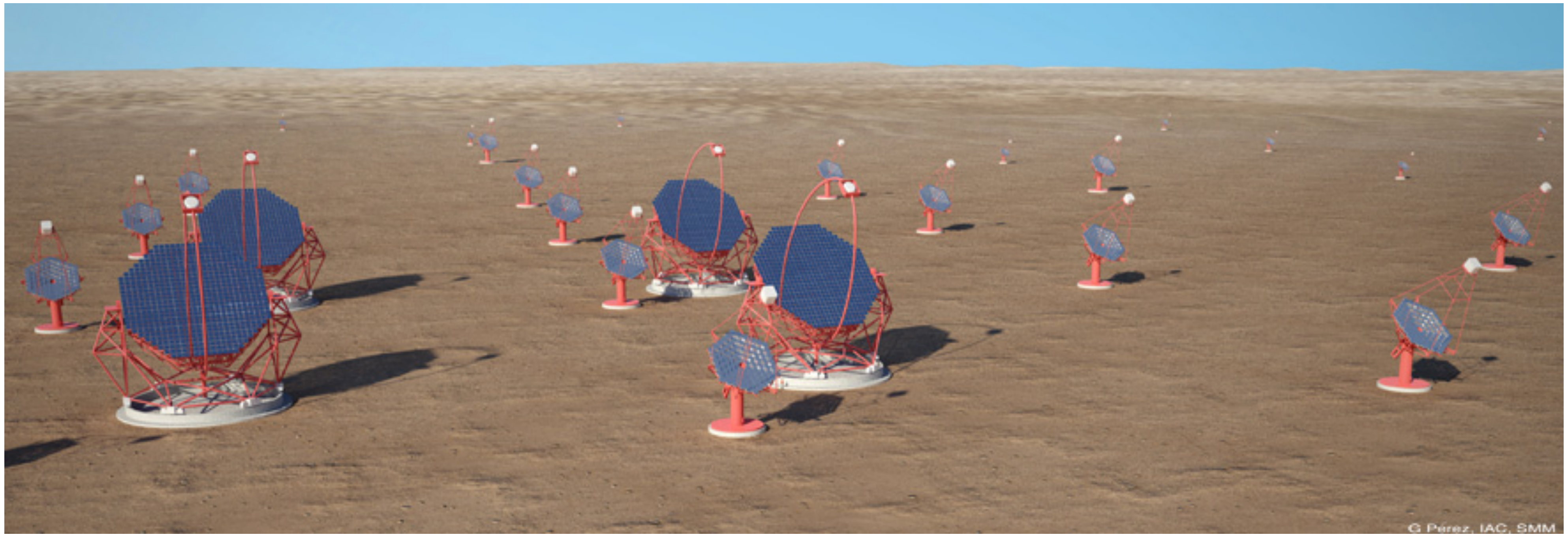
The Cherenkov Telescope Array: The Future of γ-ray Astrophysics

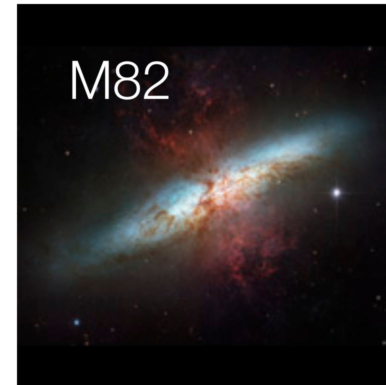


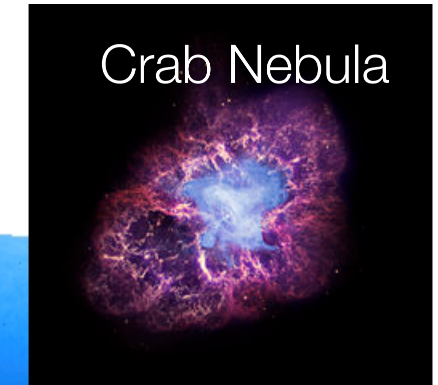
Presentation to the Mid-Decade Review
December 13, 2015

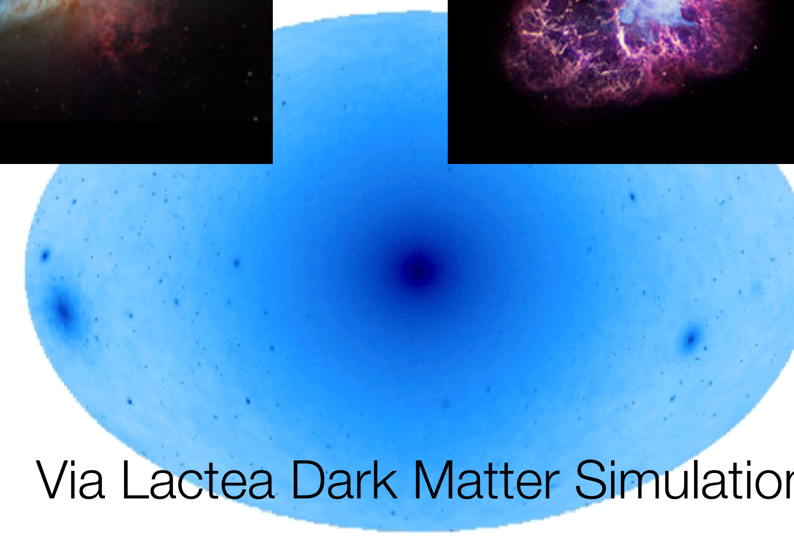
David A. Williams, University of California, Santa Cruz,
on behalf of CTA-US and the CTA Consortium

www.cta-observatory.org

CTA — A Worldwide Effort in Very High Energy Gamma-Ray Astrophysics



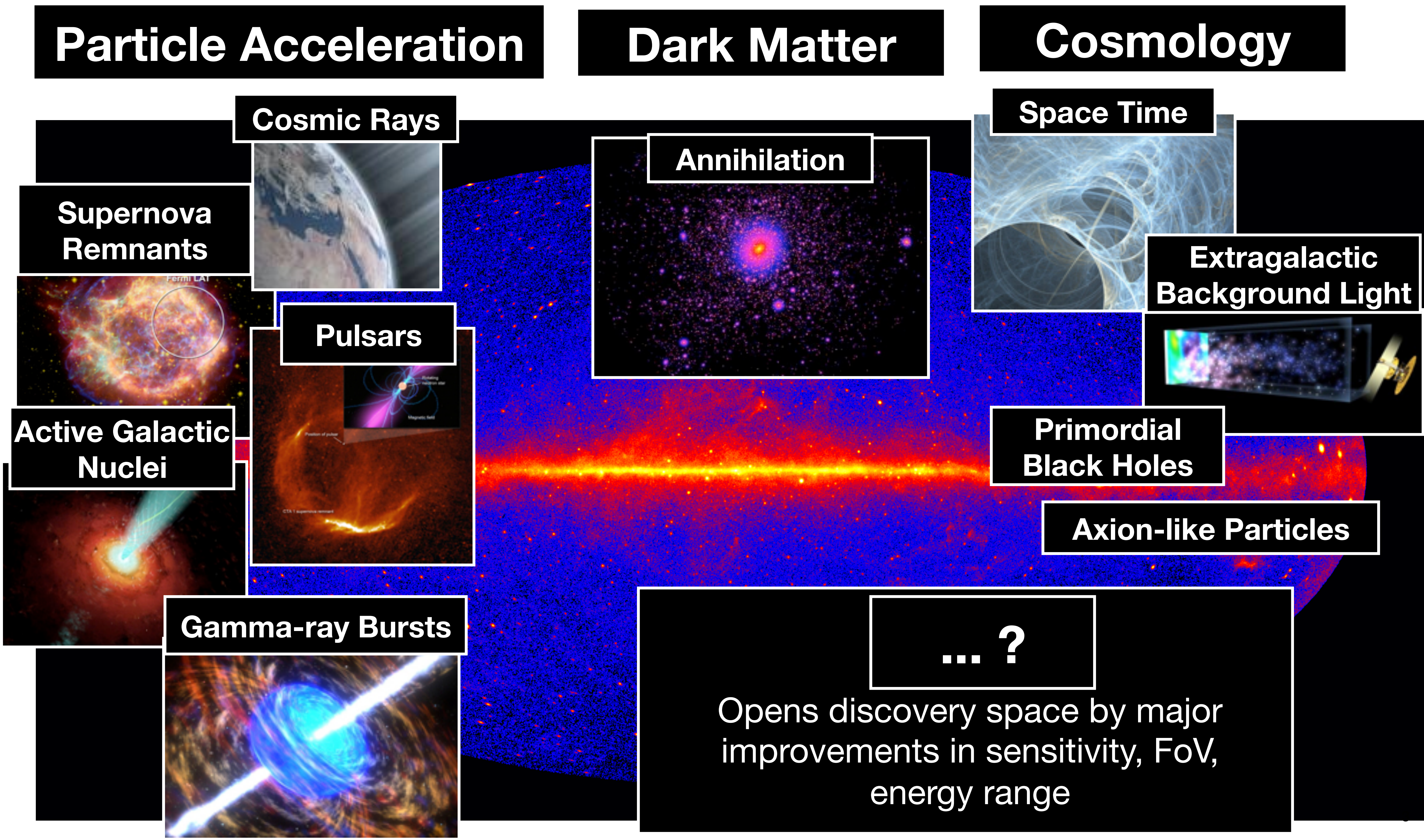




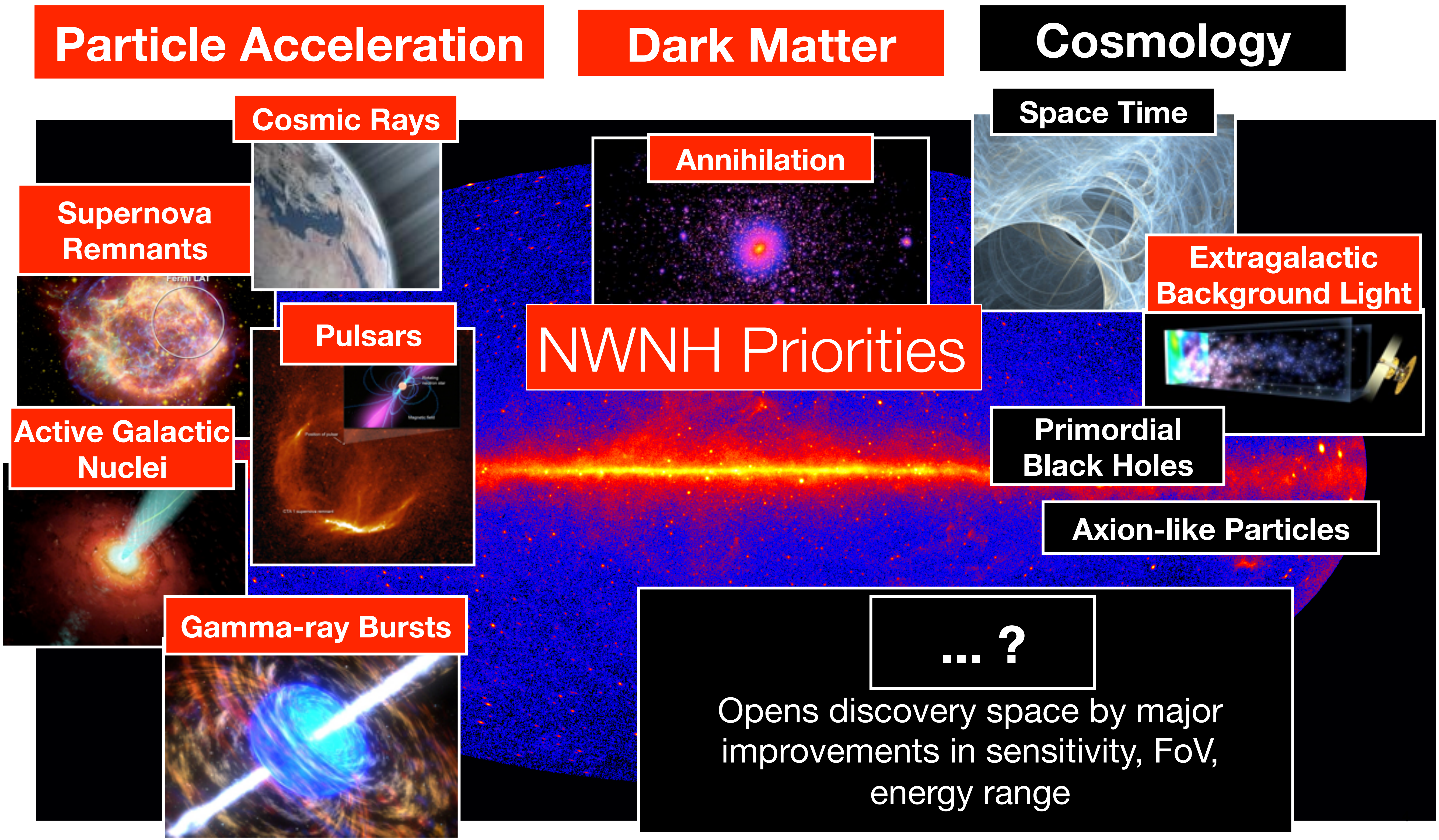
Via Lactea Dark Matter Simulation

- Great promise in astrophysics and fundamental physics revealed by the success of current instruments
  - ✓ 4th ranked large ground-based project by NWNH
  - ✓ Medium-sized budget for U.S.
- Worldwide community has come together around this single project
  - ✓ Many reviews: PASAG, NWNH, ESFRI, P5, etc..
- CTA has been in development for several years
  - ✓ Imaging atmospheric Cherenkov technique, pioneered in U.S., is well understood
  - ✓ Detailed work on design and simulations; prototypes under construction
  - ✓ Established international collaboration
- We propose significant U.S. participation so that CTA can achieve its science goals & U.S. scientists have access
  - ✓ *$25M over five years, starting in 2018*
  - ✓ Costs shared by NSF Astronomy and NSF Physics

Broad Spectrum of Science



Broad Spectrum of Science



Time Allocation & Key Science Projects

- 50% of observing time open for proposals from the astrophysics community
    - ➢ *Eligibility based on nation's contribution to CTA construction and operations*
- 40–50% of observing time for Key Science Projects
- All data will become public after a proprietary period (typically 1 year)

Big Questions / **Key Science Projects**

	Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
1	Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
		1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
		1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
2	Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
		2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
		2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
3	Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
		3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
		3.3	Do Axion-like particles exist?					✔	✔			✔✔	

Time Allocation & Key Science Projects

cherenkov telescope array

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1 Understanding the Origin and Role of Relativistic Cosmic Particles	1.1										✔	✔✔
	1.2										✔✔	✔
	1.3										✔	✔
2 Probing Extreme Environments	2.1										✔✔	
	2.2										✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
3 Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

Main science drivers for CTA in NWNH:

- Indirect detection of dark matter
- Particle acceleration
- AGN science

Time Allocation & Key Science Projects

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Big Questions | Key Science Projects

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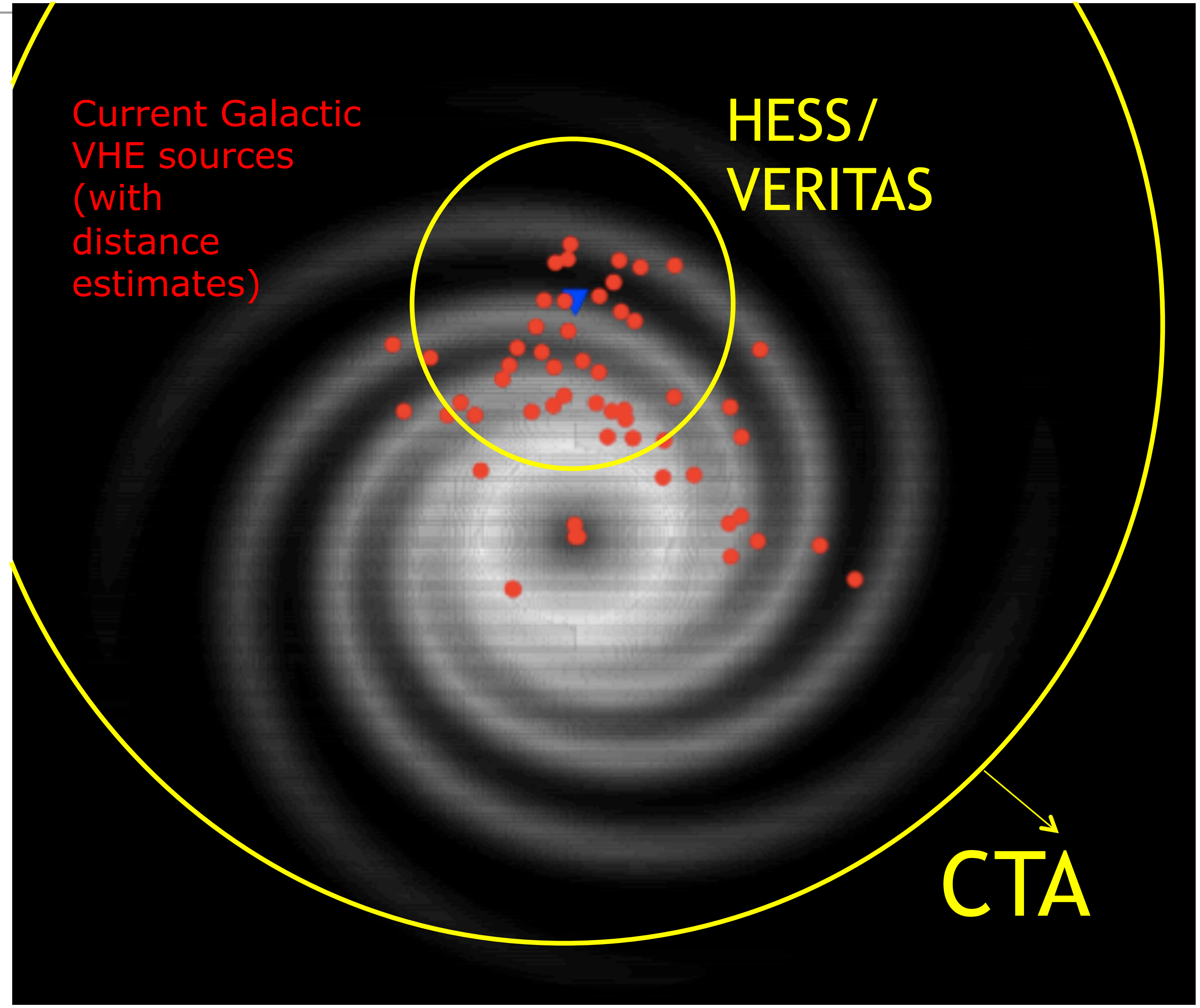
Particle Acceleration	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
		What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
2 Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Dark Matter		What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
3 Exploring Frontiers in Physics	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

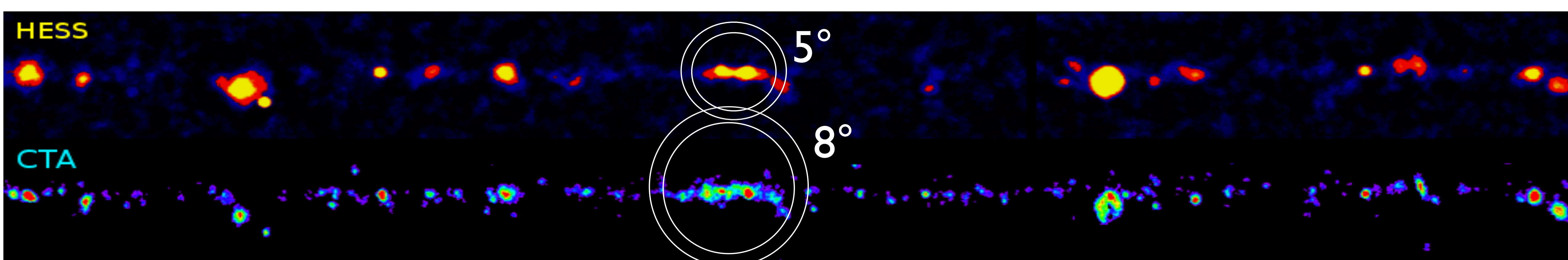
Galactic Particle Accelerators

Surveys of:

- Galactic center
- Galactic plane
- LMC

Survey speed:
x300 faster than
current instruments



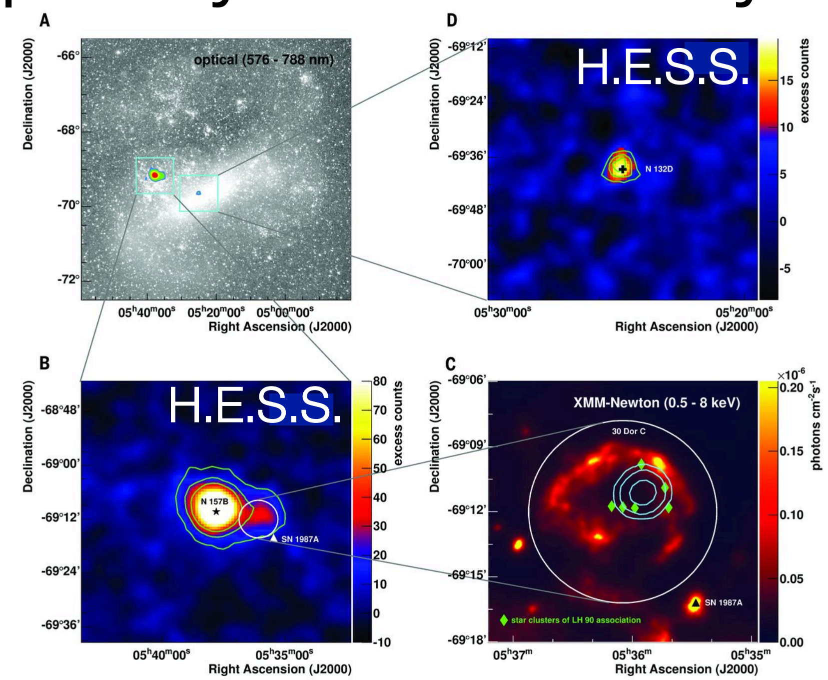


Many Discoveries since NWNH

Typically at sensitivity limit of current instruments

Multiple sources in the LMC

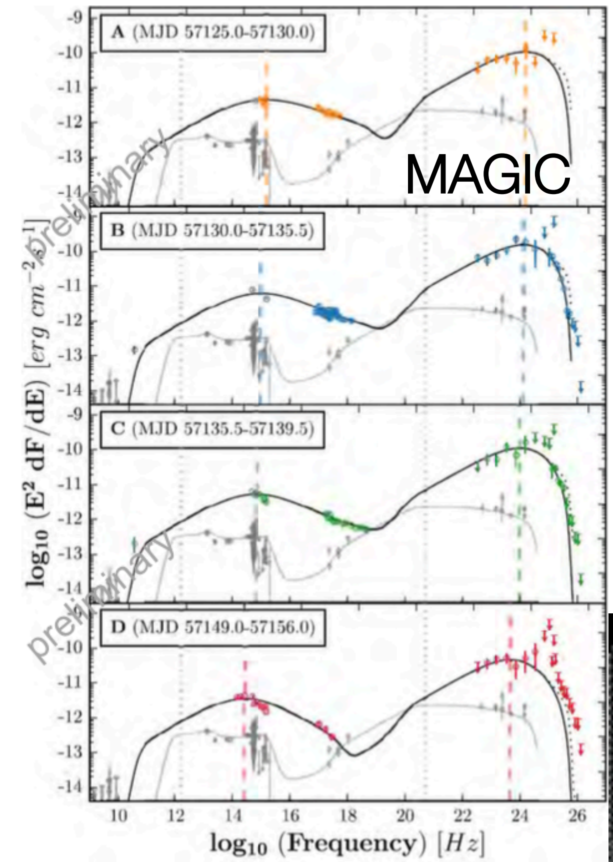
The H.E.S.S. Collaboration 2015, *Science* 347, 406

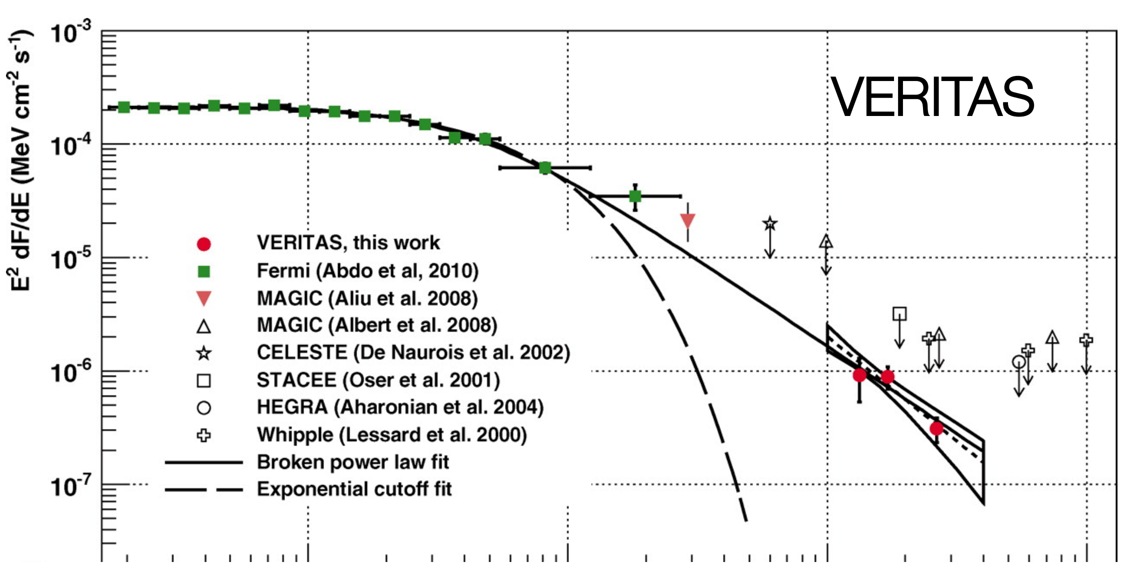


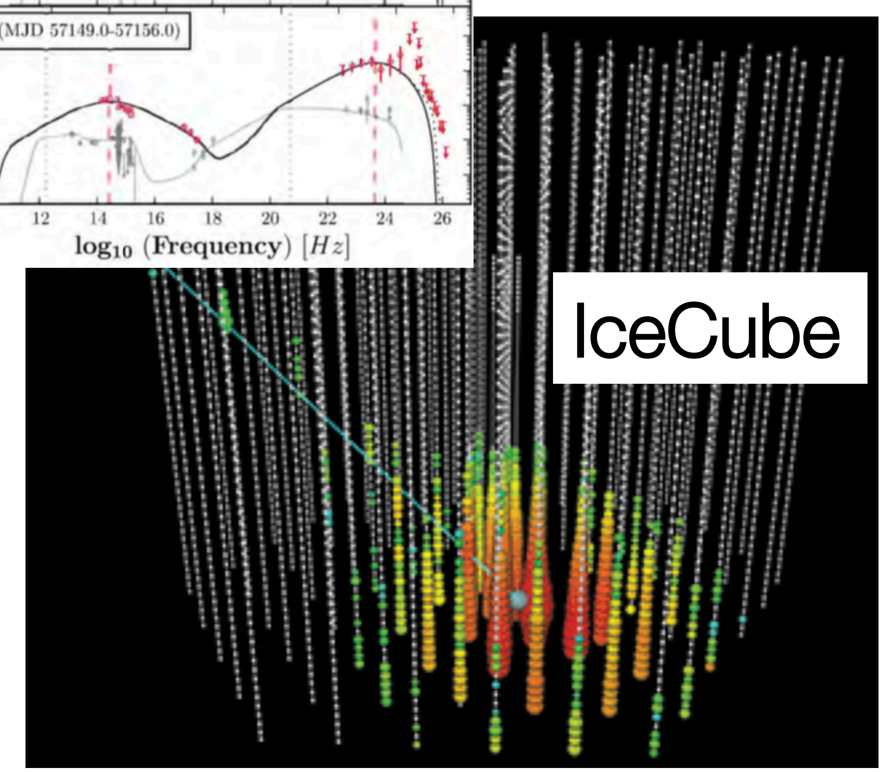
AGN out to redshift of ~1

R. Mirzoyan 2014, *ATel* #6349

Becerra, 34th ICRC *ApJL*, in press







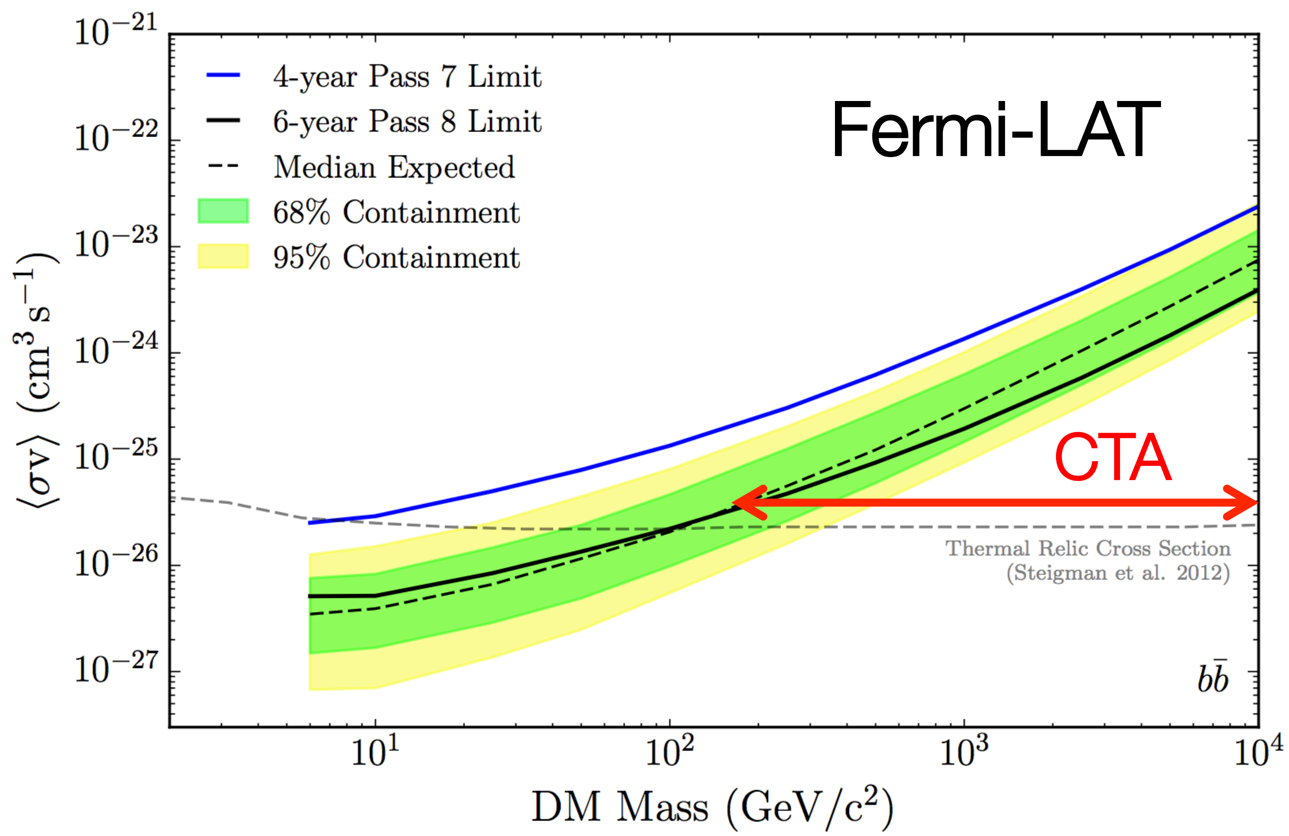
Pulsed emission from Crab > 100 GeV

E. Aliu et al. 2011, *Science* 334, 69

Cosmic neutrinos of unidentified origin

IceCube Collaboration 2013, *Science* 342, 1242856

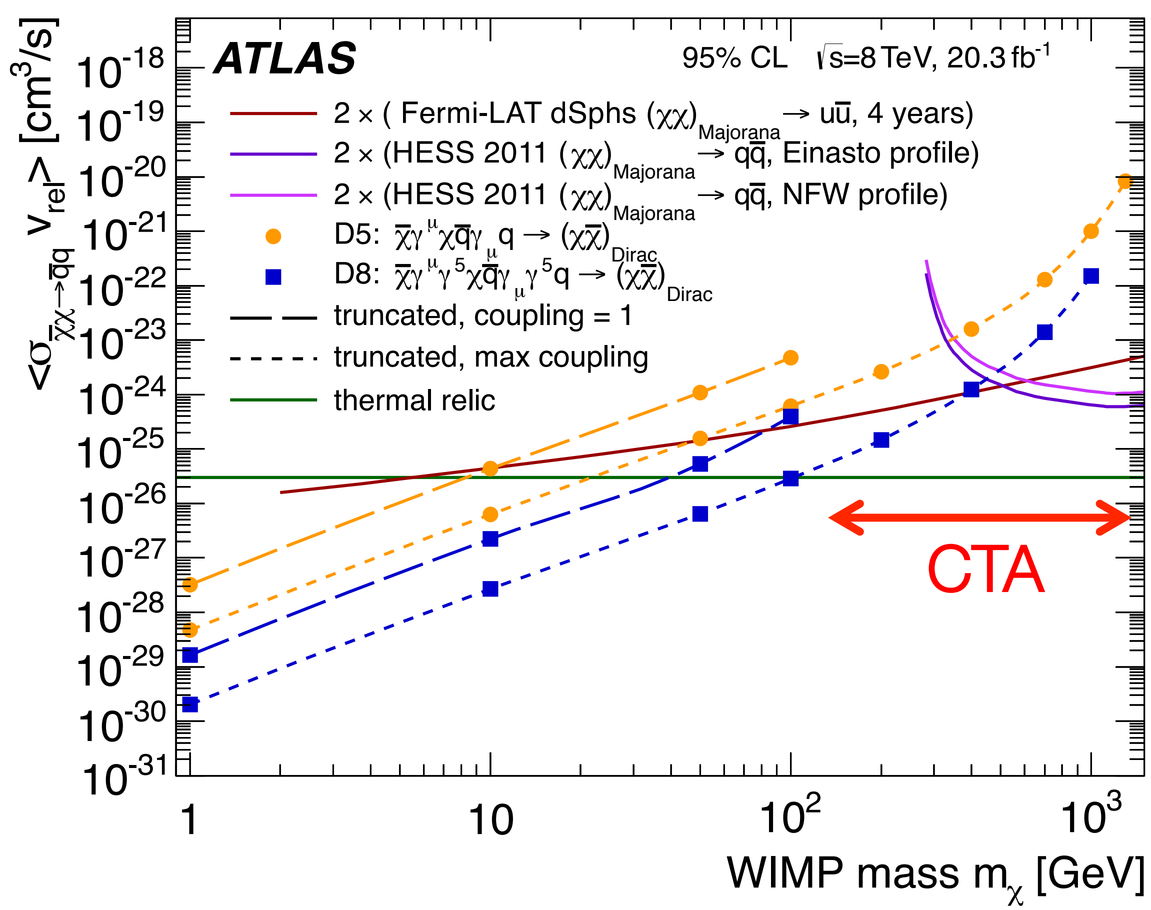
Since NWNH: Light WIMP Not Found



Ackermann et al. 2015, PRL 115, 231301

LHC direct production search and Fermi-LAT indirect search rule out light WIMPS with thermal relic cross section

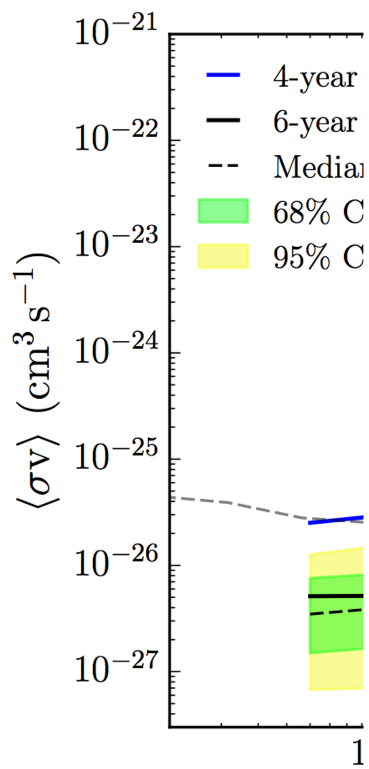
CTA probes WIMP masses not reached by these experiments



Many intriguing reports of evidence for dark matter particles— none has yet proved convincing

Aad et al. 2015, Eur. Phys. J. C 75, 299

Since NWNH: Light WIMP Not Found



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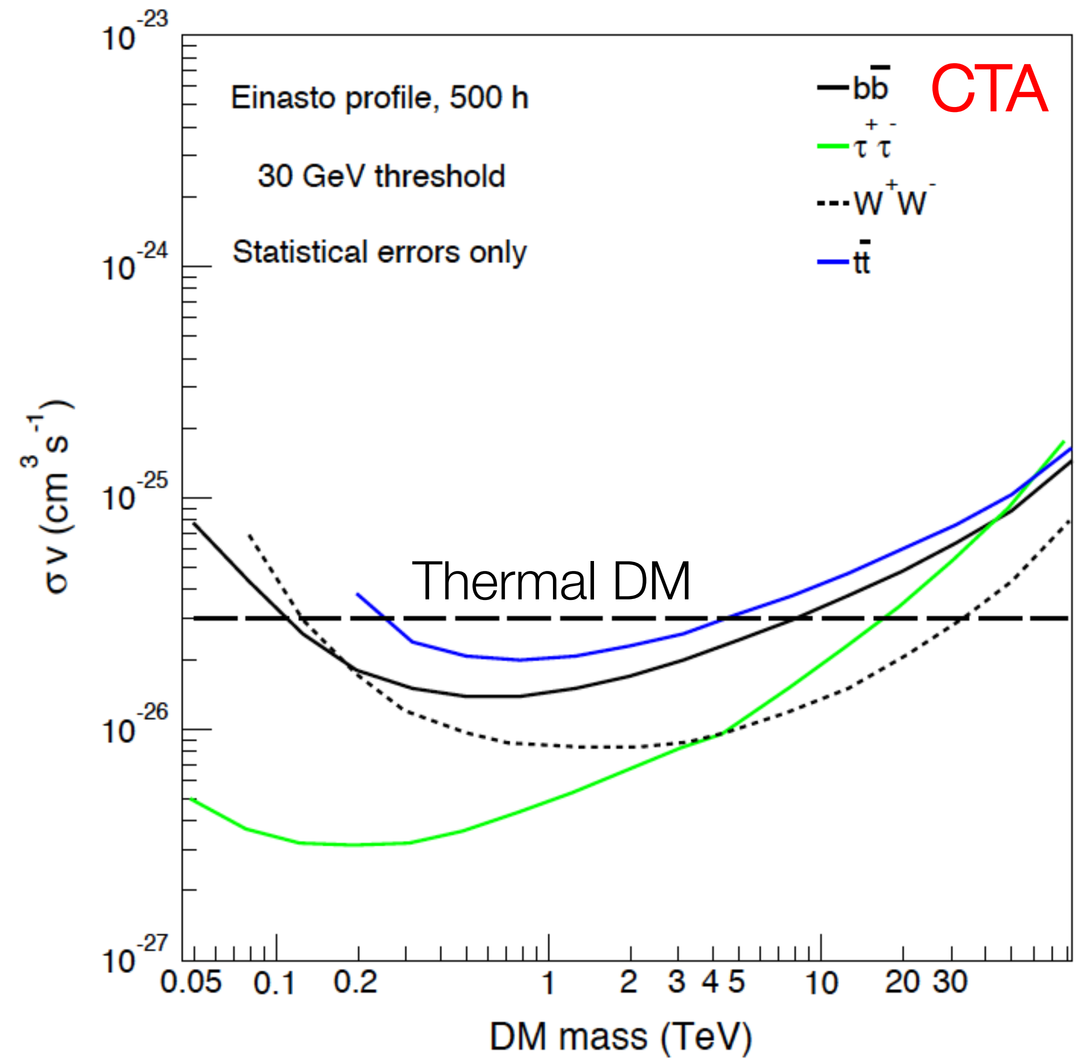

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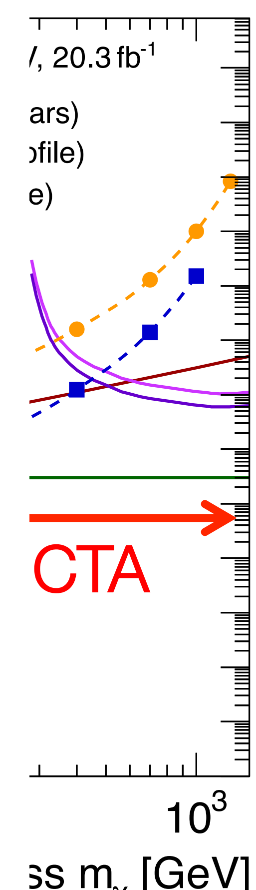
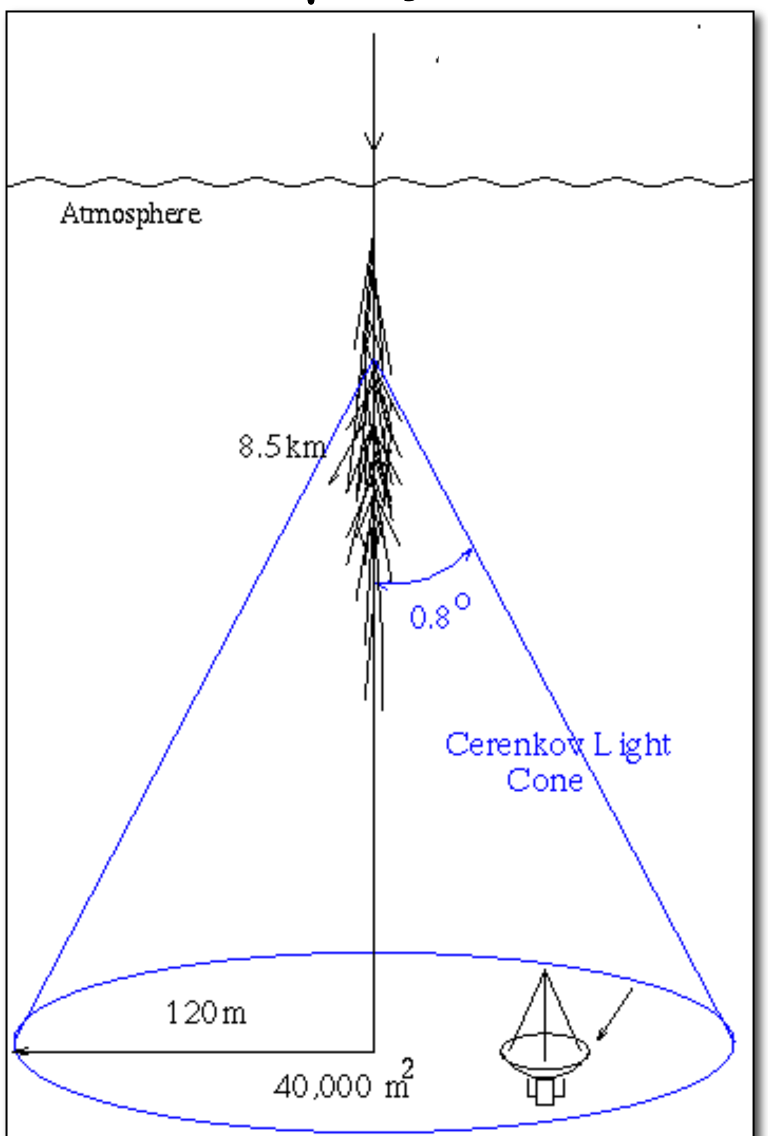


75, 299

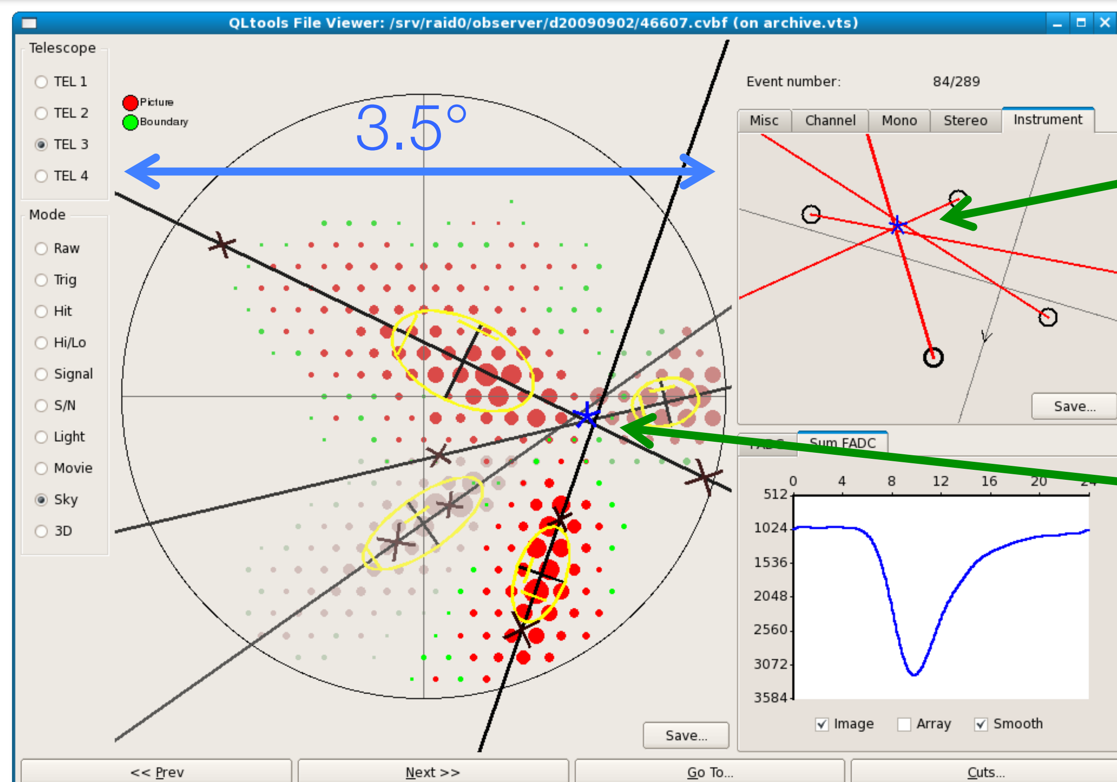
CTA will probe, *at the level of the thermal relic cross section,* WIMP masses and couplings not accessible to the LHC or direct detection

The Atmospheric Cherenkov Technique



Area = $10^4 - 10^5$ m²
~100 photons/m²/TeV

γ-rays above ~80 GeV
(12 m telescope)

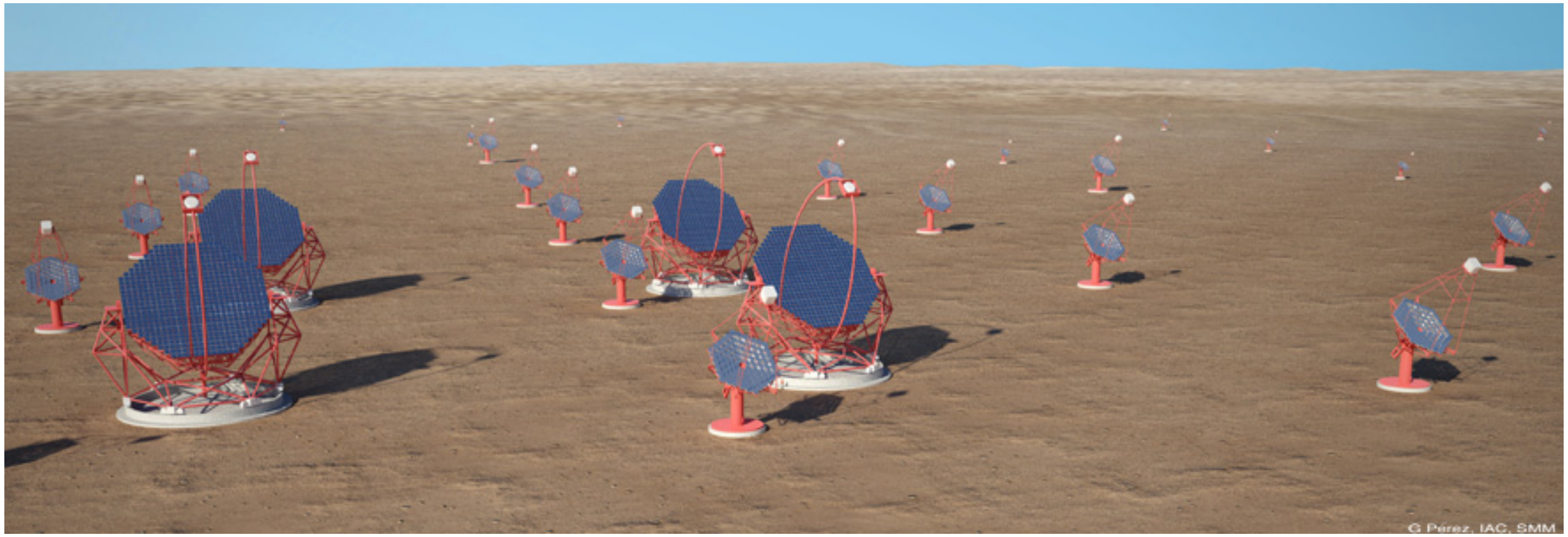


γ-ray projected impact position on the ground

γ-ray origin location on the camera focal plane (sky)

superimposed images from four cameras

The CTA Concept ("Baseline")

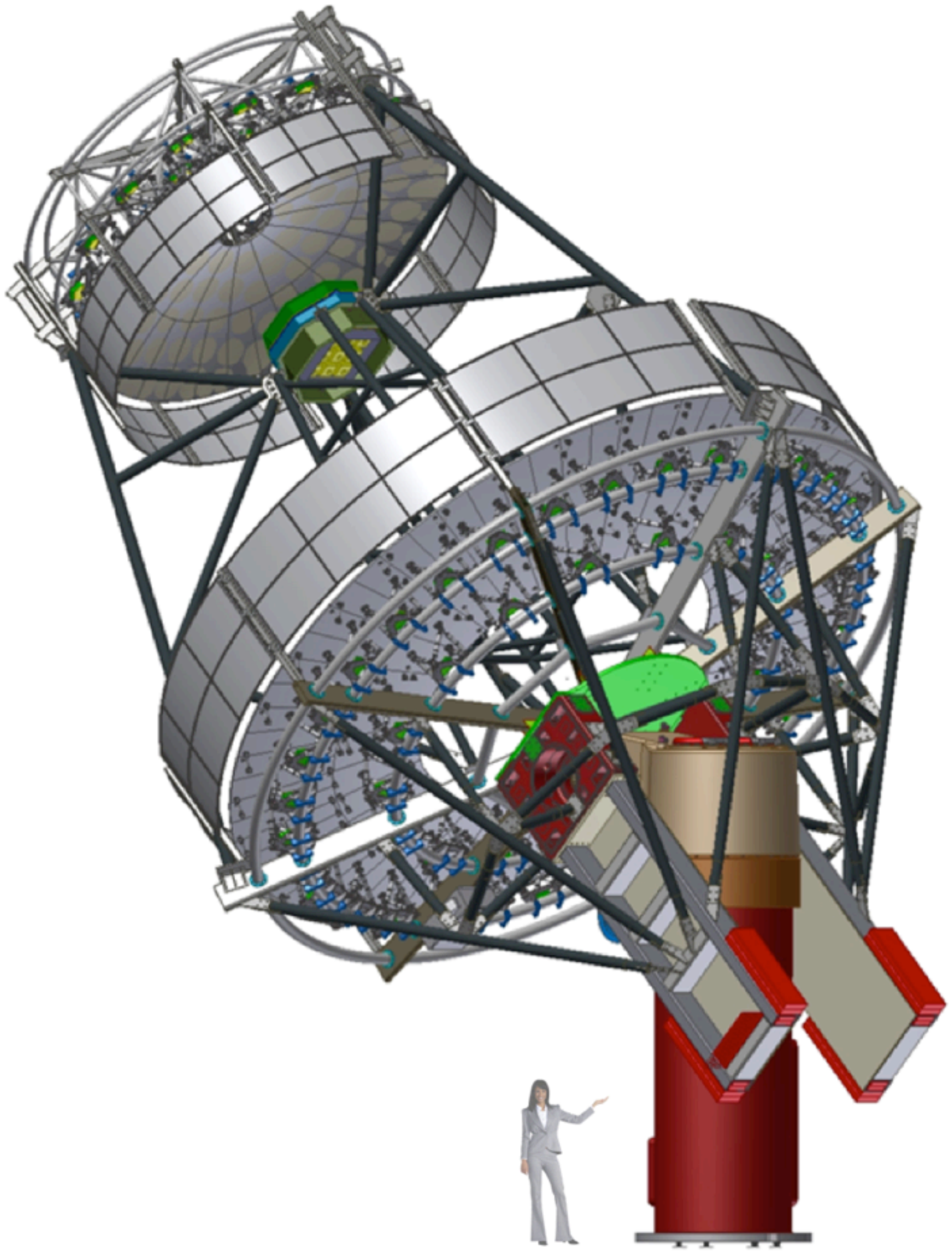


- Arrays in northern and southern hemispheres for full sky coverage
- 4 large (23 m) telescopes (LSTs) in the center — threshold of 30 GeV
- Southern array adds:
  - 25 medium (9-12 m) telescopes (MSTs) — 100 GeV – 10 TeV energy coverage
  - 70 small (~4 m) telescopes (SSTs) covering >3 km^2 — expand collection area >10 TeV for Galactic sources
- Northern array adds 15 MSTs (no SSTs)
- Project cost estimate €297M + 1480 FTE-years ~ €400M
- Operations cost estimated to be €20M/year

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

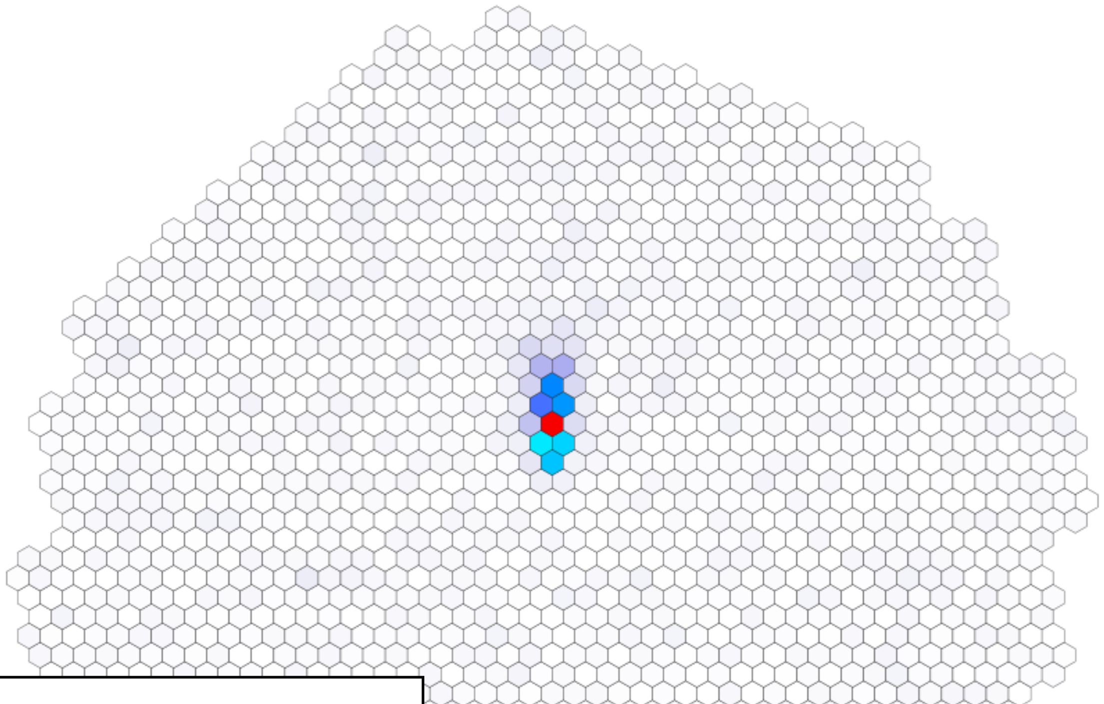
cta
cherenkov telescope array

- Designed to deliver performance close to theoretical limit of Cherekov technique
- 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 single-mirror medium-sized telescope
- Adopted now by European groups also for small-sized telescopes

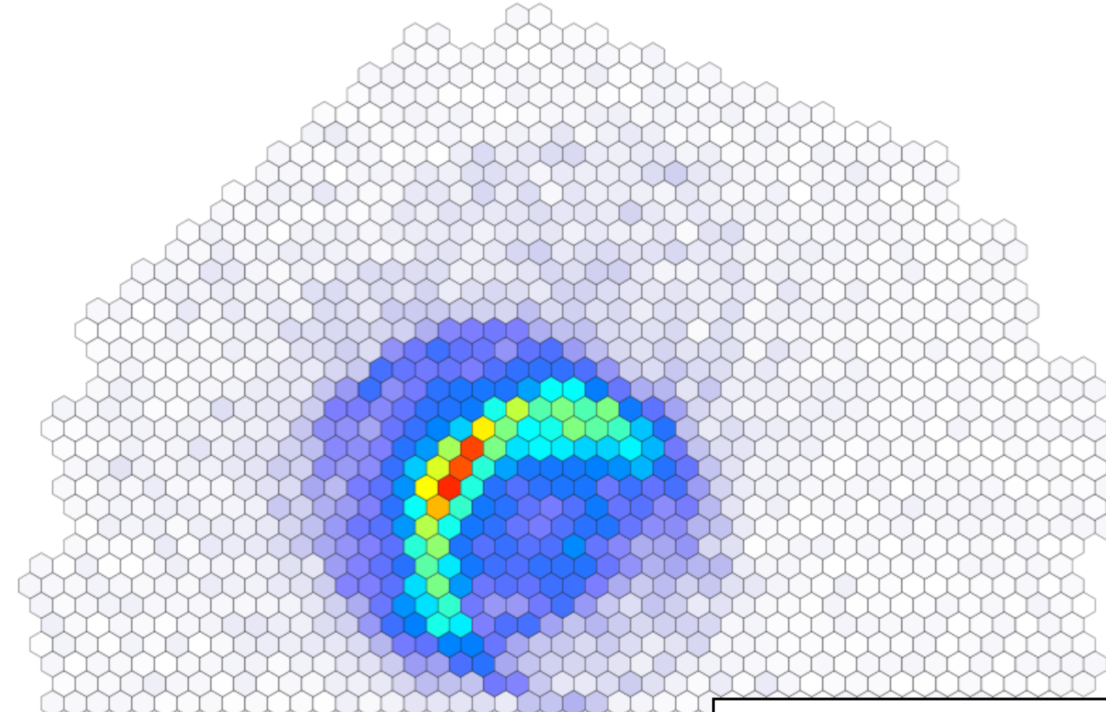


Uses the same positioner and foundation as single-mirror MST

The SCT: More Showers, Measured Better

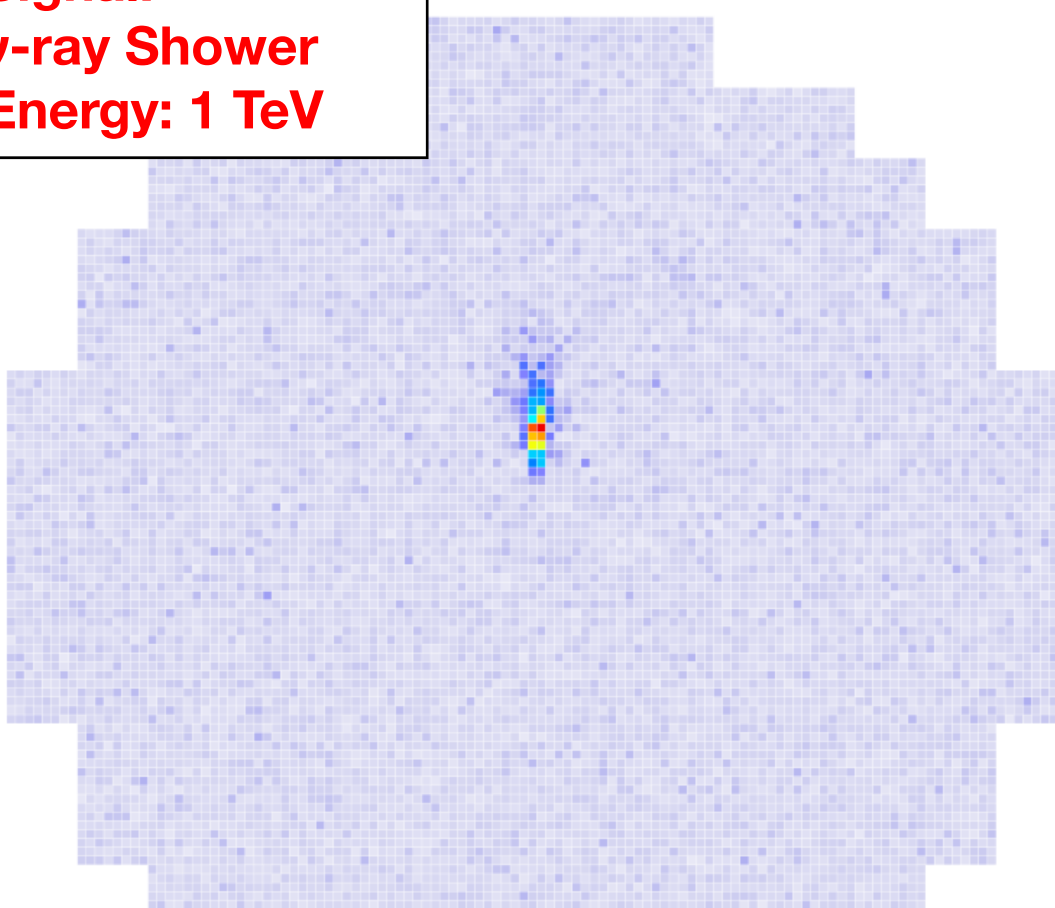


Single-Mirror
MST
Images
8° field of view
0.18° pixels
1,570 channels

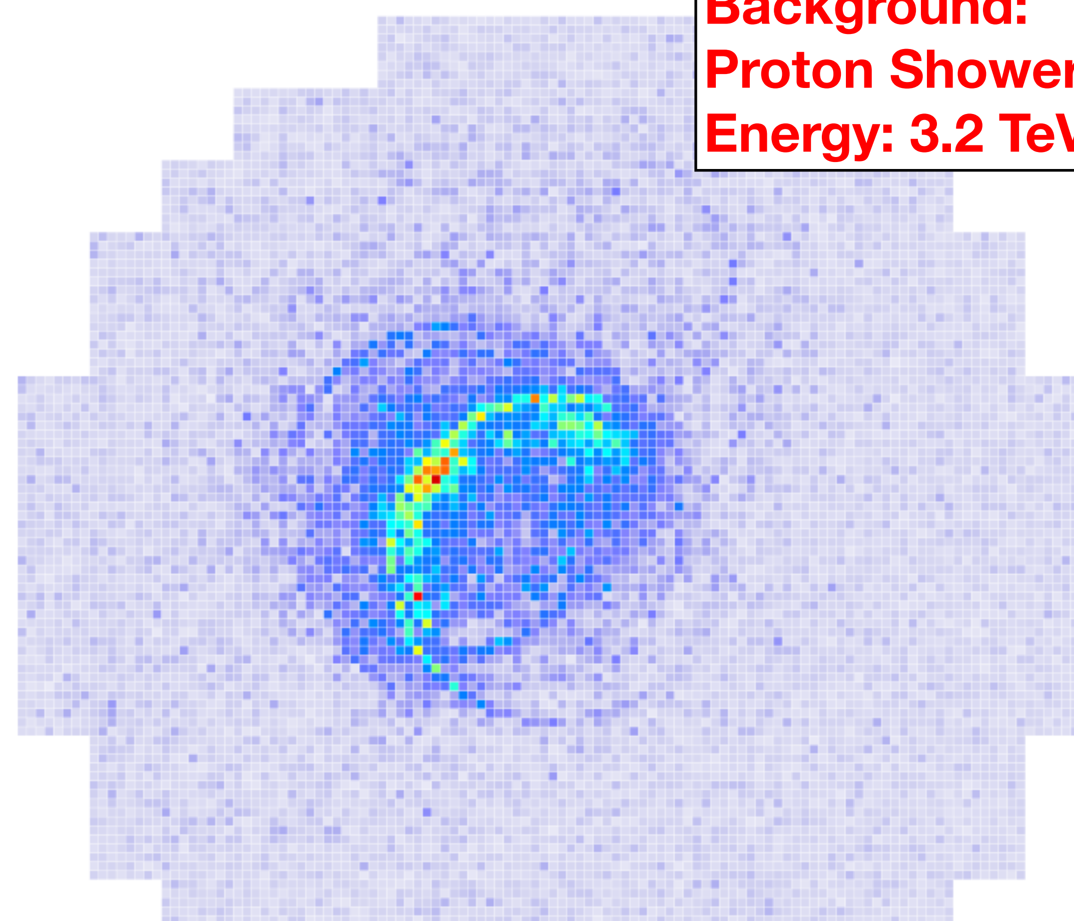


Signal:
γ-ray Shower
Energy: 1 TeV

Background:
Proton Shower
Energy: 3.2 TeV



U.S. Design
SCT
Images
8° field of view
0.067° pixels
11,328 channels



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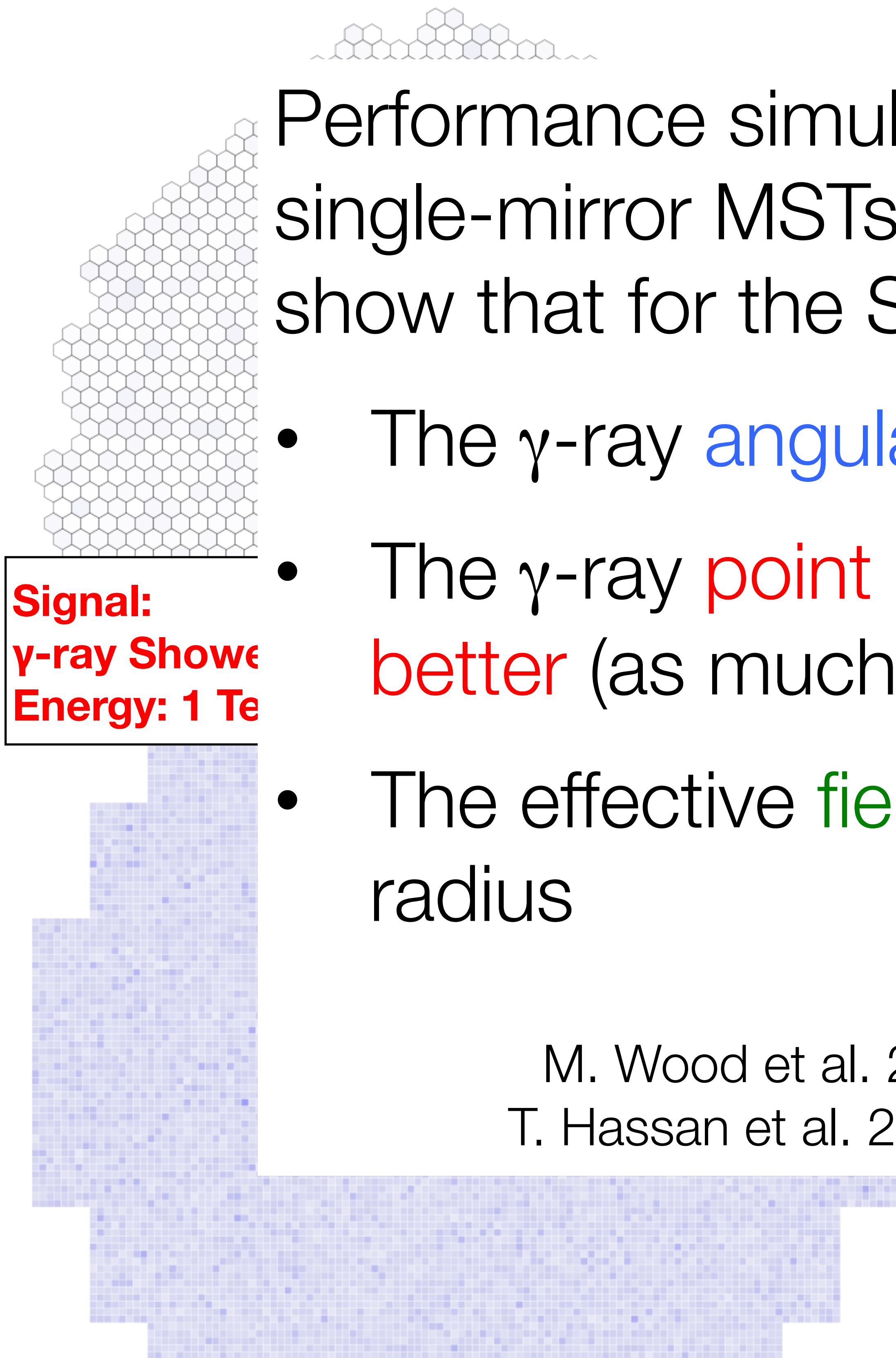
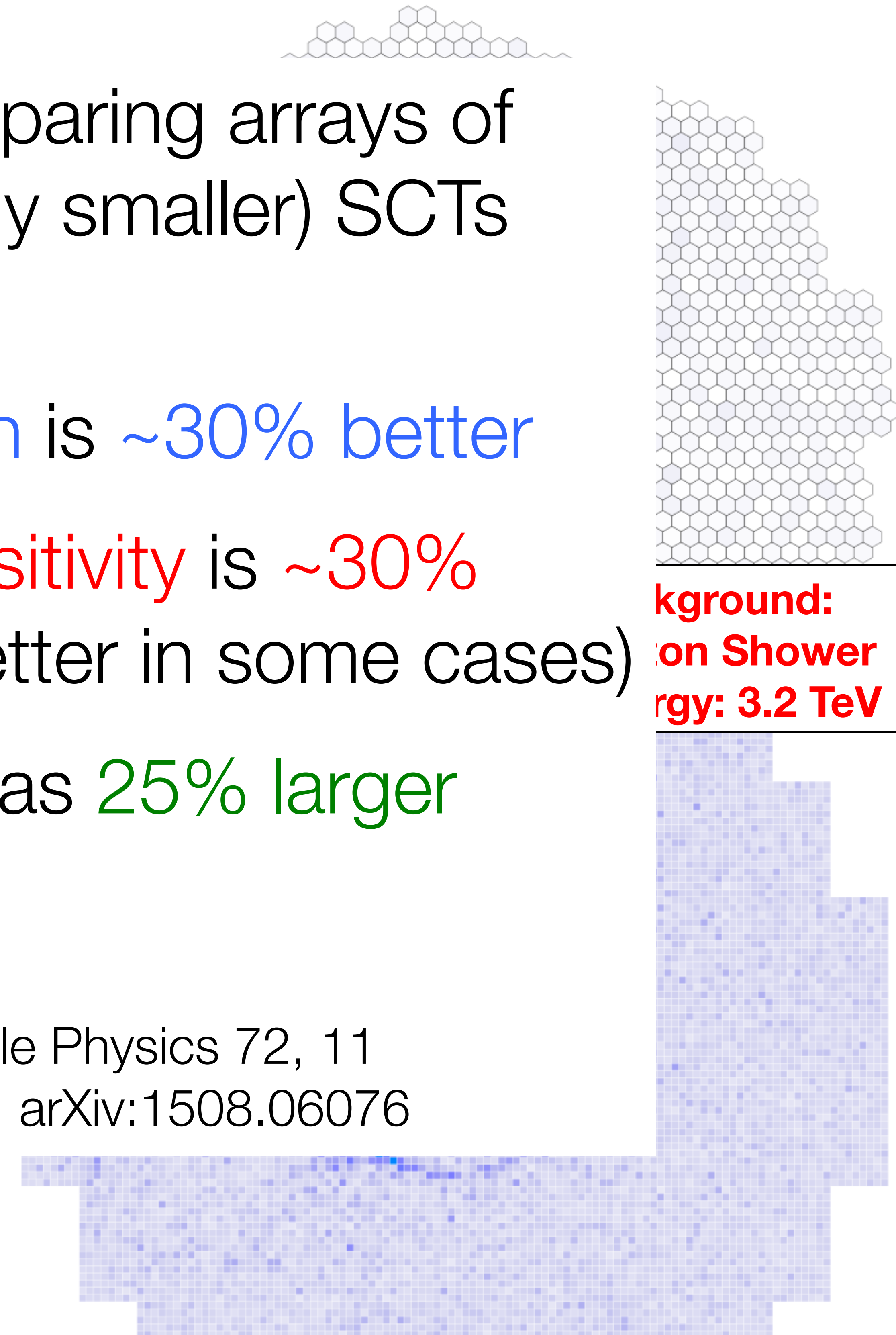


Performance simulations comparing arrays of single-mirror MSTs and (slightly smaller) SCTs show that for the SCT array:

- The γ-ray angular resolution is ~30% better
- The γ-ray point source sensitivity is ~30% better (as much as 50% better in some cases)
- The effective field of view has 25% larger radius

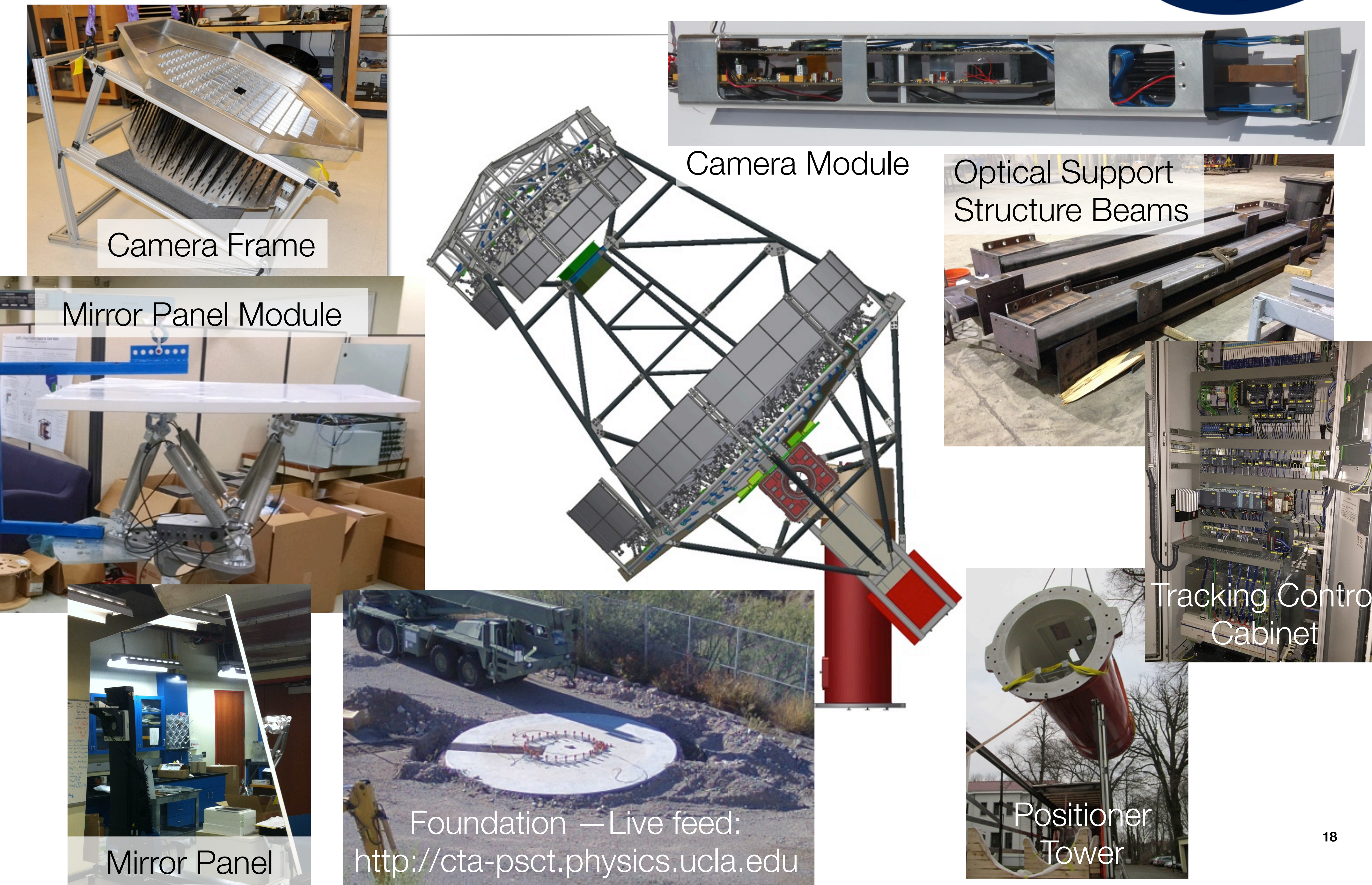
M. Wood et al. 2016, Astroparticle Physics 72, 11
T. Hassan et al. 2015, Proc. ICRC, arXiv:1508.06076



Since NWNH: CTA Development I

- U.S. AGIS effort merged into CTA in May 2010
  - ✓ As recommended by NWNH
  - ✓ CTA is now a unified effort worldwide for the next VHE γ-ray observatory
  - ✓ U.S. participation in most aspects of the project, especially SCT Work Package led by Vladimir Vassiliev (UCLA)
  - ✓ Amanda Weinstein (ISU) has been leading the array trigger group
  - ✓ Rene Ong (UCLA) elected CTA Co-Spokesperson in 2014
  - ✓ Ong and Vassiliev both members of the CTA Project Committee
- Prototype SCT construction funded by NSF MRI in 2012
  - ✓ $3.8M NSF + $1.3M cost share; >$2M university and lab funds in preparation
  - ✓ Prototype design completed & procurement largely complete
  - ✓ Assembly at Whipple Observatory will begin in early 2016
- CTA concept fleshed out and reviewed
  - ✓ Three reviews by external Science and Technical Advisory Committee (STAC) chaired by Roger Blandford
  - ✓ Many internal reviews as preparation — including SCT review September 2013
  - ✓ Next review in early 2017

The Prototype SCT Takes Shape



Since NWNH: CTA Development II

- P5* Review (2014) recommends U.S. participation in CTA
  - ✓ Particle physics science prospects justify particle physics funding investment
  - ✓ Shared science benefits with astronomy call for joint astronomy participation
- CTA Observatory gGmbH formed to manage construction
  - ✓ Governed by Council of shareholder nations; U.S. is one of several observer nations
  - ✓ Operates CTA Project Office
- Sites selected — subject to final negotiations
  - ✓ ESO, Paranal, Chile in the south
  - ✓ ORM, La Palma, Spain in the north
- Financial participation coming into focus
  - ✓ Substantial funding from Germany, Italy, Spain and Japan (€20–50M each)
  - ✓ Substantial participation hoped for from France and U.S.
  - ✓ Many participants at <€10M level
- Construction as early as late 2016 — through ~2023

*Particle Physics Project Prioritization Panel

NWNH: International Collaboration Rewarding, but Challenging

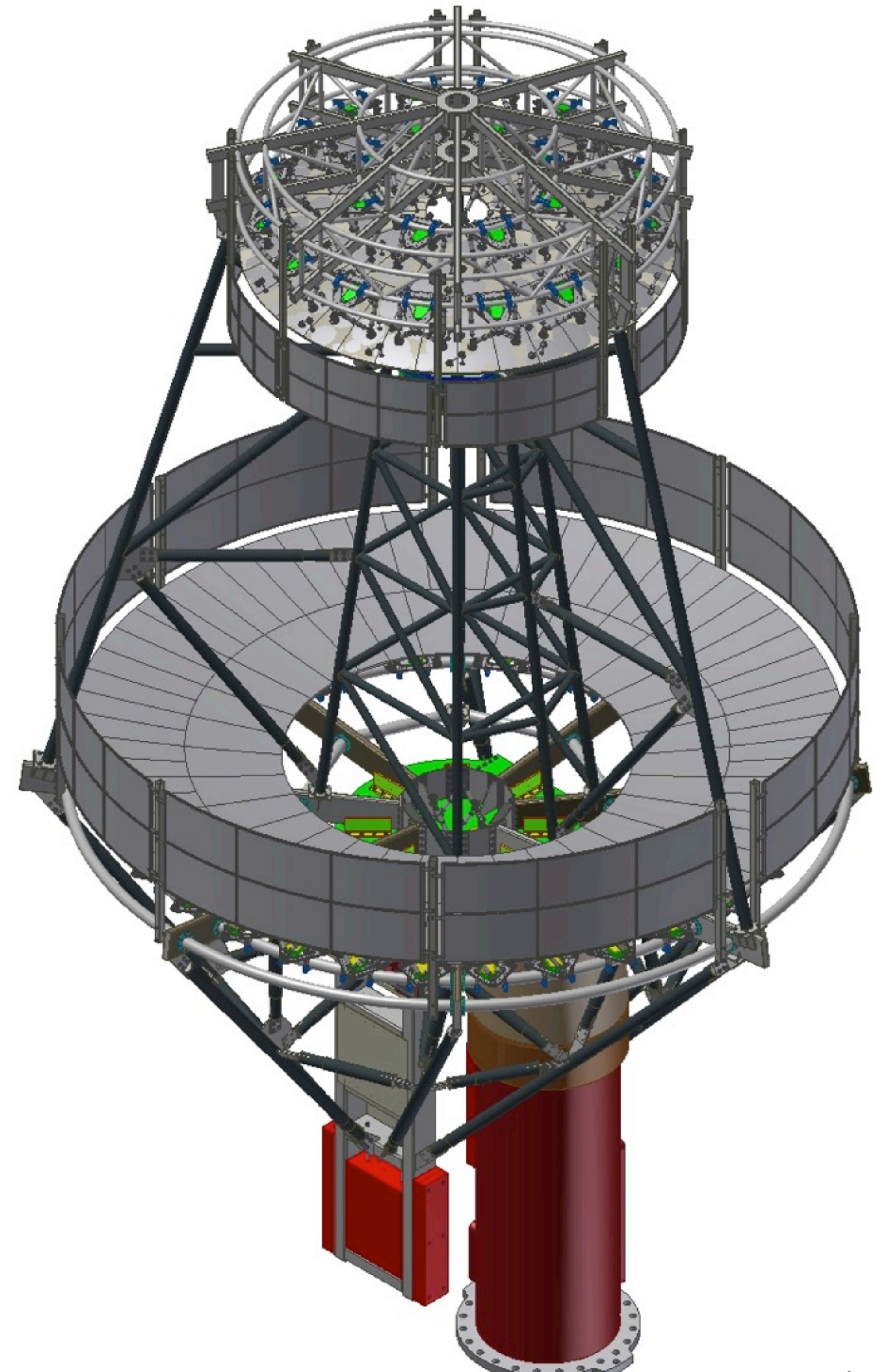
NWNH "CONCLUSION: Complex and high-cost facilities are essential to major progress in astronomy and astrophysics and typically involve collaboration of multiple nations and/or collaboration of federal and non-federal institutions. These partnerships bring great opportunities for pooling resources and expertise to fulfill scientific goals that are beyond the reach of any single country. However, they also present management challenges and require a new level of strategic planning to bring them to fruition."

NWNH "RECOMMENDATION: U.S. investors in astronomy and astrophysics, both public and private, should consider a wide range of approaches to realize participation in international projects and to provide access for the U.S. astronomy and astrophysics community to a larger suite of facilities than can be supported within the United States. The long-term goal should be to maximize the scientific output from major astronomical facilities throughout the world, …"

CTA observation: A framework for strategic planning of mid-scale projects by NSF would be very helpful for achieving these goals and recommendations.

CTA-US Goals

- **Implementation of the baseline 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 baseline MST array(s) in S or N with 15 SCTs
  - ✓ In collaboration with international partners
  - ✓ In S would add to 10 single-mirror MSTs
- 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



Putting the Pieces Together

- CTA a highly coordinated and integrated project
  - ✓ No one group foreseen to provide complete MSTs
- German groups together propose to build first 10 single-mirror MSTs in south — design-ready fast start
- Funding for additional MSTs in many pockets; in most cases the MSTs could be SCTs
  - ✓ ~€20M in Spain for northern MSTs
  - ✓ ~€10M in Germany for southern MSTs
  - ✓ Potential funding in Italy for mirrors (INAF) and cameras (INFN)
  - ✓ Potential funding in France for mirrors & cameras (specific to single-mirror design)
  - ✓ Potential interest from other participants
- Still work to do to assemble the full project
  - ✓ A coherent plan necessary for a successful U.S. proposal
  - ✓ See NWNH Conclusion on earlier slide
  - ✓ E.g. U.S. & Spanish funding would provide nearly a full northern MST solution

Science Impact of U.S. Participation

- U.S. expertise in SCT enhances the capability of CTA
  - ✓ SCT design also being used for 2 of 3 small-sized telescope implementations
- Sizable contribution to realization of baseline MST arrays
  - ✓ About 25% (S) or 40% (N) of either array alone; 15% of combined MST arrays
- U.S. participation in Key Science Projects
  - ✓ Improved outcomes from broader participation
  - ✓ U.S. shares credit for the work
- Access to CTA Observatory for U.S. scientists
  - ✓ Eligibility to compete for open time for all U.S. scientists
  - ✓ Participation in Key Science by CTA Consortium members
  - ✓ Opportunities for education and training of the next generation of scientists
- Continues the legacy of work at the Whipple Observatory in the U.S. which established the field

Impact of $25M on a €400M Project

- The highly integrated nature of the project means that it will readjust based on available resources
- Three *subjective* hypotheses do lead to some conclusions
  - ✓ With substantial U.S. and French participation, both baseline MST arrays can be complete
  - ✓ Without U.S. participation, only single-mirror MSTs will be built
  - ✓ The U.S. brings one of the MST arrays into its complete baseline configuration with 15 SCTs, and it would otherwise be 6 telescopes smaller (and all single-mirror telescopes)

	South	North
Telescopes w/o U.S.	19 single-mirror MST	9 single-mirror MST
Telescopes w/ U.S.	10 single-mirror MST + 15 SCT	15 SCT
	Improvement Factors with U.S. Participation	
Angular resolution (containment radius)	1.25	1.5
Point source sensitivity	1.3	1.7
Point source time to significance	1.7	2.9
Field of view (effective radius)	1.14	1.25
Survey speed	2.2	4.5

or

Impact of $25M on a €400M Project

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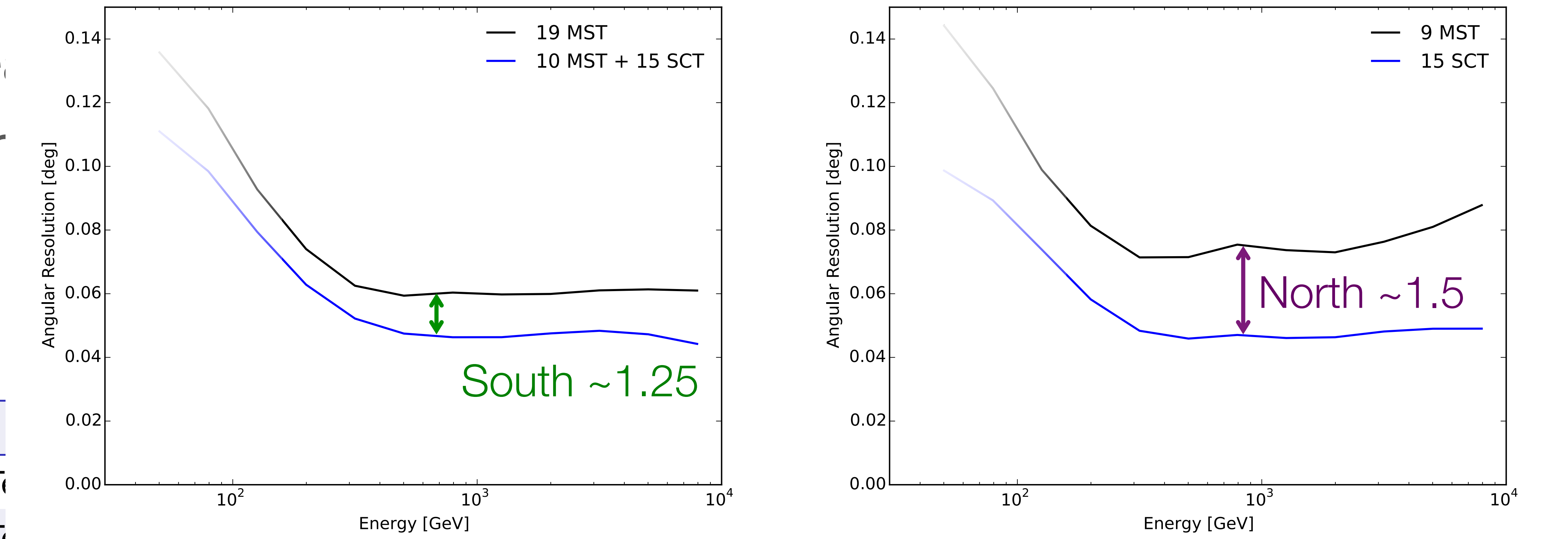

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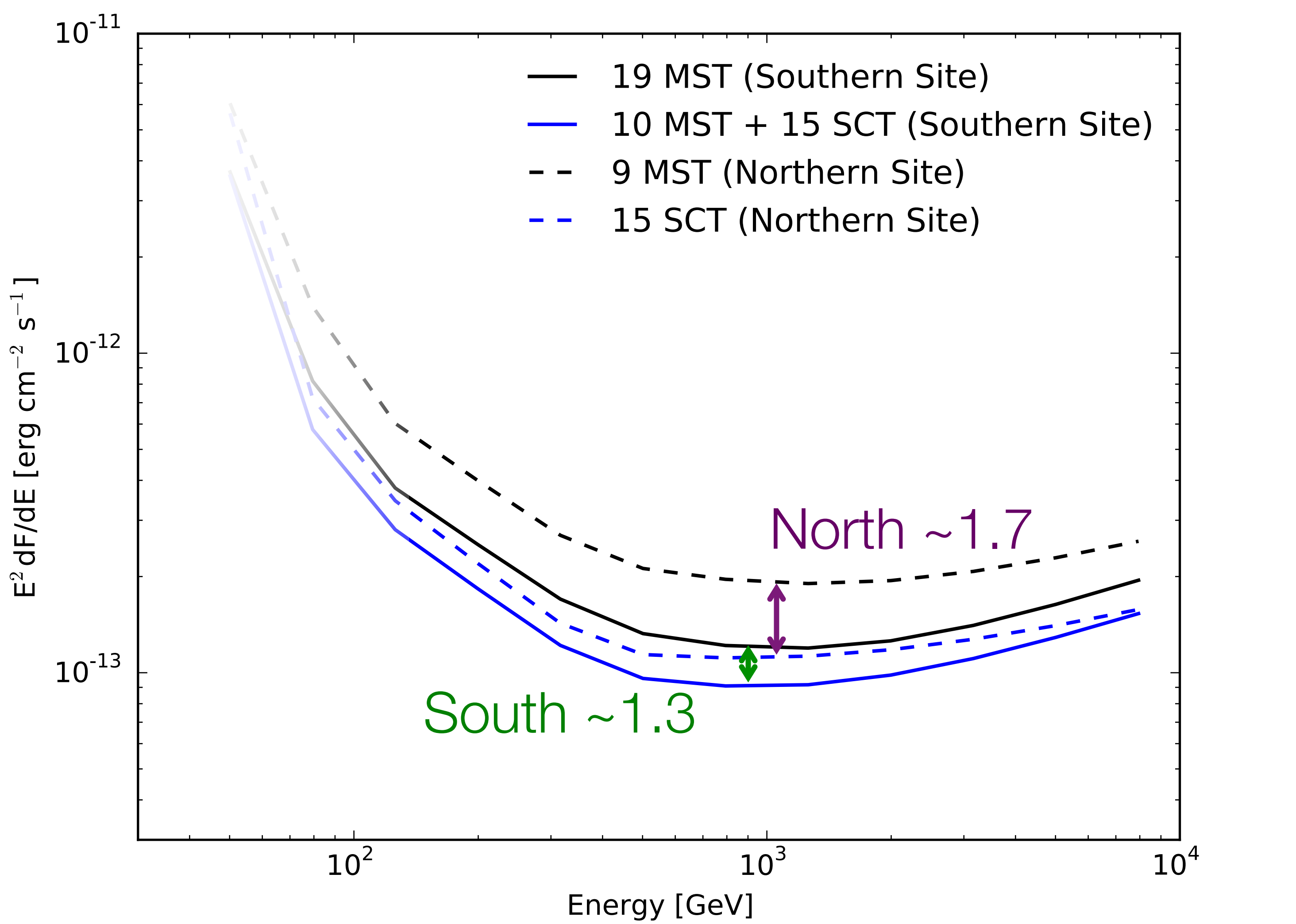
Sources resolved in more detail

or

Impact of $25M on a €400M Project

- The highly i[...] hat it will readjust bas[...]
- Three *subje*[...] clusions
  - ✓ With substanti[...] be complete
  - ✓ Without U.S. p[...]
  - ✓ The U.S. bring[...] with 15 SCTs, and it would otherw[...]



		North
Telescopes w/o U.S		e-mirror MST
Telescopes w/ U.S.		15 SCT
		cipation
Angular resolution (containment radius)	1.25	1.5
Point source sensitivity	1.3	1.7
Point source time to significance	1.7	2.9
Field of view (effective radius)	1.14	1.25
Survey speed	2.2	4.5

More sources detected;
reduced impact of systematic errors

or

Impact of $25M on a €400M Project

- The highly integrated nature of the project means that it will readjust based on available resources
- Three *subjective* hypotheses do lead to some conclusions
  - ✓ With substantial U.S. and French participation, both baseline MST arrays can be complete
  - ✓ Without U.S. participation, only single-mirror MSTs will be built
  - ✓ The U.S. brings one of the MST arrays into its complete baseline configuration with 15 SCTs, and it would otherwise be 6 telescopes smaller (and all single-mirror telescopes)

	South	North
Telescopes w/o U.S.	19 single-mirror MST	9 single-mirror MST
Telescopes w/ U.S.	10 single-mirror MST + 15 SCT	15 SCT
	Improvement Factors with U.S. Participation	
Angular resolution (containment radius)	1.25	1.5
Point source sensitivity	1.3	1.7
Point source time to significance	1.7	2.9
Field of view (effective radius)	1.14	1.25
Survey speed	2.2	4.5

More objects studied

or

Impact of $25M on a €400M Project

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Better diffuse measurements; serendipitous discoveries

Impact of $25M on a €400M Project

cta cherenkov telescope array

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Faster, deeper surveys

or

CTA — Breakthrough Science within Reach

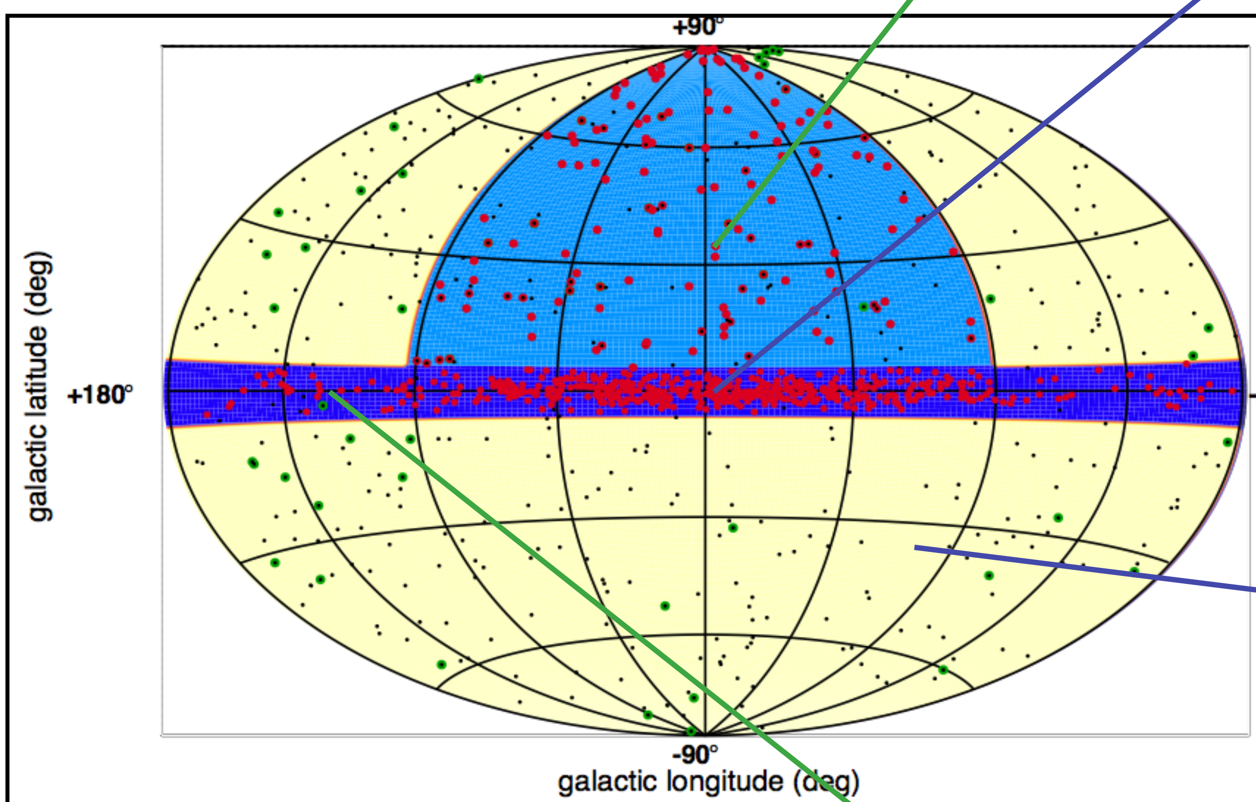
cta
cherenkov telescope array

- Science motivation as compelling as ever — still too important for the U.S. not to participate
  - ✓ Probes dark matter masses and couplings not reached by other methods
  - ✓ Much deeper sensitivity to science just surfacing with current instruments: Galactic Center region, pulsars, Galactic SNR, and distant AGN
  - ✓ VHE complement to studies at other wavelengths and with other "messengers": cosmic rays, neutrinos & gravitational waves
- Project organization on trajectory for construction
- Builds on decades of U.S. leadership, investment and success
- U.S. participation — even with a smaller budget — is essential to CTA realizing its full potential and achieving its science goals
- Strong international participation leverages U.S. contribution; a single worldwide effort
- U.S. access to the premier VHE γ-ray observatory of the decade — an opportunity not to miss!

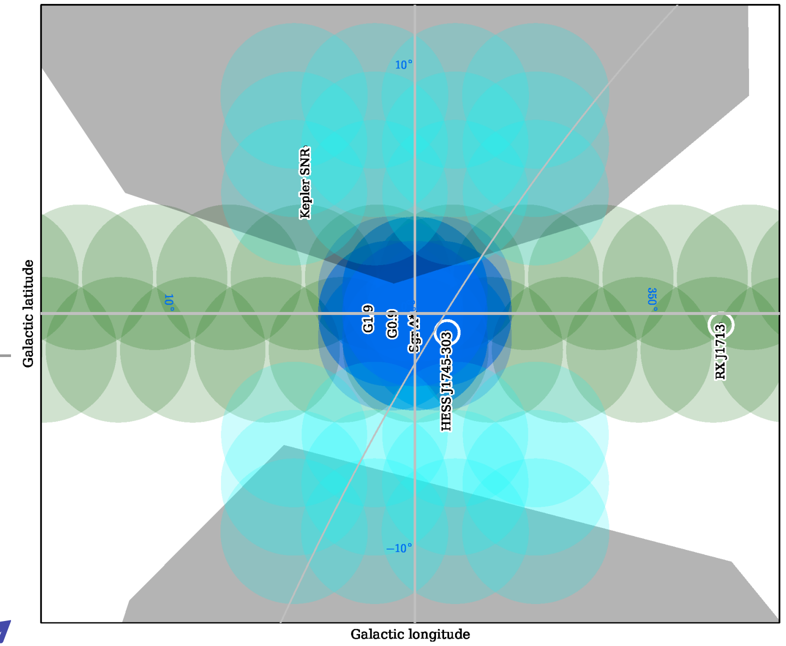
Backup

The Survey Key Science Projects

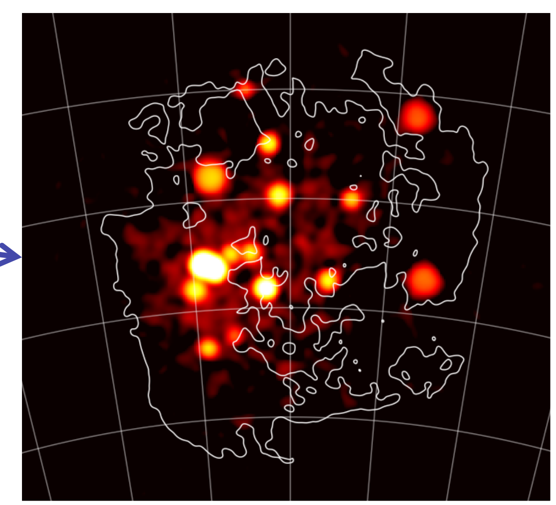
Extragalactic Survey:
Unbiased survey of ¼ sky to ~6 mCrab
VHE population study, duty cycle
New, unknown sources; 1000 h



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



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

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

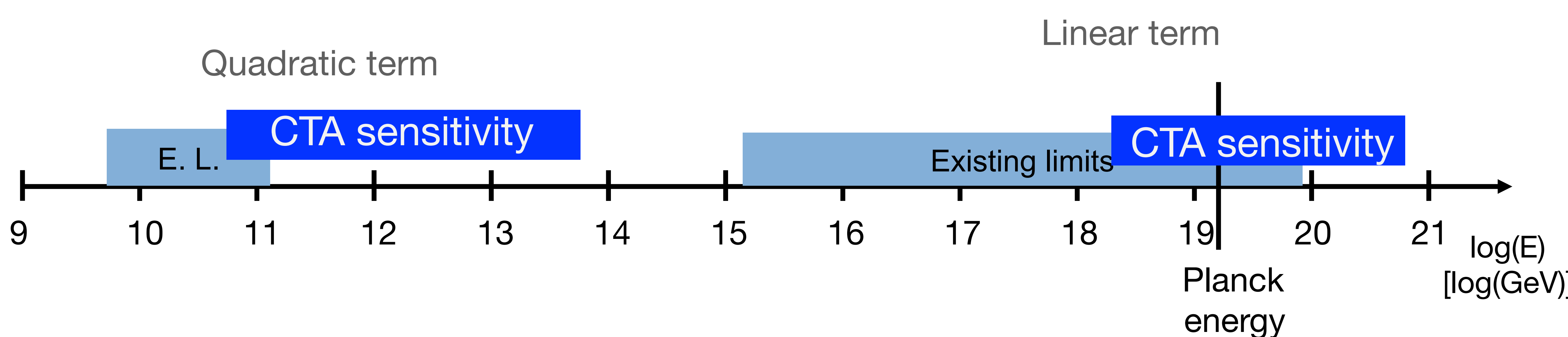
CTA will provide 10 to 300 times improved sensitivity on LIV tests
(arXiv:1305.0264)

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

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

Linear term — Quadratic term

Current best limits from Fermi-LAT
(V. Vasileiou et al. 2013, PRD 87, 122001)



U.S. Leadership in γ-ray Astrophysics

- Developed the IACT technique
  - ✓ Successfully applied in Whipple 10-m telescope to first discoveries
  - ✓ Provides by far the best angular and energy resolution of any TeV technique
  - ✓ VERITAS sensitivity unsurpassed >100 GeV
- EGRET and Fermi-LAT in the high energy regime
- Developed the water Cherenkov technique
  - ✓ Milagro the first extensive air shower array to convincingly see sources
  - ✓ HAWC the premier wide-aperture VHE instrument world wide
- Continued leadership in CTA
  - ✓ Builds on Fermi-LAT and VERITAS success
  - ✓ SCT design conceived in the U.S. – now adopted by European groups for CTA small-sized telescopes (SSTs, less demanding)
  - ✓ TARGET camera ASIC conceived in the U.S. – critical to low cost per channel and affordable, high-resolution camera (likewise adopted in Europe for SSTs)

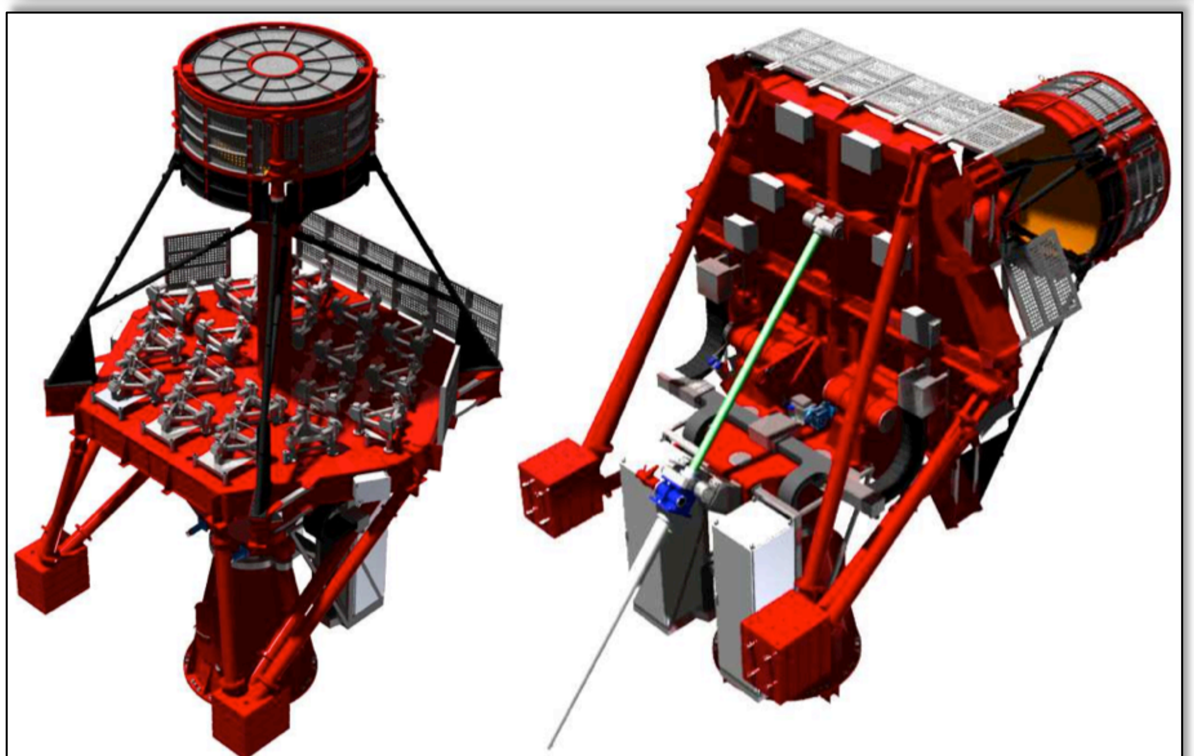
U.S. Effort Builds on VERITAS Success

- One of only a few executed projects from the 2000 decadal survey
- Built on schedule and on budget after delays related to site and funding were resolved
- Unsurpassed sensitivity in >100 GeV energy band
- Most reliable instrument operating in >100 GeV energy band
- Several of the most important VHE γ-ray discoveries
  - ✓ Gamma-ray emission from the starburst galaxy M82
  - ✓ Evidence for proton acceleration in Tycho's supernova remnant
  - ✓ The most distant (at the time) VHE gamma-ray source, PKS 1424+240
  - ✓ Best dark matter limit (at the time) for a dwarf galaxy, Segue I
  - ✓ Crab Pulsar emission >100 GeV
  - ✓ VHE morphology of IC 443
- Upgrade completed on schedule and on budget
- Design of experiment yields good understanding of systematic effects as we move into the regime of very deep observations

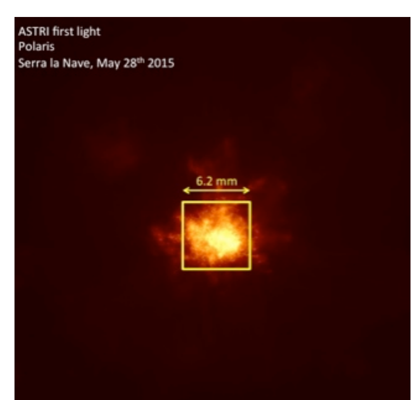
The Analogy to the LHC

- Widespread appreciation worldwide of the importance of the science goals
- Scale of the project argues for a single international facility
- International partners committed to providing the necessary basic infrastructure
- Science too important for the U.S. not to participate
- U.S. brings extensive experience, new ideas, and important resources to the project
- U.S. can be a leading participant in the science results

SC Optics shaping CTA: ASTRI

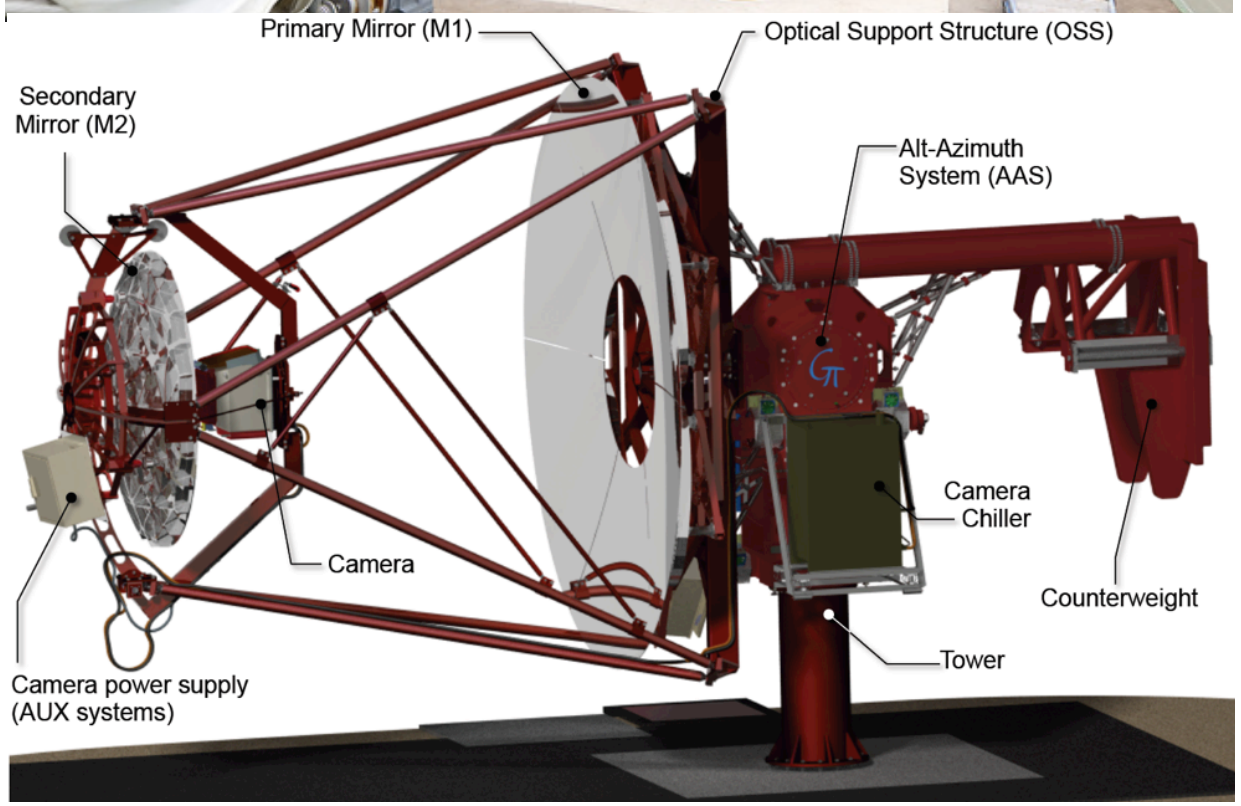


- Optical system: f/0.5, F=2.15 m
- S Aplanats: q=0.72; α=0.76
- Primary (M1) diameter: 4.3 m
- M1 type: aspheric segmented (6+6+6)
- Secondary (M2) diameter: 1.8 m
- M2 type: aspheric segmented (monolithic)
- Field of View: 9.6 deg
- Focal plane diameter: 36 cm
- Effective light collecting area: 6 m^2
- PSF (D80) less than: < 9 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 1,984



Major milestone achieved on May 28th 2015 by demonstrating the performance of the SC optical system. Image of the Polaris D80 = 7.9 mm (12.6arcmin)

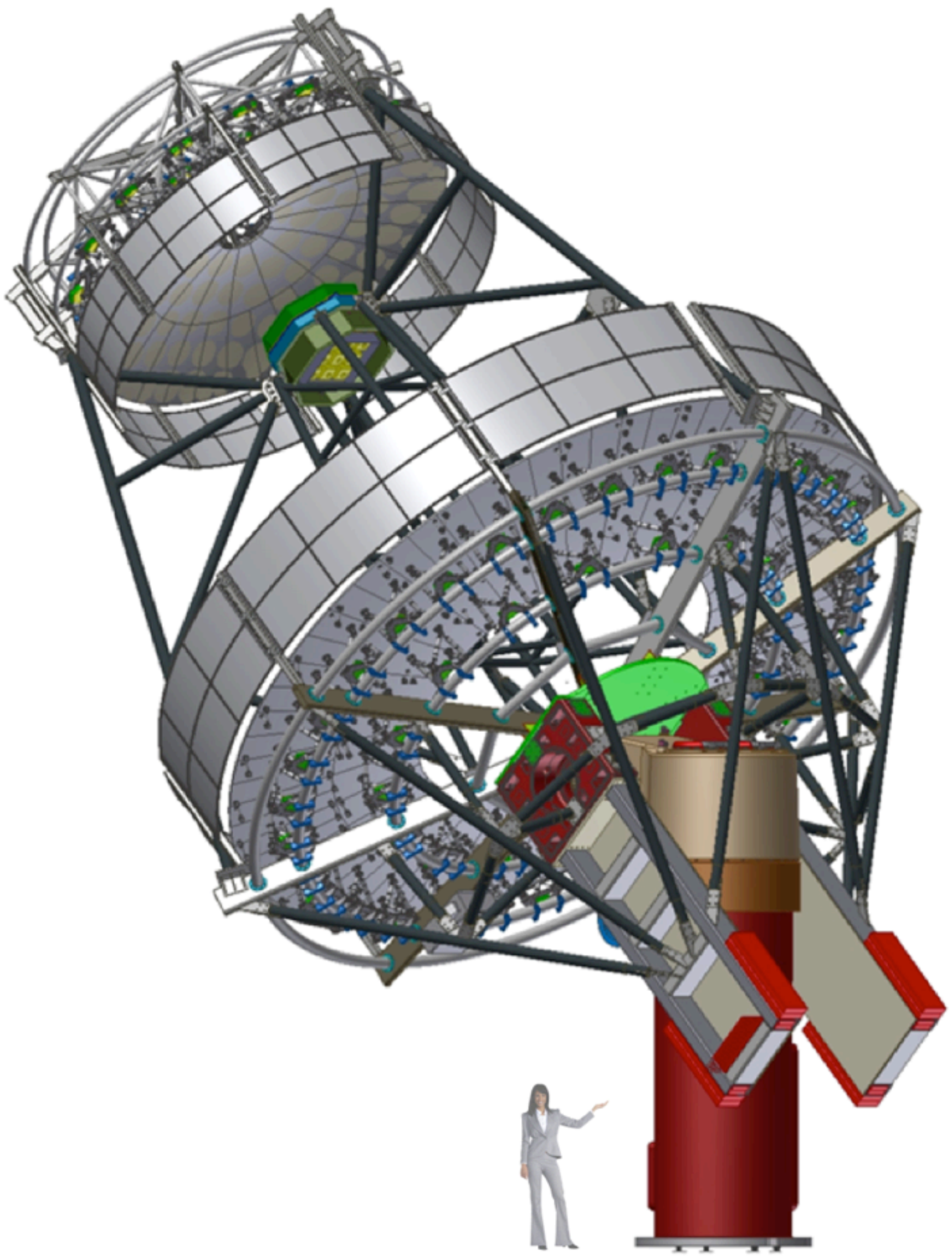
SC Optics shaping CTA: GCT



- Optical system: f/0.58, F=2.283 m
- S Aplanats: q=0.64; α=0.78
- Primary (M1) diameter: 4 m
- M1 type: aspheric segmented (6)
- Secondary (M2) diameter: 2 m
- M2 type: aspheric segmented (monolithic)
- Field of View: 8.5 -9.2 deg
- Focal plane diameter: 36 cm (9 deg)
- Effective light collecting area: 6.8 m^2
- PSF (D80) less than: < 9 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 2,048

Major milestone achieved on November 26th 2015 by demonstrating the first small plate scale SC camera and first Cherenkov image

SC Optics shaping CTA: SCT



Prototype SCT construction is underway at FLWO, AZ USA

- Optical system: f/0.58, F=5.59 m
- S Aplanats: q=0.666; α=0.666
- Primary (M1) diameter: 9.66 m
- M1 type: aspheric segmented (16+32)
- Secondary (M2) diameter: 5.42 m
- M2 type: aspheric segmented (8+16)
- Field of View: 8 deg
- Focal plane diameter: 78 cm
- Effective collecting area: >35 m^2
- PSF less than: <4.5 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in camera: 11,328
- Angular pixel size: 0.067 deg