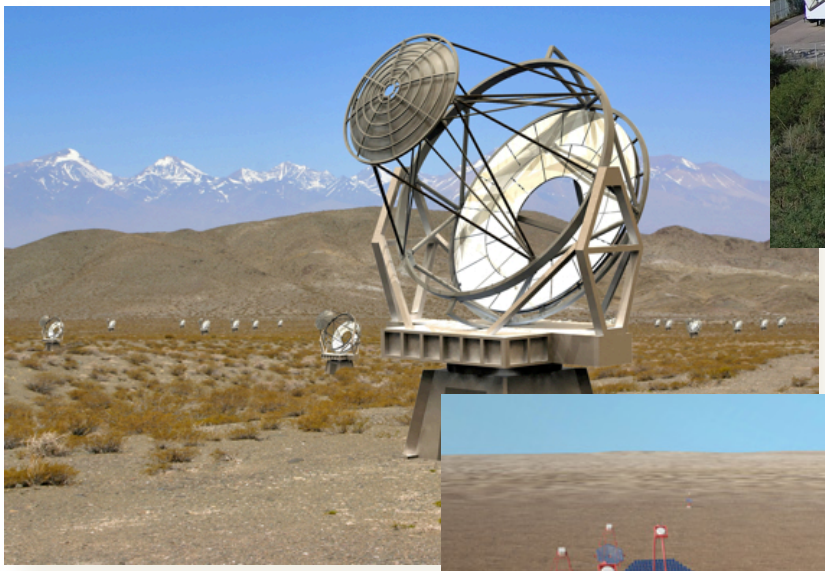
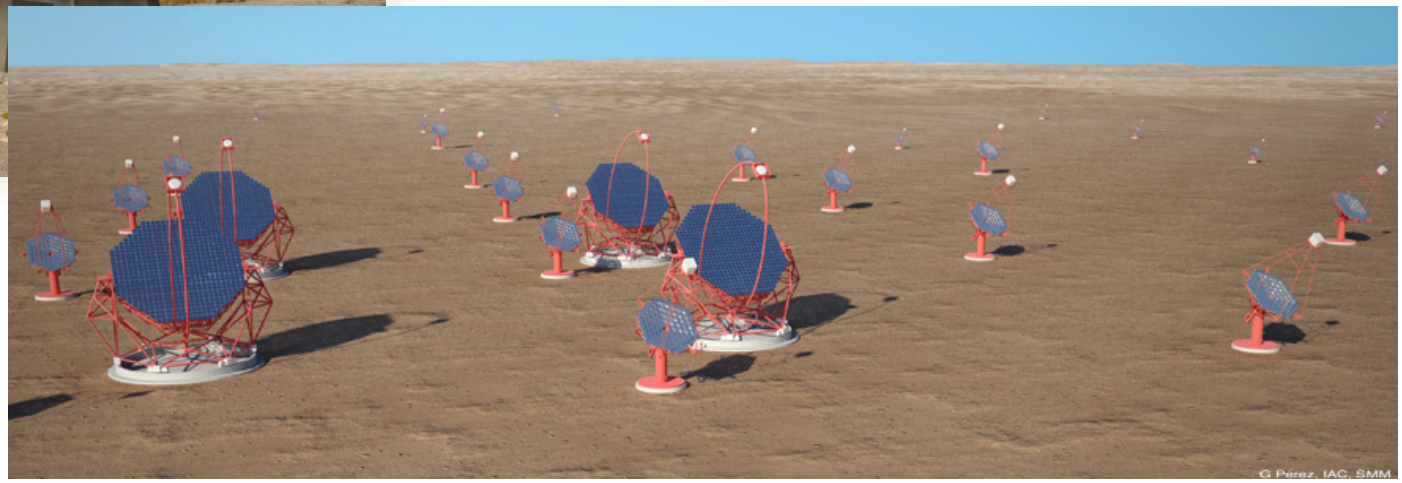
Beyond VERITAS in the U.S:



From AGIS



To CTA

David A. Williams
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

Outline

- Goals
- The AGIS Era
- The U.S. in CTA
- U.S. Aspirations

Outline

- Goals
- The ASTRI-Era
- The U.S. in CTA
- U.S. Aspirations
  - Science
  - A Large Array
  - Large Field of View
  - High Resolution

Goal: Science

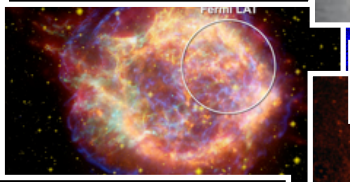
Particle Acceleration

Dark Matter

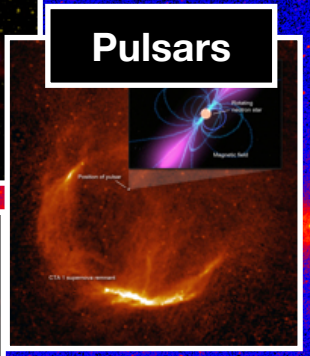
Cosmology

Cosmic Rays

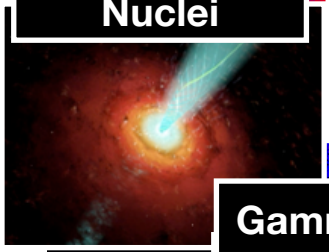
Supernova Remnants



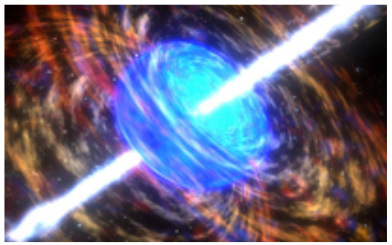
Pulsars



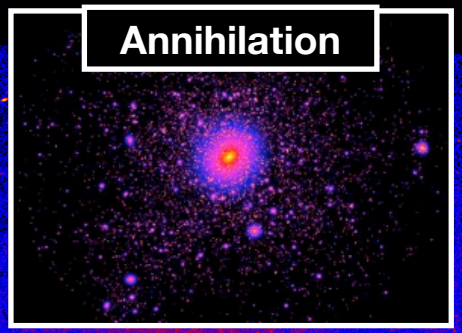
Active Galactic Nuclei



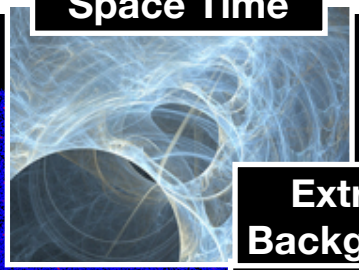
Gamma-ray Bursts



Annihilation



Space Time



Extragalactic Background Light

Primordial Black Holes

Axion-like Particles

... ?

Opens discovery space by major improvements in sensitivity, FoV, energy range

Goal: Science

Particle Accele

Cosmic Ra

Supernova Remnants

Pulsa

Active Galactic Nuclei

Gamma-ray Bu

Cosmology

Space Time

Extragalactic Background Light

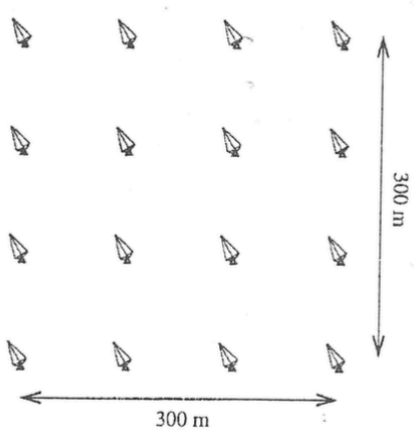
Primordial Black Holes

Axion-like Particles

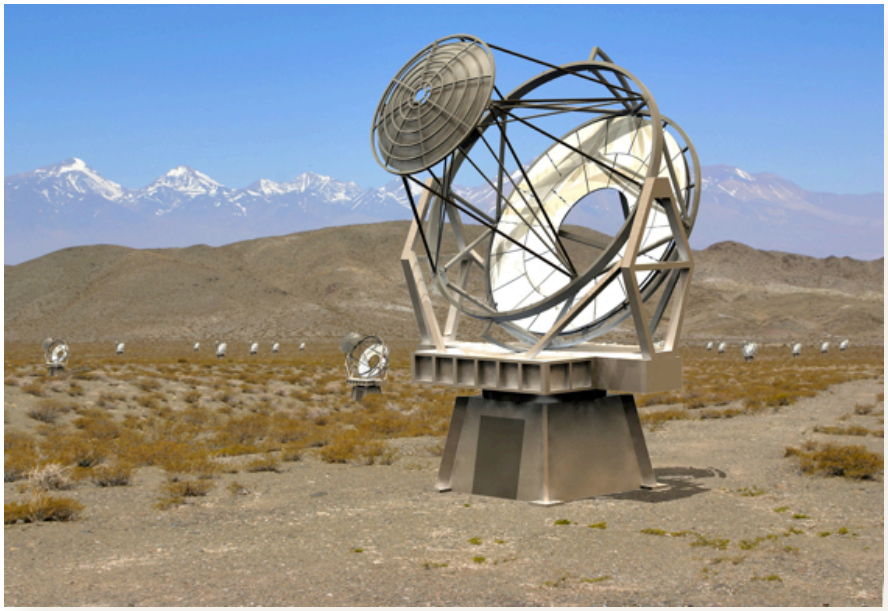
?

space by major
sensitivity, FoV,
energy range

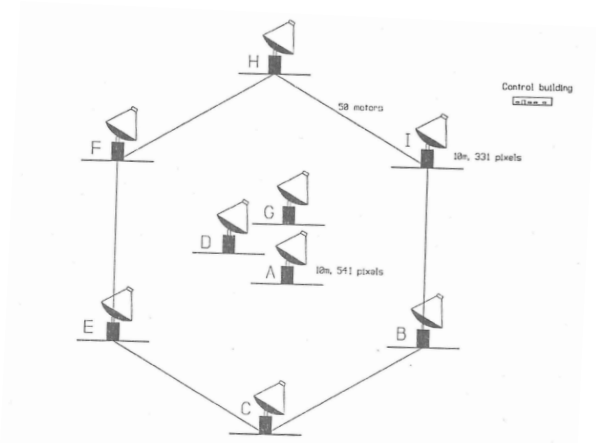
Goal: A Large Array



HESS (Hofmann Kruger Park Proceedings 1997)



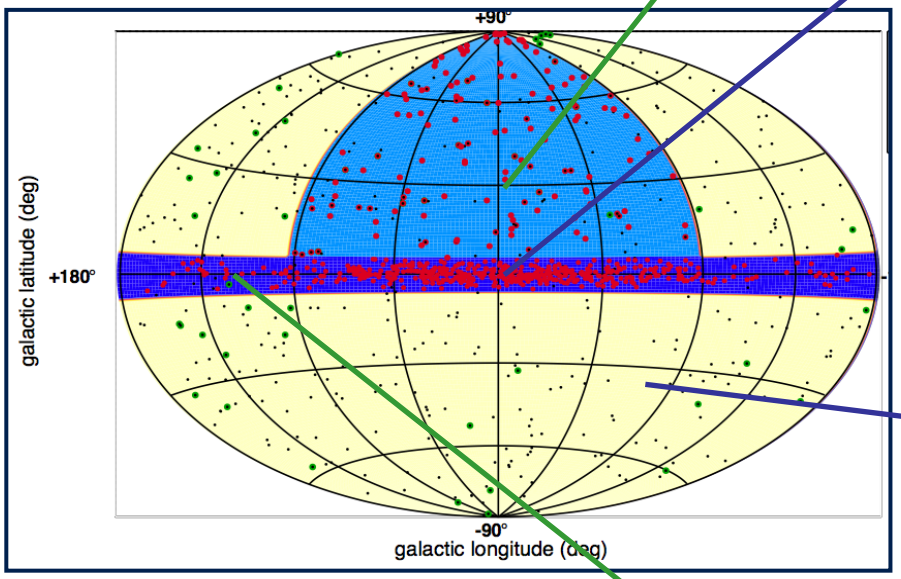
AGIS (Buckley presentation to 2010 Decadal Survey)



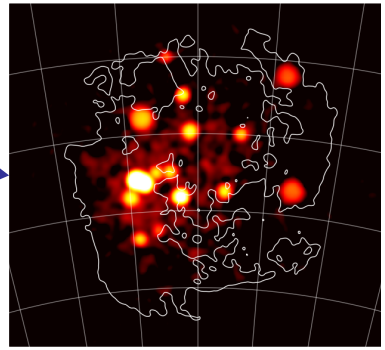
VERITAS (Weekes et al. Kruger Park Proceedings 1997)

Goal: Large Field of View

Extragalactic Survey:
Unbiased survey of ¼ sky to ~6 mCrab
VHE population study, duty cycle
New, unknown sources; 1000 h



Galactic Centre Survey:
ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search
Central exposure: 525 h, 10^{o}x10^{o} : 300 h



8° field of view for CTA compared to 3.5°–5° for current instruments

Galactic Plane Survey:
Survey of entire plane to ~2 mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, 1620 h

Large Magellanic Cloud Survey:
Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; 340 h in six pointings

Goal: Large Field of View

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Spectrum, morphology of diffuse emission
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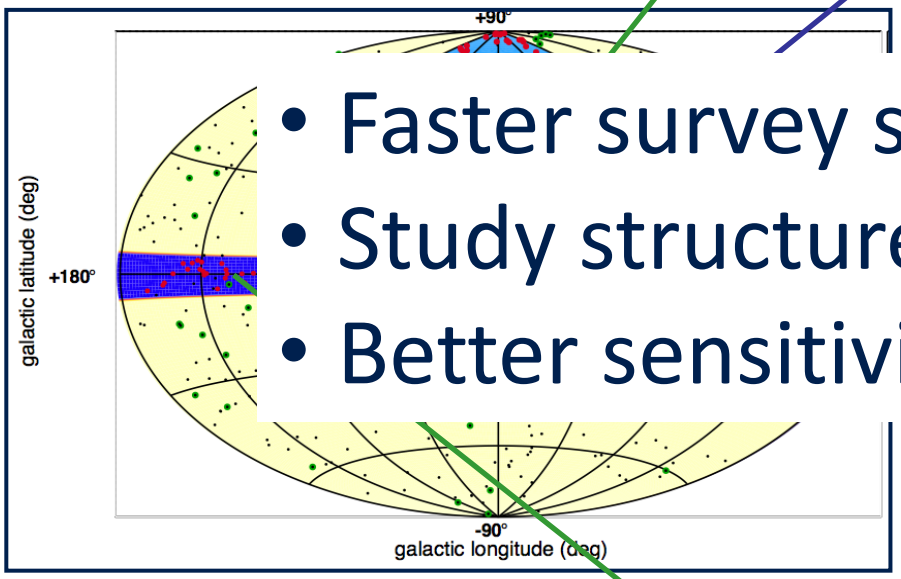
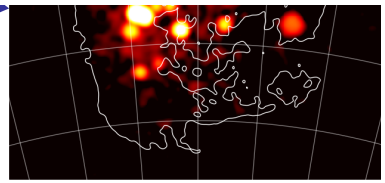


- Faster survey speed
- Study structure of extended objects
- Better sensitivity to transients

w

current instruments



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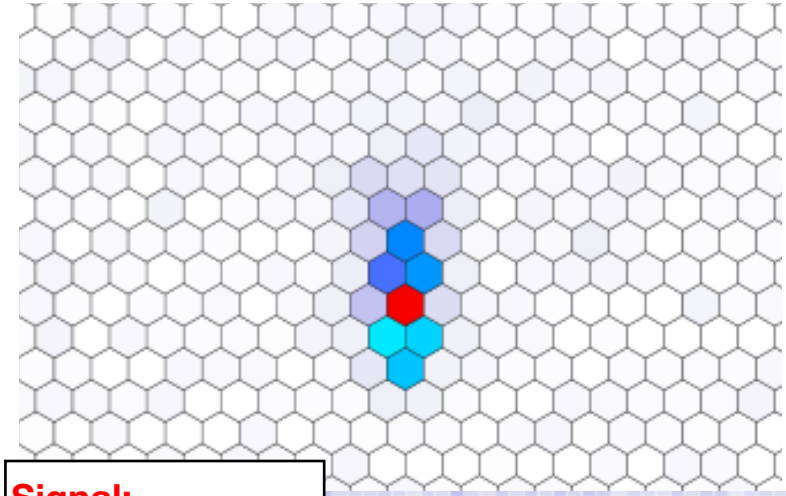
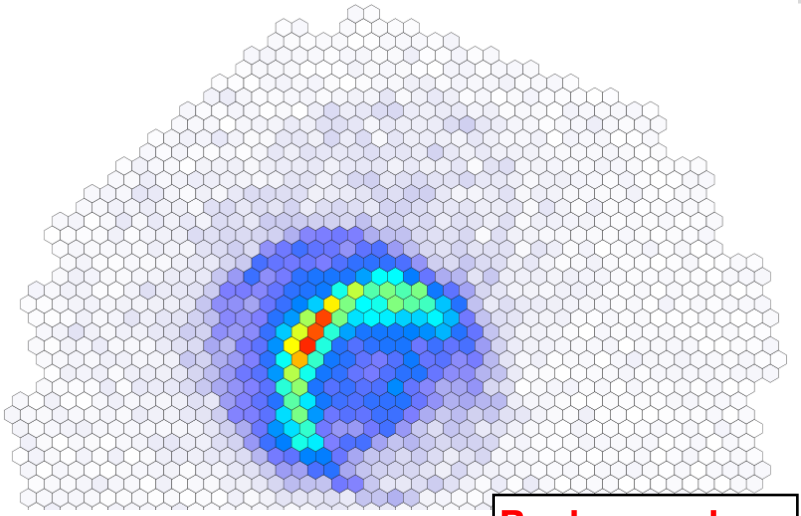
Large Magellanic Cloud Survey:
Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; 340 h in six pointings

Goal: Higher Resolution Images

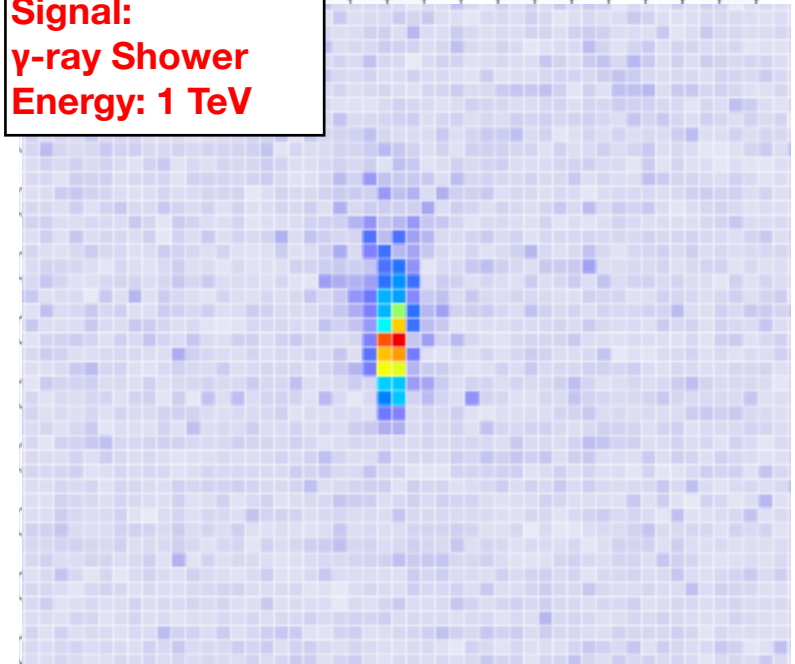


8° field of view
0.18° pixels
1,570 channels

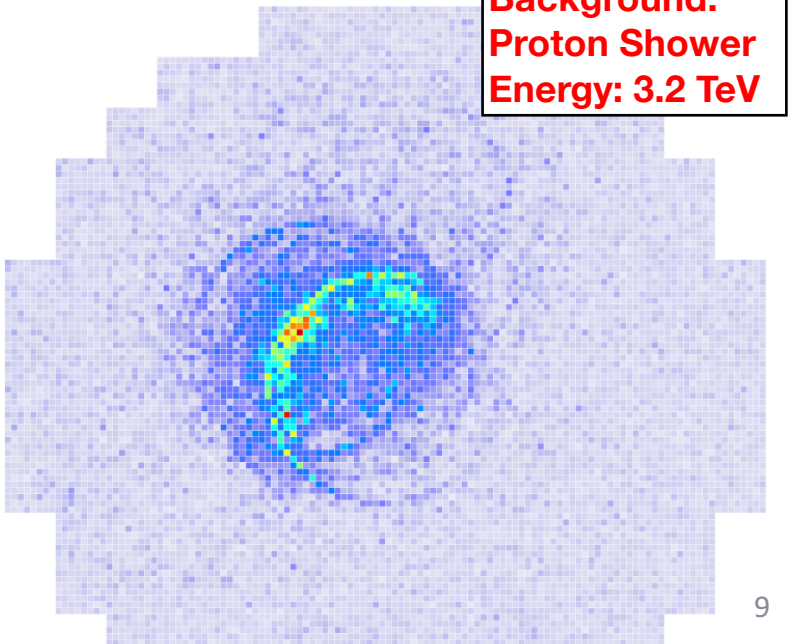


Signal:
γ-ray Shower
Energy: 1 TeV

Background:
Proton Shower
Energy: 3.2 TeV



8° field of view
0.067° pixels
11,328 channels

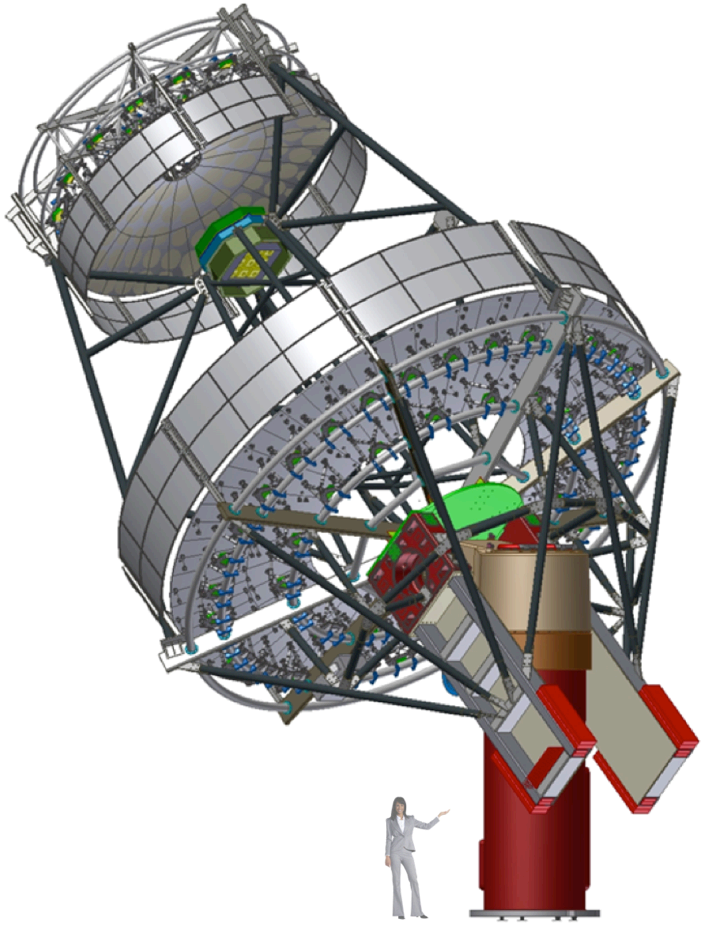


Schwarzschild-Couder Telescope

Key to achieving the three technical goals:

- Wide field of view
- High resolution optics and camera
- Cost effective for large array

See next talk by Vladimir Vassiliev



Outline

- Goals
- The AGIS Era
- The U.S. Role in CTA
- U.S. Aspirations

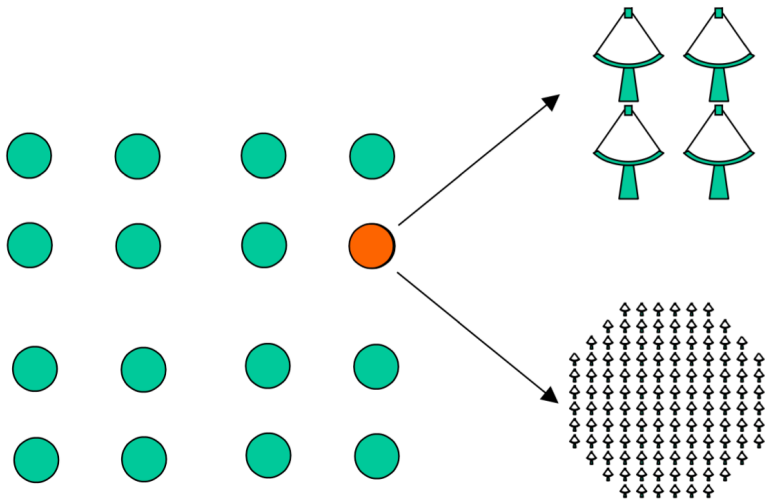
From Palaiseau 2005 to the 2010 Decadal Survey

Planning Meetings in the U.S.

- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA

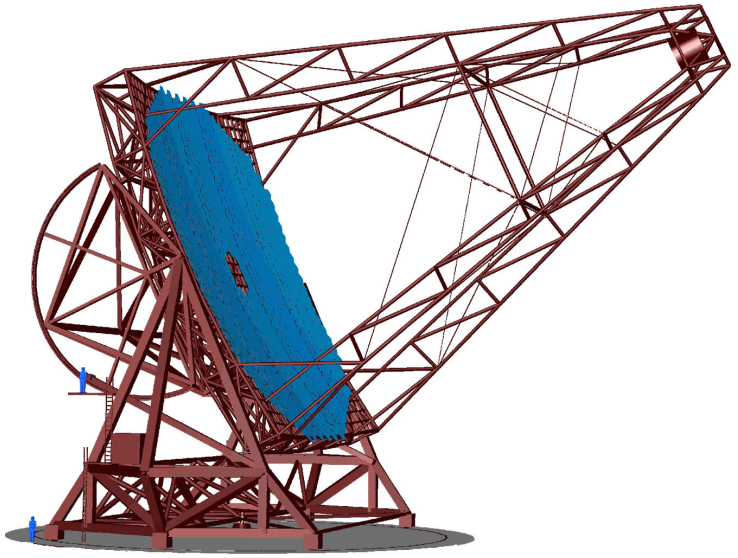
Technical Approaches at May's Landing

Henric Krawczynski
Jim Buckley
(Washington University)
Abe Falcone
(Penn State)



STARs – Small Telescope Arrays

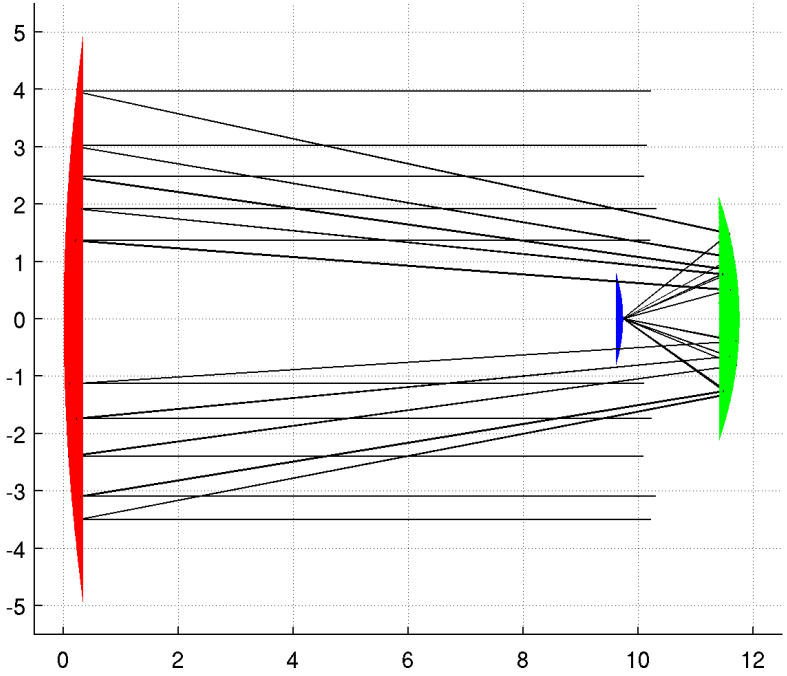
Alex Konopelko
presented by
John Finley
(Purdue University)



Five 30m HESS-II style telescopes

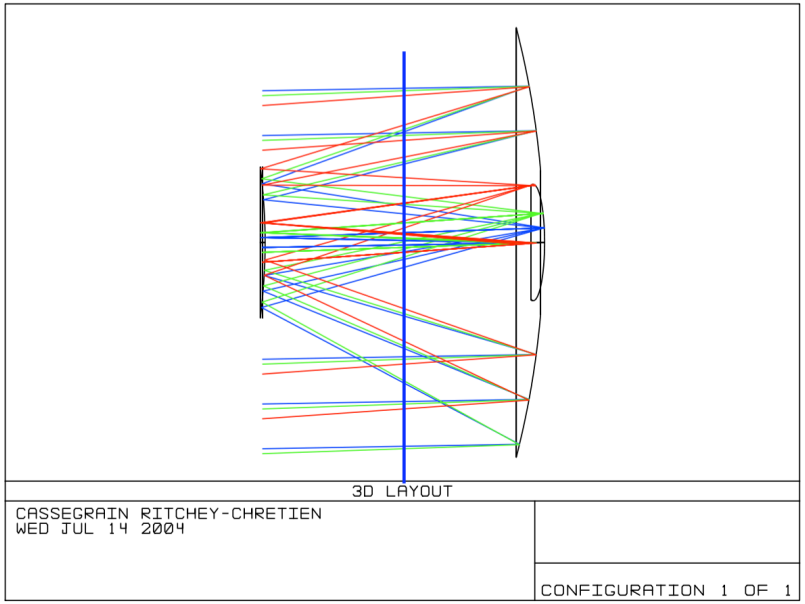
Technical Approaches at May's Landing

Vladimir Vassiliev
Pierre-Francoys Brousseau
Stephen Fegan
(UCLA)



"Detailed ray tracing in modified Ritchey-Chrétien design"

Jim Buckley
presented by
Henric Krawczynski
(Washington University)



"Ritchey-Chrétien with curved focal plane"

Planning Meetings in the U.S.

- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA
- Science with Future Gamma-Ray Detectors — May 11–12, 2006; Santa Fe, New Mexico (LANL hosts)

Launched "… white paper on the status and future of ground based TeV gamma-ray astronomy. …"

Dear Colleagues,

The Division of Astrophysics of the American Physical Society invites you to prepare a review or white paper on the status and future of ground based TeV gamma-ray astronomy. With the upcoming commissioning of VERITAS and the success of HESS and others in this emerging field, a review of the science accomplishments and potential would be welcome. Furthermore, given the long lead time for designing, developing and deploying new instruments, we need a clear path for proceeding beyond the near term.

...

On Behalf of the DAP Executive Committee,
Sincerely Yours,

James Ryan
Chair

Planning Meetings in the U.S.

- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA
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VERITAS First Light Celebration — April 28, 2007

Planning Meetings in the U.S.

- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA
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- Future in Gamma-Ray Astronomy Meeting — May 13–14, 2007; Chicago (ANL and U of Chicago hosts)

09:30-09:50	Status of CTA focusing on the science	Agnieszka Jacholkowska
09:50-10:10	Status of CTA focusing on possible instrument studies	German Hermann
10:10-11:00	Coffee Break & Poster Viewing & Mingling	
11:00-11:15	Interesting sites for Cherenkov telescopes in Argentina	Adrian Rovero
11:15-11:30	Mexican proposal for hosting Cherenkov detectors	Alberto Carraminana
11:30-11:50	The ILC detector R&D Model	Harry Weerts
11:50-12:05	Update on Decadel Survey	Brenda Dingus
12:05-13:30	Lunch (provided)	
	Afternoon Session: 13:30 pm - 18:30 pm - Chair: Dave Kieda	
13:30-14:00	Future Directions: Steps towards the future	Martin Pohl
14:00-14:30	R&D Proposal	Jim Buckley

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Involvement of CTA

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11		
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11		
11		
12		
13:30-14:00	Future Directions: Steps towards the future	Martin Pohl
14:00-14:30	R&D Proposal	Jim Buckley

Launched first proposal to NSF and DOE later that fall

"AGIS – research for the next gamma-ray telescope"

AGIS is the Advanced Gamma-ray Imaging System

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- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA
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- Toward the Future of Very High Energy Gamma-ray Astronomy — November 8–9, 2007; SLAC

Session devoted to formation of AGIS Collaboration

Planning Meetings in the U.S.

- Ground-based Gamma-ray Astronomy: Towards the Future — October 20–22, 2005; May's Landing & UCLA
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- Future in Gamma-Ray Astronomy Meeting — May 13–14, 2007; Chicago (ANL and U of Chicago hosts)
- Toward the Future of Very High Energy Gamma-ray Astronomy — November 8–9, 2007; SLAC
- First AGIS Meeting — June 26–27, 2008; UCLA

APS White Paper Participants

Editors	Affiliation
Brenda Dingus	Los Alamos National Laboratory
Henric Krawczynski	Washington University (St.Louis)
Martin Pohl	Iowa State University
Vladimir Vassiliev	University of California Los Angeles

Senior Advisors	Affiliation
Francis Halzen	University of Wisconsin, Madison
Werner Hofmann	Max-Planck-Institut für Kernphysik (Heidelberg)
Steven Ritz	NASA Goddard Space Flight Center
Trevor Weekes	The Harvard Smithsonian Center for Astrophysics

Group Chairs	Affiliation	Group
Jim Buckley	Washington University (St.Louis)	DM
Karen Byrum	Argonne National Laboratory	Tech
Abe Falcone	Penn State	GRB
Phil Kaaret	The University of Iowa	GCO
Henric Krawczynski	Washington University (St.Louis)	EG
Martin Pohl	Iowa State University	SNR
David Williams	University of California, Santa Cruz	GRB

9 of 13 from VERITAS

+

80 other members of the community

(22 from VERITAS)

APS White Paper Participants

Editors	Affiliation
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Abe Falcone	Penn State	GRB
Phil Kaaret	The University of Iowa	GCO
Henric Krawczynski	Washington University (St.Louis)	EG
Martin Pohl	Iowa State University	SNR
David Williams	University of California, Santa Cruz	GRB

Working Groups

Dark Matter – DM

Extragalactic Astrophysics – EG

Galactic Compact Objects – GCO

Gamma-ray Bursts – GRB

Supernova Remnants – SNR

Technology – Tech

Key APS White Paper Findings

Science drivers:

- Acceleration and propagation of high-energy particles
- Understanding dark matter
- Supermassive black holes – how they work and influence on their environments

Compelling synergies with other instruments:

- LOFAR, SKA, LSST, *Fermi*, IceCube, ANITA, LIGO, LISA, etc.

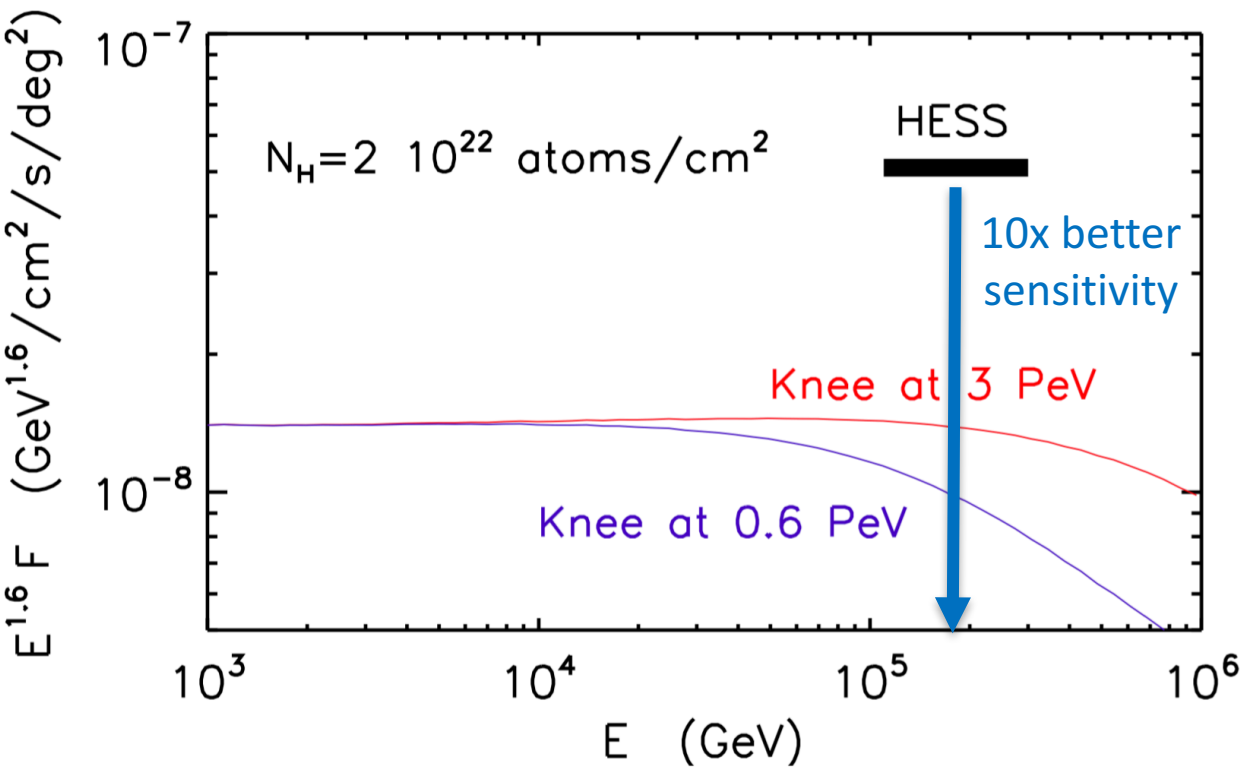
Key APS White Paper Findings

Science drivers:

- Acceleration and propagation of high-energy particles
- Understar
- Supermas influence

Compelling

- LOFAR, S LIGO, LI



Simulated gamma-ray spectra from cosmic ray interactions with molecular clouds

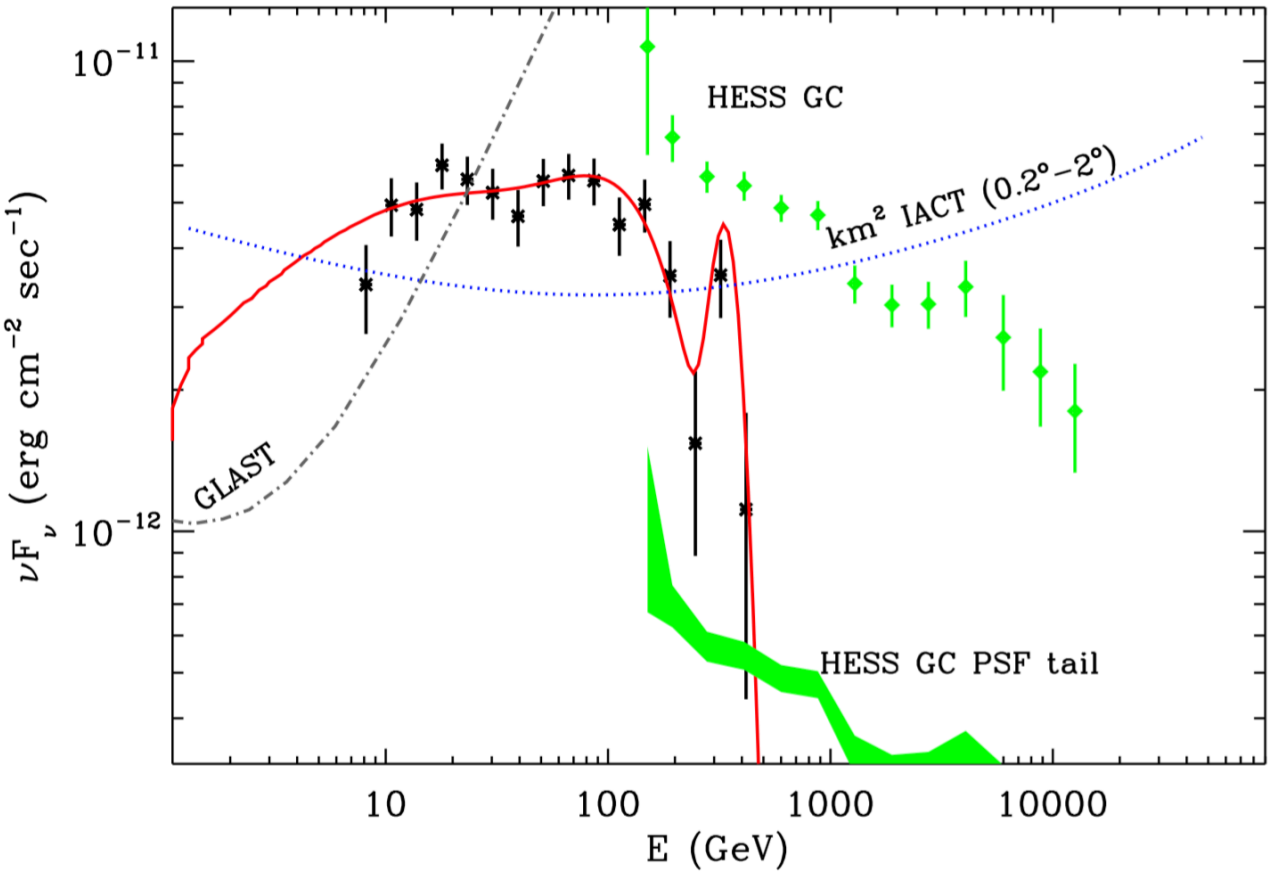
Key APS White Paper Findings

Science drivers

- Acceleration particles
- Understandi
- Supermassiv influence on

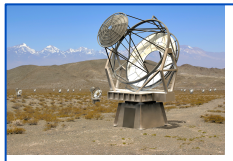
Compelling sy

- LOFAR, SK LIGO, LISA



Gamma-ray spectrum in red from a possible dark matter annihilation signal

The Decadal Survey

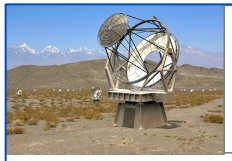


A dvanced
G amma-ray
I maging
S ystem

Overview, Technical (R&D) & Management Plan

Frank Krennrich on behalf of the AGIS Collaboration

The Decadal Survey

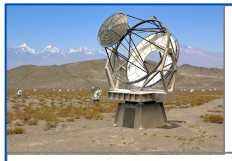


Plan for Presentations

- Overview, Technical (R&D)/Management Plan for AGIS
  F. Krennrich , Iowa State University (15 min)
- Angular/energy resolution, sensitivity (altitude, array spacing)
  S. Funk, Stanford University (15 min)
- Site survey - Candidate sites - AGIS/CTA Telescope designs
  J. Buckley, Washington University (15 min)
- Technical & programmatic relationship of AGIS - CTA
  V. Vassiliev, UCLA (15 min)

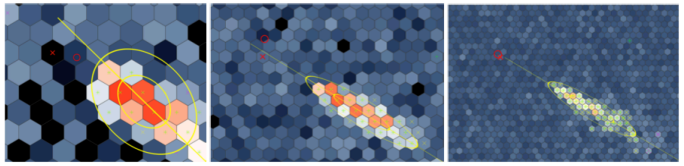
The Decadal Survey

The Decadal Survey



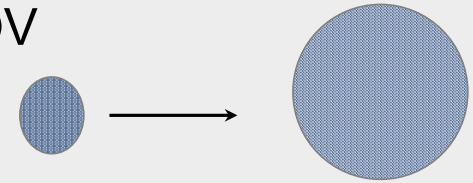
AGIS Telescope Concept

Pixelation



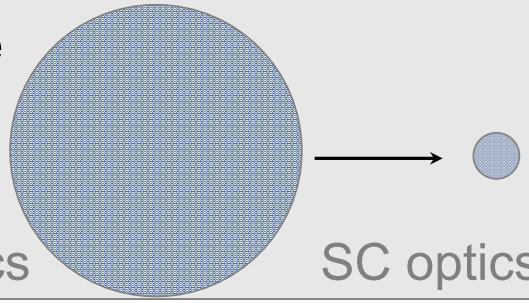
0.28º 0.20º 0.07º

FOV



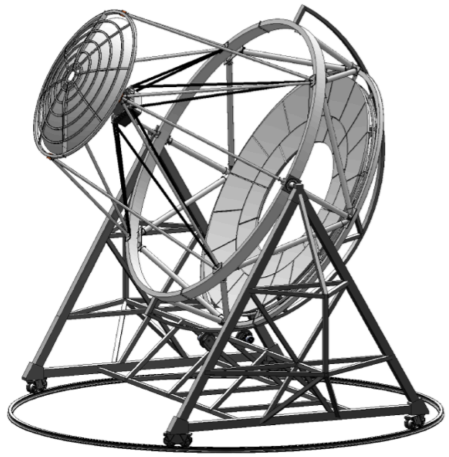
3.5 deg. 8 deg.

Relative Size

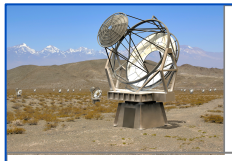


DC optics SC optics

AGIS Element:
Schwarzschild-Couder optics

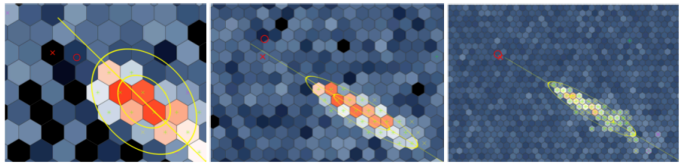


The Decadal Survey



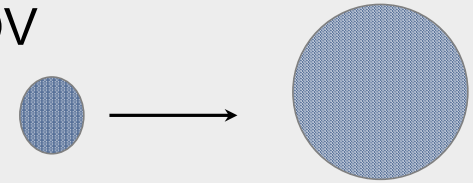
AGIS Telescope Concept

Pixelation



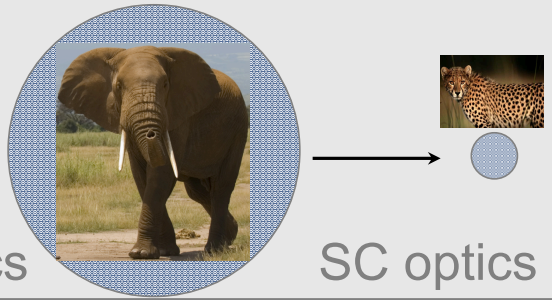
0.28º 0.20º 0.07º

FOV



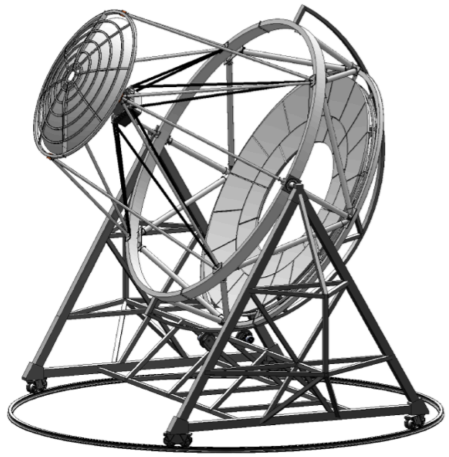
3.5 deg. 8 deg.

Actual Size



DC optics SC optics

AGIS Element:
Schwarzschild-Couder optics



Secondary optics, but telescope with short f/D & compact high resolution, wide FOV cameras!

The Decadal Survey

Recommended Large Ground-based Projects

Recommendation[b]	Science	Technical Risk[c]	Appraisal of Costs Through Construction[a] (U.S. Federal Share 2012-2021)	Appraisal of Annual Operations Costs[d] (U.S. Federal Share)	Page Reference
1. LSST - Science late 2010s - NSF/DOE	Dark energy, dark matter, time-variable phenomena, supernovas, Kuiper belt and near-Earth objects	Medium low	$465M ($421M)		
2. Mid-Scale Innovations Program - Science mid-to-late 2010s	Broad science; peer-reviewed program for projects that fall between the NSF MRI and MREFC limits	N/A	$93-200M		
3. GSMT - Science mid 2020s - Immediate partner down-select for ~25% federal share	Studies of the earliest galaxies, galactic evolution, detection and characterization of planetary systems	Medium to Medium high	$1.1B to $1.4B ($257M - $350M)		
4. ACTA - Science early 2020s - NSF/DOE; U.S. join European CTA	Indirect detection of dark matter, particle acceleration and AGN science	Medium low	$400M ($100M)	Unknown	7-36

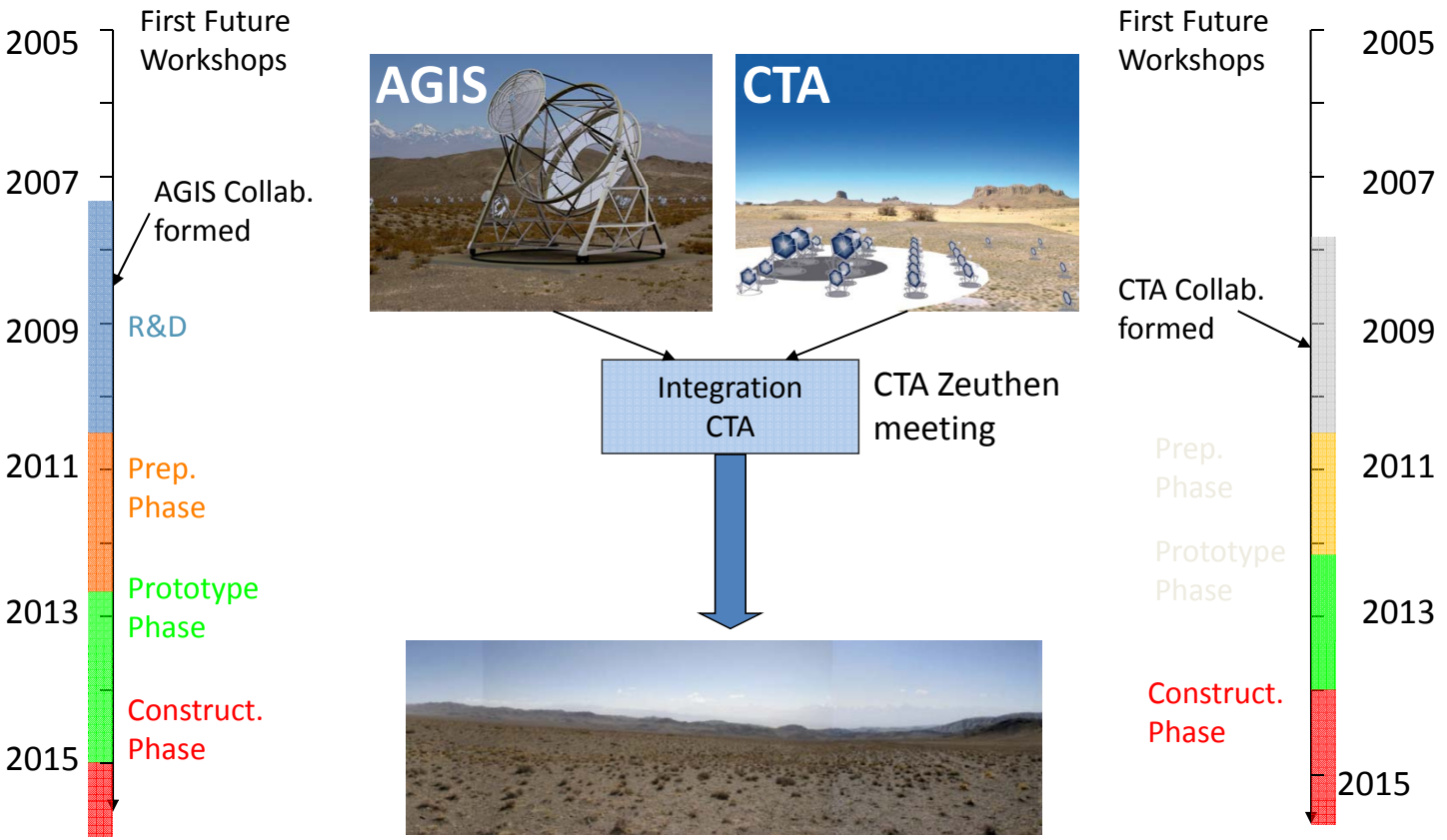
Outline

- Goals
- The AGIS Era
- The U.S. in CTA
- U.S. Aspirations

From 2010 to today

AGIS and CTA Merge

International Approach:



5/12/2010

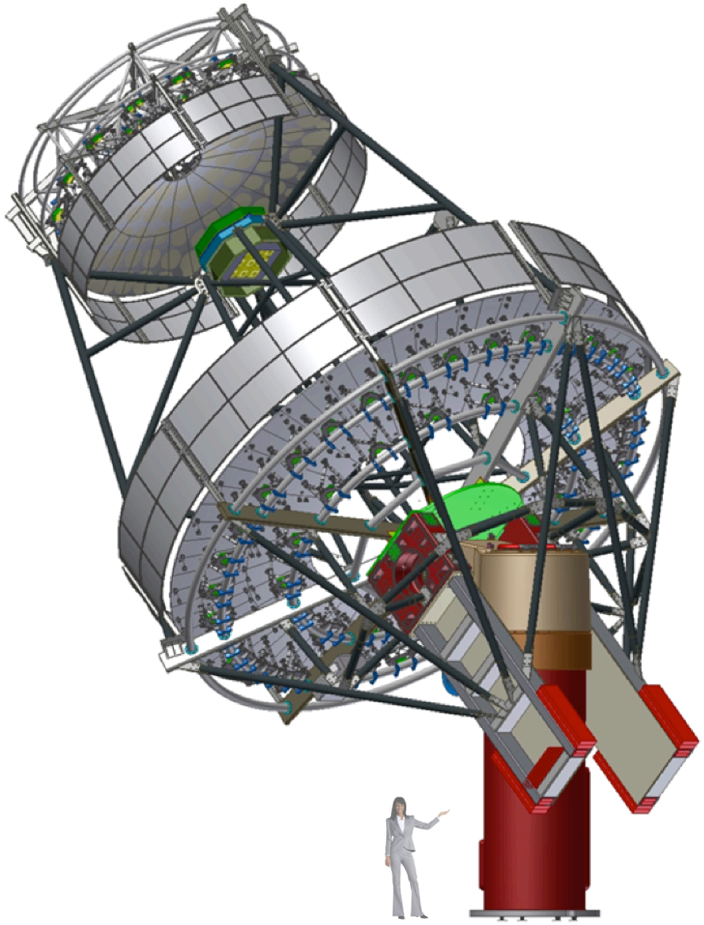
Vladimir Vassiliev's presentation to May 2010 CTA Collaboration Board in Zeuthen, Germany

Schwarzschild-Couder Telescope

Work on the Schwarzschild-Couder Telescope continued as the cornerstone of the U.S. effort.

- SCT became a work package within the CTA organization

See next talk by Vladimir Vassiliev



CTA Sites

Lowell Putnam, Rene Ong, ***Judy Prosser****, Brad Andes (CEO, Meteor Crater Enterprises)*

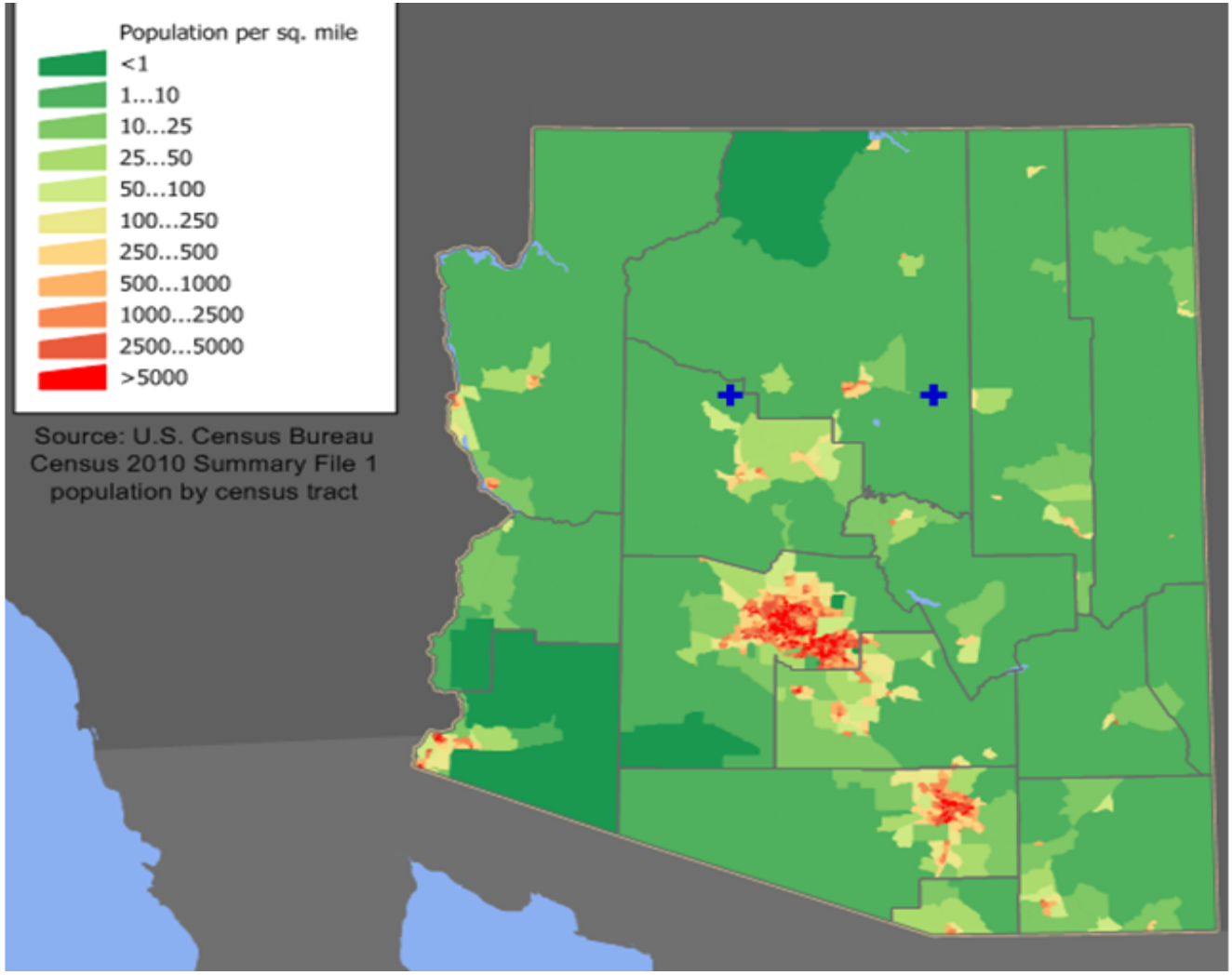
Fred Ruskin*, Tom Thurman (Yavapai County Supervisor), Dave Kieda, Jeffrey Hall*

UCLA and Utah groups, with terrific assistance from the **Lowell Observatory in Flagstaff, Arizona**

Jim Buckley, Vladimir Vassiliev and others had done earlier work for AGIS

CTA Sites

Map of population density of Arizona from the Census of 2010 [19]. The blue plus symbols indicate the locations of the two sites proposed for CTA. (The distance between the sites is approximately 200 km).

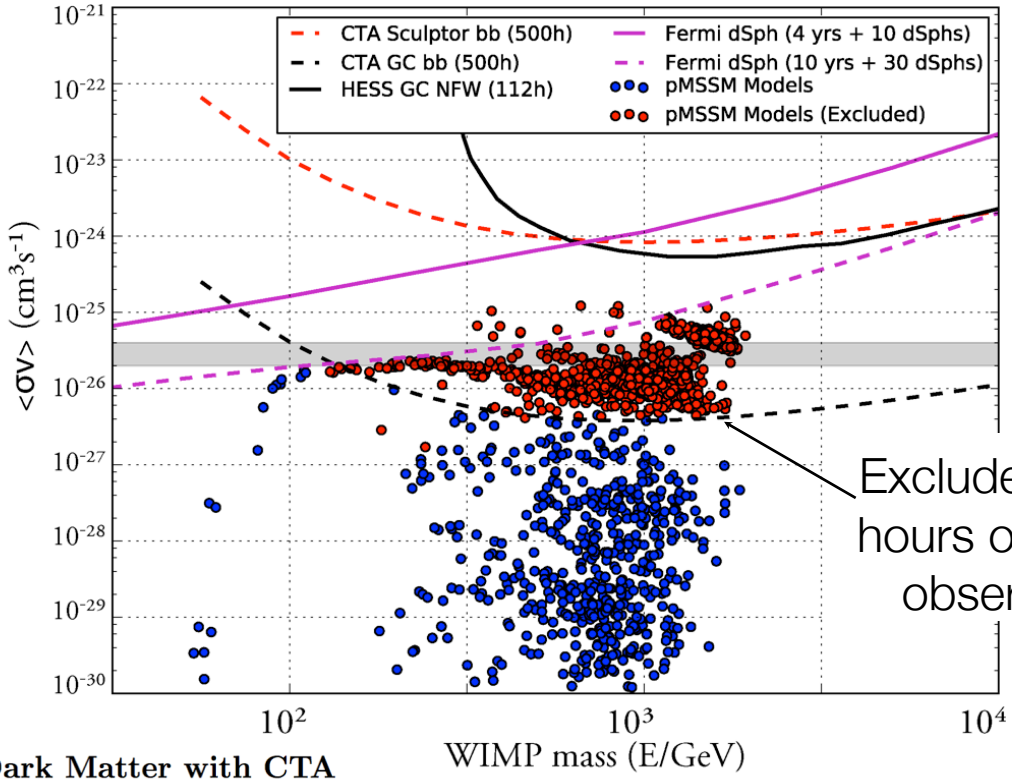


CTA Sites

Yavapai County Site, 150 km west of Flagstaff and seen here during installation of the Atmoscope . The site is about 20 km south of the small town of Seligman, Arizona.

The Snowmass 2013 Study

Vanilla dark matter WIMPs covered by ~2020



Excluded by 500 hours of GC halo observations

Prospects for Indirect Detection of Dark Matter with CTA

M. Wood,[1,*] J. Buckley,[2] S. Digel,[1] S. Funk,[1] D. Nieto,[3] and M. A. Sánchez-Conde[1]

[1] *KIPAC/SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*
[2] *Department of Physics, Washington University, St. Louis, MO, 63130, USA*
[3] *Physics Department, Columbia University, New York, NY 10027, USA*

(Dated: September 24, 2013)

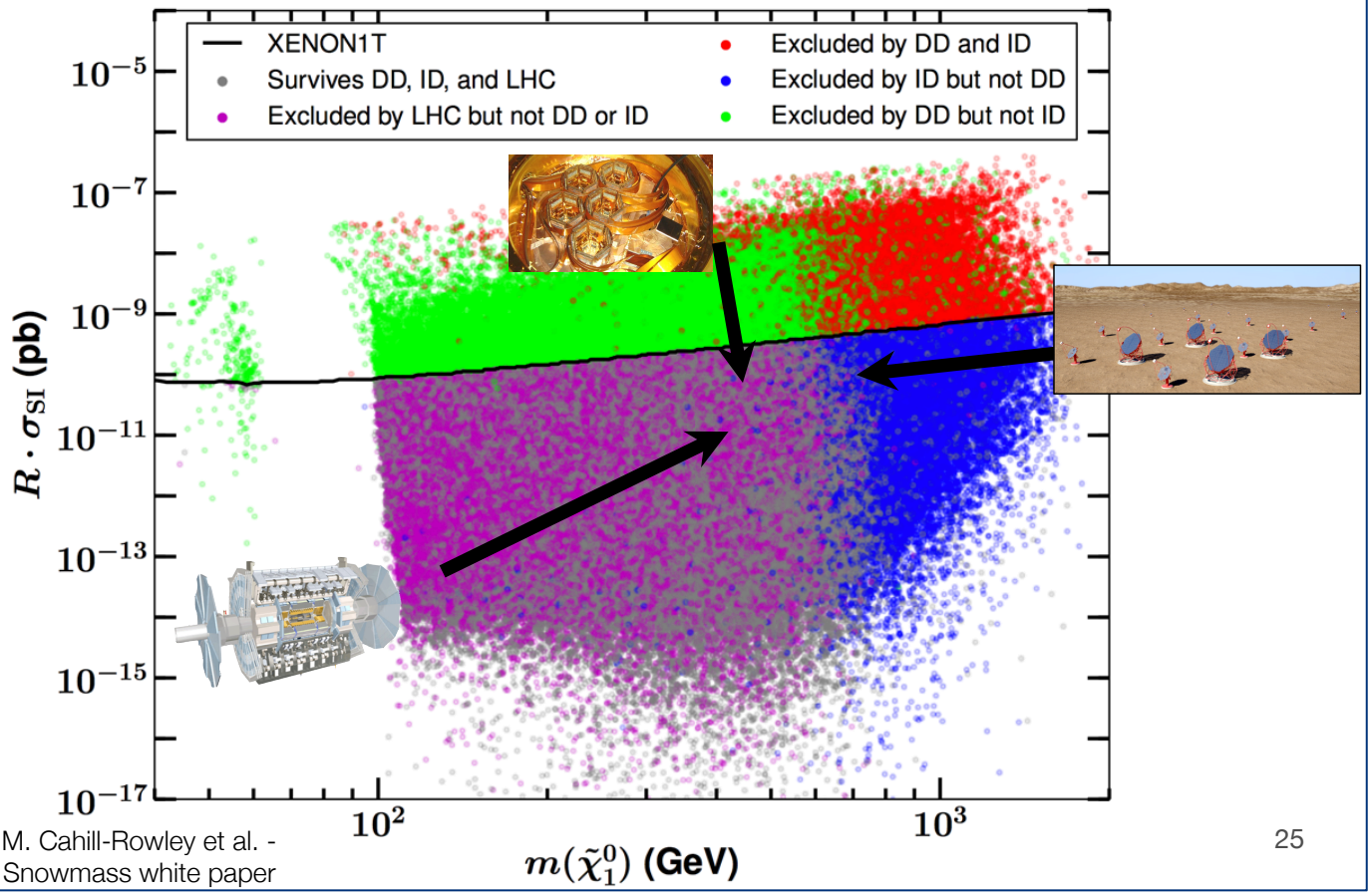
The Snowmass 2013 Study

Complementarity -SUSY scan (pMSSM)

Complementarity and Searches for Dark Matter in the pMSSM

M. Cahill-Rowley[1], R. Cotta[2], A. Drlica-Wagner[1], S. Funk[1], J. Hewett[1], A. Ismail[1], T. Rizzo[1], and M. Wood[1]

[1]SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
[2]University of California, Irvine, CA, USA†



M. Cahill-Rowley et al. - Snowmass white paper

Snowmass 2013 Study — CF2

Indirect Dark Matter Detection
CF2 Working Group Summary

Conveners: J. Buckley, D.F. Cowen, S. Profumo

A. Archer, M. Cahill-Rowley, R. Cotta, S. Digel, A. Drlica-Wagner, F. Ferrer, S. Funk, J. Hewett, J. Holder, B. Humensky, A. Ismail, M. Israel, T. Jeltema, A. Olinto, A. Peter, J. Pretz, T. Rizzo, J. Siegal-Gaskins, A. Smith, D. Staszak, J. Vandenbroucke, M. Wood

"CTA, with a critical enhancement provided by the U.S., would provide a powerful new tool for searching for dark matter, covering **parameter space not accessible to other techniques** (direct searches, accelerator)."

Snowmass 2013 Study — CF4

Dark Matter in the Coming Decade:
Complementary Paths to Discovery and Beyond

Sebastian Arrenberg, University of Zürich; **Howard Baer**, University of Oklahoma; **Vernon Barger**, University of Wisconsin; **Laura Baudis**, University of Zürich; **Daniel Bauer**, Fermilab; **James Buckley**, Washington University; **Matthew Cahill-Rowley**, SLAC; **Randel Cotta**, University of California, Irvine; **Alex Drlica-Wagner**, SLAC; **Jonathan L. Feng**, University of California, Irvine; **Stefan Funk**, SLAC; **JoAnne Hewett**, SLAC; **Dan Hooper***, Fermilab; **Ahmed Ismail**, SLAC; **Manoj Kaplinghat***, University of California, Irvine; **Kyoungchul Kong**, University of Kansas; **Alexander Kusenko**, University of California, Los Angeles; **Konstantin Matchev***, University of Florida; **Mathew McCaskey**, University of Kansas; **Daniel McKinsey**, Yale University; **Dan Mickelson**, University of Oklahoma; **Tom Rizzo**, SLAC; **David Sanford**, Caltech; **Gabe Shaughnessy**, University of Wisconsin; **William Shepherd**, University of California, Santa Cruz; **Tim M. P. Tait***, University of California, Irvine; **Xerxes Tata**, University of Hawaii; **Sean Tulin**, University of Michigan; **Alexander M. Wijangco**, University of California, Irvine; **Matthew Wood**, SLAC; **Jonghee Yoo**, Fermilab; **Hai-Bo Yu**, University of California, Riverside;
on behalf of the Snowmass 2013 Cosmic Frontier WG4 "Dark Matter Complementarity"
Conveners: **Dan Hooper**, **Manoj Kaplinghat**, **Konstantin Matchev**
(Dated: 30 October 2013)

"The sensitivity of both direct searches and colliders is increasingly diminished at high masses, and this is where indirect detection probes play an important complementary role — in the case of couplings to quarks and leptons, CTA arrays are able to **cover the relevant parameter region in the mass range around 1 TeV**."

Snowmass 2013 Study — CF6

CF6 Working Group Summary

The Bright Side of the Cosmic Frontier: Cosmic Probes of Fundamental Physics

Conveners: J.J. Beatty, A.E. Nelson, A. Olinto, G. Sinnis

A. U. Abeysekara, L.A. Anchordoqui, T. Aramaki, J. Belz, J.H. Buckley, K. Byrum, R. Cameron, M-C. Chen, K. Clark, A. Connolly, D.F. Cowen, T. DeYoung, P. von Doetinchem J. Dumm, M. Errando, G. Farrar, F. Ferrer, L. Fortson, S. Funk, D. Grant, S. Griffiths, A. Groß, C. Hailey, C. Hogan, J. Holder, B. Humensky, P. Kaaret, S.R. Klein, H. Krawczynski, F. Krennrich, K. Krings, J. Krizmanic, A. Kusenko, J. T. Linnemann, J. H. MacGibbon, J. Matthews, A. McCann, J. Mitchell, R. Mukherjee, D. Nitz, R.A. Ong, M. Orr, N. Otte,T. Paul, E. Resconi, M. A. Sanchez-Conde, P. Sokolsky, F. Stecker, D. Stump, I. Taboada, G.B. Thomson, K. Tollefson, P. von Doetinchem, T. Ukwatta, J. Vandenbroucke, V. Vasileiou, V.V. Vassileiv, T.J. Weiler, D.A. Williams, A. Weinstein, M. Wood, B. Zitzer

"CTA will usher in the era of precision VHE astrophysics and in conjunction with current instruments (Fermi and HAWC) will provide a view of the high-energy universe that will lead to an understanding of the astrophysical processes at work in these extreme objects and enable us to **probe the laws of physics** at energies, couplings, and mass scales that are **beyond the reach of traditional high-energy physics experiments**."

Snowmass Cosmic Frontier Summary

From Snowmass Cosmic Frontier Summary:

"[CTA], with the critical U.S. enhancement, will provide a powerful new tool for searching for dark matter, covering parameter space not accessible to other techniques. [It] will provide **new information to help identify the particle nature of the dark matter** and determine the halo profile."

"U.S. involvement in CTA is critical."

P5* Recommendation

From Snowmass Cosmic Frontier Summary:

"[CTA], with the critical U.S. enhancement, will provide a powerful new tool for searching for dark matter, covering parameter space not accessible to other techniques. [It] will provide **new information to help identify the particle nature of the dark matter** and determine the halo profile."

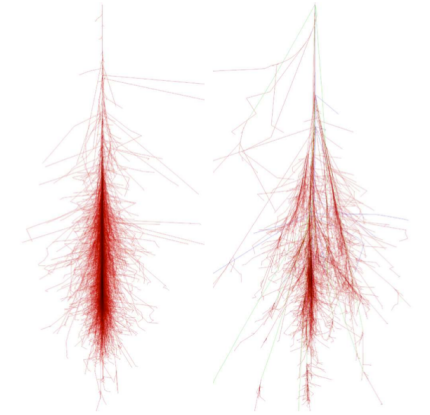
"U.S. involvement in CTA is critical."

From the P5 report:

Recommendation 21: Invest in CTA as part of the small projects portfolio if the critical NSF Astronomy funding can be obtained.

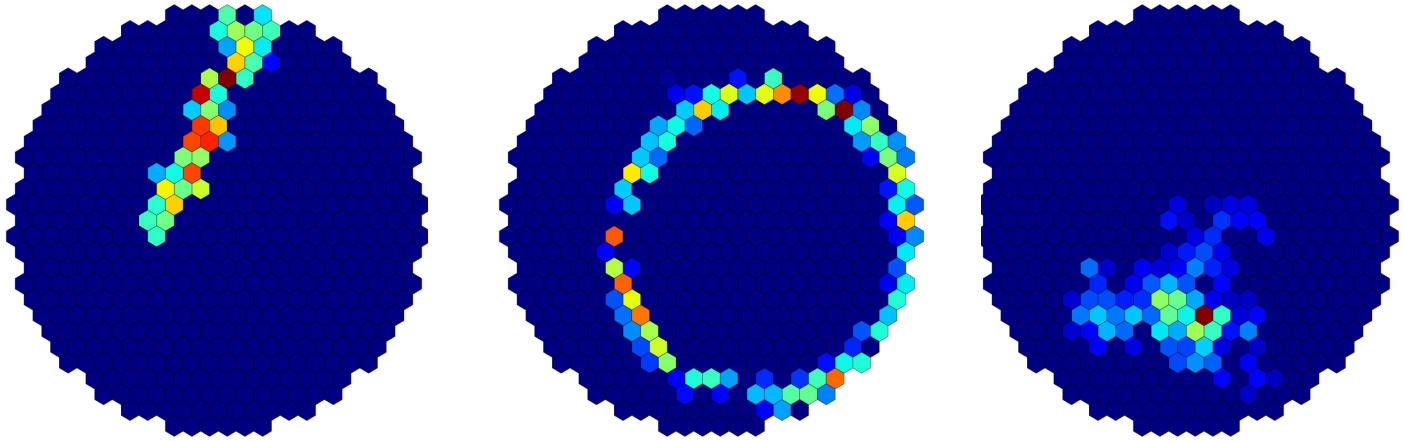
*Particle Physics Projects Prioritization Panel

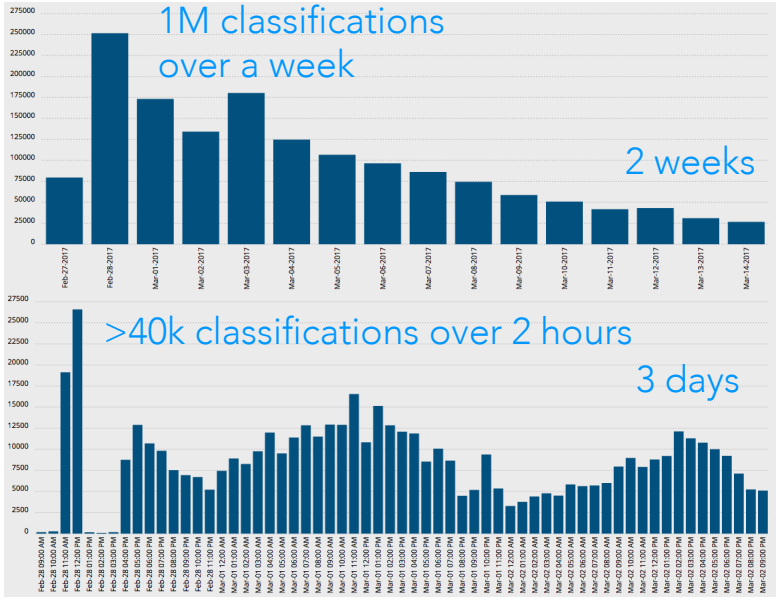
Citizen Science: Muon Hunter



(a) Longitudinal view of 100 GeV photon.

(b) Longitudinal view of 100 GeV proton.

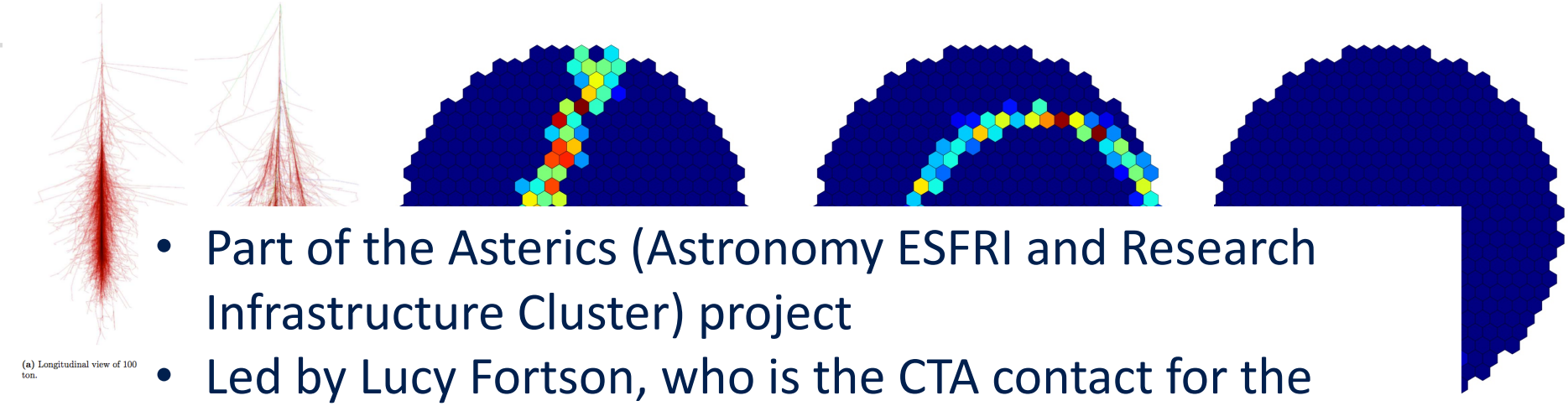




- A citizen science project hosted on the Zooniverse platform.
- VERITAS data are classified multiple times by individual users in order to select and parameterize muon events.
- Use this dataset to train and validate a convolutional neural-network model.

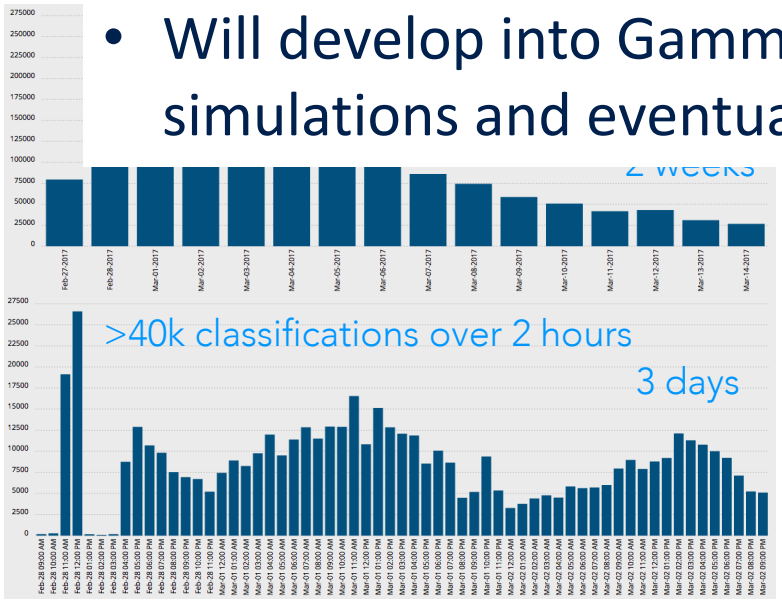
VERITAS Collaboration, ICRC 2017

Citizen Science: Muon Hunter



(a) Longitudinal view of 100 ton.

- Part of the Asterics (Astronomy ESFRI and Research Infrastructure Cluster) project
- Led by Lucy Fortson, who is the CTA contact for the citizen science portion of the project
- Will develop into Gamma Hunter and include CTA simulations and eventually data

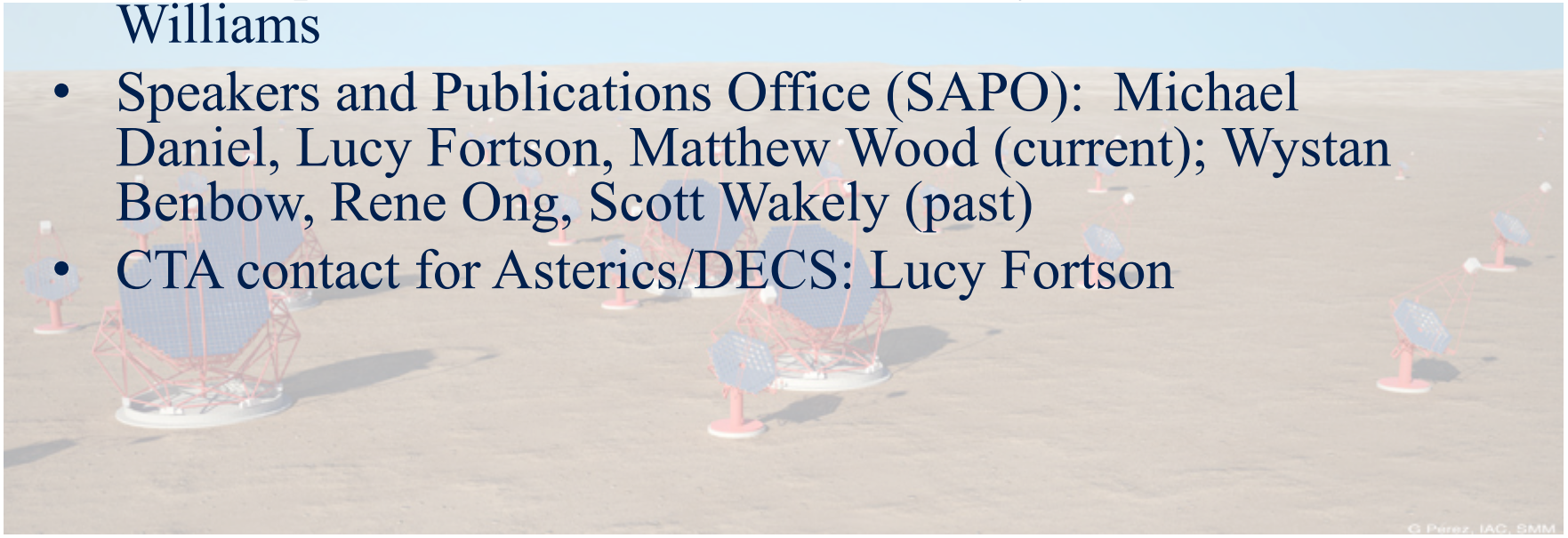


- VERITAS data are classified multiple times by individual users in order to select and parameterize muon events.
- Use this dataset to train and validate a convolutional neural-network model.

VERITAS Collaboration, ICRC 2017

U.S. Roles in CTA

- Co-spokesperson: Rene Ong
- Galactic Science Group Convener: Jamie Holder
- Intensity Interferometry Deputy Convener: Michael Daniel
- SCT Workpackage Leader: Vladimir Vassiliev
- U.S. Representative to CTA Observatory Council: David Williams
- Speakers and Publications Office (SAPO): Michael Daniel, Lucy Fortson, Matthew Wood (current); Wystan Benbow, Rene Ong, Scott Wakely (past)
- CTA contact for Asterics/DECS: Lucy Fortson

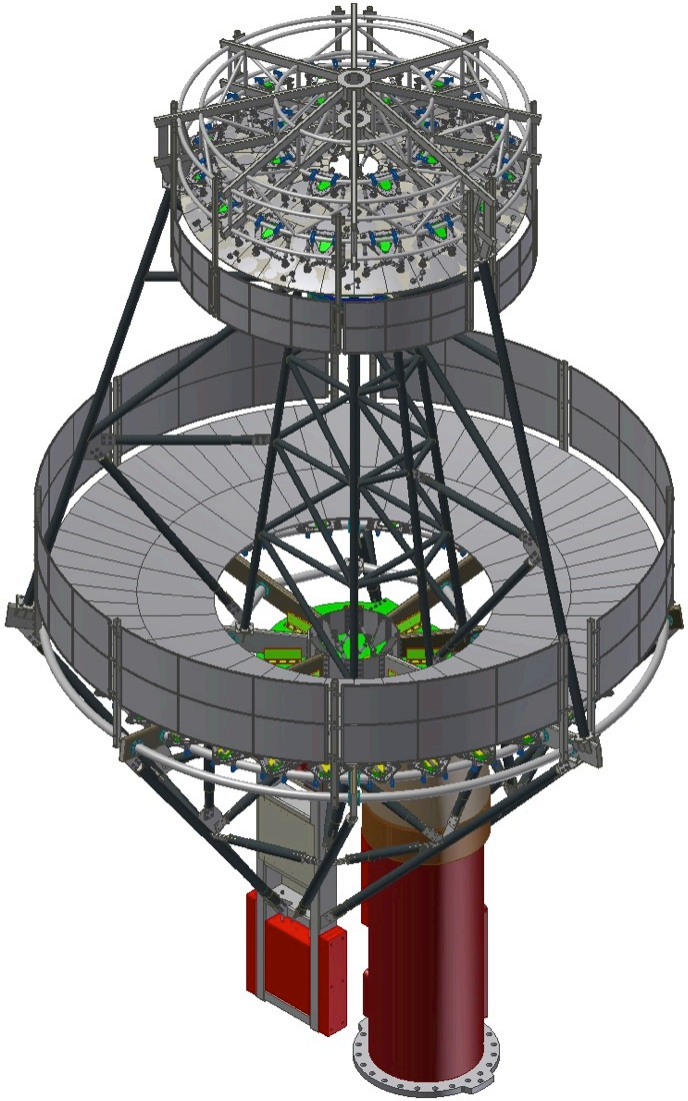


Outline

- Goals
- The AGIS Era
- The U.S. in CTA
- U.S. Aspirations
- Looking ahead

CTA-US Goals

- **Implementation of the medium-sized telescope (MST) arrays**
  - ✓ **Dominate sensitivity in the core 100 GeV – 10 TeV energy range**
- Complete prototype SCT
  - ✓ Verify performance
  - ✓ Vet performance and cost through CTA reviews — one preconstruction review already (September 2013)
- Lead completion of MST array in S or N with SCTs
  - ✓ Assembling consortium
  - ✓ In collaboration with international partners
- Secure $25M in construction funding
  - ✓ NSF Astronomy MSIP (2017 call?)
  - ✓ NSF Physics mid-scale (in parallel)
- Support CTA operations at a commensurate level
  - ✓ ~$1.8M per year for 10 years, starting ~2023
- Participate in full spectrum of CTA science
  - ✓ Key Science Projects
  - ✓ Open time proposals



CTA: A VERITAS Legacy

- VERITAS Collaboration incubated key scientific and technical ideas
- VERITAS site at SAO a critical facility for the prototype SCT
- VERITAS trained many of the scientists working on CTA — both in the U.S. and abroad