Aq-A-1

Aquarius, Springel *et al.* arXiv:0809.0898

Indirect Searches for Dark Matter with CTA

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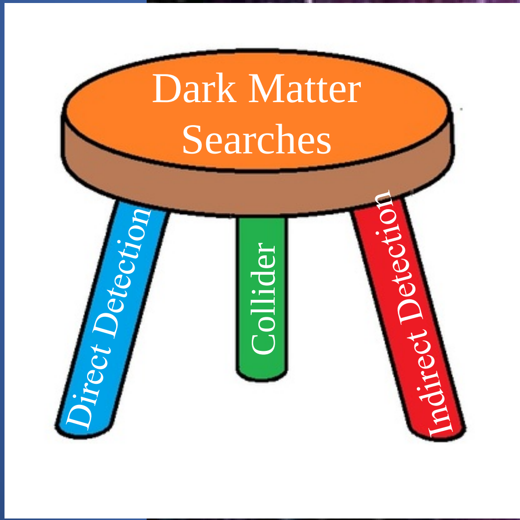
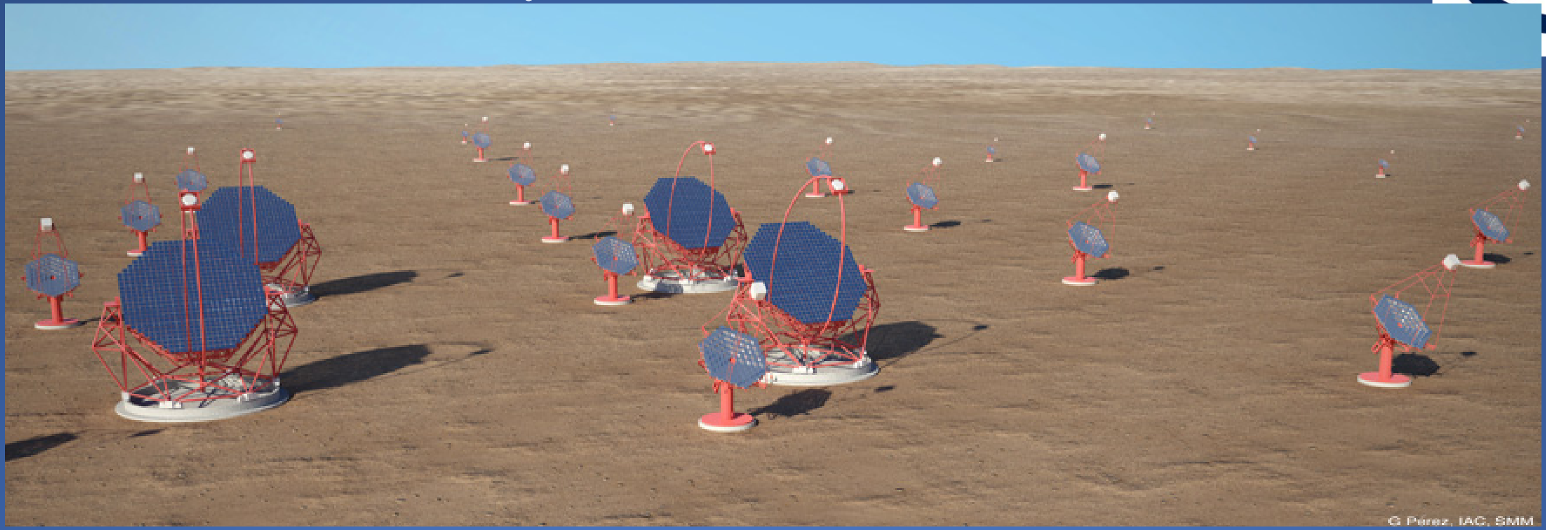
Cosmic Visions, University of Maryland
March 24, 2017



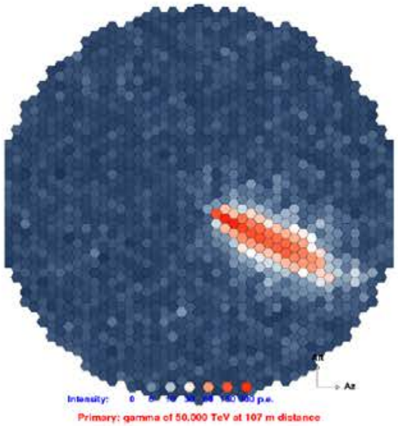
- **Cherenkov Telescope Array Concept & Timeline**
- **Dark Matter Search Plans & Complementarity**
- **U.S. Plans & Impact**
- **Summary**

The CTA Concept

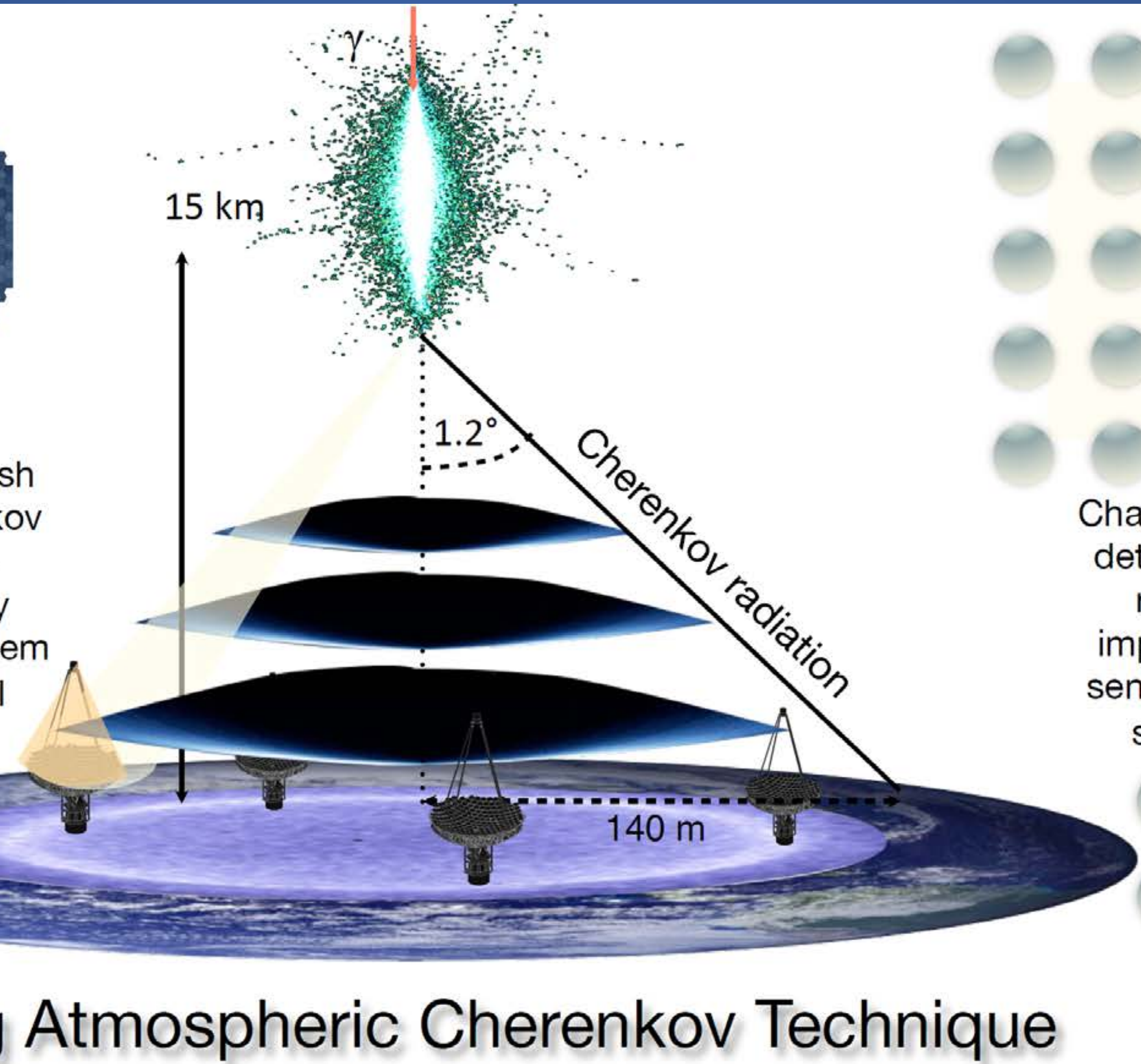


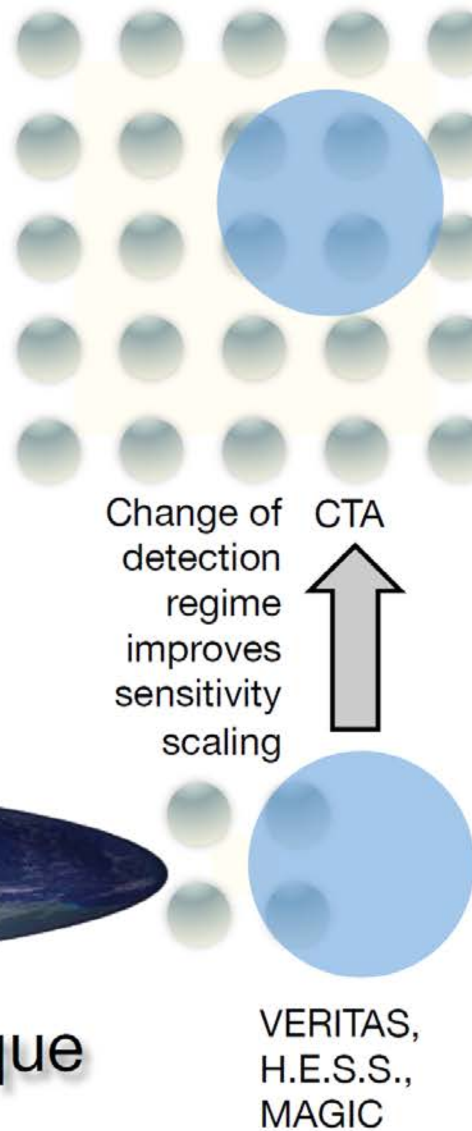
- Arrays in northern and southern hemispheres for full sky coverage.
  - 4 large (23 m) telescopes (LSTs) in the center: 20 GeV threshold.
- Southern array adds:
  - 25 medium (9-12 m) telescopes (MSTs): 100 GeV – 10 TeV.
  - 70 small (~4 m) telescopes (SSTs) covering >3 km^2 – expand collection area >10 TeV (up to 300 TeV).
- Northern array adds 15 MSTs (no SSTs).
- Project cost estimate €297M + 1480 FTE-years ~ €400M.
- Operations cost estimated to be €20M/year.

CTA Technique



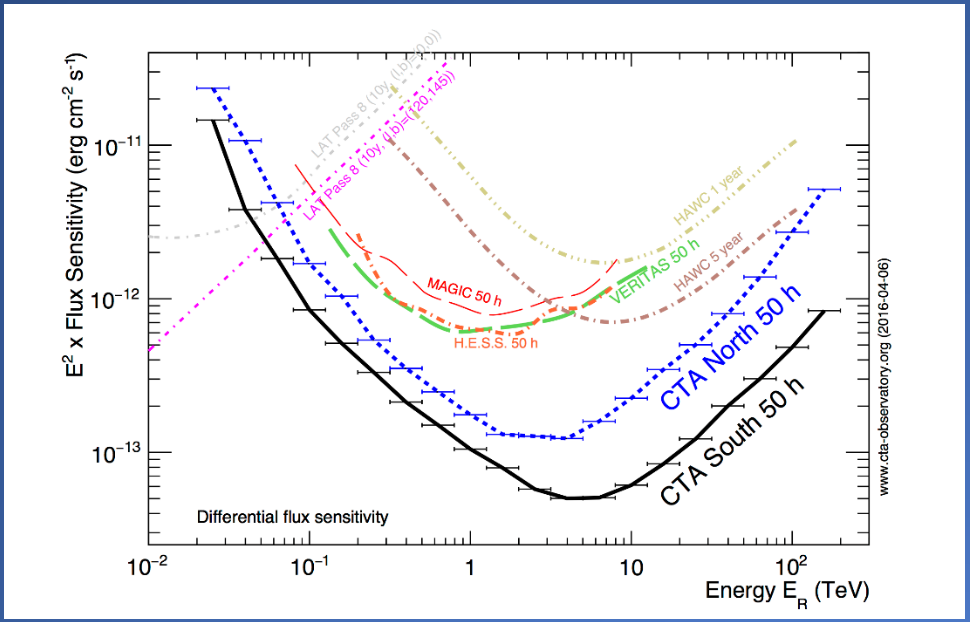
A few nanosecond flash of UV-optical Cherenkov light produced by air-showers is focused by telescope optical system onto fast multichannel cameras.

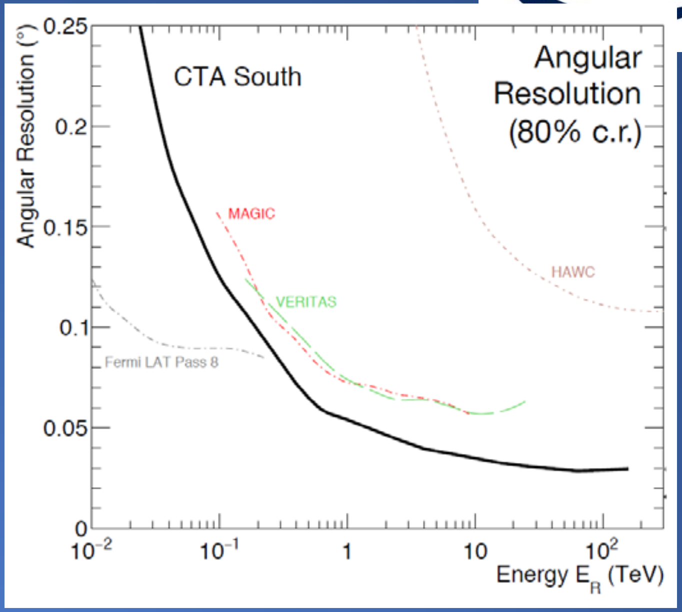




Adapted from V. Vassiliev, UCLA DM

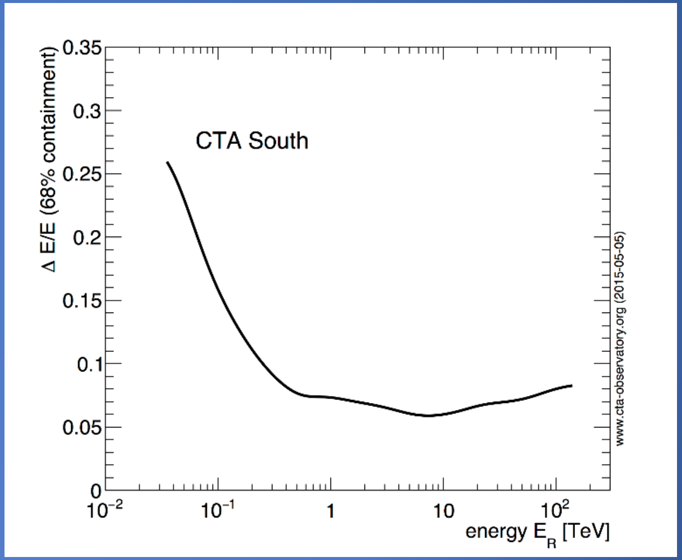
CTA Performance & Sensitivity



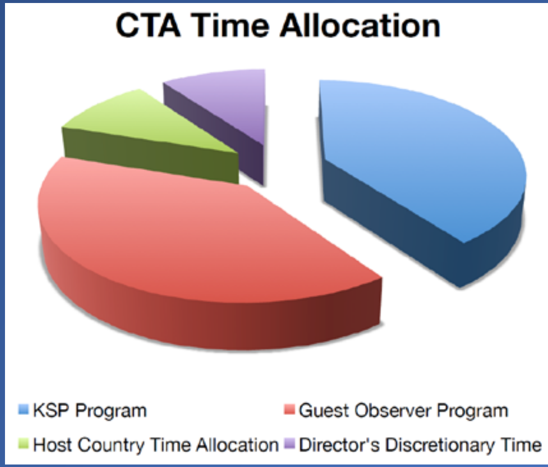


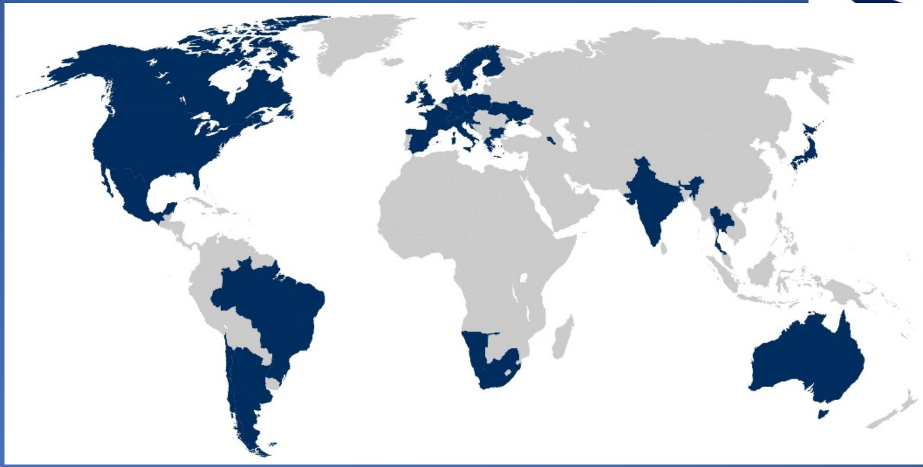
Highlights

- 10 x improved sensitivity.
- Wide FoV combined with arcmin-scale angular resolution for efficient surveys and study of extended sources.
  - LST: >4.5°, MST/SST: >7.5-8° FoV.
- Energy resolution < 10% to resolve spectral features.



CTA Globally & Data Access



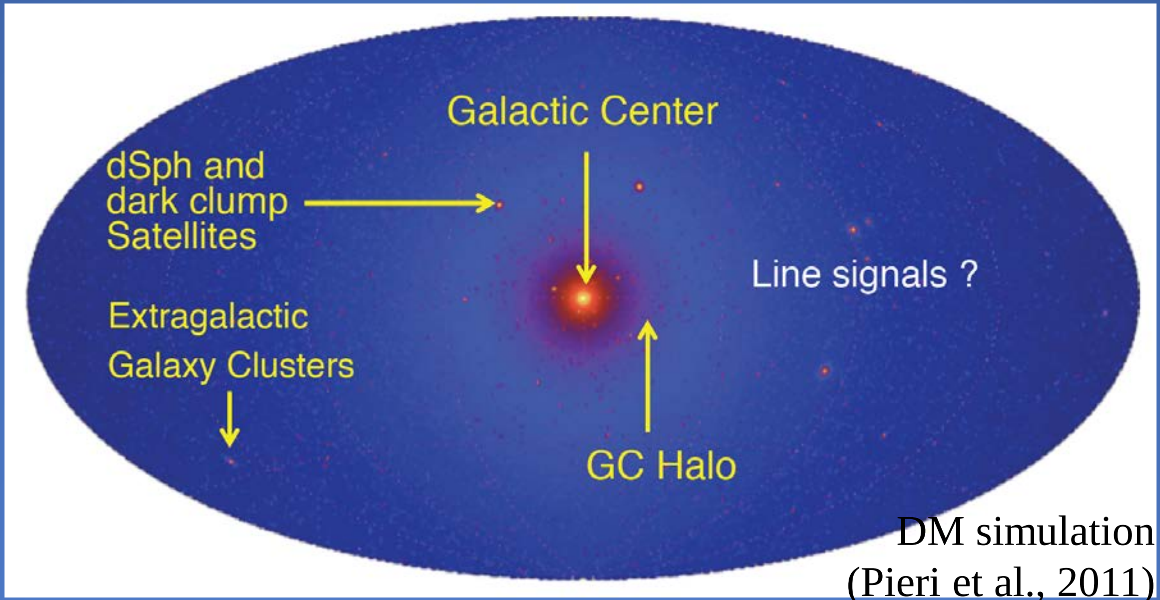


- CTA is being developed by the CTA consortium (CTAC) comprising ~1350 scientists (~420 FTEs) from ~210 institutions in 32 countries.
- All CTA data and associated tools will be fully open after a proprietary period.
- Products delivered to a user: FITS data files, FERMI-like analysis tools, etc.
- Over observatory lifetime, majority of time will go to **Guest Observer proposers from CTA member countries**. The remaining time consists of Director's Discretionary time and, **in the first decade of operations, a ~40% share used by the CTA Consortium to deliver** a Core Program consisting of a number of **Key Science Projects (KSPs)**.

https://www.cta-observatory.org/about/cta-consortium/

Dark Matter Key Science Program

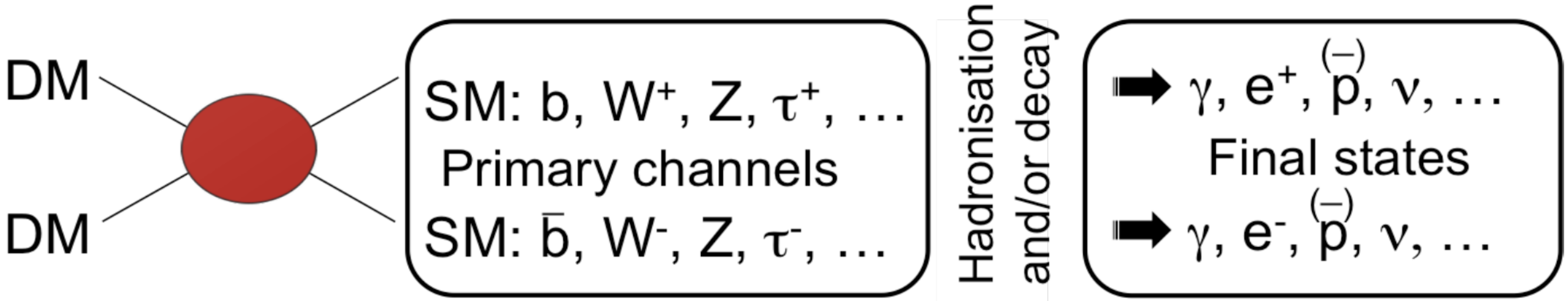
- The priority **is to discover the nature of dark matter** with a positive observation complementary to the searches for DM at LHC and in direct-detection experiments.
  - Capability to discover a thermal relic WIMP, with the "natural" velocity-averaged cross-section of 3×10^{-26} cm^{3}s^{-1}, drives the program.
    - ✓ But sensitive to wide range of DM scenarios.



DM simulation
(Pieri et al., 2011)

- The balance between the strength of expected DM annihilation signal, its uncertainty, and the strength of the astrophysical backgrounds drives the prioritization of targets.

Gamma Rays from DM Annihilation



$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_\gamma}{dE_\gamma}} \times \underbrace{\int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho^2(r[s])ds}$$

Particle Physics :

- Cross sections
- Differential photon yield
- DM particle mass

Astrophysics

Modelling required for the DM distribution in the object

- Can reveal the abundance and distribution of dark matter.
- Do not suffer from propagation effects at Galactic scale.
- May show characteristic features in their energy spectrum.

Slide adapted from E Moulin

DM Detection Strategy

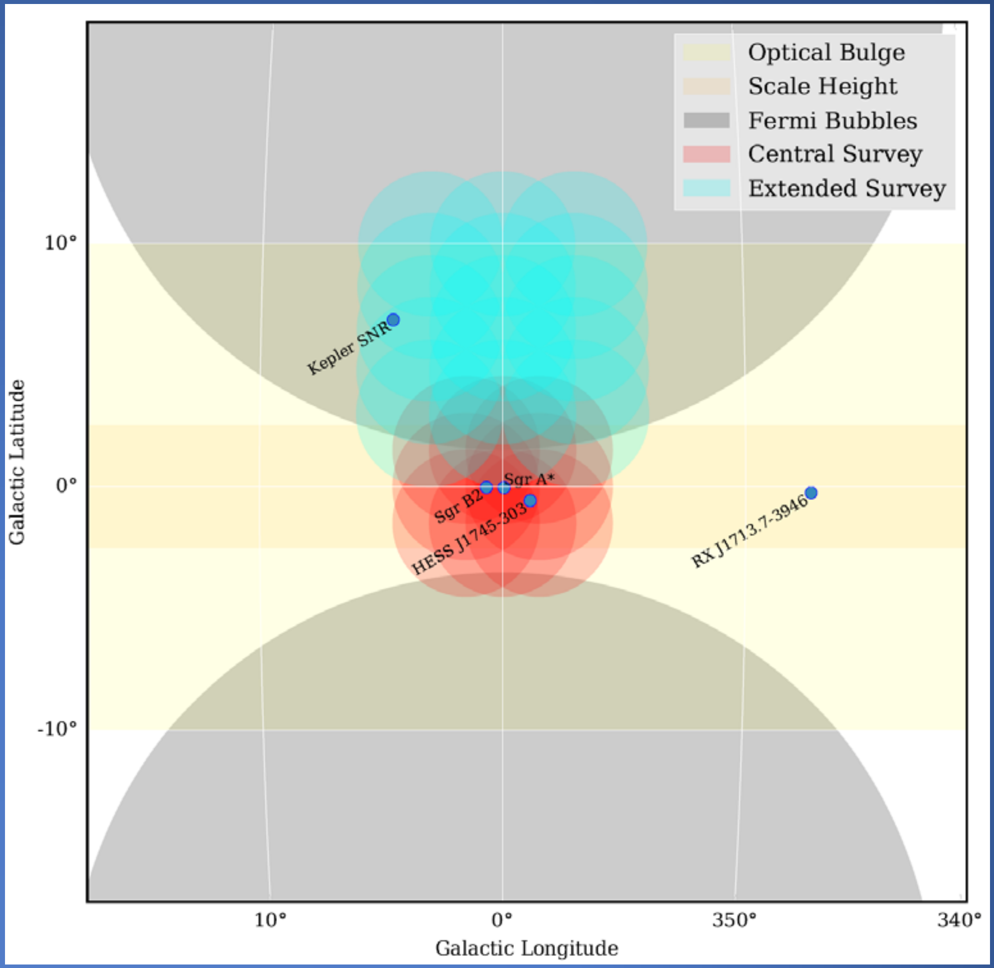
Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Best dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Best dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of no detection at GC						
Best Target				100 h	100 h	100 h	100 h	100 h	100 h	100 h

Observation times under discussion

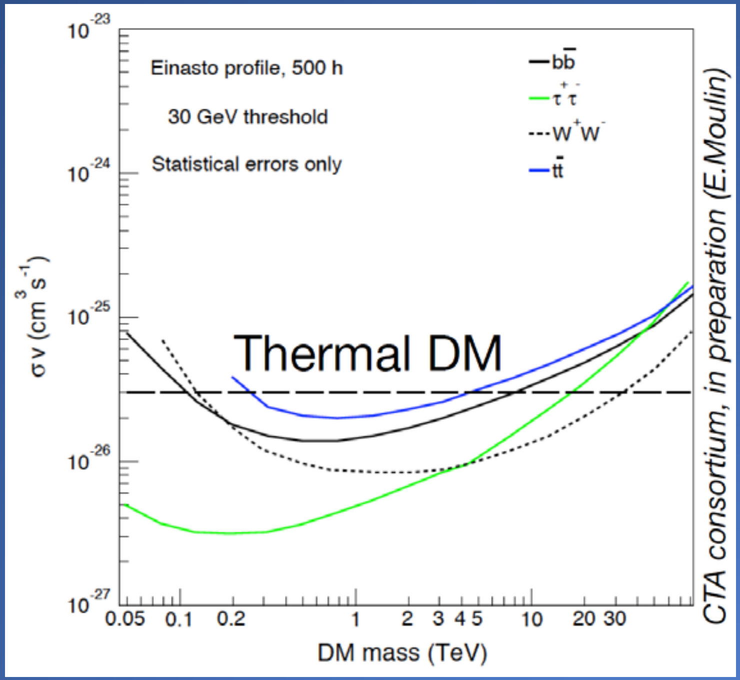
- **First 3 years**
  - The principal target is the Galactic Center Halo (most intense diffuse emission regions removed);
  - Best dSph as "cleaner" environment for cross-checks and verification (if hint of strong signal).
- **Next 7 years**
  - If there is detection in GC halo data set (525h)
    - ✓ Strong signal: continue with GC halo in parallel with best dSph to provide robust detection.
    - ✓ Weak signal: focus on GC halo to increase data set until systematic errors can be kept under control.
  - If no detection in GC halo data set, focus observations on the best target at that time to produce legacy limits.

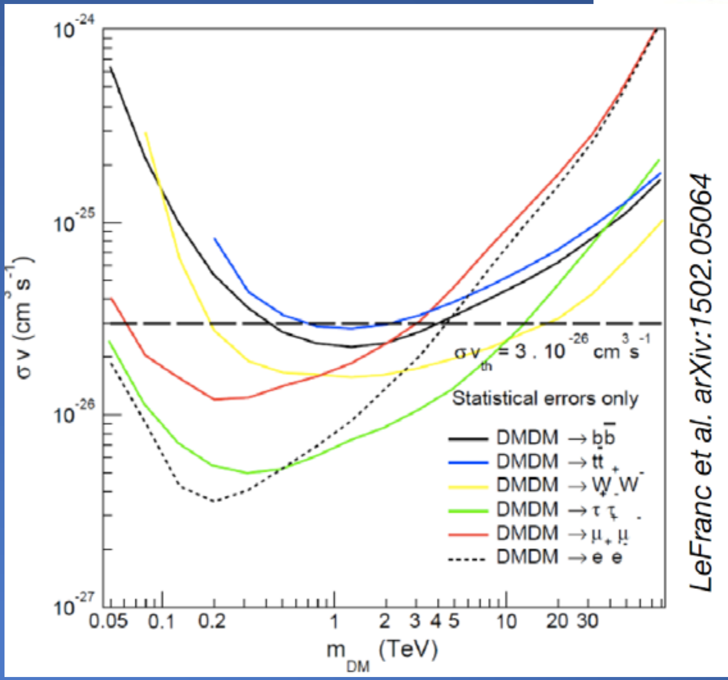
Deep Look at Galactic Center/Halo

- Deep 525 h exposure in the inner 5° around Sgr A*.
- Extended 300 h survey: 10° x 10° region.
- Produce CTA legacy data set for broad set of scientific topics:
  - GC and GC DM halo.
  - Understand astrophysical backgrounds: pin down VHE sources, map diffuse emission.
  - Astrophysics of SNRs (e.g. G1.9+0.3), PWNe, and Pulsars.
  - Extended objects such as Central Radio lobes (central ±1°) and arc features; base of Fermi Bubbles.



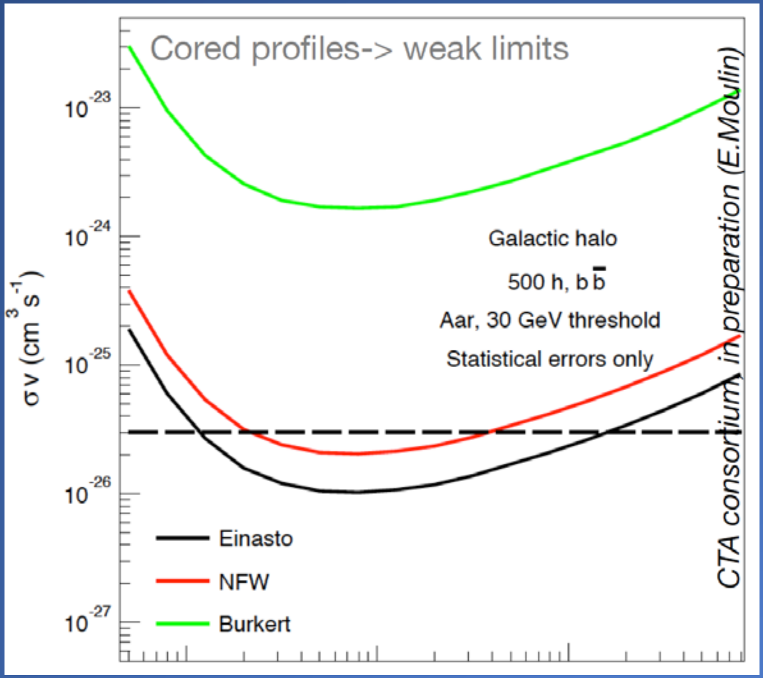
GC Halo DM Sensitivity



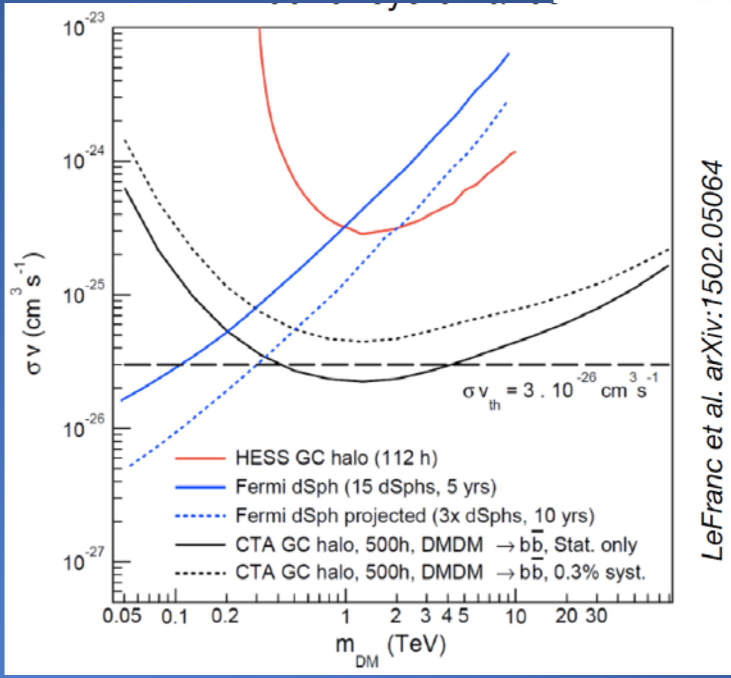


- Thermal value of the annihilation cross-section is within CTA reach – for the first time an array of IACTs will be able to probe predicted WIMP parameter space.
- The observing strategy is based on the detection of the gradient in the rings (1° - 5°; width 1°) centered on GC with the strip |b|<0.3° removed.

GC Halo DM Sensitivity



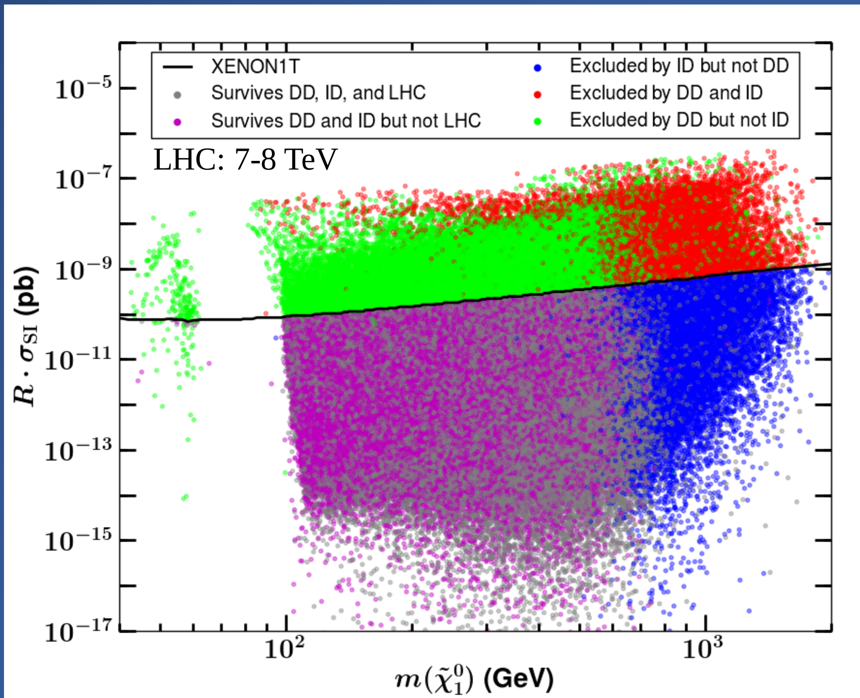
Dark Matter Profiles



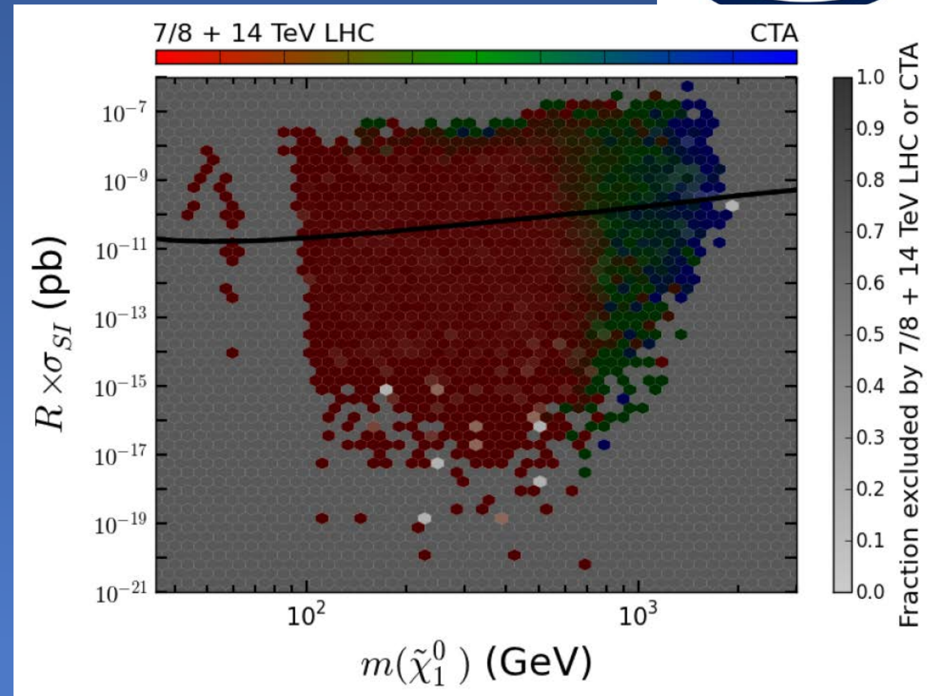
Effect of Systematics

- Cored profiles generate weaker limits and typically large systematics.
- Estimated systematic errors have dramatic effect particularly on the detectability of the hadronic channels.

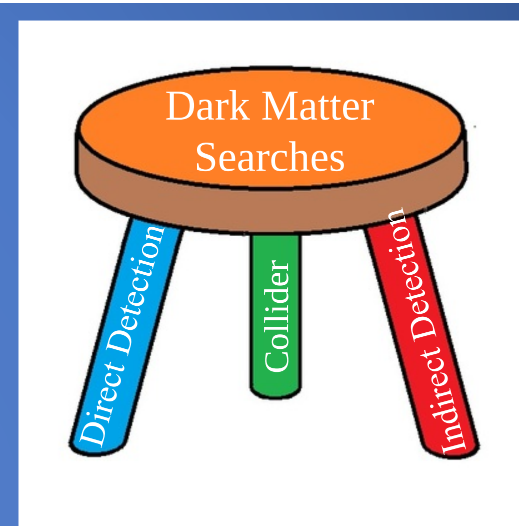
Complementarity with DD, Colliders



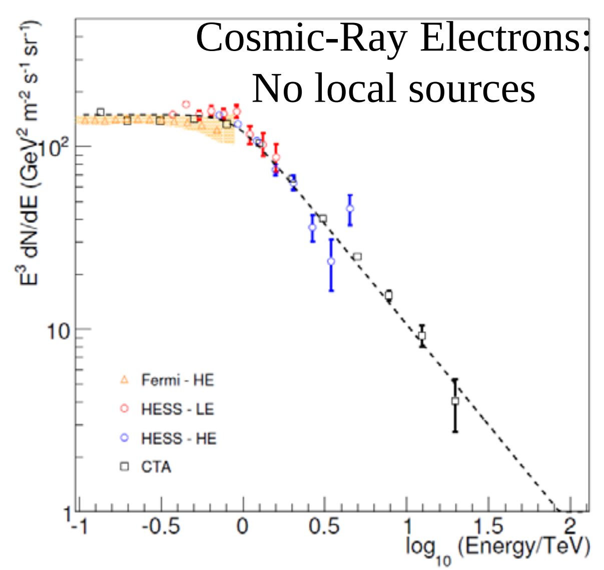
Cahill-Rowley *et al.* 2015



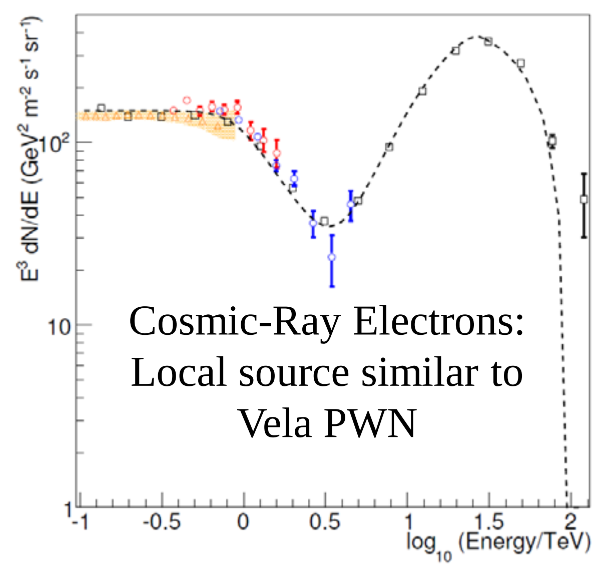
- Indirect detection (CTA), direct detection, and LHC together cover much broader parameter space than any one technique alone.
- Overlapping regions provide multiple handles constraining DM properties.
- Indirect detection key at high masses.

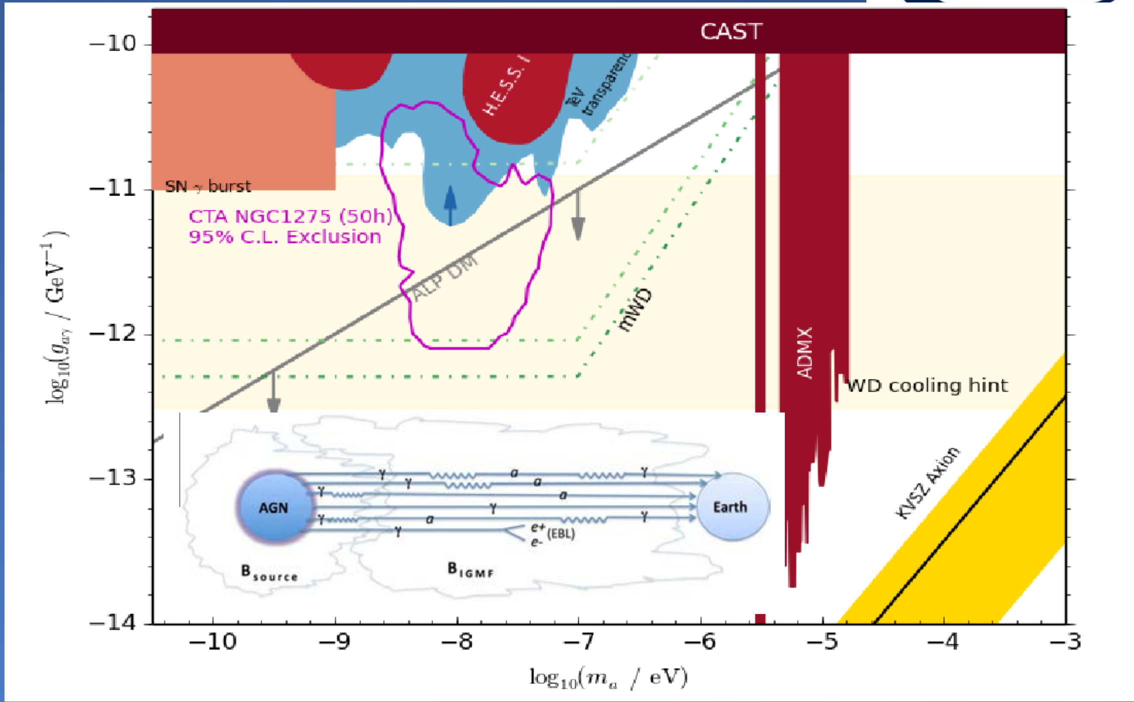


Complementarity with other Particles



Parsons 2011

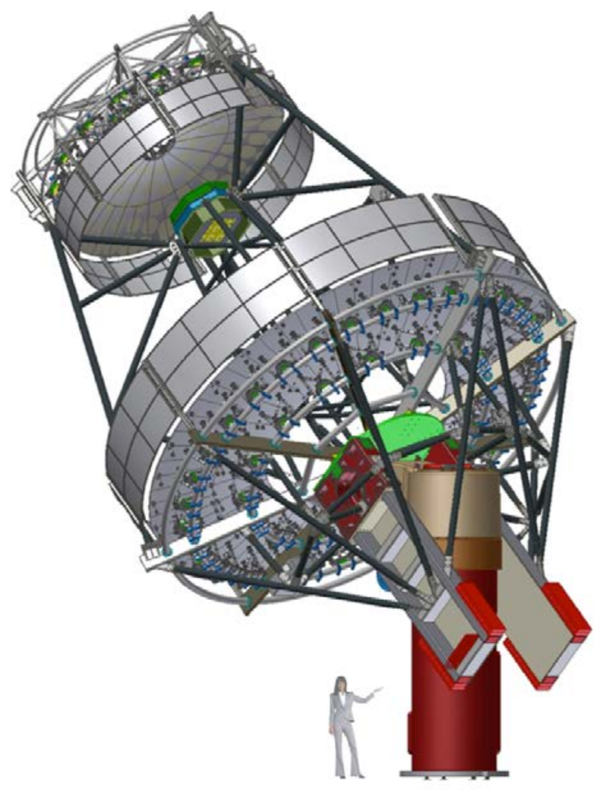




- CTA will extend the CR electron spectrum to >20 TeV.
  - ❖ Extend further if local sources or DM contribute.
- CTA is sensitive to axions /axion-like particles (ALPs) through ALP-photon conversion in magnetic fields.
  - ❖ ALPs modify γ-ray spectra of active galactic nuclei.
- CTA will test a unique region of phase space, including a region in which they would behave as cold dark matter.

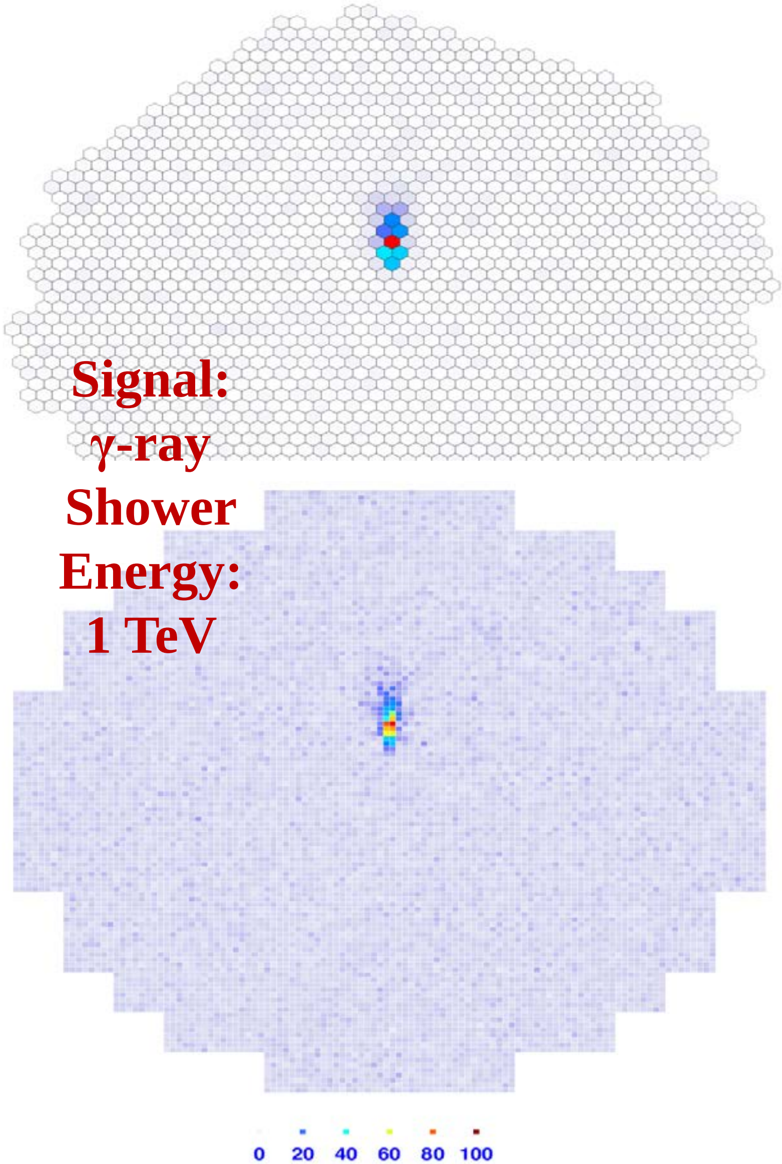
US Plans: Schwarzschild-Couder Telescope (SCT)

- Designed to deliver performance close to theoretical limit of Cherenkov technique.
- Innovative U.S. design key to boosting CTA performance.
  - Corrects aberrations → 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).
- Cost comparable to 1-mirror medium-size telescope.
- Adopted by European groups for small-sized telescopes.
- P5* Review (2014) recommends U.S. participation in CTA:
  - Particle physics science prospects justify particle physics funding investment.
  - Broad science case calls for joint astronomy participation.
- SCT now a strong international partnership: US, Germany, Italy, Mexico.



Uses the same positioner and foundation as single-mirror MST

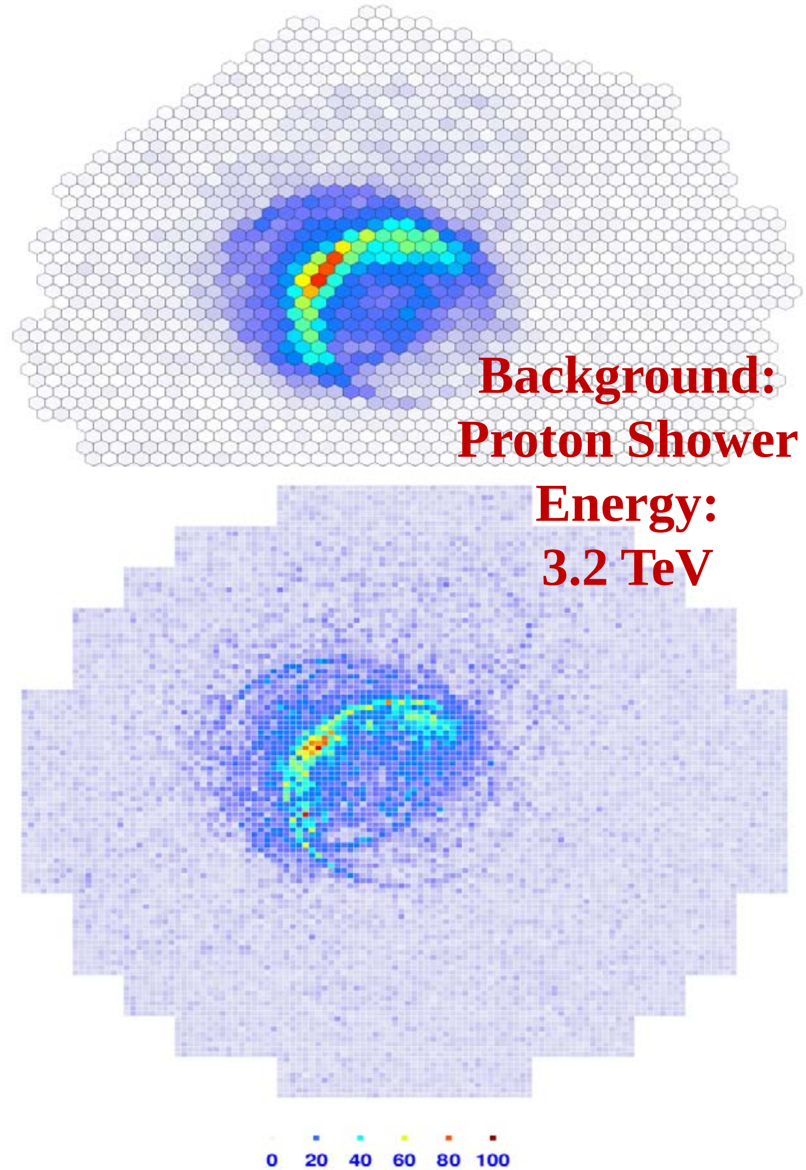
SCT: Better Shower Characterization



Signal: γ-ray Shower Energy: 1 TeV

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

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



Background: Proton Shower Energy: 3.2 TeV

SCT: Better Shower Characterization

Single-

- 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

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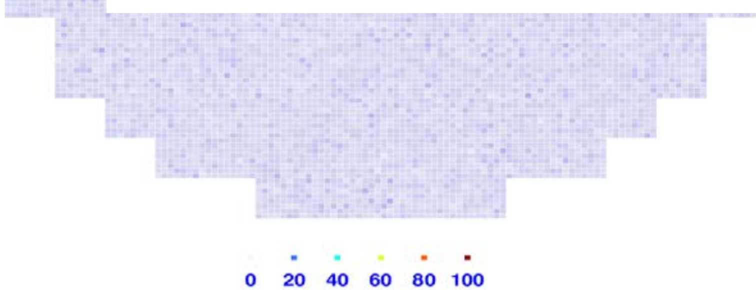
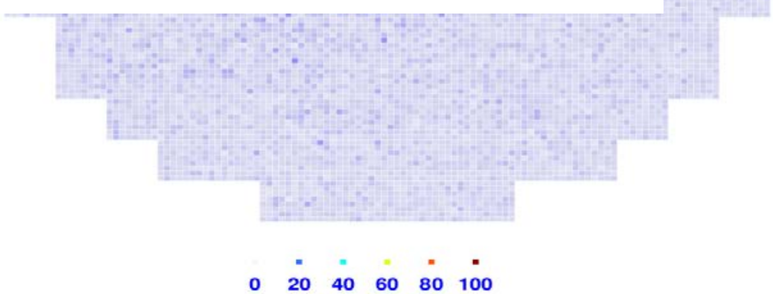
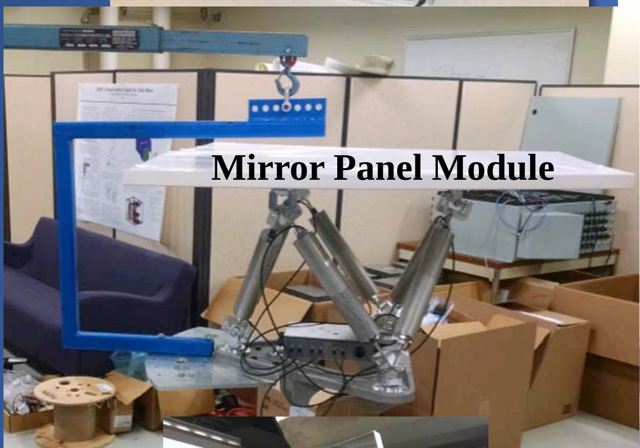




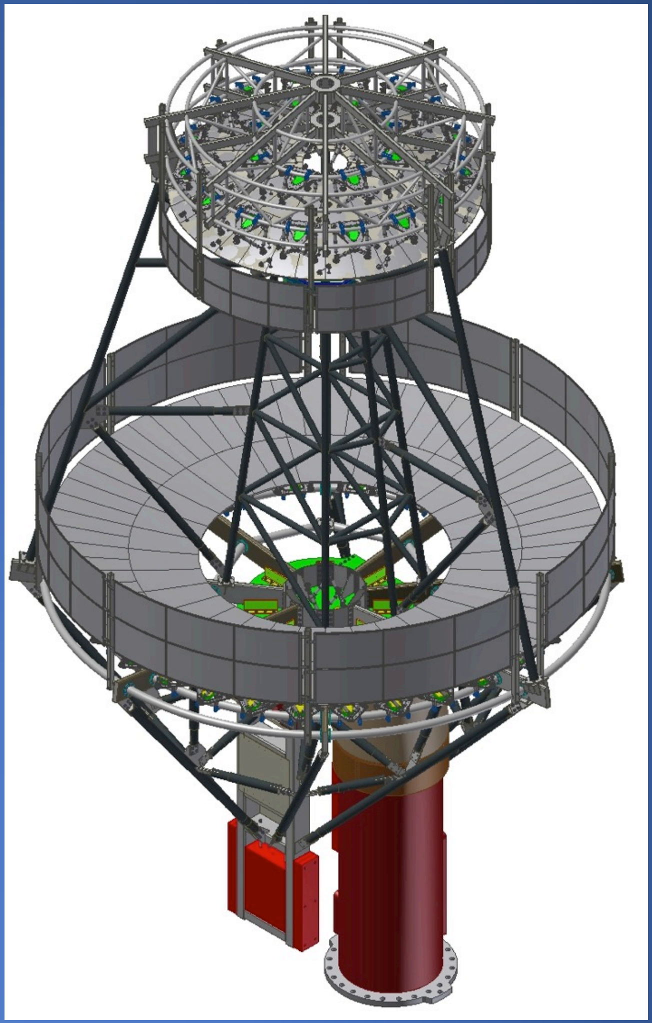
Prototype SCT Takes Shape

cta
cherenkov telescope array



CTA-US Goals

- **Implementation of the baseline MST arrays:**
  - **Dominate sensitivity over 100 GeV – 10 TeV.**
- Complete prototype SCT:
  - Verify performance.
  - Vette performance and cost through CTA reviews.
- 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 from the U.S. agencies, in part from the NSF Astronomy MSIP program (2017 call).
- 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.



Impact of $25M on a €400M Project

- The highly integrated nature of the project means that it will readjust based on available resources. MST Baseline: S – 25, N – 15 telescopes.
- 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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  - Wit… …e MST arra…
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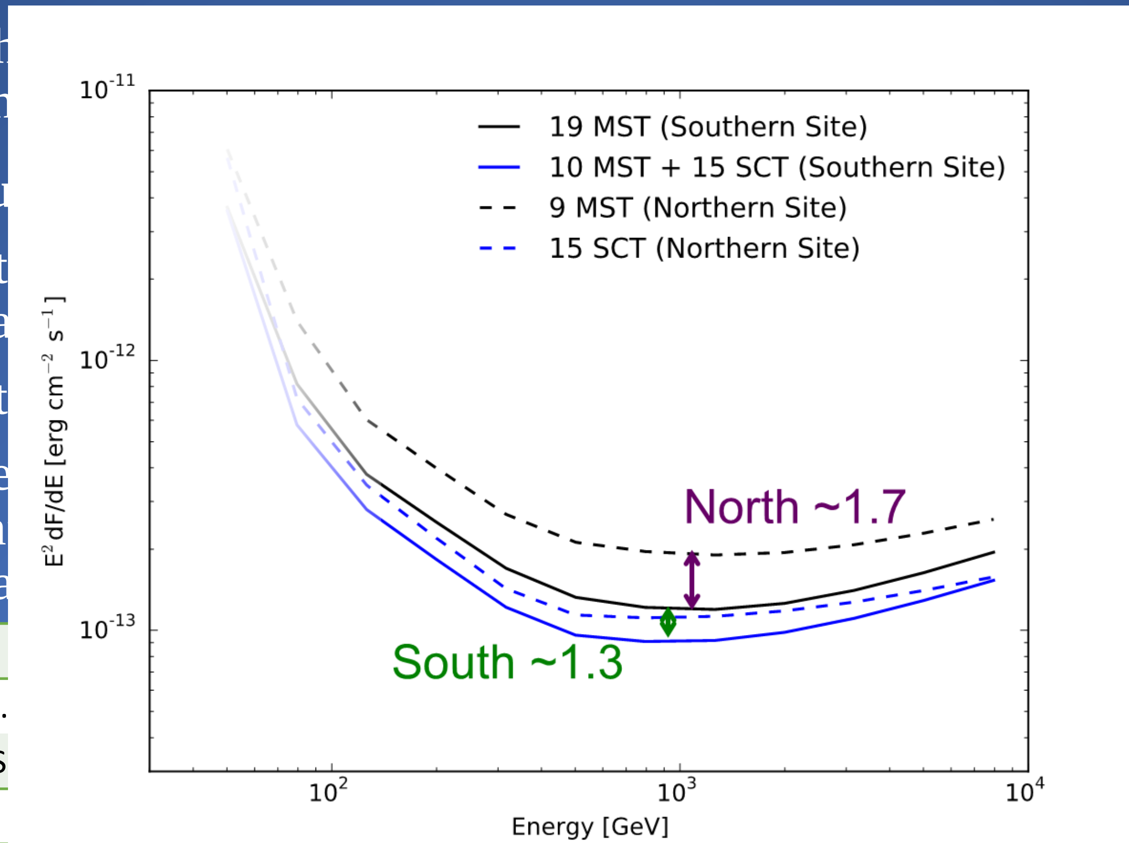

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Telescopes w/o U.		…mirror MST
Telescopes w/ U.S		…5 SCT
		…tion
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Field of view (effective radius)	1.14	1.25
Survey speed	2.2	4.5

More sources detected;
reduced impact of systematic errors

or

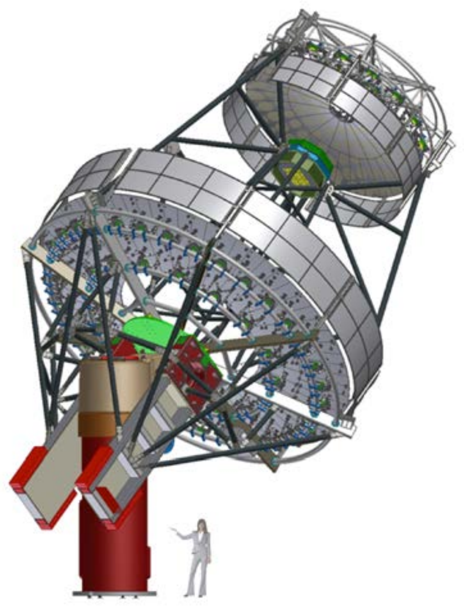
Summary: Indirect DM via CTA

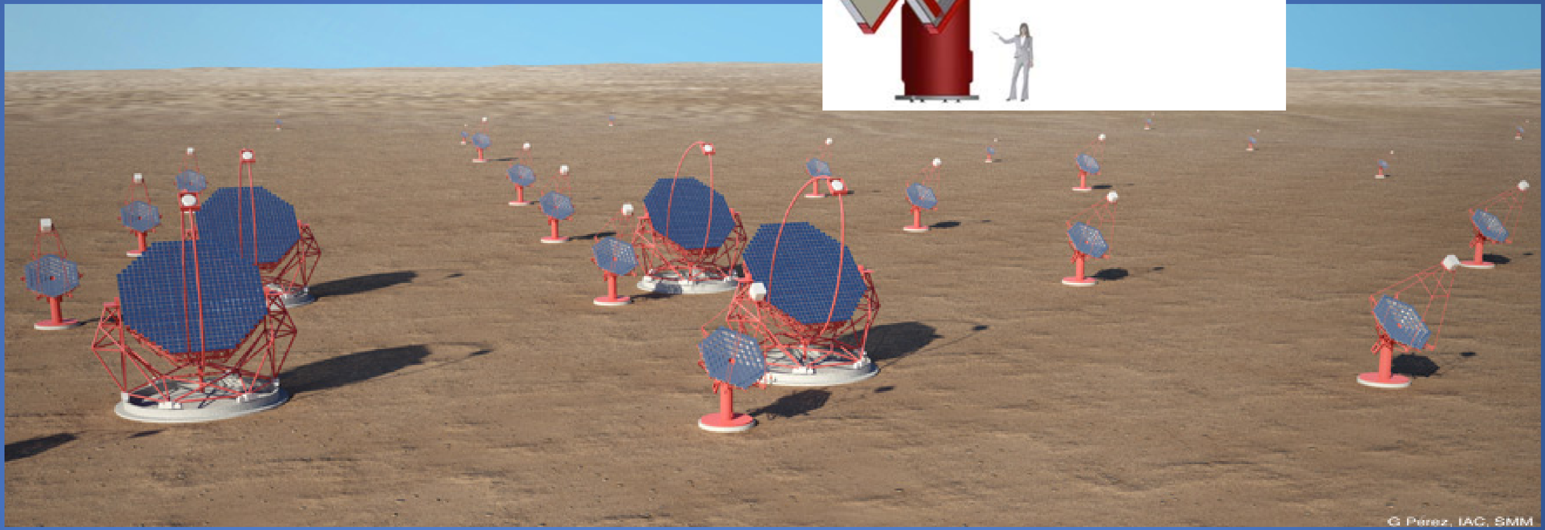
- DM science motivation as compelling as ever – too important for the U.S. not to participate
  - Together with Fermi, CTA will be able to exclude thermal WIMPs within the mass range from a few GeV up to a few tens of TeV.
  - For heavy WIMPs (>TeV) CTA will provide unique observational data to probe parameter space not reachable by any other experiments planned today.
  - CTA is complementary instrument to LHC and direct DM searches probing some non-overlapping regions of DM particle parameter space.
  - If DM is detected by CTA, it will also be possible to explore some properties of DM particle through the study of annihilation channels, etc.
  - Control of systematics in deep observations of GC halo and dSph(s) is critical for these studies; will require full knowledge of the instrumentation (hence CTA KSP)
    - ✓ Better understanding of J factors is essential for interpretation of observational data and derivation of limits.
- Builds on decades of U.S. leadership, investment and success.
- U.S. participation is essential to CTA achieving its DM science goals.
- Single worldwide effort leverages U.S. contribution.
- U.S. access to the next premier VHE γ-ray observatory – an opportunity not to miss!

Backup Slides

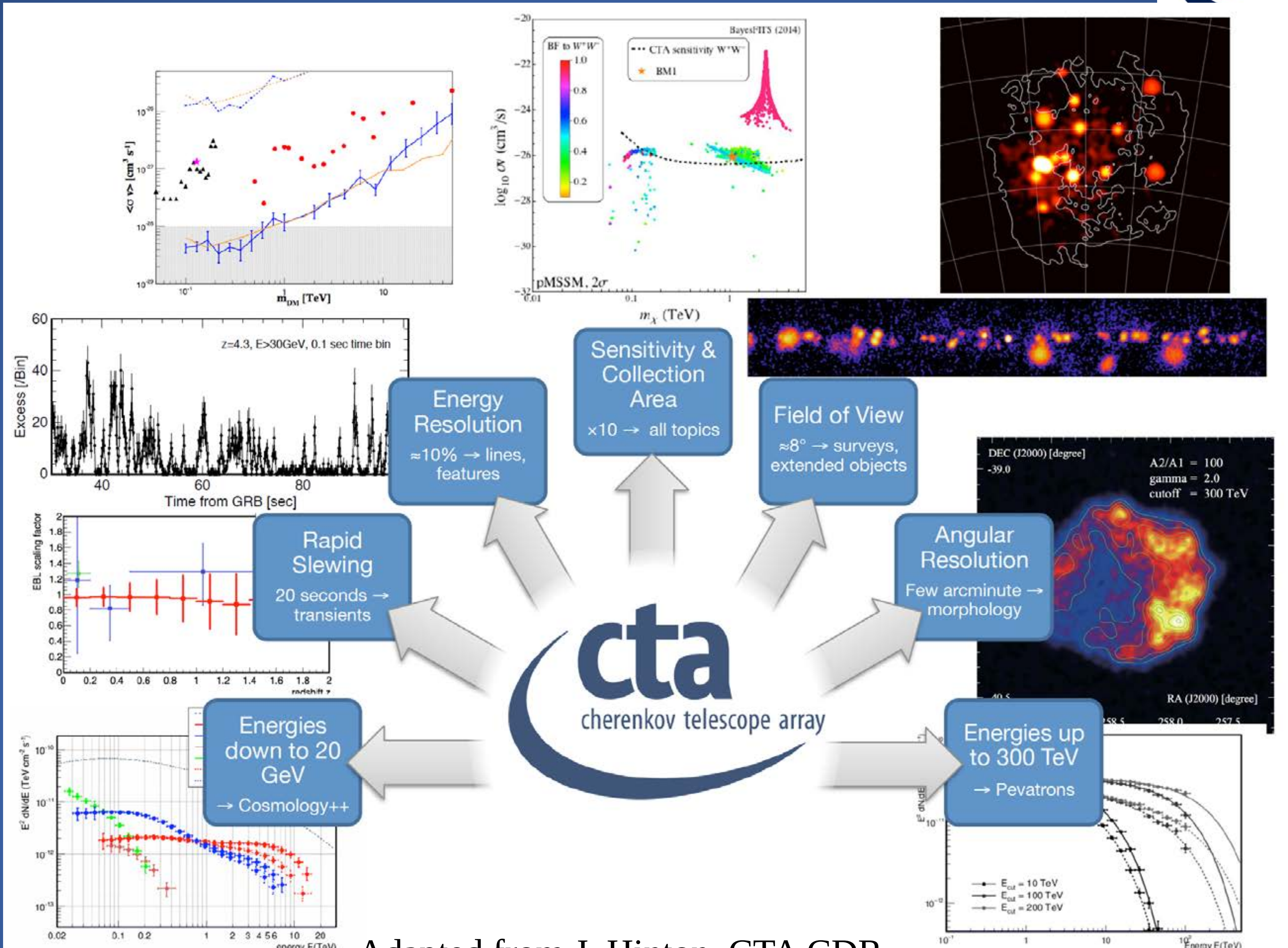
Outline

- Cherenkov Telescope Array Concept & Timeline
- Dark Matter Search Plans
- Complementarity
- U.S. Plans & Impact
- Summary



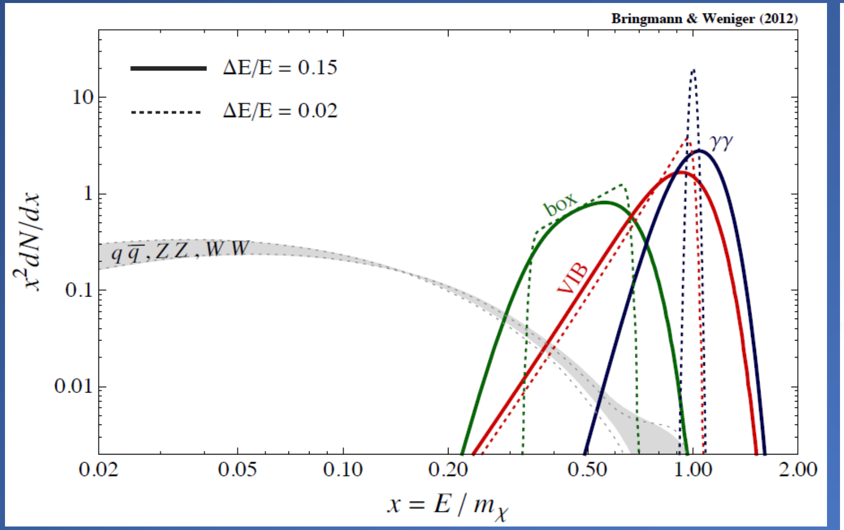


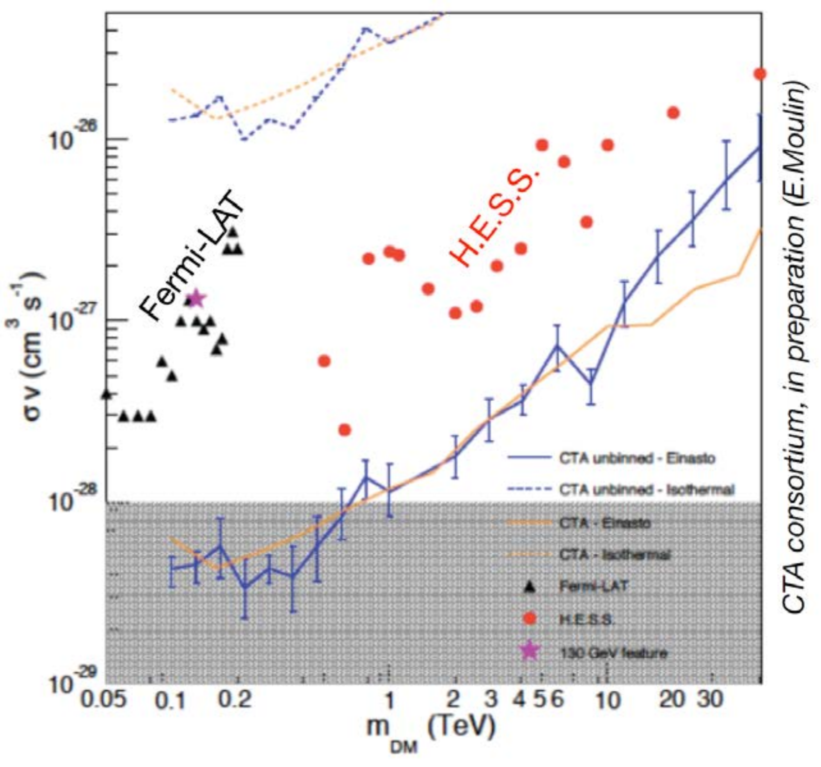
CTA Advances in State of the Art



Adapted from J. Hinton, CTA CDR

DM Annihilation Spectral Features





Gamma-ray lines

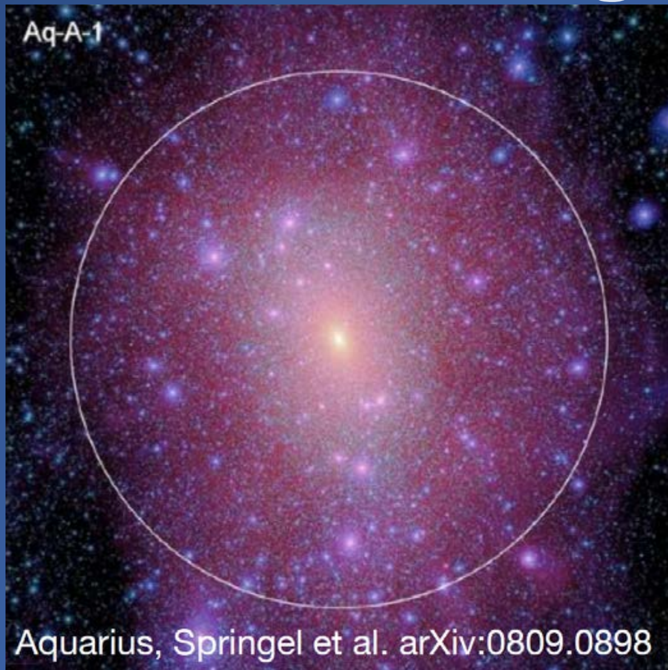
- from two-body annihilation into photons; forbidden at tree-level, generically suppressed by O(α2).

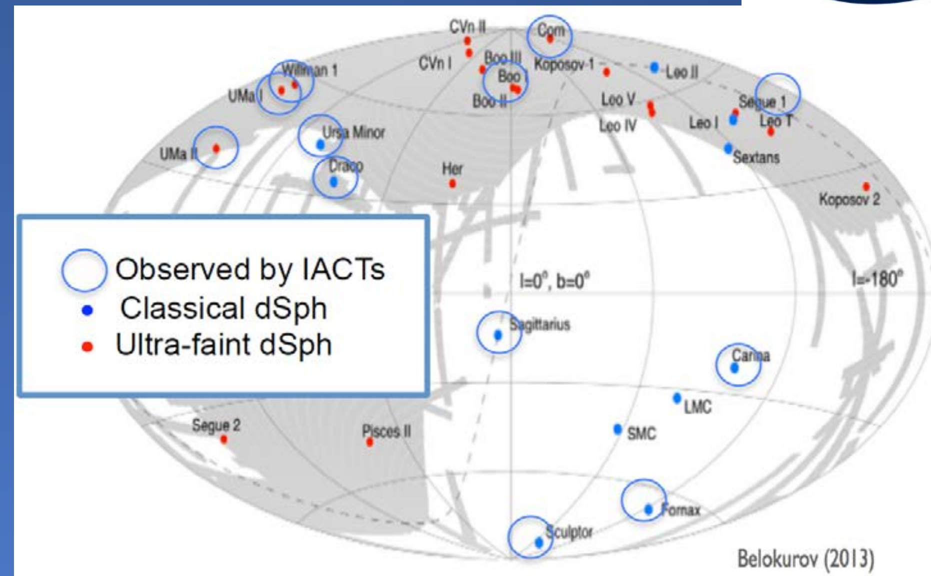
Virtual Internal Bremsstrahlung (VIB)

- radiative correction to processes with charged final states; generically suppressed by O(α).

- Owing to improved energy resolution CTA is ideally suited for search of DM annihilation spectral features, line and VIB (arguably "smoking gun" for WIMPs), in the signal from GC region.

Alternative Targets for DM

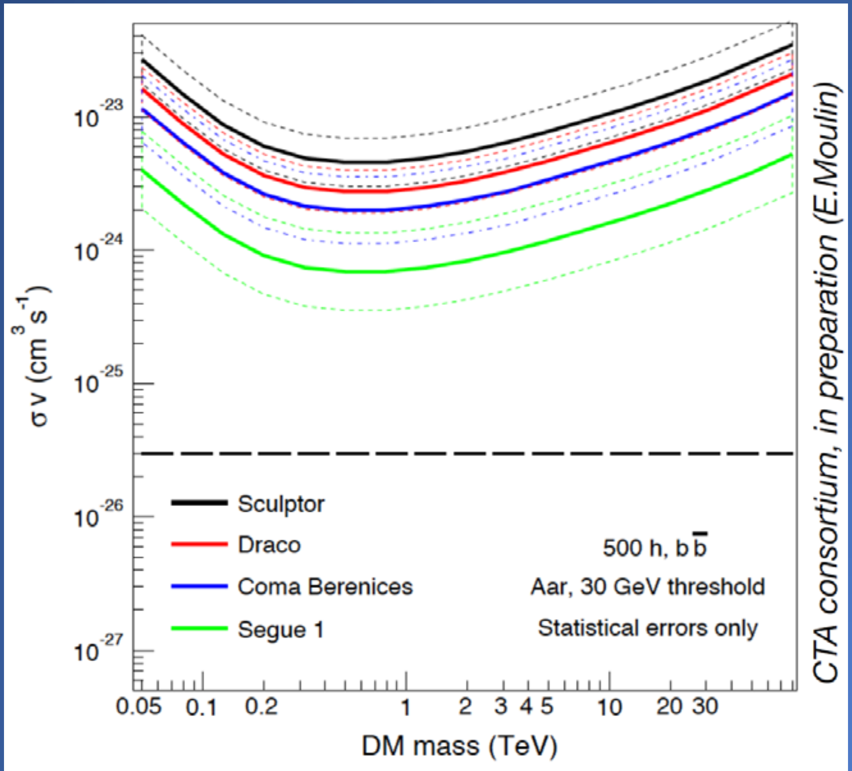




- Many DM sub-halos are predicted to populate the Milky Way DM halo.
- Both dwarf spheroidal galaxies and DM clumps (no significant baryonic matter) could potentially be detected in CTA surveys.

- Dwarf spheroidal galaxies have long been targets favored by IACTs for indirect DM searches due to
  - Arguably most DM-dominated systems in the Universe.
  - Lowest astrophysical backgrounds due to conventional VHE physics.
- No VHE detection has been reported so far.

CTA Sensitivity to dSph Galaxy DM

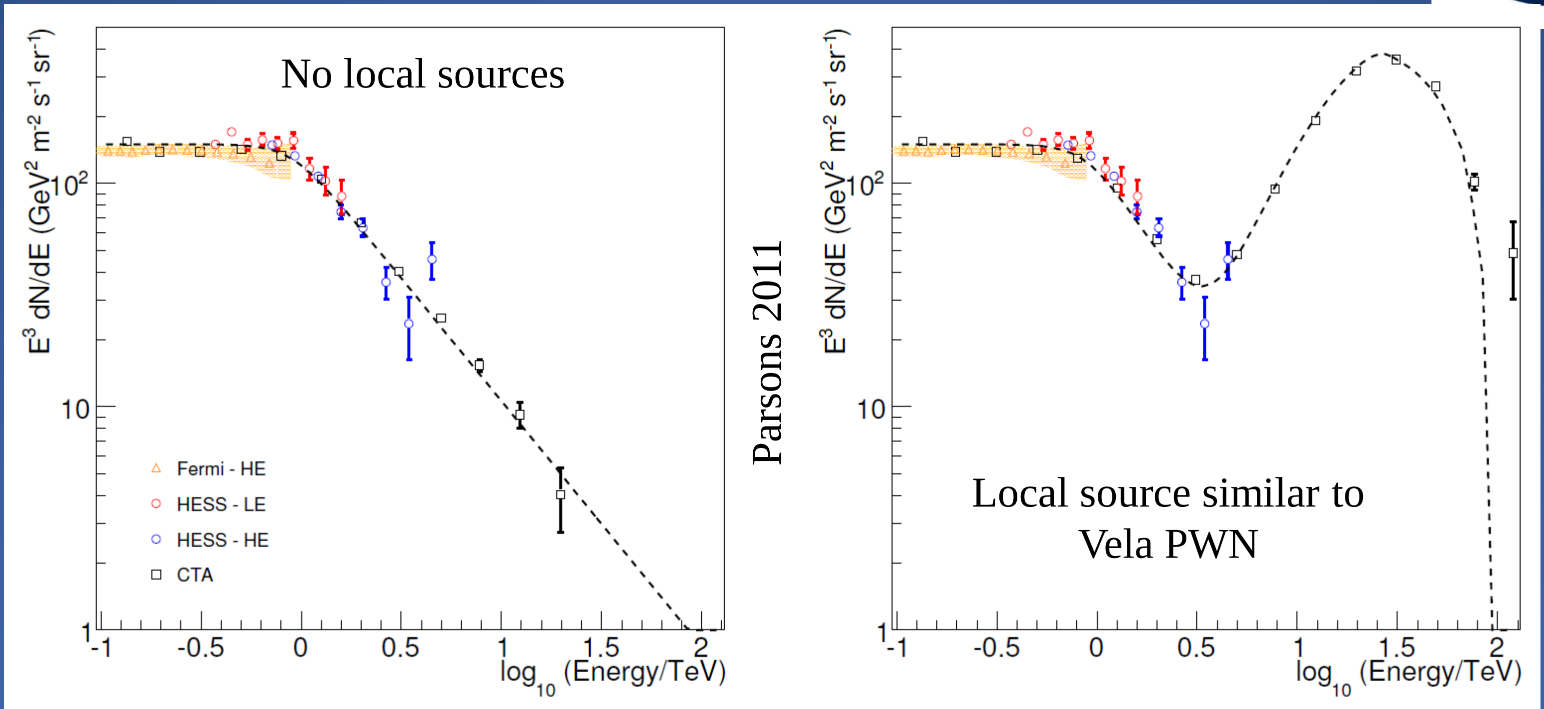


Target	Dec. [deg.]	Distance [kpc]	$\log_{10}$ (J/GeV^{2}cm^{-5})
Sculptor	-83.2	79	18.47 ± 0.18
Draco	+34.7	82	18.69 ± 0.16
Coma Berenices	+23.4	44	18.83 ± 0.25
Segue 1	+16.1	23	19.31 ± 0.29

- dSph's J-factor controversies:
  - Possible anisotropy in the velocity dispersions;
  - Possible contamination from foreground
  - Milky Way stars (Segue I's J-factor is particularly questionable Bonnivard, Maurin, Walker arXiv: 1506.08209)

- New ultra-faint dSphs discovered in DES survey in the Southern hemisphere, e.g. Reticulum II, and more such discoveries are anticipated with the start of LSST operation.
- Best dSph targets for CTA will be selected on the latest knowledge prior to the observations.

Complementarity with other Particles

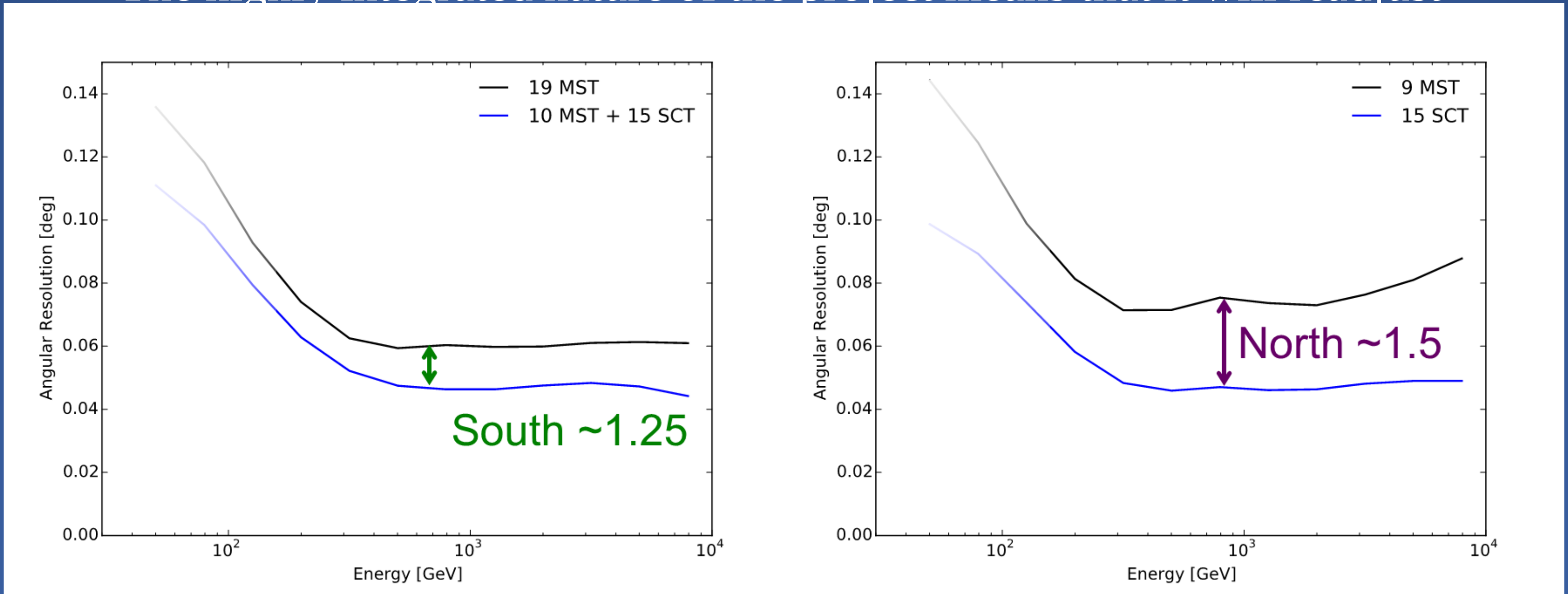


- CTA will extend the cosmic-ray electron spectrum to at least 20 TeV (assuming index G = -4.1 above 1 TeV).
- Can go further if new contributions due to local sources or DM appear.

Impact of $25M on a €400M Project

cherenkov telescope array

- The highly integrated nature of the project means that it will readjust



	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

Sources resolved in more detail

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
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More objects studied

or

Impact of $25M on a €400M Project

cta
cherenkov telescope array

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Better diffuse measurements; serendipitous discoveries

or

Impact of $25M on a €400M Project

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Faster, deeper surveys

or