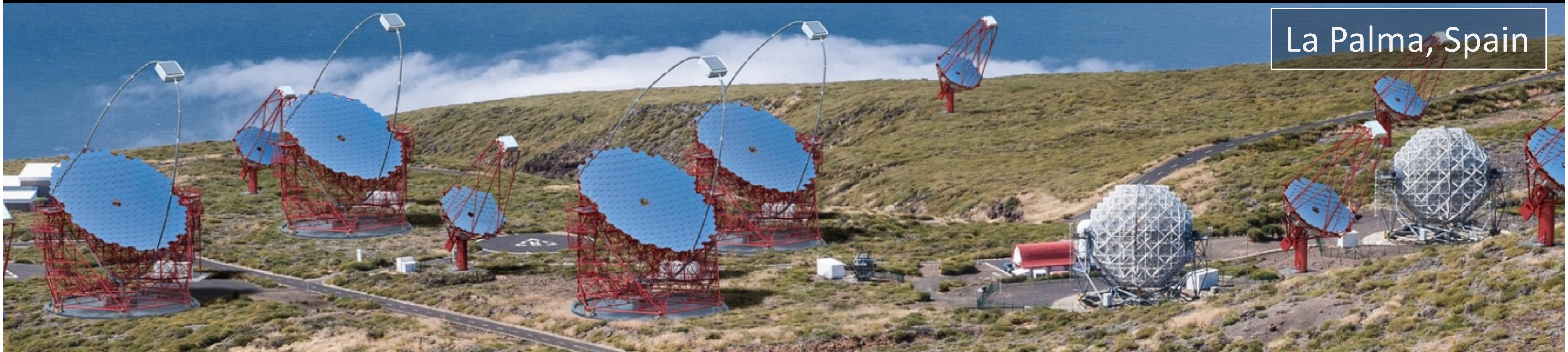
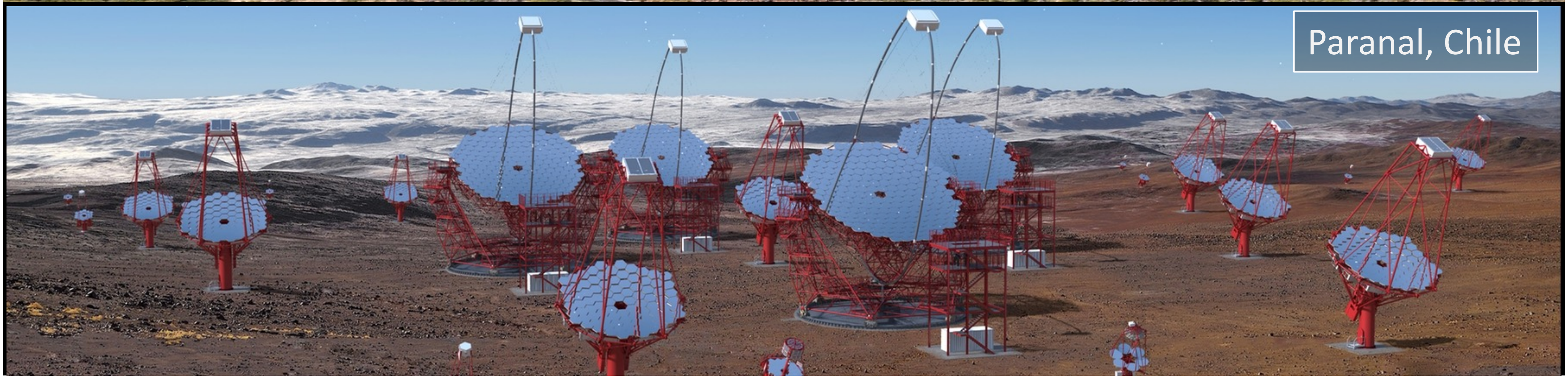
VHE Gamma-Ray Astronomy and The CTA Project

Masahiro Teshima

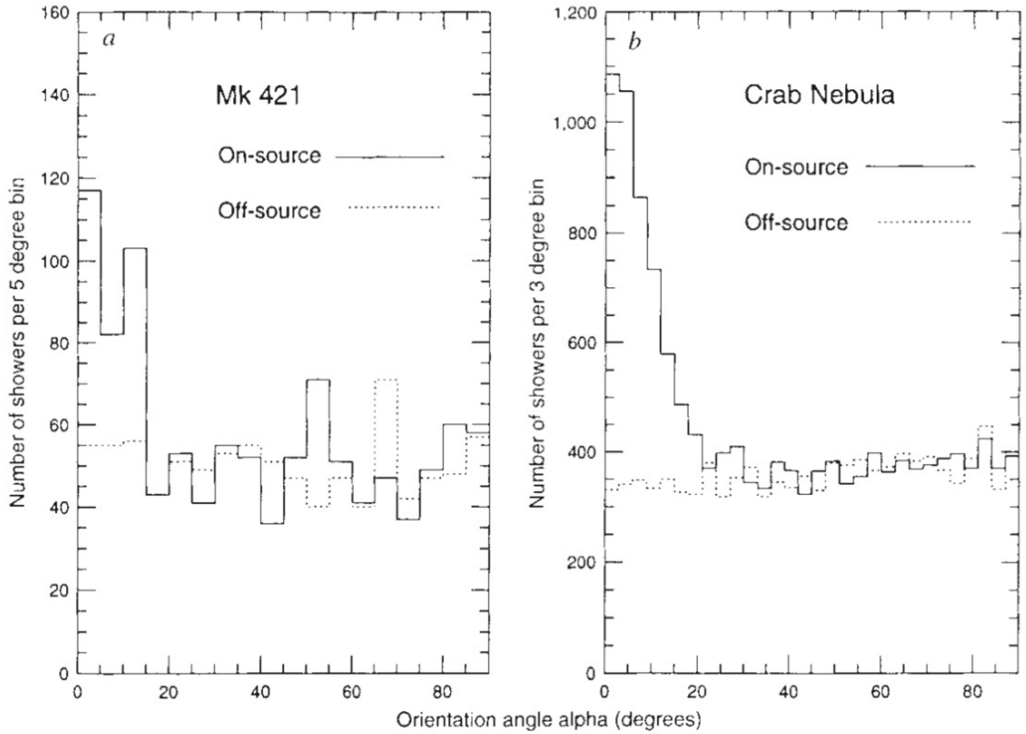
Institute for Cosmic Ray Research, The University of Tokyo, Japan
Max Planck Institute for Physics, Munich, Germany





History of VHE gamma-ray astronomy
Imaging Atmospheric Cherenkov Telescope

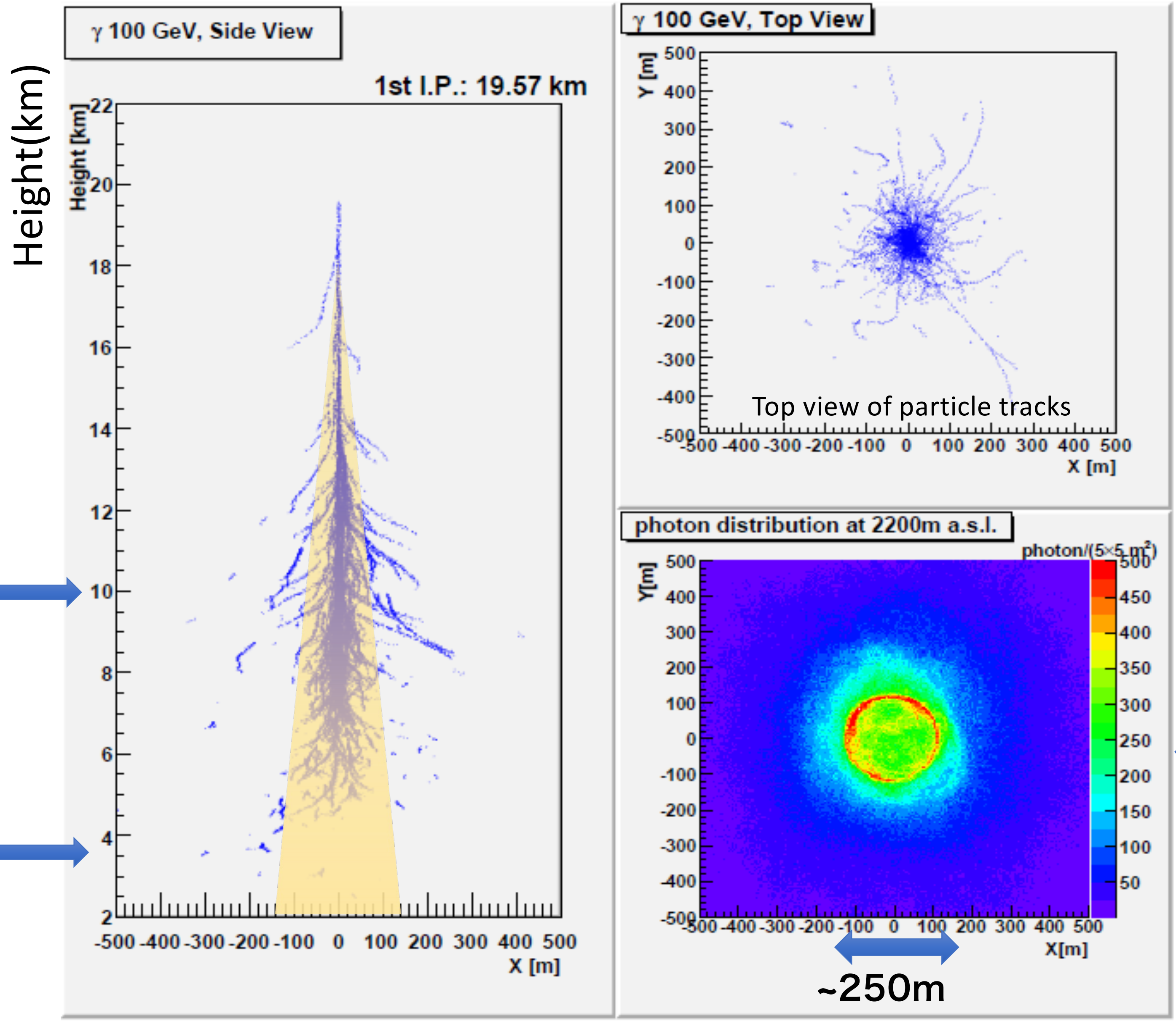
- ❑ The first idea of IACT from Michel Hillas in 1985 at ICRC in San Diego, USA
- ❑ Dr. Trever Weeks demonstrated the power of IACT with the Whipple telescope. VHE gamma rays from the Crab Nebula is discovered in 1989 (1G)
- ❑ ➔ HESS, MAGIC and VERITAS (2G)
- ❑ ➔ CTA (3G)



The observation of the first extragalactic source Mrk421
M. Punch et al., Nature 1991

cherenkov telescope array

TeV Gamma Rays ➔ EM showers ➔ Cherenkov Light



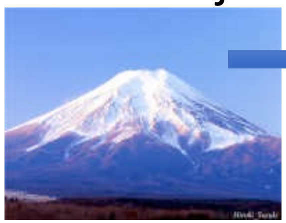
Refractive Index of Atmosphere
$n = 1.000292$

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

Particle velocity
$v \sim c$

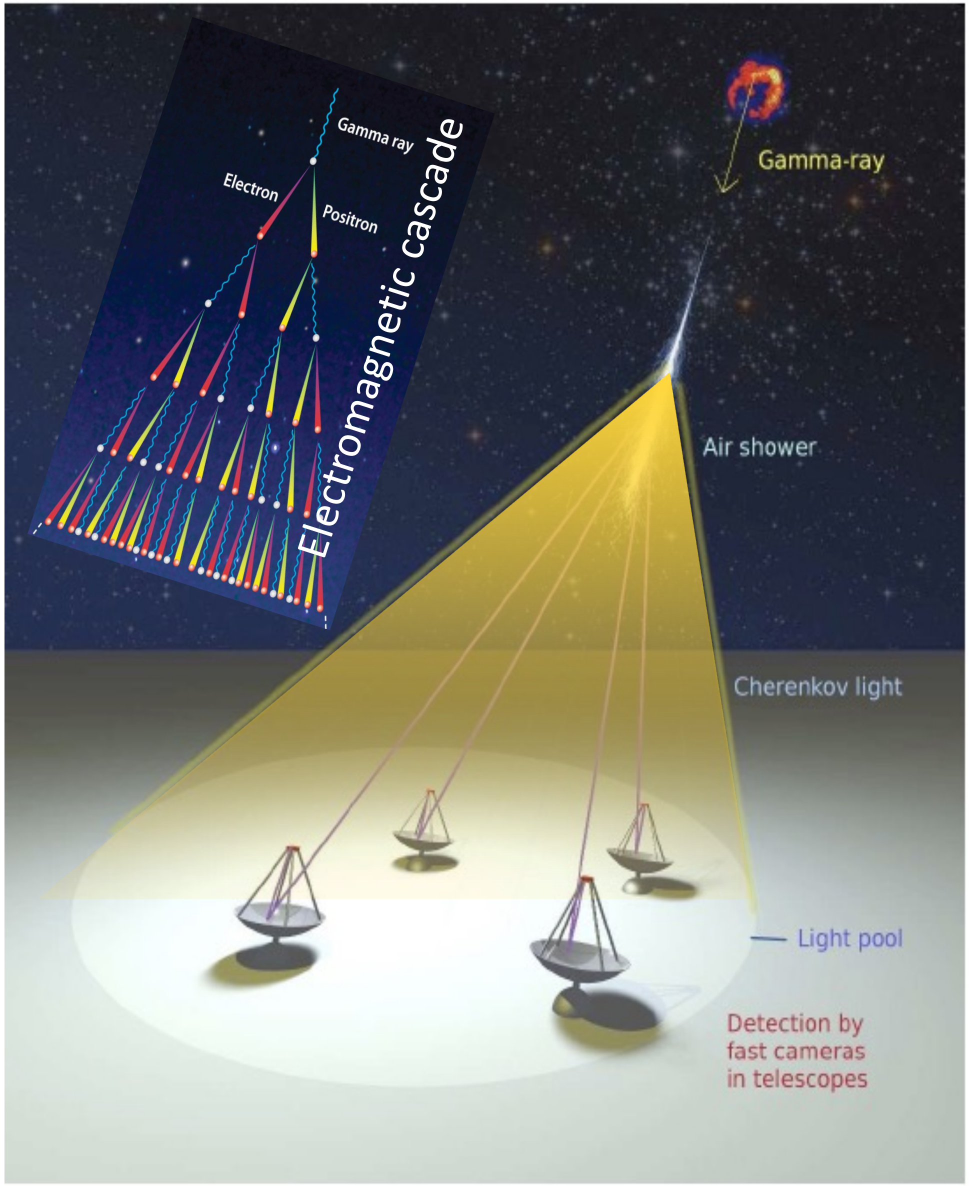
Airplane

Mt. Fuji

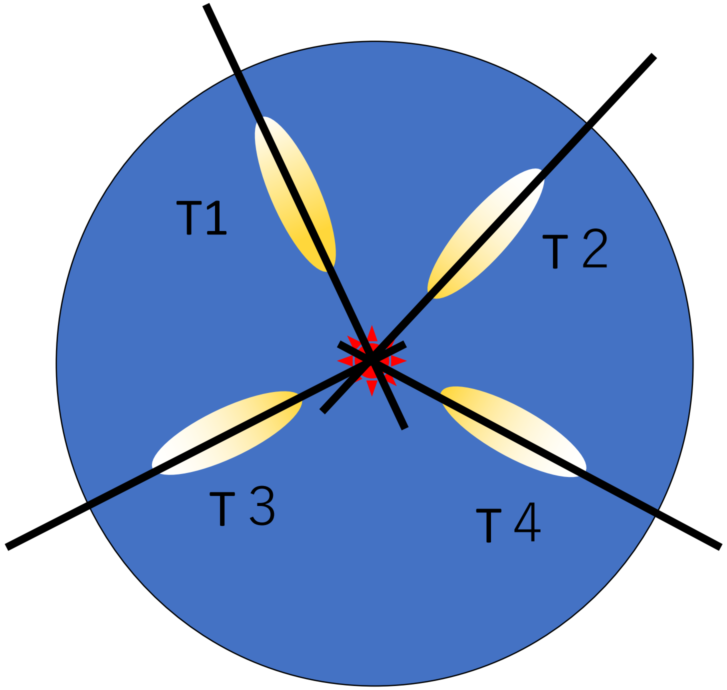


Cherenkov light Footprint

Imaging Atmospheric Cherenkov Telescopes (IACTs)



# of Photons: 50photons/m^2 at 1TeV

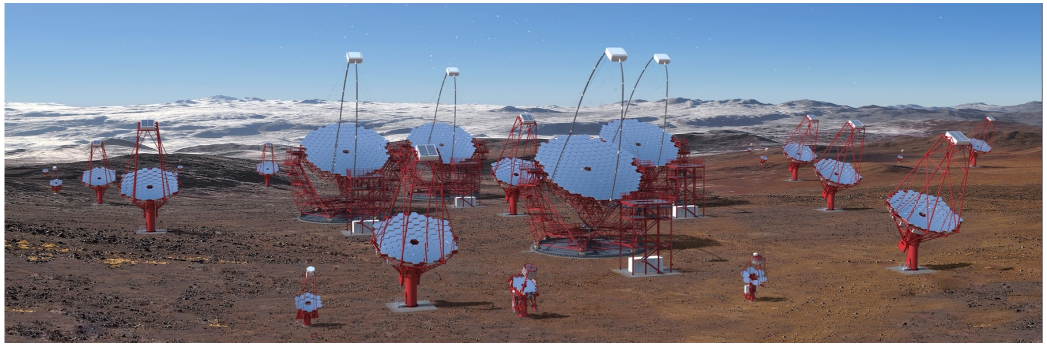


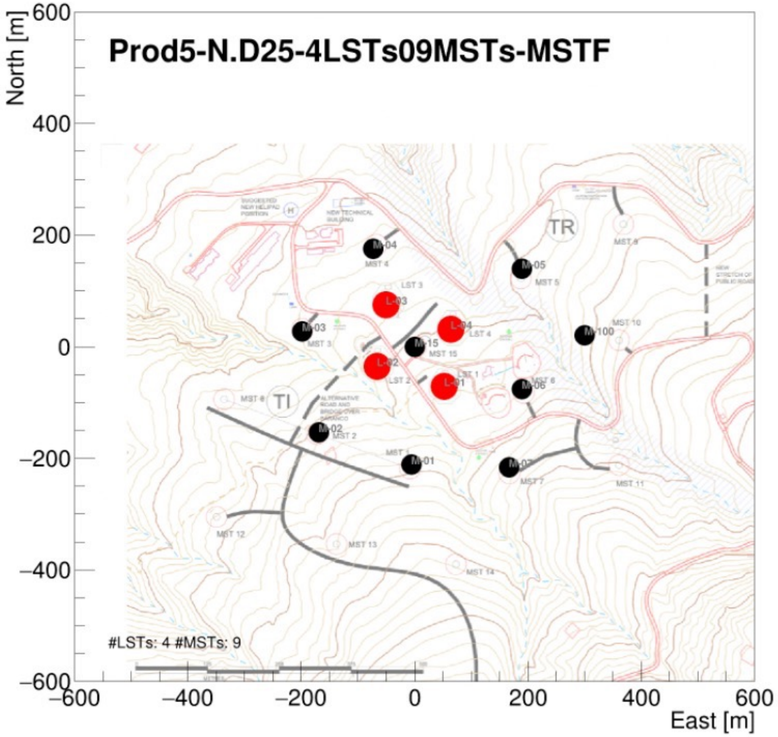
■ Energy range	100GeV ~ 100TeV
■ CR Rejection	~99.5%
■ Angular Res.	~0.06 degrees
■ Energy Res.	~15%
■ Effective Area	~10^5m^2
■ Sensitivity	~0.6% Crab Flux (10^{-13} erg/cm^{2}s)

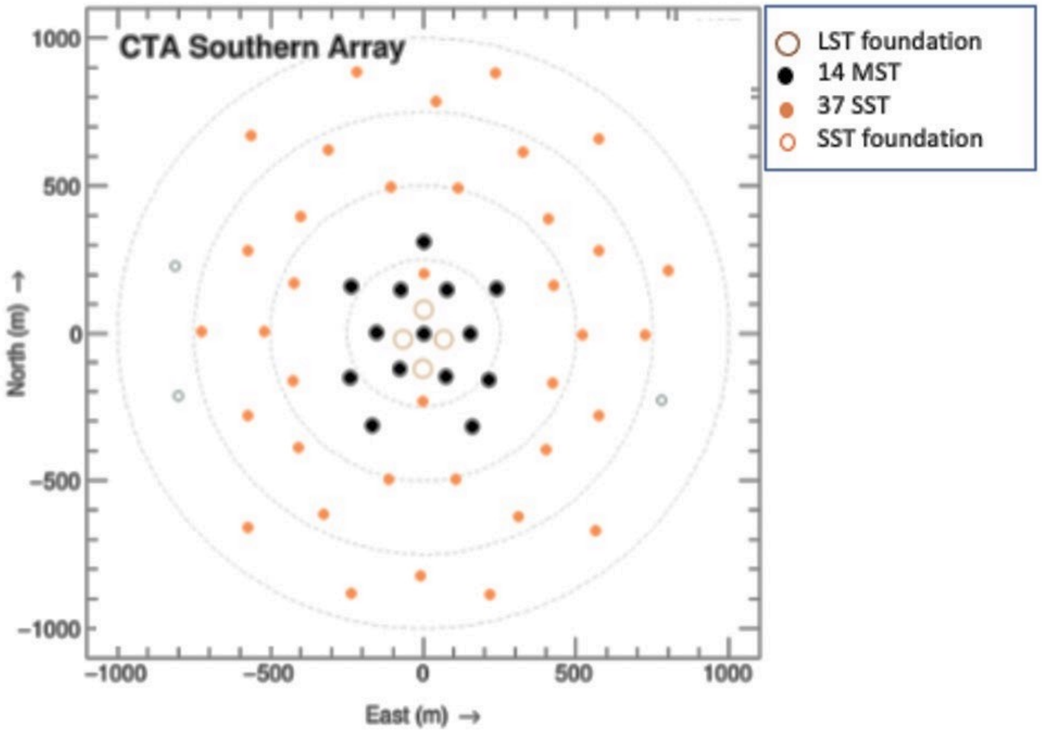
Alpha Configuration is decided with the financial constraints

Roque de los Muchachos Observatory
La Palma, Spain

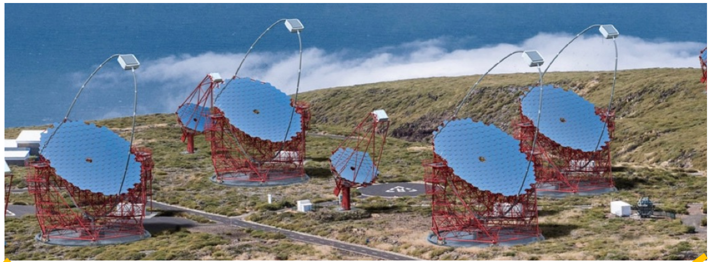
Paranal, Chile

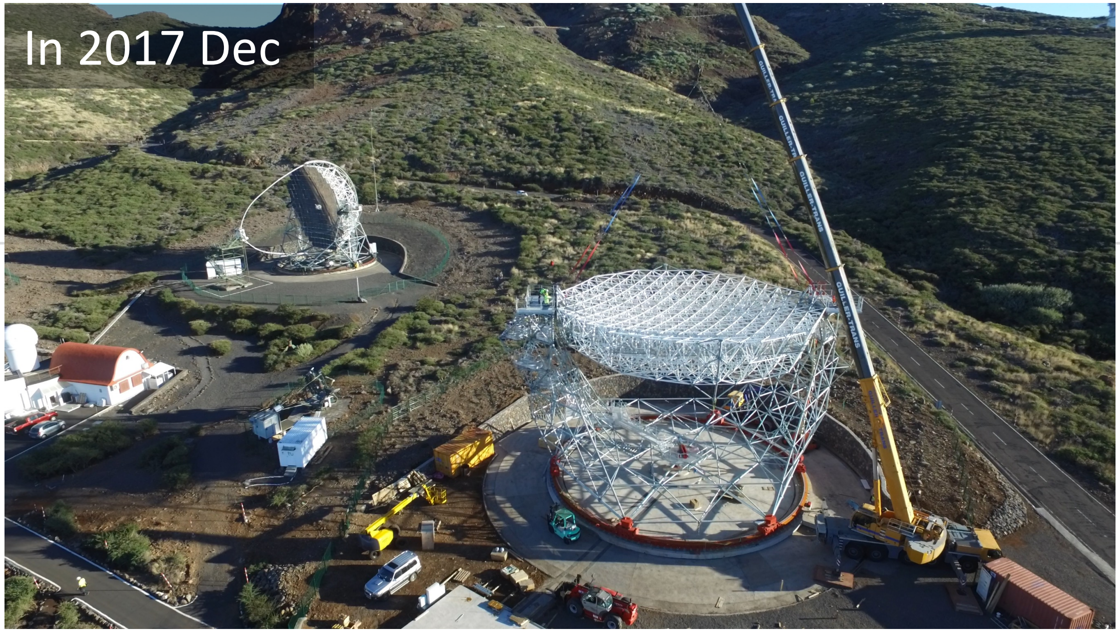


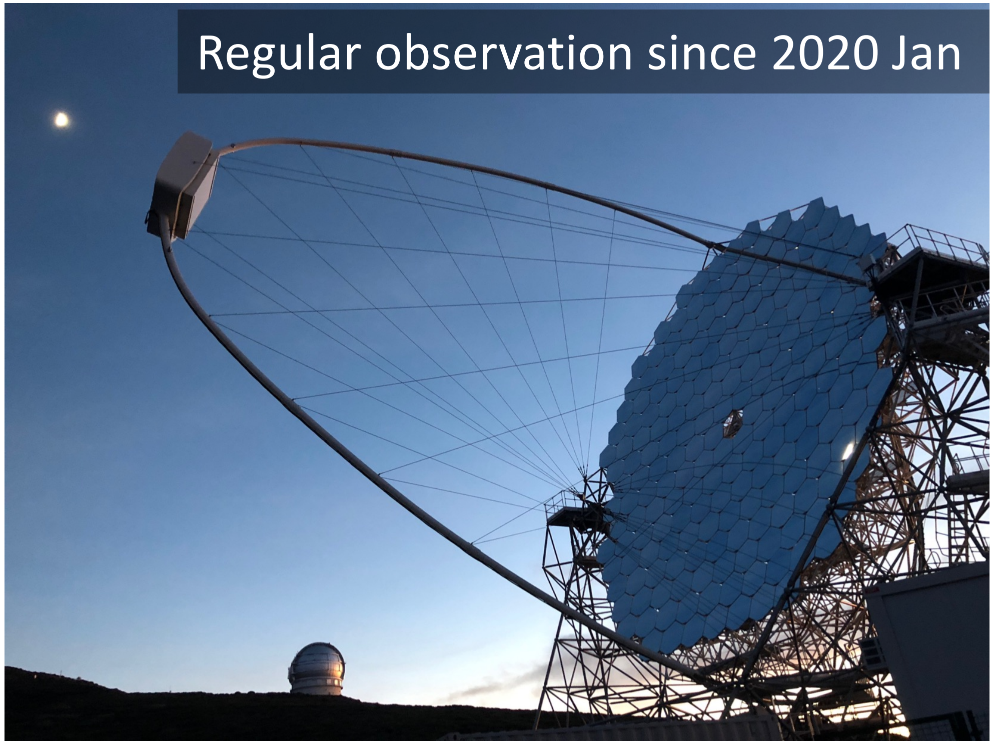


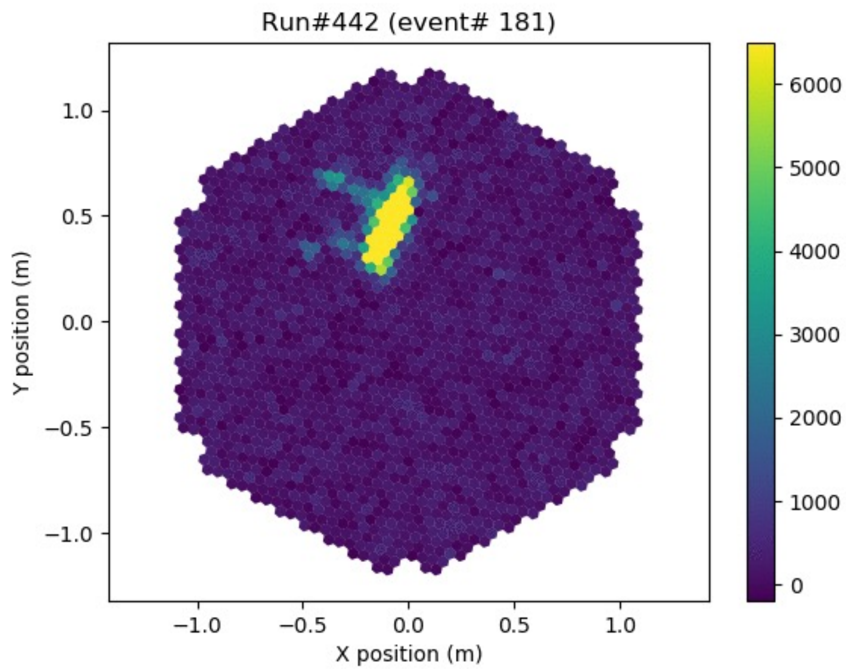


Canary Island, La Palma and ORM, Observatory Roque de los Muchachos





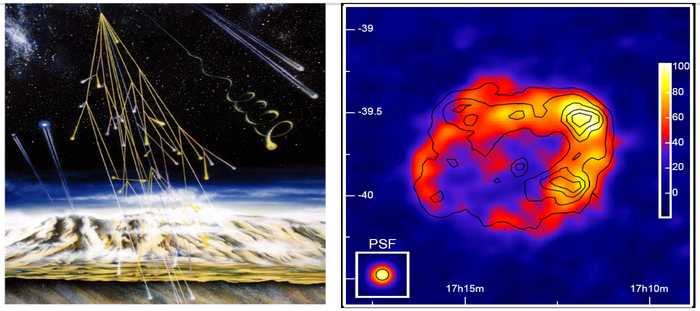




May 2019, first images of cosmic rays

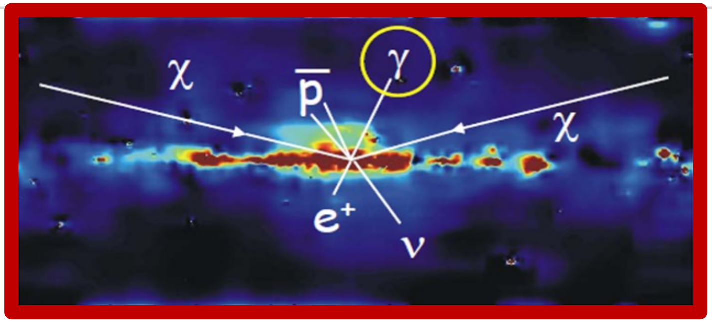
Science of CTA is very wide

SNRs, PWNe, AGNs, GRBs, Dark Matter



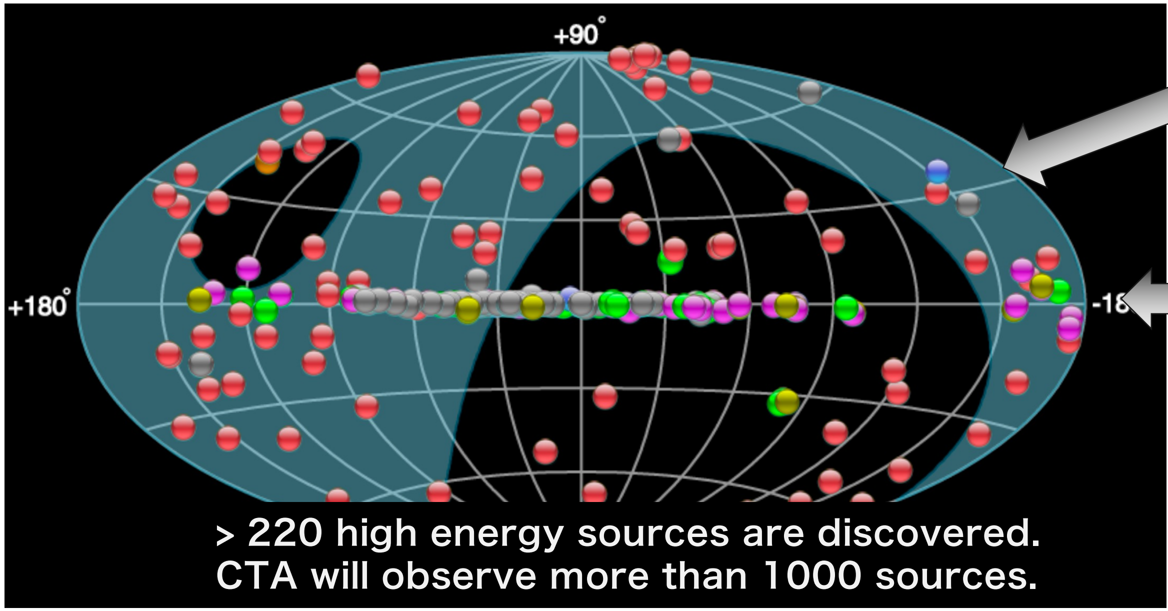
Cosmic Ray Origin

Super Massive Black Holes



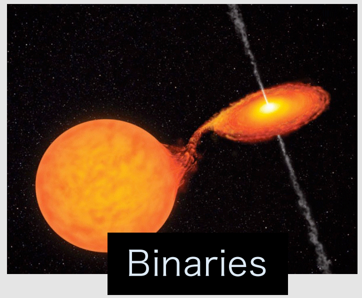
Dark Matter Search (Discovery)

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

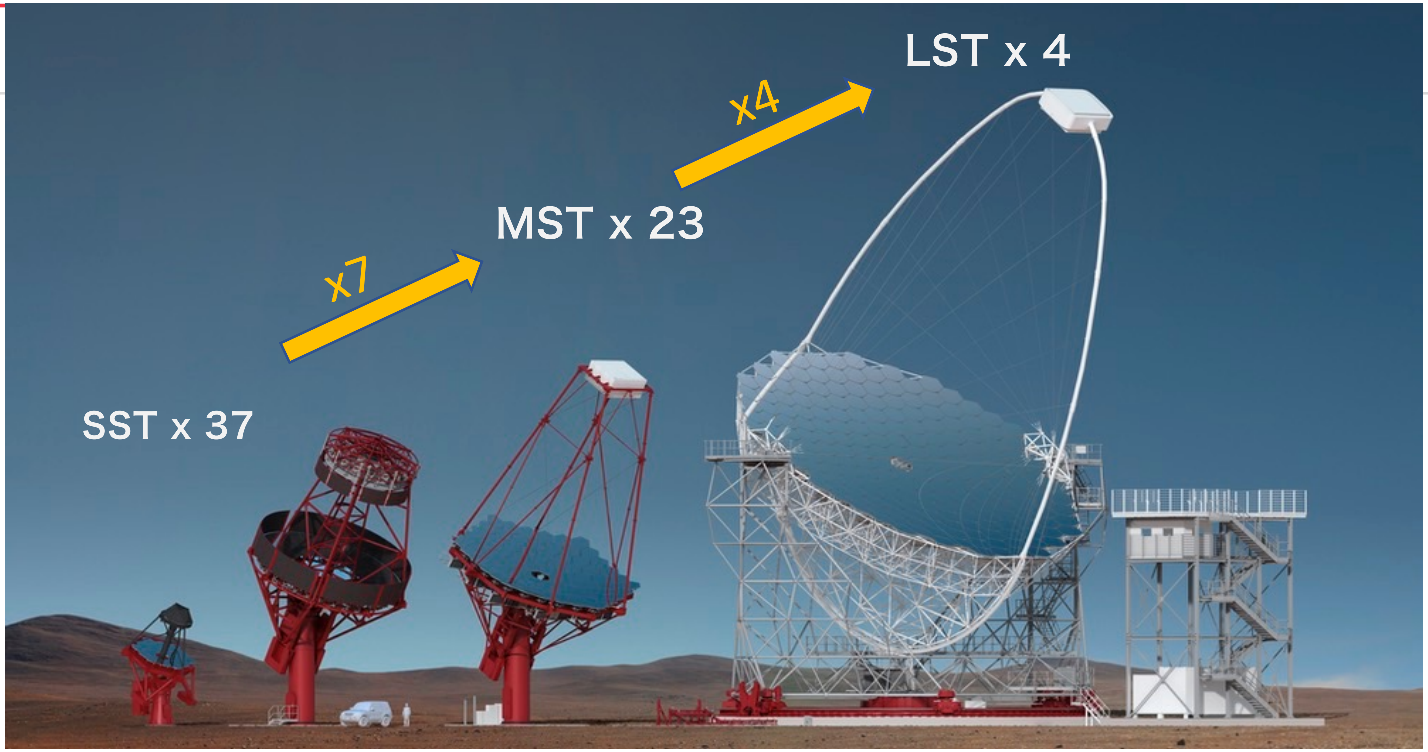


Extragalactic Sources

Galactic Sources

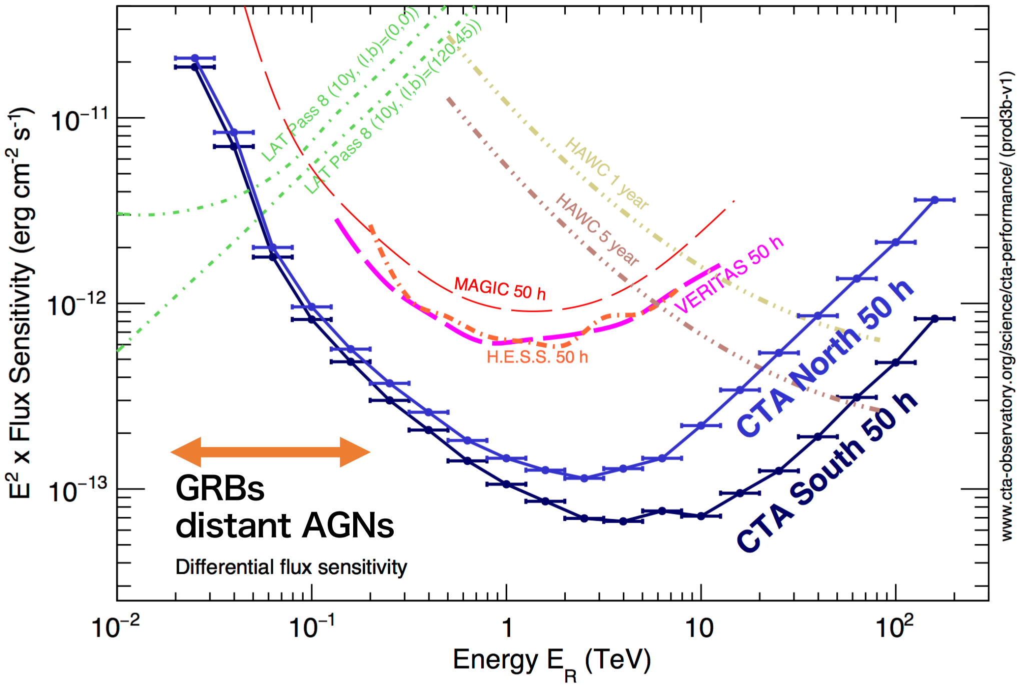


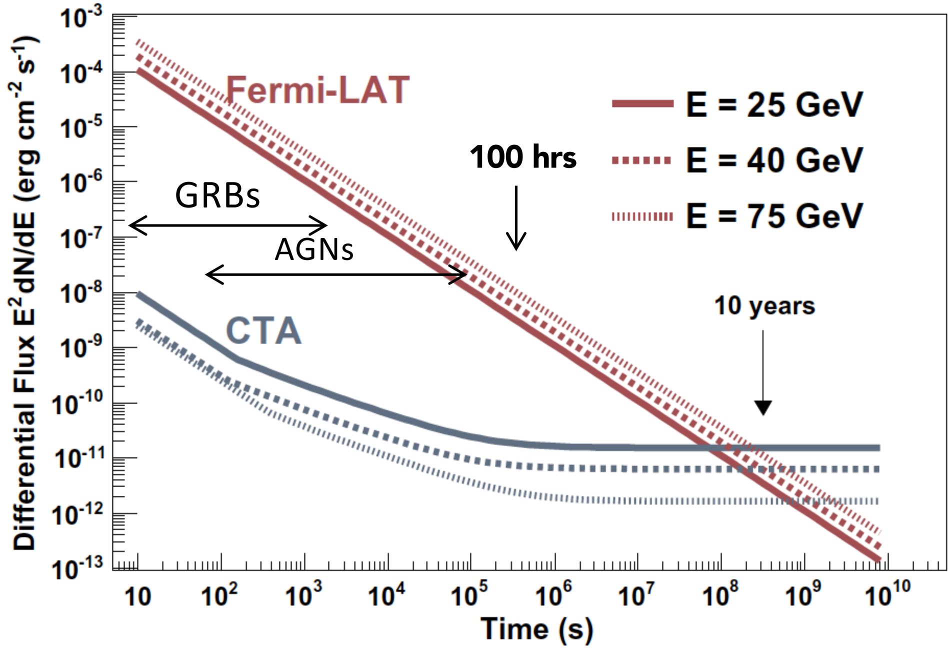
Telescope Design



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

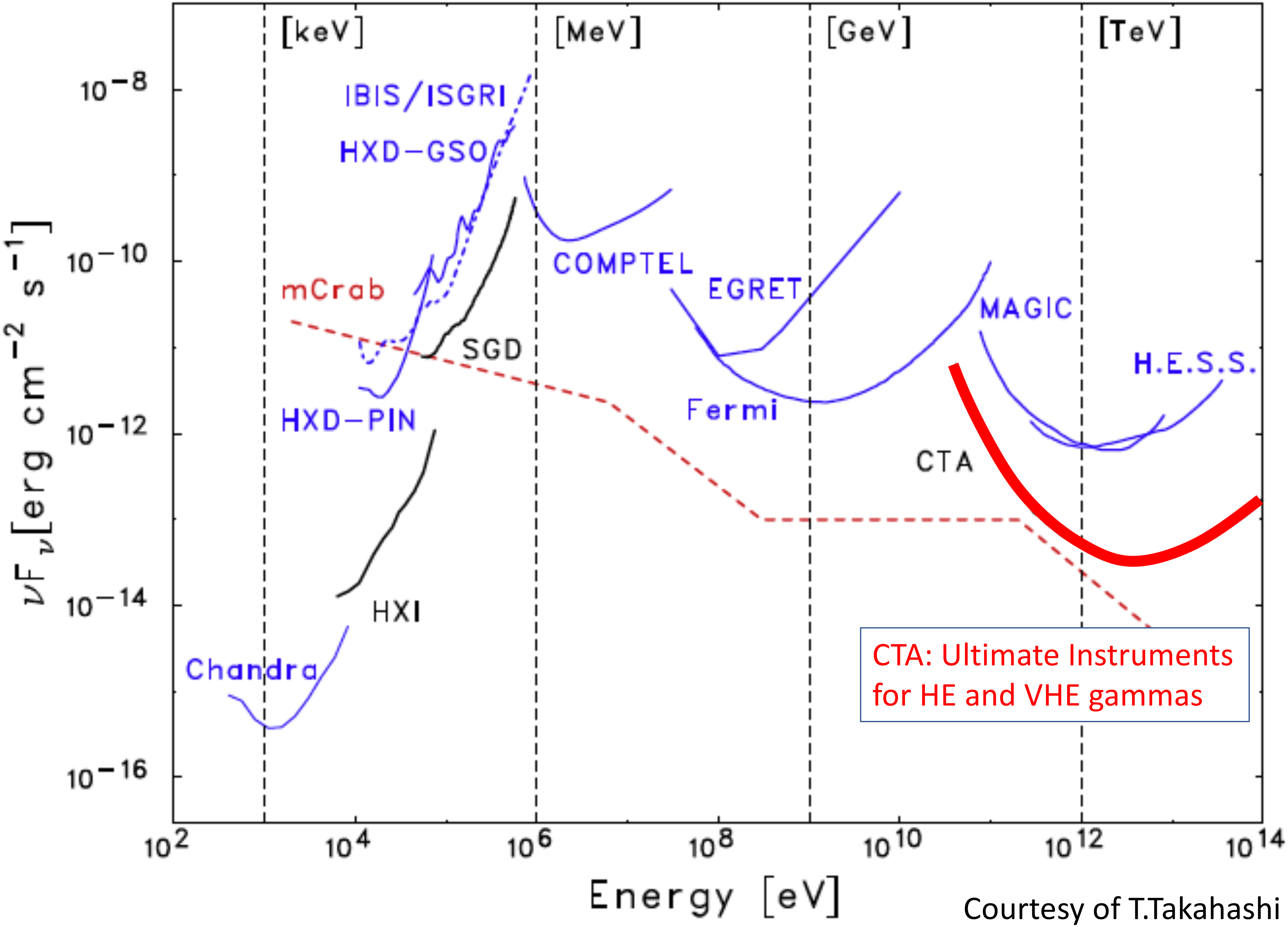
10 times better sensitivity
Wide Energy coverage 20GeV~200TeV





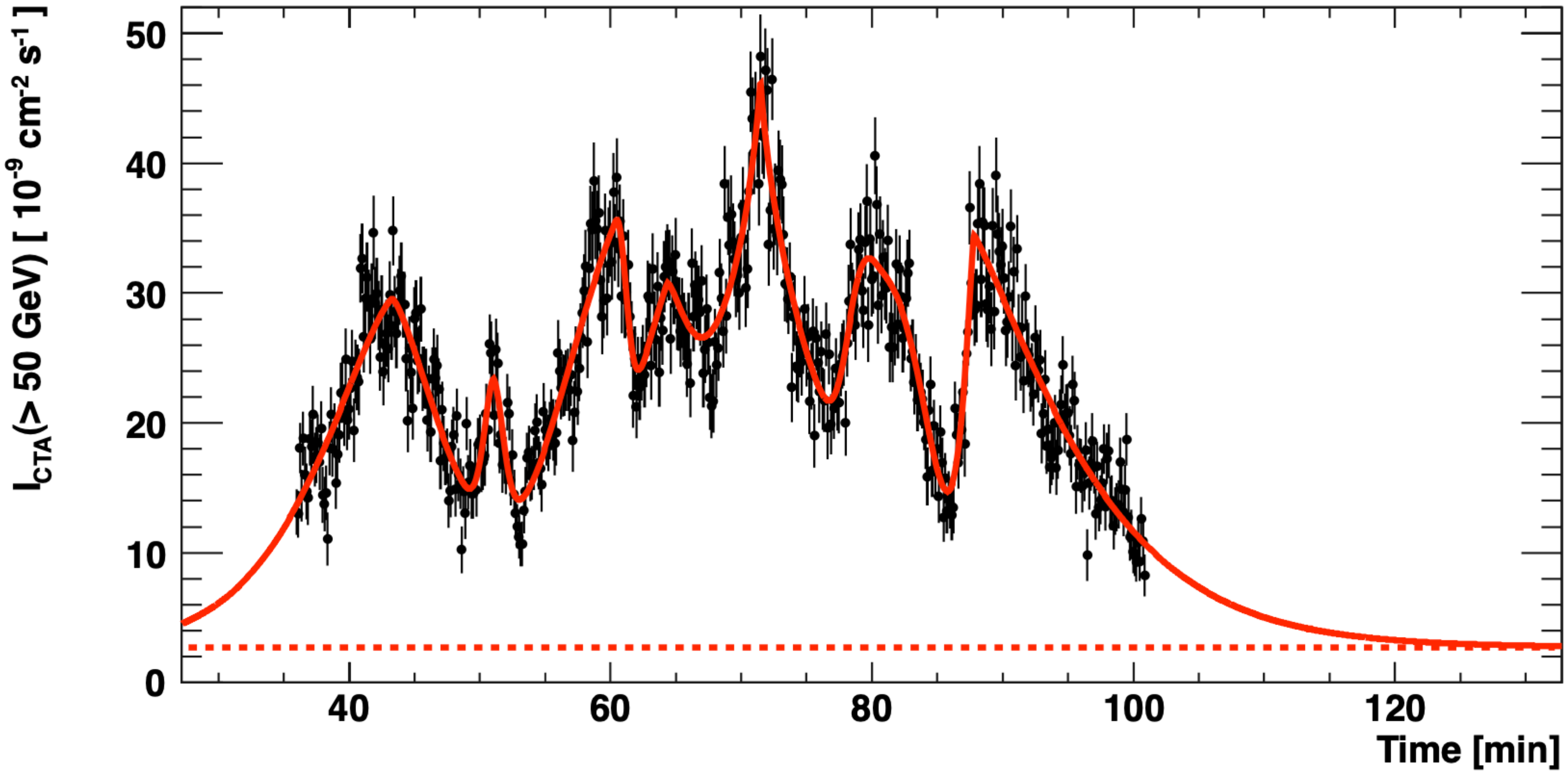
- CTA array has a 10 times better sensitivity than HESS, MAGIC, and VERITAS
- CTA covers wide energy range from 20GeV to 200TeV (4 orders of magnitude)

- 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

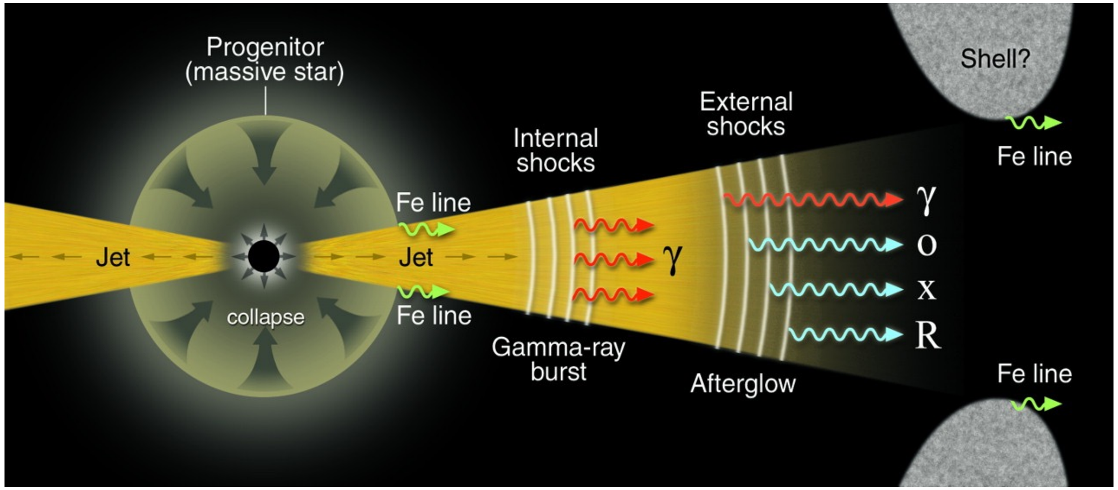
Simulated AGN Flares
Template: the 2006 flare of PKS2155-304
Low Threshold Energy → High Precision Light curve

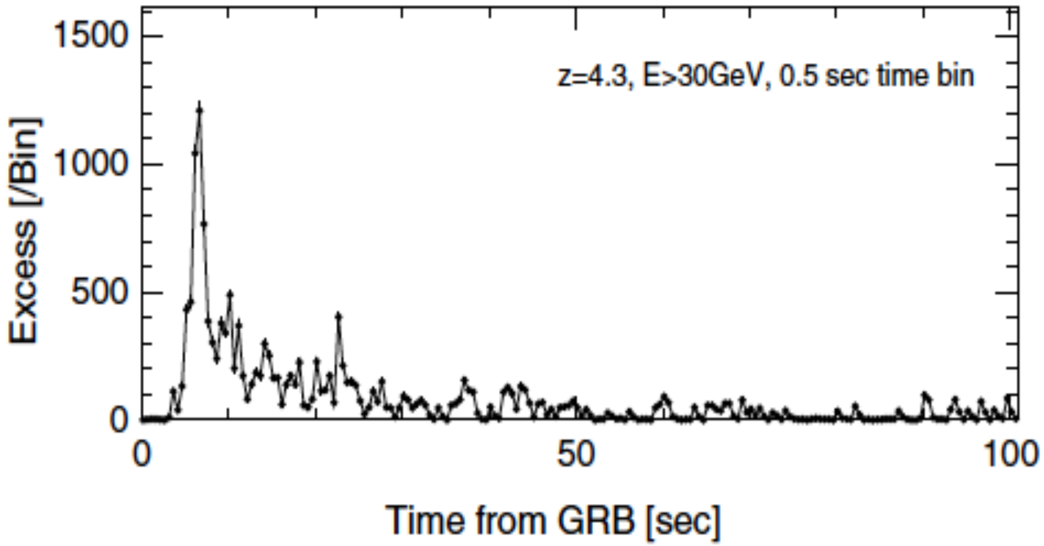


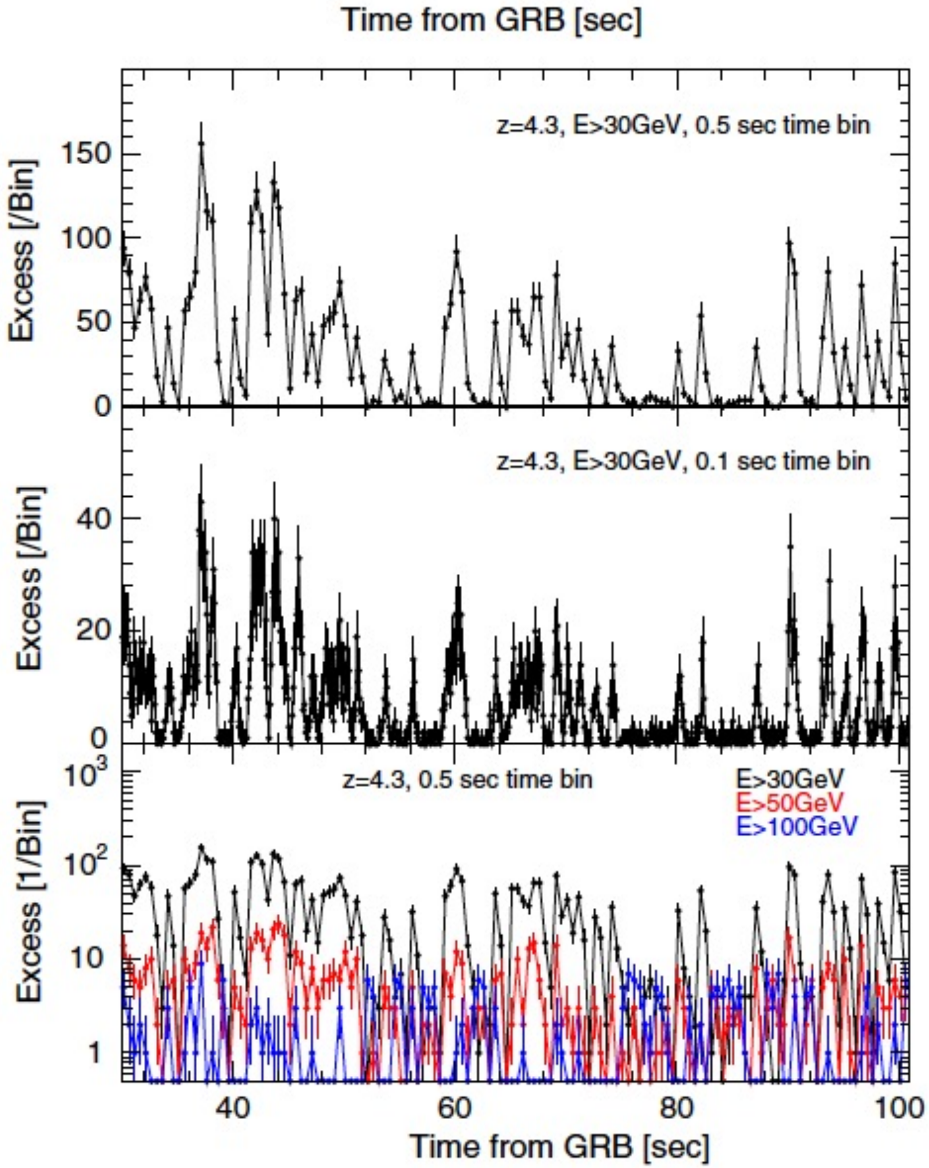
- Light curve can be examined, a few minutes scale structure → a few 10s of seconds
  - Particle acceleration mechanism, Cooling process
  - Light curve vs. Energy dependence → Q.G. Energy scale > Planck Mass scale

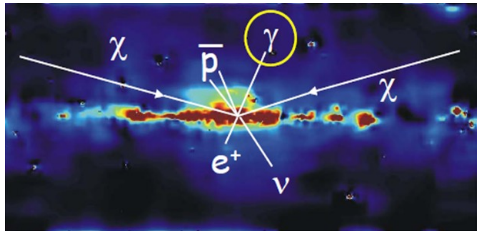
GRBs: Newly Born Black Holes

Simulated light curve (template: GRB080916C)

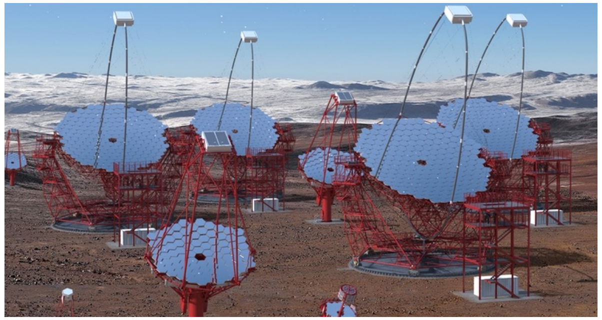


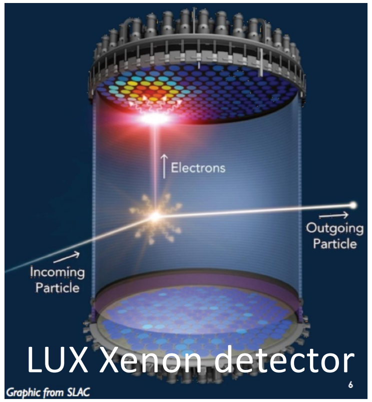


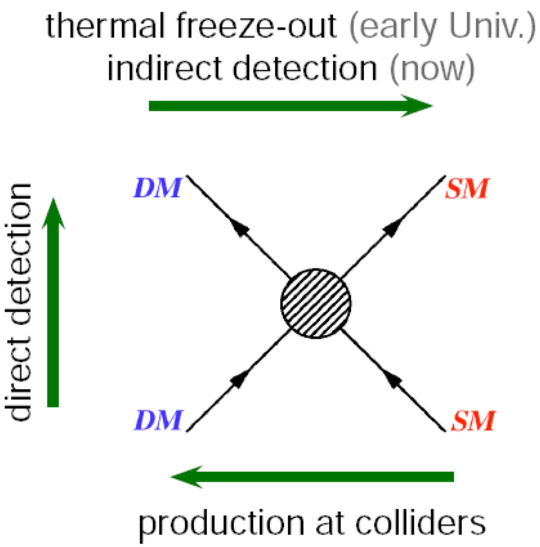


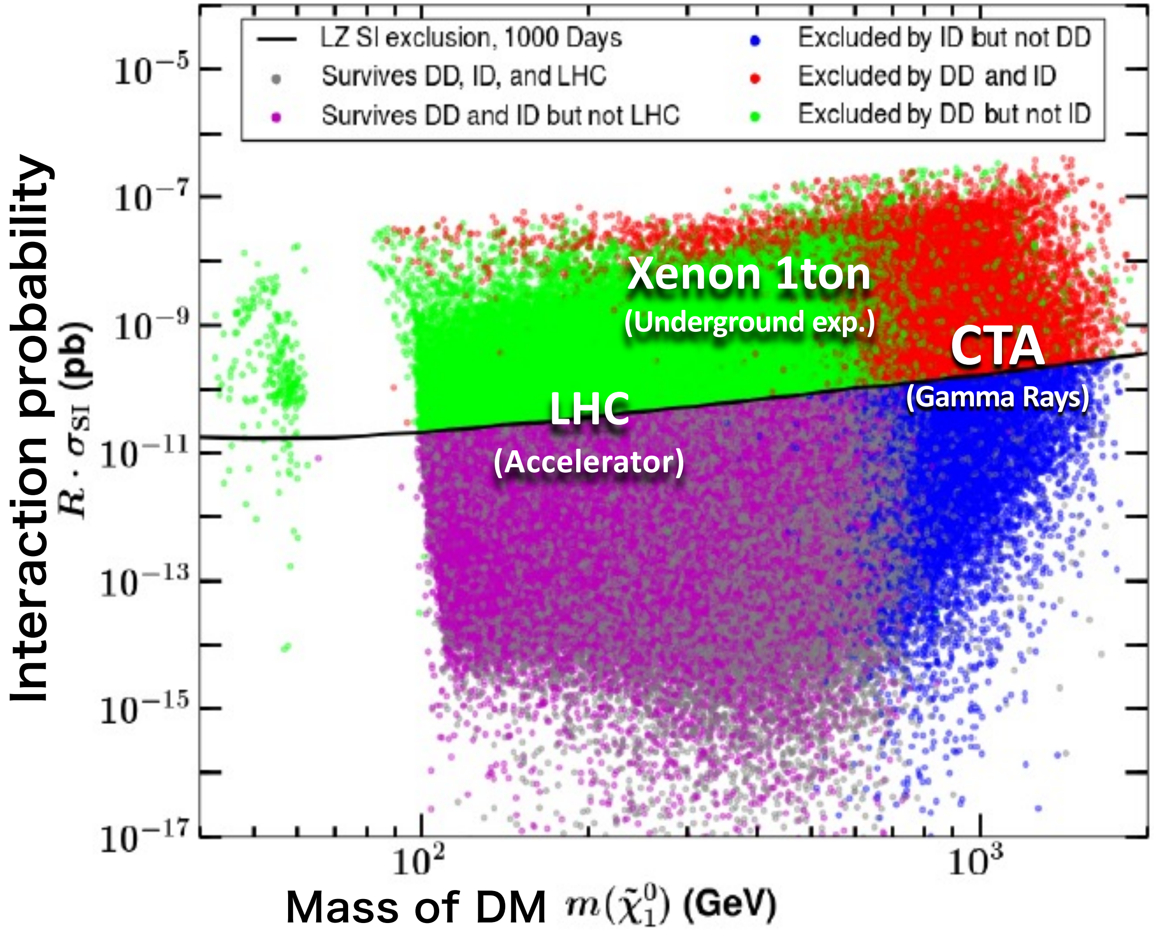


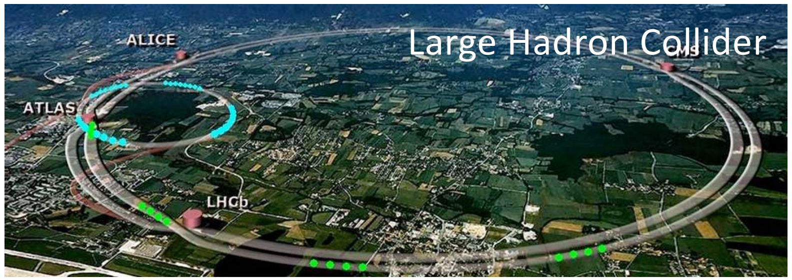
Complementarity of different approaches Direct, Indirect, and Collider Experiment



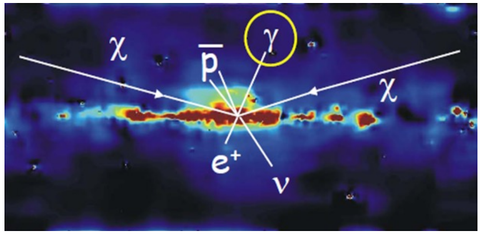






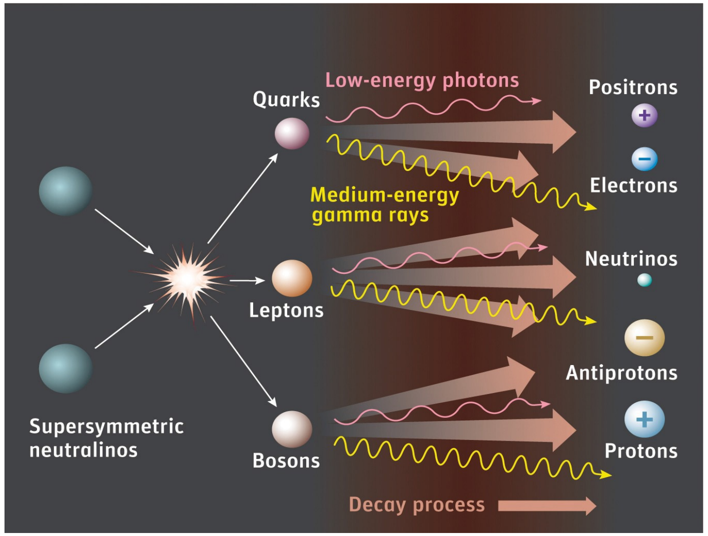


- Explore Dark Matter in the Galactic Center and Dwarf Sph. Galaxies
- CTA has the best sensitivity above 700GeV



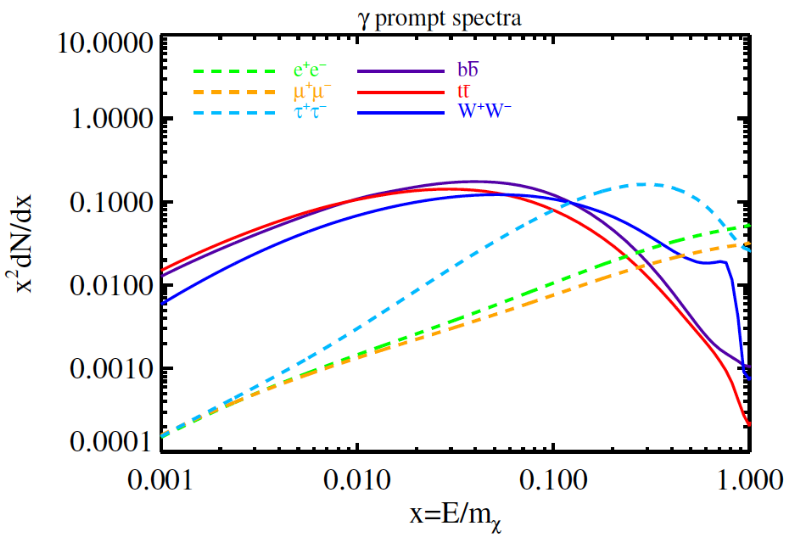
Dark Matter Search

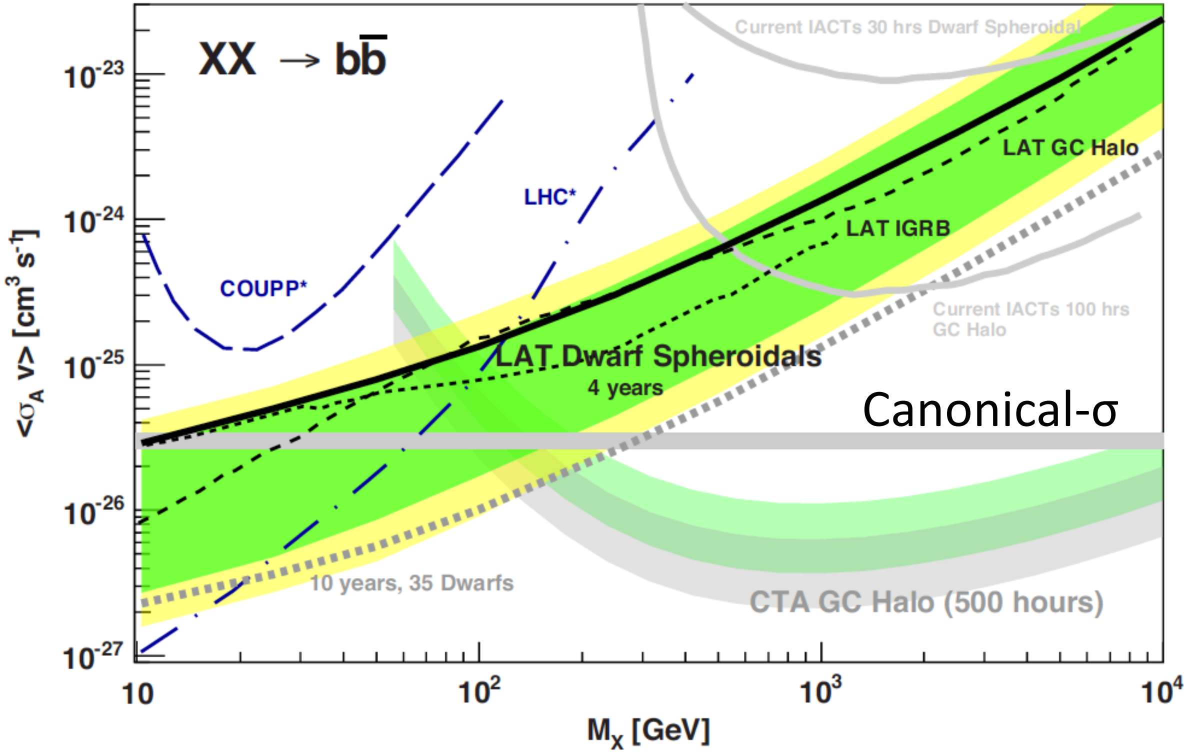
Sensitive M_χ: 200GeV - 10TeV



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

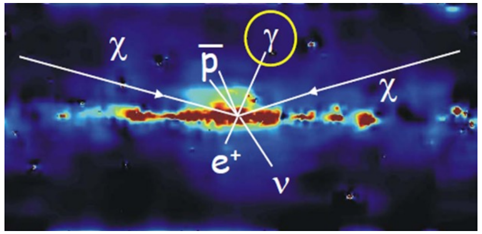
Particle Physics Astrophysics





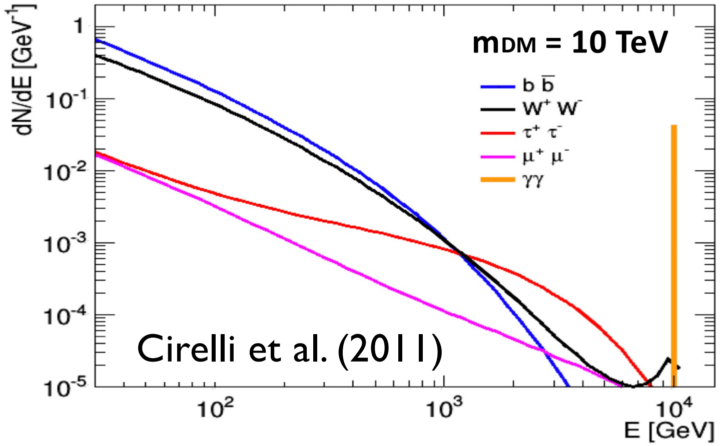
Gamma rays from Annihilation produce the bump around 1/10 -1/20 Mχ ➔ 20GeV-1TeV gamma

CTA gives the stringent upper limit.
Stefan Funk 2015

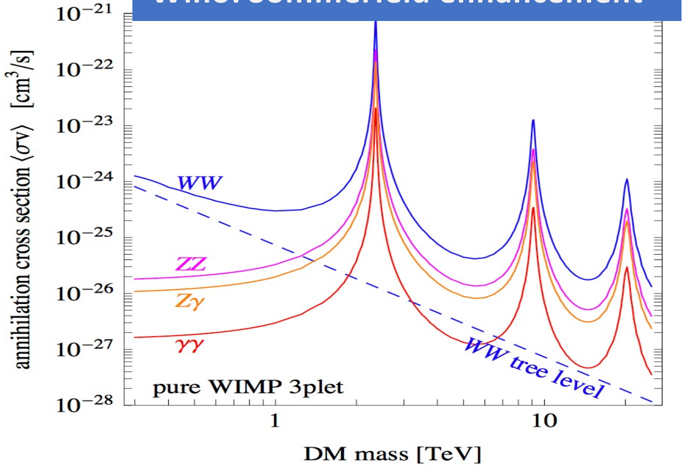


MAGIC Highlight：
Search for the Gamma-Ray Line Spectrum from DM annihilation (T. Inada, PRL, 2023)

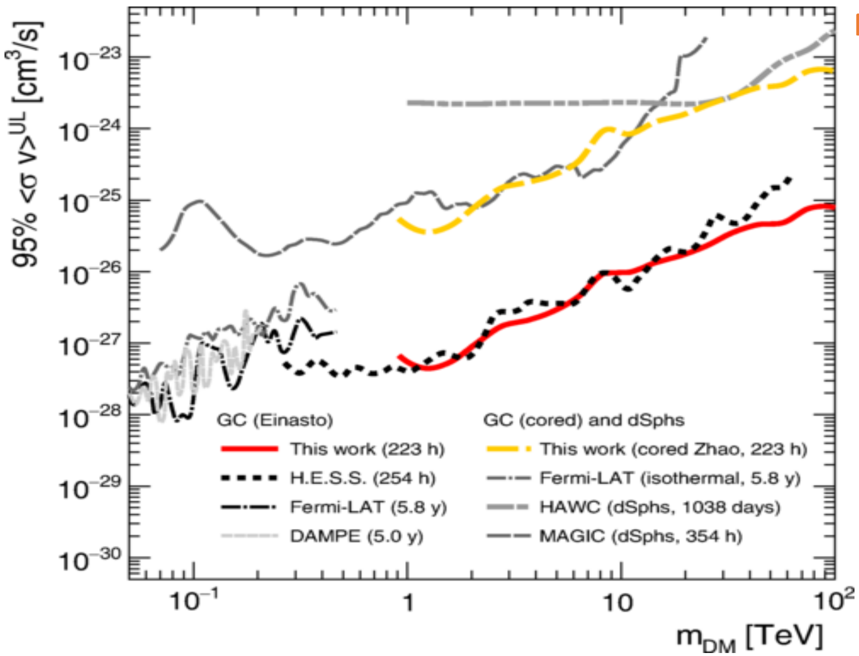
En. spectrum of Final State particles



Wino: Sommerfeld enhancement



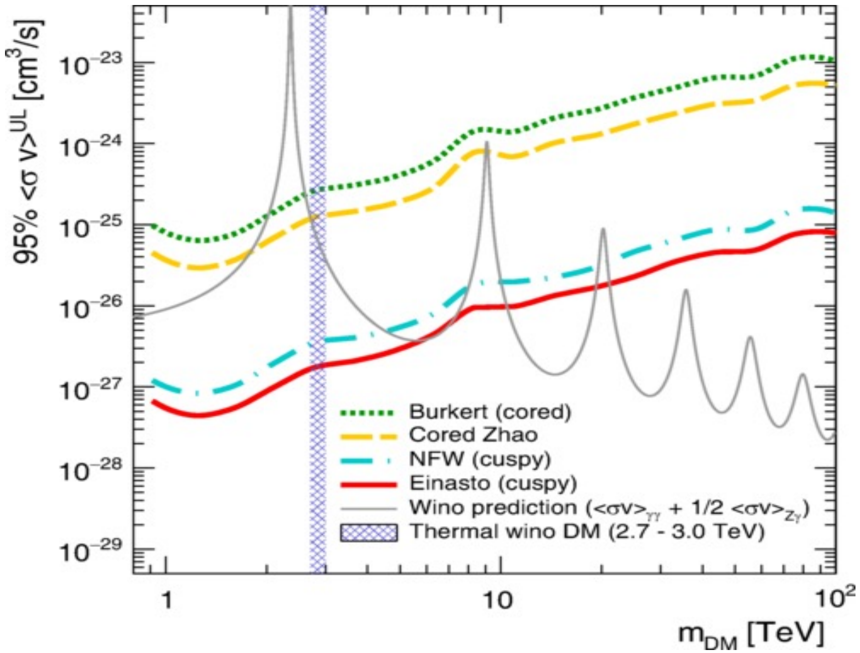
MAGIC Upper limit for Line gamma



MAGIC (Cored)

MAGIC (Cusp)

MAGIC Upper limit for Wino annihilation



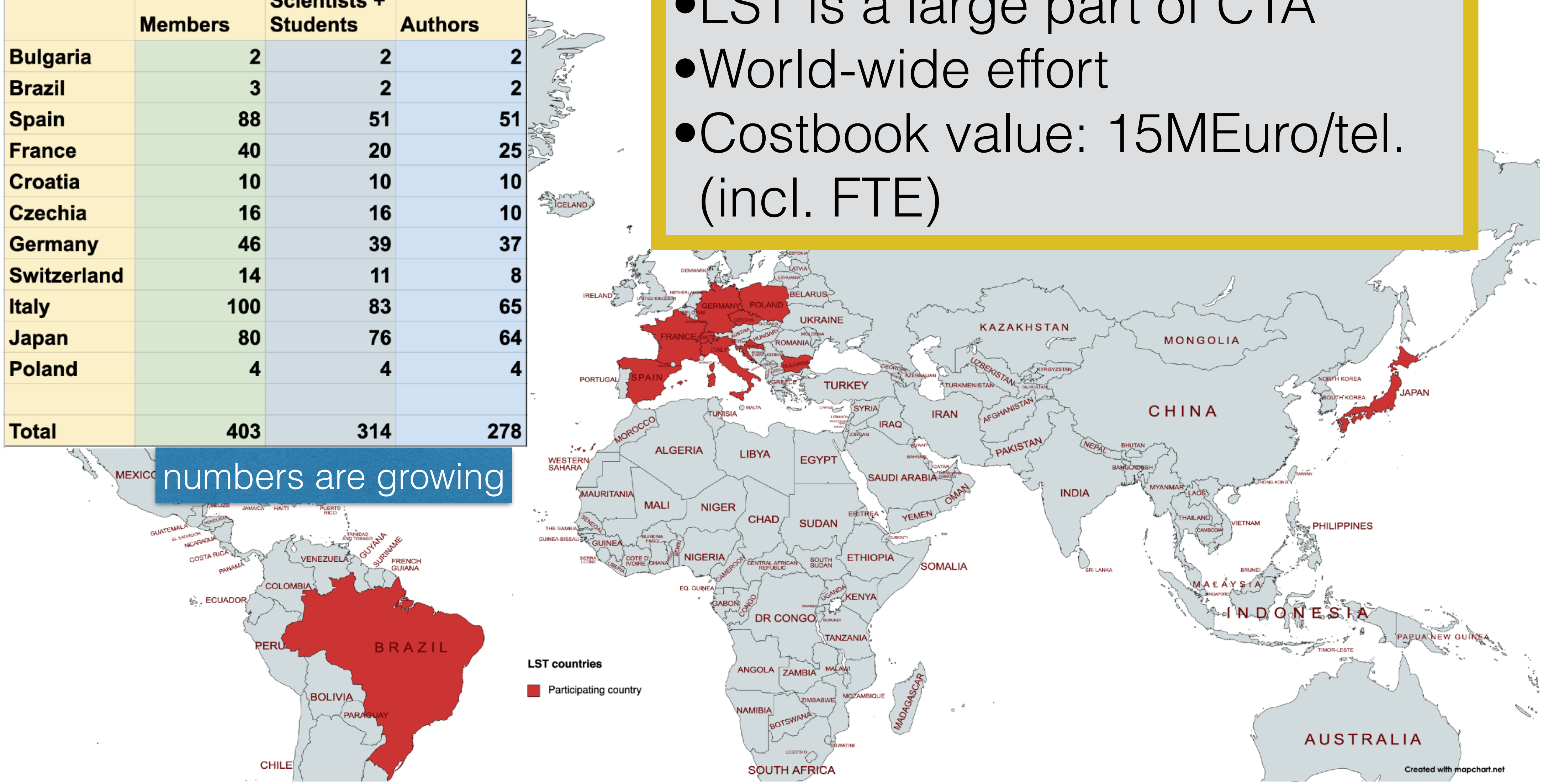
Commissioning of LST1 scientific observations

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

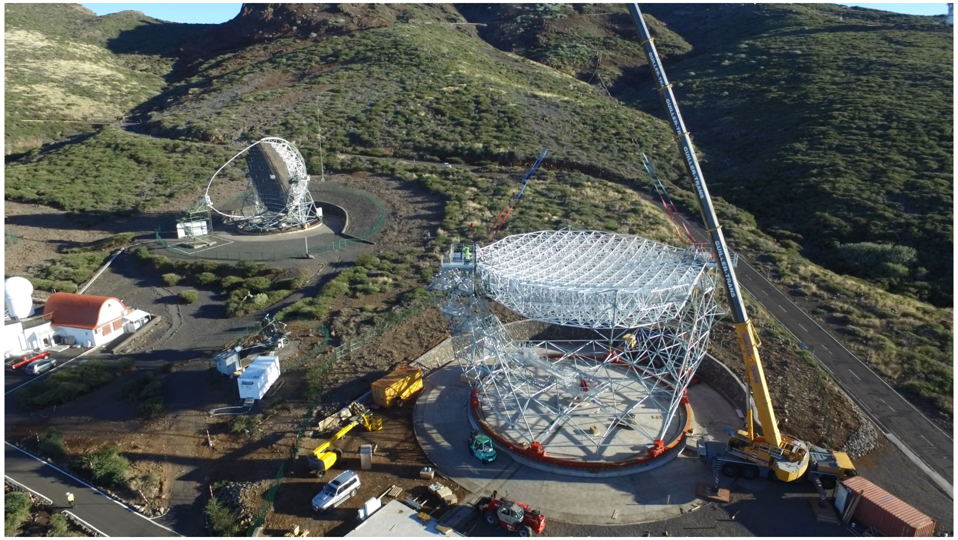
numbers are growing

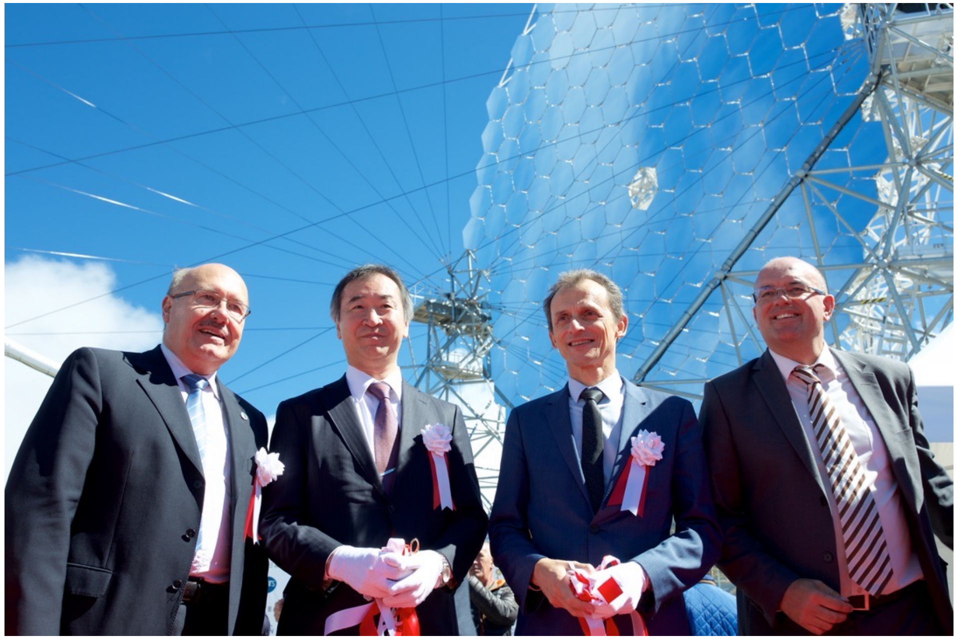
- LST is a large part of CTA
- World-wide effort
- Costbook value: 15MEuro/tel. (incl. FTE)



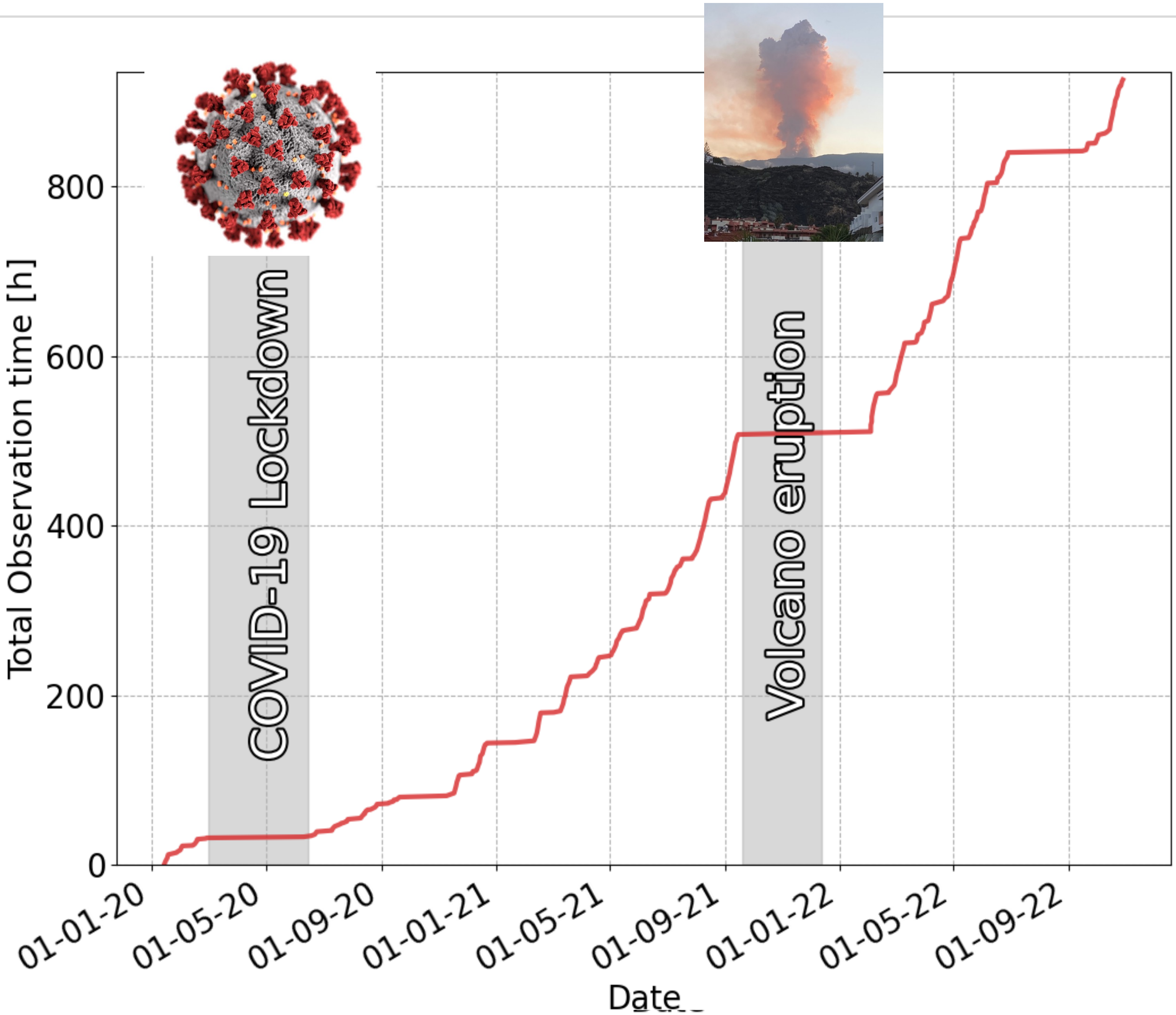
cta cherenkov telescope array

LST1 construction and Inauguration (Oct.2018)

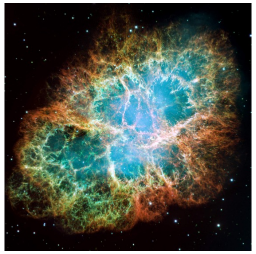


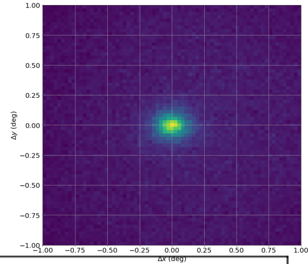


LST1 commissioning
500hrs of Scientific Observation



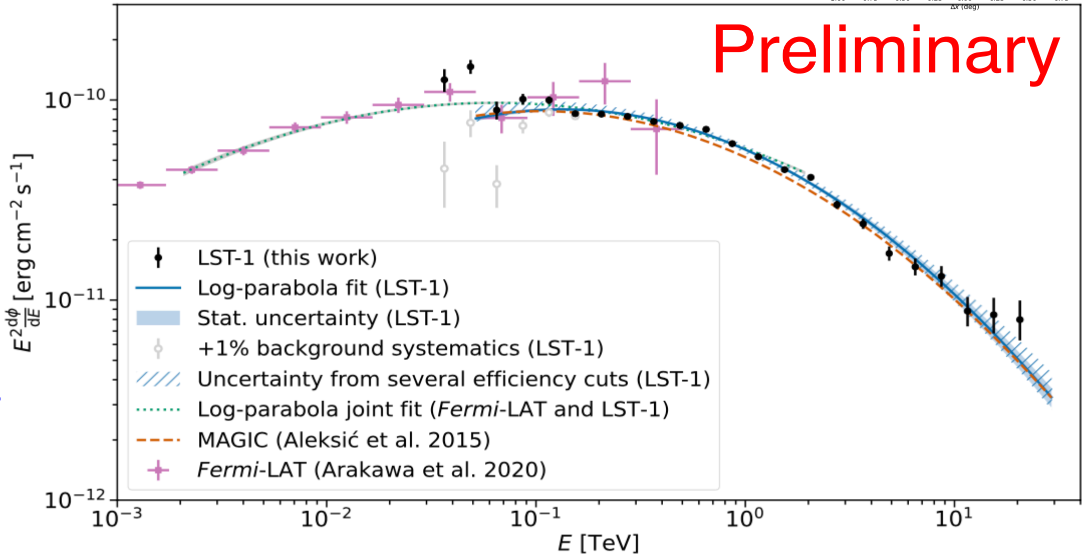
Crab Nebula and Pulsar





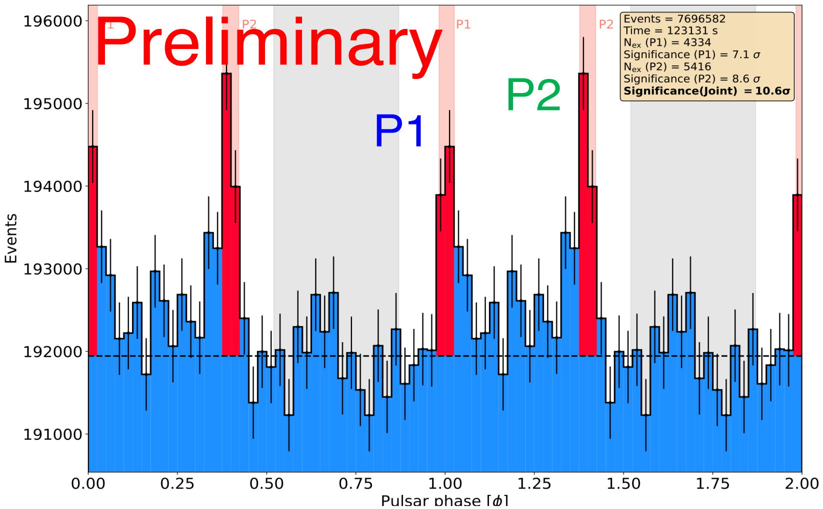
Crab Nebula spectrum

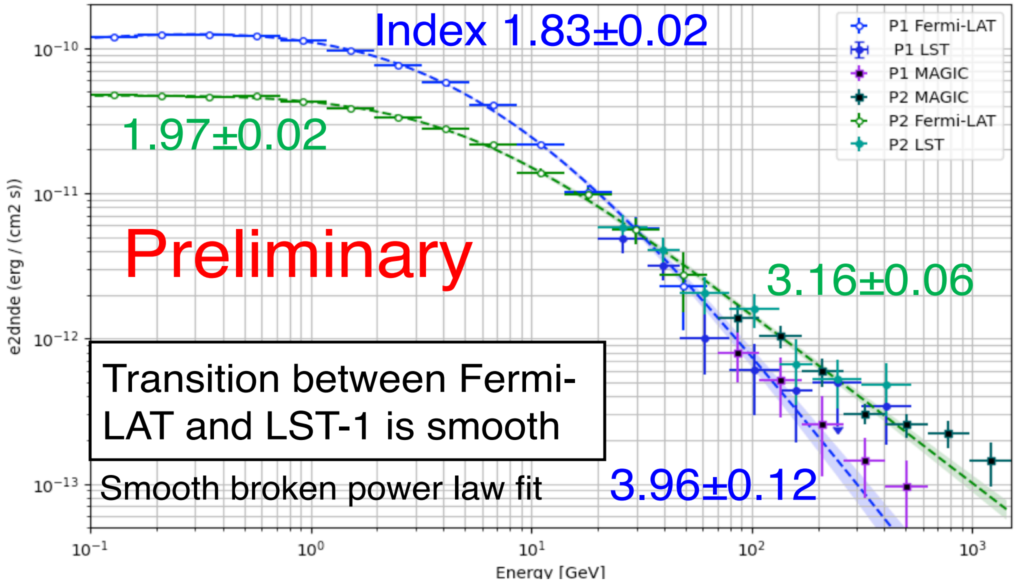
- 34.2 hours of data
- Systematic errors: gray points correspond to the effect of +1% background
- Consistent with MAGIC and Fermi-LAT



Crab pulsar

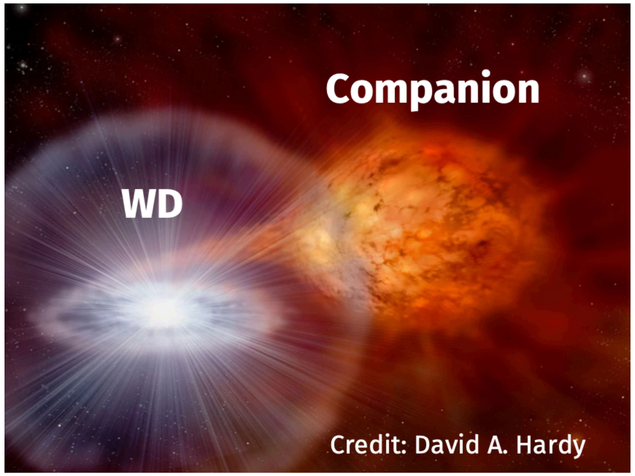
- Significant detection down to few tens of GeV
- Data from Nov 2020 - Mar 2022

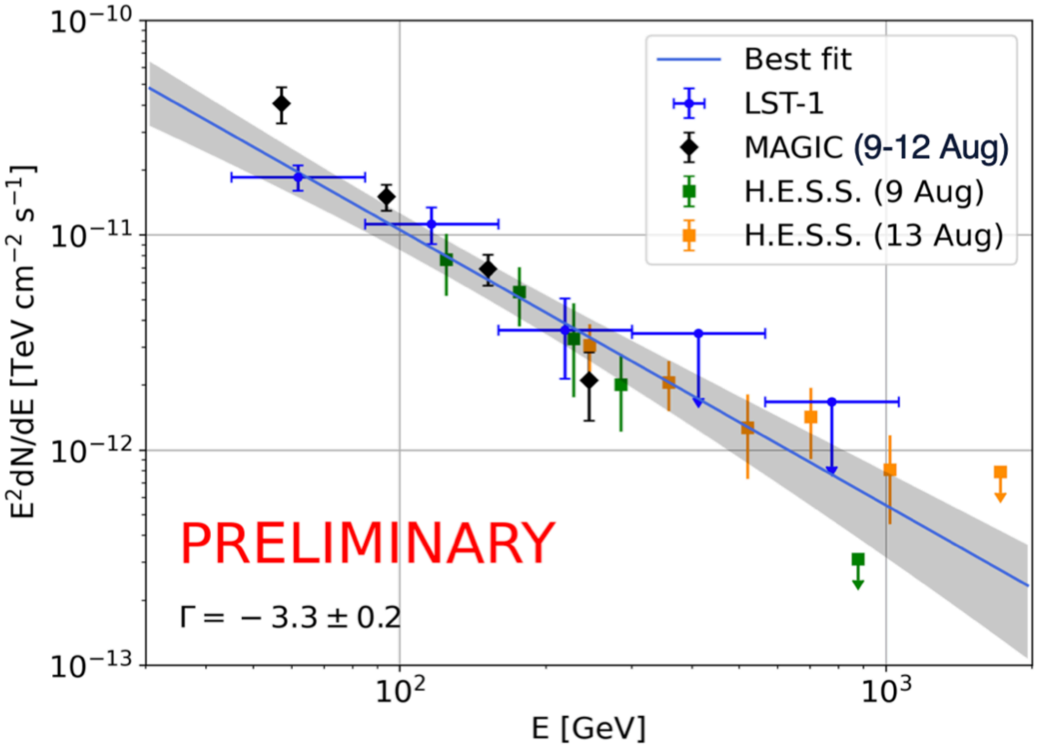


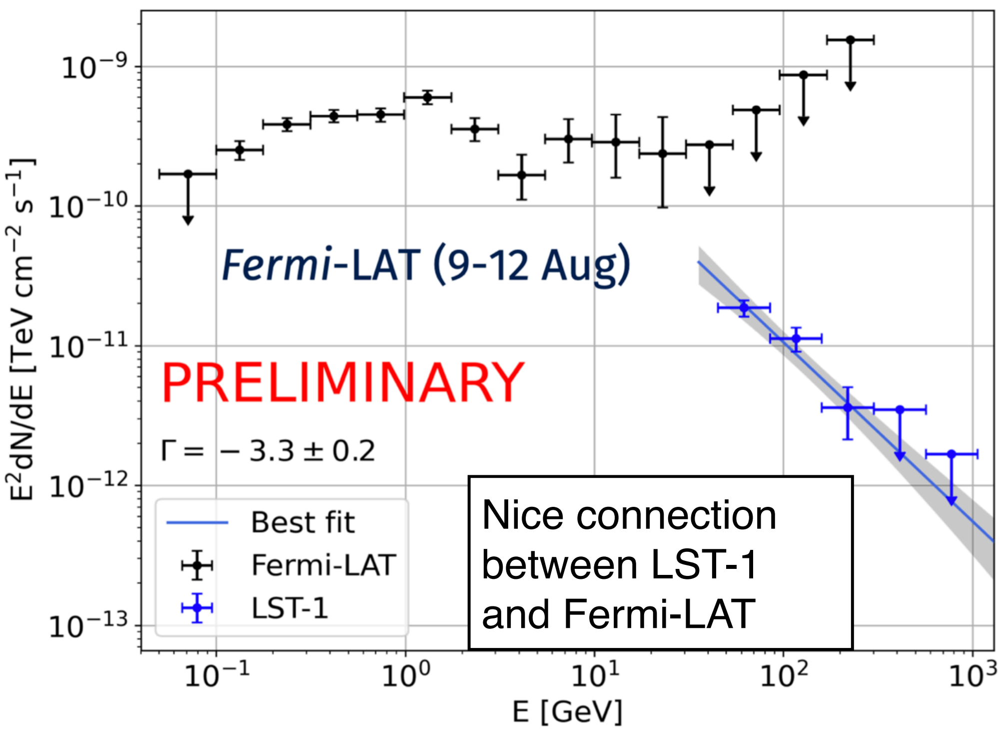


Detection of Nova RS Ophiuchi

- 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 >~6σ in each night
- Consistent SEDs between LST-1, MAGIC, H.E.S.S.

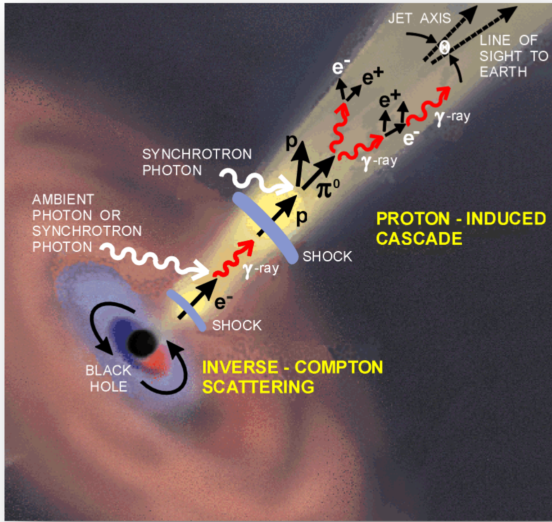




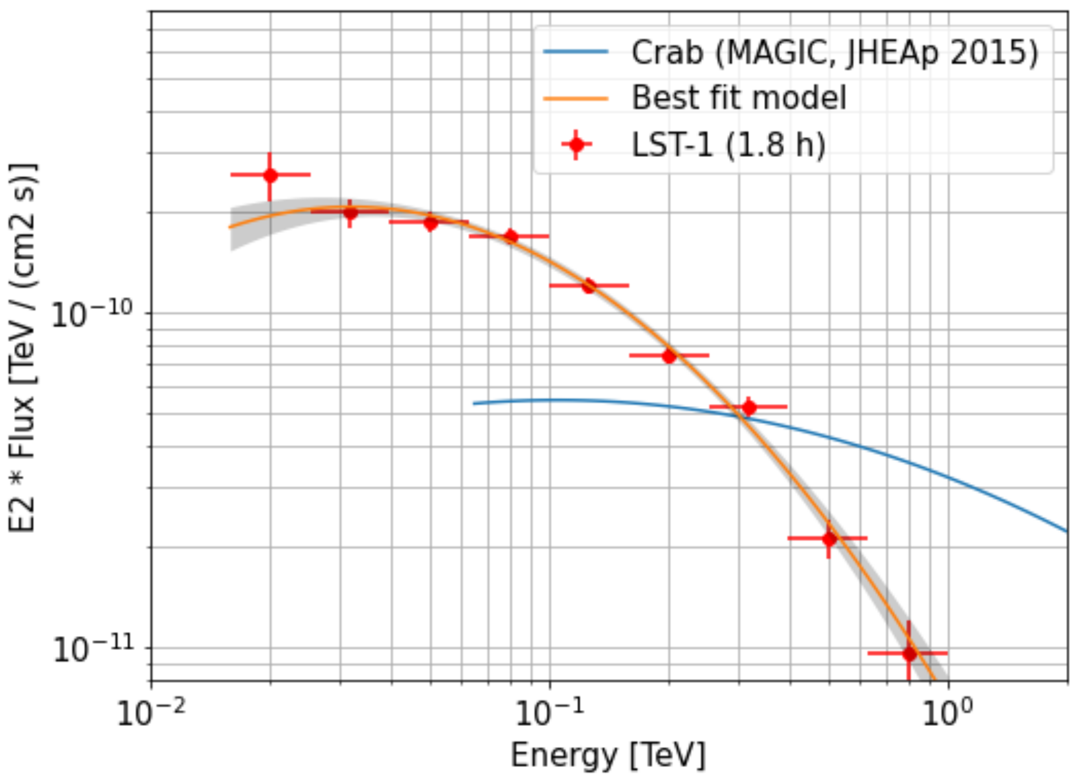


BL Lac Flare observed with LST1 by Dr. Seiya Nozaki

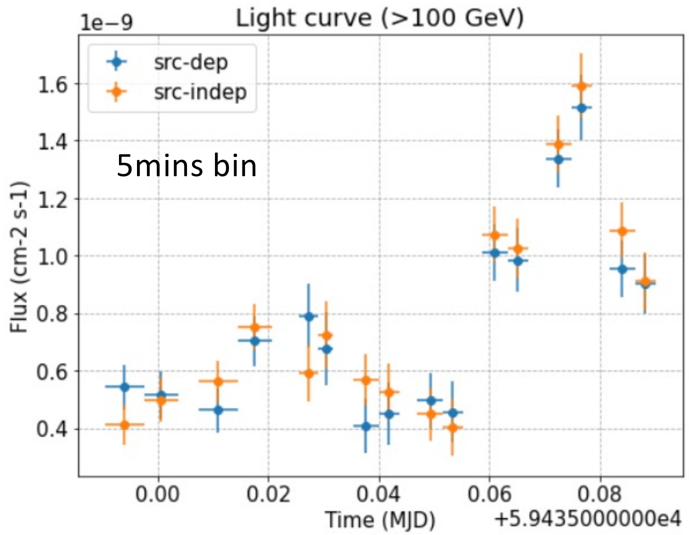
Big flare is observed in the night of 8 August 2022



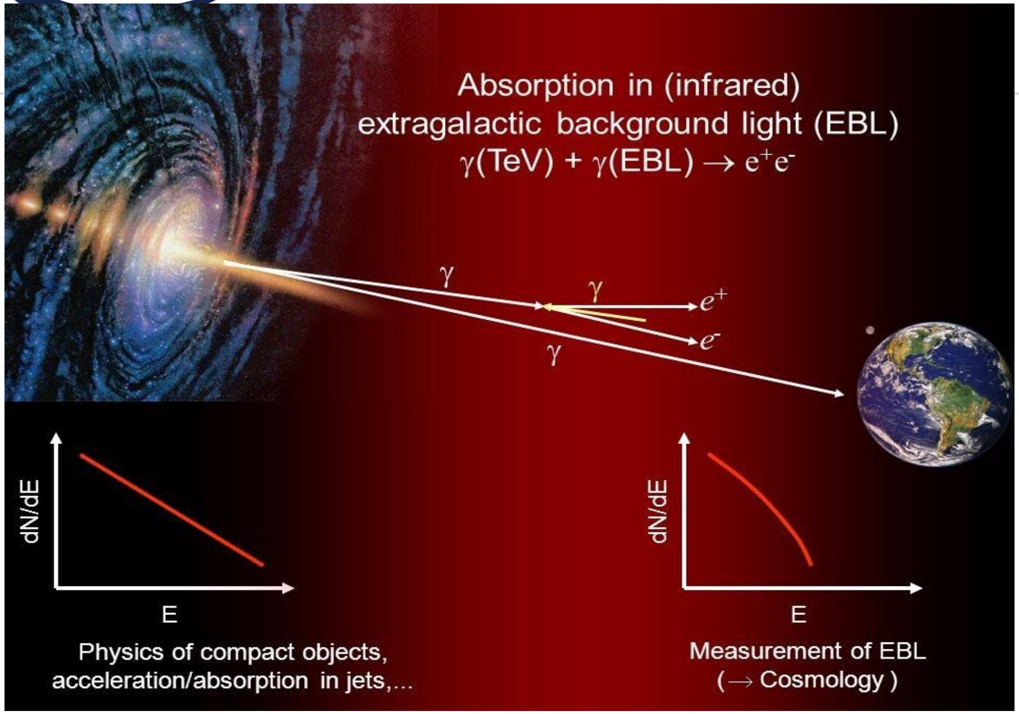
SED measured down to 20GeV

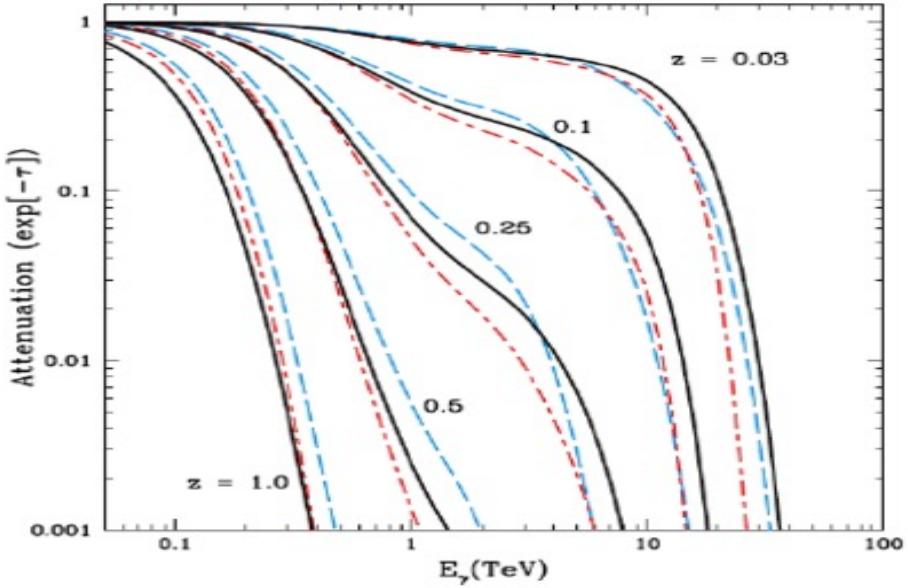


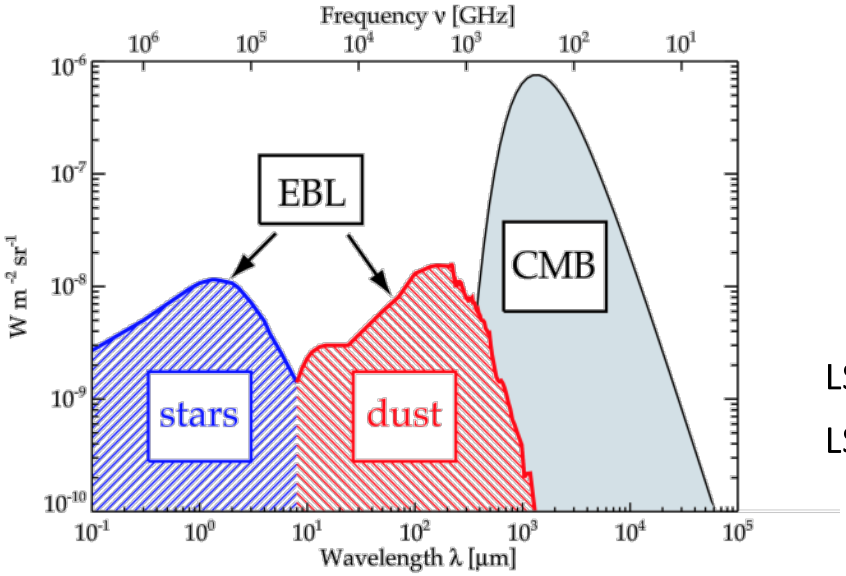
Intranight Variability

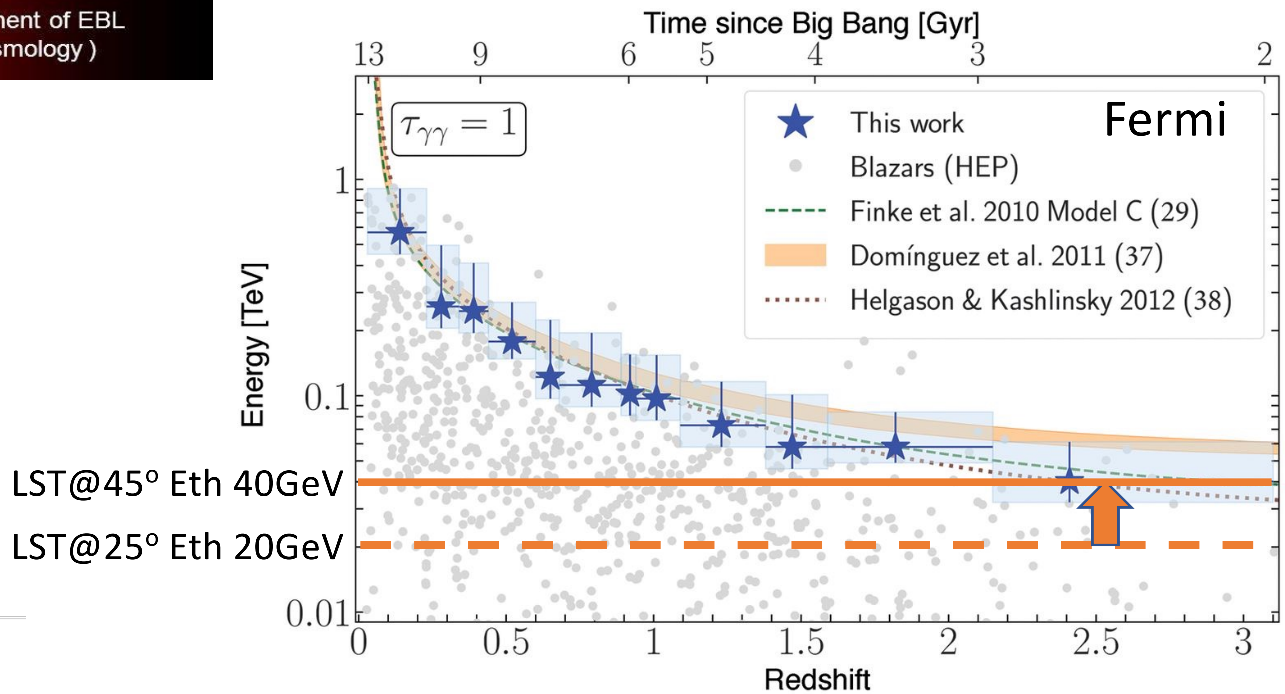


Gamma Ray Horizon
20GeV Low Threshold Energy → z~4





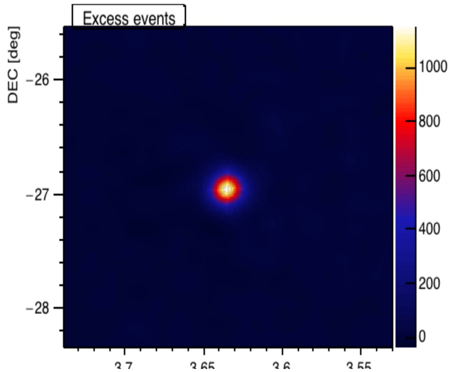


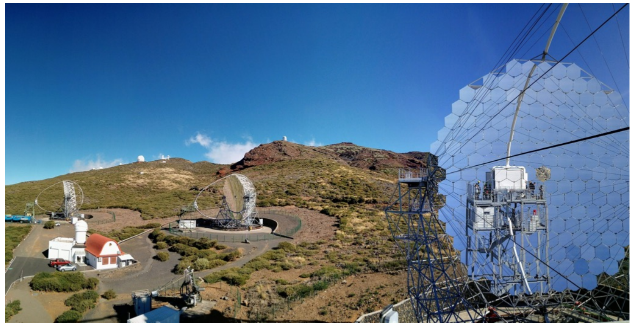


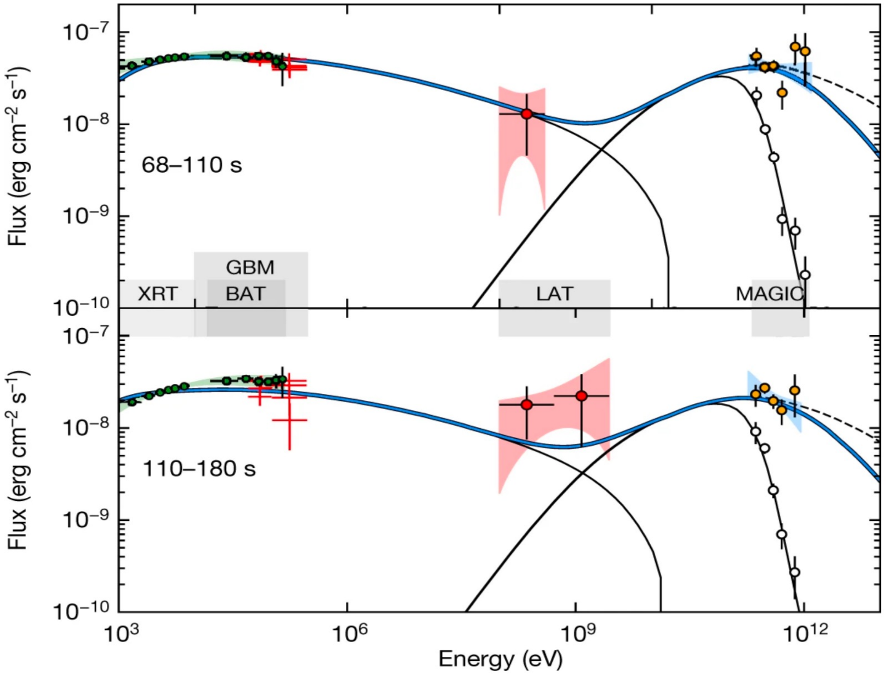
MAGIC Highlight,
Gamma Ray Burst GRB190114C (z=0.42)

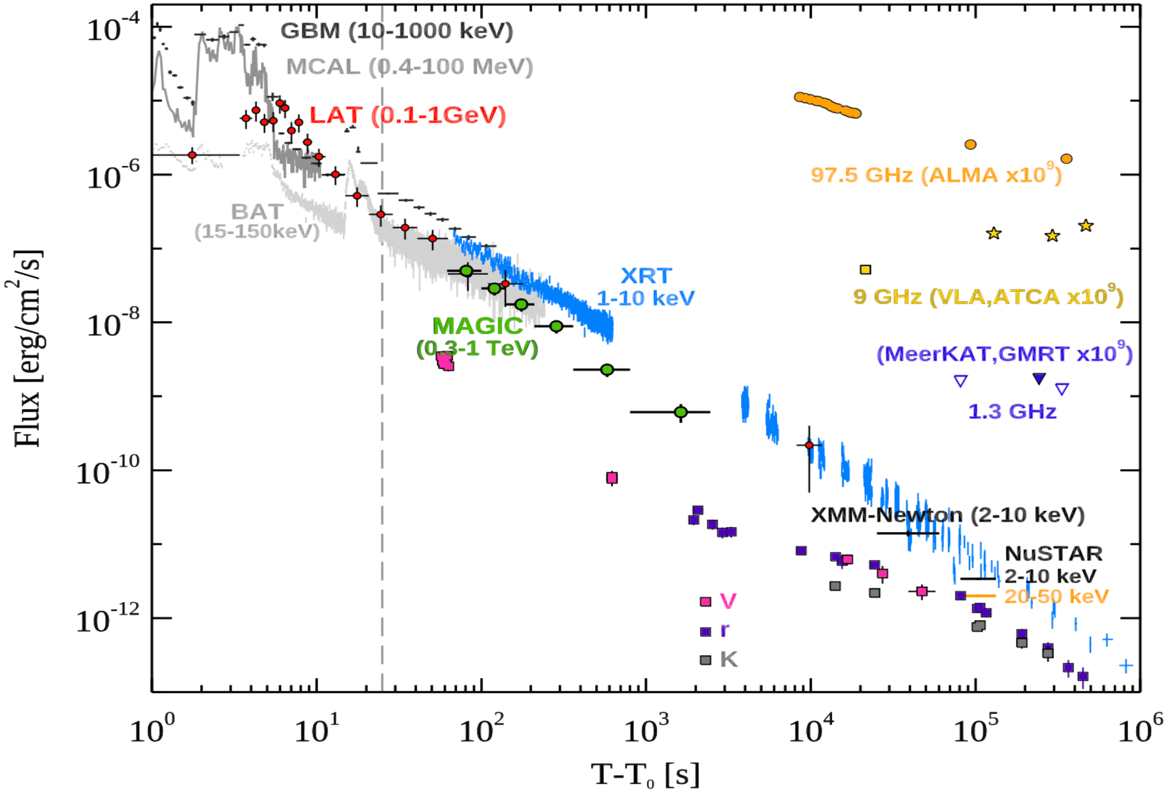
Historical achievement

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



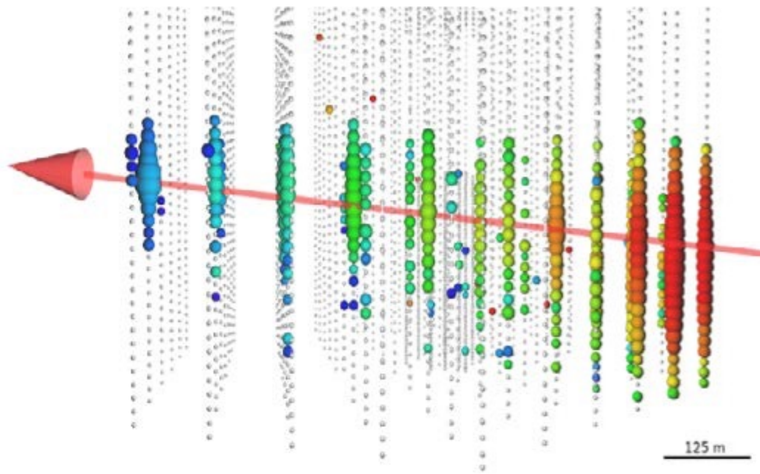




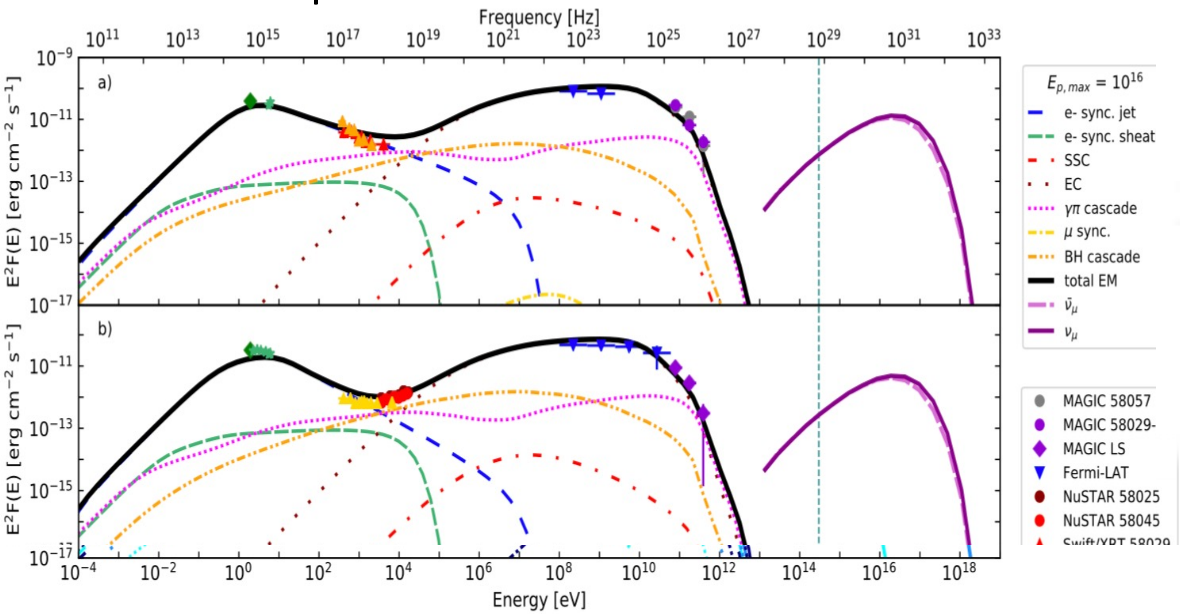


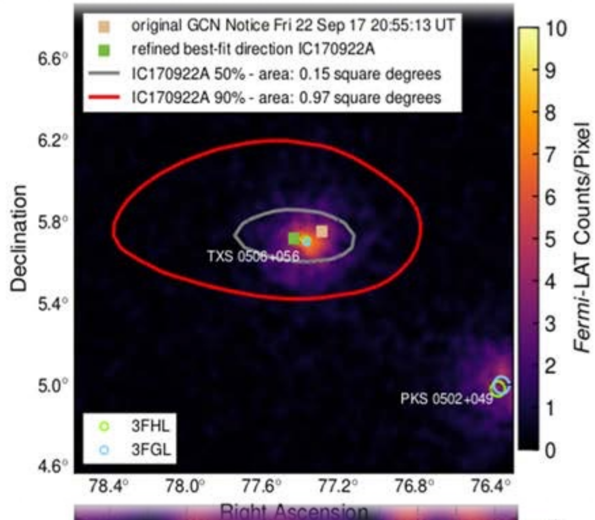
Multi Messenger Astronomy IC170922A / TXS 0506+056

Ice Cube Observation (~300TeV)

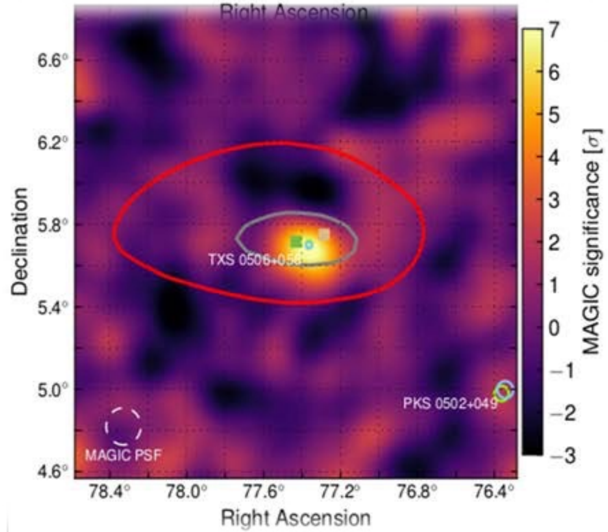


Lepto-Hadronic Scenario





Fermi LAT (>100 MeV)



MAGIC (>100GeV)

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

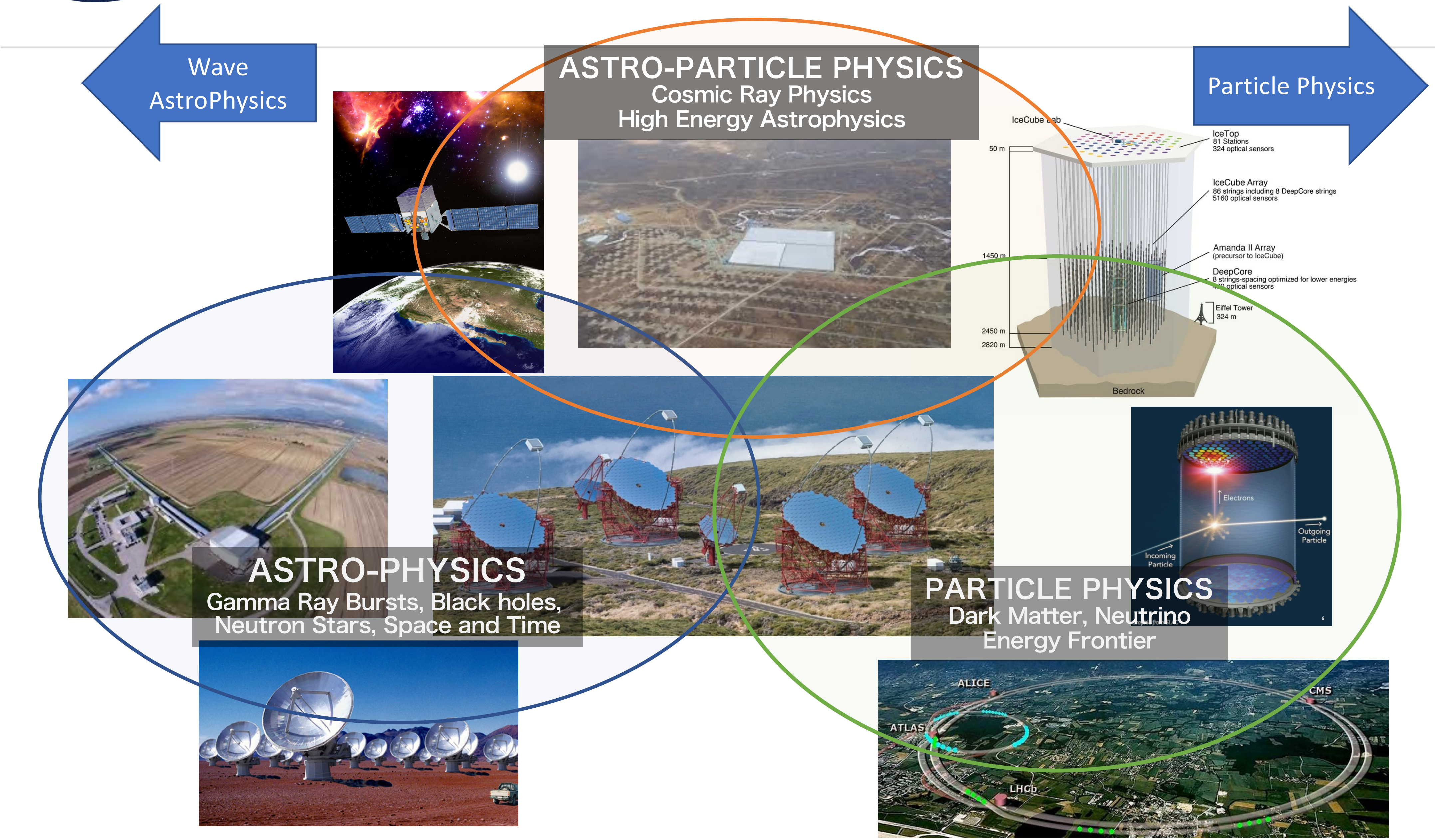
CTA and LST Timeline

- 2016-2018 LST1 was constructed
- 2018-2021 LST1 in commissioning phase
- 2022-2024 LST2-4 will be constructed, and we need to take care operation and maintenance of LSTs
  LST1 can be defined in Science-Engineering Phase after commissioning
- 2022 CTAO ERIC will be founded
- 2026-2027 The final Acceptance of LST1-LST4 and IKC process
- 2023-2025 LST5-8 construction?

<table>
<tr><th></th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td rowspan="2">Organization</td><td colspan="3">CTAO gGmbH (Heidelberg)</td><td colspan="8"></td></tr>
<tr><td colspan="2"></td><td colspan="9">CTAO ERIC (European Research Infrastructure Consortium)</td></tr>
<tr><td colspan="12"></td></tr>
<tr><td>Alpha Config</td><td>2020</td><td>2021</td><td>2022</td><td>2023</td><td>2024</td><td>2025</td><td>2026</td><td>2027</td><td>2028</td><td>2029</td><td>2030</td></tr>
<tr><td rowspan="2">LST North</td><td colspan="5">Comissioning and Operation of LST1</td><td colspan="4" rowspan="2">Operation as 4 LST Array</td><td colspan="2" rowspan="5">Observatory Operation</td></tr>
<tr><td colspan="2">CDR</td><td colspan="3">Deployment of LST2-4</td></tr>
<tr><td>MST North</td><td colspan="2">Design and Finance</td><td>INFRA</td><td colspan="6">Construction of 9MSTs</td></tr>
<tr><td rowspan="2">CTA South</td><td colspan="2" rowspan="2">Array config, Finance and CDR</td><td colspan="2" rowspan="2">INFRA</td><td colspan="5">Construction and Deplyment of 14 MSTs</td></tr>
<tr><td colspan="5">Construction and Deployment of 37 SSTs</td></tr>
<tr><td colspan="12"></td></tr>
<tr><td>Extension</td><td>2020</td><td>2021</td><td>2022</td><td>2023</td><td>2024</td><td>2025</td><td>2026</td><td>2027</td><td>2028</td><td>2029</td><td>2030</td></tr>
<tr><td>LST South</td><td></td><td colspan="2">Finance / CDR</td><td colspan="3">Construction of 4 LSTs ???</td><td colspan="5">Operation ???</td></tr>
</table>

LST2-4 status

Multi-messenger and Multi-wavelength Astrophysics



Summary

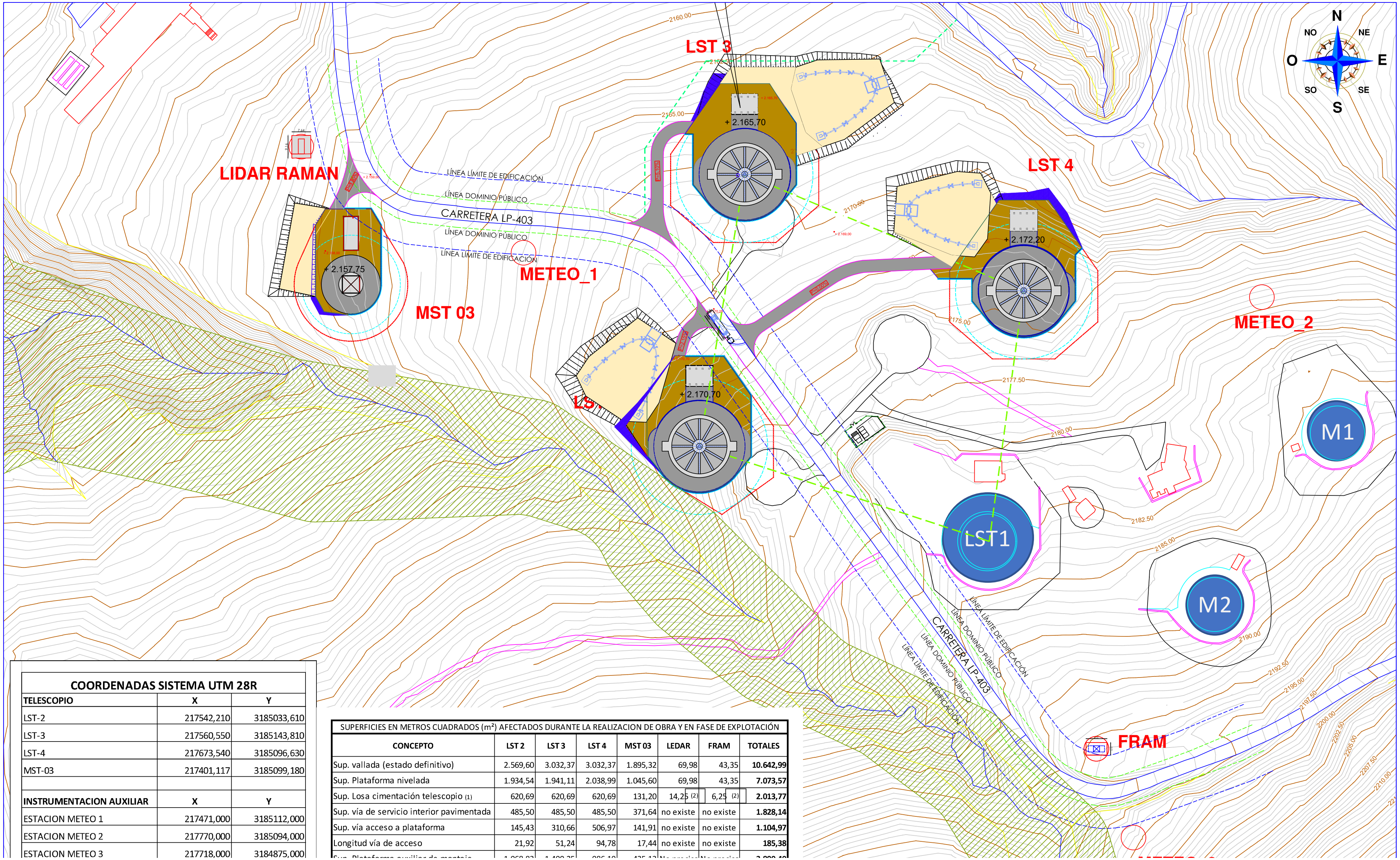
- CTA is an extensive and ambitious project
- LSTs will play an essential role in Multi-Messenger astronomy in the following decades.
- LST2-4 construction started in the winter of 2022
- CTA South (SSTs, MSTs, and LST5-6) construction will begin in 2024

- CTA and current IACT will study
  - Cosmic Ray Origin, SNRs, PWNe, AGNs, and GRBs
  - Evolution of Black Holes and Extreme environment around Black Holes and neutron stars
  - Explore the Dark Matter in the Galactic Center and halo.

cta cherenkov telescope array

Thank you very much

CTA North Phase I Installation Plan
LST1-4 location



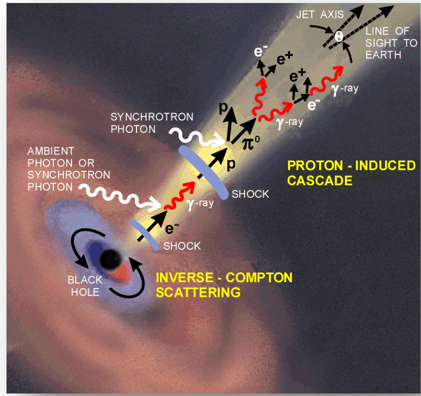
COORDENADAS SISTEMA UTM 28R		
TELESCOPIO	**X**	**Y**
LST-2	217542,210	3185033,610
LST-3	217560,550	3185143,810
LST-4	217673,540	3185096,630
MST-03	217401,117	3185099,180
INSTRUMENTACION AUXILIAR	**X**	**Y**
ESTACION METEO 1	217471,000	3185112,000
ESTACION METEO 2	217770,000	3185094,000
ESTACION METEO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

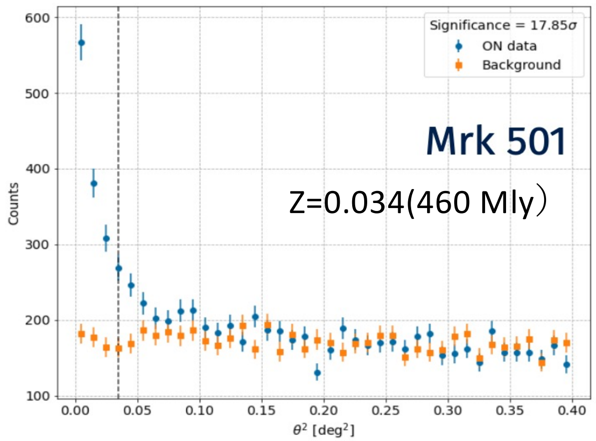
SUPERFICIES EN METROS CUADRADOS (m^2) AFECTADOS DURANTE LA REALIZACION DE OBRA Y EN FASE DE EXPLOTACIÓN

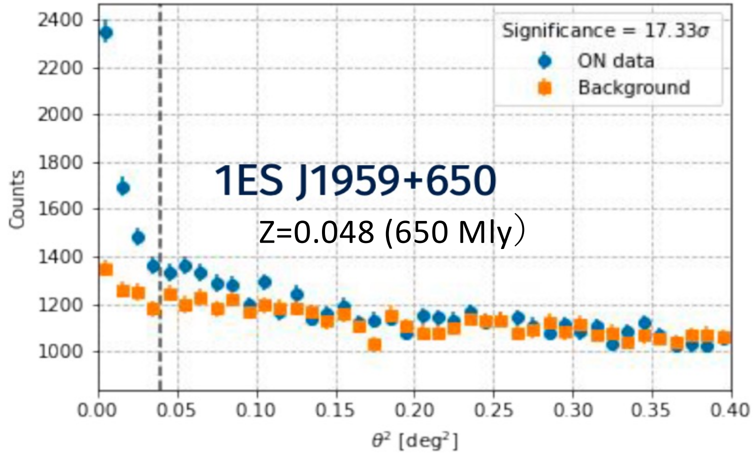
CONCEPTO	LST 2	LST 3	LST 4	MST 03	LEDAR	FRAM	TOTALES
Sup. vallada (estado definitivo)	2.569,60	3.032,37	3.032,37	1.895,32	69,98	43,35	**10.642,99**
Sup. Plataforma nivelada	1.934,54	1.941,11	2.038,99	1.045,60	69,98	43,35	**7.073,57**
Sup. Losa cimentación telescopio (1)	620,69	620,69	620,69	131,20	14,25 (2)	6,25 (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**

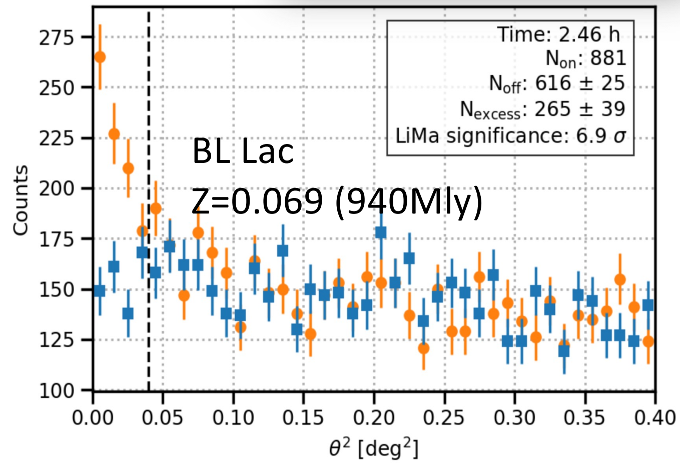
AGN observation with LST1 during 2020-2021Q1

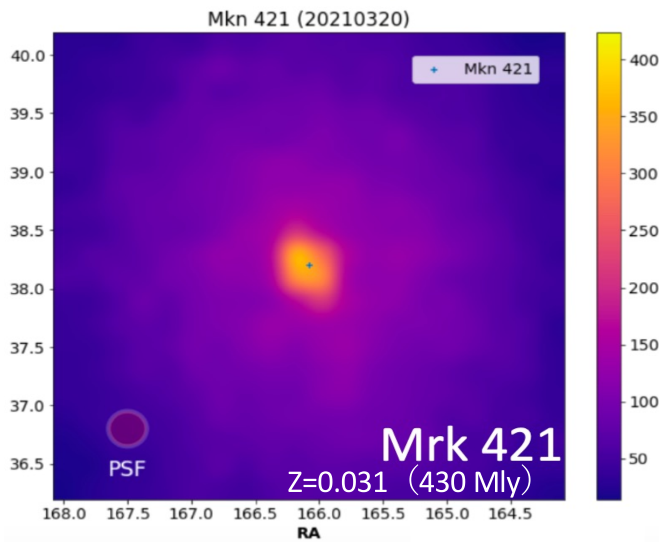
- ❑ Nearby AGNs, Mrk501, Mrk421, 1ES 1959+650, BL Lac
- ❑ Distant AGNs, 1ES0647+250, PG1553+113

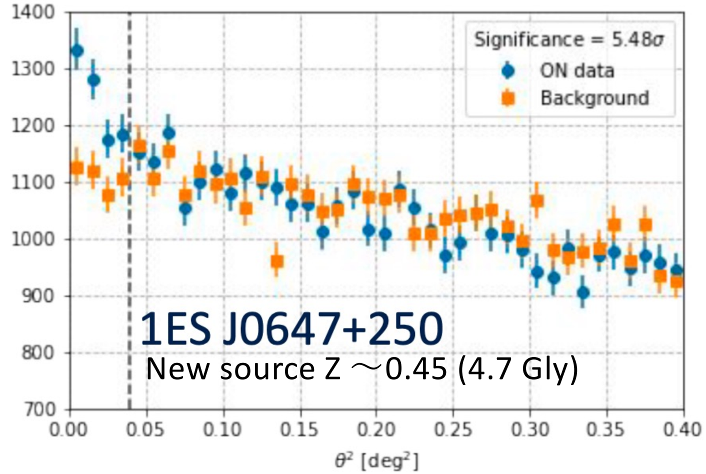


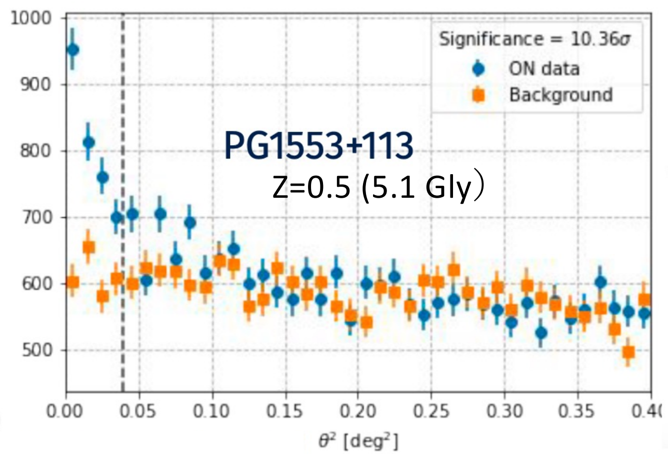


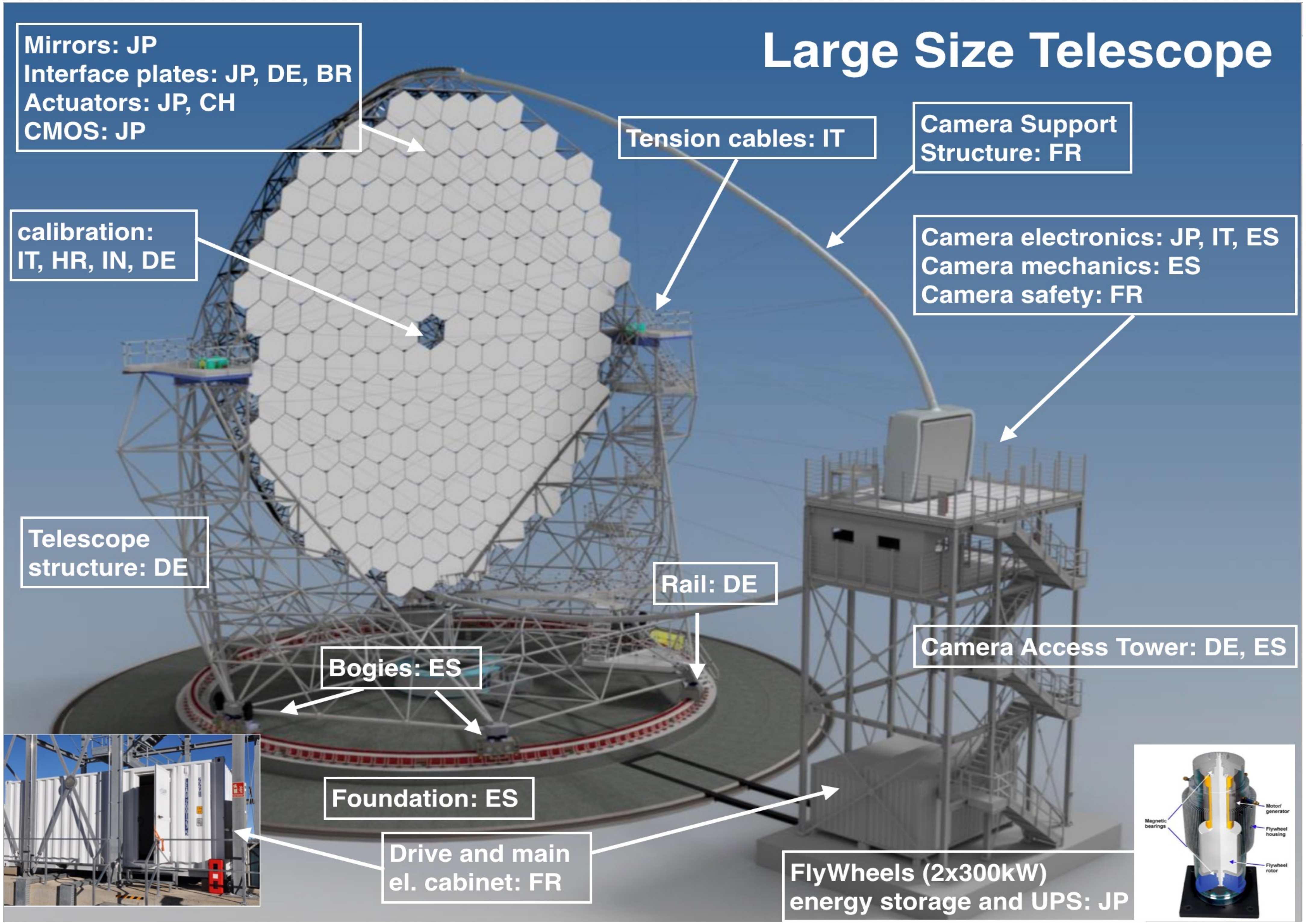




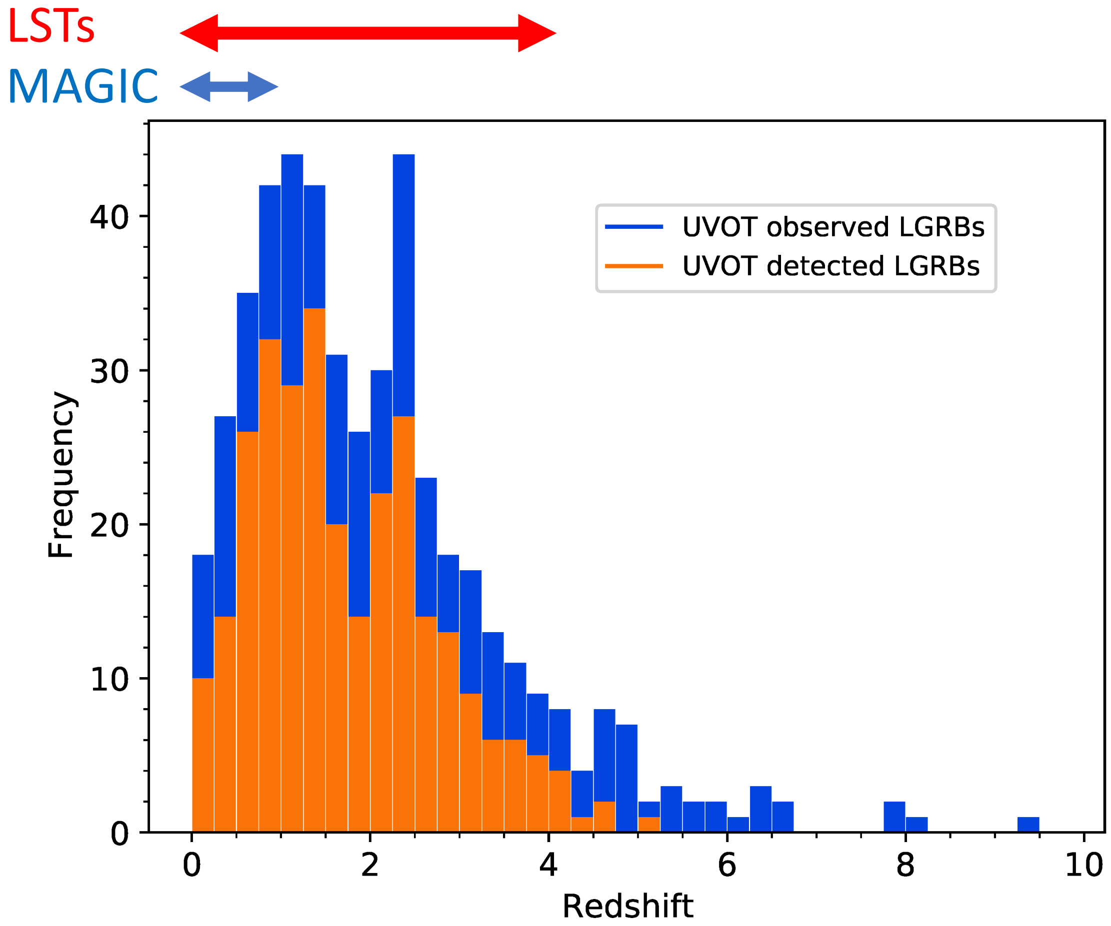




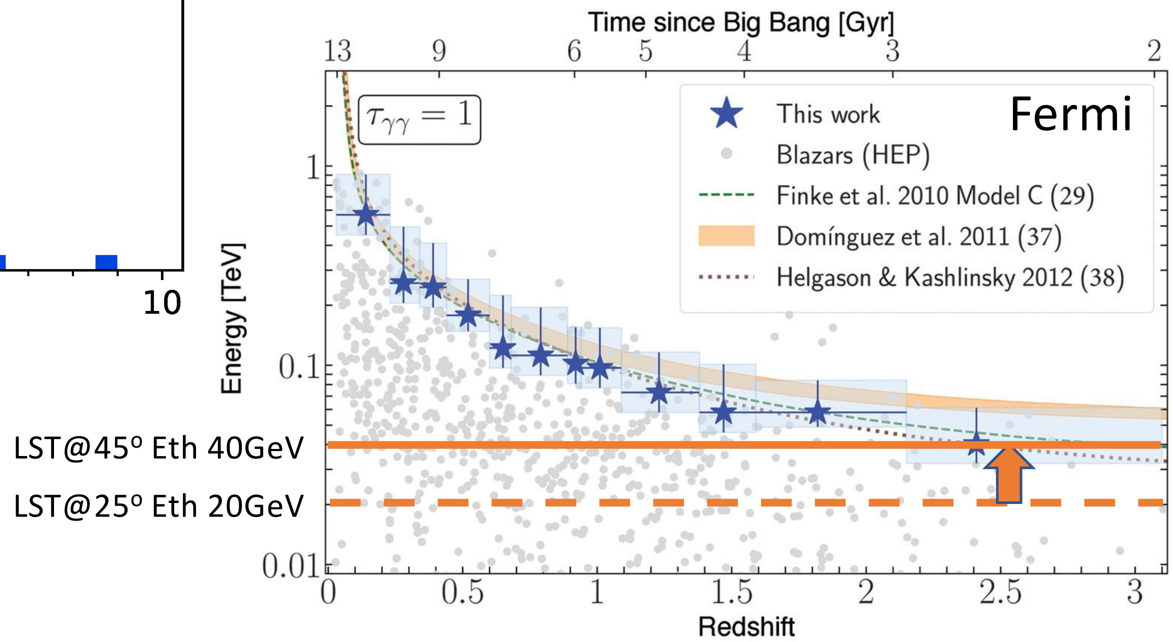



Large Size Telescope
Mirrors: JP
Interface plates: JP, DE, BR
Actuators: JP, CH
CMOS: JP
Tension cables: IT
Camera Support
Structure: FR
calibration:
IT, HR, IN, DE
Camera electronics: JP, IT, ES
Camera mechanics: ES
Camera safety: FR
Telescope
structure: DE
Rail: DE
Camera Access Tower: DE, ES
Bogies: ES
Foundation: ES
Drive and main
el. cabinet: FR
FlyWheels (2x300kW)
energy storage and UPS: JP
Magnetic
bearings
Motor/
generator
Flywheel
housing
Flywheel
rotor

CTA LSTs will observe High Redshift GRBs



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



cherenkov
telescope
array

LST Camera(1855ch High QE PMTs and ultra-fast readout) at MIRCA