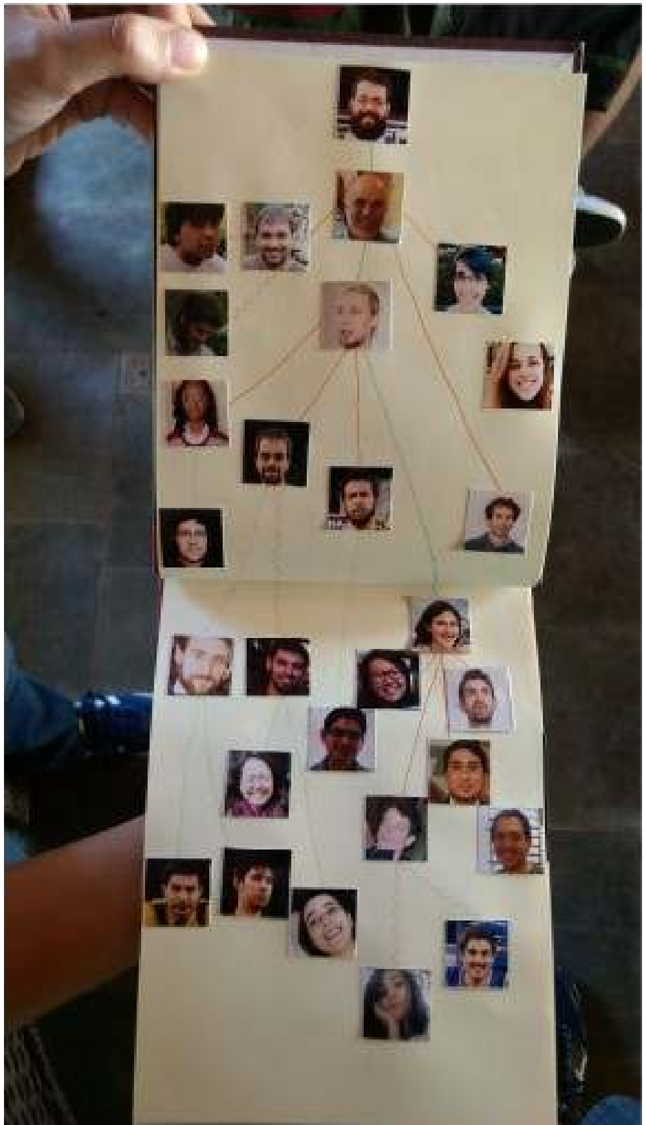
Cosmic particles: the energetic elite of the Universe

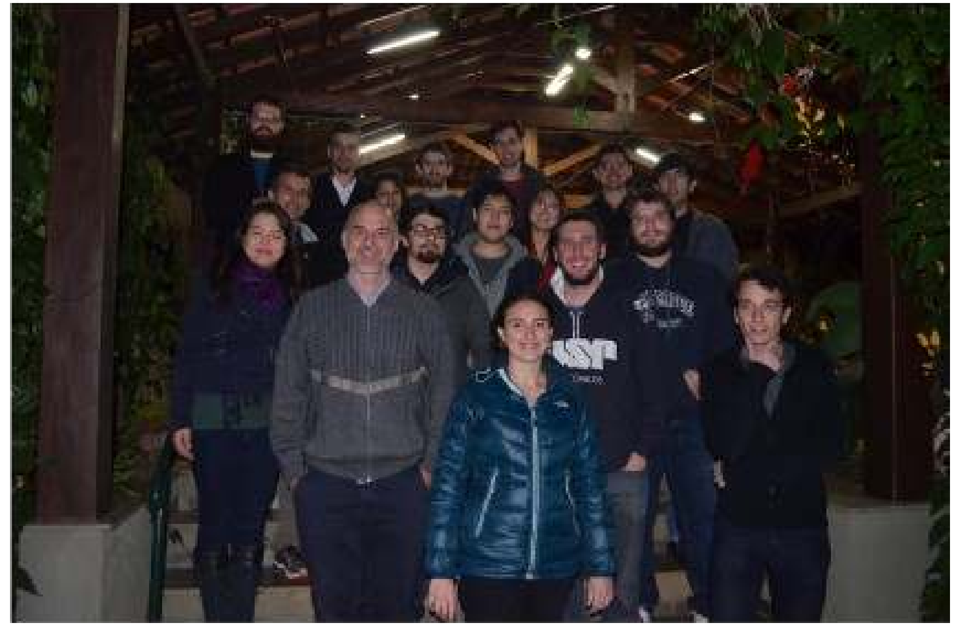
Vitor de Souza
vitor@ifsc.usp.br

APOEMA

IFSC
USP

APOEMA





CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

CAPES

FAPESP

IFSC

Universidade Federal do ABC

ufscar

ICTP SAIFR

UFPR
UNIVERSIDADE FEDERAL DO PARANÁ

EEL-USP

UFRN

IFGW
Instituto de Física Gleb Wataghin

UFRJ

UEFS
UNIVERSIDADE ESTADUAL DE FEIRA DE SANTANA

uff Universidade Federal Fluminense

CBPF

ORBITAL ENGENHARIA

opto
Science in Sight

15 Anos
ConstruAço

ITeDA

MAX-PLANCK-GESELLSCHAFT

THE UNIVERSITY OF CALIFORNIA
UCLA

DESY.

LIP

KIT
Karlsruher Institut für Technologie

Astroparticle Physics @ IFSC/USP

- Extragalactic sources: AGNs and Radio Galaxies
  - Cainã de Oliveira et al., The Astrophysical Journal, v. 925, p. 42, 2022.
  - Cainã de Oliveira et al., European Physical Journal C, v. 81, p. 517, 2021.
  - Rodrigo Lang et al., Physical Review D, v. 102, p. 063012, 2020.
- Data analysis and simulations
  - Edivânia Martins et al., Astroparticle Physics, v. 141, p. 102706, 2022.
  - Luan Arbeletche et al., European Physical Journal C, v. 81, p. 195, 2021.
  - Andrés Delgado et al., Astroparticle Physics, v. 124, p. 102508, 2021.
- Dark matter
  - Maria Kherlakian et al., JCAP, v. 2023, p. 025, 2023.
  - Aion Viana et al, JCAP v. 2019, p. 061-061, 2019.

+ ative participations in the Pierre Auger and CTA Collaborations.

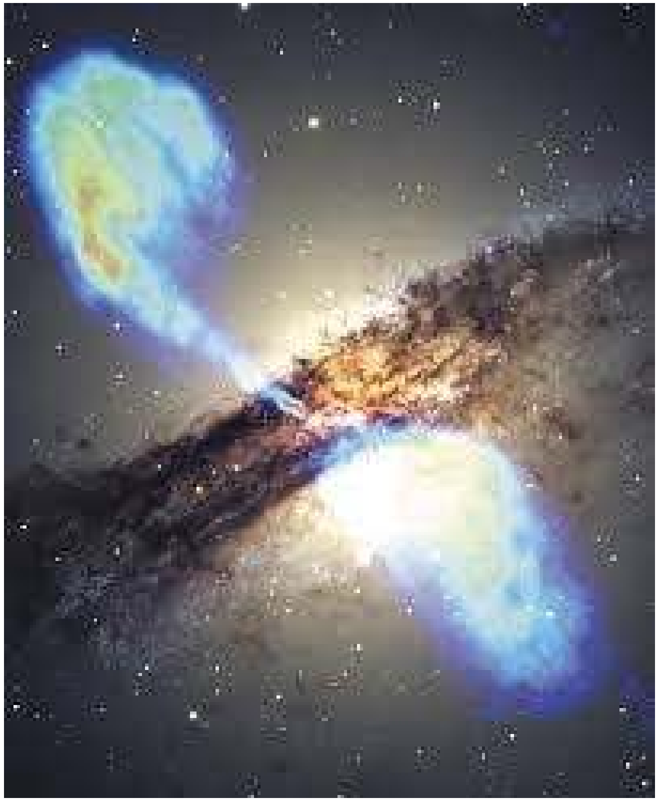
Agenda

Introduction

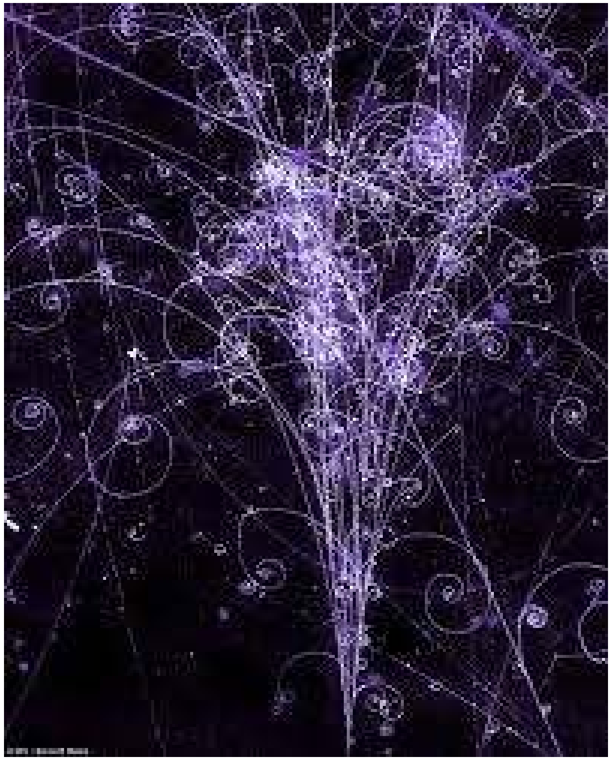
Instruments

Science

Astroparticle Physics

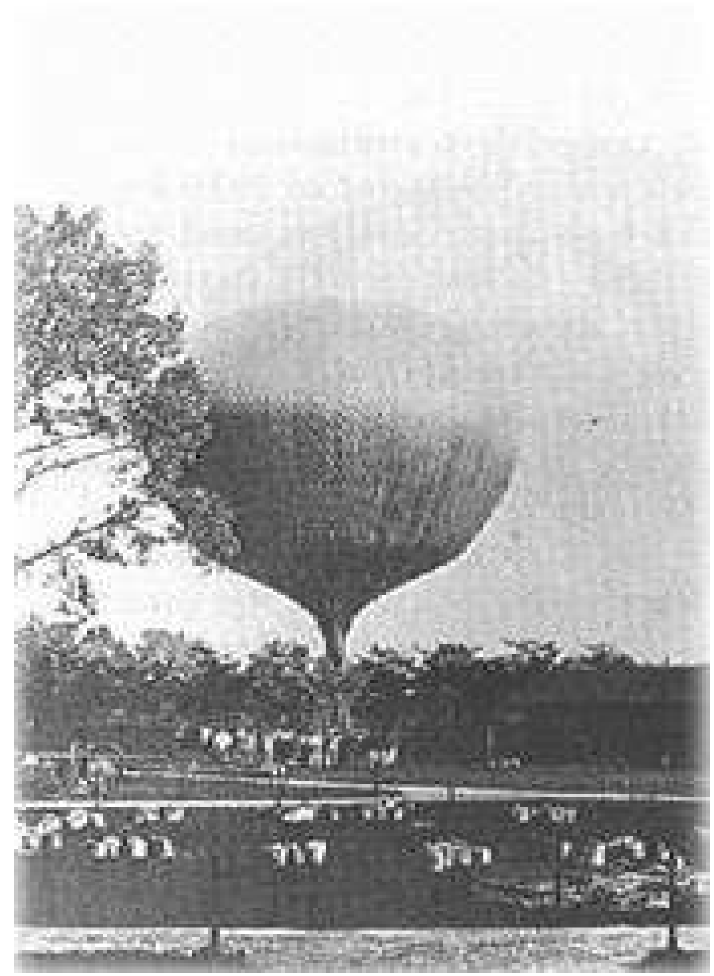


Particles

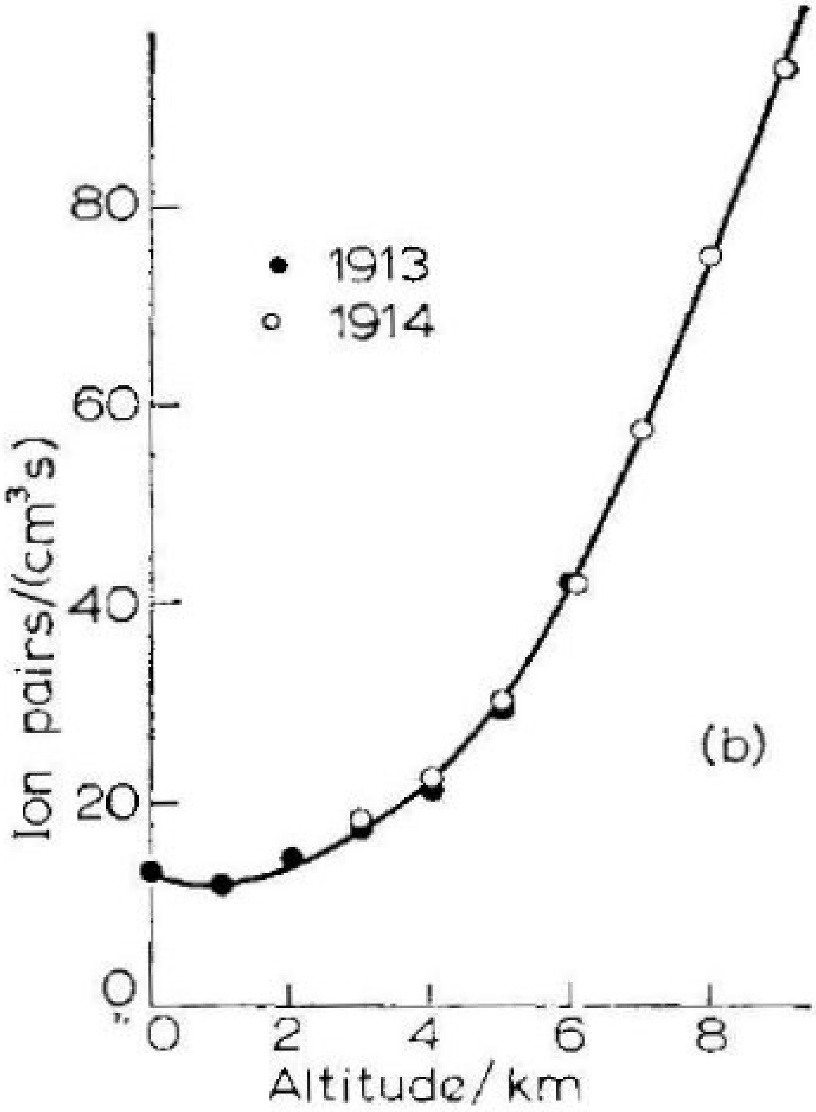


Astro

Cosmic Radiation:

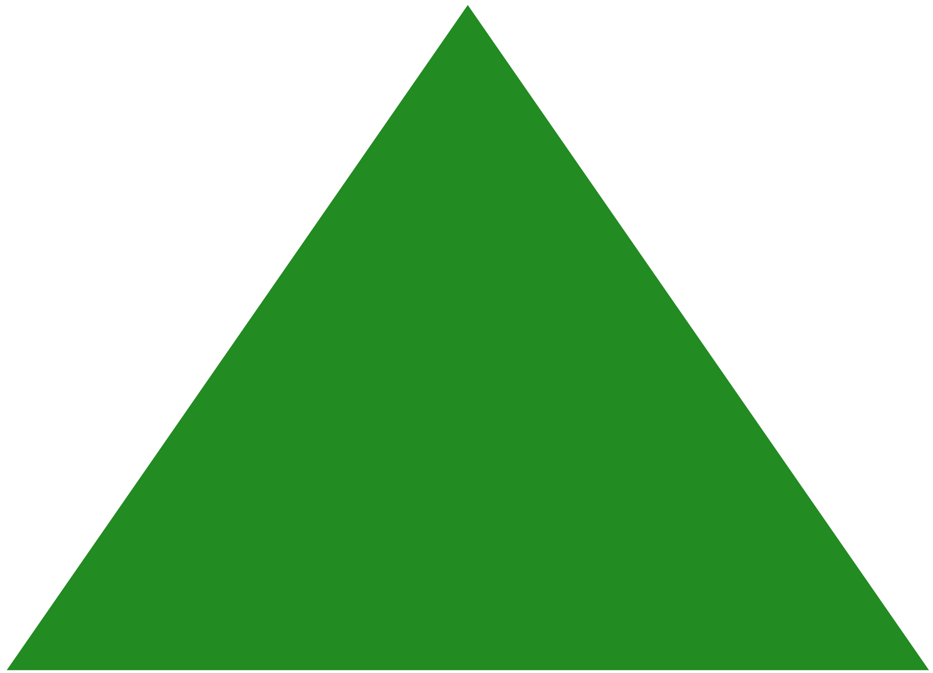


Victor Hess measured a radition increase with altitute showing the source was extraterrestrial.



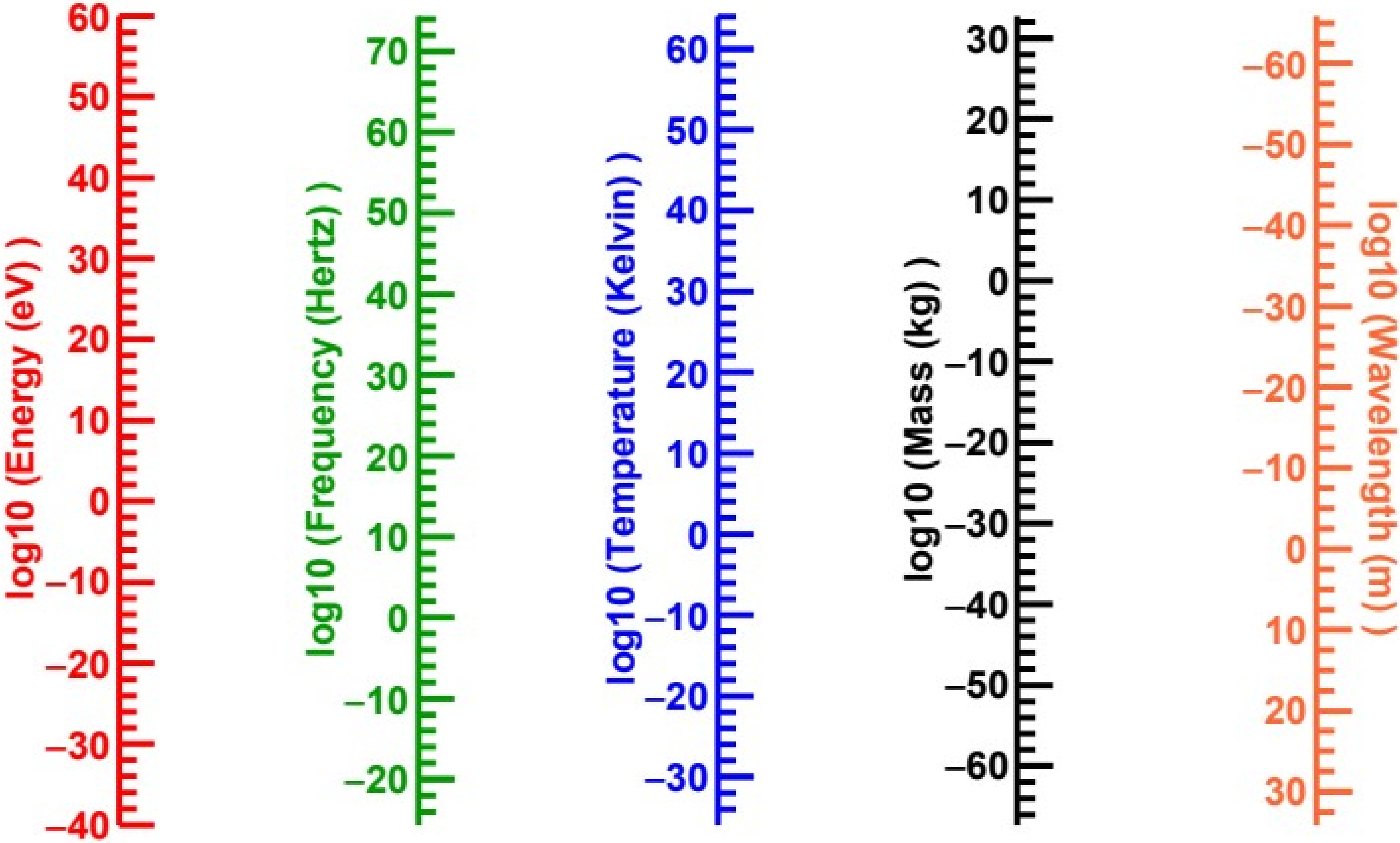
Extraterrestrial source: cosmic rays/radiation

$$E^2 = p^2c^2 + m^2c^4$$



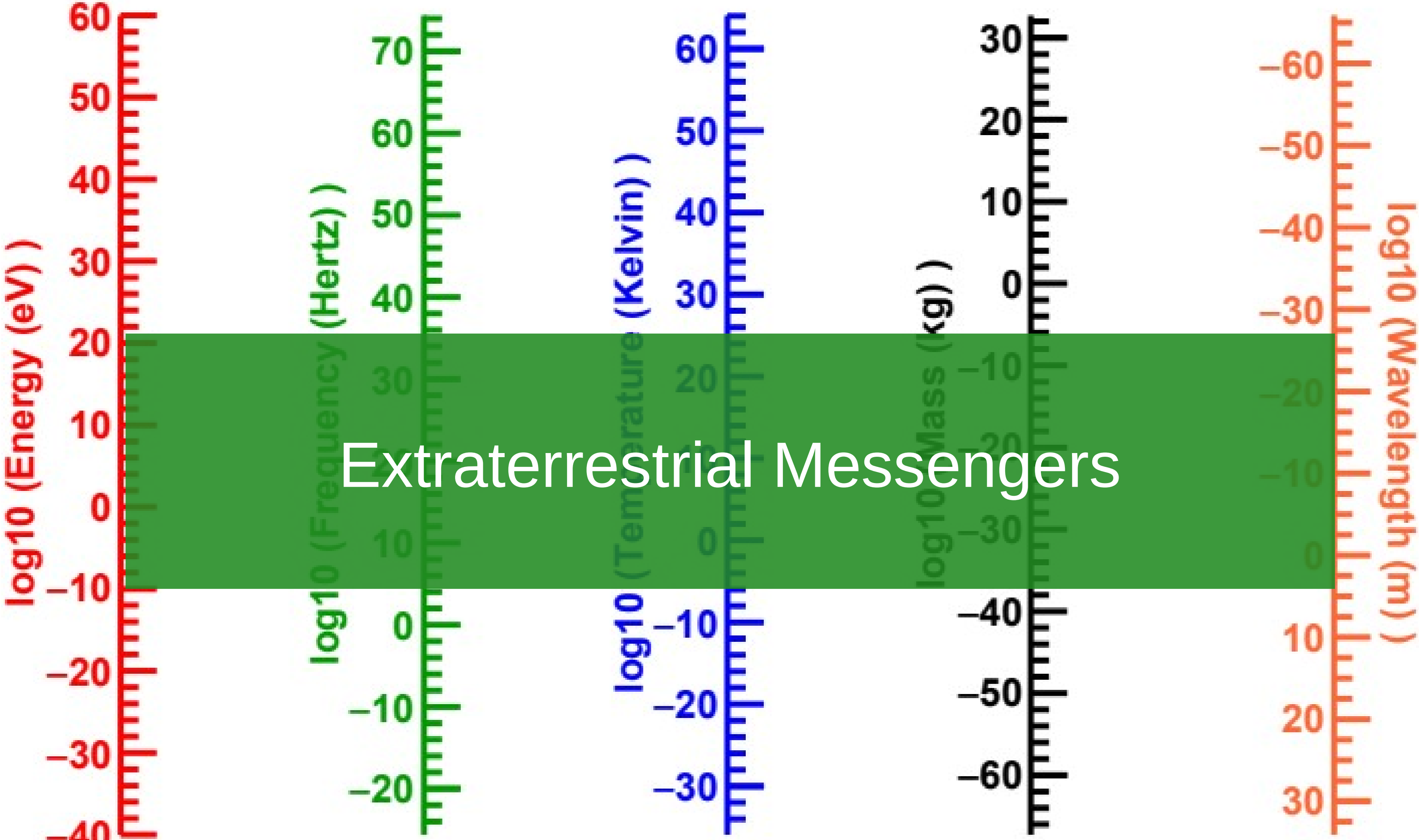
$$E \propto kT$$

$$E = h\nu = \frac{hc}{\lambda}$$



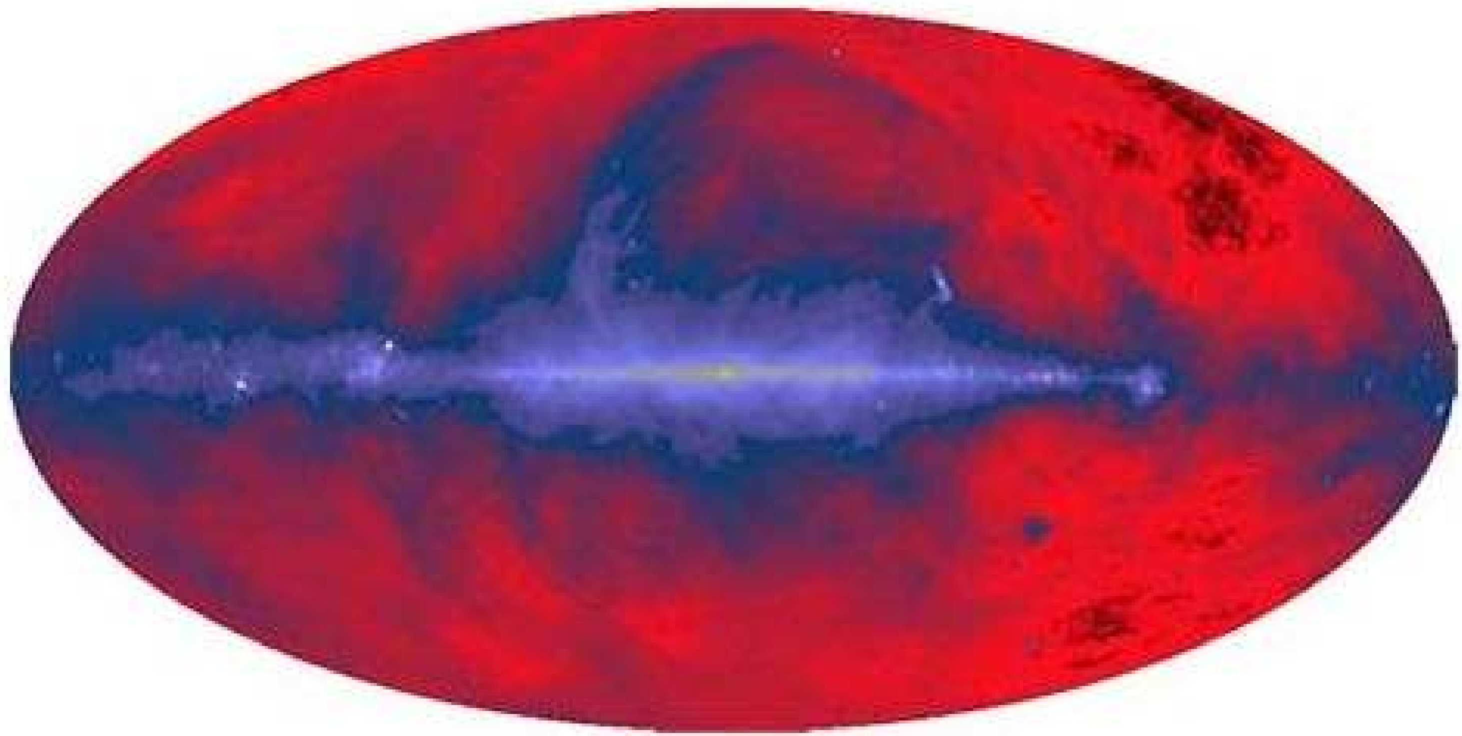
$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$

Extraterrestrial Messengers



Radio

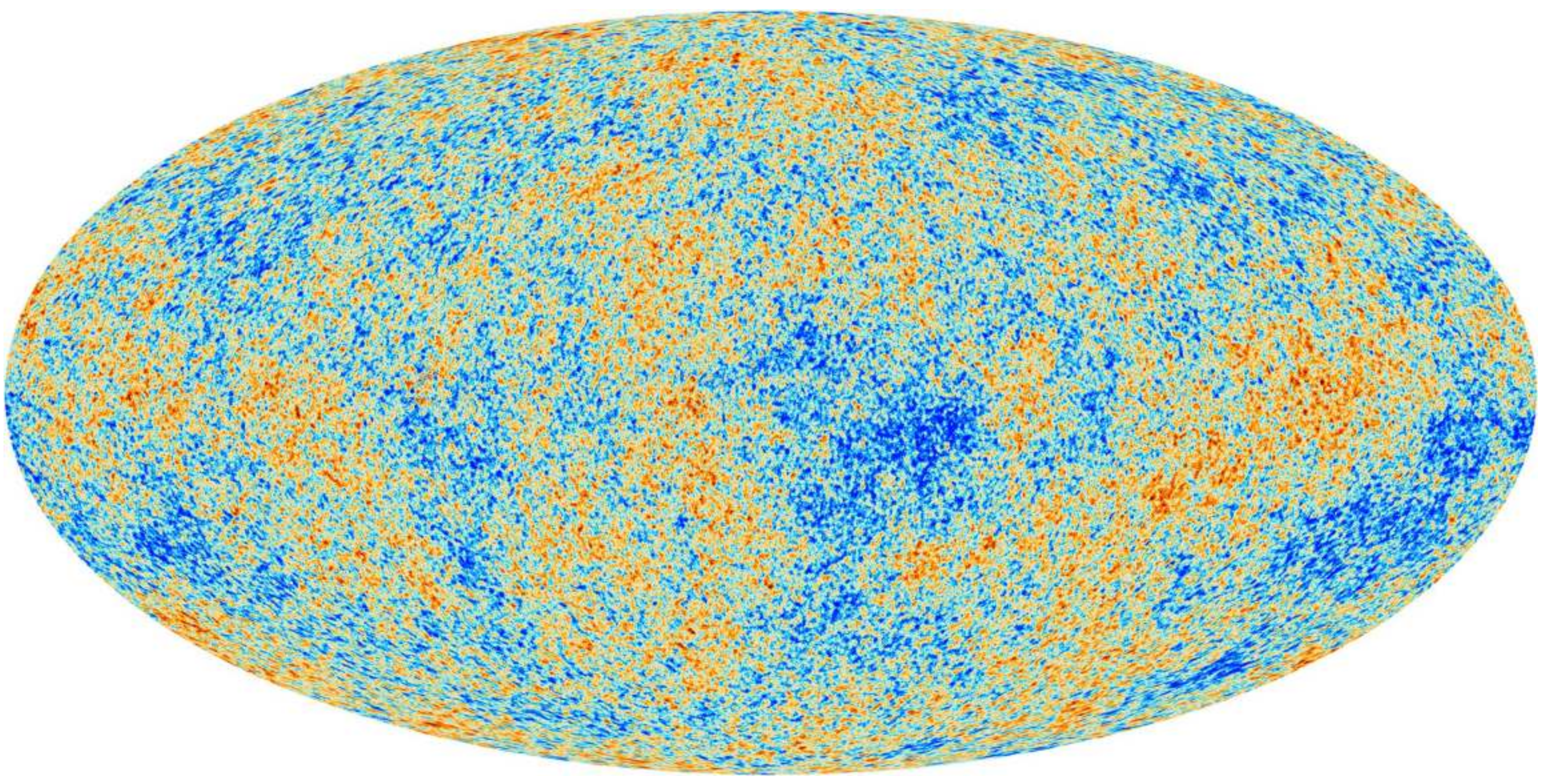
$$E \sim 10^{-6}\ \mathrm{eV} \Leftrightarrow \lambda \sim 1\ \mathrm{m}$$



C. Haslam et al., MPIfR, SkyView

Cosmic microwave radiation

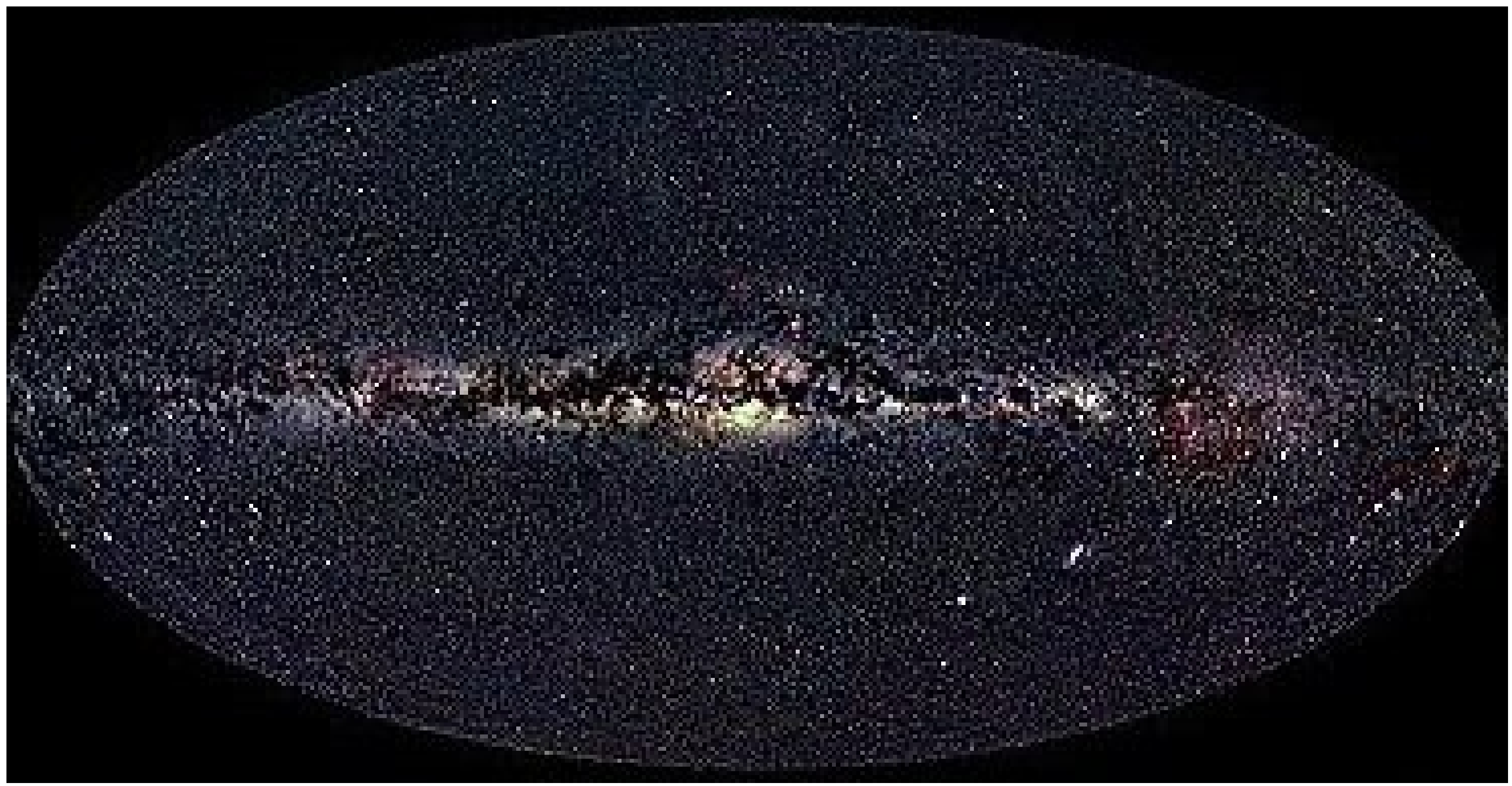
$$E \sim 10^{-4}\ \mathrm{eV} \Leftrightarrow \lambda \sim 10^{-2}\ \mathrm{m}$$



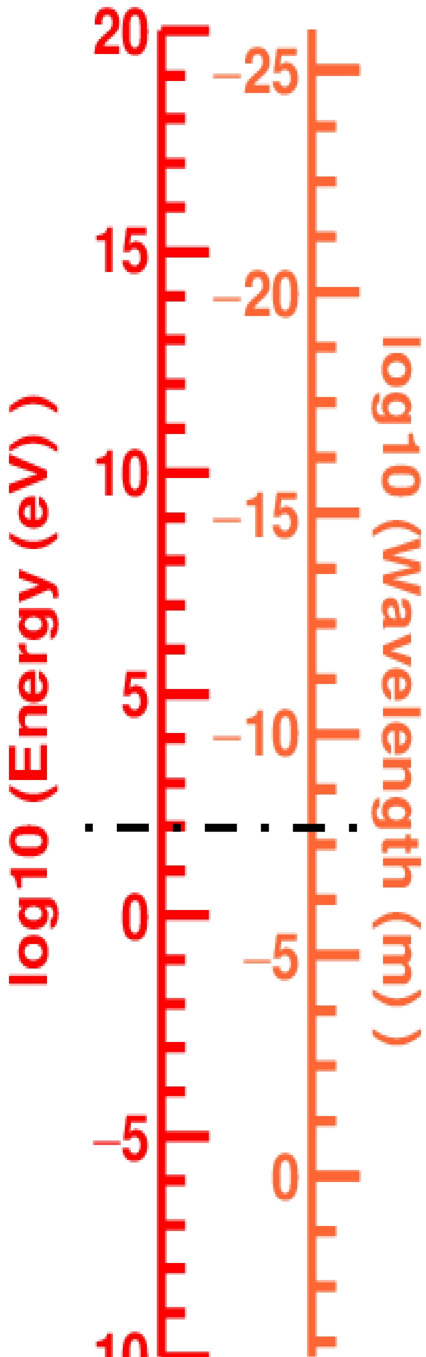
Planck Sattelite

Visible light

$$E \sim 1 \text{ eV} \Leftrightarrow \lambda \sim 10^{-6} \text{ m}$$

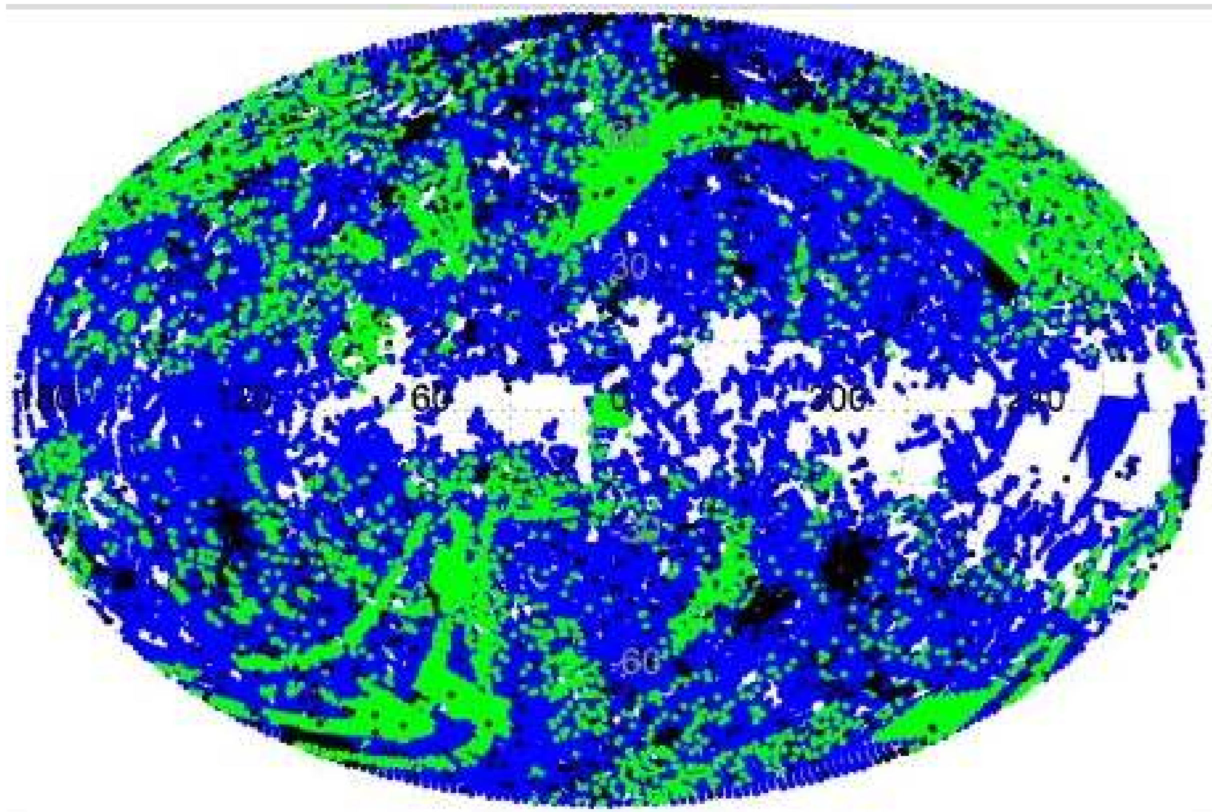


por Axel Melinger

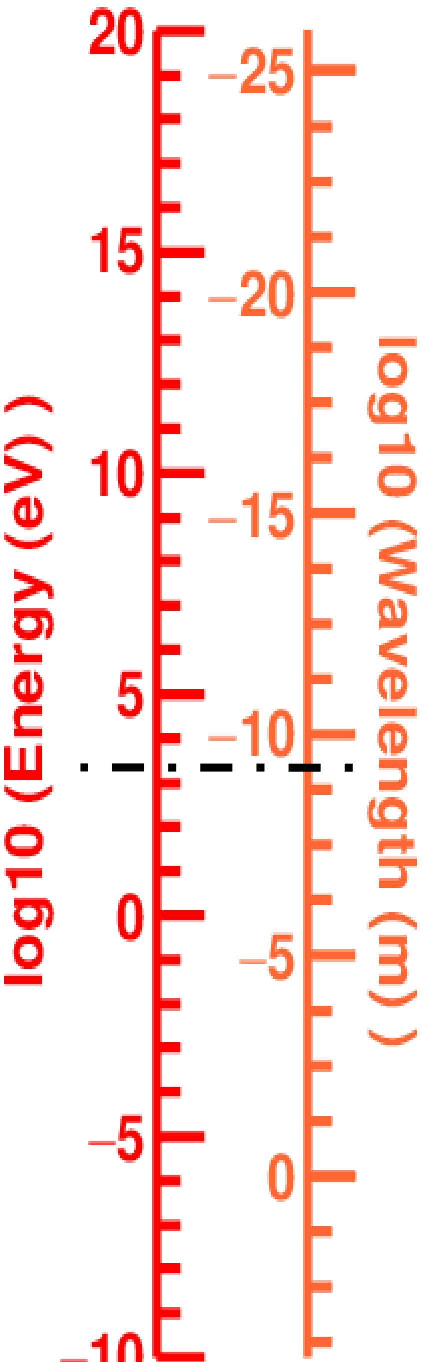


Ultraviolet

$$E \sim 100 \text{ eV} \Leftrightarrow \lambda \sim 10^{-8} \text{ m}$$

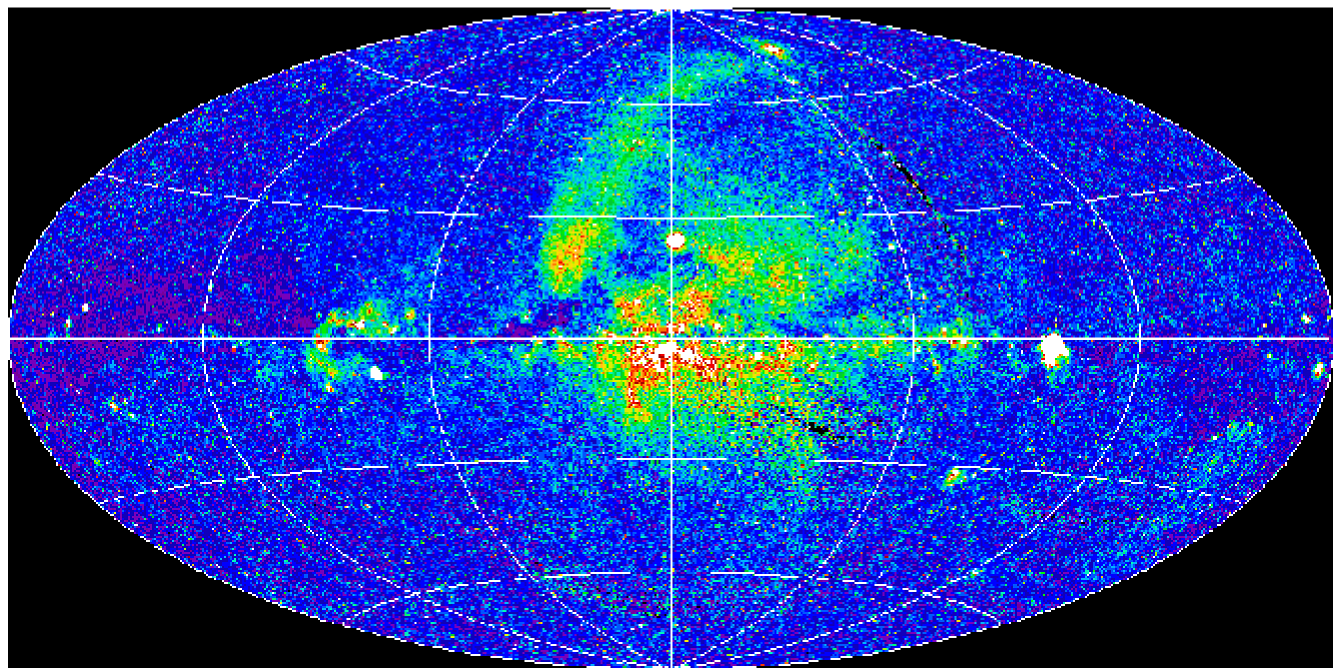


L. Bianchi et.al.,GALEX data

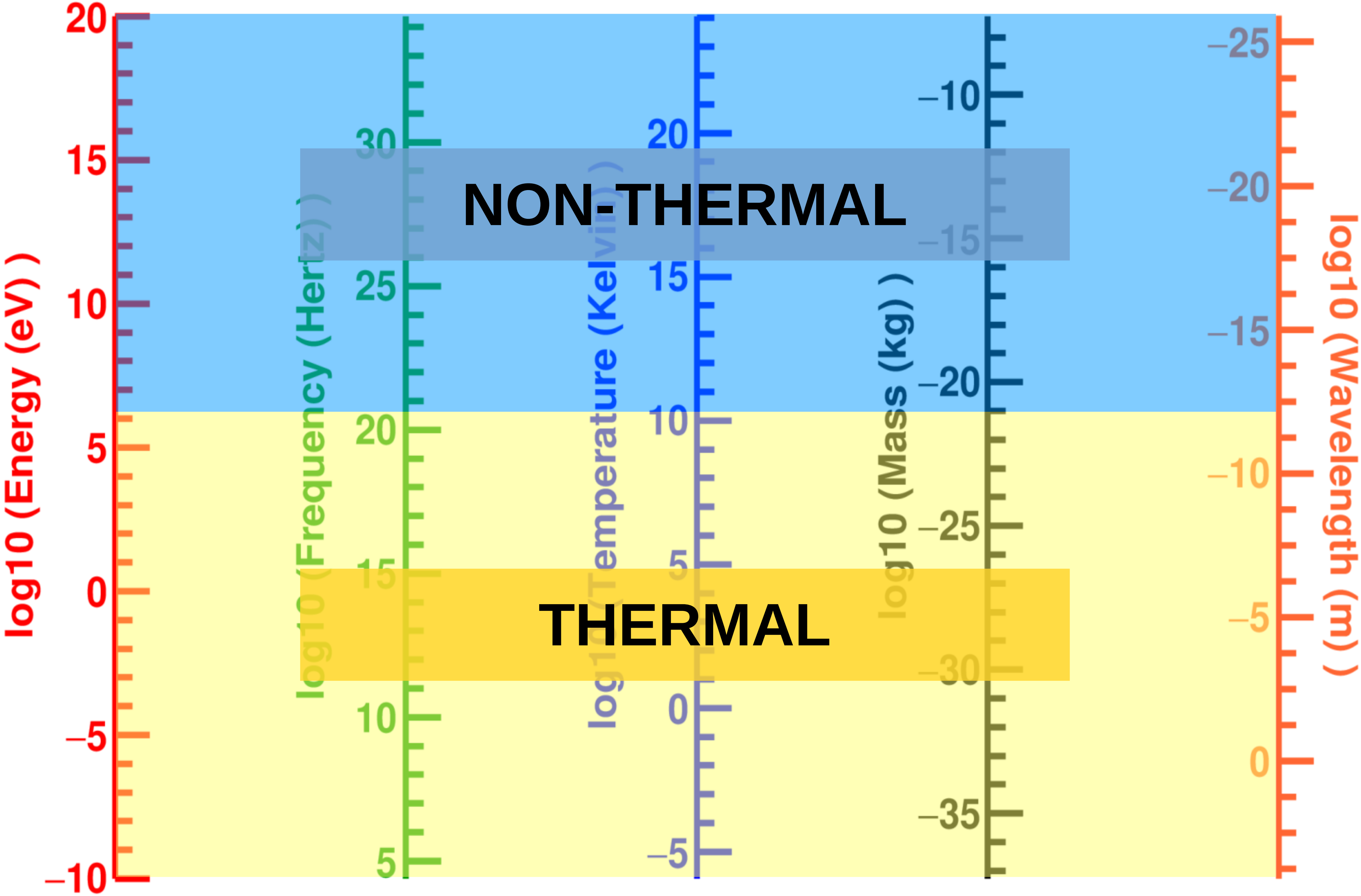


X-Rays

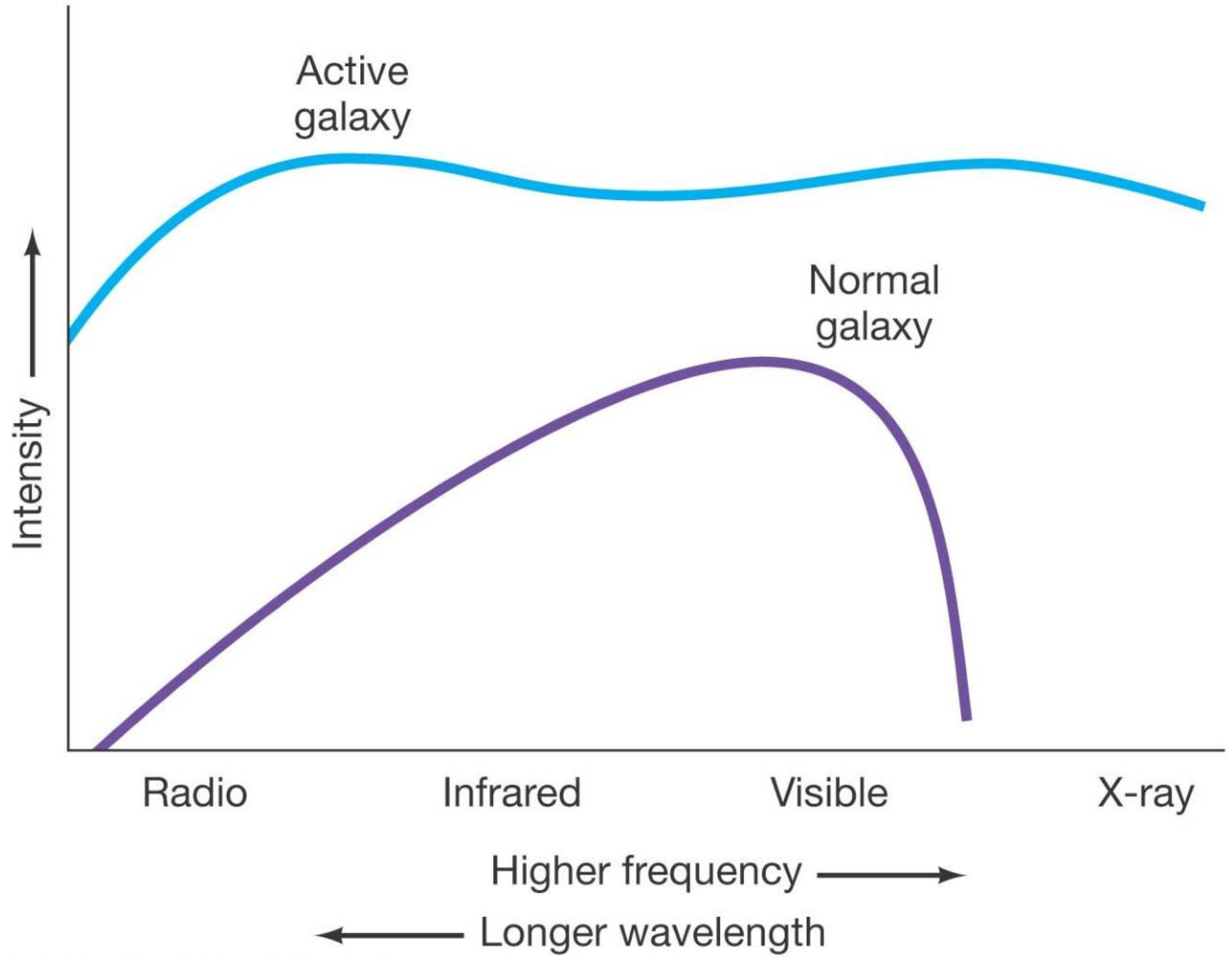
$$E \sim 1500 \text{ eV} \Leftrightarrow \lambda \sim 10^{-9} \text{ m}$$

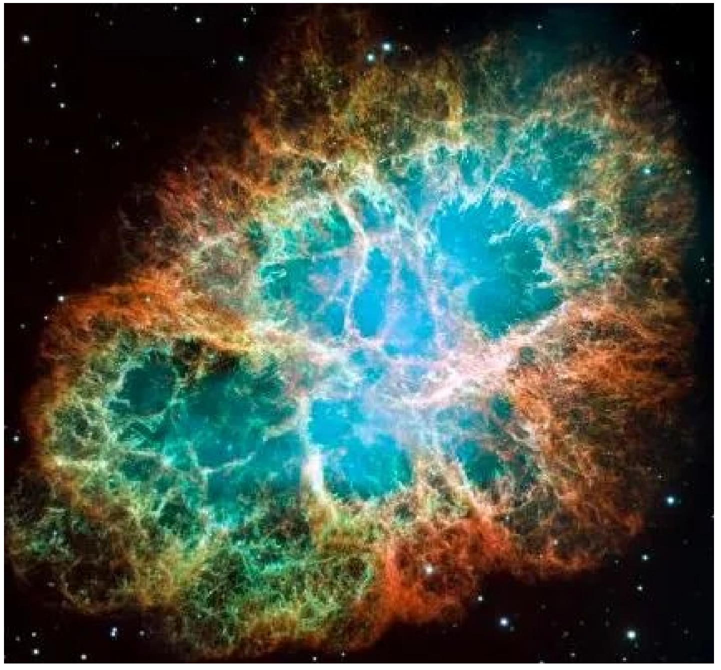


ROSAT - MPE



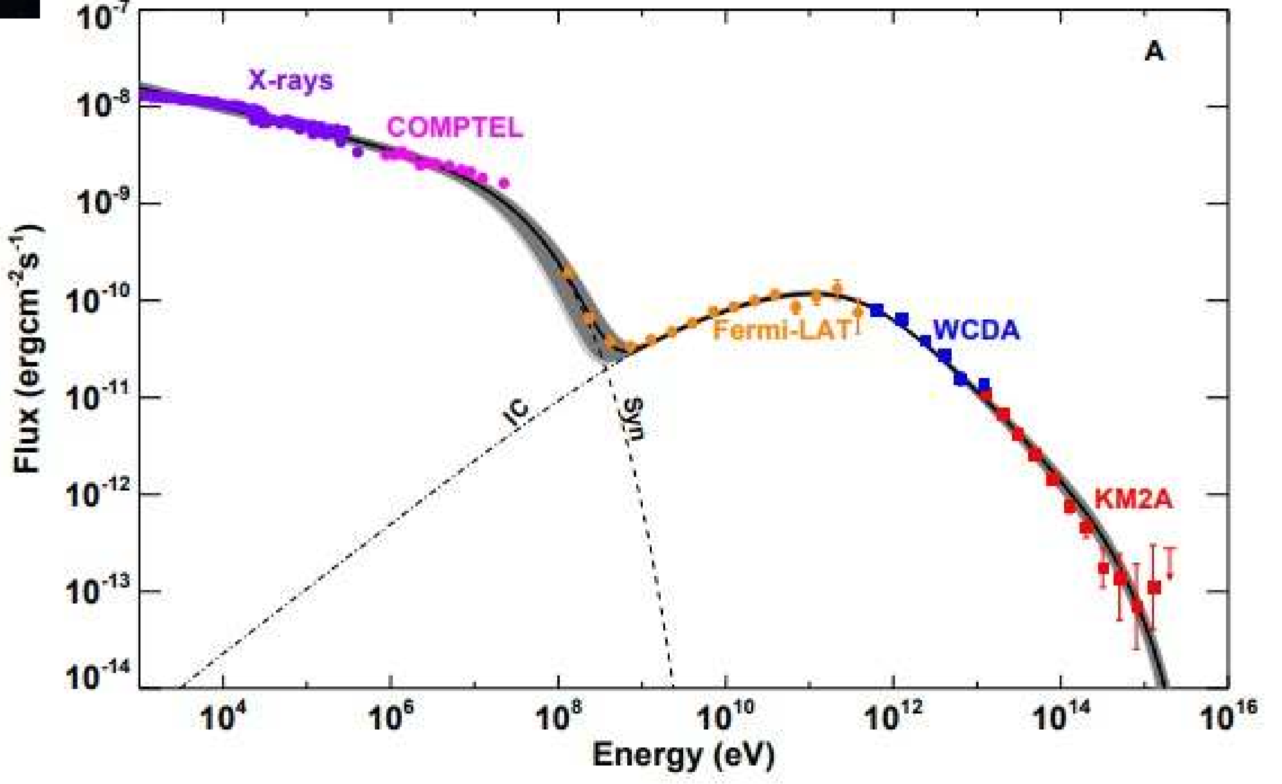
NON-THERMAL
THERMAL
log10 (Energy (eV))
log10 (Frequency (Hertz))
log10 (Temperature (Kelvin))
log10 (Mass (kg))
log10 (Wavelength (m))


Active galaxy
Normal galaxy
Intensity
Radio
Infrared
Visible
X-ray
Higher frequency
Longer wavelength



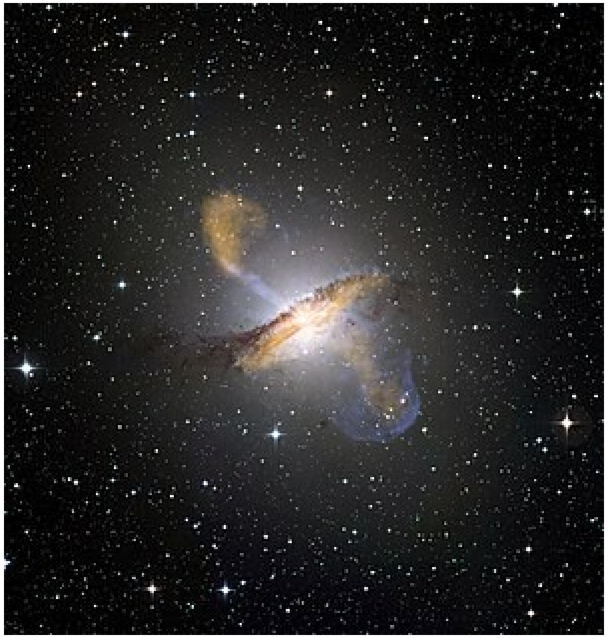
NASA, ESA, J. Hester and A. Loll (Arizona State University)

For example, the Crab Nebula

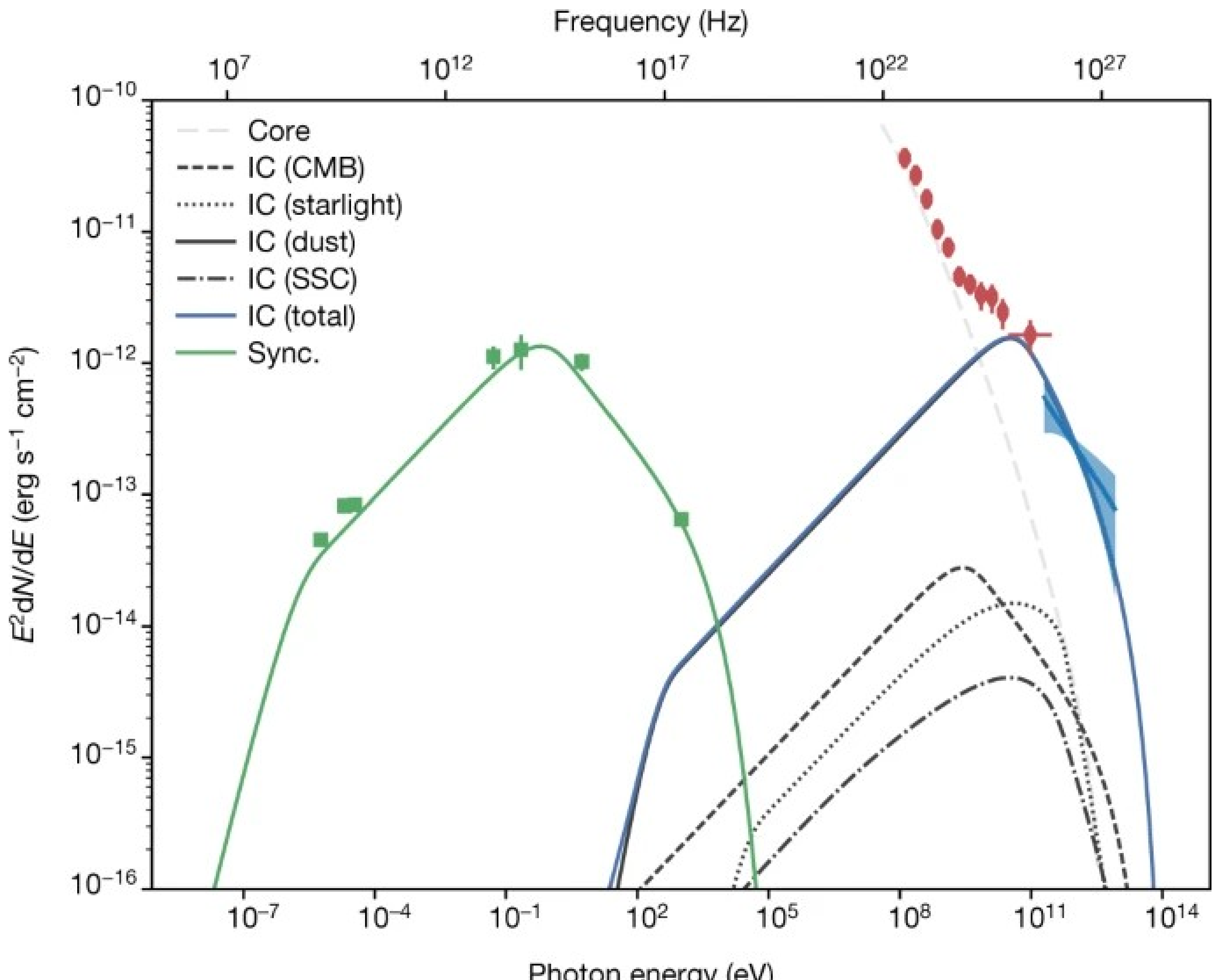


LHAASO Coll., Science, 2021, Vol 373, Issue 6553, pp. 425-430

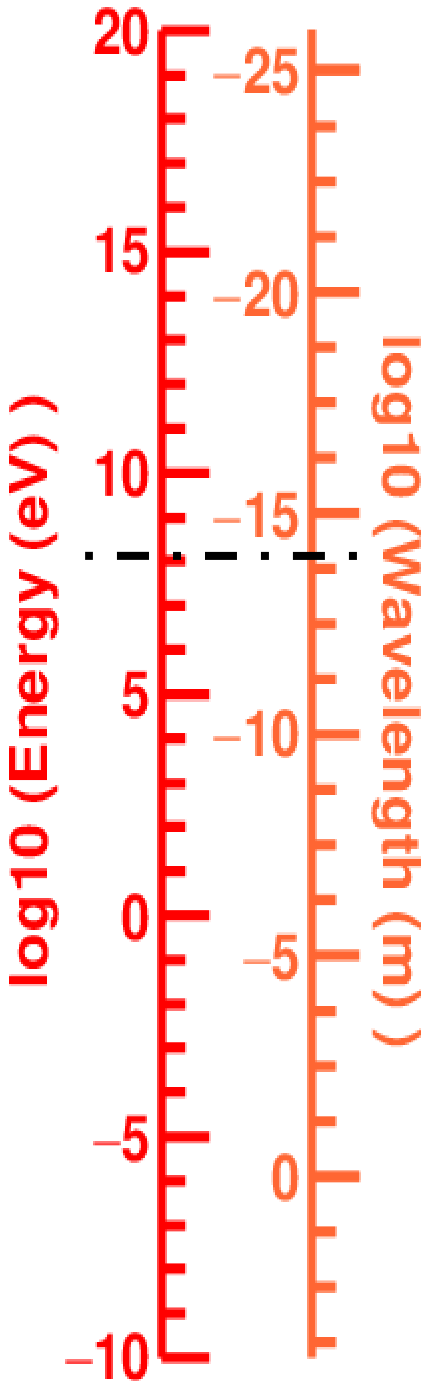
For example, Centarus A



http://www.eso.org/public/images/eso0903a/

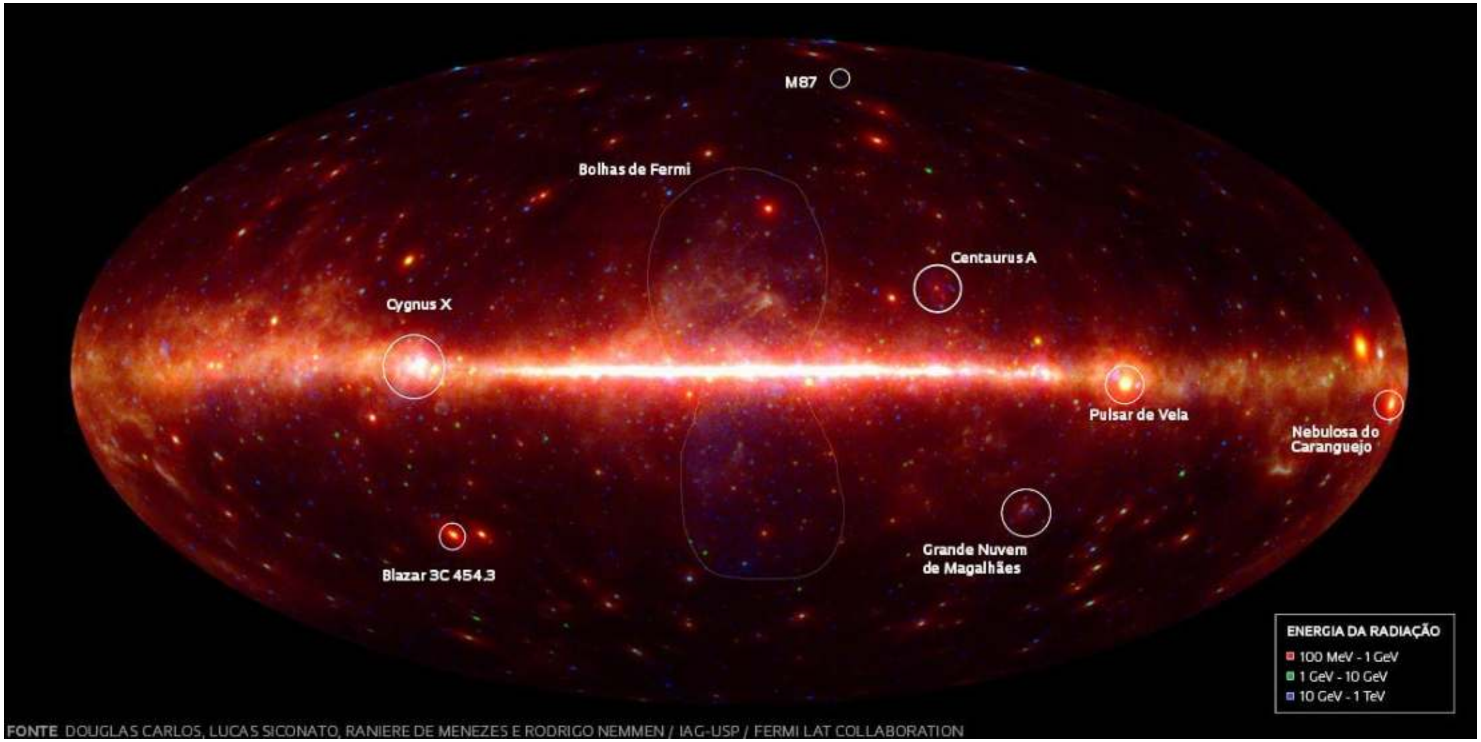


HESS Coll. - Nature, volume 582, pages 356-359 (2020)



Gamma rays

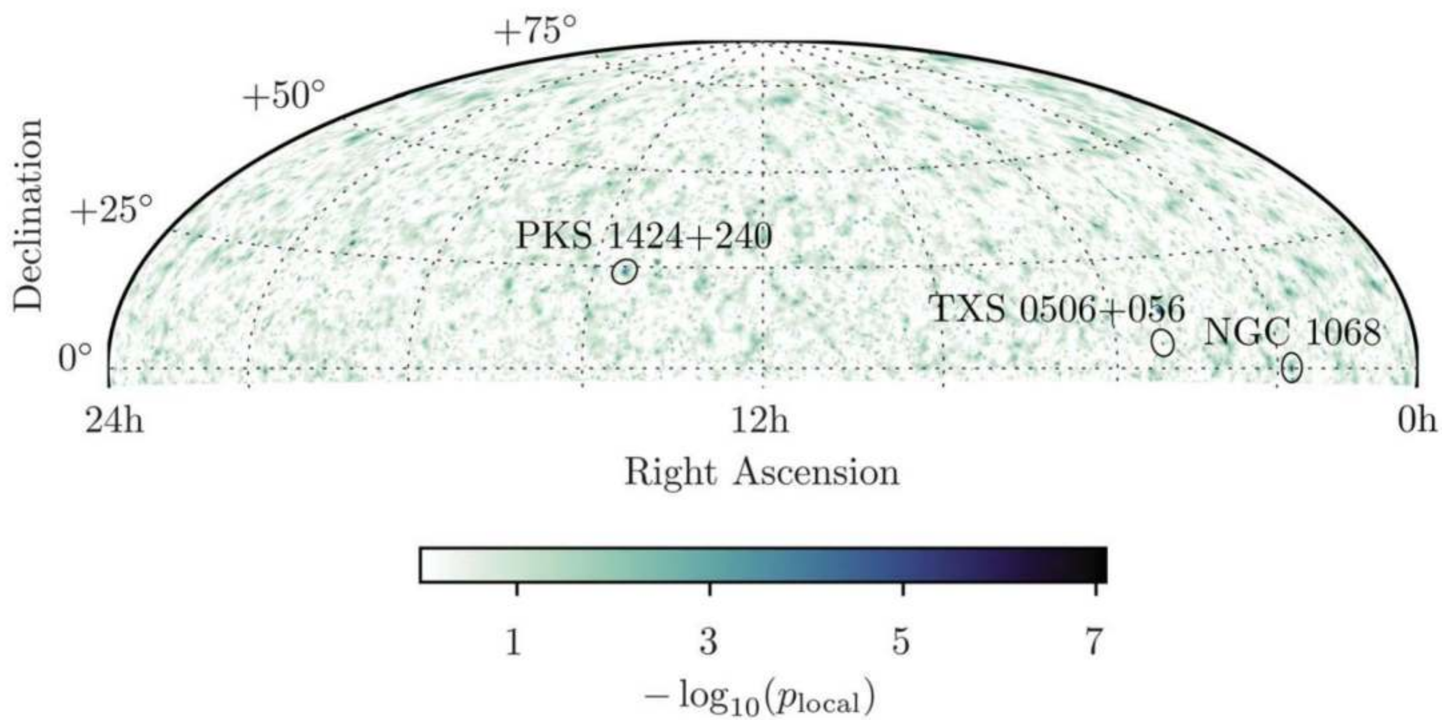
$$E > 10^8 \text{ eV} \Leftrightarrow \lambda < 10^{-14} \text{ m}$$



IAG/USP
Fermi-LAT

Neutrinos TeV

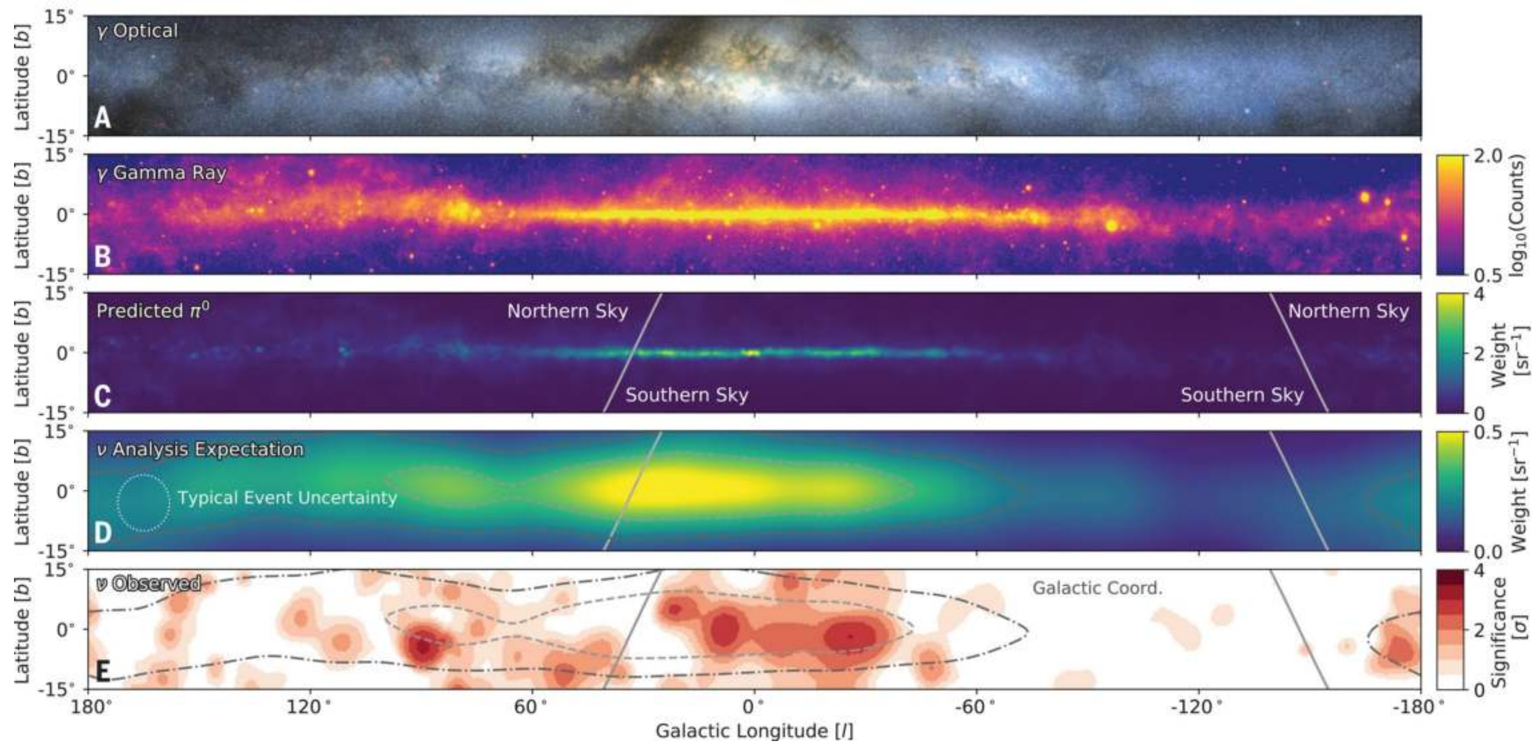
$$E > 10^{12}\ \mathrm{eV} \Leftrightarrow \lambda < 10^{-17}\ \mathrm{m}$$



IceCube Collaboration

Neutrinos TeV

$$E > 10^{12}\ \mathrm{eV} \Leftrightarrow \lambda < 10^{-17}\ \mathrm{m}$$

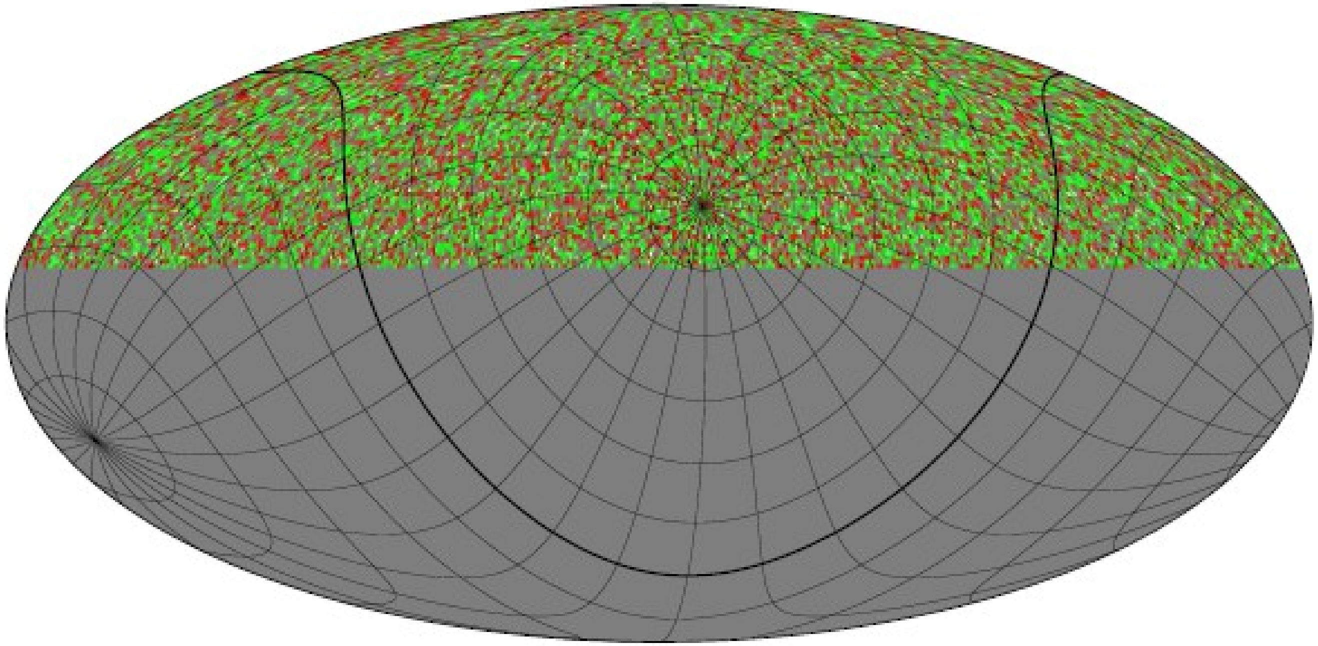


IceCube Collaboration

https://doi.org/10.1126/science.adc9818

Charged Particles

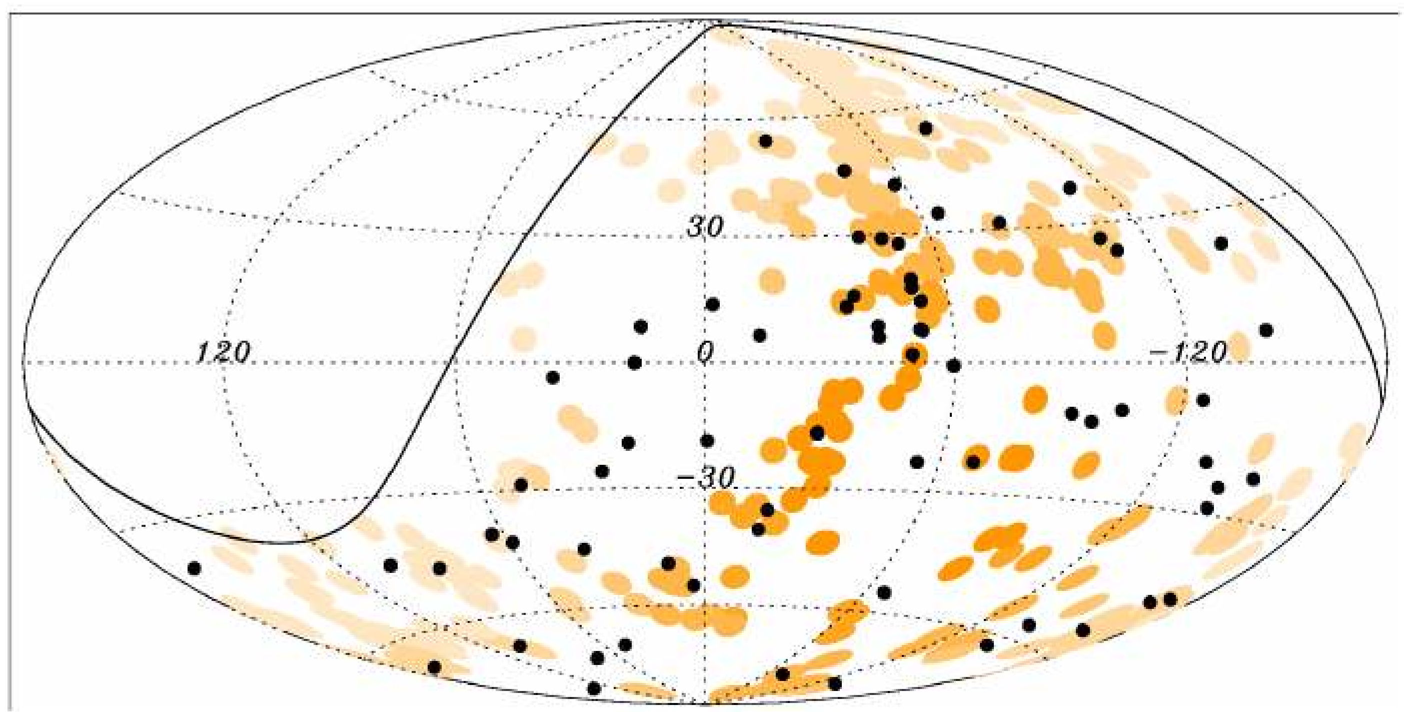
$$E > 10^{15}\ \mathrm{eV} \Leftrightarrow \lambda < 10^{-21}\ \mathrm{m}$$



KASCADE

Charged Particles

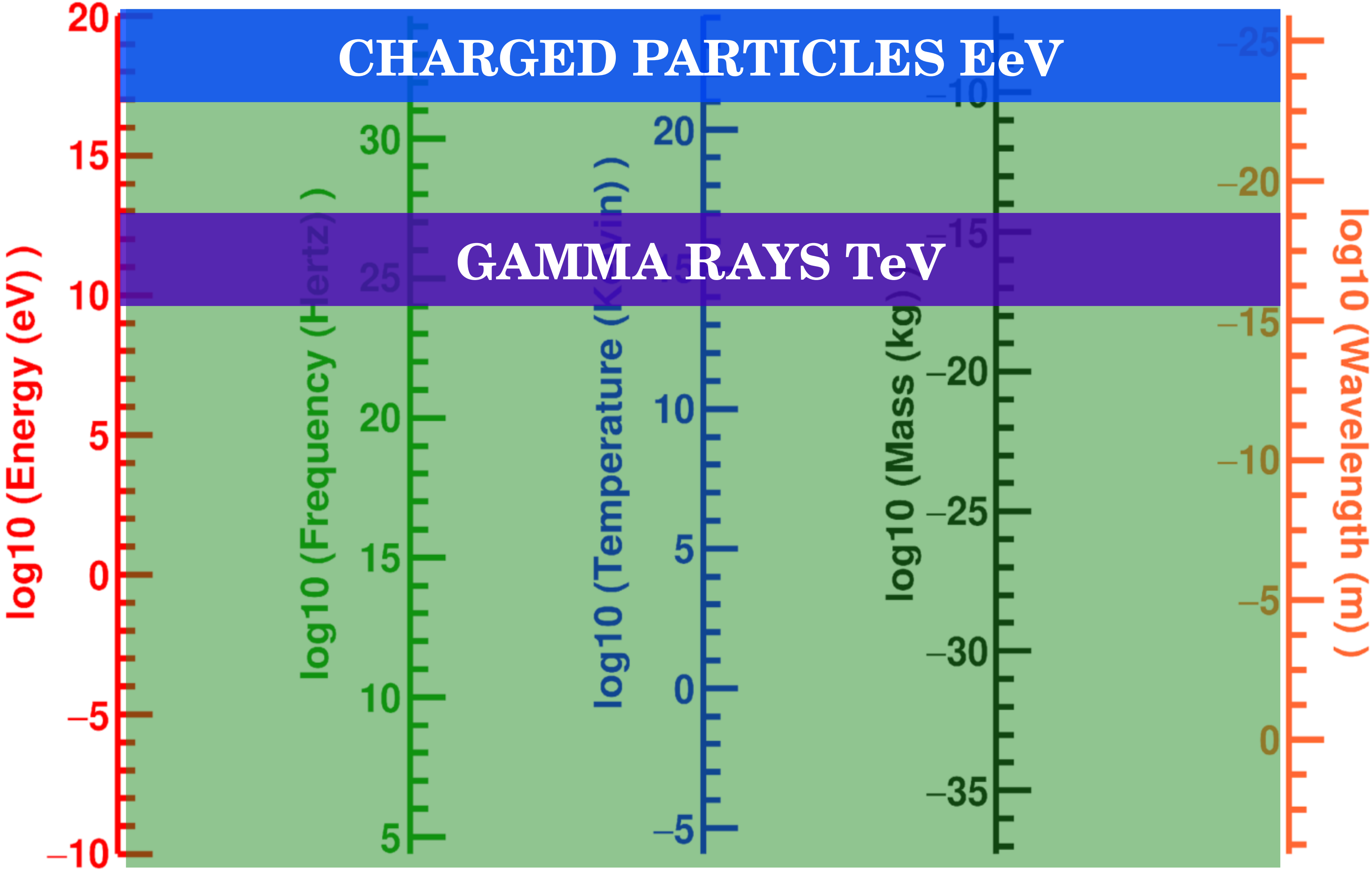
$$E > 10^{19}\ \mathrm{eV} \Leftrightarrow \lambda < 10^{-25}\ \mathrm{m}$$



$1\ \mathrm{eV} = 1.6 \times 10^{-19}$ Joule

Pierre Auger Observatory

Most energetic messengers

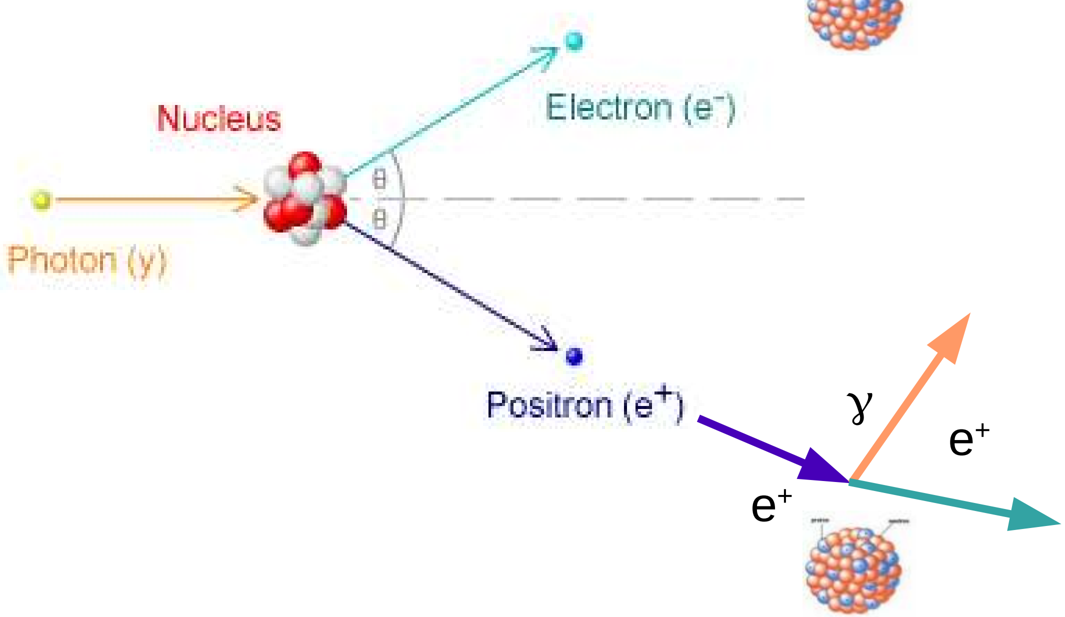


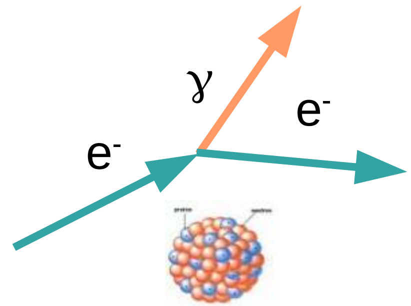
Summary of the introduction

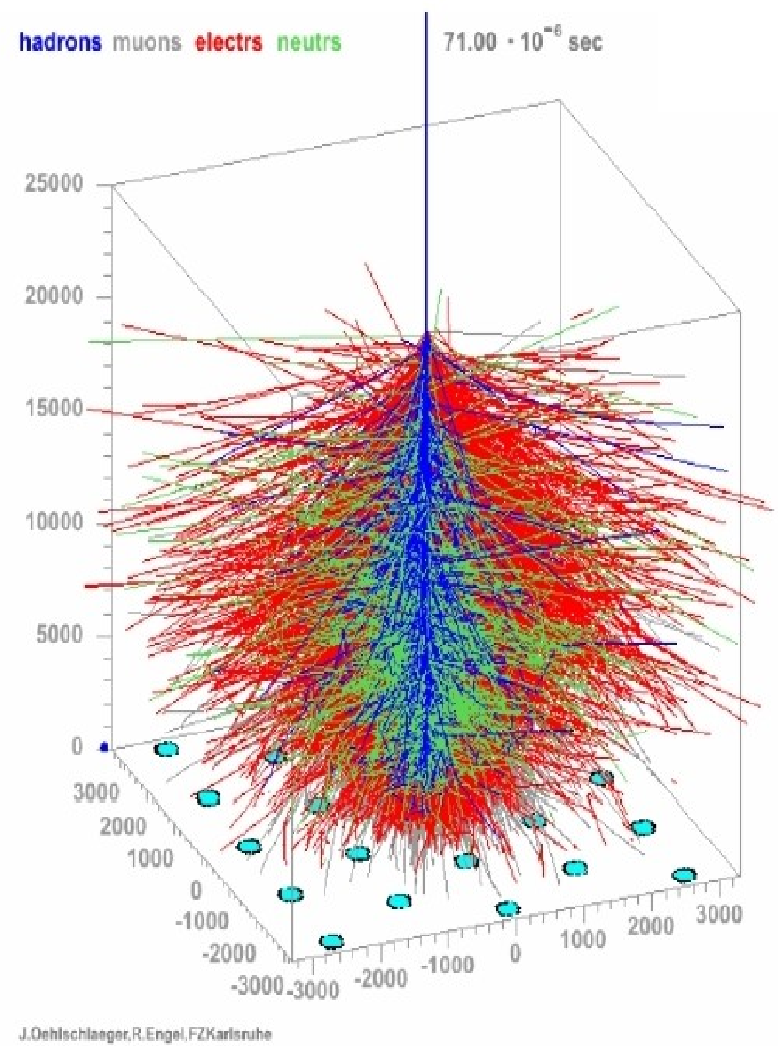
Gamma-rays TeV and charged particles EeV are the most energetic messenger of the Universe and they are related to extreme phenomena in Nature.

Air Shower

E > 1 MeV







Large amount of particles and radiation produced in the atmosphere

Instruments we participate

PIERRE AUGER OBSERVATORY

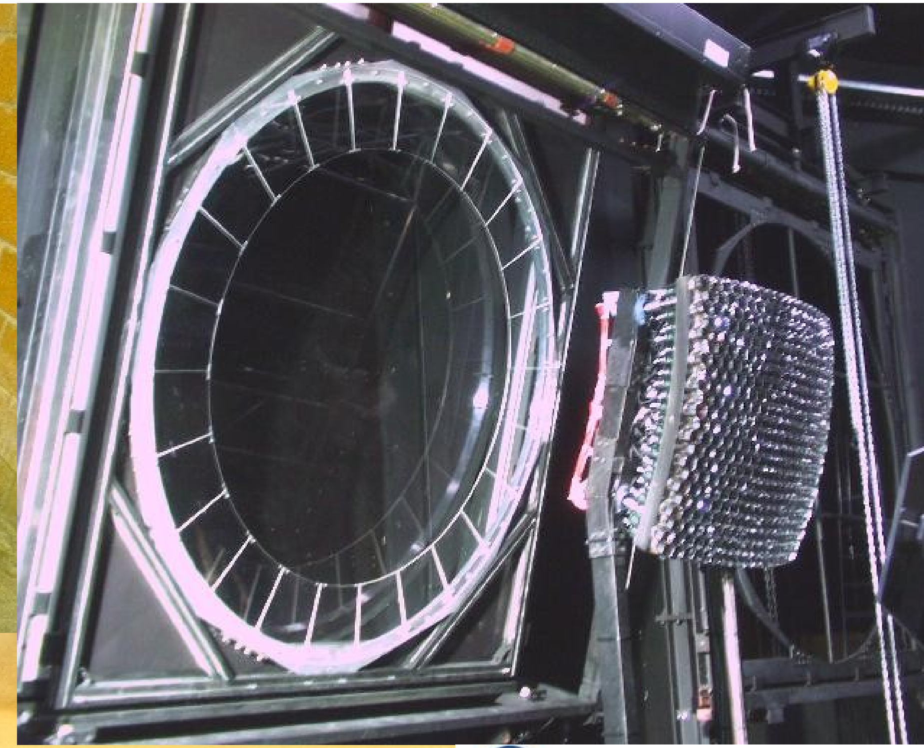
Cosmic Rays
EeV

cta
cherenkov telescope array

Gamma-rays
TeV


Cordoba
Cordoba
Santiago
Rosario
San Luis
Mendoza
Argentina
Buenos Aires
La Pampa
Buenos Aires
Neuquen
Image © 2007 TerraMetrics
© 2007 Europa Technologies
Image NASA
©2007 Google

Auger @ Brasil - Instrumentation

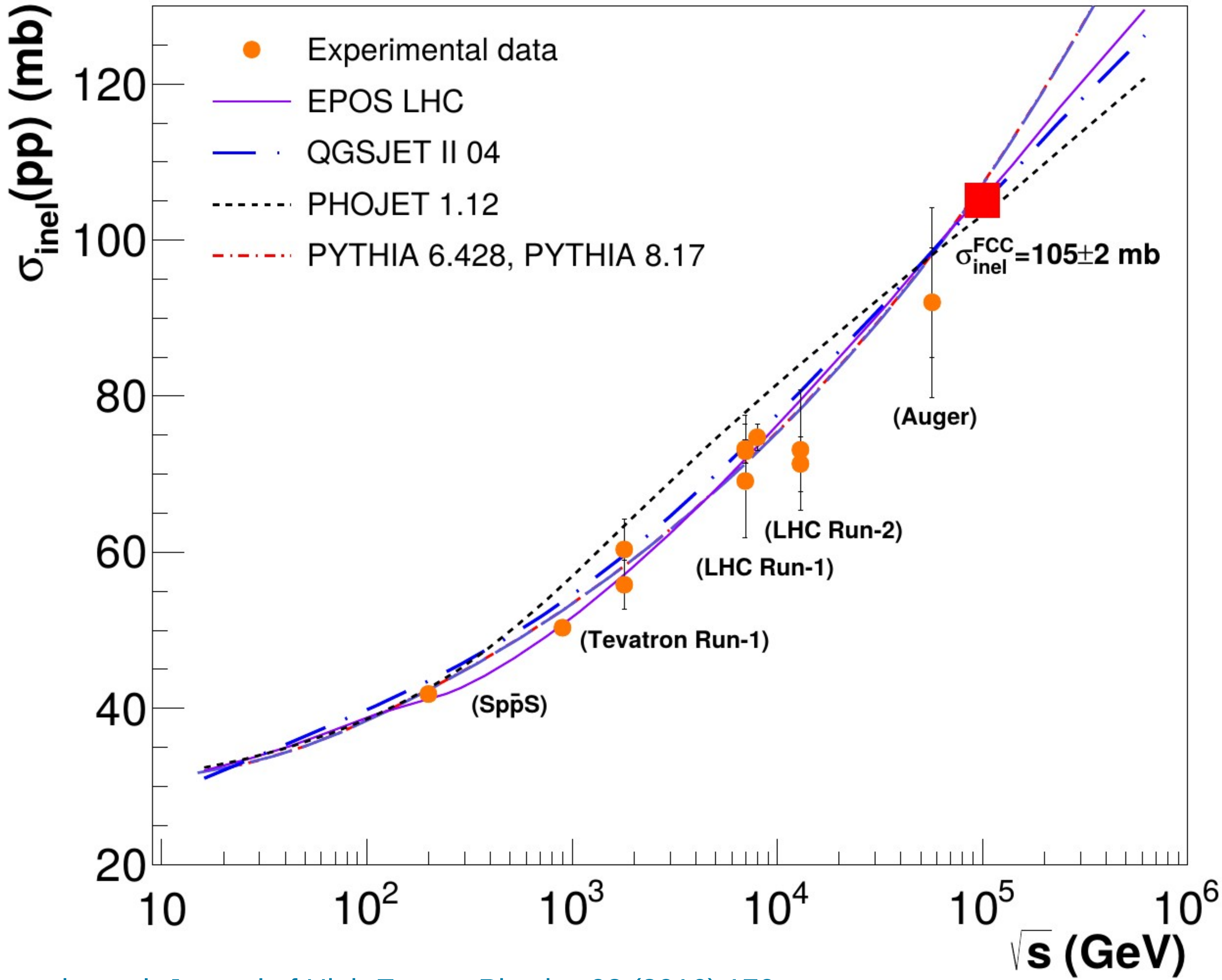


FAPESP

Anel Corretor Schmidt build in Indaiatuba/SP

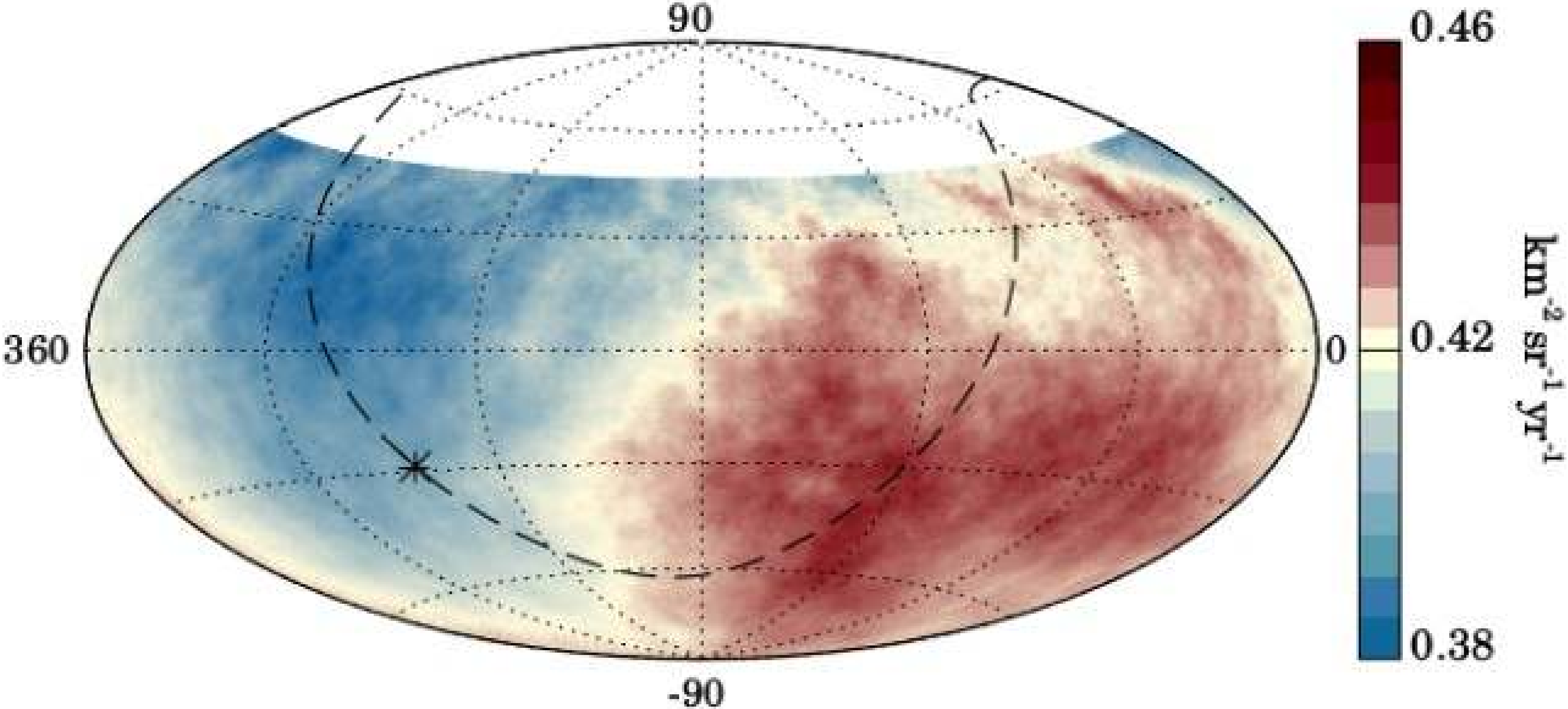
27 in operation

M. de Oliveira et al. NIM A 522 (2004) 360



D. d'Enterria et al. Journal of High Energy Physics 08 (2016) 170

Extragalactic Origem



Equatorial coordinates - Hammer projection - E > 8 EeV

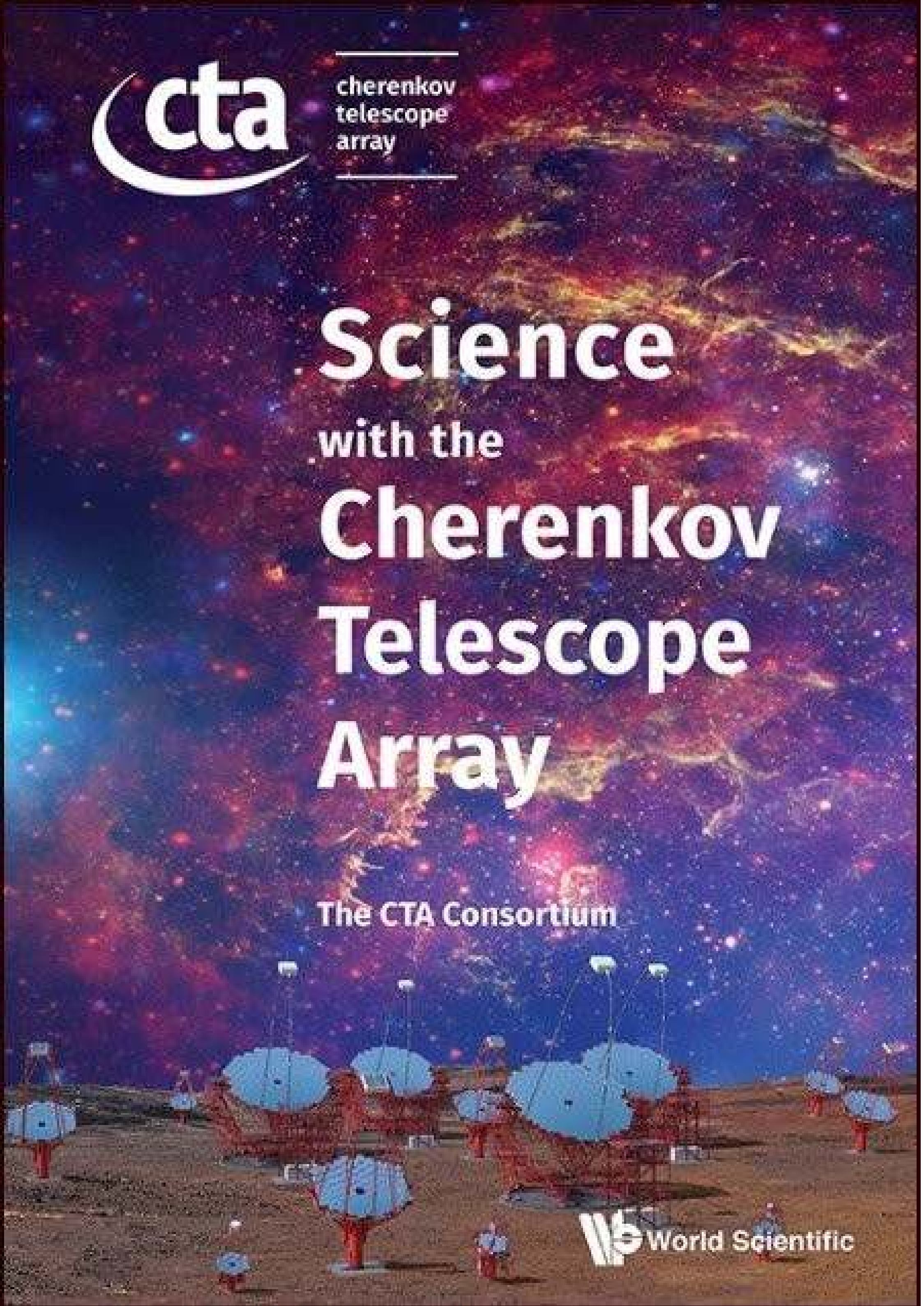
* Galactic center

- - - Galactic plane

cta

cherenkov
telescope
array


How do you discover more about the Universe
than ever before?



Unveil the extremes of the Universe

https://arxiv.org/abs/1709.07997

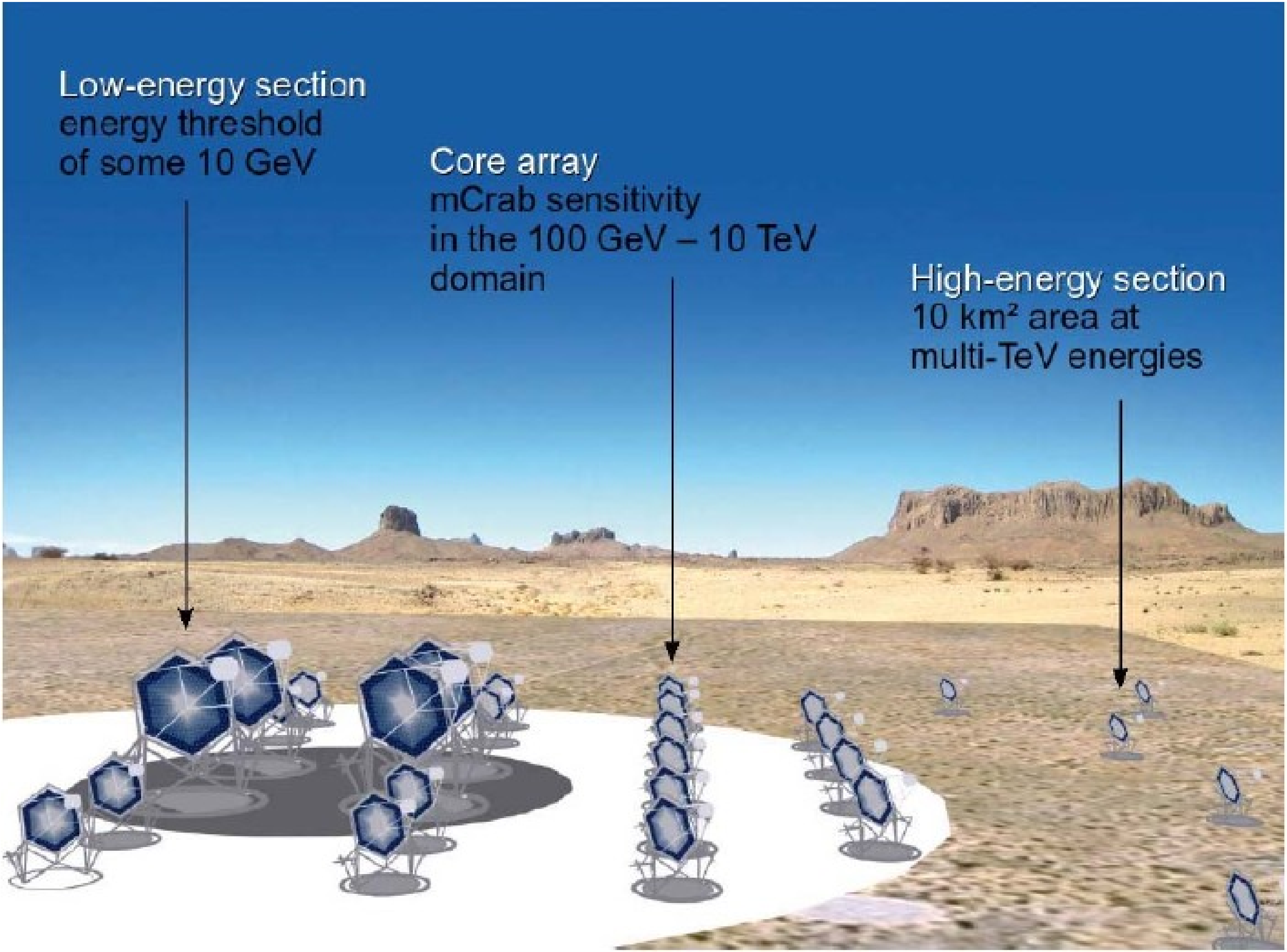
CTA Targets

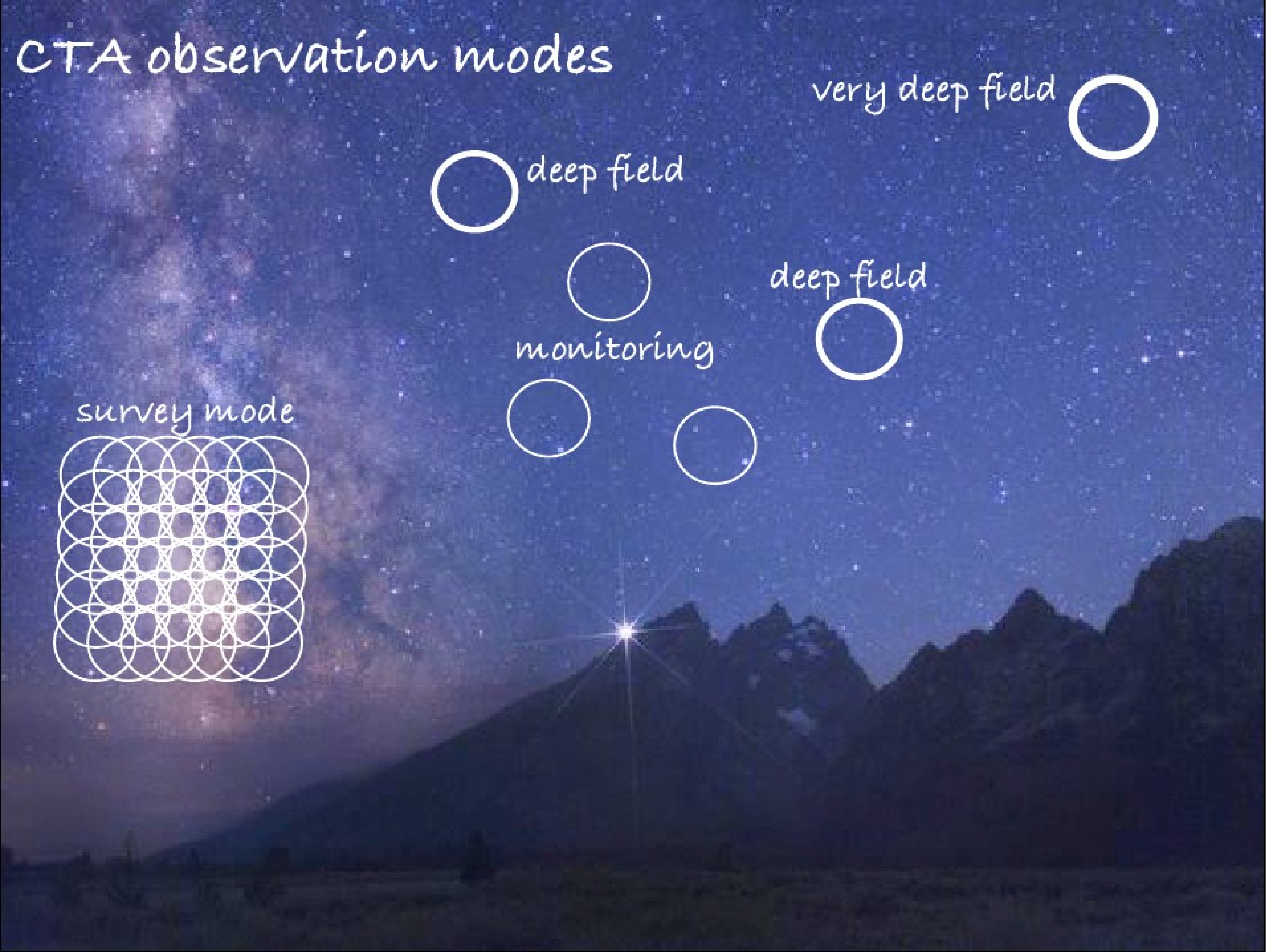
- Improve the sensitivity in one order of magnetitude
- Widen the energy range
  - 20 GeV < E < 300 TeV
- Increase the field of view
- Improve the angular resolution
  - 1- 3 arcmin
- Flexibility in operation

KEY SCIENCE PROJECTS

1. CTA Galactic Plane Survey
2. CTA Extragalactic Survey
3. Exploring extreme particle acceleration in the Galaxy
4. Probing DM with precision measurements of the Galactic Center
5. CTA studies on active galaxies
6. On the connection between cosmic rays and the star-formation process
7. Observations of clusters of galaxies
8. Observations of the LMC
9. Observations of the Cygnus region
10. Observation of Galactic DM dominated targets
11. Observations of transient phenomena

40% of the obervational time of the first 10 years


Low-energy section
energy threshold
of some 10 GeV
Core array
mCrab sensitivity
in the 100 GeV – 10 TeV
domain
High-energy section
10 km² area at
multi-TeV energies


CTA observation modes
very deep field
deep field
deep field
monitoring
survey mode

Telescopes

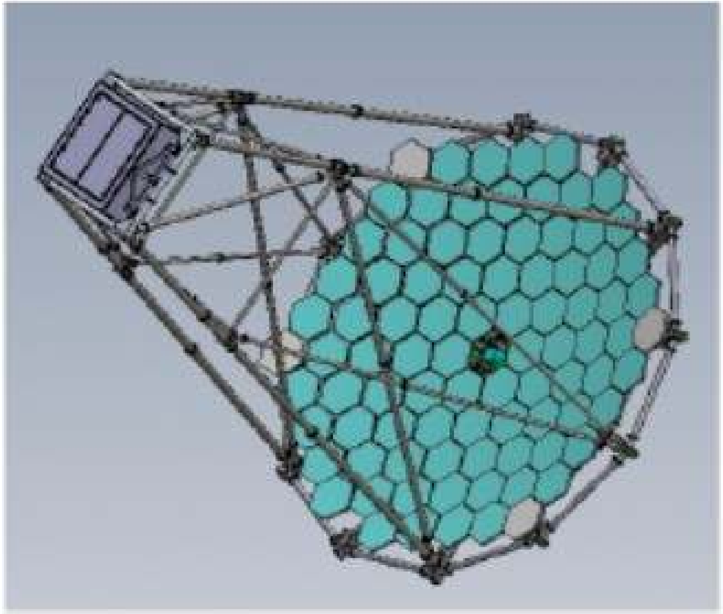
MST

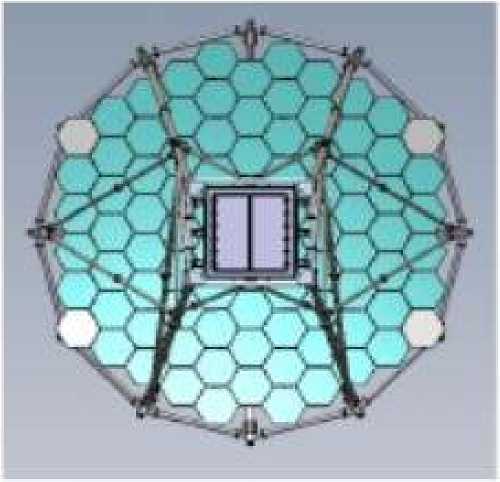
SST

LST-1: Ready and taking data

https://www.lst1.iac.es/webcams.html

Building the telescopes in Brazil





UNIVERSITY OF SÃO PAULO
São Carlos Institute of Physics

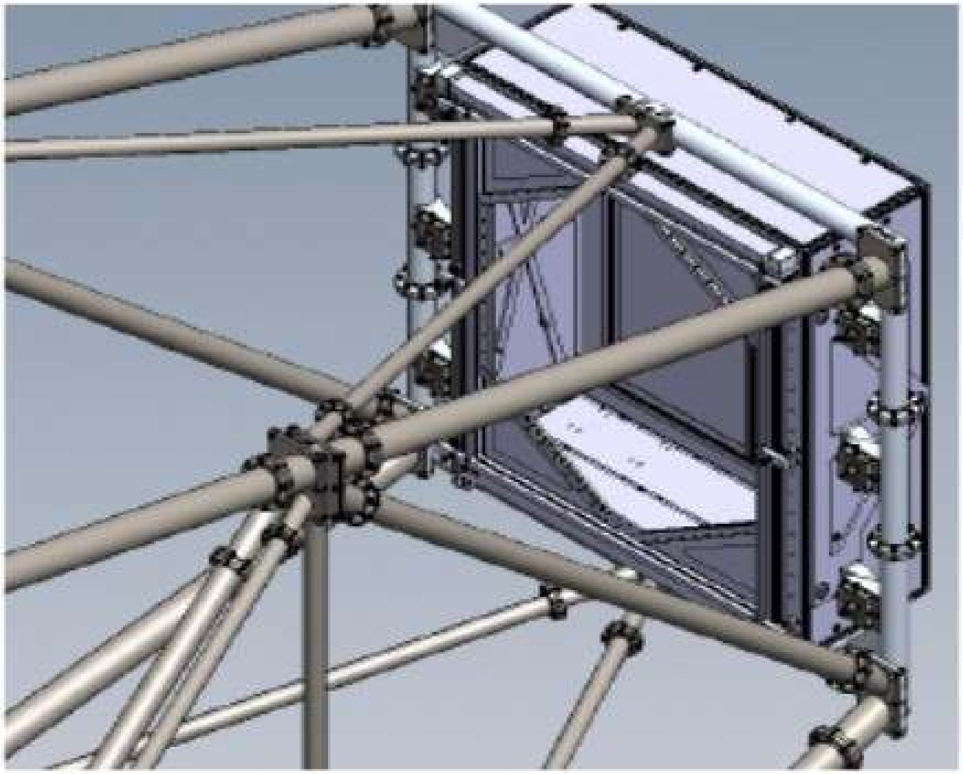
Universidade Federal do ABC

ORBITAL ENGENHARIA

15 ANOS ConstruAço CONSTRUÇÕES EM AÇO

FAPESP

Dispositivo de ajuste



Mover toneladas com precisão de milímetros

Tecnologia brasileira

Para o CTA

Patente depositada

UNIVERSITY OF SÃO PAULO
São Carlos Institute of Physics

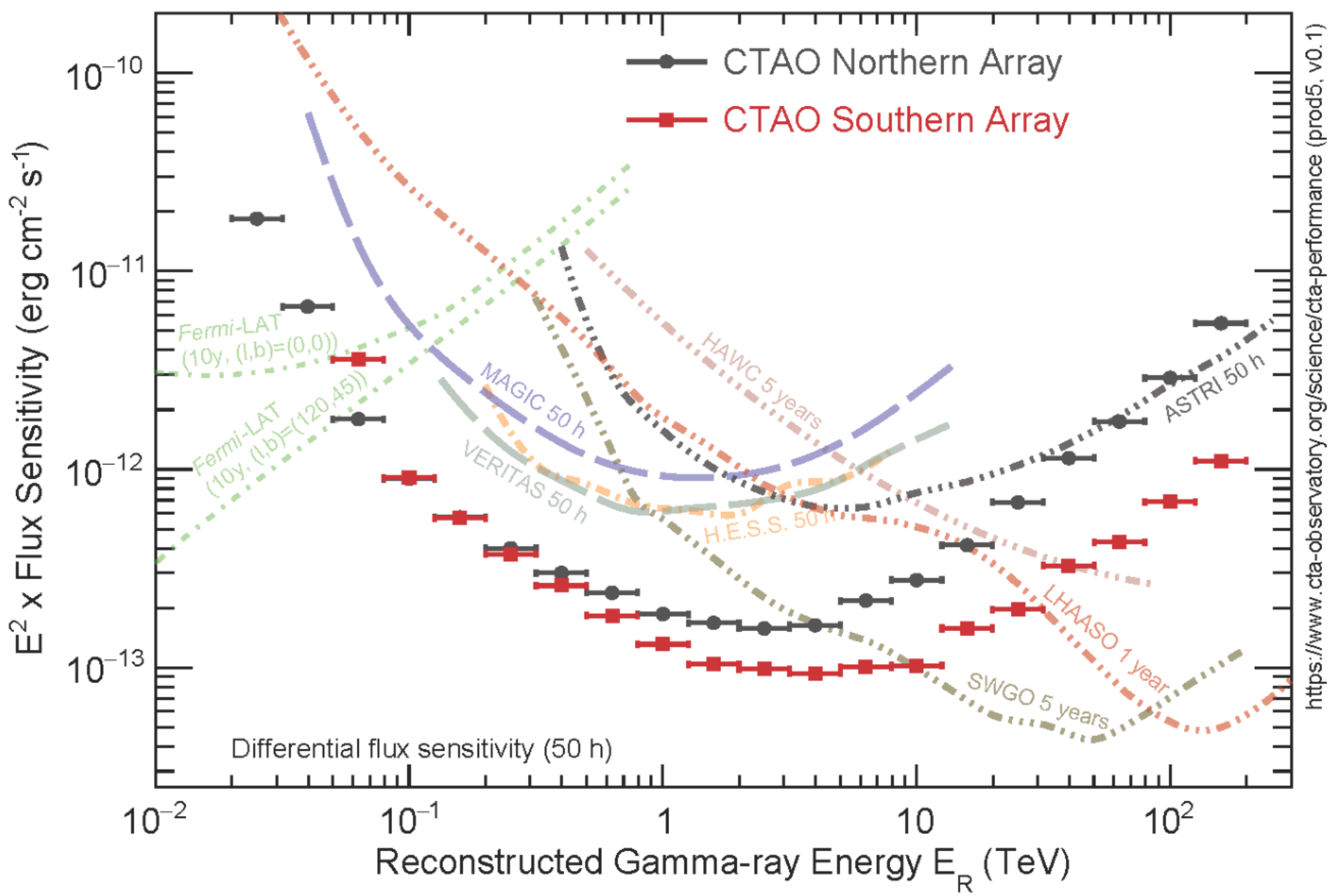
Universidade Federal do ABC

ORBITAL ENGENHARIA

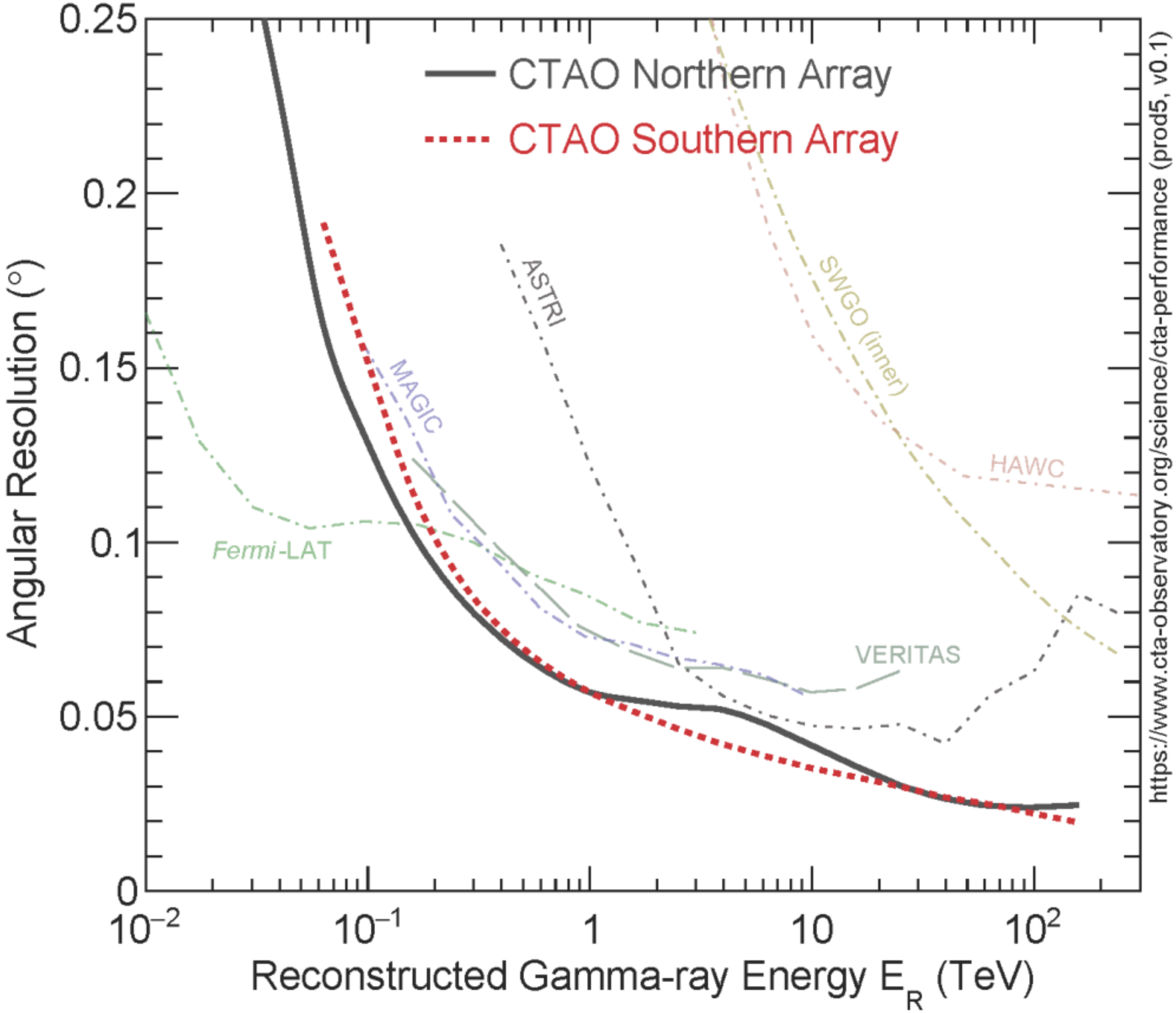
USP inovação

https://globoplay.globo.com/v/11960264/

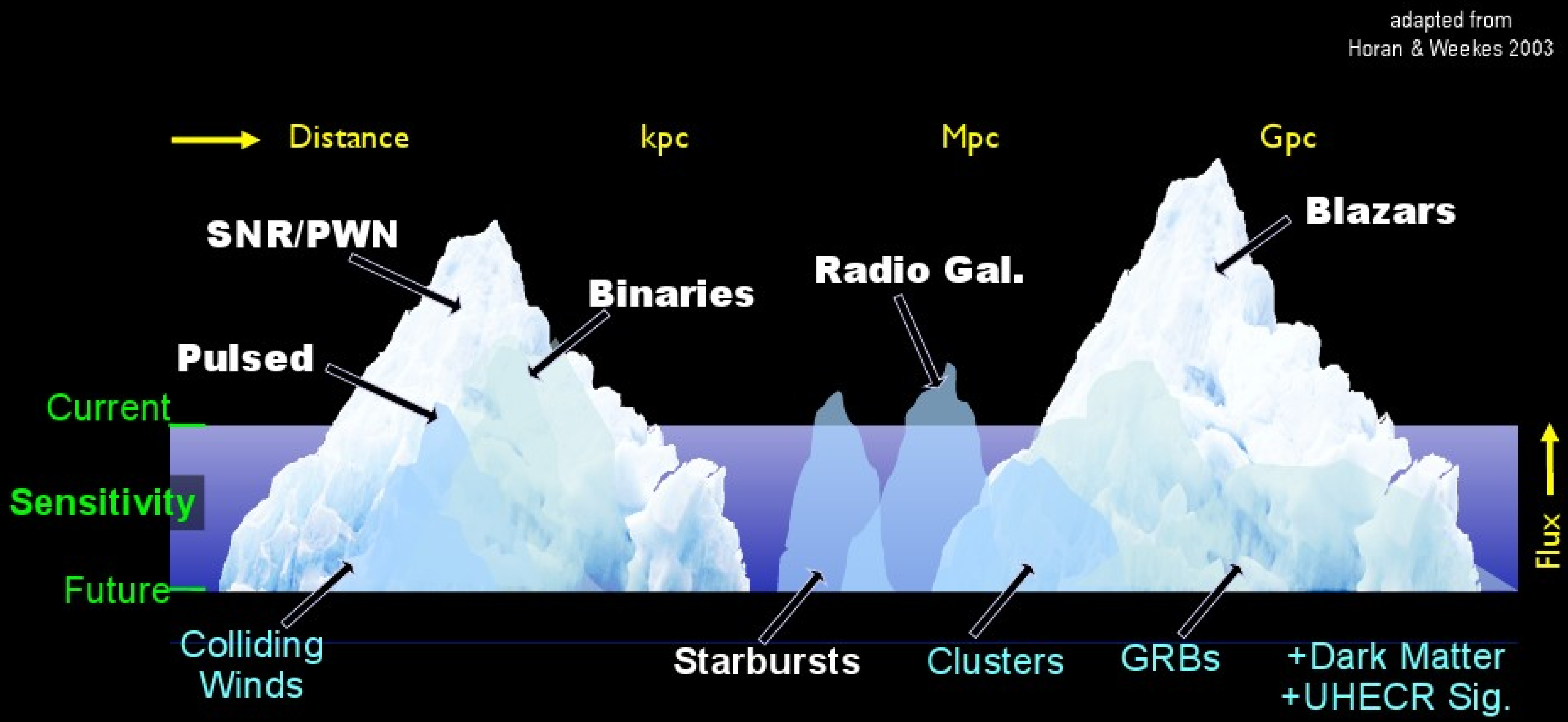
Sensitivity



Angular Resolution



Discovery Potential



Science with the CTA:

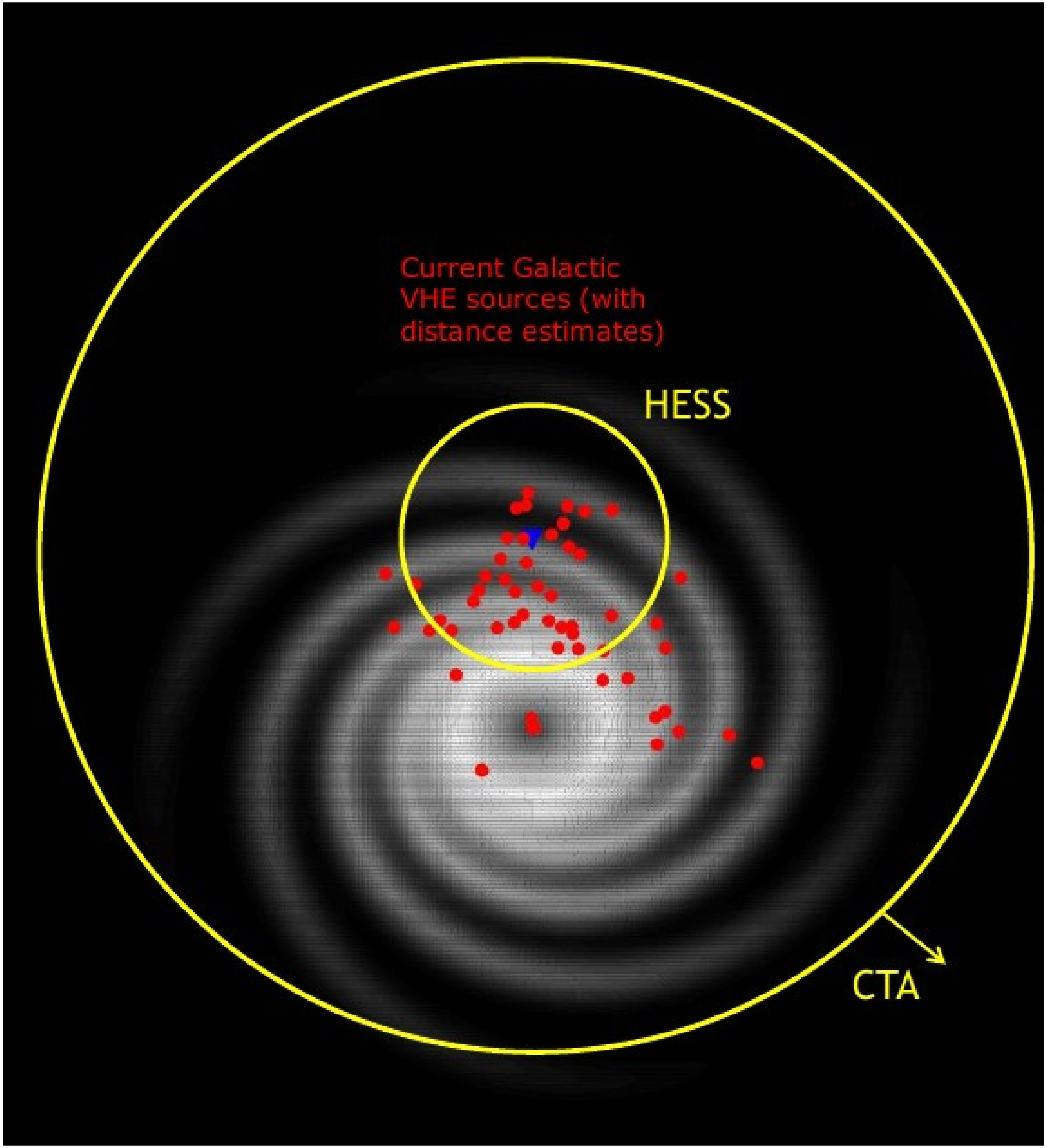
https://arxiv.org/abs/1709.07997

Summary of instruments

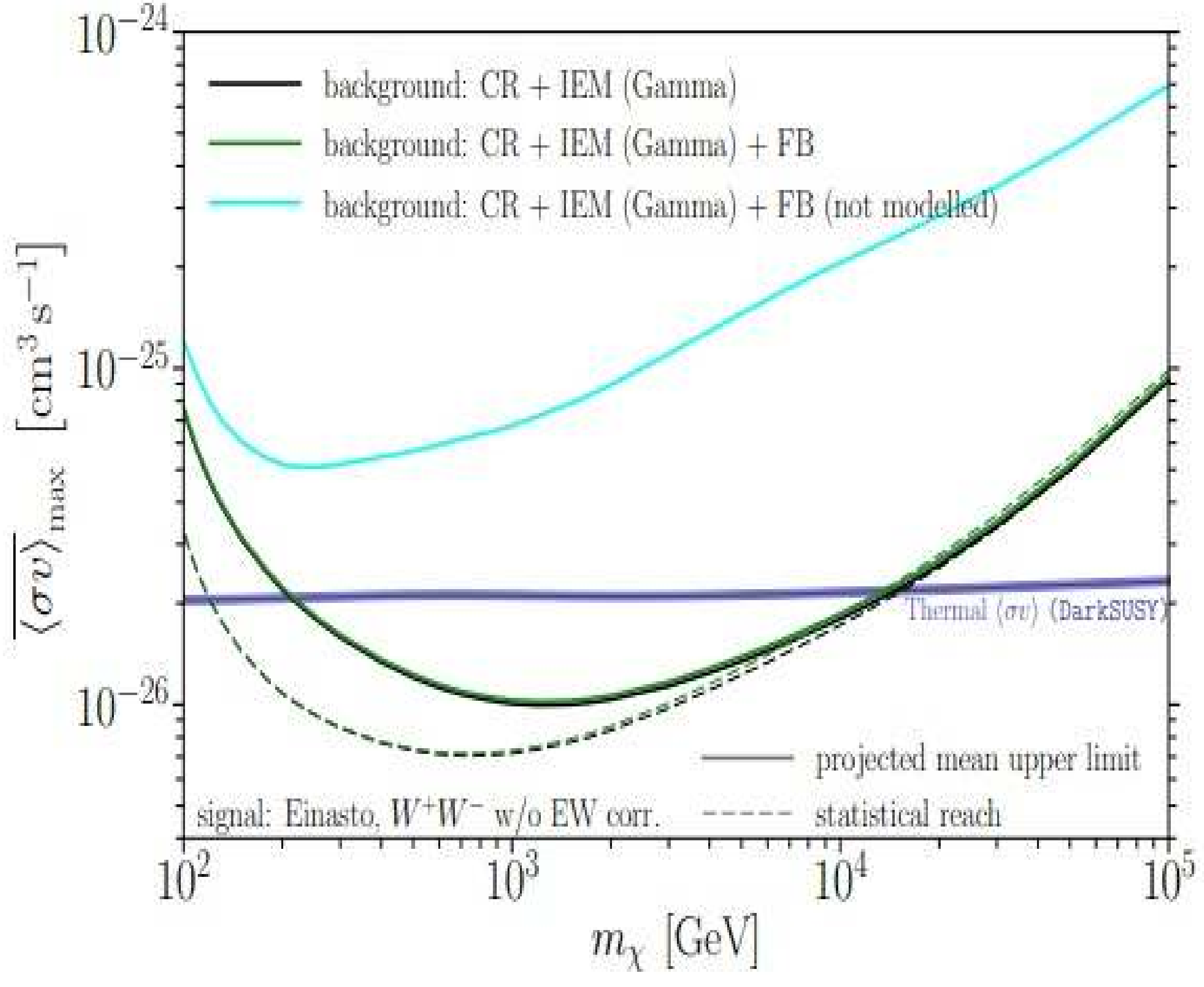
This is how we detect the

most energetic particles and radiation

of the Universe.


Current Galactic
VHE sources (with
distance estimates)
HESS
CTA

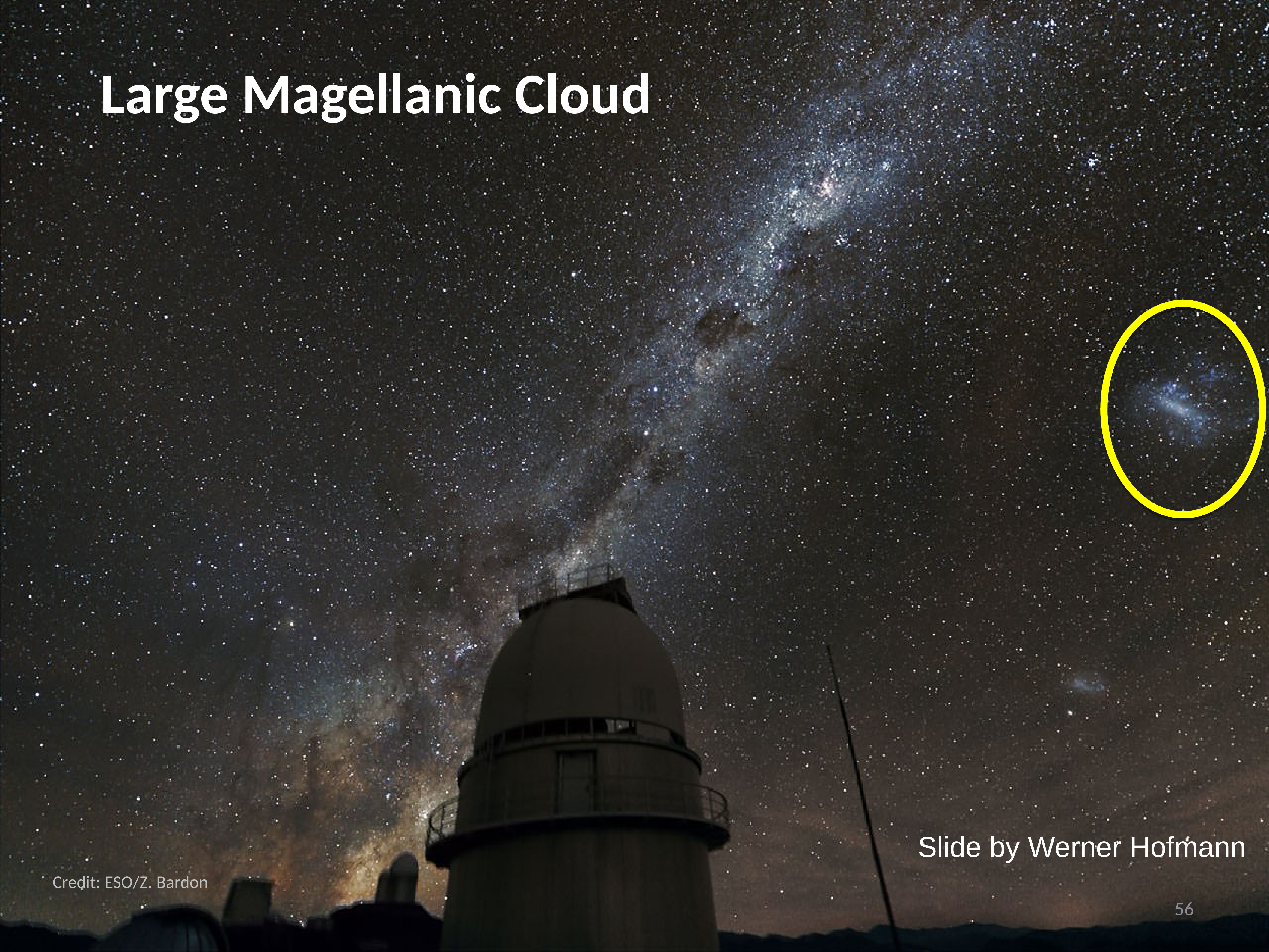
Sensitivity: DM + GC



Large Magellanic Cloud

Credit: ESO/Z. Bardon

Slide by Werner Hofmann


Large Magellanic Cloud
Slide by Werner Hofmann
Credit: ESO/Z. Bardon

Large Magellanic Cloud

Credit: NASA/CXC/M.Weiss

Slide by Werner Hofmann

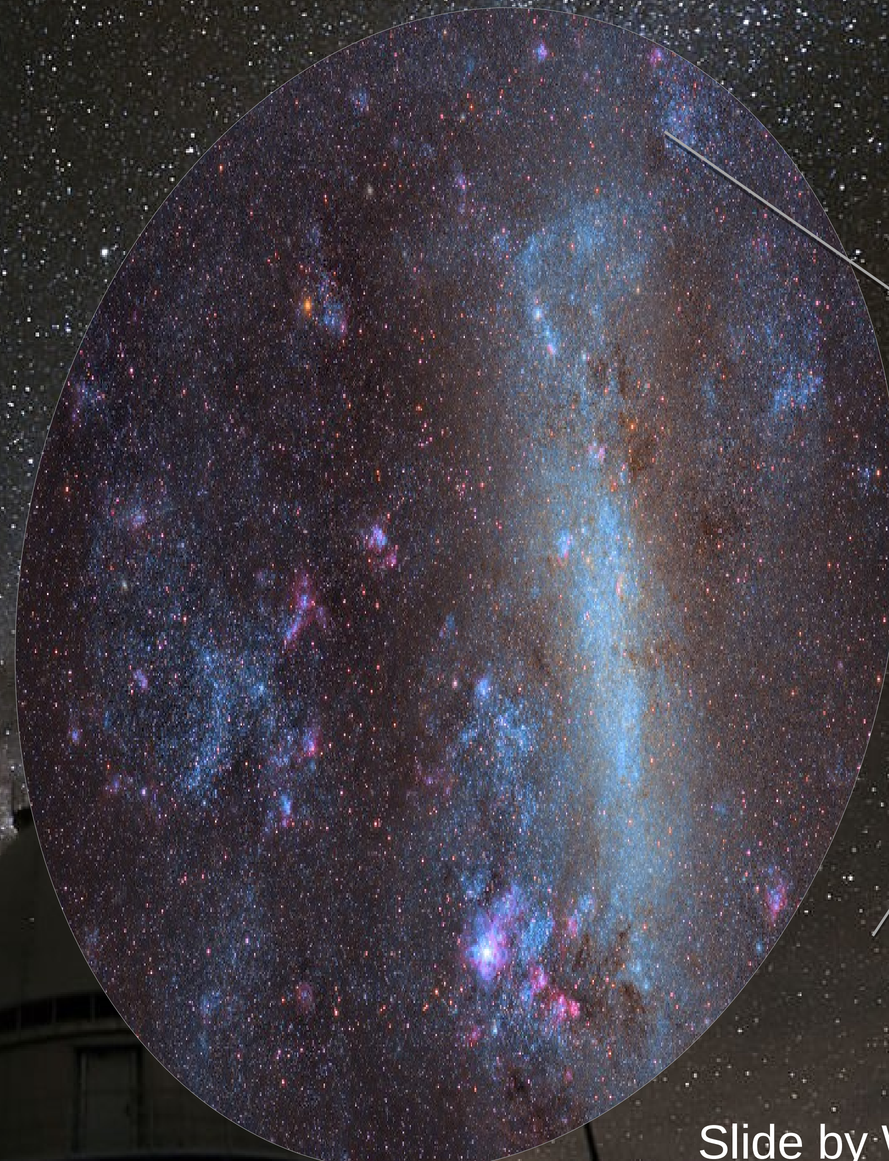
Credit: ESO/Z. Bardon

Large Magellanic Cloud

10 x higher star formation rate compared to Milky Way

harbors some extreme stellar objects

viewed face-on, known distance



Slide by Werner Hofmann

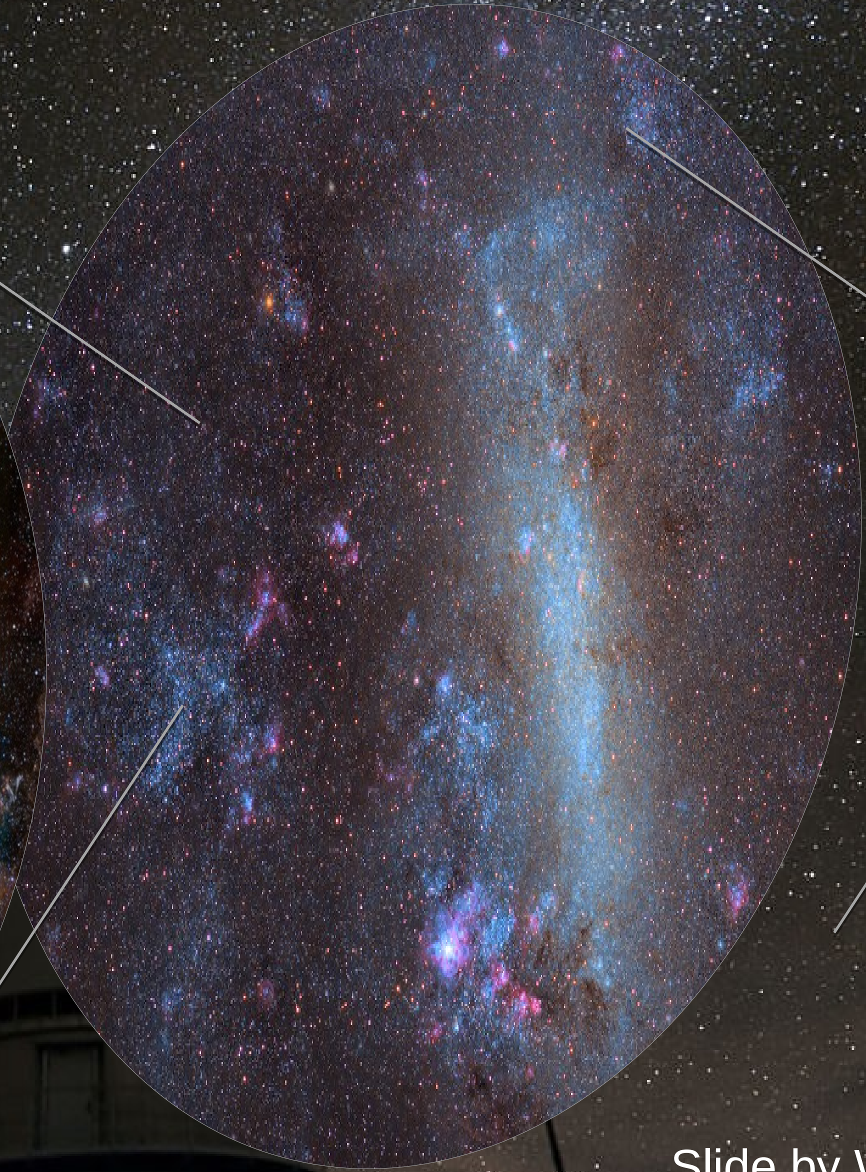
Image Credit: Alessandro Cipolat Bares

Credit: ESO/Z. Bardon

Large Magellanic Cloud

Image Credit: Hubble Space Telescope, NASA, ESA

Image Credit: Robert Gendler / ESA/ Webb



Slide by Werner Hofmann

Image Credit: Alessandro Cipolat Bares

Large Magellanic Cloud

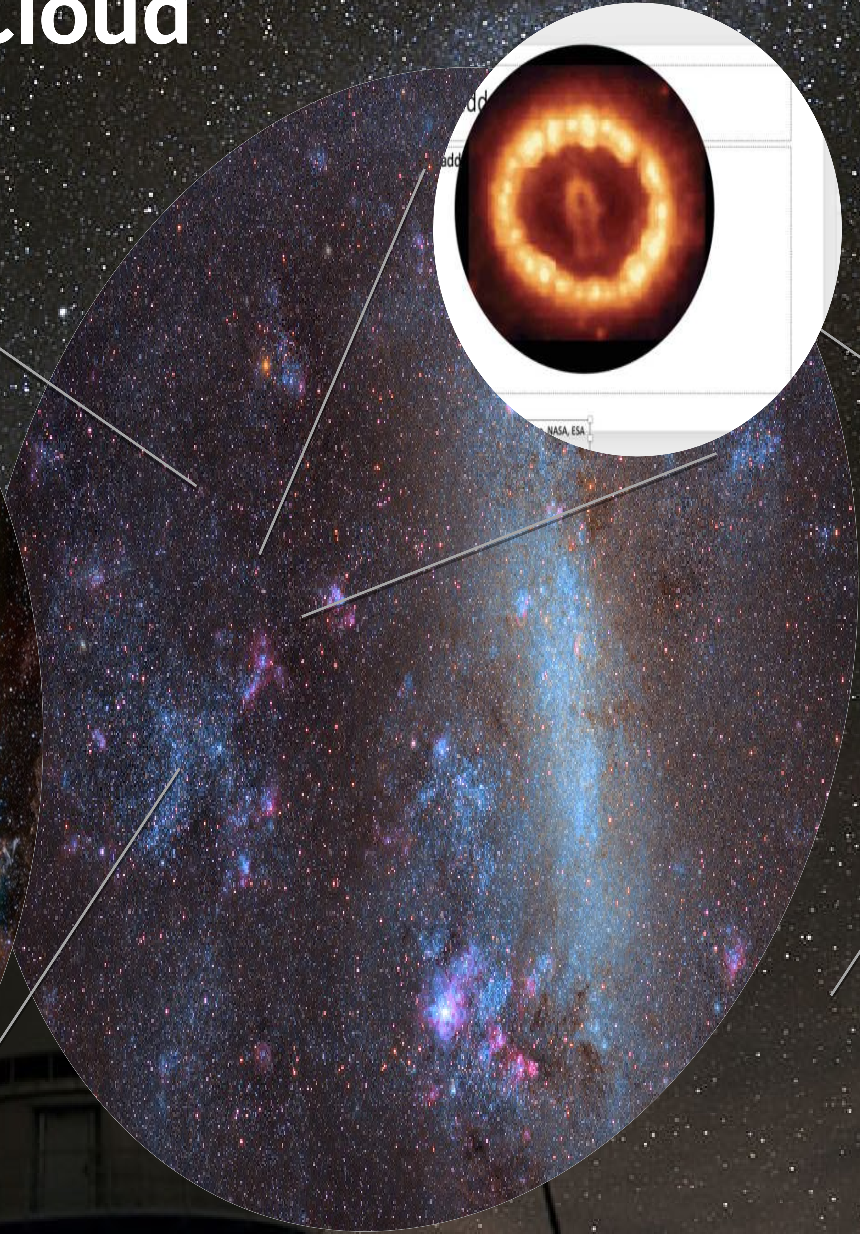


Image Credit: Hubble Space Telescope, NASA, ESA

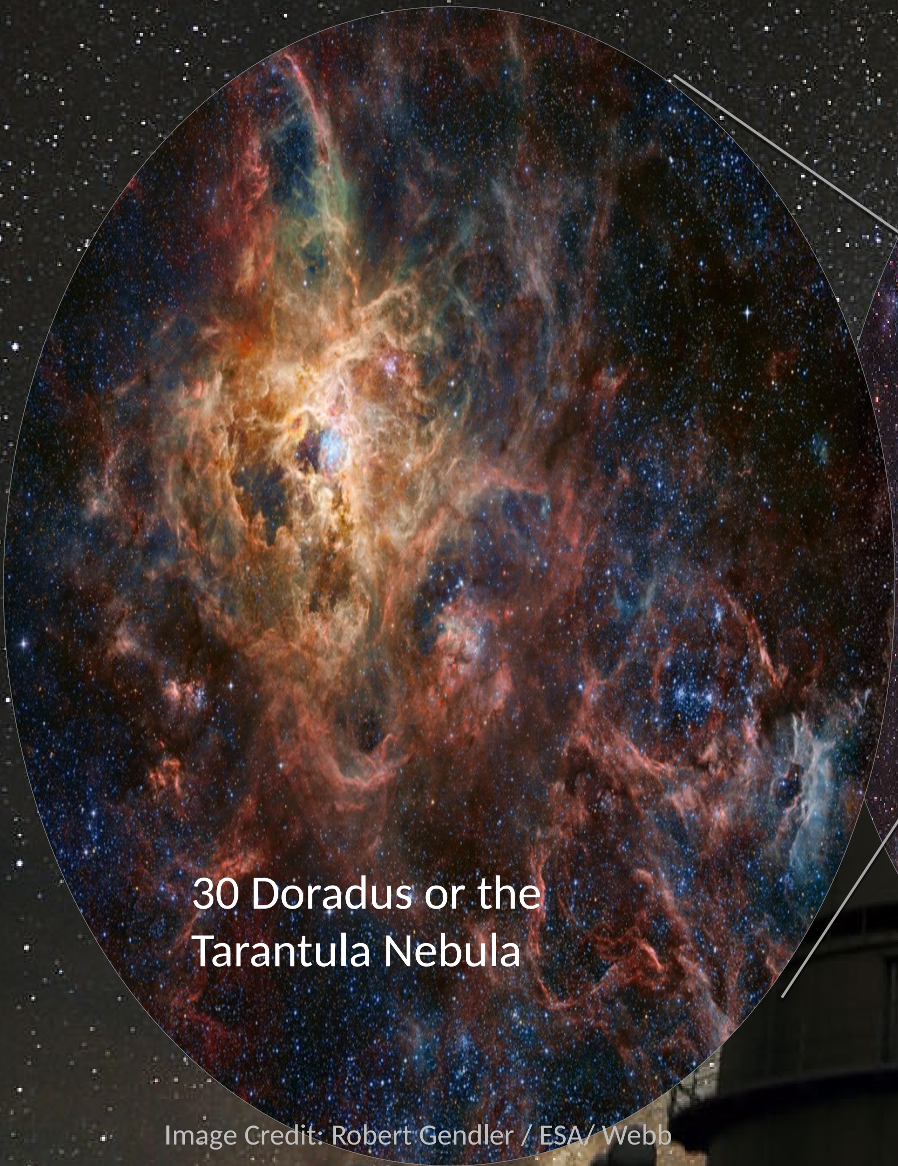
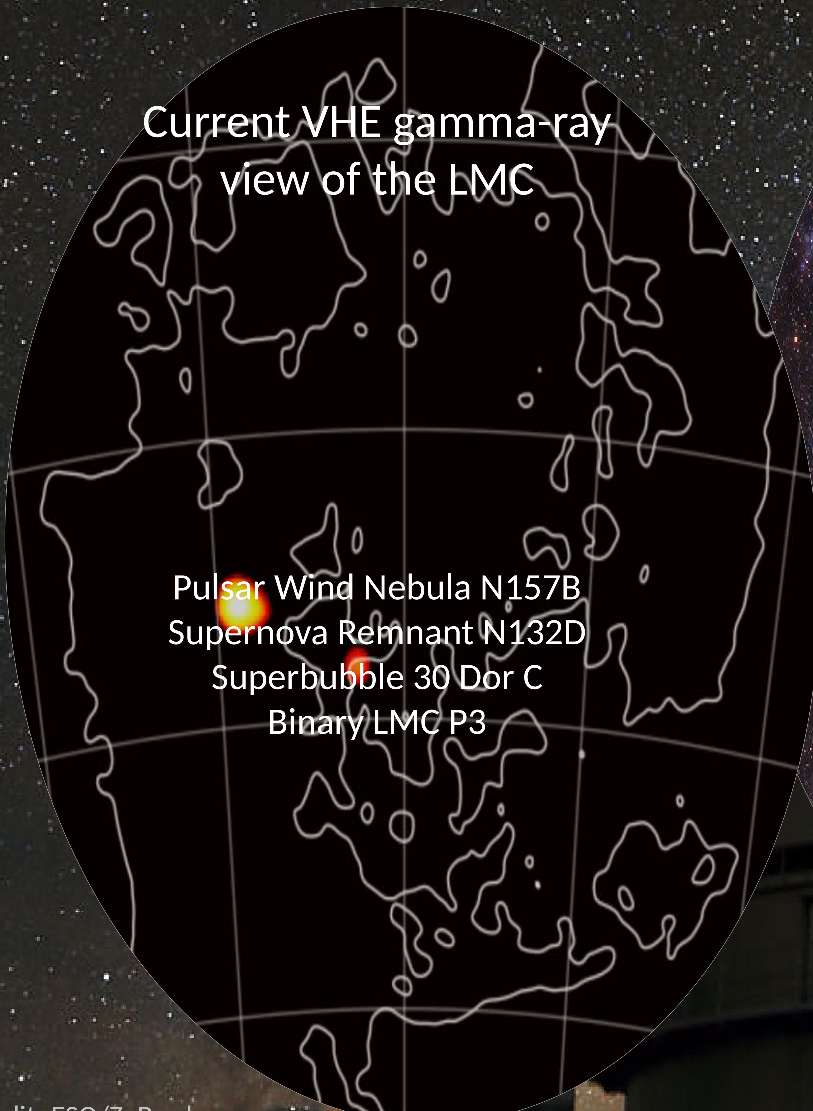
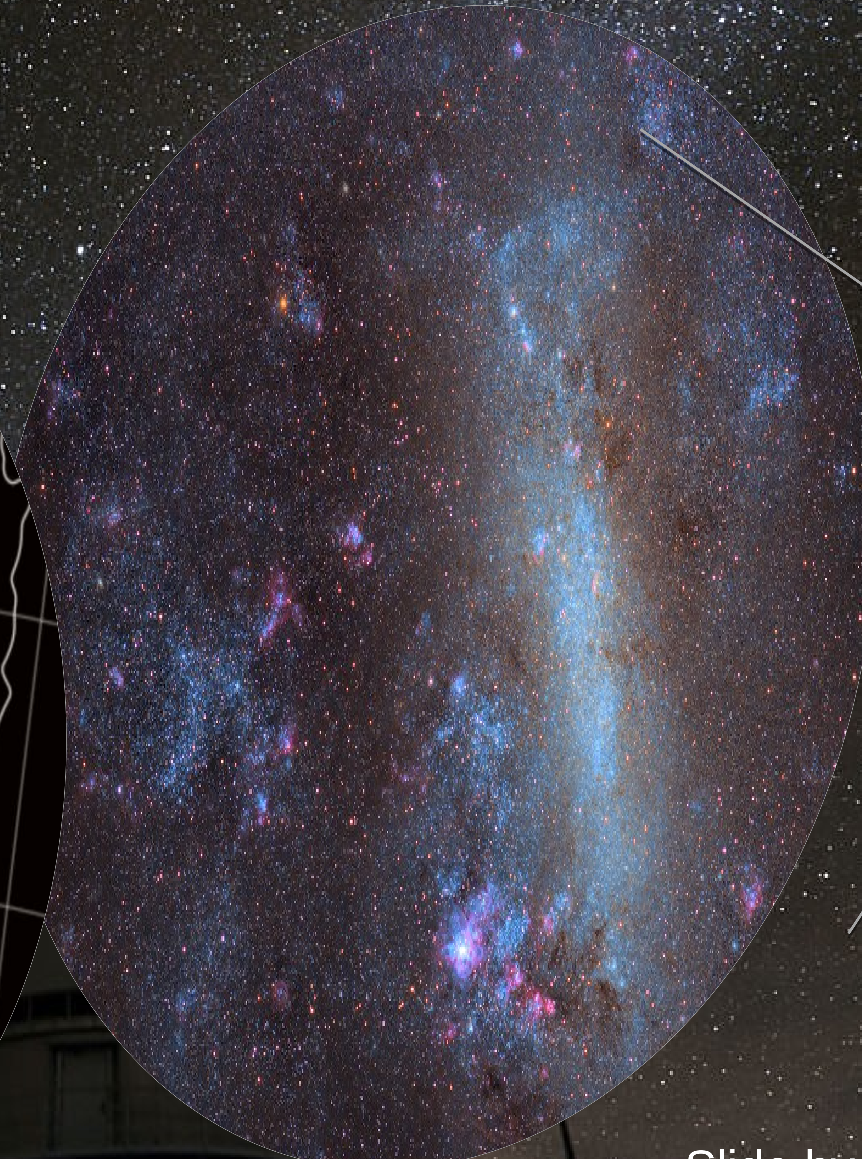


Image Credit: Robert Gendler / ESA/ Webb

Image Credit: Alessandro Cipolat Bares

Large Magellanic Cloud

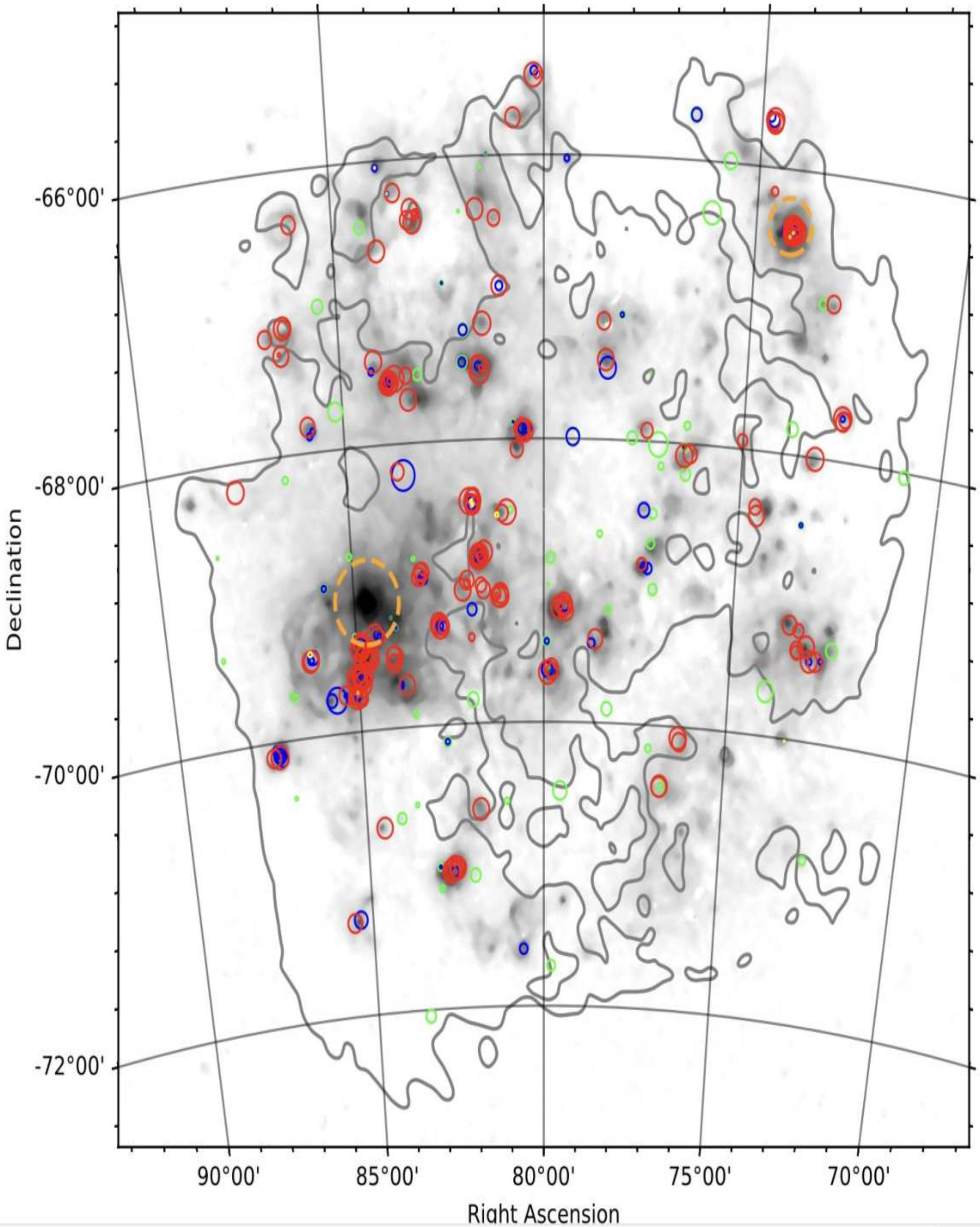




Slide by Werner Hofmann

Image Credit: Alessandro Cipolat Bares

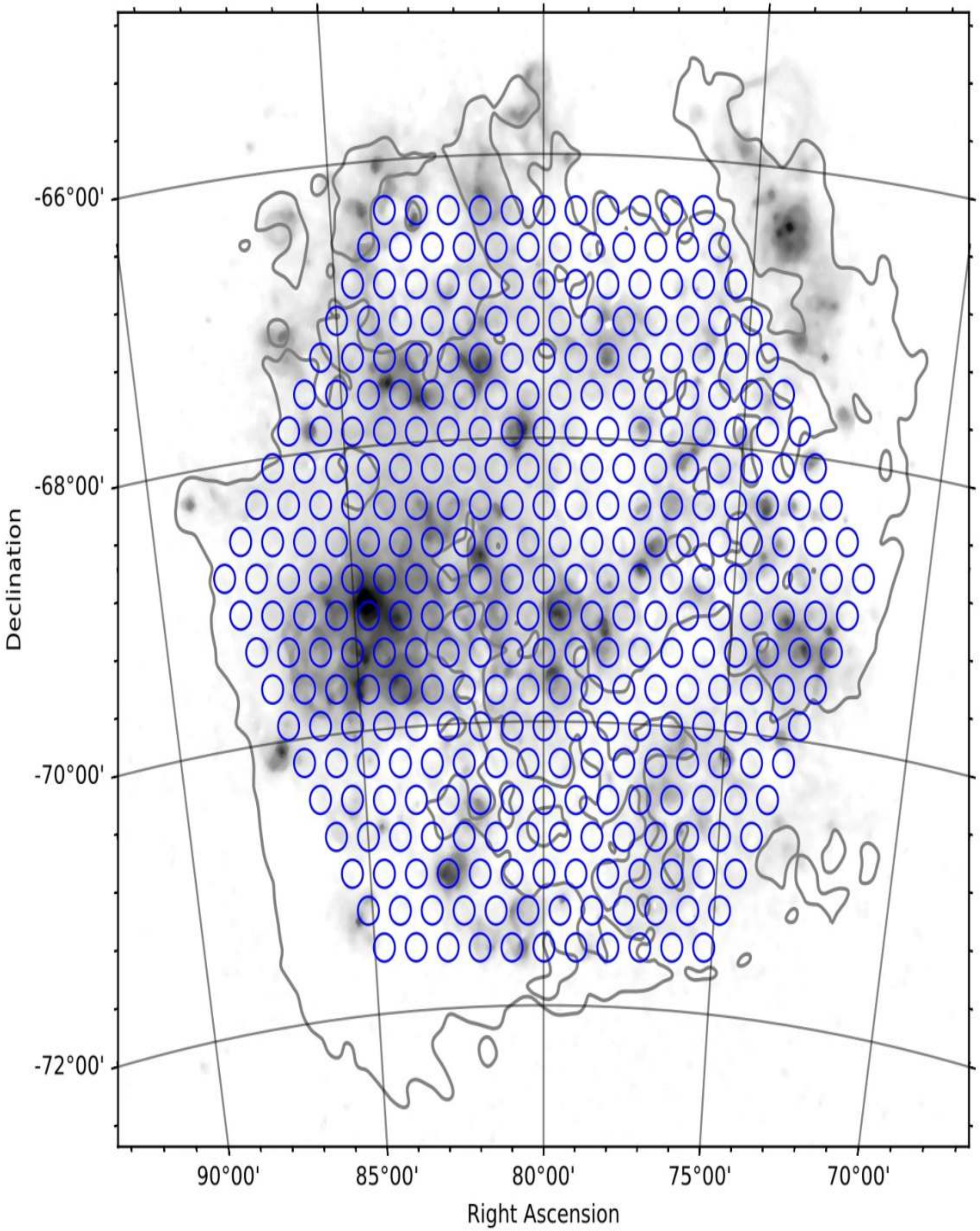
Credit: ESO/Z. Bardon



LMC model with
- 71 SNRs
- 10 iSNRs
- 91 PWNe
- 167 pulsar halos

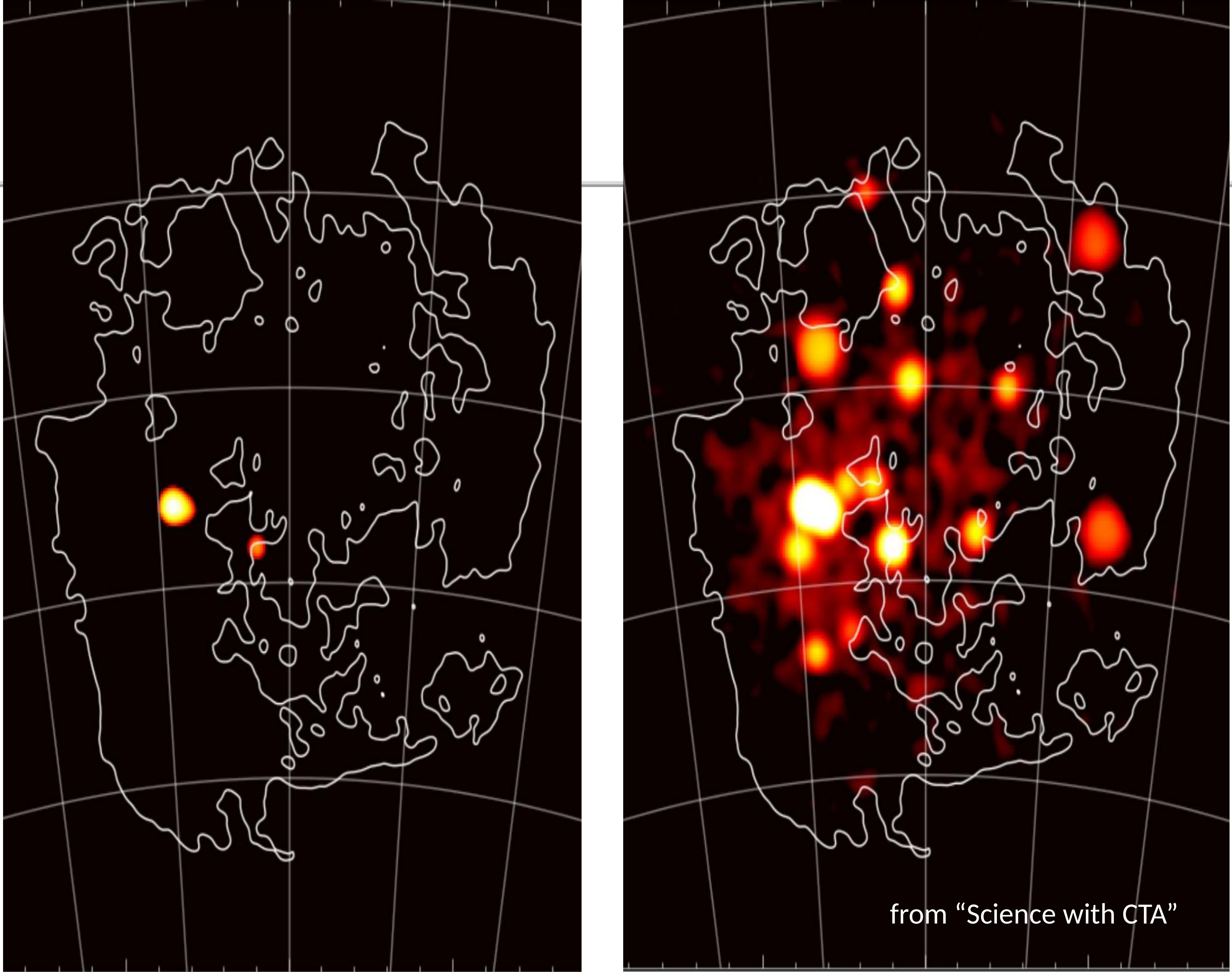
(see also Milky Way model)

https://doi.org/10.1093/mnras/stad1576

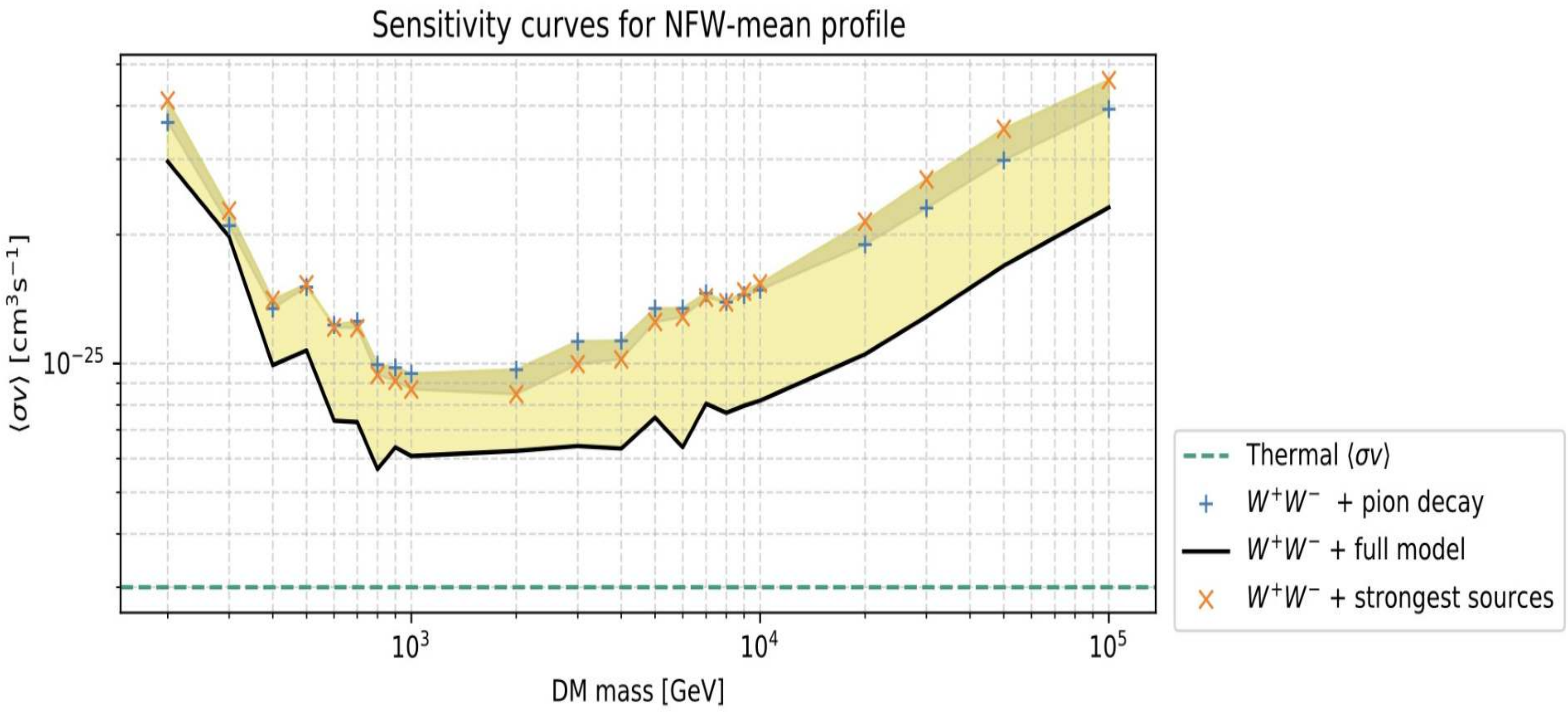


Telescope pointing pattern:
331 pointings of 1 h each

https://doi.org/10.1093/mnras/stad1576

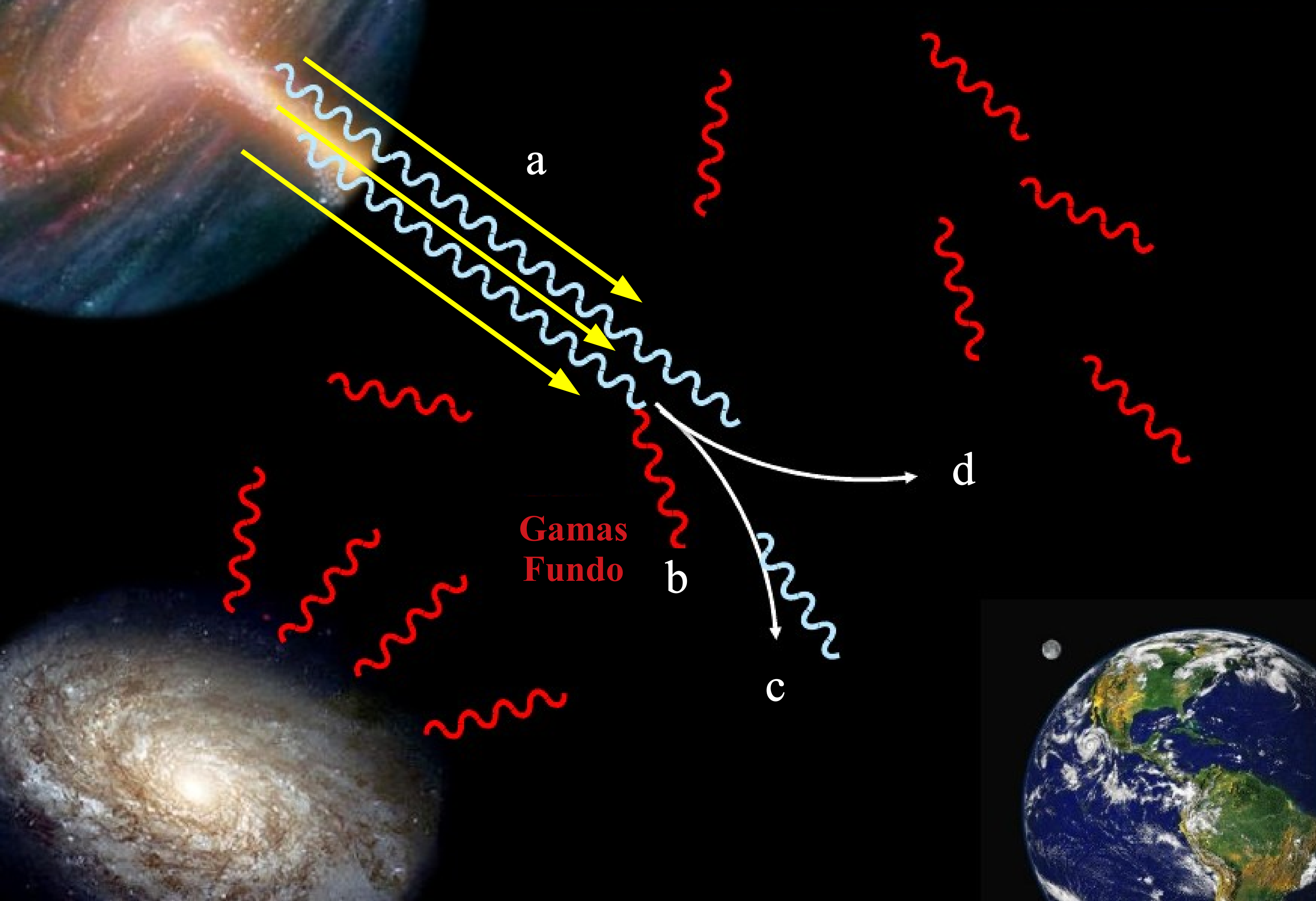

from “Science with CTA”

Dark Matter in LMC

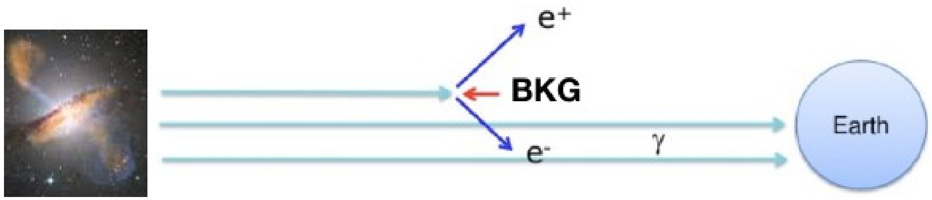


CTA Consoritum
https://doi.org/10.1093/mnras/stad1576

PROPAGATION



$$\tau(E_\gamma, z, \eta) =$$



$$\int_0^z dz' \frac{c}{H_0(1+z')\sqrt{\Omega_\Lambda + \Omega(1+z')^3}}$$

Distance

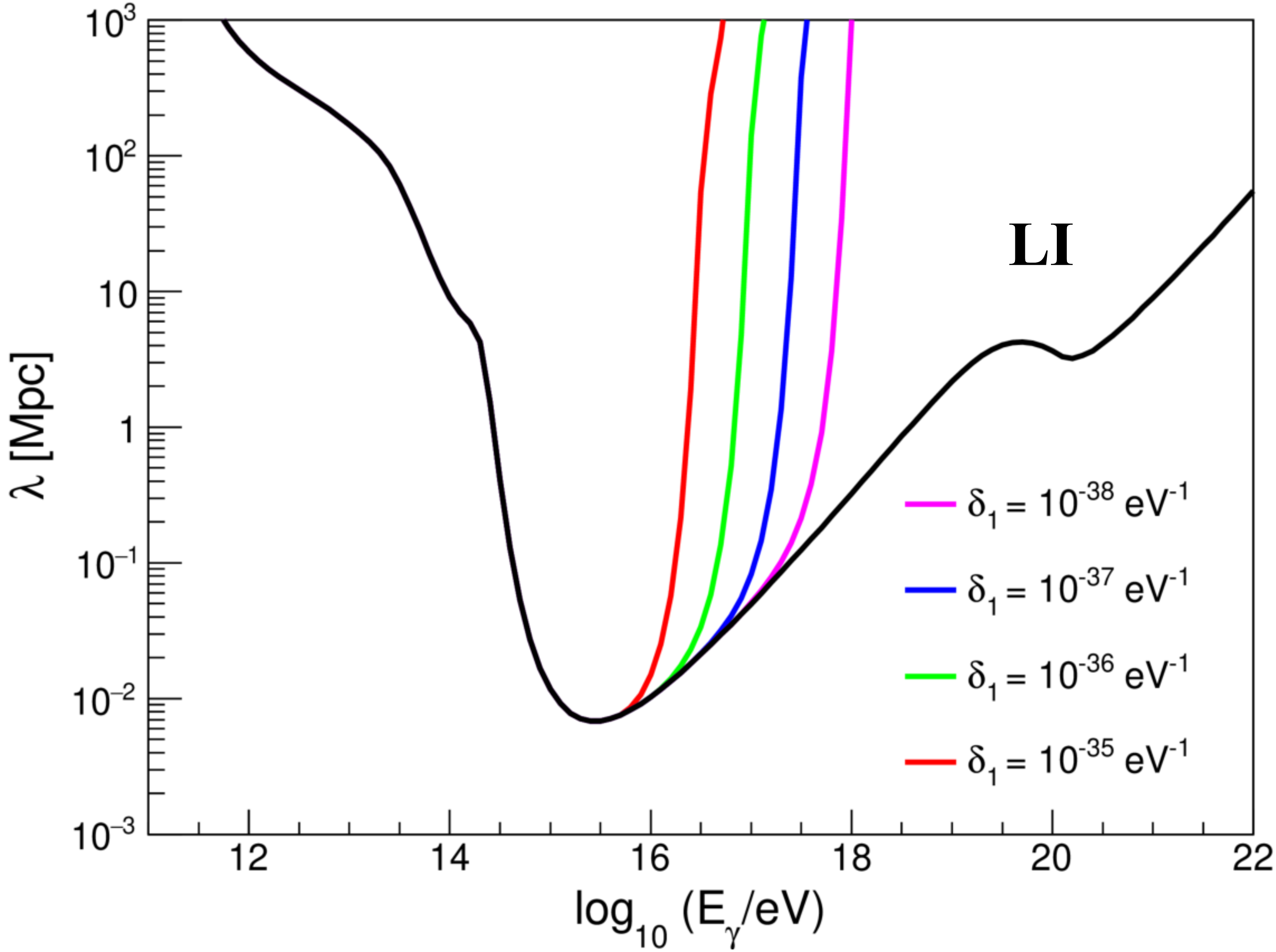
$$\otimes \int_{-1}^{1} \frac{d(cos\theta)}{2}$$

Target

Interaction

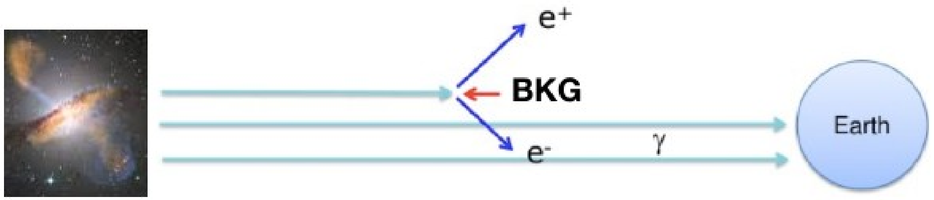
$$\otimes \int_{\epsilon_{th}}^{\infty} d\epsilon \, \eta(\epsilon, z') \, \sigma(E, \epsilon, \theta, z') \, K(E, \epsilon, \theta, z')$$

Pair-production + LIV



R. Lang et al. Phys. Rev. D 99, 043015 (2019)

$$\tau(E_\gamma, z, \eta) =$$



$$\int_0^z dz' \frac{c}{H_0(1+z')\sqrt{\Omega_\Lambda + \Omega(1+z')^3}}$$

Distance

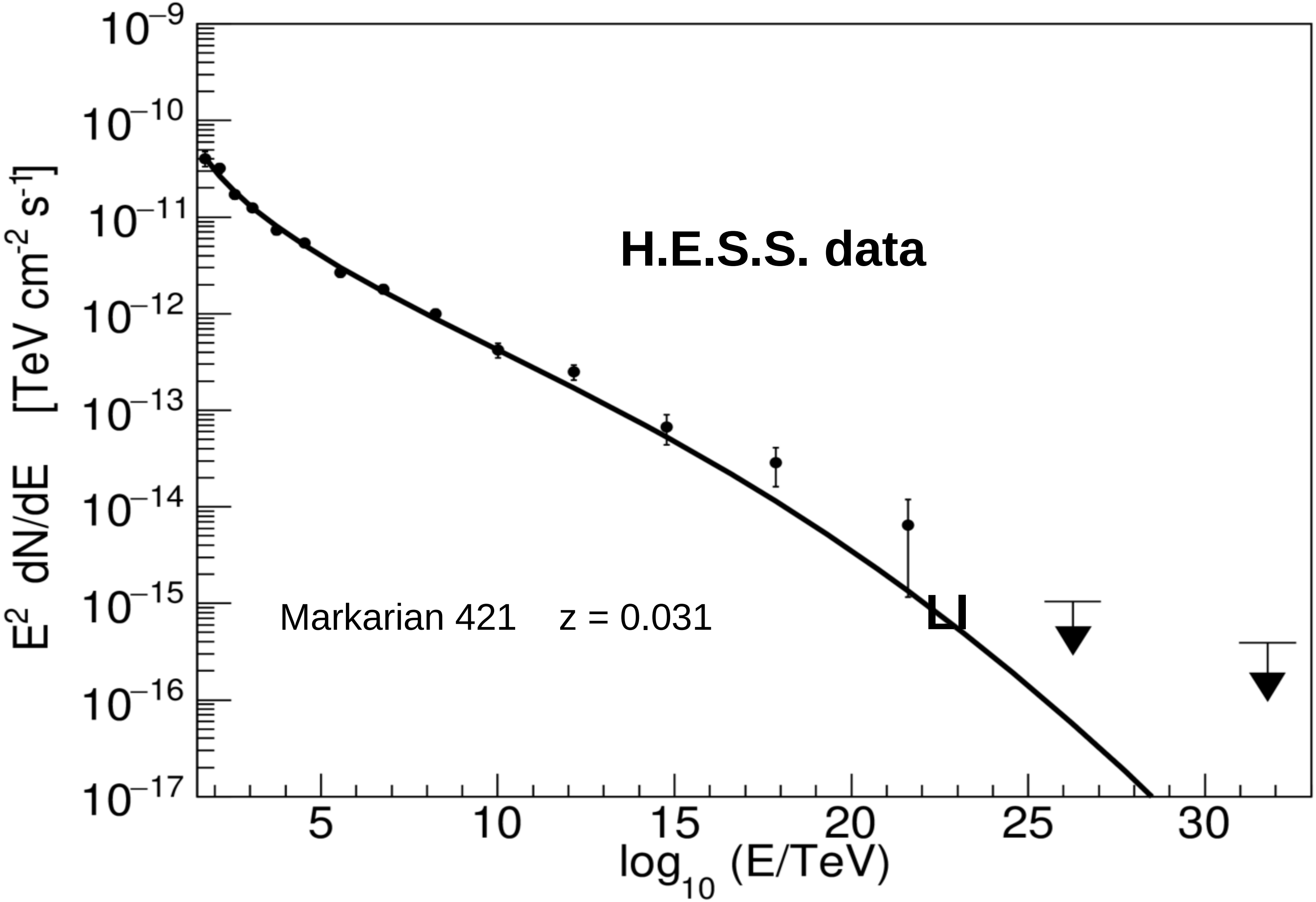
$$\otimes \int_{-1}^{1} \frac{d(cos\theta)}{2}$$

Target

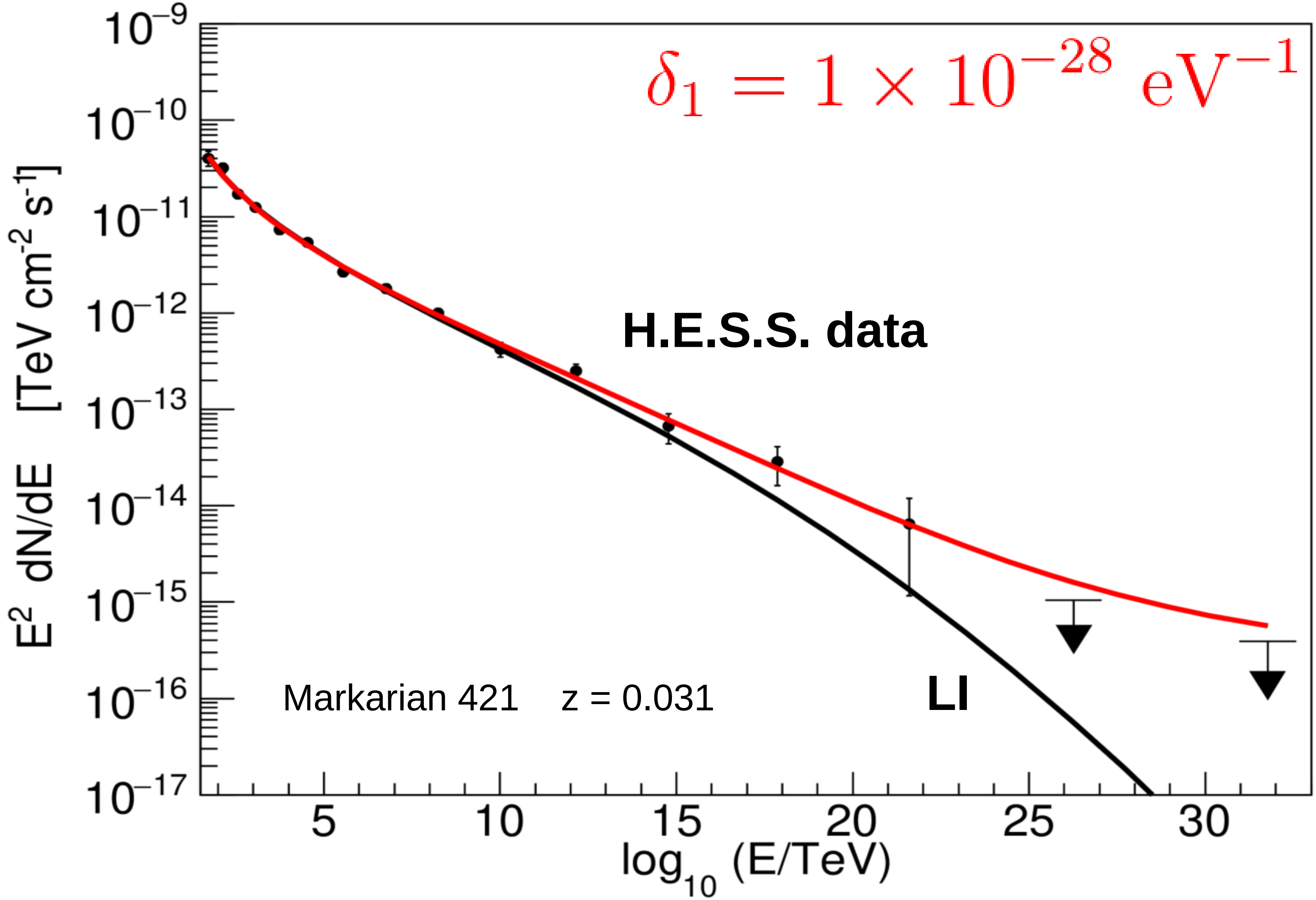
Interaction

$$\otimes \int_{\epsilon_{th}}^{\infty} d\epsilon\, \eta(\epsilon, z')\, \sigma(E, \epsilon, \theta, z')\, K(E, \epsilon, \theta, z')$$

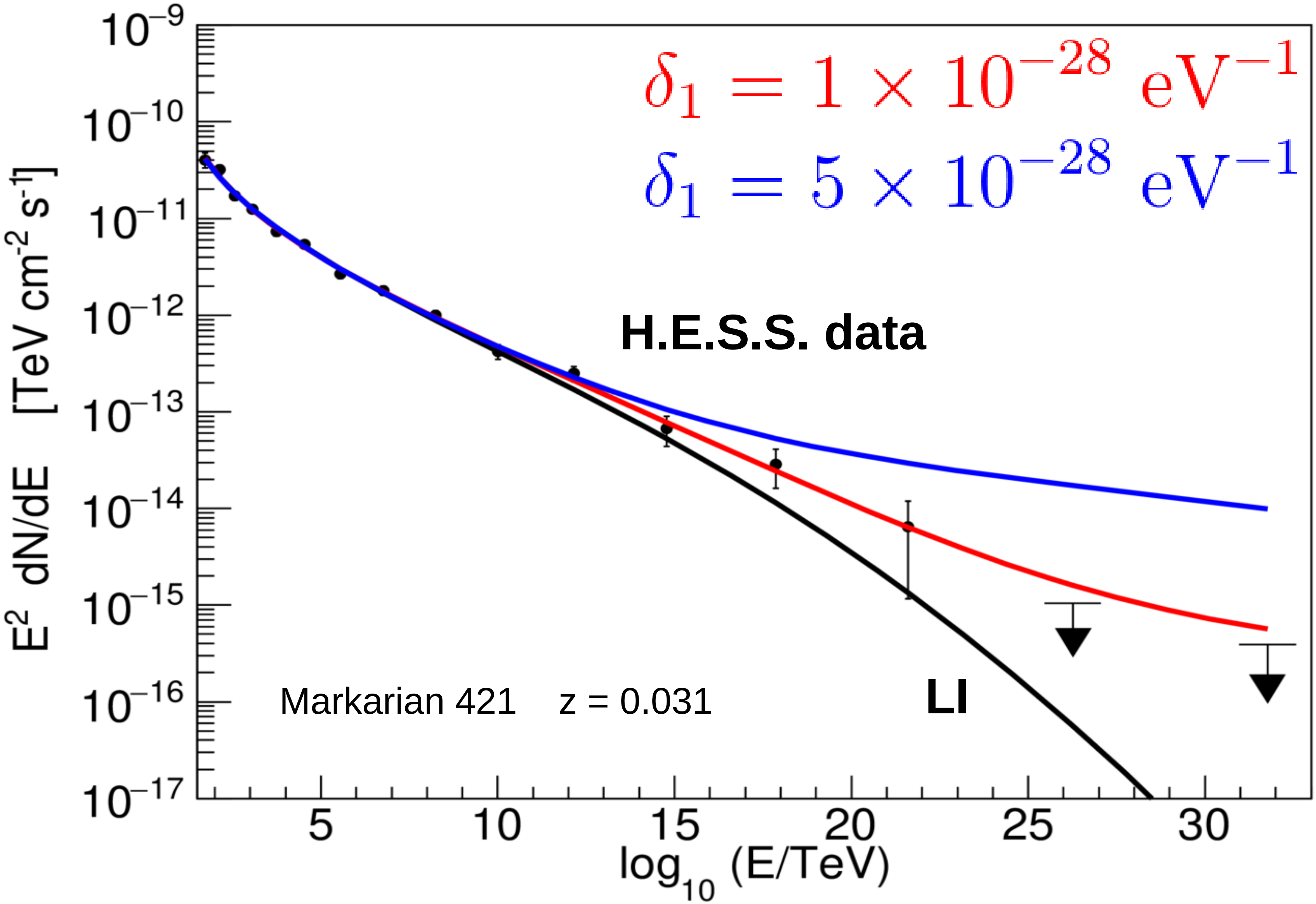
$$\epsilon_{th}^{LIV} = \frac{m_e c^2}{4E_\gamma K(1-K)} - \frac{\delta_1 E_\gamma^2}{4}$$



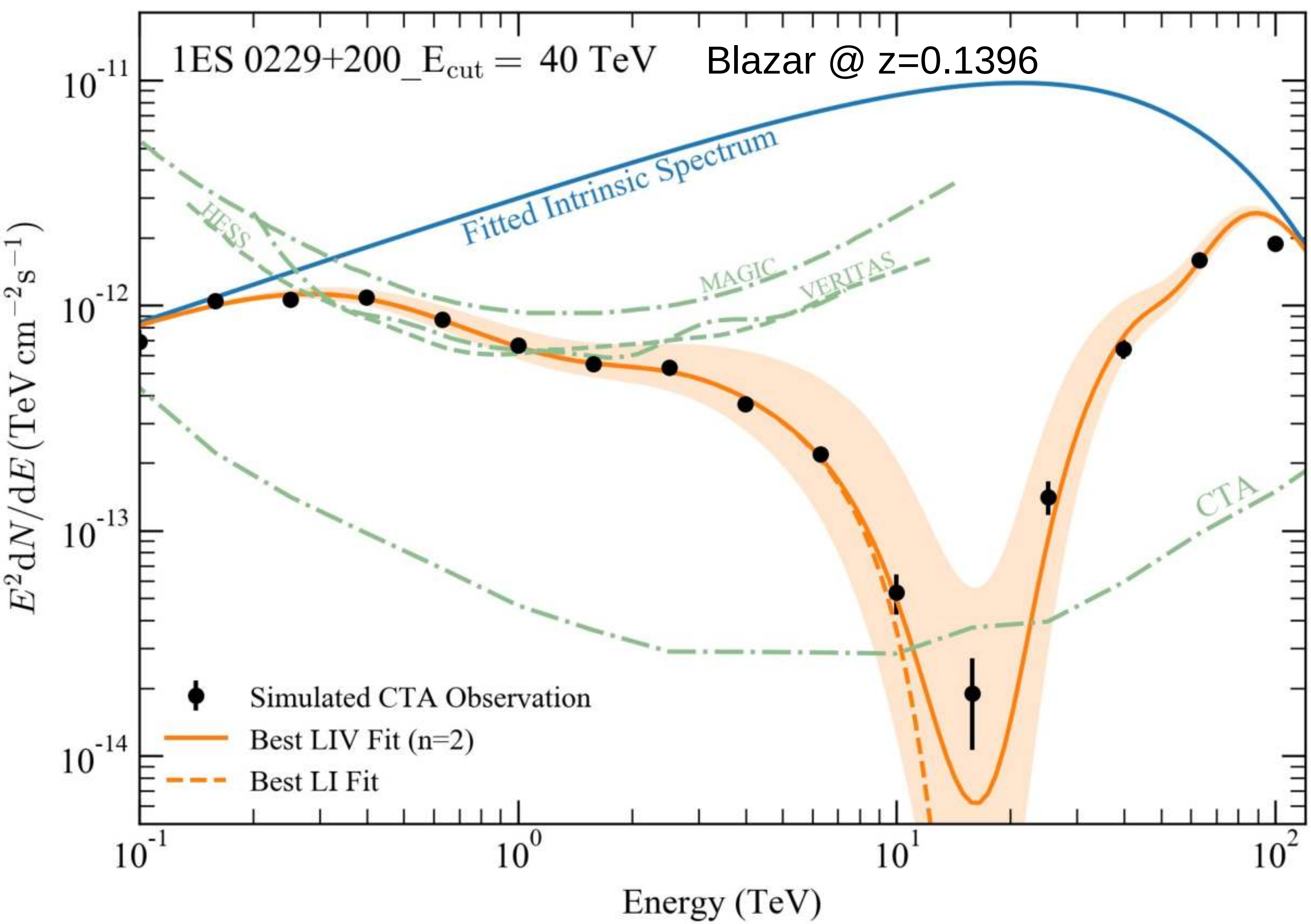
R. Lang et al. Phys. Rev. D 99, 043015 (2019)



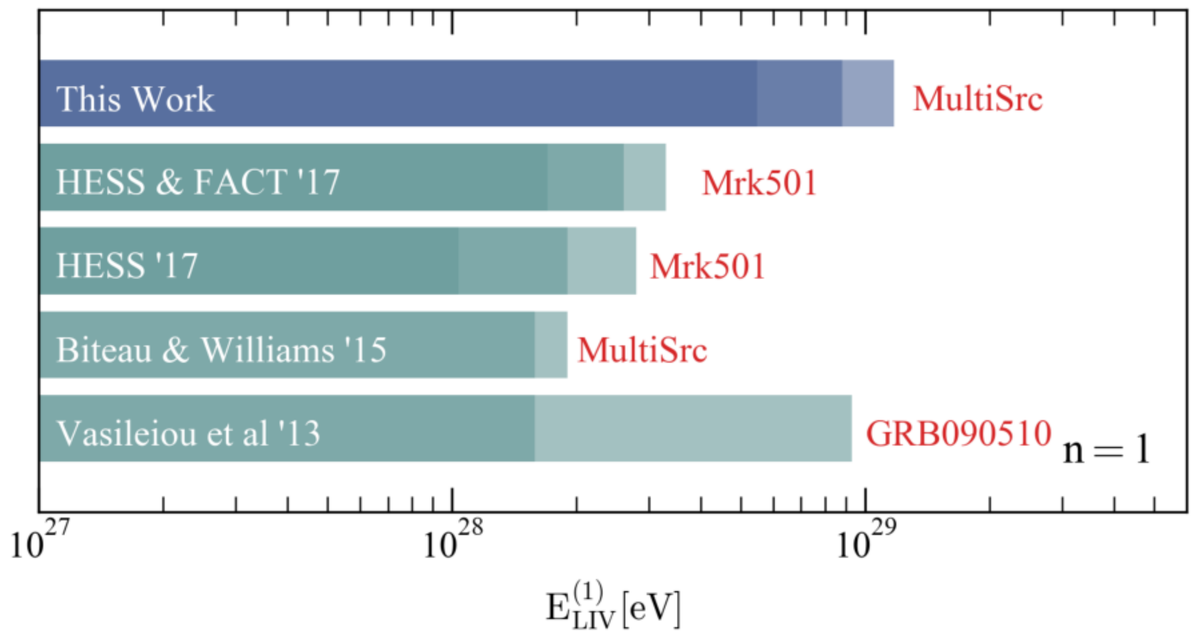
R. Lang et al. Phys. Rev. D 99, 043015 (2019)

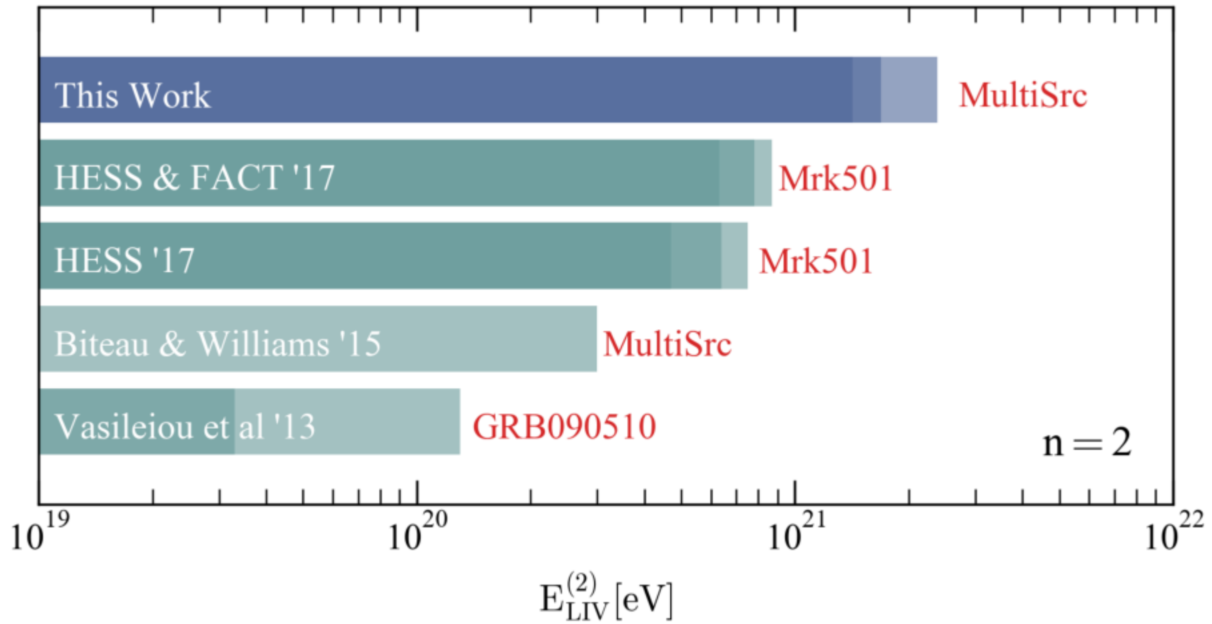


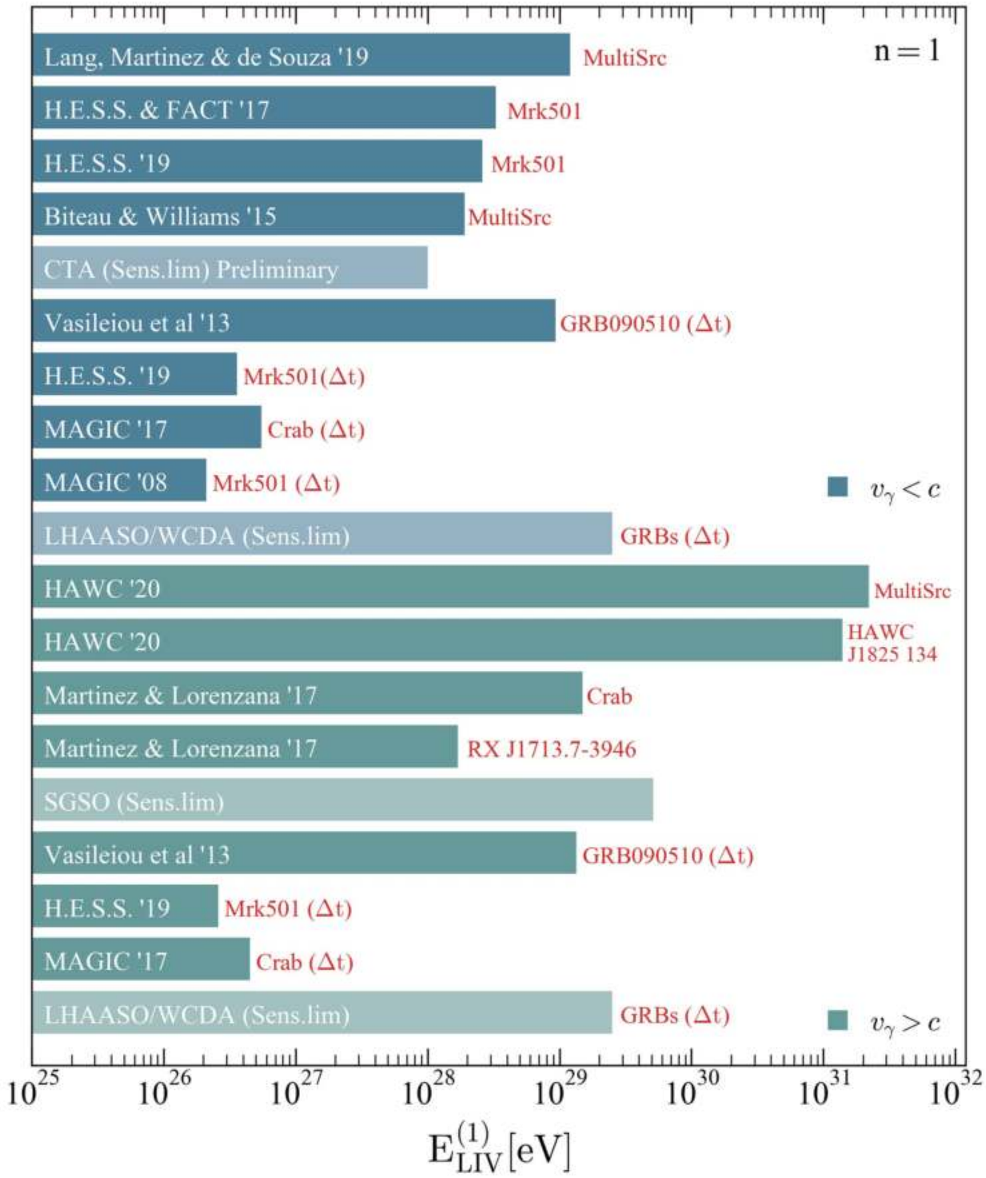
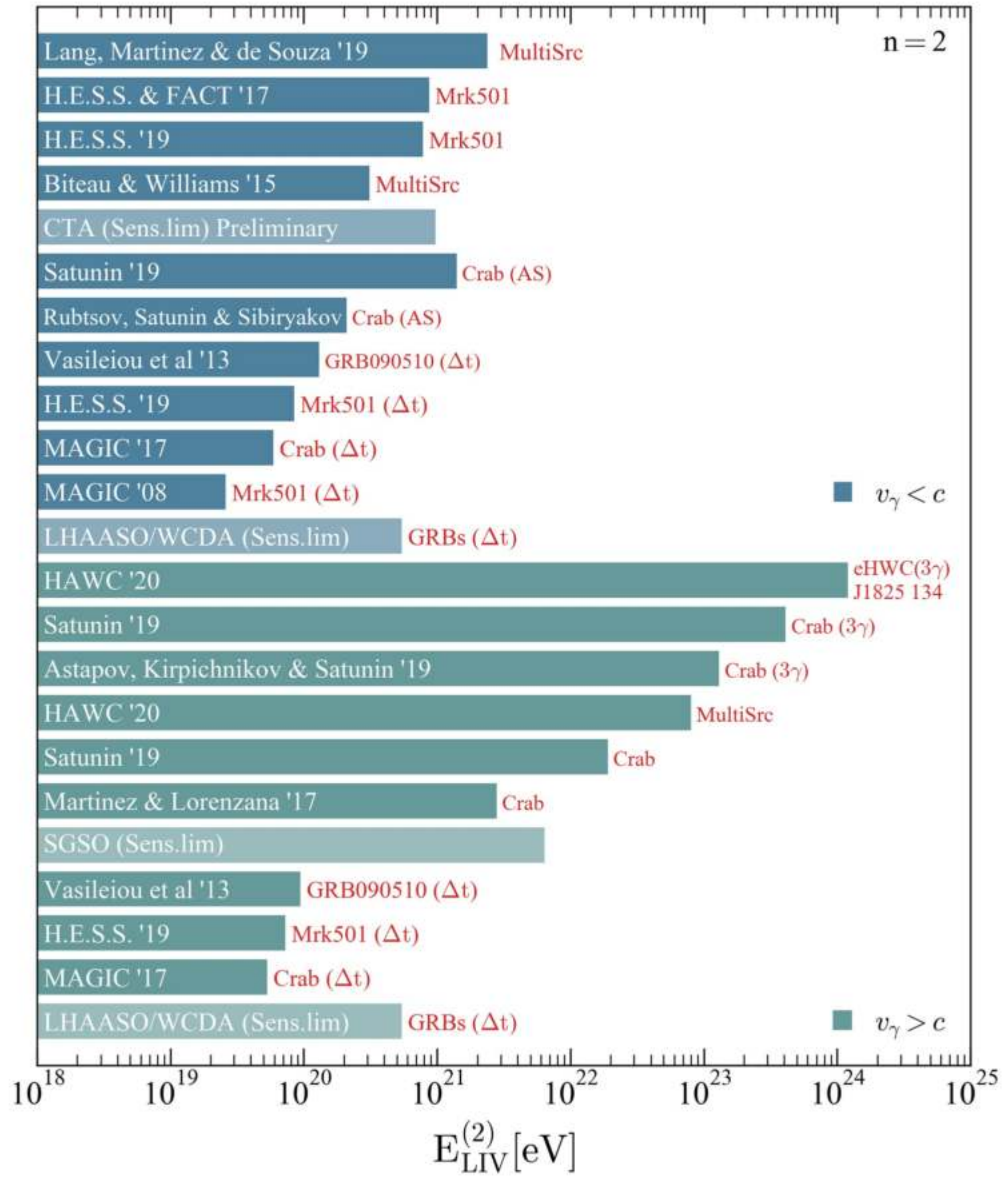
R. Lang et al. Phys. Rev. D 99, 043015 (2019)

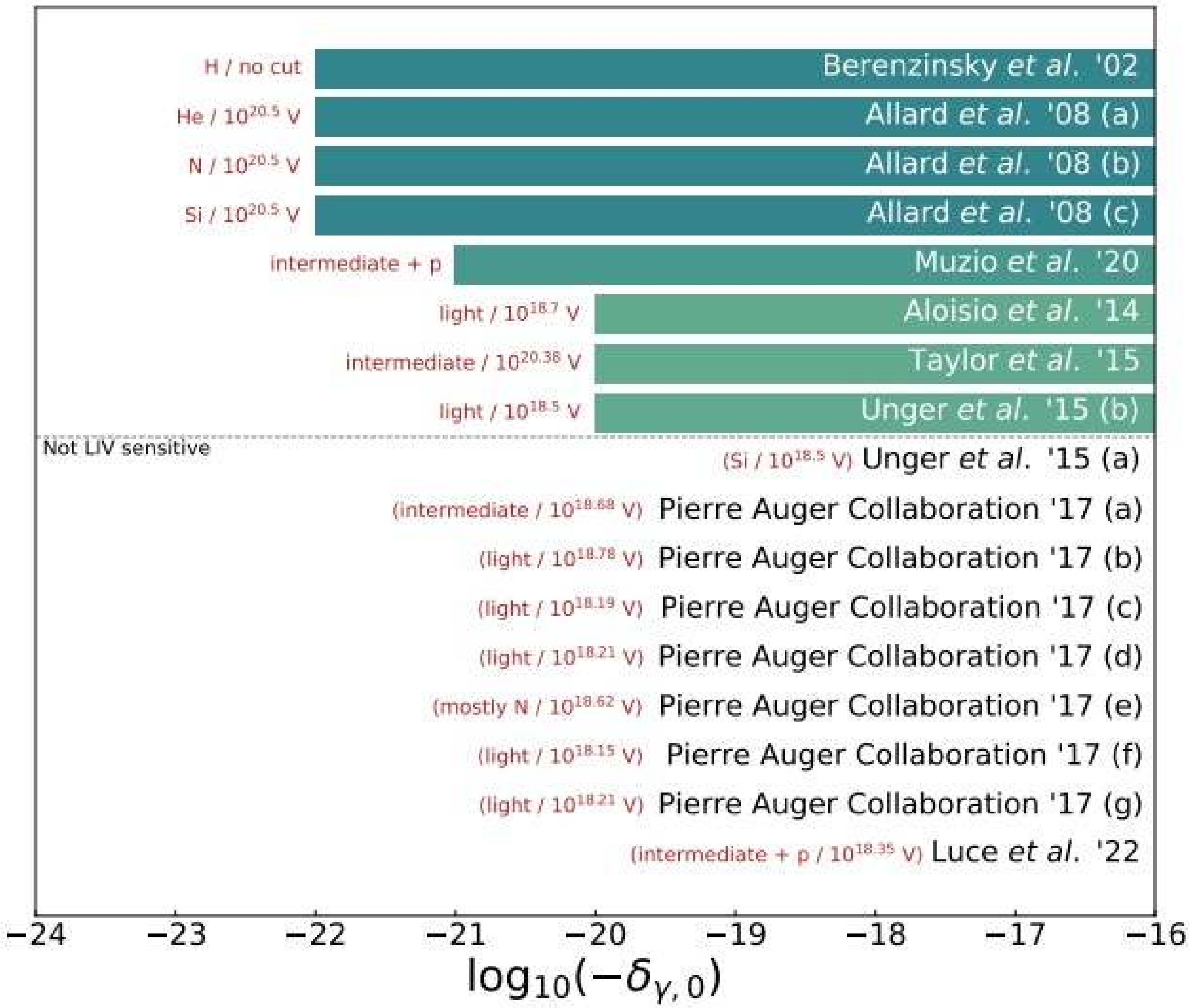


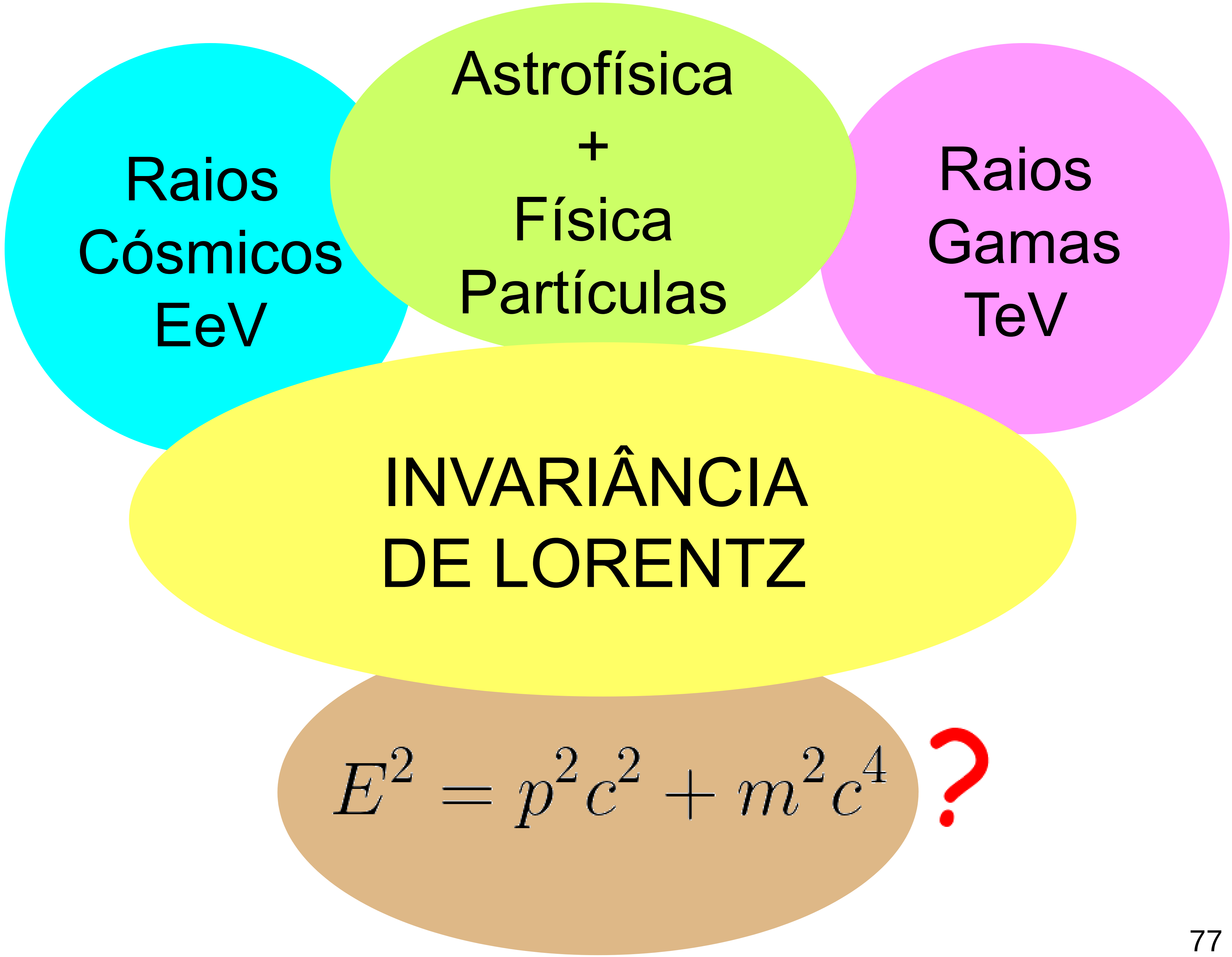
CTA Consortium JCAP 02 (2021) 048


This Work
MultiSrc
HESS & FACT '17
Mrk501
HESS '17
Mrk501
Biteau & Williams '15
MultiSrc
Vasileiou et al '13
GRB090510
n = 1
10^{27}
10^{28}
10^{29}
$E^{(1)}_{LIV}$ [eV]


This Work
MultiSrc
HESS & FACT '17
Mrk501
HESS '17
Mrk501
Biteau & Williams '15
MultiSrc
Vasileiou et al '13
GRB090510
n = 2
10^{19}
10^{20}
10^{21}
10^{22}
$E^{(2)}_{LIV}$ [eV]


n = 1
Lang, Martinez & de Souza '19
MultiSrc
H.E.S.S. & FACT '17
Mrk501
H.E.S.S. '19
Mrk501
Biteau & Williams '15
MultiSrc
CTA (Sens.lim) Preliminary
Vasileiou et al '13
GRB090510 (Δt)
H.E.S.S. '19
Mrk501(Δt)
MAGIC '17
Crab (Δt)
MAGIC '08
Mrk501 (Δt)
$v_\gamma < c$
LHAASO/WCDA (Sens.lim)
GRBs (Δt)
HAWC '20
MultiSrc
HAWC '20
HAWC
J1825 134
Martinez & Lorenzana '17
Crab
Martinez & Lorenzana '17
RX J1713.7-3946
SGSO (Sens.lim)
Vasileiou et al '13
GRB090510 (Δt)
H.E.S.S. '19
Mrk501 (Δt)
MAGIC '17
Crab (Δt)
LHAASO/WCDA (Sens.lim)
GRBs (Δt)
$v_\gamma > c$
10^{25} 10^{26} 10^{27} 10^{28} 10^{29} 10^{30} 10^{31} 10^{32}
$E^{(1)}_{LIV}$[eV]

n = 2
Lang, Martinez & de Souza '19
MultiSrc
H.E.S.S. & FACT '17
Mrk501
H.E.S.S. '19
Mrk501
Biteau & Williams '15
MultiSrc
CTA (Sens.lim) Preliminary
Satunin '19
Crab (AS)
Rubtsov, Satunin & Sibiryakov
Crab (AS)
Vasileiou et al '13
GRB090510 (Δt)
H.E.S.S. '19
Mrk501 (Δt)
MAGIC '17
Crab (Δt)
MAGIC '08
Mrk501 (Δt)
$v_\gamma < c$
LHAASO/WCDA (Sens.lim)
GRBs (Δt)
HAWC '20
eHWC(3γ)
J1825 134
Satunin '19
Crab (3γ)
Astapov, Kirpichnikov & Satunin '19
Crab (3γ)
HAWC '20
MultiSrc
Satunin '19
Crab
Martinez & Lorenzana '17
Crab
SGSO (Sens.lim)
Vasileiou et al '13
GRB090510 (Δt)
H.E.S.S. '19
Mrk501 (Δt)
MAGIC '17
Crab (Δt)
LHAASO/WCDA (Sens.lim)
GRBs (Δt)
$v_\gamma > c$
10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25}
$E^{(2)}_{LIV}$[eV]


H / no cut
Berenzinsky et al. '02
He / 10^20.5 V
Allard et al. '08 (a)
N / 10^20.5 V
Allard et al. '08 (b)
Si / 10^20.5 V
Allard et al. '08 (c)
intermediate + p
Muzio et al. '20
light / 10^18.7 V
Aloisio et al. '14
intermediate / 10^20.38 V
Taylor et al. '15
light / 10^18.5 V
Unger et al. '15 (b)
Not LIV sensitive
(Si / 10^18.5 V) Unger et al. '15 (a)
(intermediate / 10^18.68 V) Pierre Auger Collaboration '17 (a)
(light / 10^18.78 V) Pierre Auger Collaboration '17 (b)
(light / 10^18.19 V) Pierre Auger Collaboration '17 (c)
(light / 10^18.21 V) Pierre Auger Collaboration '17 (d)
(mostly N / 10^18.62 V) Pierre Auger Collaboration '17 (e)
(light / 10^18.15 V) Pierre Auger Collaboration '17 (f)
(light / 10^18.21 V) Pierre Auger Collaboration '17 (g)
(intermediate + p / 10^18.35 V) Luce et al. '22
−24 −23 −22 −21 −20 −19 −18 −17 −16
log10(−δγ,0)

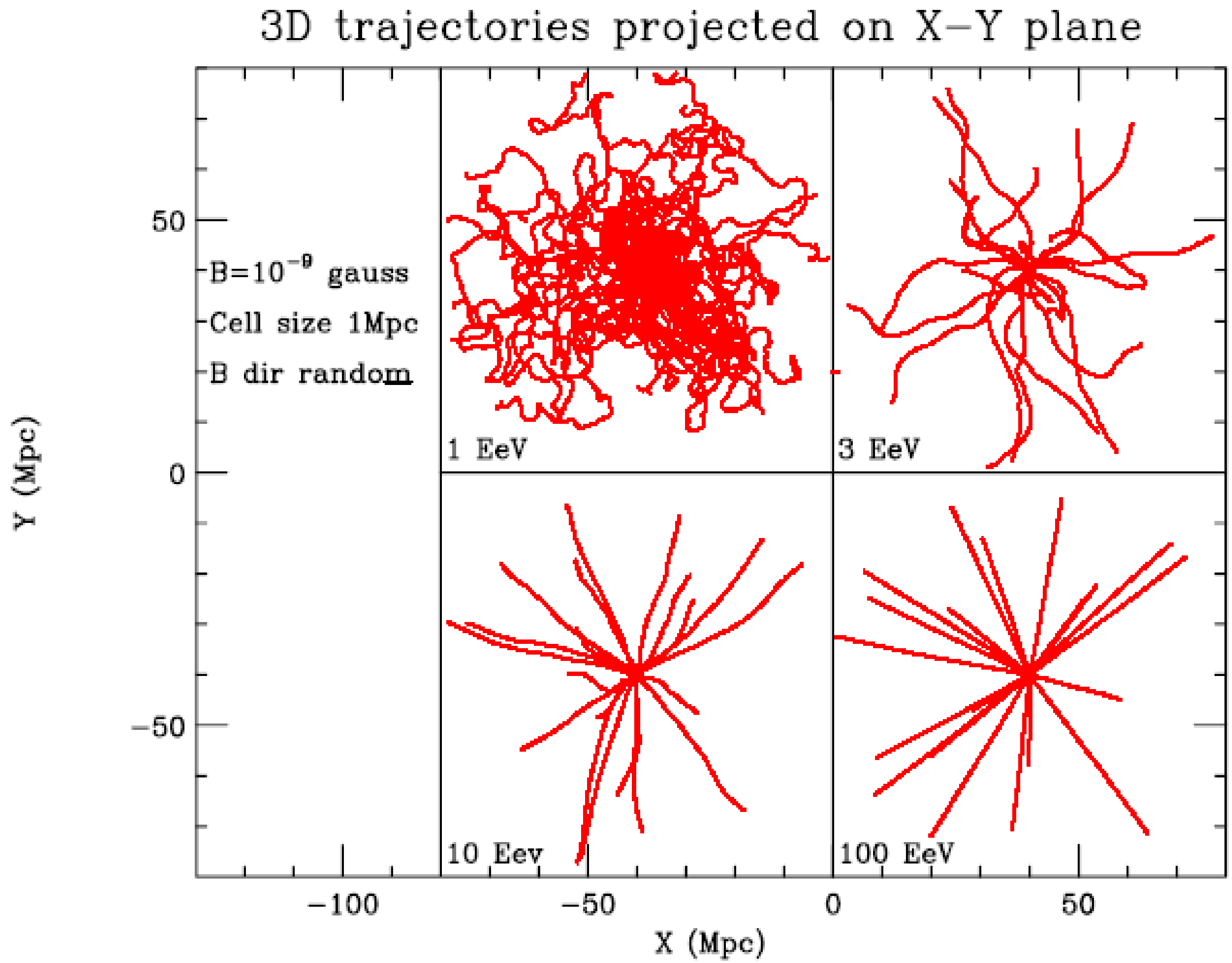

Astrofísica
+
Física
Partículas
Raios
Cósmicos
EeV
Raios
Gamas
TeV
INVARIÂNCIA
DE LORENTZ
$E^2 = p^2c^2 + m^2c^4$
?

Take away message

- CTA is launching
- Auger producing interesting results
- Even prior to launch, CTA is making many important contributions
- CTA is a great opportunities for young people
- CTA will open a new window of discoveries

EXTRAS

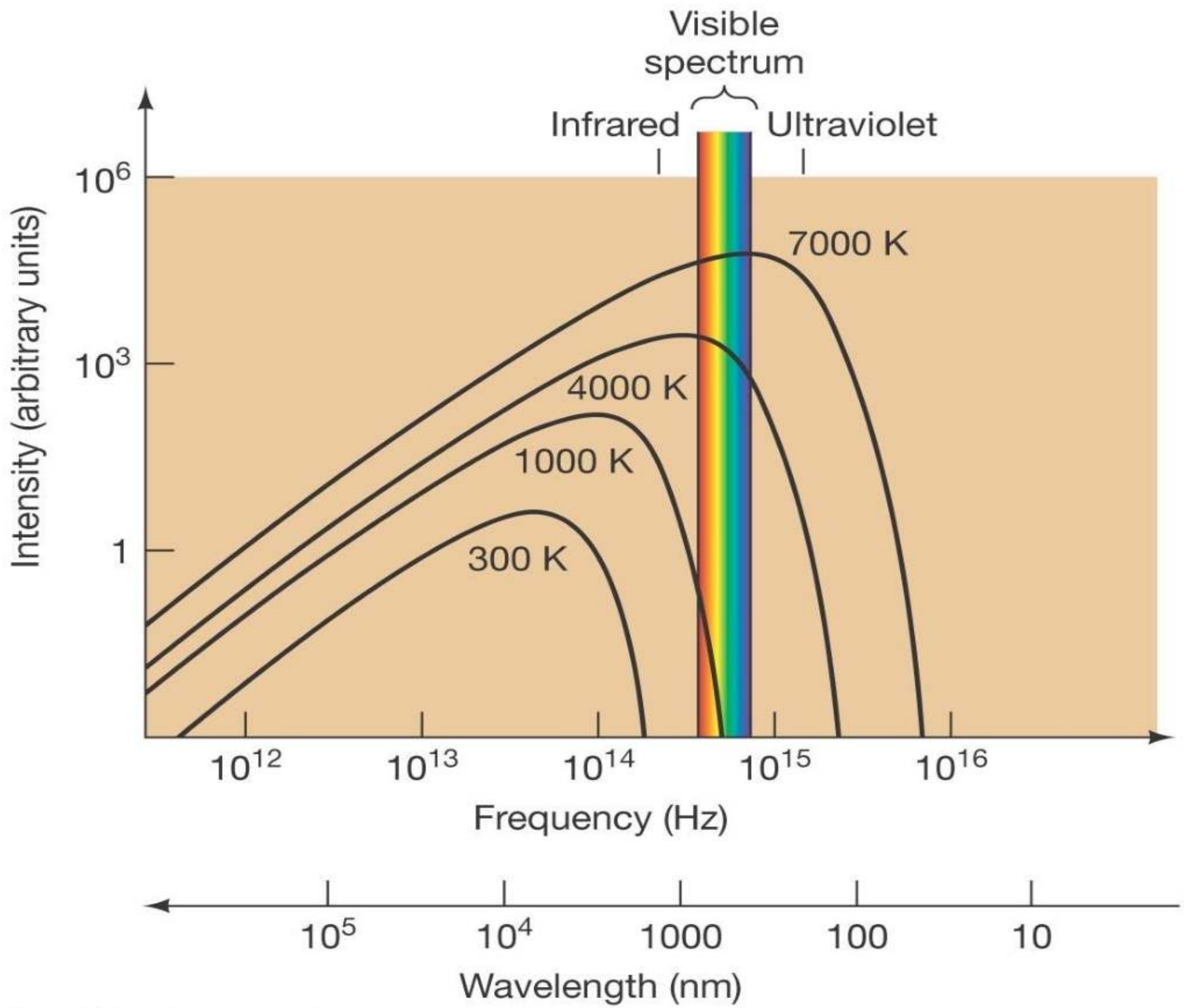
UHECR Propagação



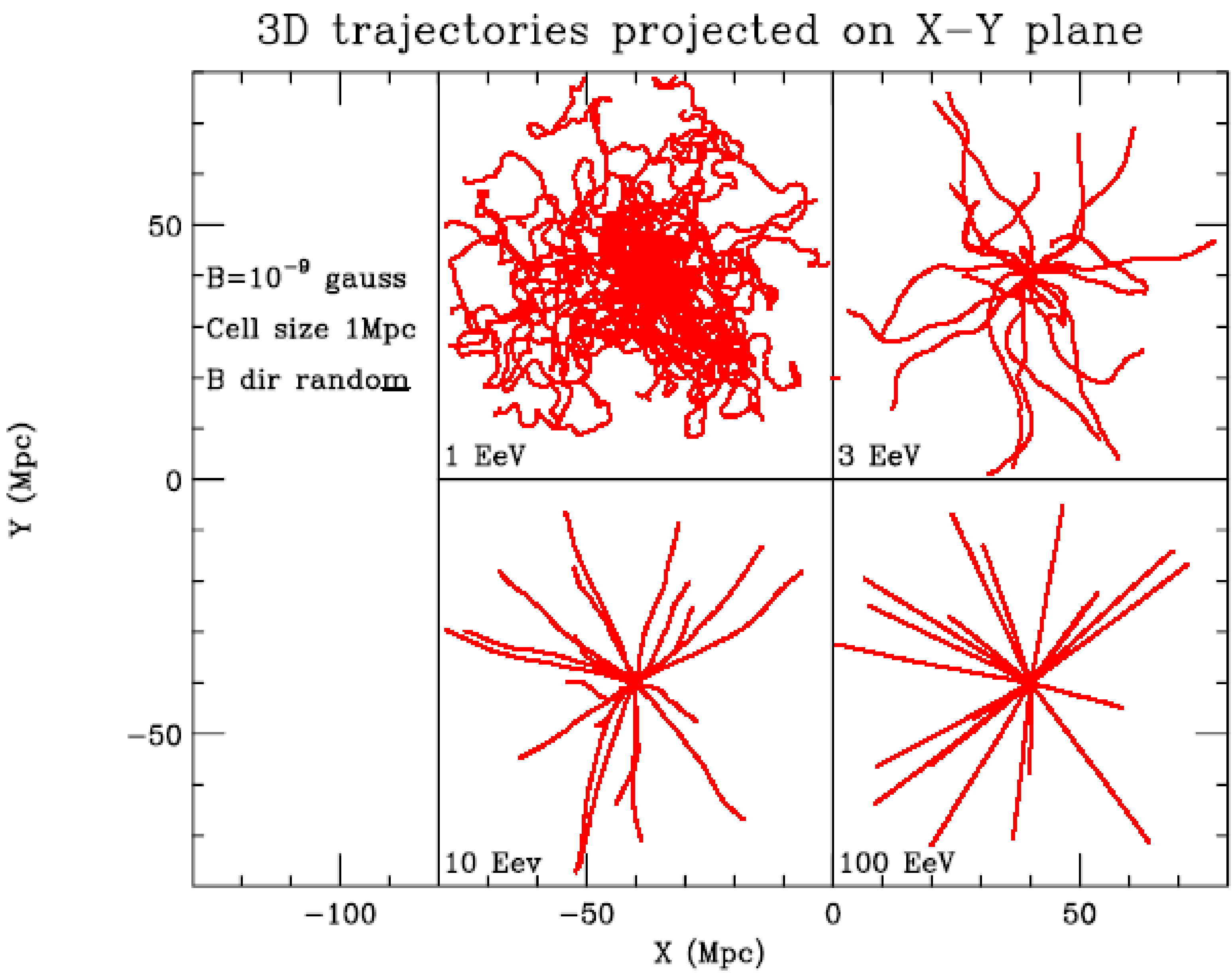
1 pc = 3 x 10^{16} m

J. Cronin

Emissão térmica
Radiação de corpo negro

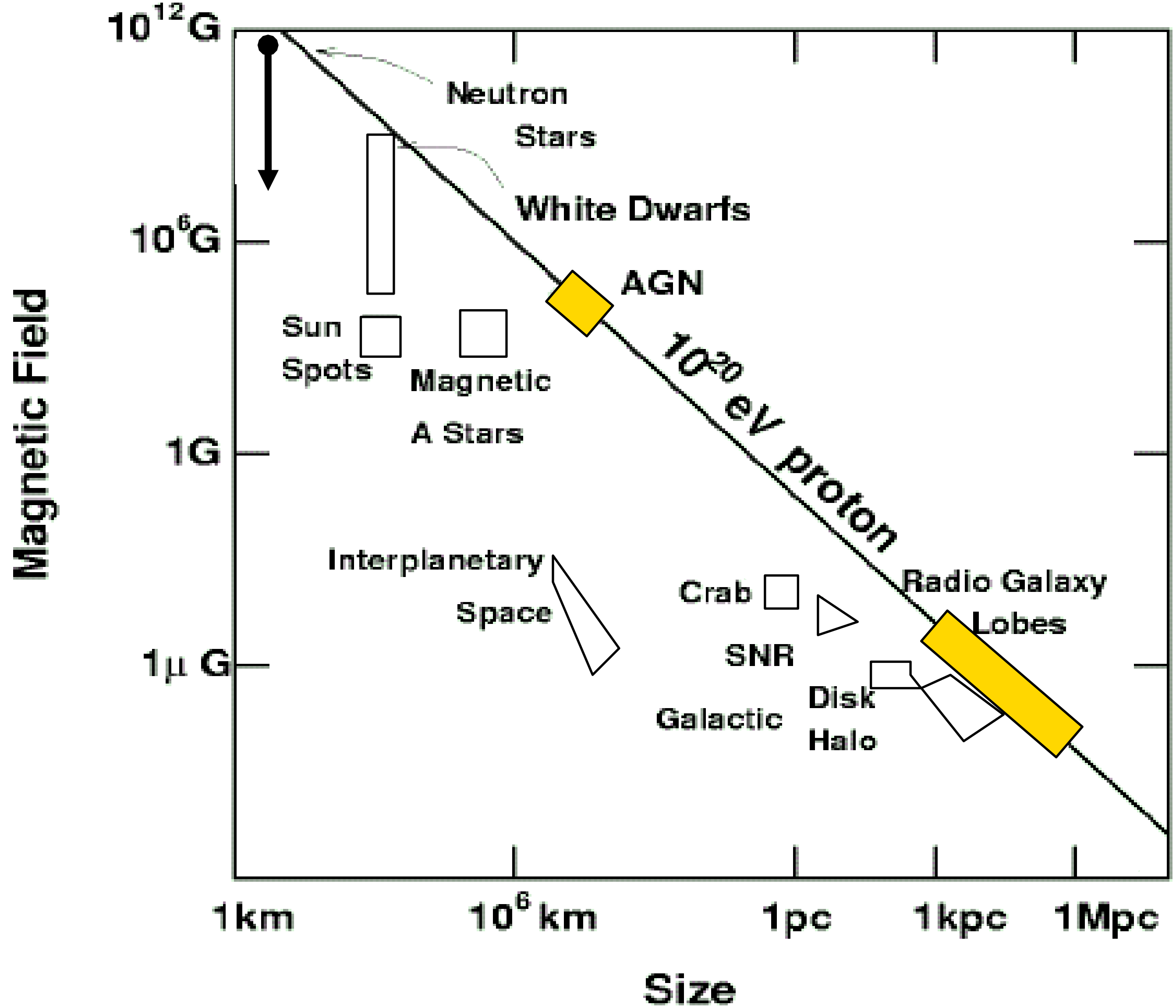


Propagação



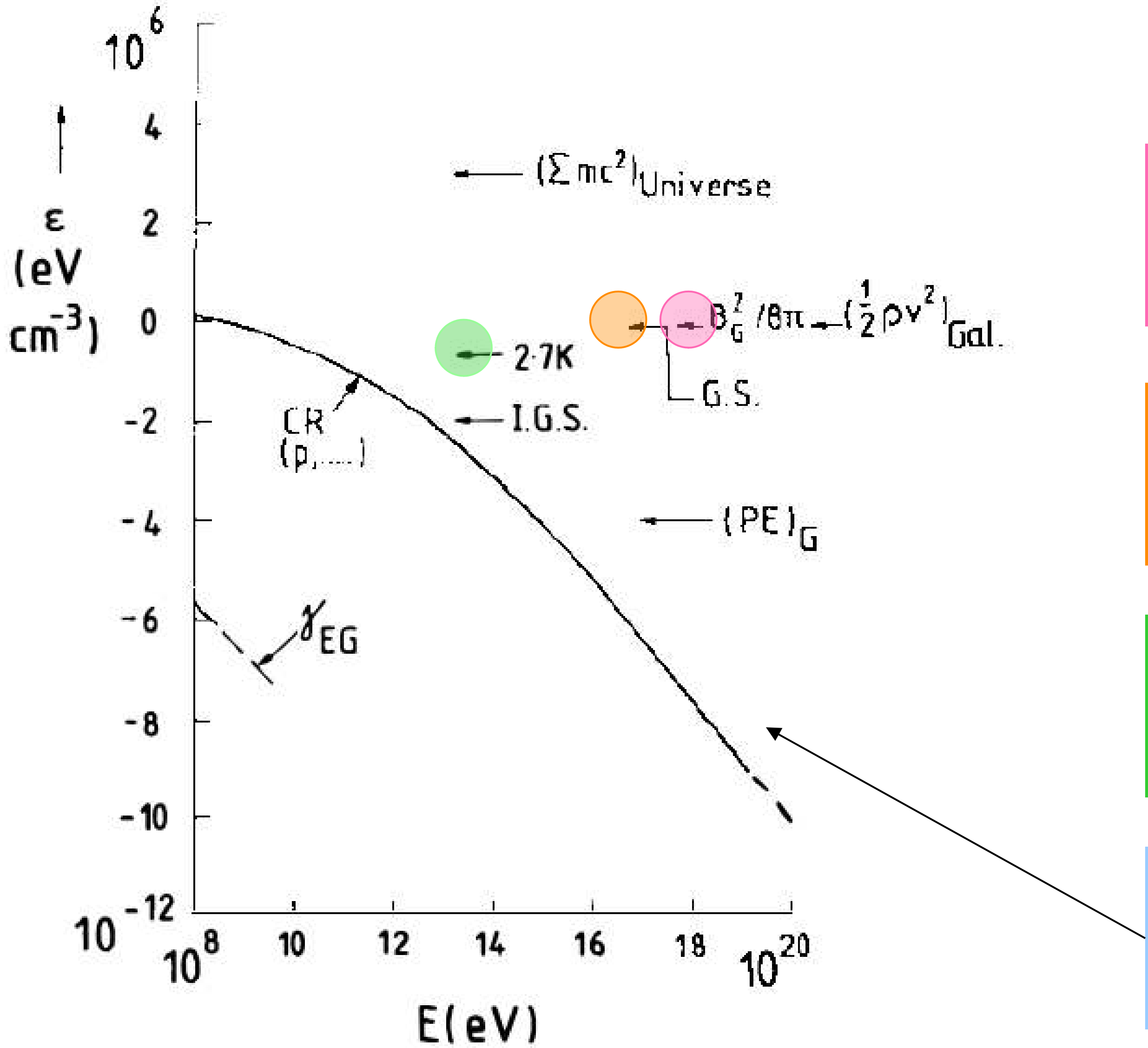
[redacted]

$$E_{eV} < 10^{15} Z \times B_{\mu G} \times R_{pc}$$



M. Hillas

Wdowczyk and Wolfendale
Annu. Rev. Nucl. Part. Sci. 1989. 39: 43-71



Densidade de Energia

Campo Magnético Gal

0.2 MeV m^{-3}

Luz - Estrelas

0.3 MeV m^{-3}

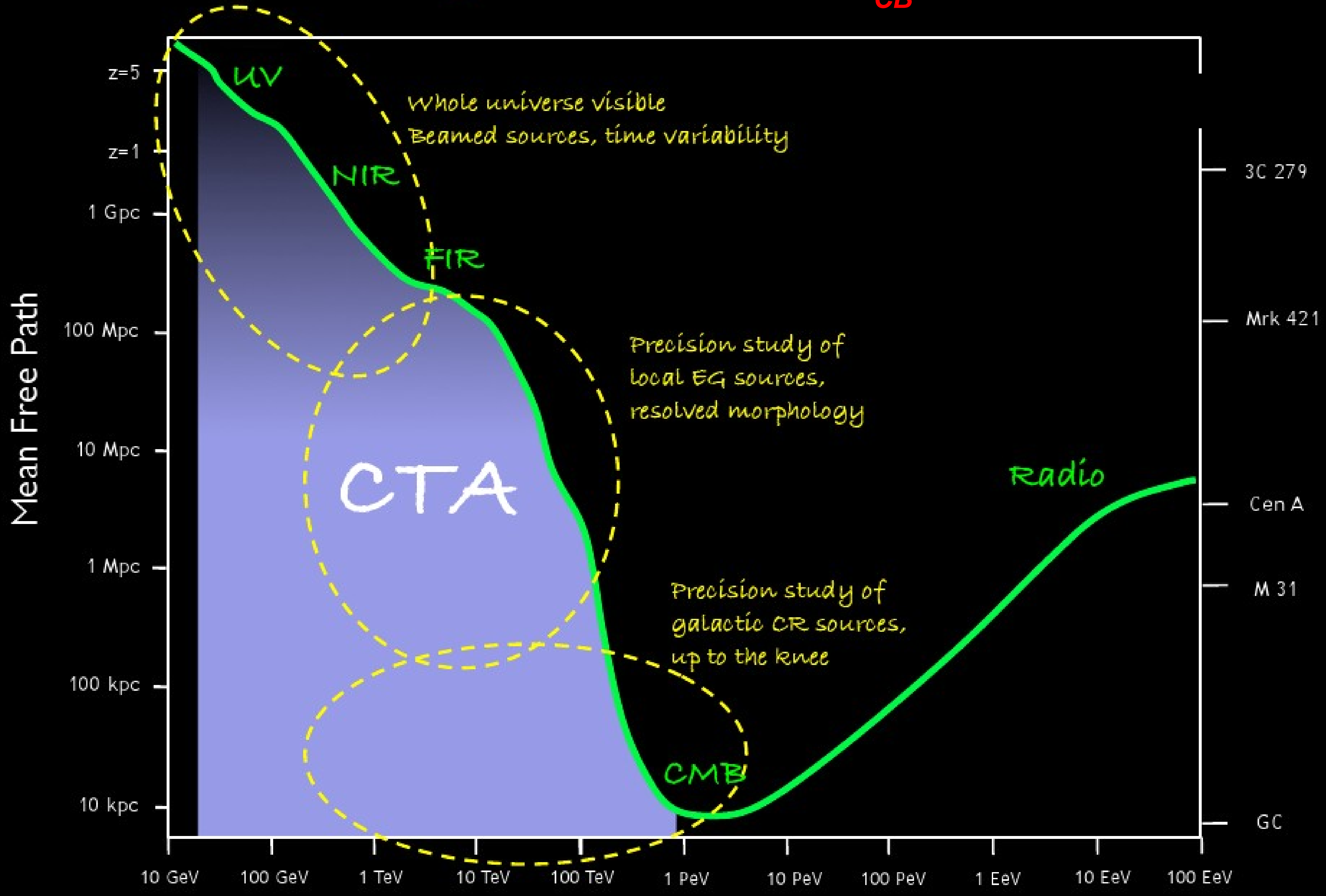
Fundo Micro-ondas

0.3 MeV m^{-3}

Raios Cósmicos

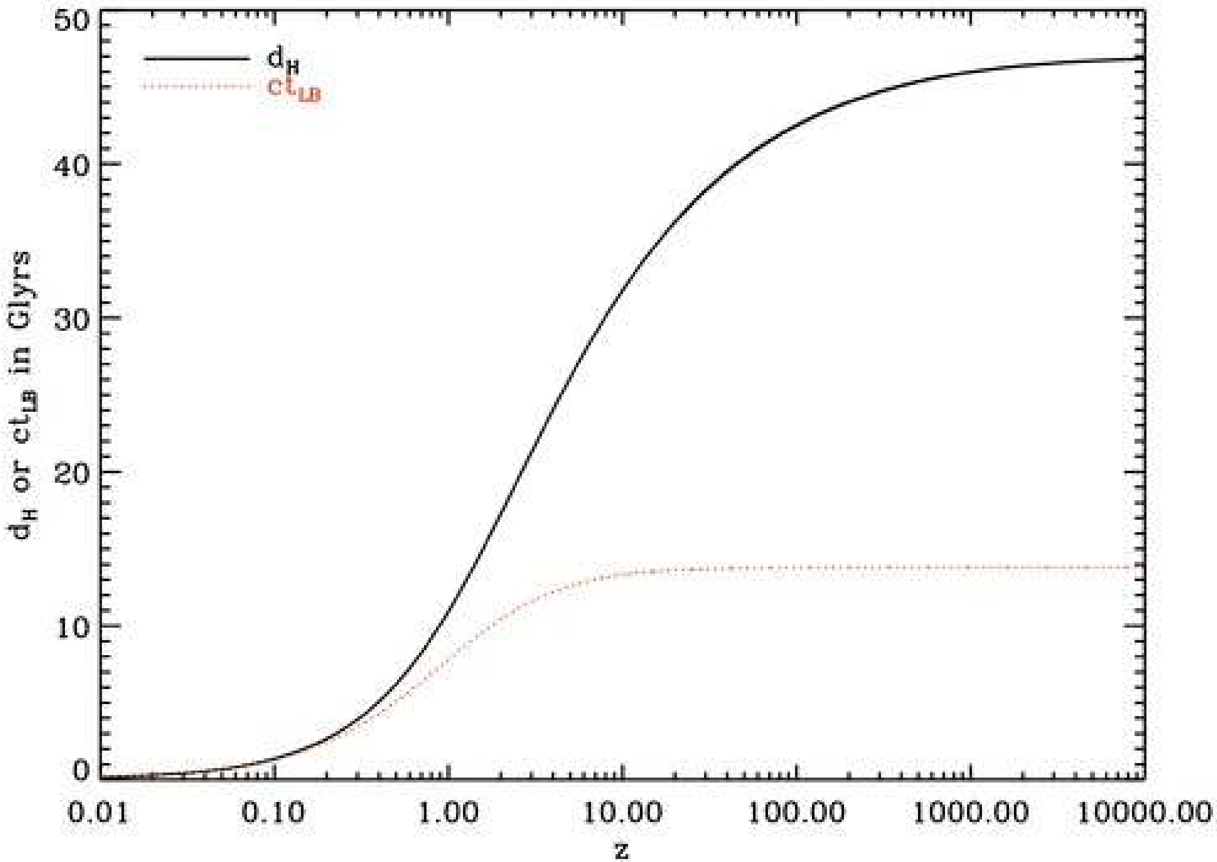
1 MeV m^{-3}

The Gamma Ray Horizon $\gamma + \gamma_{CB} \rightarrow e^+e^-$



1 pc = 3.26 anos-luz = 3,08 x 10^16 m

z = 1 = 10^10 anos-luz



Cinemática das interações

$$a + b \rightarrow c + d$$

$$p^{\mu} = \left(\frac{E}{c}, p_x, p_y, p_z \right)$$

$$p_a^{\mu} + p_b^{\mu} = p_c^{\mu} + p_d^{\mu}$$

Aproximações

$$E >> mc^2 \rightarrow E \sim pc$$

$$E_a >> E_b$$

Solução

$$s = E^2 - p^2c^2 = m^2c^4$$

$$s_i = s_f$$

$$\begin{cases} s_i = (E_a + E_b)^2 - (\vec{p}_a + \vec{p}_b)^2 c^2 \\ s_f = (E_c + E_d)^2 - (\vec{p}_c + \vec{p}_d)^2 c^2 \end{cases}$$

Inelasticidade

$$K = \frac{E_c}{E_a} \quad \Rightarrow \quad \begin{cases} E_c = K E_a \\ E_d = (1 - K) E_a \end{cases}$$

Solução

$$\begin{cases} s_i = (m_a^2 + m_b^2)c^4 + 2E_a E_b \left(1 - \cos\theta_i + \cos\theta_i \left(\frac{m_a^2 c^4}{2E_a^2} + \frac{m_b^2 c^4}{2E_b^2}\right)\right) \\ s_f = (m_c^2 + m_d^2)c^4 + K(1-K)\left(\frac{m_c^2 c^4}{K^2} + \frac{m_d^2 c^4}{(1-K)^2}\right) \end{cases}$$

Produção de pares: $\gamma + \gamma_{CB} \rightarrow e^{+} + e^{-}$

$$\begin{cases} m_a = m_b = 0 \\ m_c = m_d = m_e \end{cases}$$

Qual a energia mínima(ϵ_{th}) de γ_{CB} para que a interação aconteça ?

$$\begin{cases} s_i = 2E_\gamma \epsilon_{th}(1 - cos\theta_i) = 4E_\gamma \epsilon_{th} \\ s_f = 2m_e c^2 + K(1-K)(\frac{m_e c^2}{K^2} + \frac{m_e c^2}{(1-K)^2}) \end{cases}$$

$$\epsilon_{th} = \frac{m_e c^2}{4E_\gamma K(1-K)}$$

Qual a energia mínima (ϵ_{th}) de γ_{CB} para que a interação aconteça supondo **LIV** ?

$$E^2 = p^2c^2 + m^2c^4 + \delta_1 p^3 c^3$$

$$s_{LIV} = E^2 - p^2c^2 = m^2c^4 + \delta_1 p^3 c^3$$

$$\epsilon_{th}^{LIV} = \frac{m_e c^2}{4E_\gamma K(1-K)} - \frac{\delta_1 E_\gamma^2}{4}$$