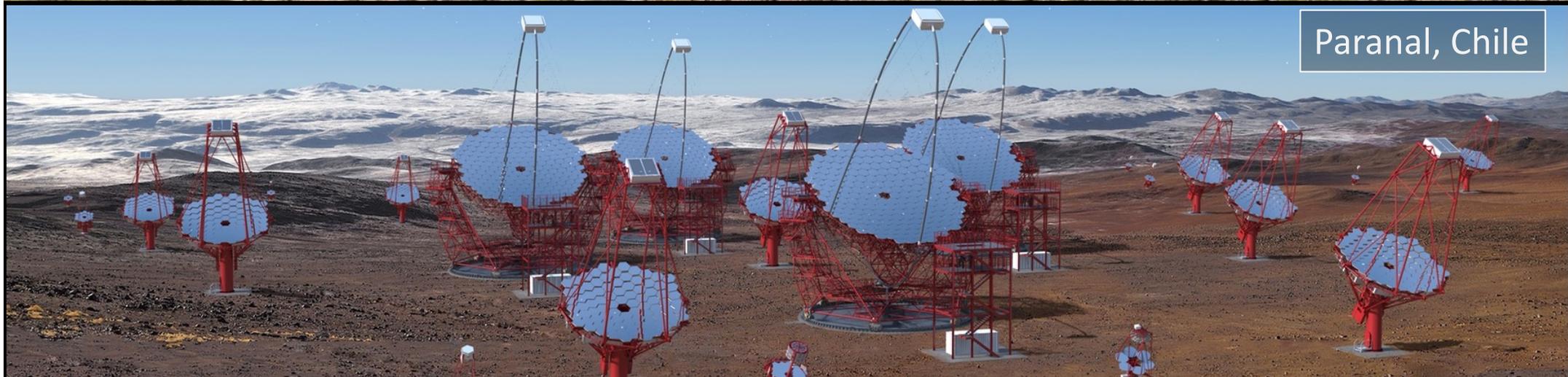
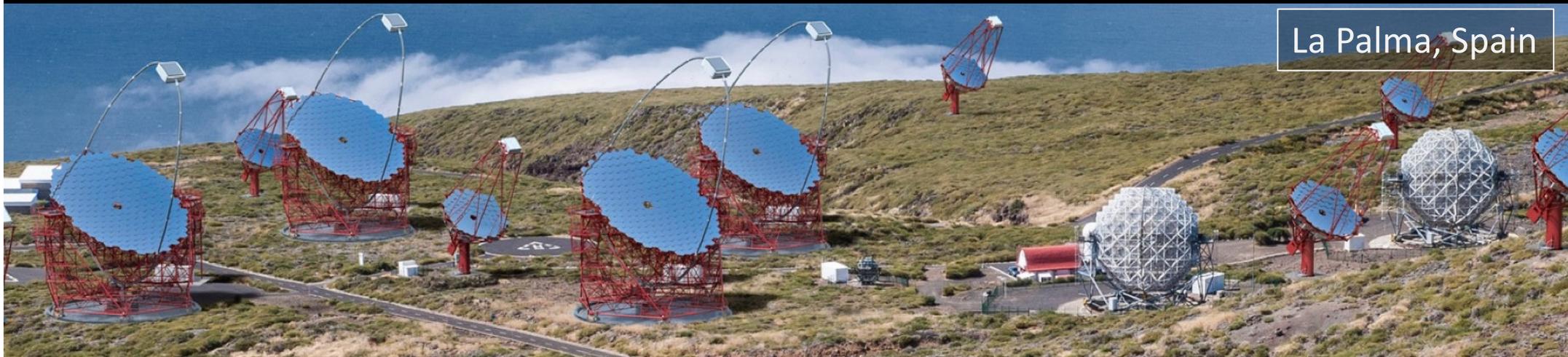


VHE Gamma-Ray Astronomy and The CTA Project

Masahiro Teshima

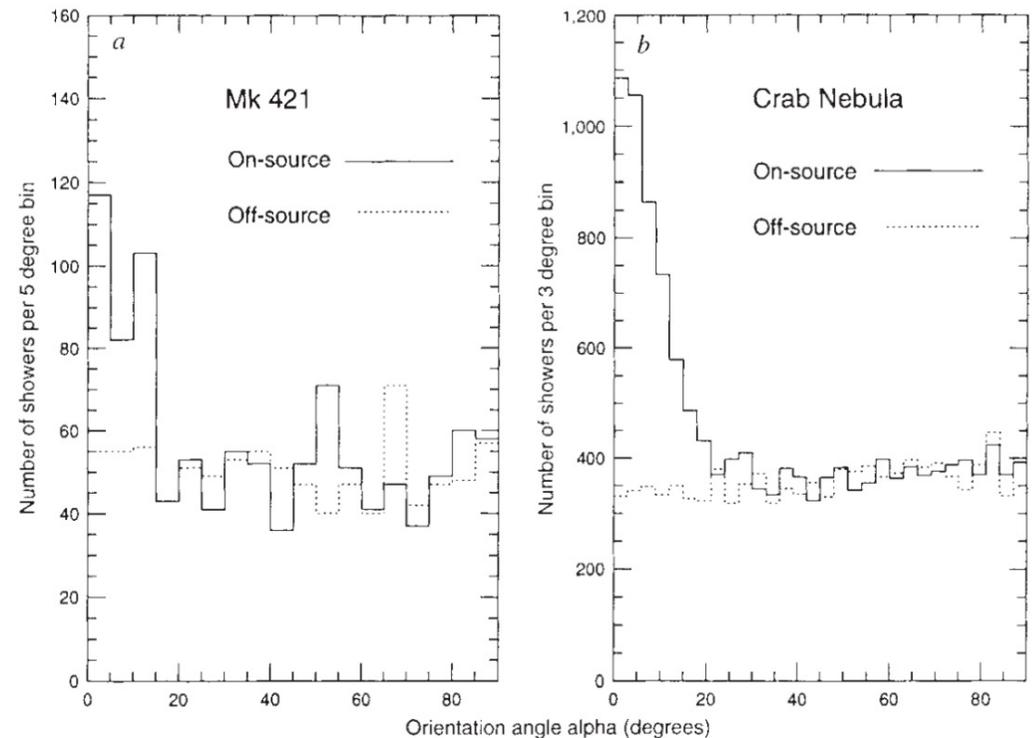
*Institute for Cosmic Ray Research, The University of Tokyo, Japan
Max Planck Institute for Physics, Munich, Germany*



History of VHE gamma-ray astronomy

Imaging Atmospheric Cherenkov Telescope

- ❑ The first idea of IACT from Michel Hillas in 1985 at ICRC in San Diego, USA
- ❑ Dr. Trevor Weeks demonstrated the power of IACT with the Whipple telescope.
VHE gamma rays from the Crab Nebula is discovered in 1989 (1G)
- ❑ → HESS, MAGIC and VERITAS (2G)
- ❑ → CTA (3G)

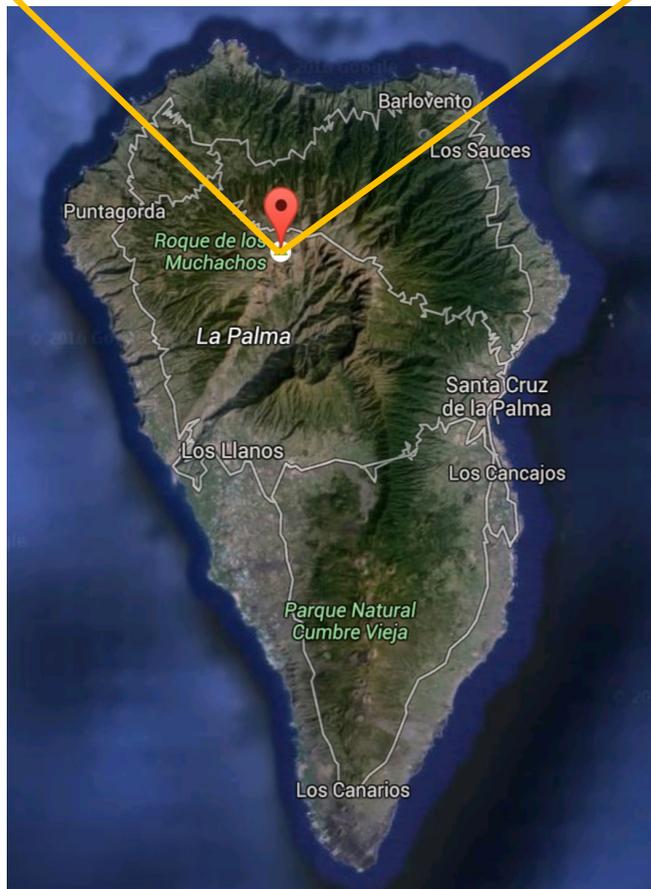


The observation of the first extragalactic source Mrk421
M. Punch et al., Nature 1921



cherekov
telescope
array

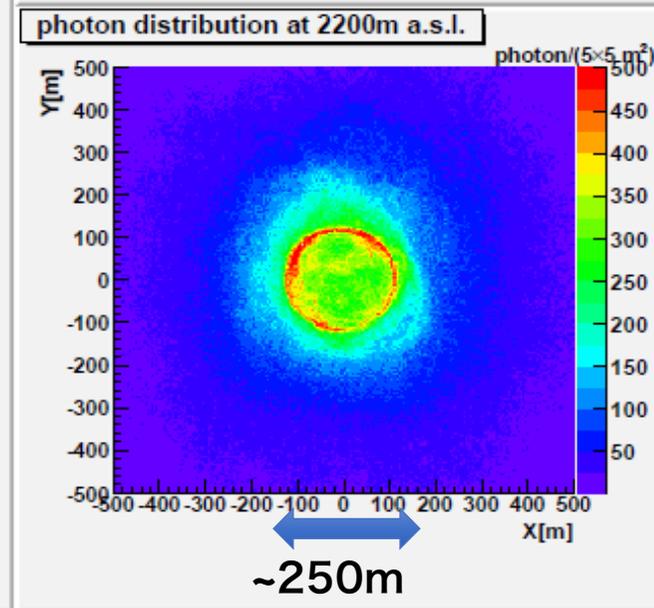
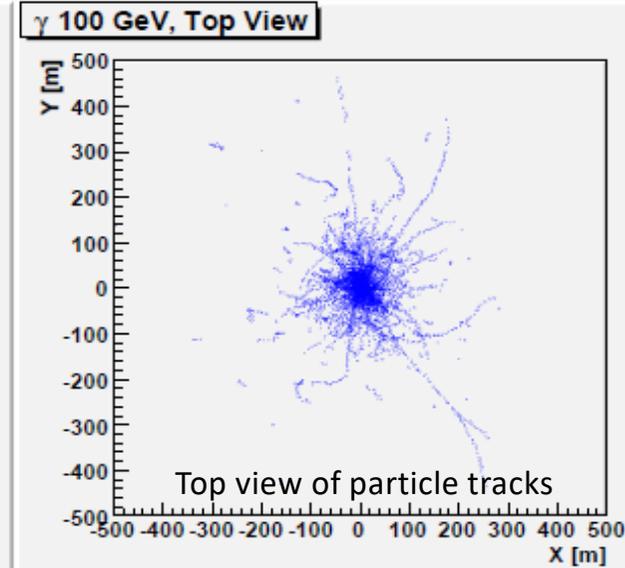
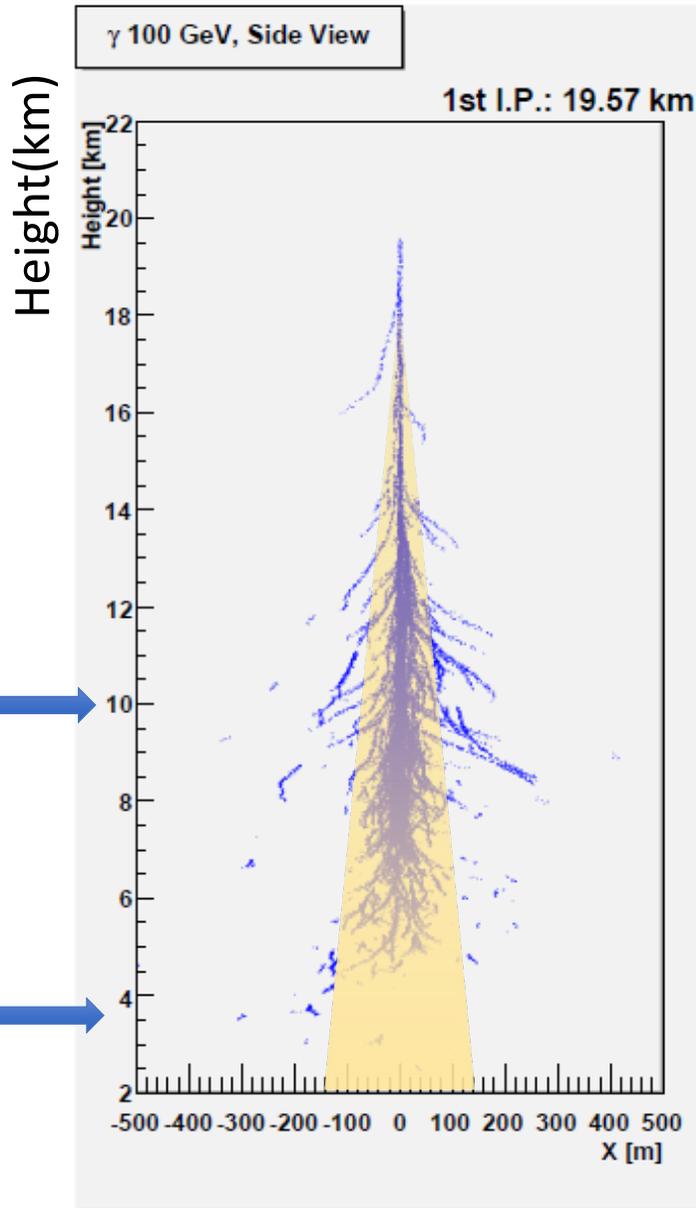
Canary Island, La Palma and ORM, Observatory Roque de los Muchachos





cherenkov
telescope
array

TeV Gamma Rays → EM shower → Cherenkov Light



Refractive Index
of Atmosphere
 $n = 1.000292$

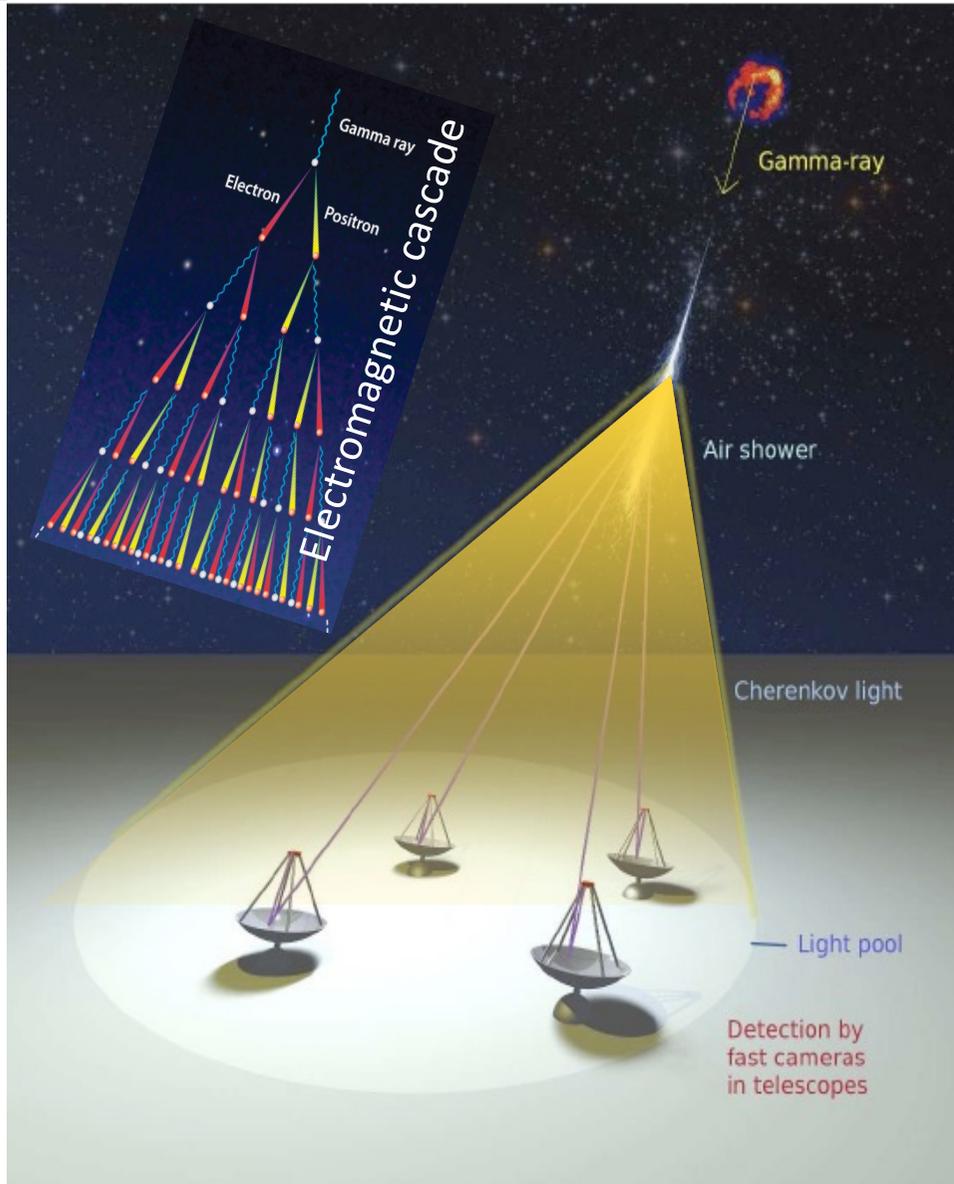
Light velocity
 $c' = c/n$
 $= 0.9997 c$

Particle velocity
 $v \sim c$

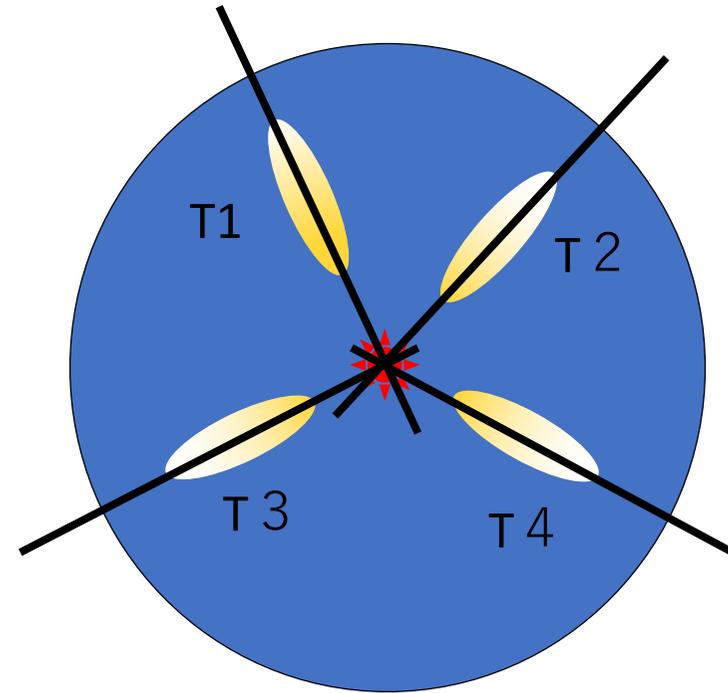
Cherenkov light
Footprint



Imaging Cherenkov Telescopes

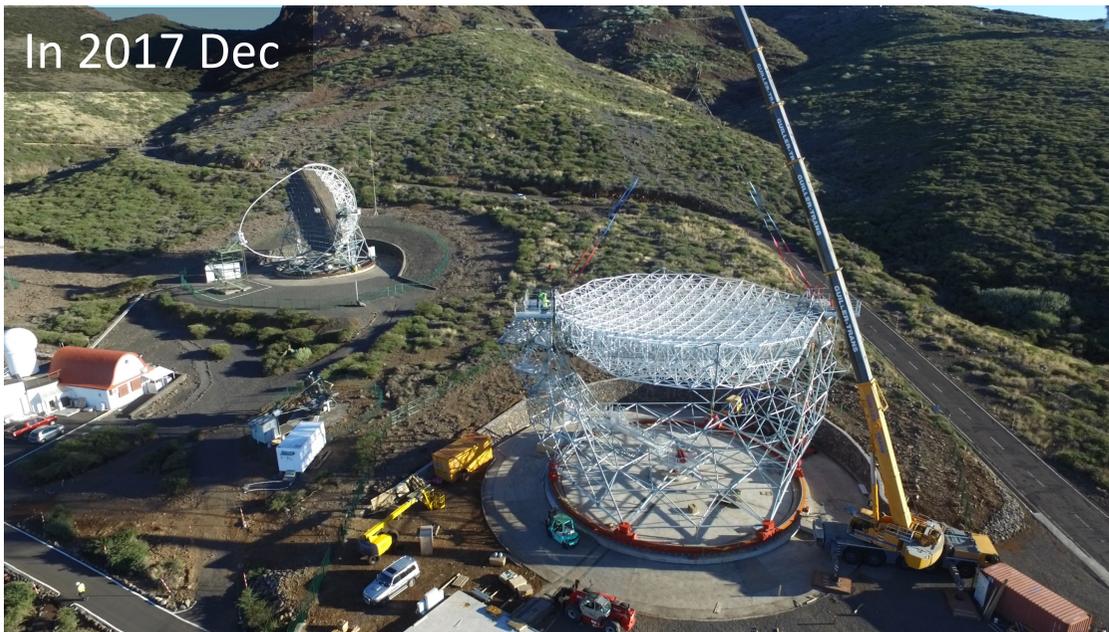


of Photons: 50photons/m² at 1TeV

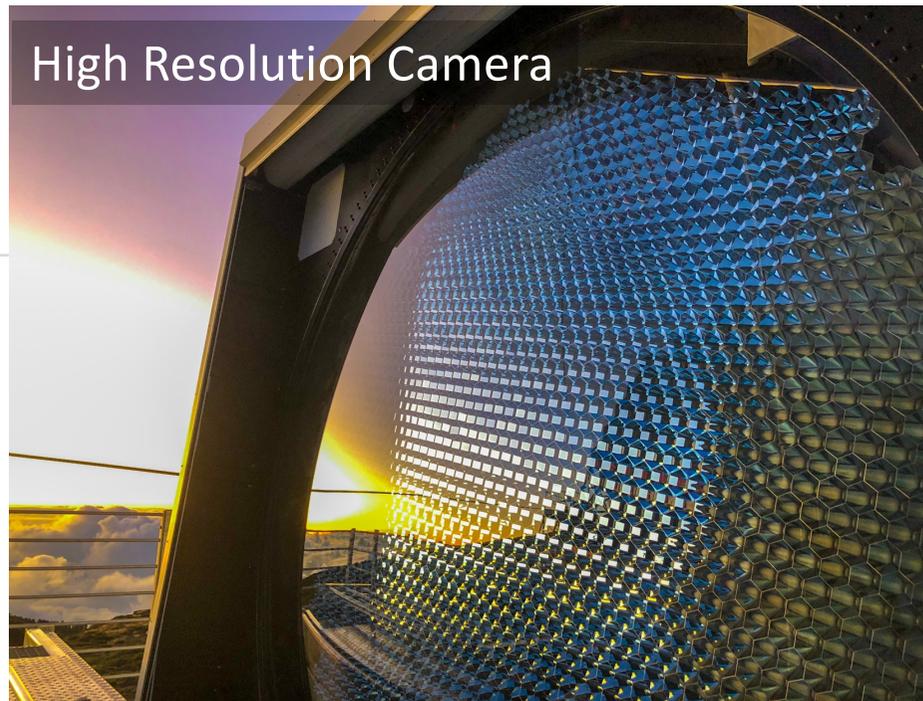


- Energy range 100GeV ~ 100TeV
- CR Rejection ~99.5%
- Angular Res. ~0.06 degrees
- Energy Res. ~15%
- Effective Area ~10⁵m²
- Sensitivity ~0.6% Crab Flux (10⁻¹³ erg/cm²s)

In 2017 Dec



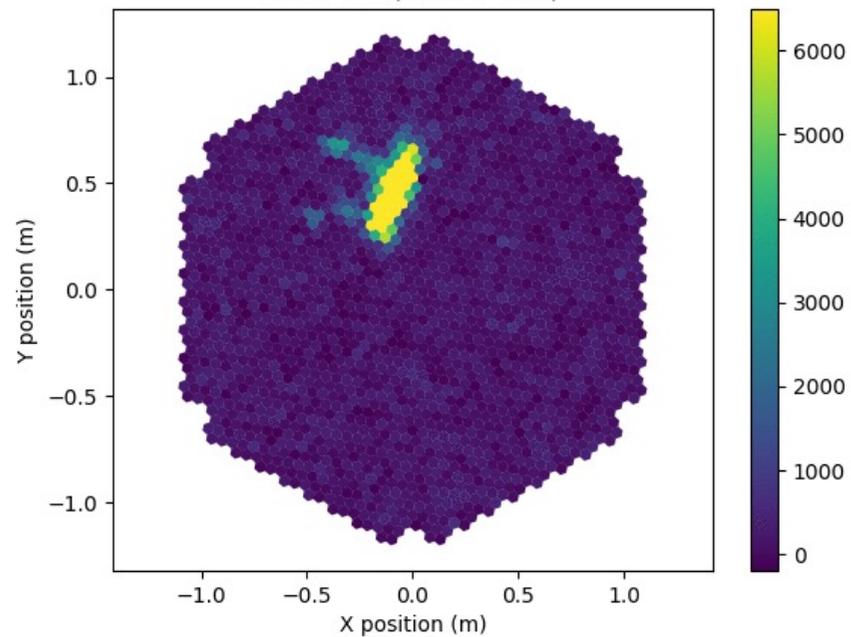
High Resolution Camera



Regular observation since 2020 Jan



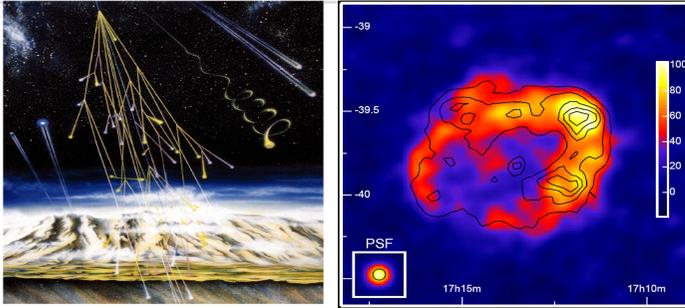
Run#442 (event# 181)



May 2019, first images of cosmic rays

Science of CTA is very wide

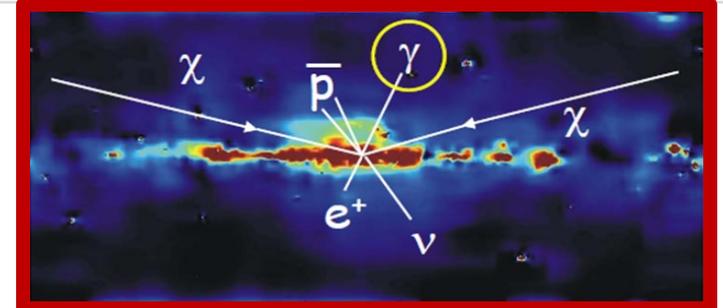
SNRs, PWNe, AGNs, GRBs, Dark Matter



Cosmic Ray Origin

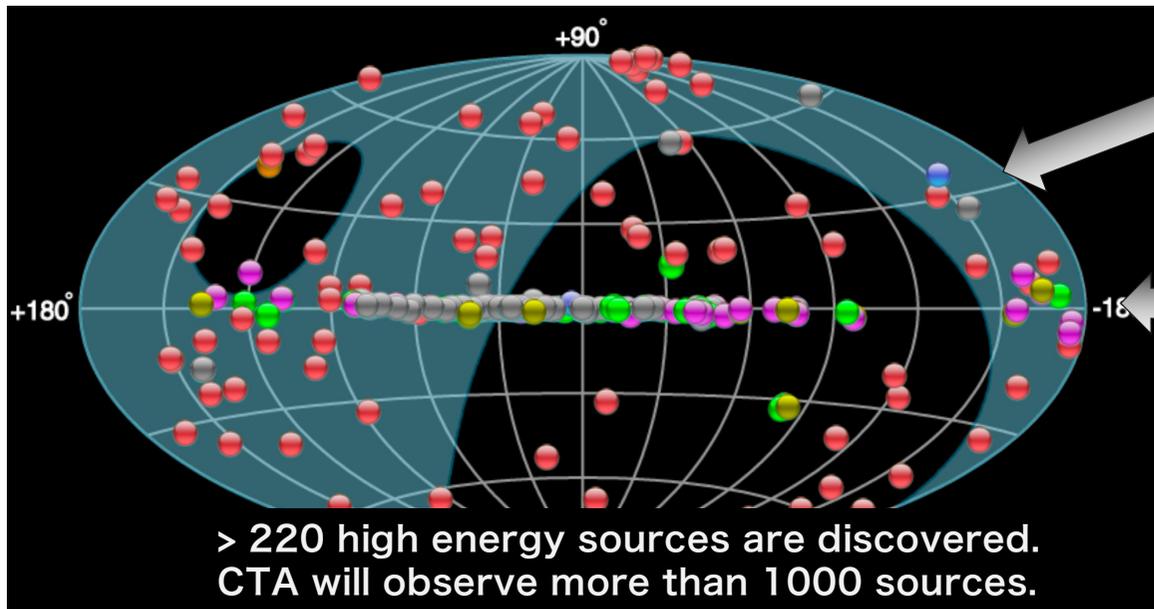


Super Massive Black Holes



Dark Matter Search (Discovery)

- Origin of Cosmic Rays (Big accelerators)
- Black Hole and S.M.B.H.
- Dark Matter Search



Extragalactic Sources



Active Galactic Nuclei

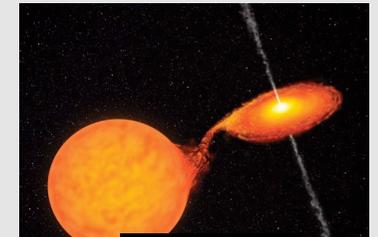


Gamma Ray Bursts

Galactic Sources



Super Nova Remnants



Binaries



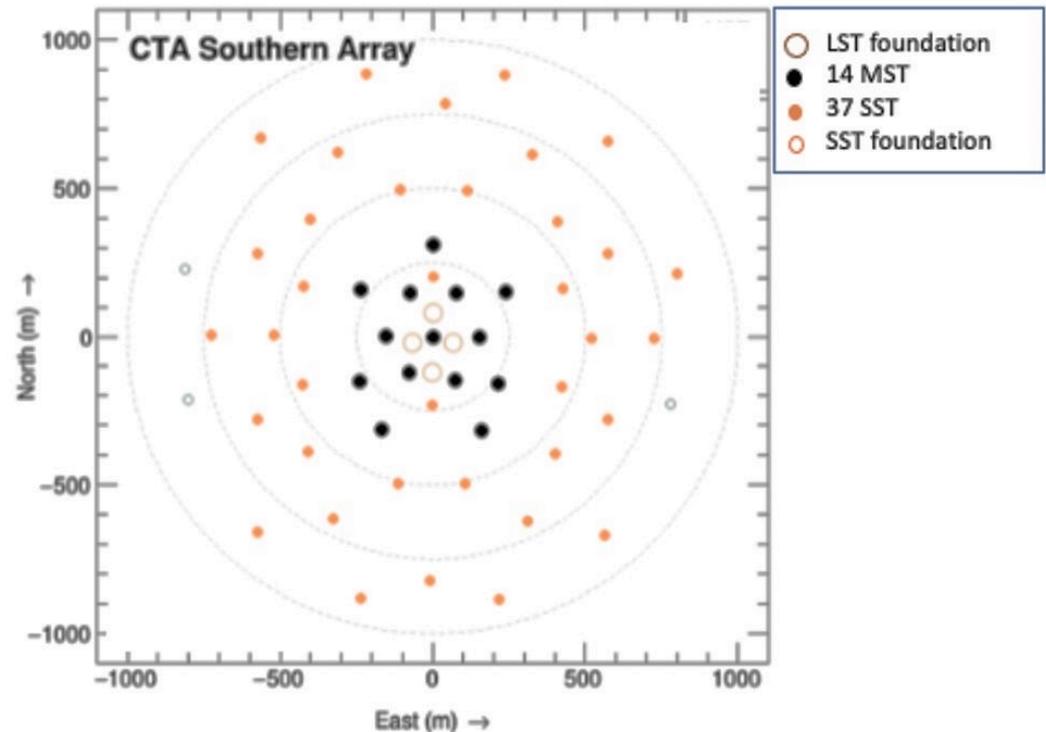
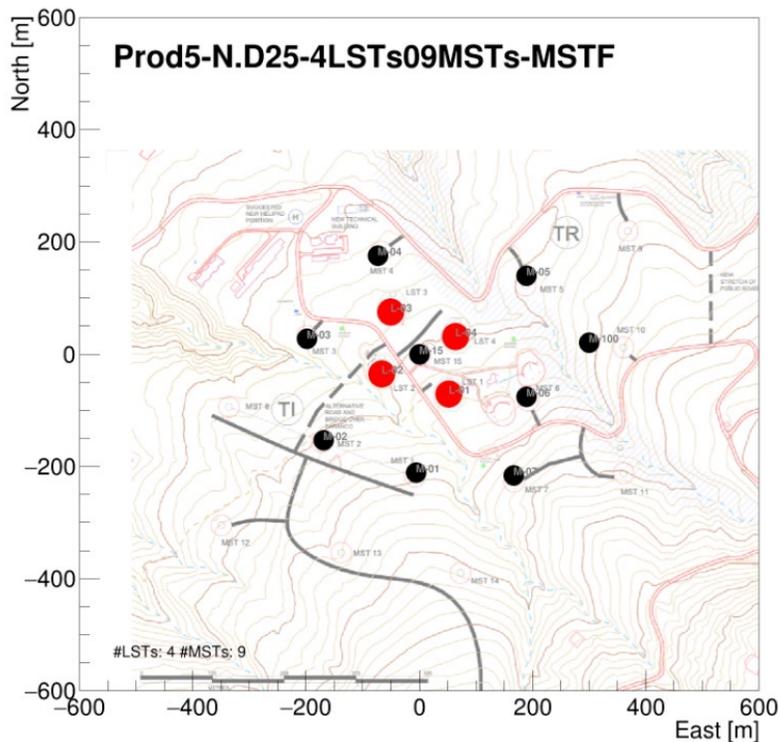
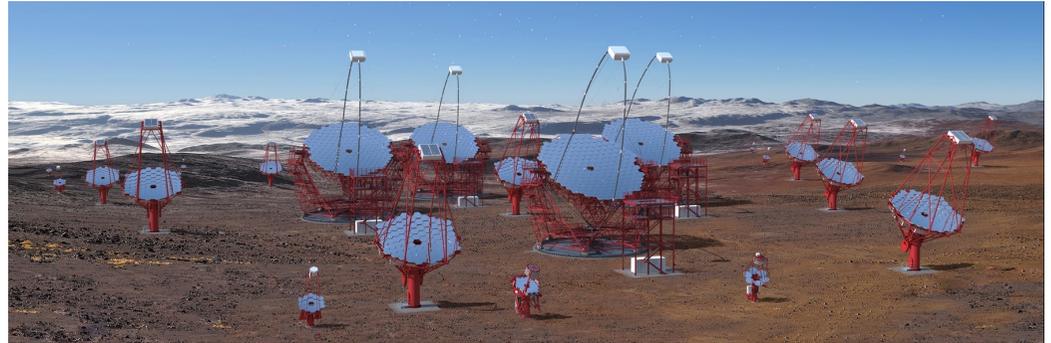
cherenkov
telescope
array

Alpha Configuration is decided with the financial constraints

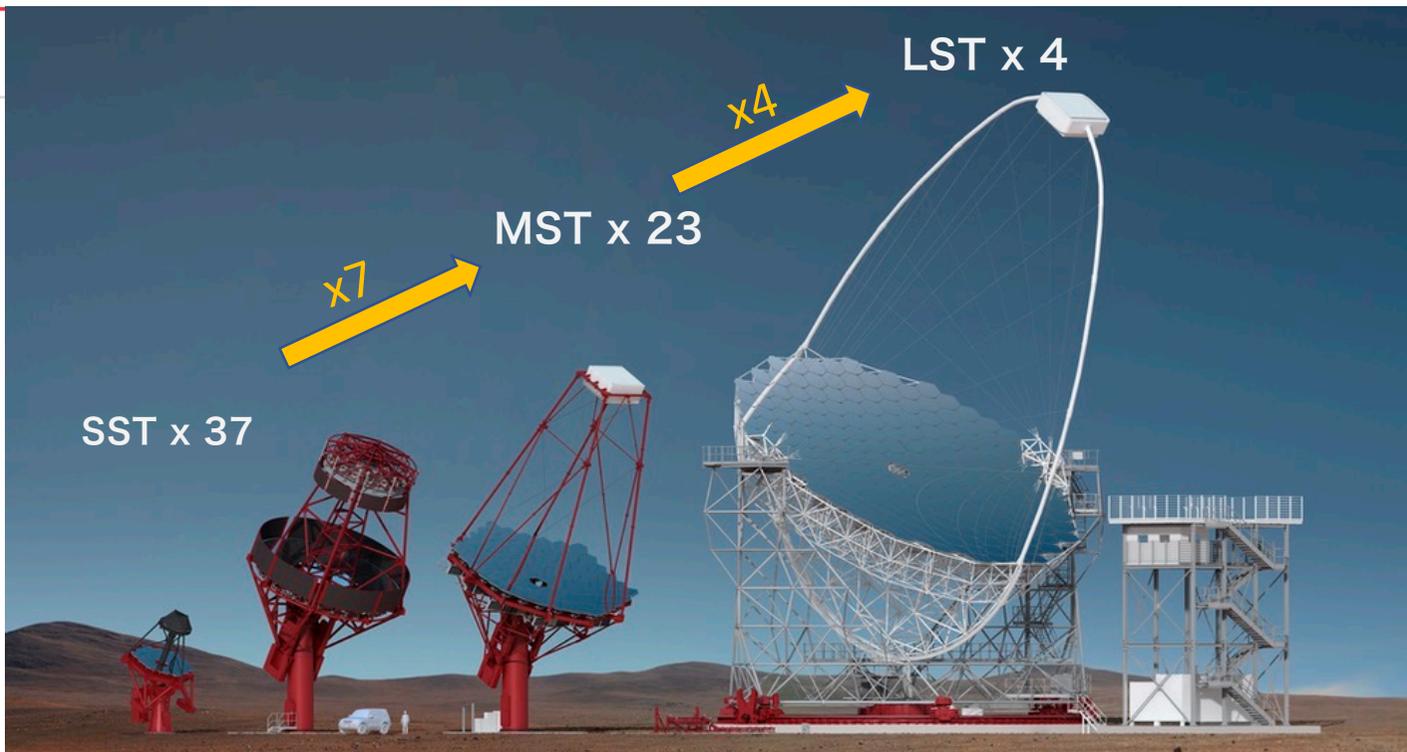
Roque de los Muchachos Observatory
La Palma, Spain



Paranal, Chile



Telescope Design



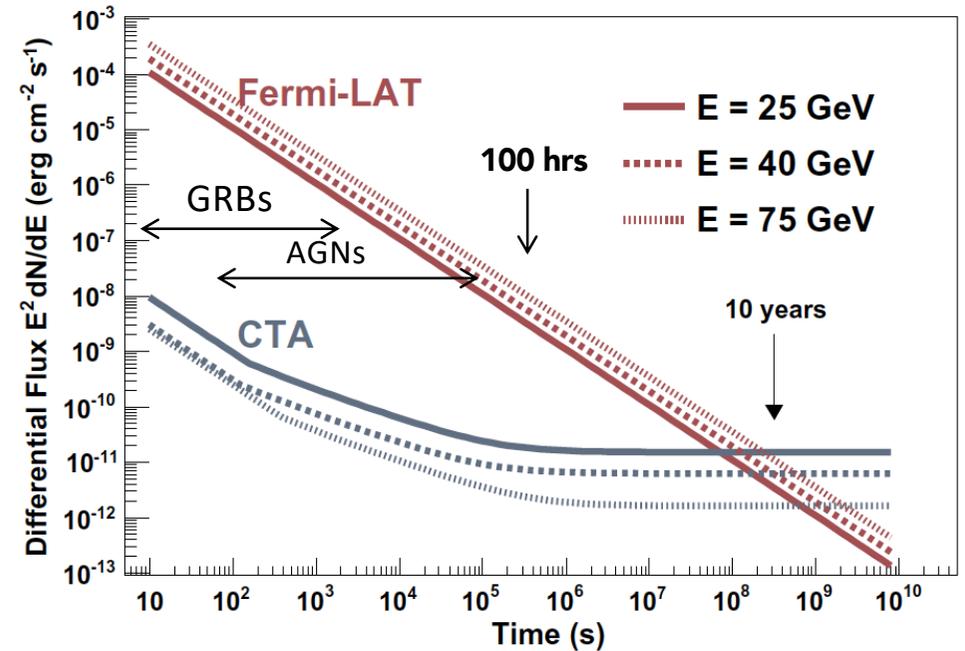
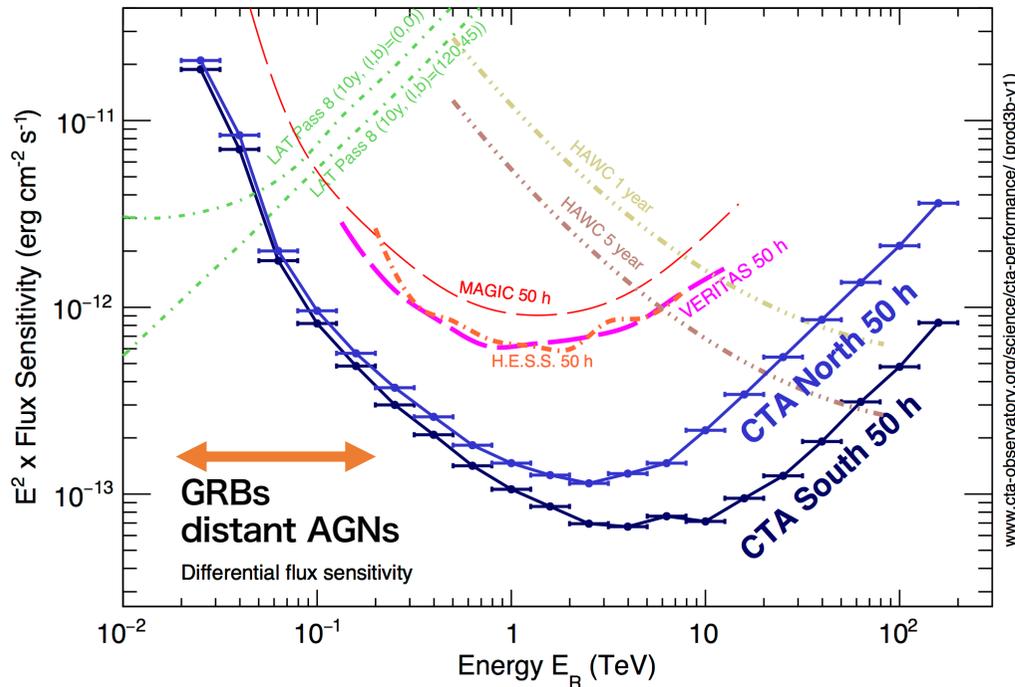
Telescope Types	SST	MST	LST
Optics	Schwarzschild-Couder	Davies-Cotton	Parabolic (Isochronous)
FoV and Camera	10.5 deg SiPM	7.5 deg PMT	4.3 deg PMT
Mirror Diameter	4.3m	11.5m	23m
Energy Range	3 TeV - 200 TeV	100GeV - 10TeV	20GeV – 2000GeV
Science Targets	Galactic Sources PeVatron (UHE CR)	Galactic Sources Nearby AGNs (z<0.5) Dark Matter	Transient Sources AGNs(z<2), GRBs(z <4) Dark Matter



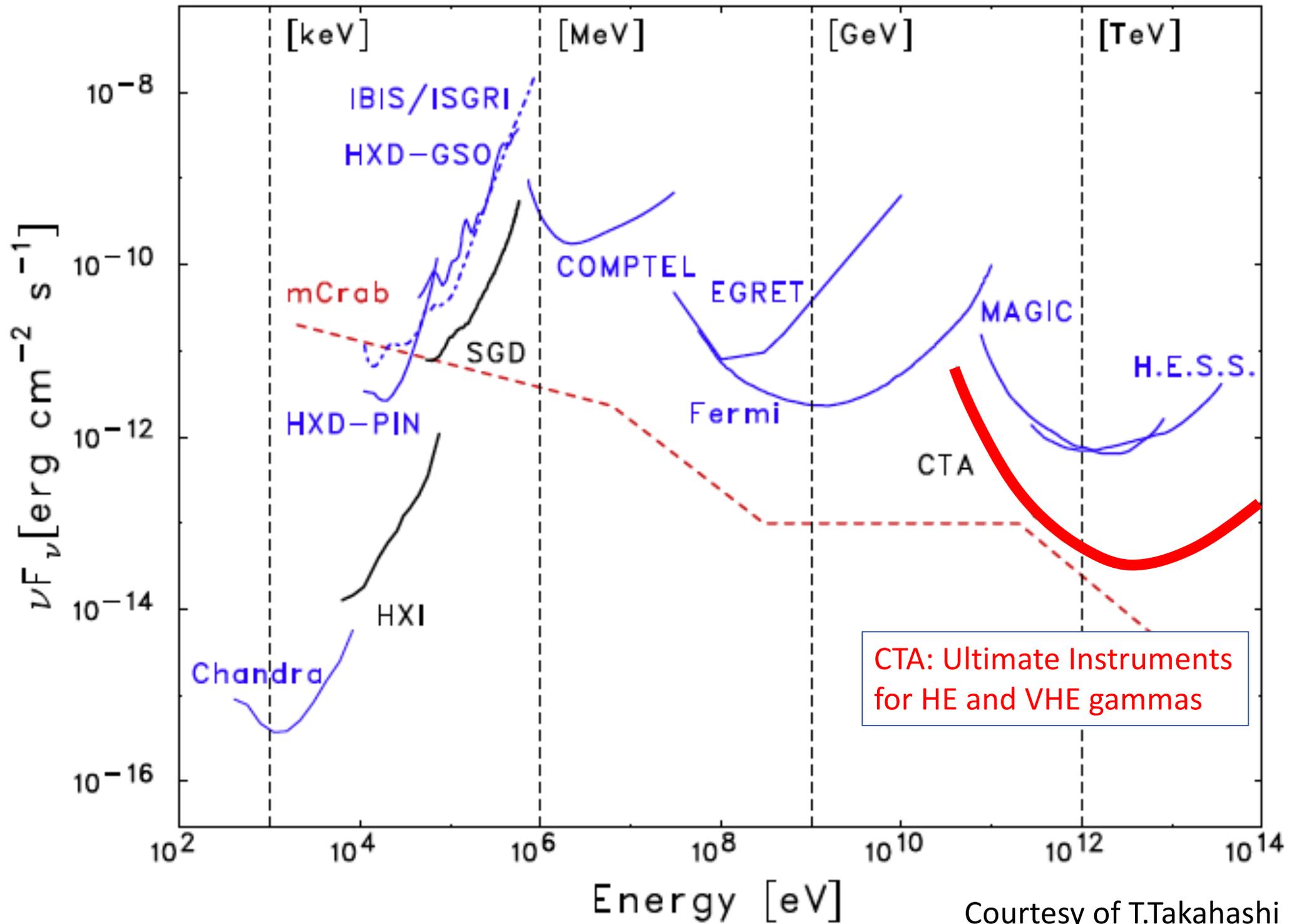
Cherenkov
telescope
array

10 times better sensitivity

Wide Energy coverage 20GeV~200TeV



- CTA array has a 10 times better sensitivity than HESS, MAGIC, and VERITAS
- CTA covers wide energy range from 20GeV to 200TeV (4 orders of magnitude)
- LSTs will offer
 - Distant AGNs up to $z = 2$ and GRBs up to $z = 4$ are observable with LSTs
 - X10000 sensitivity for GRBs and AGN flares than Fermi
 - The fast rotation (20 sec) offers the observation of GRBs even in prompt phase

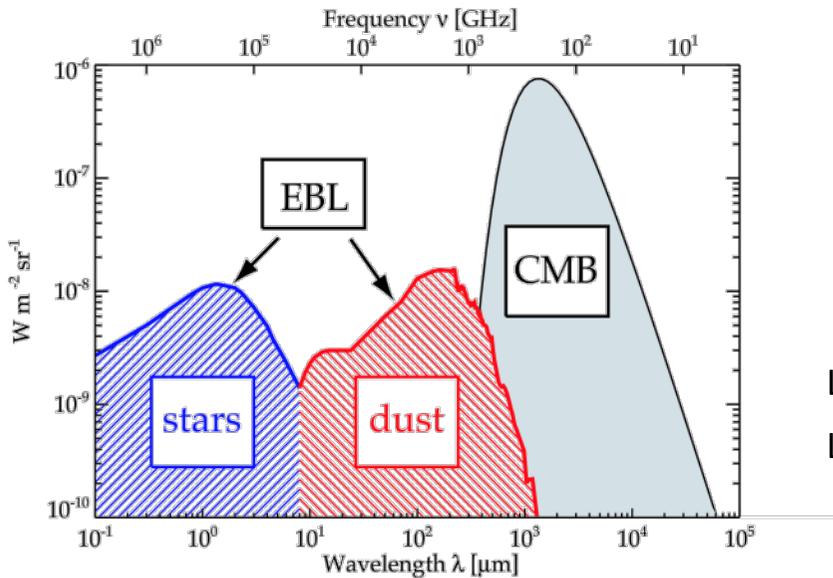
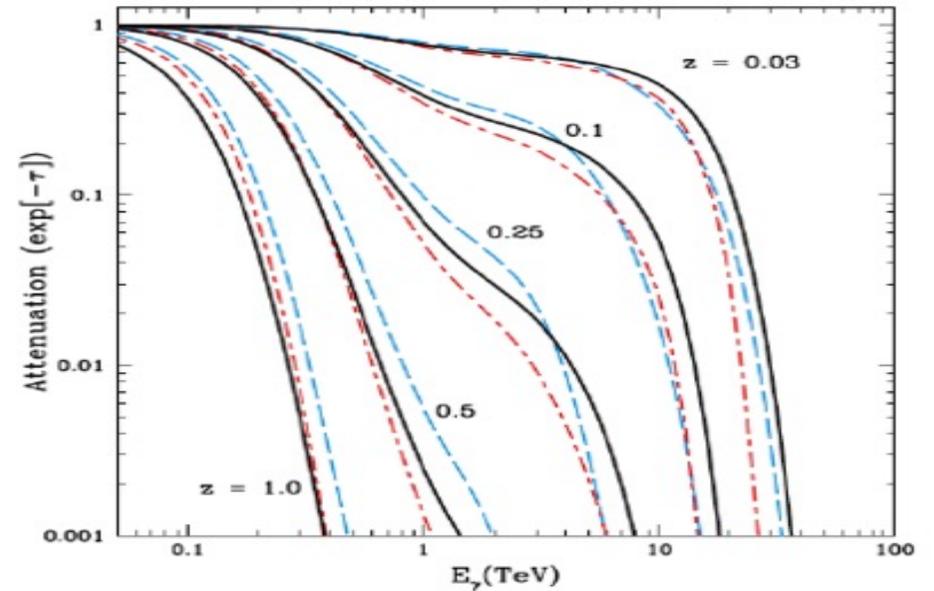
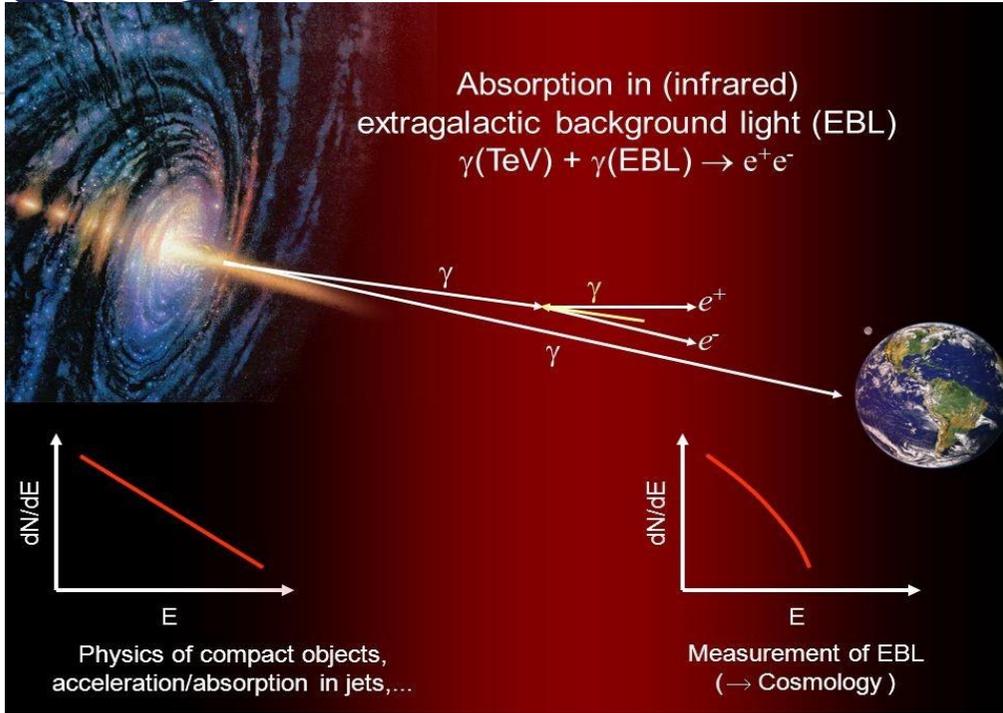


Courtesy of T.Takahashi

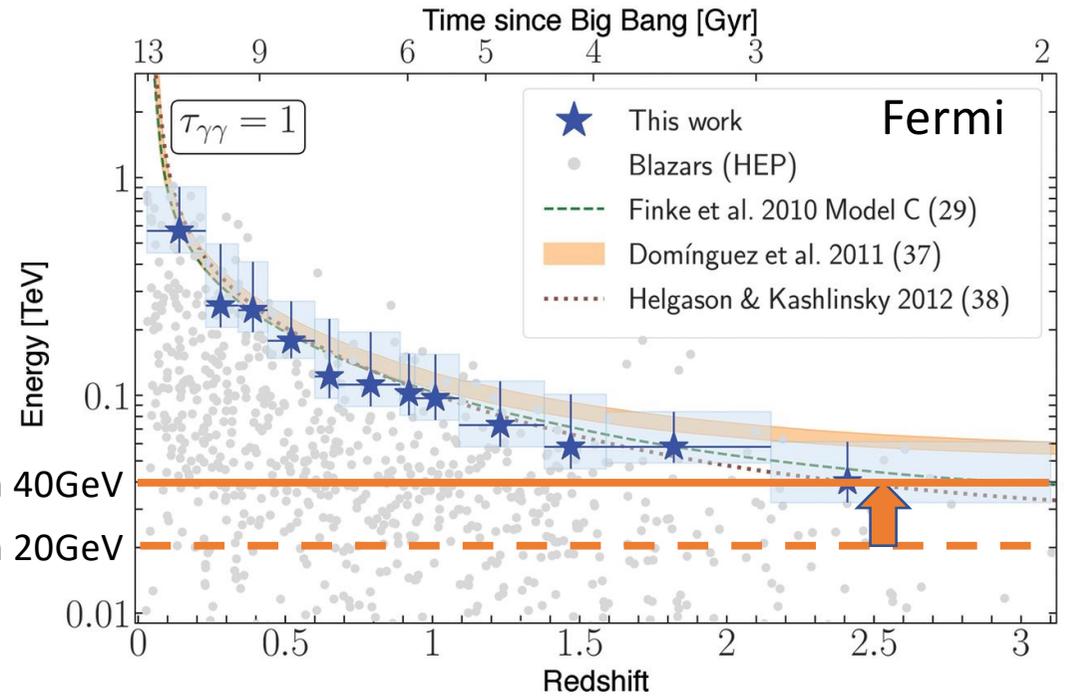


cherenkov
telescope
array

Gamma Ray Horizon 20GeV Low Threshold Energy $\rightarrow z \sim 4$



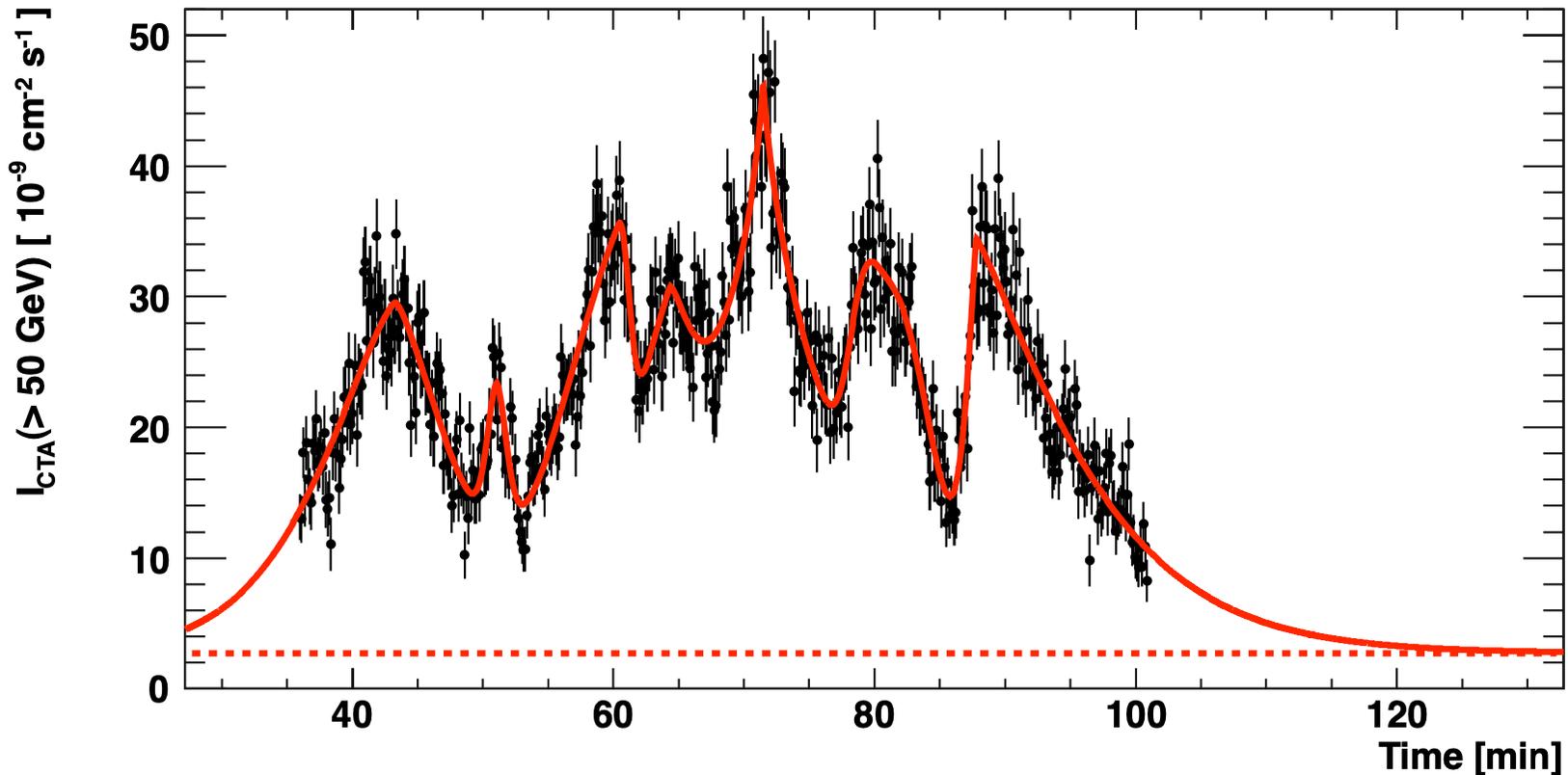
LST@45° Eth 40GeV
LST@25° Eth 20GeV



Simulated AGN Flares

Template: the 2006 flare of PKS2155-304

Low Threshold Energy \rightarrow High Precision Light curve



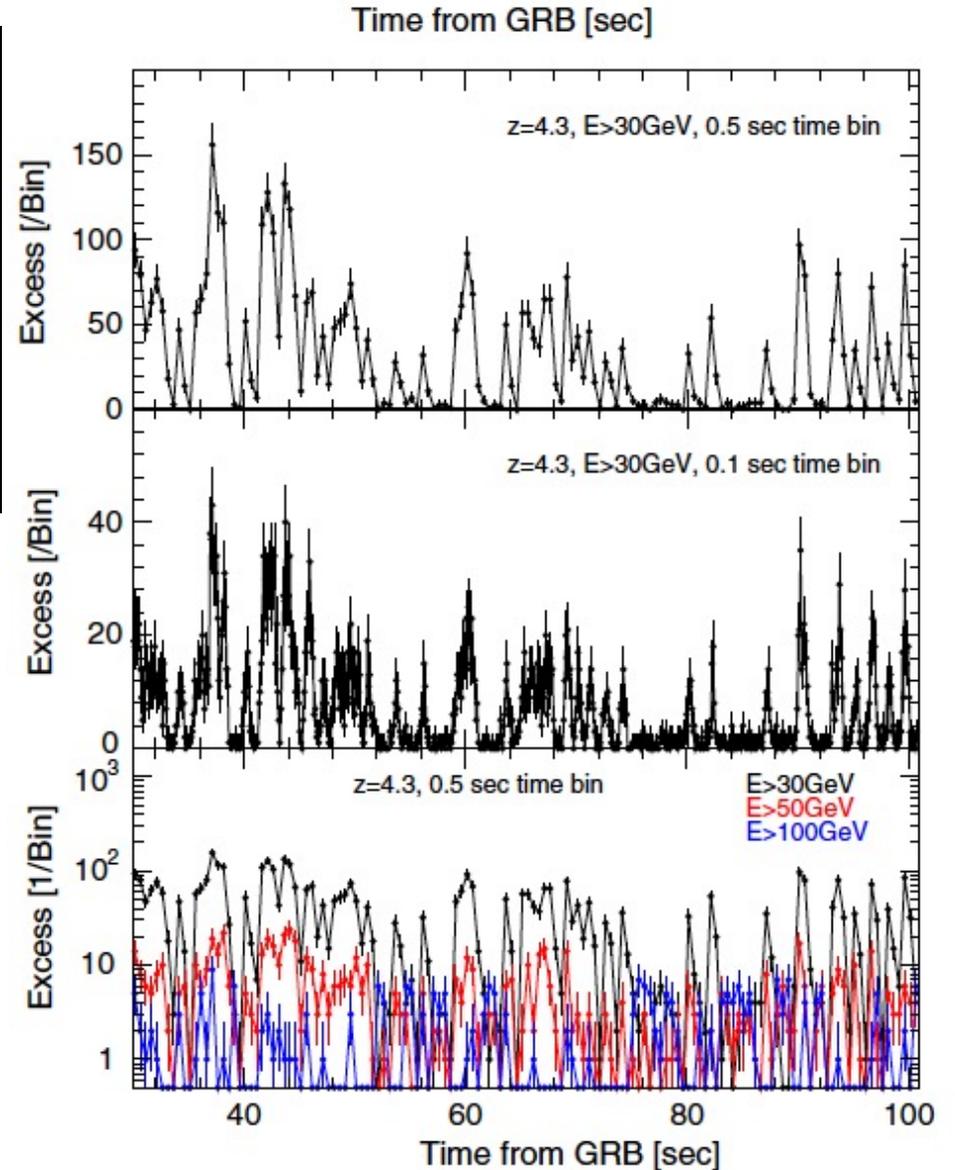
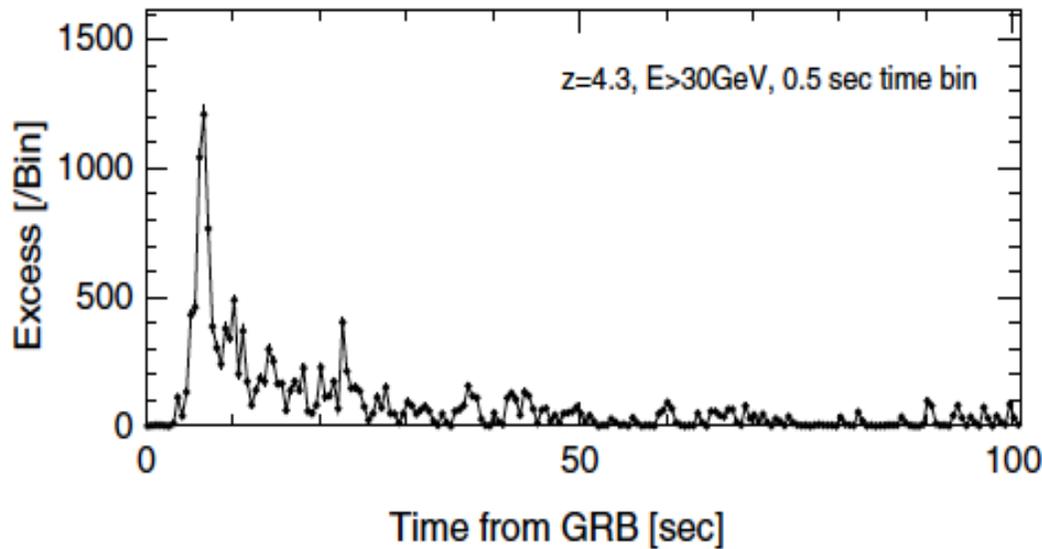
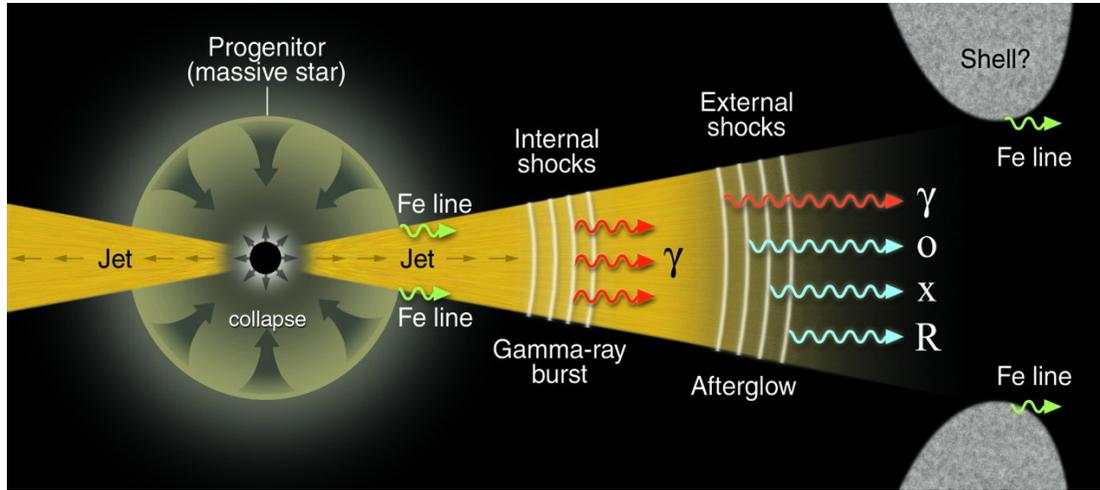
- ❑ Light curve can be examined, a few minutes scale structure \rightarrow a few 10s of seconds
 - ❑ Particle acceleration mechanism, Cooling process
 - ❑ Light curve vs. Energy dependence \rightarrow Q.G. Energy scale $>$ Planck Mass scale



cherenkov
telescope
array

GRBs: Newly Born Black Holes

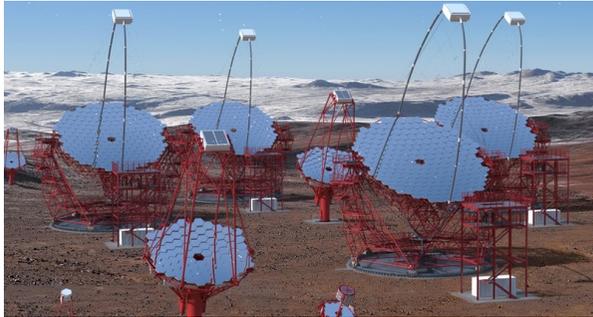
Simulated light curve (template: GRB080916C)



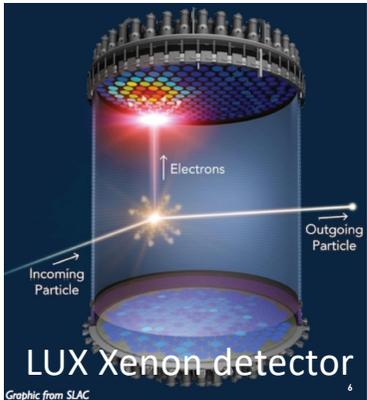


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telescope
array

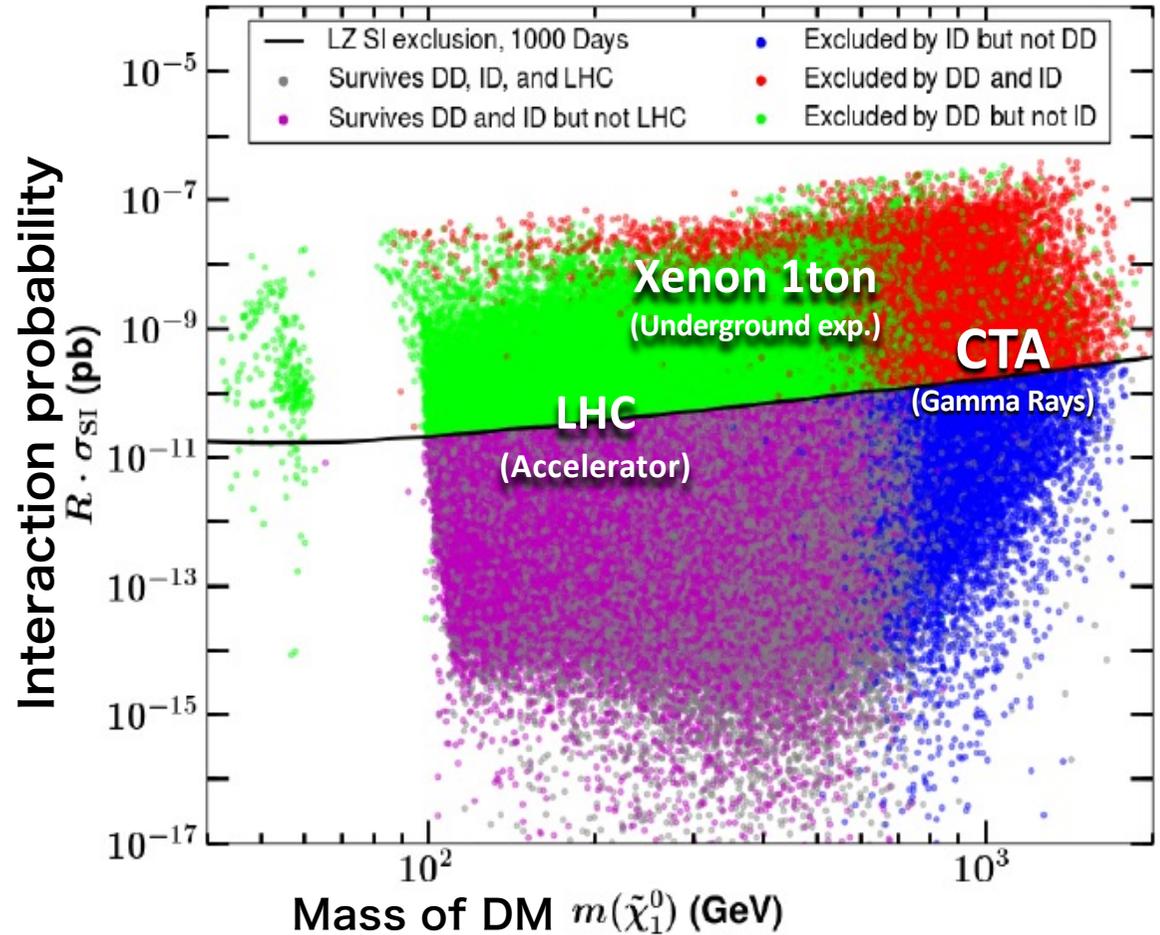
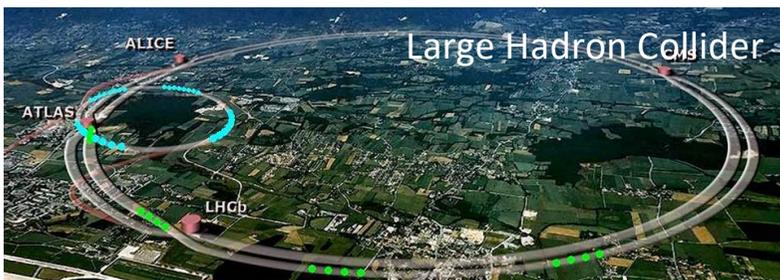
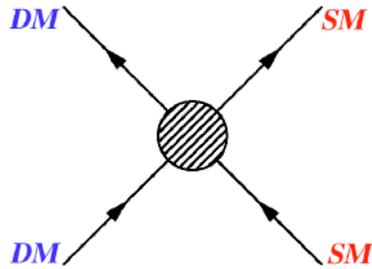
Complementarity of different approaches Direct, Indirect, and Collider Experiment



thermal freeze-out (early Univ.)
indirect detection (now)



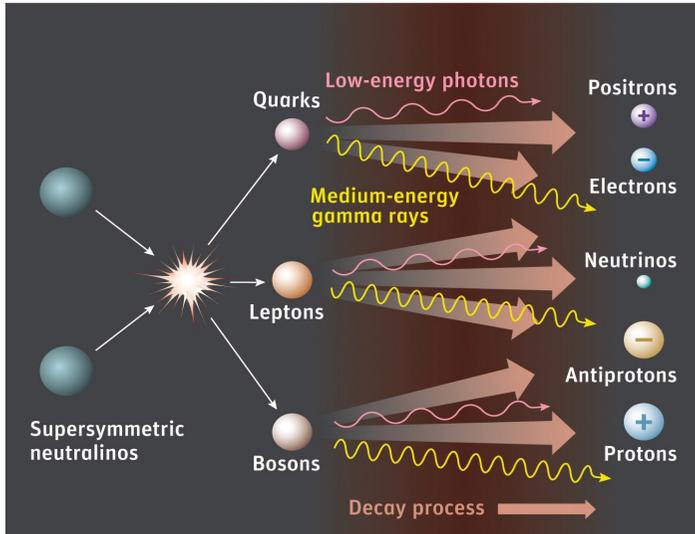
direct detection



- Explore Dark Matter in the Galactic Center and Dwarf Sph. Galaxies
- **CTA has the best sensitivity above 700GeV**

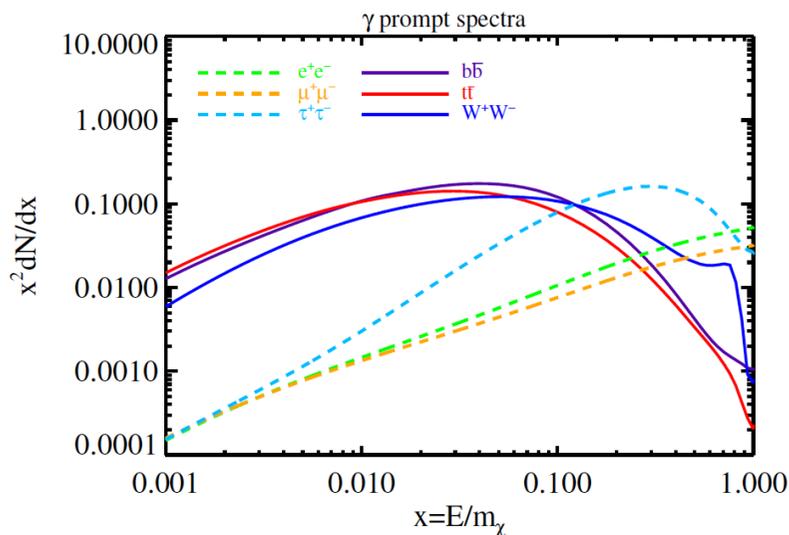
Dark Matter Search

Sensitive M_χ : 200GeV - 10TeV

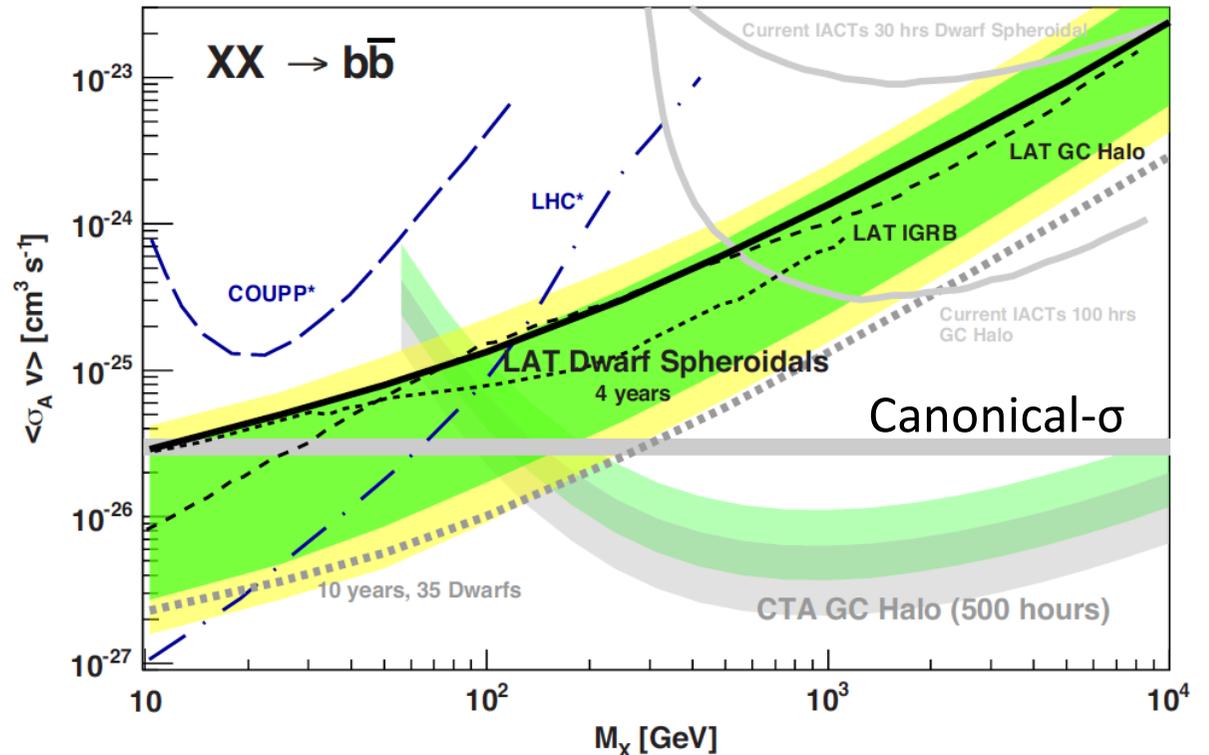


$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \underbrace{\frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{WIMP}}^2}}_{\text{'Particle Physics'}} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \times \underbrace{\int_{\Delta\Omega} d\Omega' \int_{\text{los}} \rho^2 dl(r, \theta')}_{\text{'Astrophysics' or } J(E)}$$

Particle Physics Astrophysics



Gamma rays from Annihilation produce the bump around $1/10 - 1/20 M_\chi \rightarrow 20\text{GeV}-1\text{TeV}$ gamma



CTA gives the stringent upper limit. Stefan Funk 2015



cherenkov
telescope
array

Commissioning of LST1 scientific observations



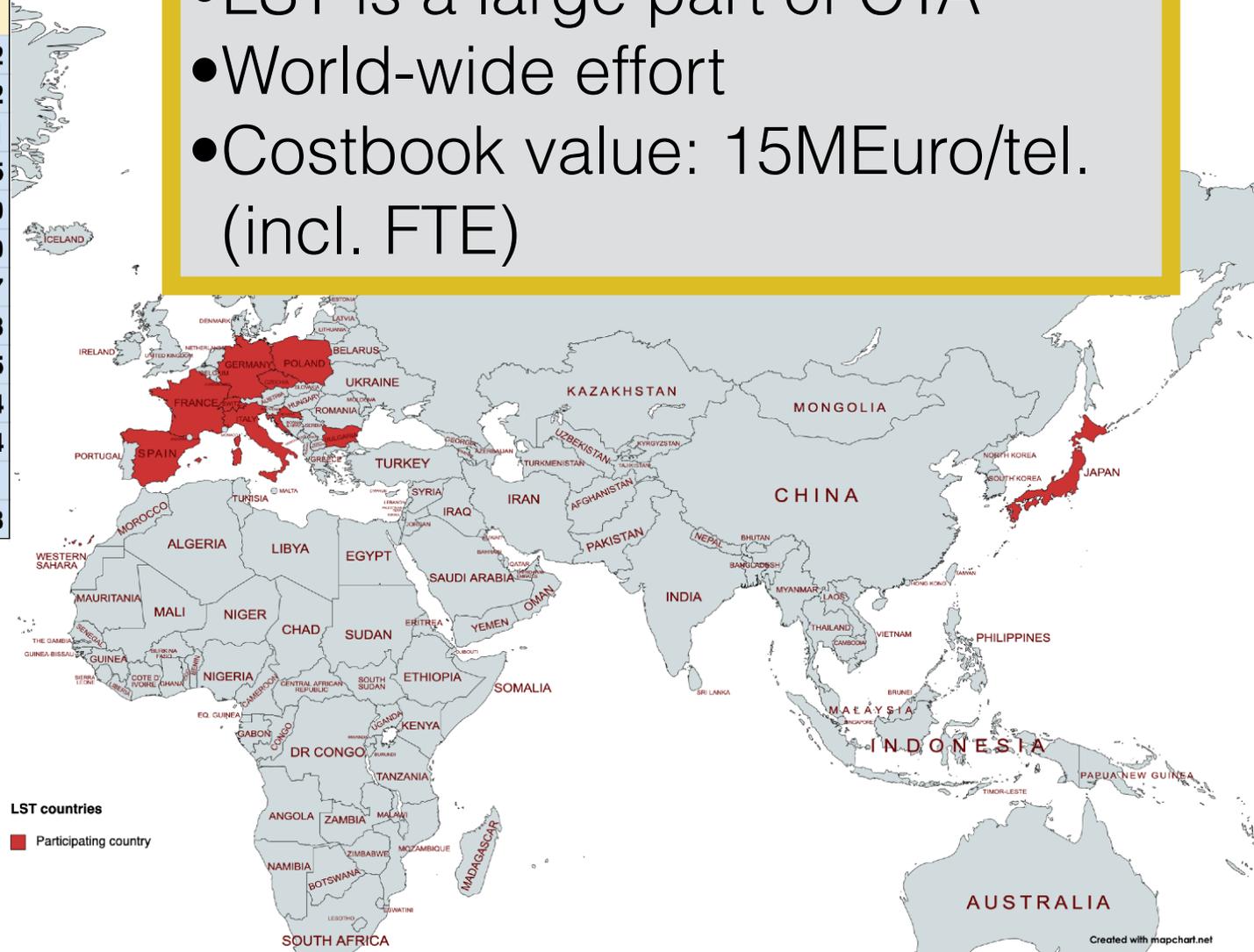
LST collaboration

LST statistics

	Members	Scientists + Students	Authors
Bulgaria	2	2	2
Brazil	3	2	2
Spain	88	51	51
France	40	20	25
Croatia	10	10	10
Czechia	16	16	10
Germany	46	39	37
Switzerland	14	11	8
Italy	100	83	65
Japan	80	76	64
Poland	4	4	4
Total	403	314	278

- LST is a large part of CTA
- World-wide effort
- Costbook value: 15MEuro/tel. (incl. FTE)

numbers are growing



Steering Committee

Composed by Party Representatives
 Chair: M. Martinez

Ex Officio: M. Teshima
 Ex Officio: J. Cortina
 Ex Officio: D. Mazin
 Ex Officio: M. Will

Version 8.37

LST EXECUTIVE BOARD

LST Project Office

Telescope Manager:

P. Marquez
 A. Donini

Operations Coordinator:

A. Berti
 NN

Principal Investigators:

M. Teshima / J. Cortina

Project Manager:

D. Mazin

Deputy: M. Will

Outreach and Publication:

C. Righi

Systems Engineering:

Lead: D. della Volpe

Deputy: M. Stodulska

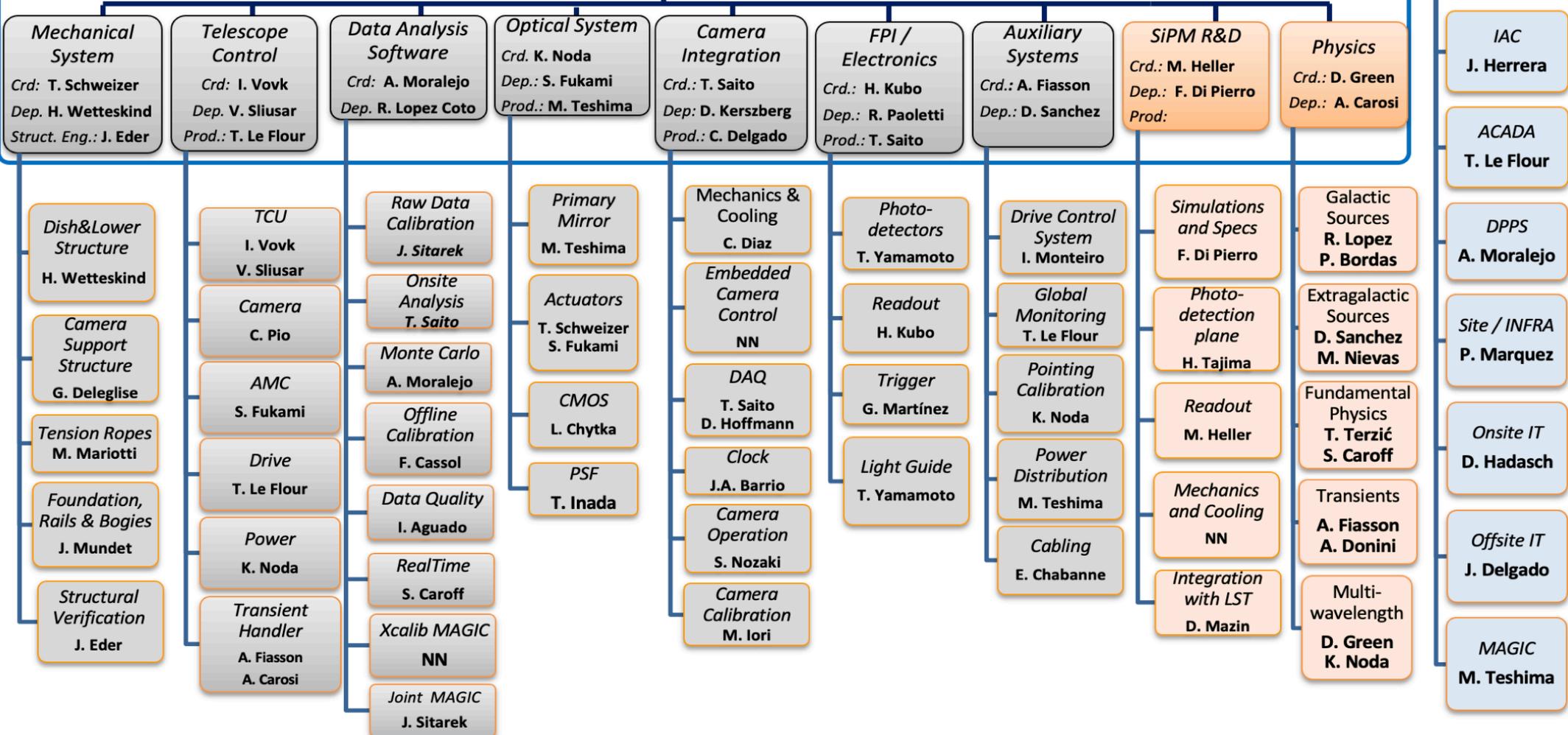
RAM: M. Stodulska

Safety: M. Will

Structure: J. Eder

R&D RAMS: JM. Miranda

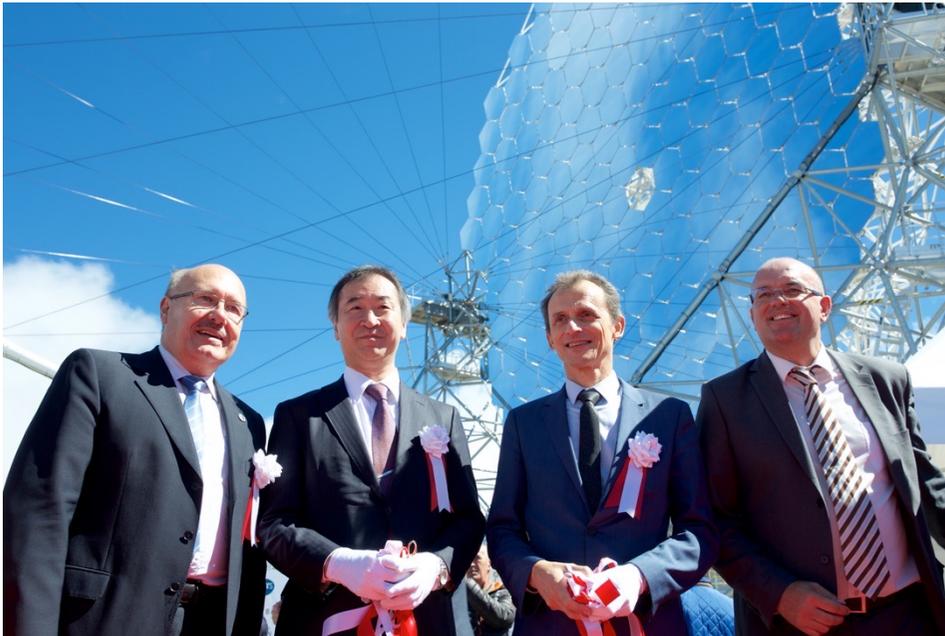
Interfaces and Integration





cherenkov
telescope
array

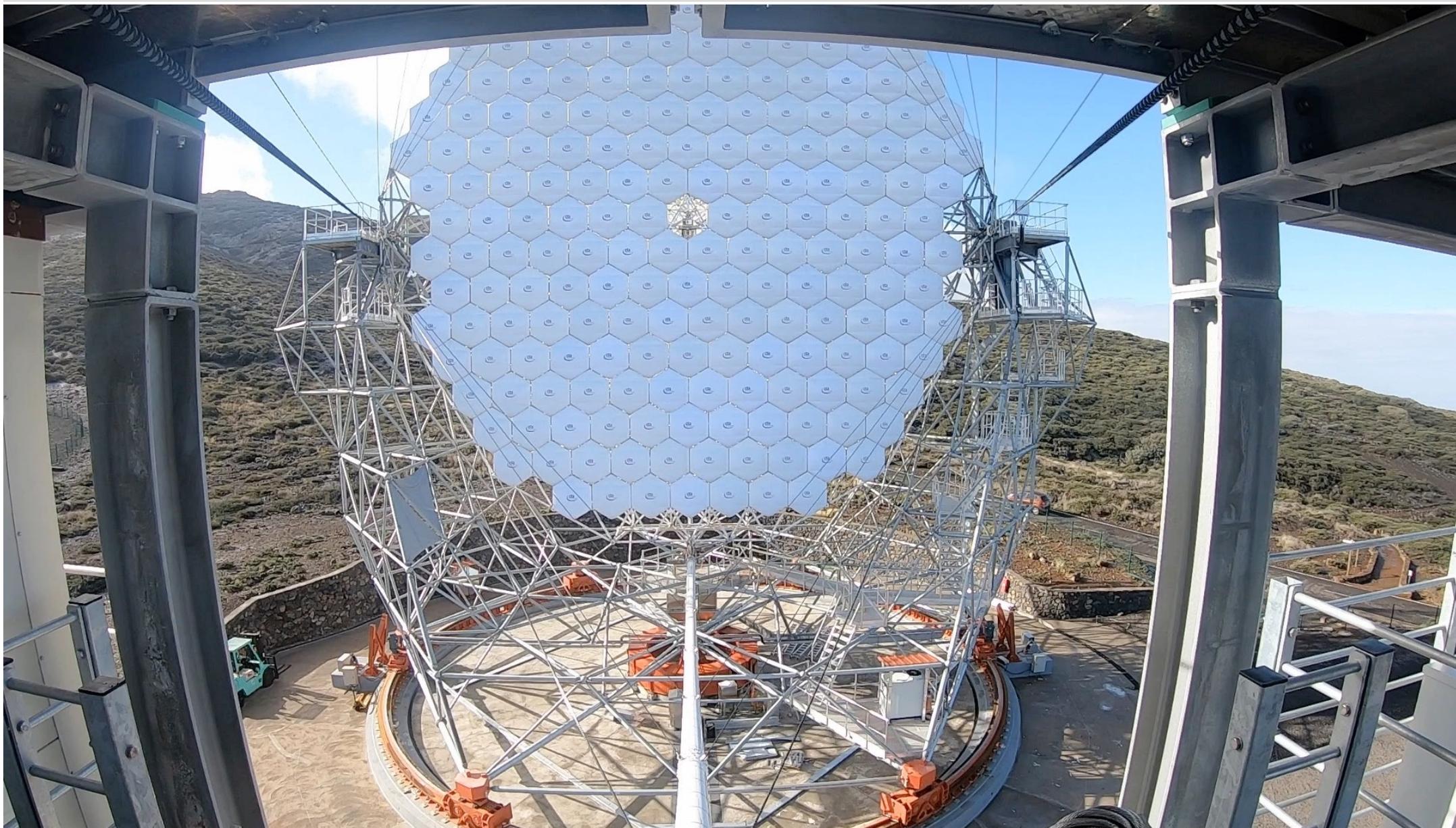
LST1 construction and Inauguration (Oct.2018)





cherenkov
telescope
array

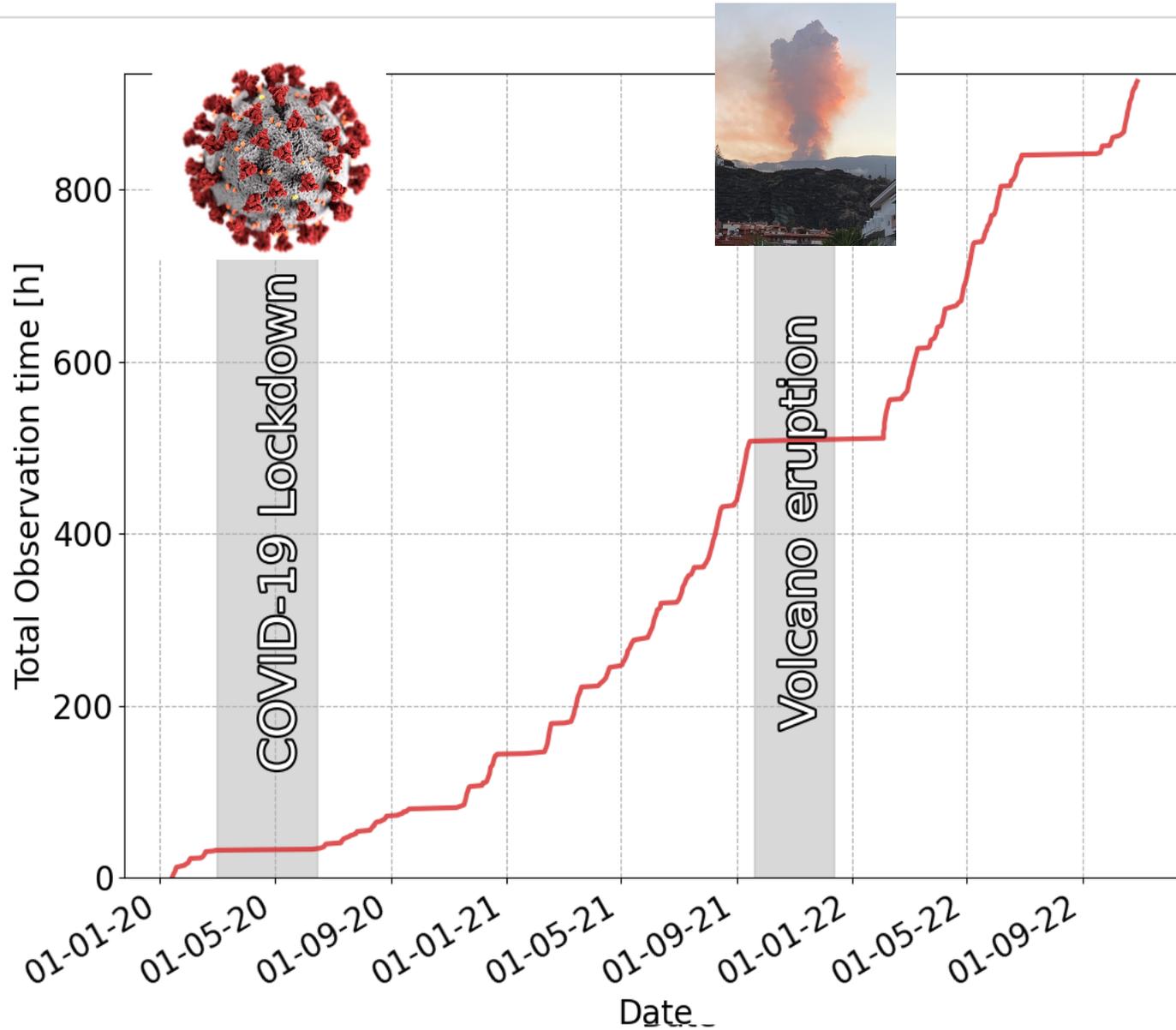
LST Feature, FAST Rotation < 20 seconds : for the fast follow-up GRB observations

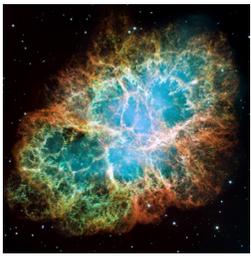




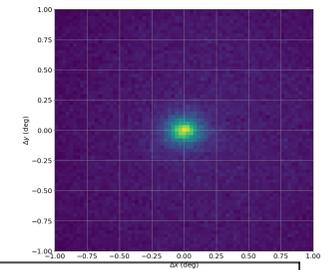
cherenkov
telescope
array

LST1 commissioning 500hrs of Scientific Observation



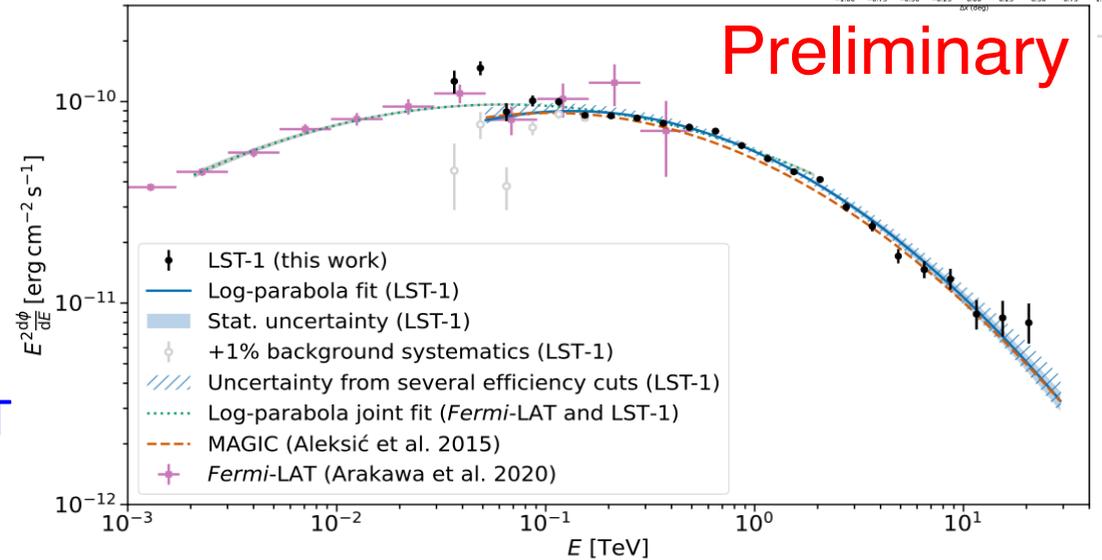


Crab Nebula and Pulsar



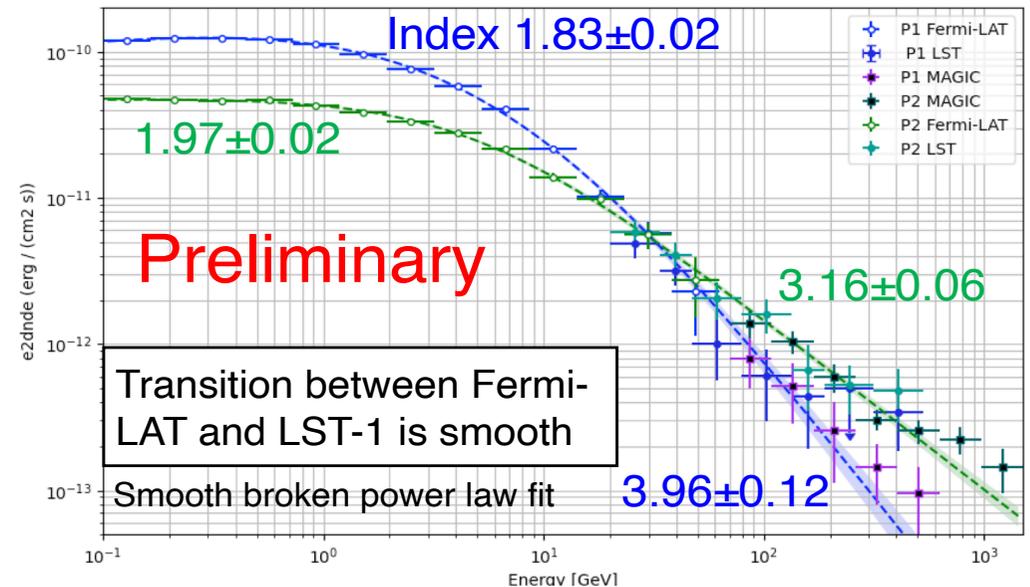
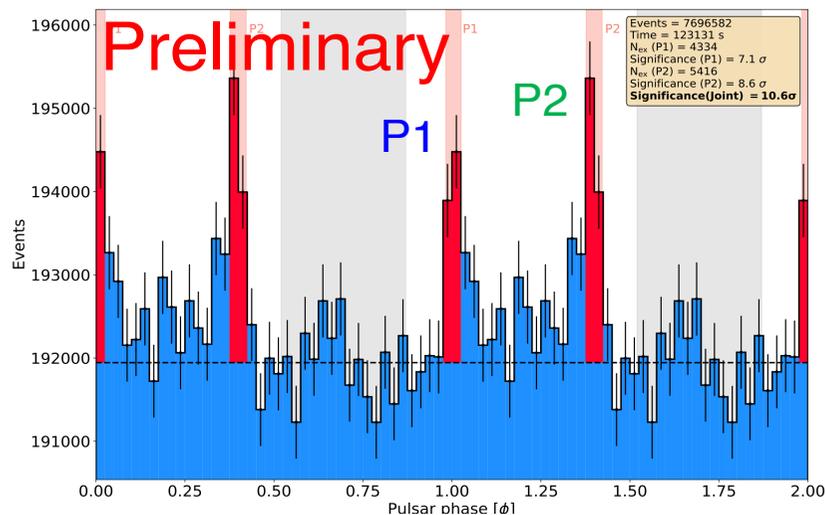
Crab Nebula spectrum

- 34.2 hours of data
- Systematic errors: gray points correspond to the effect of +1% background
- Consistent with MAGIC and Fermi-LAT



Crab pulsar

- Significant detection down to few tens of GeV
- Data from Nov 2020 - Mar 2022

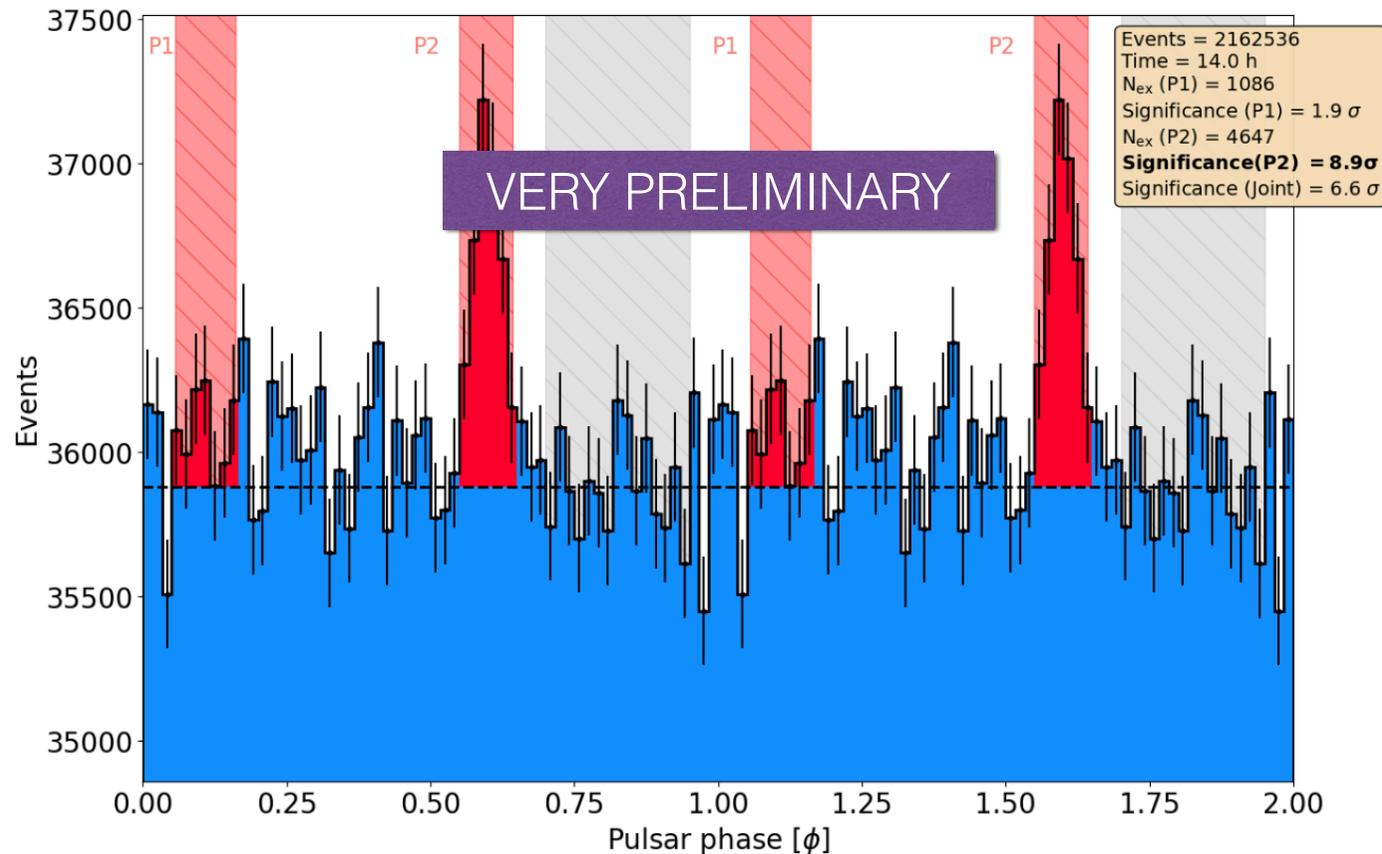


Telescope Performance: Geminga



cherenkov
telescope
array

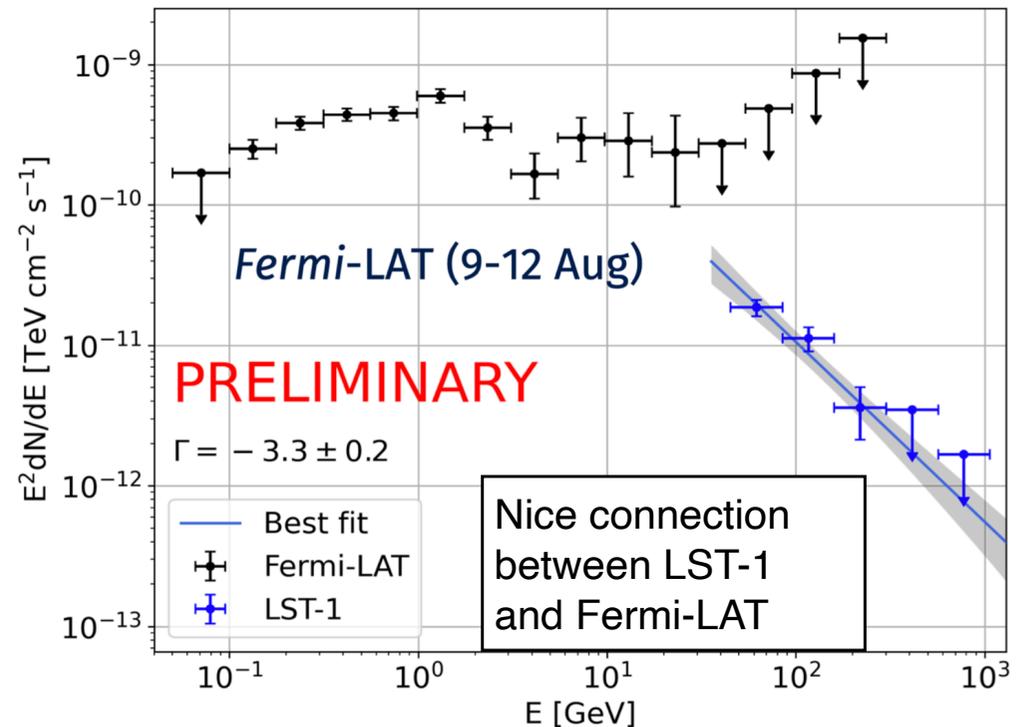
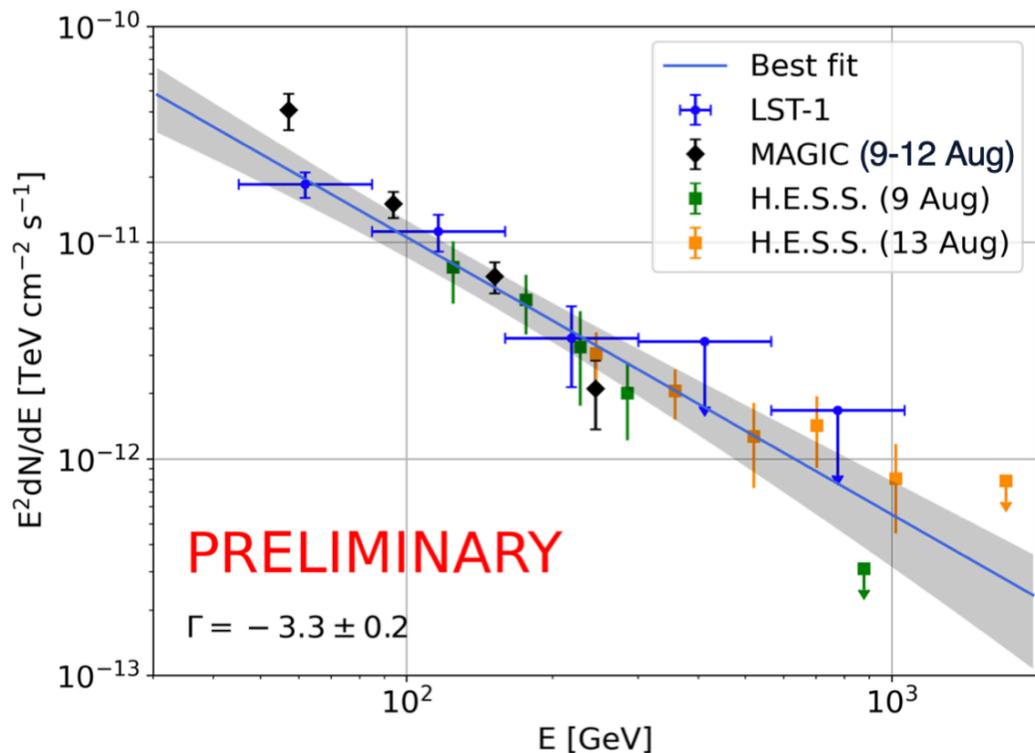
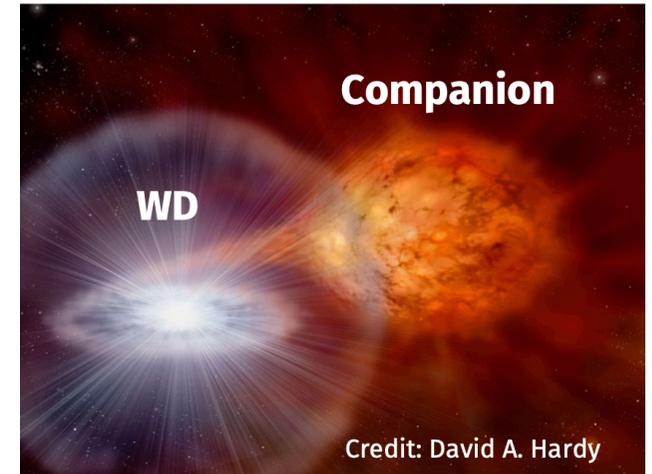
$E > 15\text{GeV}$



- P2: 8.9σ after 14 hours. Geminga has a very soft spectrum. The LST-1 result confirms an excellent performance in the 15-30 GeV regime, one of the main scientific drivers of LST
- Compared with MAGIC: 6.3σ for 80 hours for P2 (https://www.aanda.org/articles/aa/full_html/2020/11/aa39131-20/aa39131-20.html)

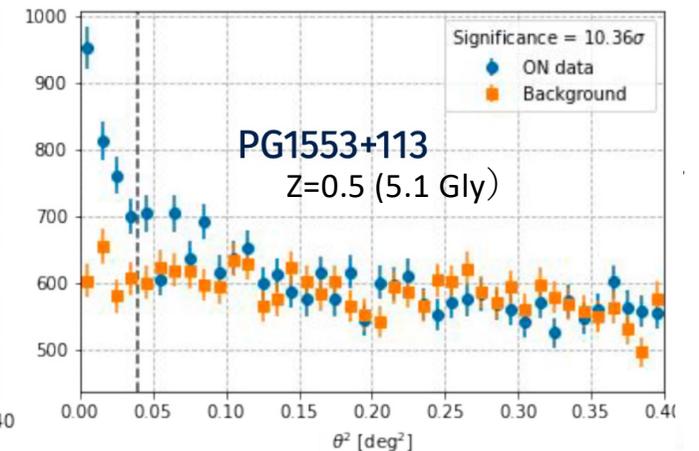
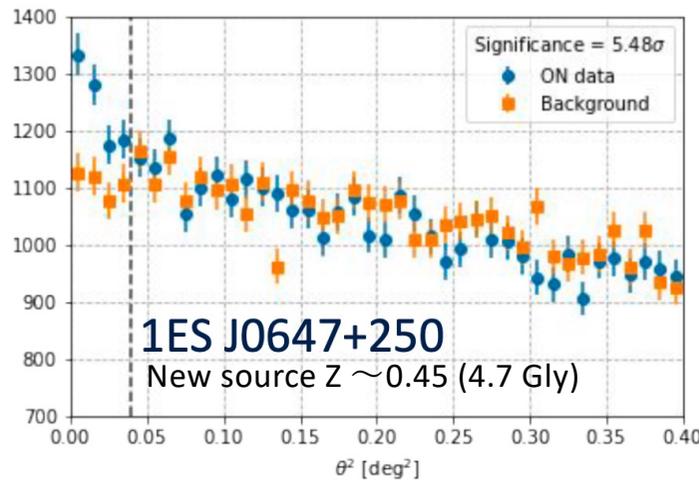
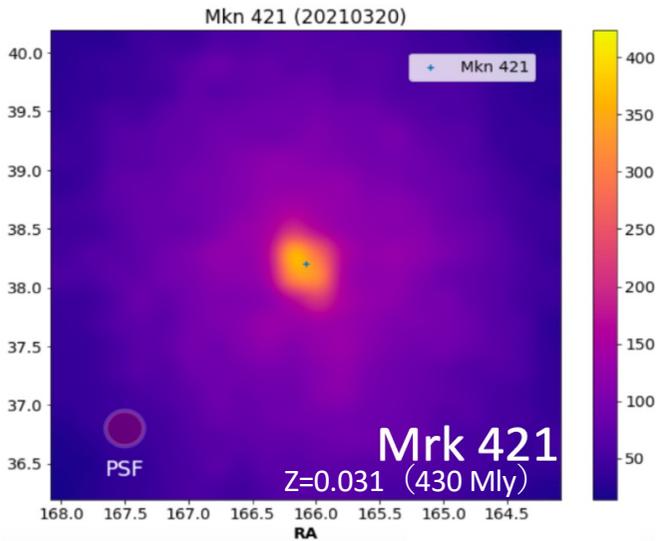
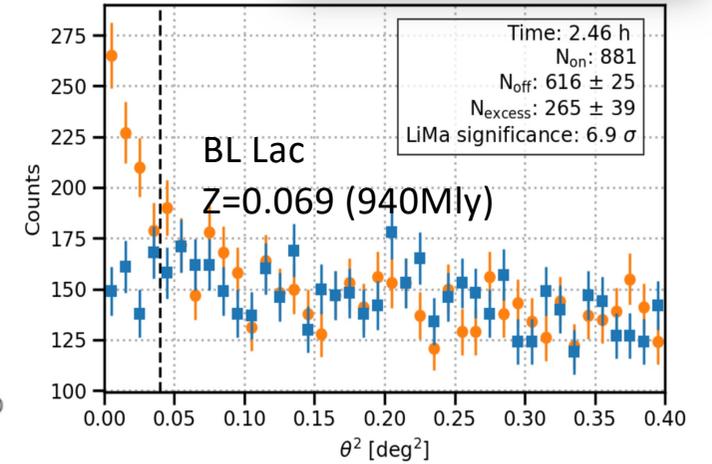
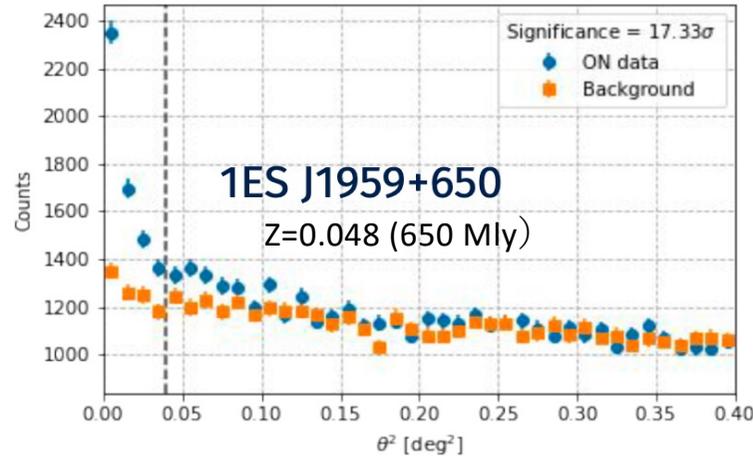
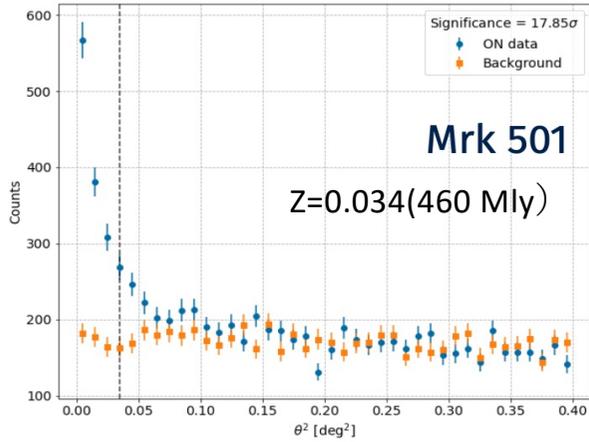
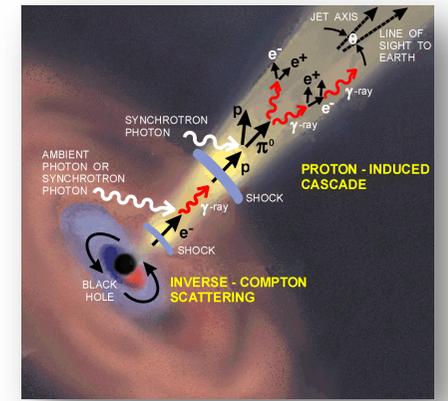
Detection of Nova RS Ophiuchi

- First detected recurrent nova in VHE gamma rays by 2021 outburst (H.E.S.S. and MAGIC)
- LST-1 took part in the first VHE gamma-ray detection with $>\sim 6\sigma$ in each night
- Consistent SEDs between LST-1, MAGIC, H.E.S.S.



AGN observation with LST1 during 2020-2021Q1

- ❑ Nearby AGNs, Mrk501, Mrk421, 1ES 1959+650, BL Lac
- ❑ Distant AGNs, 1ES0647+250, PG1553+113



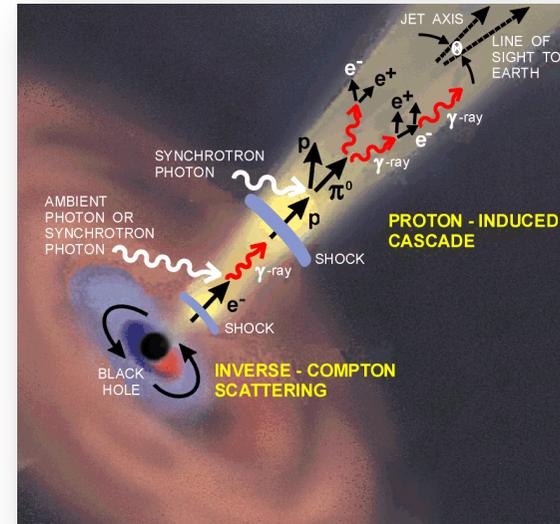
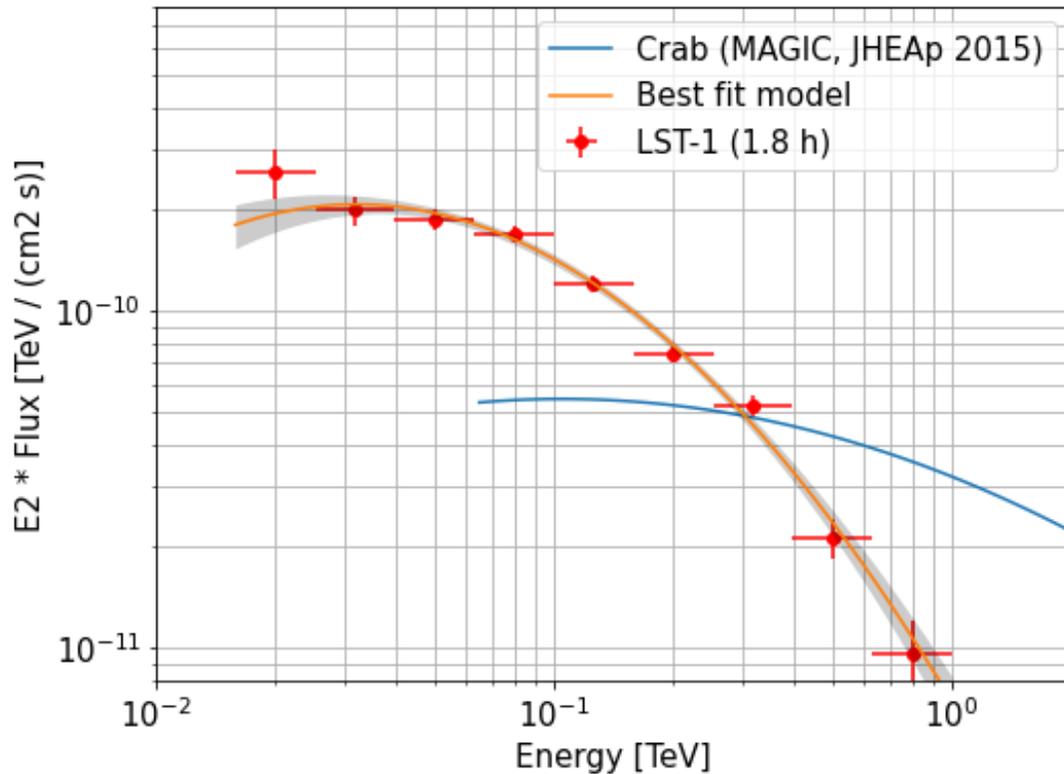


cherenkov
telescope
array

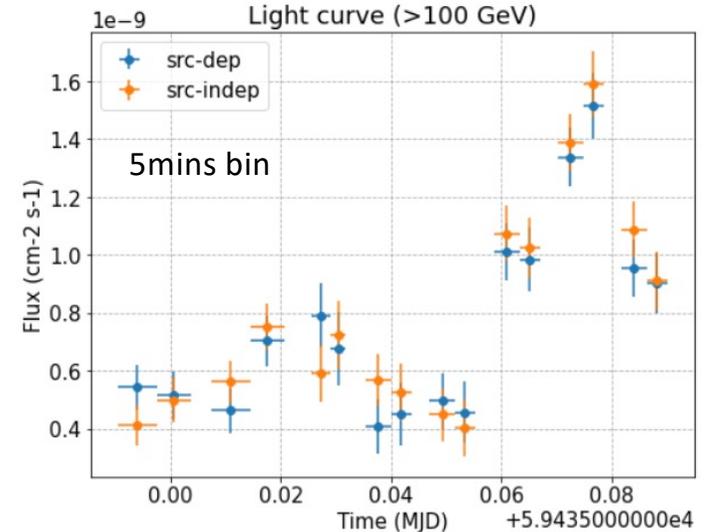
BL Lac Flare observed with LST1 by Dr. Seiya Nozaki

Big flare is observed in the night of 8 August 2022

SED measured down to 20GeV



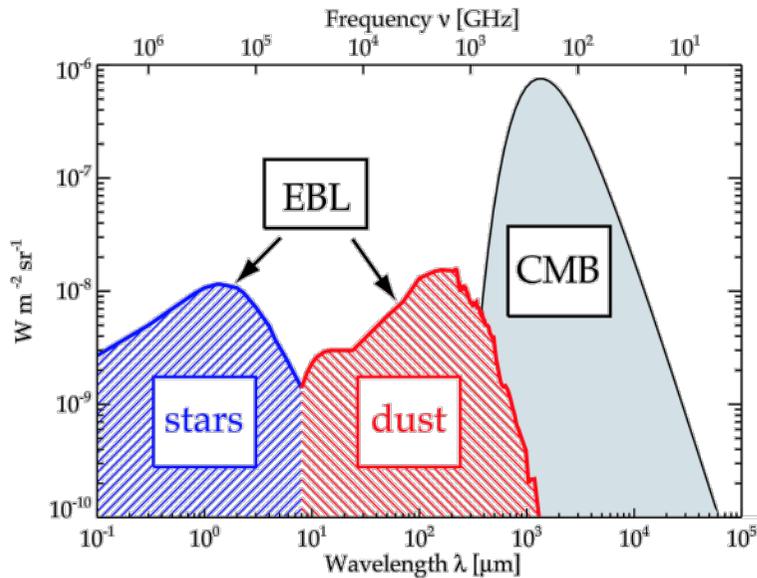
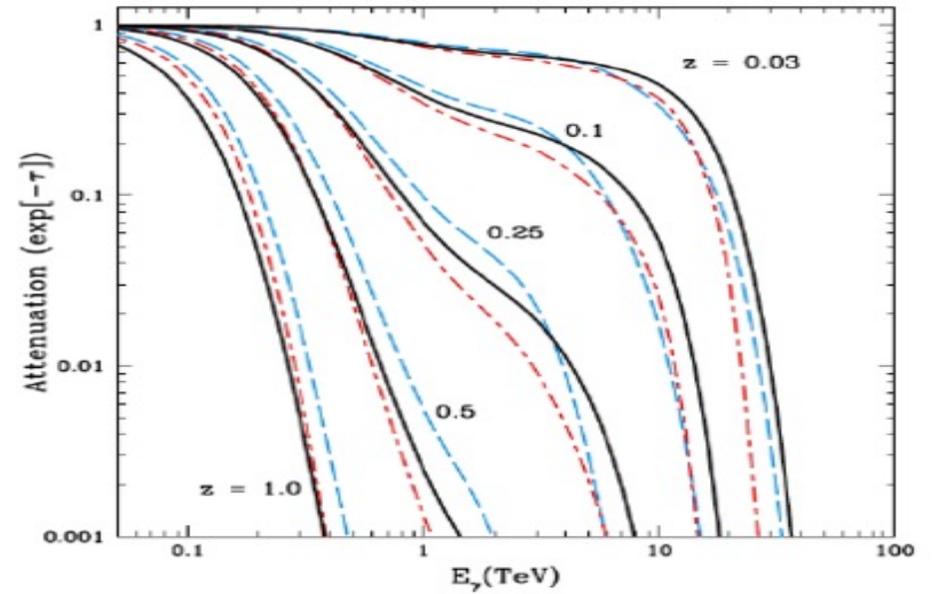
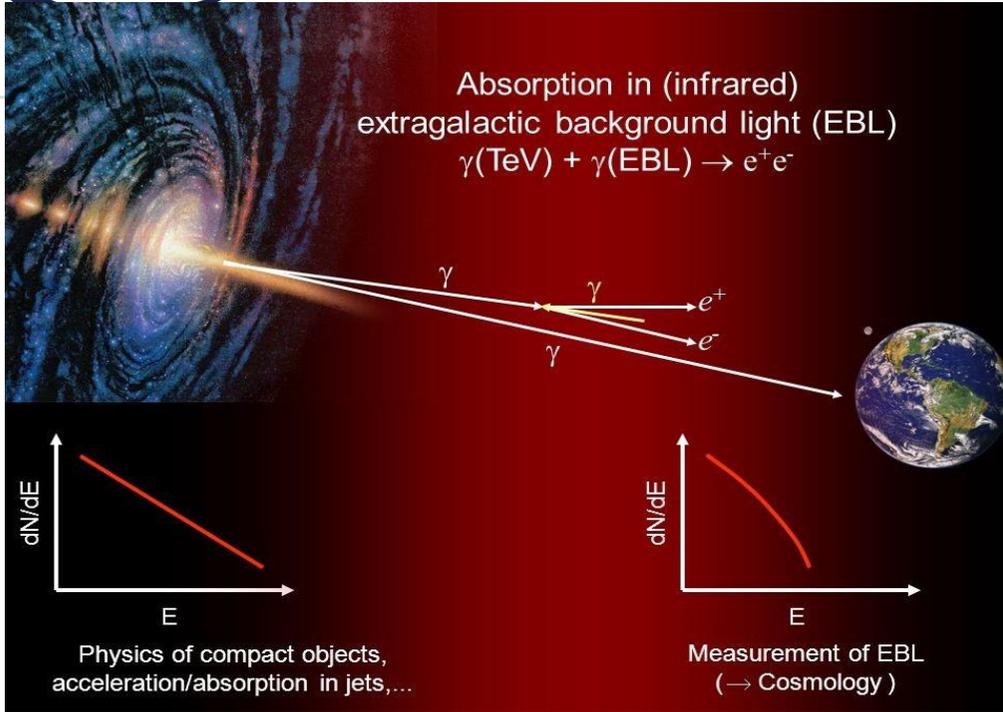
Intranight Variability



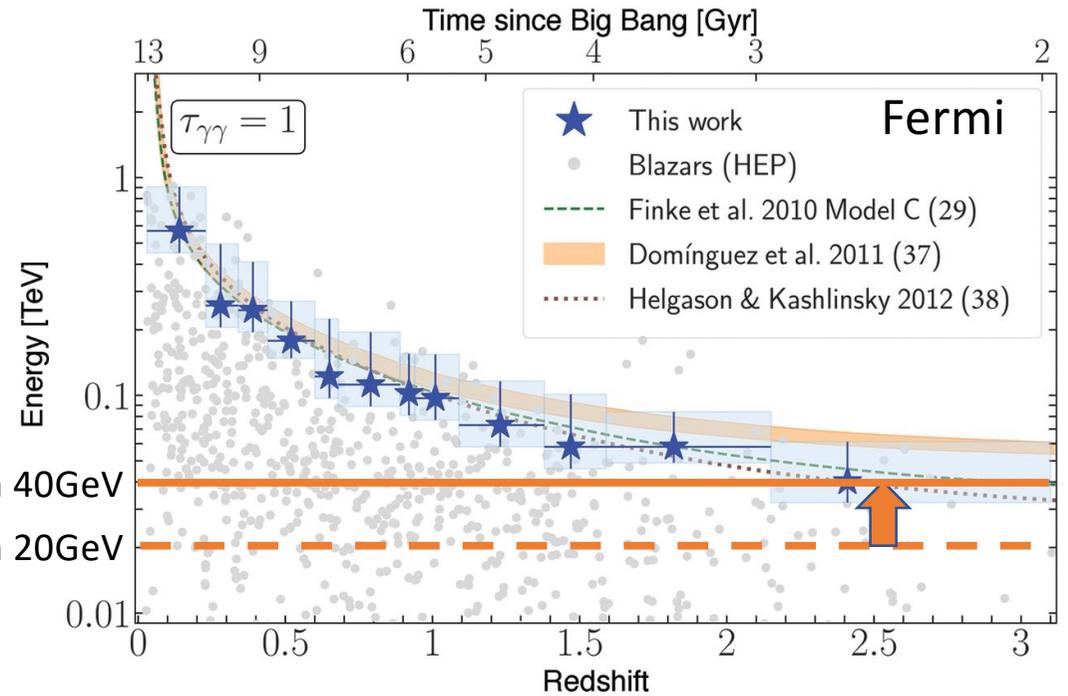


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array

Expand the Gamma Ray Horizon up to $z=4$



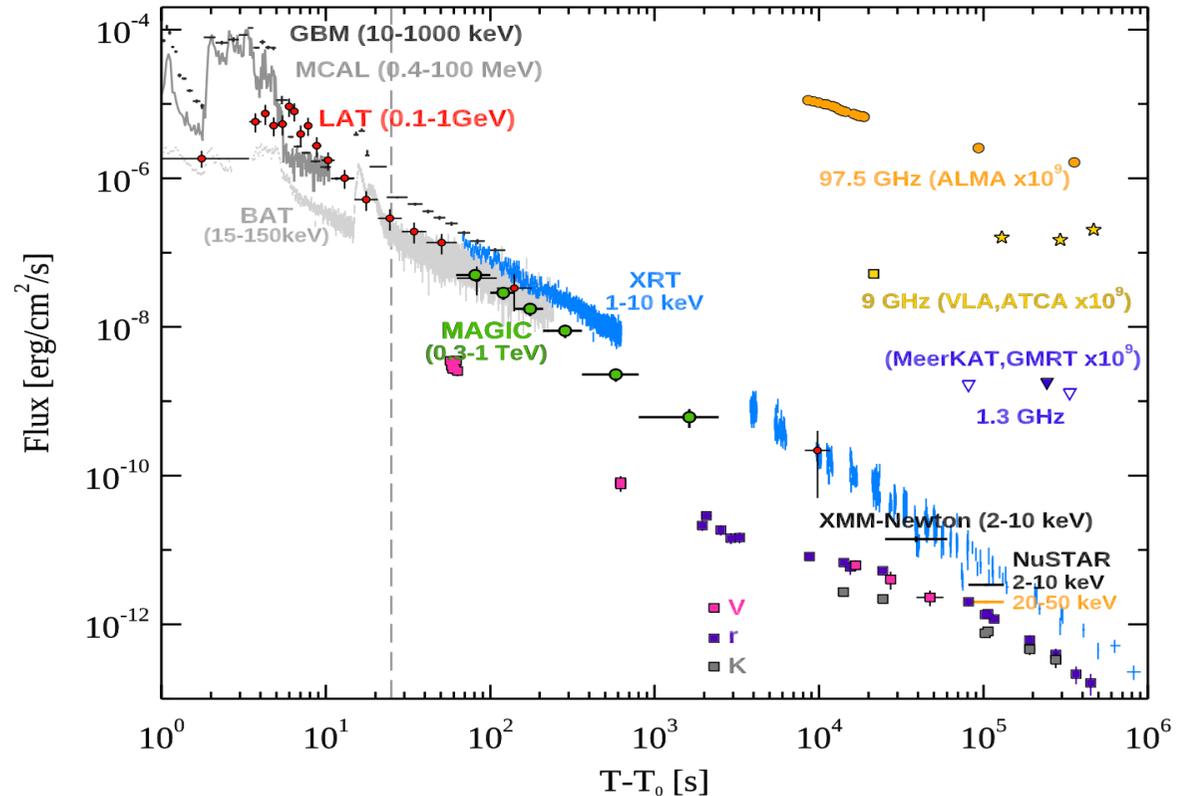
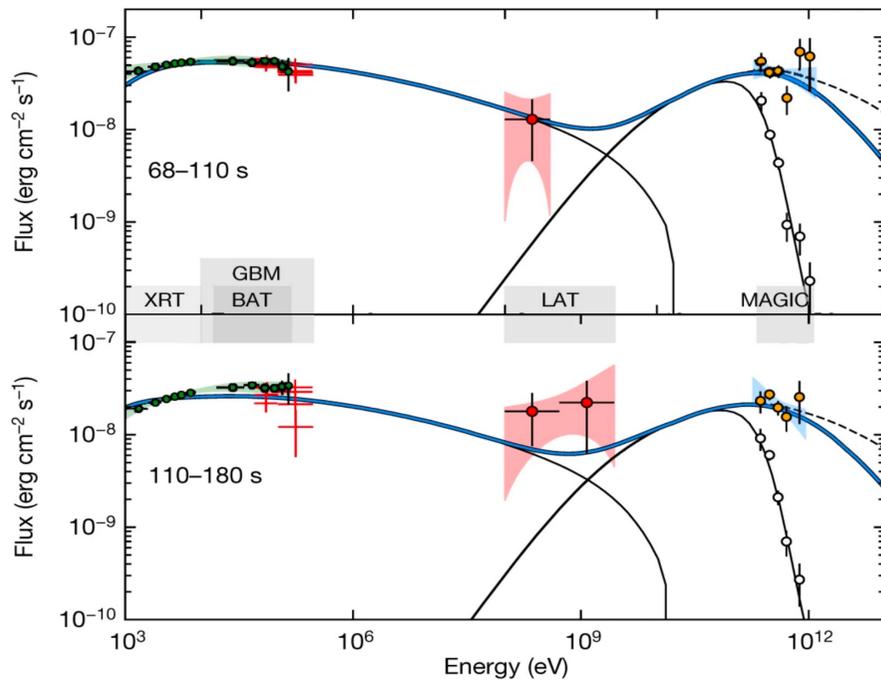
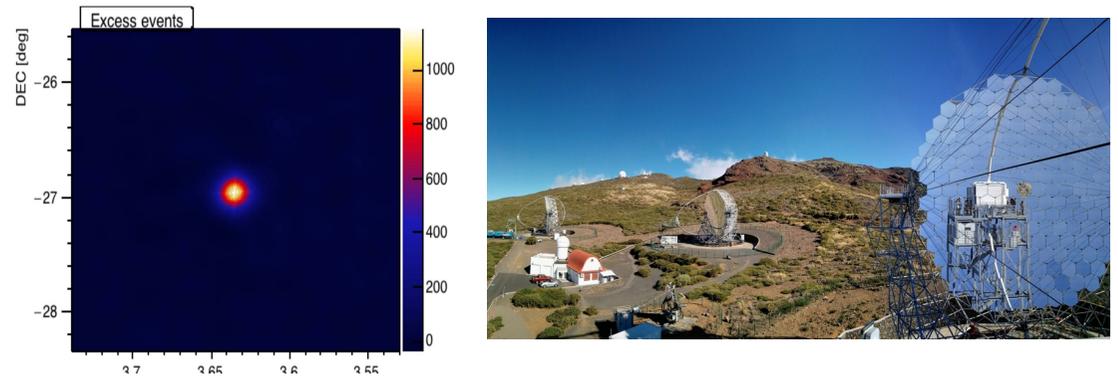
LST@45° Eth 40GeV
 LST@25° Eth 20GeV



MAGIC Highlight, Gamma Ray Burst GRB190114C (z=0.42)

Historical achievement

- ❑ First Detection of the GRB from ground.
- ❑ ~100 Crab flux in the first minutes.
- ❑ TeV bump has a similar energetics with KeV-GeV bump

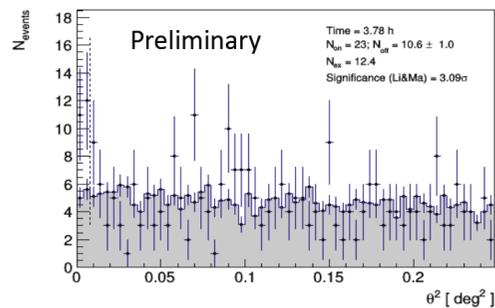
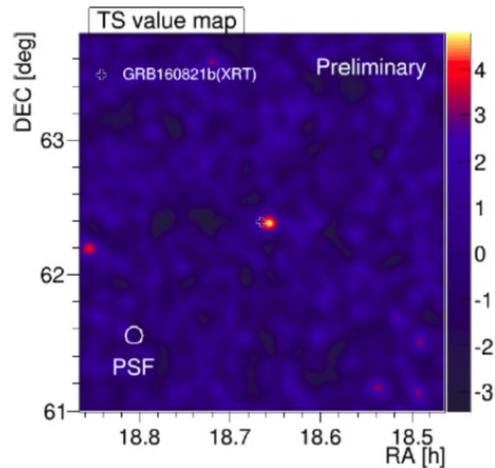


MAGIC Highlights

Other GRB observations with MAGIC

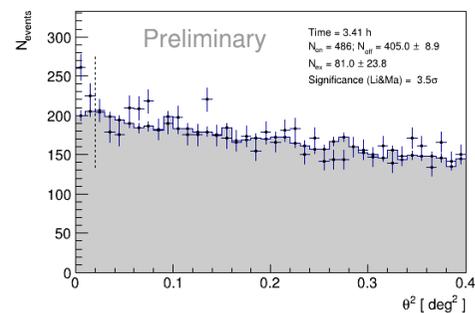
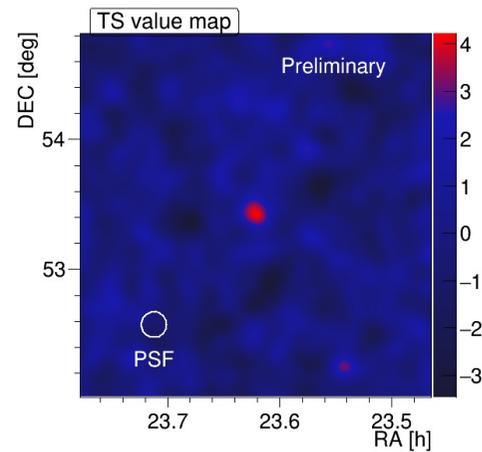
GRB 160821B

Short GRB under moon
 $E > 600\text{GeV}$
 $Z = 0.162$
 3.1σ (PostTrial)
 Published in APJ 2021



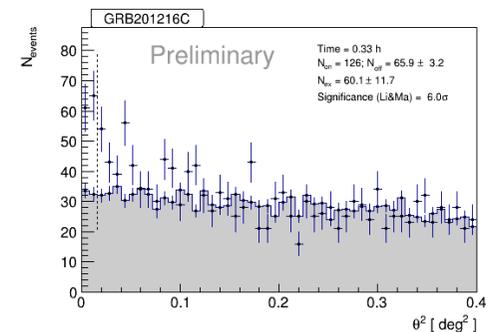
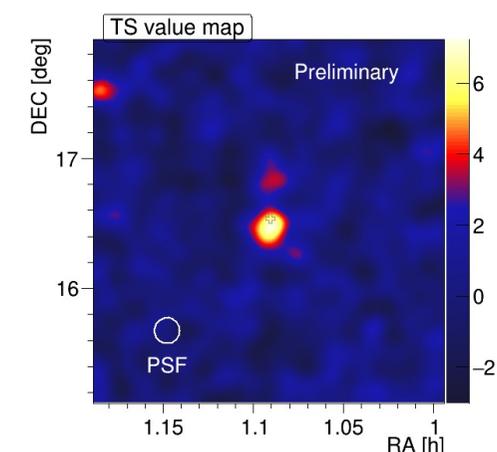
GRB 201015A

Long GRB in Dark
 $Z = 0.426$
 3.5σ (PostTrial)
 Published, ICRC 2021_797
 Y. Suda et al.



GRB 201216C

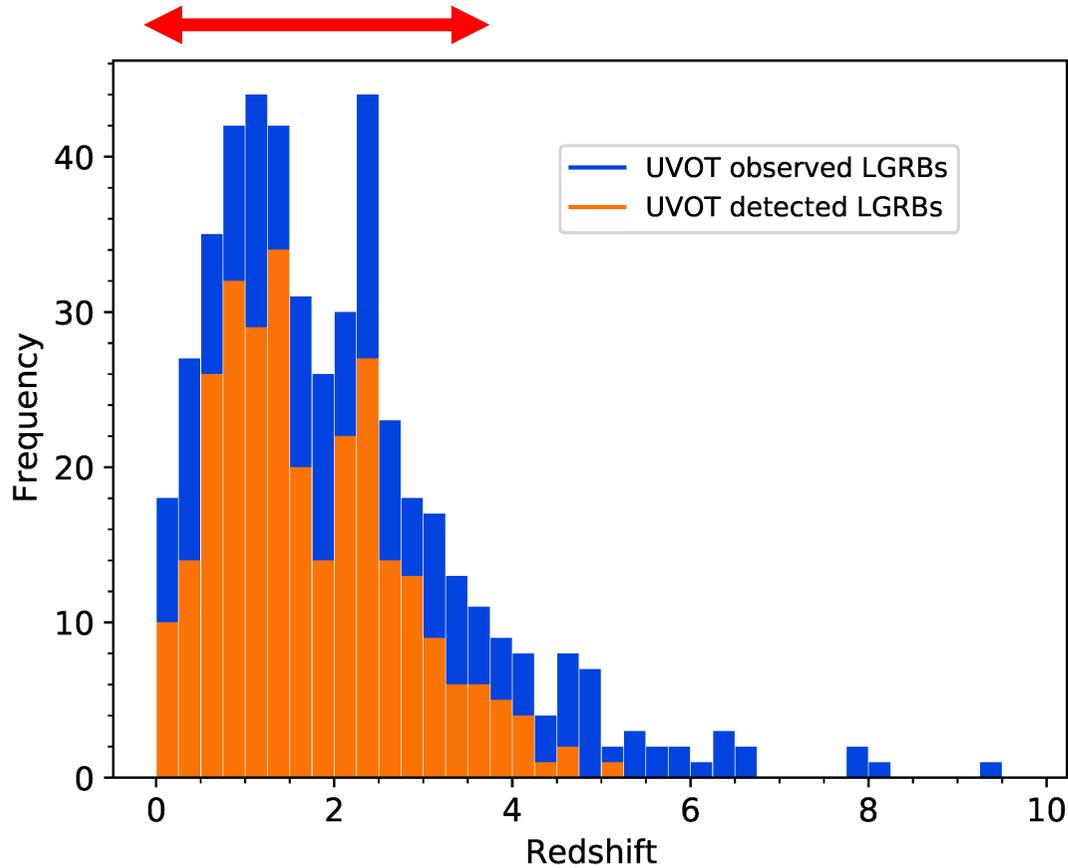
Long GRB in Dark
 $Z = 1.10$
 6σ (PostTrial)
 Published, ICRC 2021_788
 S. Fukami et al.





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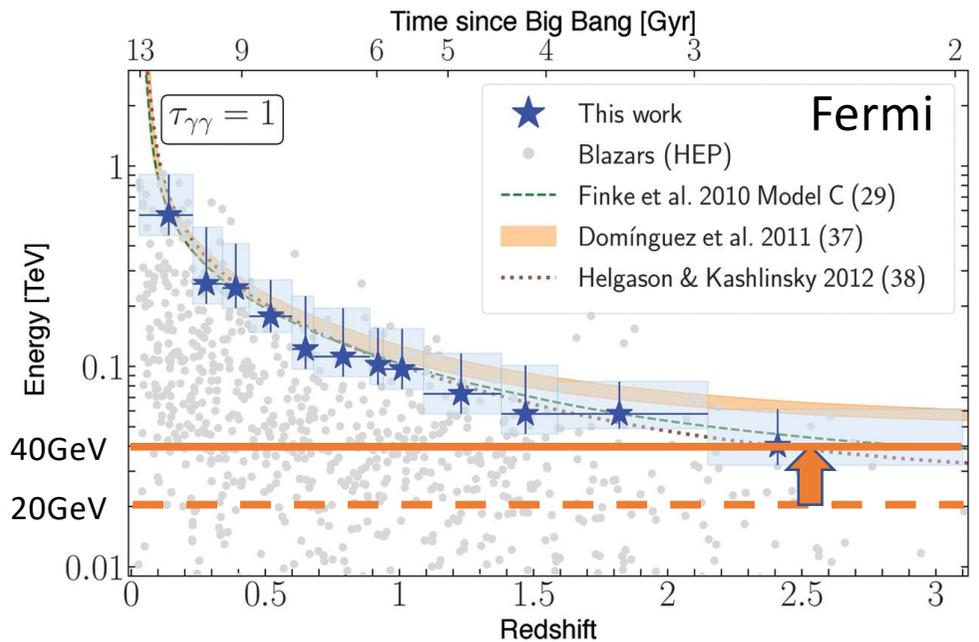
CTA LSTs will observe High Redshift GRBs



CTA LST will observe GRBs and AGNs during the structure formation period of the Universe

LST@45° Eth 40GeV

LST@25° Eth 20GeV

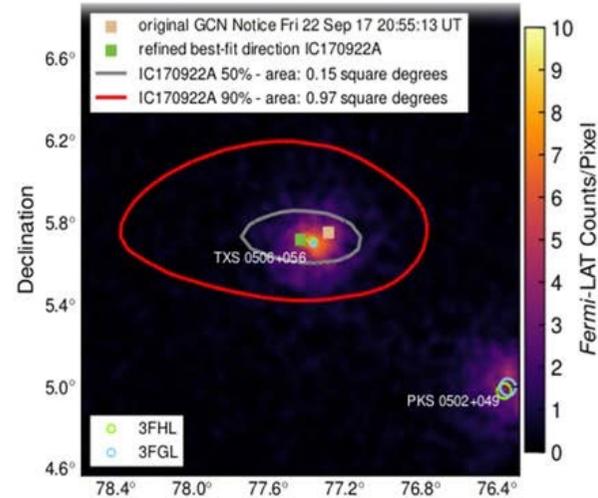
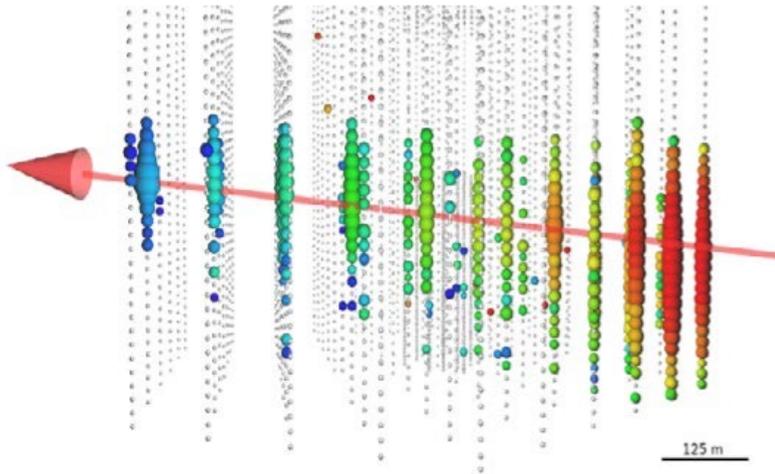




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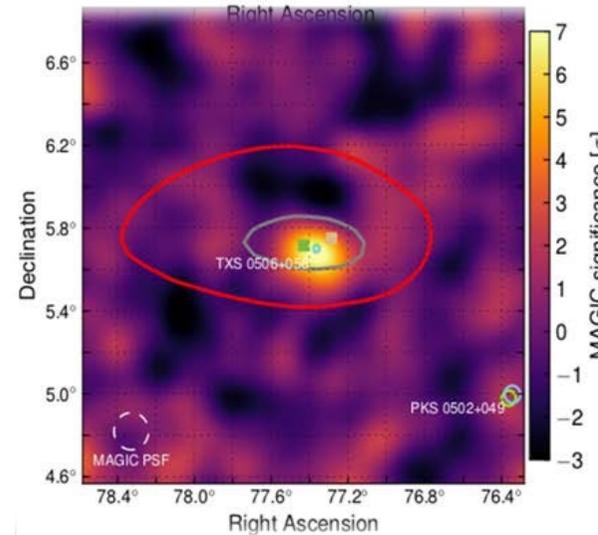
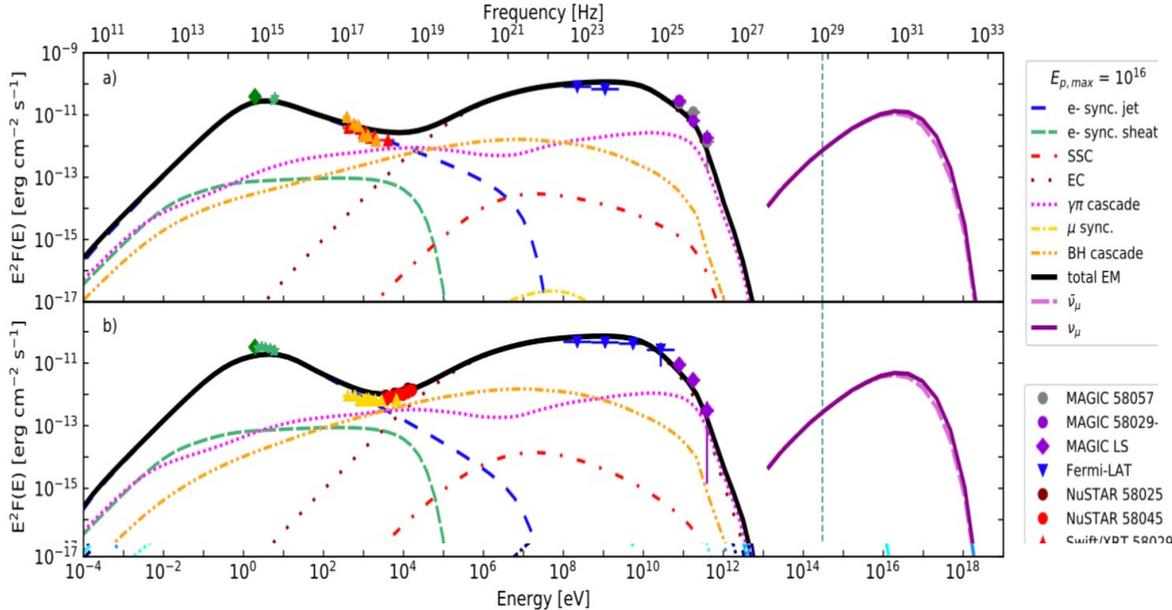
Multi Messenger Astronomy IC170922A / TXS 0506+056

Ice Cube Observation (~300TeV)



Fermi LAT
(>100 MeV)

Lepto-Hadronic Scenario



MAGIC
(>100GeV)

GTC Observation $z = 0.3365$
S. Paiano et. al 2018

Large Size Telescope

Mirrors: JP
Interface plates: JP, DE, BR
Actuators: JP, CH
CMOS: JP

calibration:
IT, HR, IN, DE

Telescope
structure: DE

Tension cables: IT

Camera Support
Structure: FR

Camera electronics: JP, IT, ES
Camera mechanics: ES
Camera safety: FR

Rail: DE

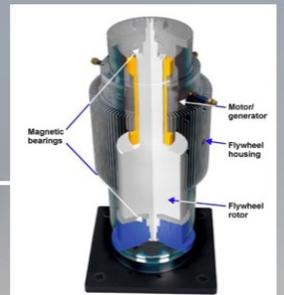
Bogies: ES

Camera Access Tower: DE, ES

Foundation: ES

Drive and main
el. cabinet: FR

FlyWheels (2x300kW)
energy storage and UPS: JP

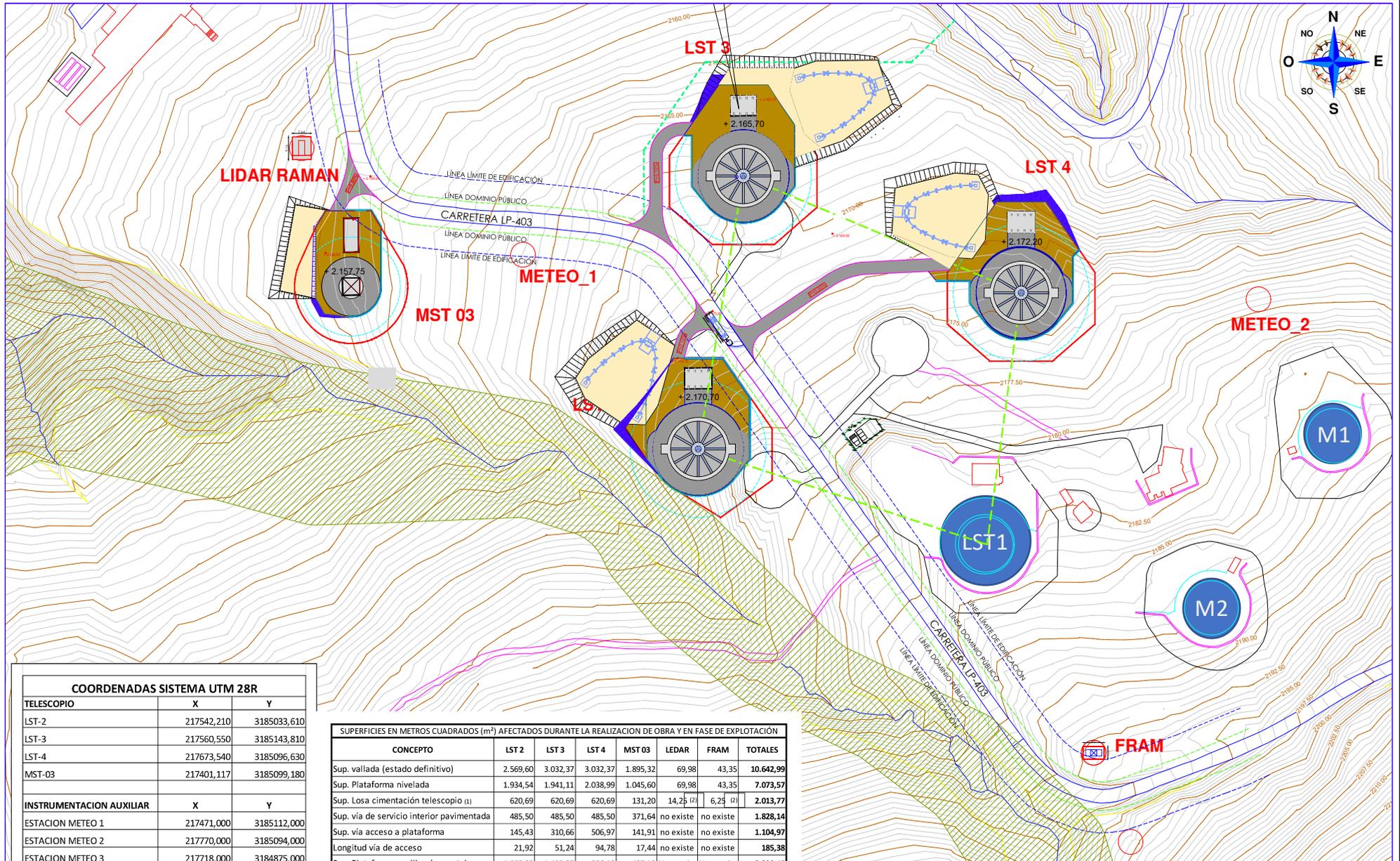




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telescope
array

CTA North Phase I Installation Plan

LST1-4 location



COORDENADAS SISTEMA UTM 28R		
TELESCOPIO	X	Y
LST-2	217542,210	3185033,610
LST-3	217560,550	3185143,810
LST-4	217673,540	3185096,630
MST-03	217401,117	3185099,180
INSTRUMENTACION AUXILIAR		
	X	Y
ESTACION METEO 1	217471,000	3185112,000
ESTACION METEO 2	217770,000	3185094,000
ESTACION METEO 3	217718,000	3184875,000

SUPERFICIES EN METROS CUADRADOS (m²) AFECTADOS DURANTE LA REALIZACION DE OBRA Y EN FASE DE EXPLOTACION							
CONCEPTO	LST 2	LST 3	LST 4	MST 03	LEDAR	FRAM	TOTALES
Sup. vallada (estado definitivo)	2.569,60	3.032,37	3.032,37	1.895,32	69,98	43,35	10.642,99
Sup. Plataforma nivelada	1.934,54	1.941,11	2.038,99	1.045,60	69,98	43,35	7.073,57
Sup. Losa cimentación telescopio (1)	620,69	620,69	620,69	131,20	14,25 (2)	6,24 (2)	2.013,77
Sup. vía de servicio interior pavimentada	485,50	485,50	485,50	371,64	no existe	no existe	1.828,14
Sup. vía acceso a plataforma	145,43	310,66	506,97	141,91	no existe	no existe	1.104,97
Longitud vía de acceso	21,92	51,24	94,78	17,44	no existe	no existe	185,38

LST2-4 status

Picture from LST1 Tower

As of Jan 25th, 2023

LST2



LST3



LST4





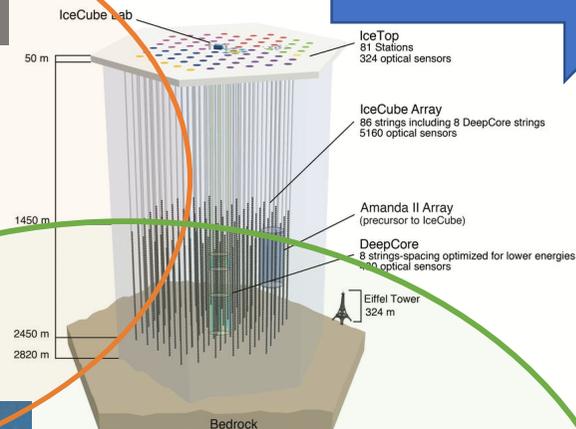
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Multi-messenger and Multi-wavelength Astrophysics

Wave
AstroPhysics

Particle Physics

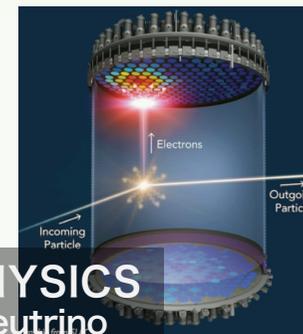
ASTRO-PARTICLE PHYSICS
Cosmic Ray Physics
High Energy Astrophysics



ASTRO-PHYSICS
Gamma Ray Bursts, Black holes,
Neutron Stars, Space and Time



PARTICLE PHYSICS
Dark Matter, Neutrino
Energy Frontier



Summary

- CTA is a big and ambitious project
- LSTs play an important role in the Multi-Messenger astronomy in the next decades
- LST2-4 construction started in the winter 2022
- CTA South (SSTs, MSTs, and LST5-6) construction will start in 2024

- CTA and current IACT will study
 - Cosmic Ray Origin
 - Evolution of Black Holes and Extreme environment around Black Holes and neutron stars
 - [Explore the Dark Matter in the Galactic Center and halo](#)



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Thank you very much

