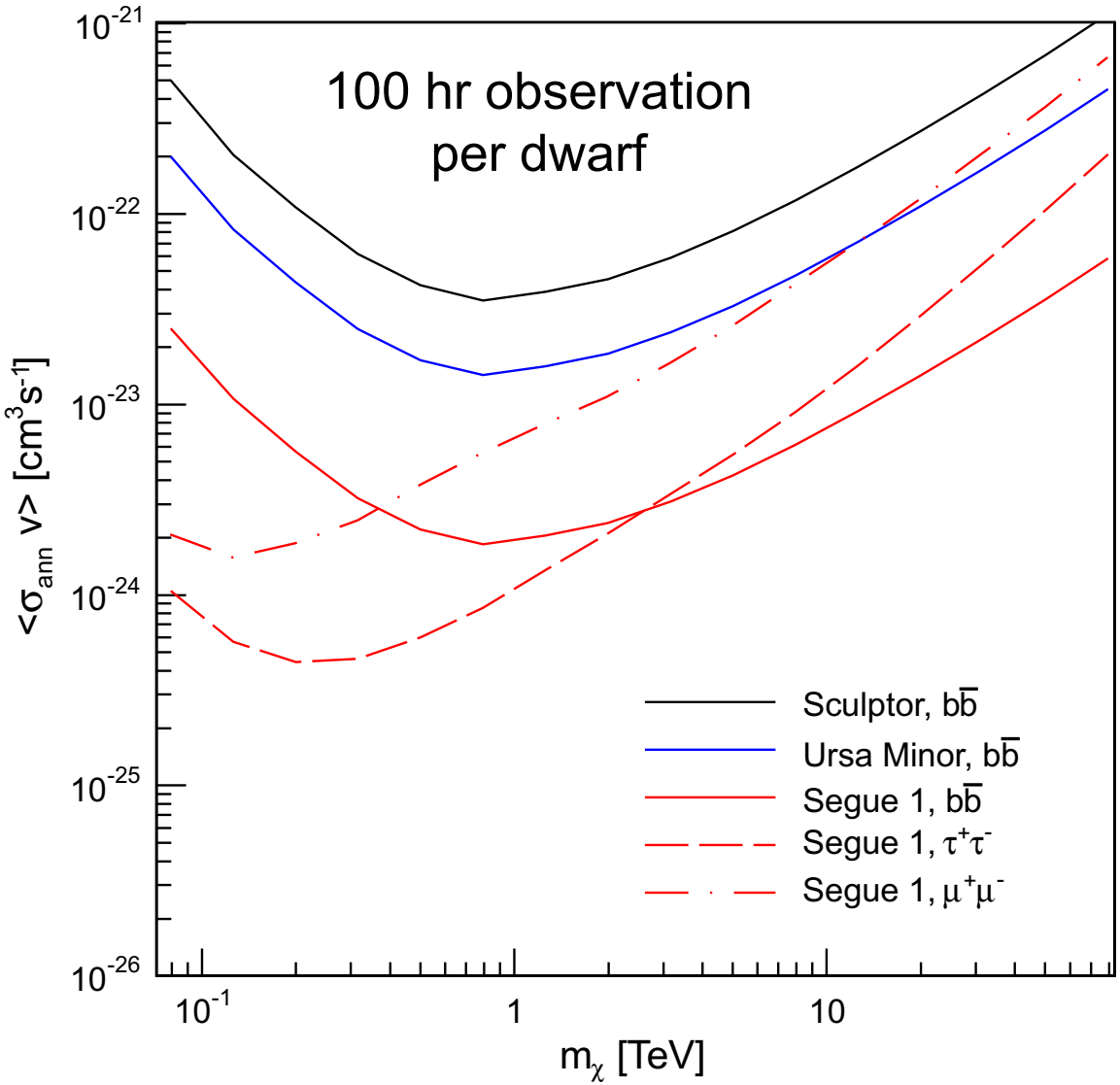
27 previously known

Discovered in past 2 years: 22 by DES and 5 by others

- DES much deeper than previous searches
- DES (and SkyMapper, Pan-STARRS, LSST) will continue to provide new dwarfs, potentially with excellent J factors

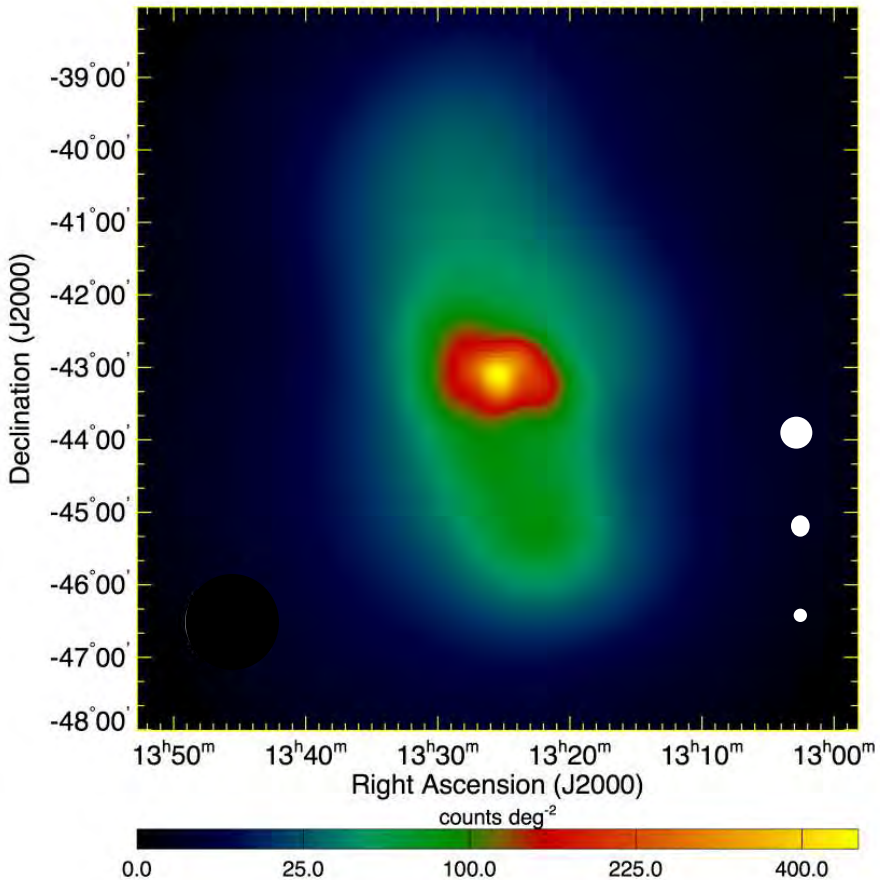
CTA sensitivity for WIMP annihilation in dwarf galaxies

- Sensitivity predicted for three known dwarf galaxies
- Southern: Sculptor
- Northern: Segue 1, Ursa Minor
- Many new dwarf galaxies are being discovered, particularly in the Southern hemisphere thanks to DES and LSST
- Some new dwarf galaxies already have J factor comparable to the best known previously



Doro et al. for CTA, APP 2012 (1208.5356)

Resolving extragalactic sources: Cen A



Fermi LAT >200 MeV background-subtracted counts map of Cen A

Abdo et al. 2010, *Science* **328**, 725

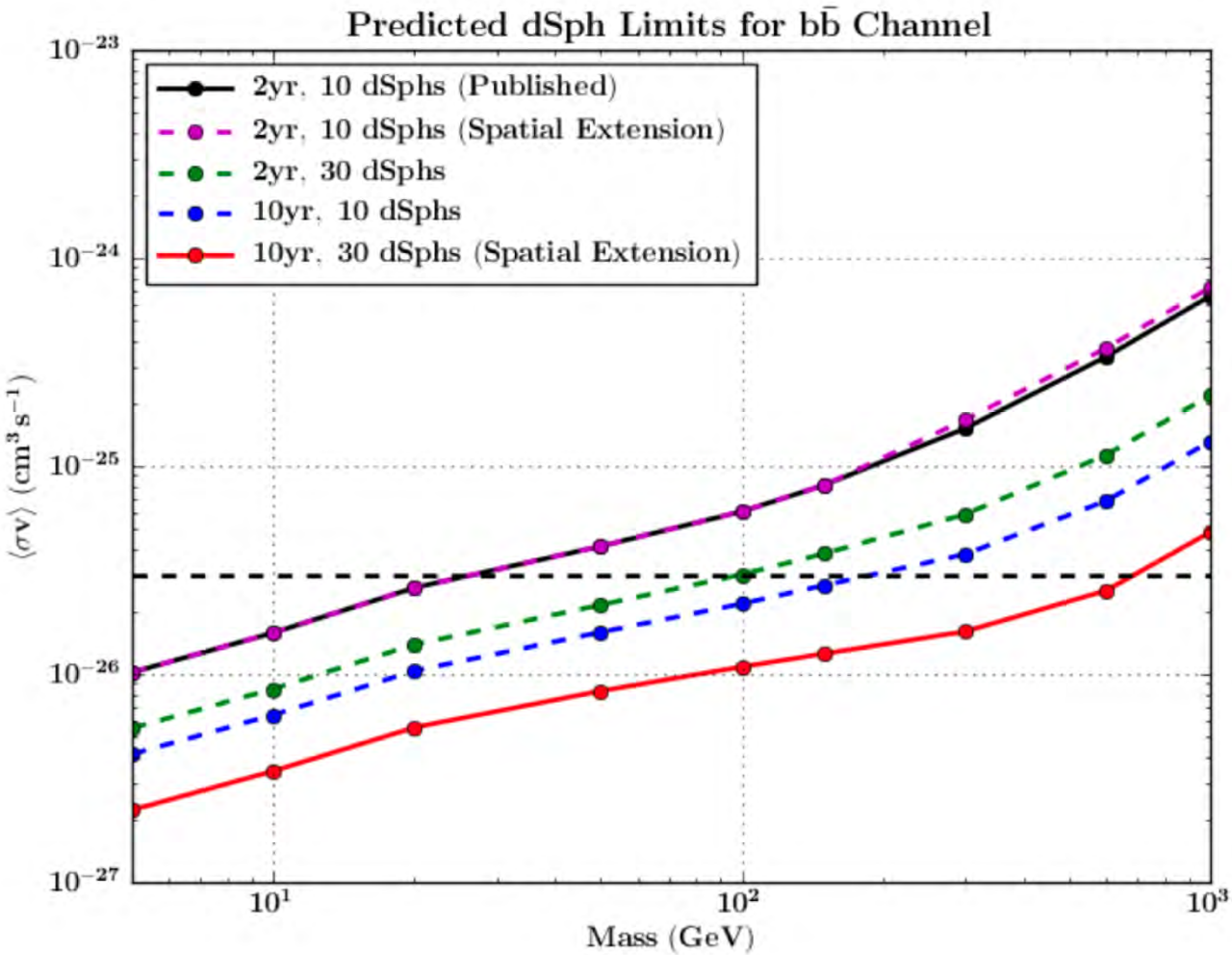
Fermi LAT PSF at 10 GeV

CTA PSF at 100 GeV (≥2 images)

CTA PSF at 300 GeV (≥10 images)

(68% containment)

Fermi limits will improve with more time and new dwarfs discovered by Southern surveys

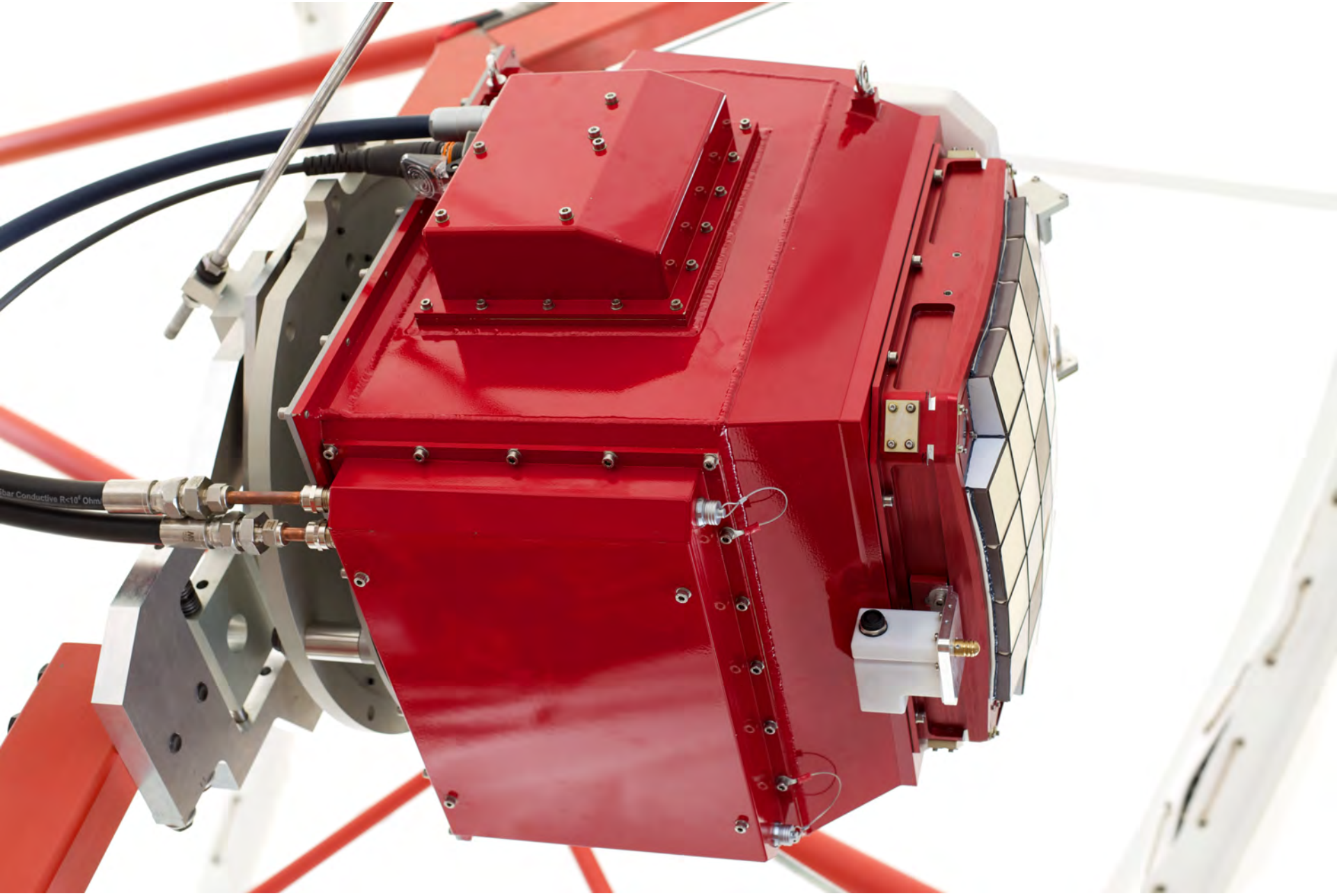


- Known dwarfs mostly in Northern hemisphere (Sloan survey)
- Current and future surveys (DES, LSST) will increase number of known dwarfs
- New surveys will increase sky coverage by factor ~3

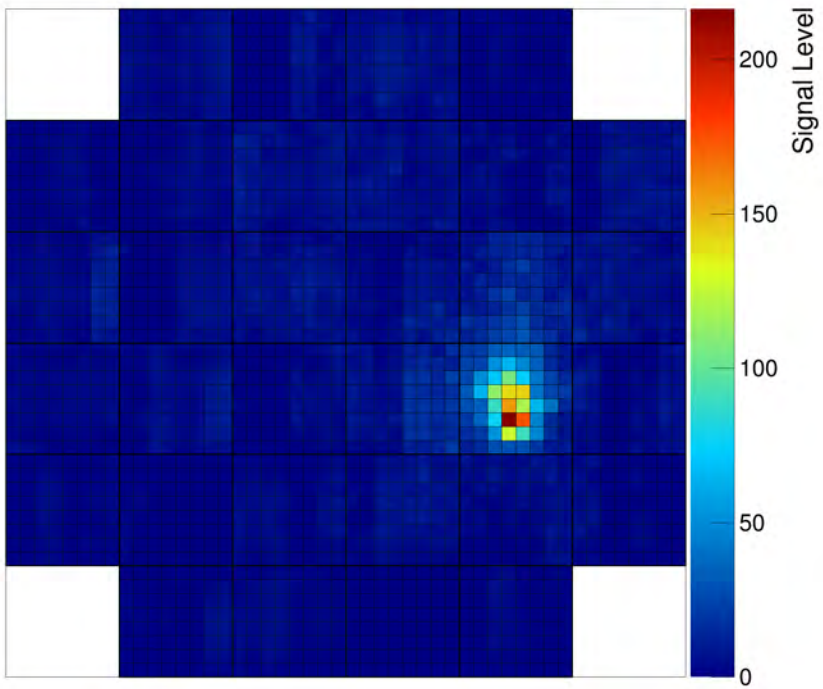
Gamma-ray Cherenkov Telescope (GCT) prototype

Inaugurated December 1, 2015

Gamma-ray Cherenkov Telescope (GCT) prototype

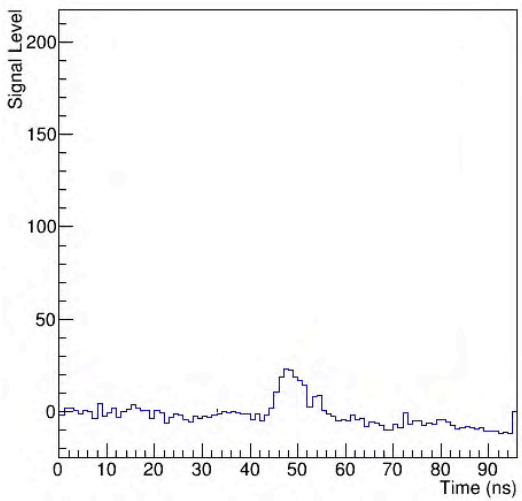


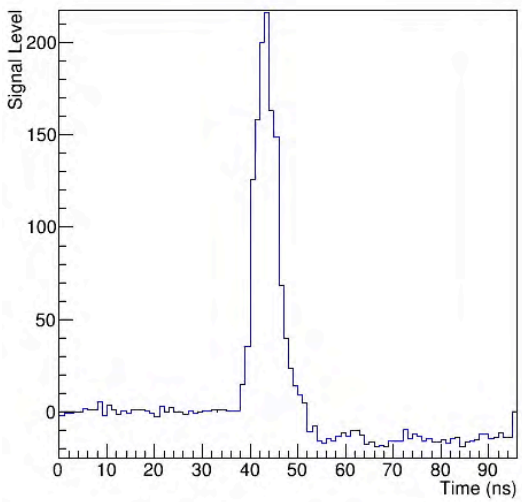
First Cherenkov light at a CTA (prototype) telescope recorded by Gamma-ray Cherenkov Telescope (GCT)

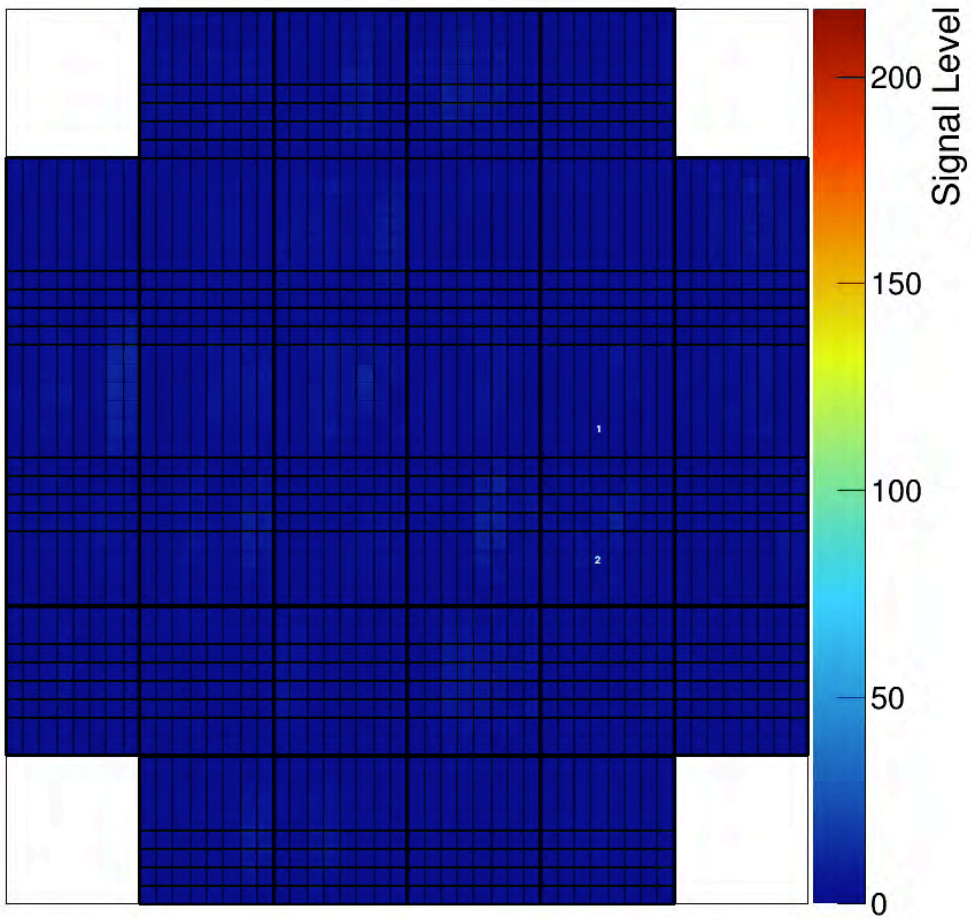


- November 26, 2015 in Meudon, France
- Pointing away from City of Light and nearly full Moon
- 12 events in 5 minutes
- 32 modules of 64 pixels each (2.048 kilopixel camera)
- Most events were due to cosmic-ray air showers
- Image shows maximum light in each pixel among 100 frames

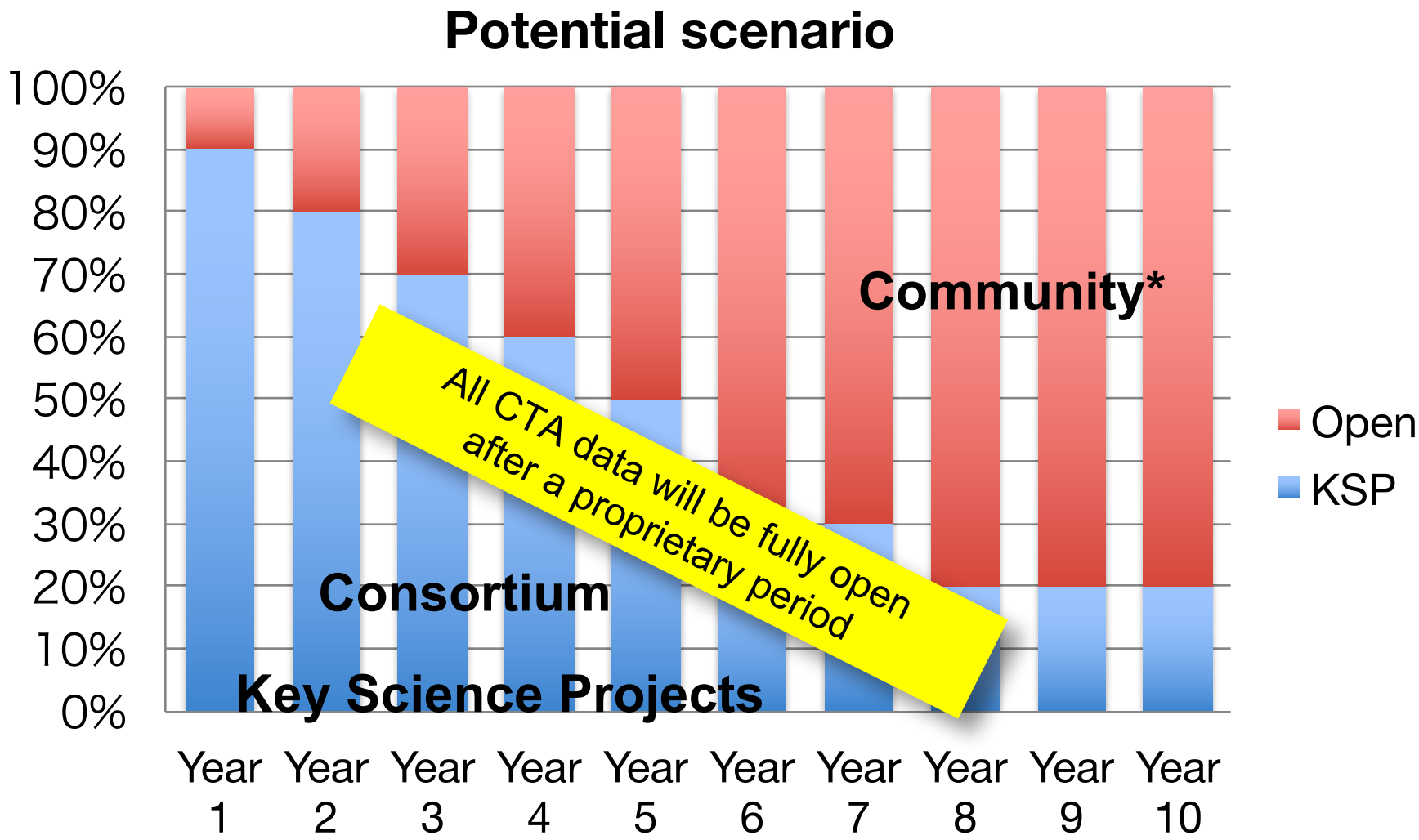
Gamma-ray Cherenkov Telescope (GCT) prototype



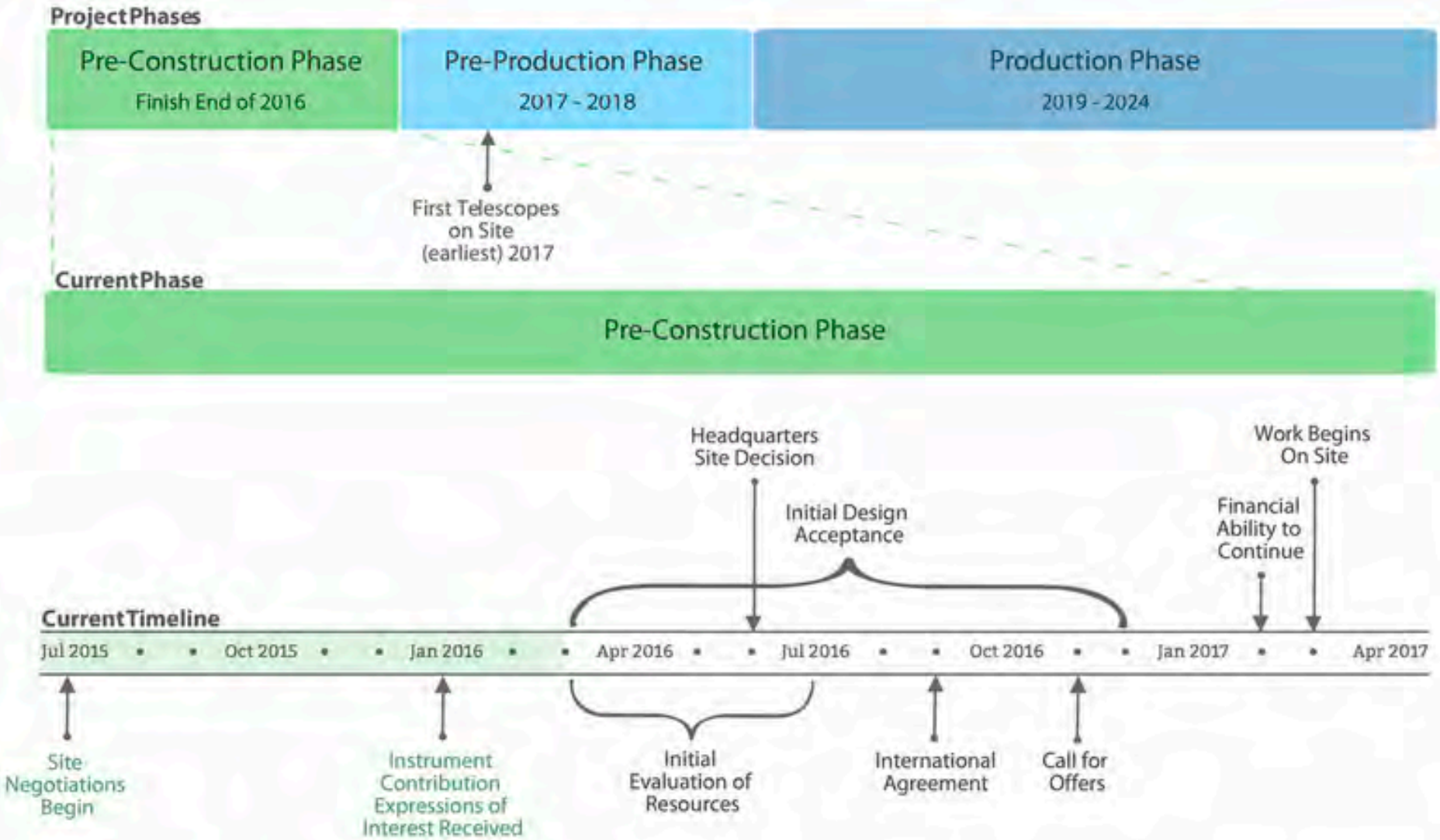




Time allocation and community access



*of scientists from nations contributing to CTA construction and operations

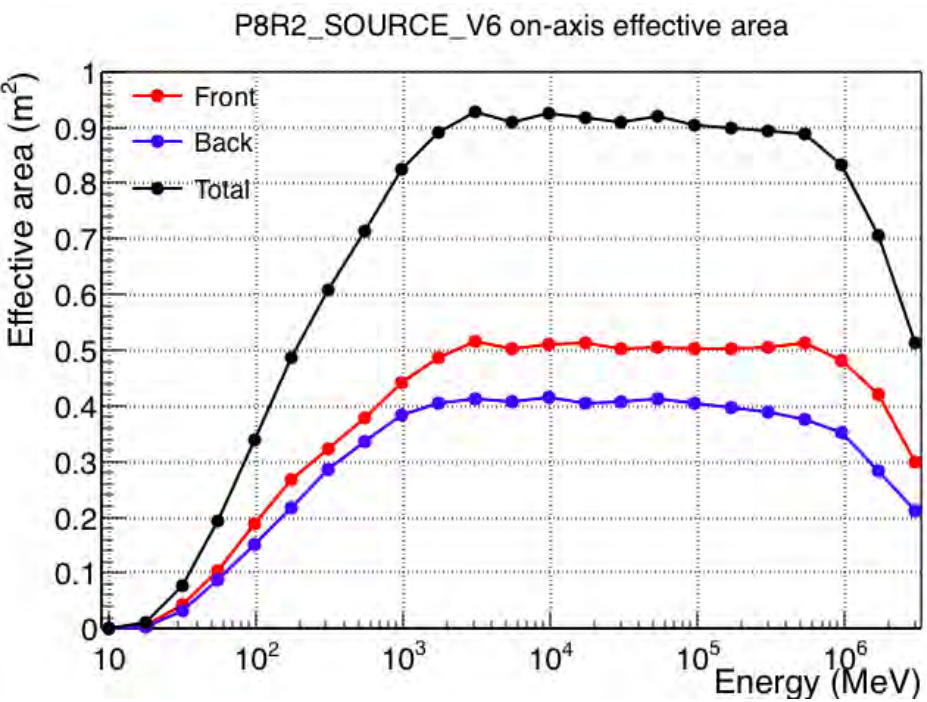

Project Phases
Pre-Construction Phase
Finish End of 2016
Pre-Production Phase
2017 - 2018
Production Phase
2019 - 2024
First Telescopes on Site (earliest) 2017
Current Phase
Pre-Construction Phase
Headquarters Site Decision
Work Begins On Site
Initial Design Acceptance
Financial Ability to Continue
Current Timeline
Jul 2015
Oct 2015
Jan 2016
Apr 2016
Jul 2016
Oct 2016
Jan 2017
Apr 2017
Site Negotiations Begin
Instrument Contribution Expressions of Interest Received
Initial Evaluation of Resources
International Agreement
Call for Offers

Prototype telescopes

- SST-1M (Krakow, Poland)
- SST-2M ASTRI (Serra la Neve, Sicily)
- GCT (Meudon, France)
- MST (Adlershof, Germany)
- SCT (Mt Hopkins, USA)
- LST (La Palma, Spain)

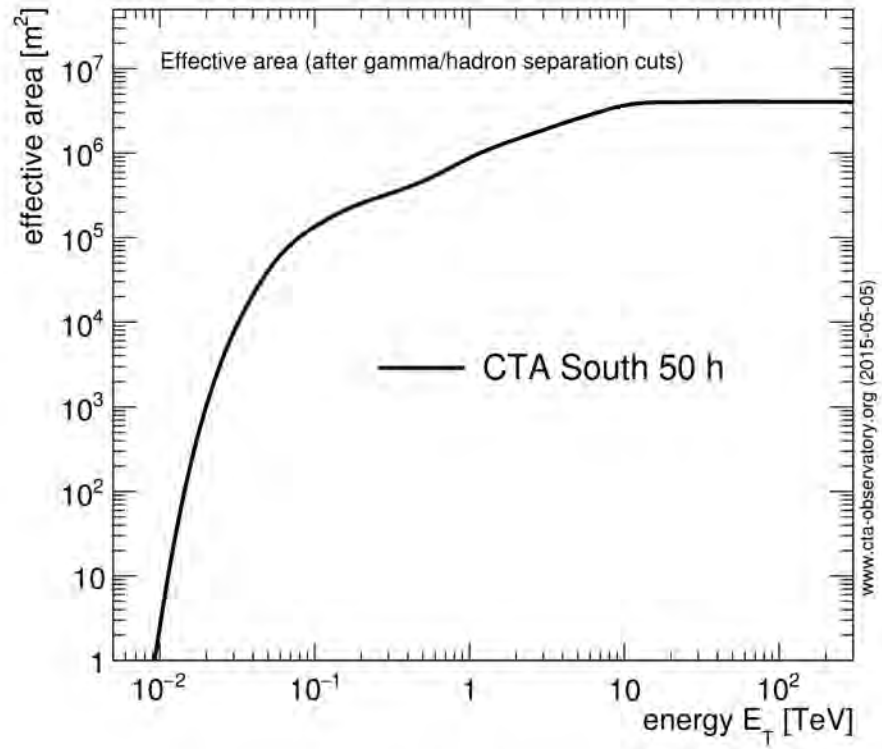
Effective area

Fermi LAT



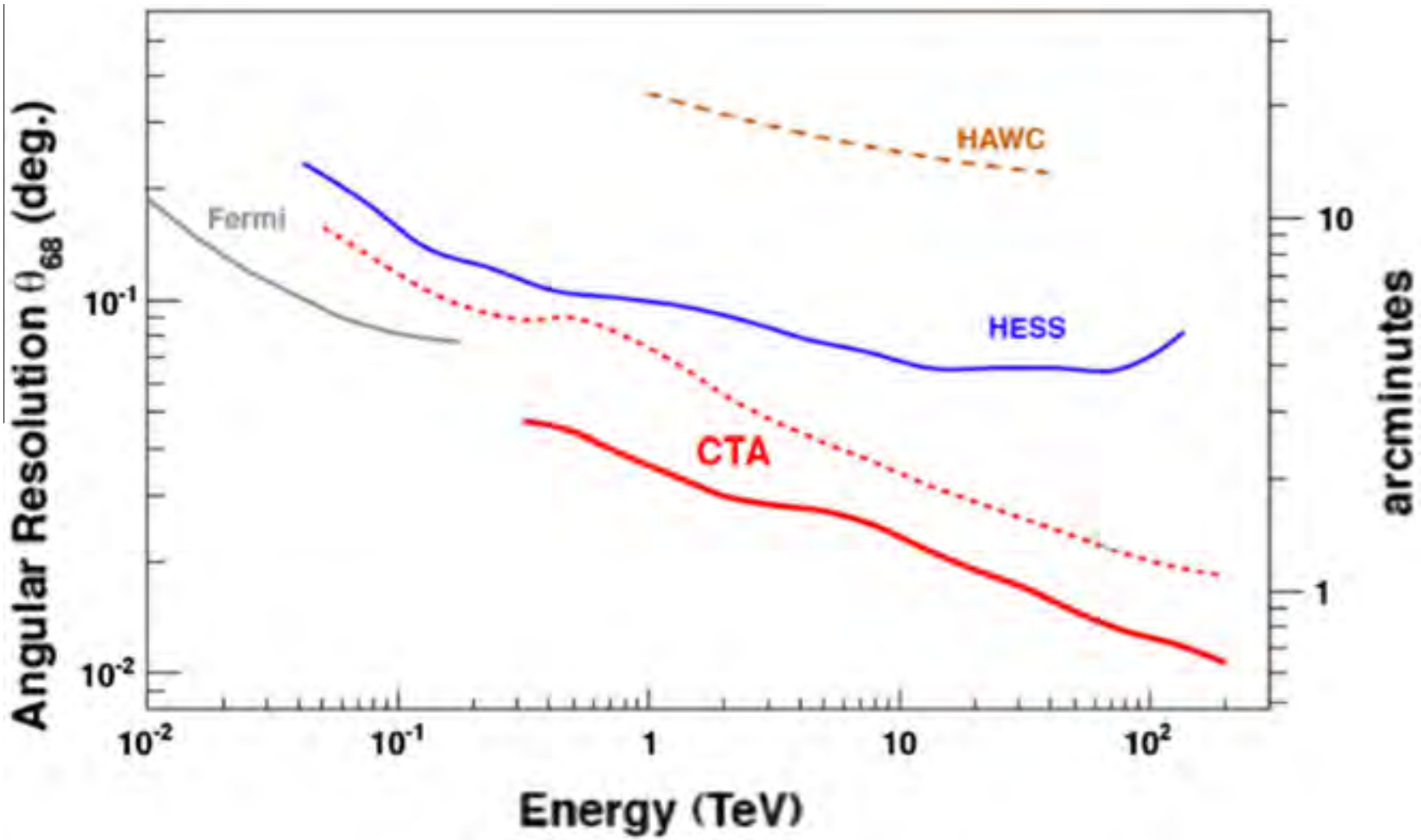
1 m^2

CTA

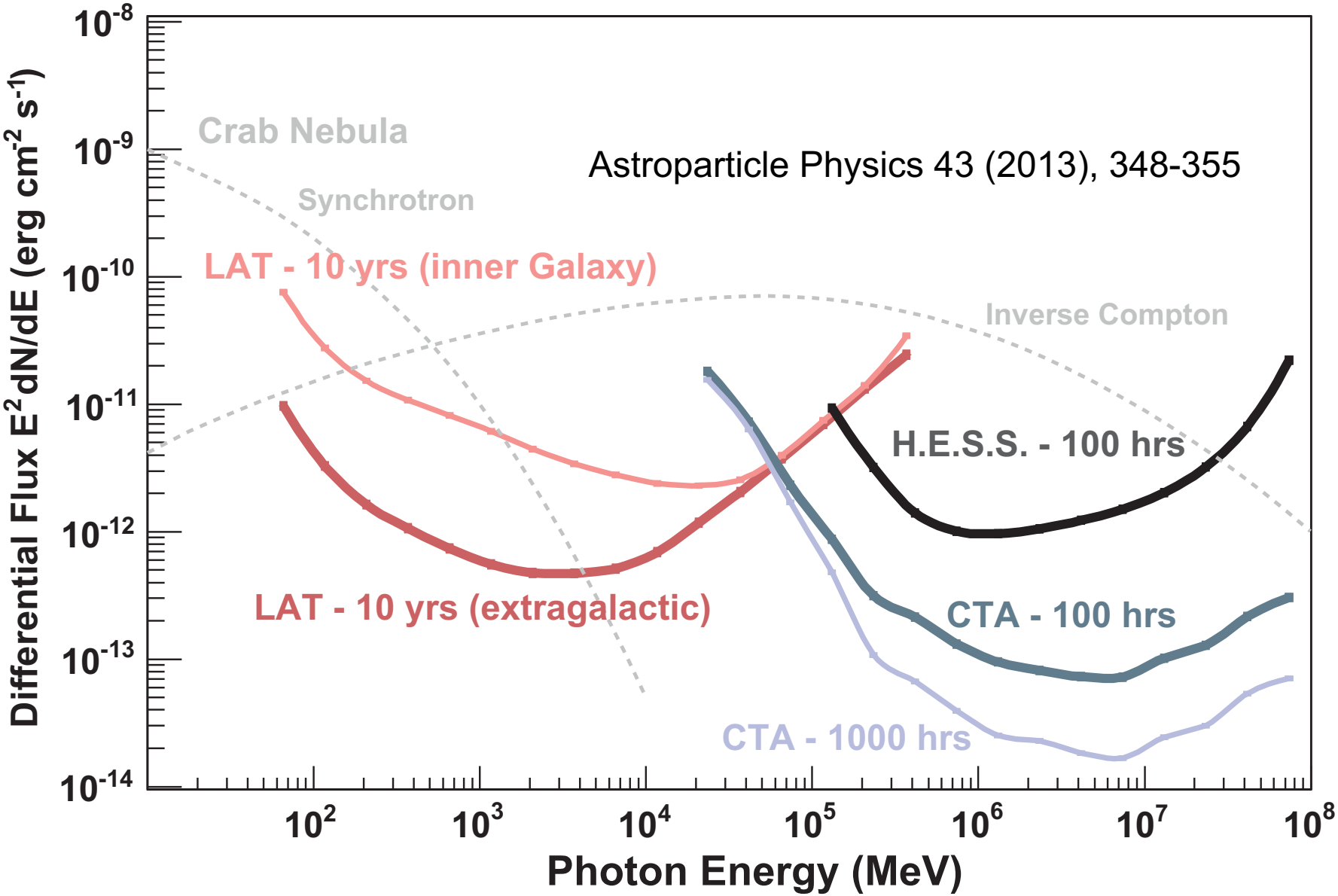


10^6 m^2

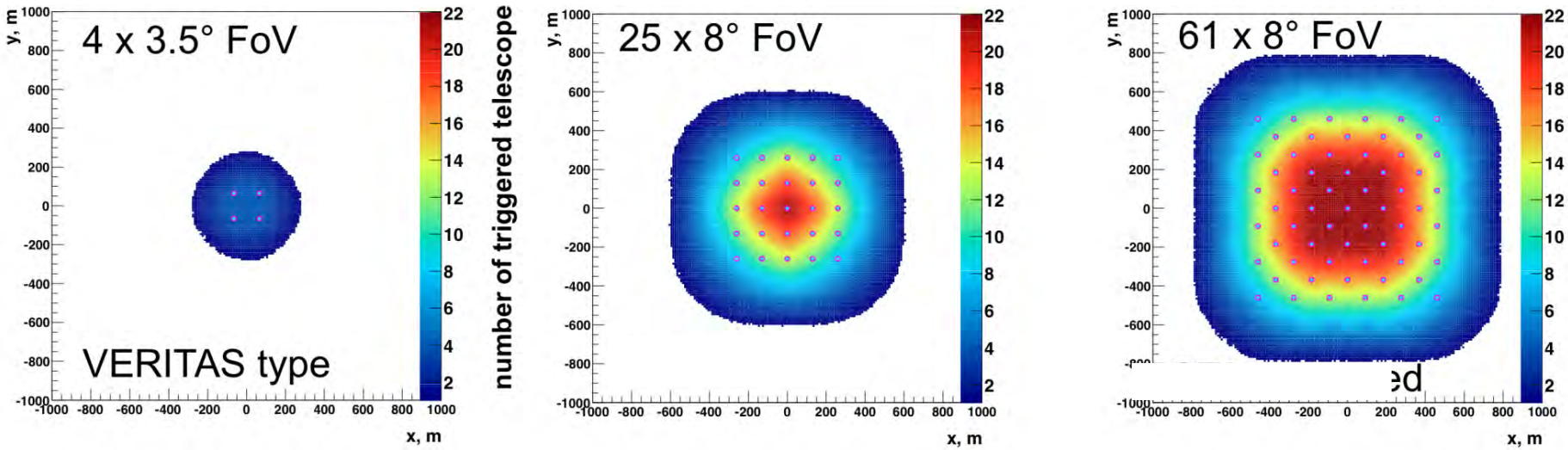
Angular resolution



CTA vs. Fermi


Crab Nebula
Synchrotron
Astroparticle Physics 43 (2013), 348-355
LAT - 10 yrs (inner Galaxy)
Inverse Compton
H.E.S.S. - 100 hrs
LAT - 10 yrs (extragalactic)
CTA - 100 hrs
CTA - 1000 hrs
Differential Flux E^{2}dN/dE (erg cm^{-2} s^{-1})
Photon Energy (MeV)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^2
10^3
10^4
10^5
10^6
10^7
10^8

More telescopes means more contained showers detected by multiple telescopes

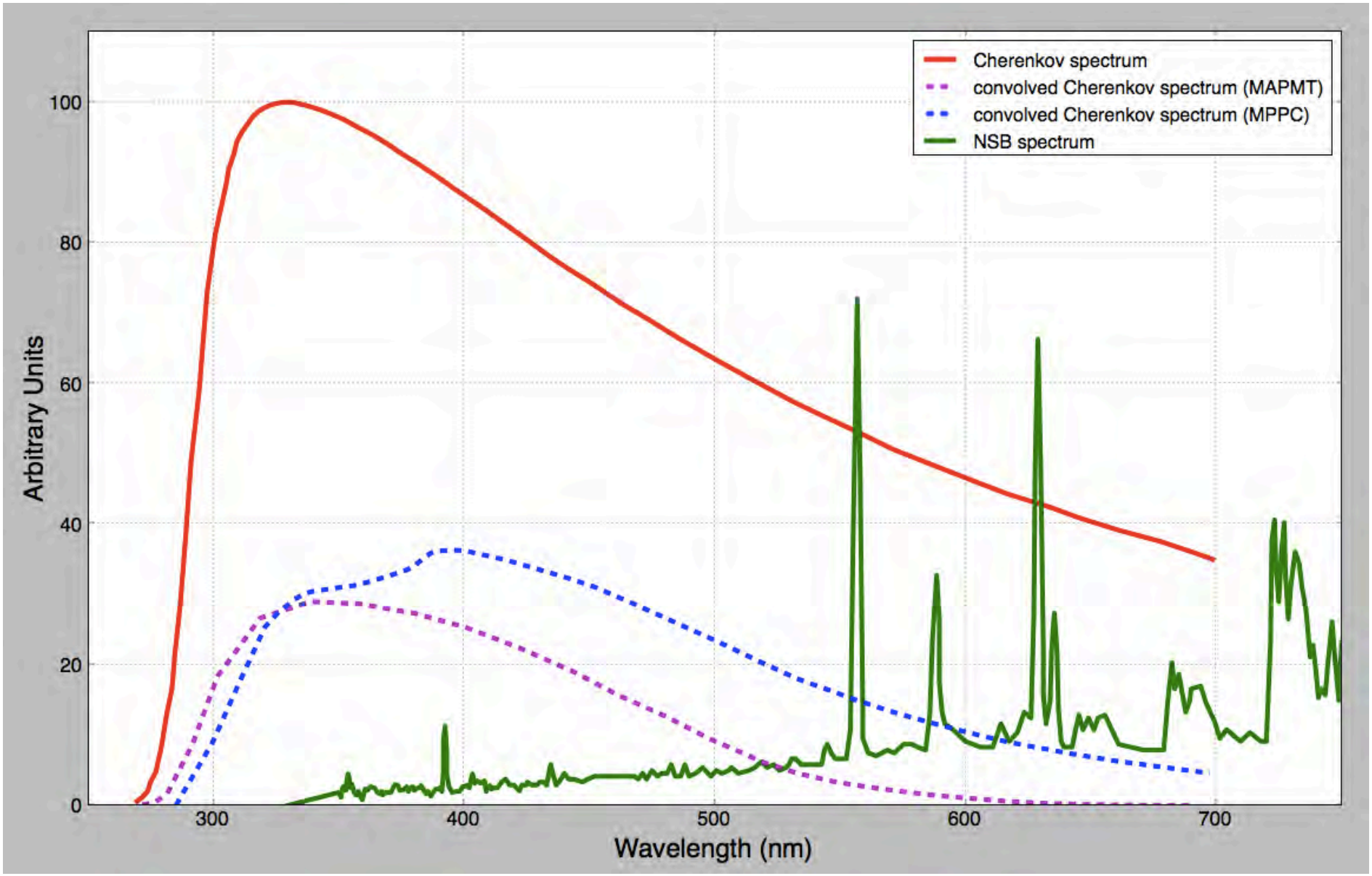


CTA Consortium

1200 members from 170 institutes in 32 countries

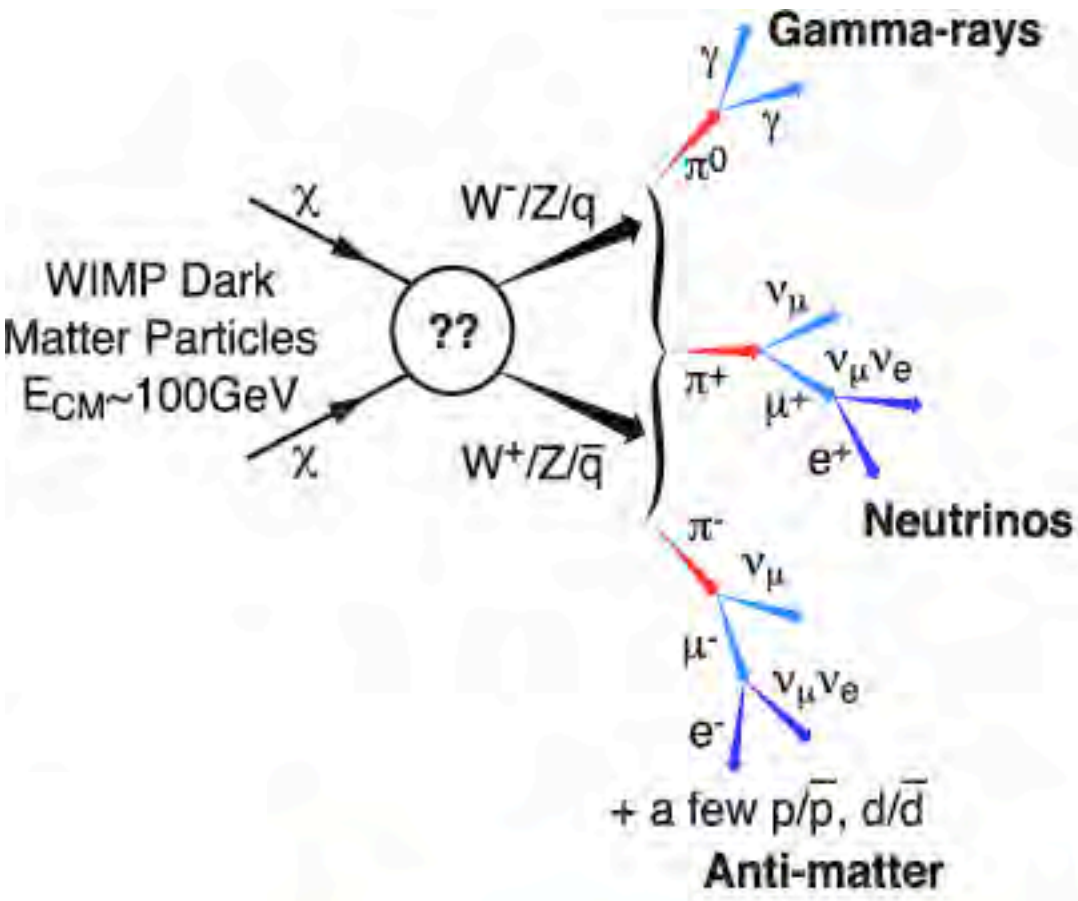
CTA consortium

Signal and background spectra

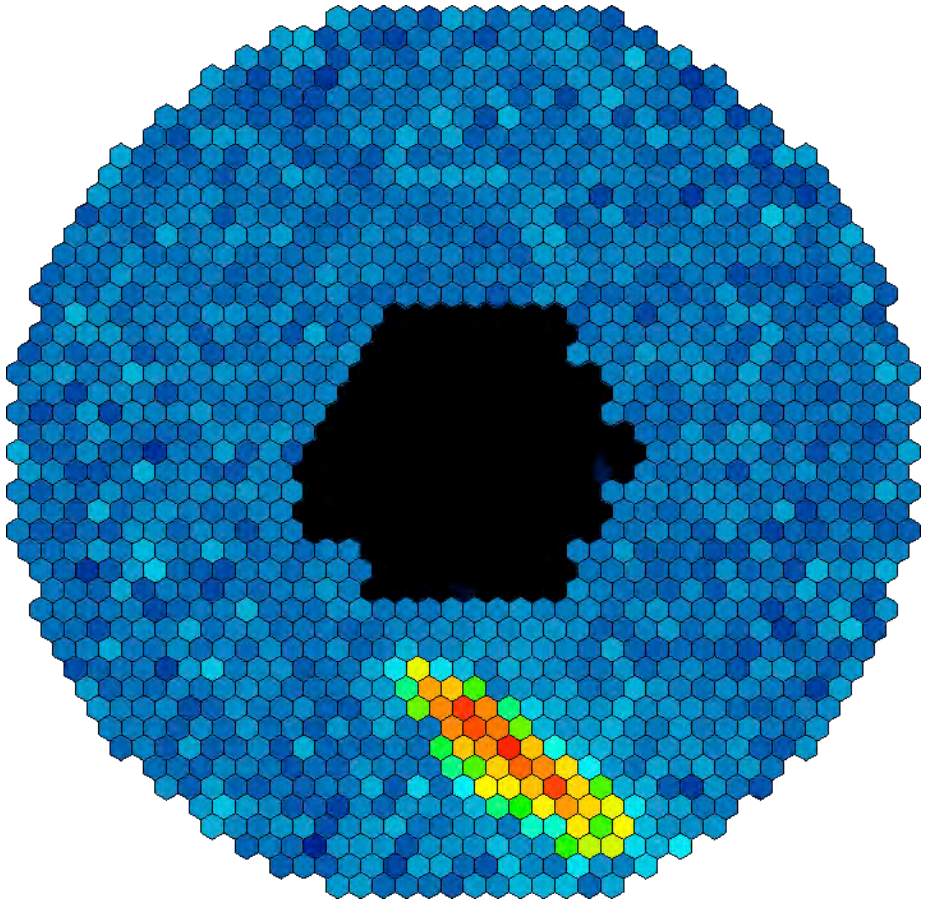


What could dark matter annihilate/decay to?

- Neutrinos
- Gamma rays
- Electrons, positrons
- Protons, antiprotons
- Deuterons, antideuterons

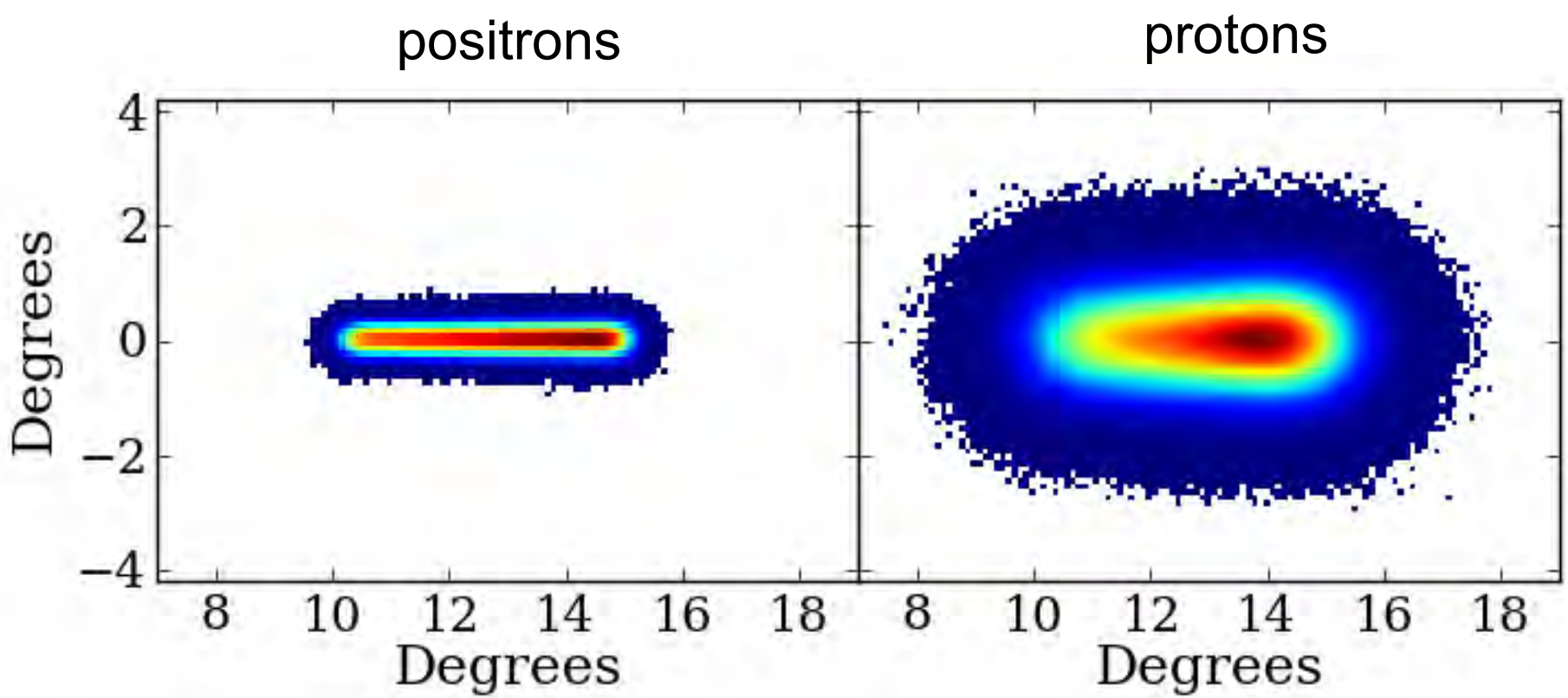


FACT has observed air showers with full Moon in center of camera



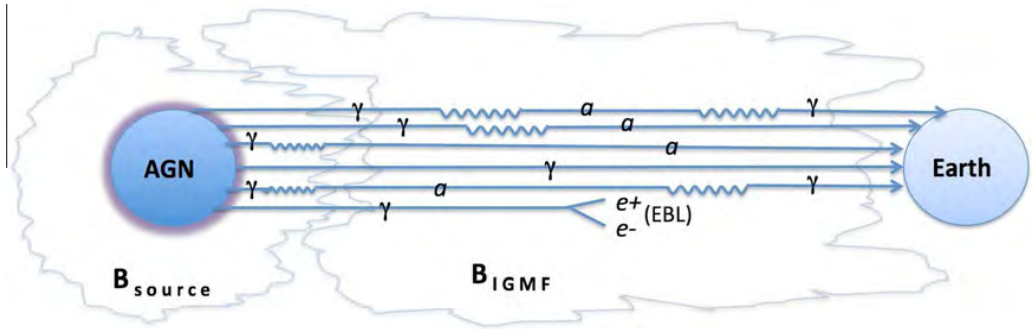
FACT Collaboration, ICRC 2013, arXiv:1307.6116

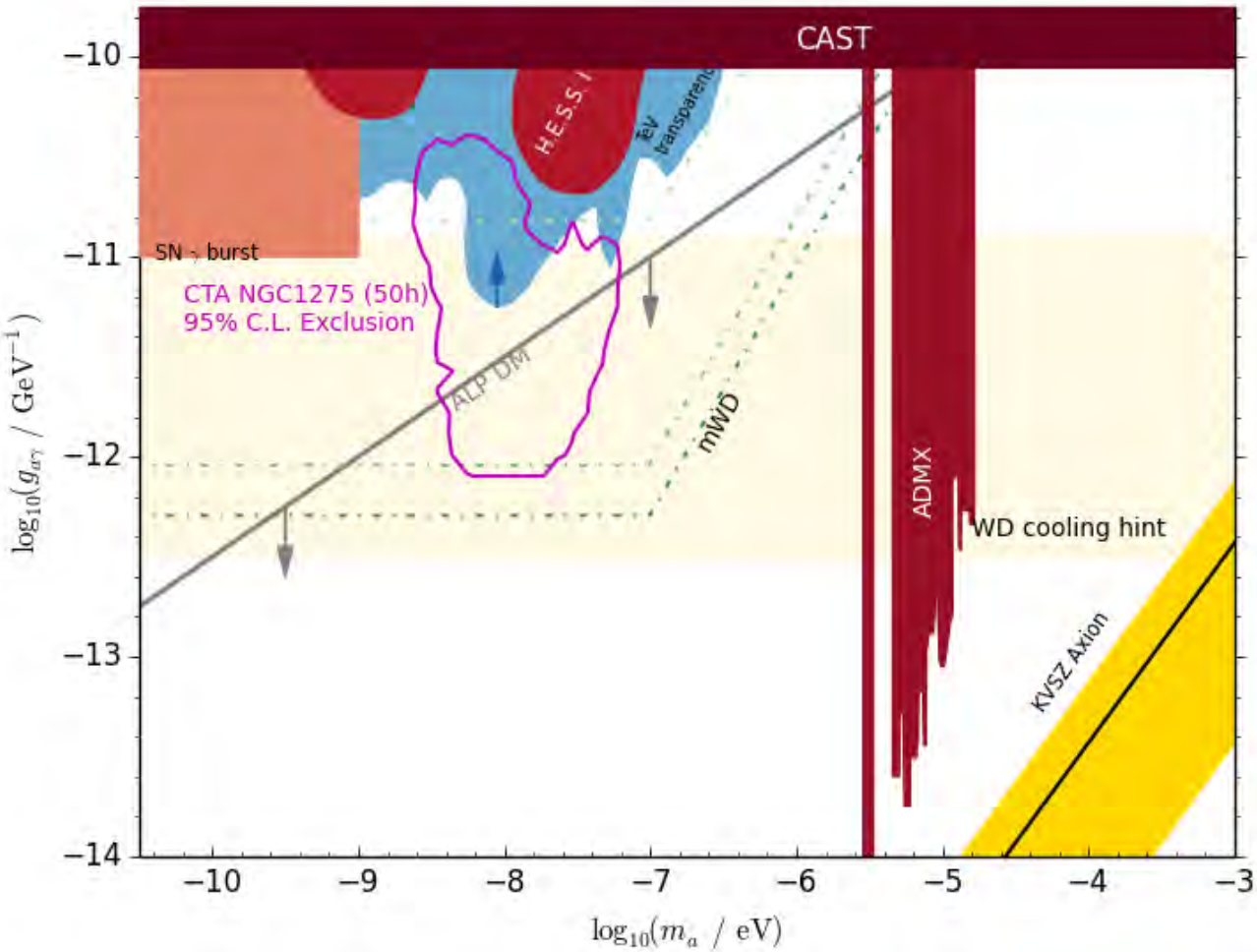
Simulated positron vs. proton Moon shadow shape (100-147 GeV)



Axion-like particles

- CTA is sensitive to axions /axion-like particles (ALPs) through ALP-photon conversion in magnetic fields
- ALPs can imprint signatures on the spectra of active galactic nuclei
- CTA will test a unique region of phase space, including a region in which they would behave as cold dark matter





10 to 300 times improved sensitivity to Lorentz invariance violation

Potential of GUT scale physics to reveal itself in LIV effects

Variable gamma-ray sources (pulsars, AGN, and GRB) provide the most stringent tests of LIV effects in the photon dispersion relation

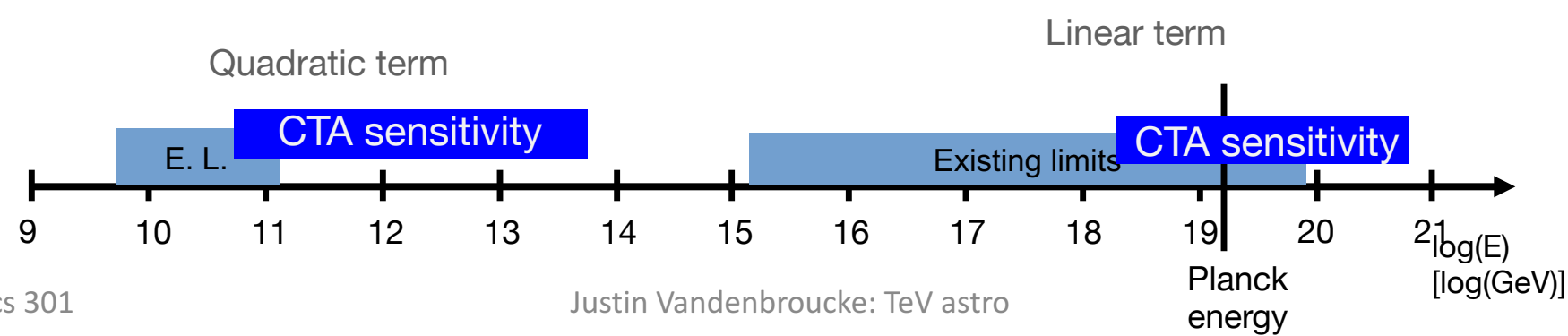
CTA will provide 10 to 300 times improved sensitivity on LIV tests (arXiv:1305.0264)

$$c'(E) = c + a \cdot \frac{E}{E_{\mathrm{LIV}}} + b \cdot \left(\frac{E}{E_{\mathrm{LIV}}}\right)^2$$

$$\Delta t_1 = \frac{d}{c} \cdot \frac{E_{\mathrm{h}} - E_{\mathrm{l}}}{E_{\mathrm{LIV}}} \qquad \Delta t_2 = \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{\mathrm{h}}^2 - E_{\mathrm{l}}^2}{E_{\mathrm{LIV}}^2}$$

Linear term Quadratic term

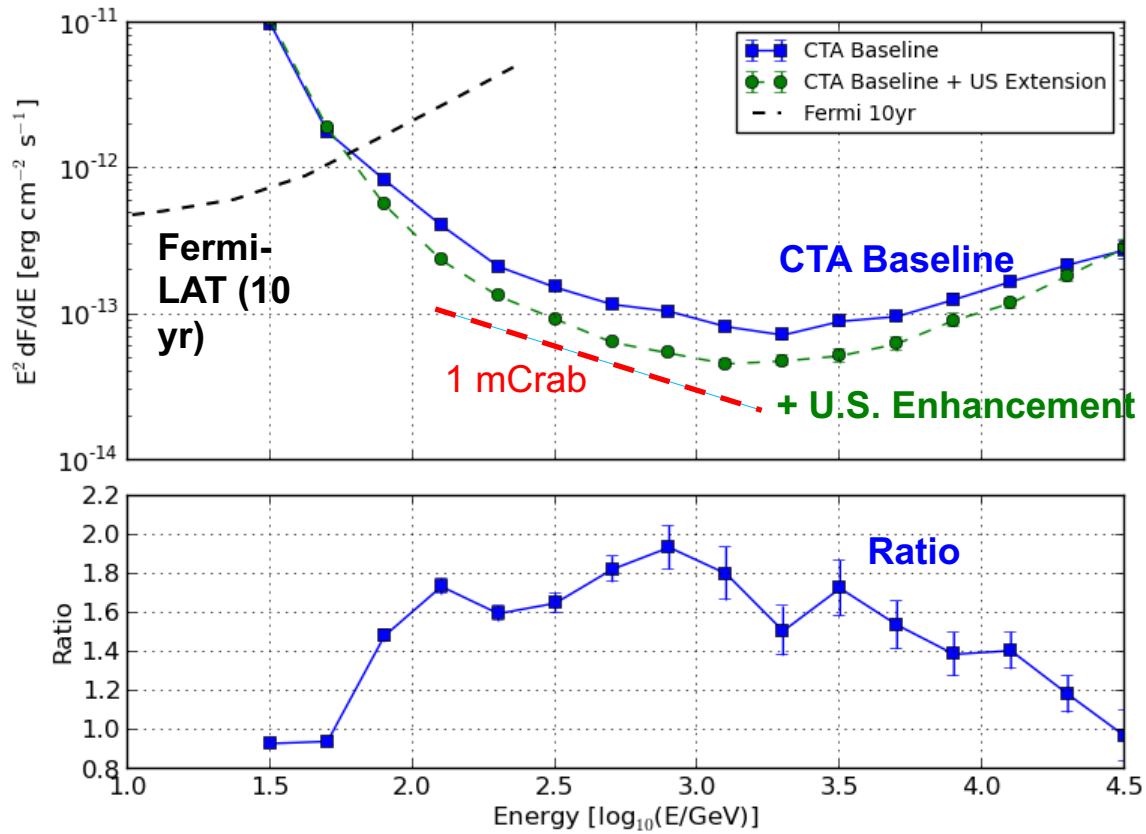
Current best limits from Fermi-LAT (arXiv: 1305.3463)



CTA expected performance: point source sensitivity

- US contribution doubles the collection area of the array (from 25 to 49 telescopes) and nearly doubles the sensitivity
- Equivalent to a factor of 3–4 reduction in observing time: Makes possible results impossible with the baseline array.

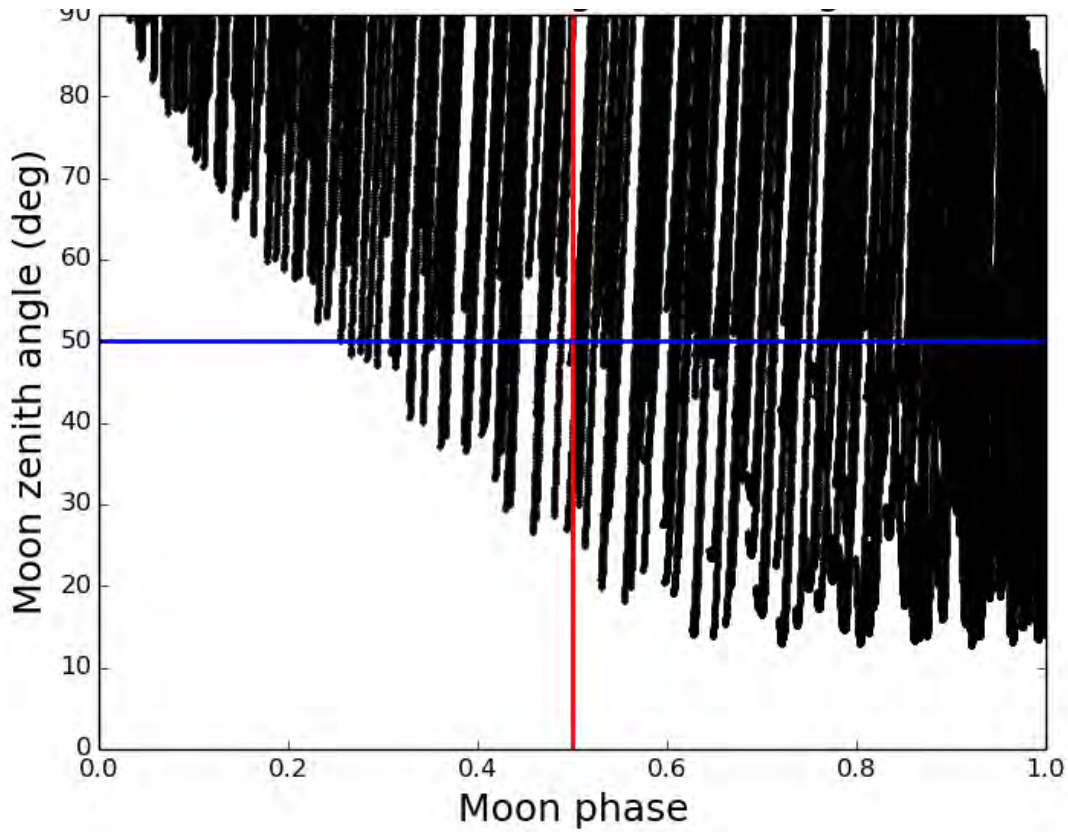
Point Source Sensitivity
50 hour observation



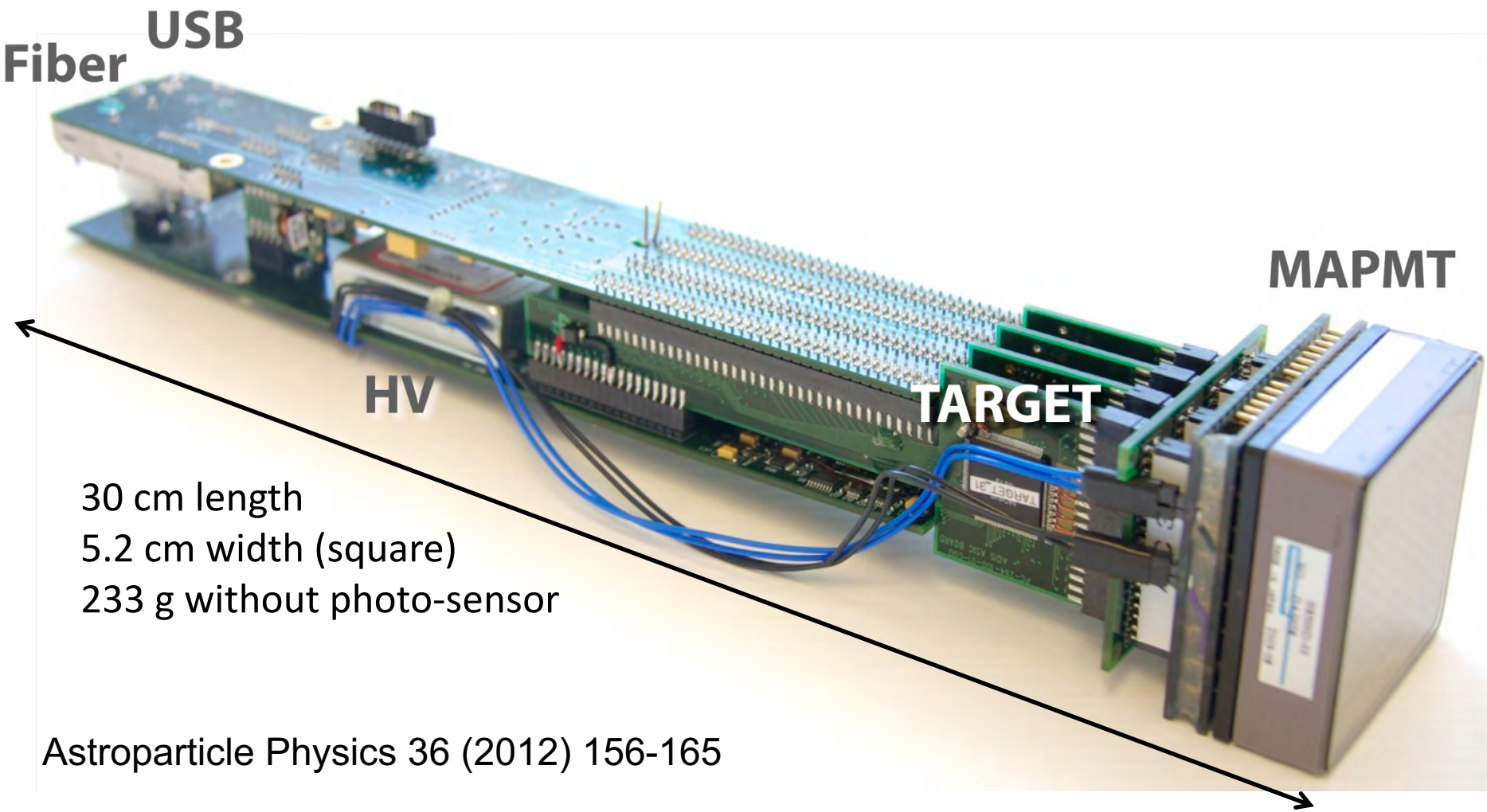
Counting Moon observation time available

- Moon phase < 0.5: 51%
- Sun zenith > 108° : 38%
- Moon zenith < 50° : 22%
- Moon zenith < 50° and sun zenith > 108° and moon phase < 0.5: 0.39% (34 hrs per year)

Moon positions for one year (with Sun zenith > 108°



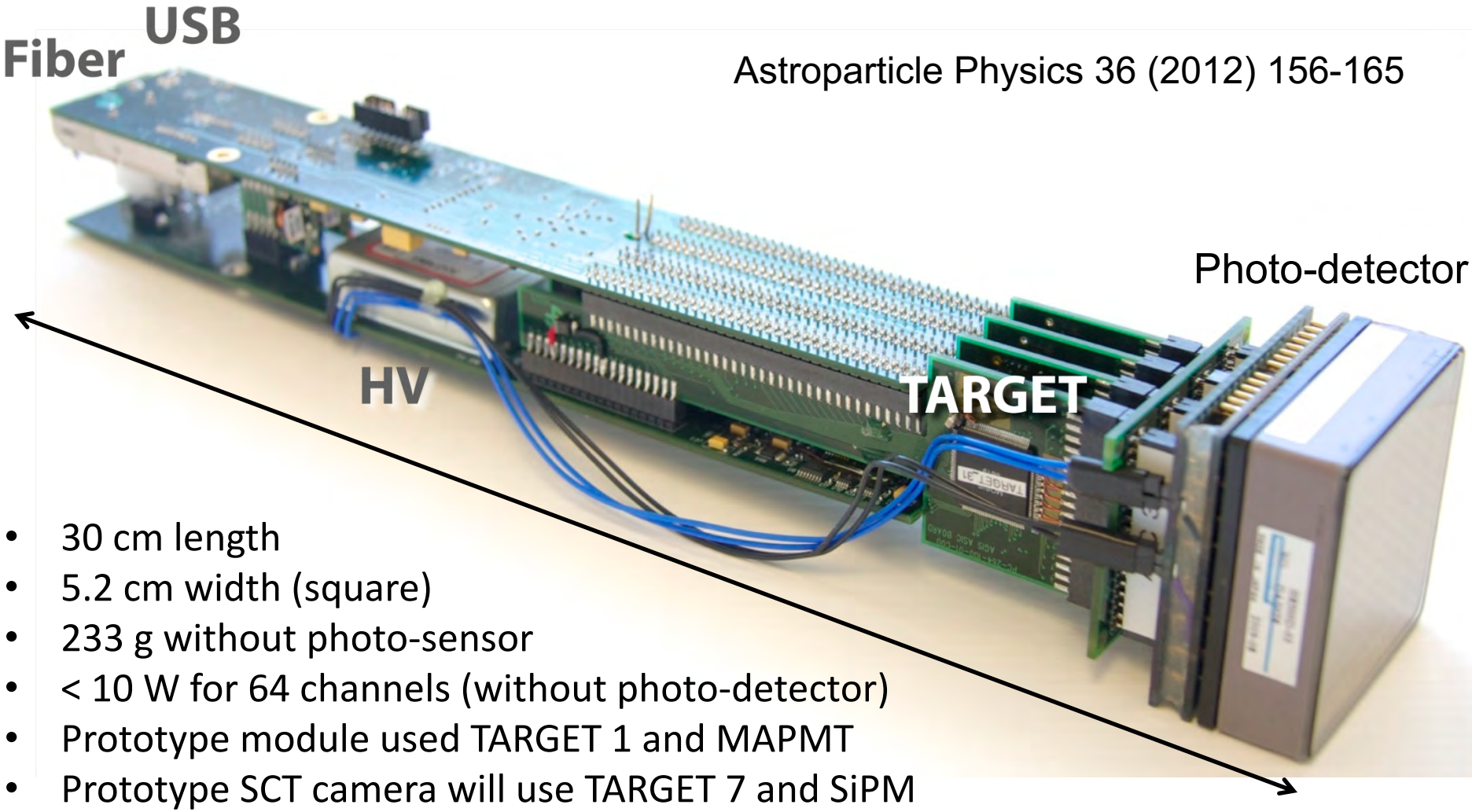
64-pixel camera module



30 cm length
5.2 cm width (square)
233 g without photo-sensor

Astroparticle Physics 36 (2012) 156-165

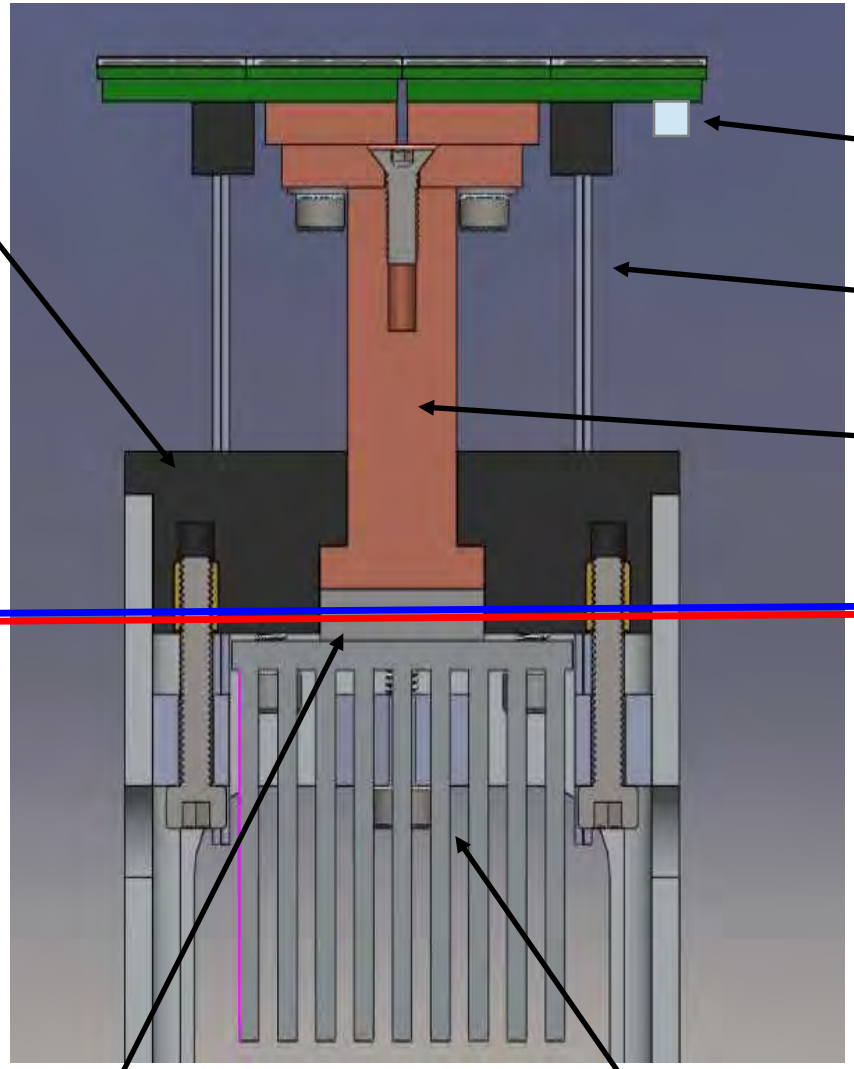
64-pixel camera module



Astroparticle Physics 36 (2012) 156-165

- 30 cm length
- 5.2 cm width (square)
- 233 g without photo-sensor
- < 10 W for 64 channels (without photo-detector)
- Prototype module used TARGET 1 and MAPMT
- Prototype SCT camera will use TARGET 7 and SiPM

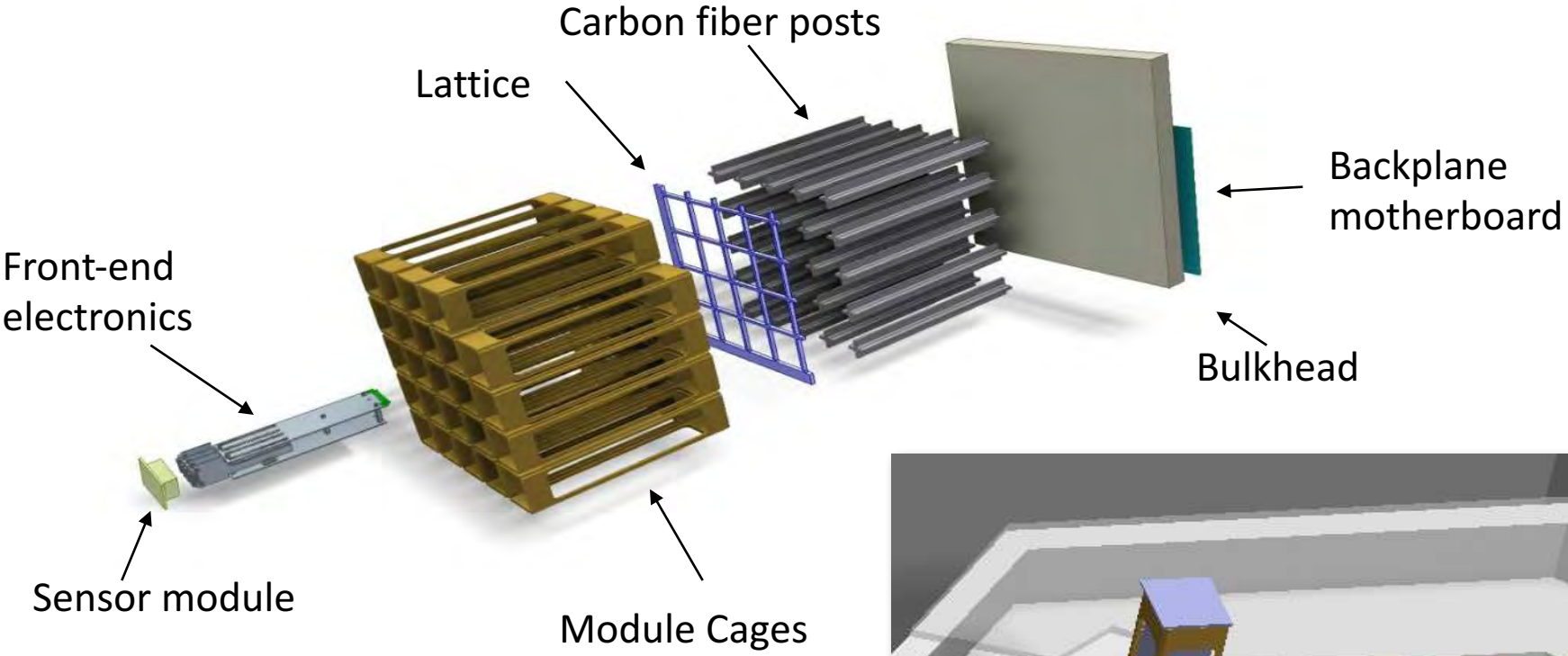
Sensor module has active temperature stabilization for stable SiPM gain

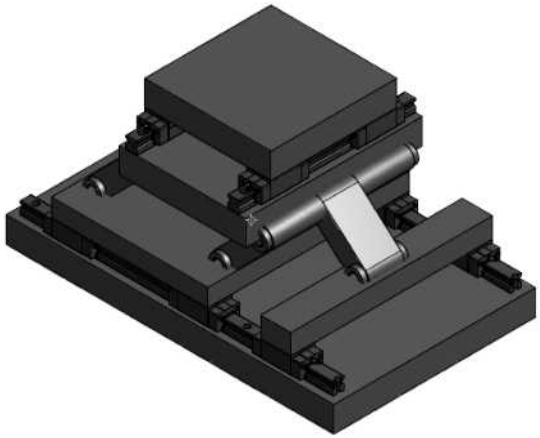


- SiPM temperatures stabilized to ±0.25 ° C
- Peltier element consumes 2-3 W per 64-channel module

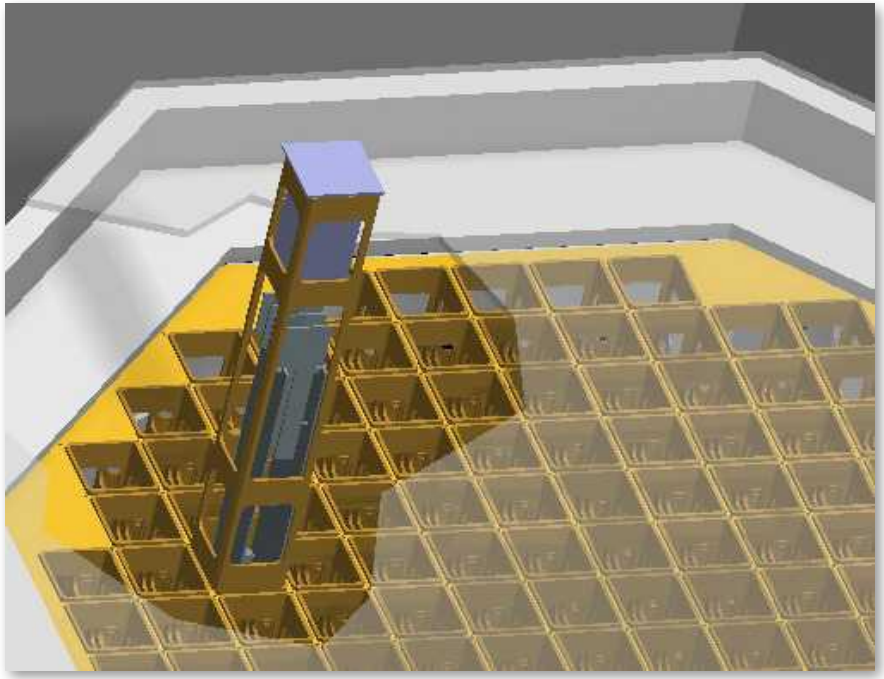
air flow to cool electronics

Camera mechanical structure





Three-axis stage controller outside of camera housing for overall camera positioning/focusing



Cooling achieved with fans blowing parallel to front-end boards

US focus in CTA: dual-mirror (Schwarzschild-Couder) telescope design

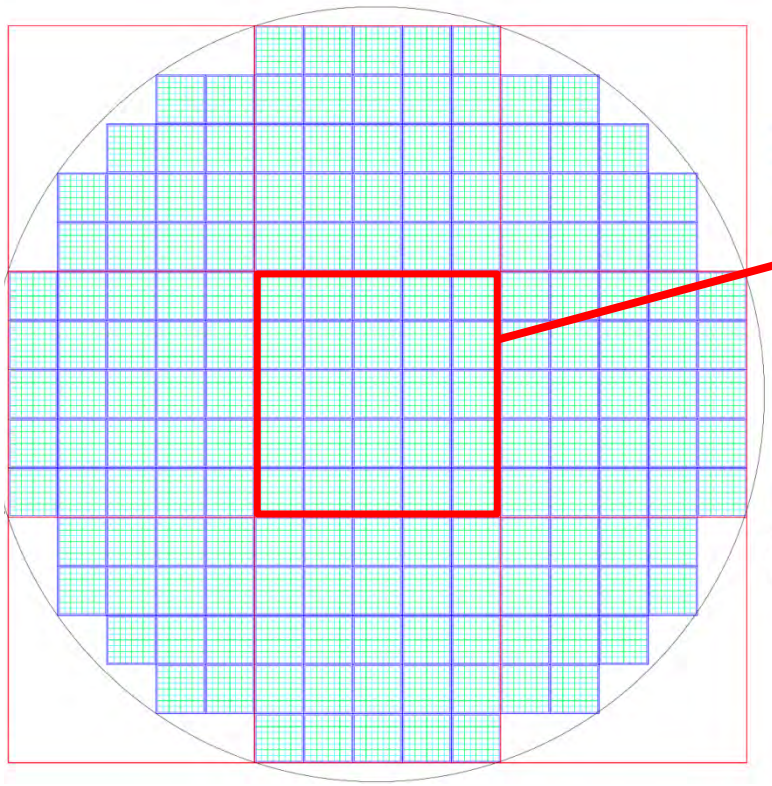
- Allows (1) better optical angular resolution over wide (8° diameter) field of view (2) small camera focal plane
- Small focal plane well suited for modern dense, highly integrated photo-detectors (MAPMTs and SiPMs) and electronics (application-specific integrated circuits)
- Improved gamma-ray angular resolution and background rejection allow qualitatively improved sensitivity

Camera design for US dual-mirror CTA telescopes

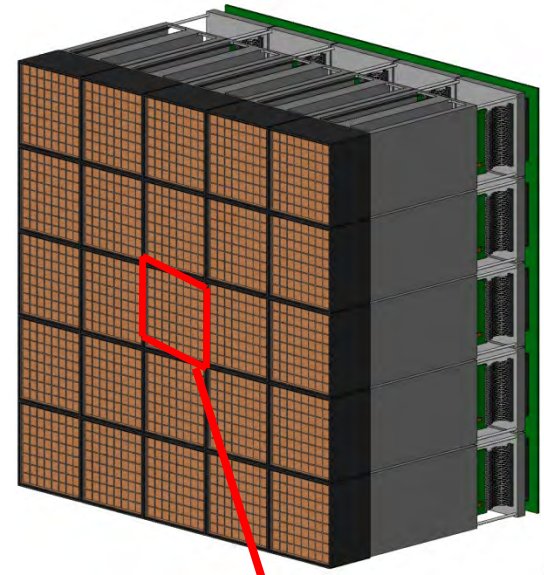
(2) Sub-field: 25 modules

(1) Full camera: 9 sub-fields

8° (0.8 m) diameter for 11,328 pixels

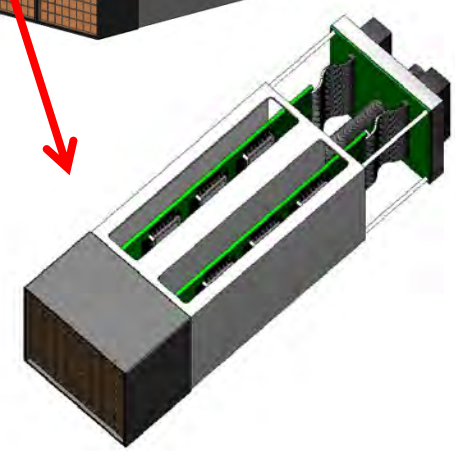


Astroparticle Physics 36 (2012) 156-165



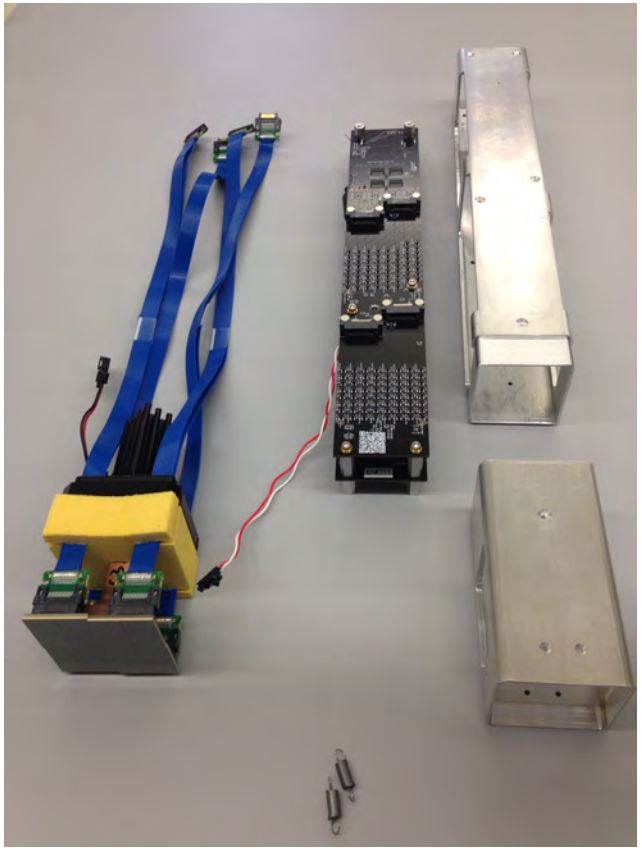
(3) Camera module:

- 2” SiPM
- 64 analog pixels
- 16 trigger pixels
- 4 TARGET chips
- Each pixel is 0.067° (6 mm) square

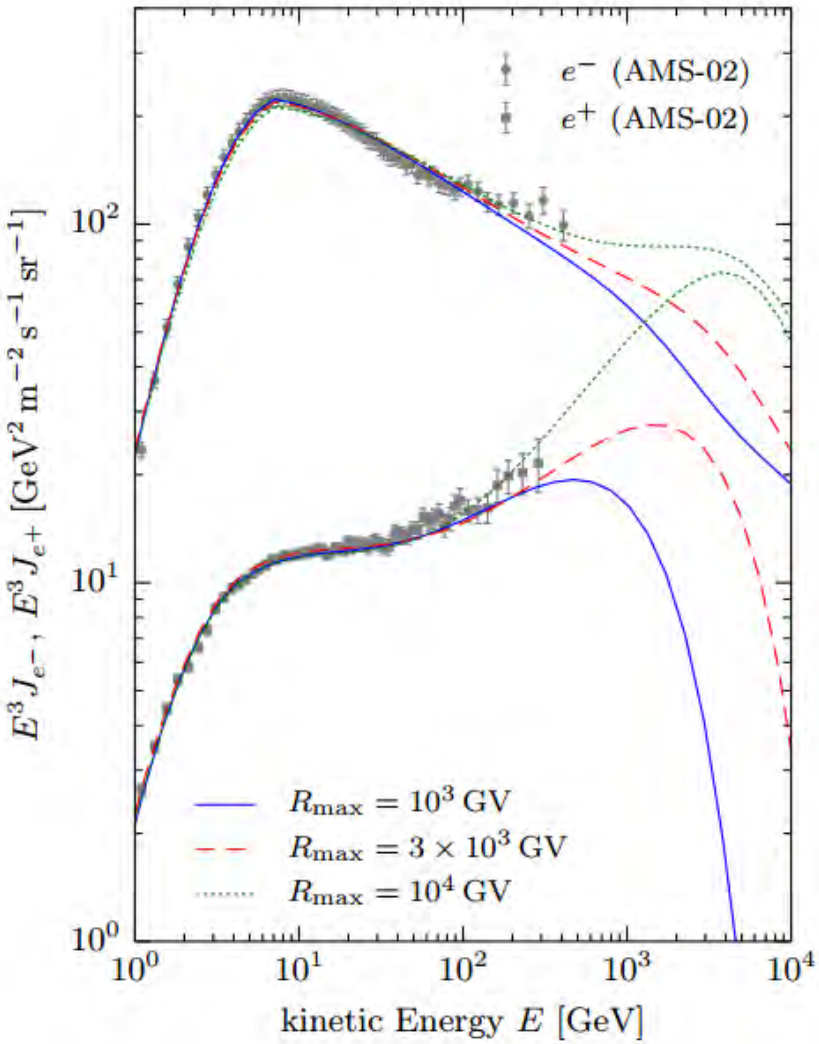


Each telescope has more pixels than VERITAS, MAGIC, and HESS combined

Modules for pSCT



Example model: secondary $e^{\pm}$ production and acceleration in supernova remnants



Mertsch & Sarkar
PRD 90, 061301
(2014)

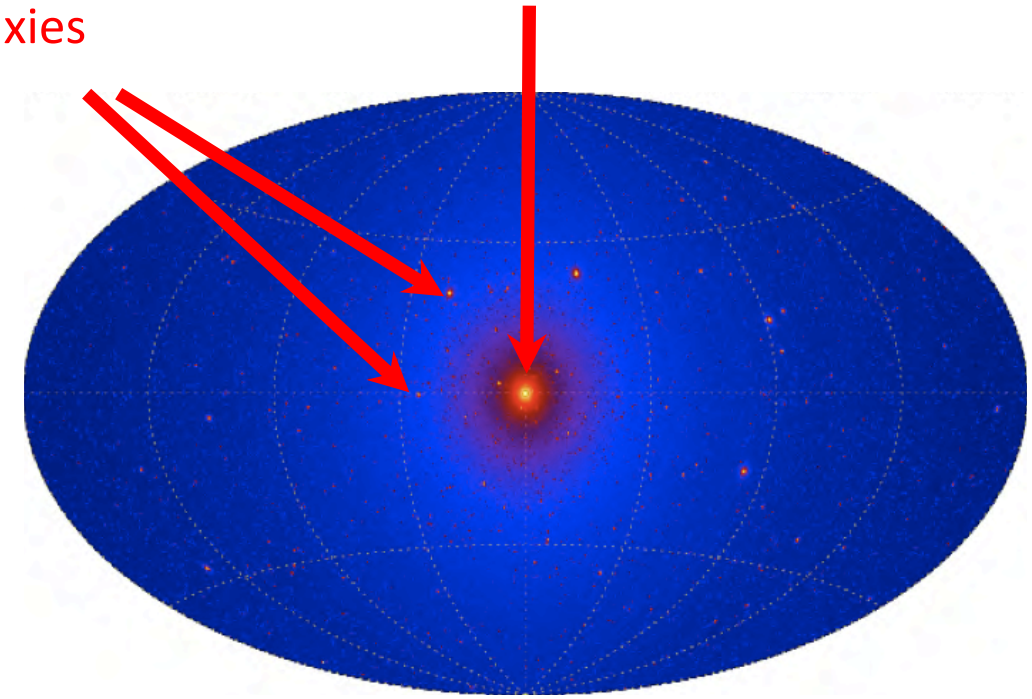
Indirect detection would provide smoking gun confirmation of particle nature of dark matter

Galactic center

Satellite galaxies

Milky Way halo

Galaxy clusters



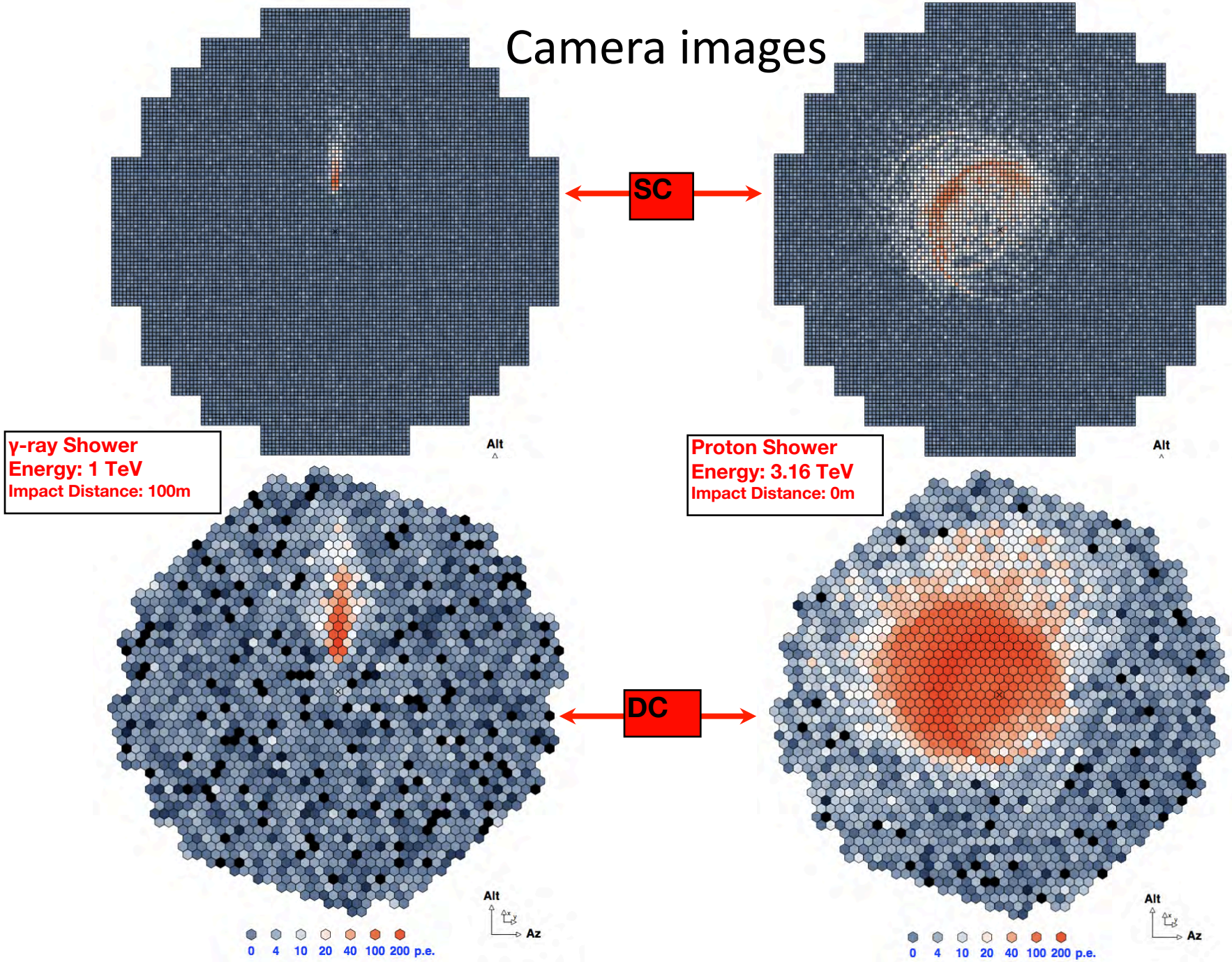
(and electrons, positrons)

Spectral lines

Extragalactic diffuse

Simulation of whole sky in gamma rays from dark matter based on Via Lactea II (Pieri et al. PRD 2011)

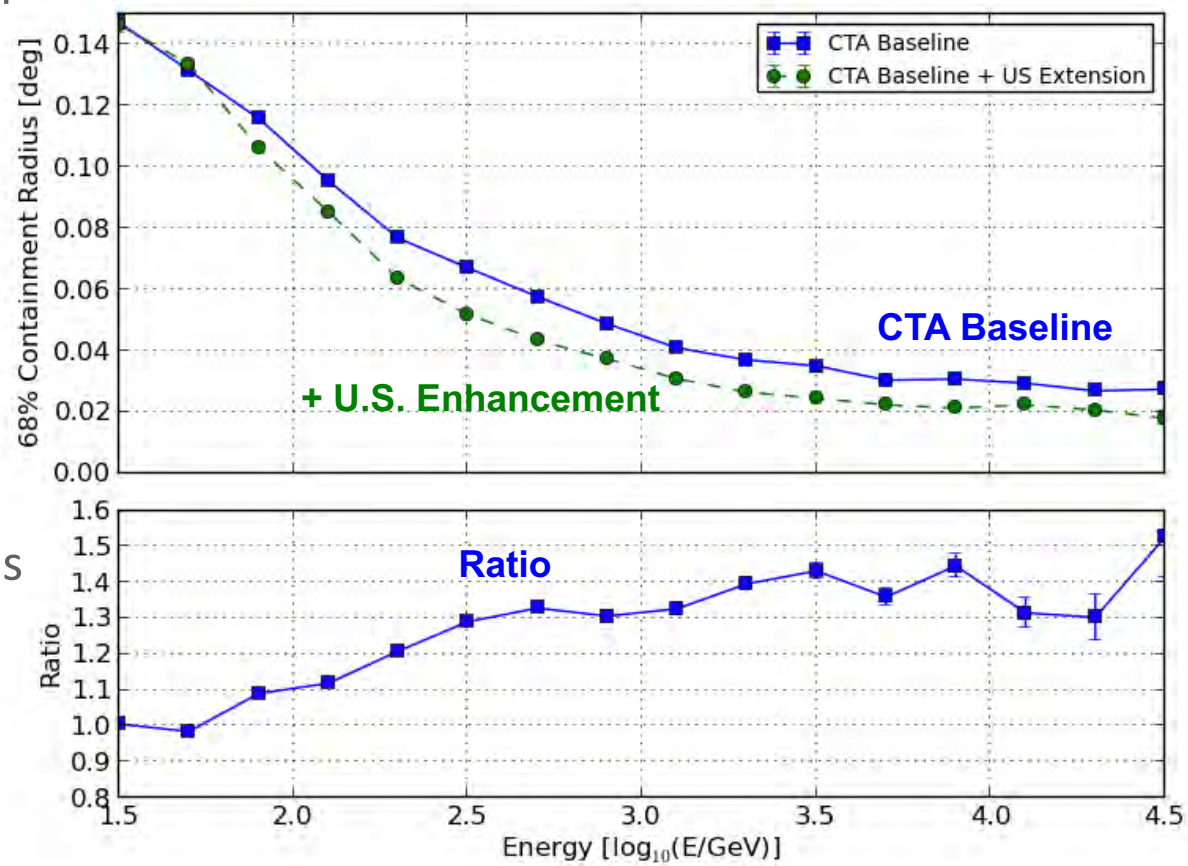
Camera images



CTA expected performance: angular resolution

- US telescopes: good angular resolution across wide field of view
- 0.1° at 100 GeV
- 0.04° at 1 TeV
- 0.02° at 10 TeV
- 0.01° at 100 TeV
- Enables good background (proton) rejection
- Enables morphological studies of Galactic sources
- Reduces source confusion

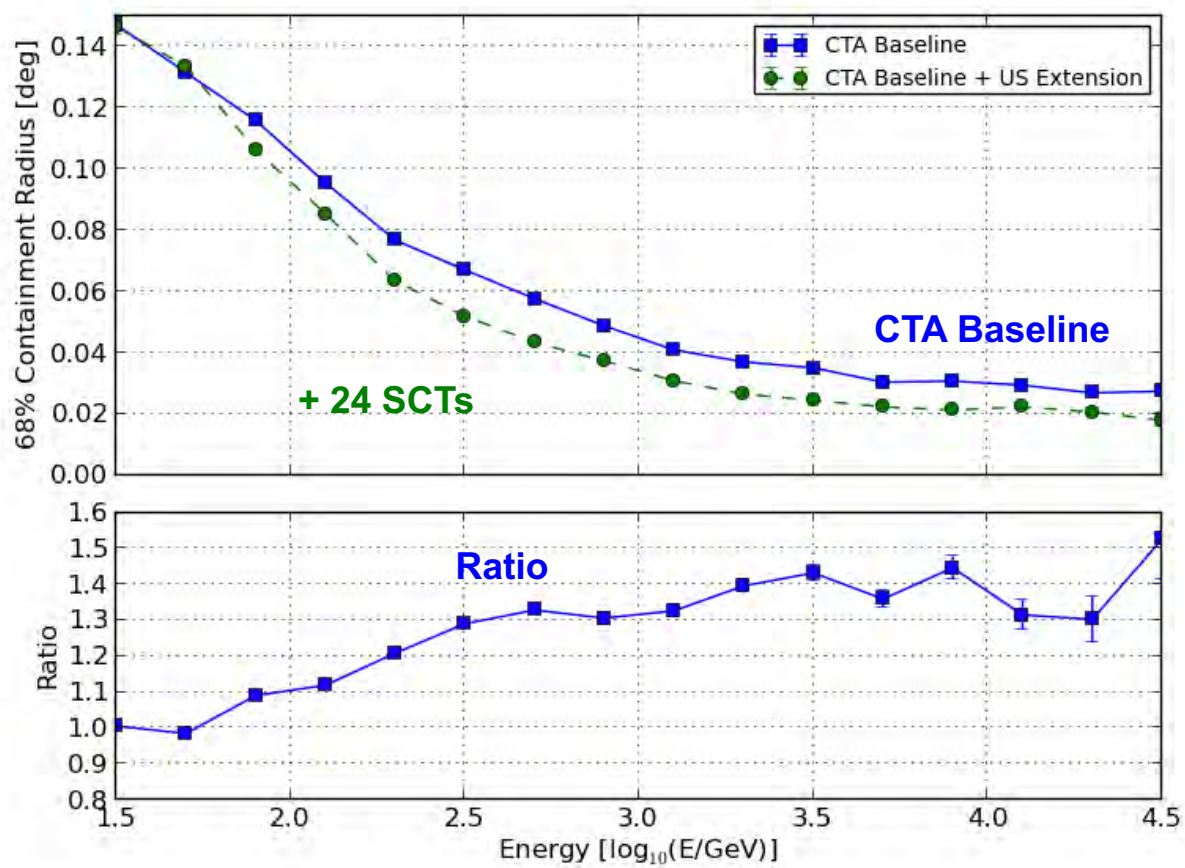
Angular Resolution
(68% containment radius)



CTA expected performance: angular resolution

- US telescopes: good angular resolution across wide field of view
- 0.1° at 100 GeV
- 0.04° at 1 TeV
- 0.02° at 10 TeV
- Enables good background (proton) rejection
- Enables morphological studies of Galactic sources
- Reduces source confusion
- Improves subtraction of discrete sources for study of extended sources such as Galactic center halo

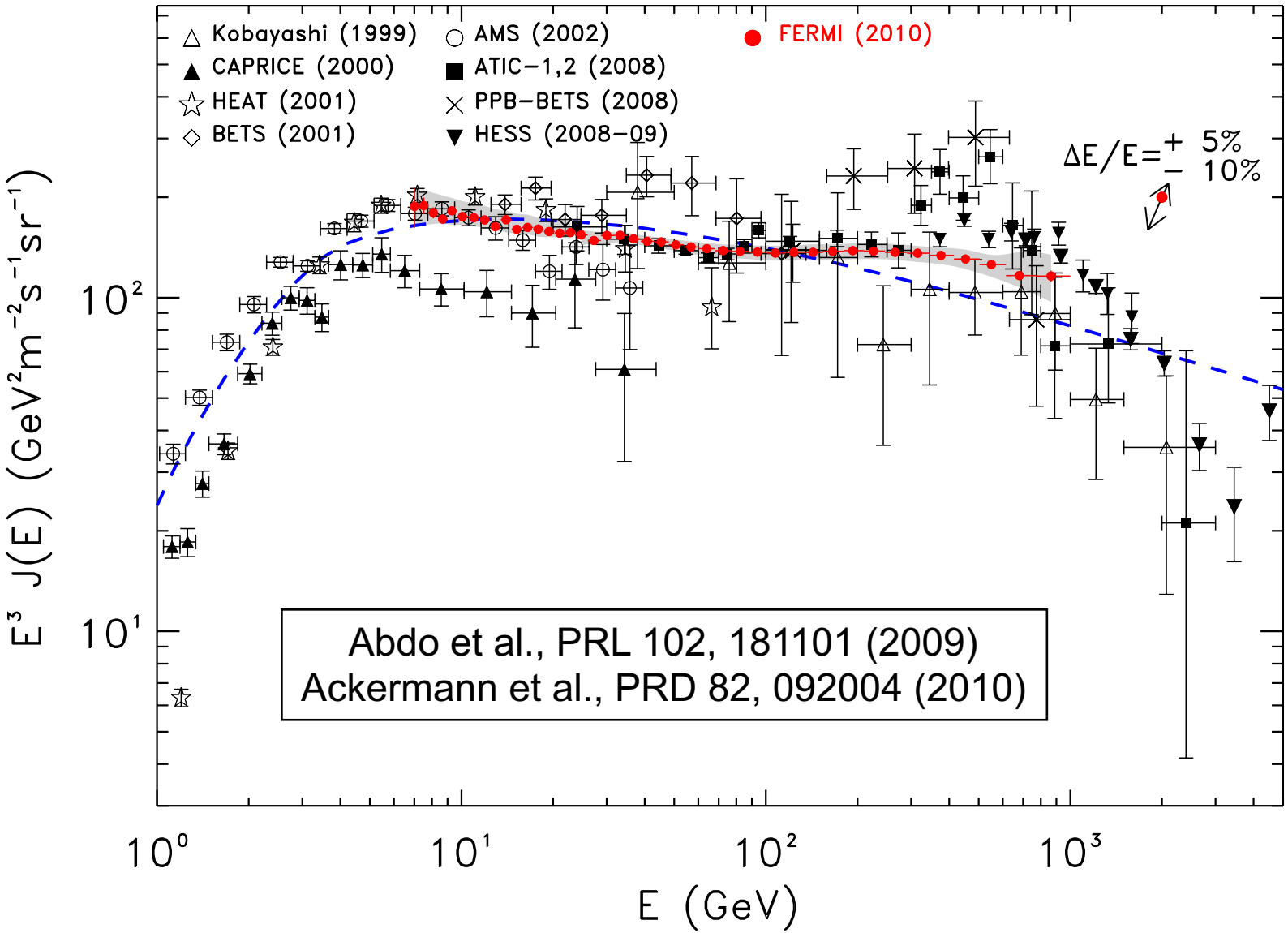
Gamma-ray angular Resolution
(68% containment radius)



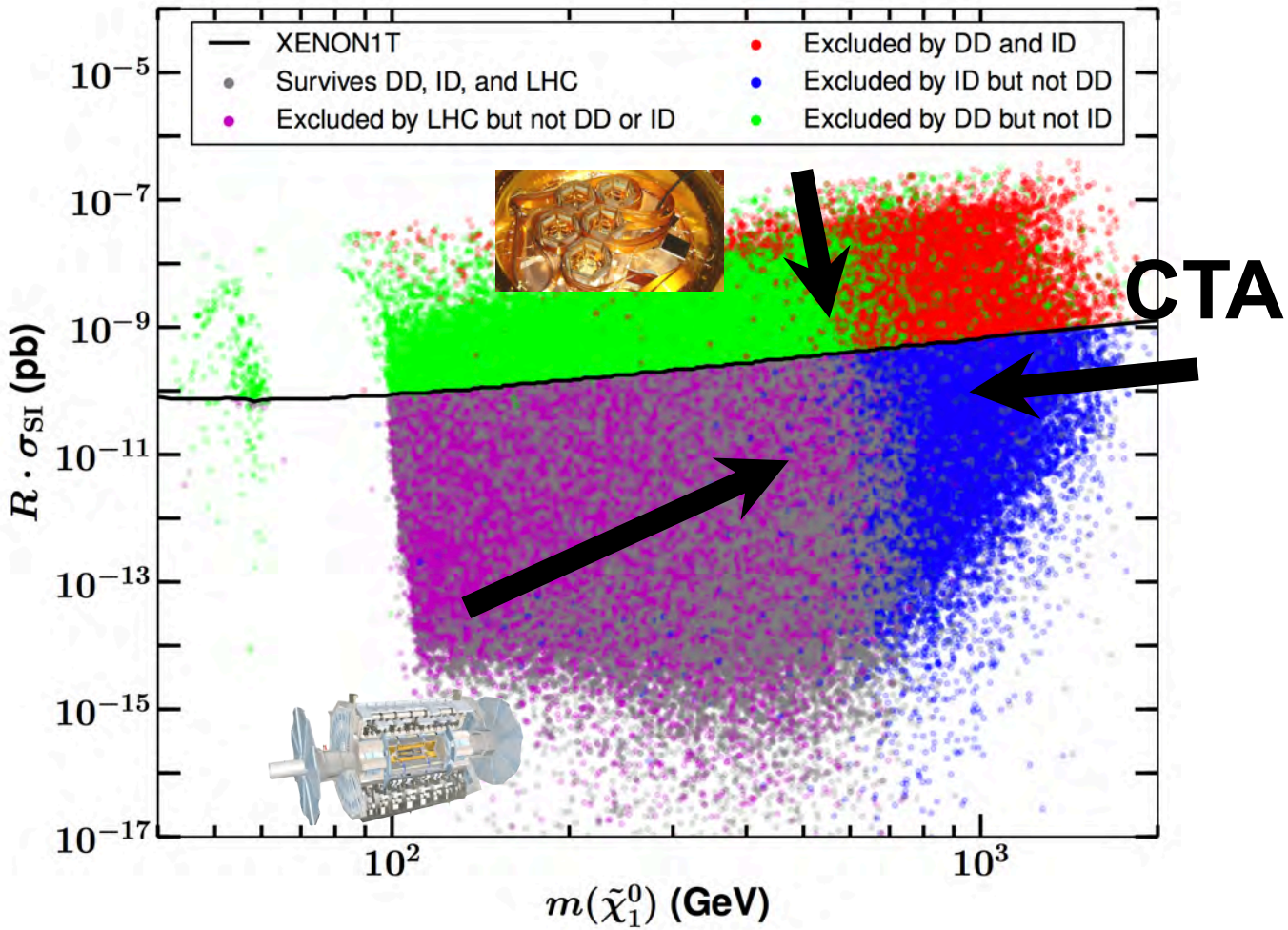
Chile

- 10 meter and (pictured) 30 meter weather towers
- Measuring temperature, humidity, pressure, wind
- 3D anemometers at several heights: wind speed and profile
- All-sky camera for cloud monitoring
- Seismometer
- Sun and moon photometer for measuring absorption and scattering of light

The total electron + positron spectrum



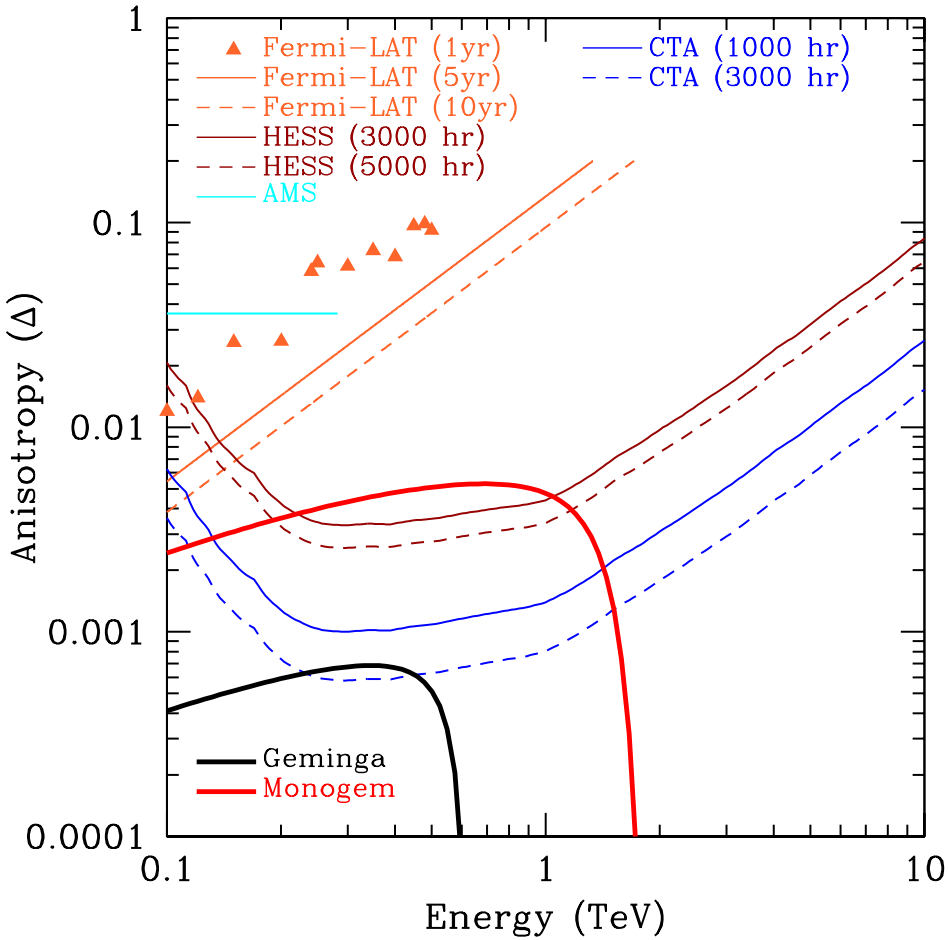
Indirect, direct, and accelerator dark matter searches are complementary



M. Cahill-Rowley et al. – Snowmass white paper, arXiv:1305.6921

Cherenkov Telescope Array capabilities: total electron + positron anisotropy

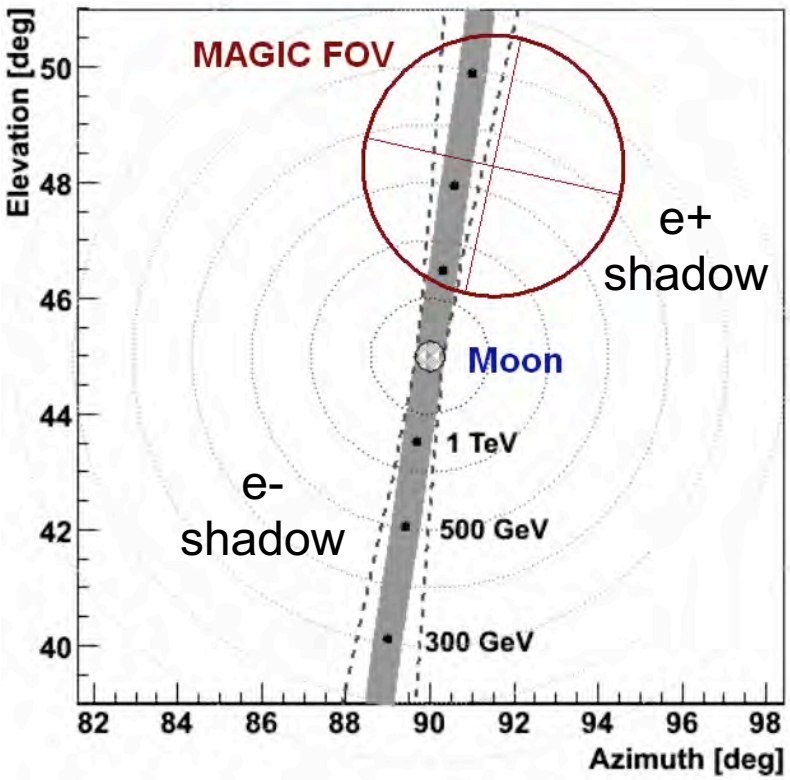
Anisotropy:



arXiv:1304.1792

Prototype single-mirror mid-size CTA telescope in Germany

Cherenkov Telescope Array capabilities: positron fraction with Moon shadow

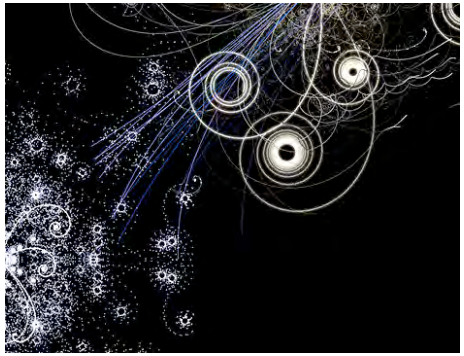


arXiv:0907.1026
arXiv:1110.0183

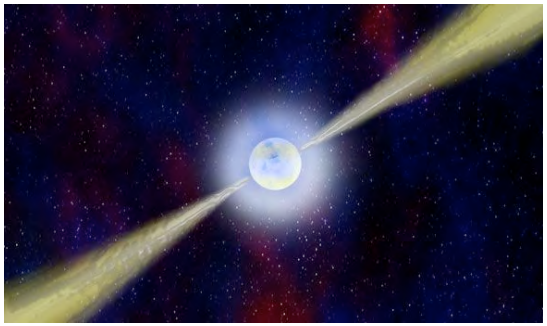
- Measure total electron + positron spectrum precisely to ~100 TeV
- CTA expected to detect Moon shadow in electrons in ~5 hours
- Use Moon shadow to separate electrons and positrons: two shadows separated by ~1.5° at ~1 TeV
- Silicon photomultipliers particularly well suited: can look in direction of bright moonlight

Three mechanisms of cosmic-ray electron and positron production

1. Interaction of cosmic-ray protons with diffuse interstellar gas (believed to dominate)

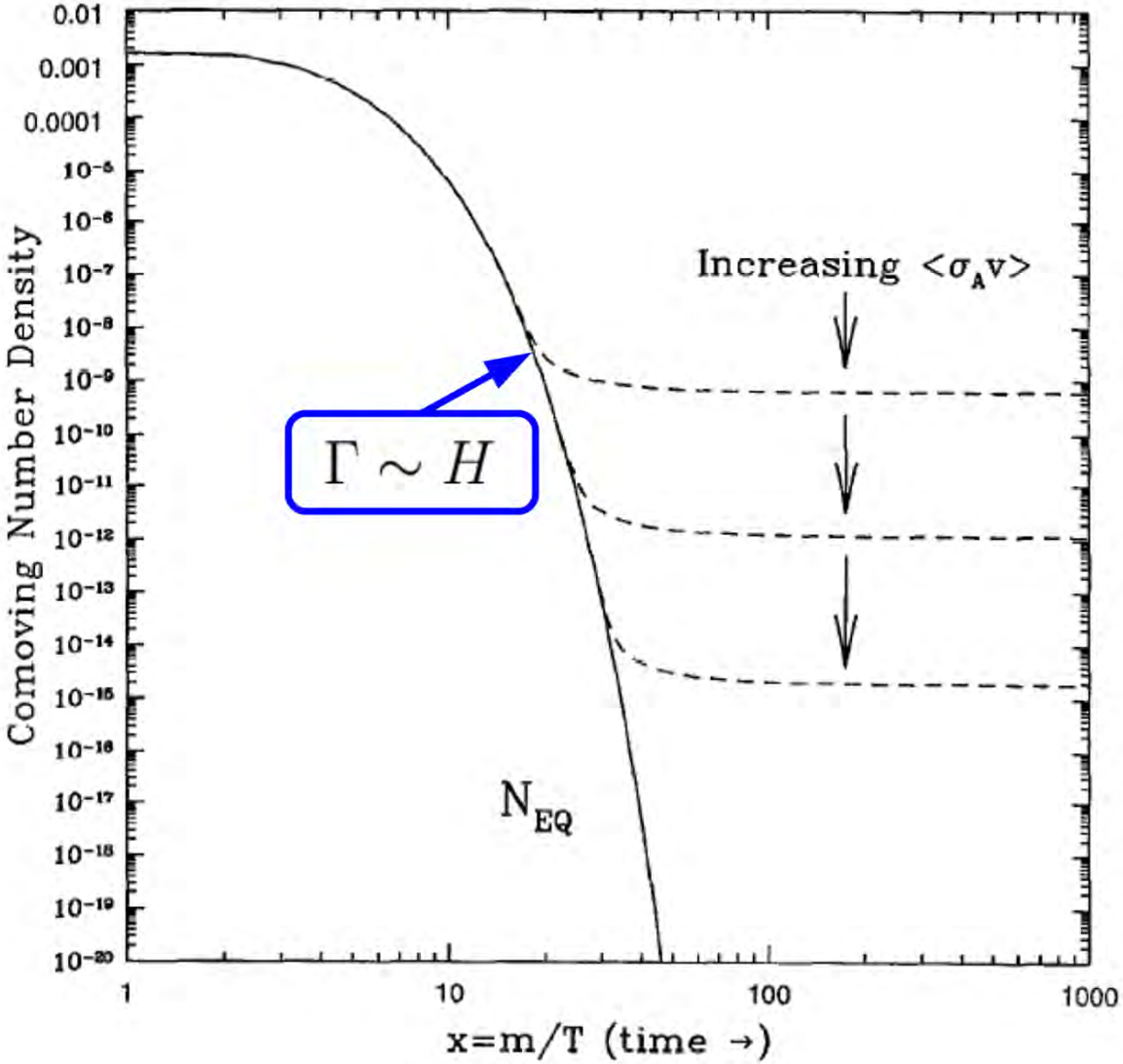


2. Primary astrophysical sources (e.g. pulsars)



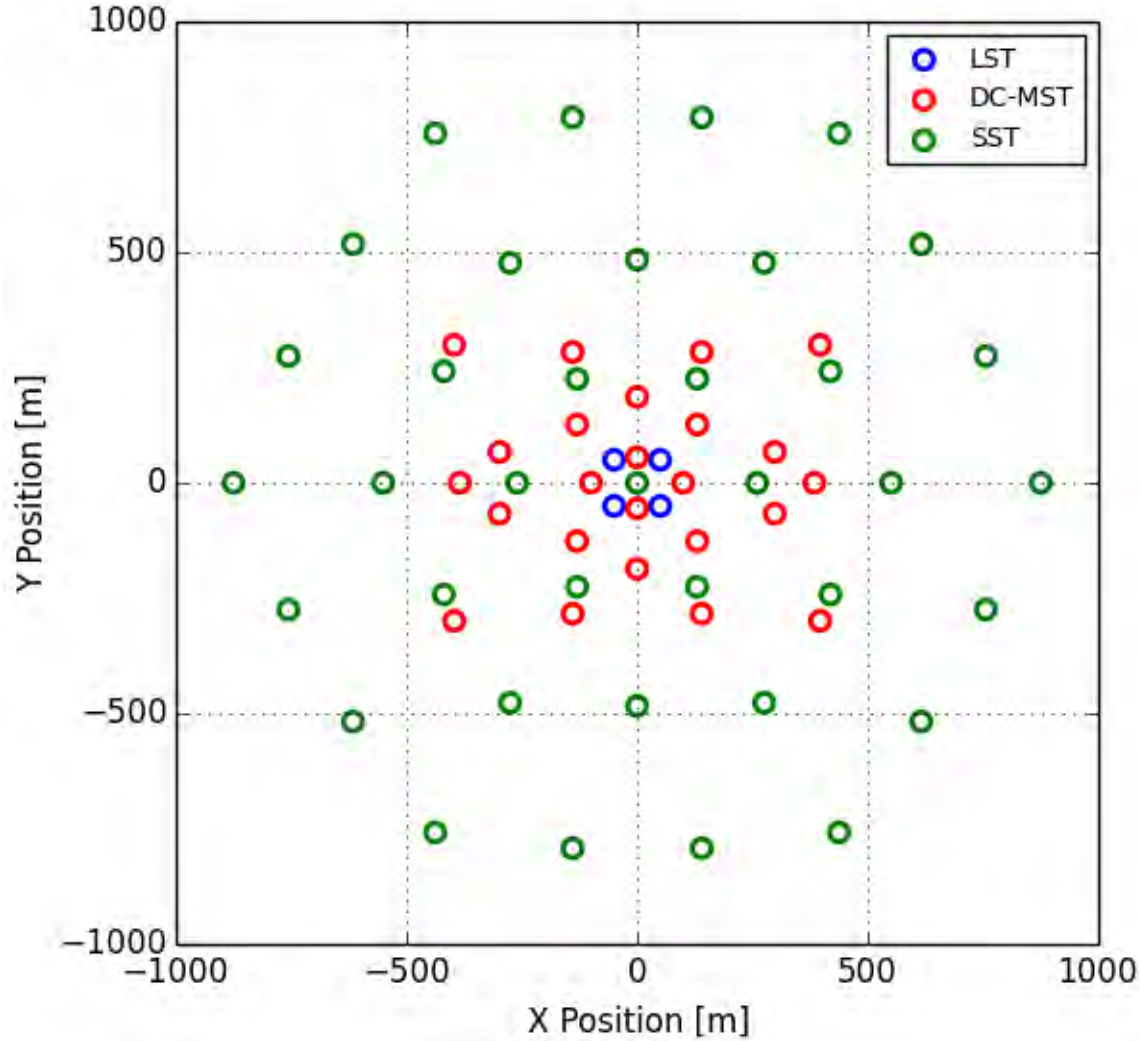
3. Dark matter annihilation or decay

Freeze-out of dark matter particles



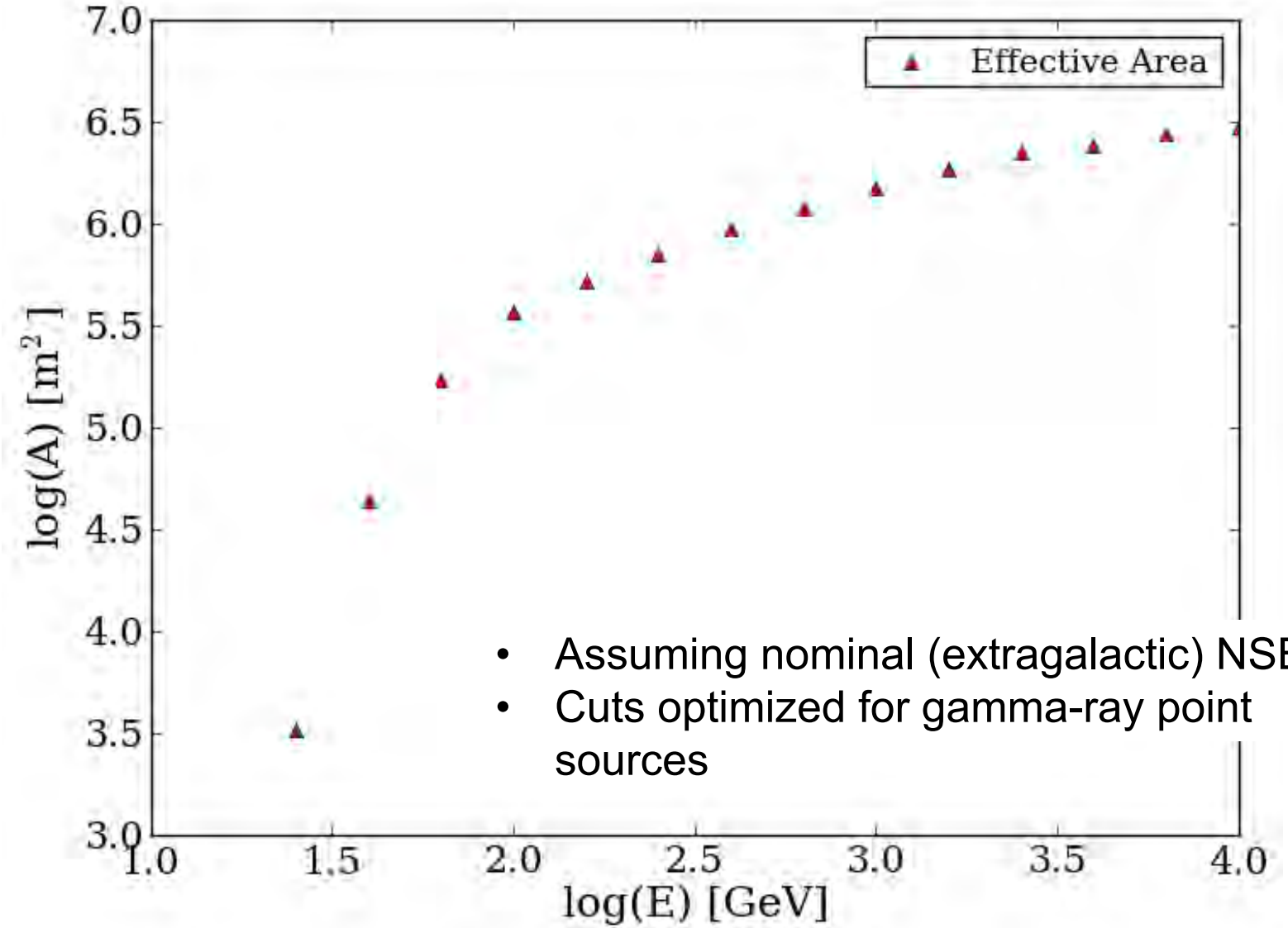
From A. Ibarra @ Zurich February 2010

Simulated CTA array



Array “2A”: 4 LST, 24 MST, 35 SST

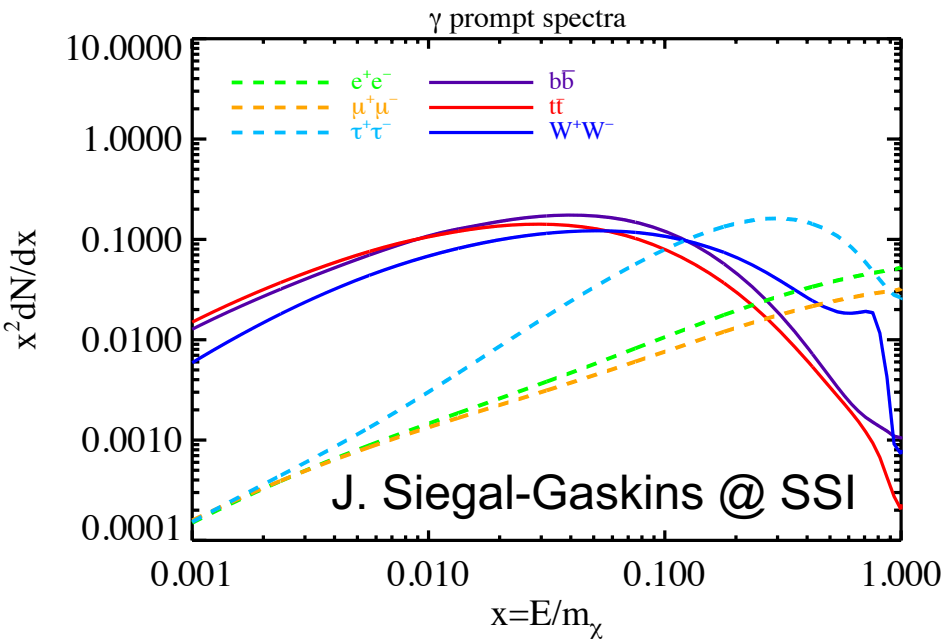
Effective area of CTA array geometry 2A



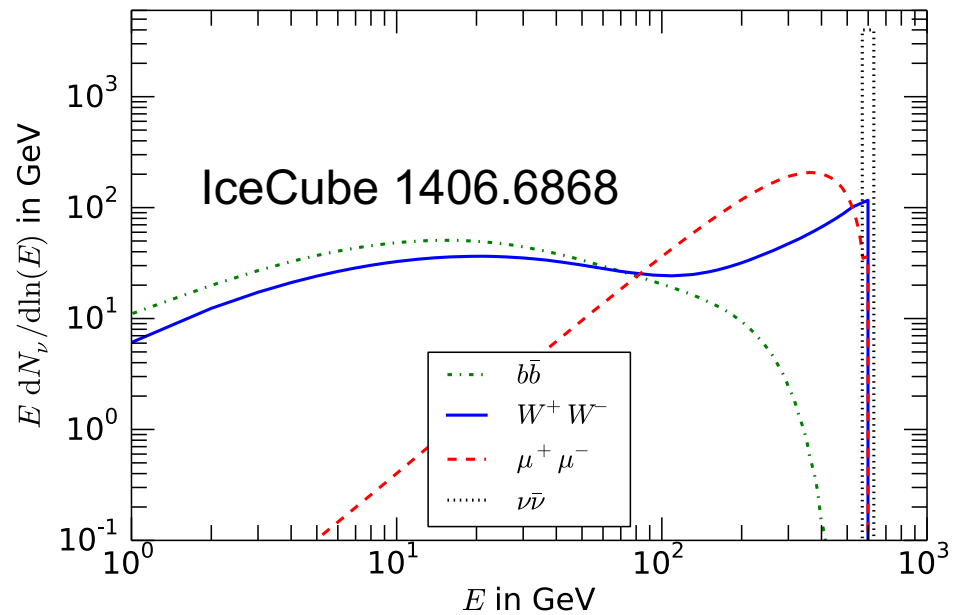
- Assuming nominal (extragalactic) NSB
- Cuts optimized for gamma-ray point sources

Gamma ray vs. neutrino spectra from WIMP annihilation

Gamma rays



Neutrinos

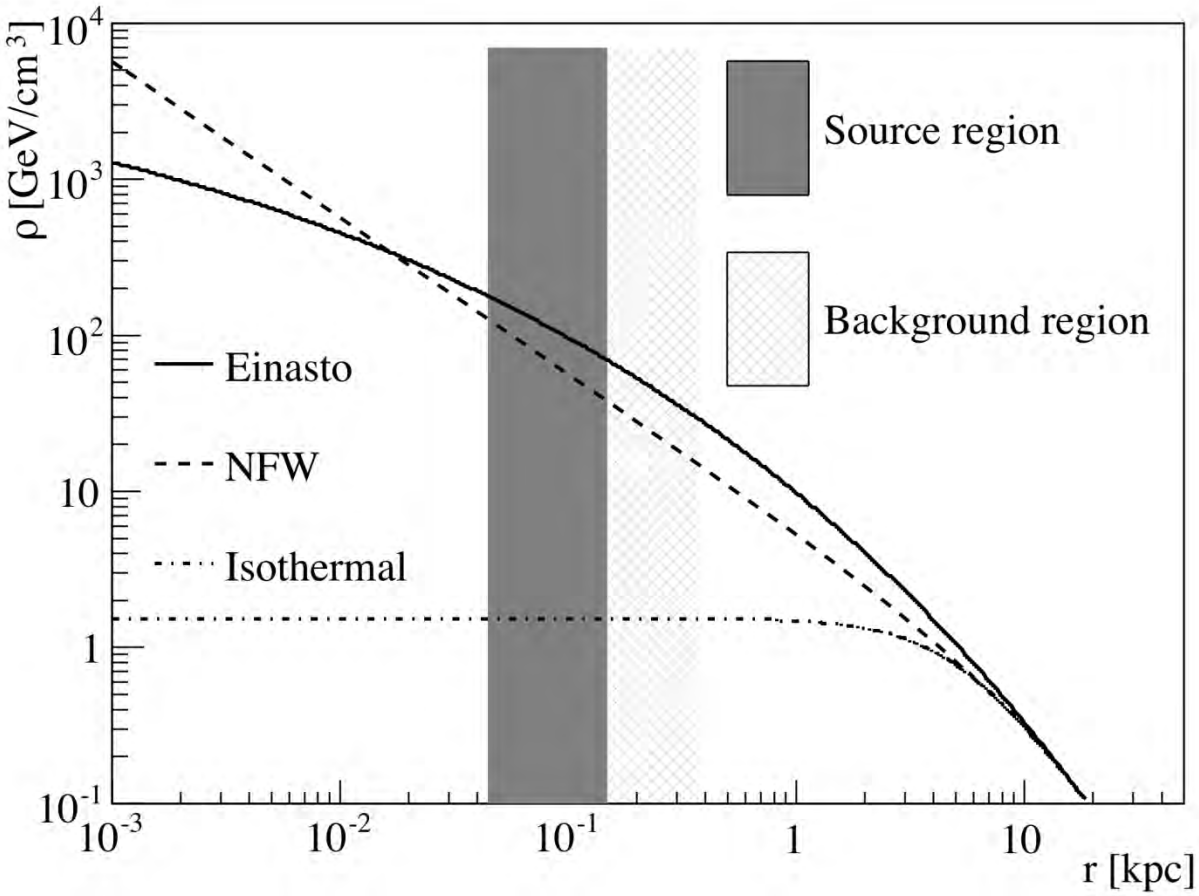


Hard: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
Soft: $b\bar{b}$, $t\bar{t}$, W^+W^-

Hard: W^+W^-, $\mu^+\mu^-$, $\nu\bar{\nu}$
Soft: $b\bar{b}$

Uncertainty of dark matter distribution in Milky Way

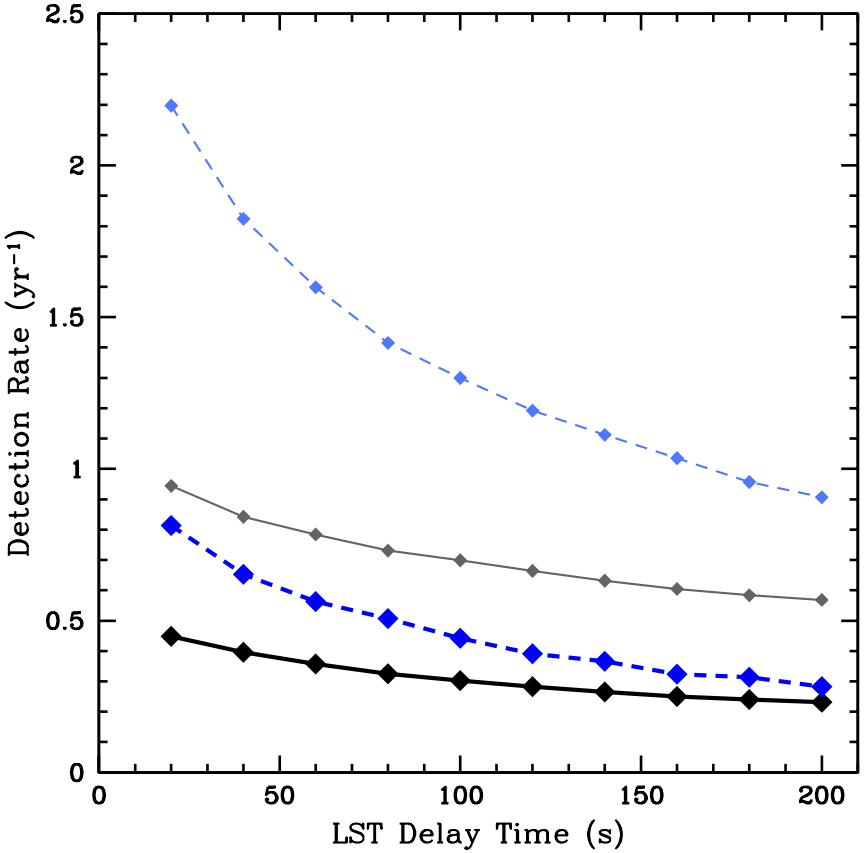
PRL 106, 161301 (2011)



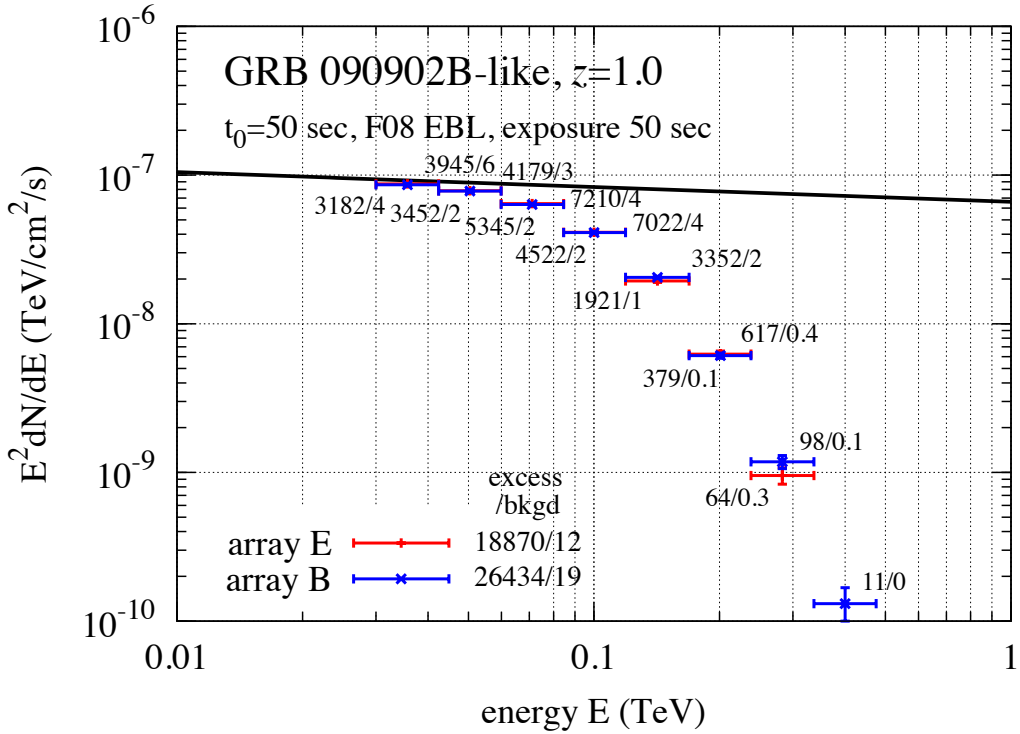
- Uncertainty in both shape and normalization
- Local density (0.2-0.4 GeV/cm³) can be used to normalize
- Gamma-ray flux scales with density squared

Gamma-ray bursts at very-high energy

Detection rate depends on slewing to target quickly

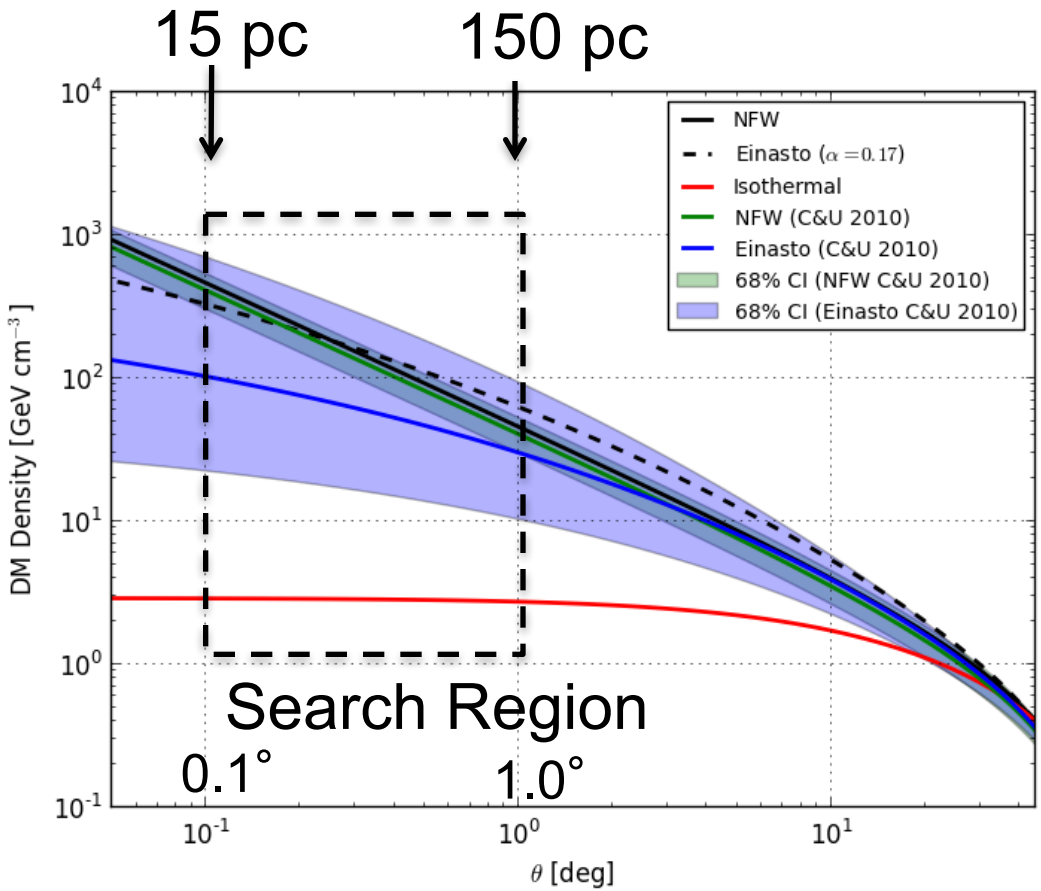


Simulated spectrum measurement for example burst



S. Inoue et al. for CTA, Astroparticle Physics 43 (2013) 252-275

Milky Way dark matter distribution



Magnetic field strength at candidate CTA sites

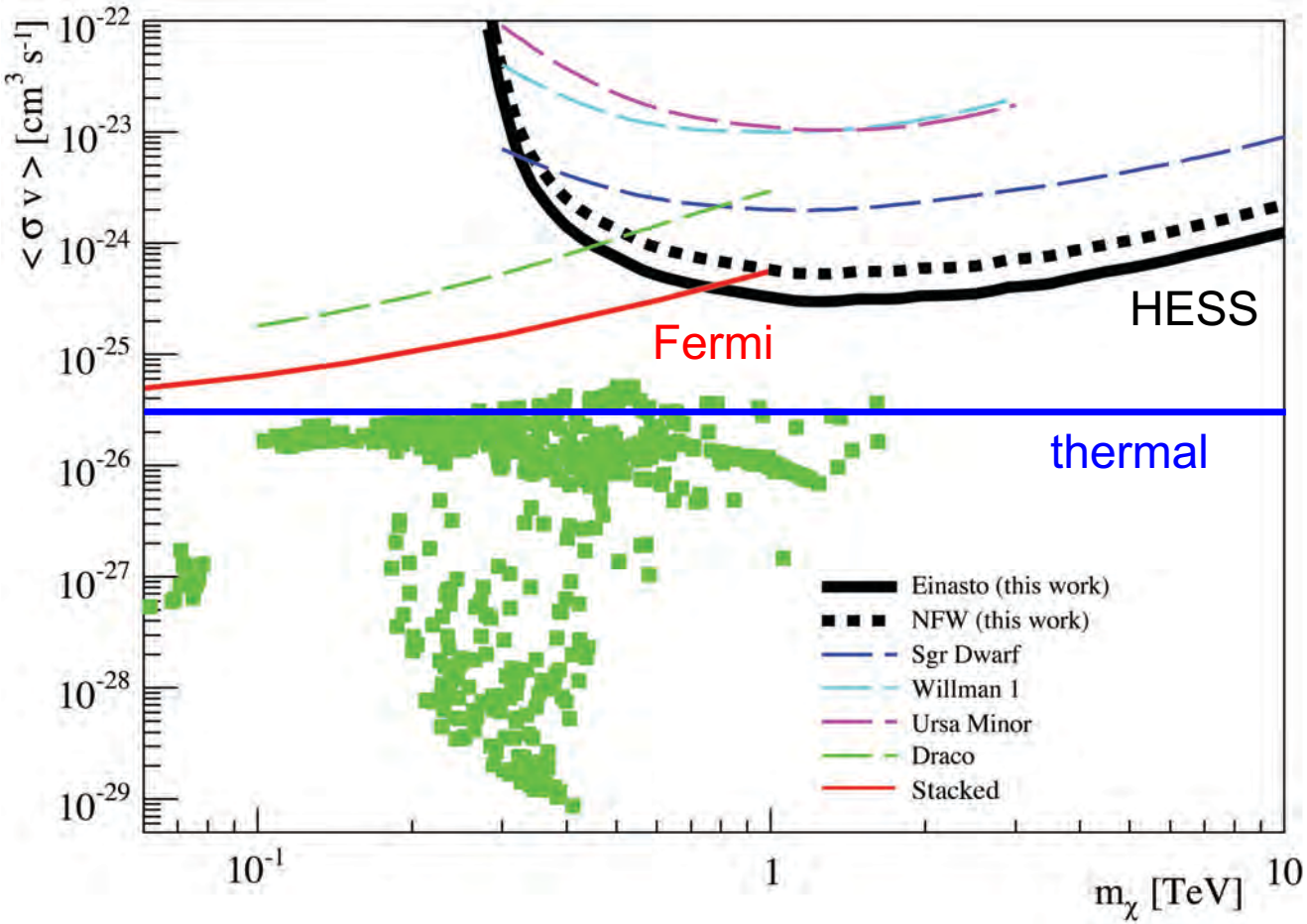
	Site		Altitude [m]	B [microtesla] Horizontal	Perpendicular - 20 deg. Zenith North	South	Average	HESS	MAGIC
	Leoncito	Argentina	2662	19.9	14.4	23.0	18.7	19.1	18.9
	Aar	Namibia	1640	10.9	1.7	18.8	10.2	15.6	13.5
South	SAC	Argentina	3600	20.9	16.6	22.7	19.6	19.6	19.7
	Armazones	Chile	2500	21.4	17.0	23.1	20.1	20.0	20.2
	HESS	Namibia	1800	12.0	2.3	18.5	10.4	16.5	14.4
	SPM	Mexico	2434	25.2	36.8	10.6	23.7	28.5	28.5
North	Meteor Crater	US	1680	23.5	36.8	7.4	22.1	28.2	28.2
	Yavapai	US	1670	23.6	36.8	7.6	22.2	28.2	28.2
	Tenerife	Spain	2290	30.8	36.9	21.0	28.9	31.0	31.0

Energy budget of the Galaxy

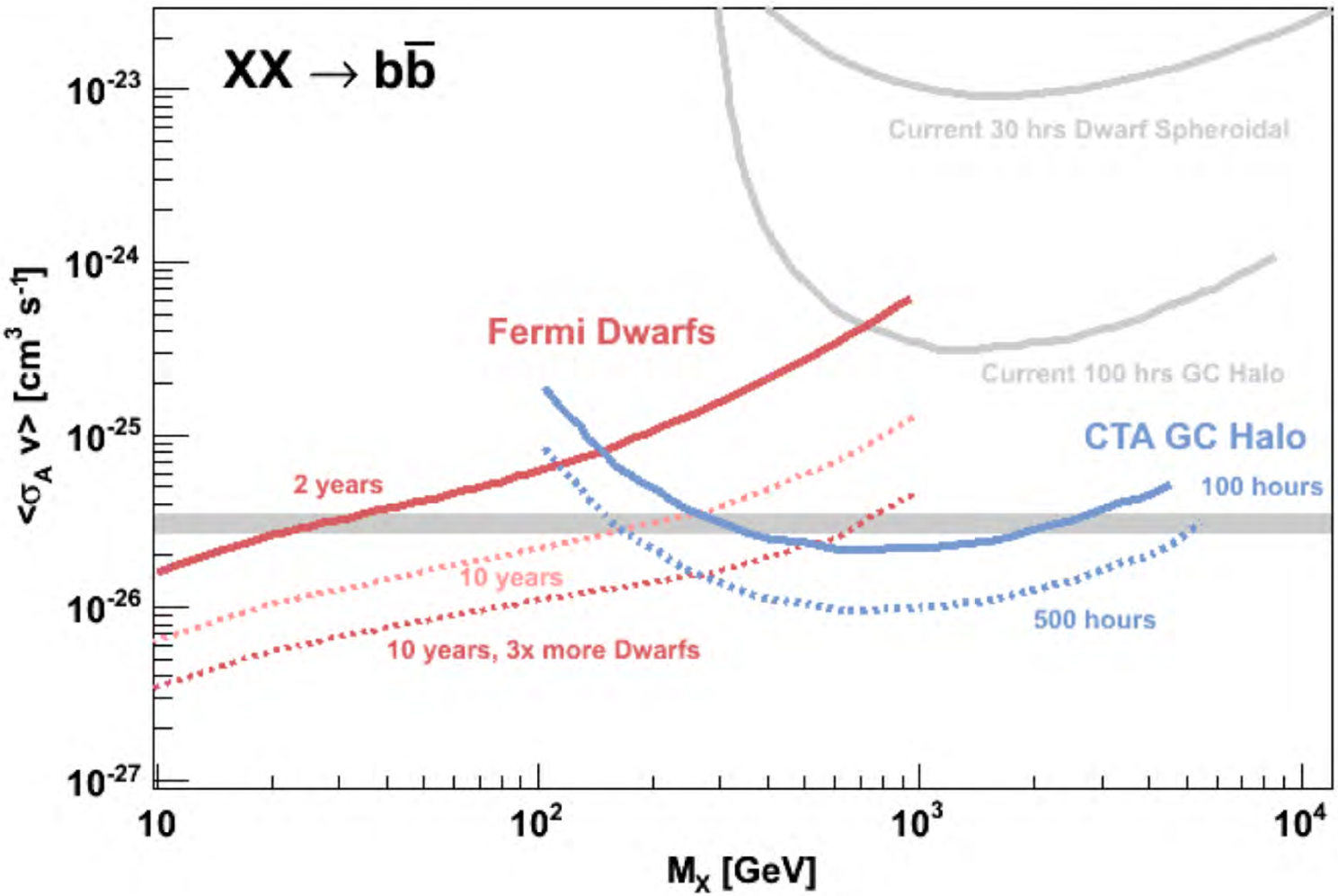
- Visible starlight: 0.3 eV/cm3
- Magnetic fields: 0.3 eV/cm3
- CMB: 0.3 eV/cm3
- Cosmic rays: 1 eV/cm3

HESS extends constraints to higher mass using Galactic center observations

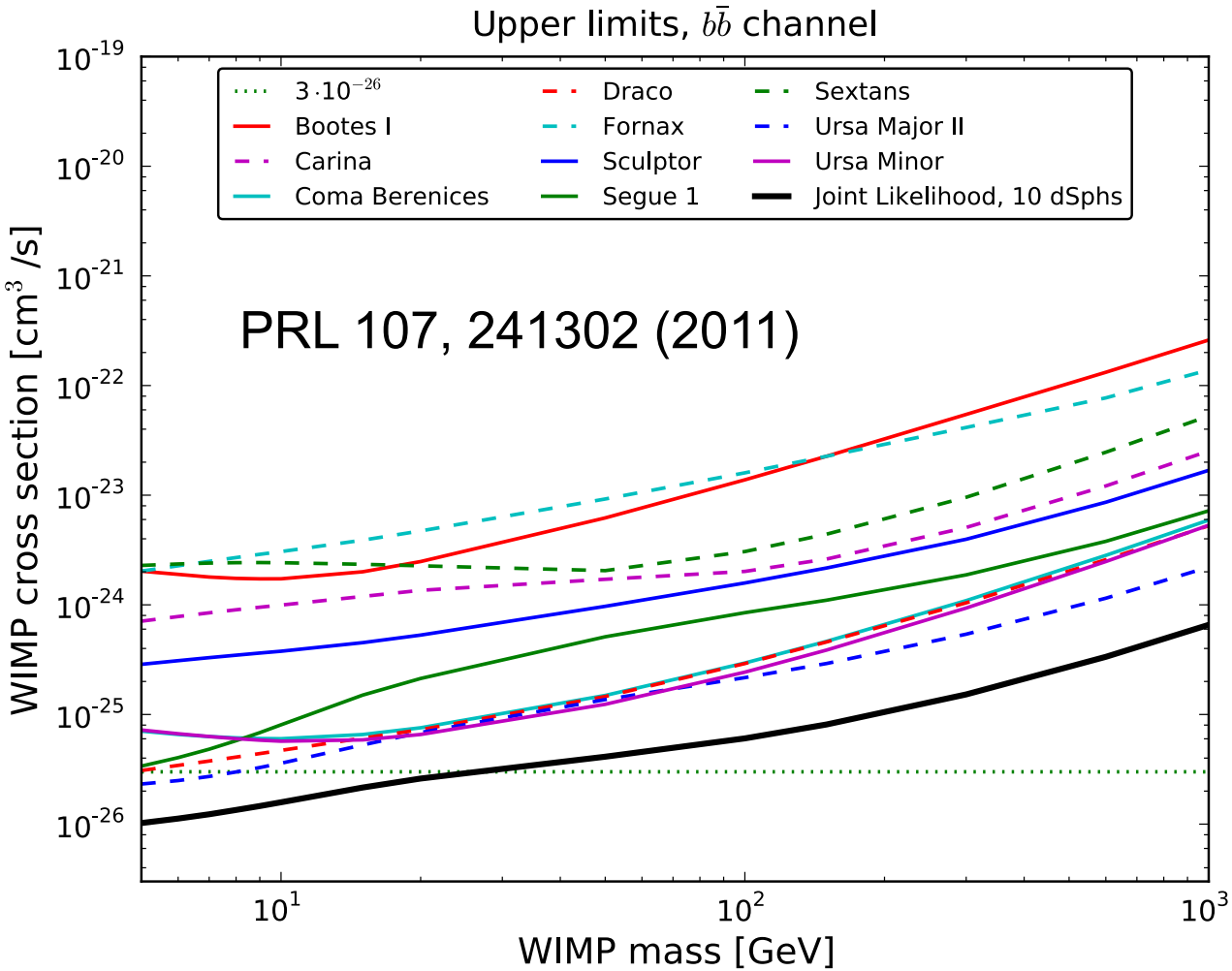
PRL 106, 161301 (2011)



Fermi and CTA together will cover the entire range of dark matter WIMP masses

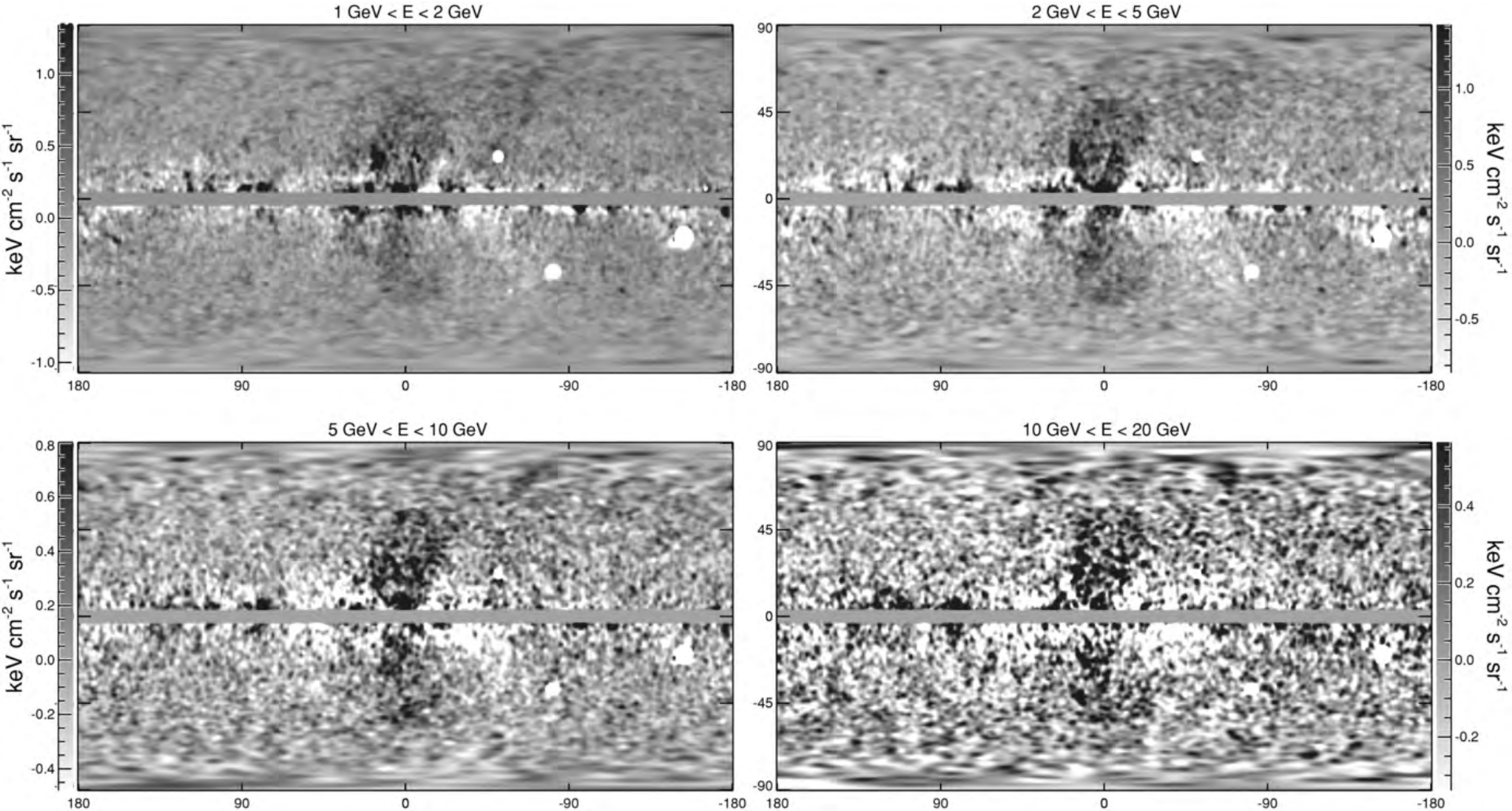


Fermi non-detection of dwarf galaxies strongly constrains dark matter



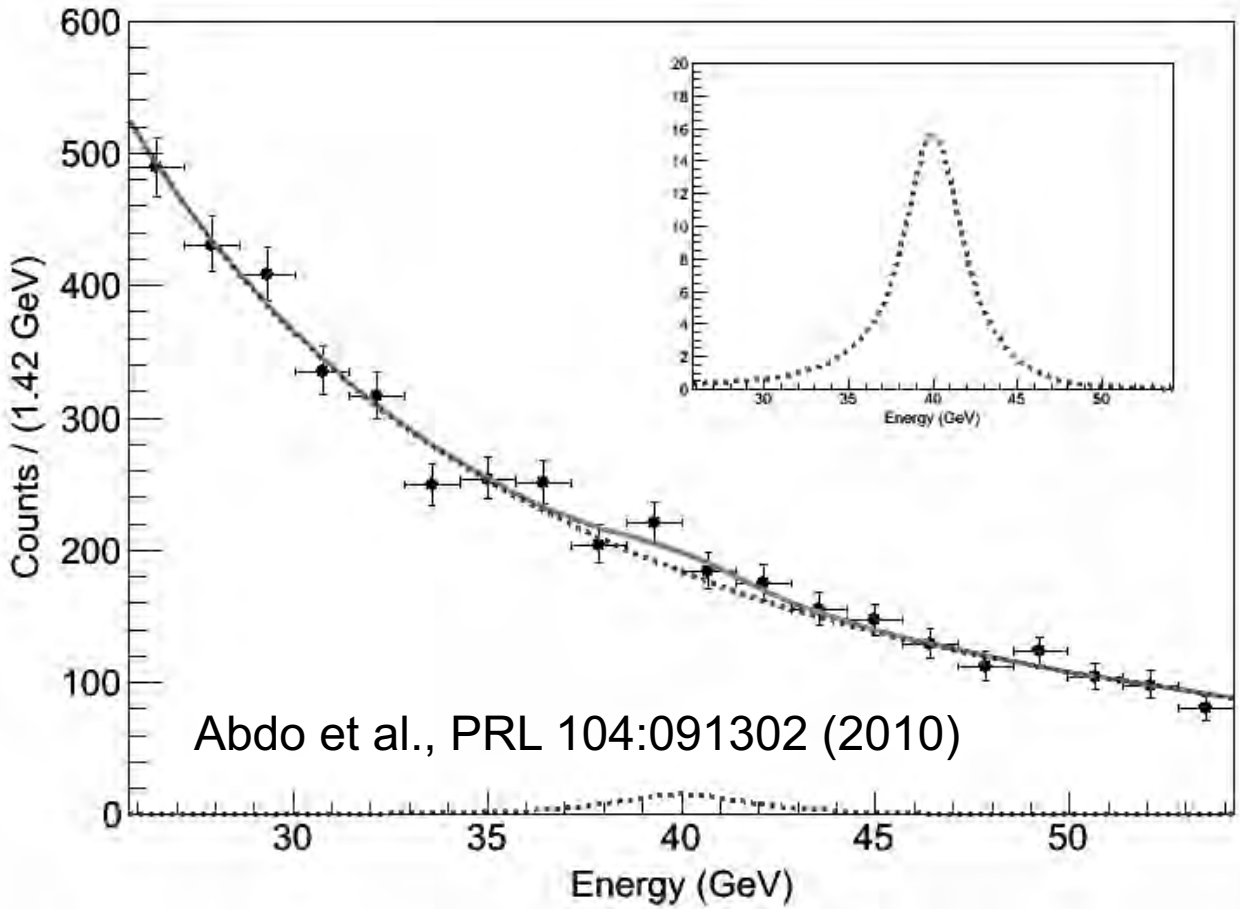
Cross section upper limit is now below that expected if WIMPs are produced thermally in early Universe (3 x 10^{-26} cm^3/s)

Fermi Bubbles



- Huge structures, ±50° from Galactic plane (residual maps after subtracting Gal. diffuse)
- Synchrotron from energetic particles from past Sgr A* or star formation activity?
- Su, Slatyer, and Finkbeiner, ApJ 2010

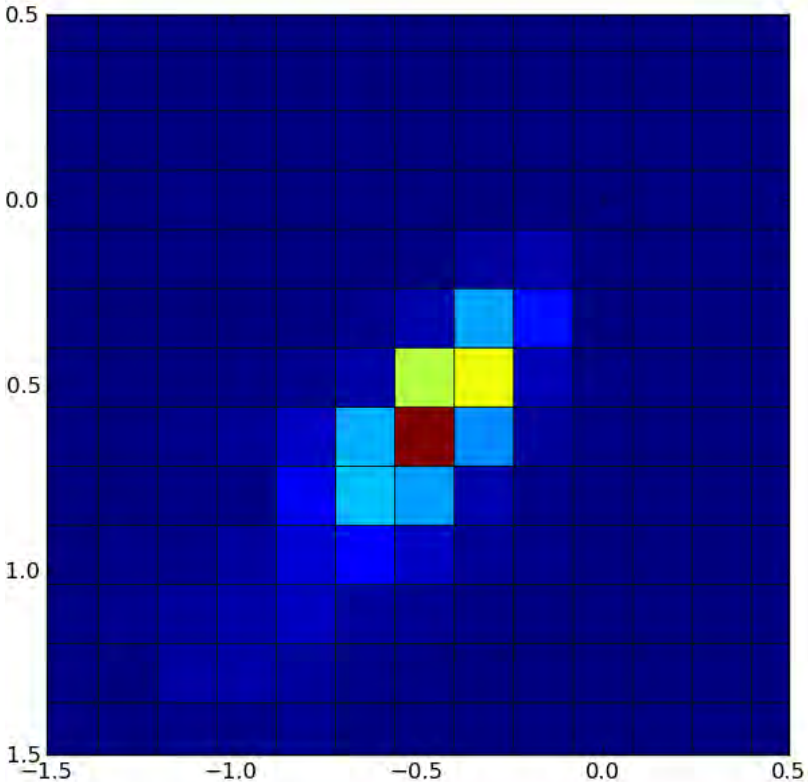
Search for spectral lines from dark matter annihilation



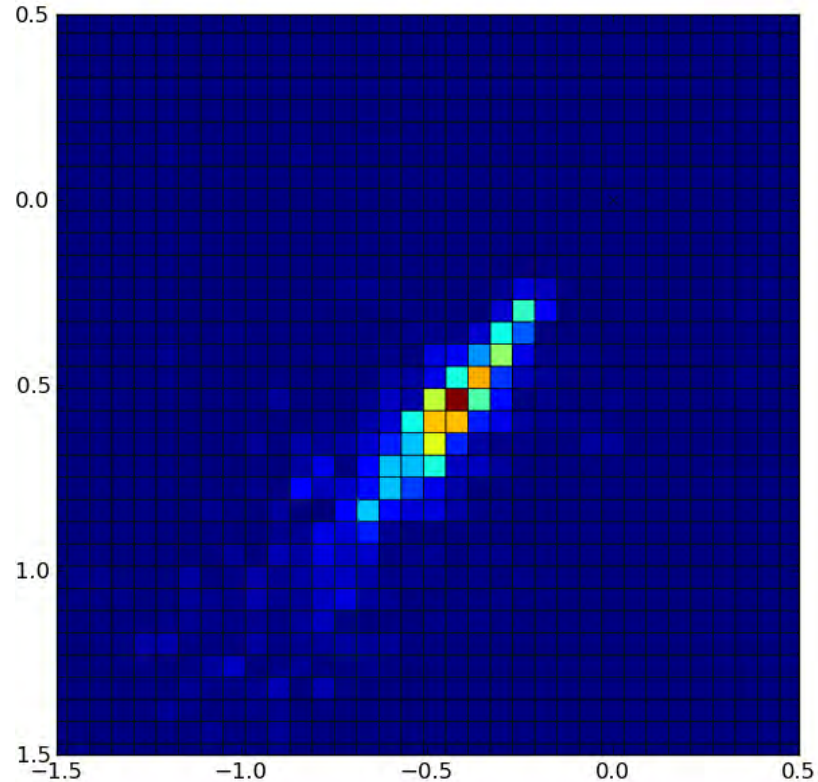
- Integrate diffuse flux over most of sky (exclude Galactic latitudes more than 10° from plane except keep 20° x 20° square centered on Galactic center), one year of data
- Search for lines in 30 to 200 GeV mass range
- Line width due to Fermi energy resolution
- Scan line energy and set flux upper limit at each energy

Simulated shower images for two-mirror vs. one-mirror telescope design

Example 1 TeV gamma-ray shower as seen by one-mirror or two-mirror telescope



DC telescope (~2k 0.16° pixels)



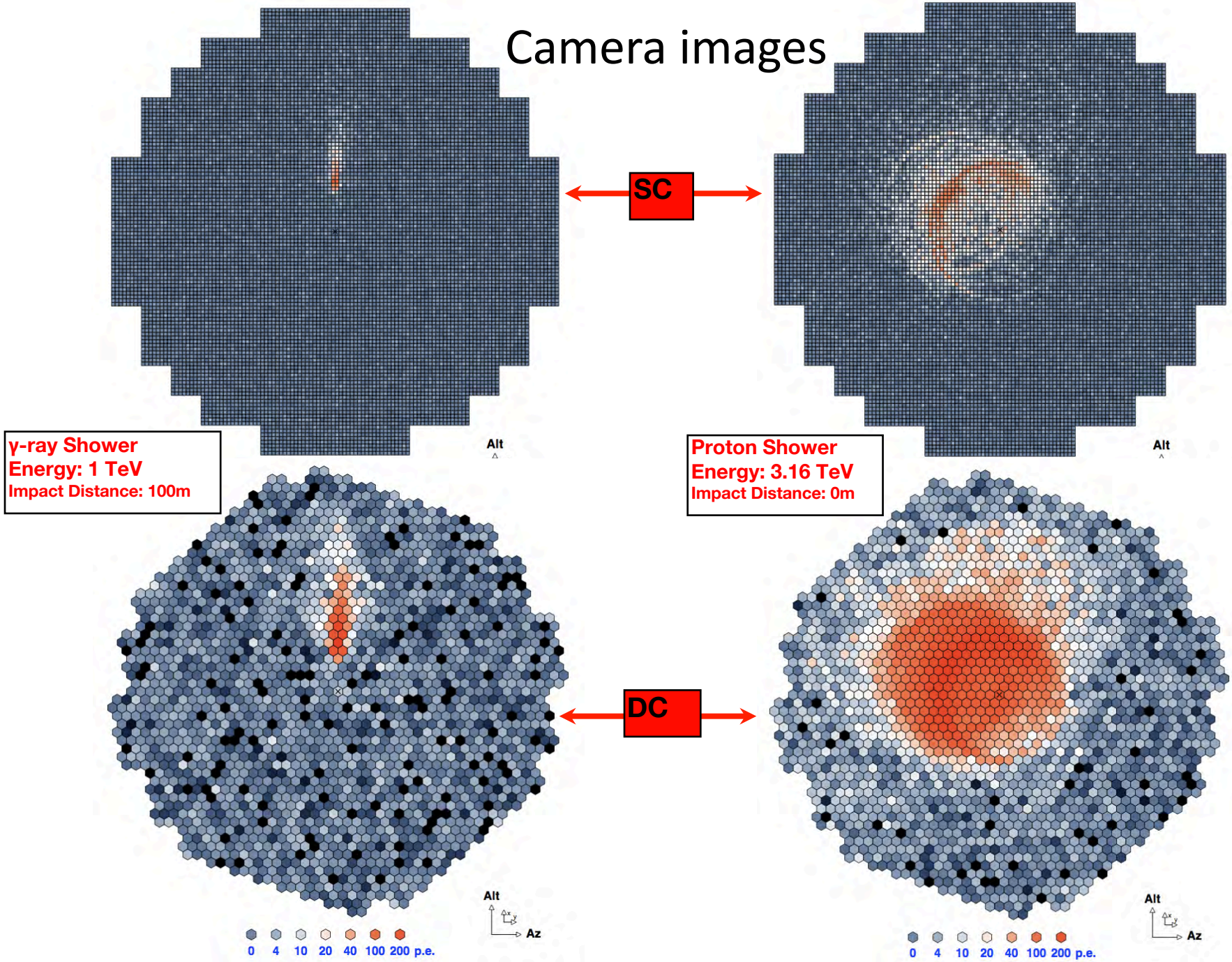
SC telescope (~10k 0.06° pixels)

Both images zoomed in (2° across, compared to 8° field of view)

PASAG and Astro 2010 strongly endorsed CTA

- PASAG
  - "Given the great excitement in the field and the success of the technique, a more ambitious and **likely very highly productive** concept for the future is an array of many (~50) atmospheric Cherenkov telescopes distributed over a square km."
- Astro 2010
  - **Ranked among top 4 priorities for large ground-based projects**
  - "The last decade has seen the coming of age of very high energy (TeV) astronomy… Further progress is now dependent on building a larger facility exploiting new detector technology and a larger field of view so that the known sources can be studied in more detail and the number of sources can be increased by an order of magnitude."
  - **"The promise of this field is so high that continued involvement is strongly recommended**."
  - "Increasing the sensitivity of atmospheric Cherenkov telescopes by another order of magnitude is our top priority for exploring the nature of dark matter." (Panel on Particle Astrophysics and Gravitation)

Camera images

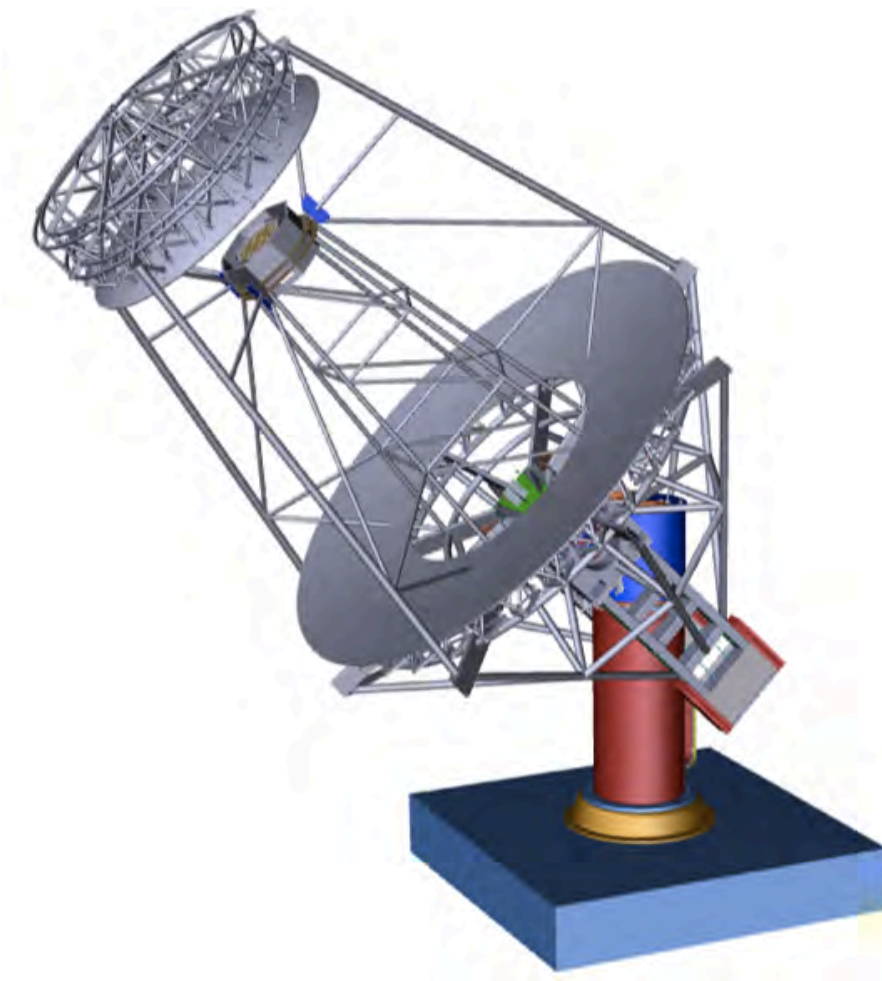


9 candidate sites

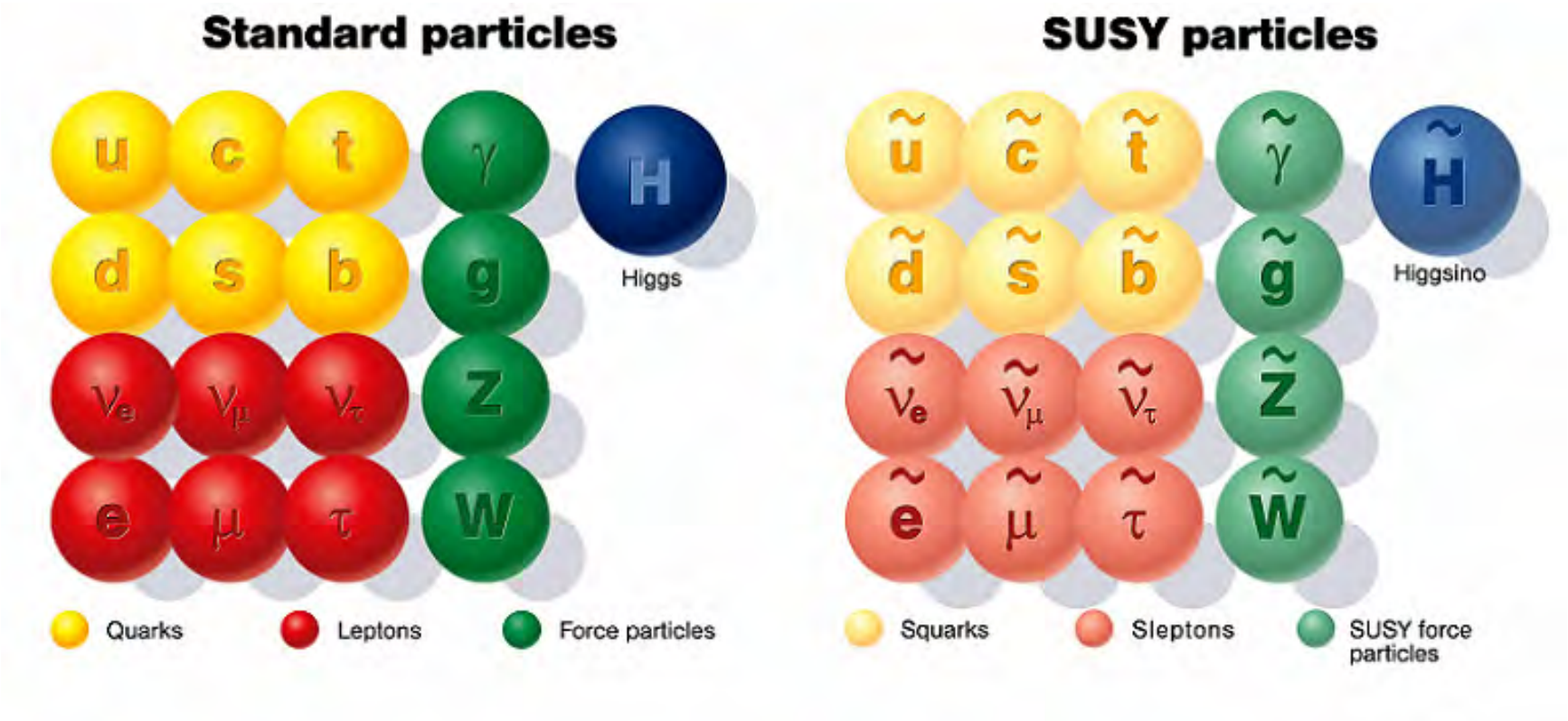
- South:
  - Aar, Namibia: private farmland 1600 masl
  - Khomas Highland, Namibia
  - Chile
  - El Leoncito, Argentina
  - San Antonio de los Cobres, Argentina
- North:
  - Metero Crater, Arizona, United States
  - Yavapai Ranch, Arizona, United State
  - San Pedro Martir, Mexico
  - Teide, Tenerife, Canary Islands

Two-Mirror Atmospheric Cherenkov Telescope: The Schwarzschild-Couder Telescope (SCT)

- Innovative U.S. design key to boosting CTA performance
- Corrects aberrations providing higher resolution, wider field
- Small plate scale enables SiPM camera
- Deep analog memory waveform samplers to minimize dead-time and allow flexible triggering
- High level of integration into ASICs allows dramatic cost savings (<$80 per channel) and high reliability (11,328 channels)
- Overall cost comparable to baseline single-mirror medium-sized telescope
- Adopted now by European groups also for small-sized telescopes

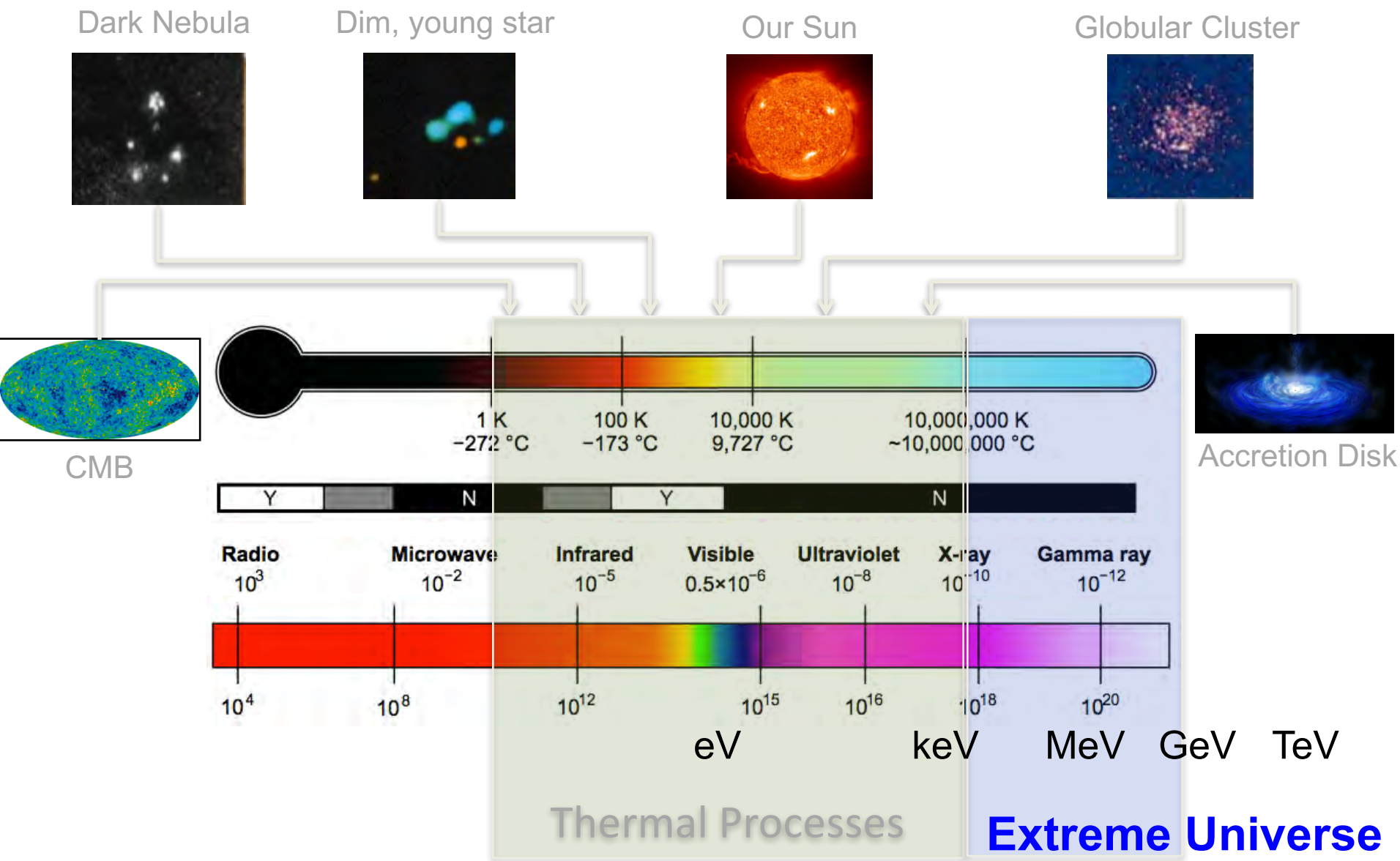


A fifth mechanism to make γ rays

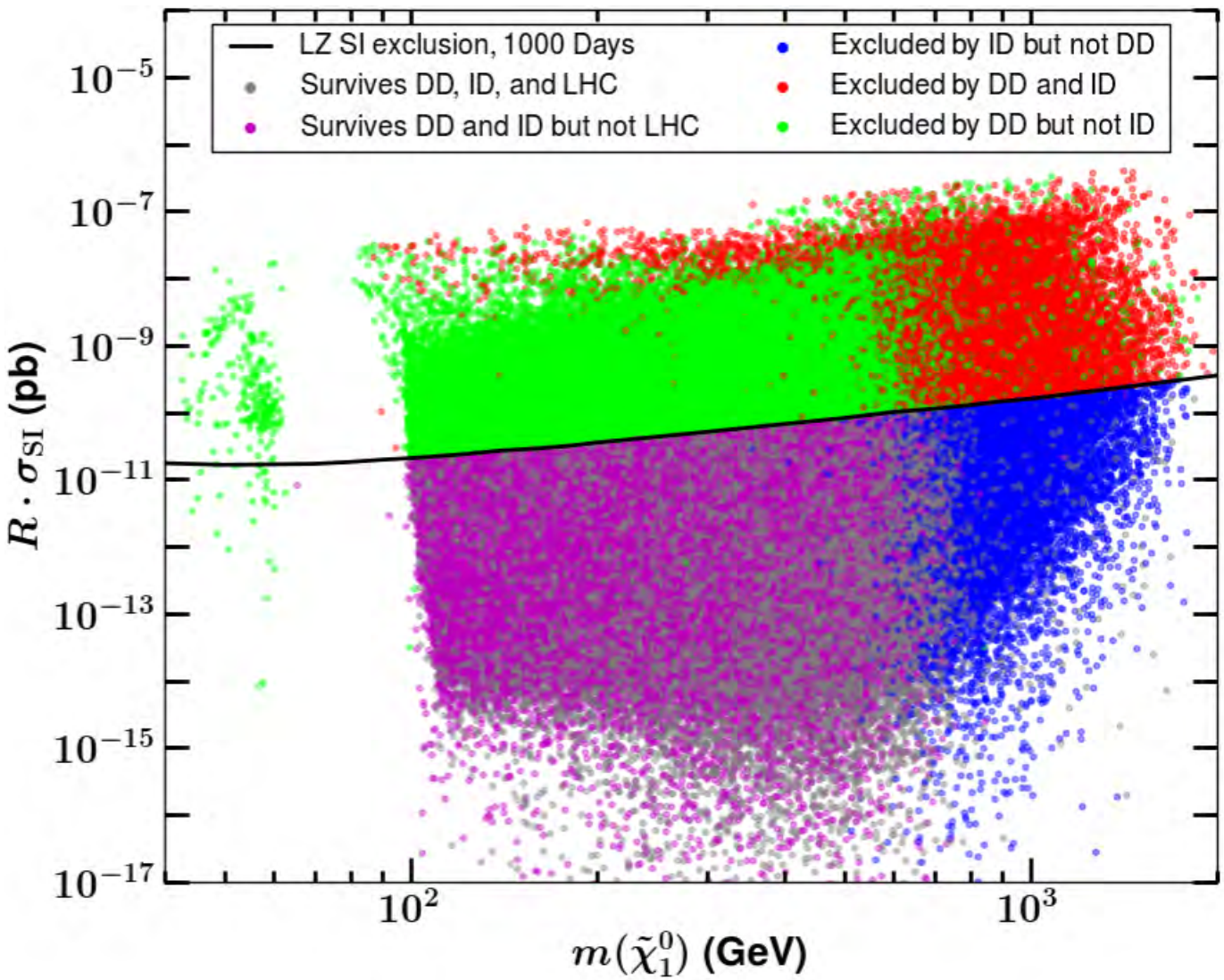


Exotic particle (e.g. dark matter) rest mass

Gamma rays probe the extreme, non-thermal, Universe



Combining indirect, direct, and accelerator WIMP searches



Cahill-Rowley et al. PRD 91, 055011 (2015)

Moon spectrometer technique: past, present, future

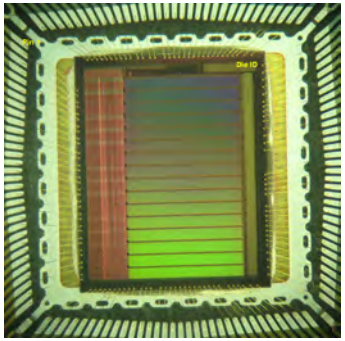
- Initial work by ARTEMIS
- MAGIC and VERITAS have continued the technique
- Challenge with PMTs: large NSB near Moon
- ~35 hours per year observable

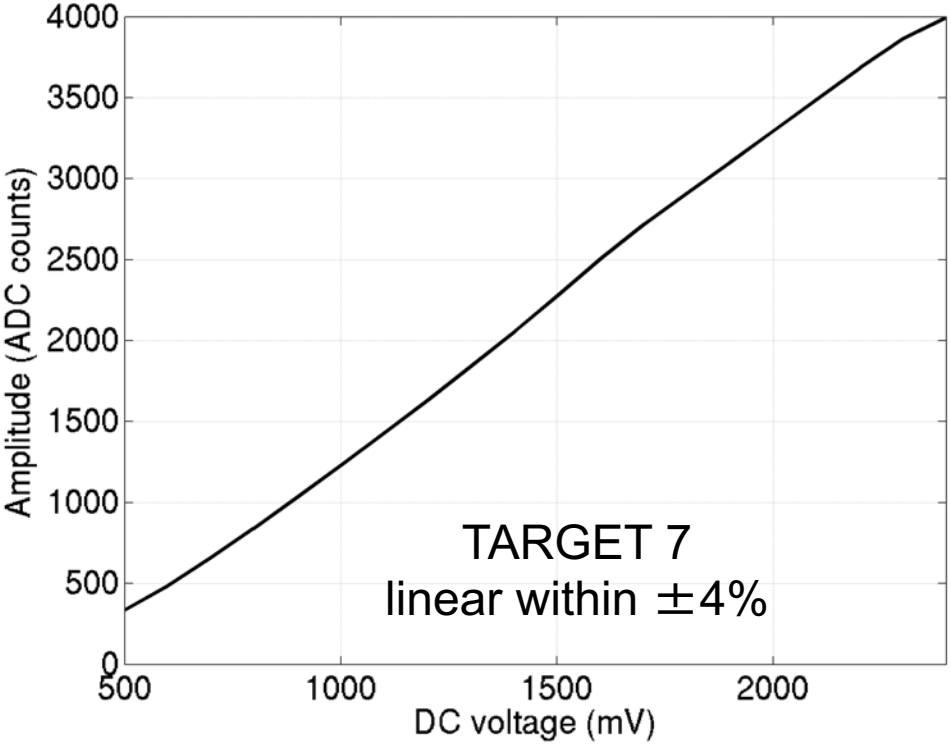
- CTA has sensitivity necessary to measure $e^{\pm}$ shadows
- Larger effective area
- Better gamma-hadron separation
- Larger field of view
- SiPM-based CTA cameras expected to observe well in moonlight
- Capabilities of PMT-based CTA cameras require further study

Justin VanderBrucke: Positron Fraction with CTA

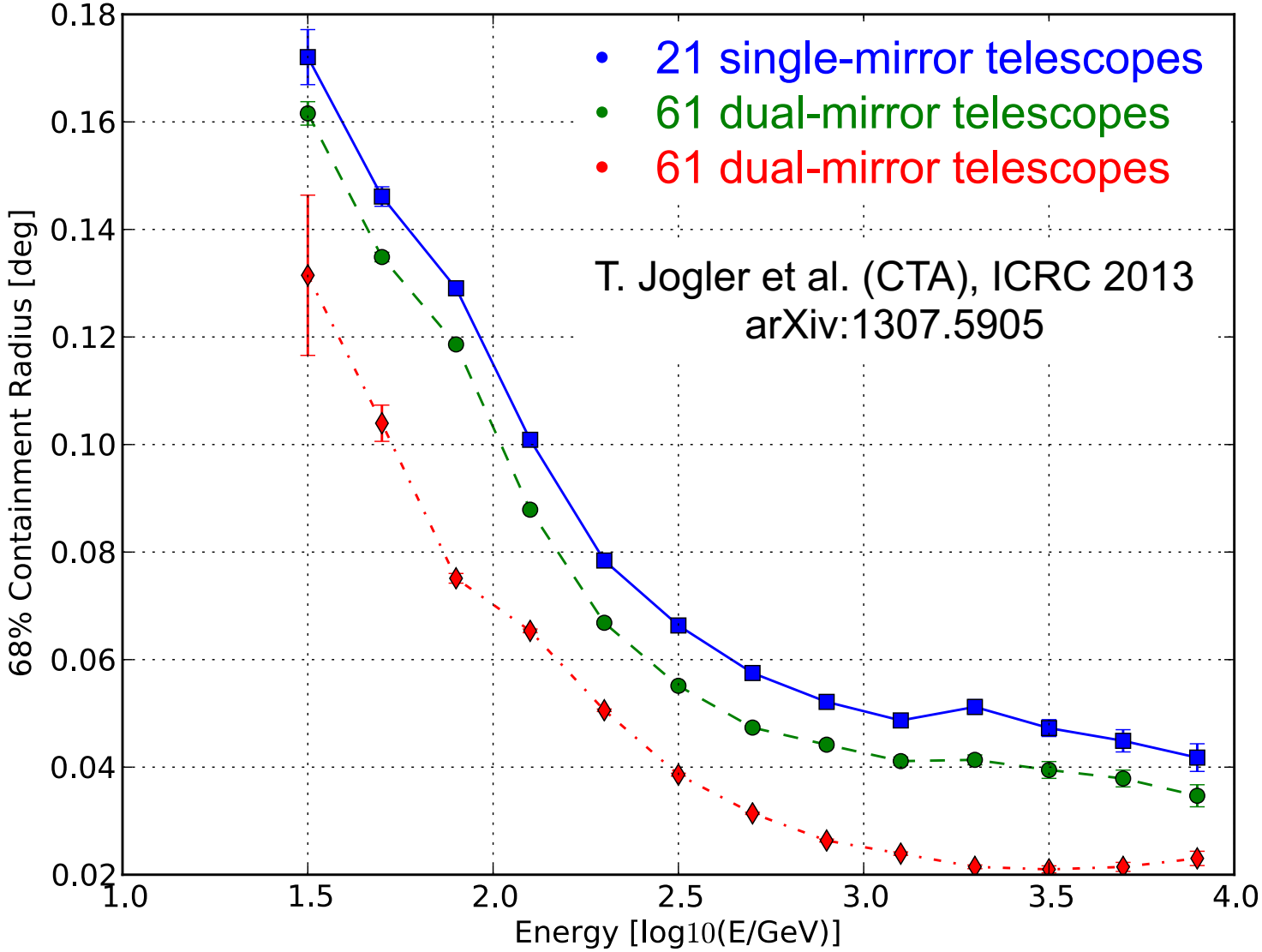
TARGET chip for triggering and waveform digitization

- Application-specific integrated circuit featuring switched capacitor array analog sampling followed by self-triggered digitization
- Designed by Gary Varner (U Hawaii)
- 1.0 or 0.5 GSa/sec analog sampling per channel
- ~380 MHz analog bandwidth
- 16 channels per chip
- 16,384 cells of analog memory per channel
- Self triggering with analog sum trigger (sum of 4 channels)
- LVDS trigger output
- Currently characterizing version 7 (to be used for prototype SCT)
- ~10 bits effective (1.9 V range, 2 mV noise)

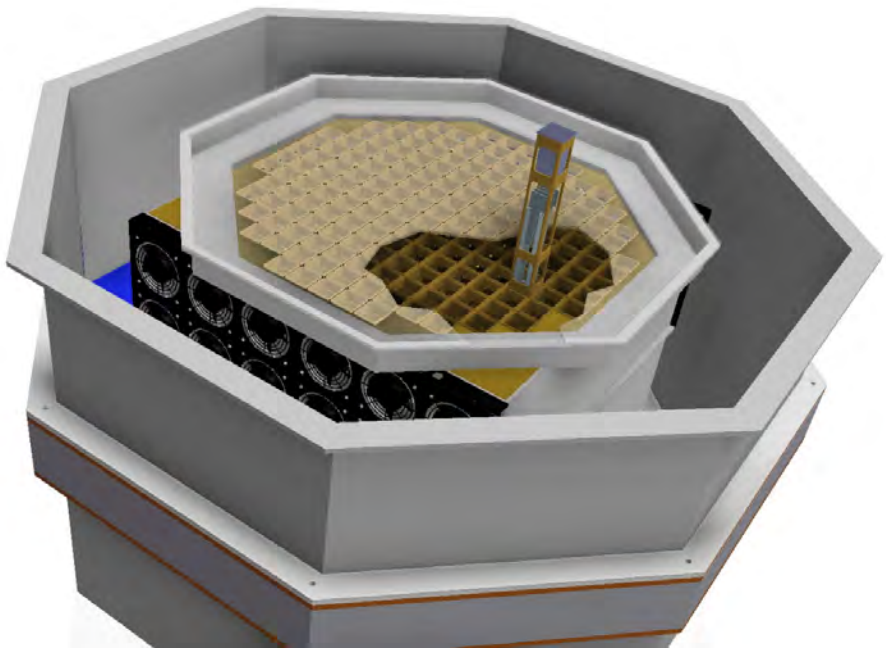




Gamma-ray angular resolution vs. energy for single-mirror vs. double-mirror telescope arrays



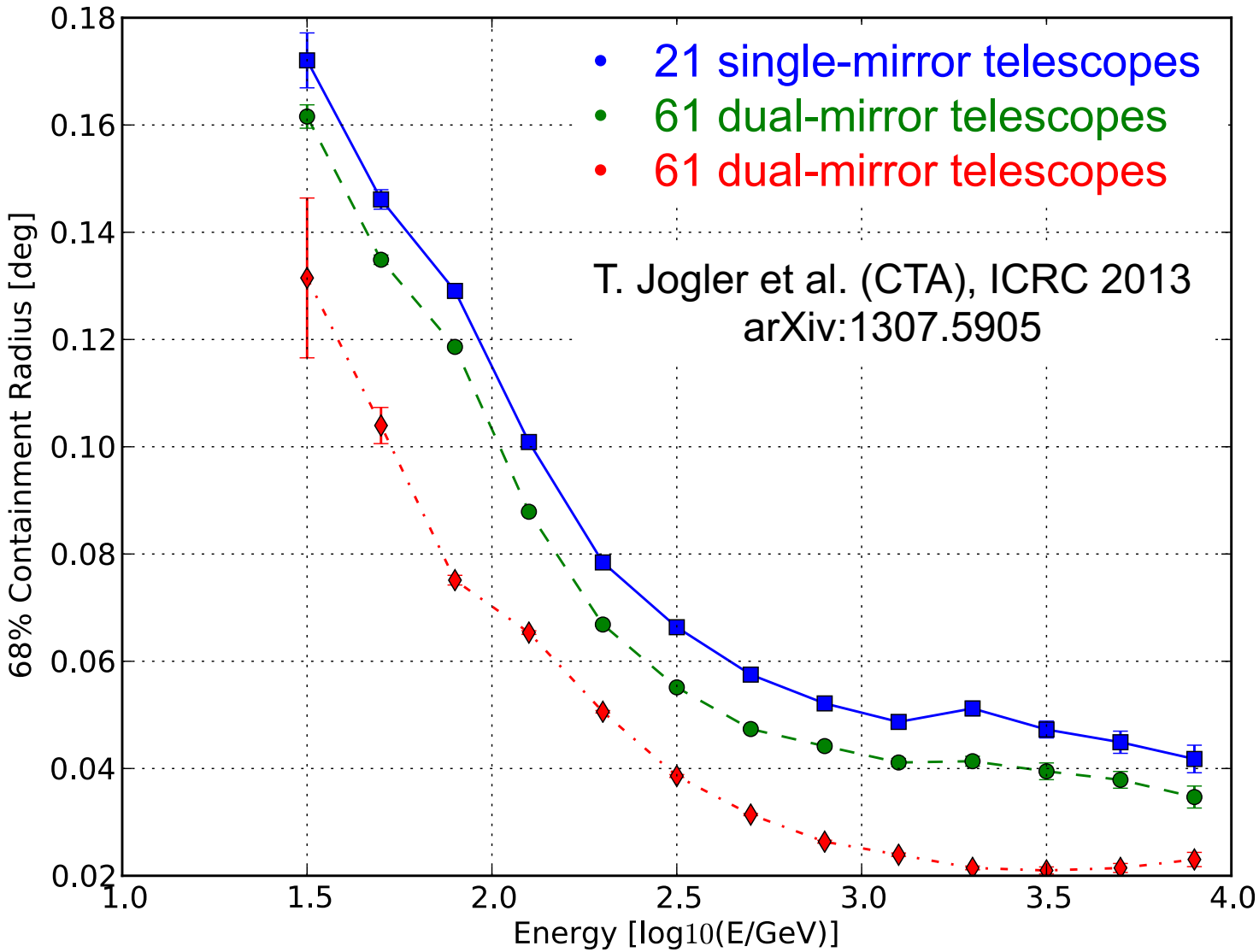
Camera design for Schwarzschild-Couder telescopes



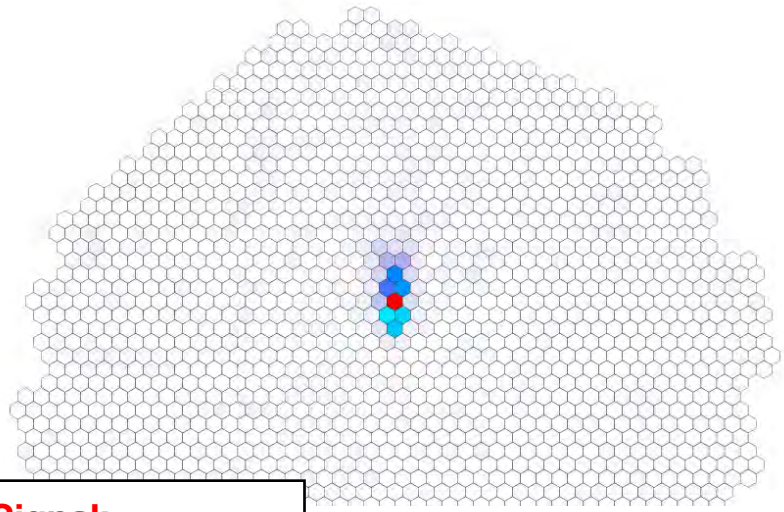
8° field of view, 81 cm diameter

- Excellent optical resolution, small plate scale of dual-mirror telescope well matched to fine pixelation supported by silicon photomultipliers and TARGET readout electronics
- 11,328 6x6 mm^2 pixels (temperature-stabilized silicon photomultipliers)
- Pixel size 0.067° (high- resolution imaging)
- Readout directly behind focal plane
- 1 GSa/s, 10 bits effective (TARGET 7)
- 3 kW power budget
- Shares many common components with the Compact High Energy Camera for CTA Small Size Telescopes

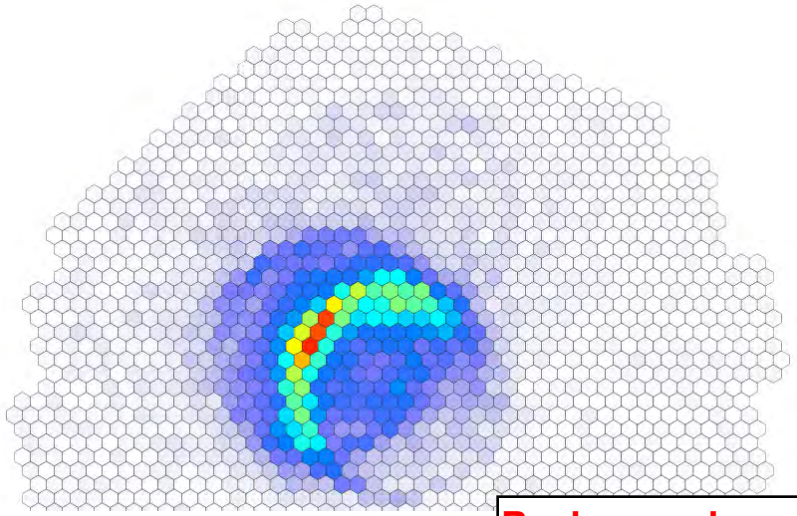
Gamma-ray angular resolution vs. energy for single-mirror vs. double-mirror telescope arrays



Telescope images with single-mirror vs. dual-mirror design

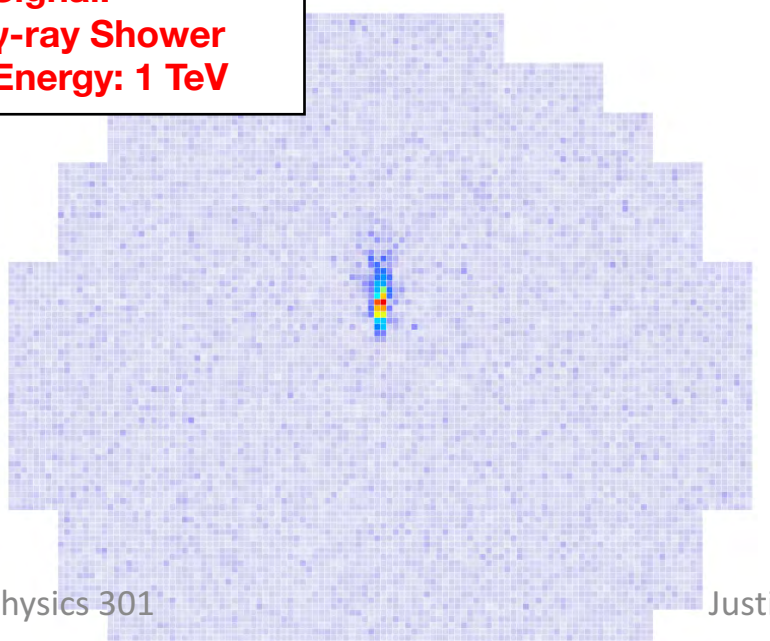


Single-Mirror
Telescope
Images
8° field of view
0.18° pixels
1,570 channels

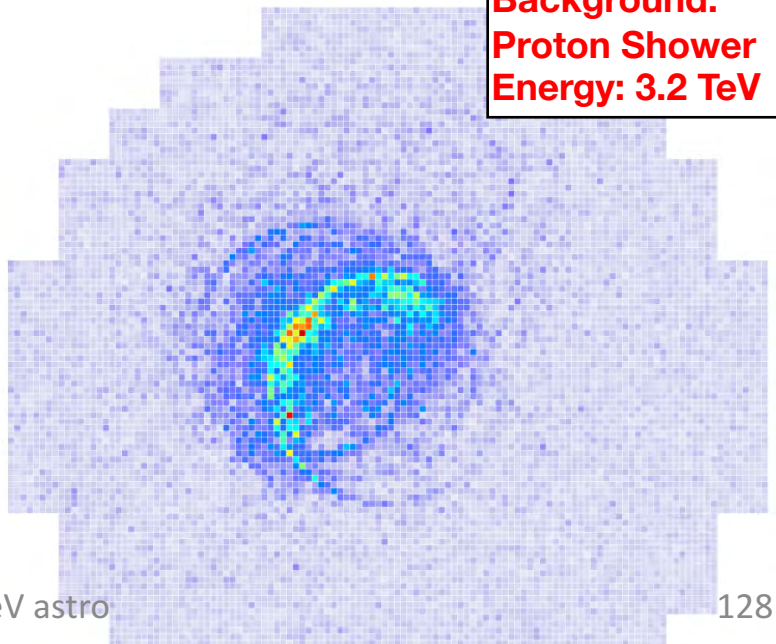


Signal:
γ-ray Shower
Energy: 1 TeV

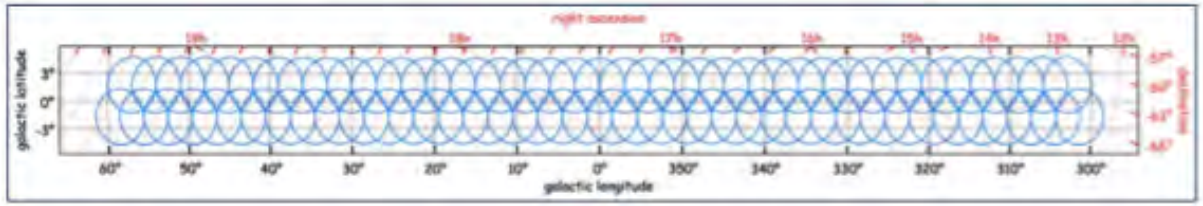
Background:
Proton Shower
Energy: 3.2 TeV



Two-Mirror
Telescope
Images
8° field of view
0.067° pixels
11,328 channels

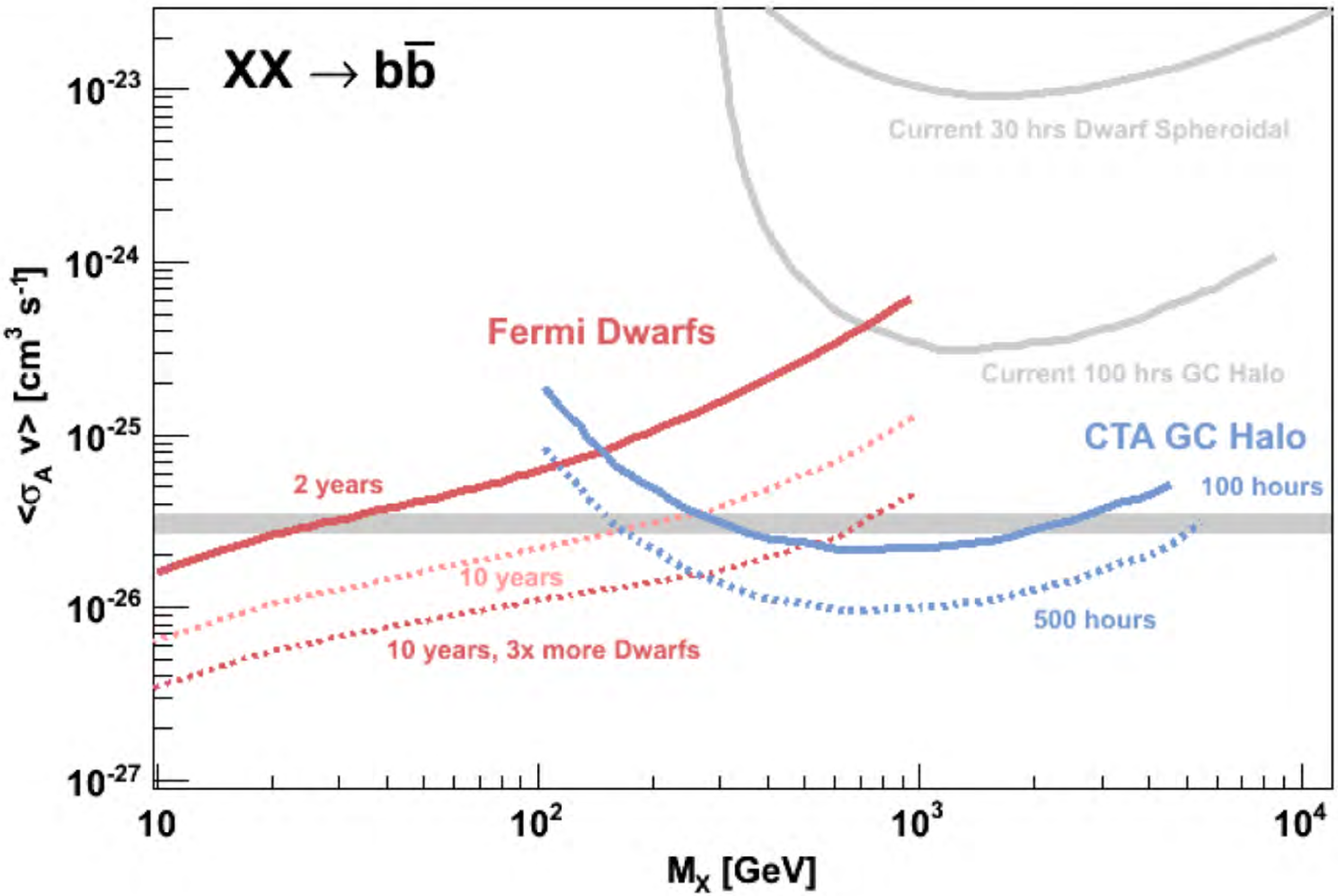


GPS IMPLEMENTATION

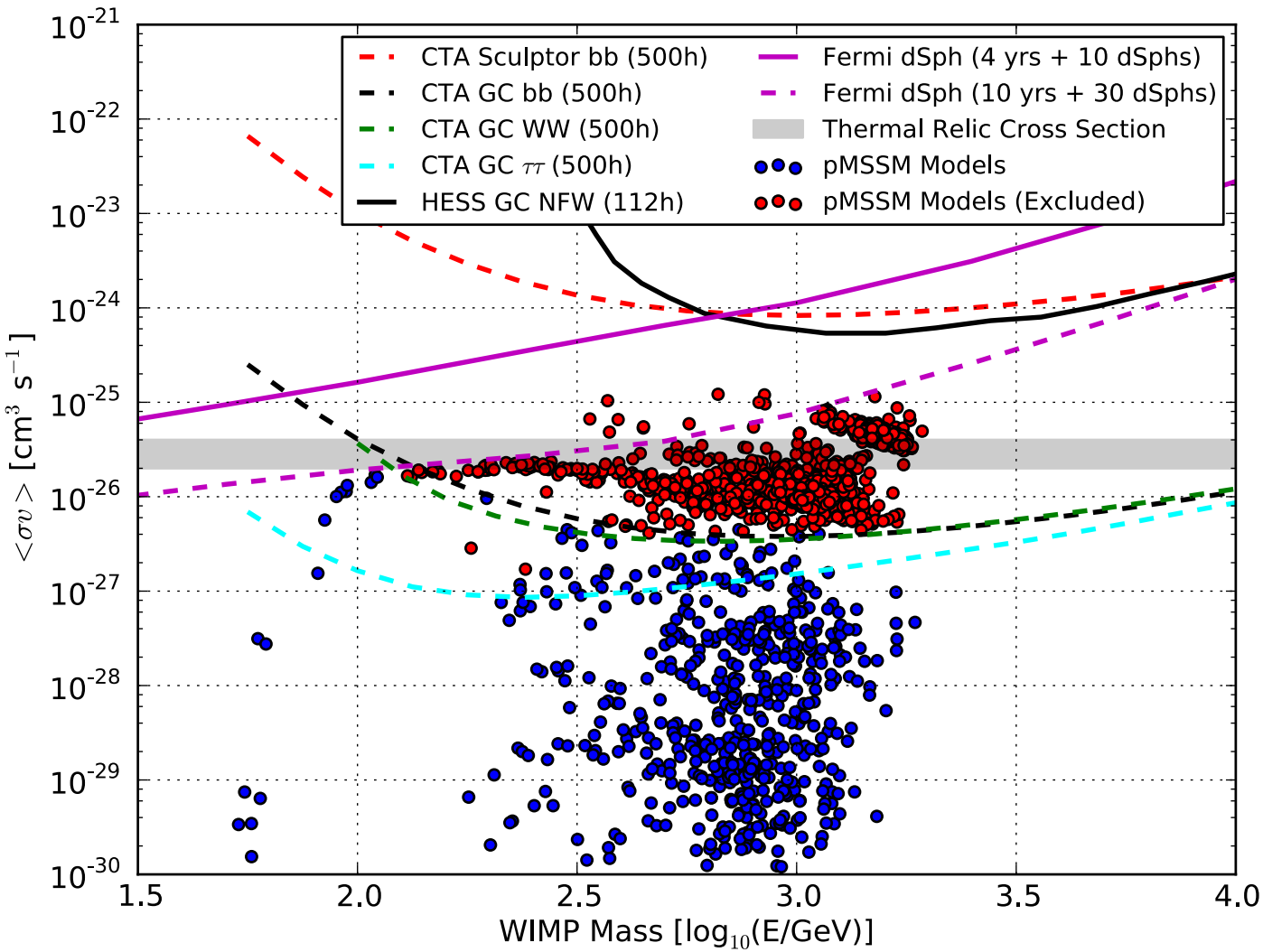


- Strategy
  - Both CTA-S and CTA-N
  - Dark time, full arrays, zenith < 45°
  - Double-row pointing scheme with 3° spacing; LST participation still under study
  - Sensitivity-graded with deepest exposure in the inner, Cygnus and Carina regions
  - Carried out over ten years, but with significant exposure in Years 1-2 to provide early bright-source list (Year 2) and first catalog (Year 3)
  - Transients detected are followed-up in context of Transients KSP
  - Total time: 1020 h (S), 600 h (N)

Fermi dwarfs & CTA Galactic center will cover entire mass range down to thermal cross section

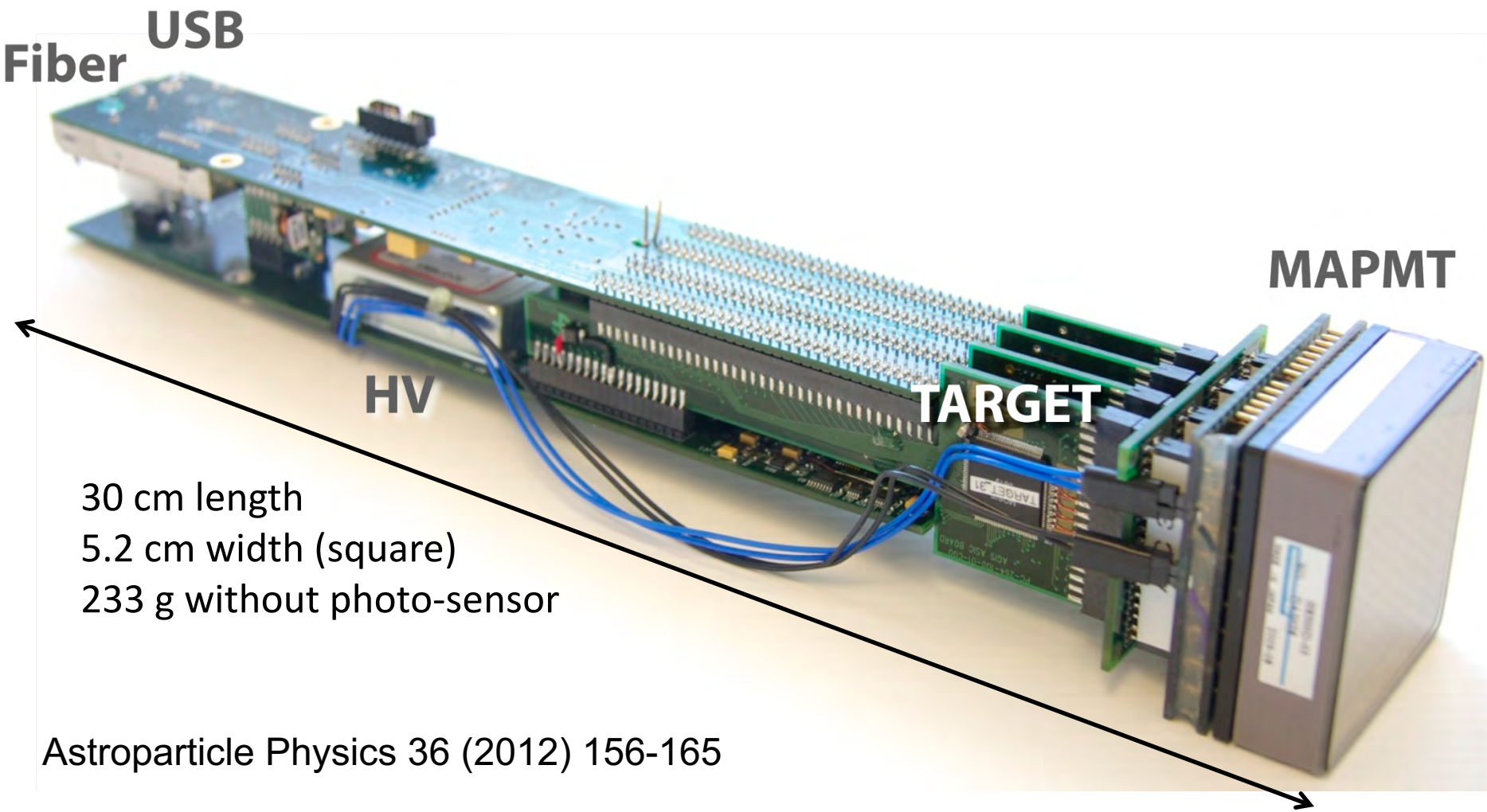


CTA will test a wide range of dark matter models with Galactic center halo and dwarf galaxy observations



M. Wood et al. Snowmass 1305.0302

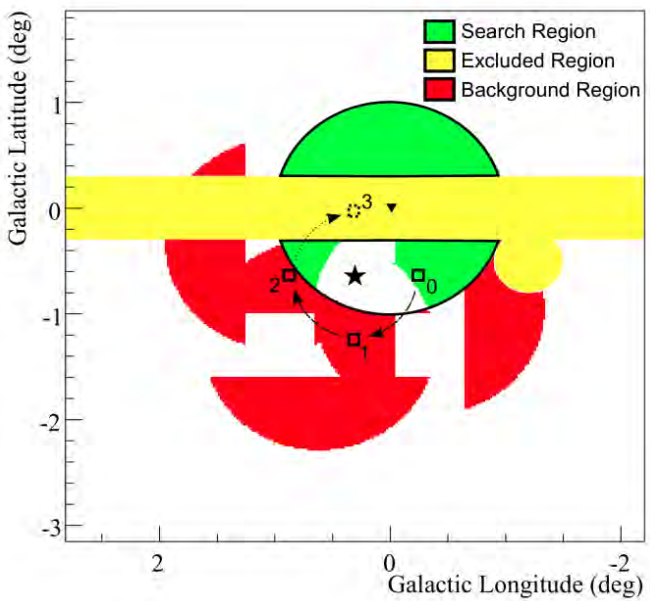
Camera module based on fast, modern, highly pixelated photo-detectors and readout electronics



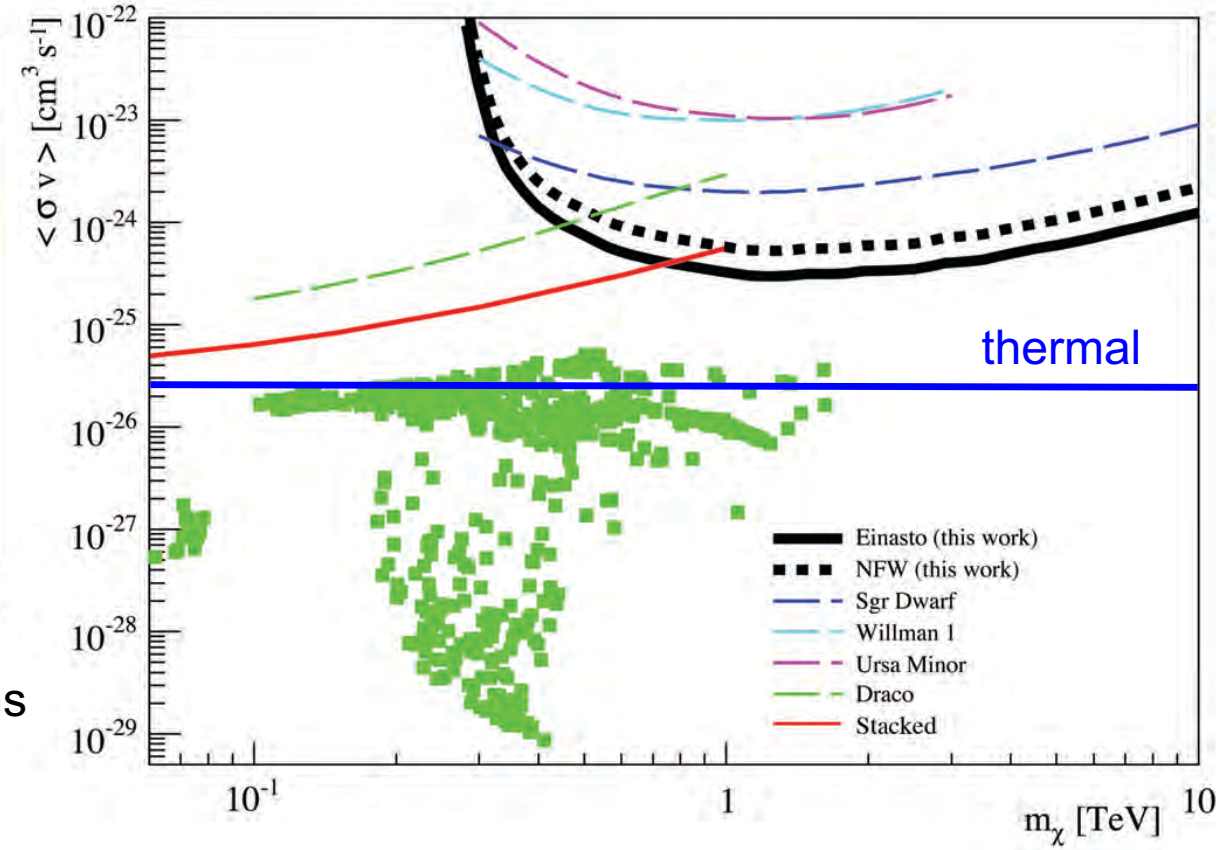
30 cm length
5.2 cm width (square)
233 g without photo-sensor

Astroparticle Physics 36 (2012) 156-165

H.E.S.S. constraints on WIMP annihilation from Galactic center halo observations



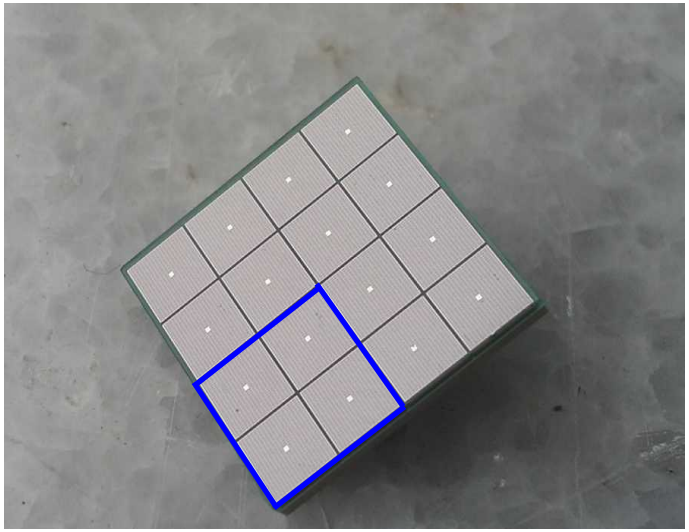
Signal and background regions



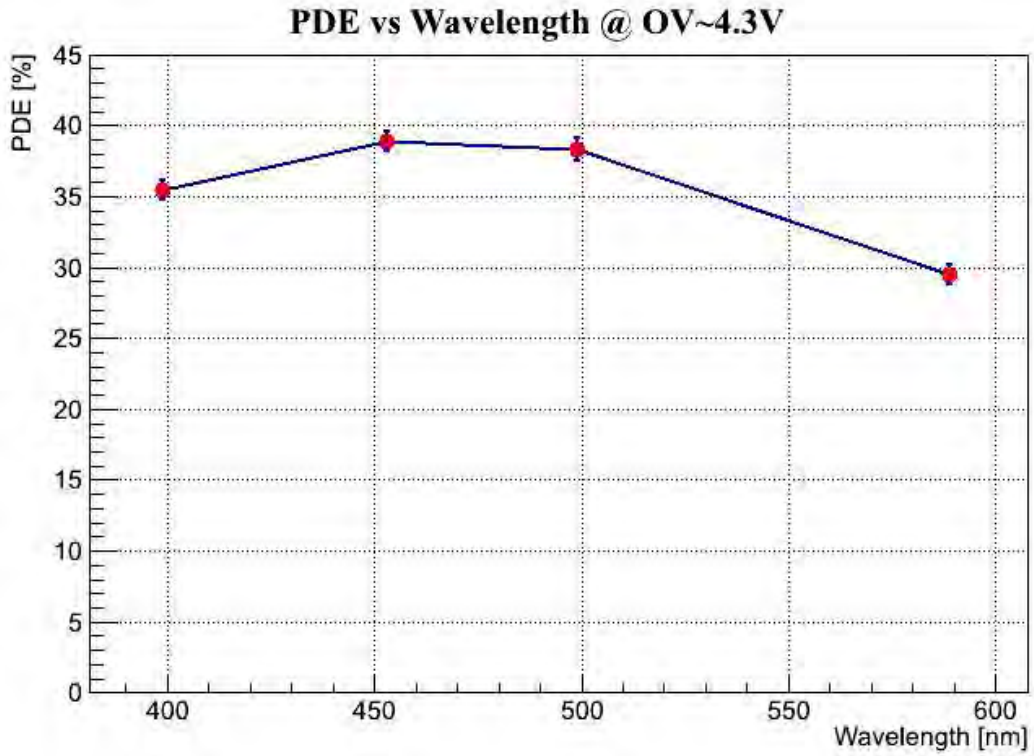
HESS, PRL 106, 161301 (2011)

Silicon photomultipliers

1 tile
(4 image pixels, 1 trigger pixel)



1 image pixel, 6 mm x 6 mm



- Operate at much lower voltage (~70 V) than PMTs
- Hamamatsu S12642-0404PA-50 selected for first sub-field of prototype SCT
- 3x3 mm^2 SiPMs in 4x4 matrix, 50 µm cell size
- Through-silicon via technology (low dead space: 21% with 54 mm module pitch)
- Peak photon detection efficiency (PDE) @ 450 nm is ~40% at center of one pixel
- 415 devices (400 for prototype telescope, plus 15 spares) received in past two months