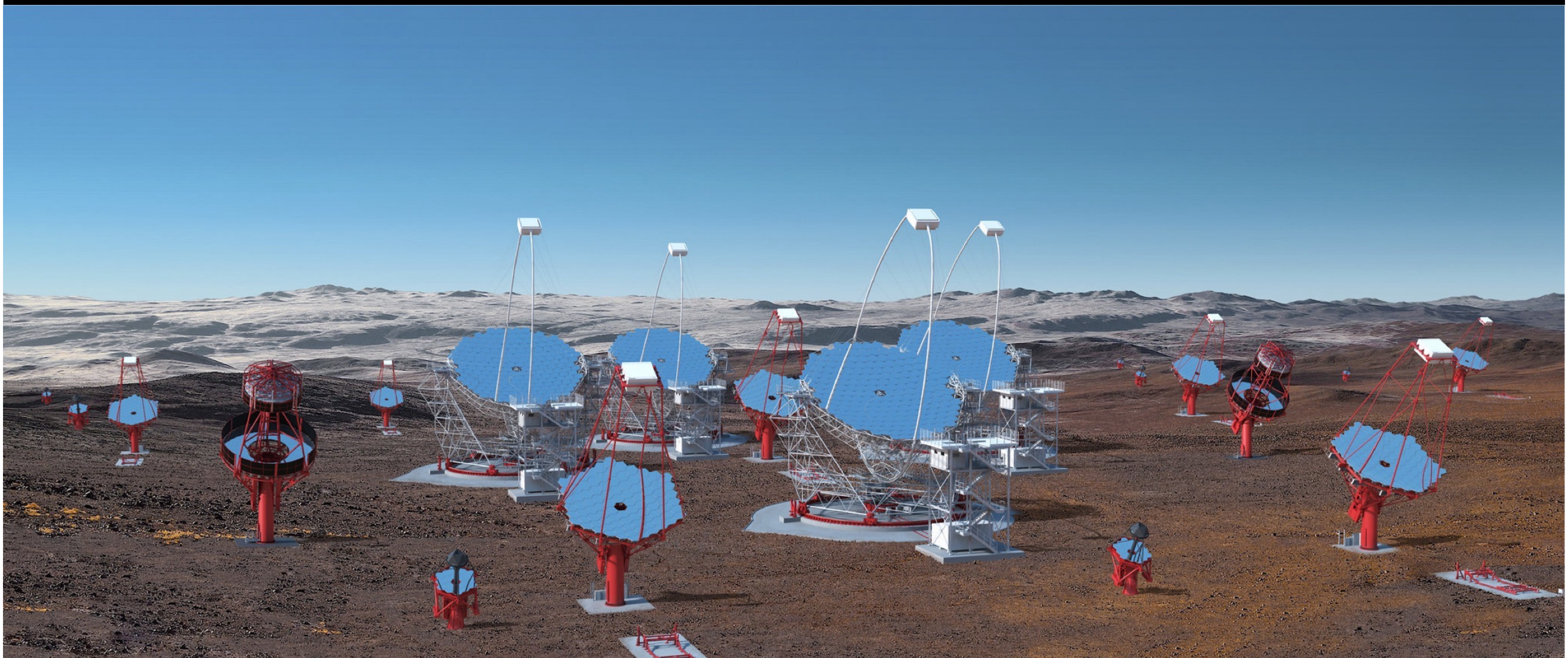
The Cherenkov Telescope Array: cosmic frontier physics with TeV gamma rays

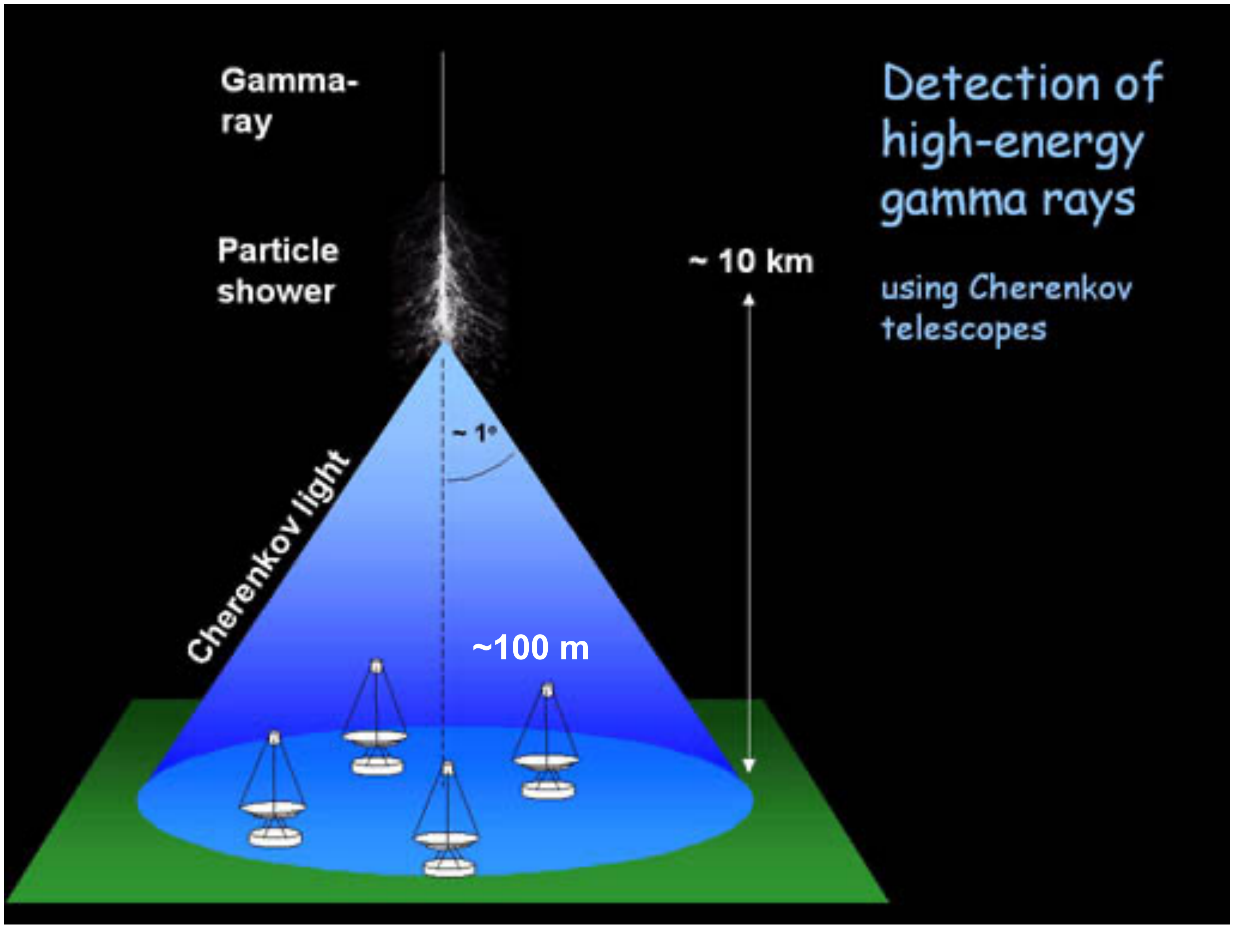


Justin Vandenbroucke (University of Wisconsin)

on behalf of CTA-US and the CTA Consortium

P5 Town Hall, Fermilab & Argonne, March 23, 2023

Detection of 20 GeV – 300 TeV gamma rays with imaging atmospheric Cherenkov telescopes



- Very short (few ns) exposure to limit night sky background: instruments use particle physics technology for photo-detectors and readout
- Technique pioneered by Whipple in U.S.
- Ongoing discoveries and searches by current instruments H.E.S.S., MAGIC, VERITAS

The Cherenkov Telescope Array: cosmic frontier physics with TeV gamma rays

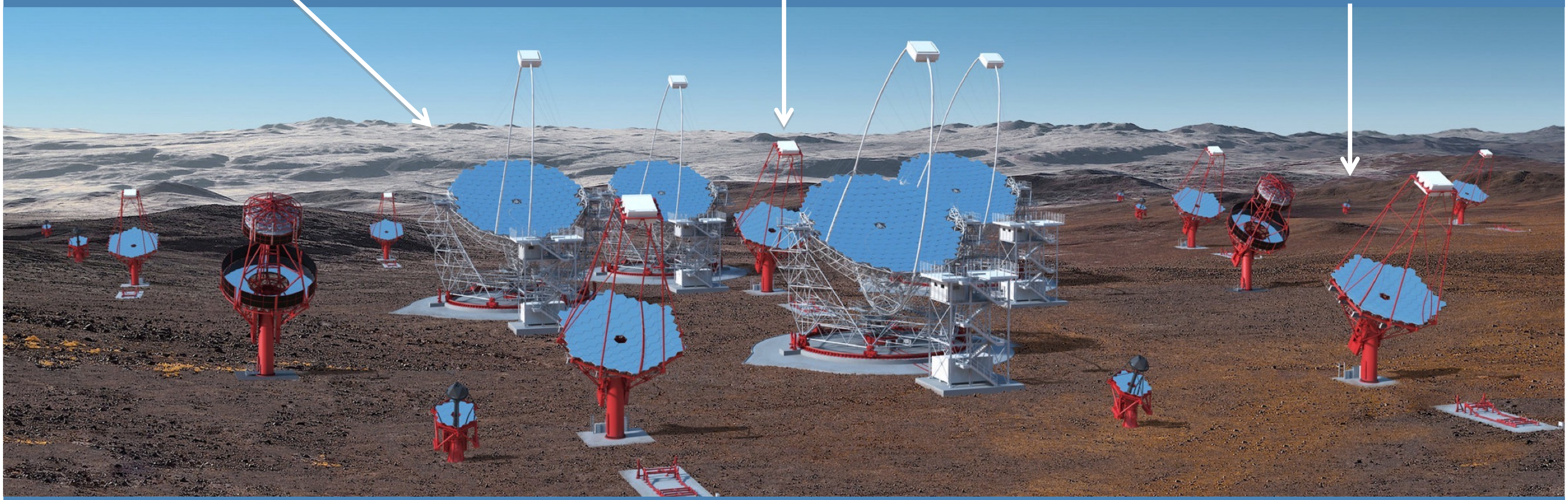
- Major worldwide project in high-energy particle astrophysics for this decade and the next
- Builds on major success of ground-based VERITAS and HAWC (NSF, DOE) and space-based Fermi (DOE, NASA)
- Gamma rays are the bridge between the new cosmic messengers (neutrinos, gravitational waves) and the electromagnetic spectrum
- Enormous potential for exploring physics of extreme universe, including unique capabilities for multi-TeV DM, out of reach of LHC and direct detection
- Currently nearing initial configuration construction, largely with European funding
- U.S. groups aim to construct a timely enhancement to CTA that will provide better capabilities, an innovative path to the future, and allow U.S. participation in the key science of CTA, including the search for dark matter

The Cherenkov Telescope Array: alpha configuration

Low energies
Energy threshold ~20 GeV
23 m diameter
4 large-sized telescopes (North)

Medium energies
100 GeV – 10 TeV
11.5 m diameter
14 medium-sized telescopes (S)
9 medium-sized telescopes (N)

High energies
4 km^2 area at few TeV
4.3 m diameter
37 small-sized telescopes
(S only)



Northern array: La Palma

Southern array: Chile

CTA prospects summarized in letter of interest

Snowmass2021 - Letter of Interest

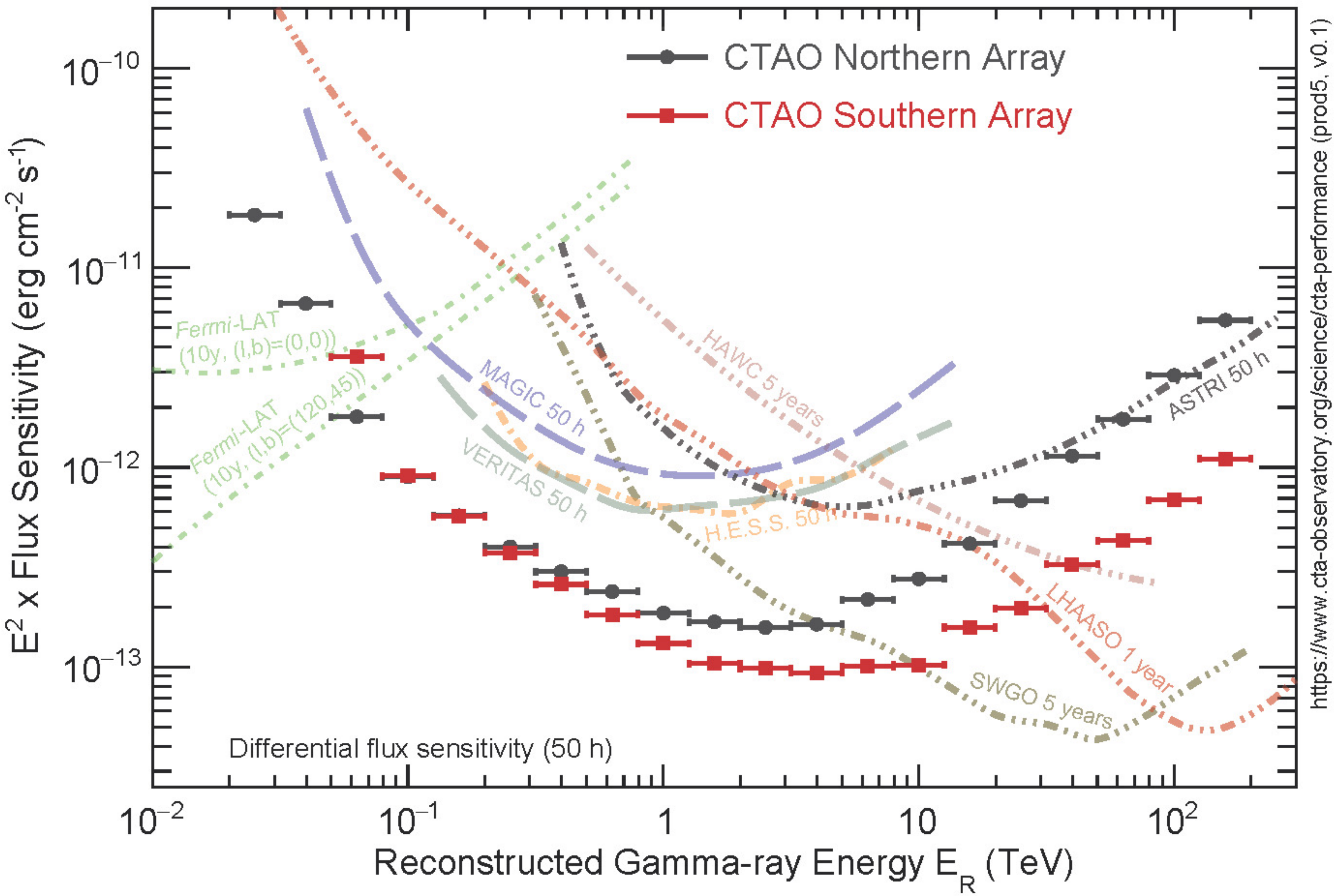
The Cherenkov Telescope Array (CTA): A Transformational Instrument for Fundamental Physics and Cosmology with Very High-Energy Gamma Rays and Cosmic Rays

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

CTA supported by several Cosmic Frontier topical group reports and by the Cosmic Frontier summary report

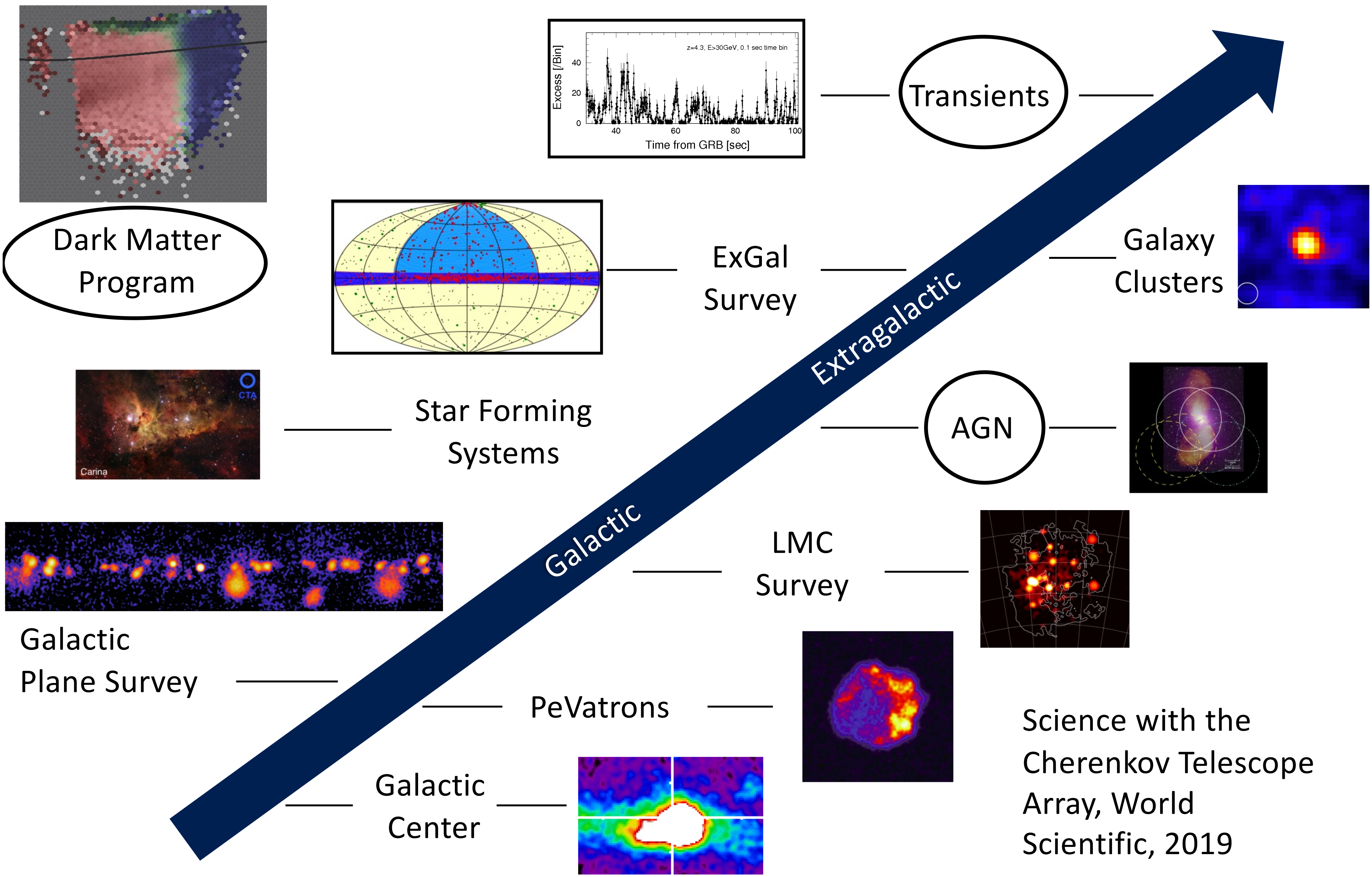
CTA sensitivity: an order of magnitude beyond current instruments



Strong endorsement of CTA by the Astro 2020 decadal survey

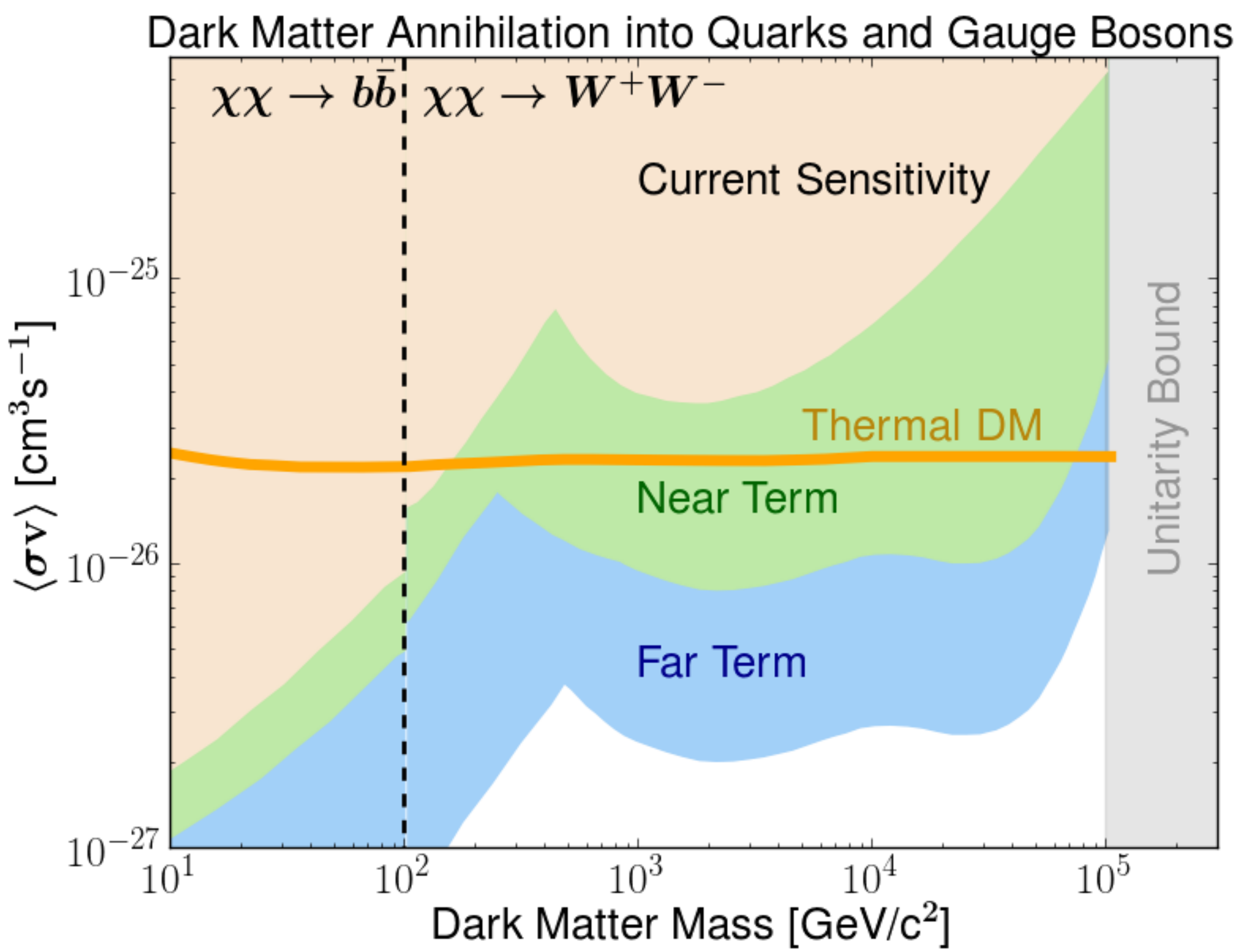
- "**What are the properties of dark matter and the dark sector?** ...and TeV-scale Cherenkov telescopes are particularly important to make progress in this field."
- "**Time Domain Astrophysics**: …new science that will come from the Laser Interferometer Gravitational-Wave Observatory (LIGO), the Cherenkov Telescope Array (CTA), and IceCube."
- "**Medium-Scale Investments: Gamma-Ray Program** …To develop discovery-class capabilities in multi-messenger astronomy, the panel endorses… U.S. participation in the Cherenkov Telescope Array (CTA)
- "The success of the broad U.S. program in **multi-messenger astrophysics** would be greatly enhanced by access to these world-leading facilities. The development of these facilities depends critically on decades of U.S. investment that cannot be capitalized upon without continued U.S. involvement."
- "The United States will contribute… **SCT telescopes** to the larger CTA array, which will roughly double the number of medium-scale telescopes."

CTA'S Key Science Projects (KSPs)



Science with the Cherenkov Telescope Array, World Scientific, 2019

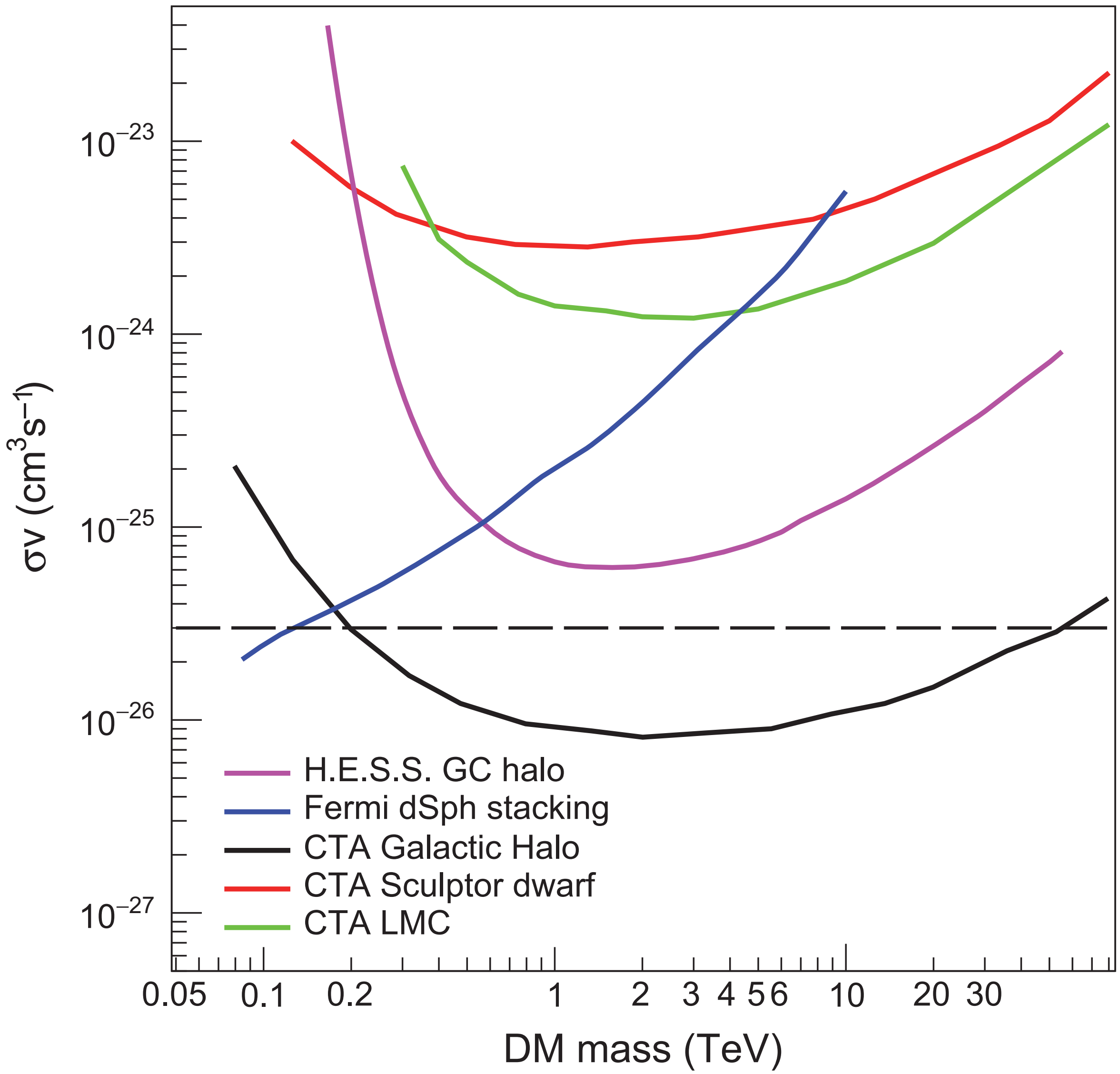
TeV gamma rays will test the remaining (high mass) WIMP parameter space down to thermal cross section



near term:
CTA, SWGO

figure from Cosmic Frontier Summary Report

CTA Galactic center observations will cover WIMP masses 200 GeV – 30 TeV down to thermal cross section



CTA sensitivity using array with 25 Medium-Sized Telescopes

Science with the Cherenkov Telescope Array, World Scientific, 2019

See also:
CTA Consortium,
JCAP 01 (2021) 057

Snowmass Cosmic Frontier Summary Report

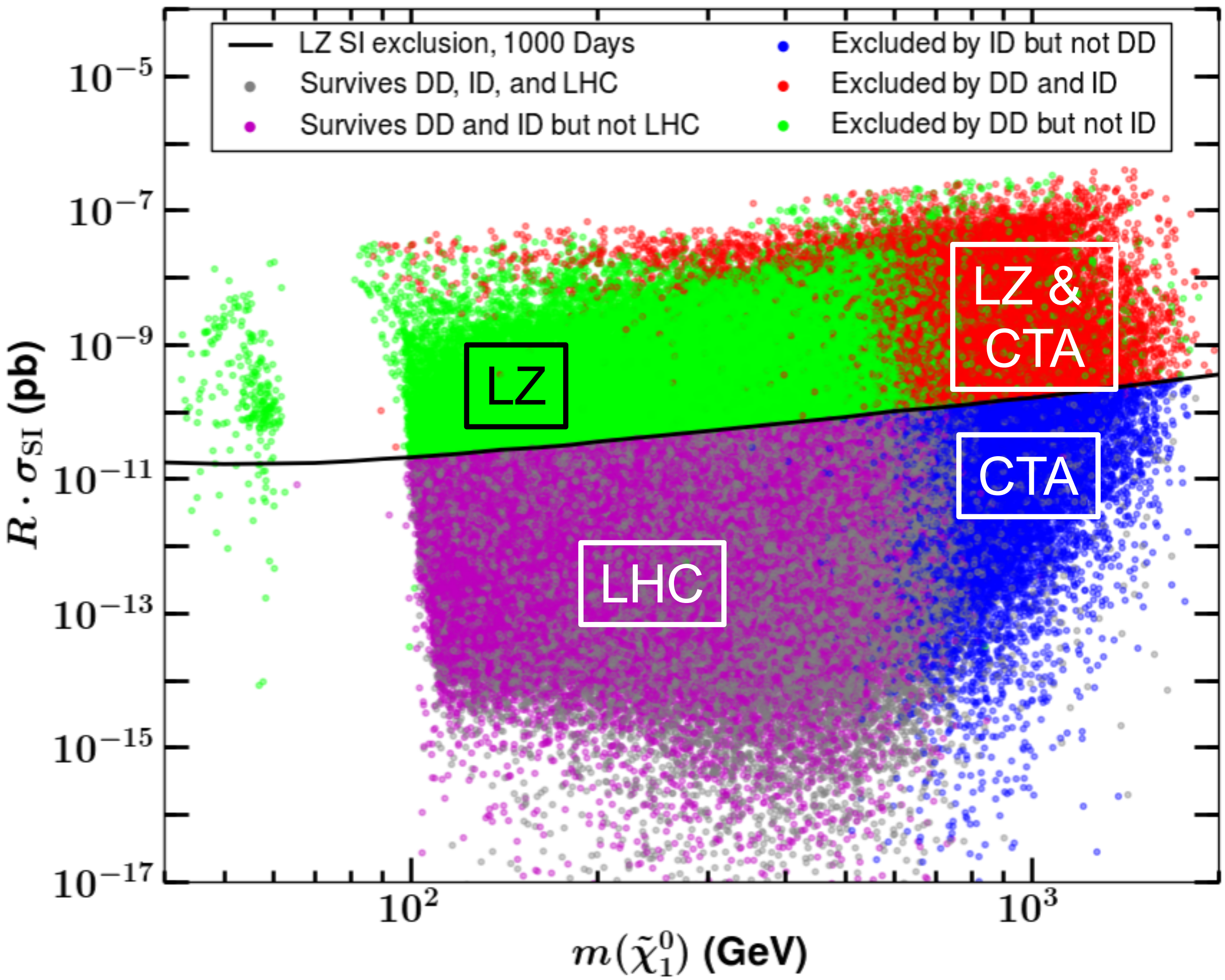
- "Support high-energy gamma-ray telescopes (e.g., SWGO and CTA) to **probe thermal WIMPs** up to tens-of-TeV mass scales."

- "Indirect detection of dark matter via high energy astrophysics: New > 100 GeV gamma ray observatories including CTA will study dark matter via its annihilations or decays, with **sensitivity to the thermal freeze-out benchmark annihilation rate up to masses approaching the 100 TeV scale**, where model-agnostic limits on the early Universe cross section come into play."

- "In the near future, the SWGO [135] (water Cherenkov) and CTA [136] (air Cherenkov) telescopes, successors using similar technology to the successful HAWC and VERITAS Cherenkov telescopes but with larger installations and Southern Hemisphere sites, have the potential to probe the thermal freeze-out scenario up to 10s of TeV masses (depending on the annihilation channel) [137, 138], **approaching the 100 TeV scale where we can begin to set unitarity-based limits on the capacity for freeze-out to generate the correct relic abundance**."

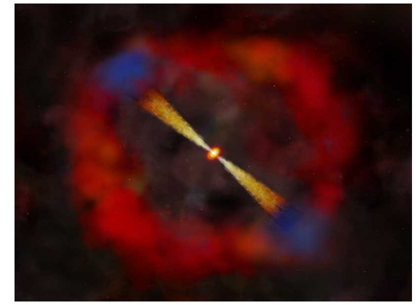
- "High energy gamma rays and neutrinos additionally offer **probes of new physics including the decays of super-heavy relics left behind from the Big Bang, cosmic strings, and axion-photon conversion in large-scale magnetic fields**. Next-generation gamma-ray telescopes such as the Southern Wide-field Gamma-ray Observatory (SWGO), the Cherenkov Telescope Array (CTA), and the All-sky Medium-Energy Gamma-ray Observatory (AMEGO) will open up the access to new sky regions and energy ranges, and **advance fundamental physics studies with significantly improved sensitivities**."

Dark matter: complementarity of CTA to direct and accelerator searches



Cahill-Rowley M. et al, "Complementarity of dark matter searches in the phenomenological MSSM", PRD 91, 055011 (2015)

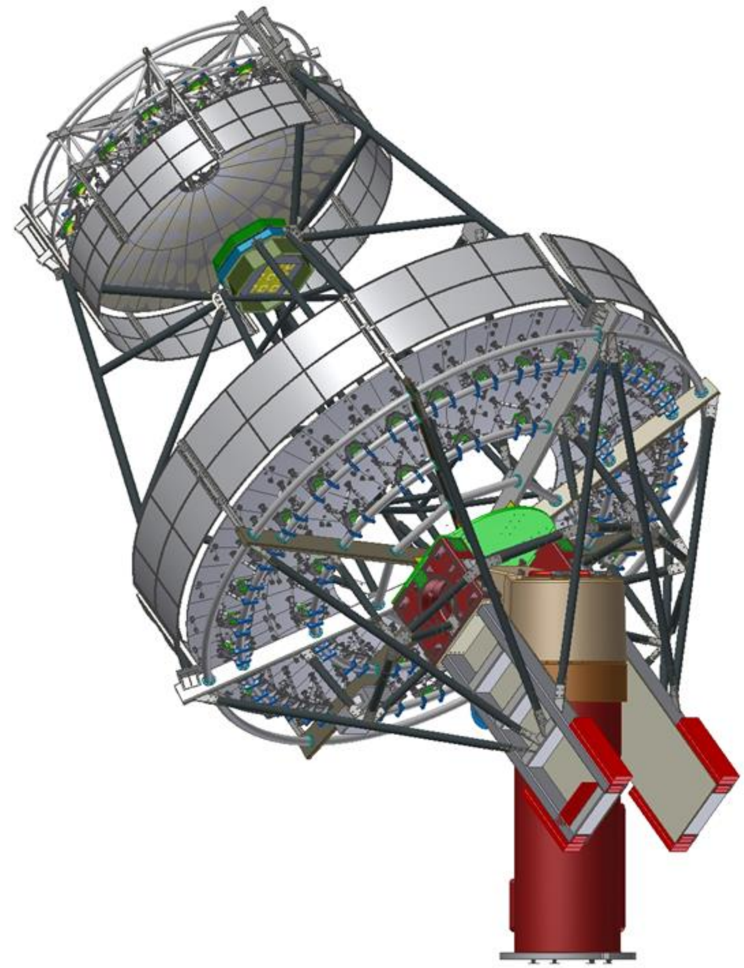
Powerful beams of TeV particles propagating over cosmic (10^{25} m) baselines



- CF2 (Wave Dark Matter): “propagation of photons through the cosmic medium, featuring magnetic fields, but also a plasma of charged particles as well as various types of photons (cosmic microwave photons, extra galactic background light etc.) is modified in the presence of axions and similar particles and therefore can provide powerful constraints but also intriguing hints”
- Search for anomalies during propagation, predicted by physics beyond the Standard Model
  – Energy-dependent speed of light
  – Coupling to axions and axion-like particles
- Multiple beams (including TeVatrons and PeVatrons), and types of beams (e.g. pulsars, blazars, gamma ray bursts), for complementary phase space and systematics
- Five gamma-ray bursts detected in very-high-energy gamma rays by ground-based instruments in the past five years
  – Including the brightest in ~10^4 years: GRB 221009A [2302.14037]
  – Detected up to ~18 TeV? Axions/ALPs?

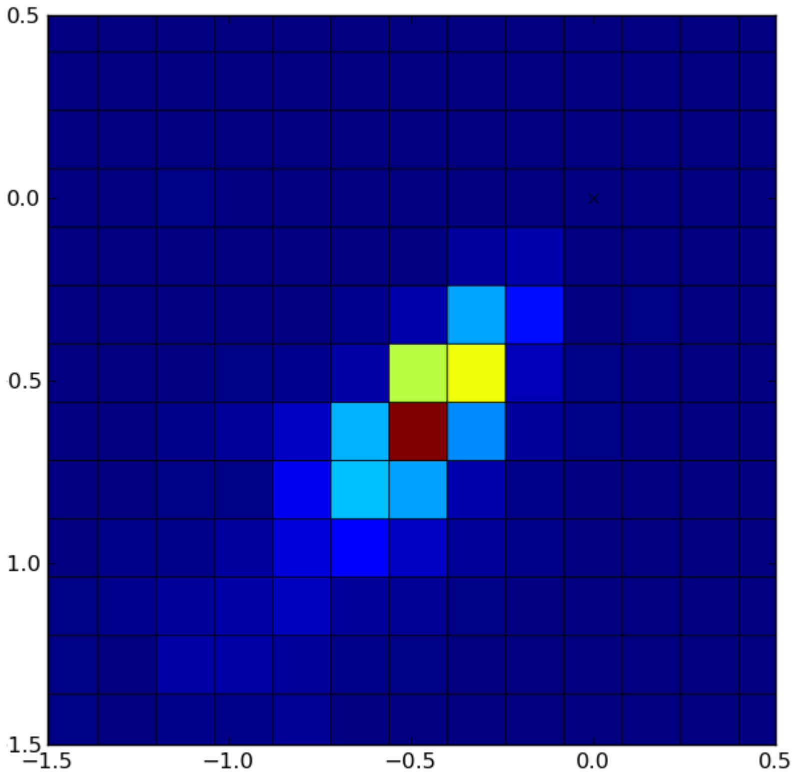
U.S. groups have innovated new dual-mirror (Schwarzschild-Couder) telescope technology for excellent sensitivity

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

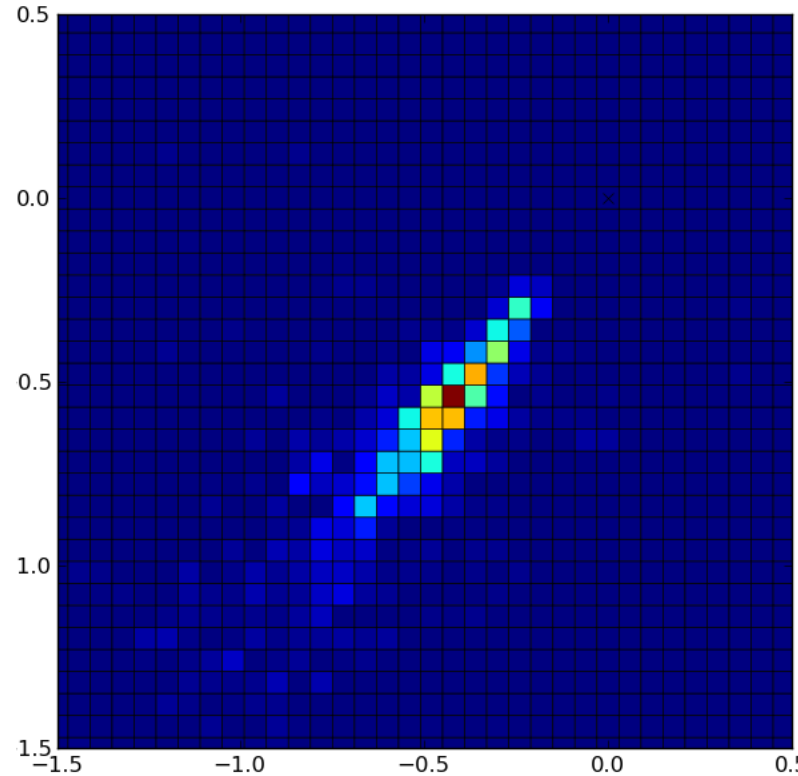


Simulated shower images for two-mirror vs. one-mirror telescope design

1 mirror telescope (~2k 0.17° pixels)



2 mirror telescope (~11k 0.07° pixels)

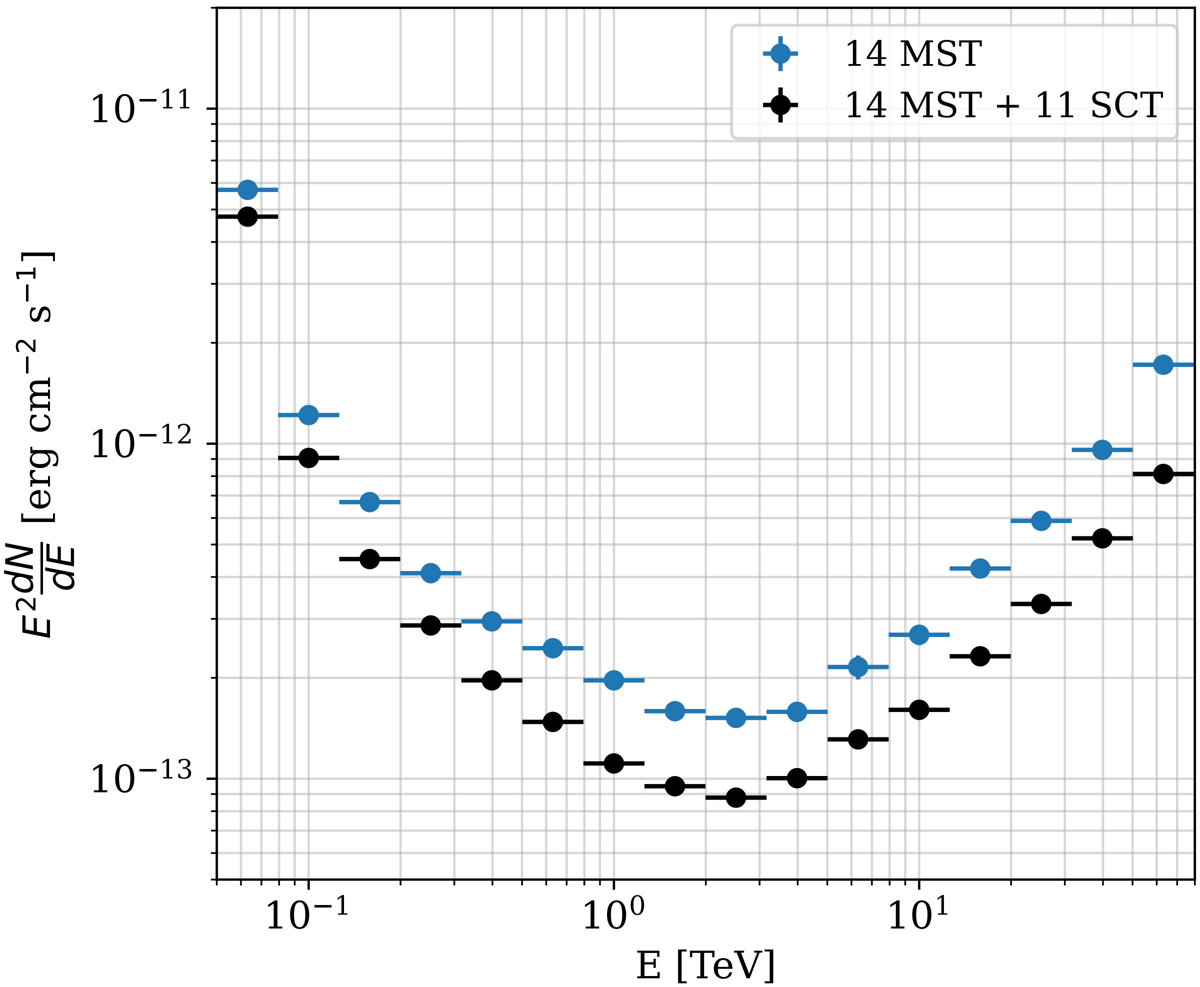


Both images of 1 TeV showers, zoomed in (2° across, compared to 8° field of view)

Construction and operation of the prototype Schwarzschild-Couder Telescope (pSCT)

- Supported by NSF MRI along with international partners
- Constructed next to VERITAS at Fred Lawrence Whipple Observatory
- Inaugurated in 2019, detected Crab Nebula in 2020
- Camera upgrade (full field of view, low threshold) now underway: second NSF MRI
- 30 CTA institutions (~80% U.S.) have contributed to SCT development

US contribution of 11 Medium-Sized Telescopes to CTA-South



- Will enable detection of sources 2-3 times faster than without US contribution
- Plan endorsed by Astro 2020

CTA Observatory: international context

- 330 million euro secured for CTA-alpha construction (2023-2028)
  - Includes 14 Medium-Sized Telescopes in CTA-South
- Unified project since 2010; operating as German nonprofit (GmbH)
- ERIC (European Research Infrastructure Consortium) application successfully reviewed by European Commission, will transition from GmbH this year
- Stuart McMuldroch (Harvard/SAO, leading CTA-US management) recently hired as new Director General of ERIC

CTA-North: first telescope (LST-1) published first scientific paper [2210.00775]

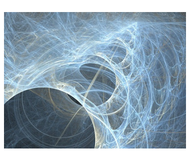
CTA-South: access road constructed

CTA-US in the international CTA context

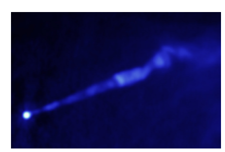
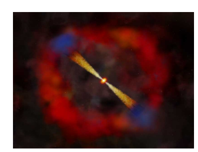
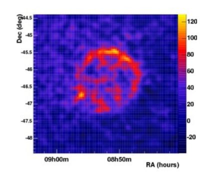
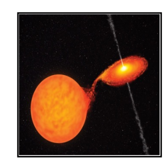
- U.S. groups, along with international partners, aim to enhance CTA with 11 SCTs at CTA-South by ~2030
- SCT development over past decade supported by 2 NSF MRI projects
- CTA Small-Sized Telescopes also use Schwarzschild-Couder design
- Pending NSF MSRI proposal requests $8.7M to optimize the SCT design for manufacture and reliability and will bring the project through critical-design and manufacturing-readiness reviews
- Pending NSF MRI proposal requests $3.9M for optics alignment systems development for first 7 CTA medium-sized telescopes — including prototype SCT
- These would complete most remaining R&D prior to SCT construction
- Subsequent proposal for construction of 11 SCTs would have ~$50M U.S. cost over five years
- Seek ~$3M per year after construction to support CTA operations, continuing for ten years to complete CTA science program, especially Key Science Projects
- Expect 50-75 FTEs throughout CTA phases

Conclusion and outlook

- CTA builds on technical and scientific success of previous and current gamma-ray instruments, including U.S. pioneering work and leadership through Whipple, Milagro, Fermi, VERITAS, HAWC, and the pSCT
- Order of magnitude more sensitive than current gamma-ray instruments, for a wide range of breakthrough physics
- New dual-mirror telescope design pioneered by U.S. provides excellent signal reconstruction and background rejection (medium and small telescopes)
- CTA will provide important discoveries and constraints concerning dark matter, axion-like particles, Lorentz invariance, quantum gravity, multi-messenger (including gravitational wave and neutrino) astrophysics
- Aim to construct 11 Medium-Sized Telescopes: led by U.S. groups in collaboration with international partners to enhance CTA-South
- Ongoing NSF investment in CTA; resumed DOE investment welcome

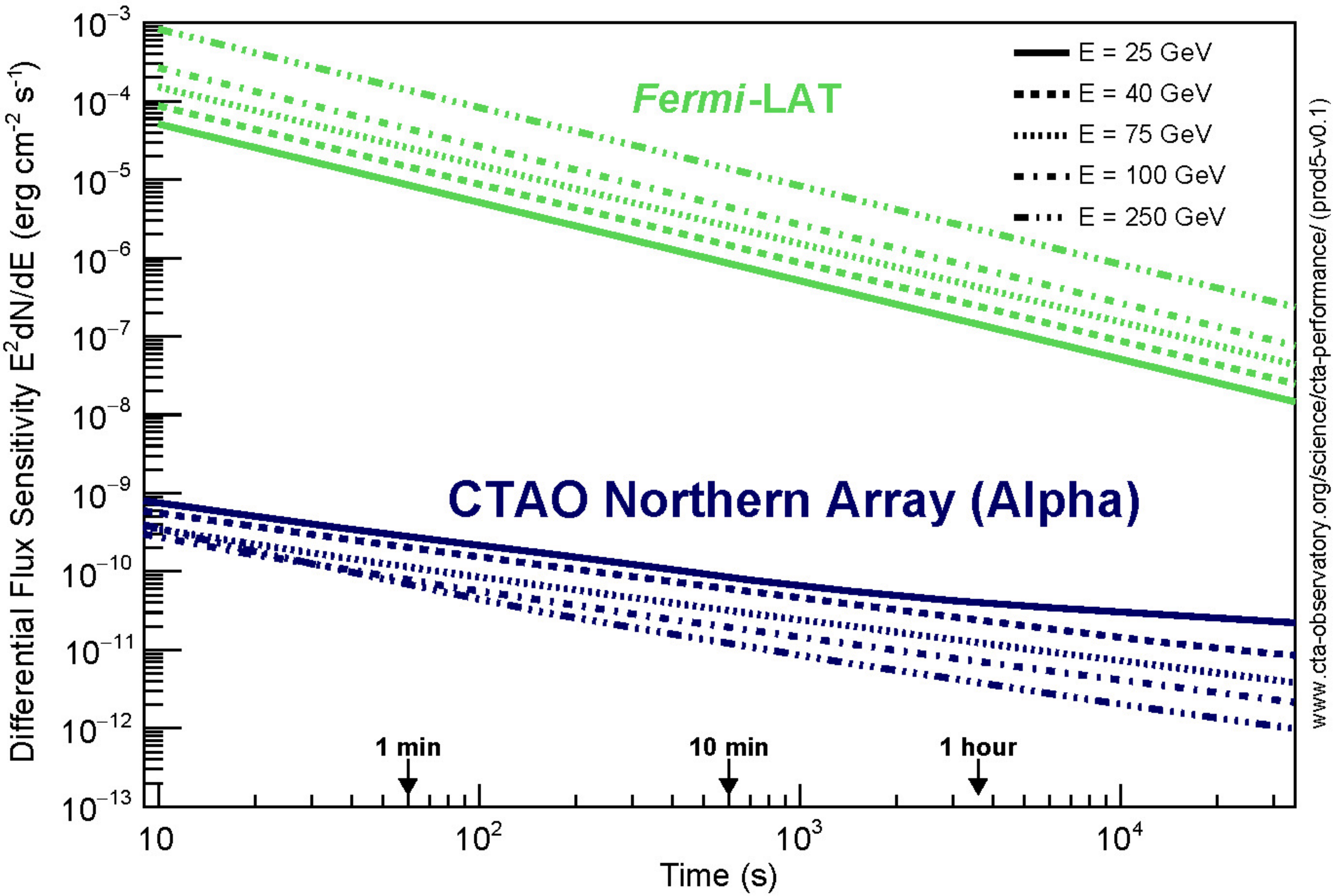




Additional slides

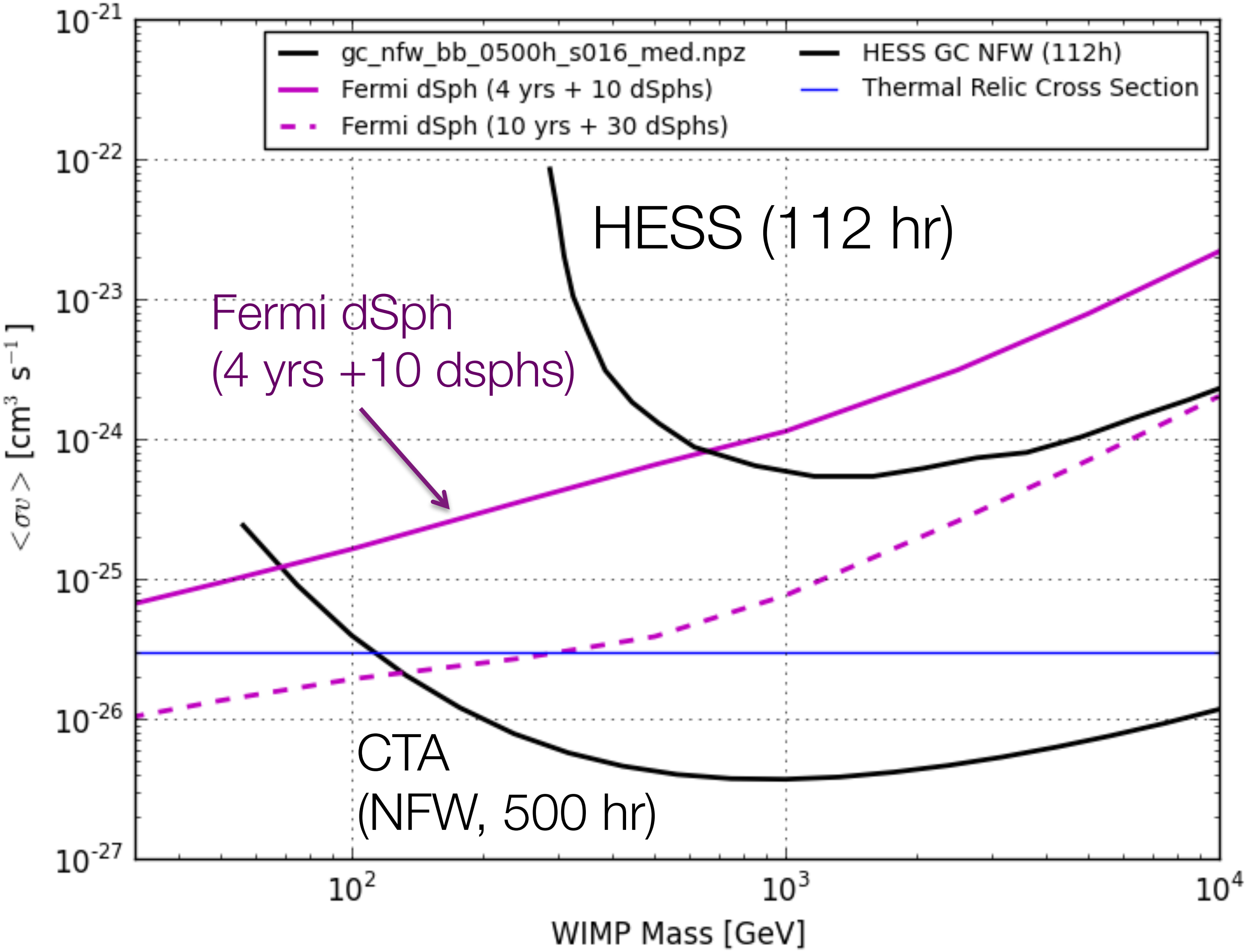
Opening up the time domain



Contributed remarks

- Pat Harding, “Particle physics beyond the Standard Model with cosmic accelerators” (Fermilab Wednesday)
- Qi Fing, “CTA and IceCube: the prospects of multi-messenger astrophysics with next-generation gamma-ray and neutrino observatories” (Argonne Thursday)
- Andrea Albert, “WIMPs are not dead”

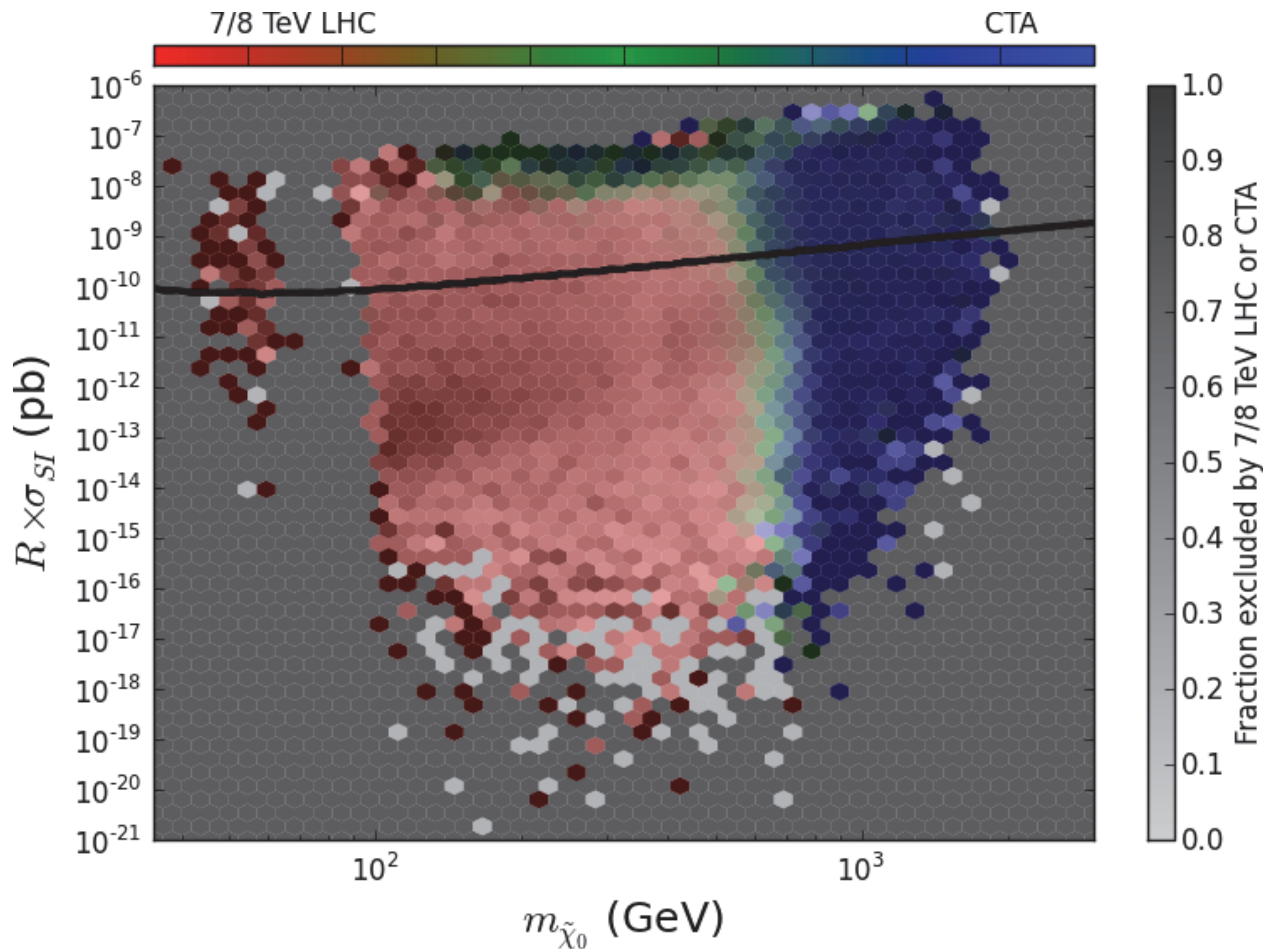
CTA Galactic center observations will cover WIMP masses above 100 GeV down to thermal cross section



CTA Consortium, JCAP 01 (2021) 057

CTA sensitivity using array with 25 Medium-Sized Telescopes

Dark matter: complementarity of CTA to direct and accelerator searches

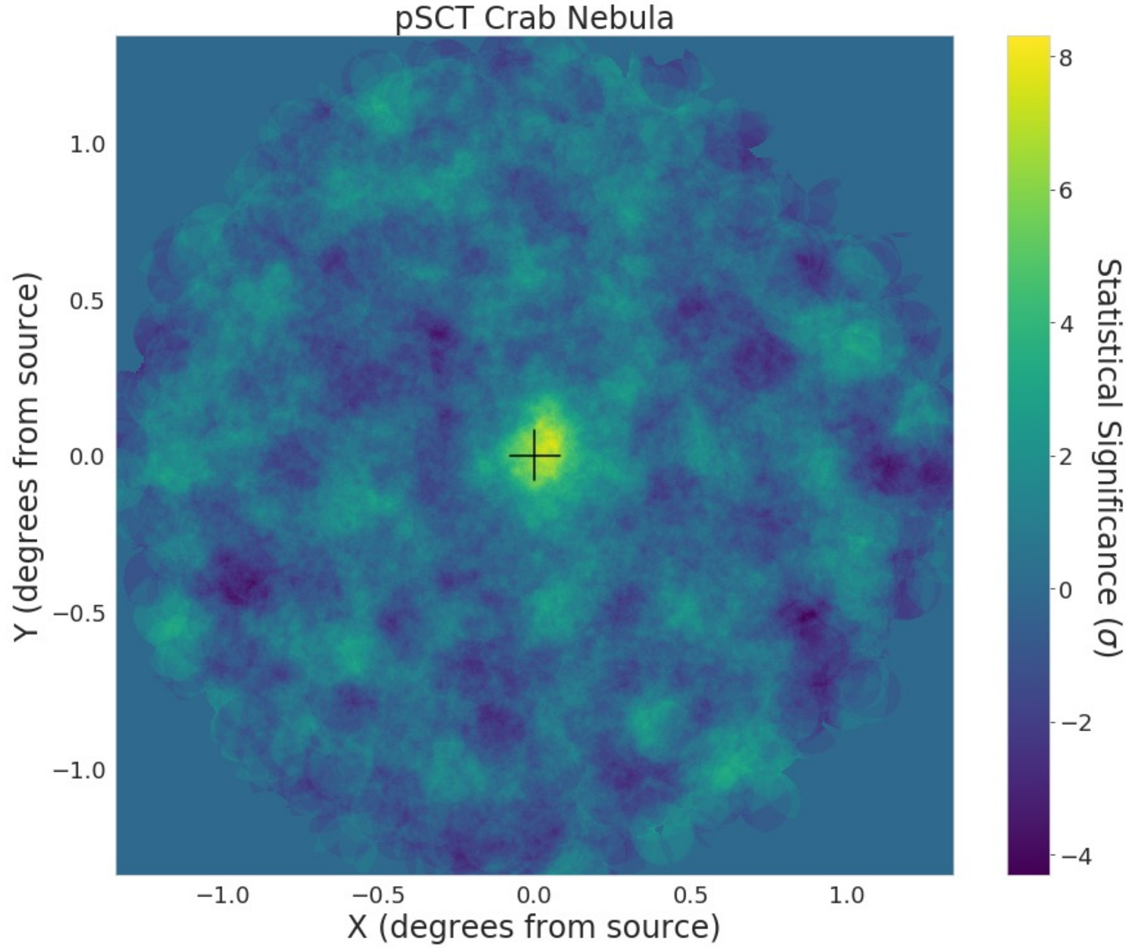


Cahill-Rowley M. et al, "Complementarity of dark matter searches in the phenomenological MSSM", PRD 91, 055011 (2015)

Five gamma-ray bursts detected at very high energies by ground-based instruments

GRB	Redshift	Energy range (TeV)	Time range	Luminosity distance	Duration (s)
180720B	0.653		10 hr		48.9
190114C	0.4245	0.2-2	10^2 – 10^3 sec		
190829A	0.0785	0.18-3.3	4-56 hr		
201216C	~1.1	0.1	20 min		30-48
221009A	0.151	up to 18 (!?)			

Detection of the Crab Nebula by the prototype Schwarzschild-Couder Telescope

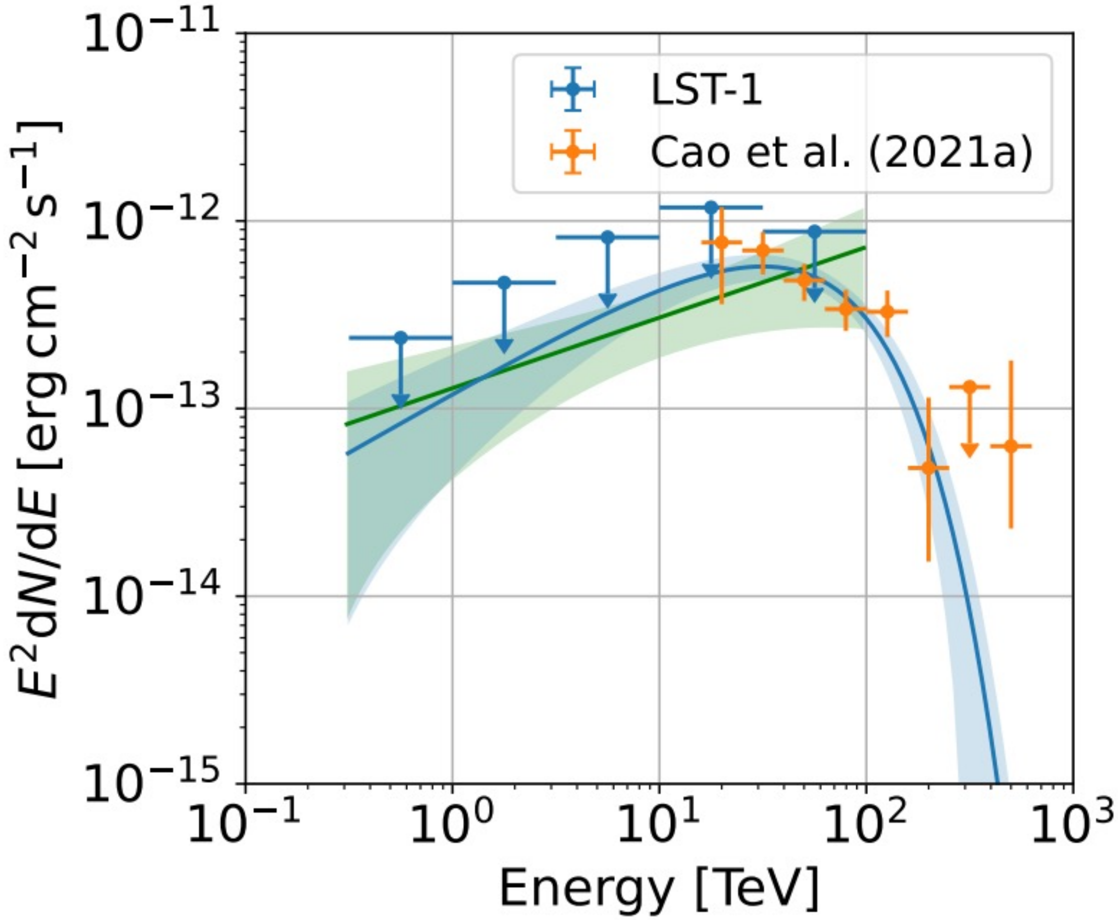


Establishes innovative dual-mirror technology

C. B. Adams et al., Astroparticle Physics 128 (2021) 102562

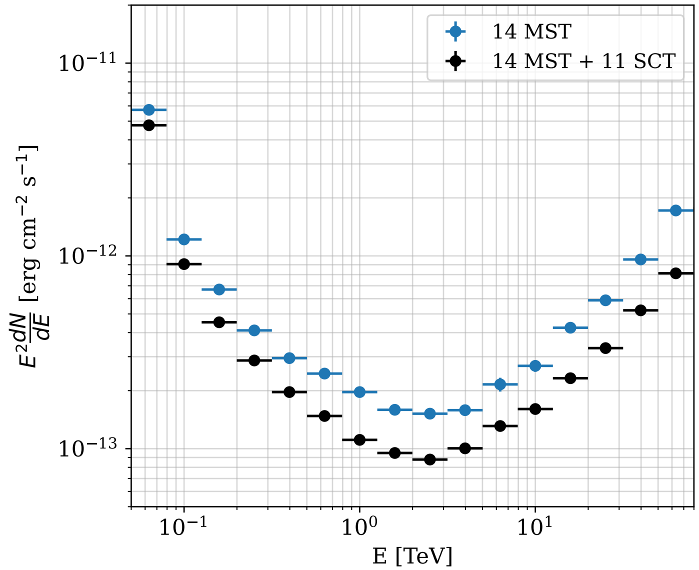

Heidelberg
MPIK
Zeuthen
DESY
Spain
La Palma
Bologna
INAF
Northern array
northern hemisphere
southern hemisphere
Chile
Paranal
Southern array
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google
Array Sites
CTAO Offices
Science Data Management Centre

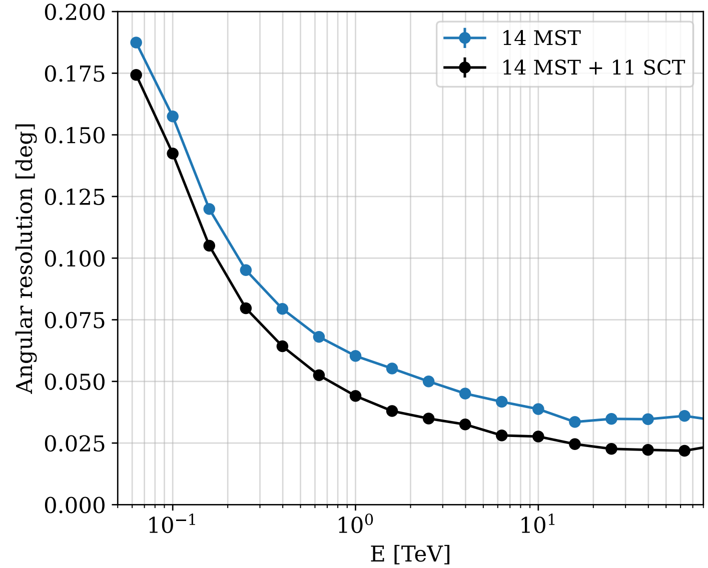
First scientific paper from a CTA telescope, LST-1

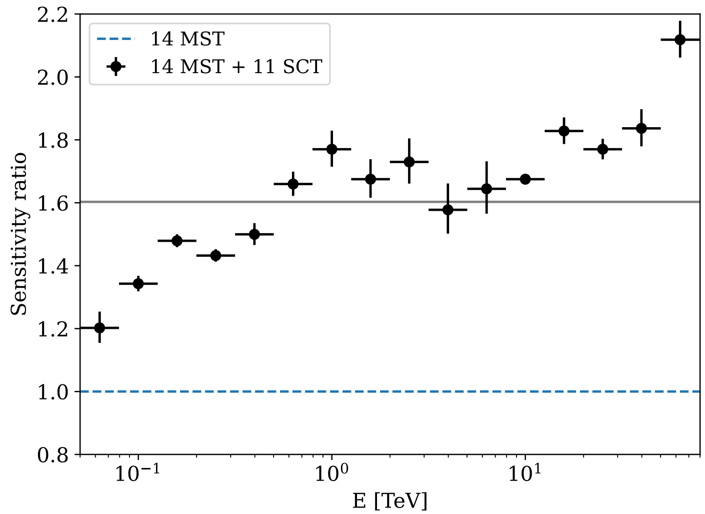


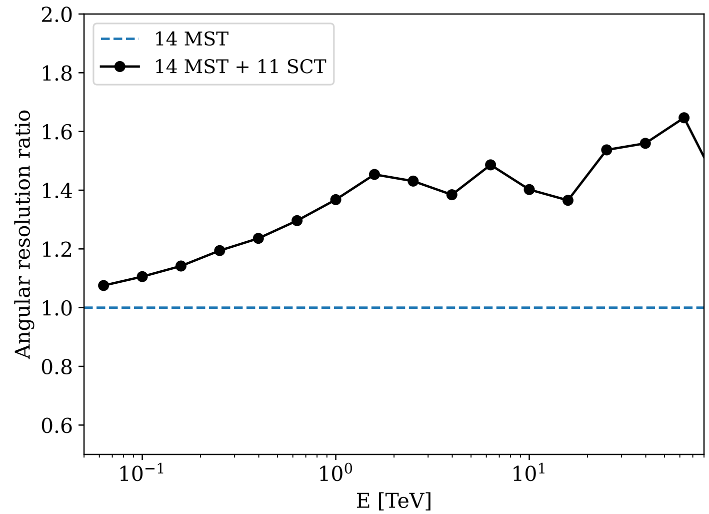
- Search for TeV counterpart of LHAASO J2108+5157
- One of several unidentified sources detected at ~100 TeV by LHAASO
- CTA-LST Project, A&A in press, 2210.00775

US contribution of 11 Medium-Sized Telescopes to CTA-South



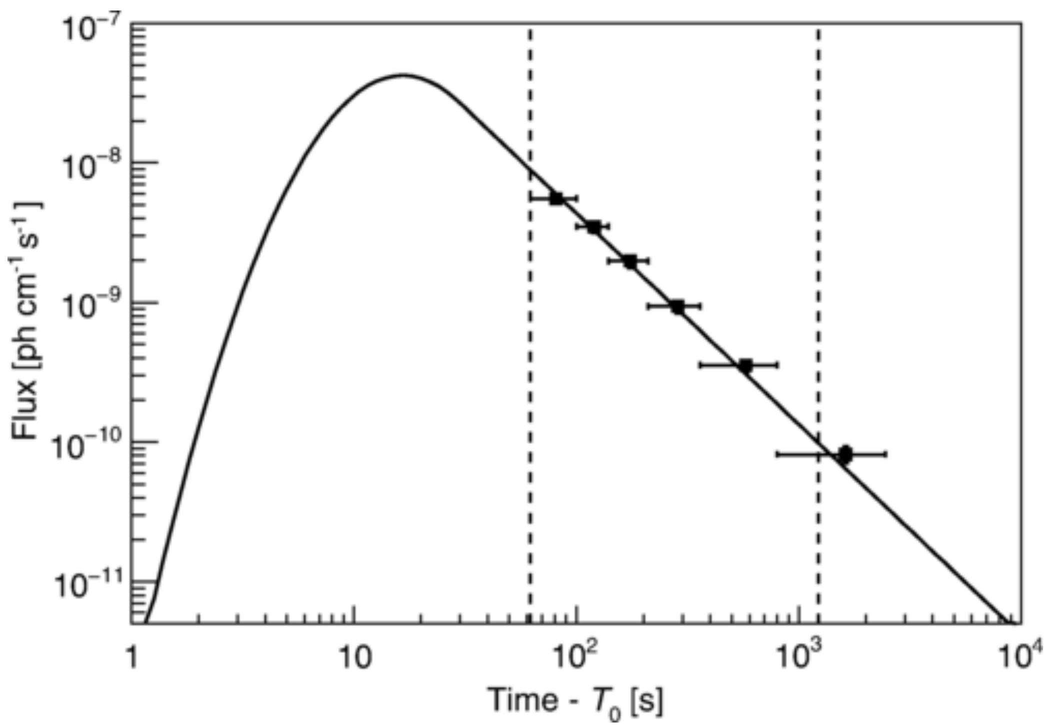






- Will enable detection of sources 2-3 times faster than without US contribution
- Plan endorsed by Astro 2020

Testing Lorentz invariance with gamma ray bursts



- MAGIC upper limit from GRB 190114C: 1.7 x 10^{-15}
- 4.5 billion light years, but high energy: 2 TeV
- Test quadratic dependence of light speed on energy
- Under invariance violation model, unification scale must be >5.6 x 10^{10} GeV (compare Planck 1.2 x 10^{19} GeV)