The MAGIC of gamma-ray astronomy

David Paneque
Max Planck Institute for Physics, Munich
on behalf of the MAGIC collaboration

LHC days in Split, Hvar, September 30 – October 4, 2024

The MAGIC Stereoscopic system

- **MAGIC: Two Imaging Atmospheric Cherenkov Telescopes (IACTs) of 17 meter diameter mirror dish to perform Very High Energy (VHE) gamma-ray astronomy**
  - **Operational energy range: from ~50 (~20) GeV to >100 TeV**
  - Sensitivity: 0.7% the Crab Nebula flux (above 220 GeV) after 50 hours observation

    → About 5% of the Crab Nebula flux in 1 hour of observation

MAGIC-1 **Control house** **MAGIC-2**

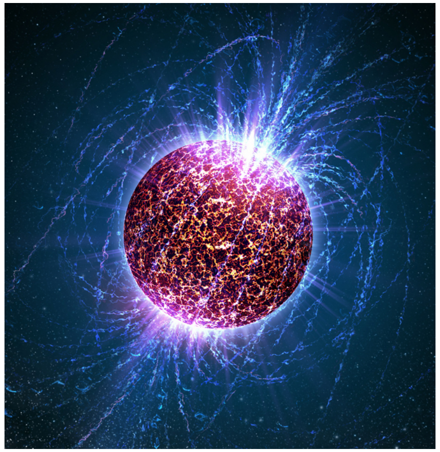
Shifters that operate telescopes (and trigger, DAQ …)

The MAGIC collaboration

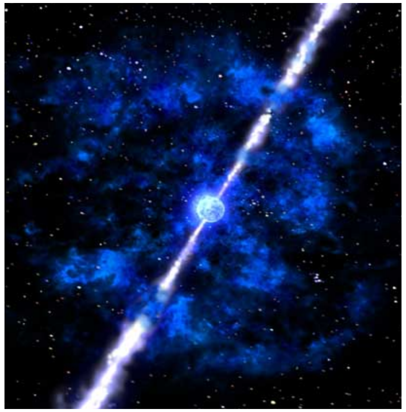
MAGIC started operations in October 2003

In year 2023, MAGIC turned 20 years & reached milestone of 200 peer-reviewed publications (211 publications in Oct.2024)

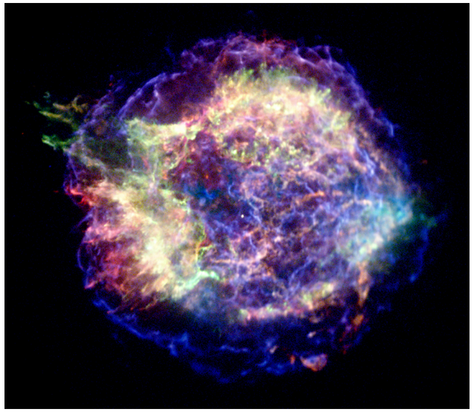
Pulsars



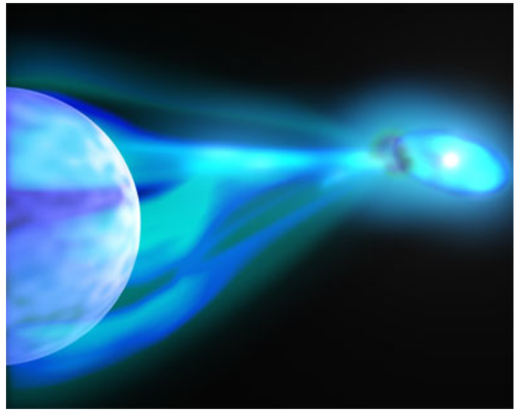
GRBs



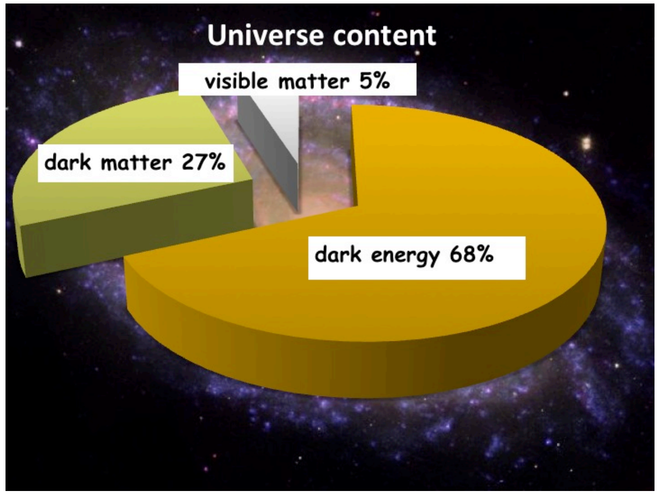
SNR+PWN

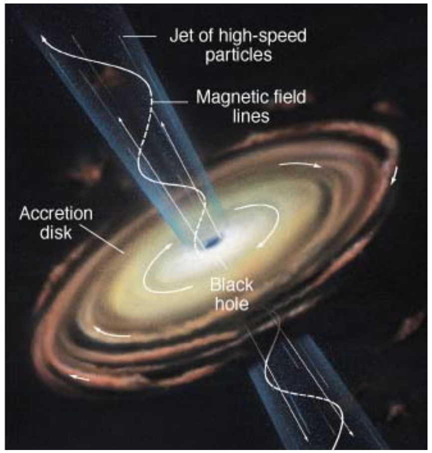


Binary systems & Novae

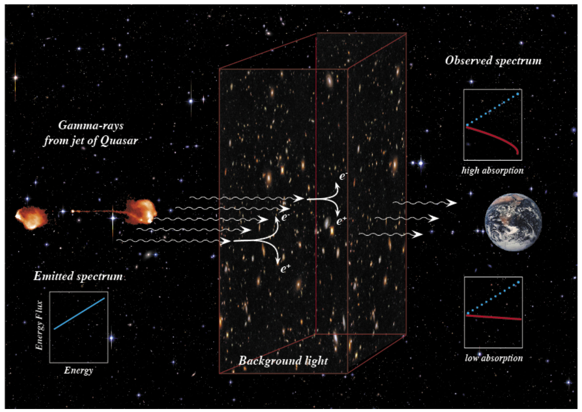


Dark Matter searches





AGNs



EBL
IGMF
ALPs
LIV

https://indico.mpp.mpg.de/event/9652/

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

20 MAGIC Years Conference & Symposium

4–7 Oct 2023
H10 Taburiente Playa, La Palma
Europe/Lisbon timezone

Enter your search term

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- Registration
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- Confirmed Speakers
- Accommodation / Symposium Venue
- Social Events
  - Welcome Reception
  - Excursion to ORM & Celebration
  - Vulcano Excursion - Cumbre Vieja Vulcano
  - Gala Dinner

https://indico.mpp.mpg.de/event/9652/

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

20 MAGIC Years Conference & Symposium

About 150 participants (100 from MAGIC and 50 externals)

Several external scientists celebrated with us:

Francis Halzen, Stuart McMuldroch, Rafael Rebolo, Elena Amato, Enrique Zas, Giulia Zanderighi, Giancarlo Ghirlanda, Emma de Oña Wilhelmi, Roberta Zanin, Marcello Giroletti, Om Sharan Salafia, Marcos Santander, Mathieu de Naurois, Deirdre Horan, Manel Errando, Carlotta Pittori, Petra Huntenmeyer, Min Zha …

Ceremony on Thursday, October 5th

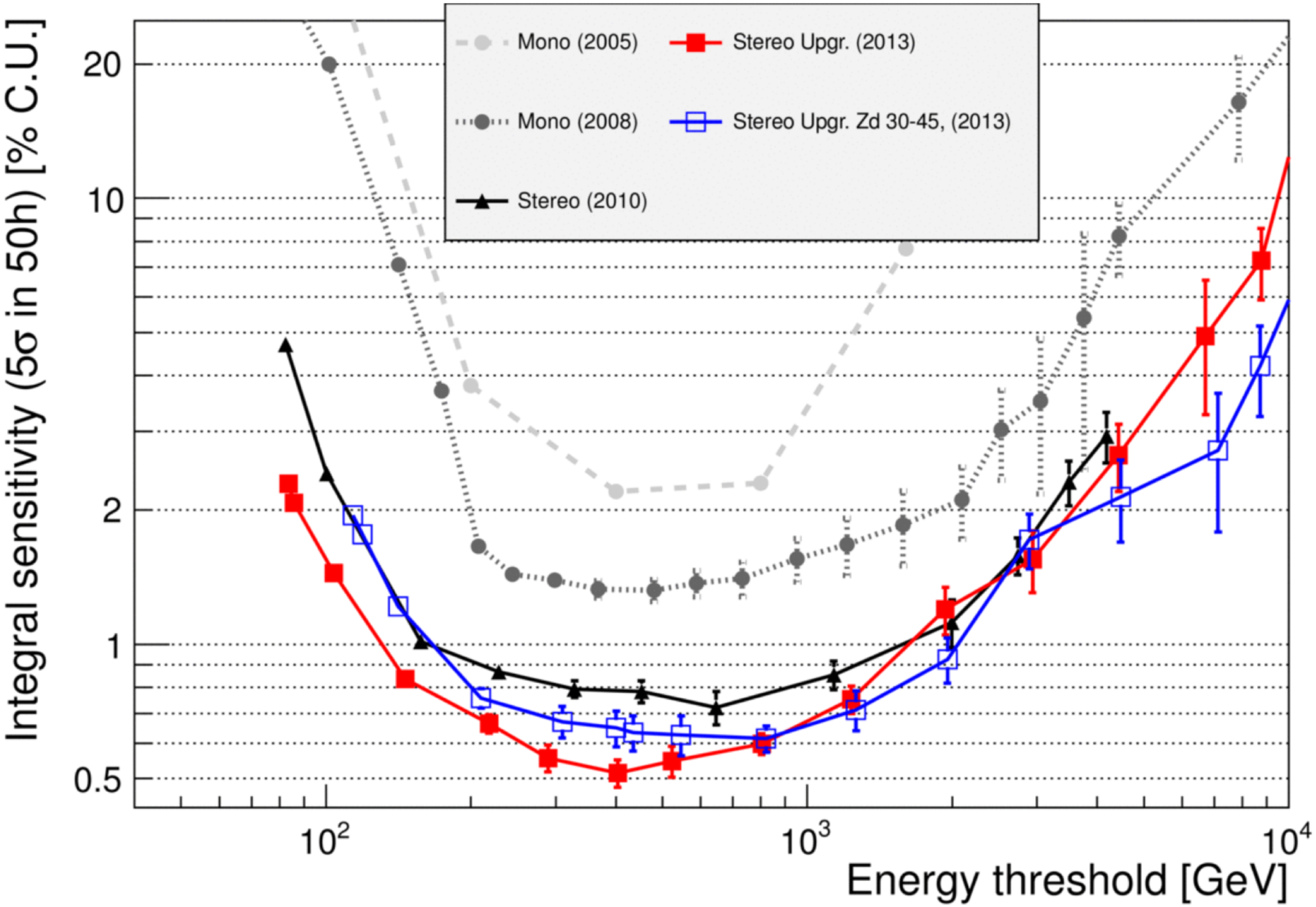
Included:

- → **Tour over the visitor center (from before 13:00 to about 16:30)**
- → **MAGIC dedicated exhibition (running for 3 months)**
  - → Since December 2023, a (much smaller) permanent exhibition

Evolution of the MAGIC Performance

4-fold improvement in sensitivity over the last 20 years

The multiple improvements vs time is one of the reasons why MAGIC has maintained competitivity over the last two decades



Aleksic et al., (MAGIC collab.) Astroparticle Physics 72, 76-92, 2016

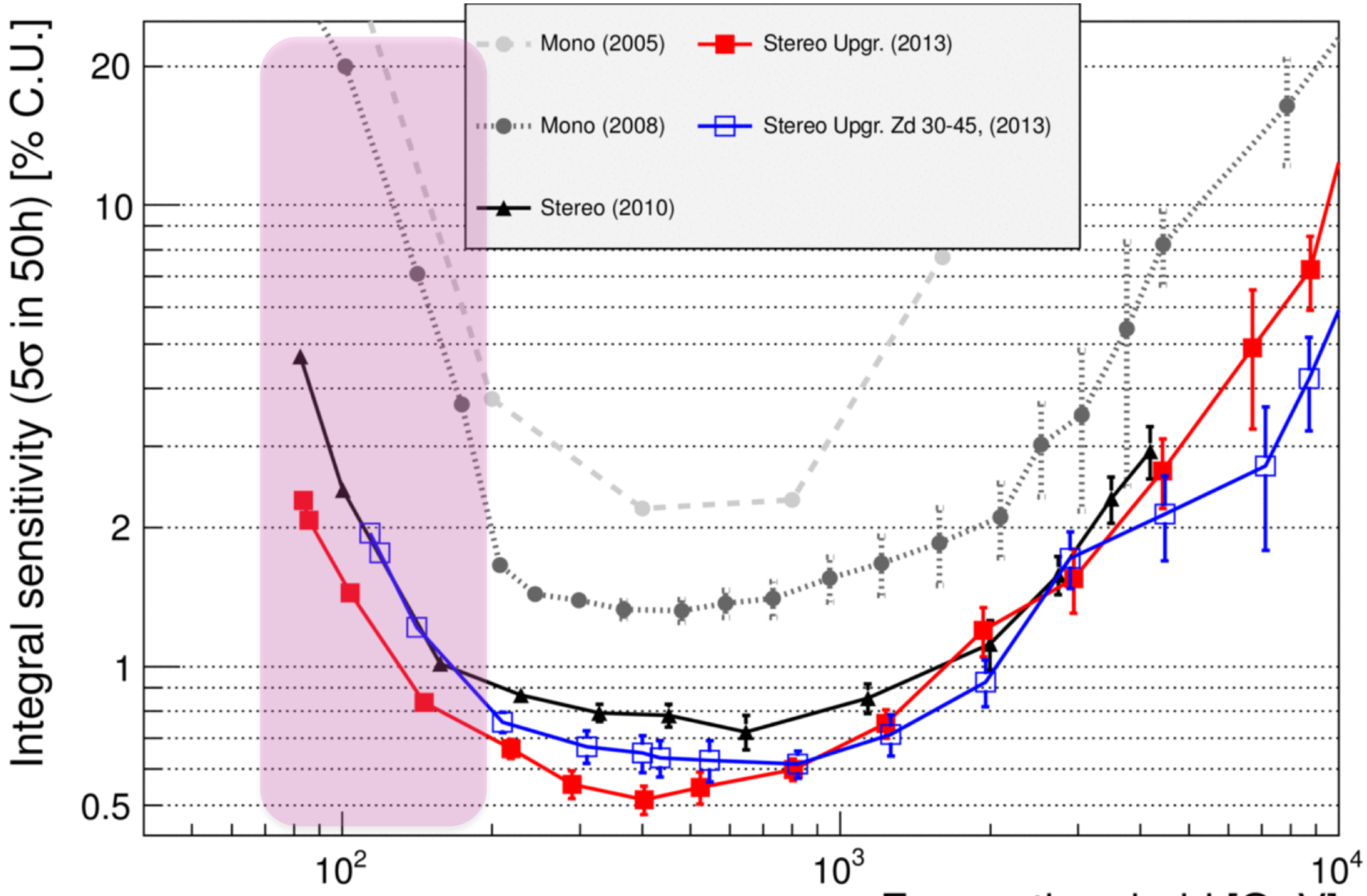
Better sensitivity + Lower energy threshold = **More science !!**

Evolution of the MAGIC Performance

4-fold improvement in sensitivity over the last 20 years

→ More than 10-fold improvement below 200 GeV

→ Obs. time for detection reduced 100 times below 200 GeV



Aleksic et al., (MAGIC collab.) Astroparticle Physics 72, 76-92, 2016

Huge improvement E<200 GeV

Better sensitivity + Lower energy threshold = More science !!

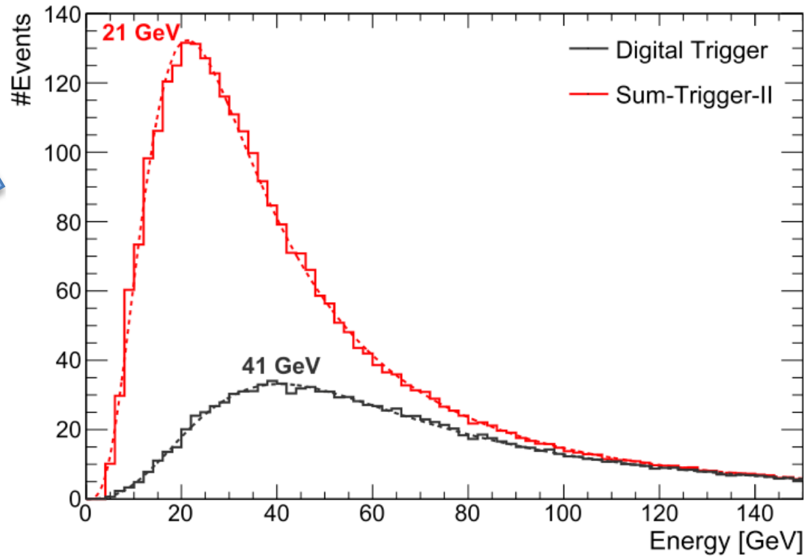
Performance improvements in last years

(non standard observations)

Sum-Trigger-II

→ Decrease energy threshold (from ~40 GeV to ~20 GeV) and improve sensitivity below 100 GeV

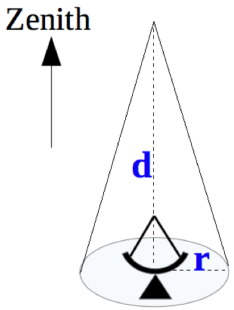
Dazzi et al. 2021, IEEE Transactions on Nuclear Science, 68, 1473



Very Large Zenith angle

→ Increase sensitivity for multi-TeV energies

Vertical observations



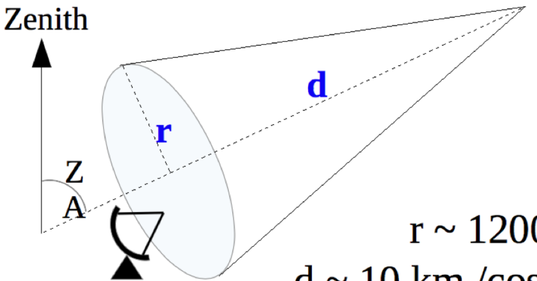
typical for IACTs

d ~ 10 km

r ~ 120 m

Acciari et al., 2020, A&A, 635, A158.

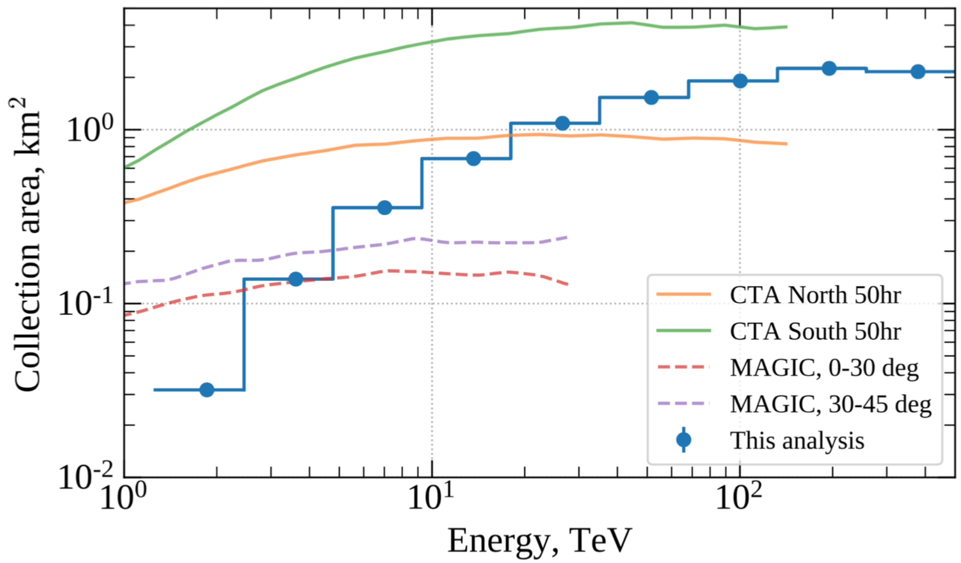
Large zenith angle observations



proposed

r ~ 1200 m

d ~ 10 km /cos(ZA) ~ 100 km



Need small pixels and good time information

MAGIC started operations in October 2003

A few major historical breakthrough observations published by MAGIC

Detection of minute timescale variability from Mrk501 in 2005, **First** time observed in BL Lacs
→ **2007ApJ...669..862A**

Detection of 3C279 in 2006, **First** detection of a Flat Spectrum Radio Quasar (FSRQ) at VHE
→ **2008Sci...320.1752M**

Detection of pulsed emission from Crab in 2008, **First** detection of pulsed VHE emission
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Detection of minute timescale variability from IC310 in 2012, **First** time in radio galaxies
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Detection of TeV pulsed emission from Crab, announced in 2015, **First** time for a pulsar
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Detection of TXS 0506+056 in 2017, **First** 3+sigma association of neutrino and a VHE source
→ **2018Sci...361.1378I and 2018ApJ...863L..10A**

GRB190114C in 2019, **First** GRB at TeV energies & **First** measurement of GRB inverse-Compton
→ **2019Natur.575..459M and 2019Natur.575..459M**

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MAGIC telescopes, an instrument to explore & measure new things

Gamma Ray Bursts (GRB), the most powerful transients

- **GRB were serendipitously discovered at MeV in the late 60s**, becoming the brightest objects in the sky during minute timescales
- **GRBs @ Cosmological distances**, most luminous sources in Universe

Observationally, <u>two kinds of GRBs:</u>

Short (T_{90} < 2s): Binary neutron star mergers (*produce GWs*)

Long (T_{90} > 2s): Collapse of dying massive stars

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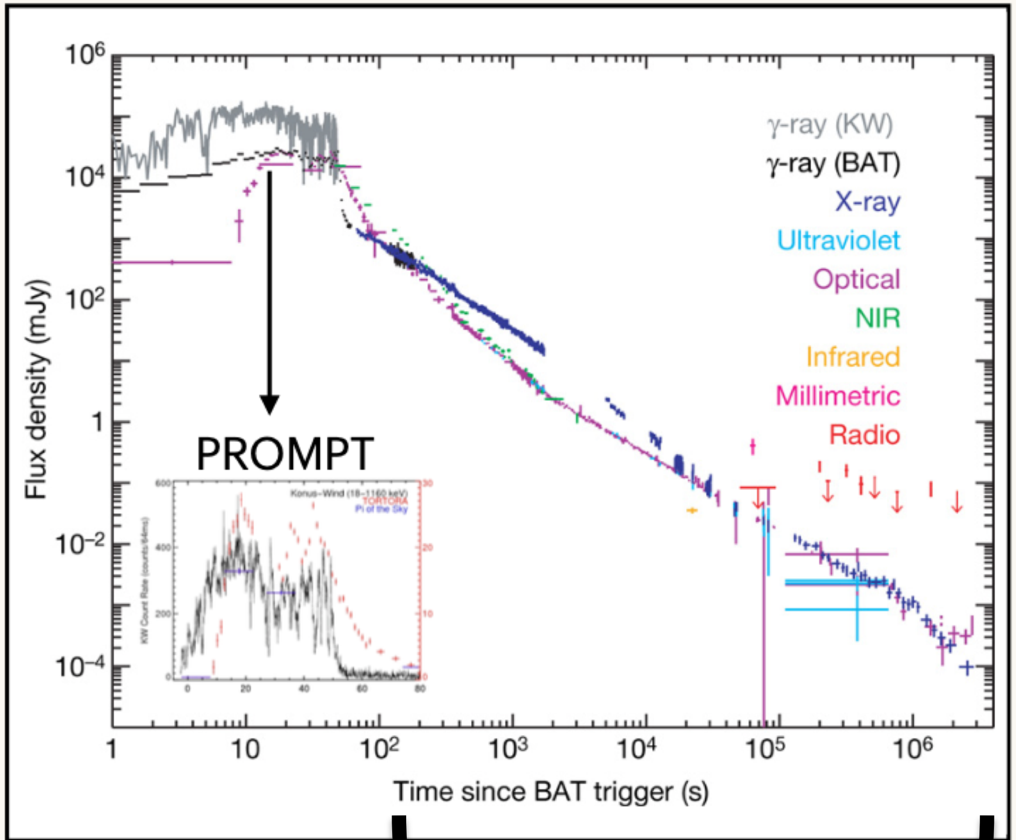
Two emission stages or phases, both produced in collimated jets:

Prompt: primarily at MeV, lasts less than a few hundred seconds

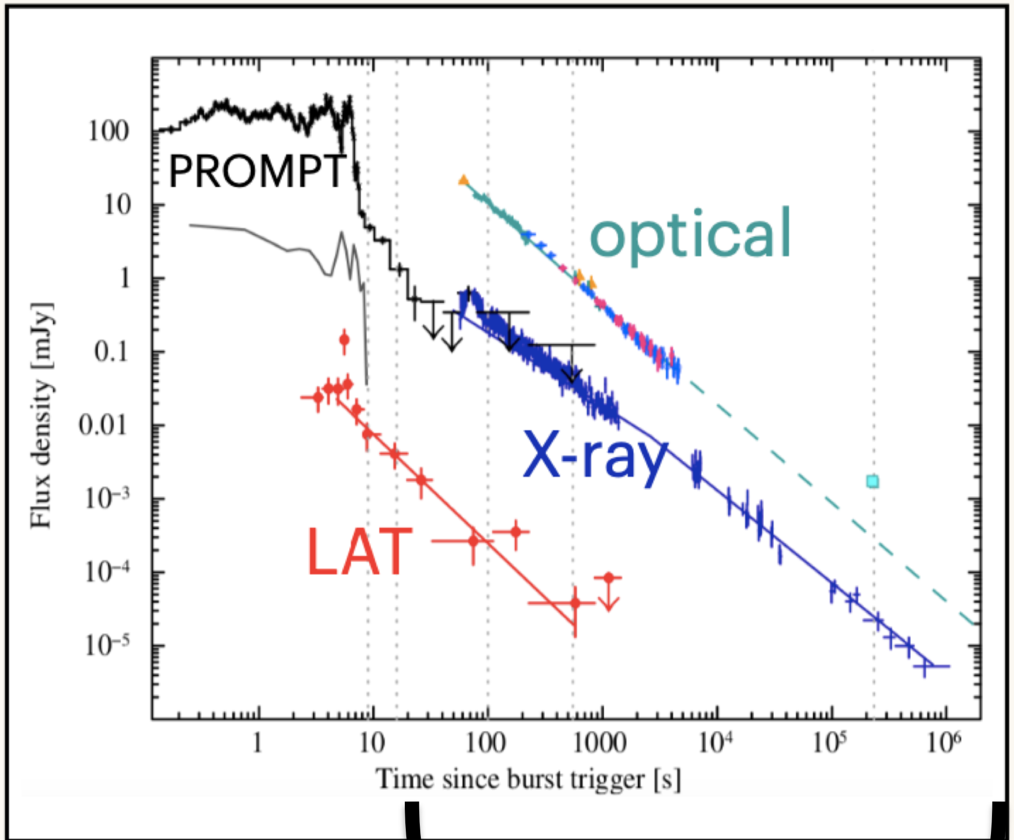
Afterglow: from gamma rays to radio, decays gradually, longer times

Gamma Ray Bursts (GRB), the most powerful transients

GRB 080319B
Racusin et al., 2008

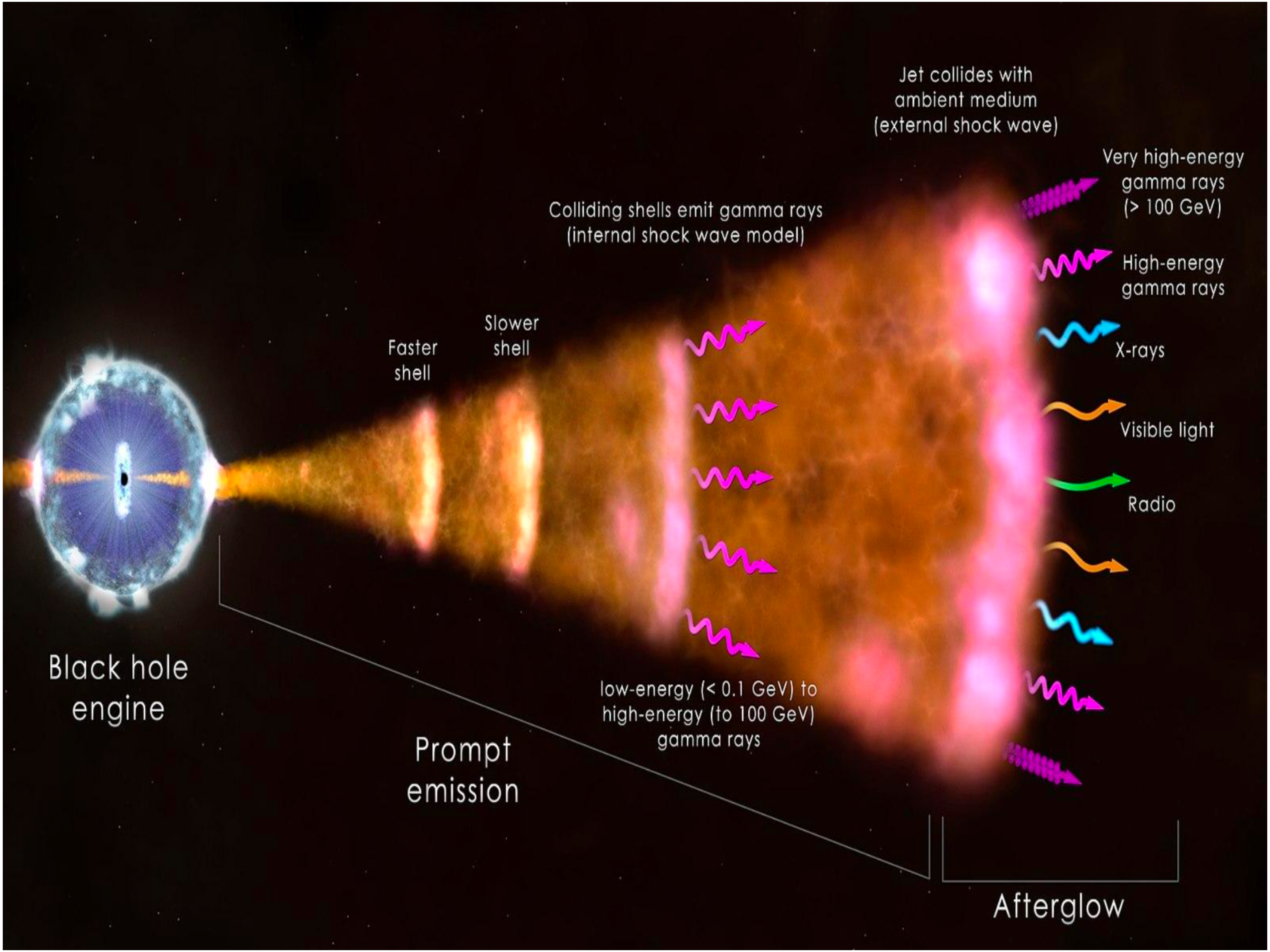


GRB 110731A
Ackermann et al., 2013



Afterglow

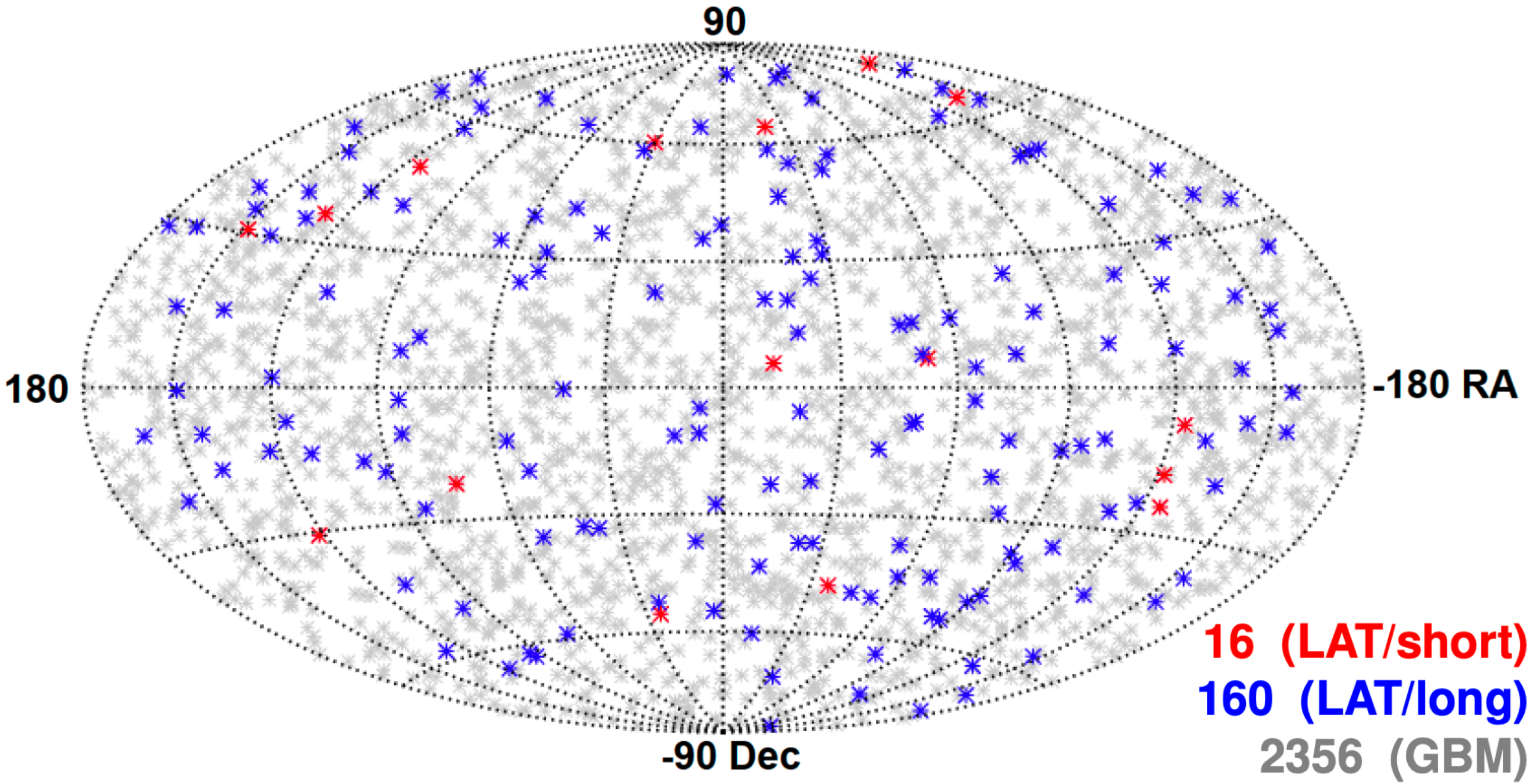
Afterglow



Jet collides with
ambient medium
(external shock wave)
Very high-energy
gamma rays
(> 100 GeV)
Colliding shells emit gamma rays
(internal shock wave model)
High-energy
gamma rays
Slower
shell
Faster
shell
X-rays
Visible light
Radio
Black hole
engine
low-energy (< 0.1 GeV) to
high-energy (to 100 GeV)
gamma rays
Prompt
emission
Afterglow

Sky distribution of GRBs detected with Fermi

Isotropic distribution → confirms extragalactic origin



Fermi collaboration (Ajello et al 2019)

No detection of GRB VHE gamma rays until 2019

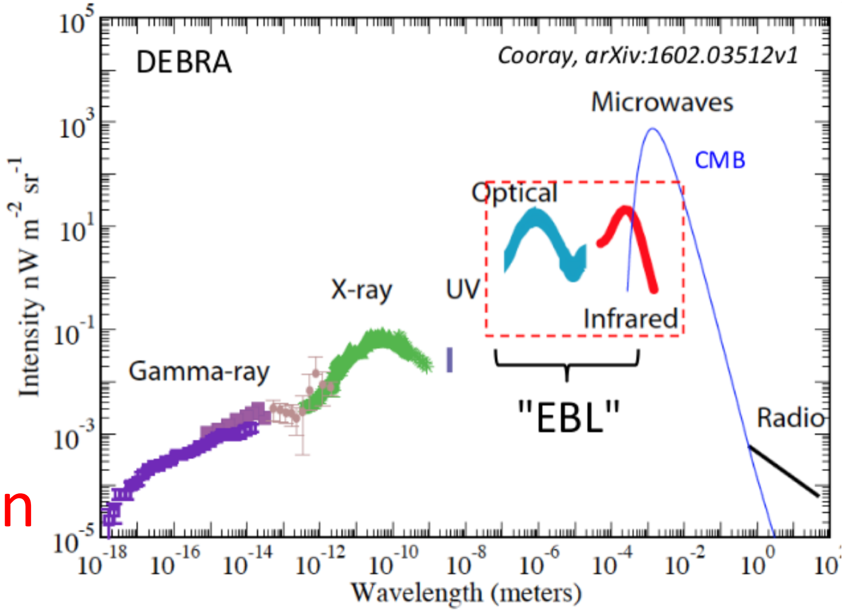
The current generation of IACTs (HESS, MAGIC and VERITAS) had observed hundreds of GRBs, but, until the year 2019, never detected.

Do GRBs emit Very-High-Energy gamma rays ?

Two big challenges to overcome:

1 - GRBs occur at random location and, while Fermi has a large chance to detect them (because of the large FoV), IACTs need to be informed, and need more than 20-30 seconds to point at the source.

2 - Most of the GRBs are distant sources (z>1), and the VHE gamma rays of hundreds of GeV will be strongly absorbed (pair production) in the Extragalactic Background Light (EBL).



Gamma + EBL-photon → electron + positron

David Paneque

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
*on **15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

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Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

Final analysis yielded > 50 sigma

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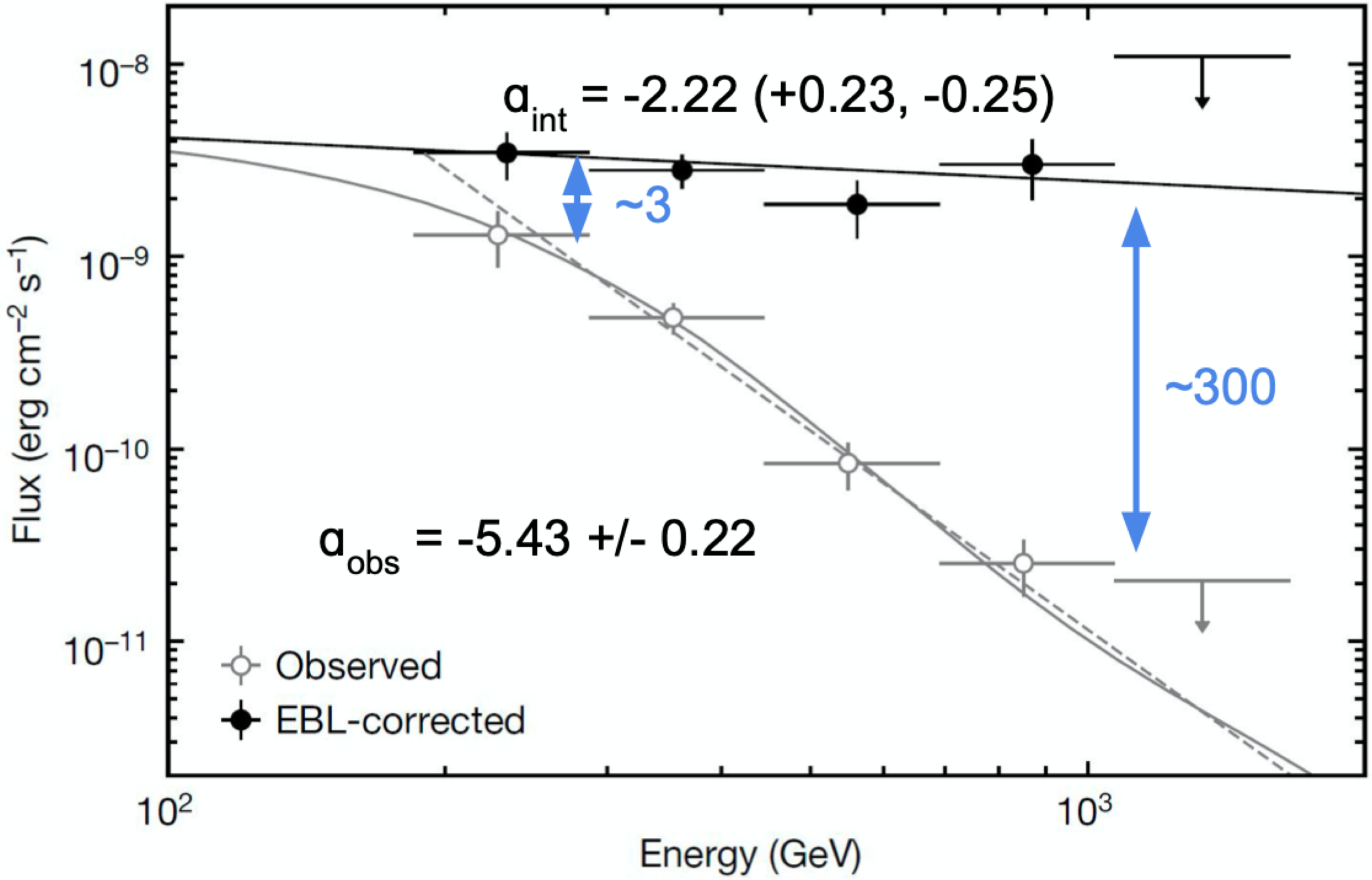
First detection of a gamma-ray burst at TeV energies

@ January 14th, 2019

GRB190114C
(z=0.42, ~2 Gpc)

First VHE gamma-ray spectrum of a GRB



Large attenuation of gamma-ray flux because of pair conversion with the low-energy photons from the EBL

→ Sensitivity at 100GeV and below crucial to detect distant sources

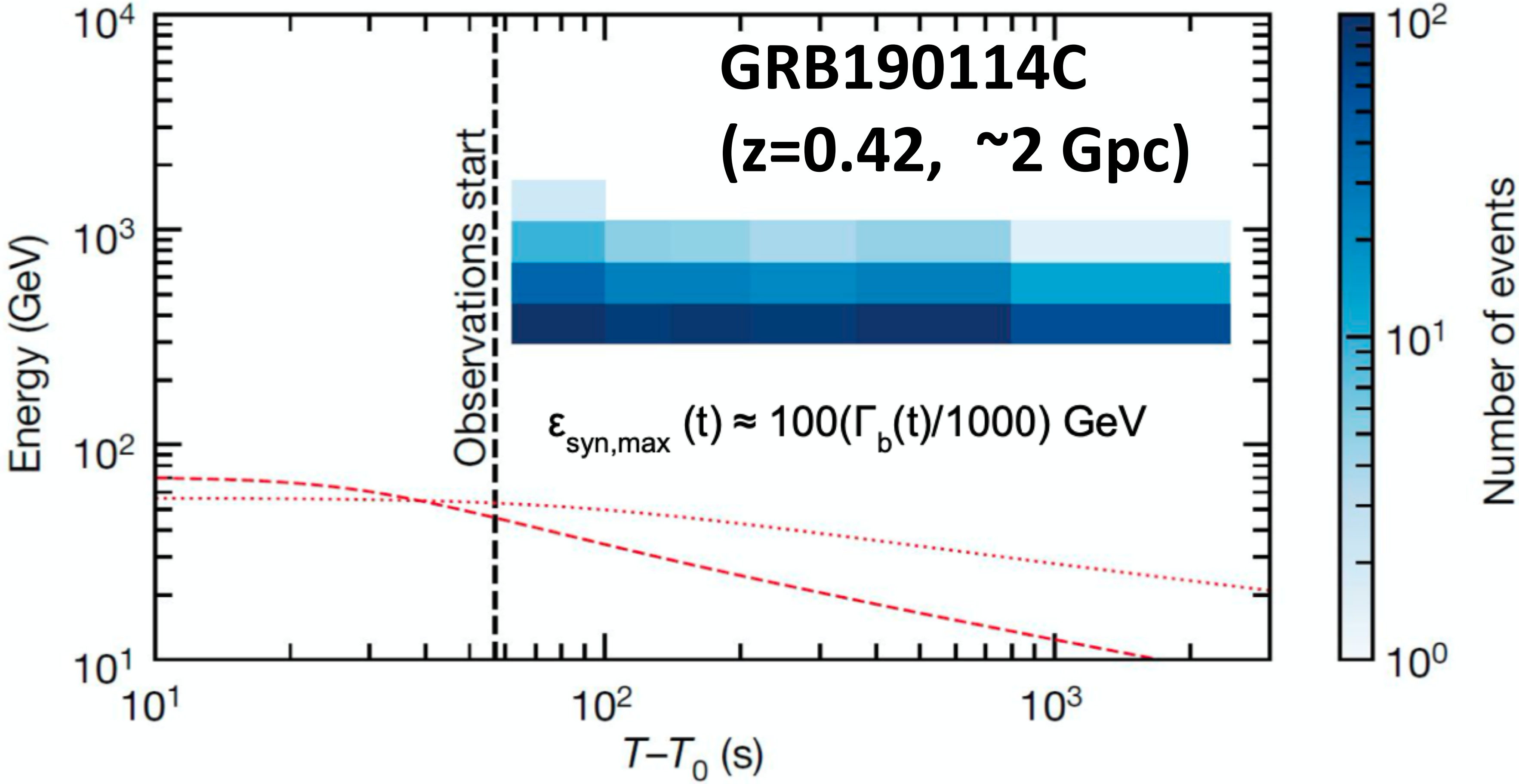
MAGIC Coll. et al. 2019, Nature 575, 455

Time integrated spectrum (T_0+62s to T_0+2454s) → huge absorption by EBL, emission extending up to 1 TeV, intrinsic spectrum compatible with α=-2

First detection of a gamma-ray burst at TeV energies

Distribution of VHE gamma rays in energy versus time for GRB 190114C

MAGIC Coll. et al. 2019, Nature 575, 455 (aka: discovery paper)

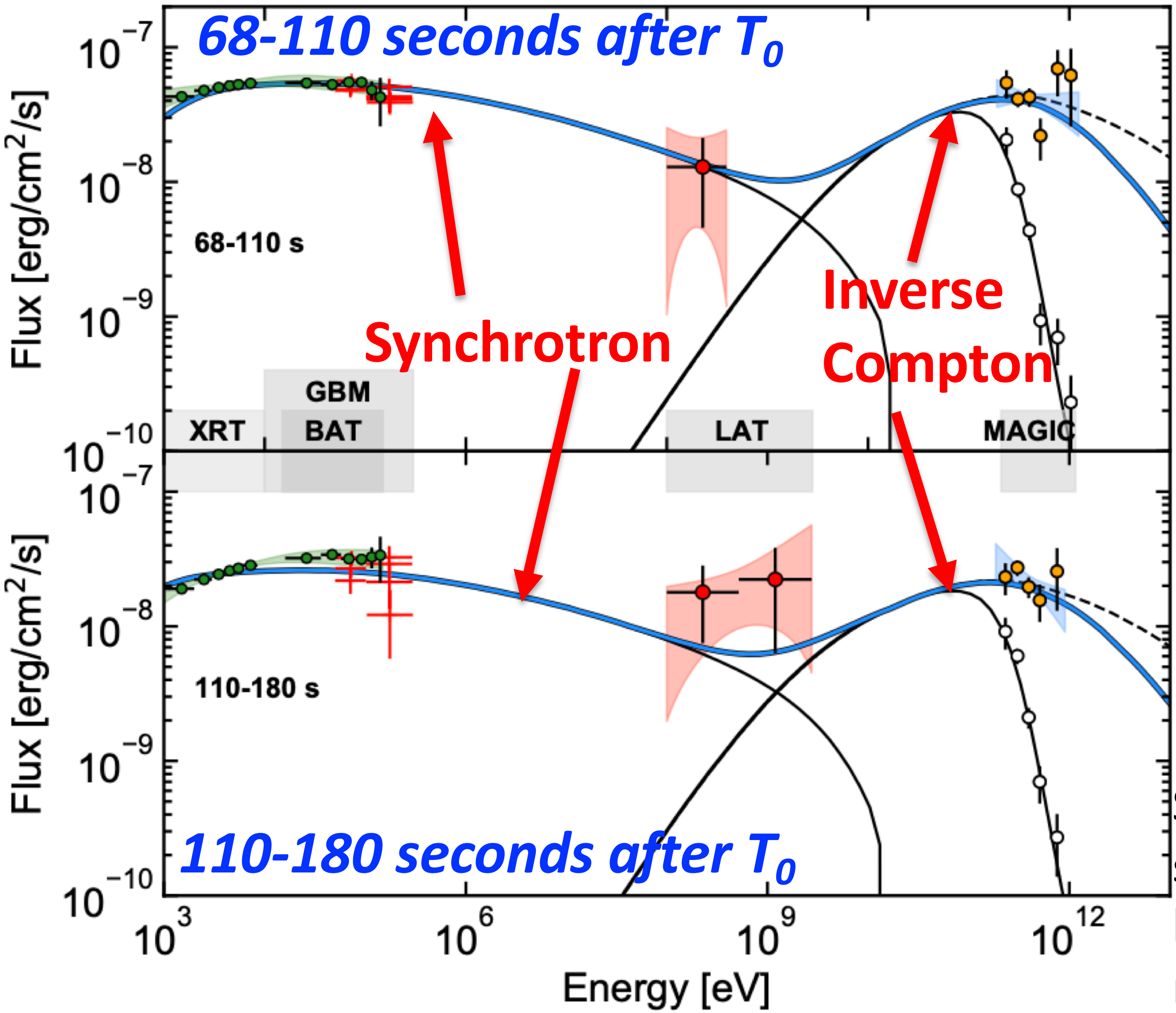


Energy of photons detected by MAGIC is well above the synchrotron "burnoff limit", hence the emission process responsible for VHE gamma rays cannot be the one producing the X-rays (synchrotron)

First detection of a gamma-ray burst at TeV energies

GRB190114C (z=0.42, ~2 Gpc)

MAGIC Coll. et al. 2019, Nature 575, 459



The emission process responsible for the VHE gamma rays cannot be the one producing the X-rays (→ *synchrotron*), and hence **we measured for the <u>first time</u> a new spectral emission component** (→ Inverse Compton)

Synchrotron self-Compton (SSC) scenario can describe well the broadband data, using typical model parameter values

First detections of a gamma-ray burst at TeV energies

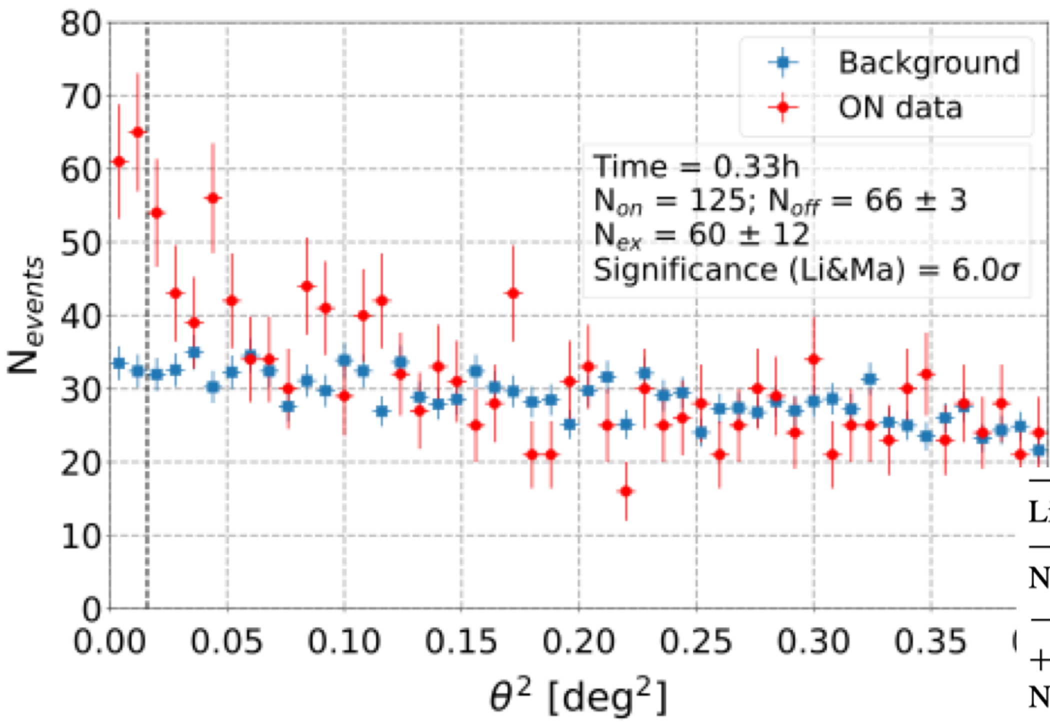
Since January 15th 2019 (GRB190114C), the detection of 4 additional long GRBs have been announced at VHE energies

GRB 180720B (z=0.65), detected by **HESS** at 5 sigma
→ announced at the *CTA symposium*, **May 2019**

GRB 190829A (z=0.08), detected with **HESS** at 22 sigma
→ announced with *Astronomer's Telegram* on **Aug 30th, 2019**

GRB201216C (**z=1.1**), detected with **MAGIC** at 6 sigma
→ announced with *Astronomer's Telegram* on **Dec 17th, 2020**
→ **Most distant VHE gamma-ray source to date**

GRB 221009A (z=0.15), detected with **LHAASO** at >200 sigma
(**BOAT** → Brightest Of All Times) → announced with *GCN Circular* on **Oct 11th, 2022**



MAGIC detection of GRB 201216C at *z* = 1.1

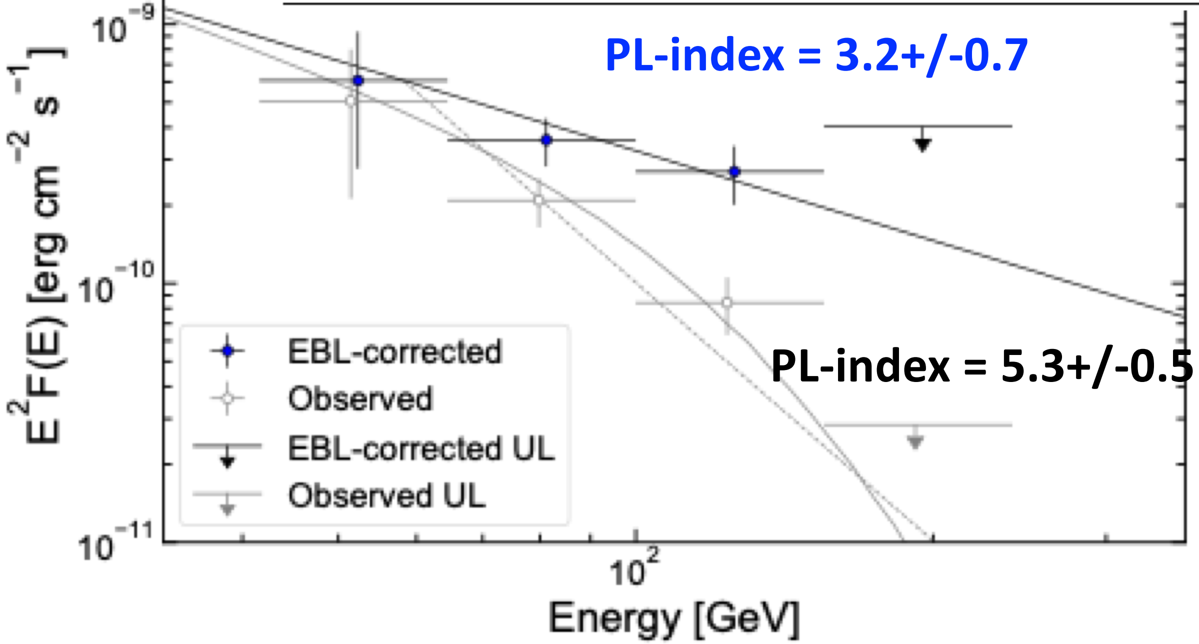
(most distant VHE source)

Abe et al., MNRAS 527, 5856–5867 (2024)

Light scale	EBL	Normalization [TeV^{-1} cm^{-2} s^{-1}]	Index
Nominal	D11	2.03 ± 10^{-8}	-3.15 ± 0.70
−15 per cent	D11	1.14 ± 10^{-8}	-3.19 ± 0.52
+15 per cent	D11	2.99 ± 10^{-8}	-2.17 ± 0.57
Nominal	F08	1.95 ± 10^{-8}	-3.19 ± 0.70
Nominal	FI10	2.76 ± 10^{-8}	-2.65 ± 0.73
Nominal	G12	3.99 ± 10^{-8}	-2.45 ± 0.71

Gamma-ray spectrum down to 40 GeV, and source not visible above 150 GeV

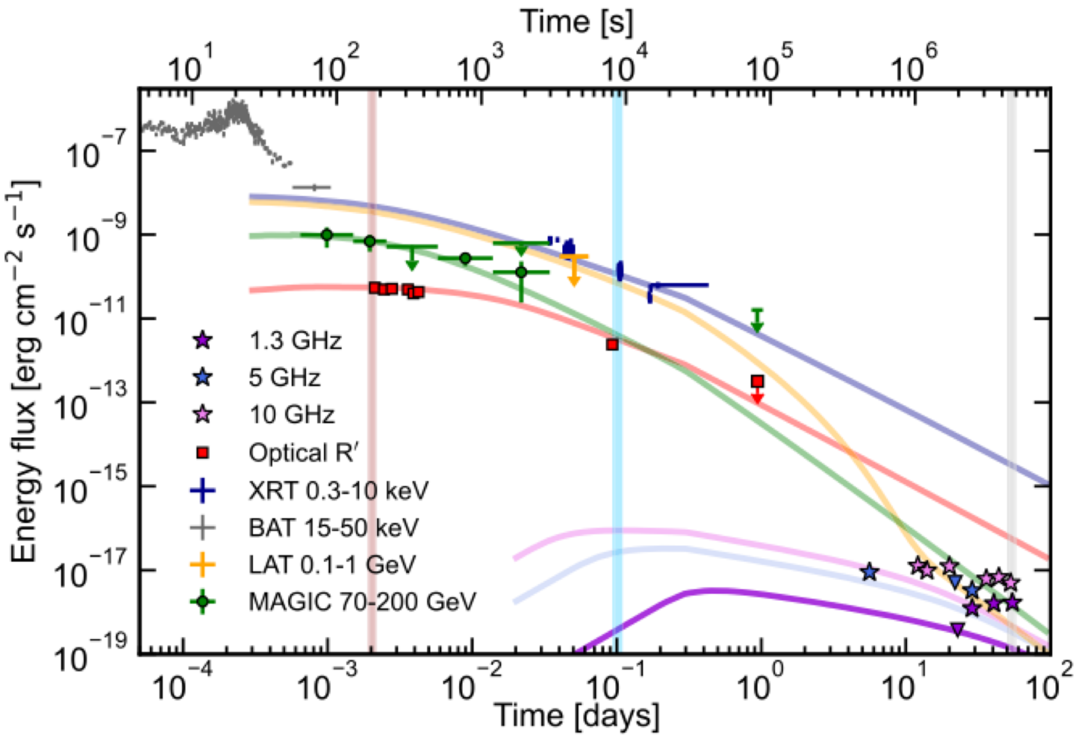
Importance of low energy threshold gamma-ray instruments to observe GRBs (distant sources)

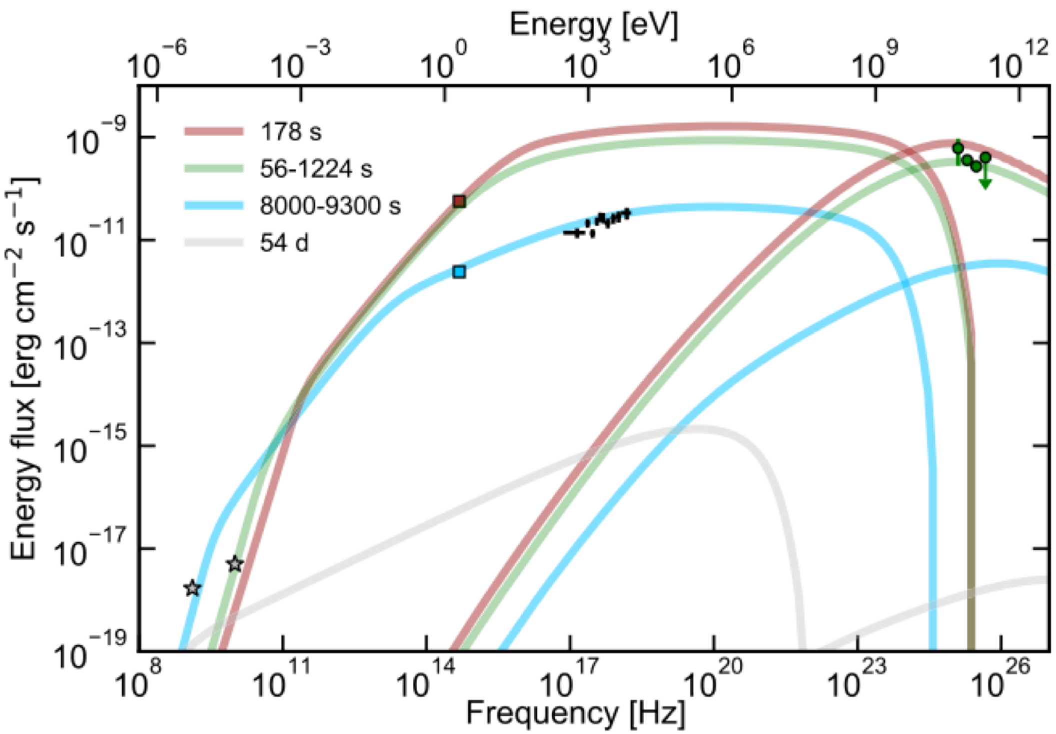


MAGIC detection of GRB 201216C at z = 1.1

(most distant VHE source)

Abe et al., MNRAS 527, 5856–5867 (2024)





One-zone SSC can explain the broadband SED, and related temporal evolution

Table 2. List of the input parameters for the afterglow model. For each parameter, the range of values investigated by means of the numerical model are listed in the second column. Solutions are not found for an homogeneous density medium (s = 0). The last column list the values that better fit the observations and used to produce the model light curves and model SEDs in Figs 5 and 6.

Parameter	Range	Best fit value
E_k [erg]	$10^{50} - 10^{54}$	4×10^{53}
θ_{jet} [degrees]	$0.5 - 3$	1
Γ_0	80–300	180
n_0 [cm^{-3}] ($s = 0$)	$10^{-2} - 10^{2}$	-
$A_\star$ ($s = 2$)	$10^{-2} - 10^{2}$	2.5×10^{-2}
p	2.05–2.6	2.1
ϵ_e	0.01–0.9	0.08
ϵ_B	$10^{-7} - 10^{-1}$	2.5×10^{-3}

ue

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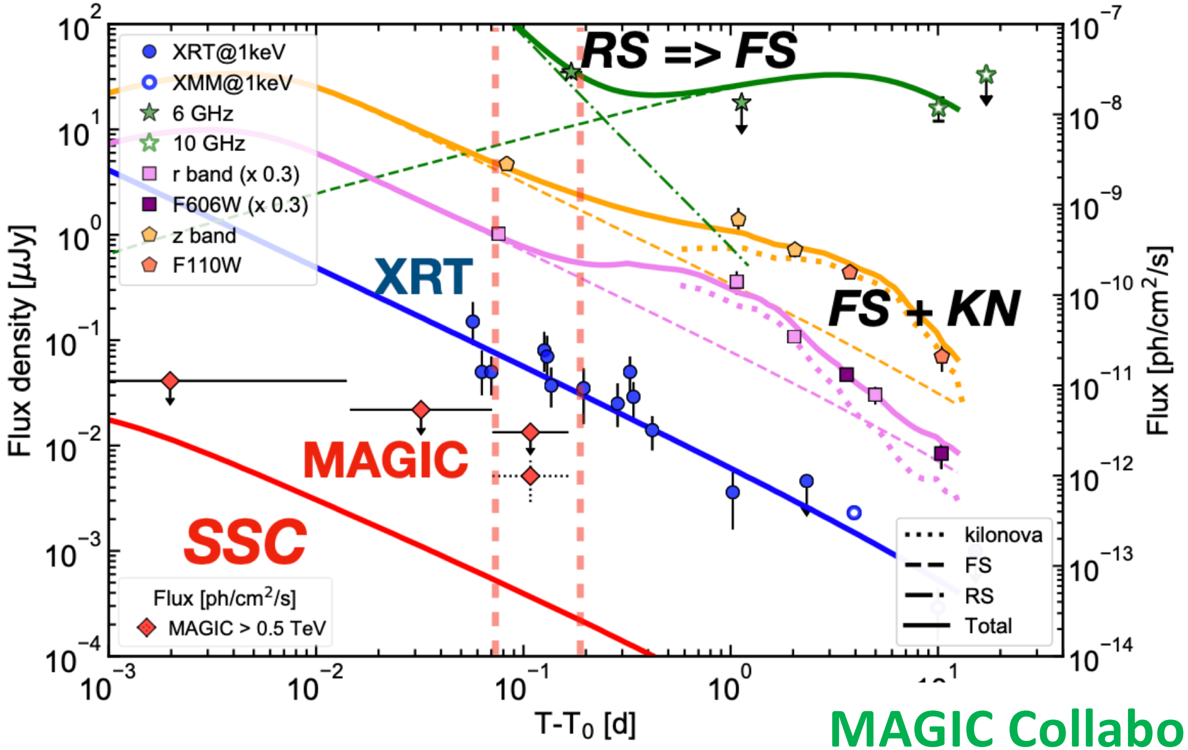
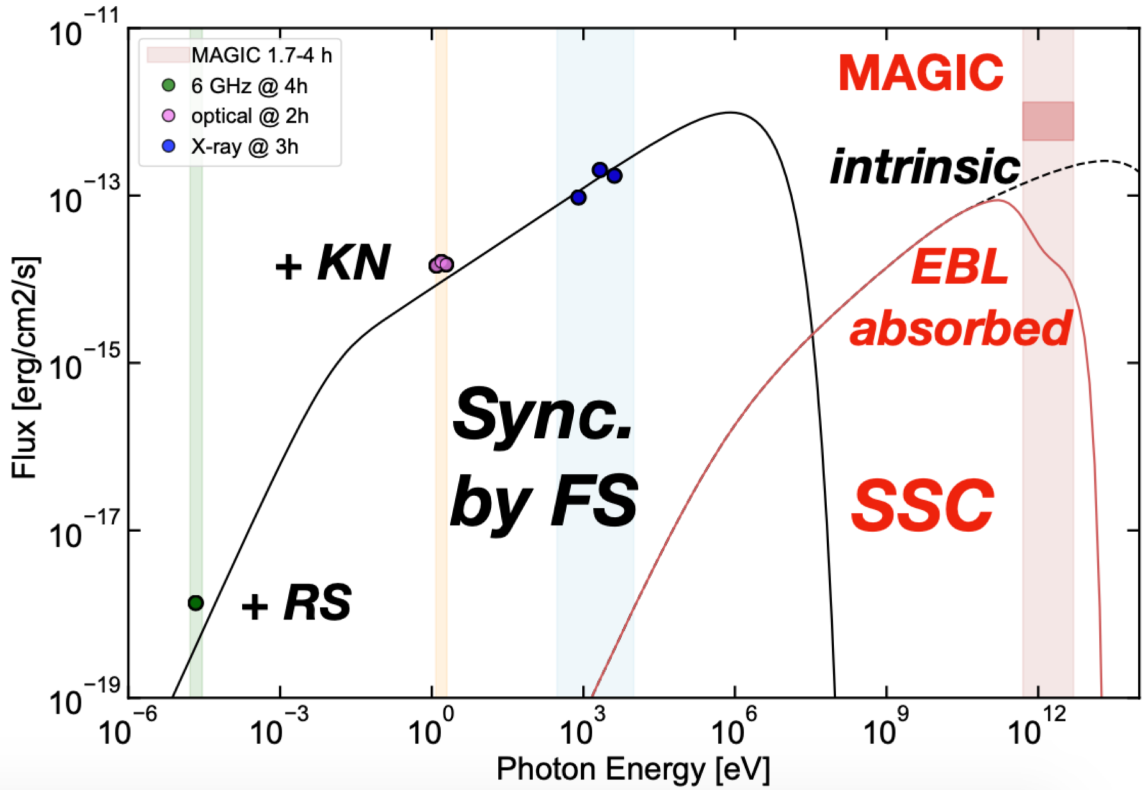
After decades of search, many TeV GRBs come „at the same time" !!
Most can be explained within the Synchrotron self-Compton scenario
It seems SSC component is indeed common among long GRBs
→ Need more TeV GRBs: time will confirm/reject this testable scenario

MAGIC detects the first hint (~3σ) of a VHE emission in a short GRB

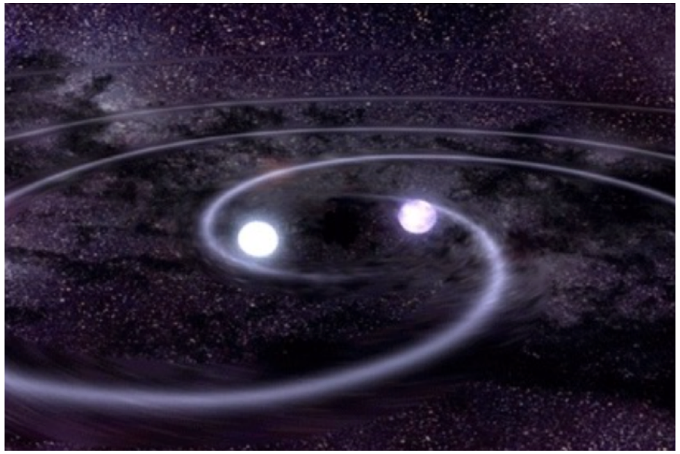
GRB160821B (z=0.16)

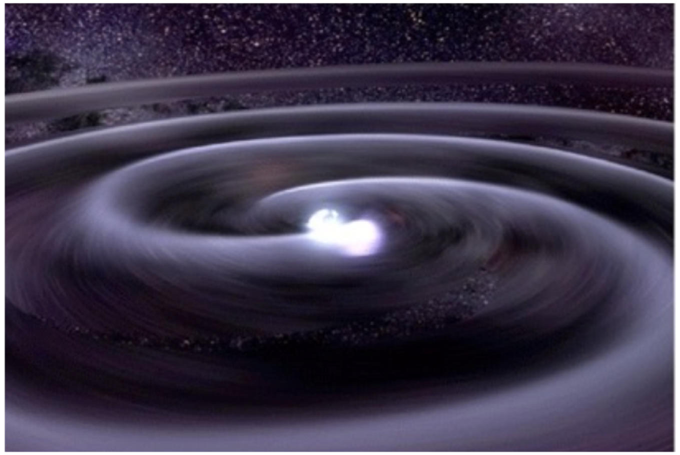


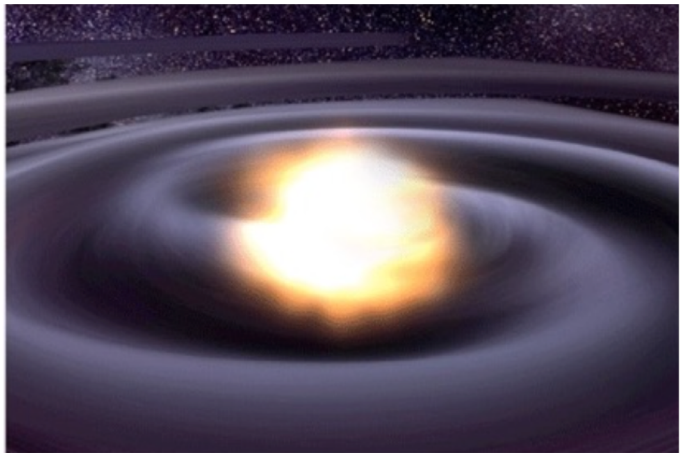
MAGIC Collaboration 2021, ApJ, 908, 90



In this case (contrary to long GRBs) the explanation with SSC model does not work well (neither the LC nor the SED)







Short GRBs are expected to be produced by NS-NS mergers.

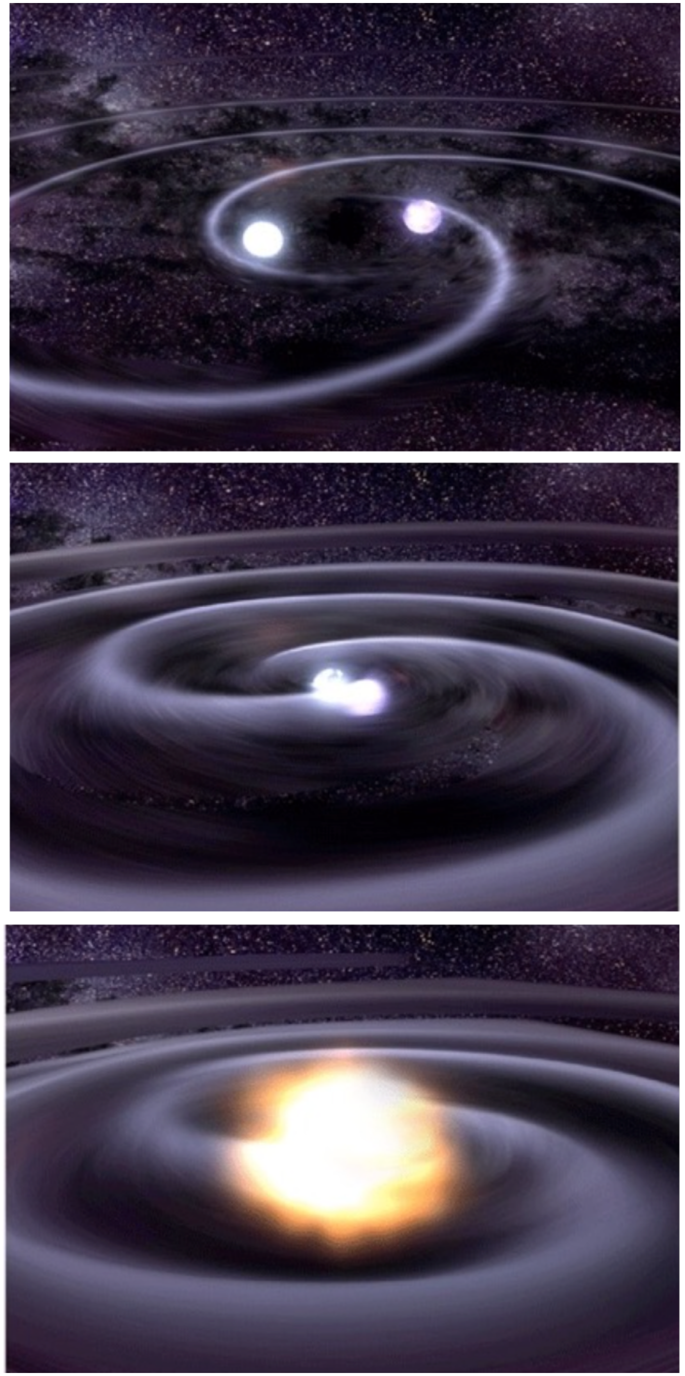
They are particularly interesting because

1) they are rare at gamma rays
10 times less abundant than long GRBs in Fermi-LAT

2) They are expected to produce gravitational waves that could be detected

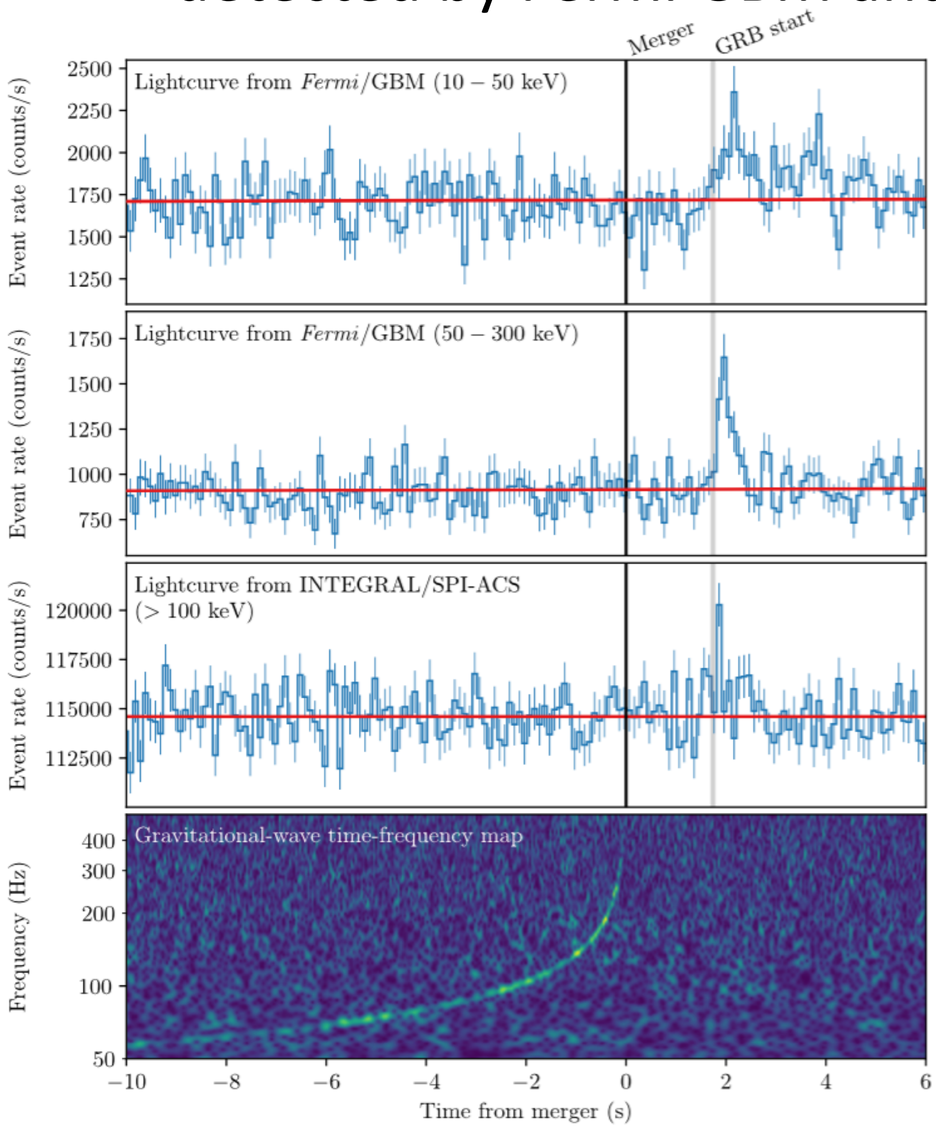
First and only EM-GW event to date is a short GRB

17th, August 2017



First Neutron Star – Neutron Star merger

→ GW170817 correlated with short GRB detected by Fermi GBM and INTEGRAL



Fermi-GBM 10-50 keV

Fermi-GBM 50-300 keV

INTEGRAL >100 keV

Abbot et al (LIGO) ApJ, 848, 13A 2017

Gamma rays (*and MAGIC*) play a fundamental role in the time domain & multi-messenger astronomy

The three most relevant (significant) multi-messenger sources reported in the last years "benefit from gamma-rays"

→ GW170817 (*GW+Photons, year **2017***)

Merger of two neutron starts, observed with Advanced Ligo and Fermi/INTEGRAL

Abbott et al. 2017, Astrophisical Journal Letters Vol. 848, 12

→ IceCube170922 (*Nu+Photons, **2017***)

High-energy neutrino from IceCube arrived during gamma-ray enhanced activity of the blazar TXS 0506+056, as measured with Fermi and **MAGIC**.

Aartsen et al. 2018, Science, Vol. 861, 1378

→ NGC1068 (*Nu+**Lack** of TeV Photons, Flux ULs, **year 2022***)

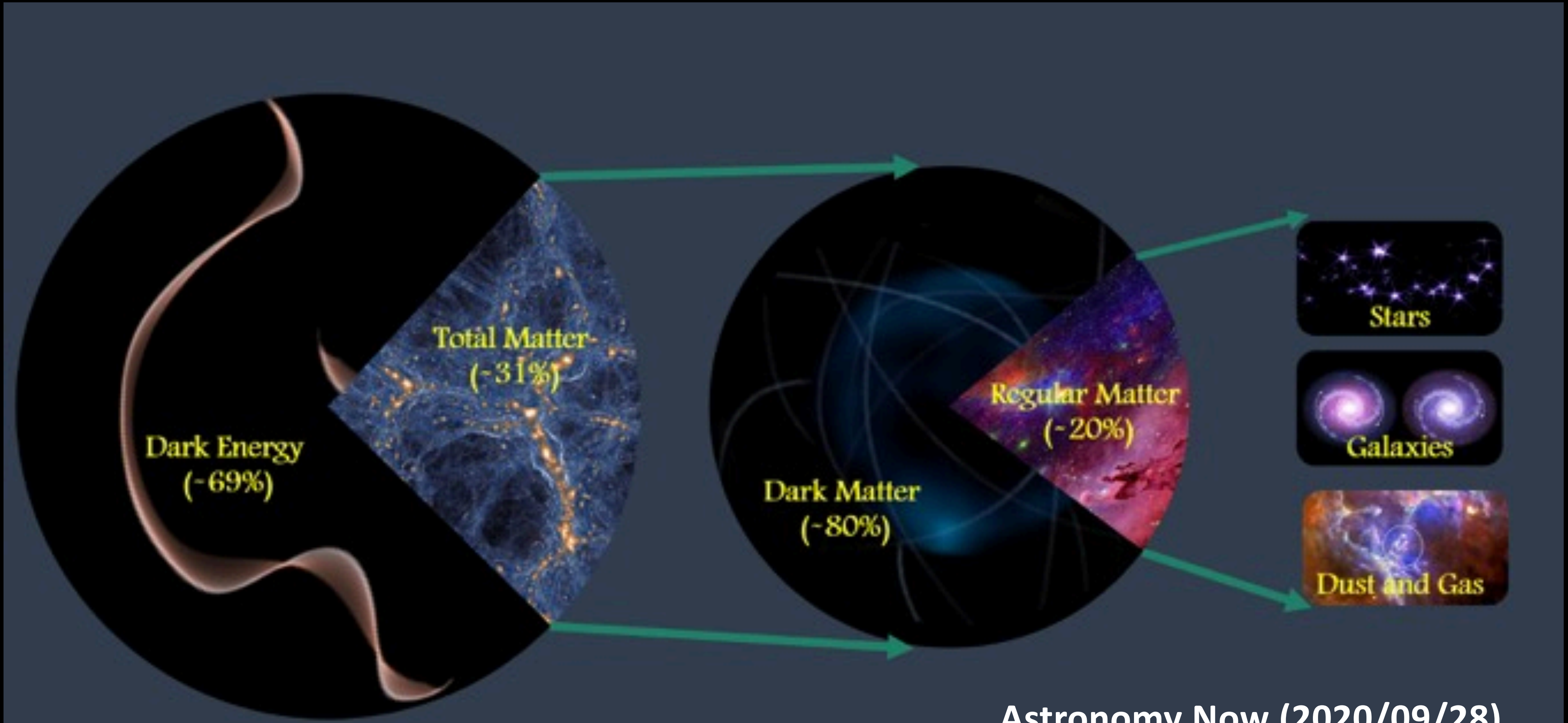
Starburst galaxy detected with IceCube (4+ sigma). The lack of TeV photons (strong upper limits with **MAGIC**) essential for interpretation of the results.

Abbasi et al. 2022, Science, Vol. 378, 538

The hunt for Dark Matter (DM) Particles

Most of the matter content in the Universe is not visible to us (it is Dark), but we can feel its presence gravitationally, and hence infer its existence, and even its location.

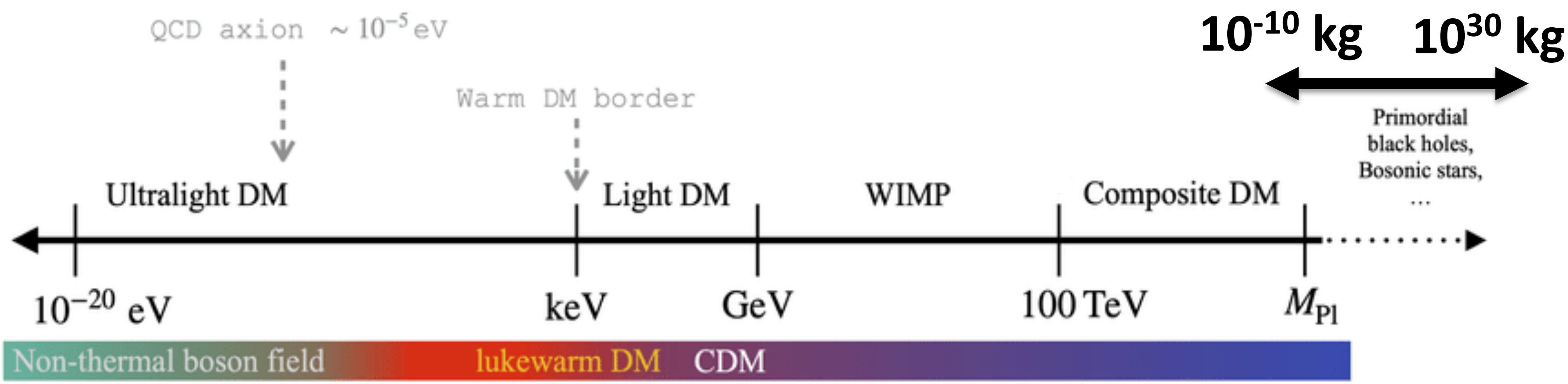
→ one of the biggest mysteries addressed by the community



Astronomy Now (2020/09/28)
Image: UCR/Mohamed Abdullah

The hunt for Dark Matter (DM) Particles

Dark Matter mass range extends over 90 orders of magnitude !

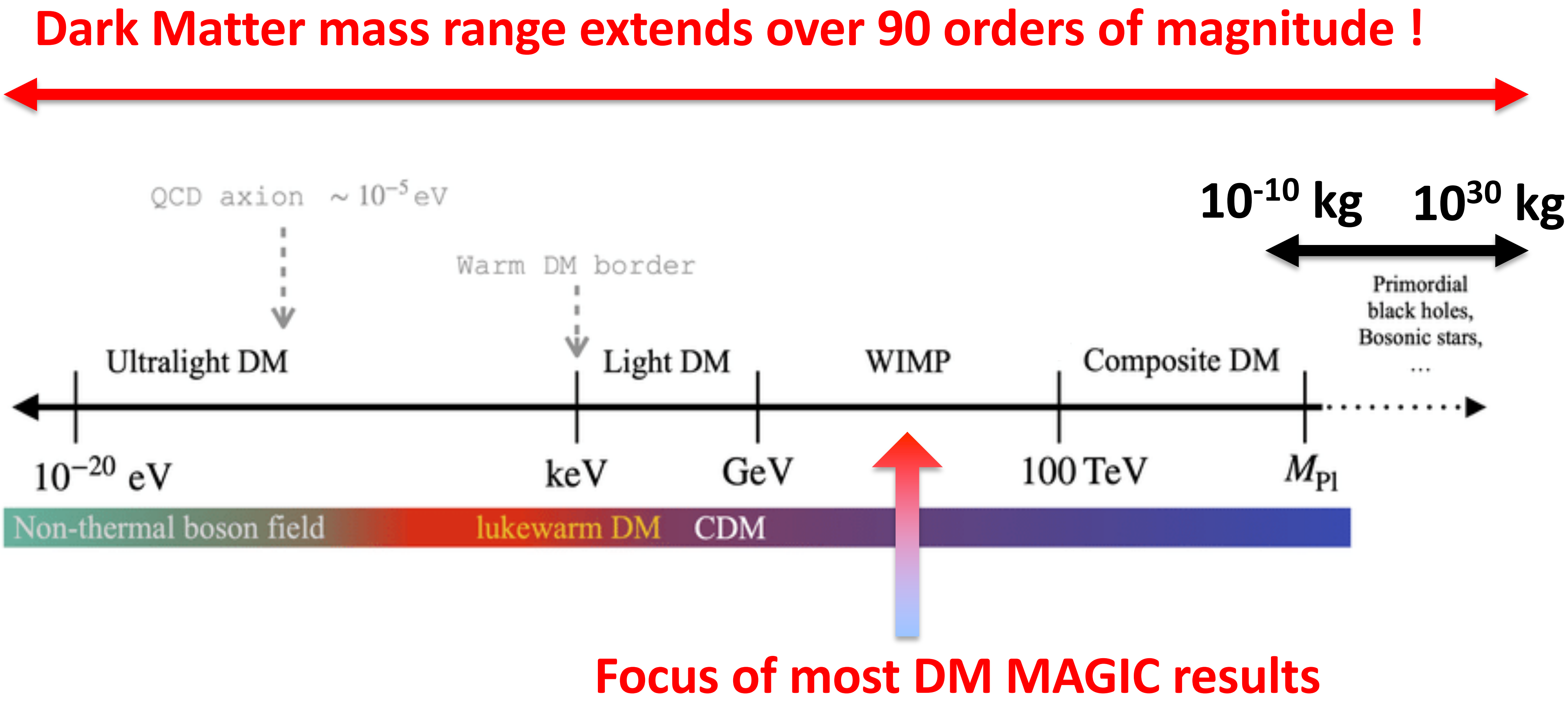


Dark Matter is an important problem for the physics (+astrophysics) community, but we are all "shooting in the dark". A priori, it could be anywhere in this huge range of masses.

Some (majority ?) scientists worship the religion of the WIMP miracle:

10GeV-10TeV particle, with weak interaction, would lead to the correct DM abundance. **Would be nice**... but no hint so far...

The hunt for Dark Matter (DM) Particles

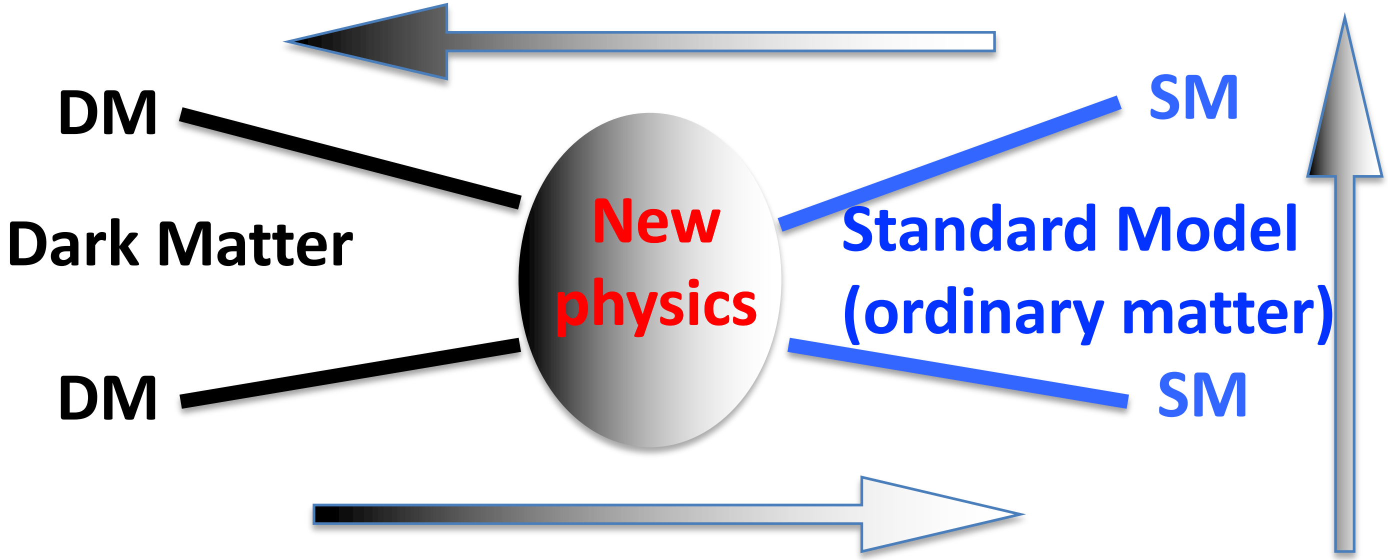


But the MAGIC telescopes can also search for ultralight Dark Matter (e.g. Axion Like Particles) and super heavy Dark Matter (e.g. primordial black holes)

The hunt for Dark Matter (DM) Particles

General: Three different ways of searching for Dark Matter particles

Collider searches: ATLAS, CMS …



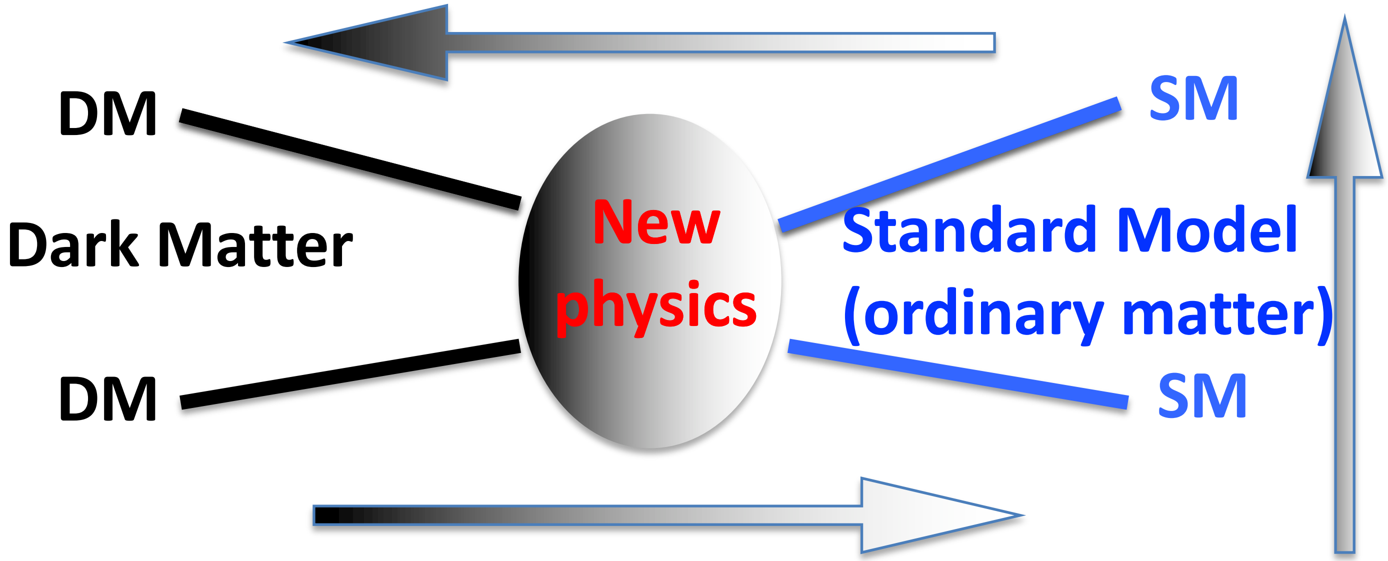
Direct searches: CRESST, CDMS …

Indirect searches: **MAGIC,** HESS, VERITAS, Fermi**,** IceCube, AMS…

The hunt for Dark Matter (DM) Particles

General: Three different ways of searching for Dark Matter particles

Collider searches: ATLAS, CMS …



Direct searches: CRESST, CDMS …

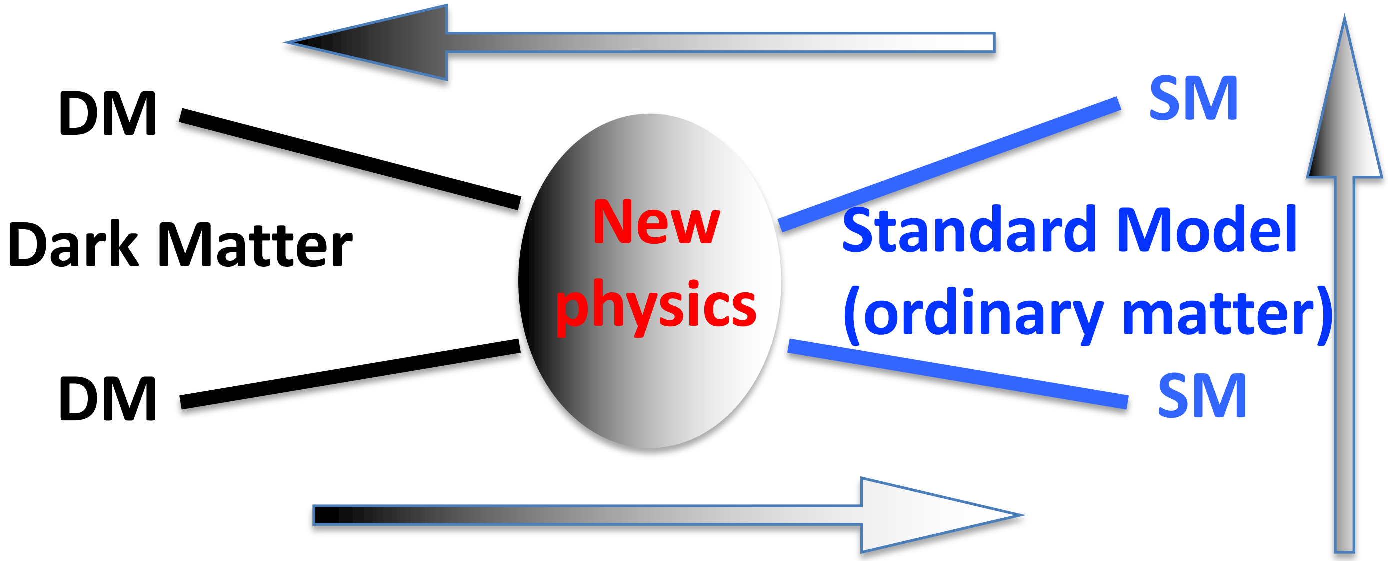
Indirect searches: **MAGIC,** HESS, VERITAS, Fermi, IceCube, AMS…

Indirect searches are crucial to understand the DM problem

The hunt for Dark Matter (DM) Particles

General: **Three different ways of searching for Dark Matter particles**

Collider searches: ATLAS, CMS …



Direct searches: CRESST, CDMS …

Indirect searches: **MAGIC,** HESS, VERITAS, Fermi**,** IceCube, AMS…

Even if a signal was found in collider experiments or direct detection experiments, we would still **need indirect detection searches in order to**:

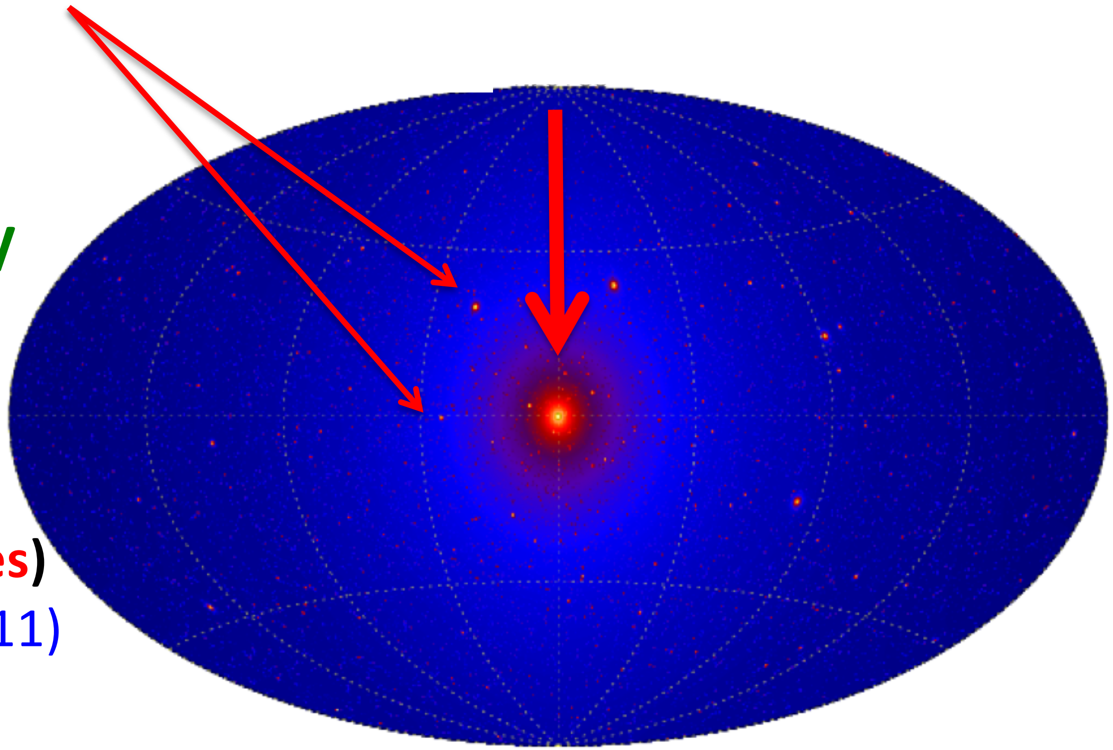
1) confirm that whatever we find in the Lab is the same "dark matter" responsible for astrophysical and cosmological observations.

2) access particle information not otherwise available in the Lab (annihilation cross section or decay time, b.r.'s)

The hunt for Dark Matter (DM) Particles

Galactic Center and Halo

Dwarf Galaxies (dSph)



Simulated all-sky map of gamma-rays from DM annihilation

(Galactic coordinates)

PRD 83, 023518 (2011)

N-Body simulation

Via Lactea II

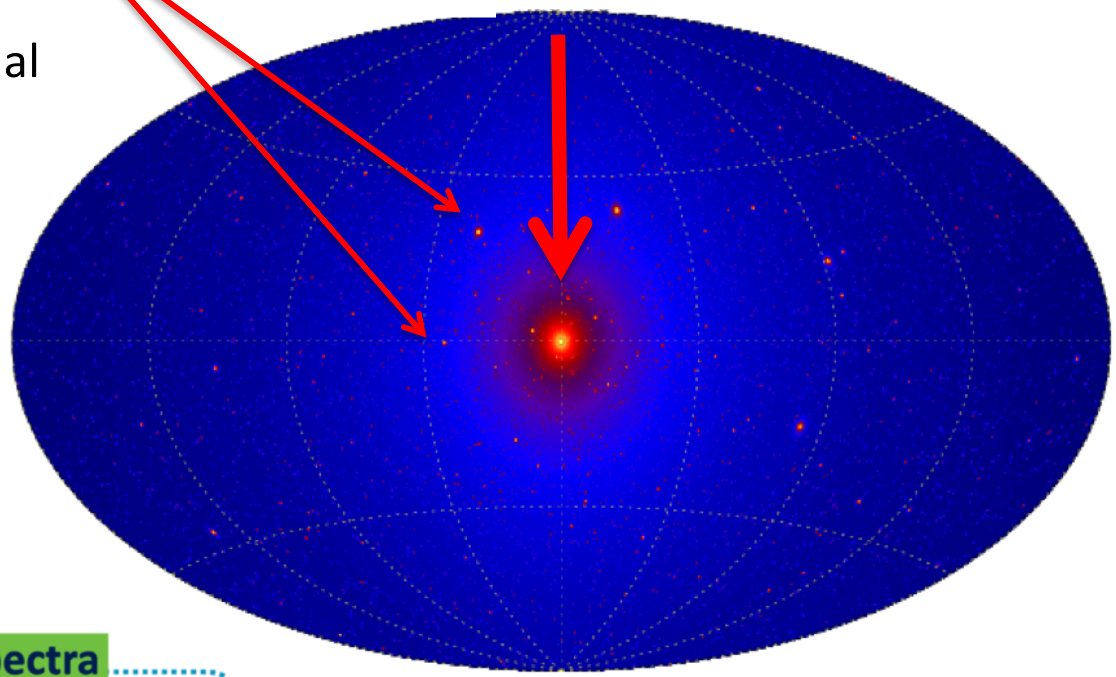
The hunt for Dark Matter (DM) Particles

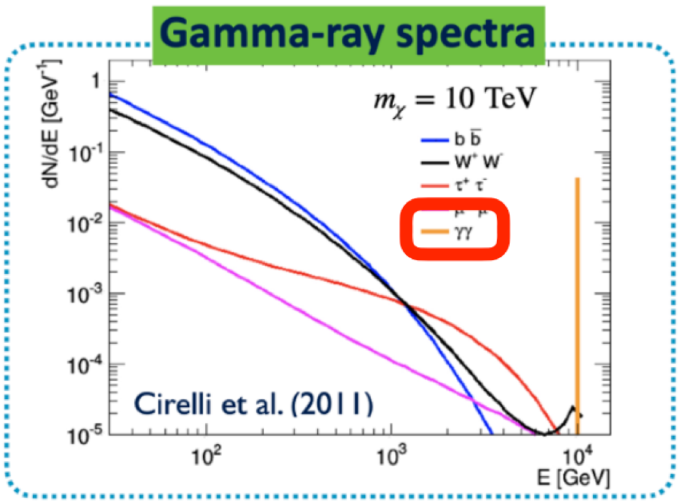
Galactic Center and Halo

Good statistics, but extended, src confusion, diffuse BKG and large uncertainties in J-factor

Dwarf Galaxies (dSph)

No BKG and close to us, small extension, but typically low DM signal





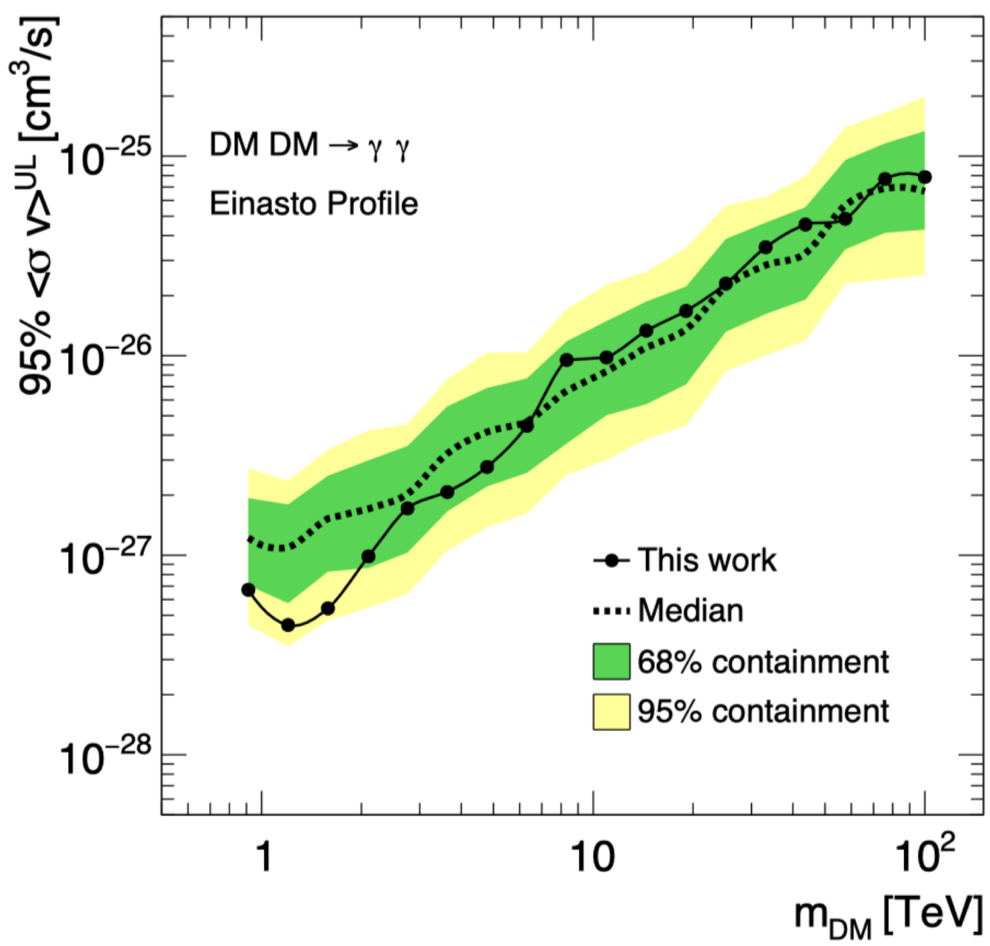
We can search the **gamma-continuum**, or we can search for **gamma-lines** (→ *easier to separate from bkg, because more difficult to fake with known astrophysical sources*)

Easiest DM search → annihilation into lines

The Galactic Center is the most DM populated region in our vicinity

No signal found in **223 hours** of Galactic Center MAGIC observations

The lack of signal (flux upper limits) can be used to set constraints on the annihilation cross section into two gamma rays, when considering a DM profile distribution at the Galactic Center



Set upper limits at 95% C.L. on 18 DM particle masses in the range spanning **from 0.9 TeV to 100 TeV**

MAGIC collaboration 2023, Physical Review Letters 130, 061002

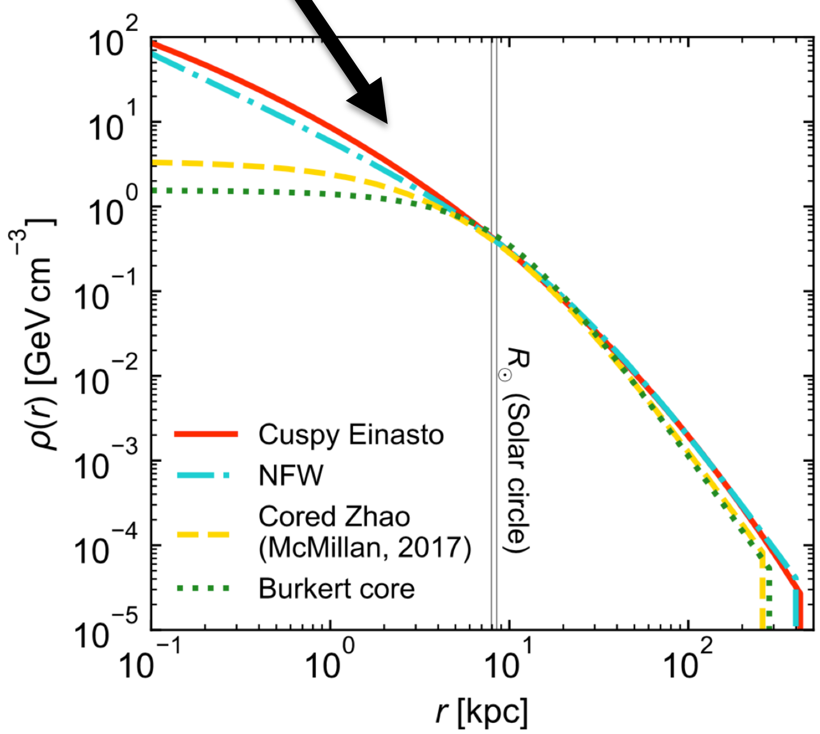
(Study led by T. Inada, D. Kerszberg and M. Hütten)

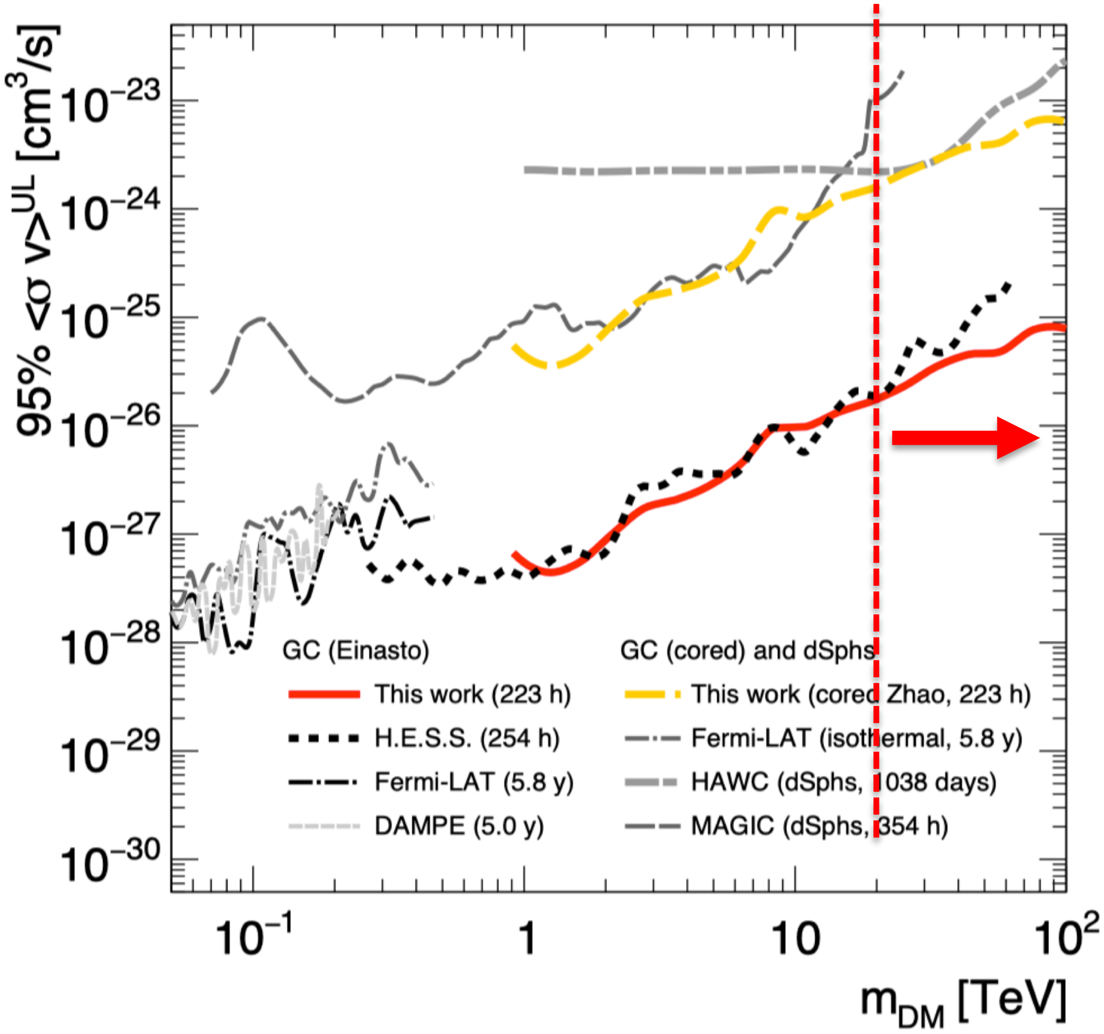
Easiest DM search → annihilation into lines

The Galactic Center is the most DM populated region in our vicinity

MAGIC collaboration 2023, Physical Review Letters 130, 061002

Search for gamma lines (from DM annihilation) in 223 hours of observation of the Galactic Center considering various <u>DM density profiles</u>





MAGIC data yielded the most sensitive DM search with lines above 20 TeV

Most competitive search with dSphs

The hunt for Dark Matter (DM) Particles

MAGIC collaboration 2022, Physics of the Dark Universe 35, 100912

(study led by C. Maggio, D. Kerszberg, D. Ninci, V. Vitale)

Deep MAGIC observations of 4 dwarf spheroidal galaxies: 354 hours

Table 1: List of the dSphs investigated in the MAGIC multi-year dSph DM project. For each dSph, we report: the logarithm of its total J-factor and its respective uncertainty, the maximum angular distance $\theta_{\max}$ and the one containing 50% of the assumed DM emission $\theta_{0.5}$ (i.e. $J(\theta_{0.5}) = 0.5 \times J(\theta_{\max})$) taken from [15], as well as the effective observation time T_{eff} and the year of data taking by MAGIC. The maximum angular distance is the angular distance of the outermost member star used to evaluate the velocity dispersion profile. It coincides with the most conservative truncation radius of the assumed DM annihilation emission.

Target	$\log_{10} J(\theta_{\max})$ [$\mathrm{GeV}^2\mathrm{cm}^{-5}$]	$\theta_{\max}$ [deg]	$\theta_{0.5}$ [deg]	T_{eff} [h]	Year
Coma Berenices	$19.02^{+0.37}_{-0.41}$	0.31	$0.16^{+0.02}_{-0.05}$	49.5	2019
Draco	$19.05^{+0.22}_{-0.21}$	1.30	$0.40^{+0.16}_{-0.15}$	52.1	2018
Ursa Major II	$19.42^{+0.44}_{-0.42}$	0.53	$0.24^{+0.06}_{-0.11}$	94.8	2016–2017
Segue 1	$19.36^{+0.32}_{-0.35}$	0.35	$0.13^{+0.05}_{-0.07}$	157.9	2011–2013

Unfortunately, <u>no gamma-ray excess found from these sky locations</u>

→ Lack of signal leads to constraints for the annihilation cross section

Most competitive search with dSphs

The hunt for Dark Matter (DM) Particles

MAGIC collaboration 2022, Physics of the Dark Universe 35, 100912

Deep MAGIC observations of 4 dwarf spheroidal galaxies: 354 hours

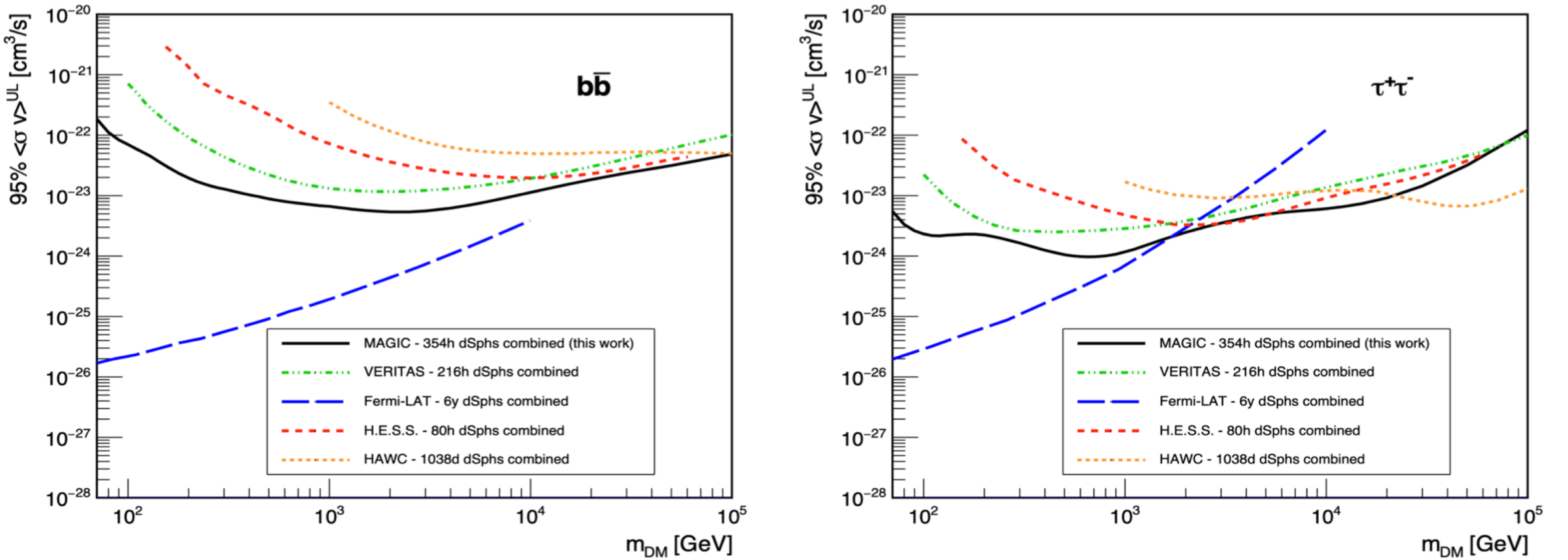


Figure 11.20: Upper limits at 95% confidence level on the WIMP velocity-averaged cross-sections $< \sigma_{ann} v >$ for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels, obtained with dSph data from various γ-ray instruments (see legends).

MAGIC data yielded the most sensitive DM search with dwarf Spheroidals at multi-TeV energies

Most competitive search with dSphs

The hunt for Dark Matter (DM) Particles

LHAASO collaboration 2024 (published in August),

Physical Review Letters 133, 061001

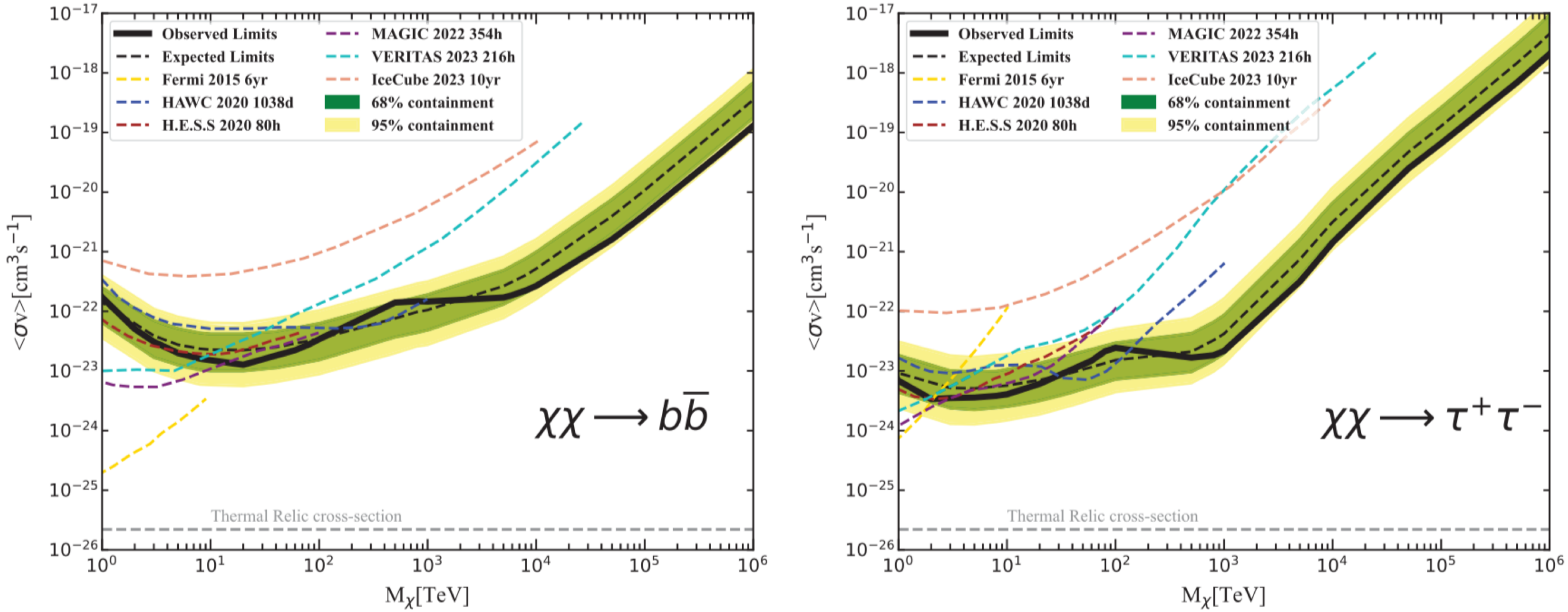


FIG. 1. The 95% C.L. upper limits on the DM annihilation cross section for $b\bar{b}$, $\tau^+\tau^-$ channels and comparing to other experiments (Fermi-LAT [18], HAWC [20], H.E.S.S. [21], MAGIC [22], VERITAS [23], IceCube [53]). The solid black line represents the observed combined limit of this Letter. The dashed black line, green band, and yellow band represent the expected limits and their 1σ and 2σ uncertainties. The dashed gray line is the thermal relic cross section [54], and the other dashed colored lines show the results of other experiments.

LHAASO has the strongest limits with dSph above 10 TeV

Most competitive search with dSphs from Combined analysis from many instruments

- **Initiative by 5 gamma-ray experiments to combine their observations of dwarf galaxies:**
  - Fermi-LAT
  - HAWC
  - H.E.S.S.
  - MAGIC
  - VERITAS

Manuscript close to submission

Most competitive search with dSphs from Combined analysis from many instruments

Multi-instrument observations of dSphs

- **In this project we use a list of 20 dwarf galaxies for which individual collaborations already published results**
- **In total, 45 different data sets used**

Fermi, HAWC, HESS, MAGIC, VERITAS Manuscript close to submission

	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS		
Source name	Exposure (10^{11} s m^2)	$\|\Delta\theta\|$ (°)	IACT	Zenith (°)	Exposure (h)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0
Canes Venatici I	2.9	14.6	–	–	–
Canes Venatici II	2.9	15.3	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4
			MAGIC	5 – 37	49.5
Draco	3.8	38.1	MAGIC	29 – 45	52.1
			VERITAS	25 – 40	49.8
Fornax	2.7	–	H.E.S.S.	11 – 25	6.8
Hercules	2.8	6.3	–	–	–
Leo I	2.4	6.7	–	–	–
Leo II	2.6	3.1	–	–	–
Leo IV	2.4	19.5	–	–	–
Leo V	2.4	–	–	–	–
Leo T	2.6	–	–	–	–
Sculptor	2.7	–	H.E.S.S.	10 – 46	11.8
Segue I	2.5	2.9	MAGIC	13 – 37	158.0
			VERITAS	15 – 35	92.0
Segue II	2.7	–	–	–	–
Sextans	2.4	20.6	–	–	–
Ursa Major I	3.4	32.9	–	–	–
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8
Ursa Minor	4.1	–	VERITAS	35 – 45	60.4

Most competitive search with dSphs from Combined analysis from many instruments

Combined likelihood analysis

- **Expected gamma-ray flux from DM annihilation:**

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\text{ann}}v\rangle}{2m_{\text{DM}}^2}\frac{dN}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{\text{l.o.s.}} dl\,\rho^2(l,\Omega')$$

- **Using as many common ingredients as possible:**
  - Common range of channels and DM masses:
    - From 5 GeV to 100 TeV using the DM spectra from Cirelli et al. [JCAP 1103:051, 2011]
    - Studied 7 annihilation channels in total
  - Same J-factor values and statistical uncertainties

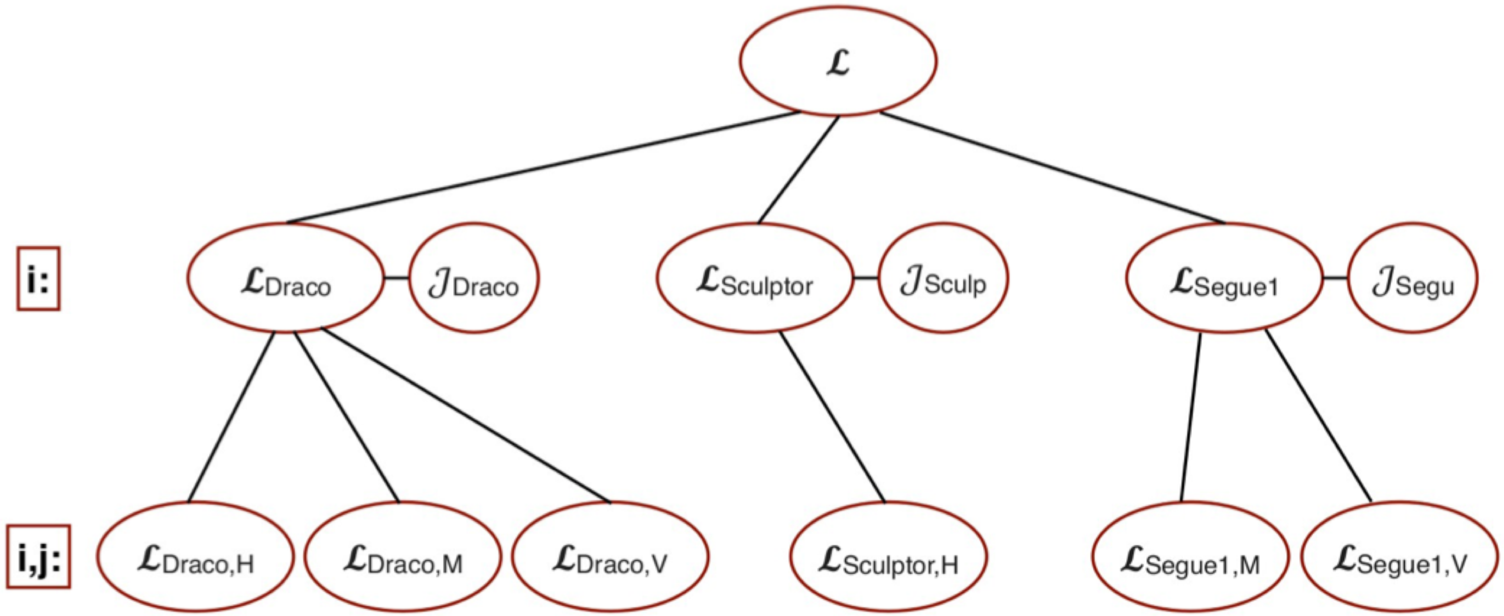
- **Individual experiments shared likelihood profile for each dSph/channel/mass combination for a fixed value of the J-factor**
  - statistical uncertainties on the J-factor are taken into account (the J-factor being a **nuisance parameter** in the combined likelihood)

Most competitive search with dSphs from
Combined analysis from many instruments

Combined likelihood analysis

- **Combined likelihood:**

$$\mathcal{L}\left(\langle\sigma v\rangle;\boldsymbol{\nu}\mid\boldsymbol{\mathcal{D}}_{\text{dSphs}}\right)=\prod_{l=1}^{N_{\text{dSphs}}}\mathcal{L}_{\text{dSph},l}\left(\langle\sigma v\rangle;J_l,\boldsymbol{\nu_l}\mid\boldsymbol{\mathcal{D}}_{\boldsymbol{l},\text{measured}}\right)\times\mathcal{J}_l\left(J_l\mid J_{l,\text{obs}},\sigma_{\log J_l}\right)$$

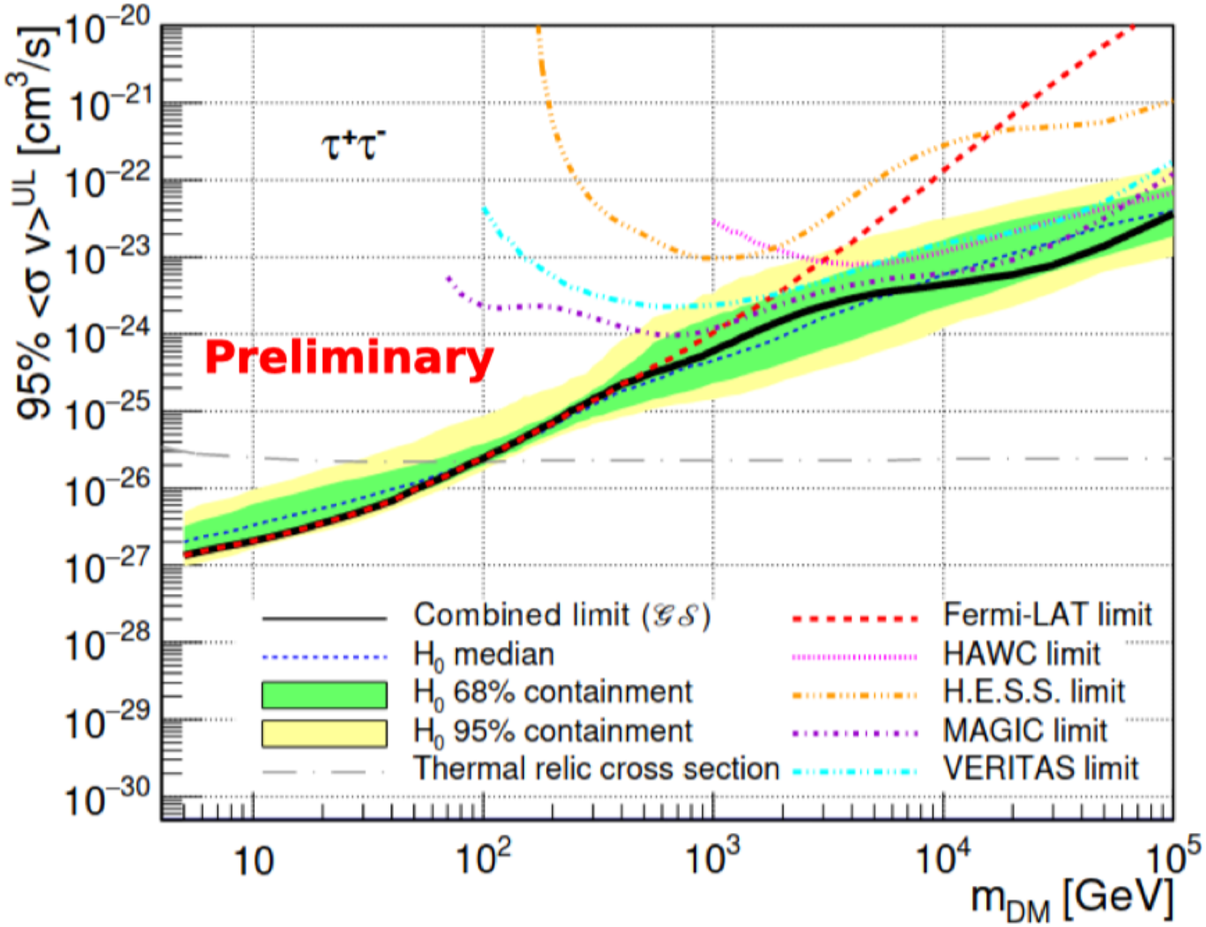


- **The combination was performed with two independent softwares:**
  - glike: https://doi.org/10.5281/zenodo.4028908
  - LklCombiner: https://doi.org/10.5281/zenodo.4450884

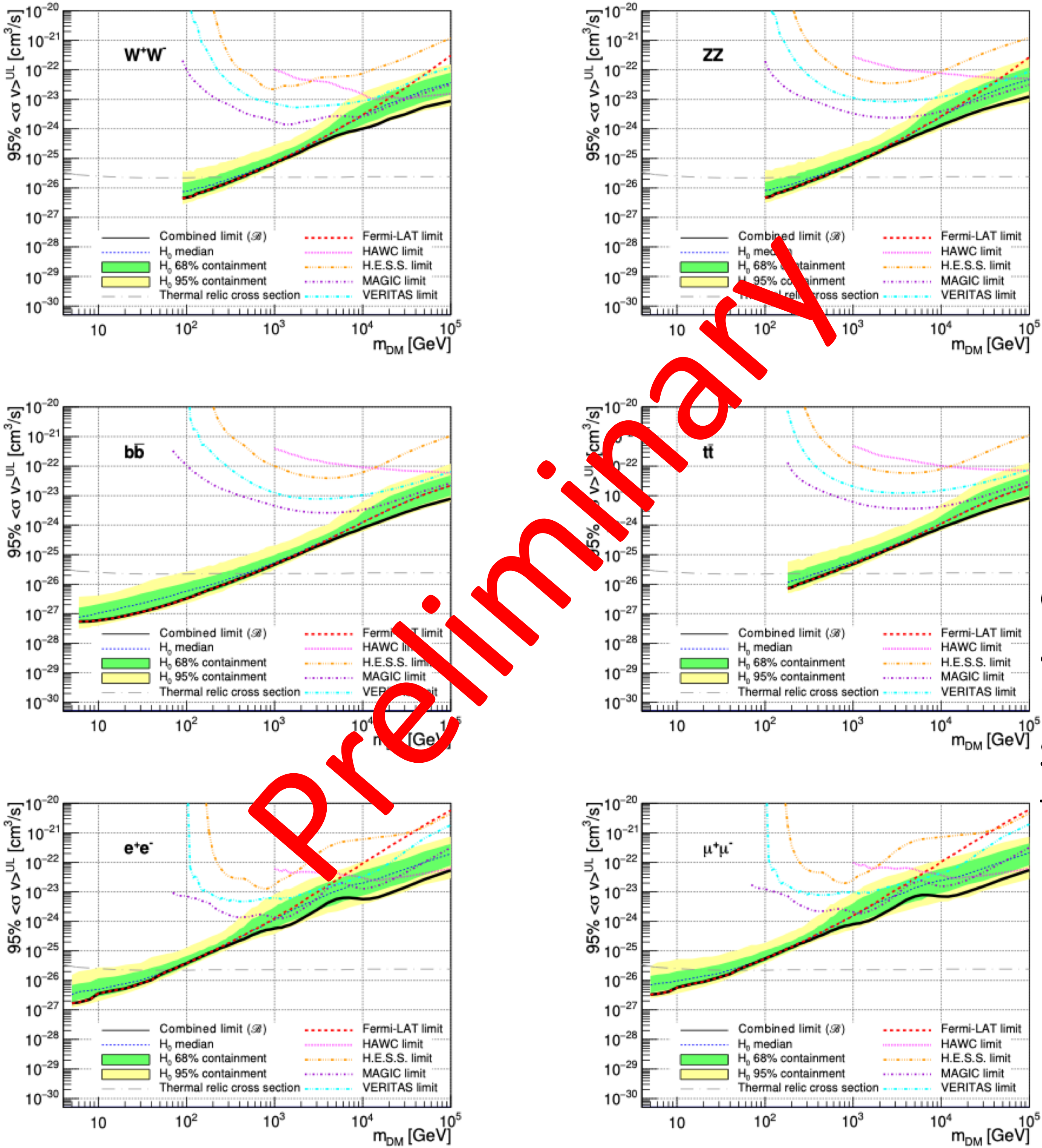
Most competitive search with dSphs from
Combined analysis from many instruments

Combined limits for one channel

Fermi, HAWC, HESS, MAGIC, VERITAS Manuscript close to submission



Combined limits are up to a factor 2-3 more constraining



Combined analysis from many instruments

Combined limits for the other six channels

Combining many targets allows to minimize the importance of single dSphs. Specially relevant when J-factor is (very) uncertain

Fermi, HAWC, HESS, MAGIC, VERITAS

Manuscript close to submission

The hunt for Dark Matter (DM) Particles

Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC

MAGIC collaboration, Physics of the Dark Universe 44 (2024) 101425

(study led by I. Batković and G. D'Amico)

Besides looking for DM at the "TeV energy range " (expected for "classical WIMPs), MAGIC also looks at very light DM particles, like Axions and Axion Like Particles

The constraints come from the lack of "oscillating features" in the gamma-ray spectra from NGC1275. Big overlap with previous exclusions

<u>**See in this conference:**</u>
- Searching for Axion-like particles: insights from blazar observations with the LST1 telescope (*Ivana Batković*)

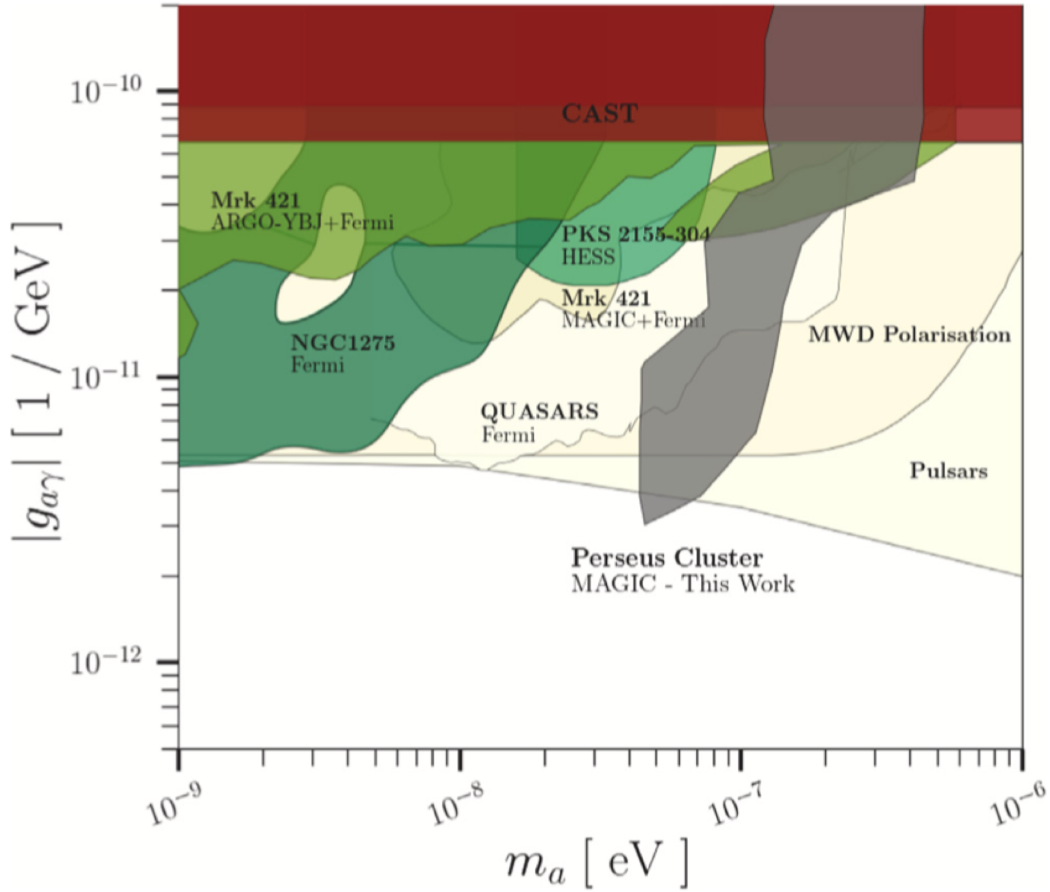
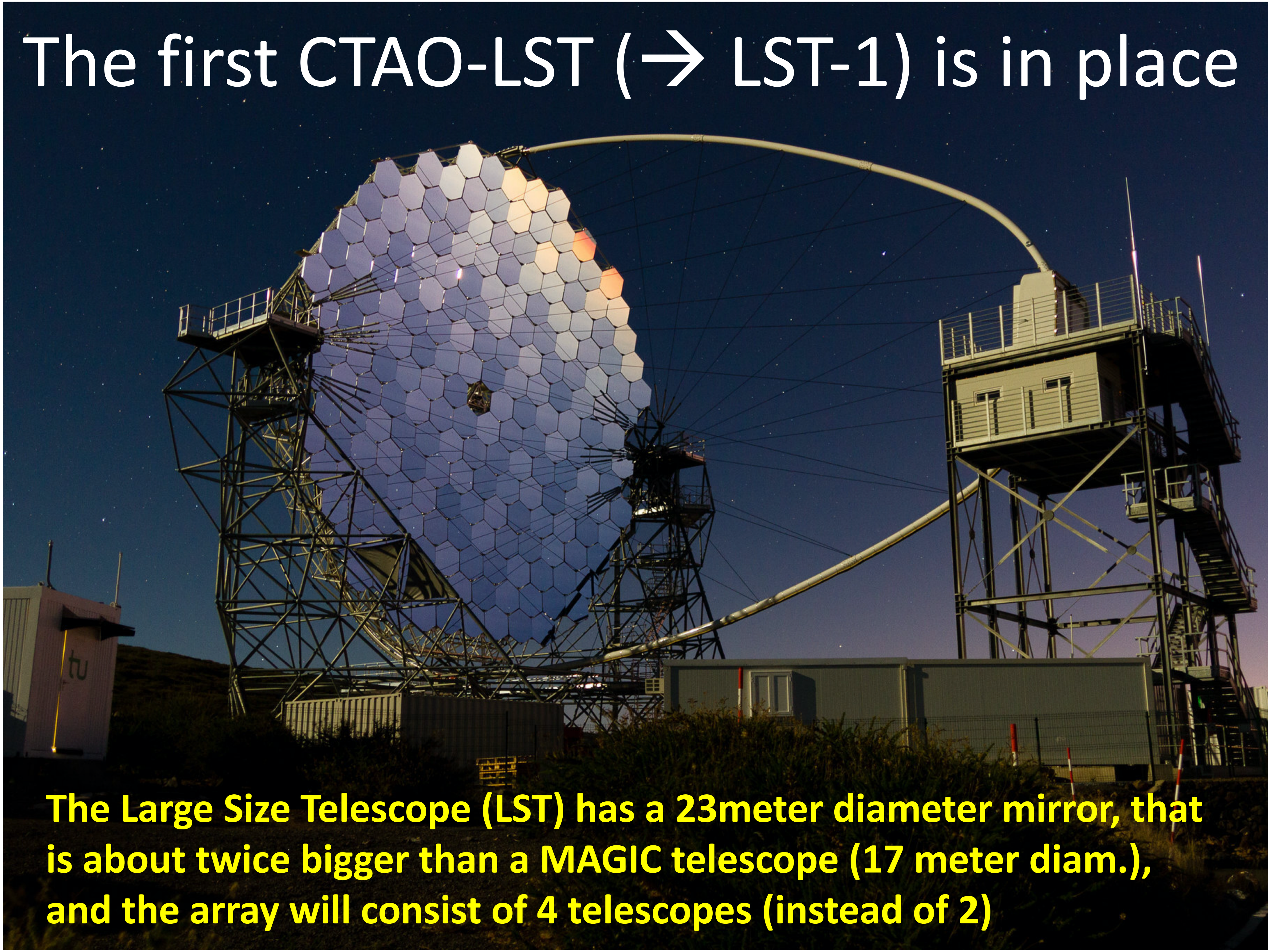


Fig. 5. The 99% CL limits obtained with this work in comparison with current 95% CL limits in similar part of the parameter space, gathered in [72].

Outlook into the future

The first CTAO-LST (→ LST-1) is in place



The Large Size Telescope (LST) has a 23meter diameter mirror, that is about twice bigger than a MAGIC telescope (17 meter diam.), and the array will consist of 4 telescopes (instead of 2)

The first CTAO-LST (→ LST-1) is in place

Virtual visit to the CTAO-North observatory:
https://tour.klapty.com/NH20OJ5Iae/?deeplinking=true&startscene=0&startactions=lookat(-67.07,23.81,90,0,0)

MAGIC-LST1 proximity allows joint observations for better angular & energy resolution, and better sensitivity (*Soft. and Hard. trigger*)

Abe H. et al (LST+MAGIC collab.), 2023, A&A, 680A, 66A

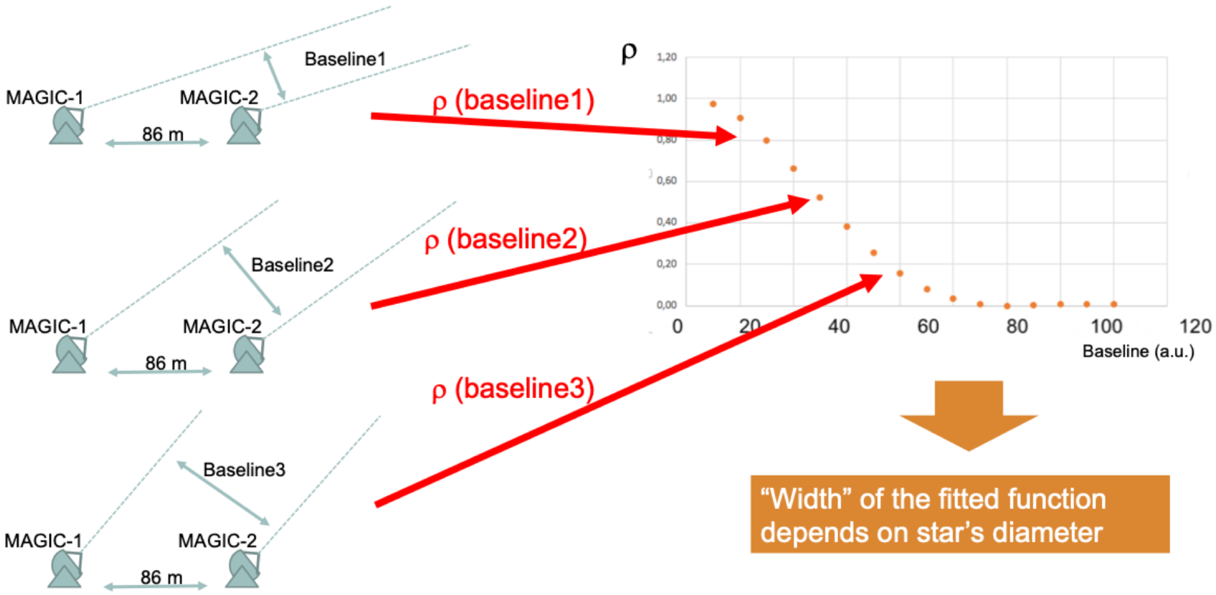
About 1.3-1.5 better sensitivity → *reduction of obs. time by ~2.0*

→ New opportunities to detect faint or very distant sources

We are already performing some joint MAGIC-LST1 observations for scientific purposes, and decided to increase and better coordinate these observations next year.

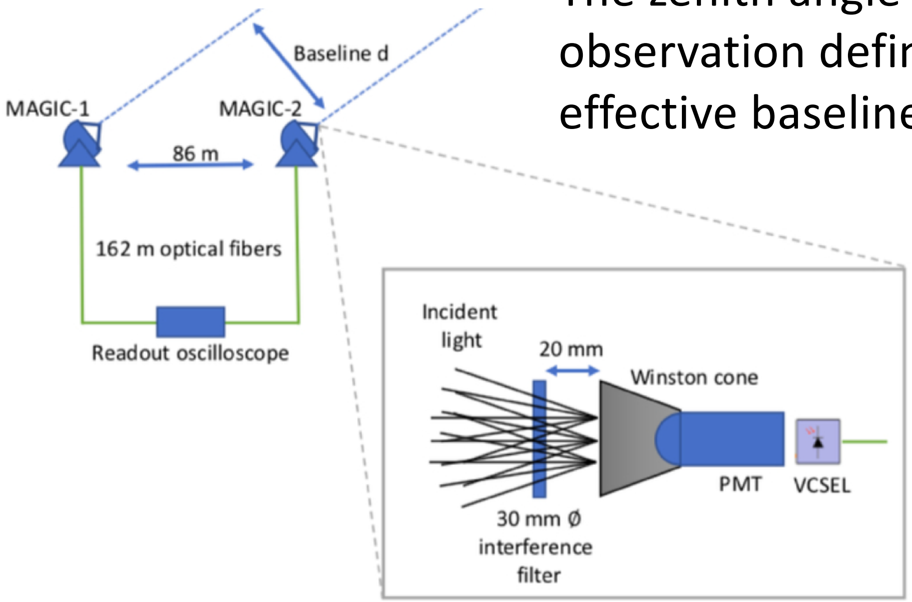
Intensity interferometry with MAGIC (& LST in future)

→ Hardware upgrade to expand physics portfolio of Cherenkov telescopes



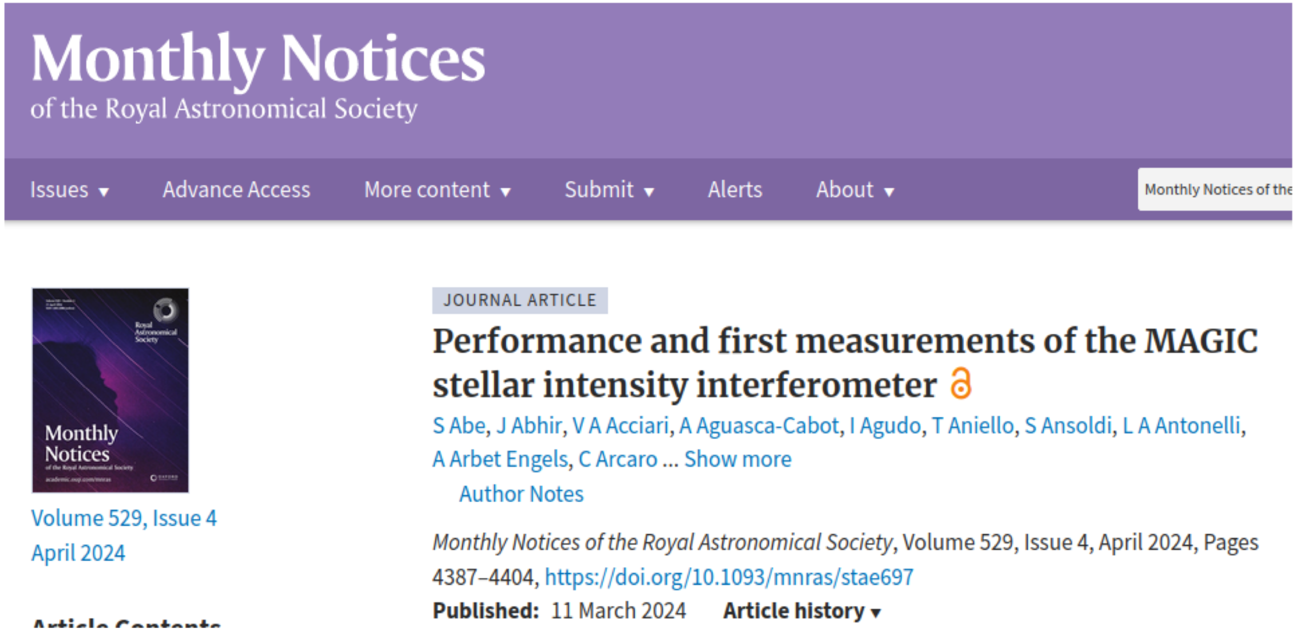
Ideally suited for this task:

- **Large collecting mirrors**
- **Time resolutions of ns**



The zenith angle of the observation defines the effective baseline

Filters can be set/removed remotely by shifters from control house (no HW intervention needed)



Monthly Notices
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Volume 529, Issue 4
April 2024

JOURNAL ARTICLE

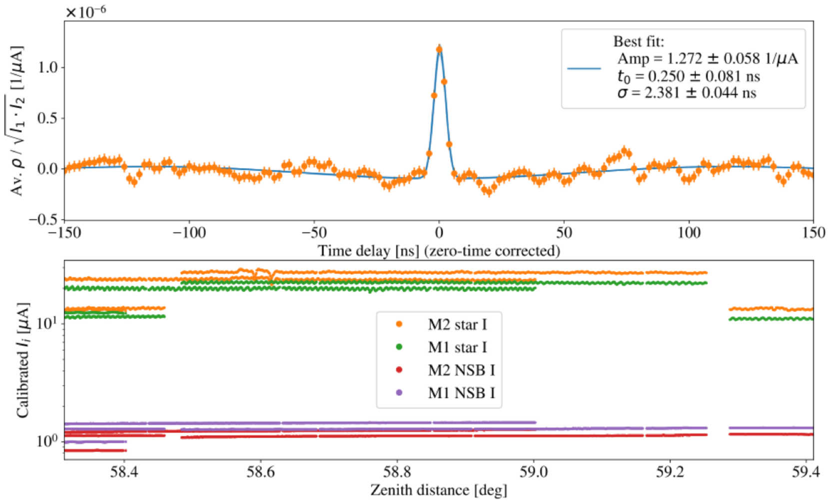
Performance and first measurements of the MAGIC stellar intensity interferometer

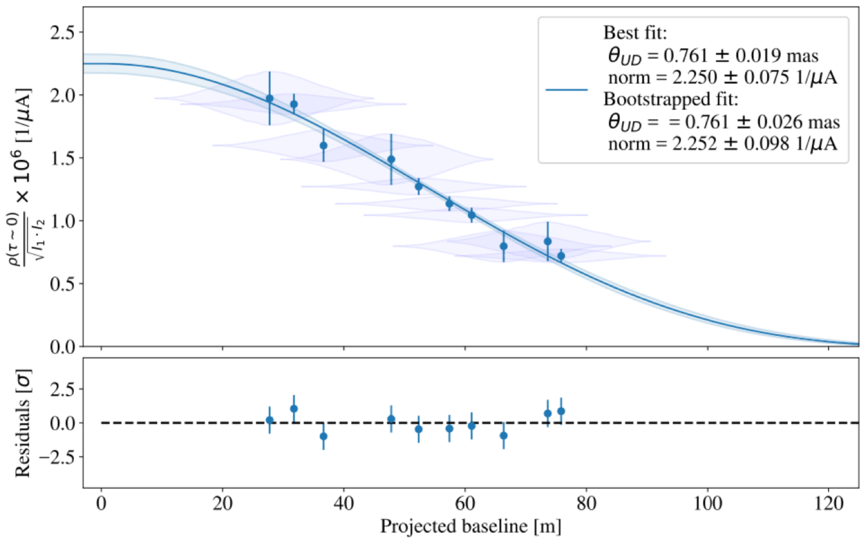
S Abe, J Abhir, V A Acciari, A Aguasca-Cabot, I Agudo, T Aniello, S Ansoldi, L A Antonelli, A Arbet Engels, C Arcaro ... Show more
Author Notes

Monthly Notices of the Royal Astronomical Society, Volume 529, Issue 4, April 2024, Pages 4387–4404, https://doi.org/10.1093/mnras/stae697
Published: 11 March 2024 **Article history** ▾

Opening yet another window to perform astronomy/astrophysics with the MAGIC telescopes

Study led by T. Hassan, M. Fiori, I. Jimenez, C. Wunderlich

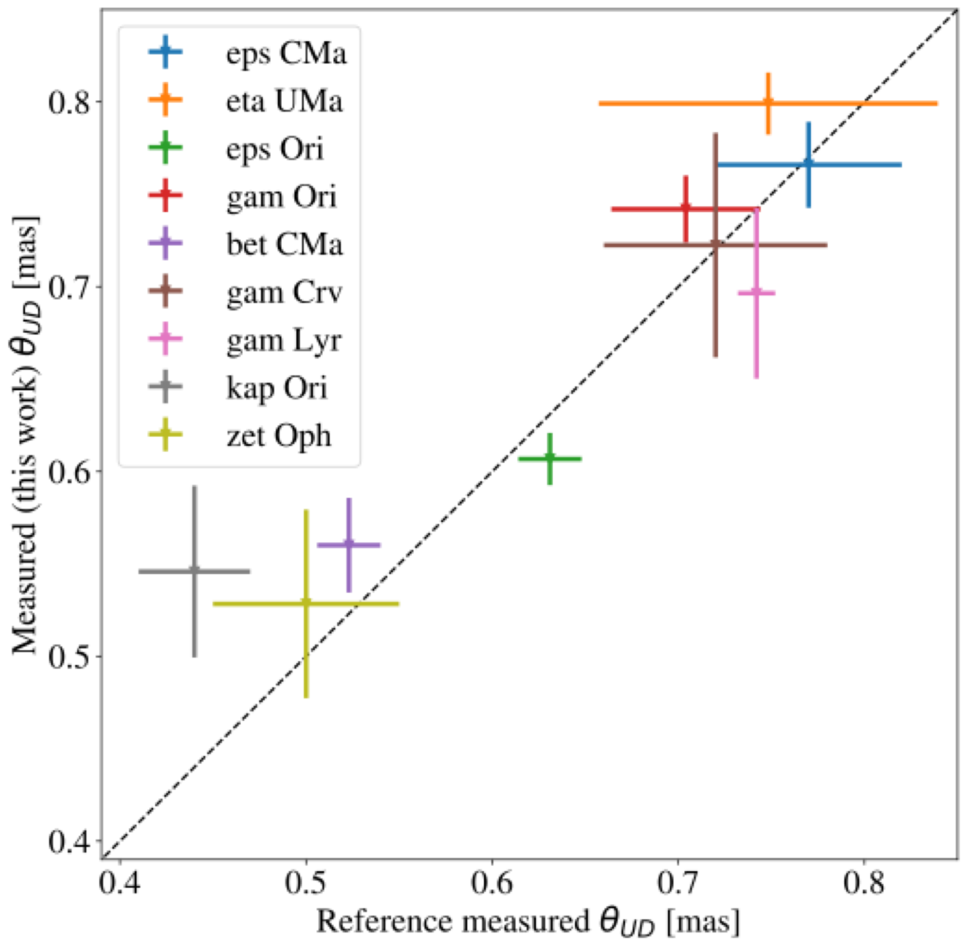




Intensity interferometry with MAGIC (& LST in future)

Candidate measured UD diameters vs estimated diameter

MAGIC collab., MNRAS **529,** 4387–4404 (2024)



We have demonstrated that MAGIC can already measure the diameter of multiple stars, down to a fraction of mas

Next step is to upgrade the system, and to implement the technique in the LST-1 (and later on the other LSTs)

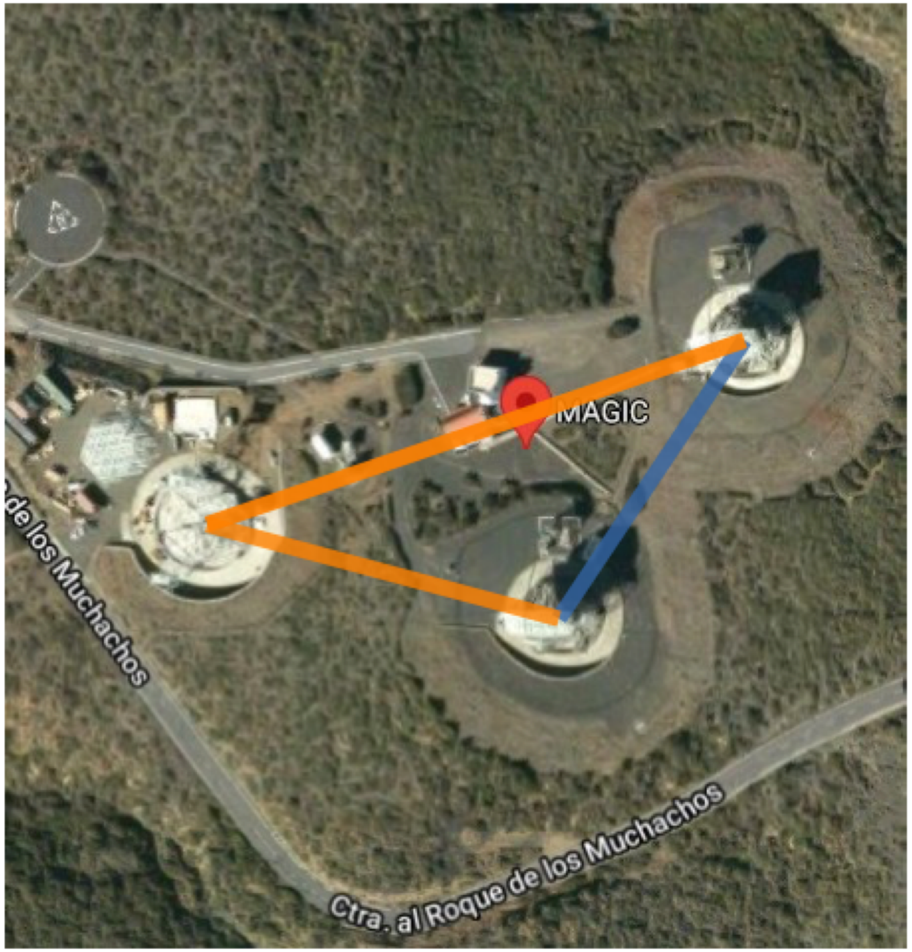
Will be done with help of ERC grant
(PI: T. Hassan, MAGIC/LST group from Madrid)

European Research Council
Established by the European Commission

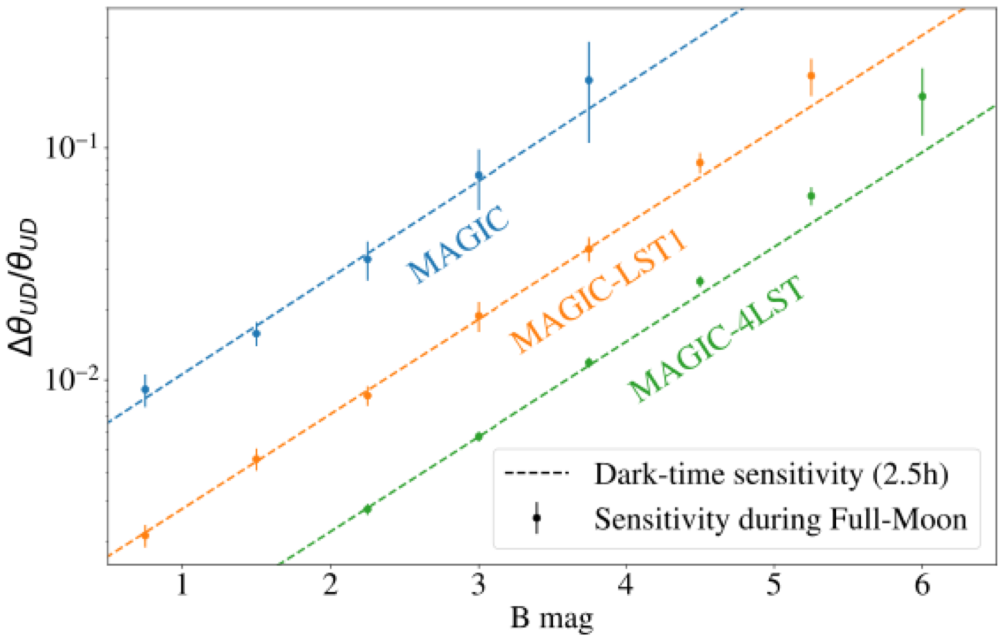
Intensity interferometry with the MAGIC telescopes

Adding LST telescopes would be a game-changer

→ Many more possible baselines and more sensitivity



MAGIC collab., MNRAS **529,** 4387–4404 (2024)

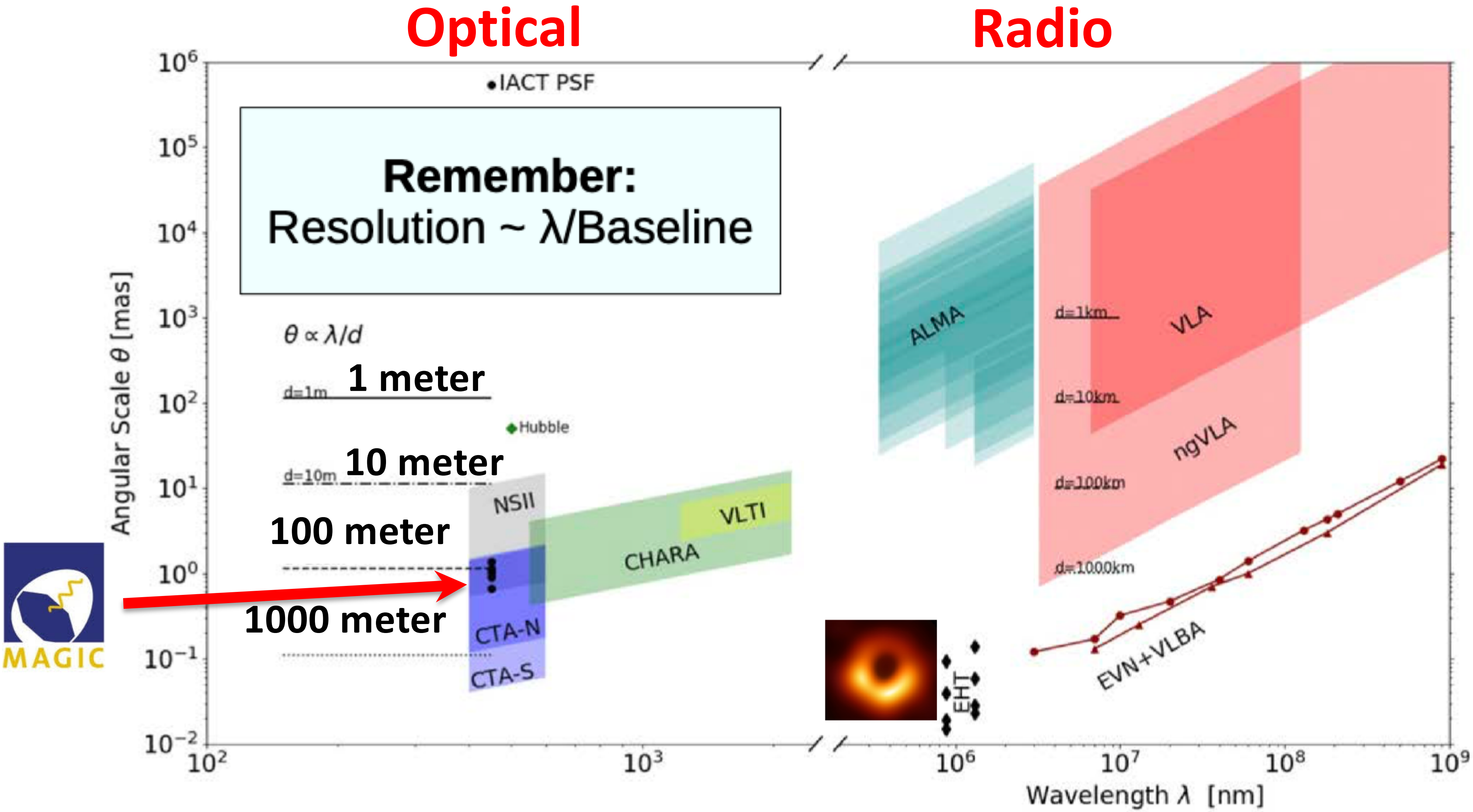


For relatively “low investment” (cost and people) we can expand the physics portfolio of the MAGIC+LSTs gamma-ray telescopes

And in the long round, merge also with the other LSTs, so that we have more sensitivity and more baselines

Intensity interferometry with MAGIC (& LST in future)

→ Hardware upgrade to expand physics portfolio of Cherenkov telescopes



MAGIC already reaches angular resolutions of below 0.5 mas

Measure diameter & shape of stars, binary systems, Nova explosions ...

Outlook and Concluding Remarks

MAGIC collaboration has published 211 scientific publications (*Oct.2024*), and **continues to be highly productive after 20+ years of operation** *(since Oct. 2003)*
Today I briefly mentioned a few historical breakthroughs from last two decades, and reported a few recent highlight results on *GRBs and DM searches*

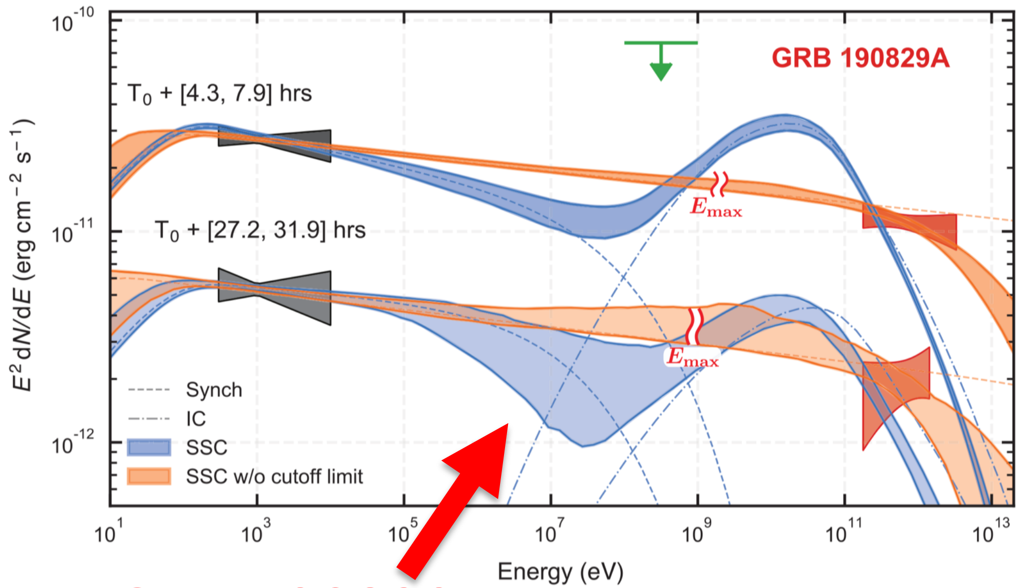
MAGIC collaboration has extended the MoU until June 2029

In near future, additionally to regular gamma-ray observations, we will
- Perform MAGIC and CTAO-LST1 joint observations, a joint (partial) physics program will be defined (by both collaborations)
- Expand the physics portfolio through intensity interferometry observations

Backup slides

First detections of a gamma-ray burst at TeV energies

Some controversy in the theoretical interpretation of the data

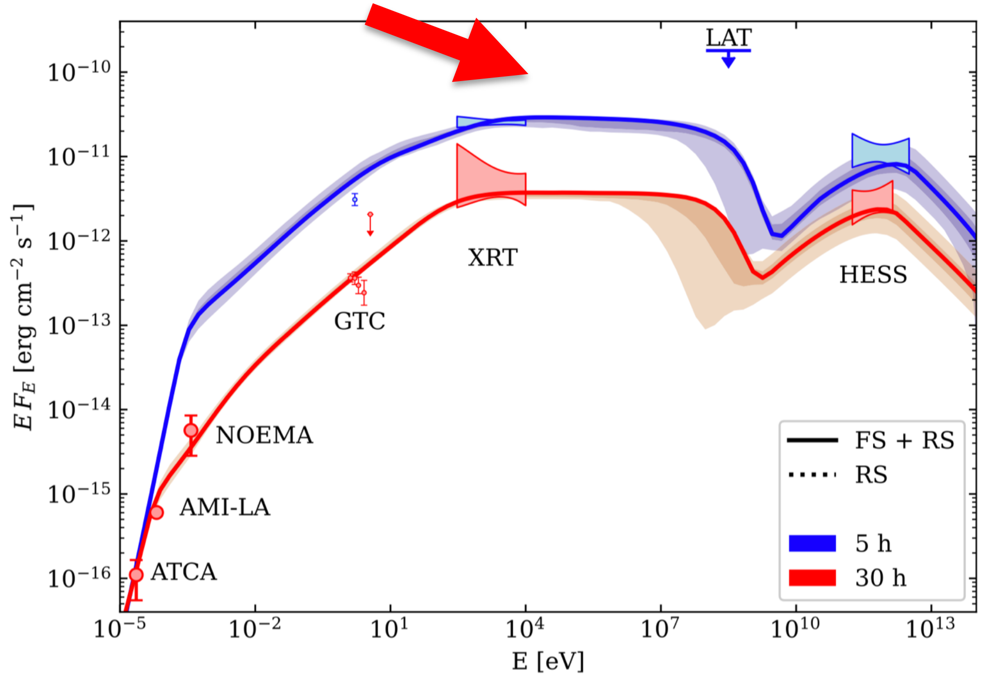


H.E.S.S. Collaboration et al., Science 372, 1081–1085 (2021)

Synchrotron (by electrons) extending to TeV energies *(no synchrotron cut-off energy)*

GRB 190829A

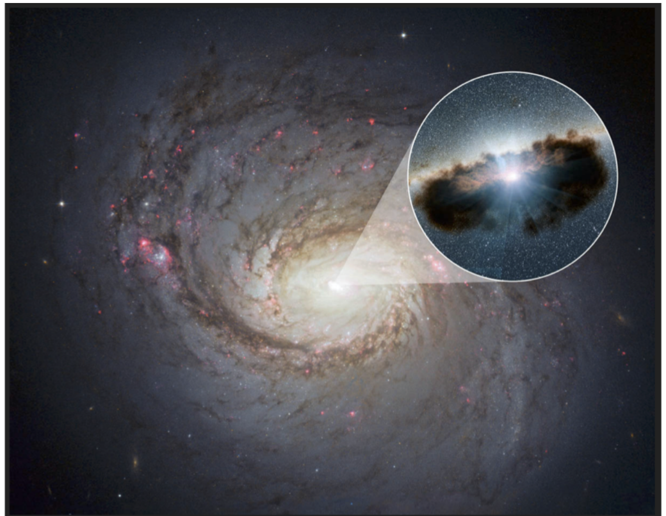
VS



Synchrotron Self-Compton (synchrotron cut-off energy considered)

Salafia et al., ApJL, 931:L19 (21pp), 2022

Composite Starburst/Seyfert 2 Galaxy NGC1068: the hottest spot in the IceCube data (2011-2020)



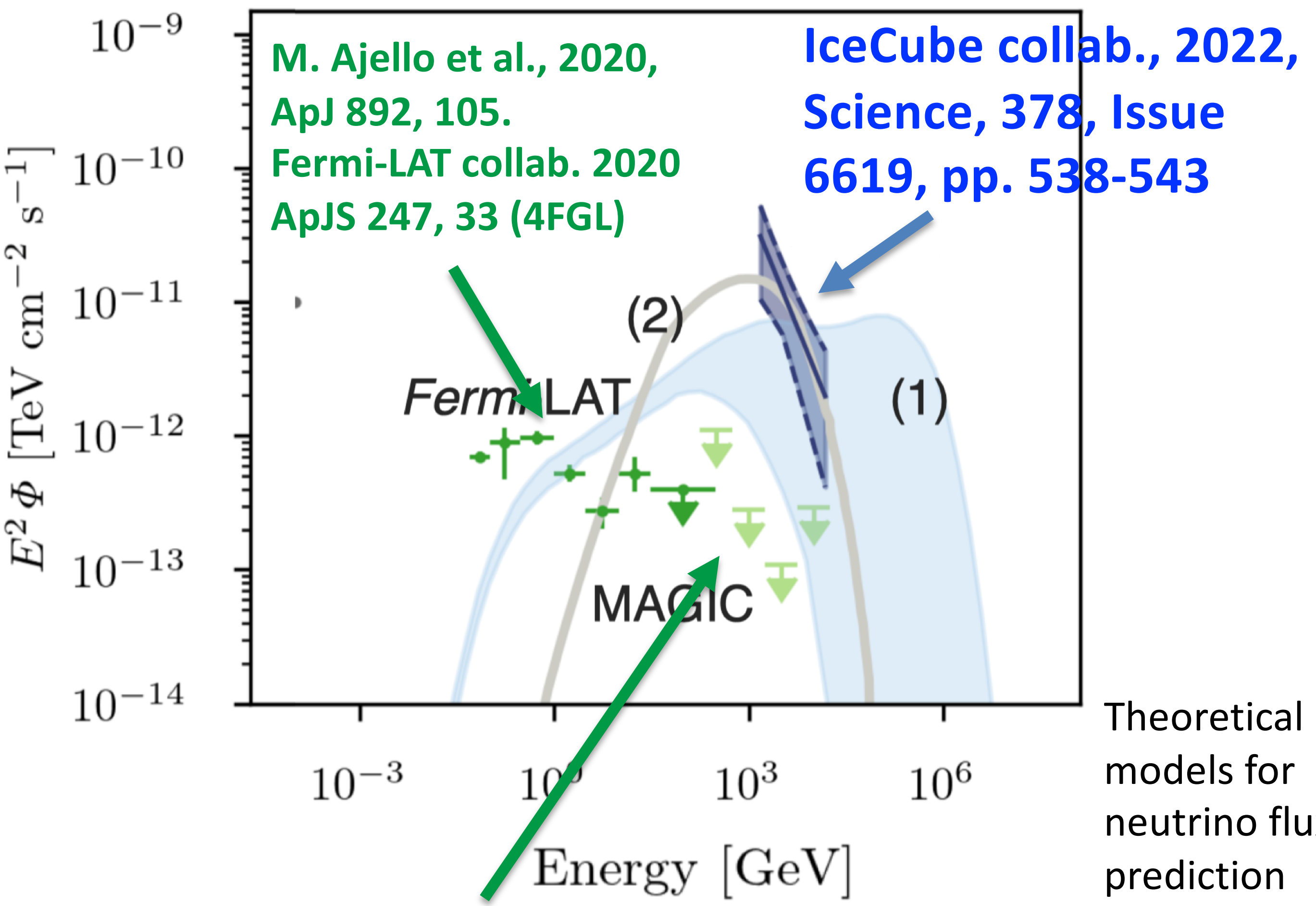
NGC 1068 as seen by Hubble Space Telescope (HST) with an artistic impression zoom-in on the central active galactic nucleus. Image credit: NASAESA/JPL-Caltech.

Global significance: 4.2σ

Astrophysical neutrino events = 79^{+22}_{-20}

Spectral index = 3.2 ± 0.2

MAGIC upper limits on NGC1068 (95% C.L.) imply strong gamma ray absorption, and hence crucial for the interpretation of the IceCube neutrino excess



MAGIC collaboration, 2019, ApJ 883, 135

(1) Y. Inoue et al., ApJL'20

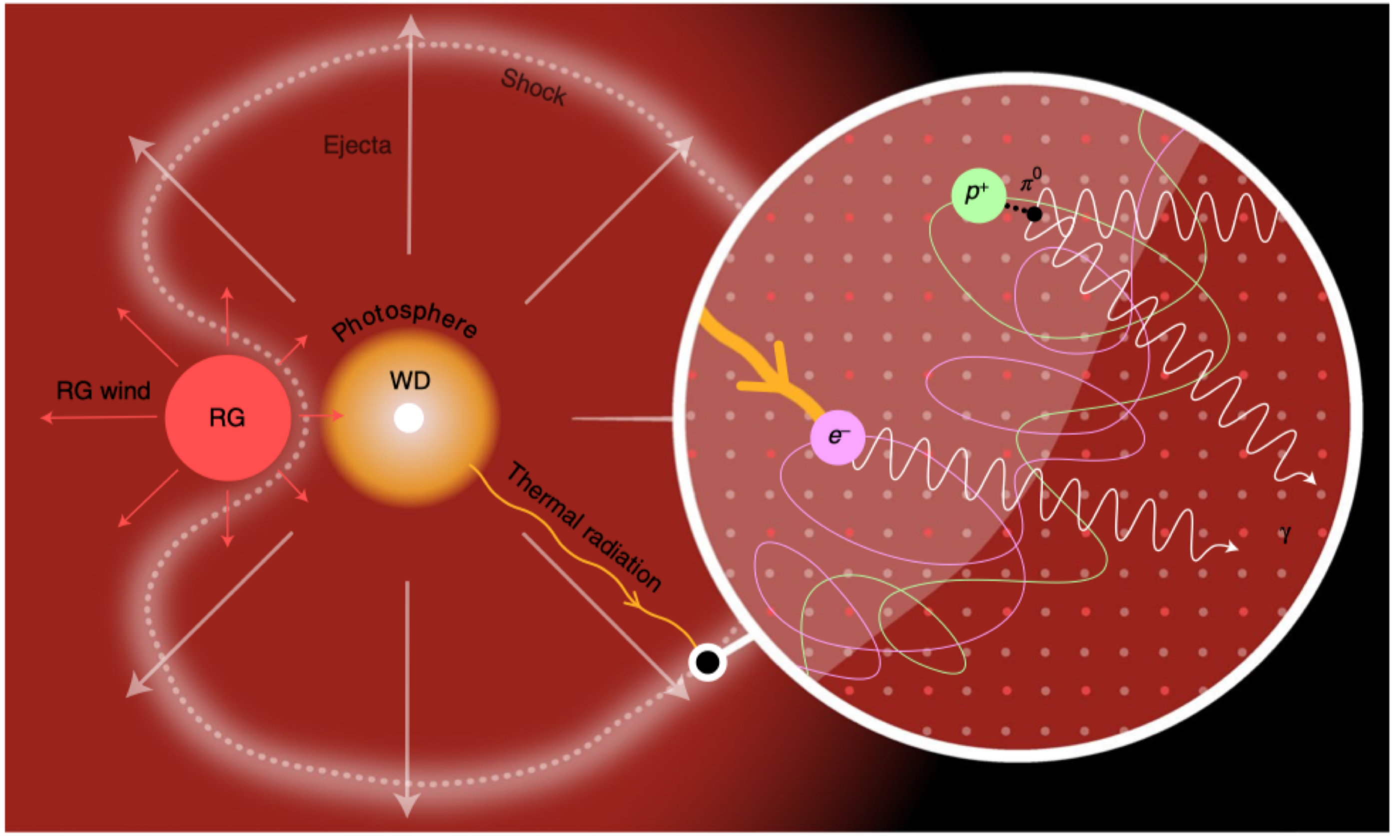
(2) K. Murase et al., PRL'20

Explosive result: Gamma rays reveal proton acceleration in thermonuclear nova explosions

RS Ophiuchi (RS Oph) is a recurrent nova in a symbiotic binary (white dwarf + red giant)

First Nova explosion at VHE gamma rays

H.E.S.S. announced first detection of VHE signal *from this event on Aug10, 2021 (**ATel #14844**)*



Explosive result: Gamma rays reveal proton acceleration in thermonuclear nova explosions

MAGIC coll. (Acciari) at al 2022, Nature Astronomy, Vol. 6, p. 689-697

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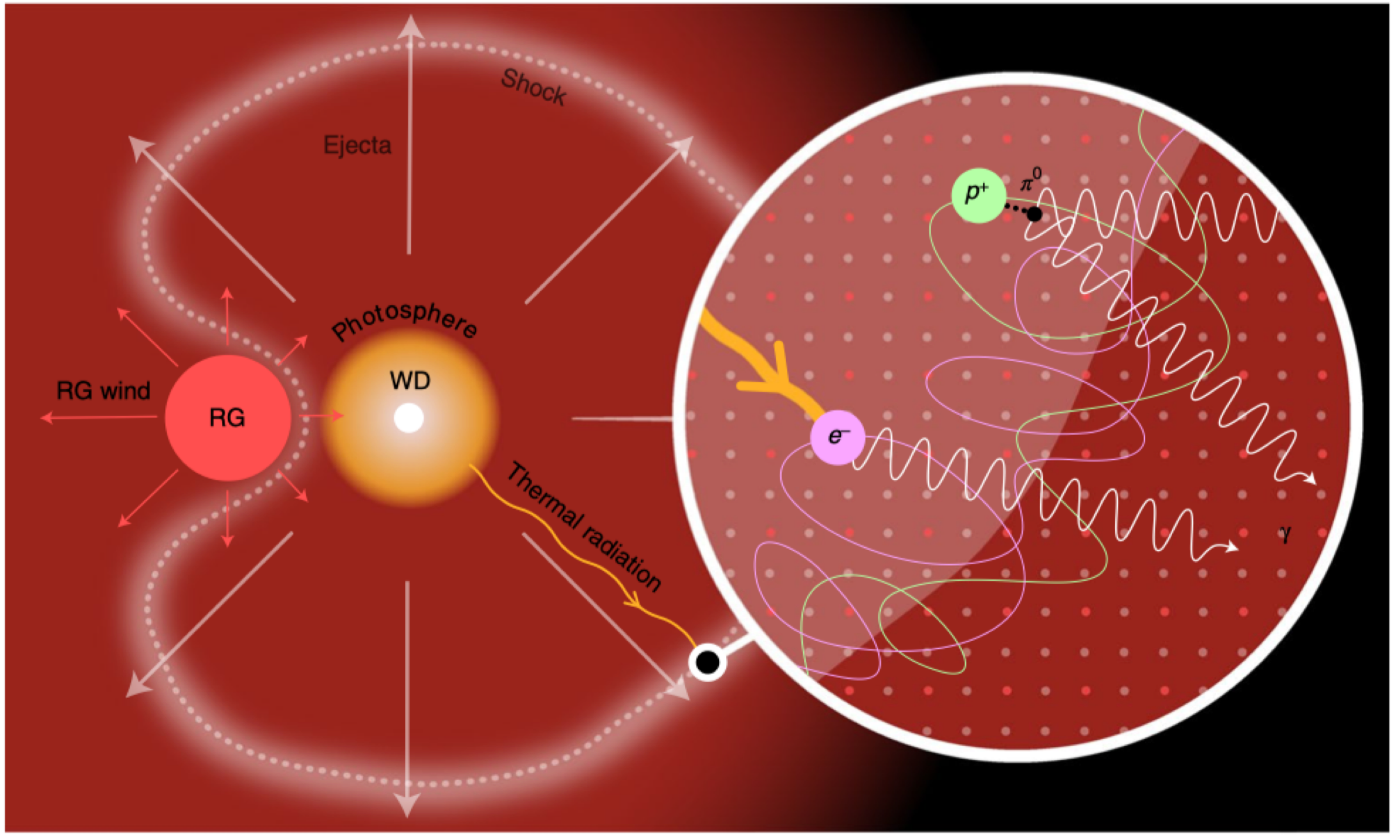
How are the VHE gamma rays produced ?



First scientific interpretations of the event:

MAGIC collaboration → arXiv:2202.07681 [v1] Tue, 15 Feb 2022 19:05:28 UTC

H.E.S.S. collaboration → arXiv:2202.08201 [v1] Wed, 16 Feb 2022 17:24:39 UTC

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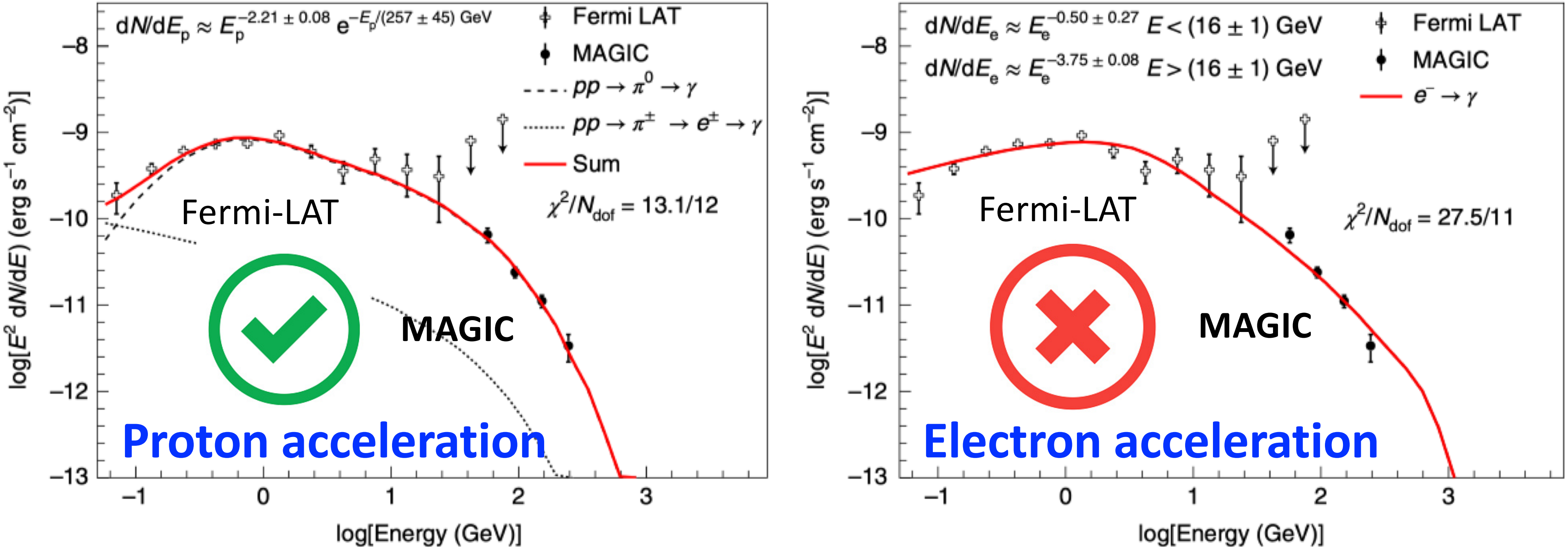
Fig. 3 | Gamma-ray spectrum of RS Oph observed over the first 4 d of the outburst, and modelled with both a hadronic and a leptonic scenario. Observations are averaged over the first 4 d of the outburst. Left: a hadronic model. Right: a leptonic model. The dashed line shows the gamma rays from the π^0 decay and the dotted line shows the inverse Compton contribution of the secondary $e^{\pm}$ pairs produced in hadronic interactions. dN/dE_p and dN/dE_e report the shapes of the proton and electron energy distributions obtained from the fit.



Scenario with proton acceleration (with natural PL index of ~2) provides a better description of the gamma-ray emission than scenario with electron acceleration (that needs an additional break in the high-energy particle population)

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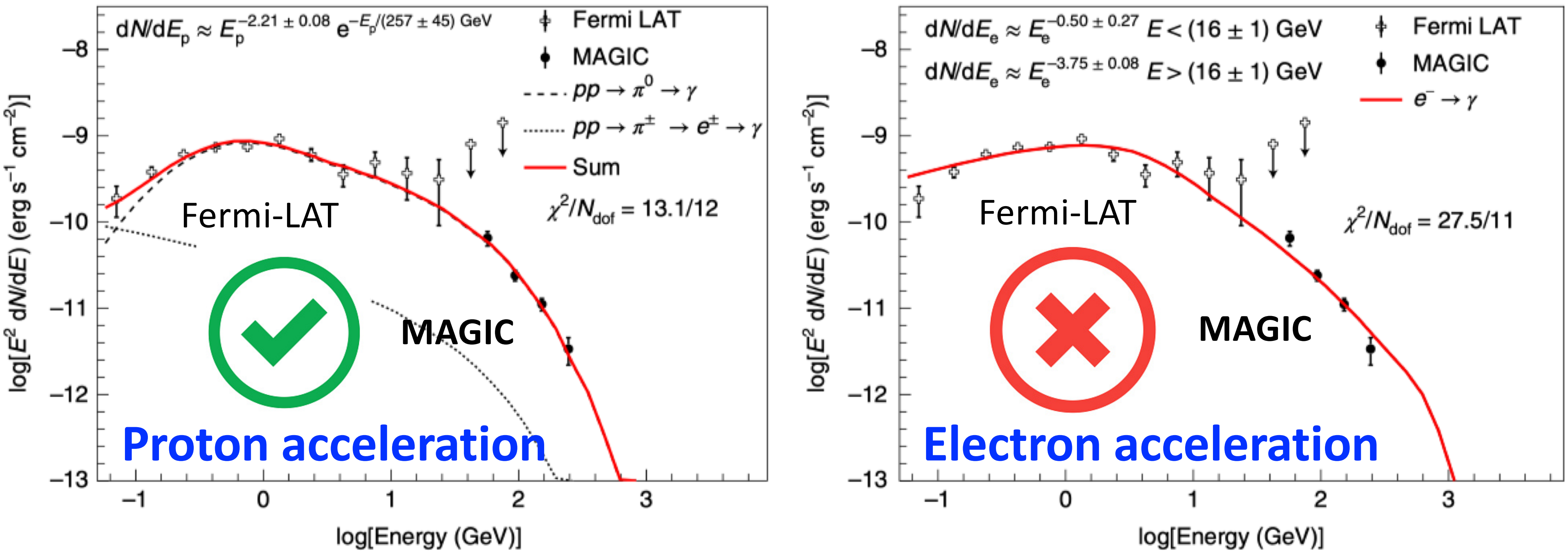

Assuming all novae behave in this manner, we found out that the protons accelerated in Novae explosions have significant contribution to Cosmic Ray spectrum ONLY in the vicinity (1-10pc) from the Novae.

→ **In general, Novae-produced CRs are only 0.2% of those from in Supernova Remants**