cherenkov
telescope
array

# Prospects on the content of cosmic voids with the Cherenkov Telescope Array

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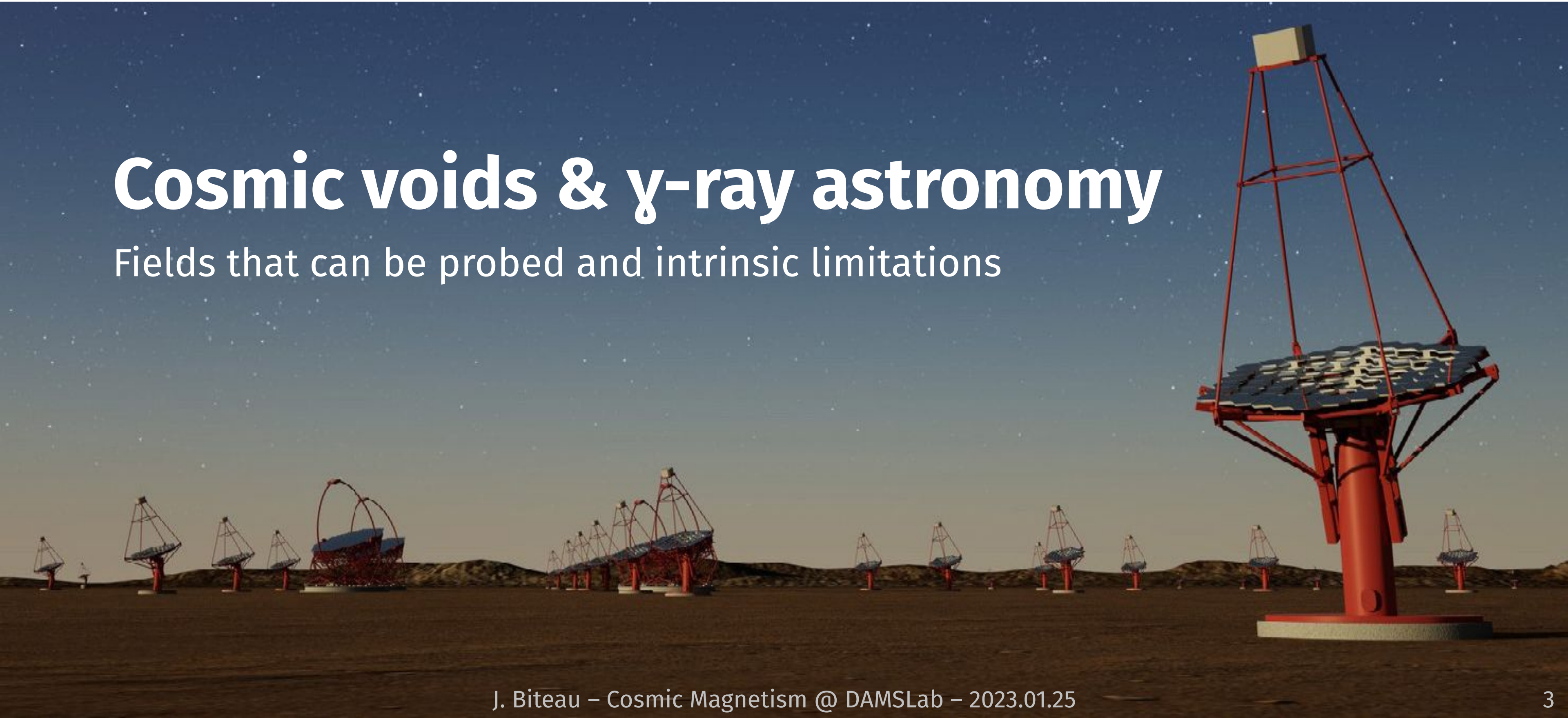
Université Paris-Saclay, IJCLab

# Contents

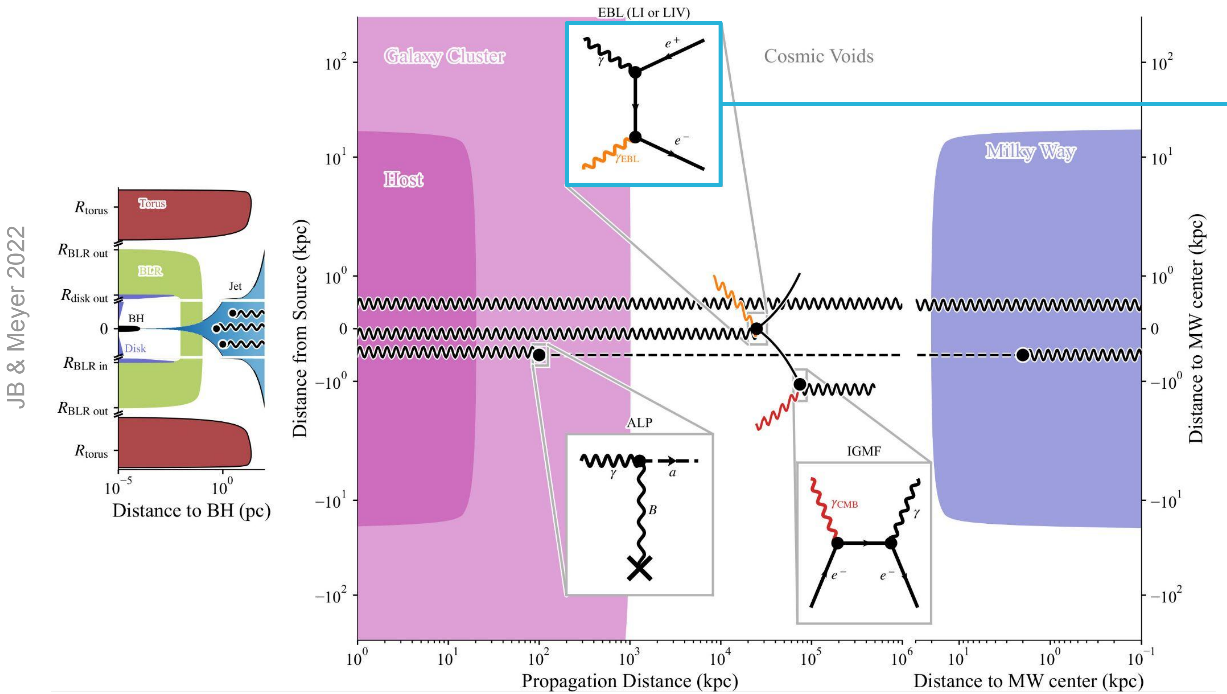
cherenkov telescope array

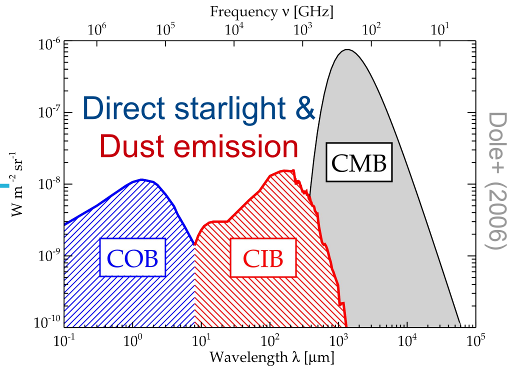
# Cosmic voids & γ-ray astronomy

Fields that can be probed and intrinsic limitations



# Ɣ-ray propagation on cosmic scales



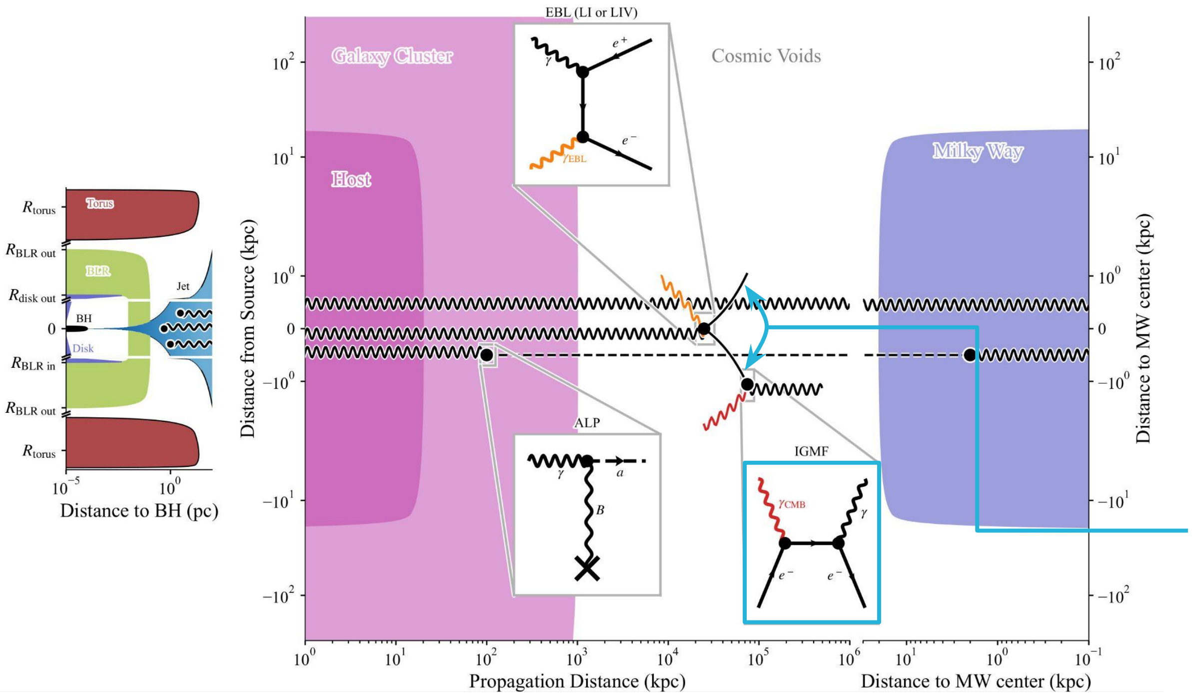

Limitations:

- Ɣ-ray sources ≠ standard candles
- Tensions in COB/CIB estimates

→ overcome over past 10 yrs

# γ-ray propagation on cosmic scales

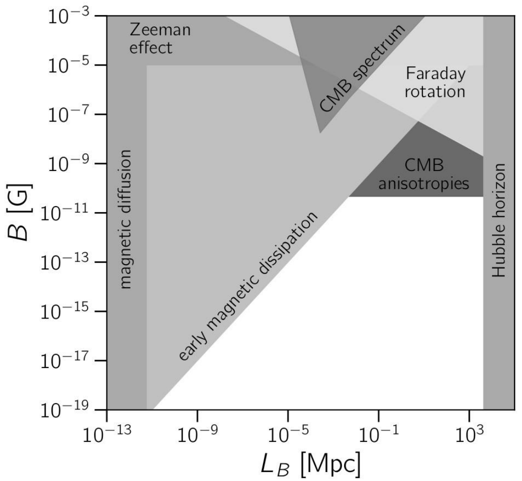
JB & Meyer 2022




Limitations:

- Inverse Compton may not be the only cooling mechanism
- Wide range of B-fields to test

→ to overcome in the next yrs

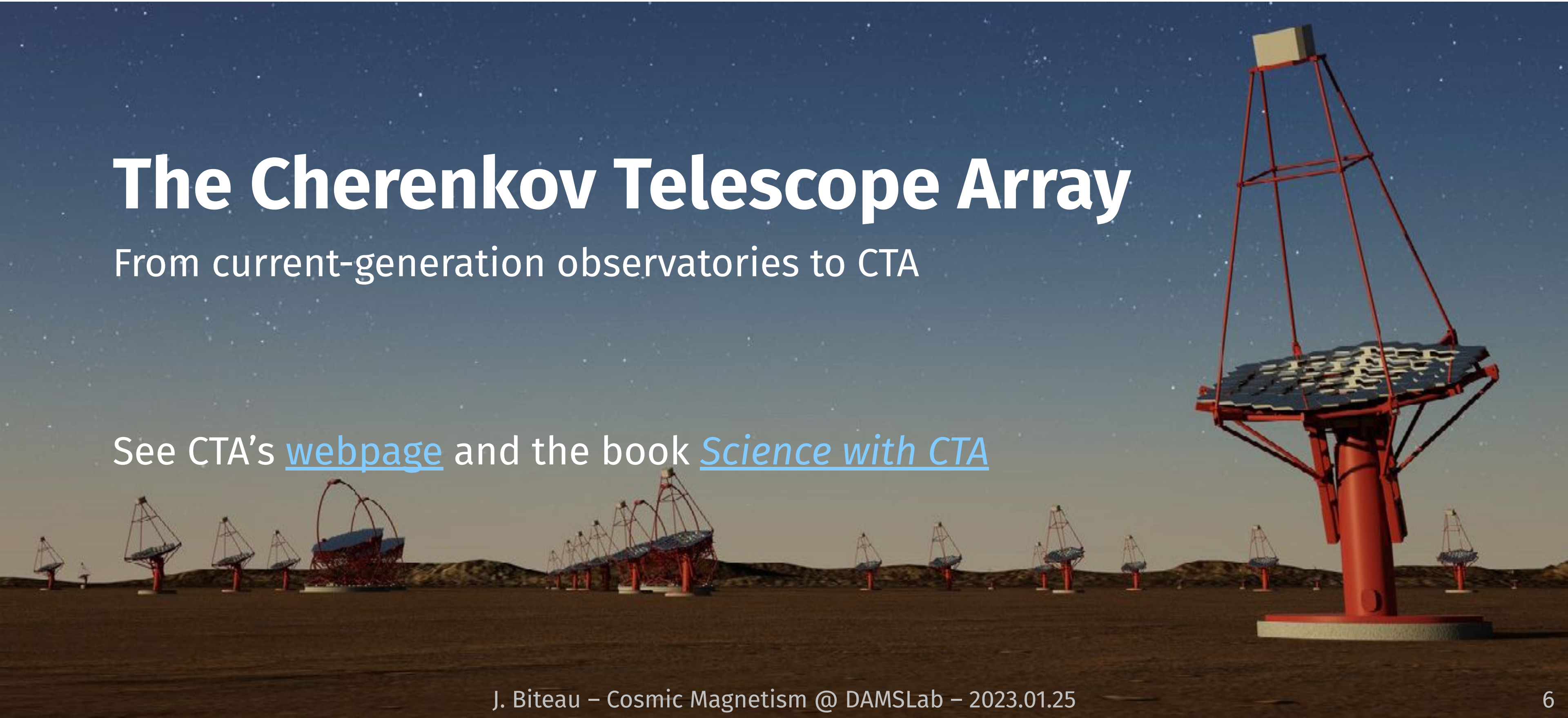



Alves-Batista in Pueschel & JB 2021

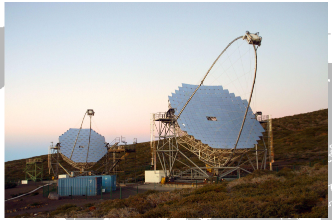
# The Cherenkov Telescope Array

From current-generation observatories to CTA

See CTA's [webpage] and the book *Science with CTA*



# Major TeV observatories

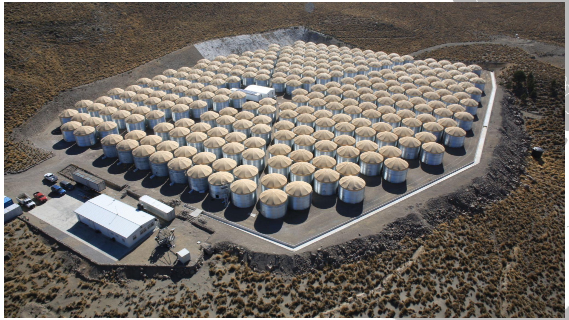


**VERITAS**

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

**HAWC**

Particle-detector water tanks (2015)



**MAGIC**

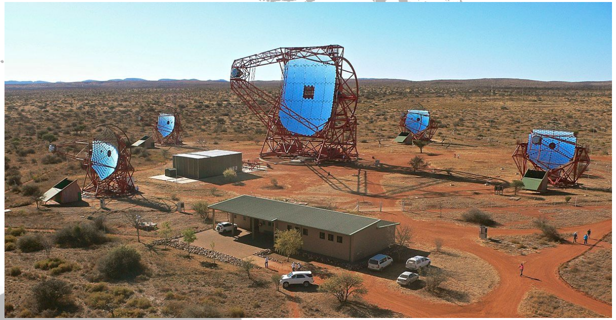
2 Large-Sized Tel. ('LSTs')
2004: MAGIC-I
2009: MAGIC-II
2012: PMT upgrade

**LHAASO**

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

**H.E.S.S.**

4 MSTs (2003)
+ 1 LST (2012)



# Evolution the TeV sky

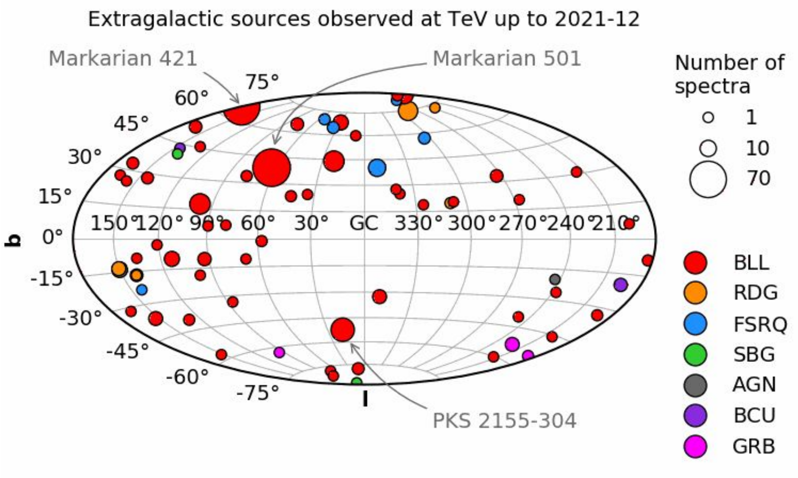
## 1989 – early 2000s

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

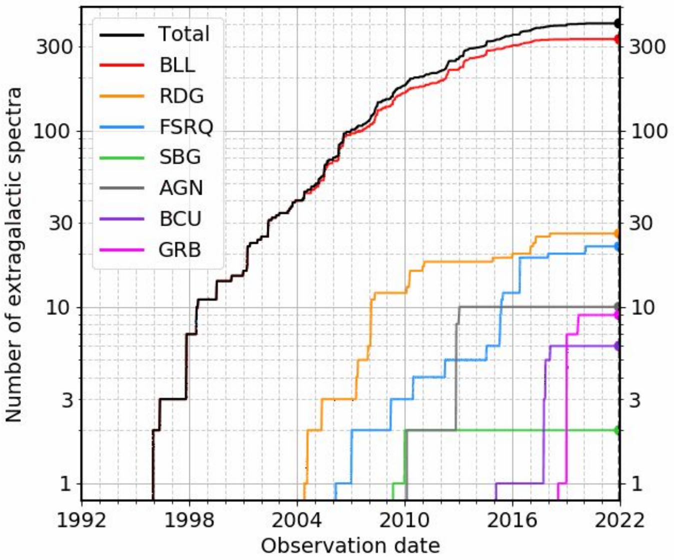
## 2003-Now

Growth triggered by H.E.S.S./MAGIC (2003/04), VERITAS (2007), HAWC (2015), LHAASO (2019)

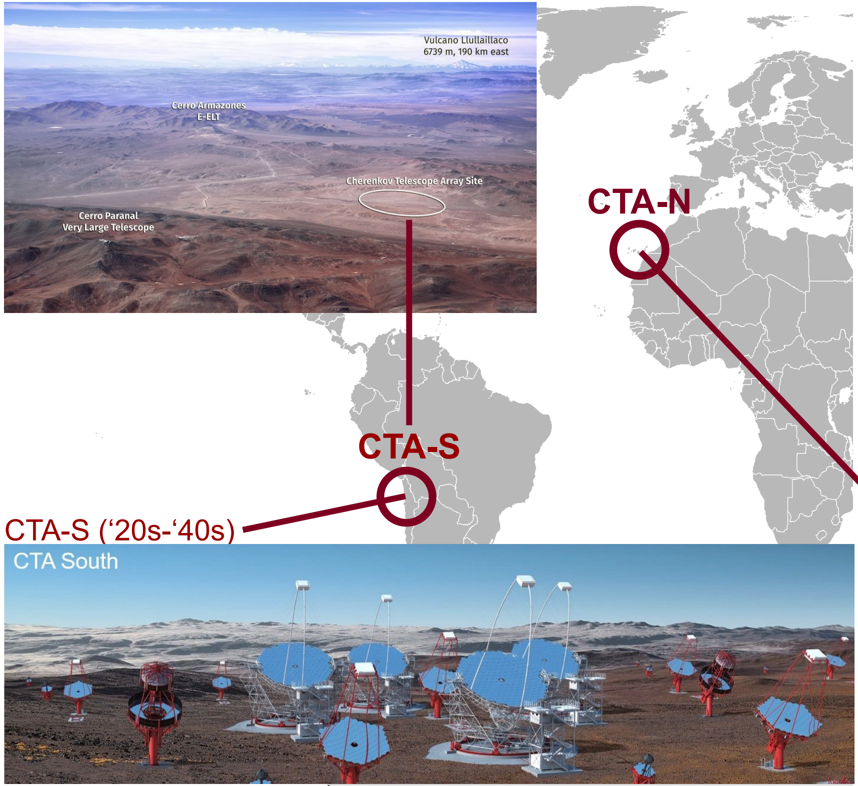
**>250 sources!** A much-larger-than-expected **variety** of objects! **E.g. for the extragalactic sky**



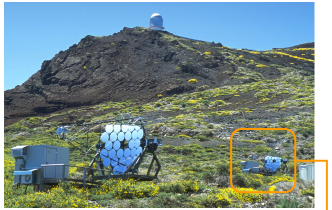

Credits: Lucas Gréaux, IJCLab (upcoming STeVECat)



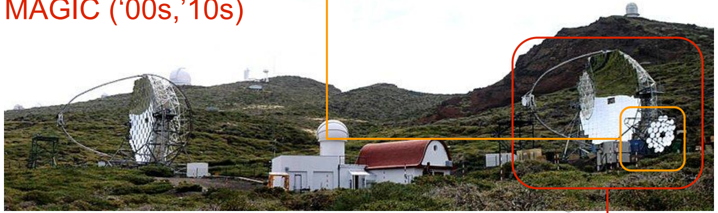
# Why do we build CTA




HEGRA ('90s)



MAGIC ('00s,'10s)



CTA-N ('20s-'40s)


**2 sites to access the entire sky**

Sensitivity: 5-10× better than current

E-range: 0.02-300TeV (vs 0.1-10TeV)

$\Delta E/E$ <10% (vs <17%) >0.2TeV

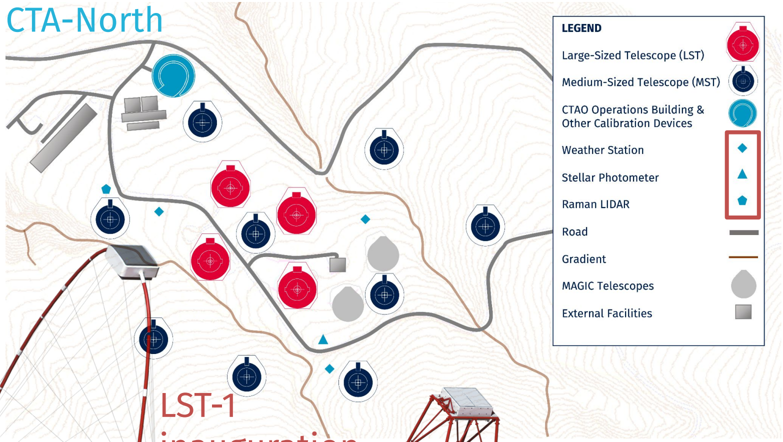
$\Delta\theta$ <3' at $E$ > 1 TeV (vs 5')

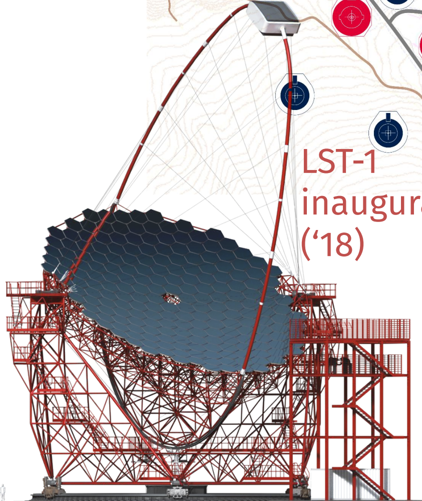
# Optimized layout (α configuration)

## Science-based optimization

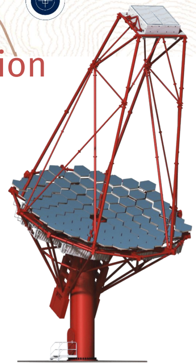
North: extragalactic oriented (high-*E*/*z* absorption)

CTA-North

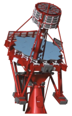


LST-1 inauguration ('18)



MST camera agreement ('20)

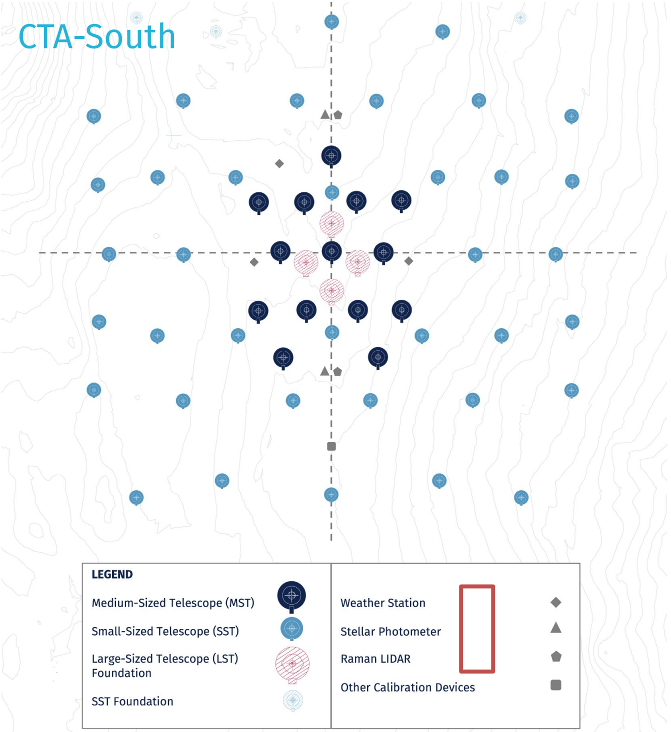


Single SST design ('18-19)

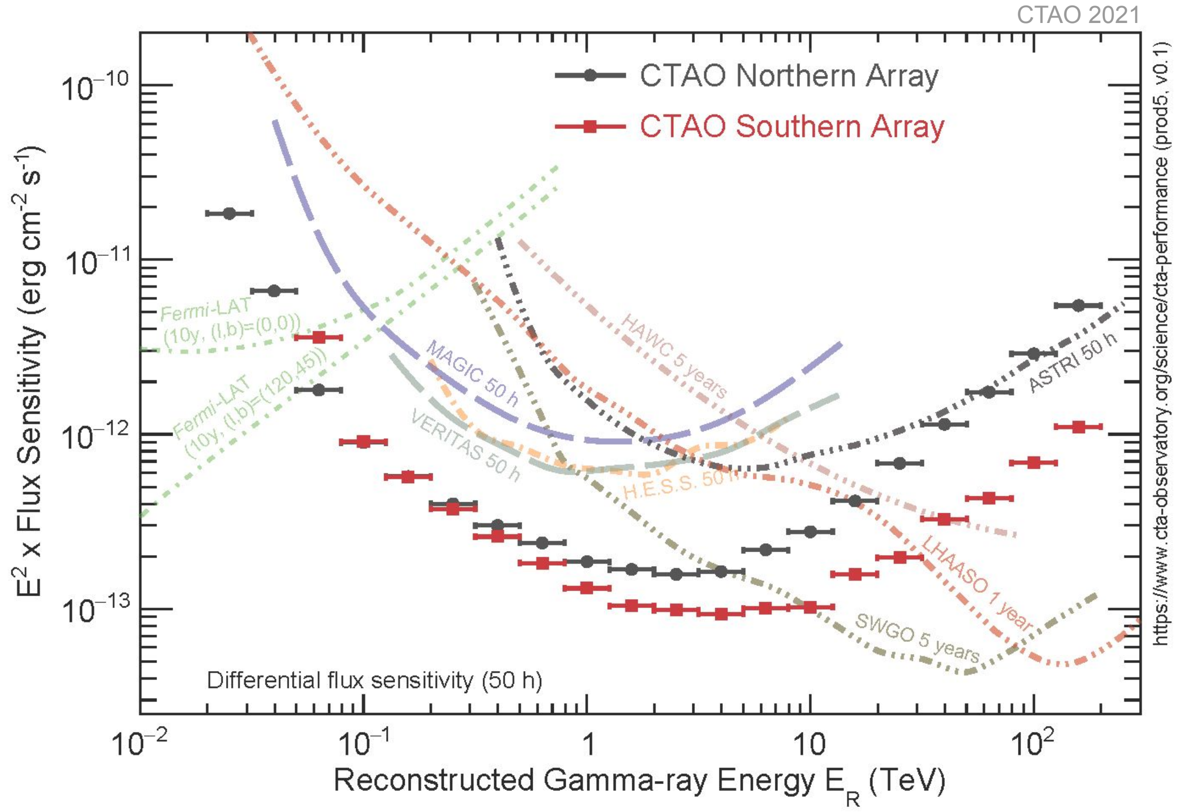
## Shower-based optimization

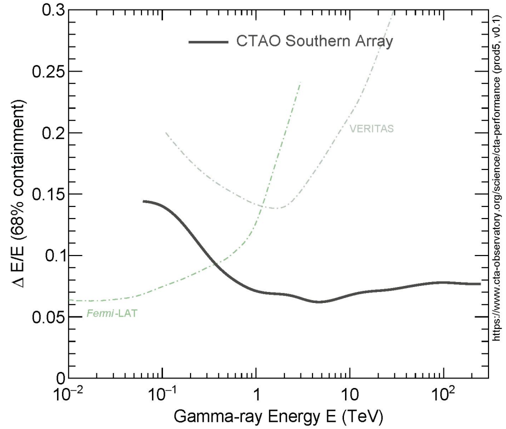
LSTs 20-150 GeV, MSTs 0.15-5 TeV, SSTs >5 TeV

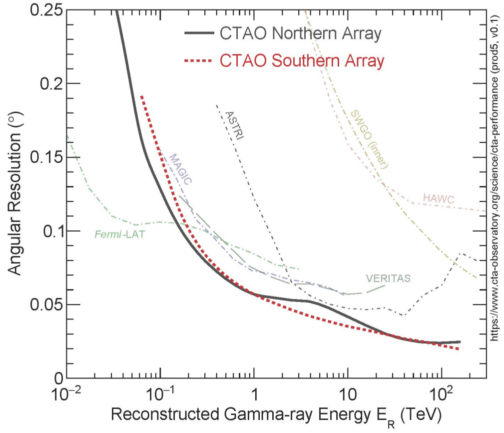
CTA-South



# Comparative performance



# Users of the CTA observatory

## The CTA Observatory

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

## Time distribution (first 10 years)

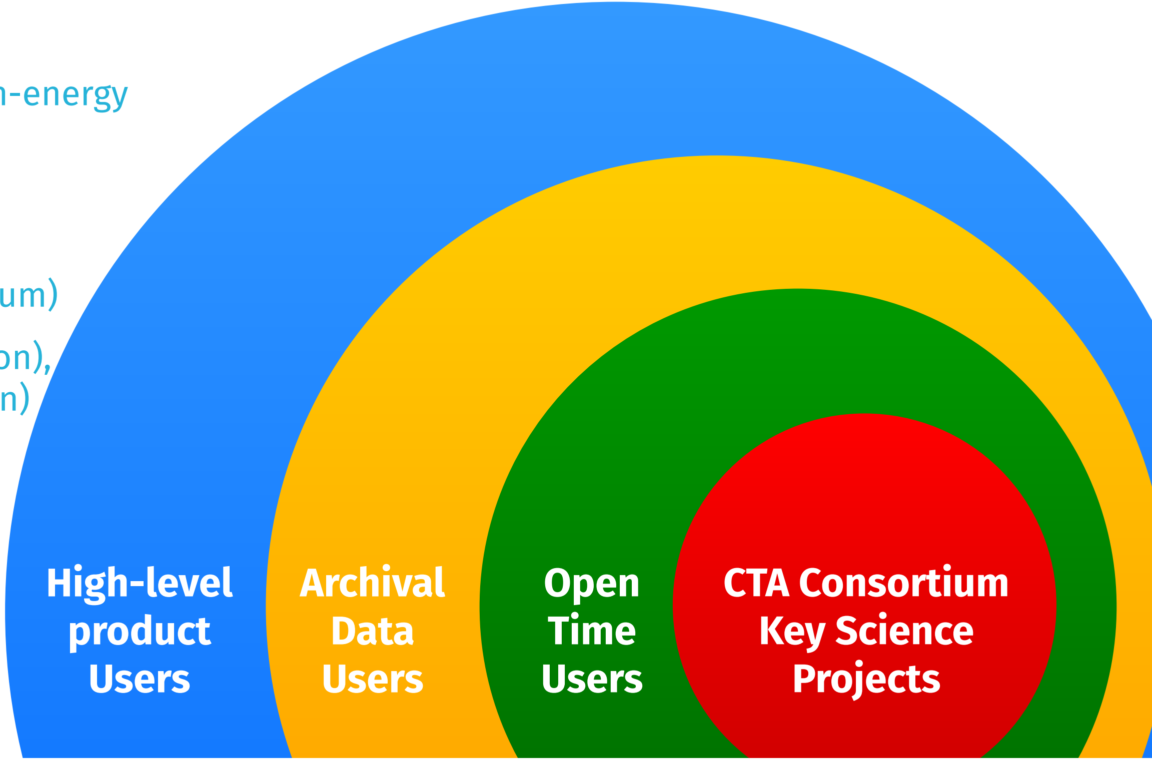
~40% Key Science Projects (CTA Consortium)

~60% remaining: User time (larger fraction),
Host-country time (smaller fraction)

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

## Open data

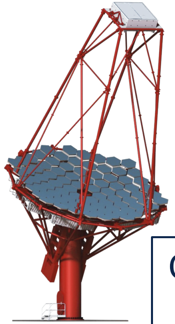
High-level data accessible after a one-year proprietary period

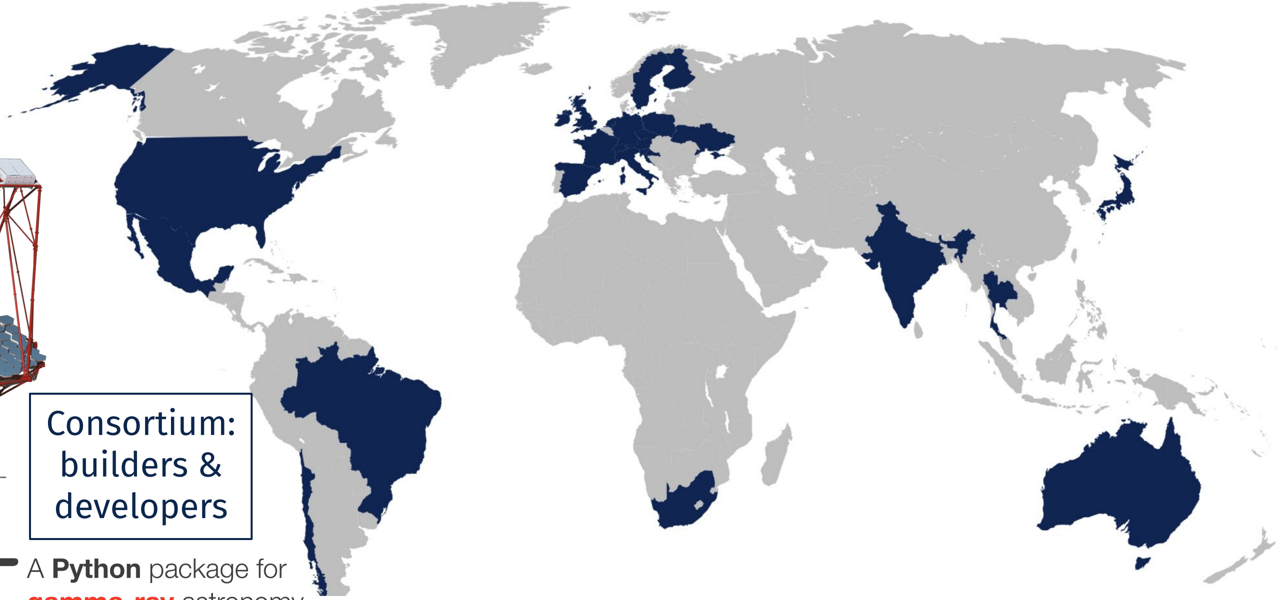


# Core Science and Observations

## The CTA Consortium

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





Consortium: builders & developers

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

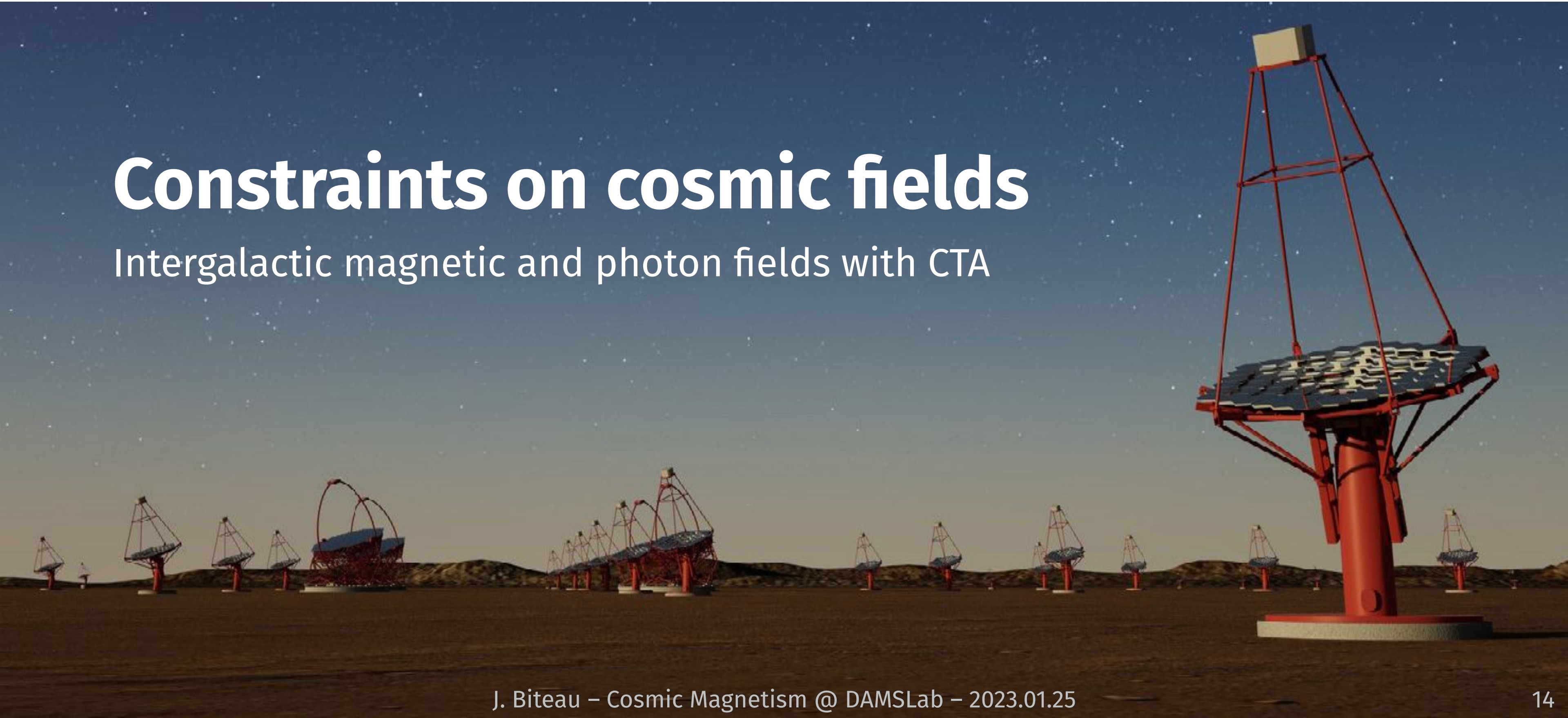

https://doi.org/10.1142/10986

**CTA Consortium Key Science Projects**

cherenkov telescope array

# Constraints on cosmic fields

## Intergalactic magnetic and photon fields with CTA



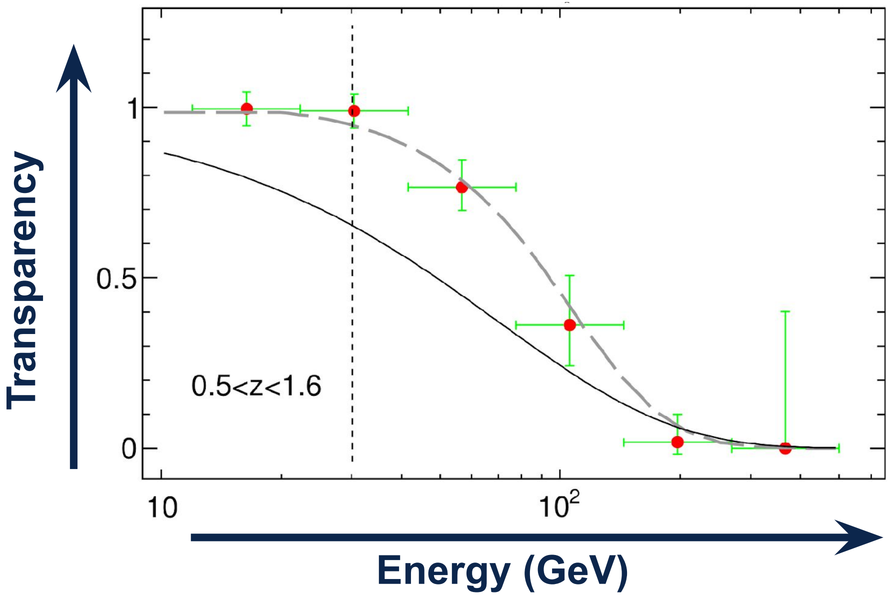
# Cosmic γ-ray absorption

## First model-dependent detections

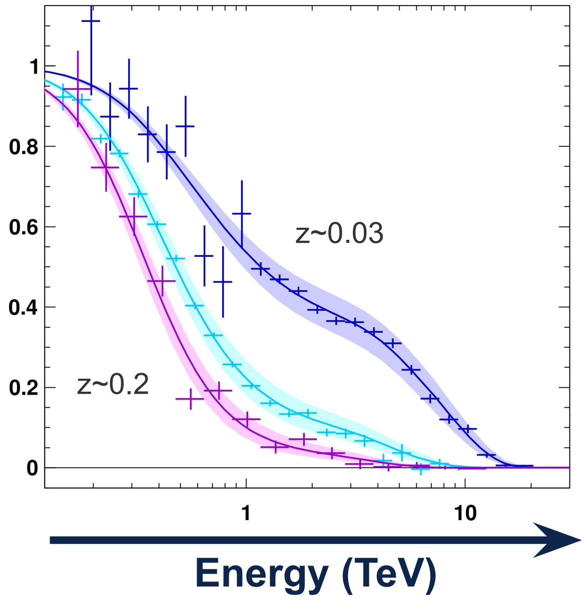
Reconstruct normalization of EBL density, α, wrt models of galaxy-counts: $\Phi_{\mathrm{obs}} = e^{-\alpha\tau(E_0,z_0)}\,\Phi_{\mathrm{intr}}$

Imprint now detected at > 11σ, compatible galaxy counts. Current precision on α: 20-30%.

Fermi-LAT 12



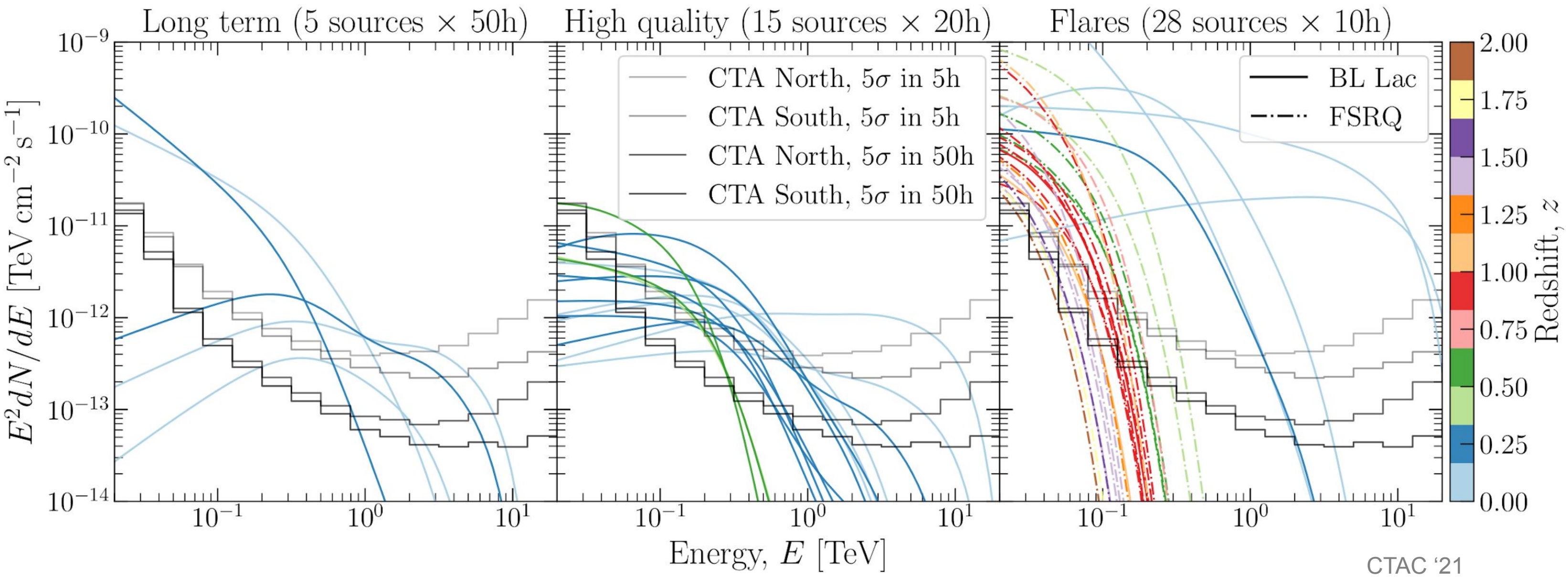

H.E.S.S. 13



# Simulations for CTA-N and CTA-S

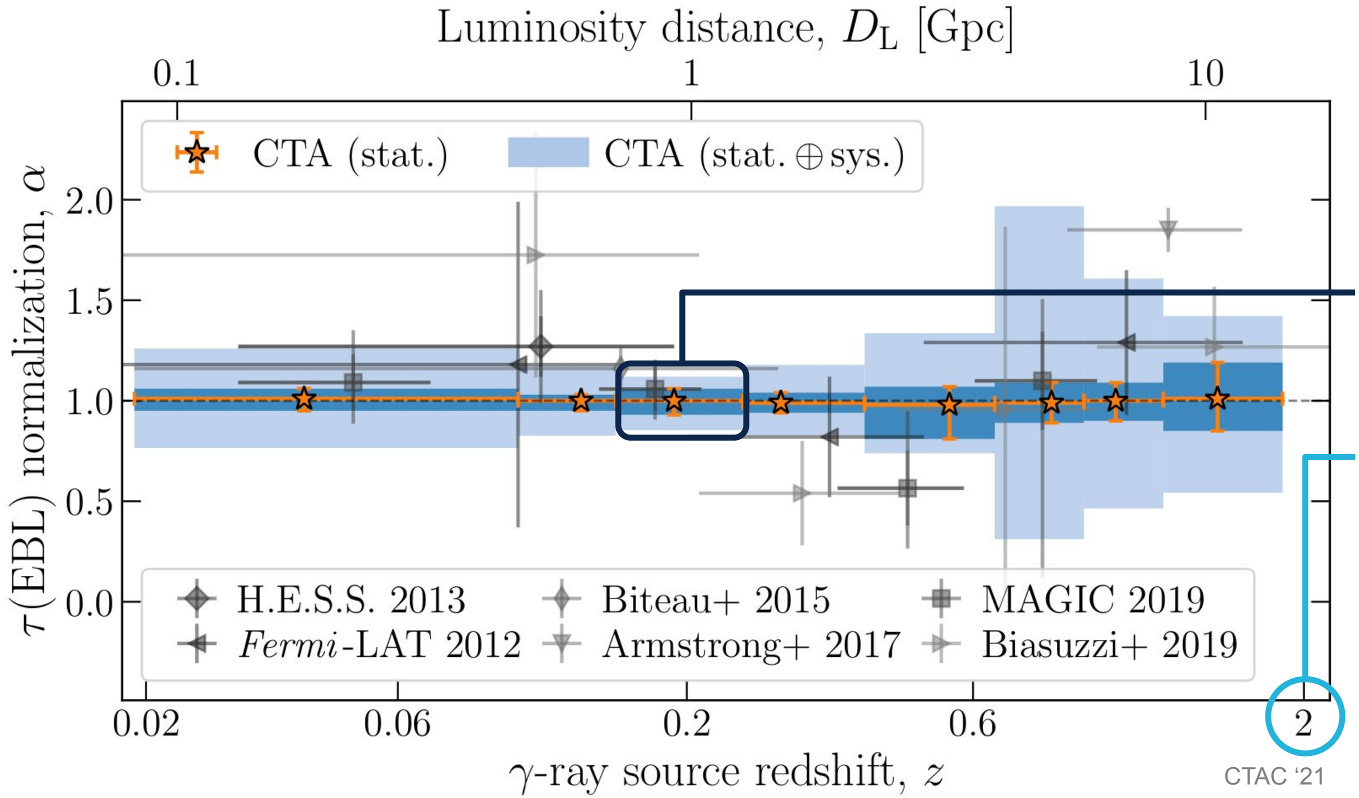
## Observation time anticipated as part the AGN Key Science Project

Selection of ~50 sources detectable at high optical depths → 830h i.e. ~10 months full-time from one site
Quiescent / flaring states from current-generation GeV-TeV observations, including high-*E* cutoff




CTAC '21

# Measurement as a function of $z$




Best at $z \sim 0.2$:
$\pm$ 5%$_{\text{(stat)}}$ $\pm$ 12%$_{\text{(syst)}}$

Up to $z \sim 2$
($z \sim 1$ for current TeV observatories)

*Constraints limited by instrument systematics*

# Cosmic γ-ray cascades

## Observables

1) Time delays

$\Delta t \sim 3$ yrs $(E/0.1\text{TeV})^{-1}(B/10^{-16}\text{G})^2$

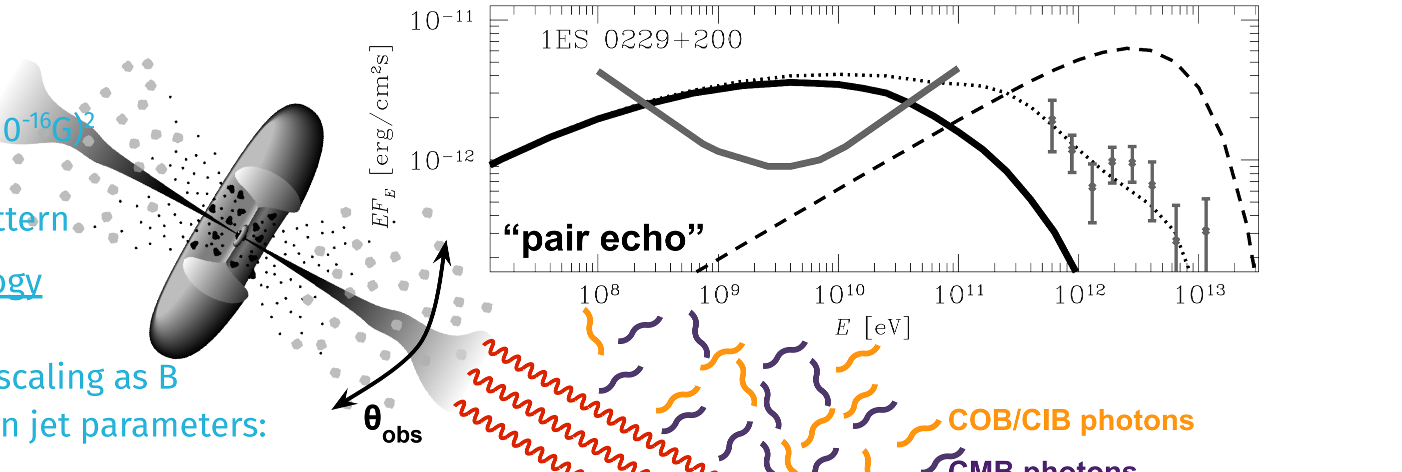
Useful for low B-field,
limited by variability pattern

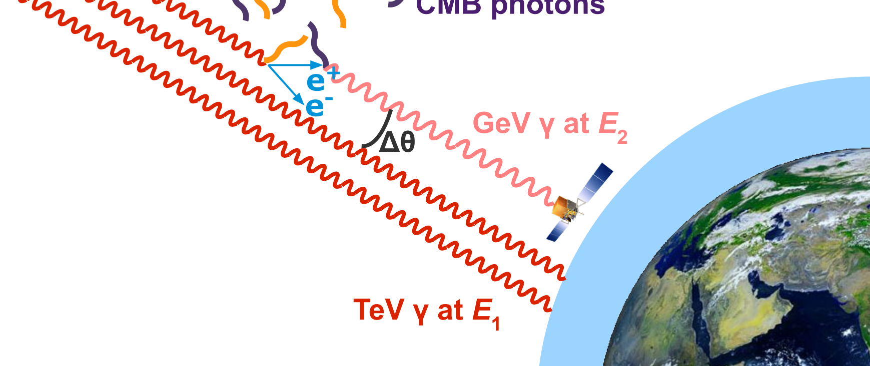
2) Spectrum & morphology

$E_2 \sim 80$ GeV $(E_1/10\ \text{TeV})^2$

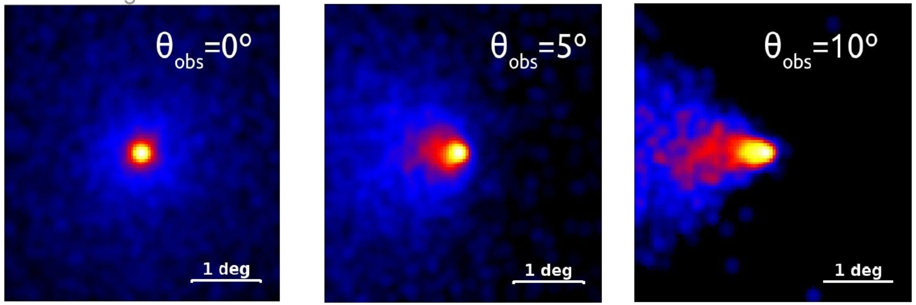
Degree-scale extension scaling as B
whose shape depends on jet parameters:

Neronov & Vovk ‘10

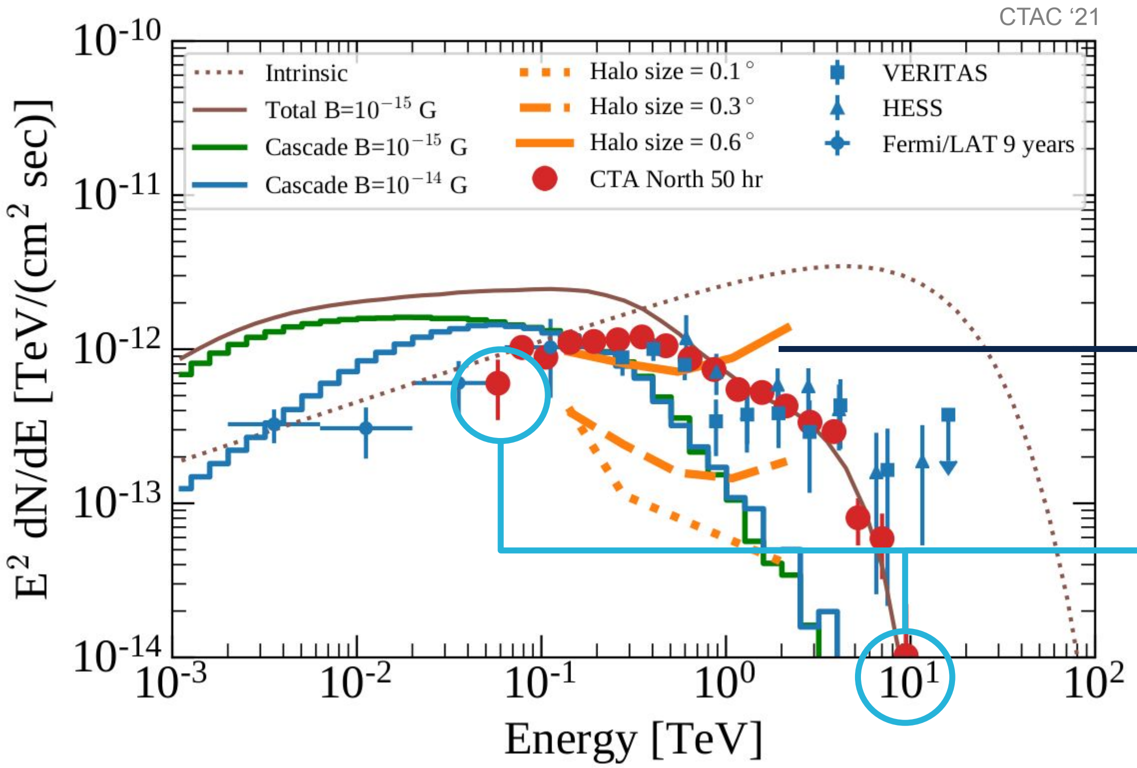



Credits: Ievgen Vovk



# Simulations for CTA



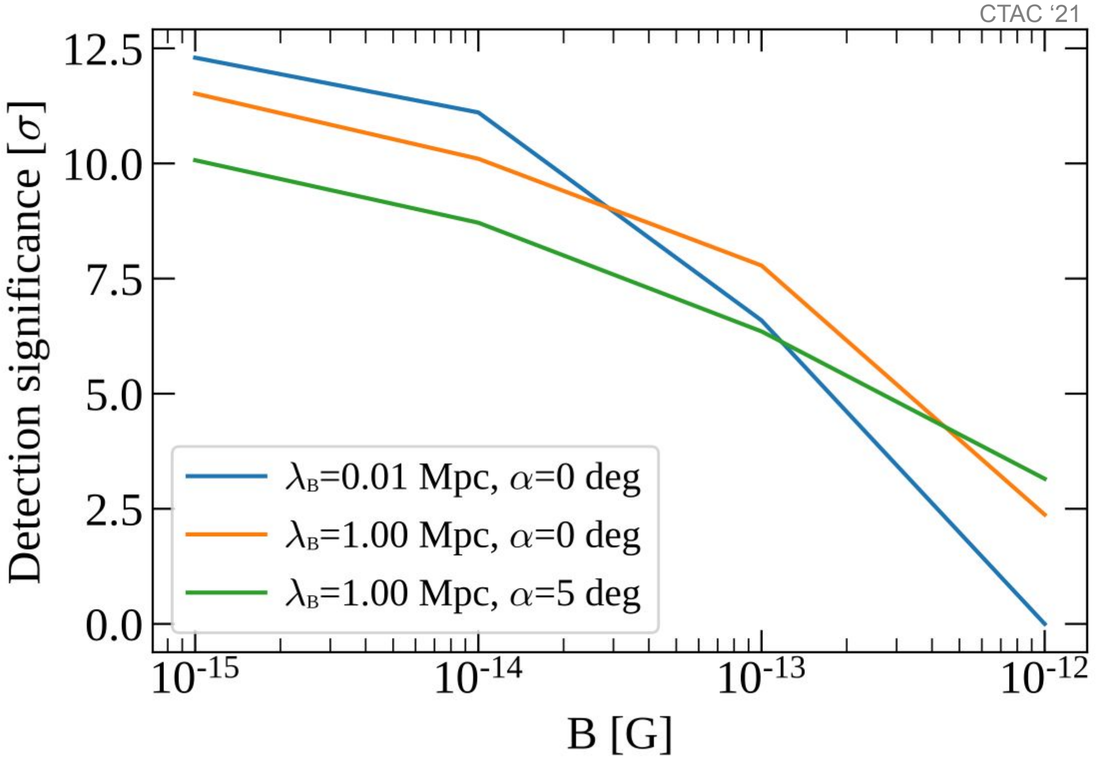

**Single-source test**

1ES 0229+200 ($z = 0.14$)
50h of observation
Cascade from 10 Myr activity

3σ sensitivity to extended secondary component

Sufficient reach to jointly probe surviving primaries and secondaries

# Single-source discovery power




**Single-source test**

1ES 0229+200 ($z$ = 0.14)

50h of observation

Cascade from 10 Myr activity

Detectability for different coherence lengths (unknown) and jet orientation (unknown)

# Probed parameter space

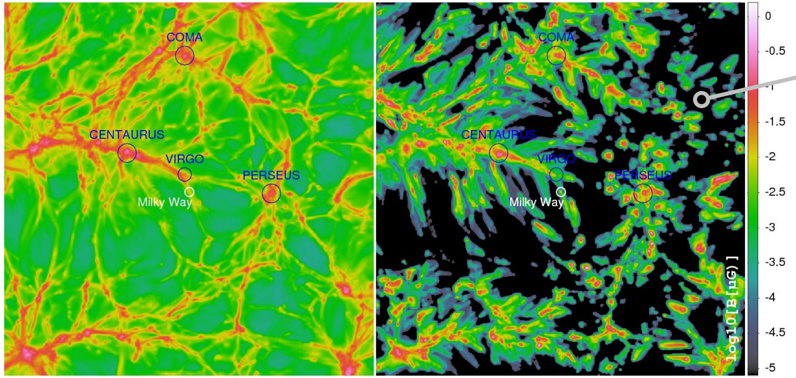
## Status and expectations

Current-generation (GeV-TeV, TeV extension):
→ $B$ > 10-100 fG

CTA (TeV spectrum & extension):
→ Single-source discovery up to 300 fG

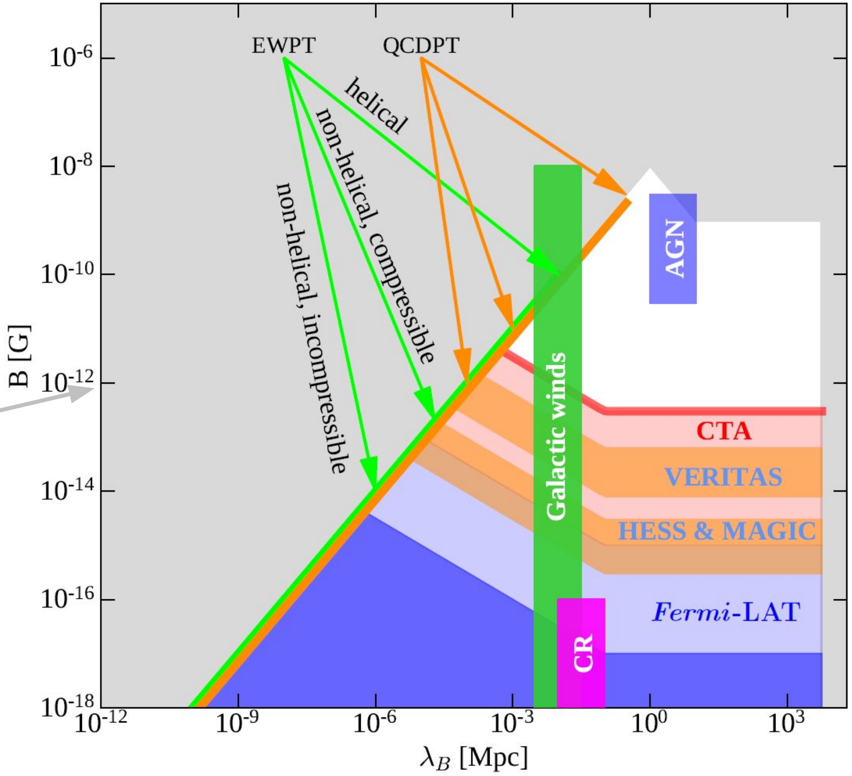
Primordial origin
$B$(void) < 1 nG

Astrophysical origin
$B$(void) < 1 pG




Hackstein+ '18

CTAC '21



cherenkov
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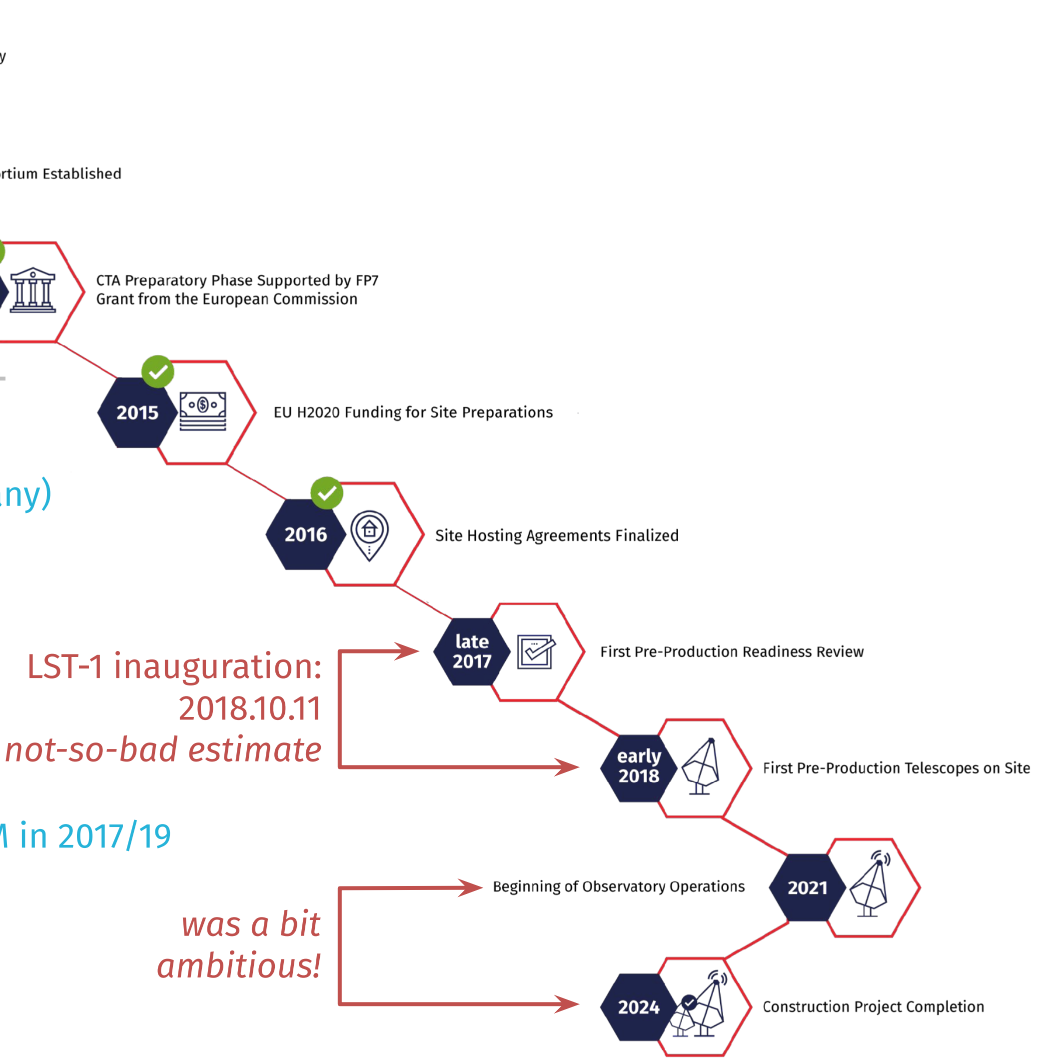
# The advent of CTA

Timeline – CTA is (almost) now!

# CTA Timeline
# as it was in ‘17




## Observatory

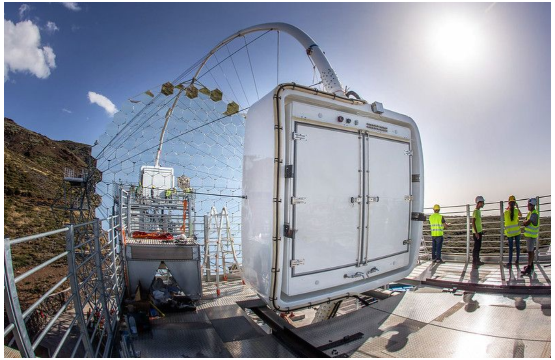
→ Was a gGmbH (German non-profit company)
→ ERIC in 2023 (European Research Infra.)
*a configuration & cost book approved by board of government representative in June 2021*

## Cameras and Telescopes

→ 1st LST in La Palma since 2018
→ Prototype MST with FlashCAM/NectarCAM in 2017/19
→ First MSTs in Paranal and La Palma (+ some other LSTs) by 2024
→ SSTs: in product review

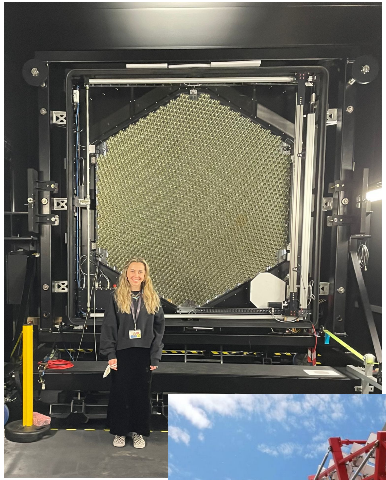
# Cameras & telescopes

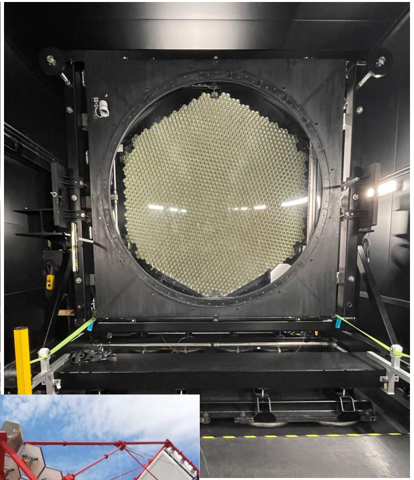
### LST-1 on site



### 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

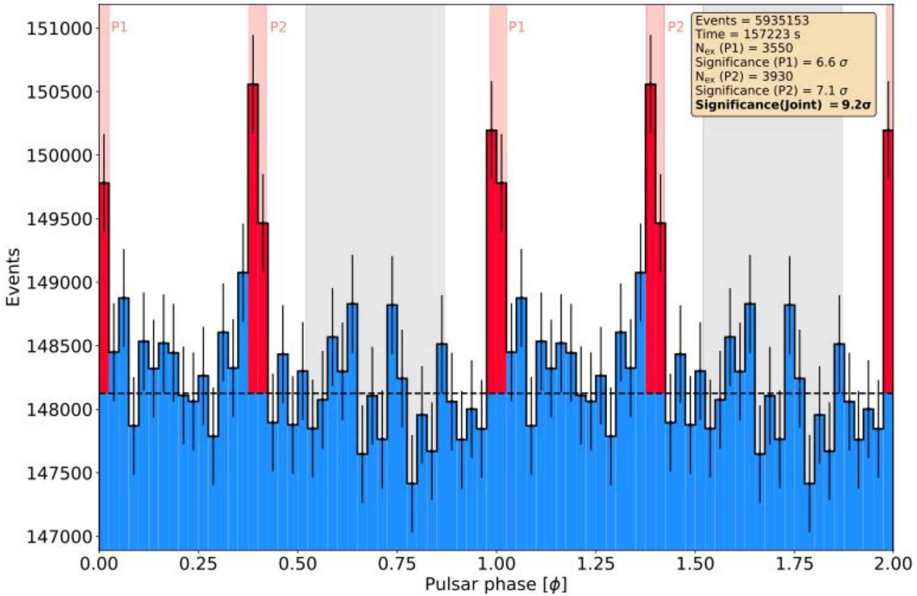
**Crab Nebula detection in Nov. '19**

**AGN Detections**

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

**Crab Pulsar detection in June '20**

López-Coto for CTA LST '21



# Until...

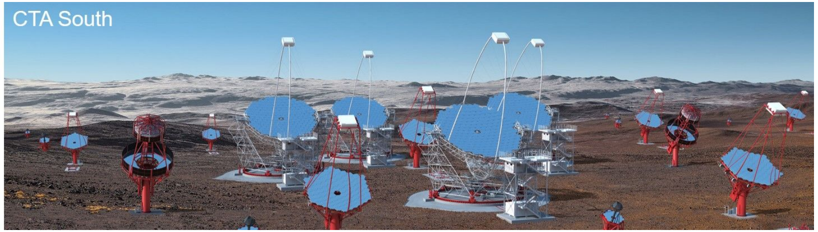
**Sep. to Dec. 2021**

No permanent damage on LST1

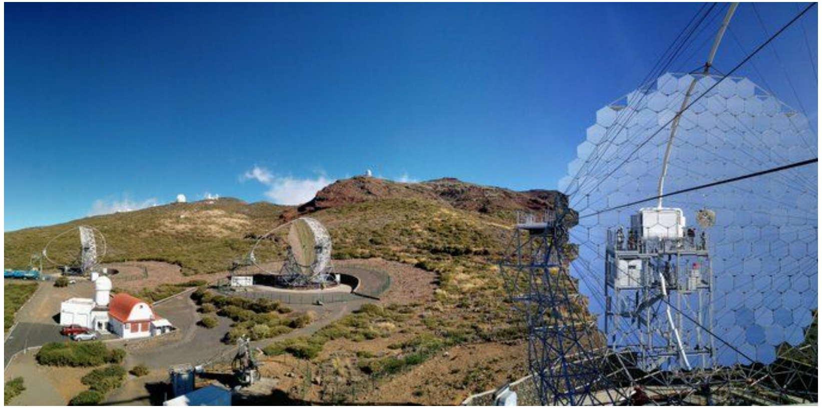


**LST back on track since early 2022**

# First scientific observations?





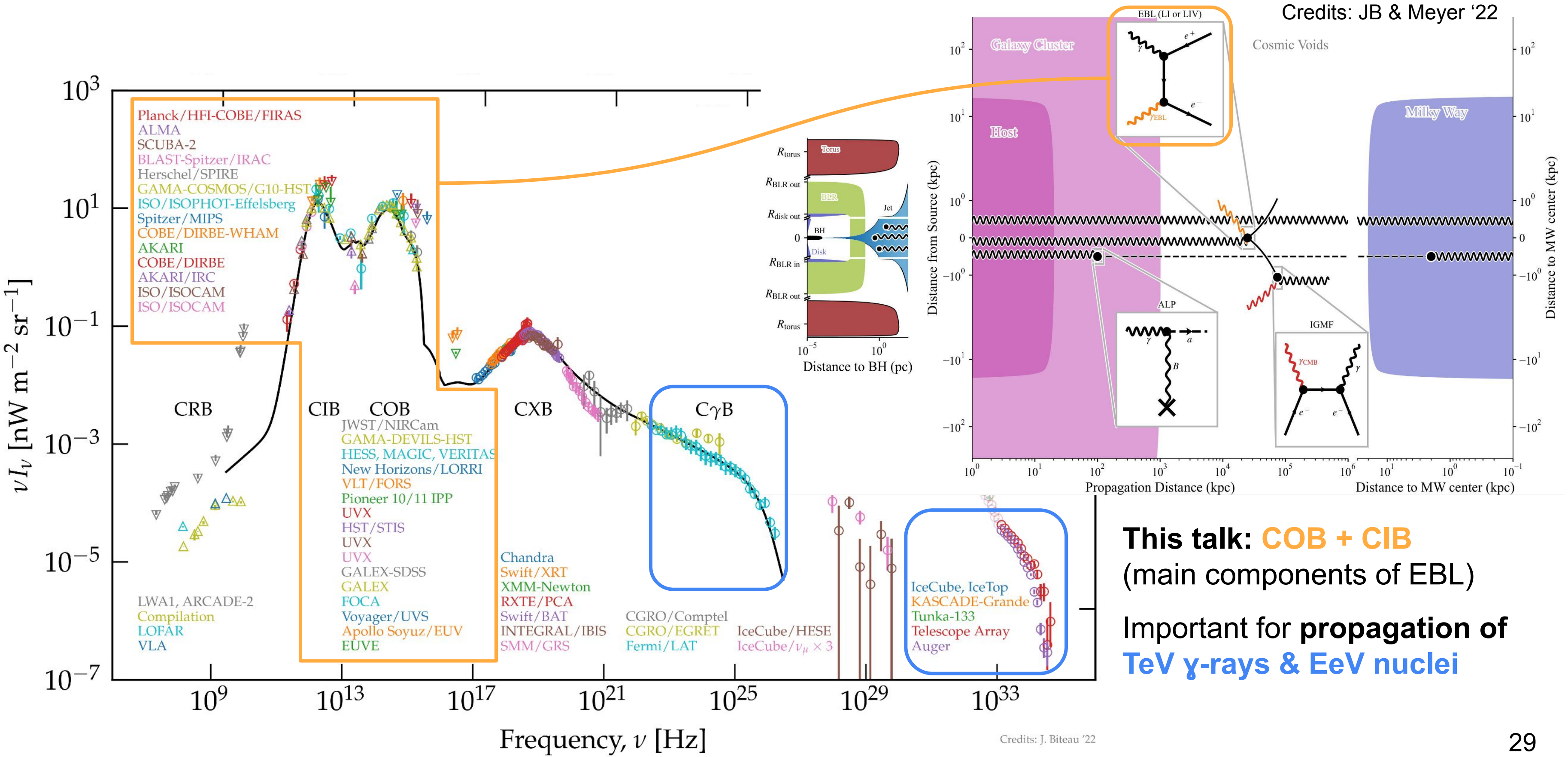


**Until we have both CTA-S and CTA-N**

**Step-by-step ramp up with the 1st telescopes on CTA-N!**

# Backup

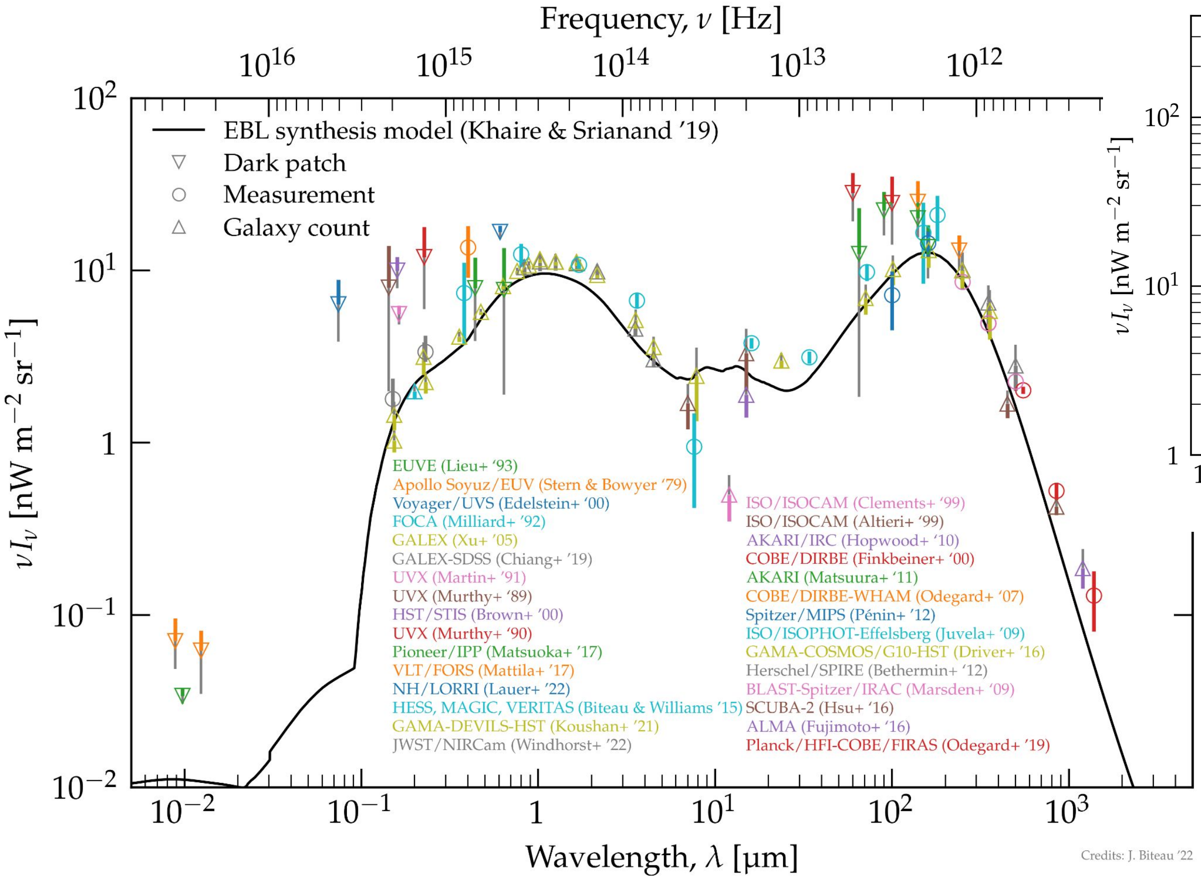
# The cosmic optical and infrared backgrounds

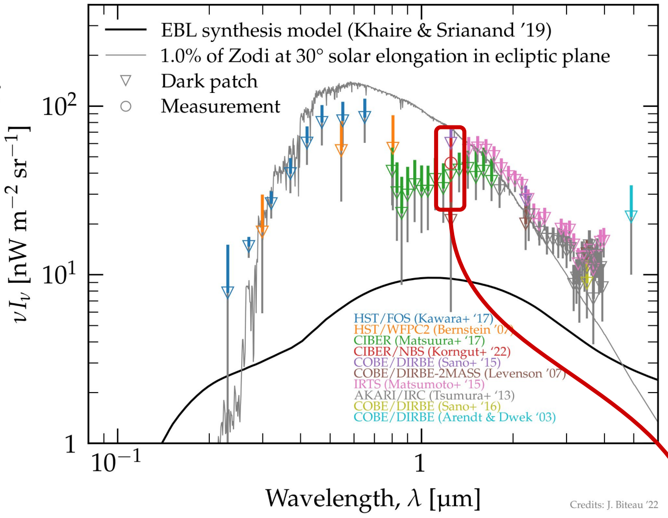



**This talk: COB + CIB**
(main components of EBL)

Important for **propagation of TeV γ-rays & EeV nuclei**

# COB & CIB: the Zodi contaminant

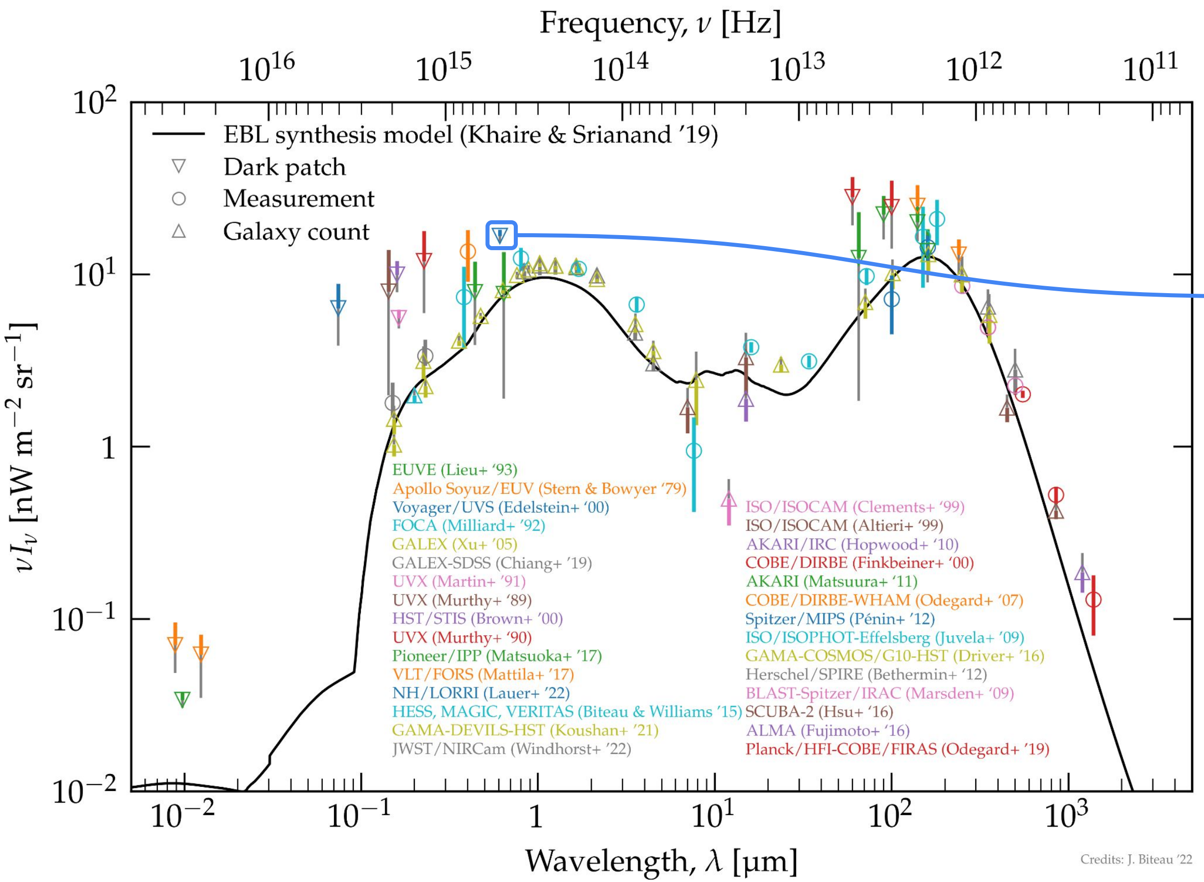



Dark-patch estimates in 0.3-5μm roughly consistent with 1% Zodi

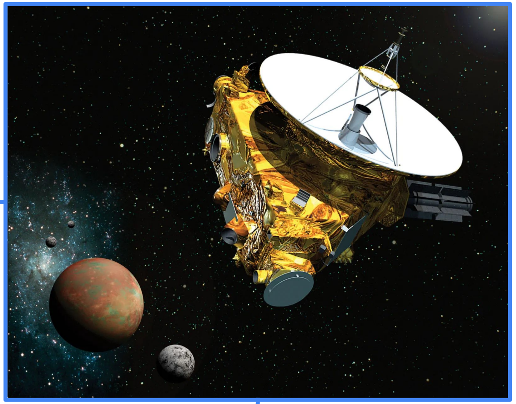
Ca-II absorption lines by CIBER
→ unaccounted for (Kelsall+ '98)
faint spherical Zodi component

# The optical controversy from New Horizons

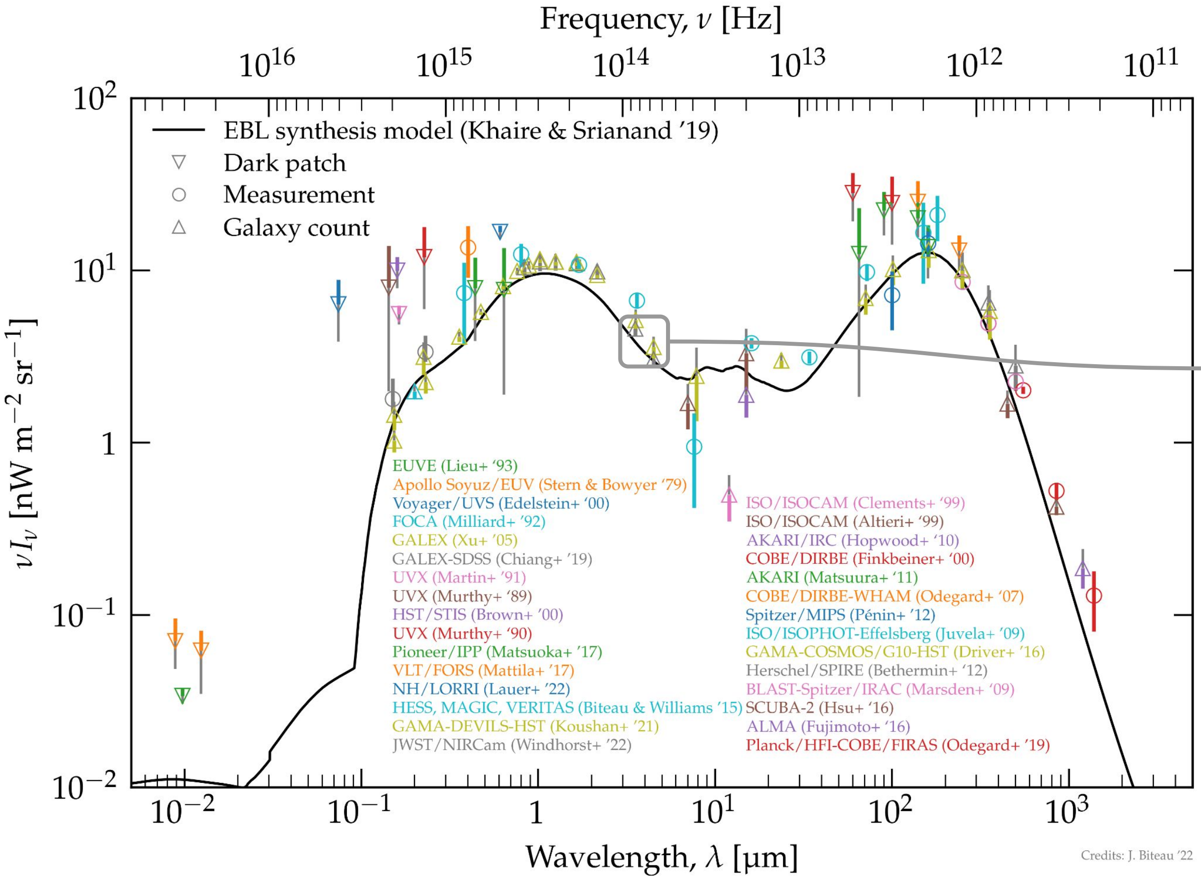



Credits: J. Biteau '22

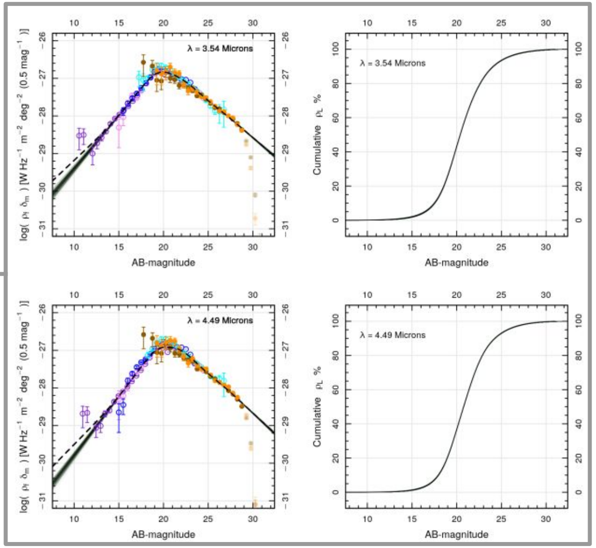
Credits: NASA; Note: Brian May's song



# COB & CIB: integrated galaxy light




Credits: Windhorst+ '22 (JWST's PEARLs program)
also Windhorst+ '21, '22 (HST's SKYSURF program),
Driver+ '16, Koushan+ '21 (GAMA/HST)



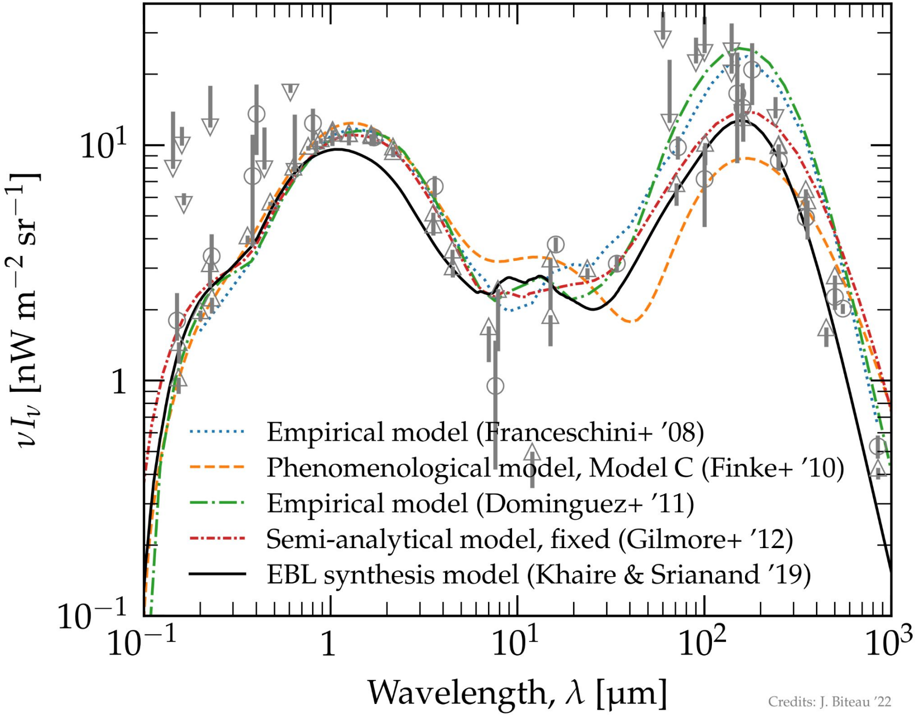

Current limitation (± 5-10%):
**cosmic variance → future: 1%**

Unknowns (<30%):
**intra-halo, -group, -cluster light**

# Models of the COB and CIB: prior to γ-ray measurements

**Three main categories of models:**

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-z
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback



Credits: J. Biteau '22

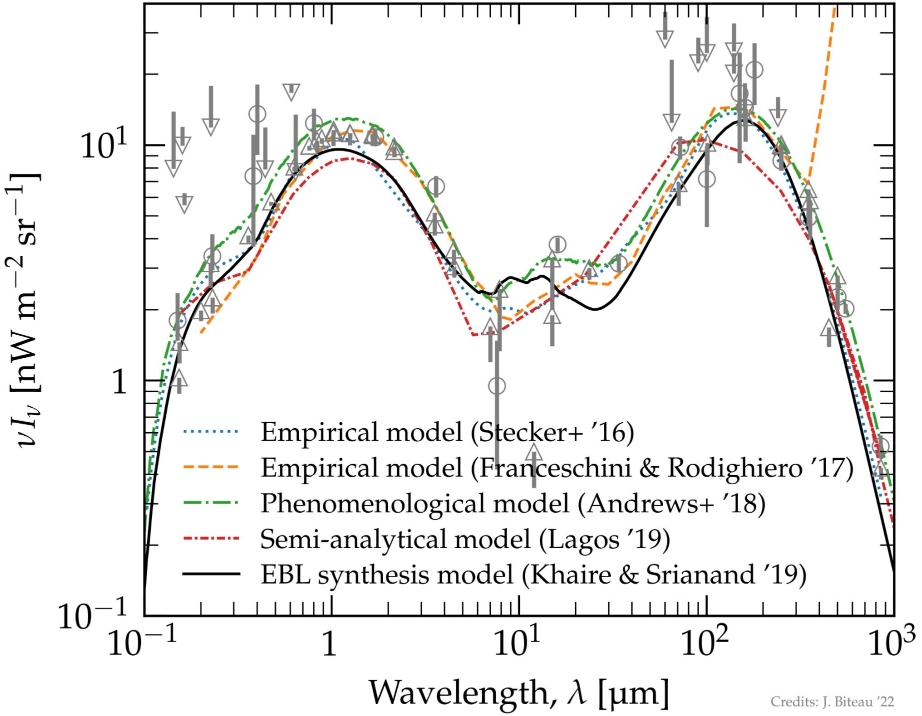
**All models** aim at matching observations, in particular galaxy counts (**unknowns = 0**)

# Models of the COB and CIB: post γ-ray measurements

**Three main categories of models:**

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-z
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback

**All models** aim at matching observations, in particular galaxy counts (**unknowns = 0**)

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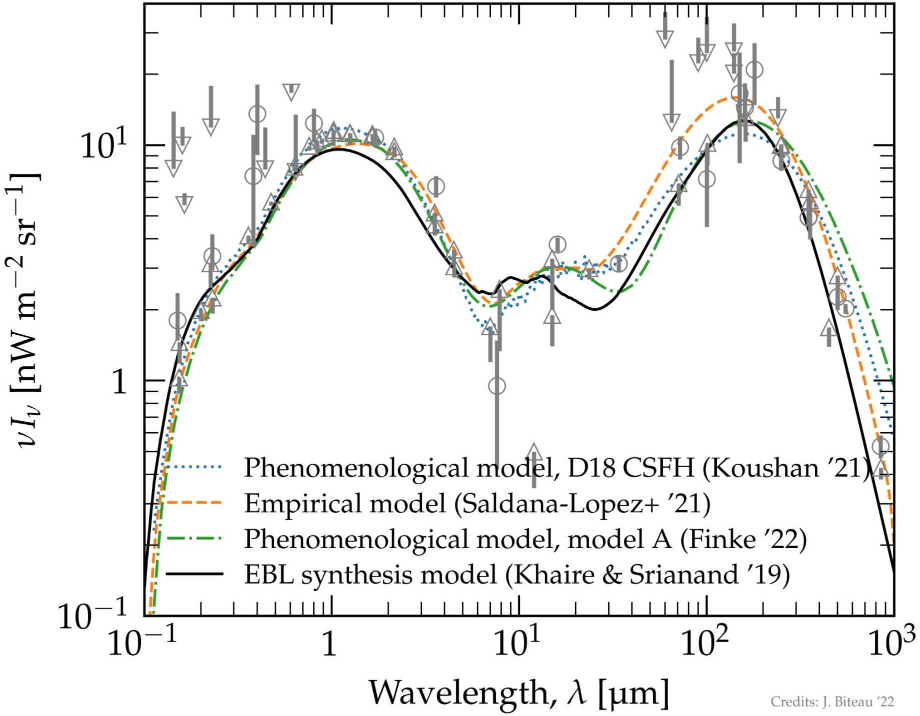
# Models of the COB and CIB: most recent

**Three main categories of models:**

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-z
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback



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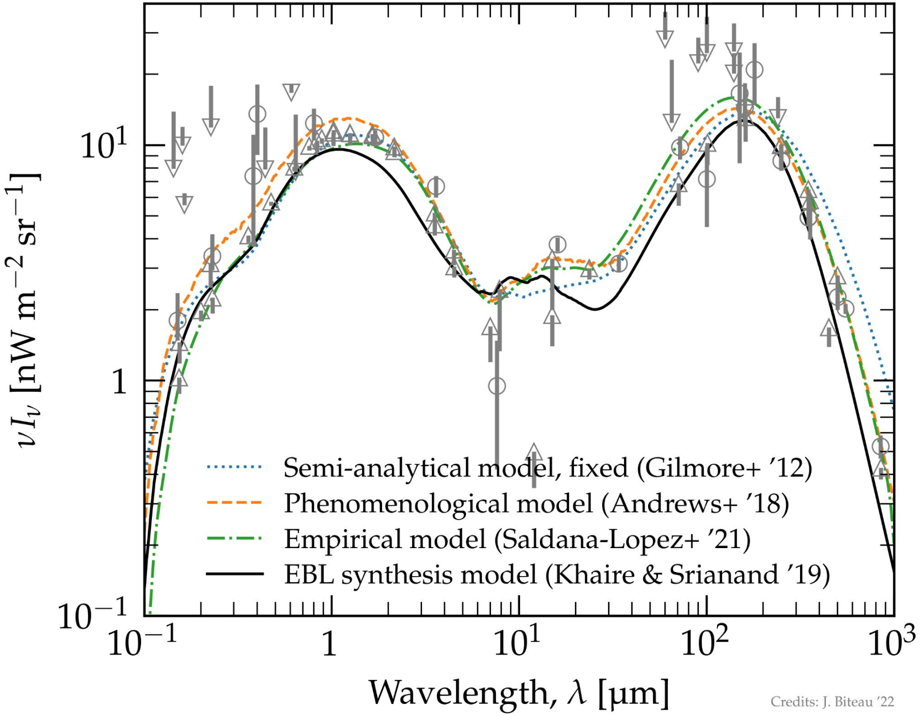
**All models** aim at matching observations, in particular galaxy counts (**unknowns = 0**)

# Models of the COB and CIB: possibly best of each type

**Three main categories of models:**

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-z
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback

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**All models** aim at matching observations, in particular galaxy counts (**unknowns = 0**)