cherenkov
telescope
array

High-precision γ-ray astronomy

The Key Science Projects of the Cherenkov Telescope Array

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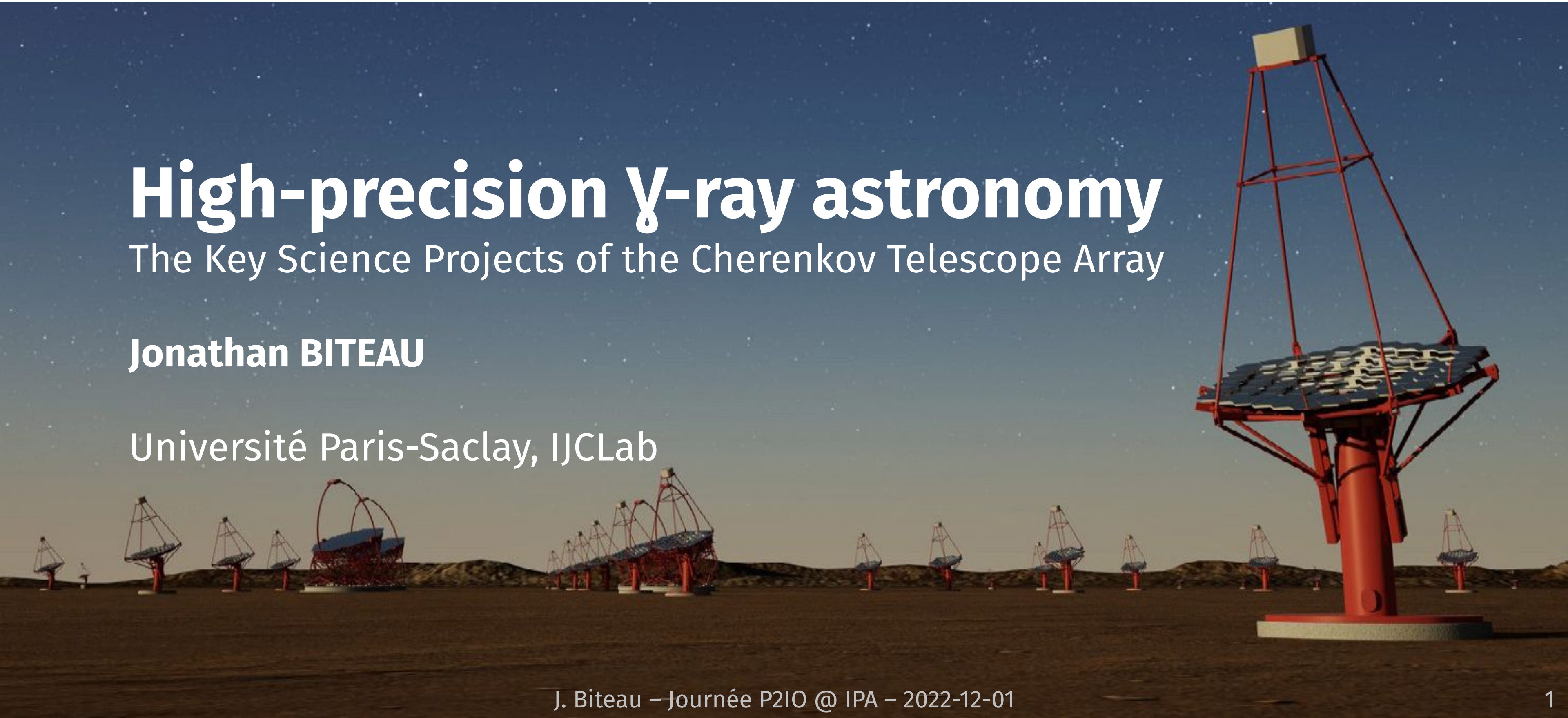


Contents

Why?
Lessons learned and open questions

How?
Making the most of ground-based gamma-ray telescopes

Core Science
The Key Science Projects of CTA

Status of CTA
Timeline – CTA is now!

Note: this is an update of a November 2017 talk (LIV workshop @ LPNHE)

In red: what happened over the past 5 years?

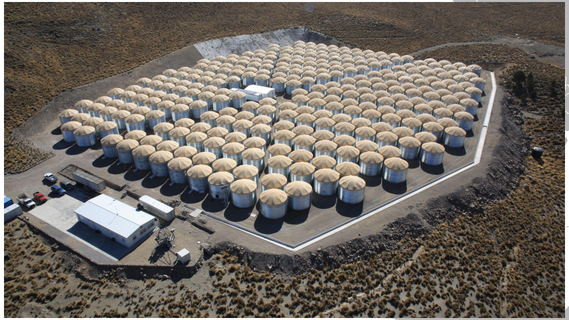
cherenkov telescope array

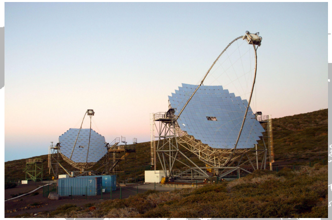
CTA – Why?

Major TeV observatories

VERITAS
4 Medium-Sized Tel. ('MSTs')
2007: Full operation
2009: Relocation of T1
2012: PMT upgrade

HAWC
Particle-detector water tanks (2015)

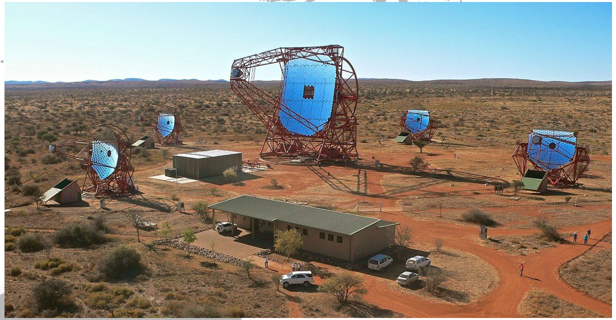




MAGIC
2 Large-Sized Tel. ('LSTs')
2003: MAGIC-I
2009: MAGIC-II
2012: PMT upgrade

LHAASO
Particle-detector water tanks
+ 18 Small-Sized Tels ('SSTs')
since 2018 (New)

H.E.S.S.
4 MSTs (2003)
+ 1 LST (2012)



Evolution the TeV sky

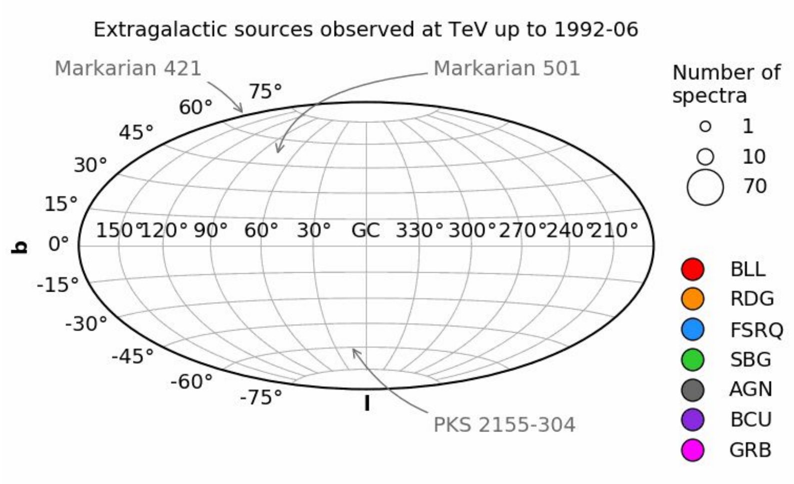
1989 – early 2000s

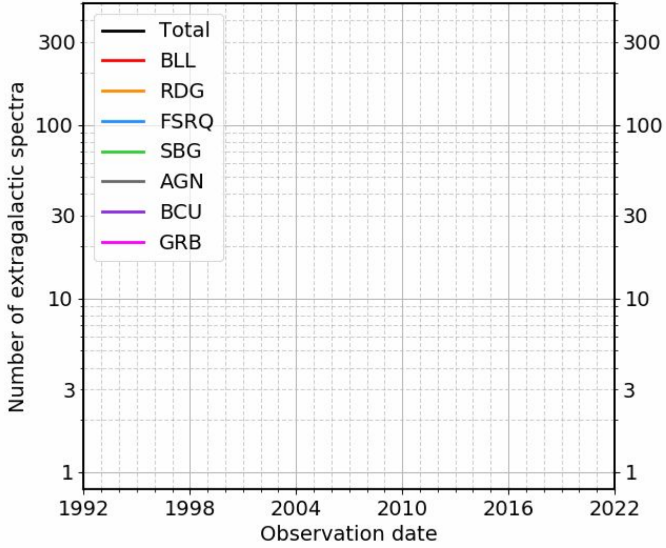
Childhood of gamma-ray astronomy, triggered by Whipple → Crab Nebula + ~5 AGNs

2003-Now

Growth triggered by H.E.S.S./MAGIC (2003), VERITAS (2007), HAWC (2015), and more recently LHAASO (2019)

>250 sources! A much-larger-than-expected **variety** of objects! **E.g. for the extragalactic sky**

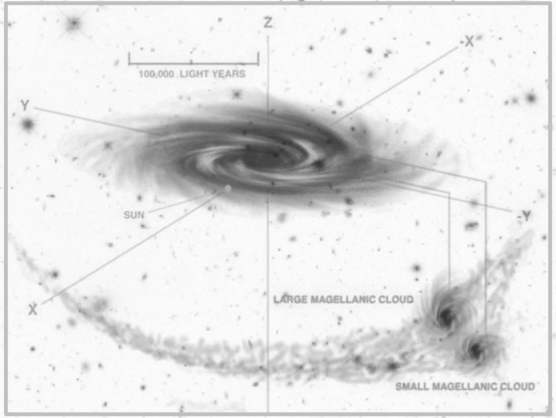




Credits: Lucas Gréaux, IJCLab

TeV astronomy: birth in the 1990s

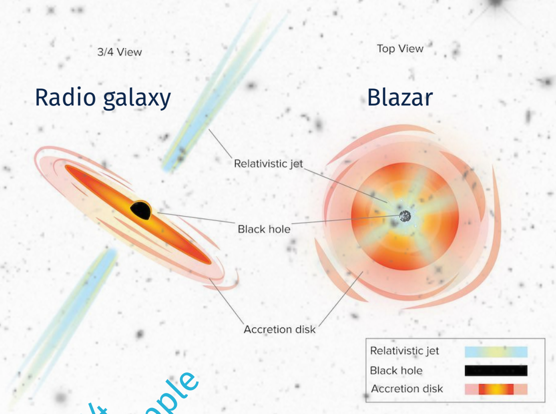
Nature & Science selection (a least-effort selection criterion)

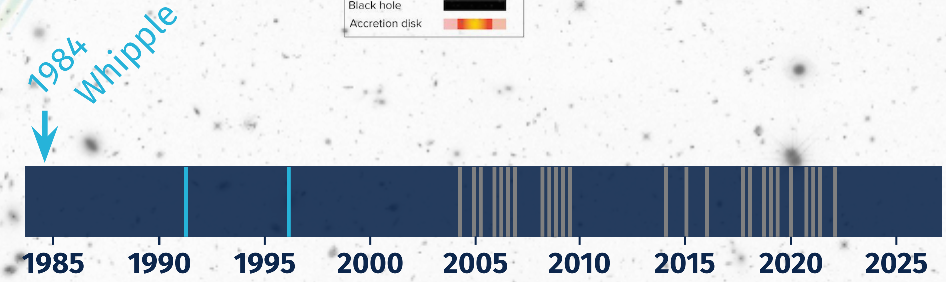


Blazar

. Detection of TeV photons from the active galaxy Markarian 421, Nature 358, 477 (1992)

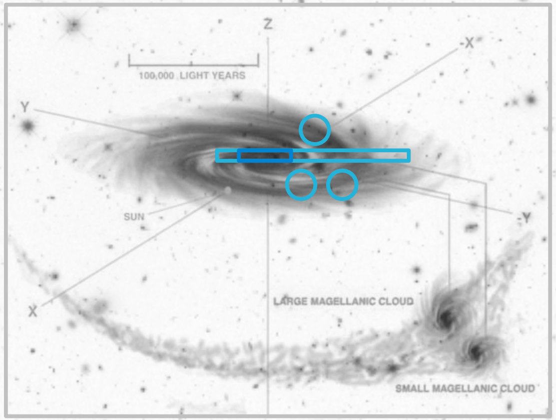
. Extremely rapid bursts of TeV photons from the active galaxy Markarian 421, Nature 383, 319 (1996)





TeV astronomy: 2003-2007

Nature & Science selection



Radio galaxy Science 314, 1424 (2006)

Fast Variability of TeV γ Rays from the Radio Galaxy M87

Extragalactic Background Light Nature 440, 1018 (2006)

A low level of extragalactic background light as revealed by γ-rays from blazars

Supernova Remnant Nature 432, 75 (2004)

High-energy particle acceleration in the shell of a supernova remnant

X-ray binary / microquasar

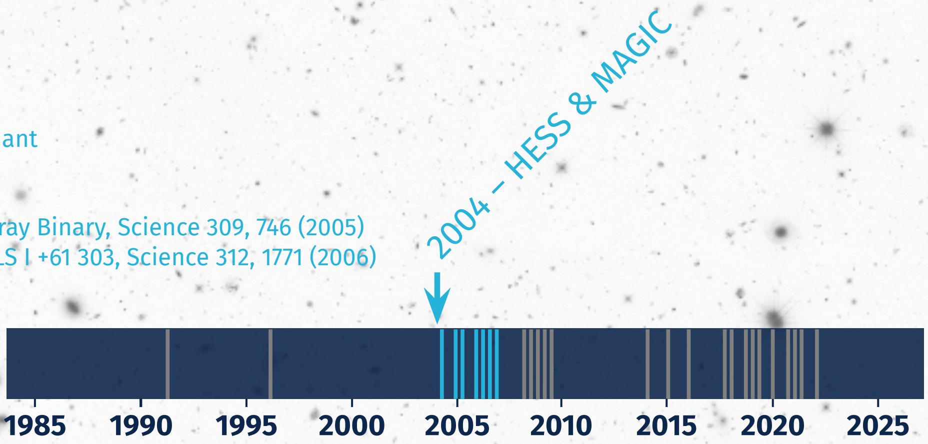
. Discovery of Very High Energy Gamma Rays Associated with an X-ray Binary, Science 309, 746 (2005)
. Variable Very-High-Energy γ-Ray Emission from the Microquasar LS I +61 303, Science 312, 1771 (2006)

Galactic Plane Survey Science 307, 1938 (2005)

A New population of VHE γ-ray sources in the Milky Way

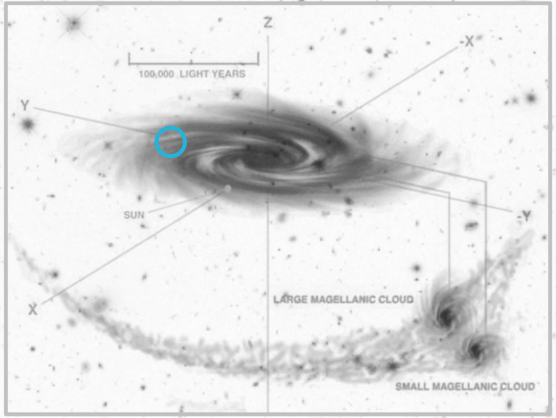
Galactic Center Ridge Nature 439, 695 (2006)

Discovery of VHE γ-rays from the Galactic Centre ridge



TeV astronomy: 2008-2012

Nature & Science selection



Radio galaxy Science 325, 444 (2009)

Radio Imaging of the VHE γ-Ray Emission Region in the Central Engine of a Radio Galaxy

Extragalactic Background Light Science 320, 752 (2008)

VHE γ-rays from a Distant Quasar: How Transparent Is the Universe?

Starburst galaxies

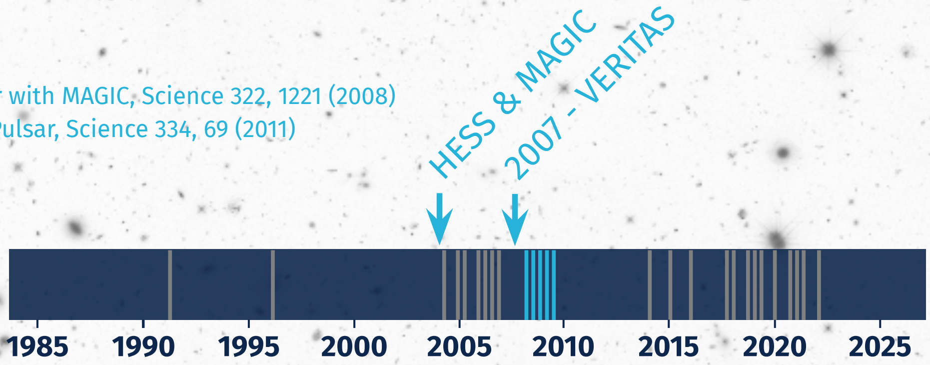
. A connection between star formation activity and cosmic rays in M82, Nature 462, 770 (2009)

. Detection of Gamma Rays from a Starburst Galaxy, Science 326, 1080 (2009)

Crab Pulsar

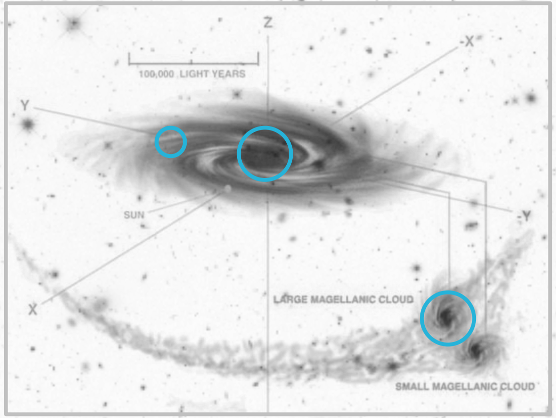
. Observation of Pulsed γ-Rays Above 25 GeV from the Crab Pulsar with MAGIC, Science 322, 1221 (2008)

. Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar, Science 334, 69 (2011)



TeV astronomy: 2013-2017

Nature & Science selection

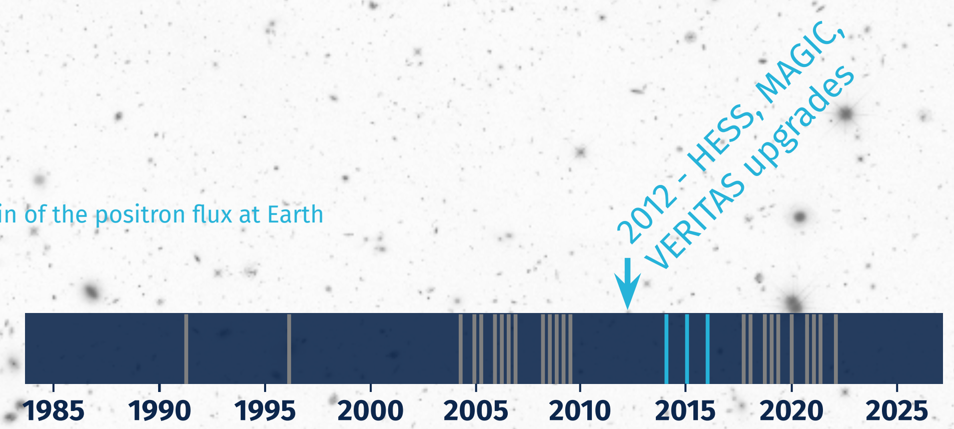


AGN IC310 Science 346, 1080 (2014)
Black hole lightning due to particle acceleration at subhorizon scales

Pevatron Galactic Centre Nature 531, 476 (2016)
Acceleration of petaelectronvolt protons in the Galactic Centre

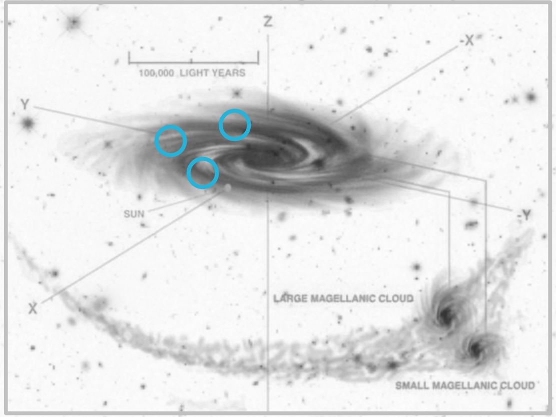
Pulsar Wind Nebula Science 358, 911 (2017)
Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

Large Magellanic Cloud Science 347, 406 (2015)
The exceptionally powerful TeV γ-ray emitters in the LMC



TeV astronomy: 2018-2022

Nature & Science selection (NEW since the 2017 talk)



Radio galaxy Nature 582, 356 (2020)

Resolving acceleration to very high energies along the jet of Centaurus A

Gamma-ray burst

. Revealing X-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, Science 372, 1081 (2021)

. A very-high-energy component deep in the gamma-ray burst afterglow, Nature 575, 464 (2019)

. Observation of inverse Compton emission from a long γ-ray burst, Nature 575, 459 (2019)

. Teraelectronvolt emission from the γ-ray burst GRB 190114C, Nature 575, 455 (2019)

Neutrino and flaring blazar hint Science 361, 1378 (2018)

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

Nova Science 376, 77 (2022)

Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi

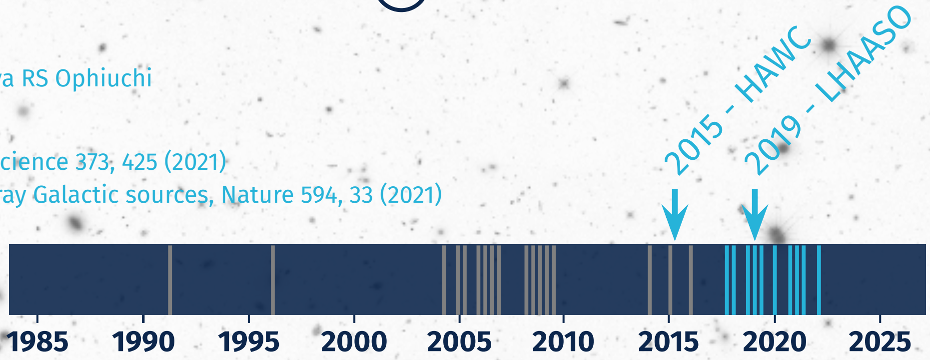
PeV gamma rays

. Peta-electron volt gamma-ray emission from The Crab Nebula, Science 373, 425 (2021)

. Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources, Nature 594, 33 (2021)

Microquasar Nature 562, 82 (2018)

Very high energy particle acceleration powered by the jets of the microquasar SS 433



CTA – How?

Accessing the entire sky

Two sites (1 per hemisphere)

Access the entire sky

→ Archetypal sources

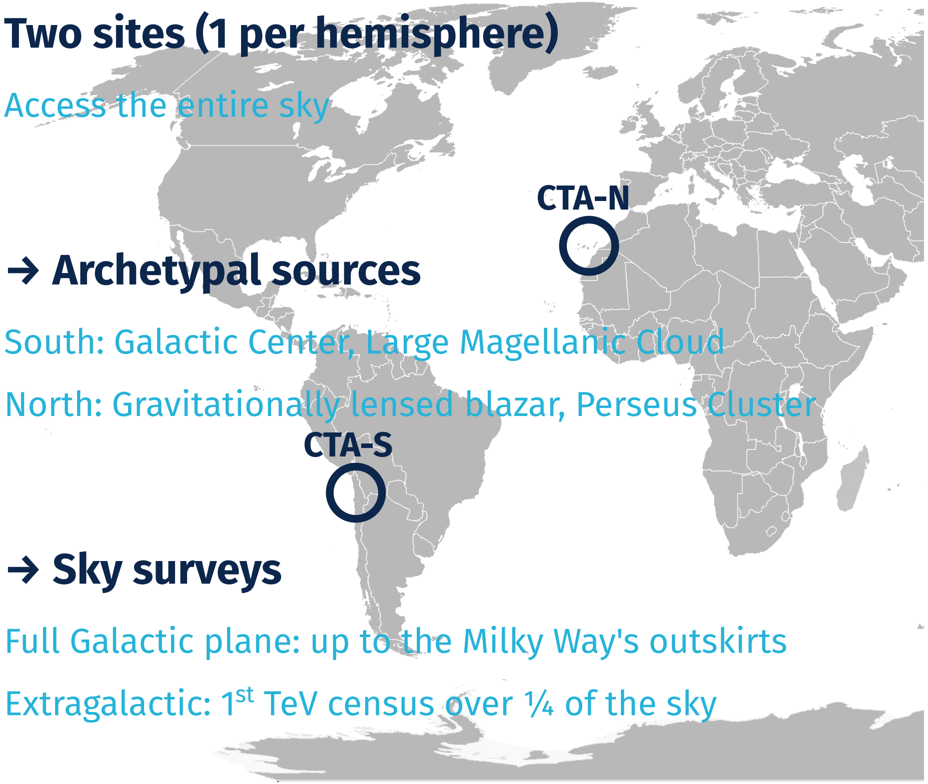
South: Galactic Center, Large Magellanic Cloud

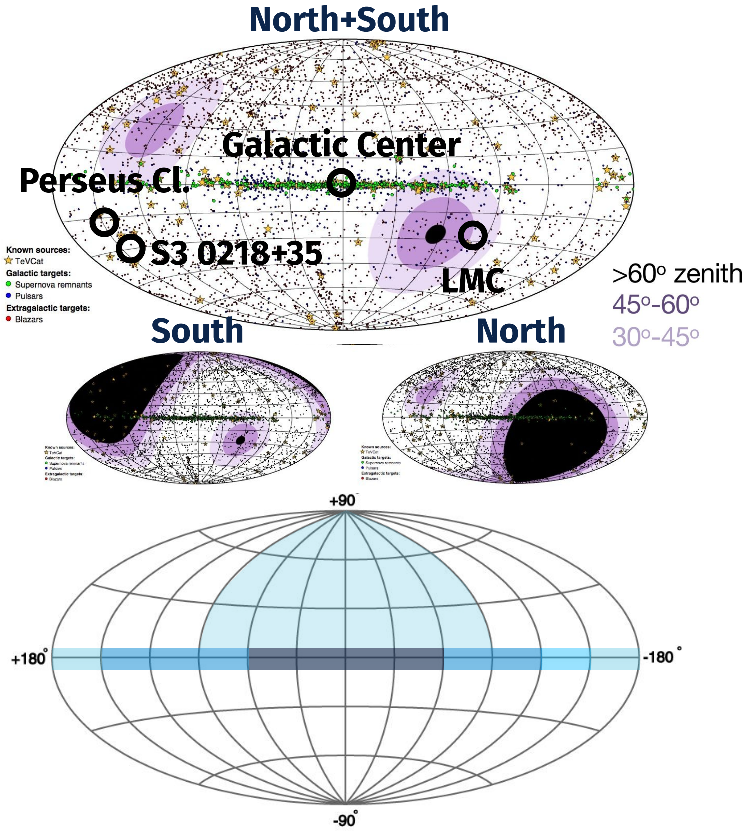
North: Gravitationally lensed blazar, Perseus Cluster

→ Sky surveys

Full Galactic plane: up to the Milky Way's outskirts

Extragalactic: 1st TeV census over ¼ of the sky





Čerenkov measurements

Imaging Atmospheric Č Technique

a. Shape of the shower → bckgd rejection
b. Size of the shower → energy estimator

Multiplicity is key

Coincidence from ++ telescopes
→ a, b, angular resolution

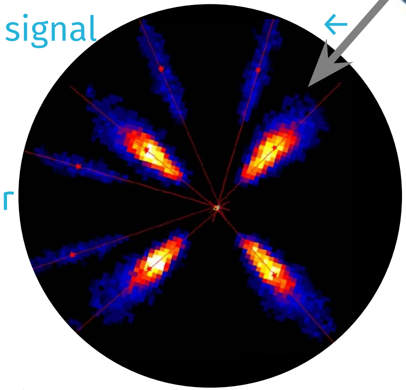
Telescope Size

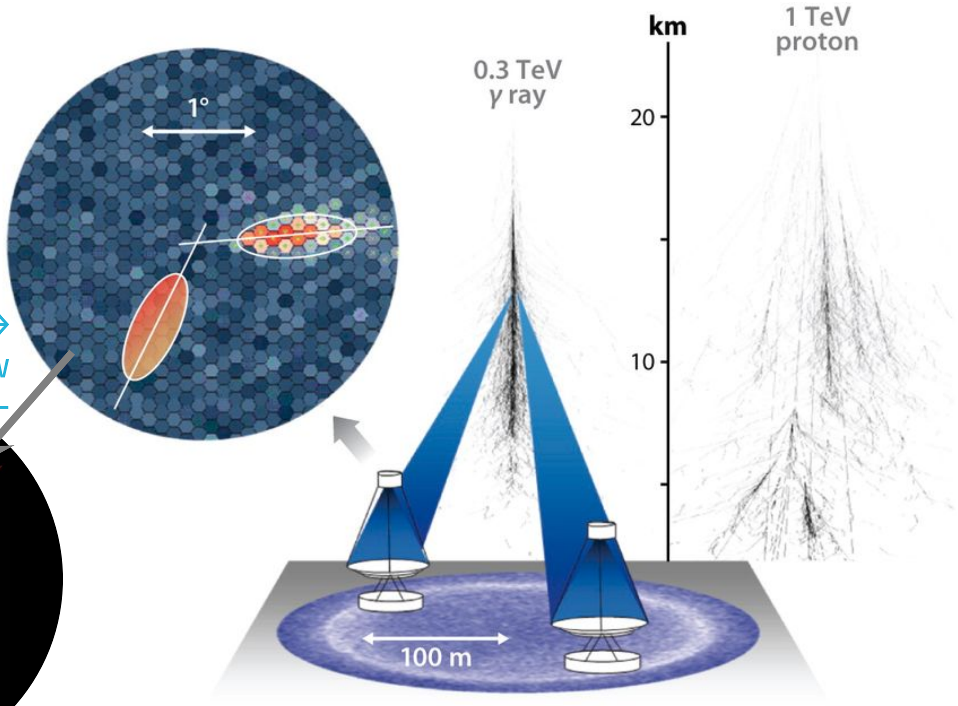
Low-energy γ rays: faint Č signal
→ Large mirrors

Array size

High-energy γ rays: scarcer (PWL spectra)
→ Large array layout

Today →
Tomorrow ←

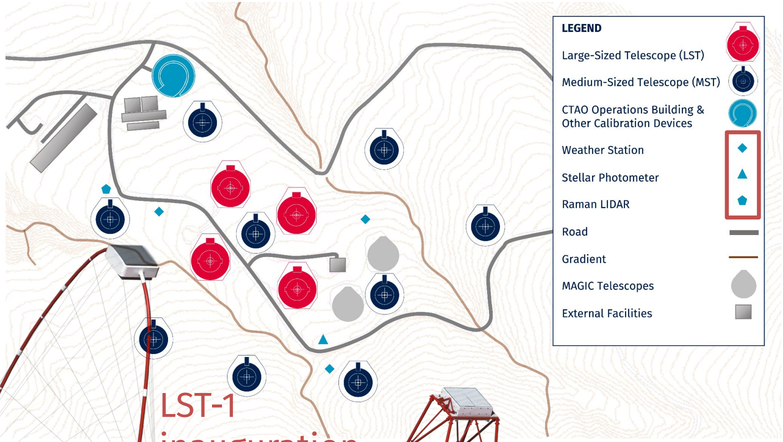


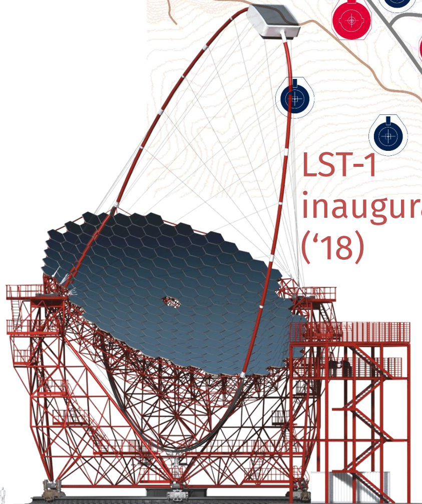


Optimized layout (α configuration)

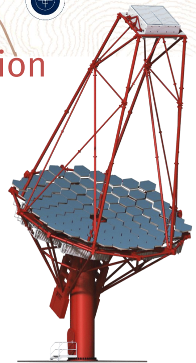
Science-based optimization

North: extragalactic oriented (high-*E*/*z* absorption)

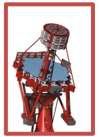




LST-1 inauguration ('18)



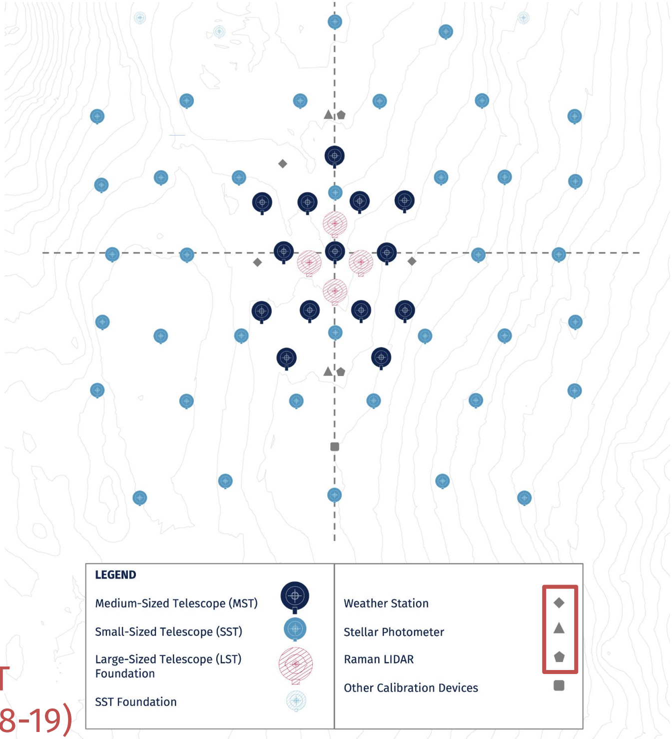
MST camera agreement ('20)



Single SST design ('18-19)

Shower-based optimization

LSTs ~*20-200 GeV*, MSTs *0.2-2 TeV*, SSTs *>2 TeV*



Key performance

Sensitivity

5-10× better than current tels.

From 20 GeV to 200 TeV
(current: 100 GeV to 10 TeV)

Field of view

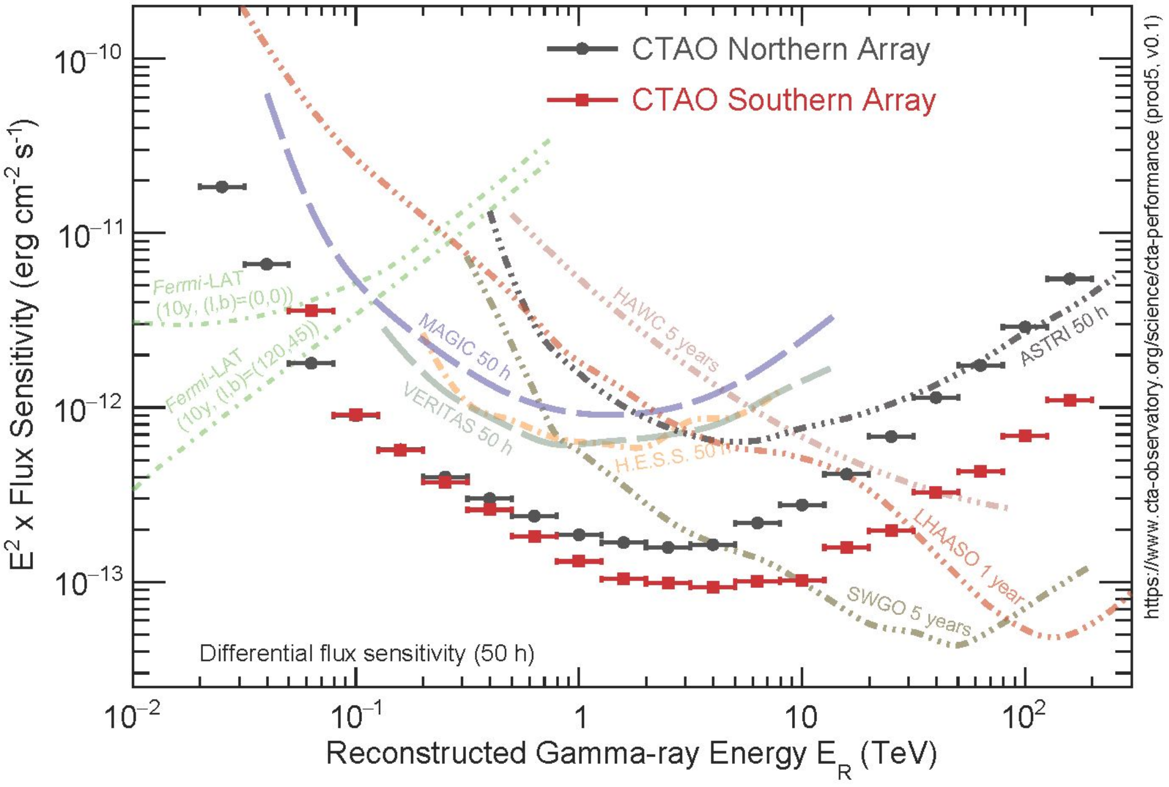
MSTs: 8°x 8°(current: 5°x 5°)

Angular resolution

Better than 3' > 1 TeV
(current: 5')

Energy resolution

< 10% above 200 GeV
(current: <17%)



Key performance

Sensitivity

5-10× better than current telescopes, from 10s of GeV to 10s of TeV

Field of view

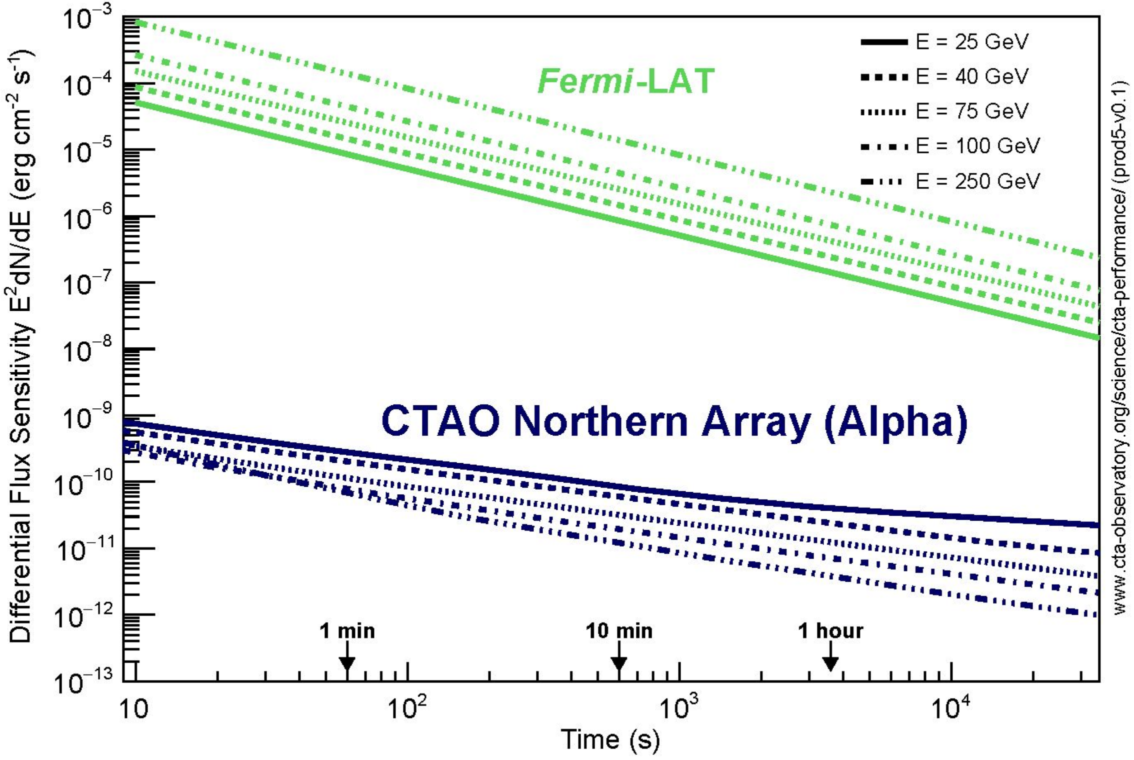
MSTs: ~5° x 5° → ~8° x 8°

Angular resolution

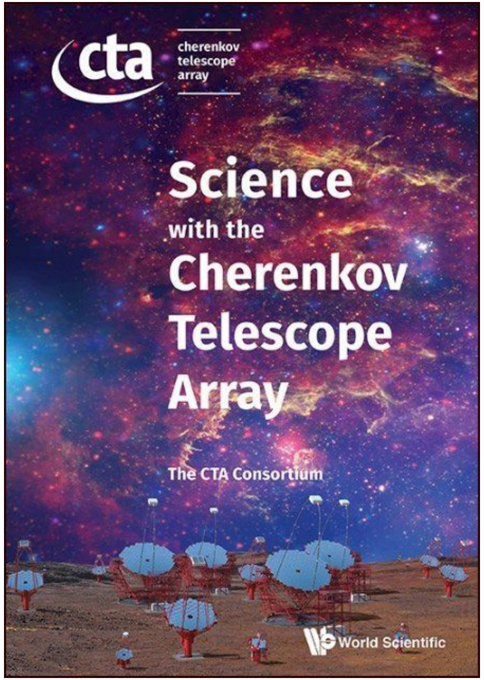
Better than 3' > 1 TeV

Energy resolution

< 10% above 200 GeV



CTA – Core Science



https://doi.org/10.1142/10986

By: The CTA Consortium | March 2019

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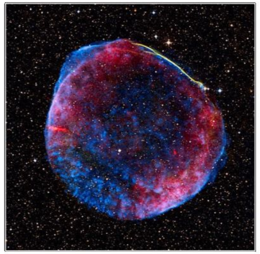
Key Questions

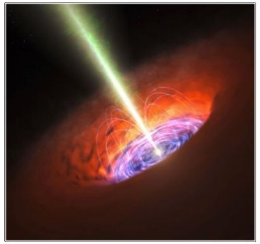
Understanding the Origin and Role of Relativistic Cosmic Particles

. Sites of high-energy particle acceleration?
. Mechanisms for cosmic particle acceleration?
. Feedback on their environment?



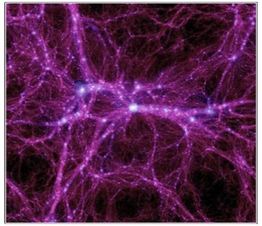
Probing Extreme Environments

. Processes close to neutron stars and black holes?
. Characteristics of jets, winds and explosions?
. Cosmic voids: their radiation and magnetic fields?



Exploring Frontiers in Physics

. Nature of dark matter?
. Photon propagation: quantum gravitational effects?
. Do axion-like particles exist?

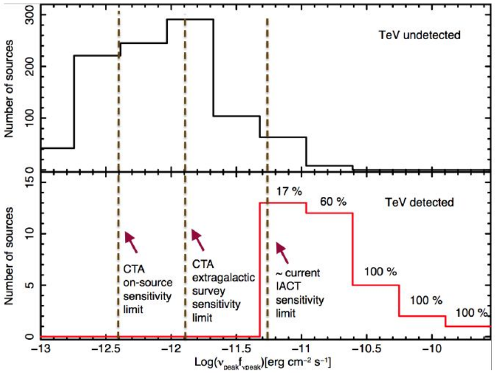


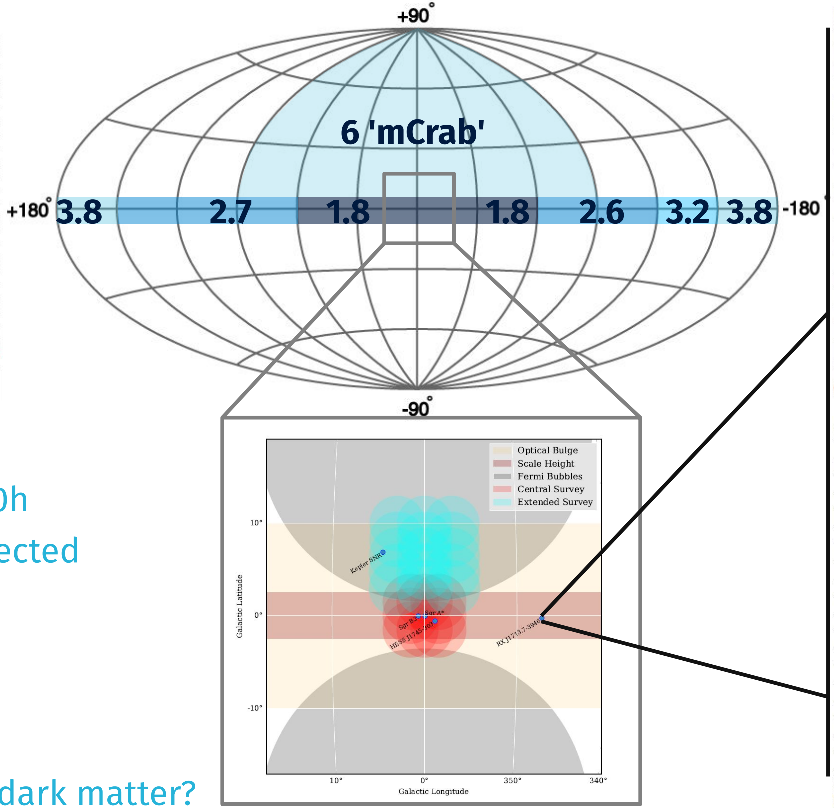
Key Science Projects

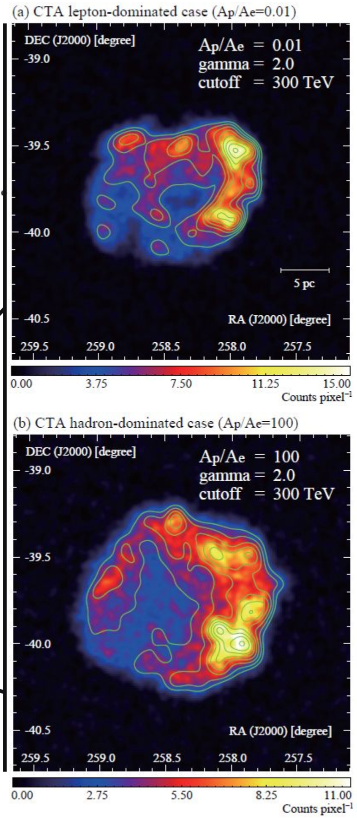
Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of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

Large / deep surveys

Field of view & Two hemispheres







Extragalactic Survey - 1000h

30-150 srcs + unbiased + unexpected

Galactic Plane - 1600h

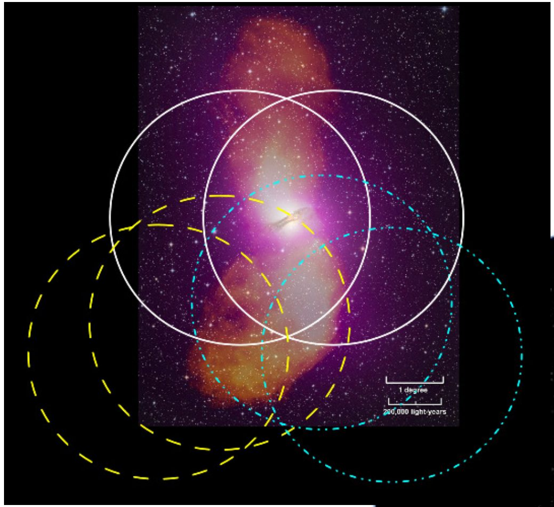
300-600 srcs + unexpected

Galactic Center - 800h

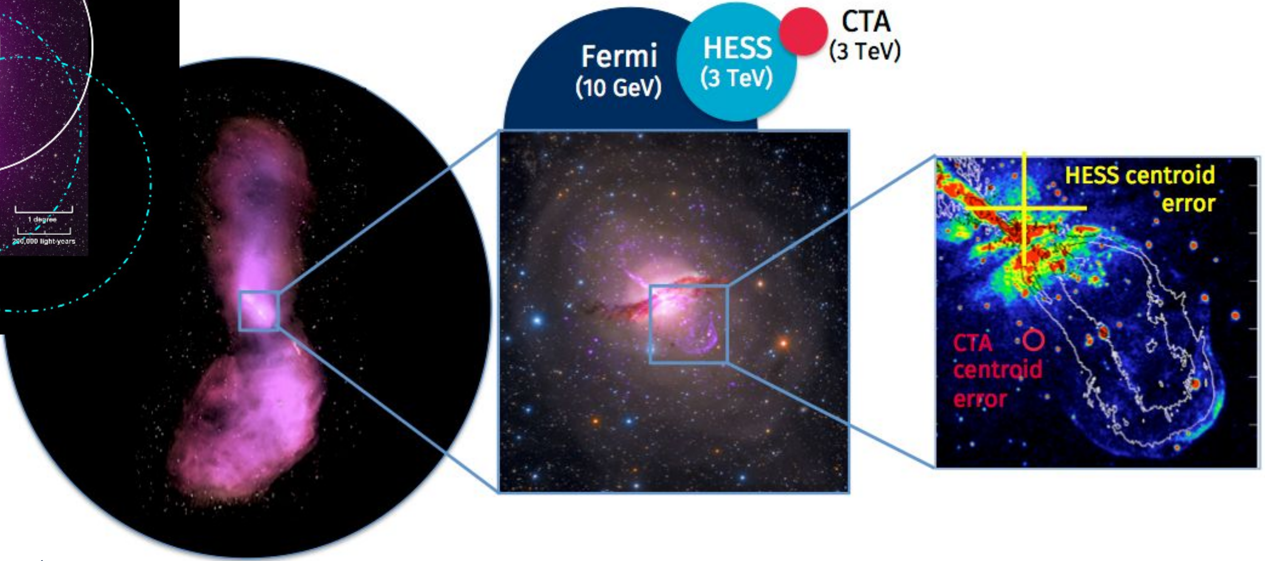
SgrA*+ ridge + dozen sources + dark matter?

High-quality imaging

Field of view & Angular resolution



Example: Cen A - 150h **(within AGN KSP)**
. southern radio lobe fully covered
. kpc scales can be resolved (already demonstrated by HESS)
. high-fidelity centroid location



+ M87 - 100h **(AGN KSP)** - radio lobe

High-quality spectra

Energy dispersion

Cosmic-ray Pevatrons - 300h

RX J1713.7-3946 + candidate PeVatrons detected in the Galactic Plane Survey

Active Galactic Nuclei

- 300h on high-quality spectra
- 200h on M87 & CenA

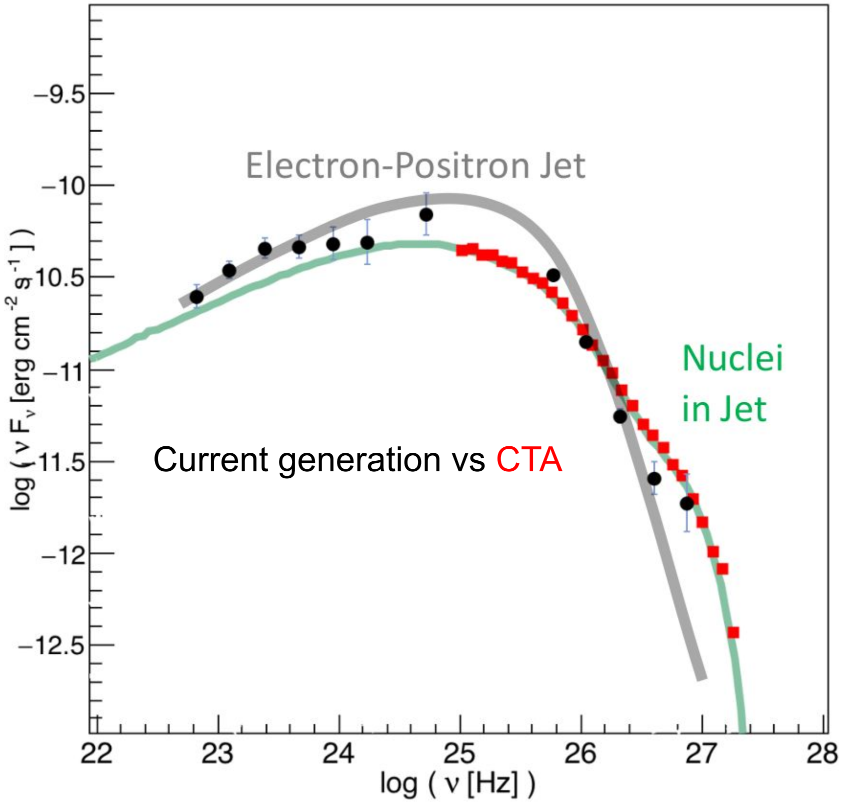
~40 objects targeted:

- ¾ already detected at TeV energies
- ¼ based on *Fermi*-LAT extrapolations

→ acceleration processes

→ radiative processes

→ propagation

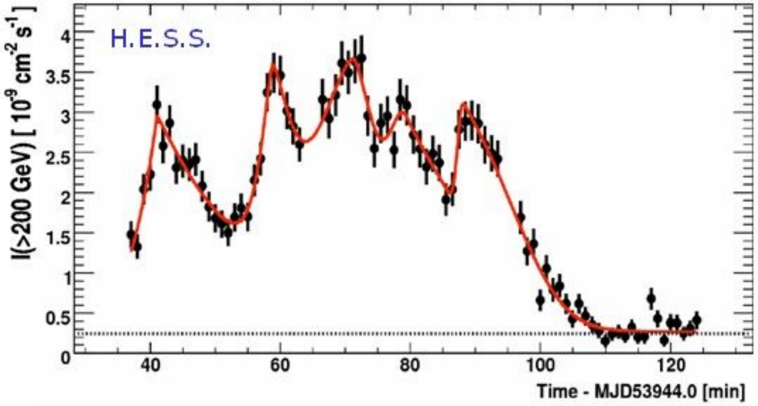


Transients & Outbursts

Effective area, Slewing & Alerts

Transients - 2000h (full-array follow-up)

Galactic transients (e.g Novae), Gamma-ray bursts, ν & gravitational waves



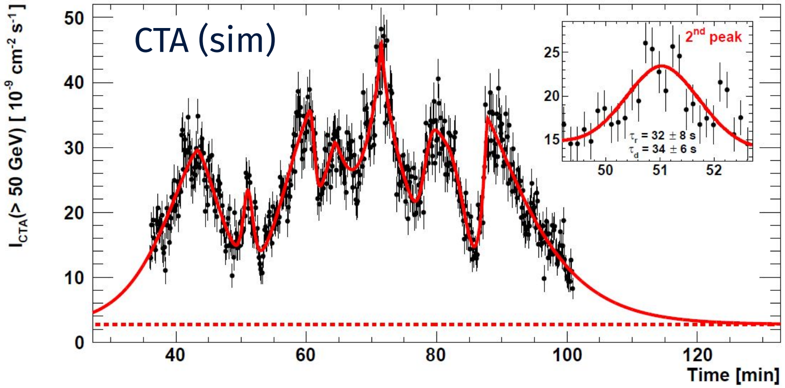
Active Galactic Nuclei

- 1500h of long-term monitoring (full array)

+ snapshots with sub-arrays & external alerts follow up

+ follow-up + 1200 h (full-array)

→ AGN variability on time scales from >10 years down to sub-minute



Triggers to/from the outside world

Minute time-scale response (slewing, processing)

Open-question (investigated e.g. in the Paris area): how to deal with external alerts in time-domain astronomy era (Rubin: > 10 million alerts per night)

Astrophysics & beyond

Fundamental physics & cosmology

Galaxy clusters - 300h on Perseus

Perseus: structure formation shocks + cosmic-ray content of the intra-cluster medium + NGC 1275 & IC 310
+ decaying DM and γ-WISPs (axion-like) coupling

Dark Matter Program - Gal. Center + dSphs(300h) + 700h

Down to the thermal cross section for WIMPs

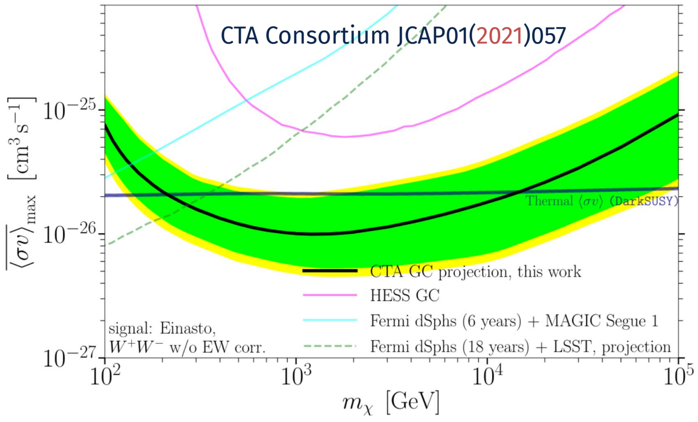
γ-ray propagation - AGN + Transients + Pulsars (GPS)

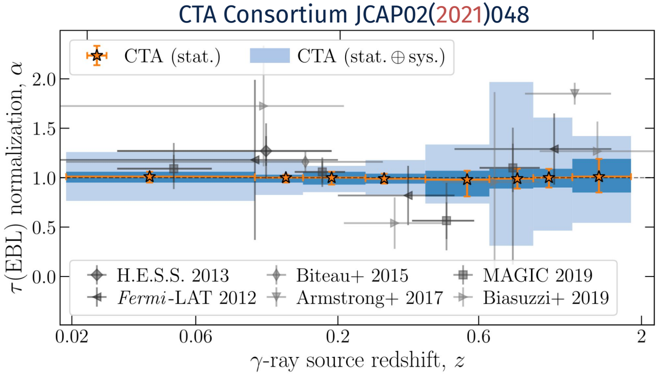
Extragalactic Background Light, down to 5% (stat.), 12% (syst.)

Intergalactic Magnetic Fields: > 0.3 pG

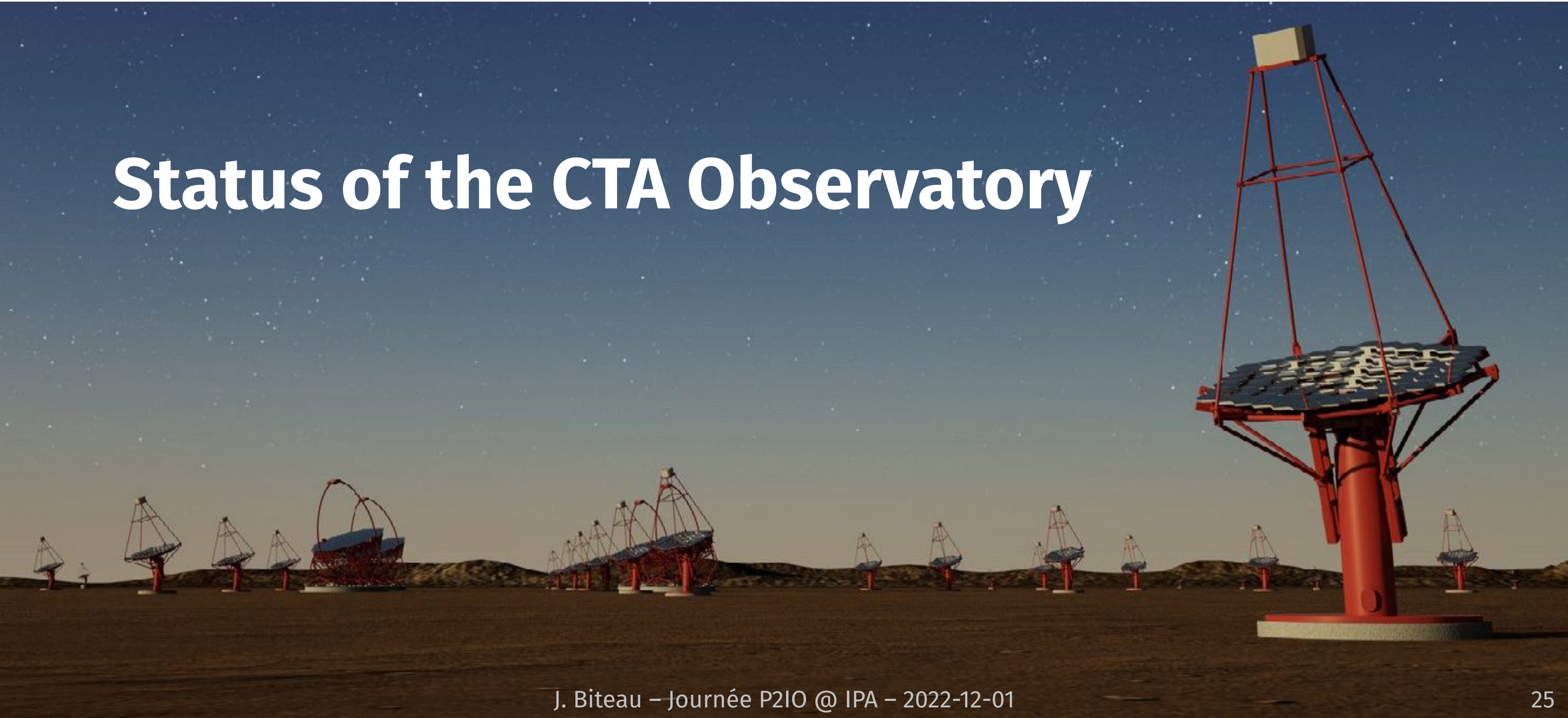
Lorentz Invariance Violation: 2-3× better than current

Axion-like Particles: probe of dark-matter parameter space





Status of the CTA Observatory



CTA Timeline as it was in ‘17

Observatory

→ Was a gGmbH (German non-profit company)
→ ERIC in 2023 (European Research Infra.)
α configuration & cost book approved by board of government representative in June 2021

Cameras and Telescopes

→ SSTs: in product review
→ Prototype MST with NectraCAM (FR) in 2019
→ First MSTs in Paranal and La Palma (+ some other LSTs) by 2024
→ 1st LST in La Palma since 2018

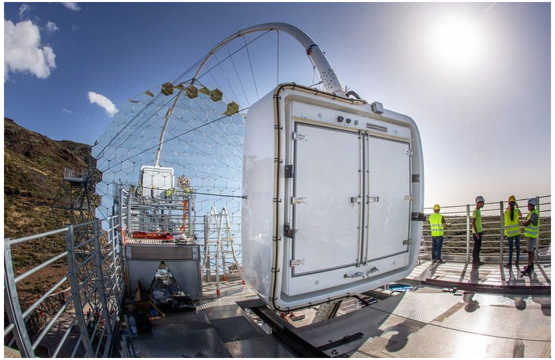
2007 — Definition of the CTA Design Study
2008 — CTA Consortium Established
2010 - 2014 — CTA Preparatory Phase Supported by FP7 Grant from the European Commission
2015 — EU H2020 Funding for Site Preparations
2016 — Site Hosting Agreements Finalized
late 2017 — First Pre-Production Readiness Review
early 2018 — First Pre-Production Telescopes on Site
2021 — Beginning of Observatory Operations
2024 — Construction Project Completion

LST-1 inauguration: 2018.10.11
not-so-bad estimate

Don’t be so hasty!

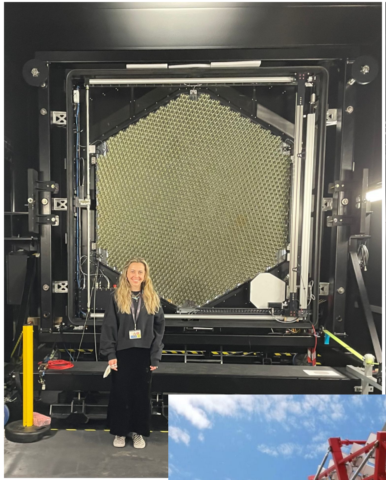
Cameras & telescopes

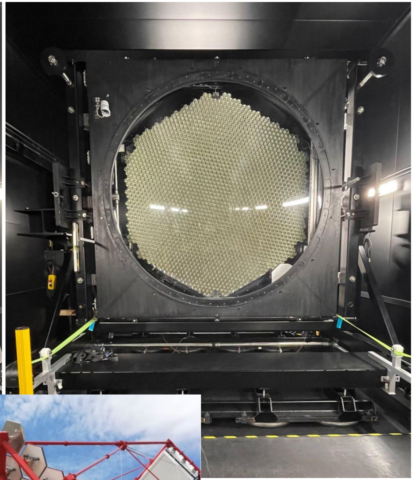
LST-1 on site



LST-2/4 in prod

1st full MST cameras





Credits: F. Bradascio, IRFU-CEA

LST-1 commissioning

LST-1 inauguration on Oct. '18

Commissioning, science verification

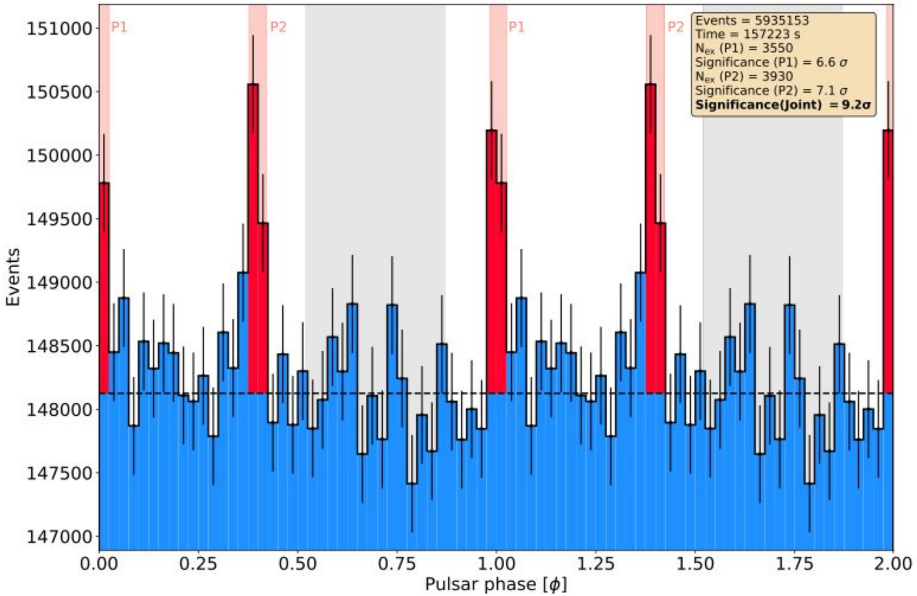
Crab Nebula detection in Nov. '19

AGN Detections

Mrk 501, Mrk 421, 1ES 1959+650,
1ES 0647+250 and PG 1553+113

Crab Pulsar detection in June '20

PoS(ICRC2021)806



Until...

Sep. to Dec. 2021

No permanent damage on LST1

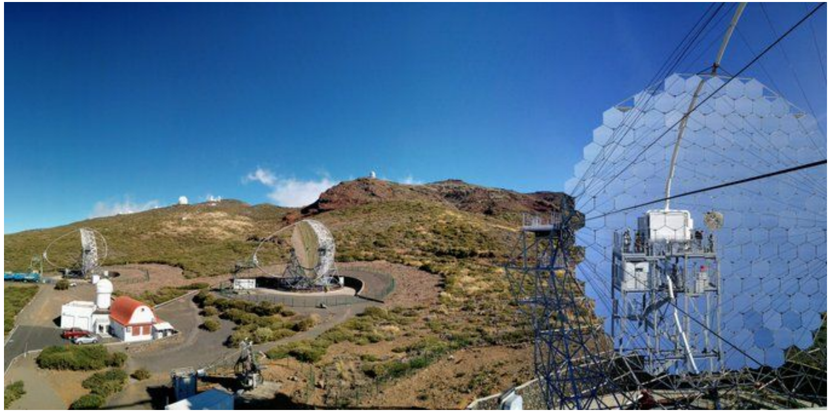
First scientific observations?

Until we have this

hopefully by the time of my next talk on the Key Science Projects of CTA

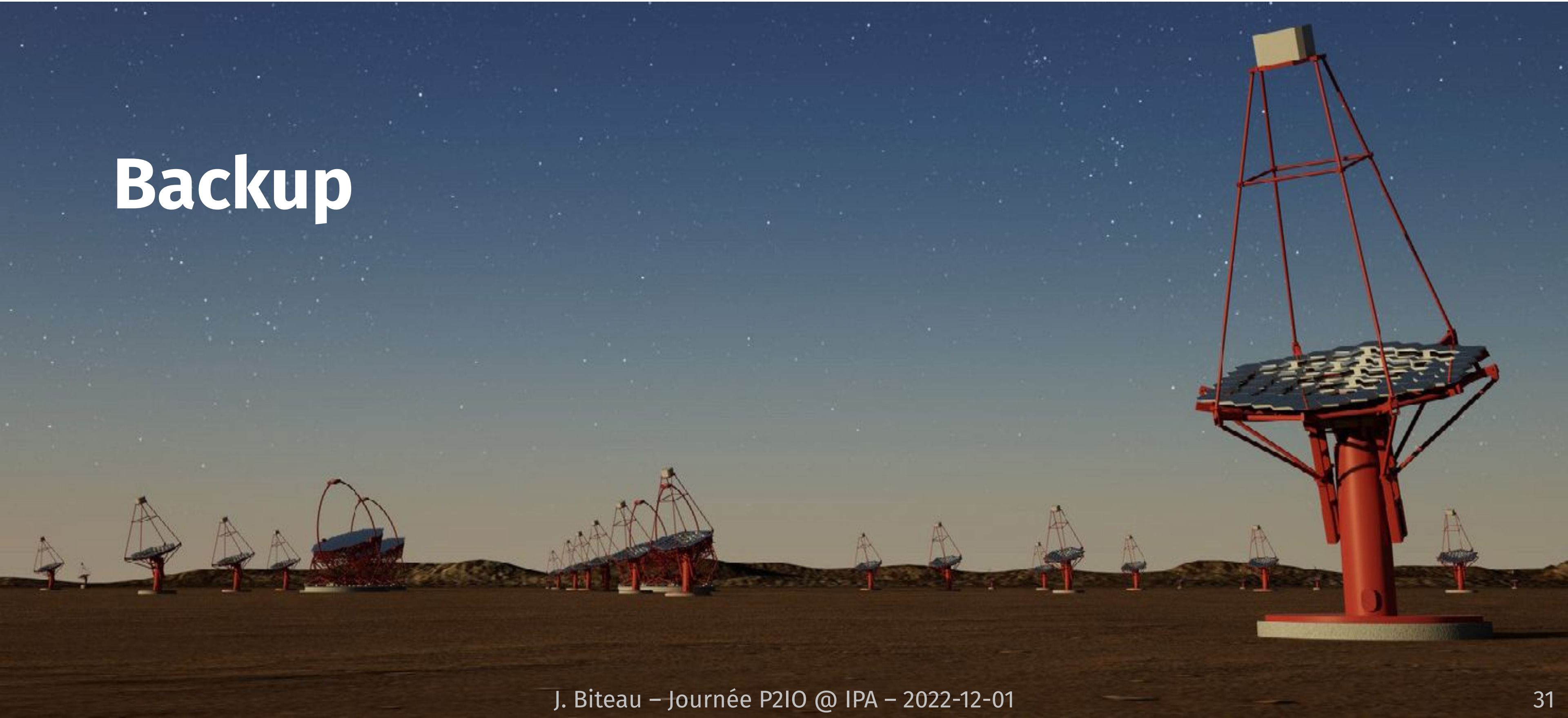
Initiate relevant observations with that

e.g. long-term monitoring of brightest AGNs



cta cherenkov telescope array

Backup



CTA Users

The CTA Observatory

First true open observatory for very-high-energy gamma-ray astronomy

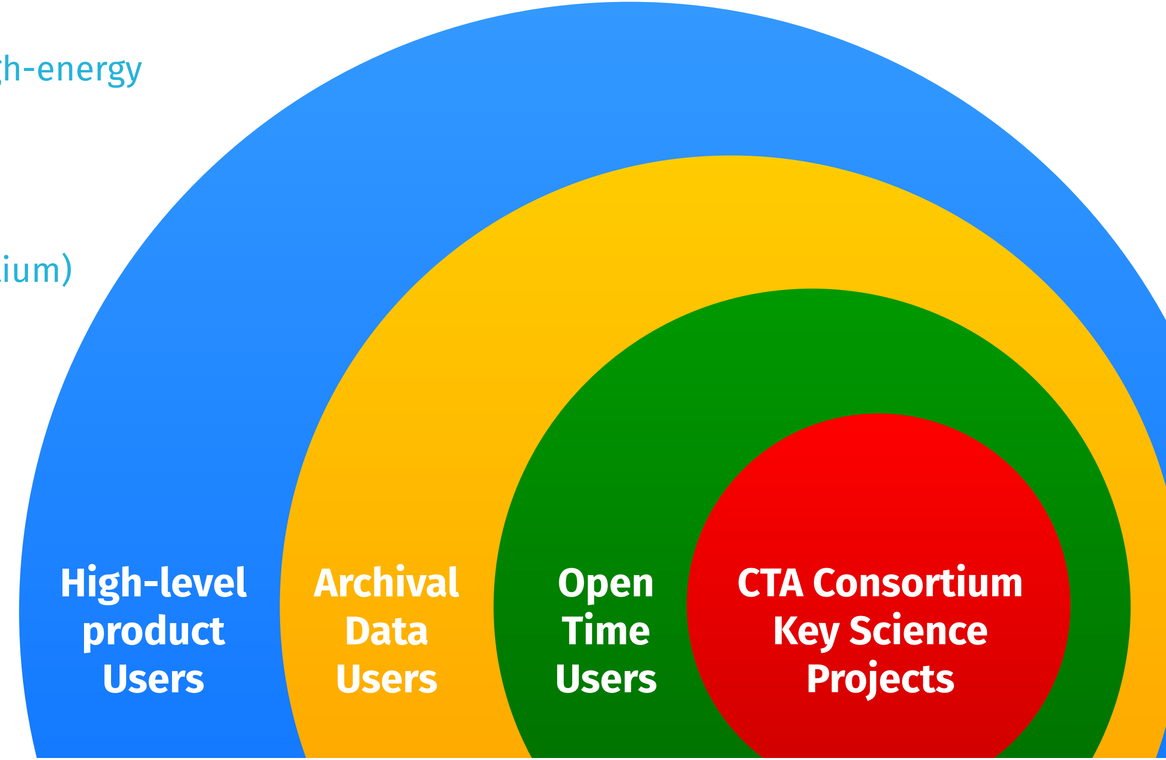
Time distribution

~40% Key Science Projects (CTA Consortium)
~20% Host-country time
~40% User time

Annual Guest Observer proposals with P.I. from contributing countries or non-contributing (small fraction)

Open data

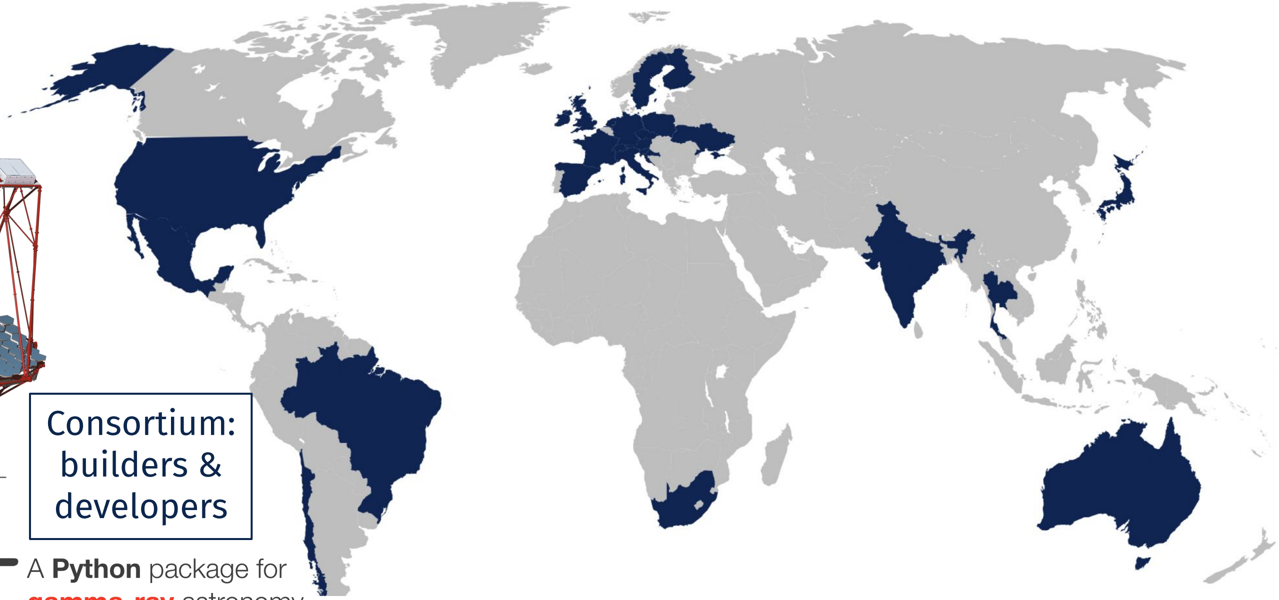
High-level data accessible after a one-year proprietary period

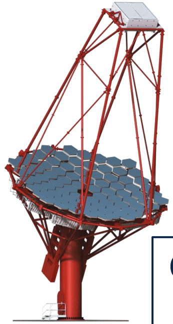


CTA Users

The CTA Consortium

25 countries, 150 institutes: 1500 members (~500 FTE) *as of June 2021*
Definition of the project and of its component - definition of the Key Science Projects
Release of catalogs, maps, likelihood/posterior profiles…





Consortium: builders & developers

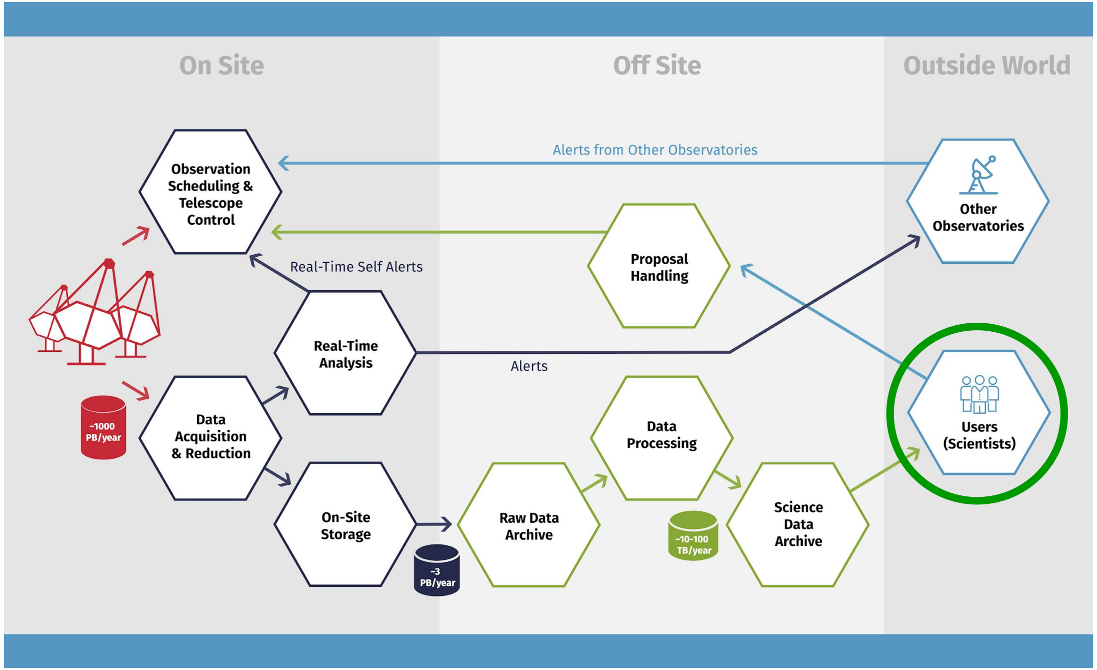
A **Python** package for **gamma-ray** astronomy

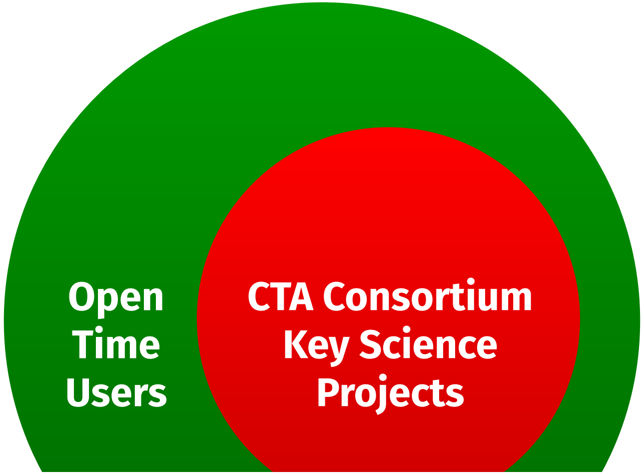
CTA Consortium Key Science Projects

CTA Users

Guest observers

Estimated Co-Is of guest-observer proposals O(5000). CTA → data products and support.





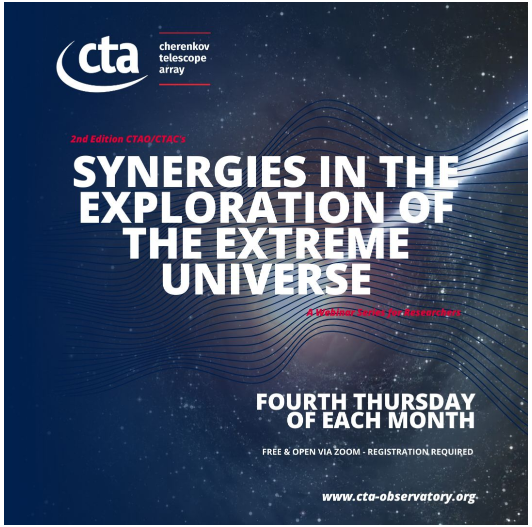
CTA Users

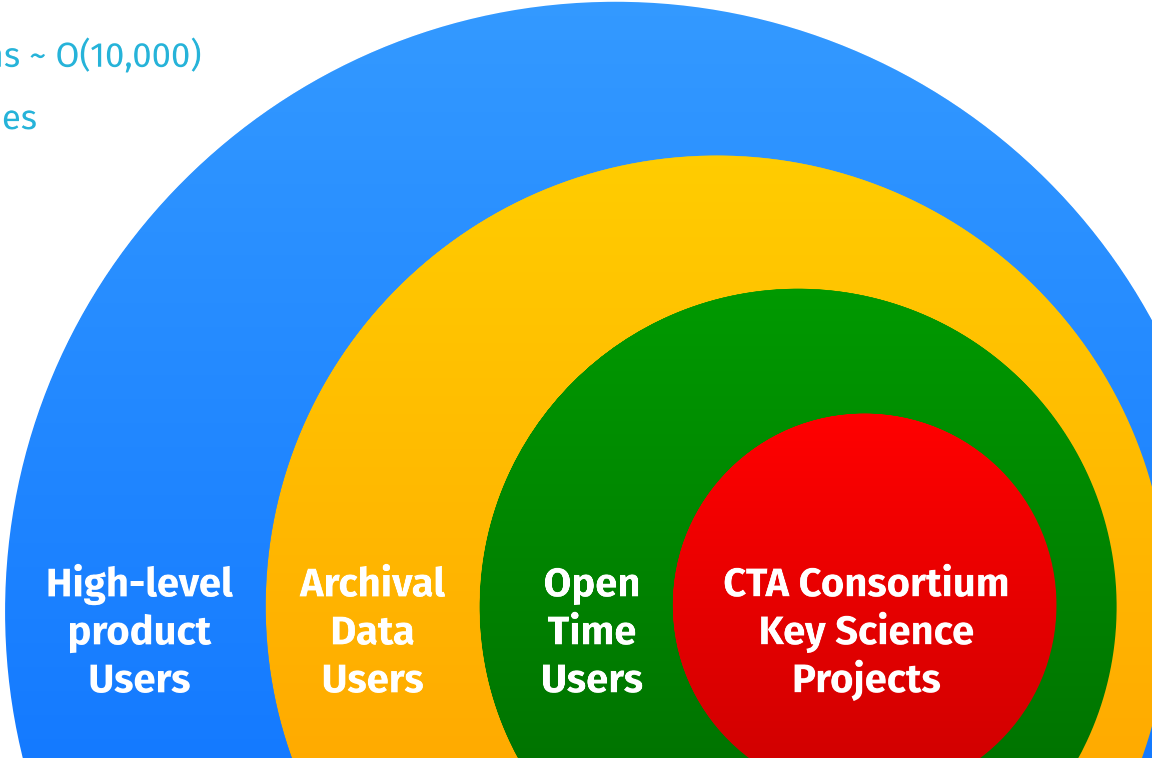
Archival data and high-level-product users

Co-authors of archive-based publications ~ O(10,000)

Wide community engaged through a series of workshops and webinars

Next webinar on 2022.12.15





High-quality imaging

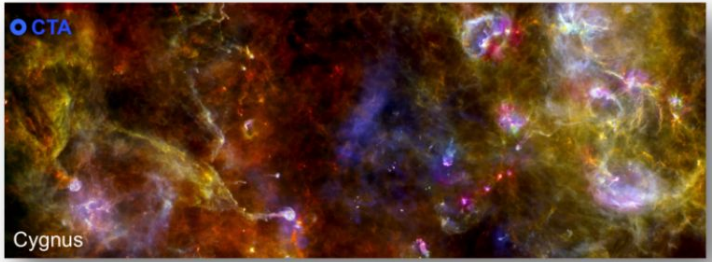
Field of view & Angular resolution

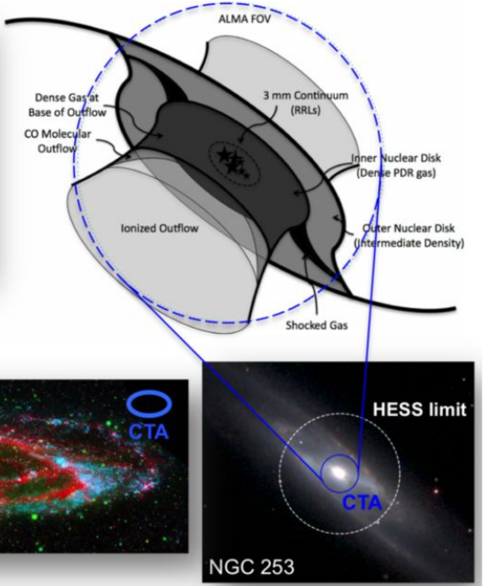
Large Magellanic Cloud Survey - 250h

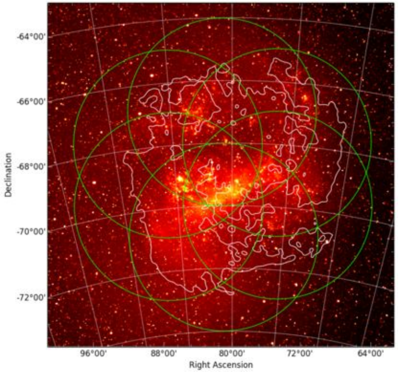
Face-on, dozen sources incl. SN 1987A, superbubble, two powerful pulsars

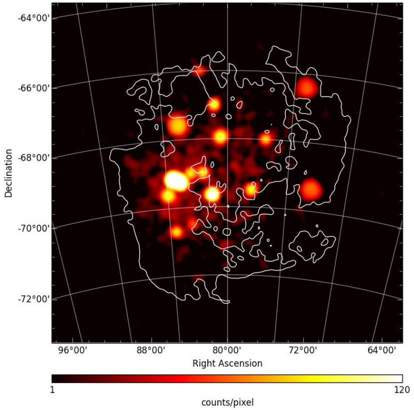
Star-forming systems - GPS + 450h: M31, NGC253, M82, Arp220

From stellar clusters to starburst glaxies

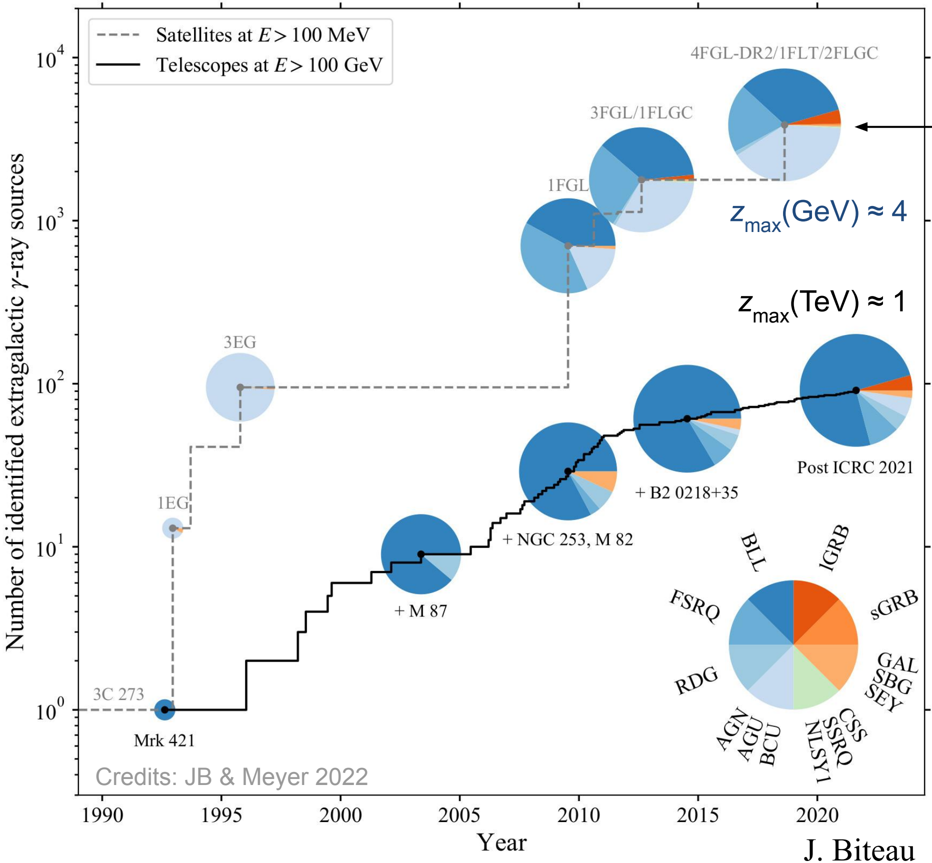


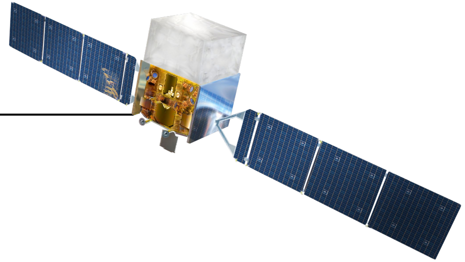


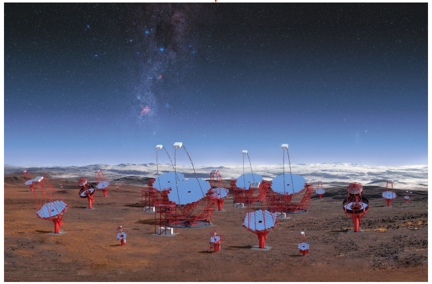




Status of extragalactic ɣ-ray astronomy



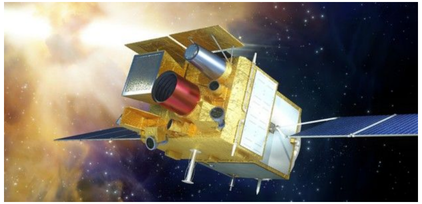


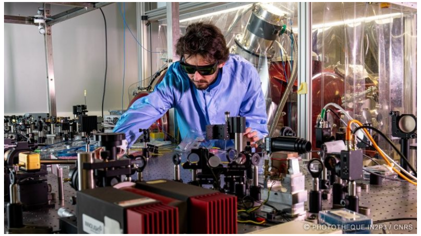


J. Biteau

Multi-wavelength / -messenger observatories

Ongoing @ IJCLab





cta cherenkov telescope array

VERA C. RUBIN OBSERVATORY

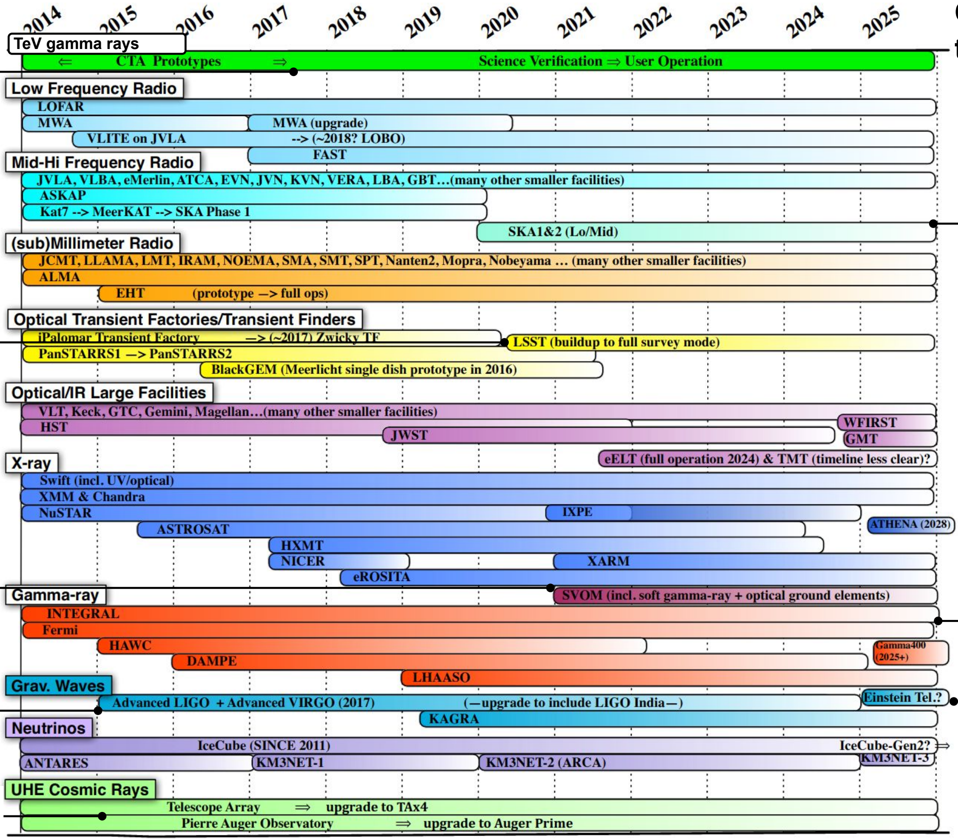
LSST Large Synoptic Survey Telescope

SVOM

GRANDMA

VIRGO

PIERRE AUGER OBSERVATORY



Credits: CTA (2019)

Others, in the future?

SKA?

COMCUBE + e-ASTROGAM

Einstein Telescope

Some fundamental questions in blazar (jetted AGN) physics

Jet formation: Accretion - Ejection

Blandford-Znajek (*B*-field in ergosphere)
or Blandford-Payne (*B*-field in disk)?

Jet composition: Baryons & Leptons

Pure e^+/e^- jet excluded for stability
but which e/p ratio, and baryon origin?

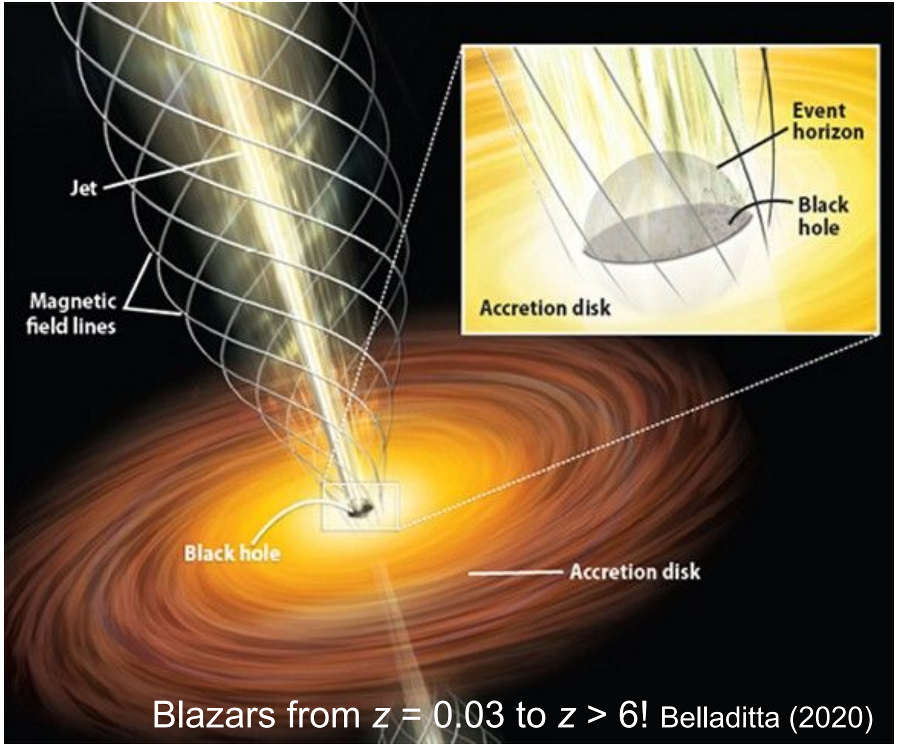
Jet bulk acceleration

Poynting dominated at basis
→ $\Gamma \sim 10$ bulk motion beyond pc scales

Particle acceleration

Transfer of magnetization / bulk motion to leptons (& baryons?) up to $\gamma > 10^5$:

- Shock acceleration?
- Magnetic reconnection?
- Others?



Blazars from $z = 0.03$ to $z > 6$! Belladitta (2020)

Some of Fermi's lessons on blazars

Detections

- 2863 sources at |b| > 10° 4LAC, Fermi-LAT 2019
  - > 79% are AGNs
    - ~98% of these AGNs are blazars
      - 24% FSRQs, 38% BL Lacs, 38% unclear

Blazar sequence?

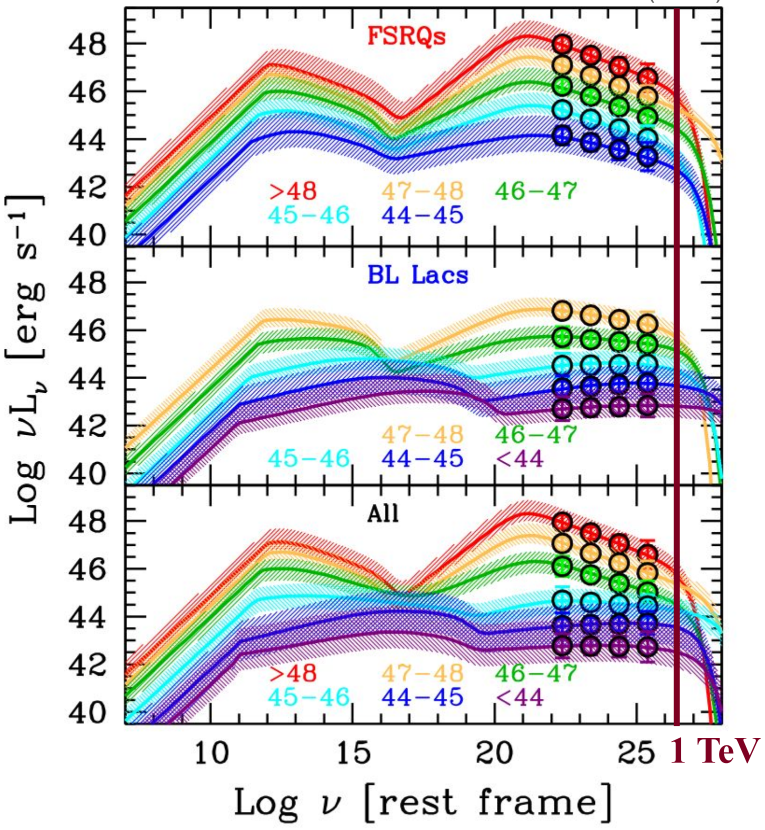
- Inferred anti-correlation of peak power with peak frequency
- Initially: (biased?) X-ray/radio selection Fossati et al. (1998)
- Confirmed with Fermi-only selection Ghisellini et al. (2017)

→ links maximum energy, jet power and accretion rate (FSRQ / BL Lac lines = reprocessed disk emission)

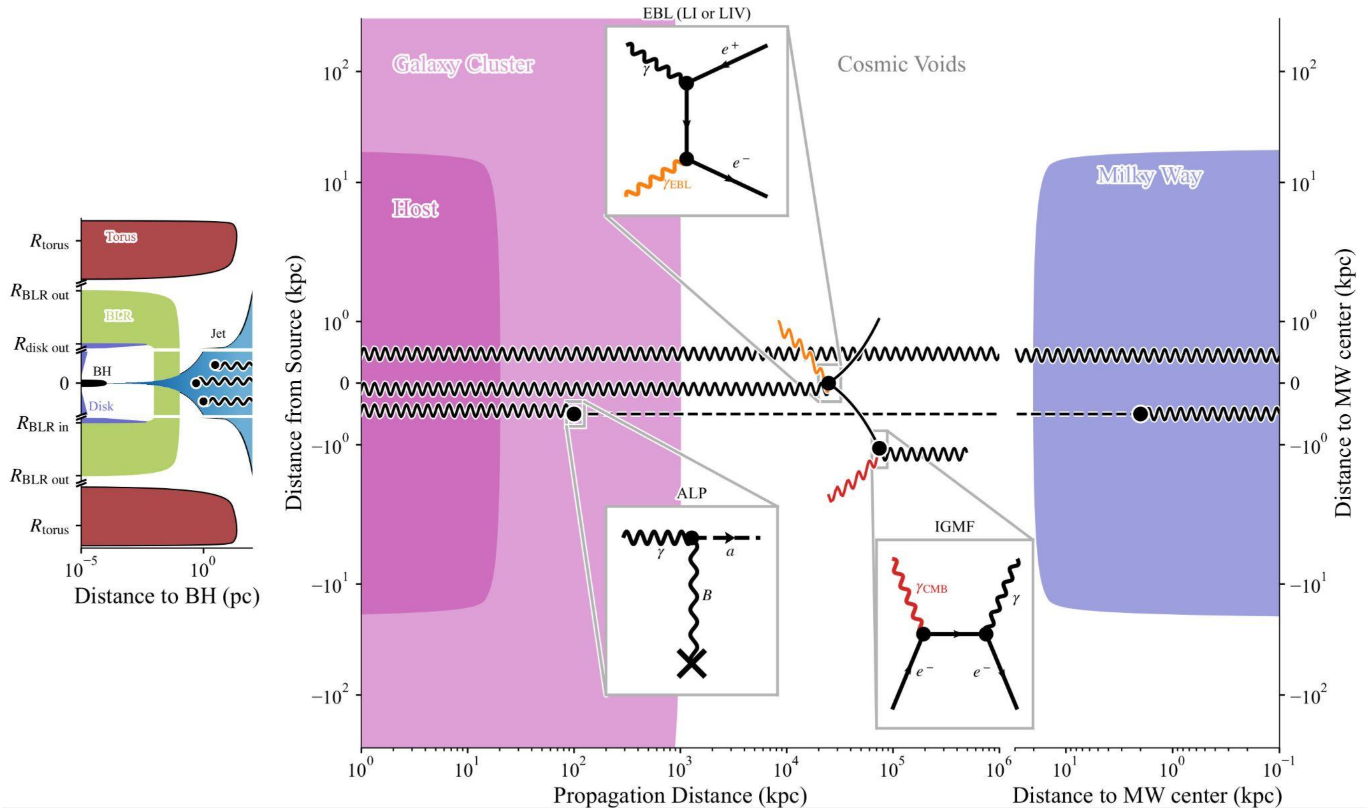
Extreme blazars

The high-energy frontier of the sequence
→ two dozen known to date Biteau et al. (2020)

Ghisellini et al. (2017)



ɣ-ray propagation from sources down to Earth



Status of the COB and CIB as of 2022

Measurements

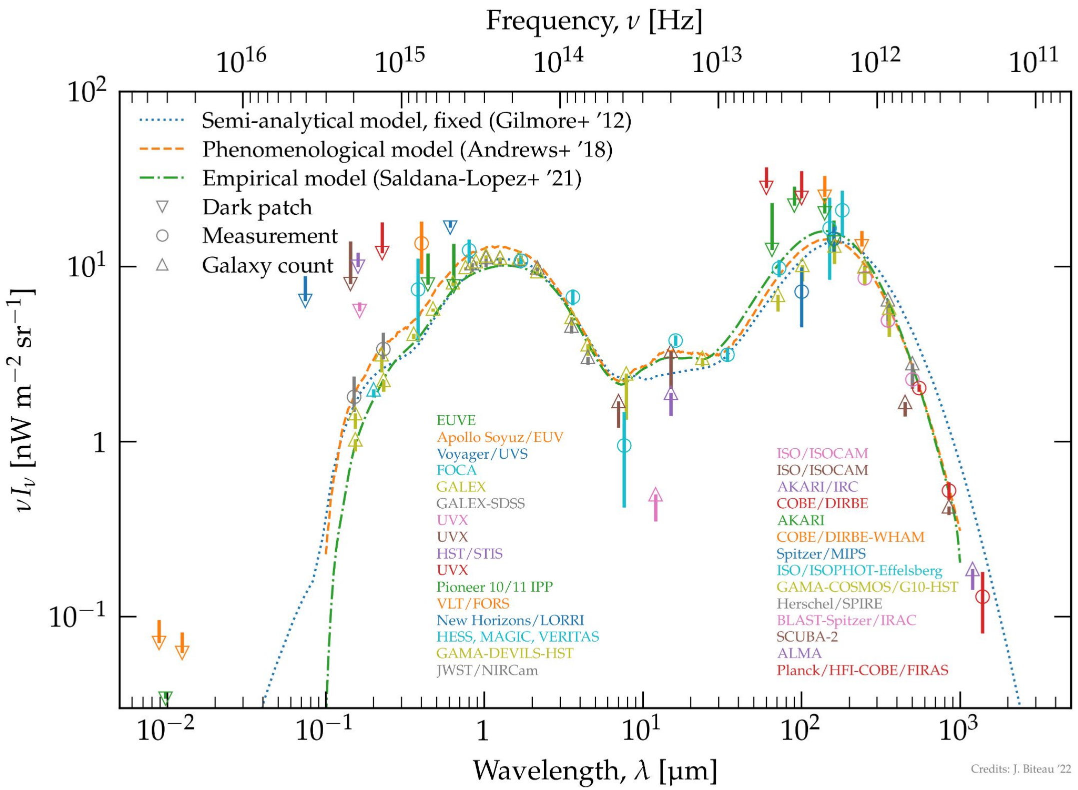
- ❑ Galaxy counts: 5-10% accuracy, 1% in coming years?
- ❑ Dark-patch estimates suggest unaccounted Zodi component. Puzzle from New Horizons.
- ❑ ɣ-ray measurements still lack accuracy to solve the puzzle.

Models

- ❑ Impressive convergence over the past ten years.

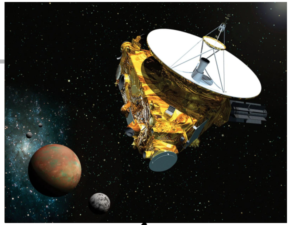
CTA and precursors

- ❑ Beat the systematics.
- ❑ Solve the optical controversy.
- ❑ Measure AGN & PAH contributions.



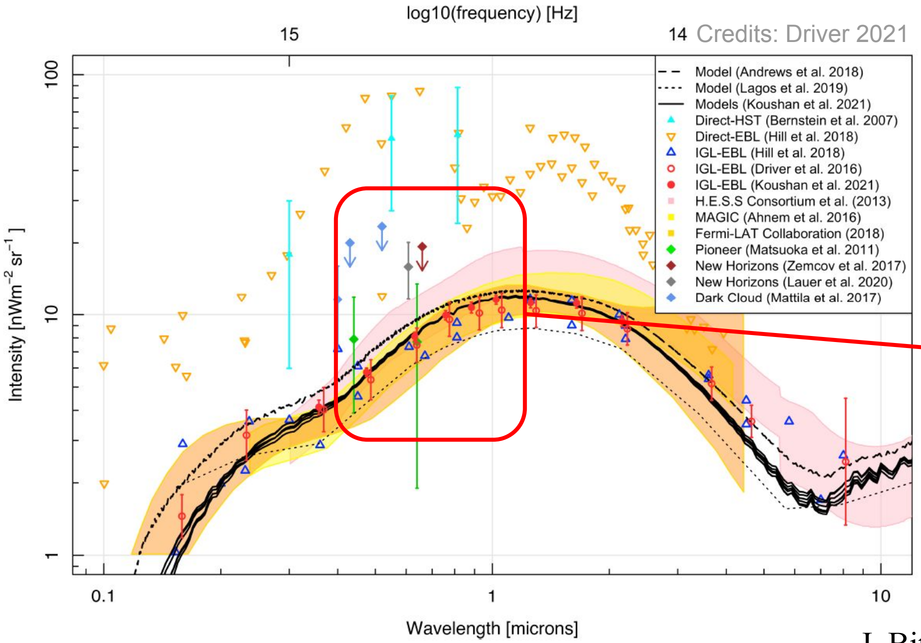
The “optical controversy”

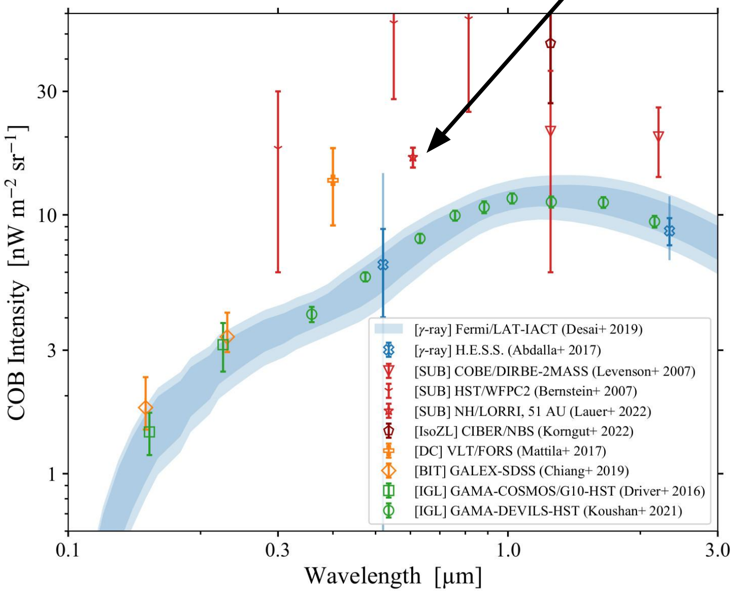
Spacecrafts out of the Solar System at [this link]



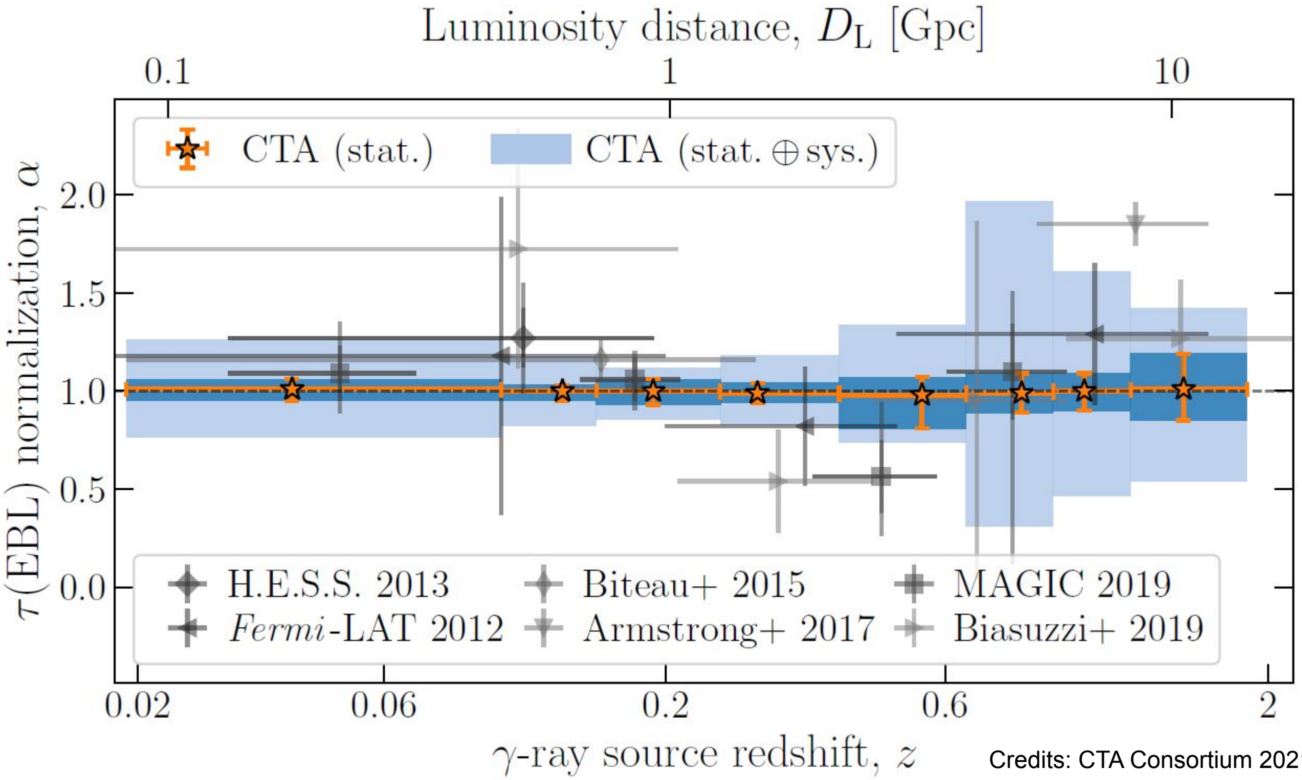
Recent news: New Horizons / LORRI

- Darkest, reliable field: 16.4±1.5 nW m^{-2} sr^{-1} (Lauer+ 2022)
- If of extragalactic origin: galaxy counts = half of EBL @ 0.6μm



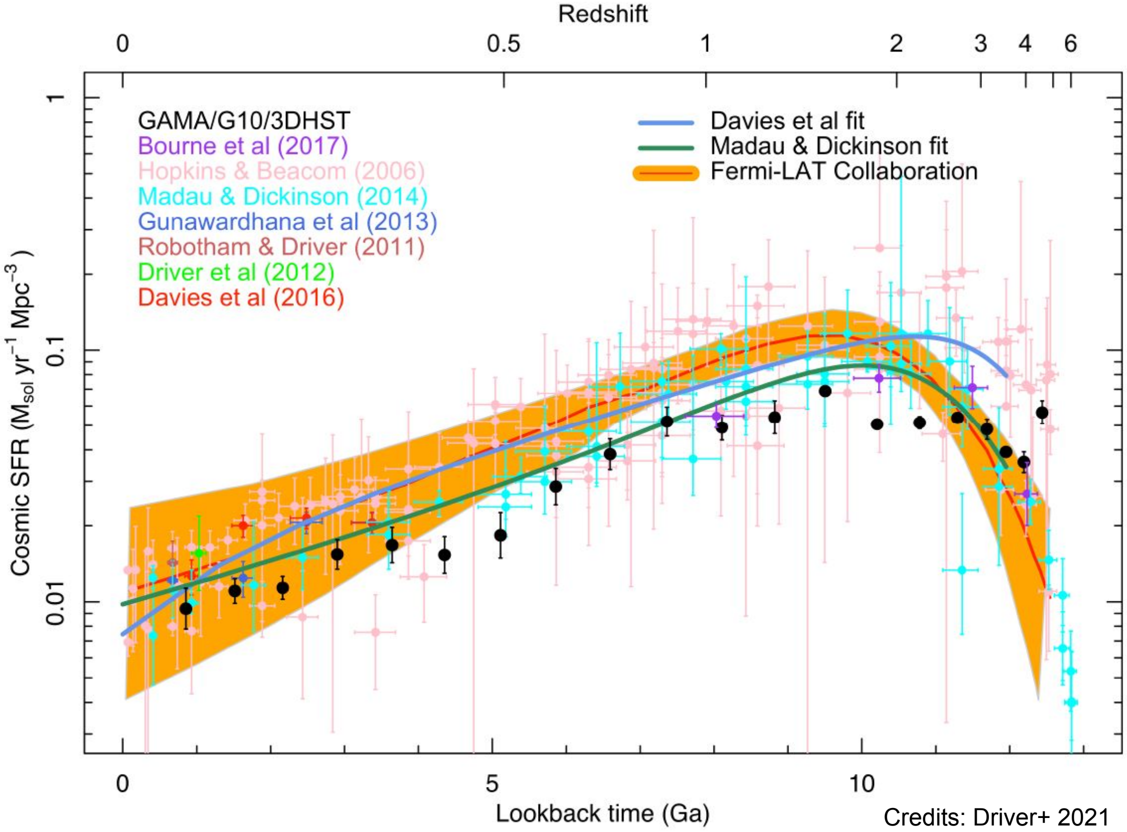


EBL (and SFR): expectations from CTA



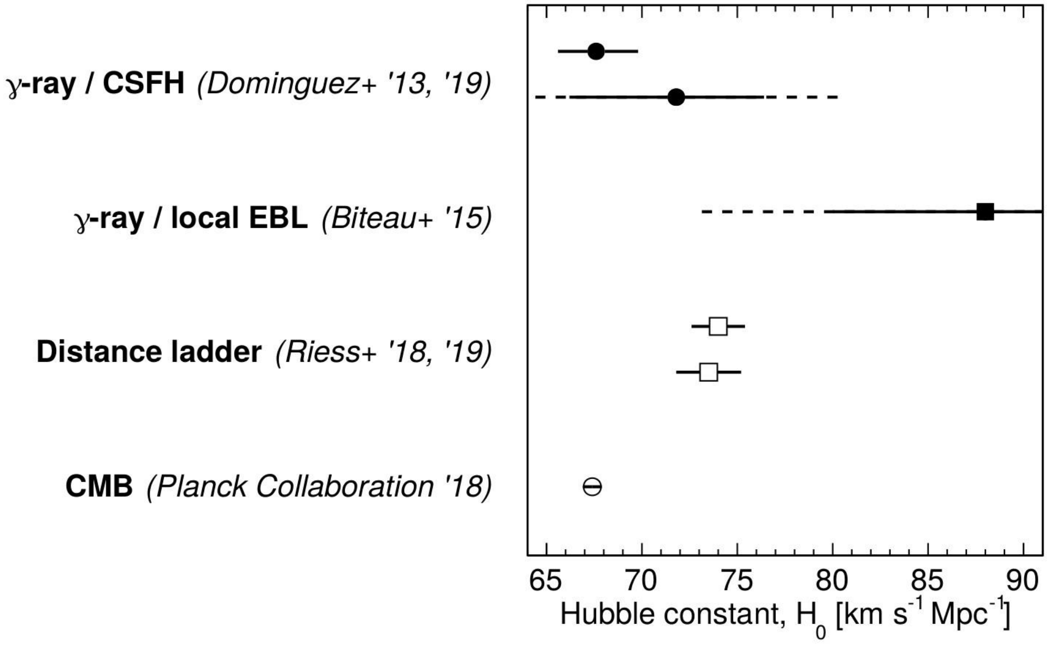
Credits: CTA Consortium 2021

Cosmic star-formation history



Credits: Driver+ 2021

Hubble constant



Credits: Pueschel & JB 2021

How to:

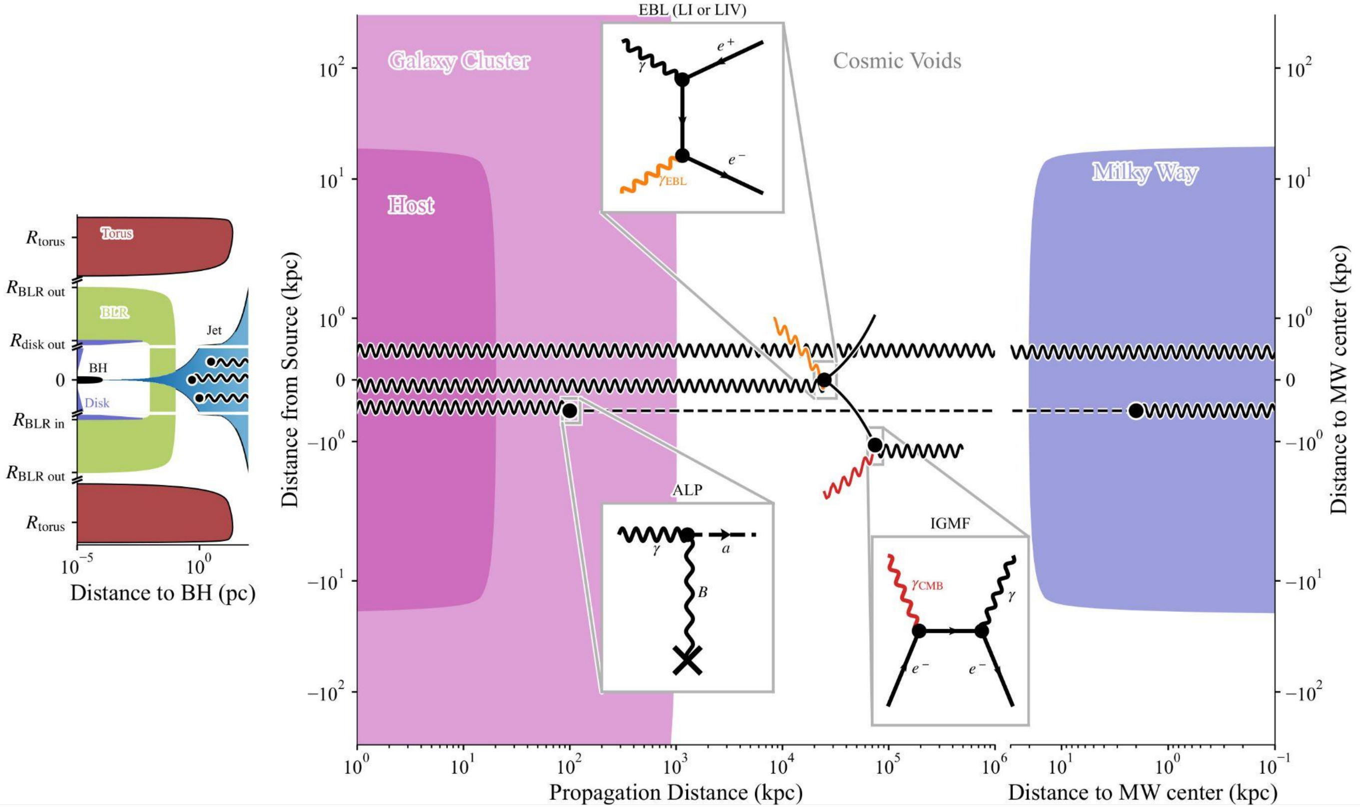
$$F_{\rm obs}(E) = F_{\rm emitted}(E(1+z_0)) \times \exp[-\tau_{\gamma\gamma}(E, z_0)]$$

$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} \Gamma_{\gamma\gamma}^{-1}(E(1+z), z) \frac{d\ell(z)}{dz} dz$$

$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^{\infty} d\epsilon' \frac{dn(\epsilon', z)}{d\epsilon'} \int_{-1}^{1} d\cos\theta' \frac{1-\cos\theta'}{2} \sigma_{\gamma\gamma}(\beta') \Theta(\epsilon' - \epsilon'_{\rm th})$$

$$\partial n/\partial\epsilon = (1+z)^3/c \times \int_z^{\infty} dz' \, d\ell/dz' \times j(\epsilon', z')/\epsilon'$$

ɣ-ray propagation from sources down to Earth

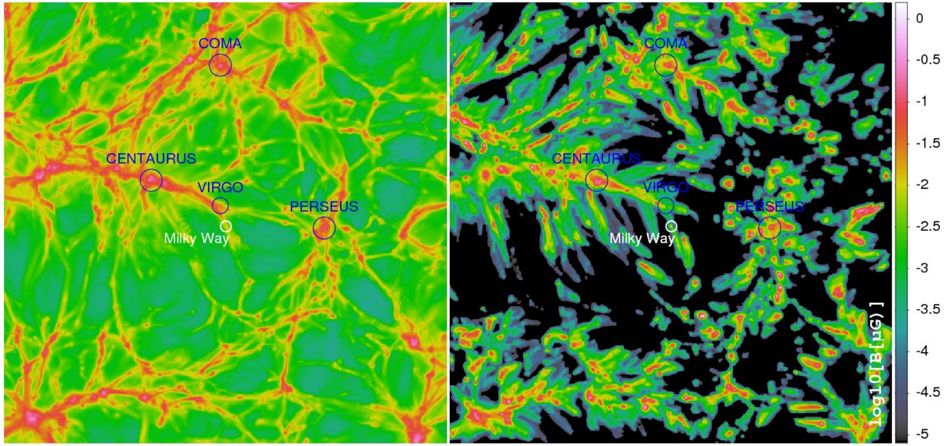


Magnetic fields in voids

Status and expectations (if low plasma instabilities)

Current-generation (GeV+TeV - TeV extension): B > 10-100 fG

5σ CTA-discovery potential up to 300 fG



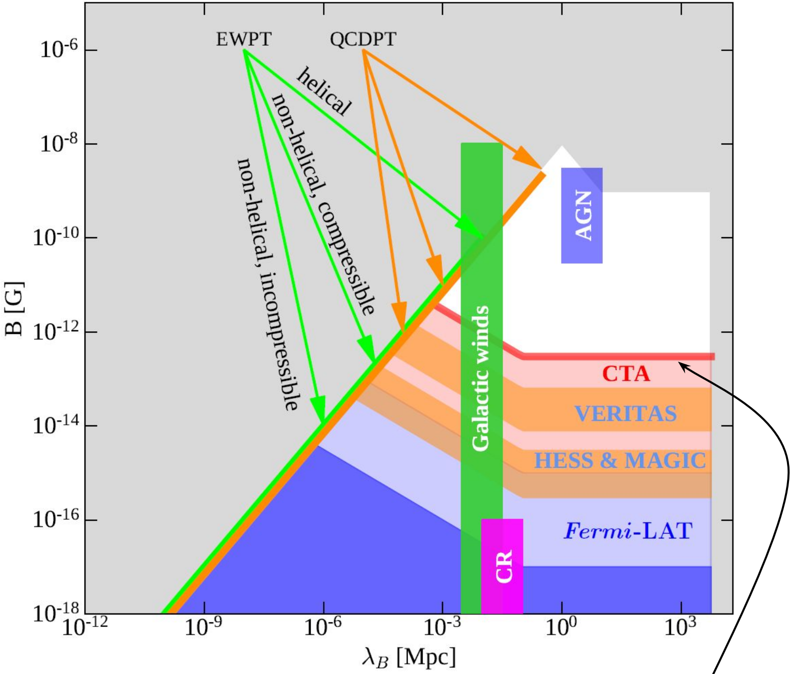
Credits: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG

Astrophysical origin simulation
B(void) < 1 pG

In practice… largely unknown!

Credits: CTA Consortium 2021

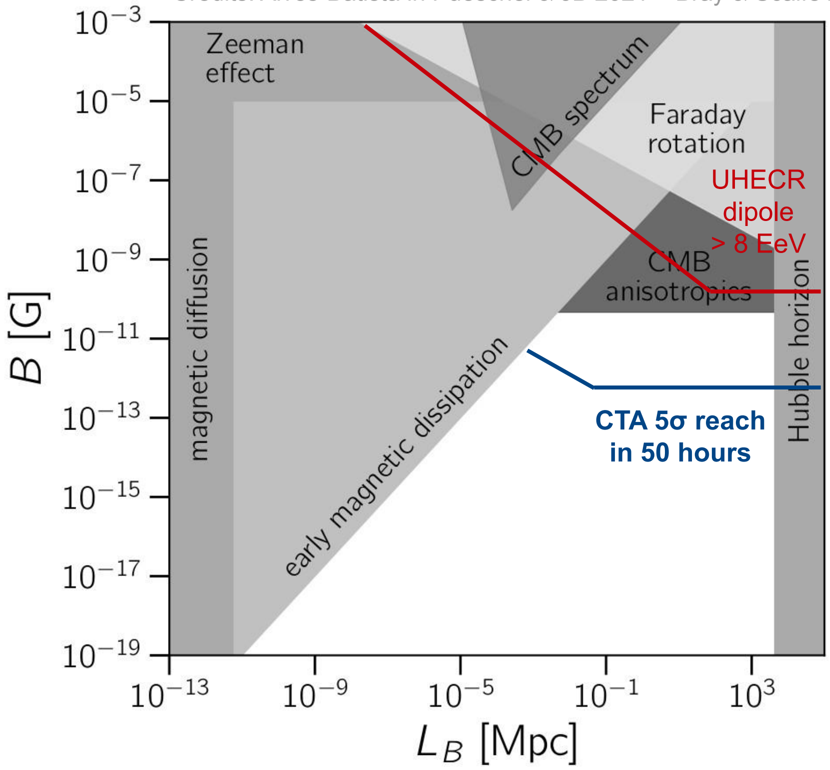


1ES 0229+200 (z=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

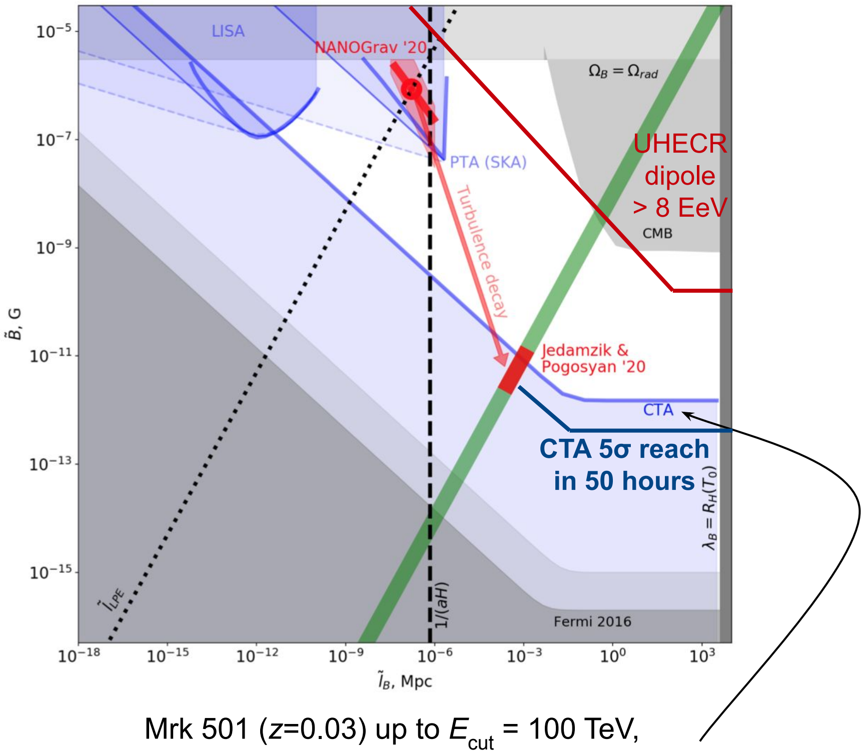
J. Biteau

Multi-wavelength and multi-messenger constraints

Credits: Alves-Batista in Pueschel & JB 2021 + Bray & Scaife 2018 (UHECR)

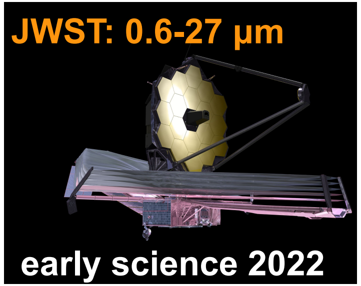


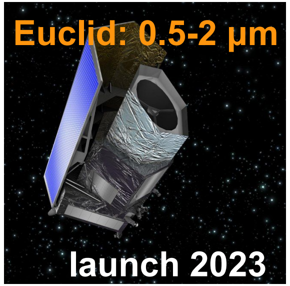
Credits: Neronov+ 2021+ Bray & Scaife 2018 (UHECR)

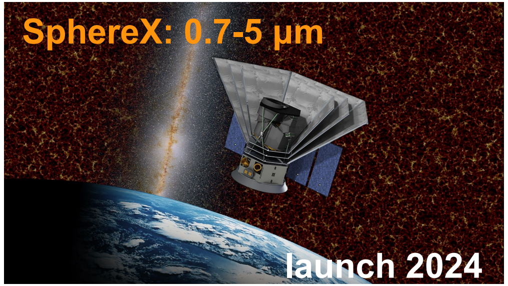


Mrk 501 (z=0.03) up to E_{cut} = 100 TeV,
350h of CTAO-North to reach 5σ

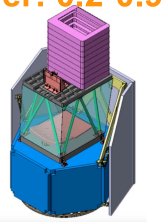
Gamma-ray cosmology in the upcoming CTA era







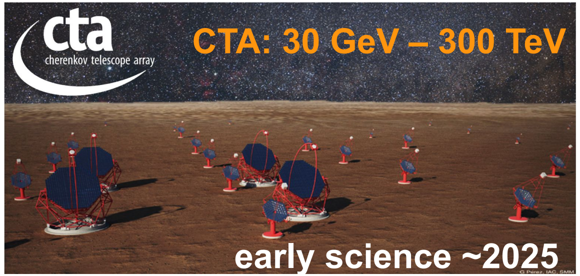
Messier: 0.2-0.9 µm



proposed to ESA-F2
not selected

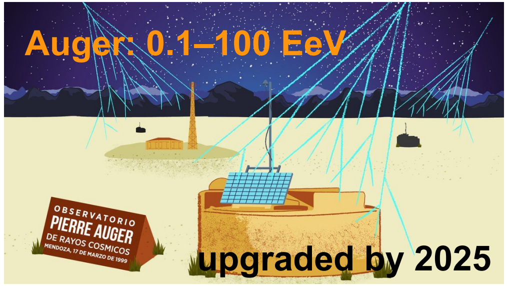
Light in voids and faint galaxies

- Low-end of the galaxy luminosity function
- Redshift surveys ∩ Broadband intensity mapping
- Low-surface brightness universe
- Gamma-ray absorption



Cosmic magnetism

- Gamma-ray halo and spectral bump
- UHECR deflections in the cosmic web
- Synchrotron mapping and Faraday rotation

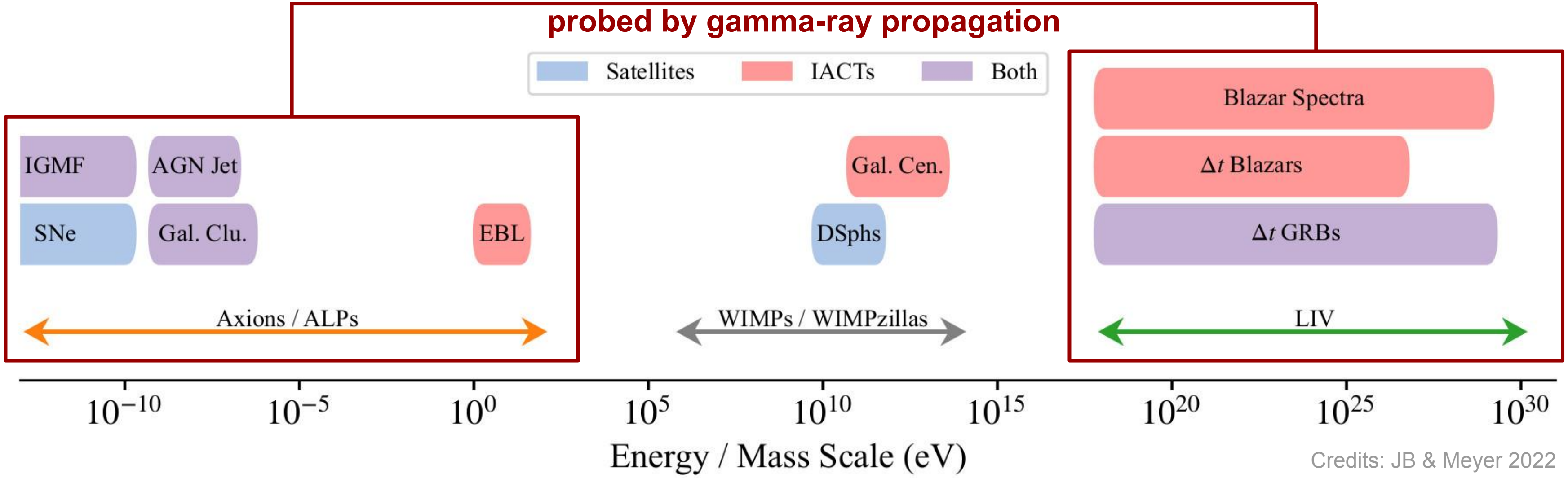


Aparté: ɣ-ray propagation and fundamental physics

Dark matter: what is that? Theories beyond QFT and GR: is there anything to observe?

- Top-down processes (*heavy axion-like particles* /*or WIMPs*/): decay /*or self annihilation*/ into photons
- Mixing with light axion-like particles (ALP): CTA will start probing ALP dark-matter parameter space CTA 2021
- LIV linearly modified dispersion relation (CPT-odd): Planck scale ~excluded by spectra & Δt!

⇒ *High-risk / high-gain themes. Notes: ALP constraints dependent upon B-field morphology in jet*



Credits: JB & Meyer 2022

Extreme-TeV blazars as cosmological beacons

Absorption on the line of sight - *observed since 2012*

- γ(TeV) + γ(eV) → $e^+ + e^-$
  → 0.1-10 eV target photon field: extragalactic background light
- Extreme-TeV emission > 10 TeV: unique integral probe of EBL at ~0.1 eV (mid- to far-infrared), complementarity with JWST!

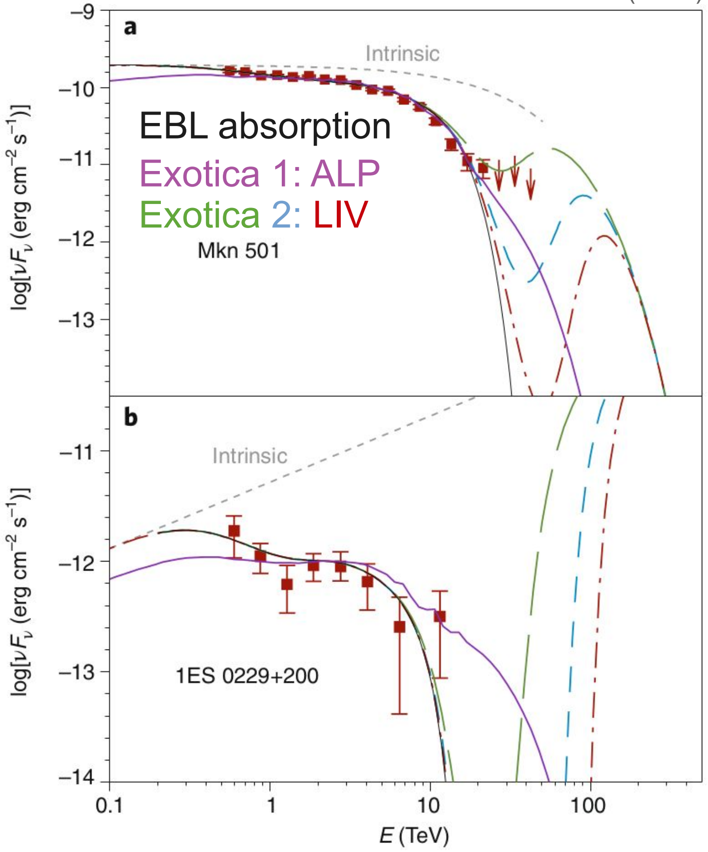
Cooling of e^+/e^- pairs - *not observed, tight constraints*

- Either plasma instabilities
  → intergalactic medium heating
- Or inverse Compton on CMB (secondary γ-rays >1 GeV)
  → probe of intergalactic *B*-fields up to pG level CTA (2021)

Exotic physics - *not observed, tight constraints*

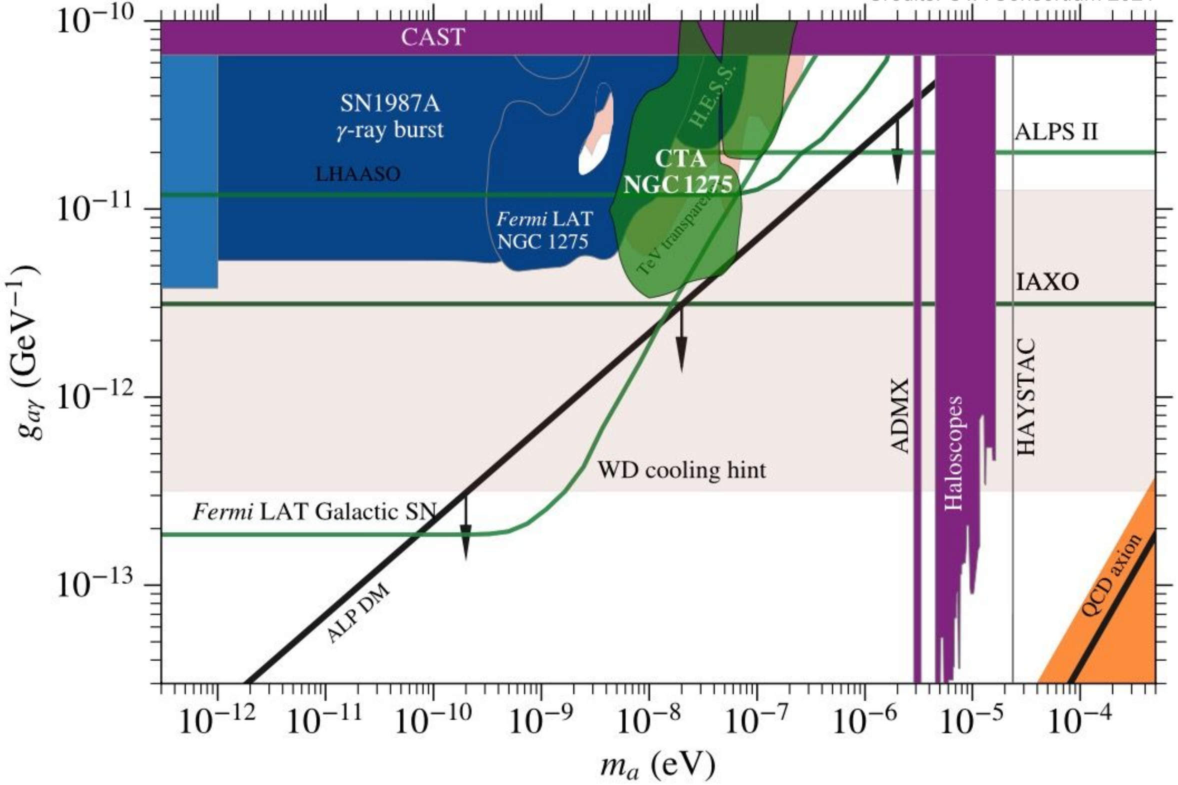
- Lorentz invariance violation (LIV) or axion-like particles (ALPs)
  → increased transparency at highest energies / optical depths

Biteau et al. (2020)



Constraints on ɣ-ray coupled axions

Credits: CTA Consortium 2021

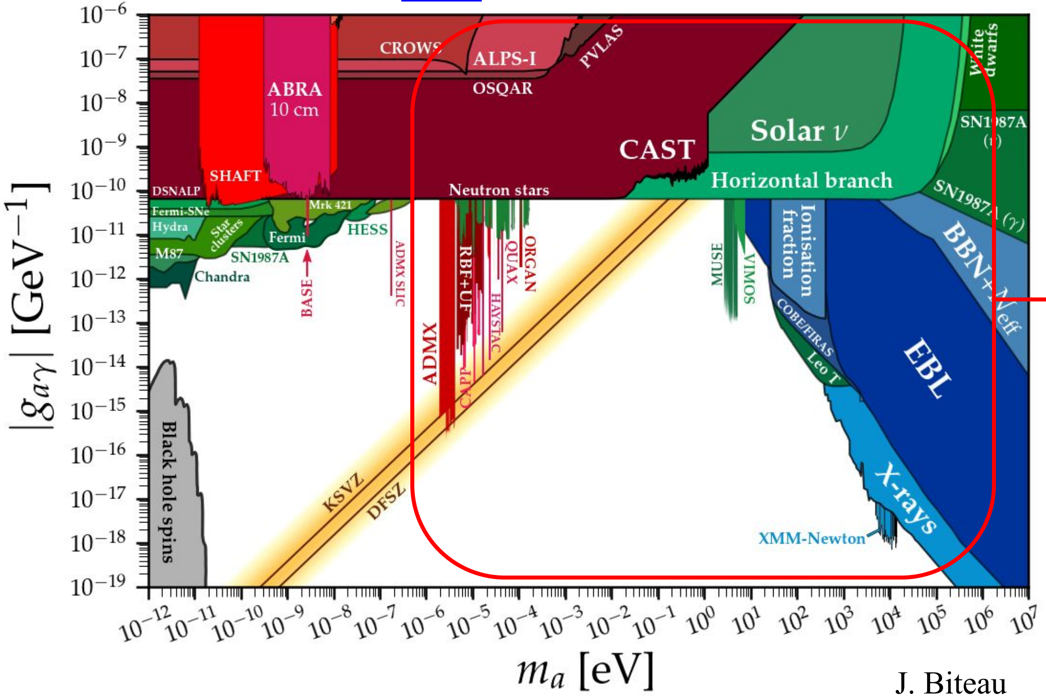


Constraints on decaying axions

Exotic contributions to the night-sky brightness?

- Top-down process: decay of heavy (eV) axion-like particles. Update of ALP constraints from EBL TBD!

Credits: O'Hare 2020 at this link



Credits: Arias+ 2012