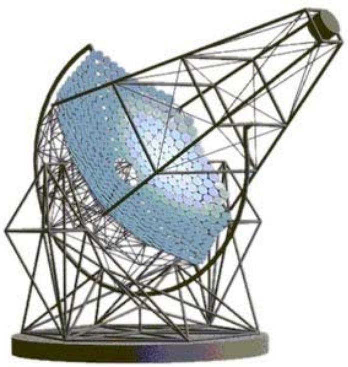
Cherenkov Telescope Array (CTA-US)

Stefan Funk, Hiro Tajima, Justin Vandenbroucke

KIPAC

September 14, 2010

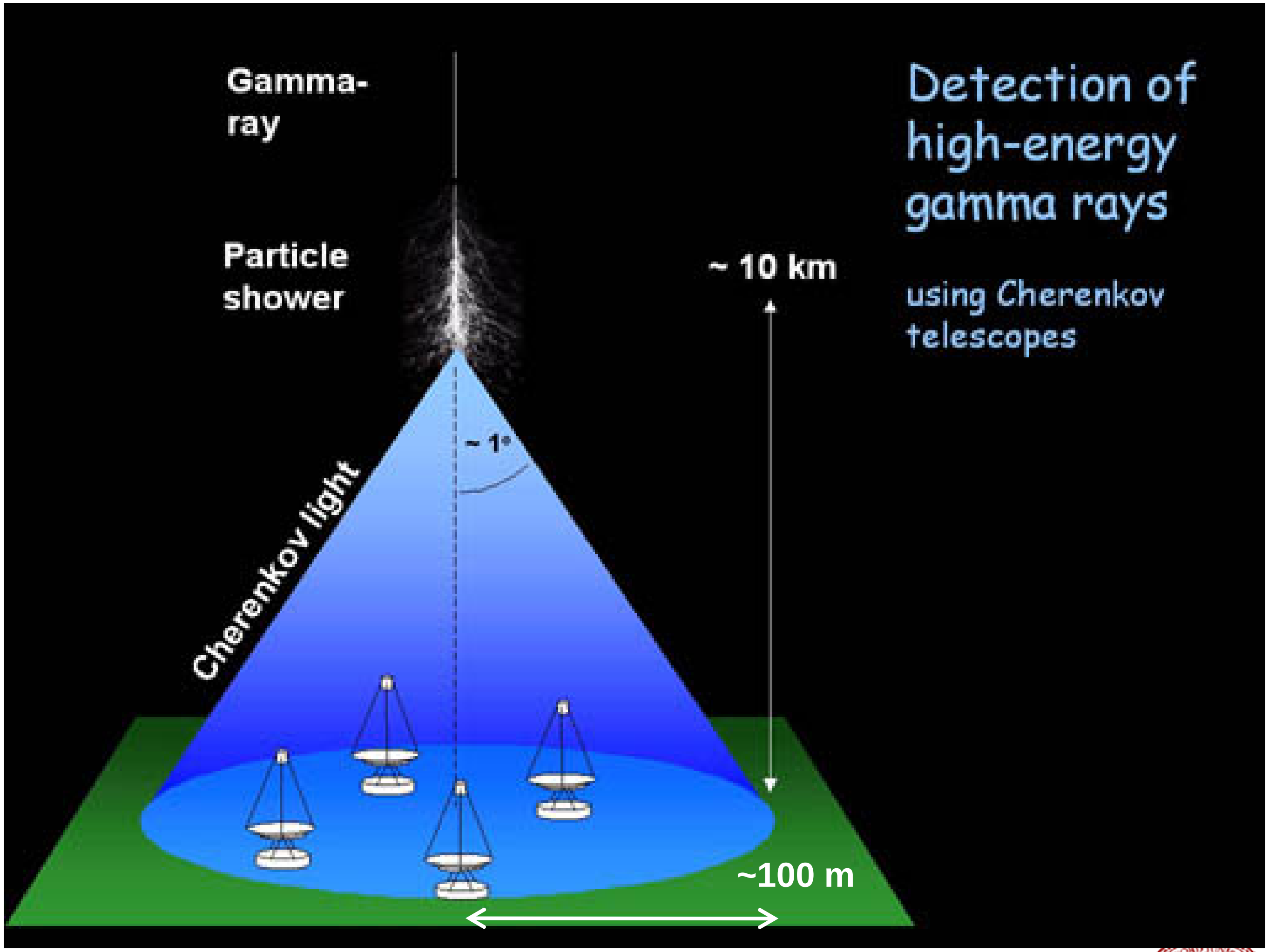


SLAC NATIONAL ACCELERATOR LABORATORY

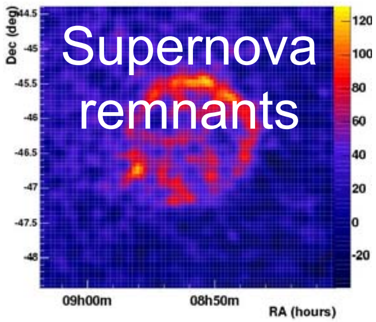
The imaging atmospheric Cherenkov telescope (IACT) technique for ground-based TeV astrophysics

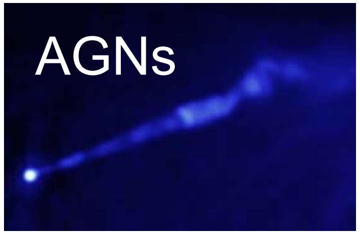
- Optical frequency (blue) light
- Very short (few ns) exposure to limit night sky background
- Cherenkov cone very narrow, ~1°:

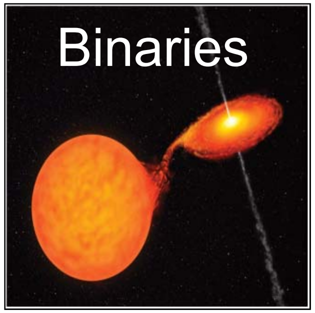
$$\theta = \cos^{-1}\frac{1}{n\beta}$$

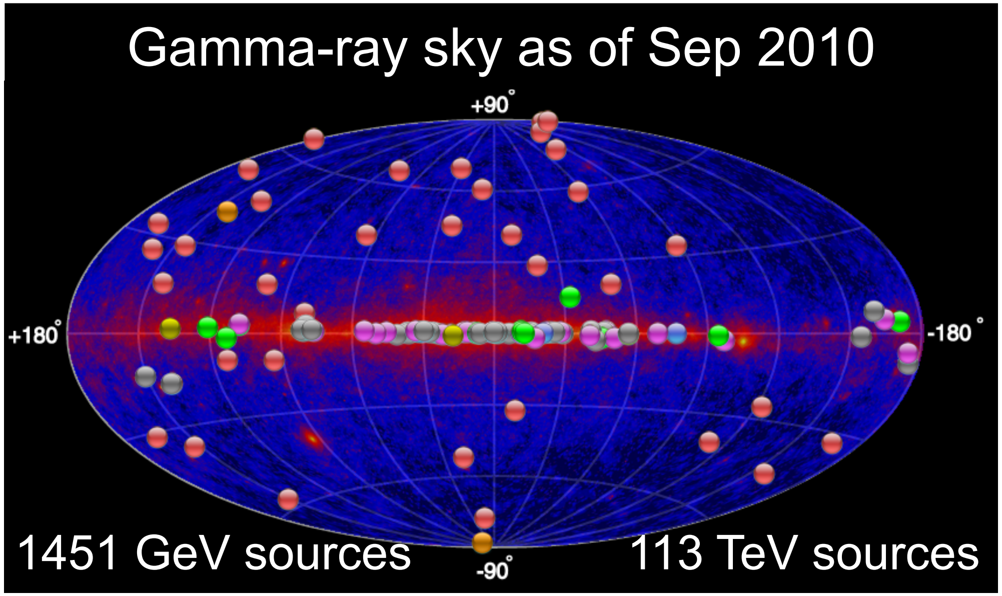


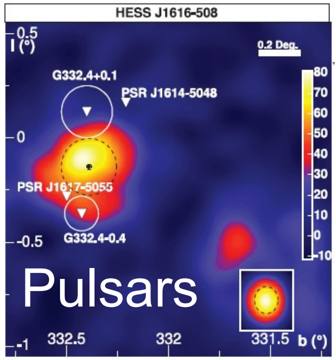
GeV and TeV gamma-ray physics and astrophysics

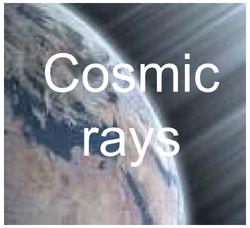




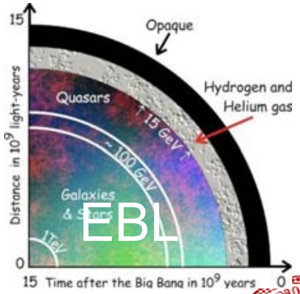








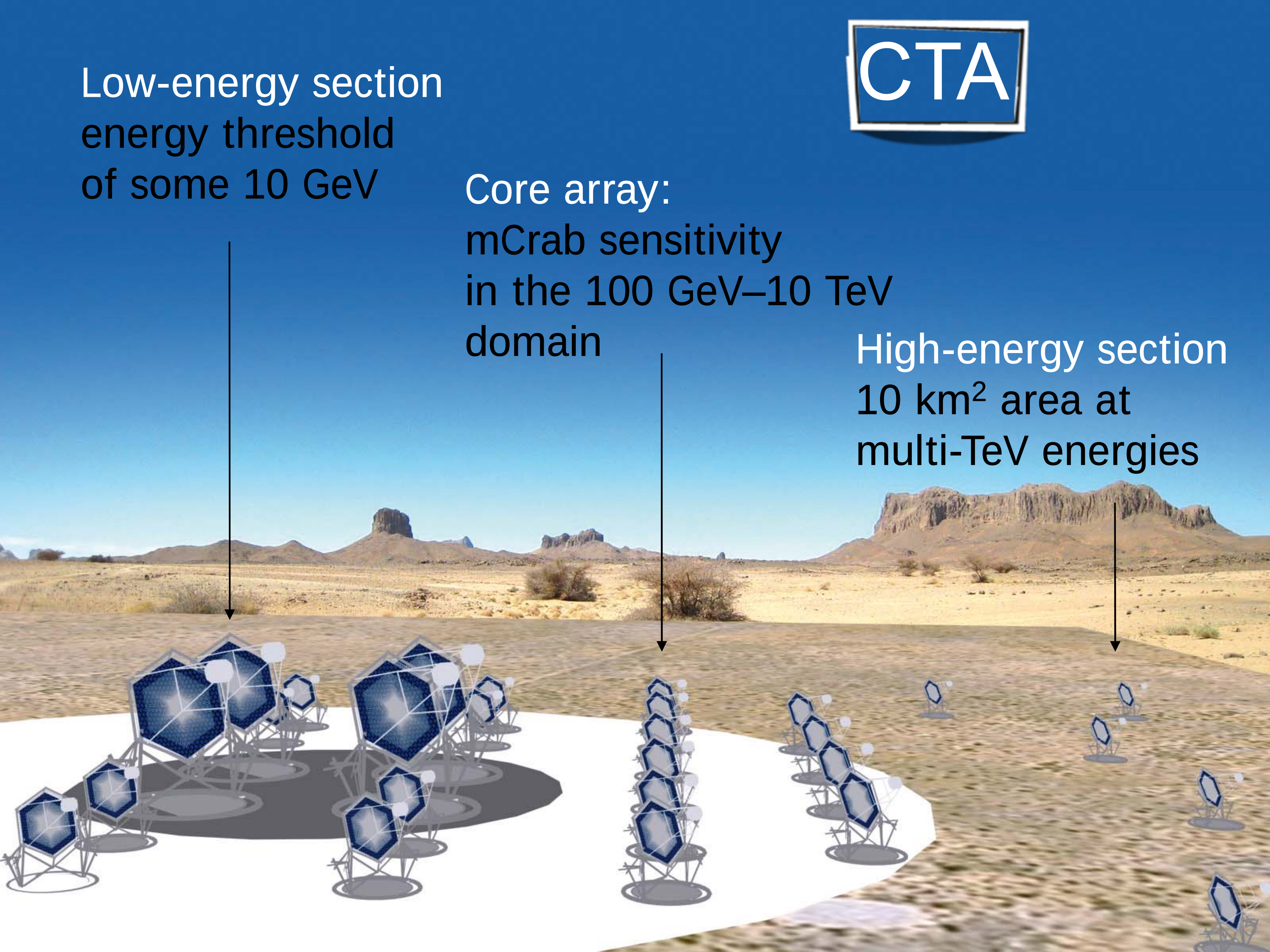
…?



NATIONAL ACCELERATOR LABORATORY

Cherenkov Telescope Array (CTA)

- American collaboration (AGIS) merged with European CTA in May 2010, now known as CTA-US
- Array of atmospheric Cherenkov telescopes
- Increased effective area, back ground rejection, angular resolution, field of view relative to current generation
- Hierarchy of 3 telescope sizes to span broad energy range >50 GeV (nominally 6, 12, 24 m diameter)
- ~1 km^2 effective area
- ~0.1° pixel resolution (2x better than VERITAS)
- 8° diameter field of view (4x current generation)
- Two possible telescope designs: Davies-Cotton and Schwarzschild-Couder
- Prototyping 2012-2013, construction starting 2014
- >700 scientists


CTA
Low-energy section
energy threshold
of some 10 GeV
Core array:
mCrab sensitivity
in the 100 GeV–10 TeV
domain
High-energy section
10 km^2 area at
multi-TeV energies

PASAG and Astro 2010 strongly endorsed CTA

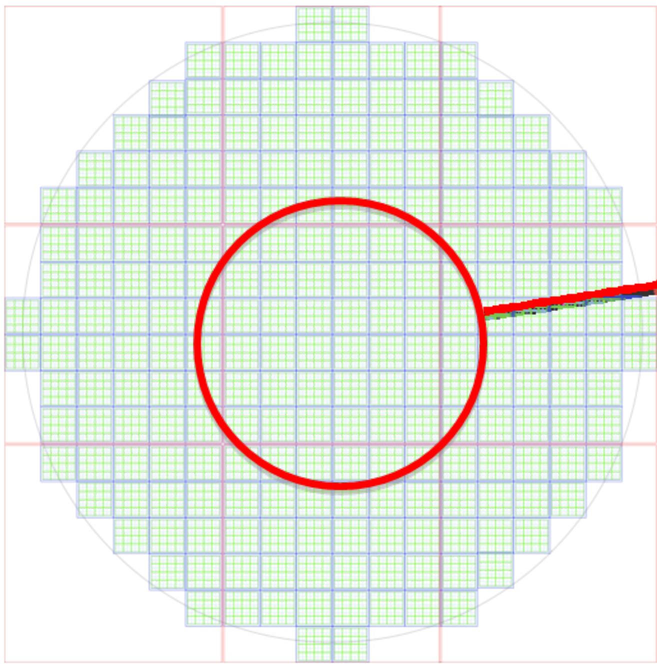
- PASAG
  - “Given the great excitement in the field and the success of the technique, a more ambitious and **likely very highly productive** concept for the future is an array of many (~50) atmospheric Cherenkov telescopes distributed over a square kilometer.”
- Astro 2010
  - **Ranked among top 4 priorities for large ground-based projects, after LSST and Giant Segmented Mirror Telescope**
  - “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**.”

Why now? Why SLAC?

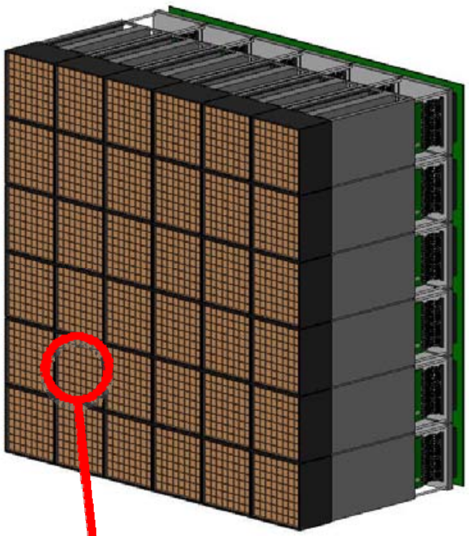
- **Why now?** Era of rapid discoveries with GeV and TeV gamma rays
  - Handful of TeV sources known prior to 2005 (when HESS started), now >100 and growing each month: tip of iceberg
  - Much progress to be made following recent discoveries
    - Increase number of sources in each class to understand whole populations
    - For individual sources, transition from *detection* to *understanding*: need enough statistics for spectral, temporal, morphological studies
  - Capitalize on Fermi's leap forward in GeV by following up in TeV
    - Existing TeV instruments do not have sensitivity or time to observe all Fermi sources (~half of which are still unidentified)
    - Simultaneous operation of Fermi and CTA for follow-up and temporal studies
- **Why SLAC?** Engineering, management, scientific expertise
  - Excellent electrical engineering: SLAC can lead electronics for CTA
  - With continuing success of Fermi Gamma-ray Space Telescope, SLAC/KIPAC is a world leader in gamma-ray astronomy
  - SLAC a potential leader of US component of CTA

Modular camera design developed by SLAC (FY10)

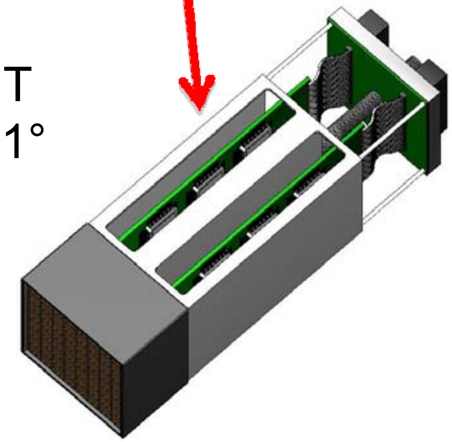
9 "subfields" in telescope focal plane
each with 36, 32, or 15 camera modules:



Example subfield
with 36 camera modules:



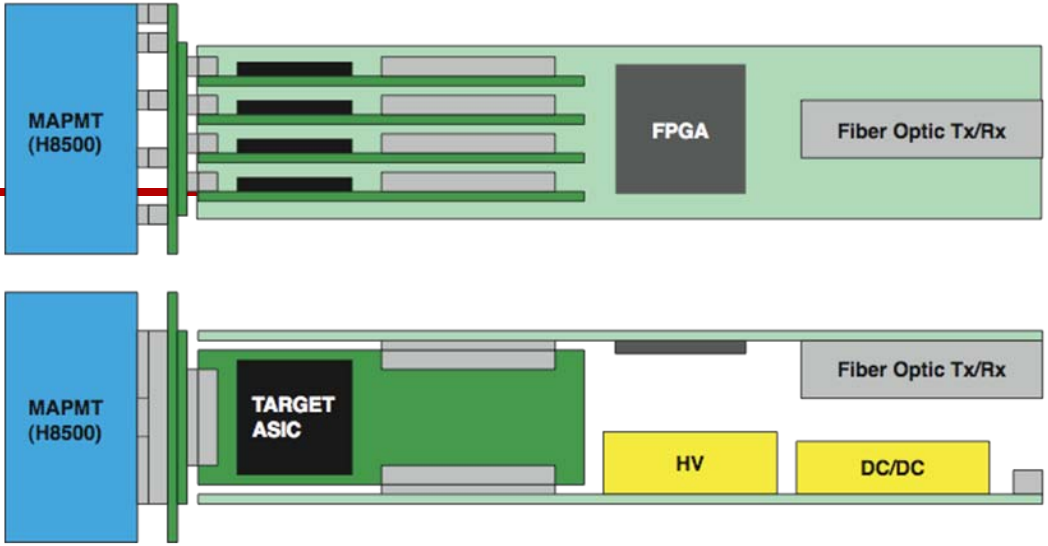
Camera module:
- 2" multi-anode PMT
- readout electronics
- 64 pixels per MAPMT
- each pixel is 0.05-0.1°



36 telescopes x 224 modules x 64 pixels
= ~500k channels total for CTA

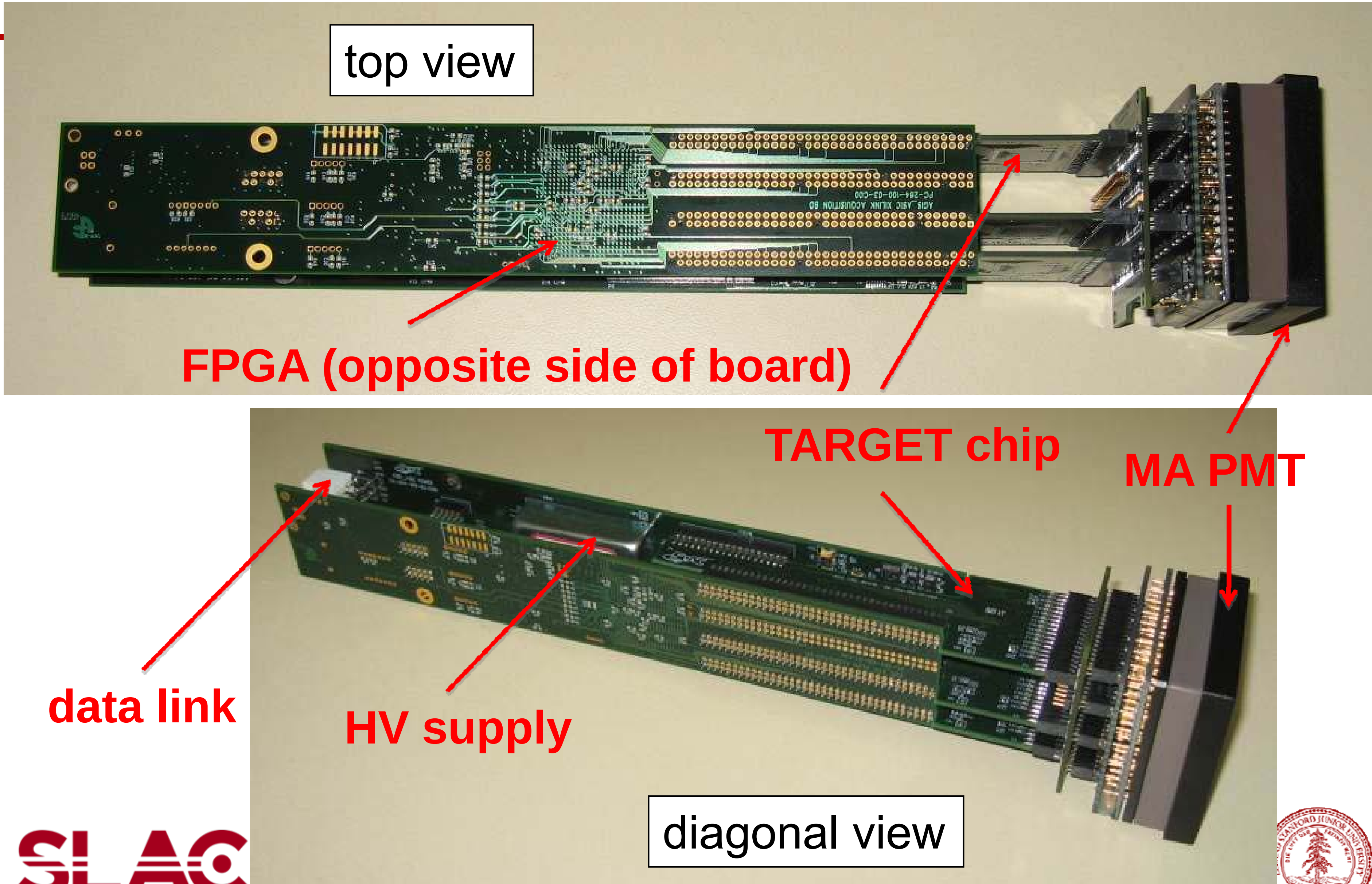
SLAC NATIONAL ACCELERATOR LABORATORY

Electronics module(SLAC design, FY10)

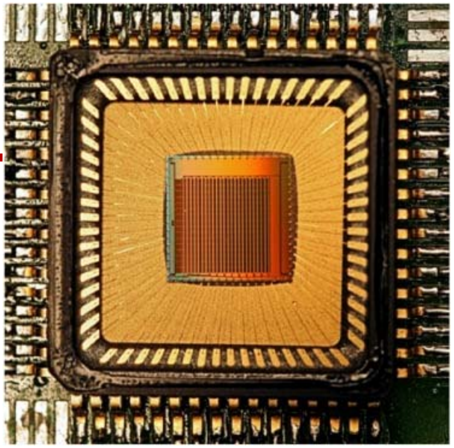


- Scaling from ~3k (current generation) to ~500k total channels requires
  - **Robust** design: modular
  - **Low cost** per channel
- 4 TARGET digitizer chips per MAPMT
- 16 channels per TARGET chip
- 1 GSample/s sampling of each channel
- Goal: $10-20/channel (electronics + MAPMT)
  - Current generation is ~$1k/channel
- Schwarzschild-Couder telescope allows small pixels and low cost per pixel

Camera module prototyping at KIPAC (FY10)

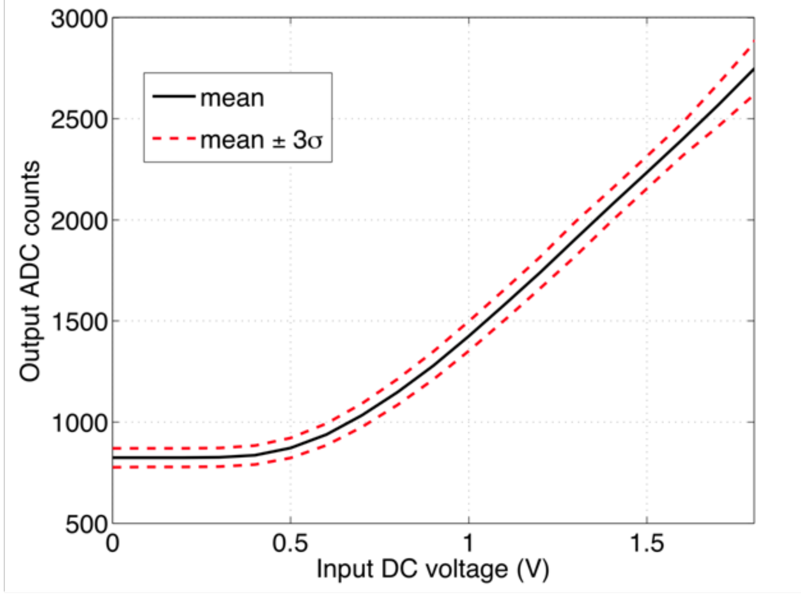


TARGET v1 digitizer chip (FY10)



- TARGET v1 produced, tested, characterized
- Low cost ($20 / channel)
- Large number of channels per chip (16), with deep buffer (4096 samples per channel = ~4 μs)
- 1 GSample/s demonstrated
- 7.1 mW/channel demonstrated
- Transfer function, noise, temperature dependence measured
- FY11: TARGET v2 being designed with experience from v1 in FY10

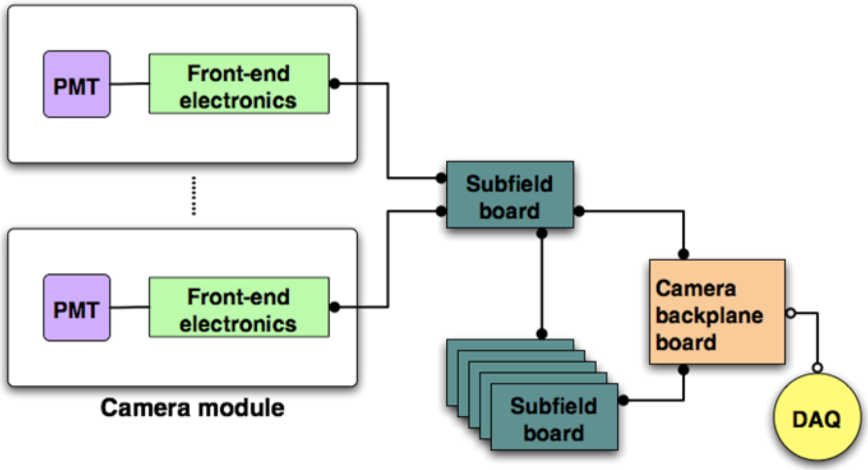
transfer function



FY11 plans: TARGET v2; integration with CTA; camera backplane

- Design, fabricate, test, characterize TARGET v2
  - Increase from 4k to 16k capacitors per channel (4 μs to 16 μs buffer) to allow sophisticated multi-telescope triggers and improve signal-to-background
  - Faster digitization for reduced dead time (from 300 to 30 μs to read out all 16 channels per chip)
  - More automated calibration capability
- Integrate SLAC electronics design with Small Size Telescope design

- Design camera backplane electronics (performs camera trigger and communicates with outside of telescope):



Issues and risks

- Level of US participation in CTA
  - Astro 2010 suggested US contribute $100M of $400M total
- Telescope design selection
  - Davies-Cotton more established, Schwarzschild-Couder more risky but could achieve better field of view and resolution and camera cost
- Electronics design selection
  - SLAC design with TARGET chip well received by CTA (esp. for Small Size Telescopes) but there are competing designs (e.g. Swiss DRS chip, optimized for other projects)
  - TARGET design especially good for Schwarzschild-Couder telescopes, multi-anode PMTs, small pixel size with large channel multiplicity (small cost per channel and compact physical size)

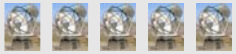
Extra slides

Timeline

Goal:
Build Prototype

Prototype

Test



...

Minimize cost
OSS, mirrors

Prototype R&D

Conceptual R&D

Done!

Develop management: procurement, reviews, site, WBS, …

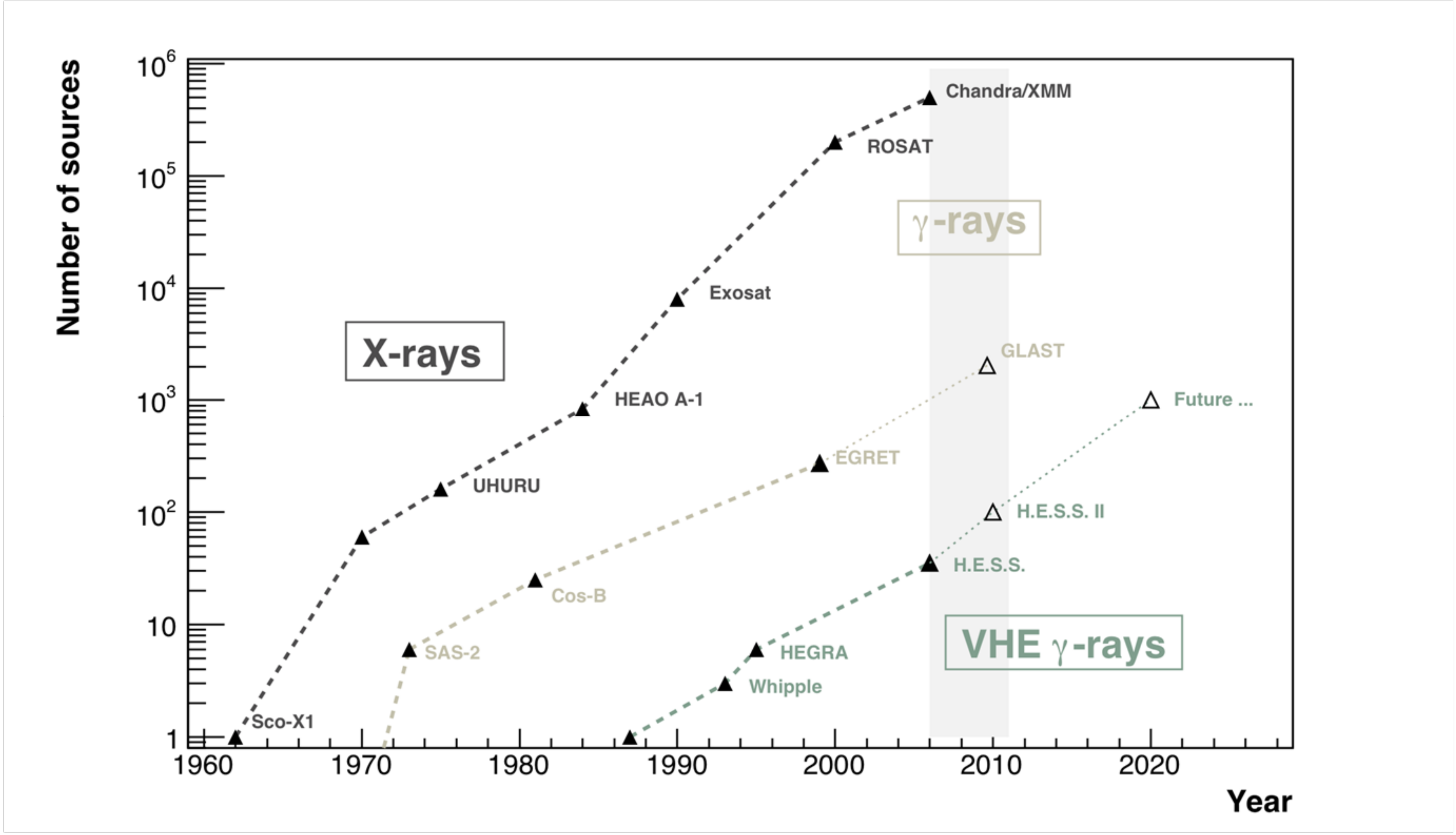
2009 2010 2011 2012 2013 2014 2015

SLAC
NATIONAL ACCELERATOR LABORATORY

Finances and Manpower

- Finances:
  - FY09, FY10: Laboratory Directed Research and development (LDRD) funding (~$300k / year)
  - FY11 LDRD funding approved August 23, 2010 ($360k)
- Manpower (each is fractional FTE)
  - Stefan Funk
  - Hiro Tajima
  - Seth Digel
  - Richard Dubois
  - Leonid Sapozhnikov
  - Justin Vandenbroucke
  - Akira Okumura
  - Keith Bechtol

Number of X-ray, GeV, and TeV sources over time ("Kifune plot")



Pair production telescopes	Atmospheric Cherenkov tels.	Particle detector arrays
	 MAGIC, HESS, VERITAS +	
0.1 - 100 GeV	30 GeV - 70 TeV	100 GeV - 100 TeV
Space borne: limited in area	Large effective area	Large effective area
Background free	Excellent background rejection	Very good background reject.
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

SLAC NATIONAL ACCELERATOR LABORATORY

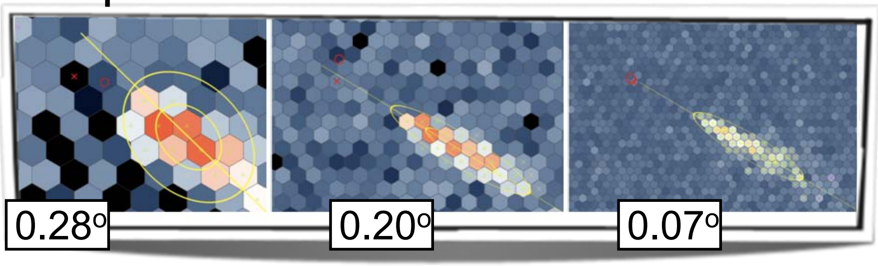
Current generation of imaging atmospheric Cherenkov telescopes

- **HESS:** telescopes (13 m diameter; 5th with 28 m diameter under construction) in Namibia (Southern Hemisphere)
- **MAGIC**: 2 telescopes (1 since 2004 and 2 since 2009, both 17 m diameter) on La Palma, Spain (Northern hemisphere)
- **VERITAS**: 4 telescopes (12 m diameter) in Arizona, USA (Northern hemisphere)
- **CANGAROO III**: 4 telescopes (10 m diameter) in Woomera, South Australia

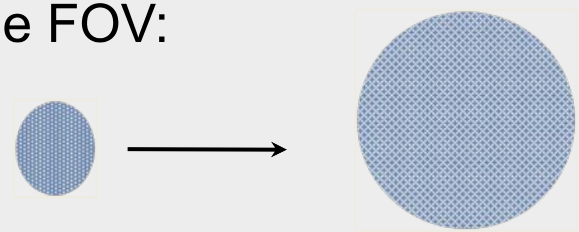
Optical design: two-mirror Schwarzschild-Couder telescopes

Vassiliev et al. 2007

Fine pixelation:

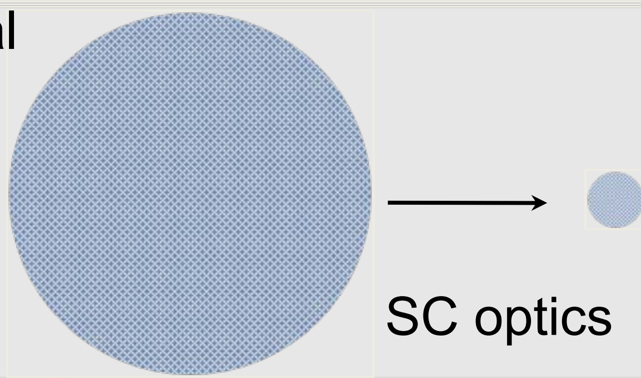


Large FOV:

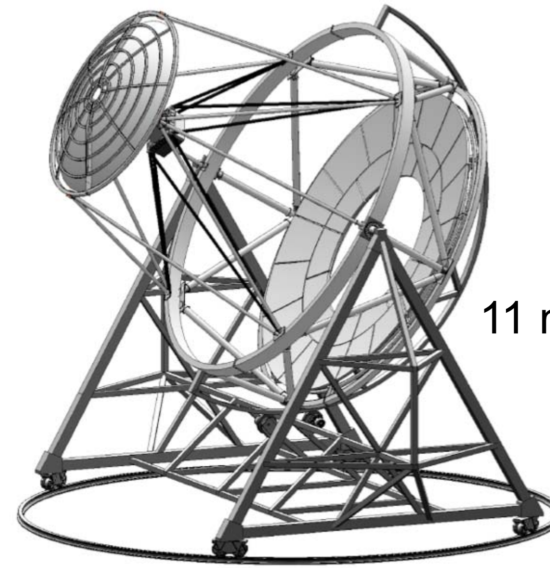


3.5 deg. 8 deg.

Small focal plane:



DC optics SC optics

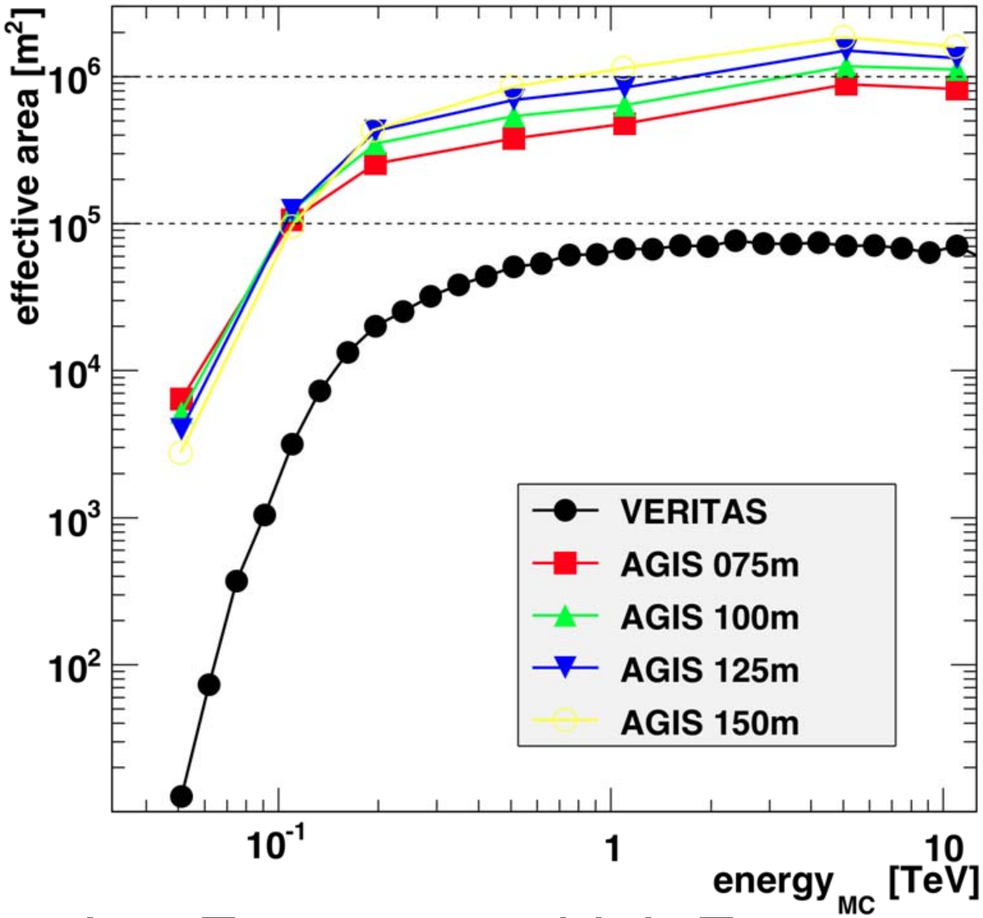


11 m primary

- AGIS (Advanced Gamma-ray Imaging System):
  - Improve sensitivity by ~x10 (0.1-10 TeV)
  - 36 telescopes (cf. 4 for H.E.S.S. & VERITAS)
  - Wide field-of-view, high angular resolution (small pixel size)
    - Sharper image, better BG rejection
  - $220M includes construction and operation for 10 years
- Favorably reviewed by PASAG and by P5

CTA / AGIS effective area

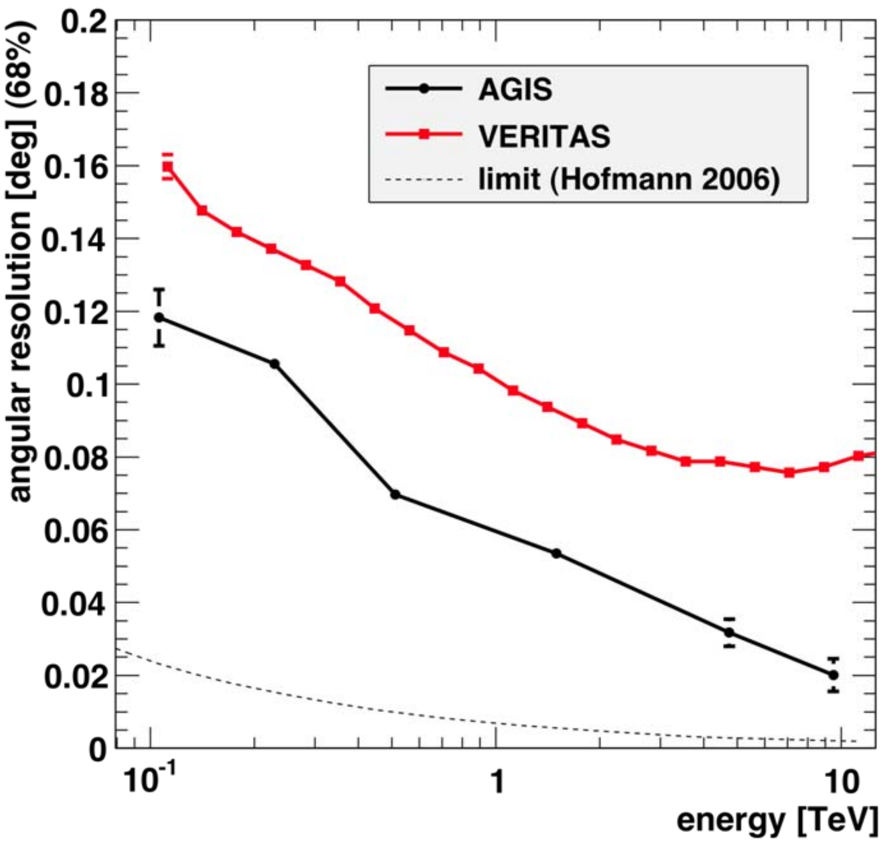
arXiv:0907.5118

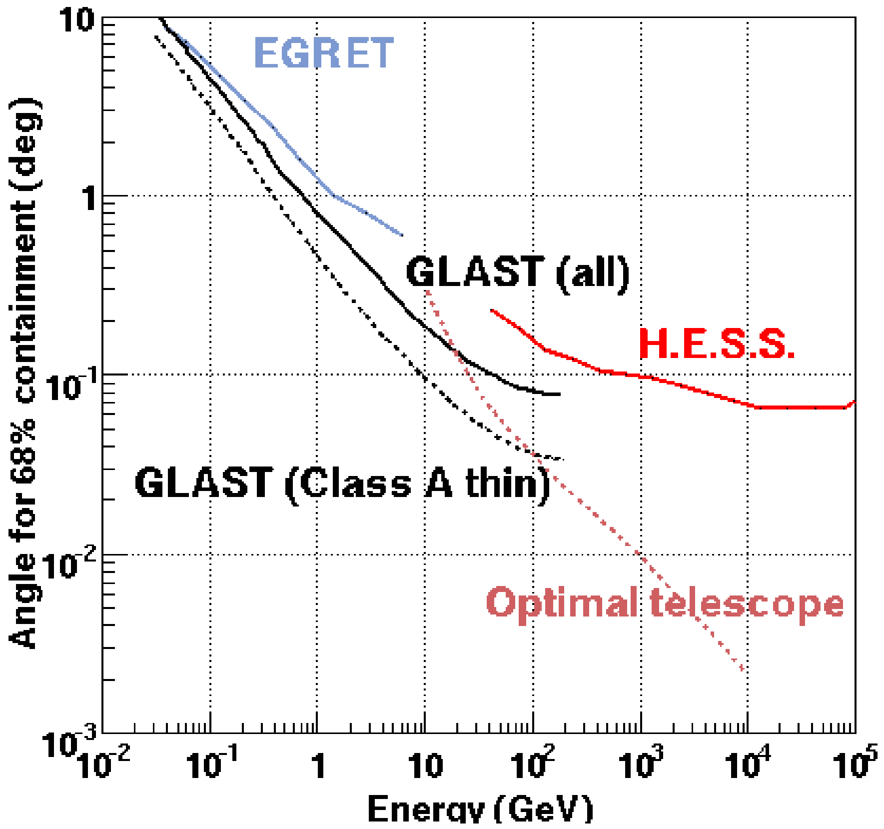


- ~1 km^2 above 1 TeV
- ~10x improvement
- Dense spacing preferred at low E; sparse at high E

CTA / AGIS angular resolution

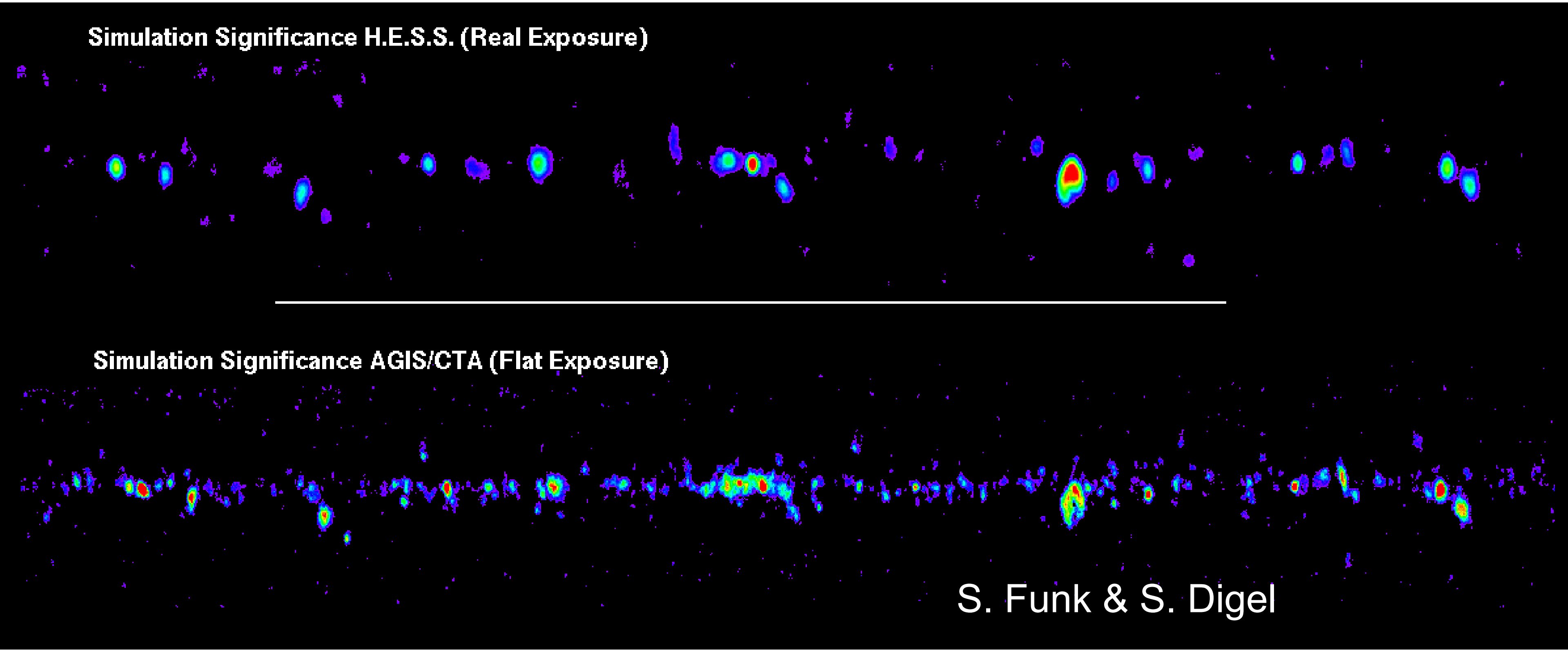
astro-ph/0603076 arXiv:0901.2153 arXiv:0907.5118





At 1 TeV: improve from ~0.1° to ~0.06°

CTA science example: Galactic sources



- ±3° in Galactic latitude, ±30° in Galactic longitude
- simulated Galactic plane survey
- detect ~300 Galactic (+ hundreds of extragalactic) sources
- good spatial resolution for existing and new sources
  - determine spatial extension and morphology
  - determine emission regions and correlate with other wave bands

TeV Catalog legend

Source Types

- PWN
- XRB PSR Gamma BIN
- HBL IBL FRI FSRQ LBL
- Shell
- Starburst
- DARK UNID Other
- uQuasar Cat. Var. BIN WR

http://tevcat.uchicago.edu/

Fermi sources by category (first catalog)

Source class	EGRET sources: 271	Fermi sources: 1451
Pulsars	5	39 radio loud + 24 radio quiet
Pulsar wind nebulae	0	5
Supernova remnants	0	44
Globular clusters	0	8
X-ray binaries	0	3
Active galaxies	94	661
Normal galaxies	1 (LMC)	2 (LMC + SMC)
Starburst galaxies	0	2
Solar flare	1	0 (but pp + IC detected)
Unassociated	170	630

Abdo et al., ApJS 188, 405 (2010)

- 5 new source classes
- 5-7% of 821 associations are by chance
- 43% unassociated! Large discovery potential: multi-wavelength campaigns

LDRD budget breakdown

Title: Development of an integrated TeV γ-ray camera readout system

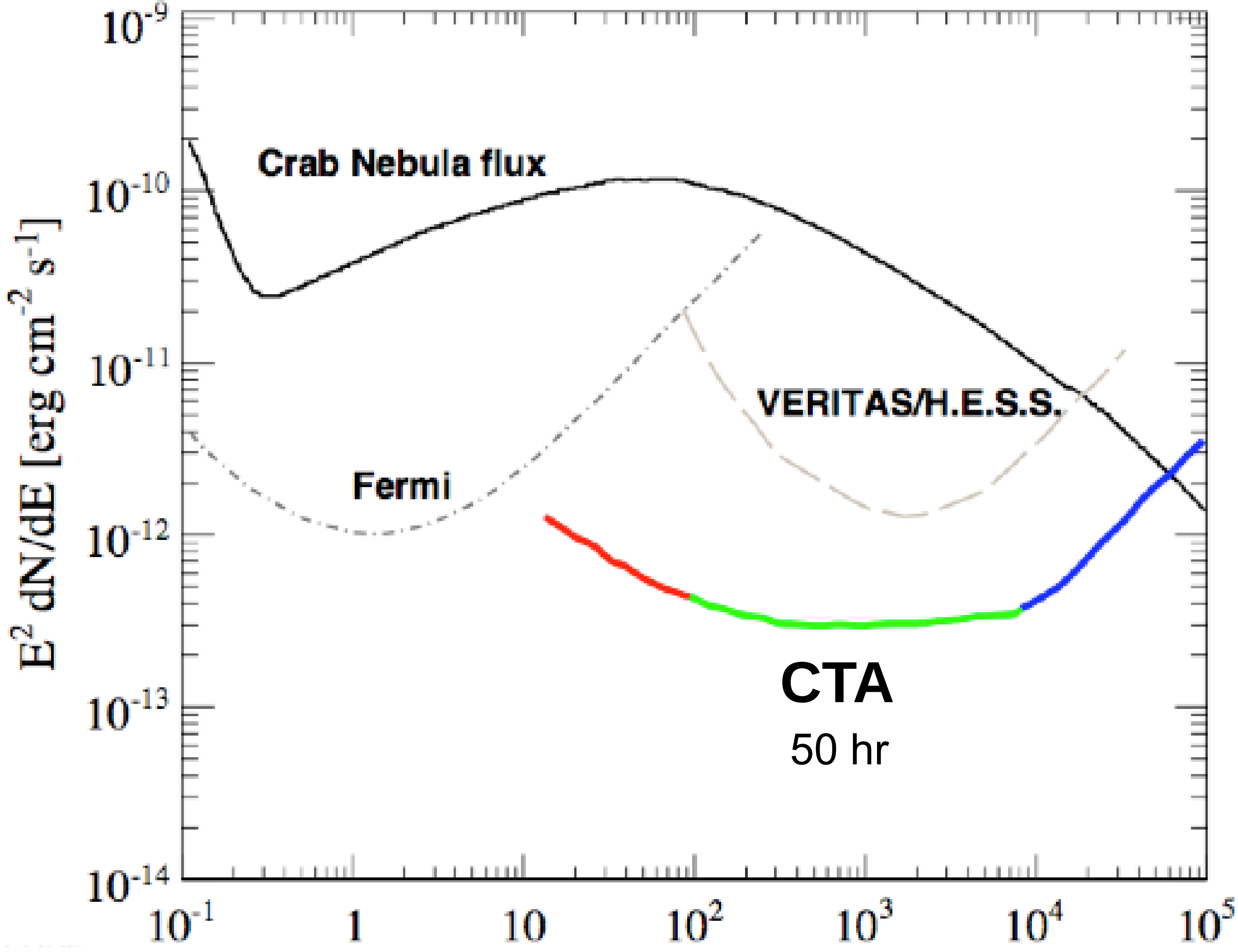
Lead Scientist: Stefan Funk

COST ELEMENT	FTE %	**Fiscal Year 2010 ($000)**	FTE %	**Fiscal Year 2011 ($000)**	FTE %	**Fiscal Year 2012 ($000)**
Labor (give levels of effort with names,or if unknown indicate TBD) FTE						
Scientific & Professional	**41.67**		41.67			
		$64,670		$66,610		$0
Post Doc	**100**		100			
		$50,400		$59,007		$0
Other						
		$0		$0		$0
Total Labor		**$115,070**		**$125,617**		**$0**
Labor Burdened @ 54.6%*		$62,828		$68,587		$0
Total labor Burdened		**$177,898**		**$194,204**		**$0**
Indirects @ 45%		$80,054		$87,392		$0
Total Labor & Indirects		**$257,952**		**$281,596**		**$0**
TRAVEL						
		$6,000		$6,000		$0
Indirects @ 45%		$2,700		$2,700		$0
Total Travel & Indirects		**$8,700**		**$8,700**		**$0**
DISTRIBUTED TECHNICAL SERVICES						
Materials		$50,000		$61,000		$0
Supplies		$2,000		$2,000		$0
Services		$200		$200		$0
Indirects @ 8%		$4,176		$5,056		$0
Total Services & Indirects		**$56,376**		**$68,256**		**$0**
TECHNICAL COLLABORATORS / CONSULTANTS						
Sub-contracts						
Contracts Burden @ ______%						
TOTAL PROJECT COST		**$323,028**		**$358,552**		**$0**

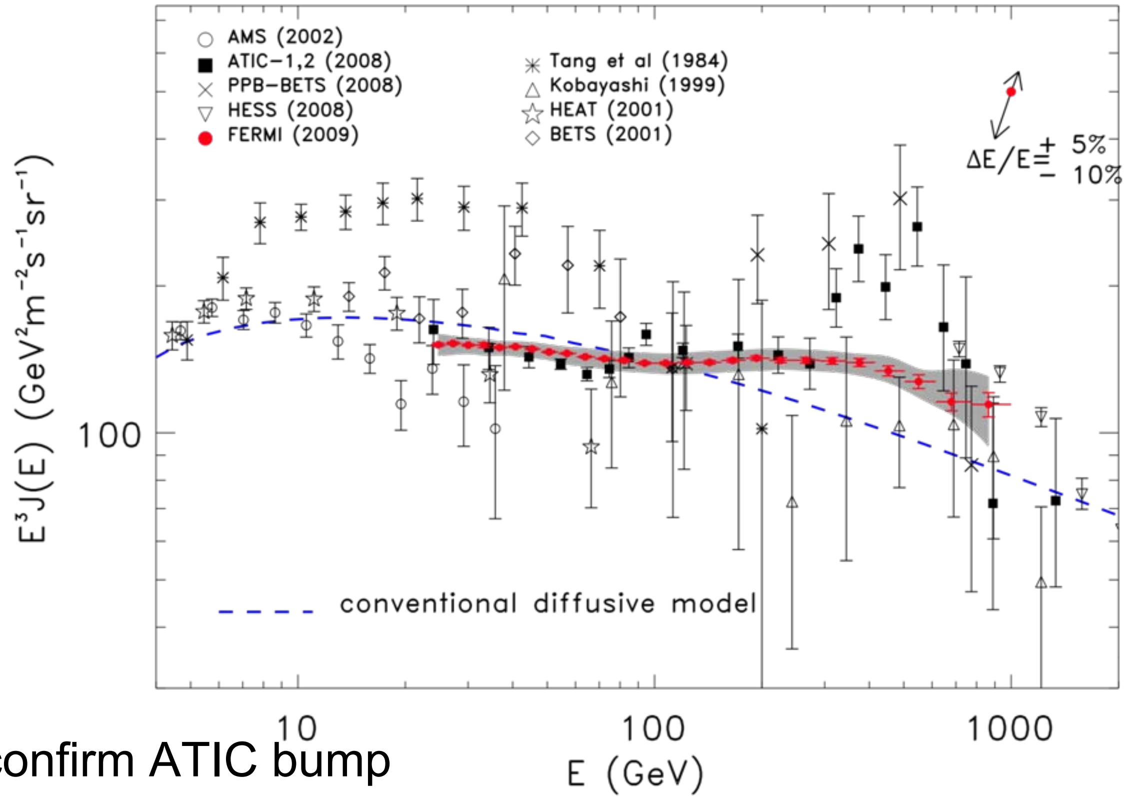
TeV sources (from TeVCat, September 2010)

Source type	Number of sources
Dark	1
Fanaroff-Riley Type I radio galaxy	2
Flat-spectrum radio quasar	3
High-frequency-peaked BL Lac	24
Intermediate-frequency-peaked BL Lac	4
Low-frequency-peaked BL Lac	3
Other	3
Pulsar wind nebulae	25
Shell-type supernova remnants	11
Starburst galaxies	2
Unidentified	29
Wolf-Rayet stars	3
X-ray binaries	3
Total	**113**

CTA sensitivity



Fermi measurement of cosmic ray electron + positron spectrum from 20 GeV to 1 TeV

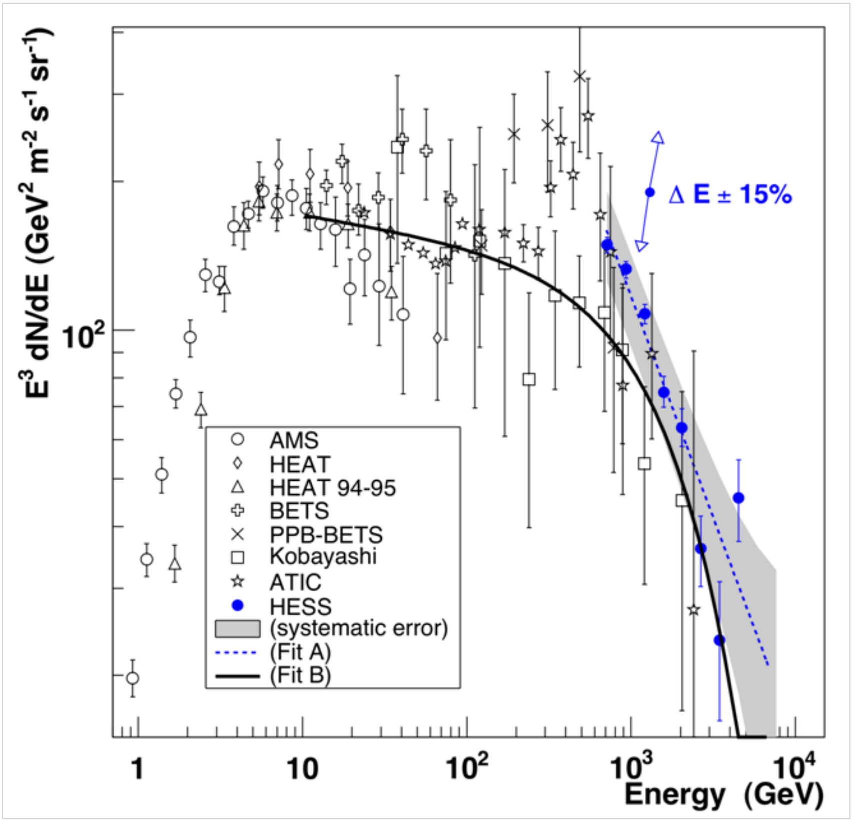


- Does not confirm ATIC bump
- Most cited Fermi paper and 8th most cited paper of 2009 (ADS) [not a gamma-ray result!]
- Power law index -3.0
- Now extended down to 7 GeV: arXiv:0912.3611

Abdo et al., PRL 102, 181101 (2009)

29

HESS measurement of cosmic ray electron + positron spectrum from 600 GeV to 4 TeV



PRL 101, 261104 (2008)

- Select events away from Galactic plane and point sources
- Discriminate hadron background
- Steepening above 600 GeV: index = -3.9 ± 0.1 (stat) ± 0.3 (syst)

Site candidates

- Northern hemisphere:
  - Canary Islands (2400 m above sea level)
  - Baja California (2800 m asl)

- Southern hemisphere
  - Namibia (1800 m asl)
  - Chile (2400 m asl)
  - Argentina (2600 or 3700 m asl)
  - South Africa?

Dark matter with CTA

- Observe local galaxies, dwarf spheroidals, globular clusters, galactic center
- Improve energy threshold from 150 GeV (VERITAS) to 30-50 GeV (CTA)
- Search for spectral signatures of dark matter (e.g. line or cutoff at WIMP mass)