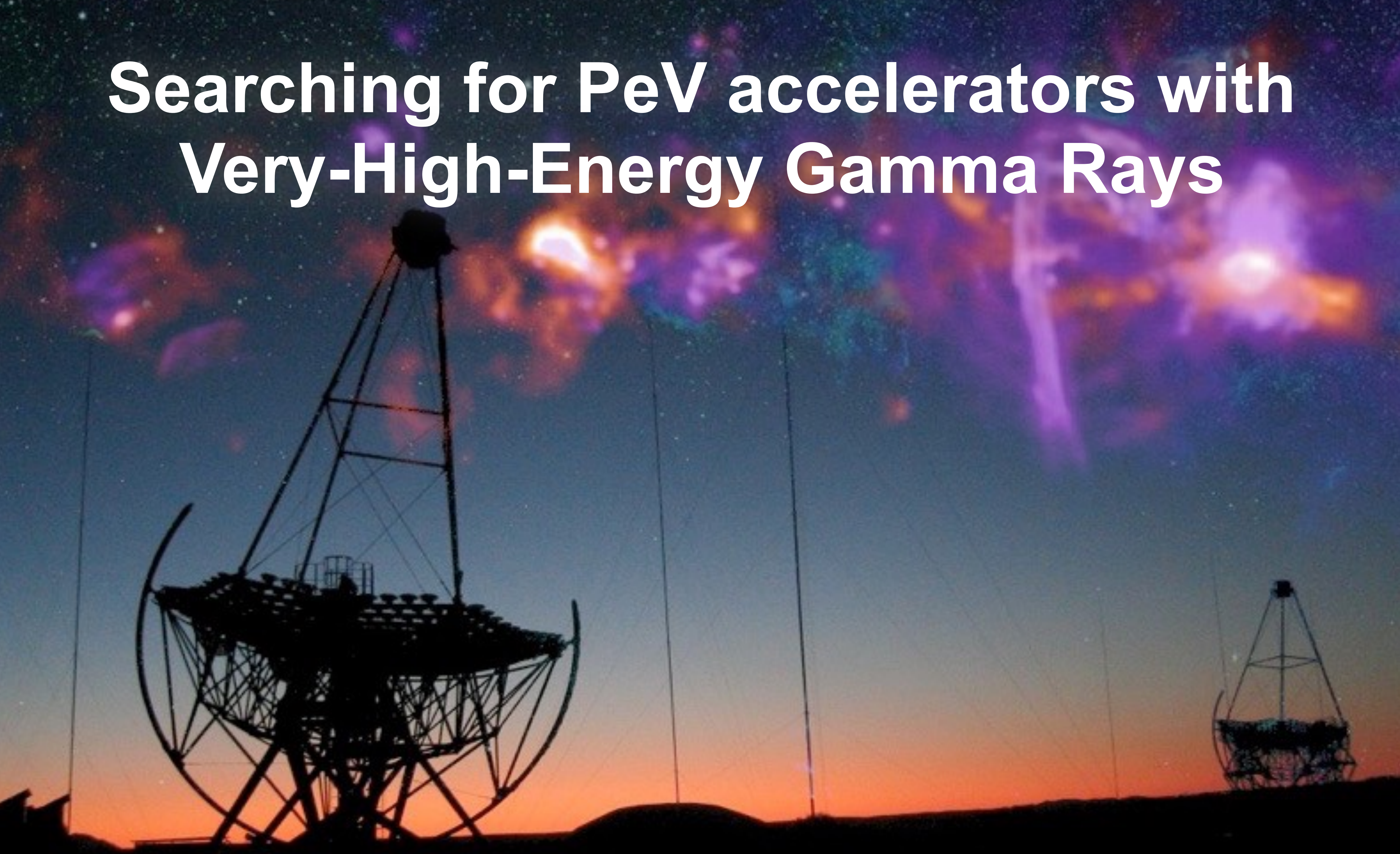
Searching for PeV accelerators with Very-High-Energy Gamma Rays



Karl KOSACK

CEA / IRFU / **DAp / LEPCHE**

CTA Observatory

OVERVIEW

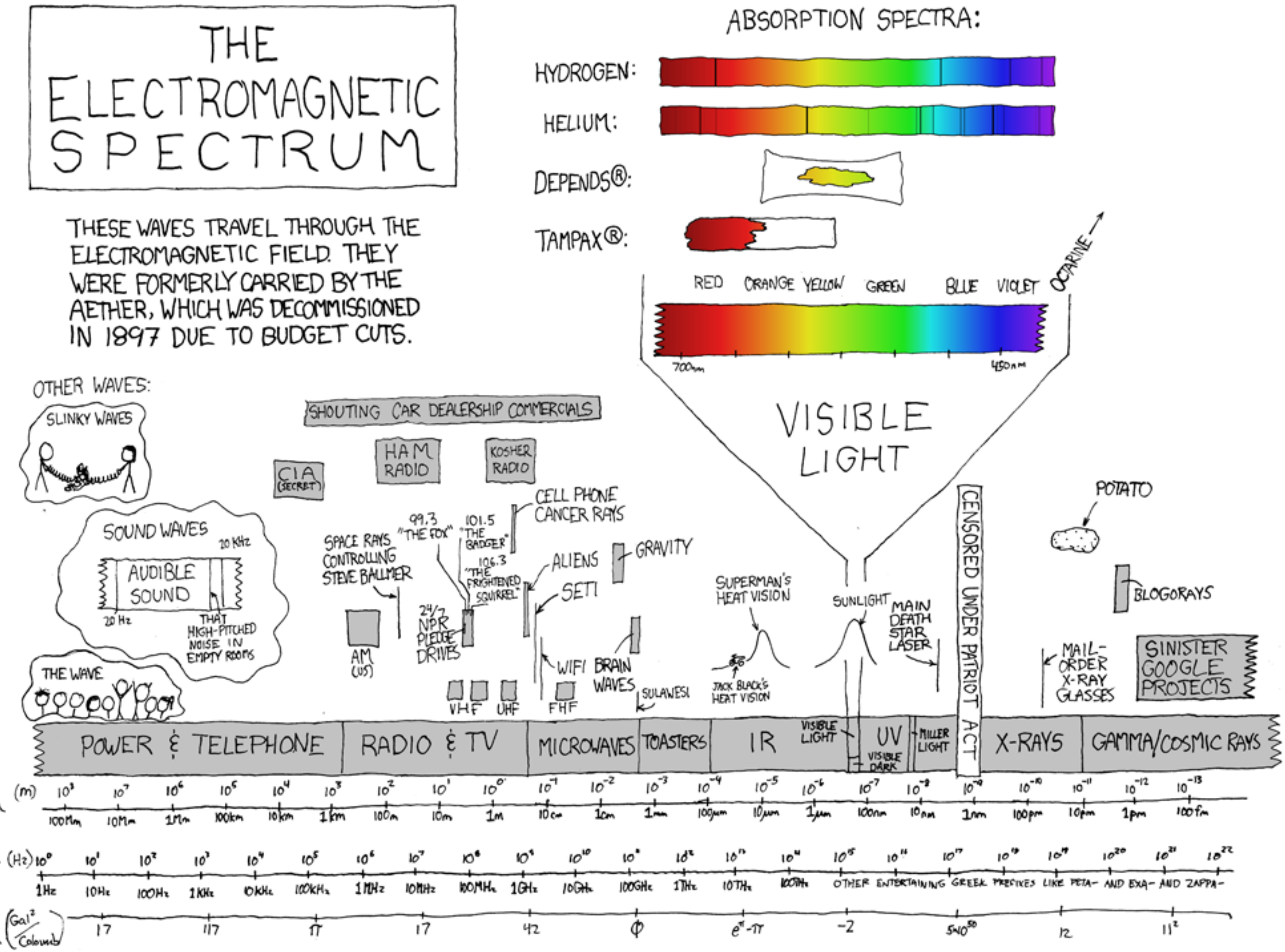
Introduction to
High Energy Astrophysics

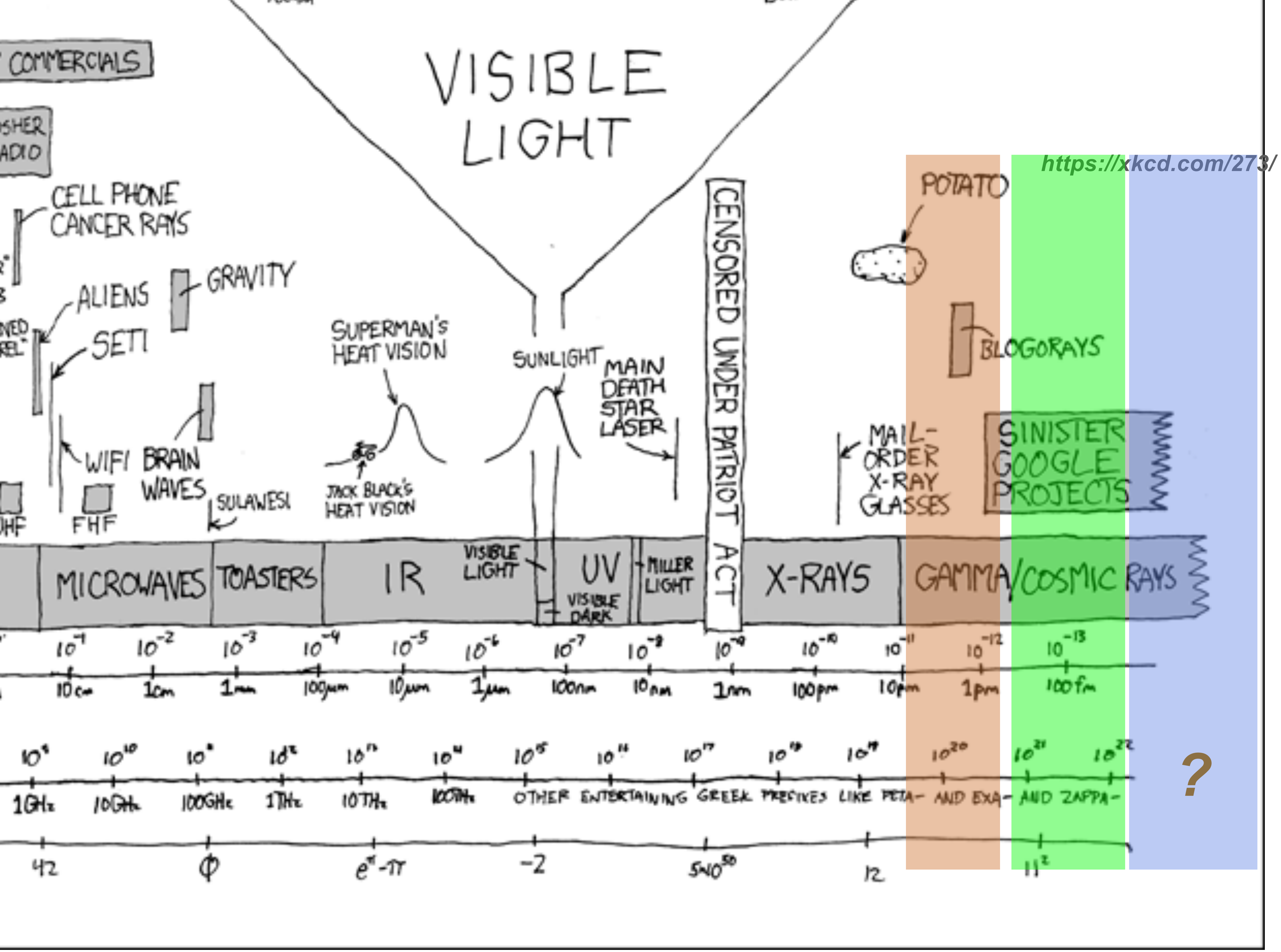
Detecting Gamma Rays

The Hunt for PeVatrons

Future Prospects

https://xkcd.com/273/





COMMERCIALS
VISIBLE LIGHT
CELL PHONE CANCER RAYS
ALIENS
GRAVITY
SETI
SUPERMAN'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
WIFI
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SULAWESI
JACK BLACK'S HEAT VISION
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
FHF
MICROWAVES
TOASTERS
IR
VISIBLE LIGHT
UV
VISIBLE DARK
MILLER LIGHT
X-RAYS
GAMMA/COSMIC RAYS
10cm 1cm 1mm 100µm 10µm 1µm 100nm 10nm 1nm 100pm 10pm 1pm 100fm
1GHz 10GHz 100GHz 1THz 10THz 100THz OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-
42 Φ -2 12
https://xkcd.com/273/
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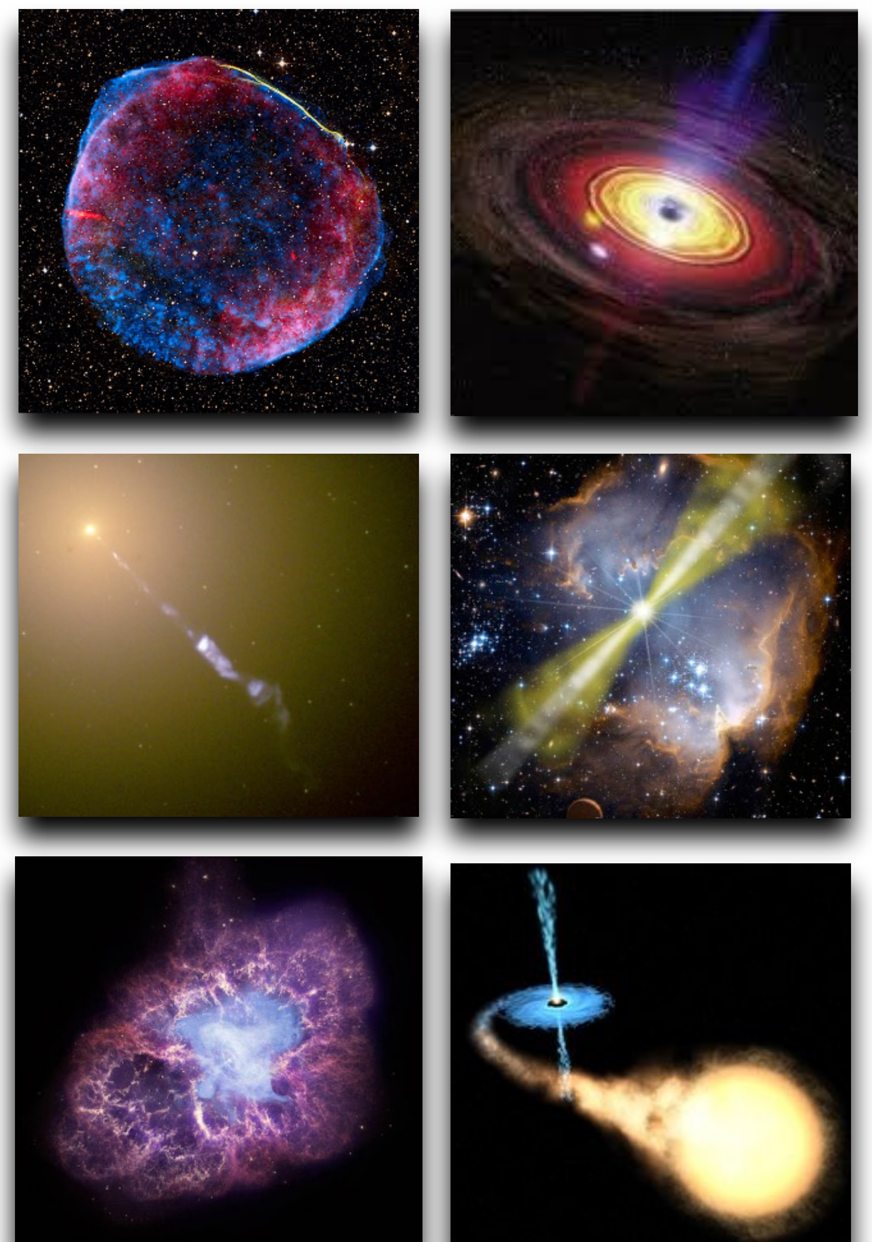
(Very) High Energy Gamma-Ray Astrophysics



The study of *non-thermal* phenomena in the universe

- black holes and neutron stars
- active galactic nuclei
- compact binary systems
- supernovae and remnants
- pulsars and PWNe
- gamma-ray bursts / hypernovae
- starburst regions and galaxies
- galaxy clusters
- ***cosmic rays and their origin***
- dark matter

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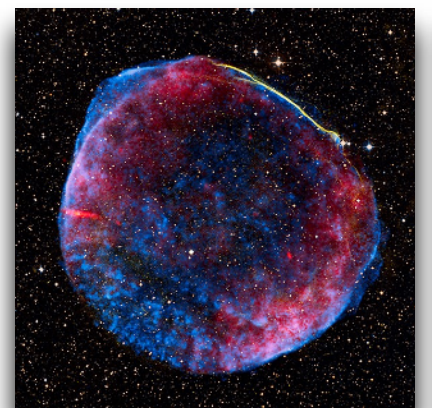


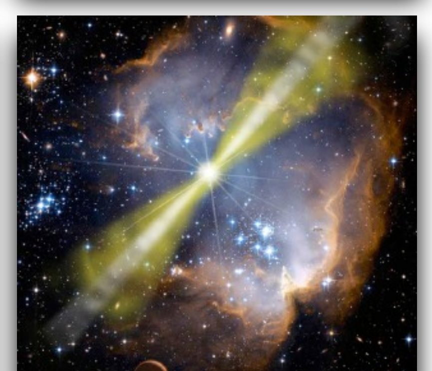

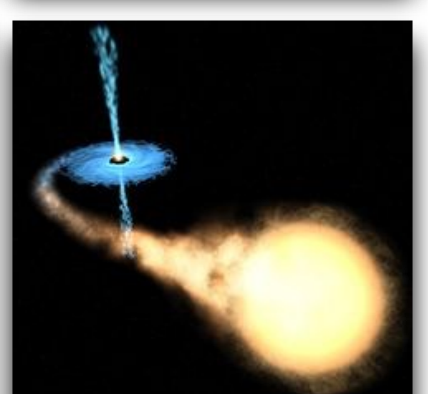

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Accretion

Jets

Winds

Explosions

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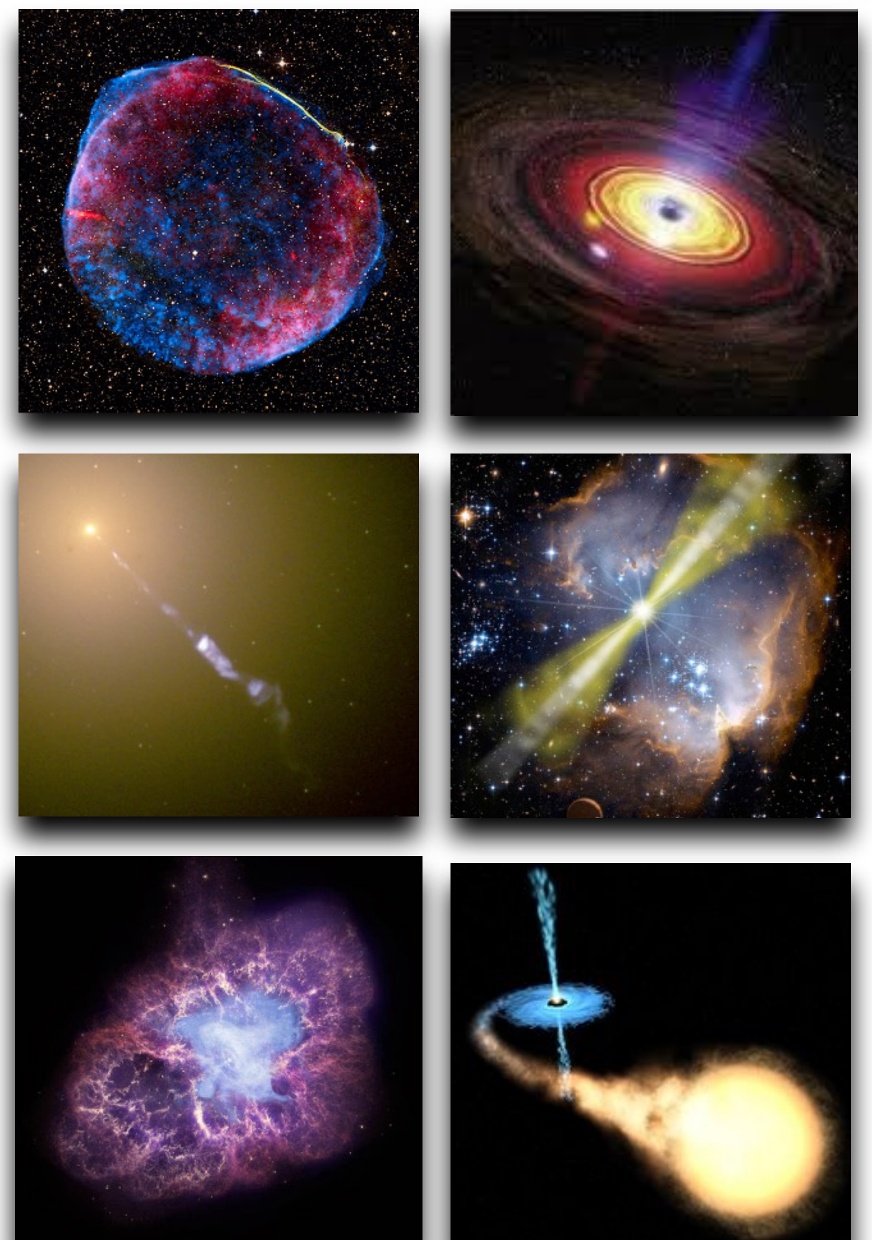

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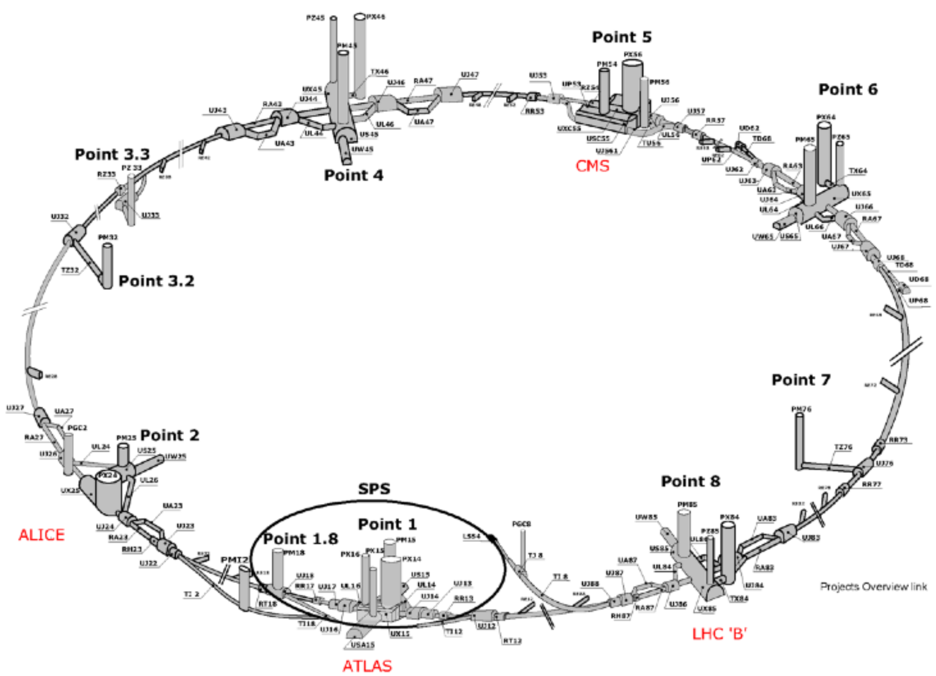
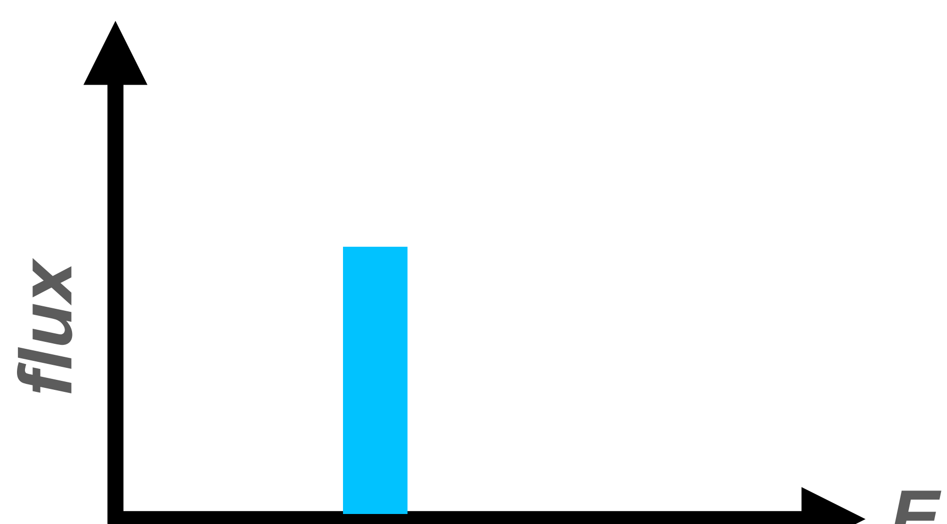
Particle Acceleration

Particle Acceleration

Man-made particle acceleration





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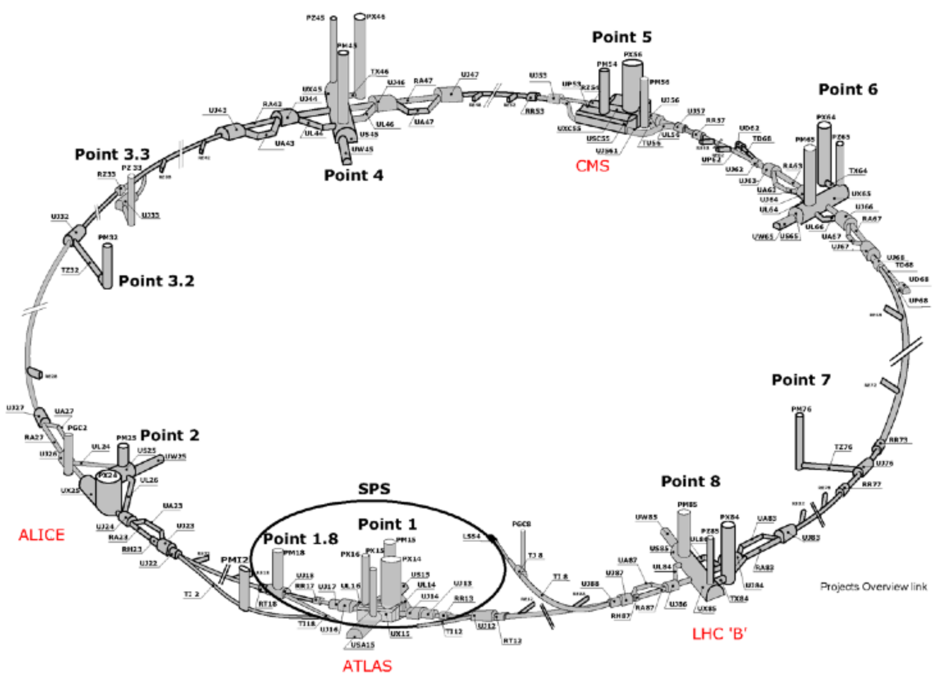
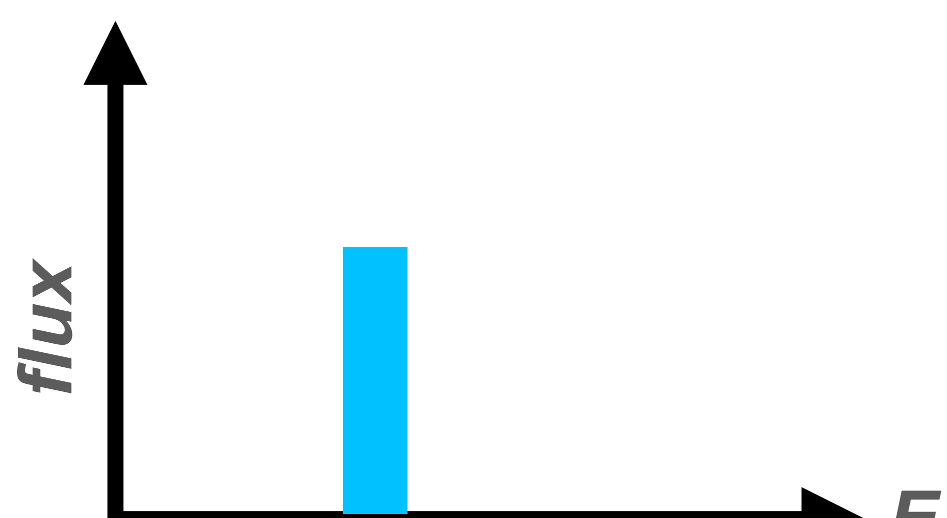


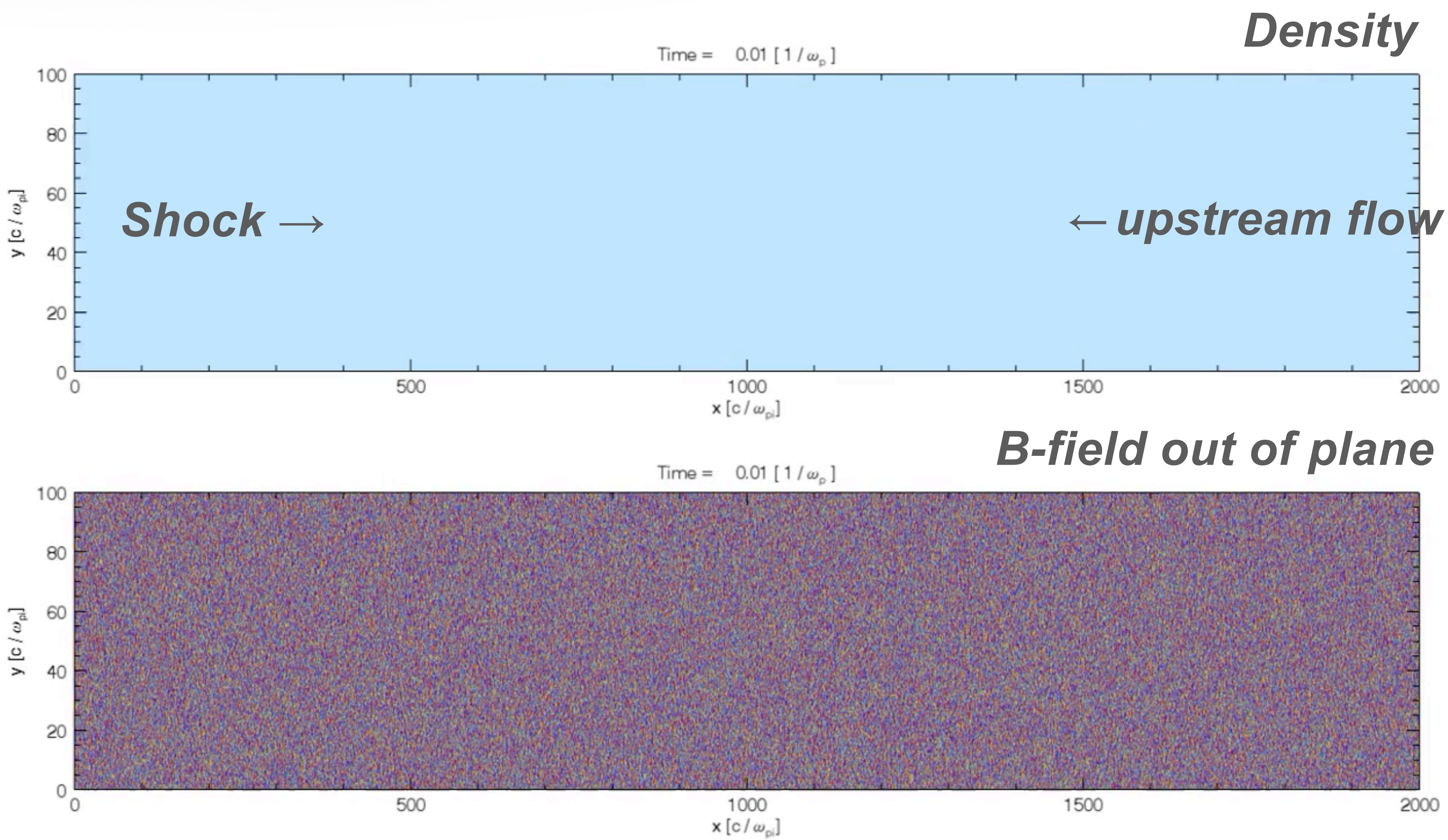


Diffusive Shock Acceleration (1st Order Fermi Process)

→ Power-law particle distribution

Diffusive Shock Acceleration

Fermi Process



Credit: Damiano Caprioli, ICRC 2015 Dhybrid code (Gargaté et al. 2007), DC & Spitkovsky 2014

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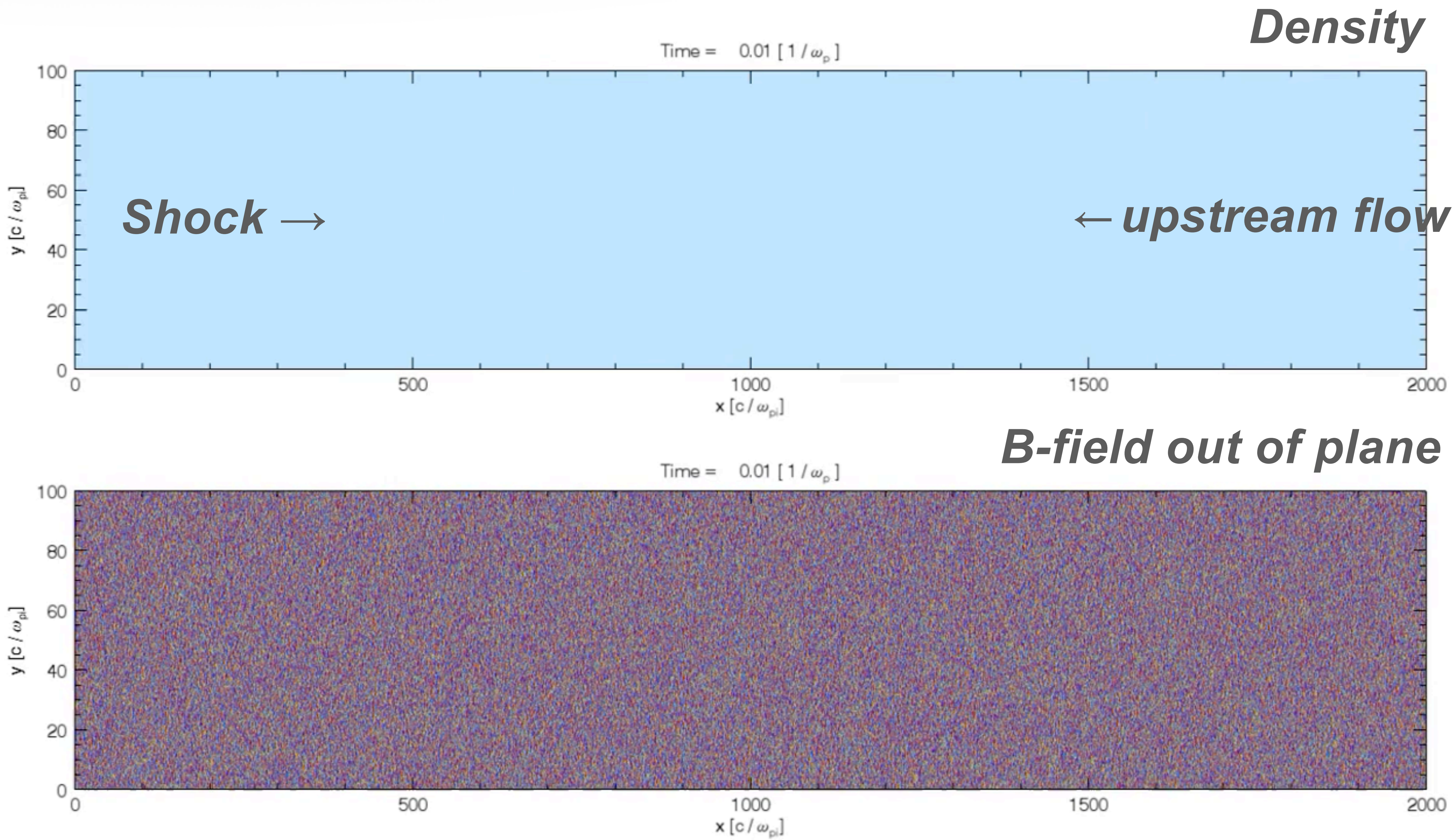

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Cosmic Rays

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Discovery!

- Victor Hess , 1912

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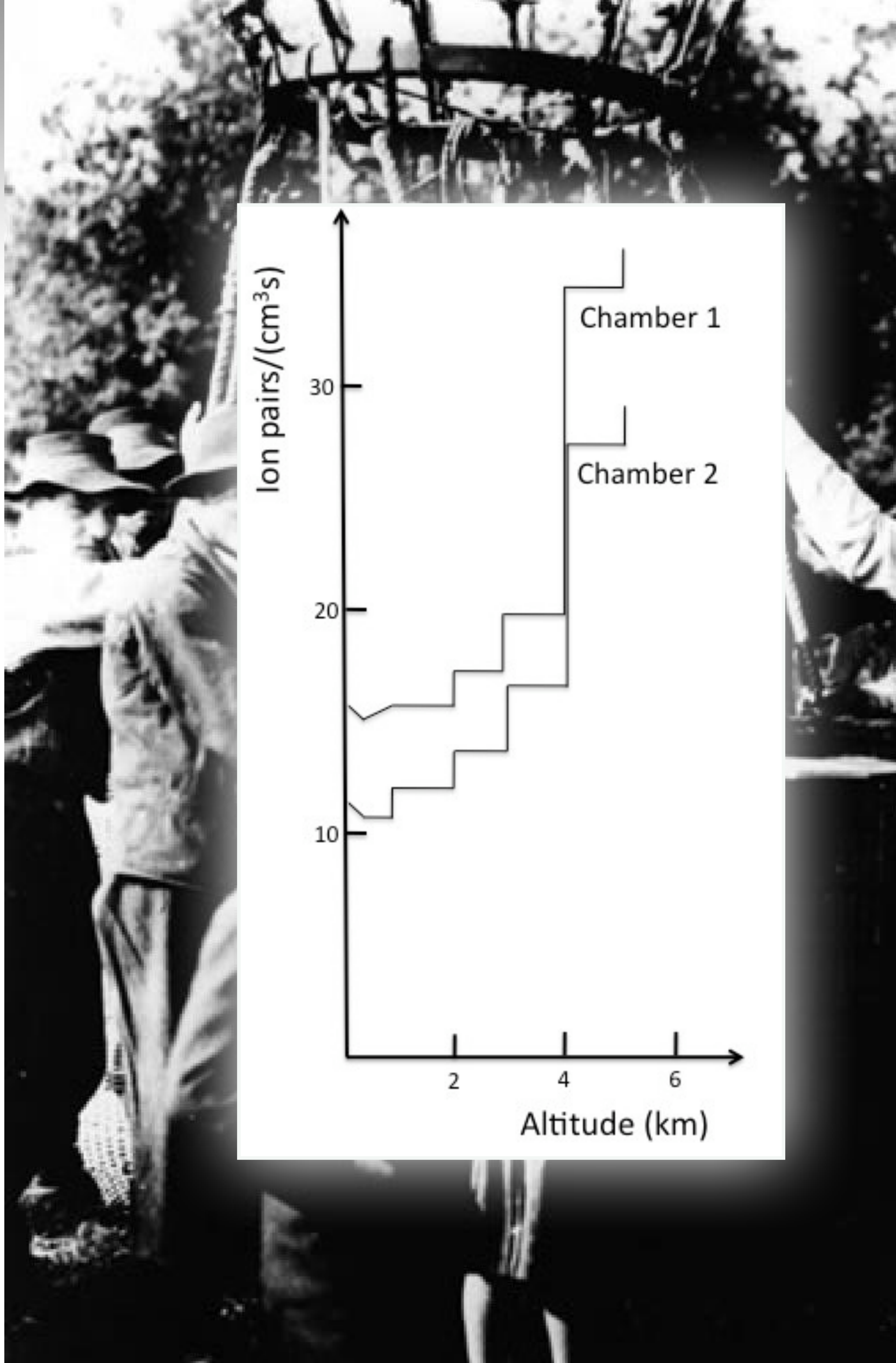


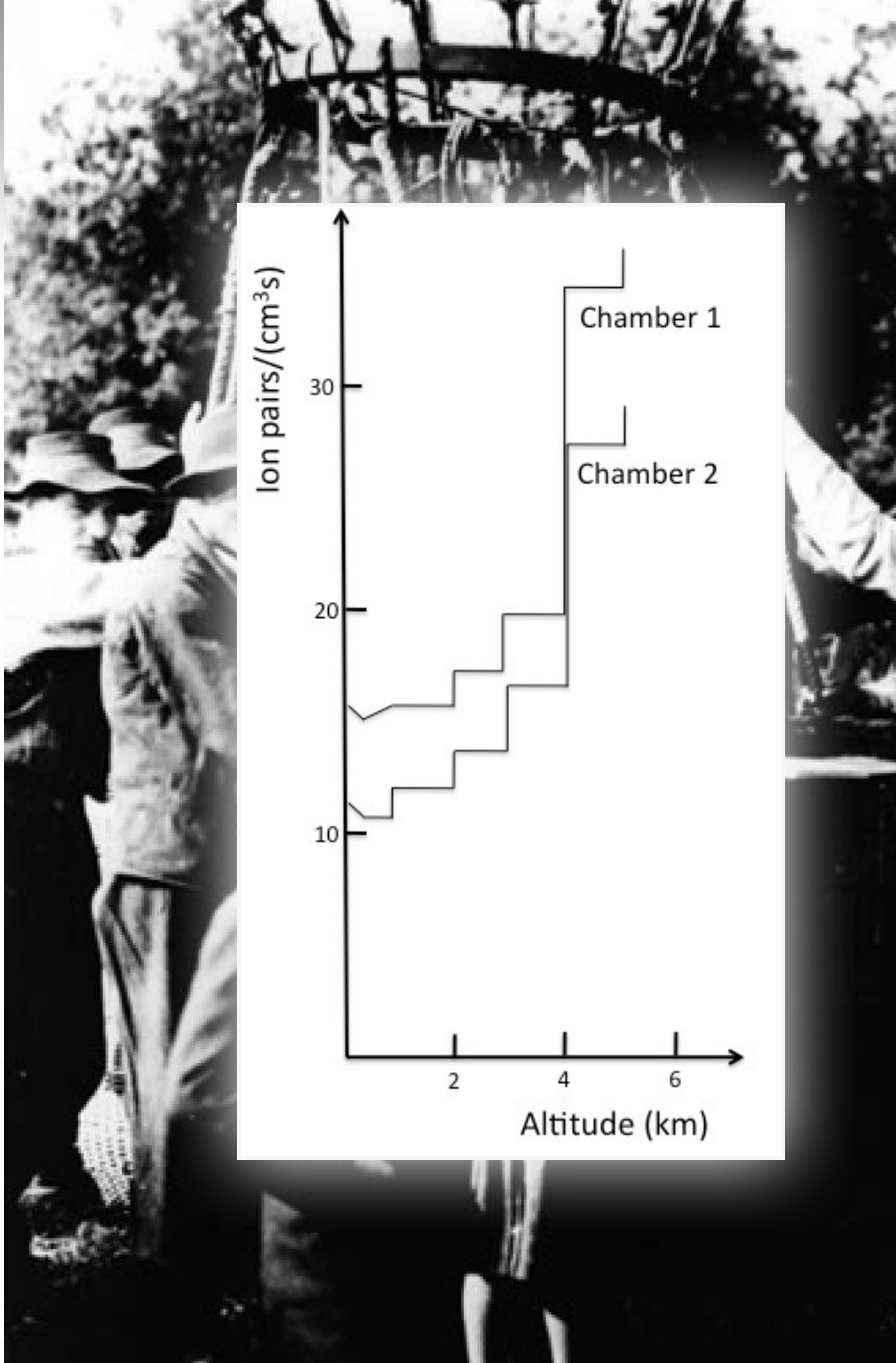
Cosmic Rays

Discovery!

- Victor Hess , 1912

Composition: ionized nucleii

- 90% protons
- 9% helium nucleii (α)
- rest: higher Z



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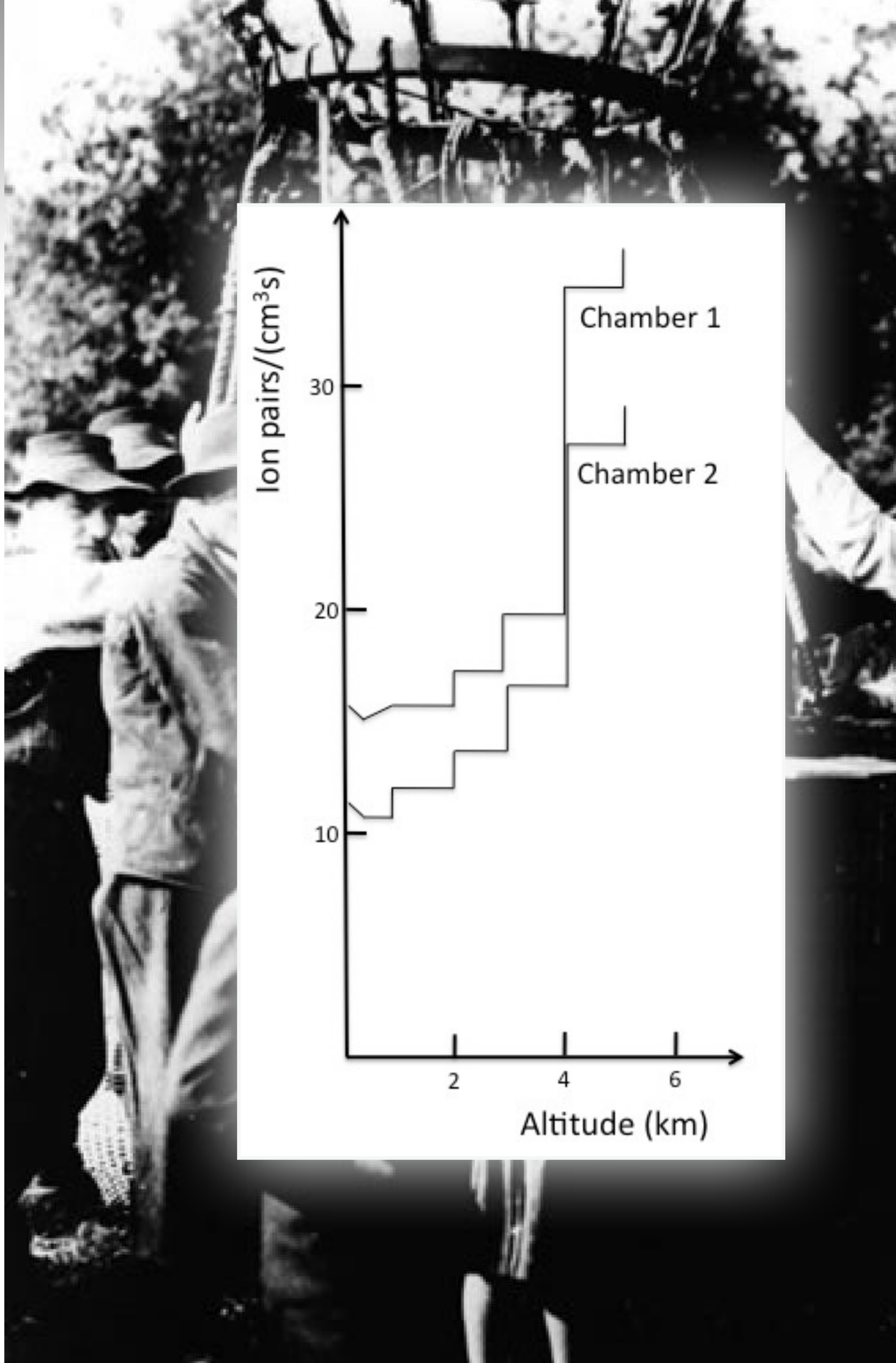

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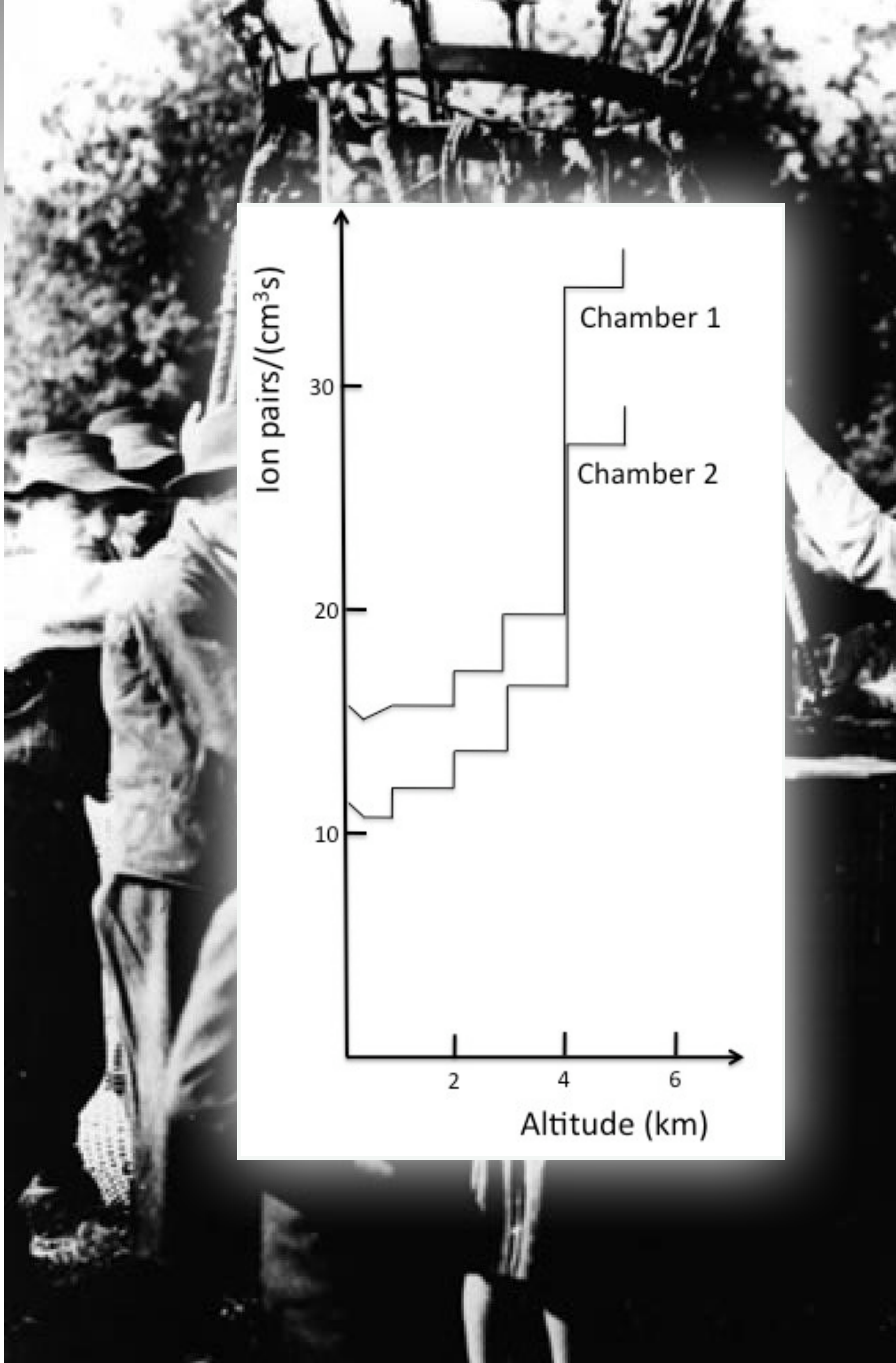
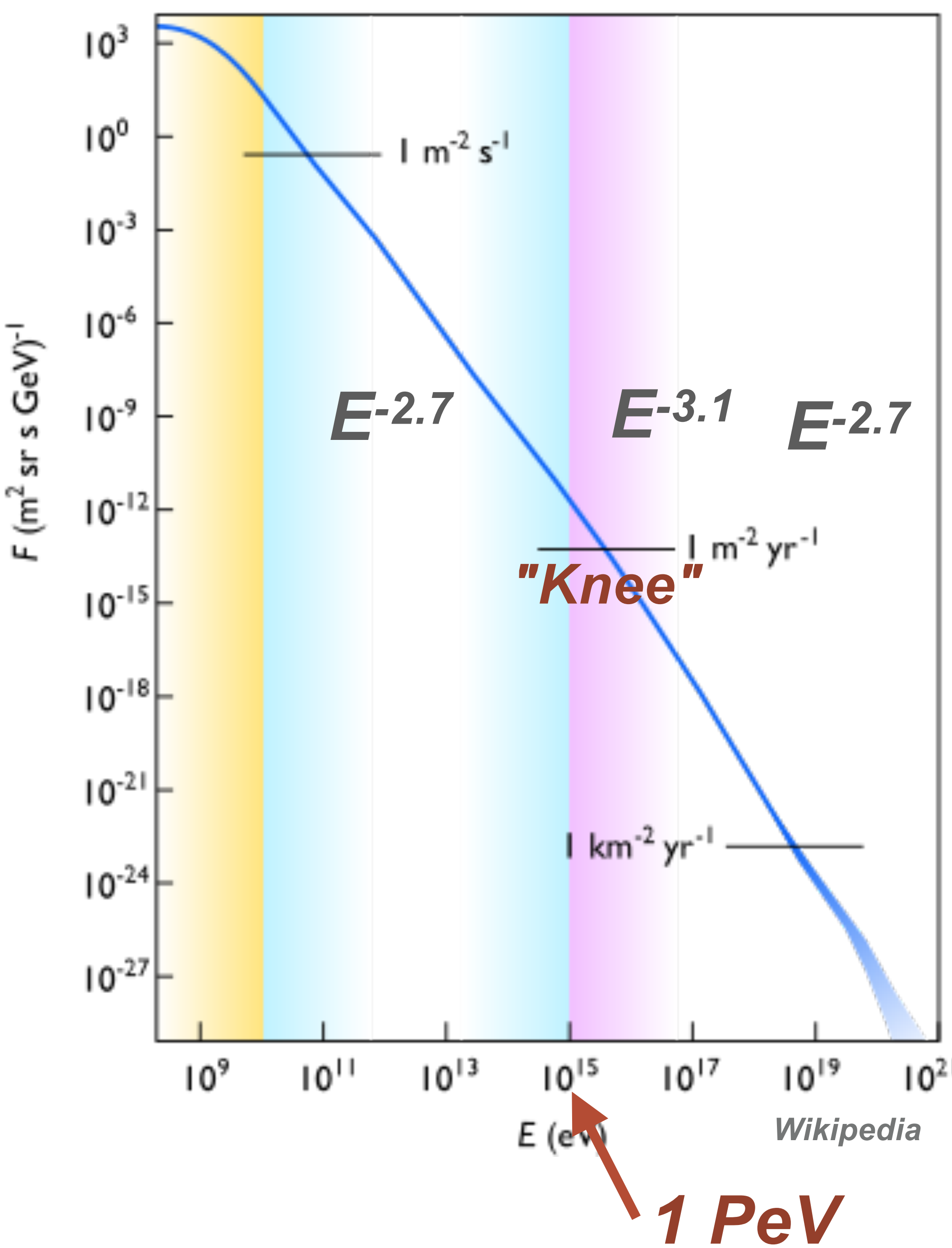
Energy Density in the Galaxy

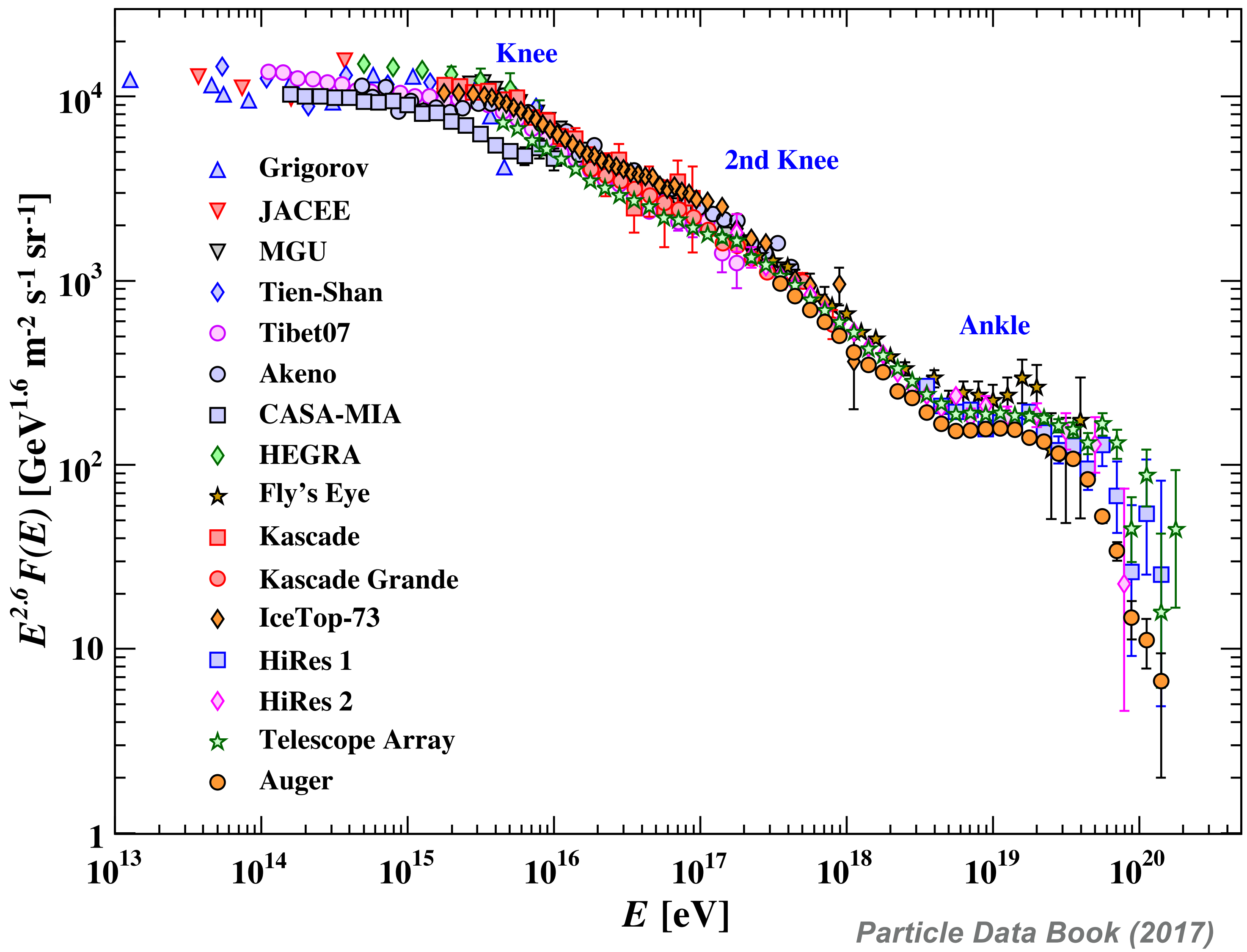
- $u_{CR} \approx 1$ eV/cm^3
  - ➤ **stellar light**: 0.3 ev/cm^3
  - ➤ **CMB**: $\approx$0.25 eV/cm^3
  - ➤ **magnetic fields**: $\approx$0.25 eV/cm^3



The Cosmic Ray Spectrum

The origin of CRs and the search for their accelerators





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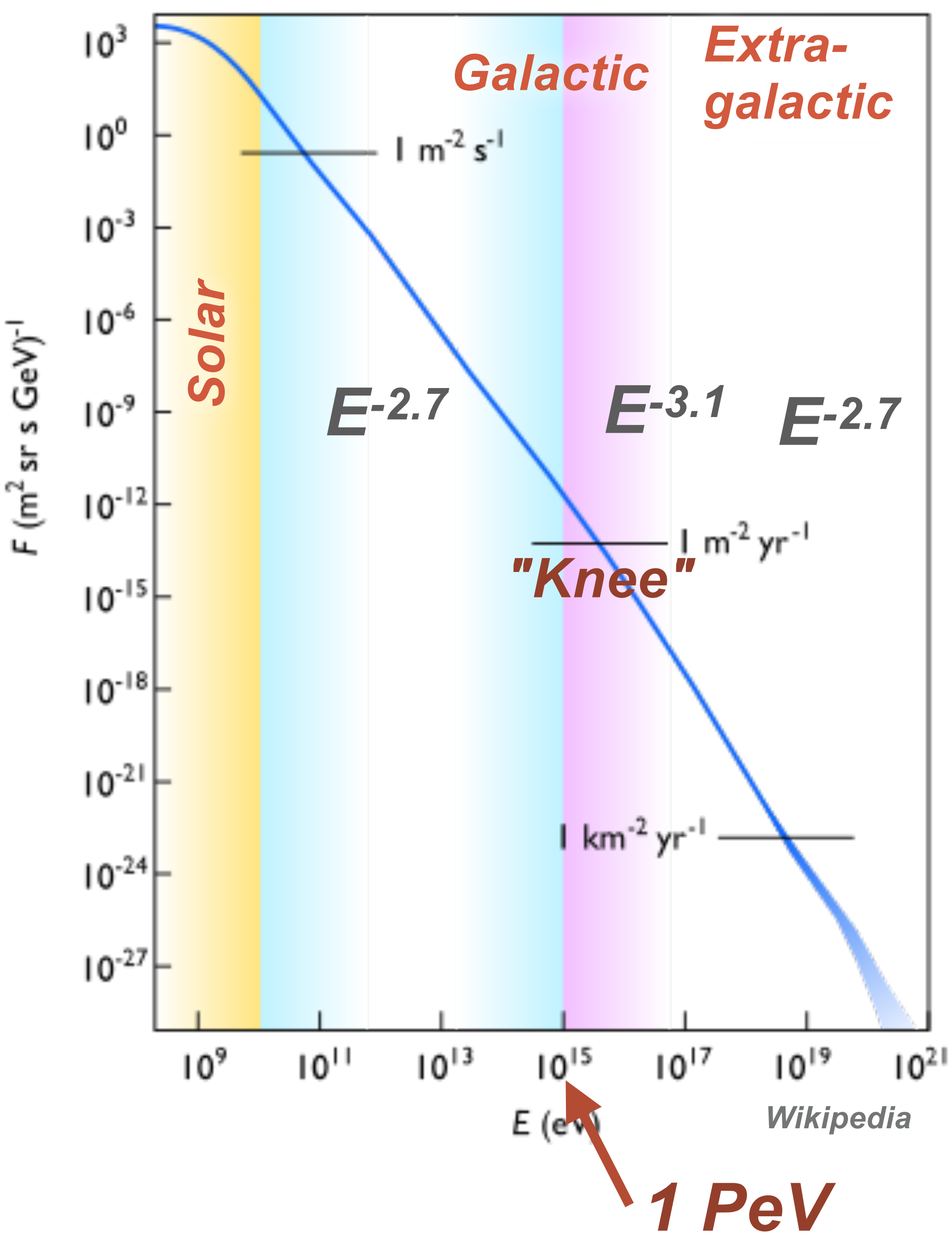
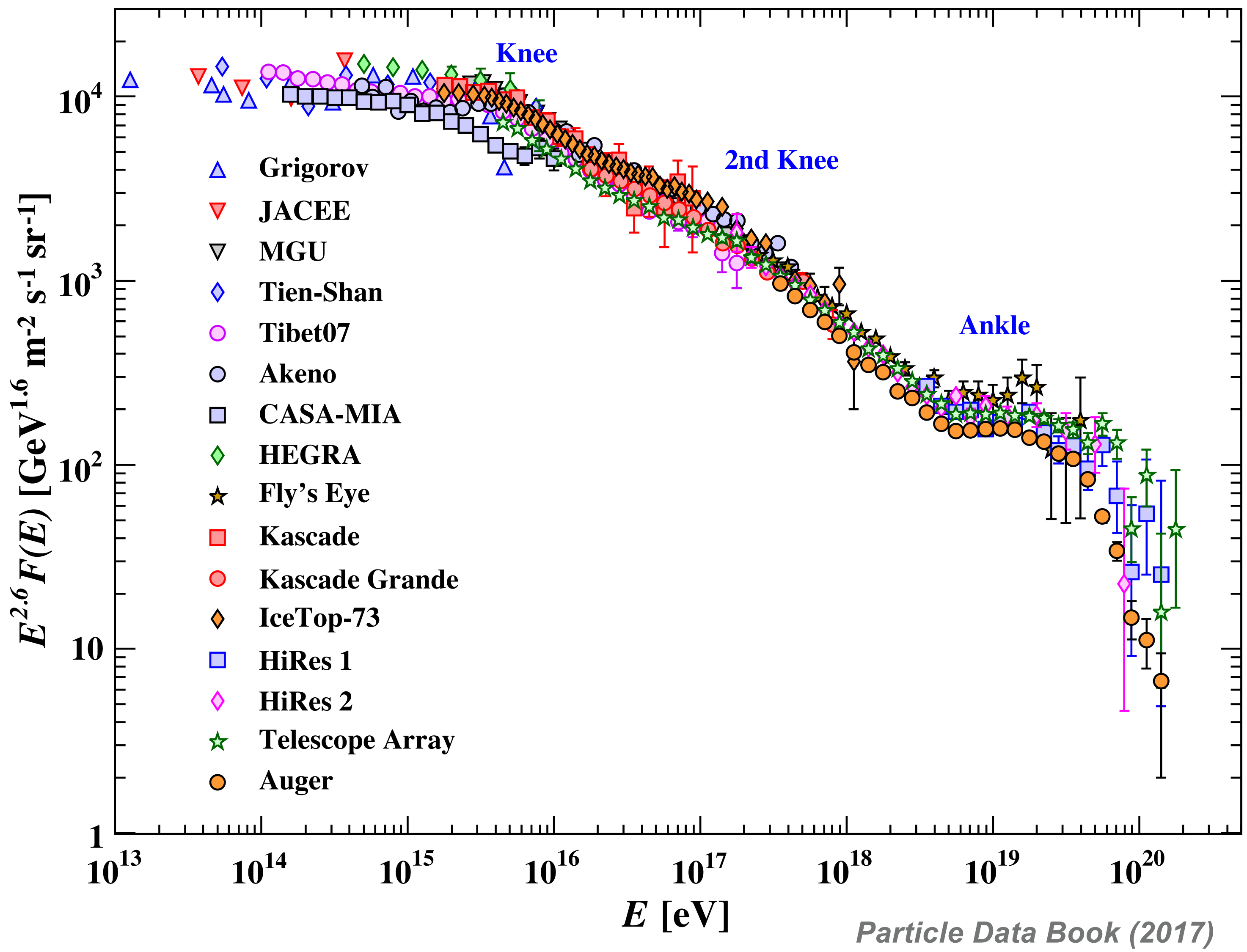
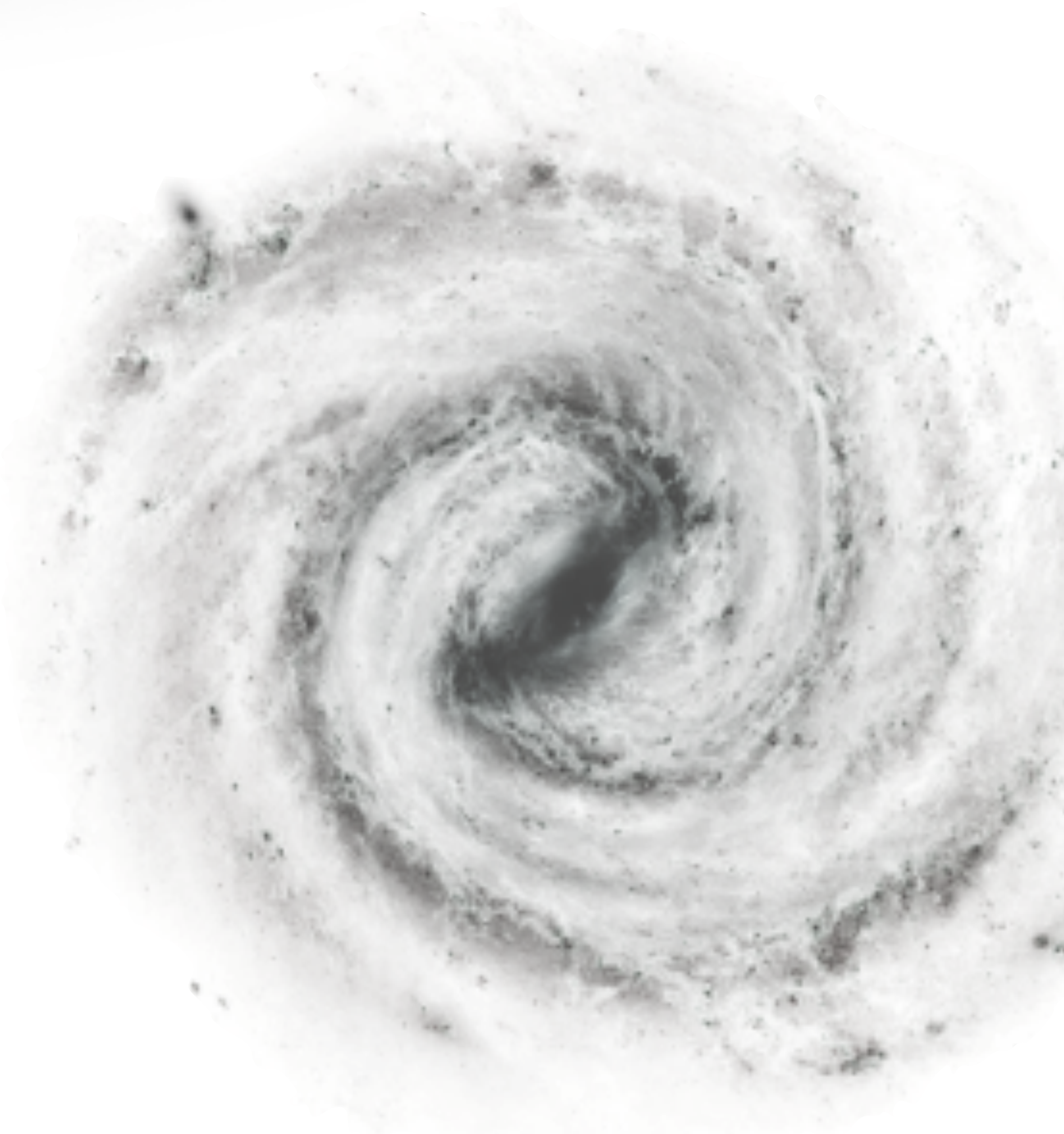




PeV Cosmic Rays

- **1 PeV proton**
  - ➤ in galactic B-field (3 μG)
    → Gyro-radius ≈ 0.4 pc
  - ➤ *confined* to galaxy (20 kpc across)
  - ➤ does not point back to origin (unless *really* close)



1 GeV particle diffusion in uniform galactic B field

F. Effenberger et al. A&A 547, A120 (2012)

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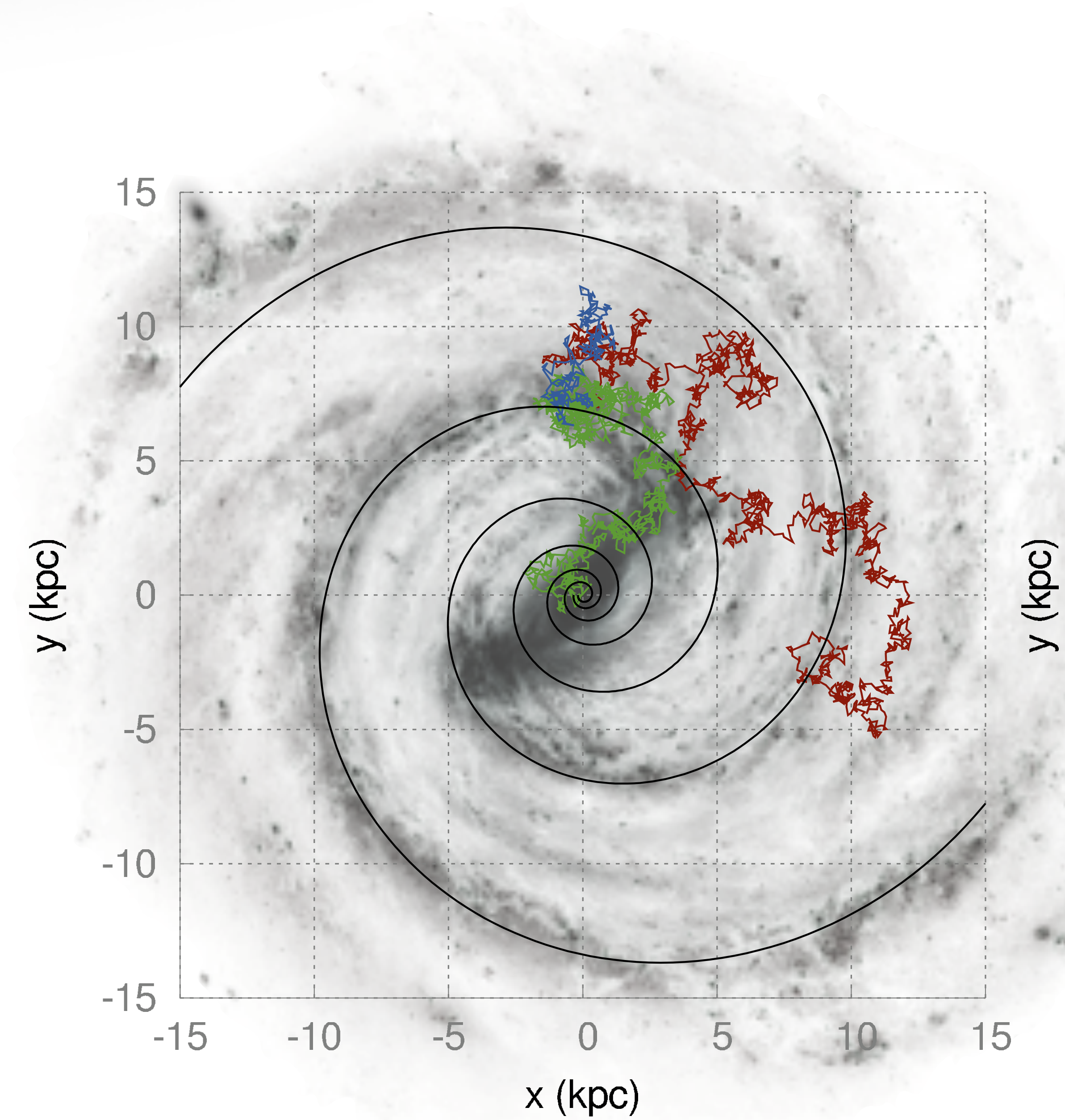

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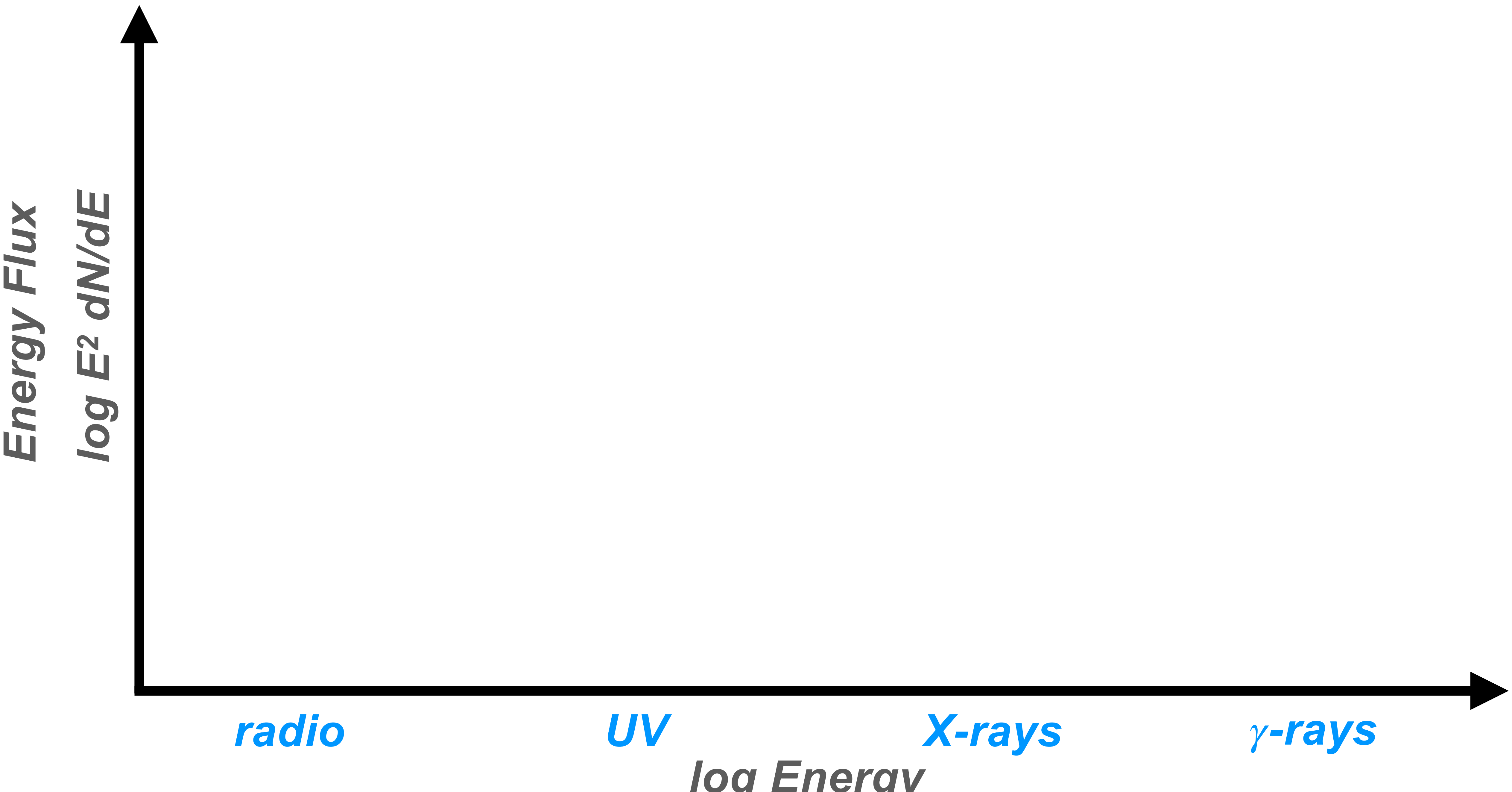
Non-Thermal Emission

Spectral Energy Distribution for various processes:

Electron population **Proton Population**



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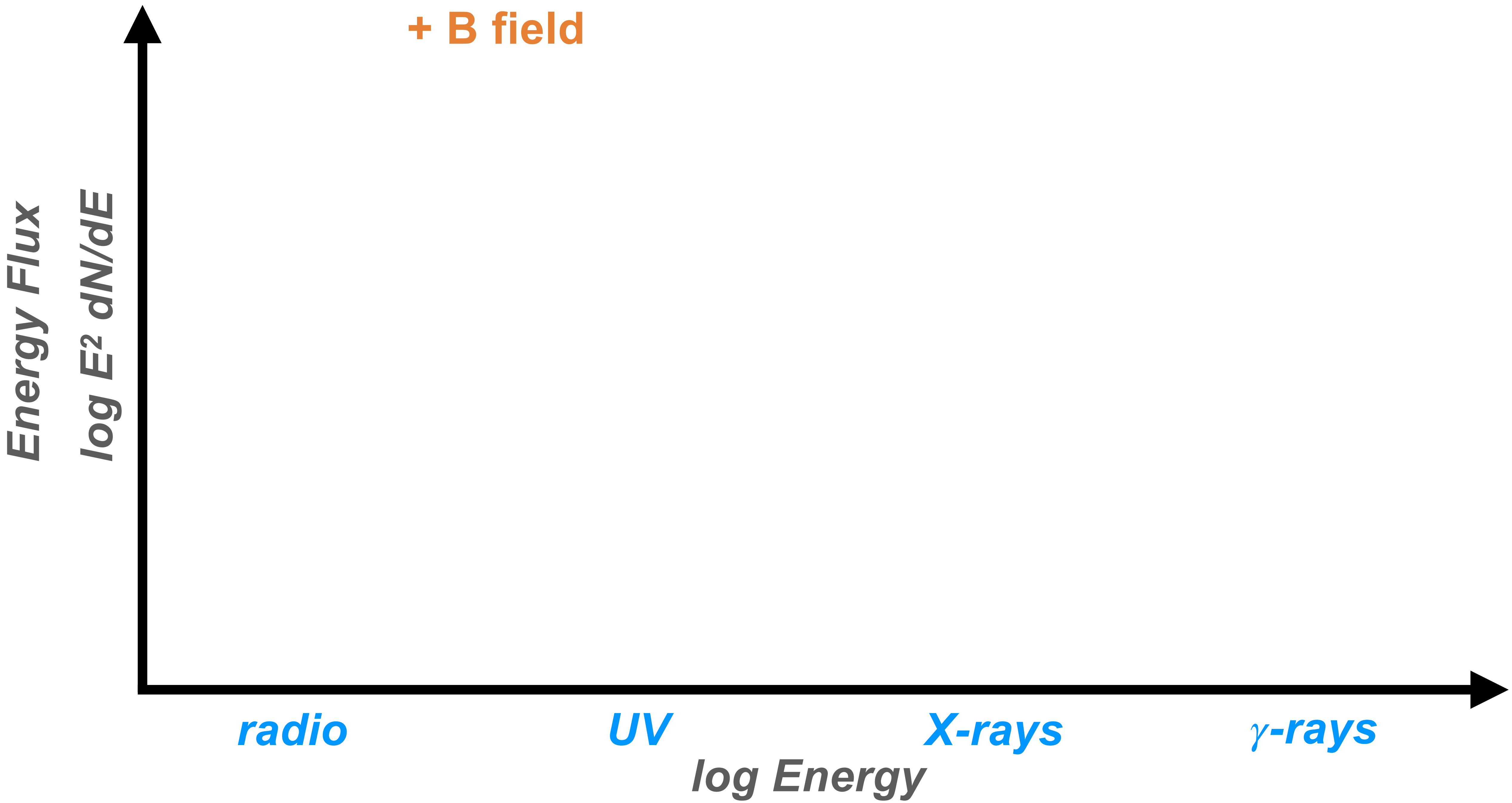

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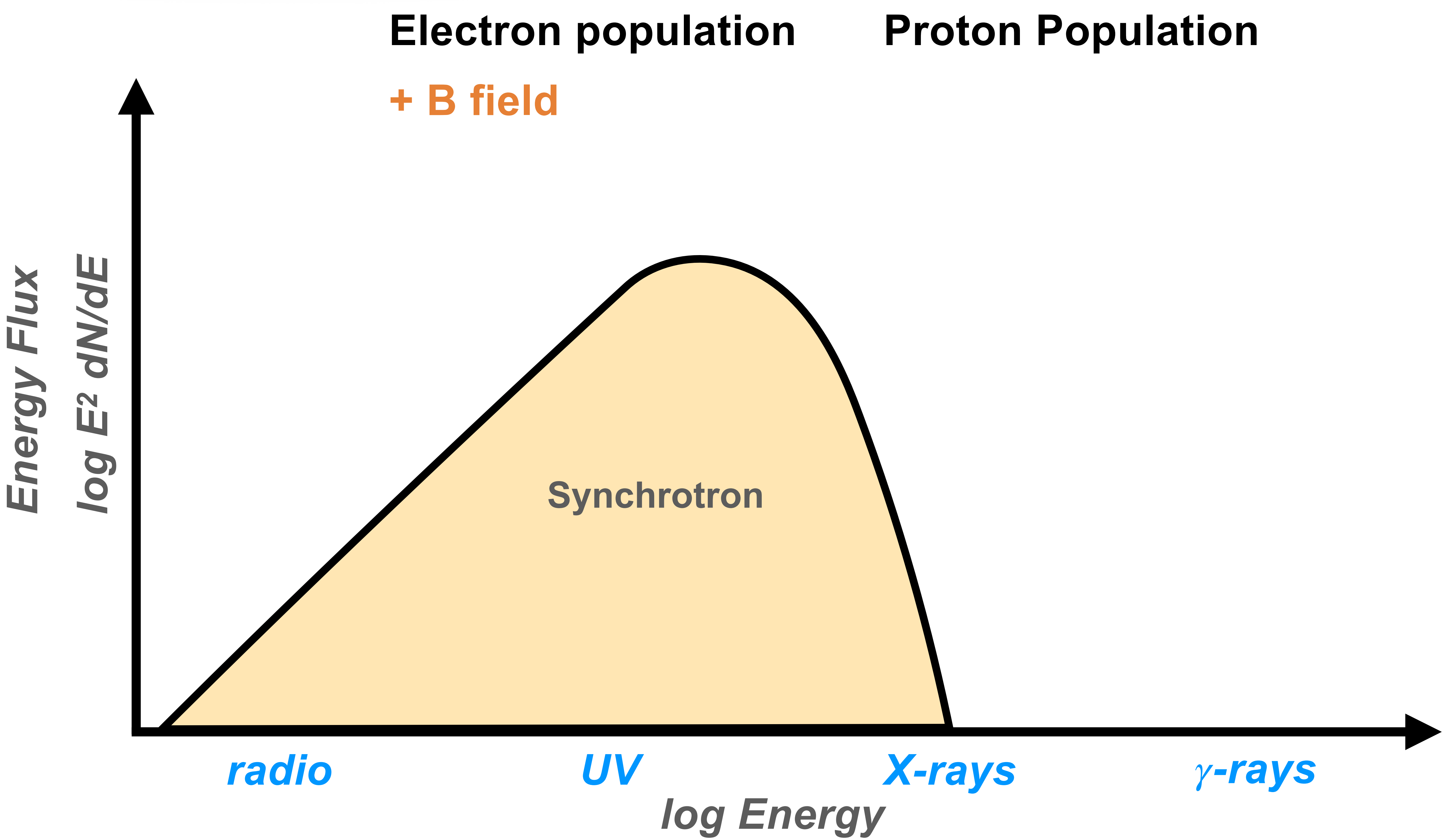

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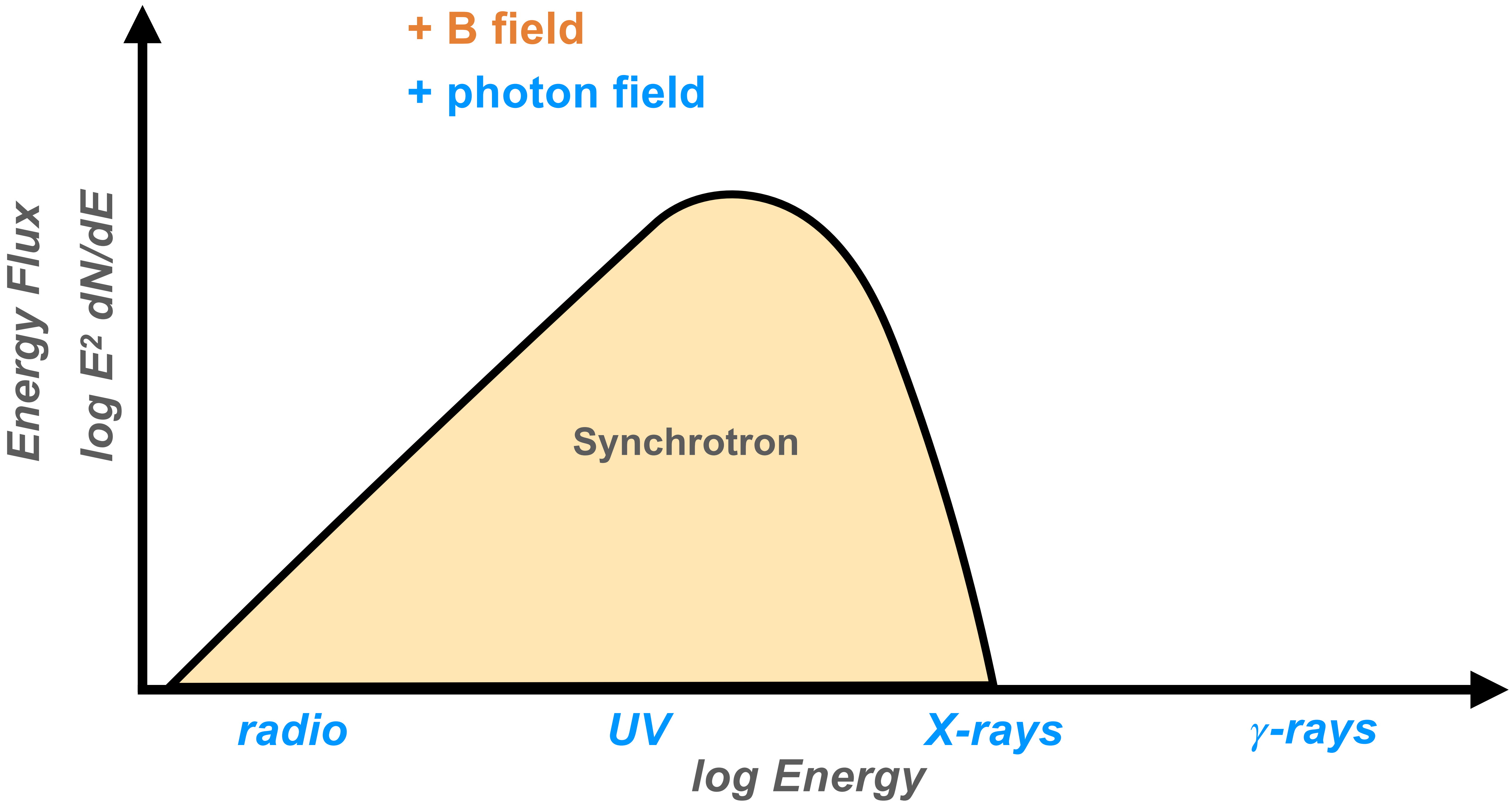
+ photon field



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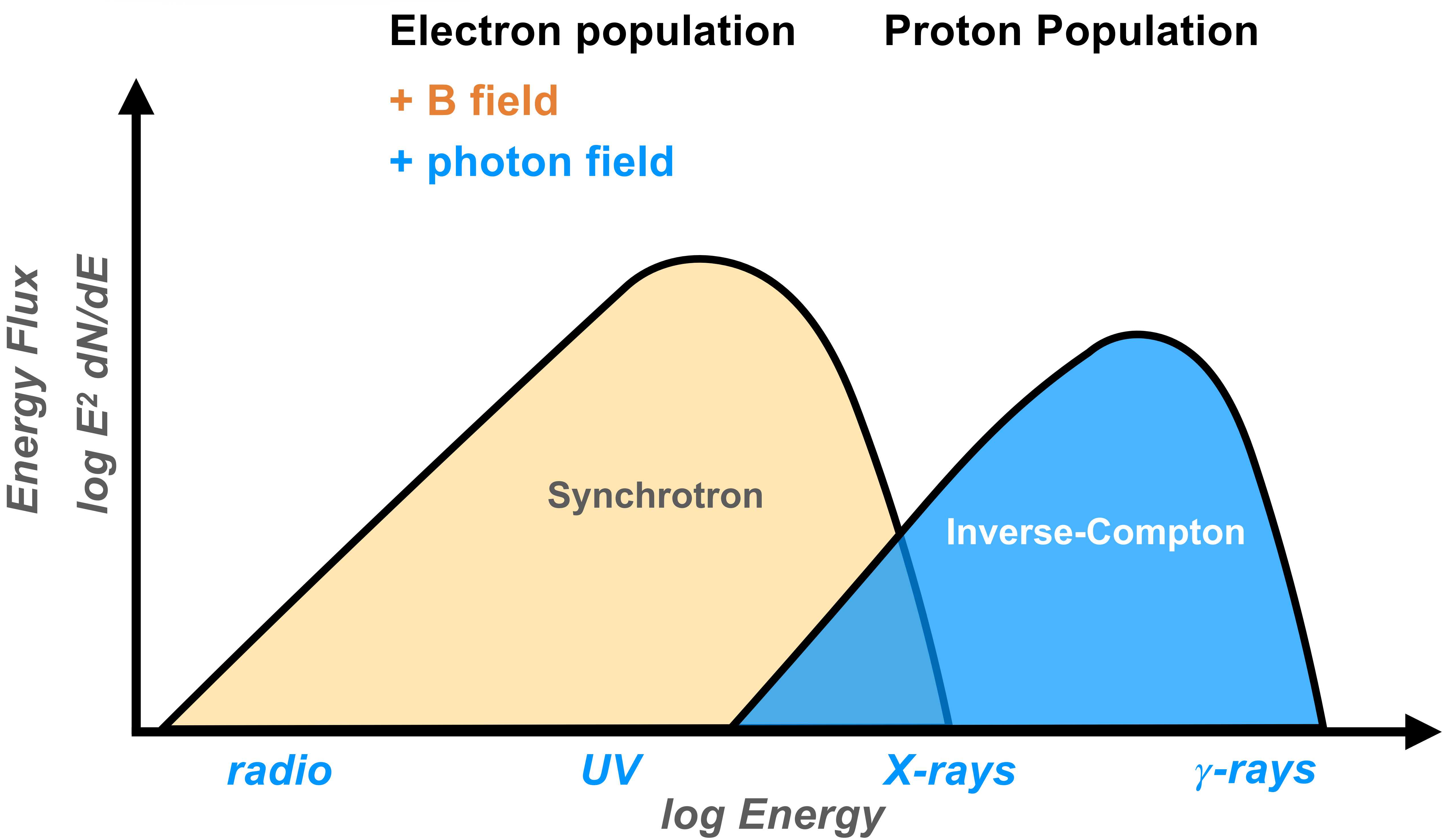

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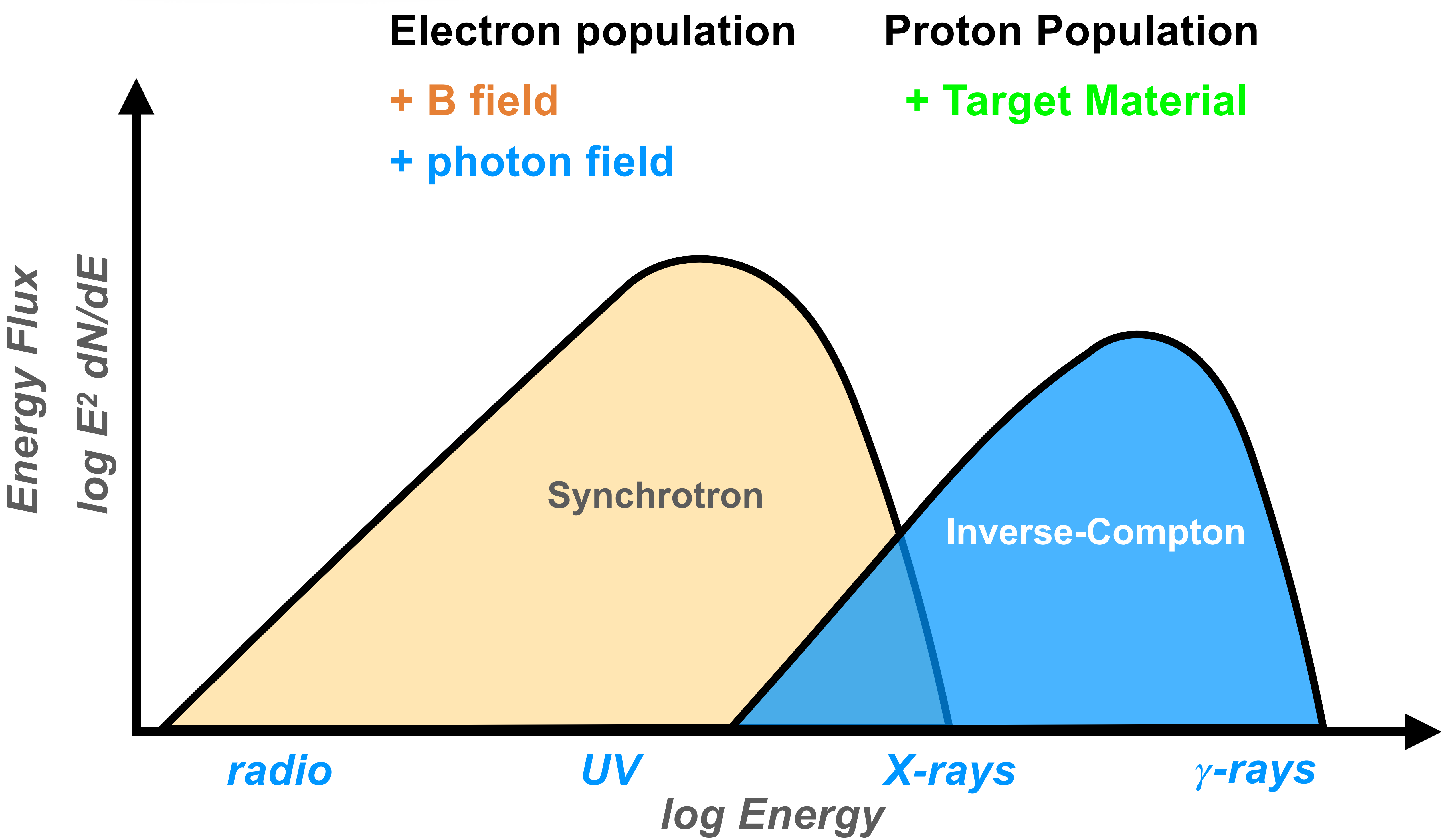

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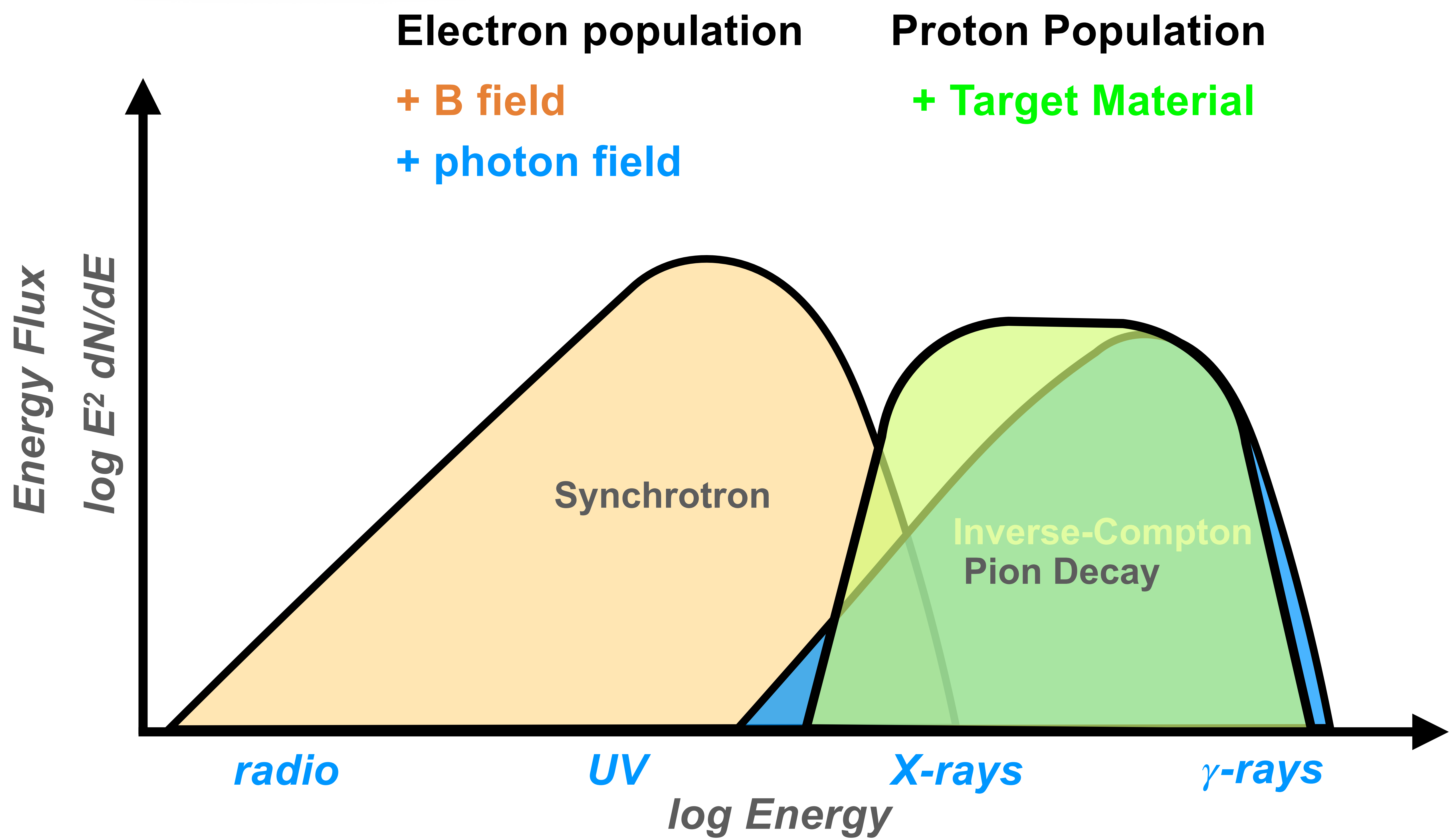

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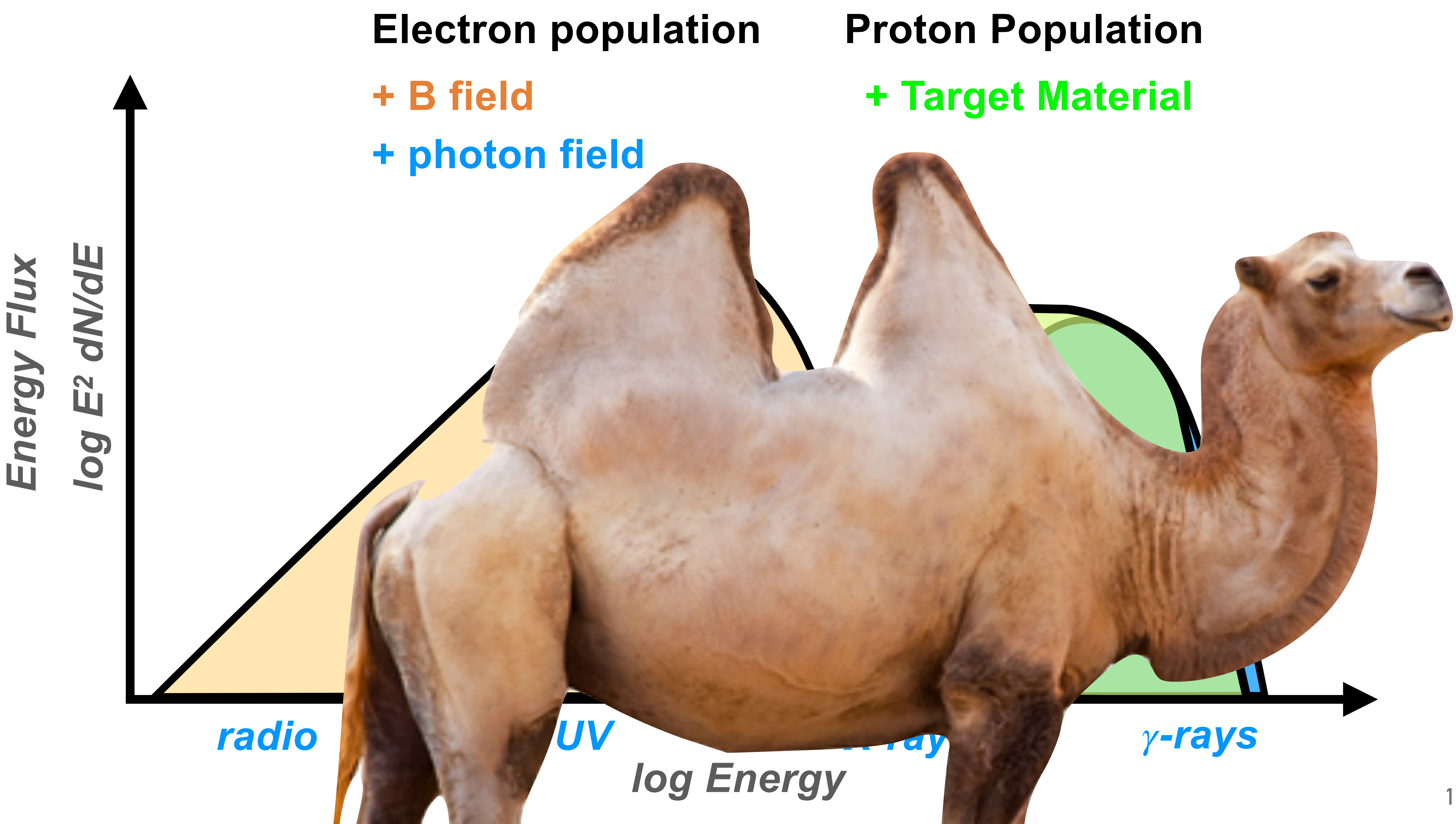

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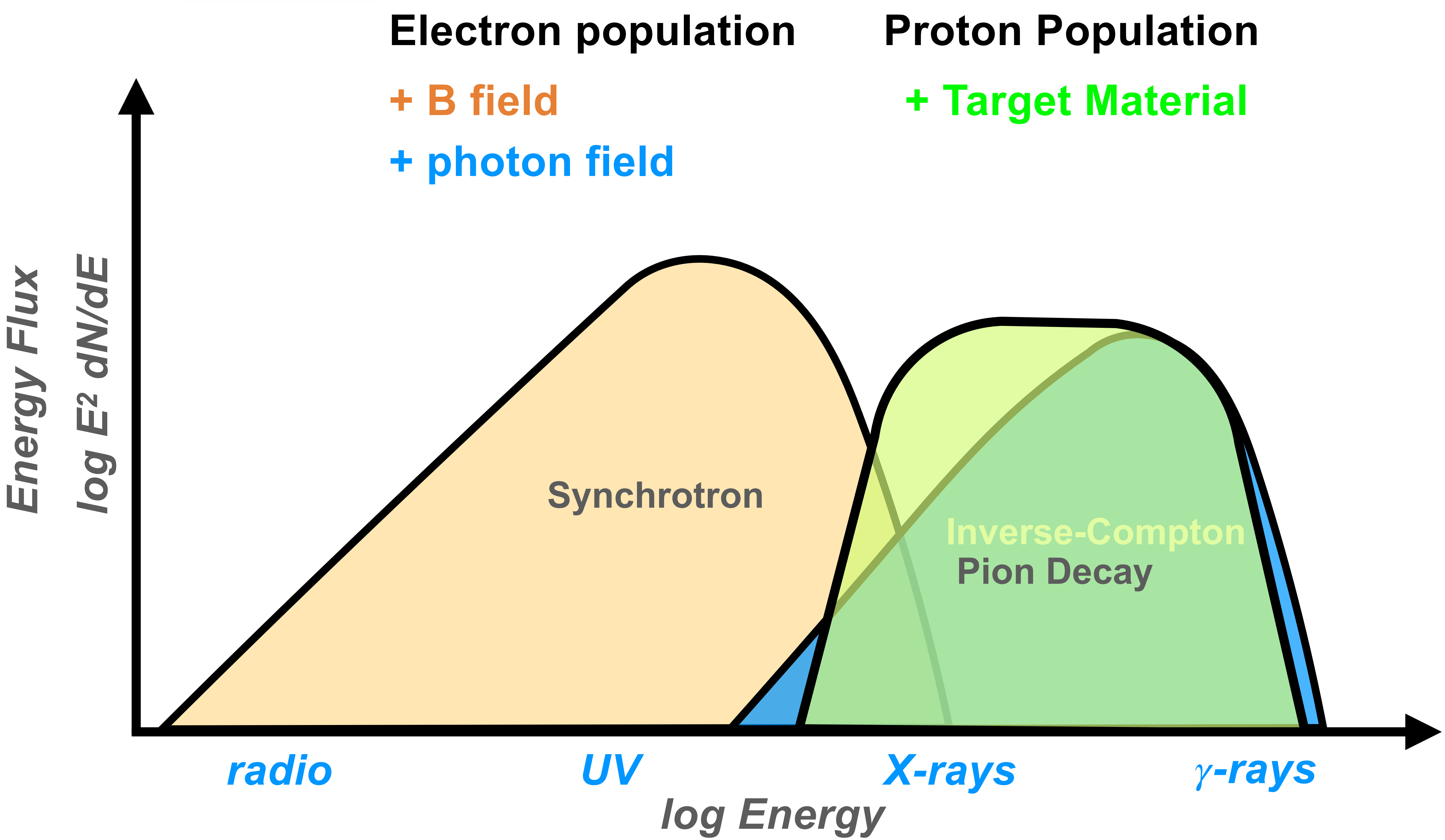

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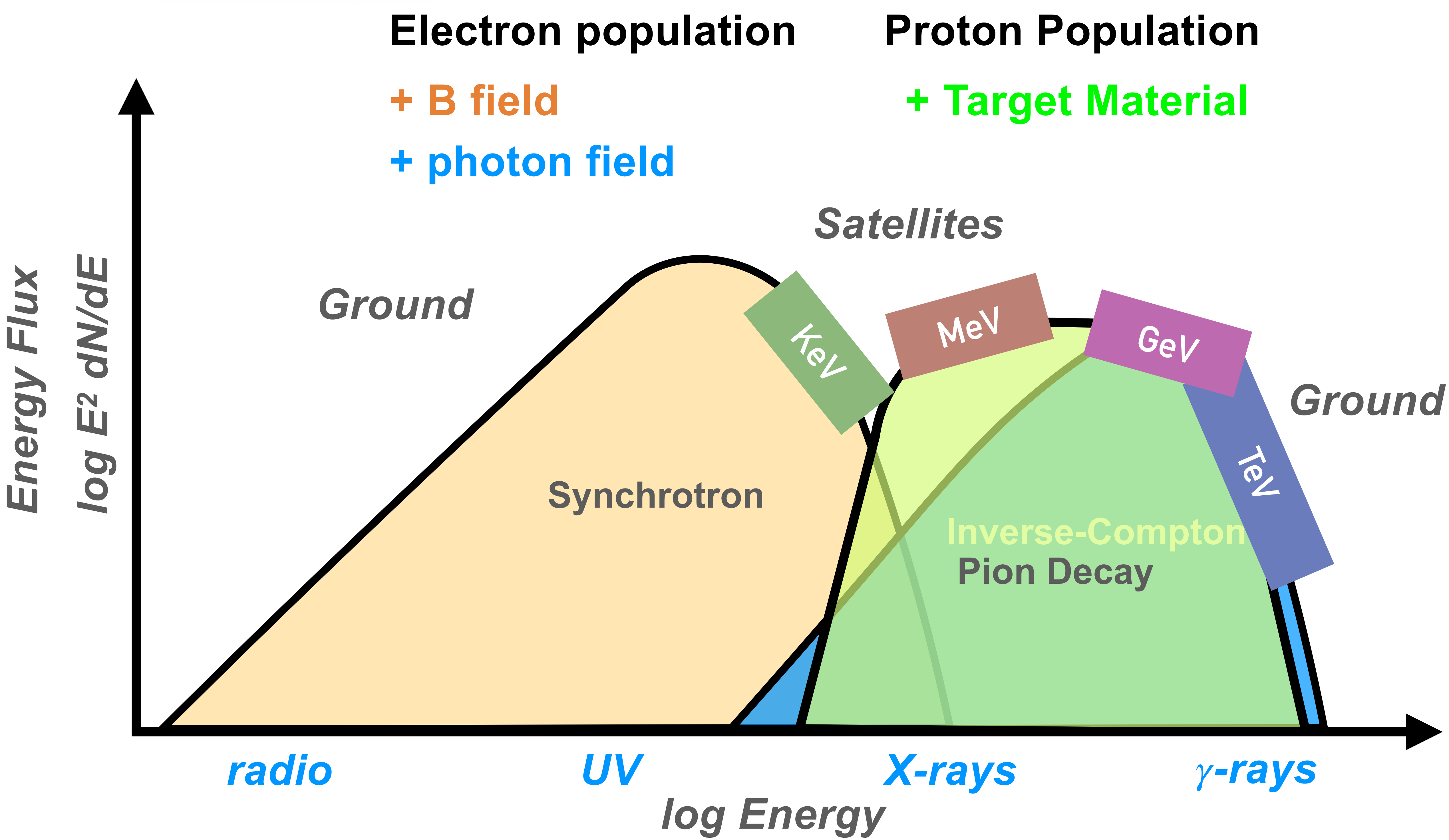
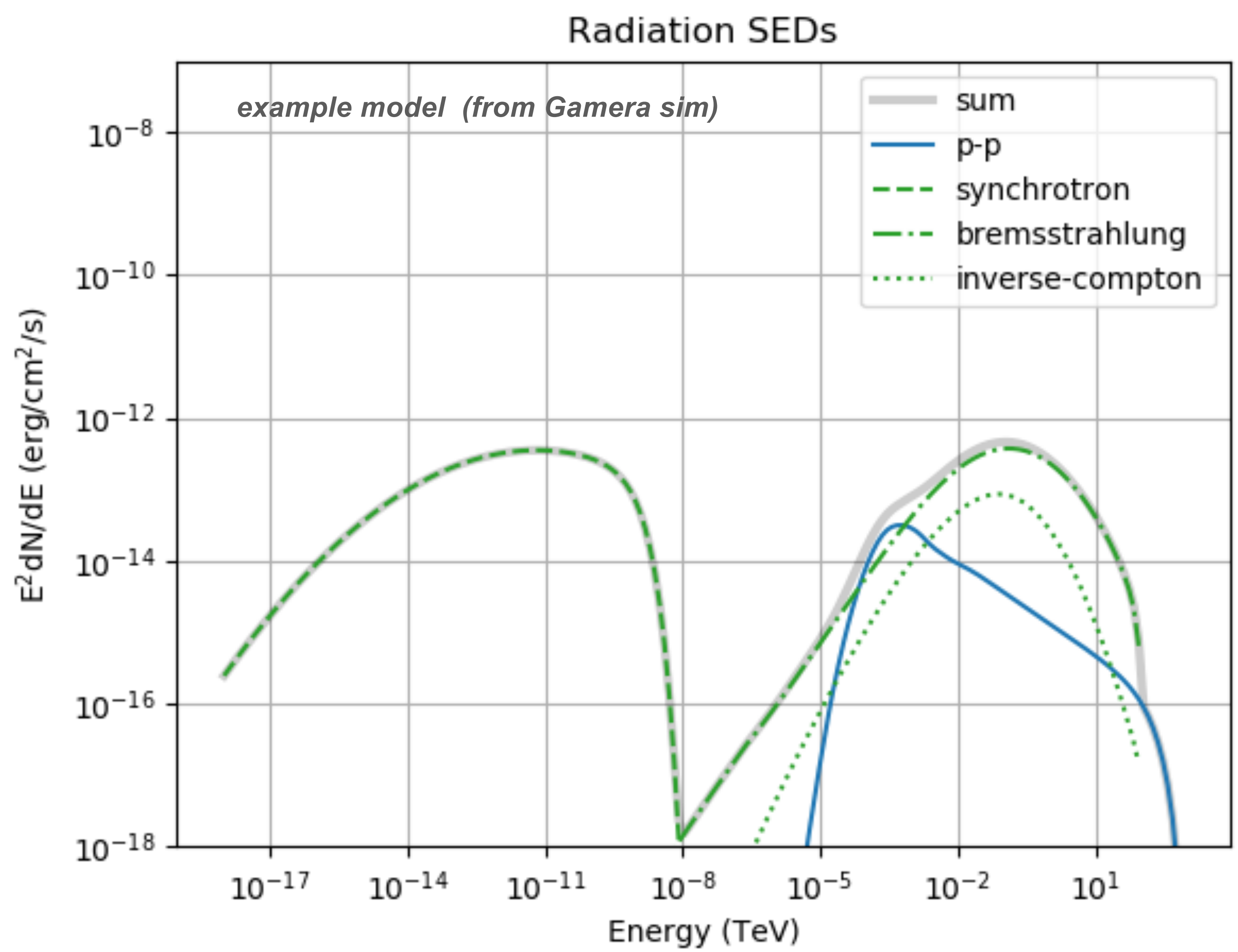


"PeVatron" Signatures

Goal is to distinguish between:

- "***leptonic***" *scenario (electrons, Inverse-Compton emission)*
- "***hadronic***" *scenario (protons+, pion-decay emission)*
- *derive the characteristics of the* ***parent particle population*** *by model fitting*

A Cosmic Ray "PeVatron" will fit the ***hadronic scenario****, and have a parent particle population that is a cut-off power-law in energy with* $\boldsymbol{E_{cut\text{-}off} > 1}$ ***PeV.***



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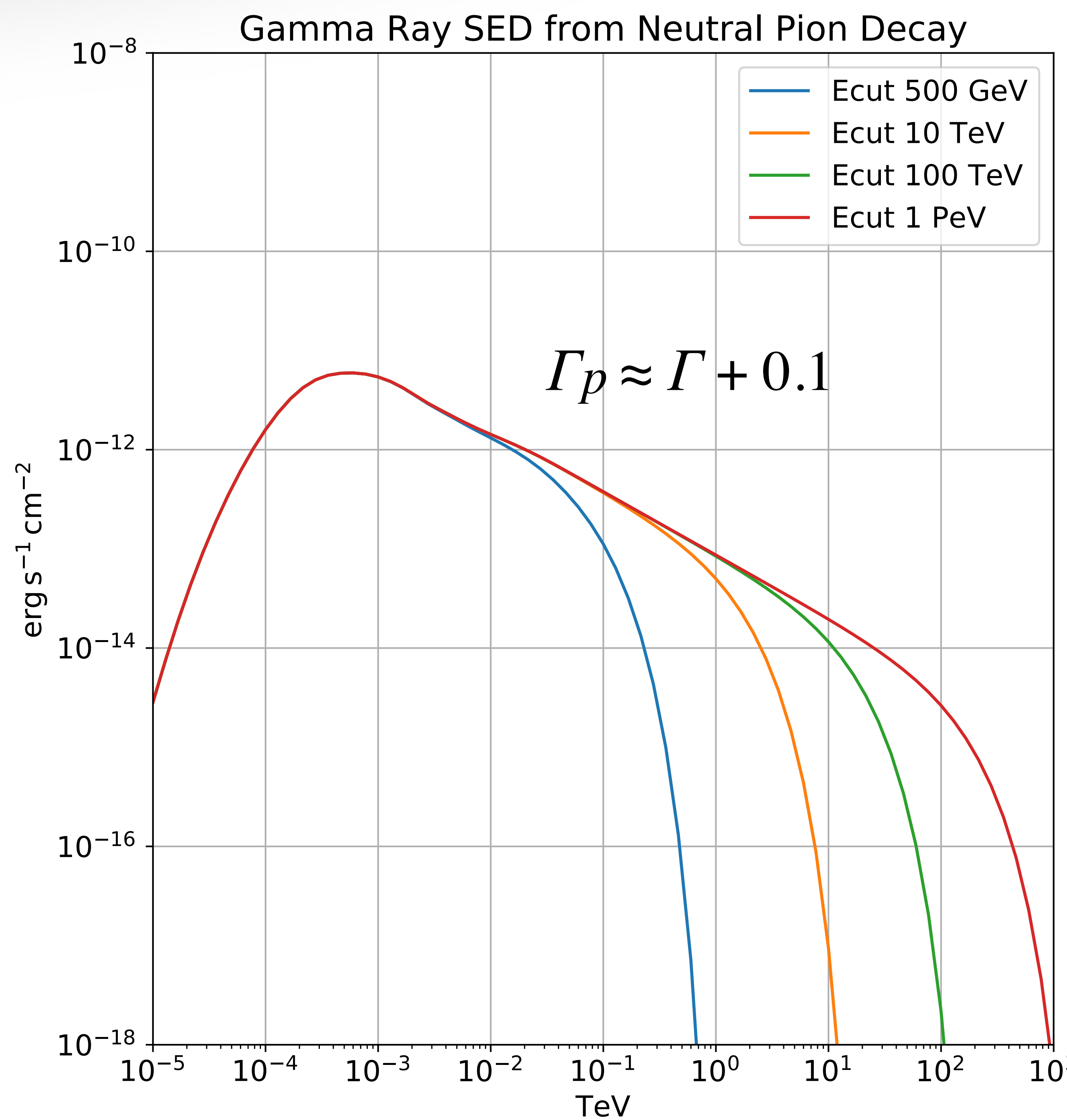

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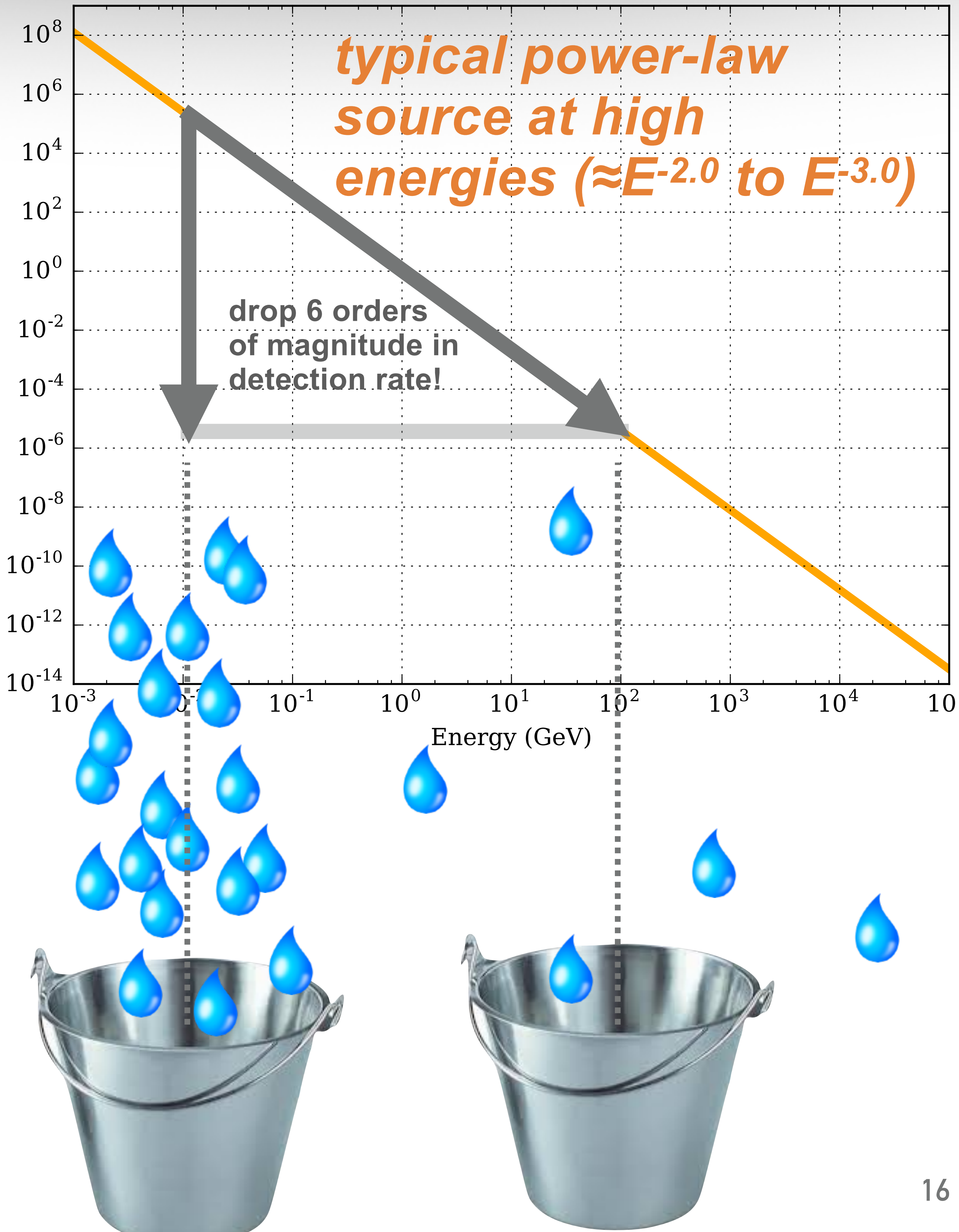
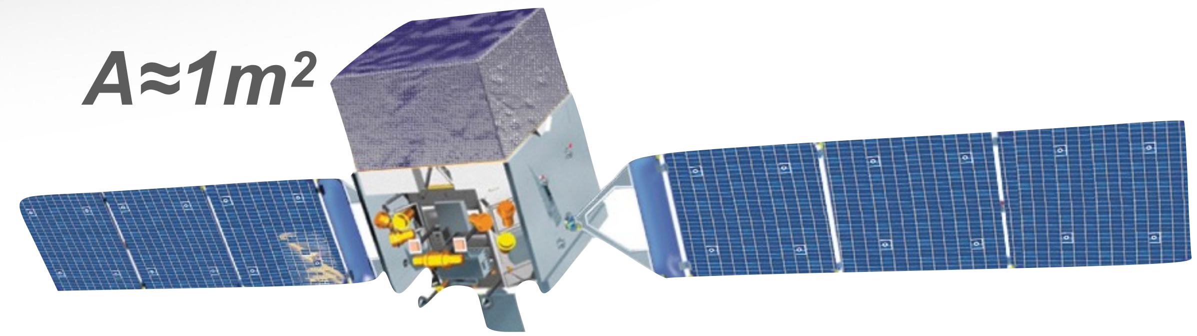
The highest energies have few photons!





beyond a few hundred GeV we need a detector with **100,000x larger collection area** than a satellite...

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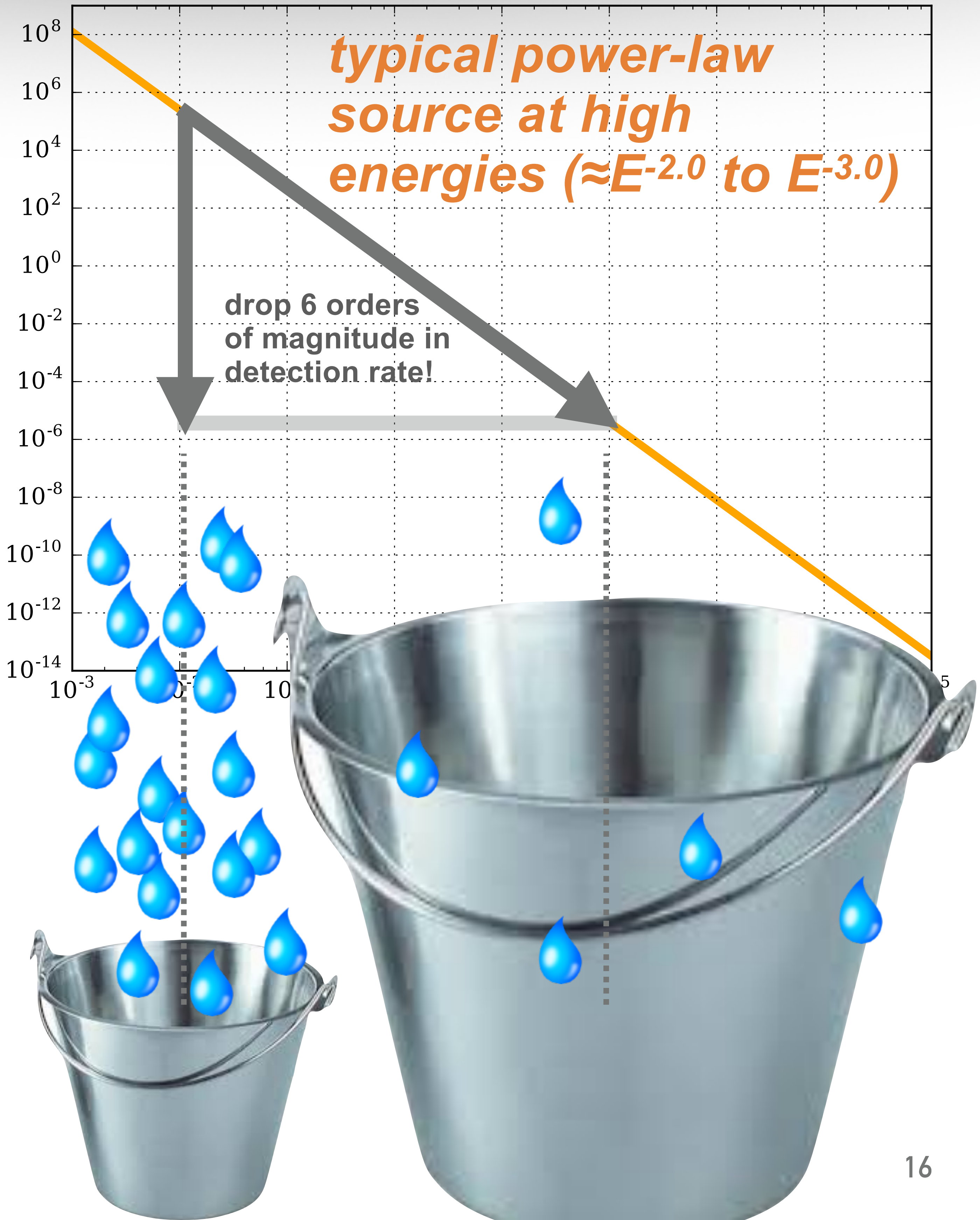

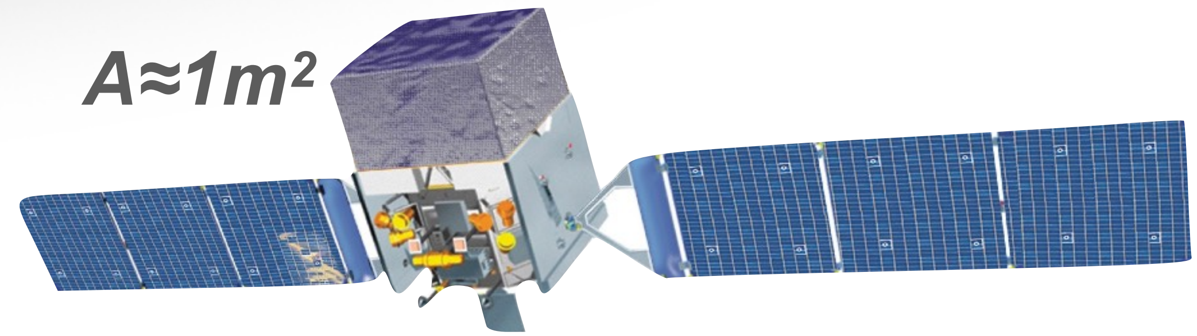

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16

Pair production to EAS

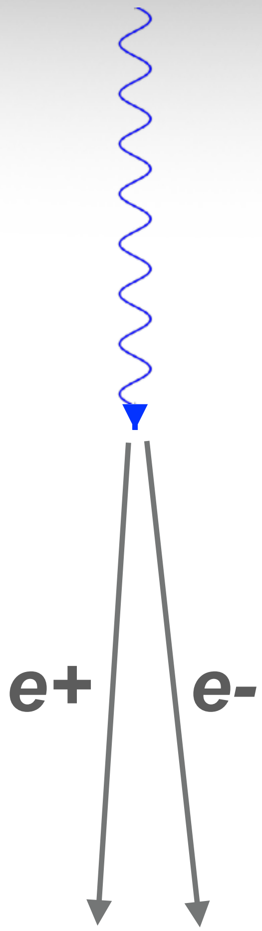
0

1

2

3

4



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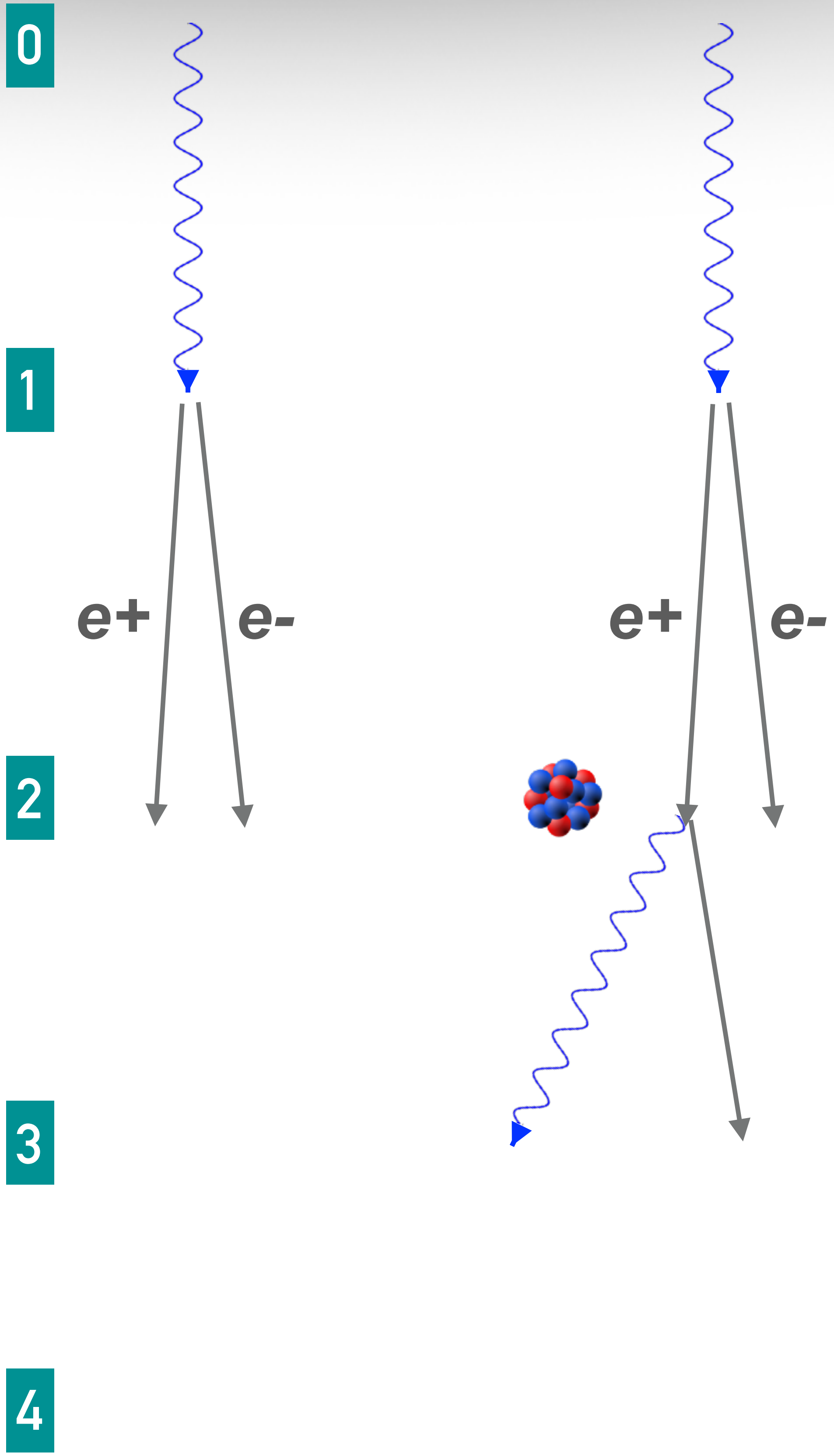

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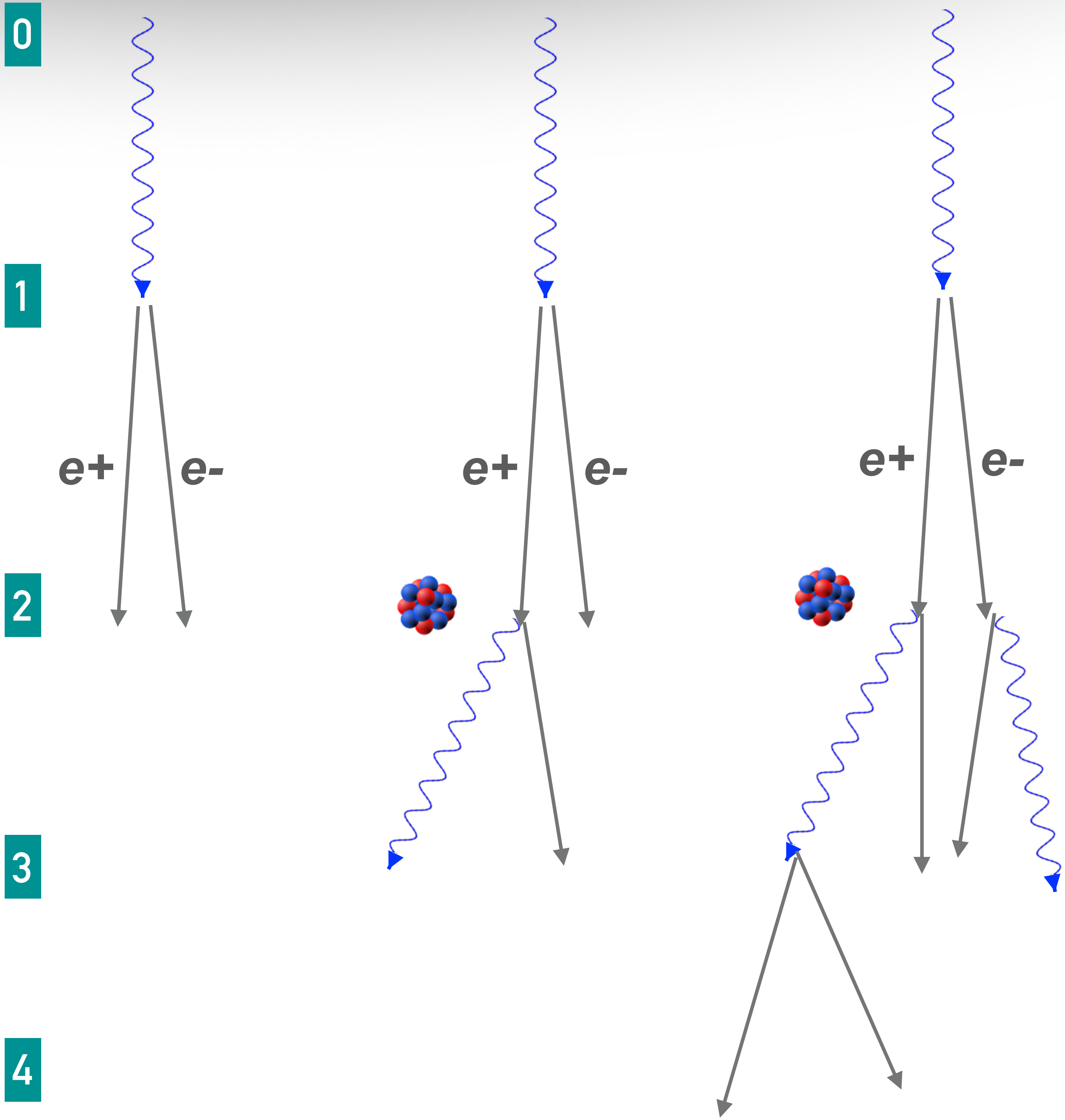

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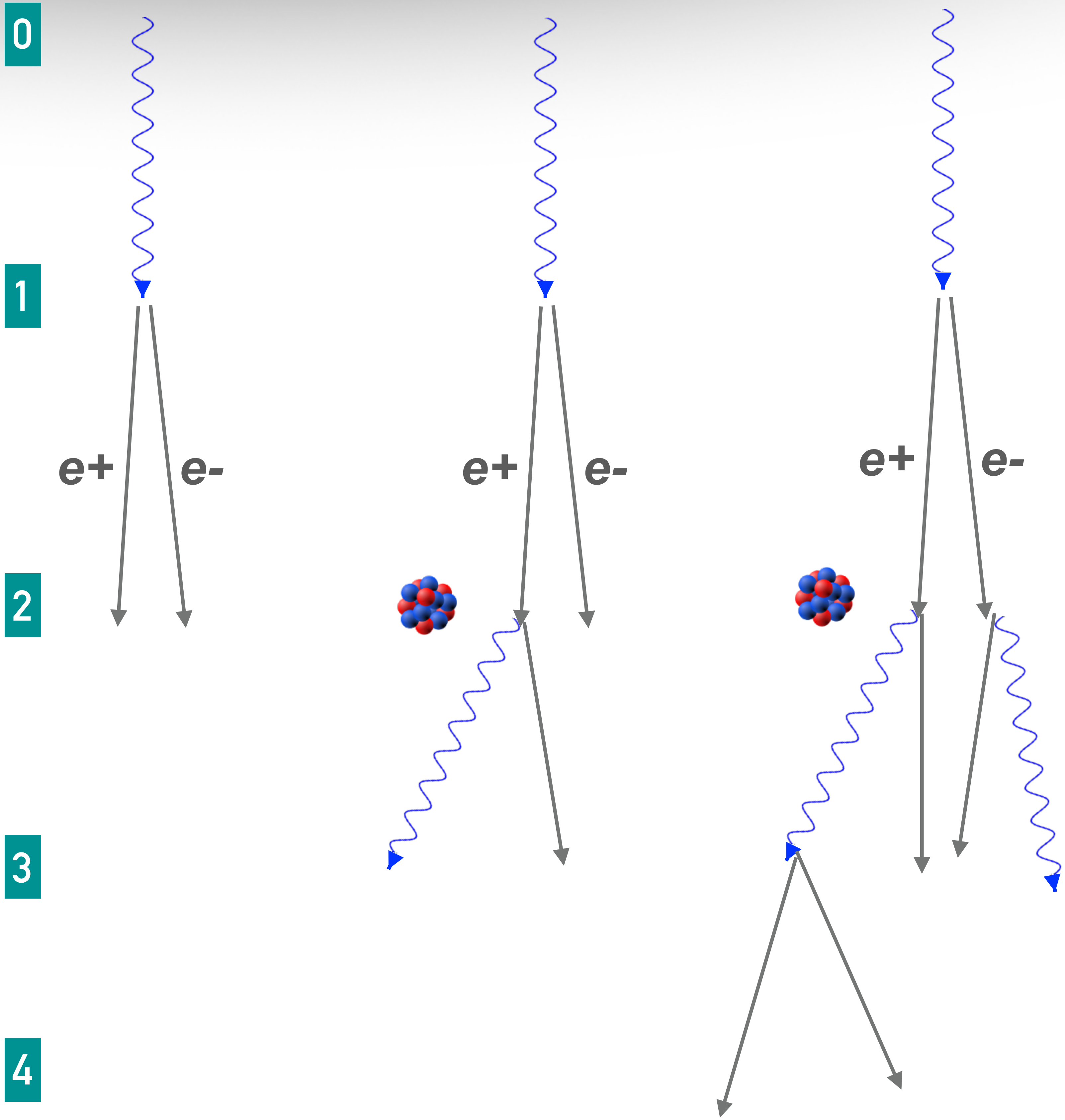
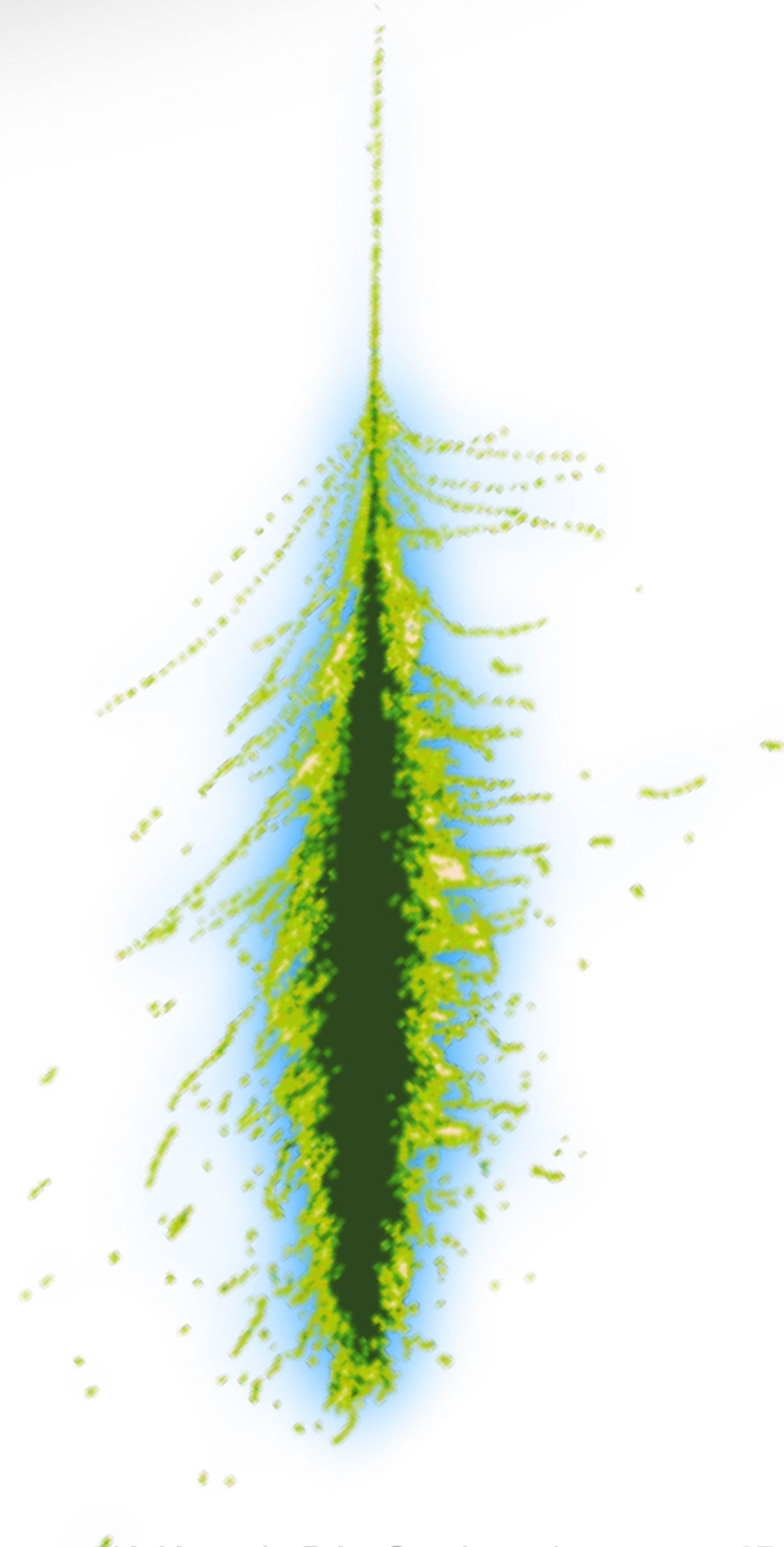
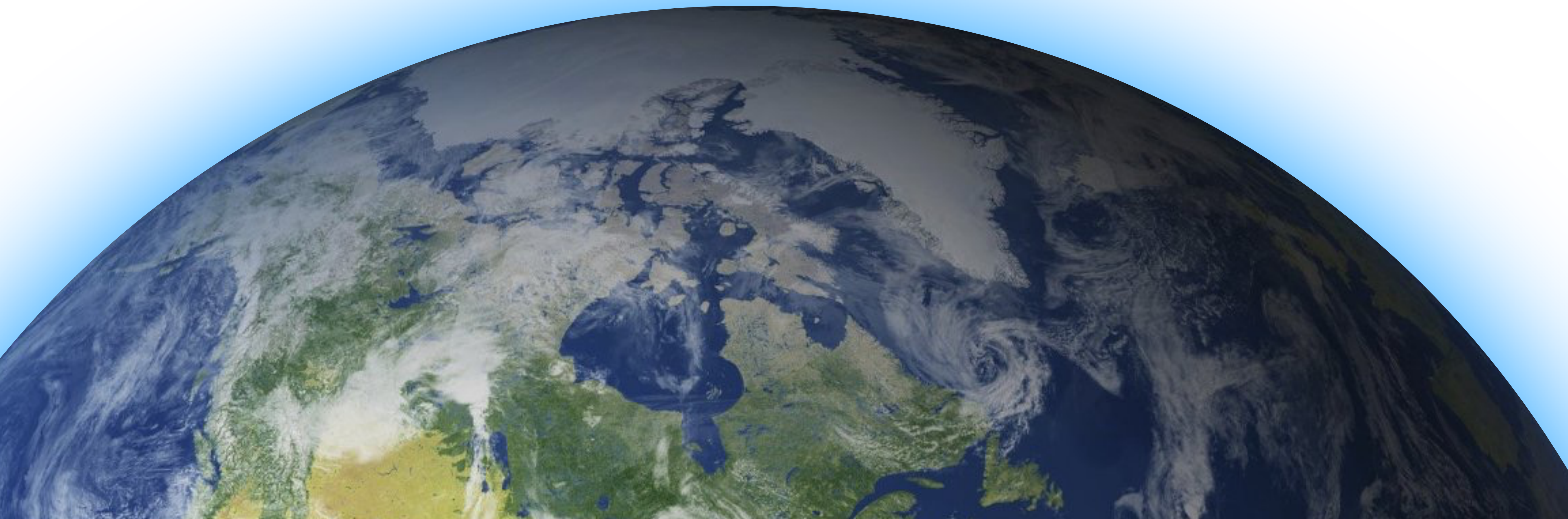




Atmospheric Cherenkov Technique

Showers can be produced in many media, but we want a large detection volume (100,000+ m^2 needed!):

- Radiation and interaction length ≈ 37 g/cm^2
- Earth's Atmosphere is ≈1000 g/cm^2 thick
- Showers form and complete before hitting ground
- Just need a detector...



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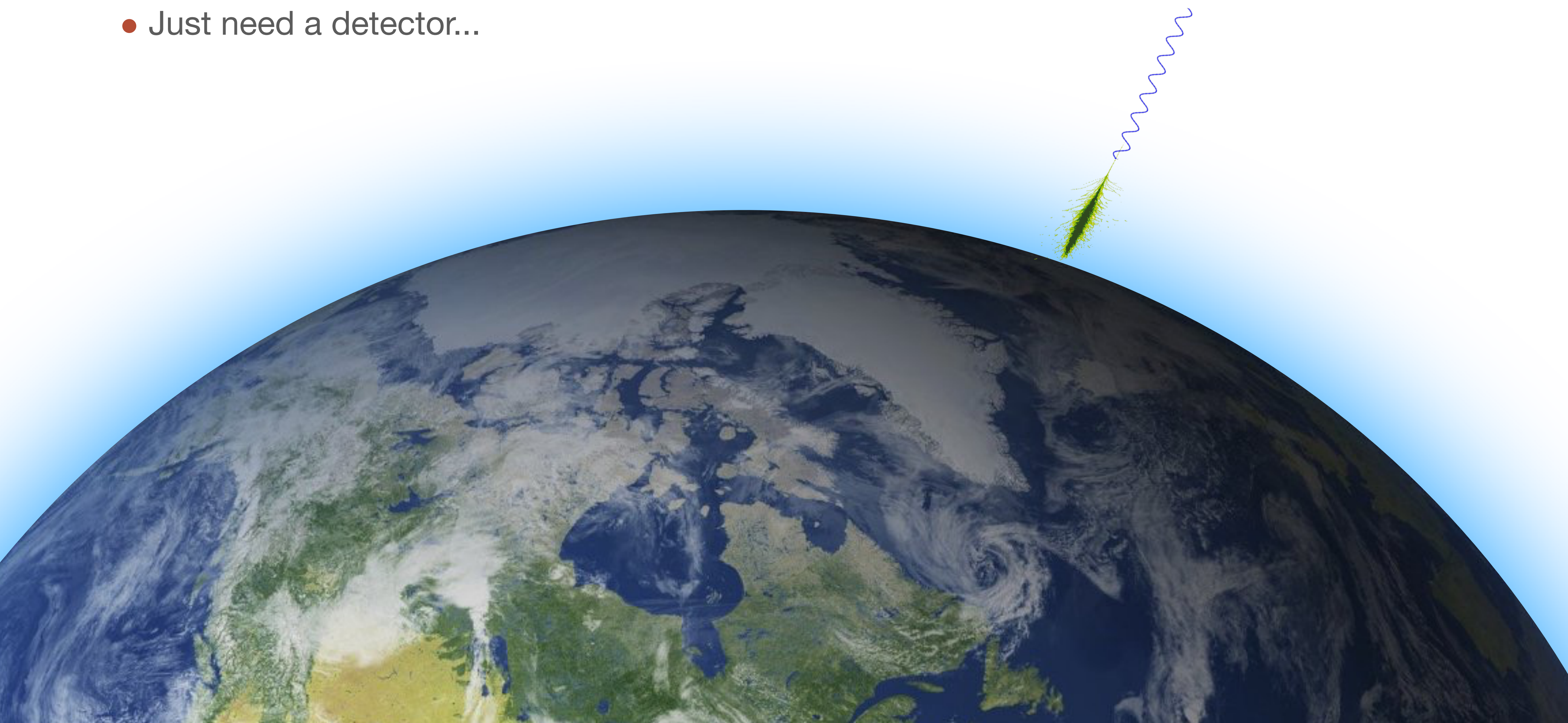
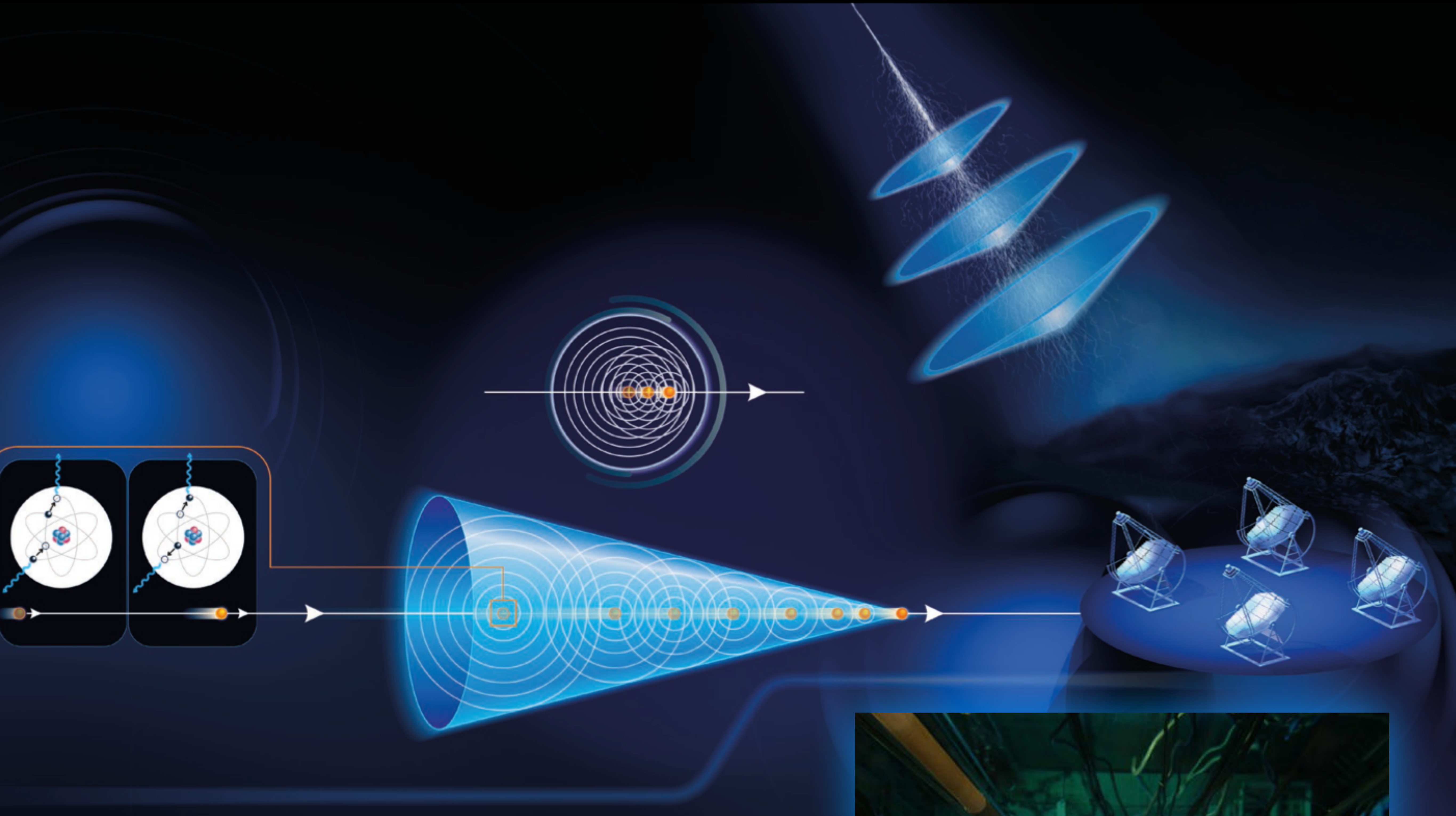
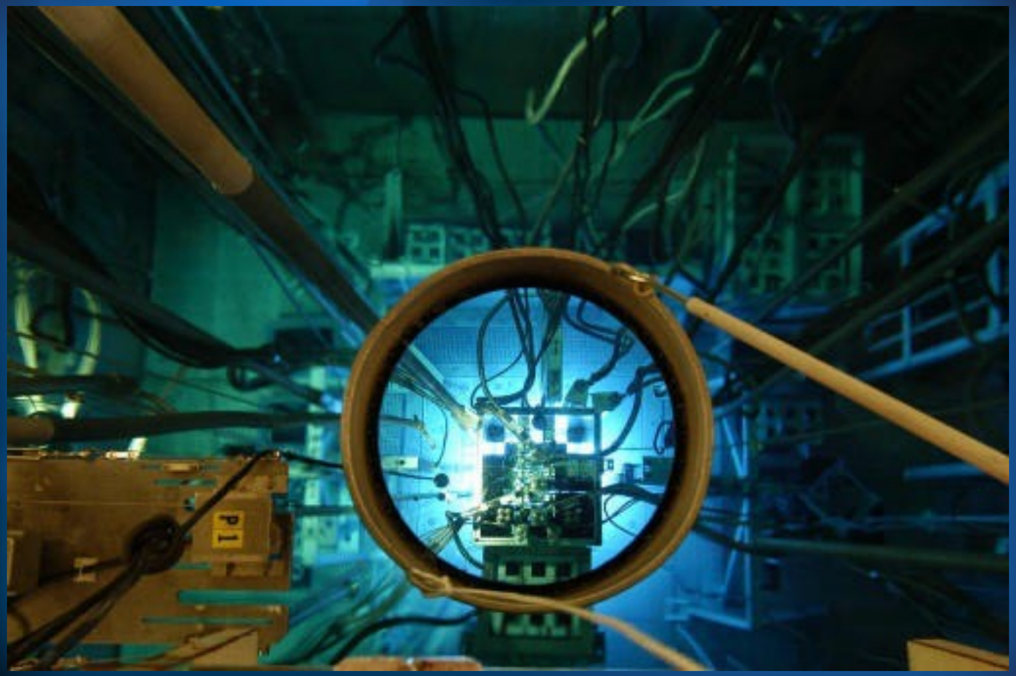


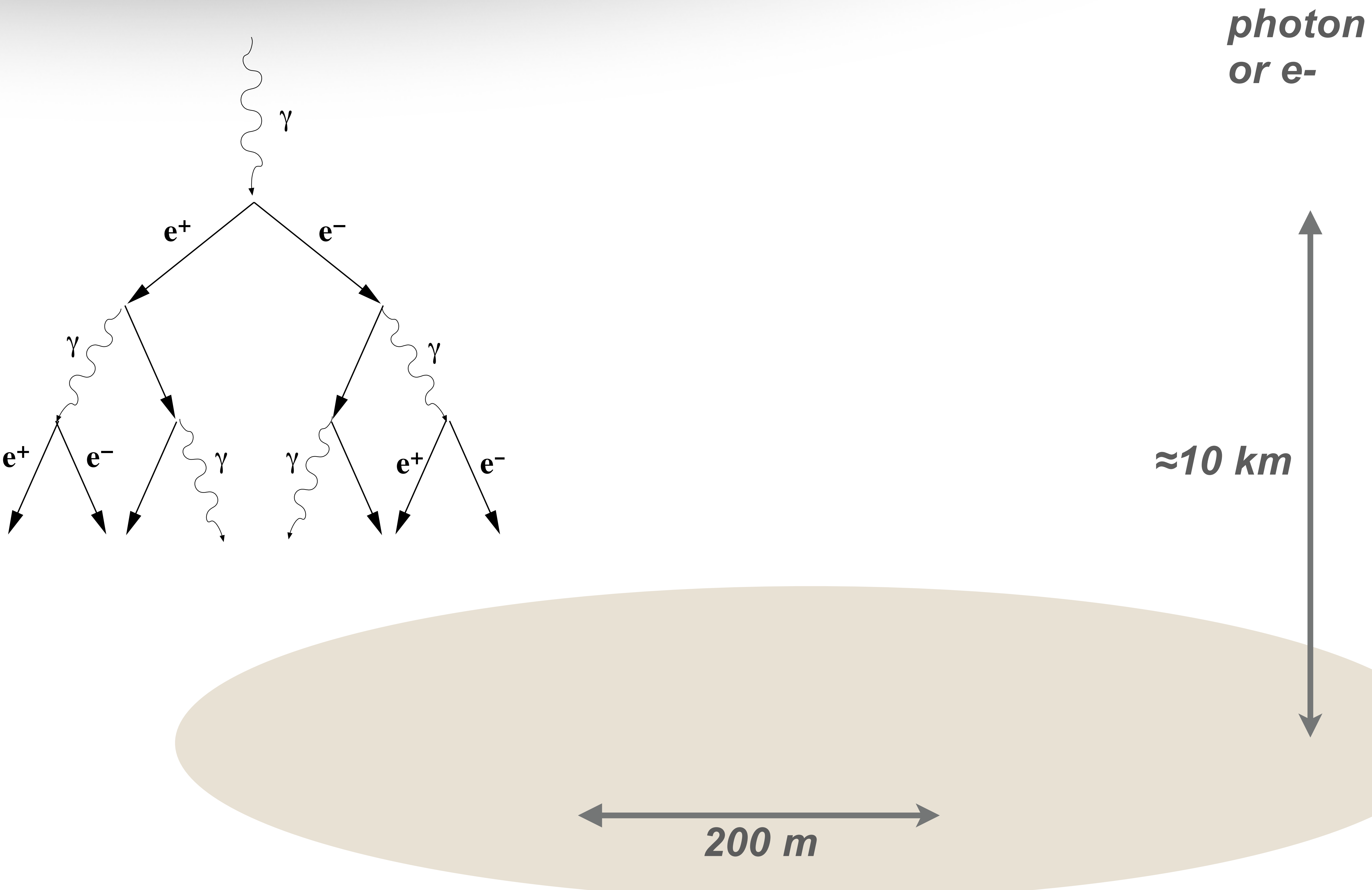




Osiris reactor, CEA Saclay

Credit: Les Défis du CEA, N°197 , March 2015- ©CEA/ Fabrice Mathé

Electromagnetic Showers



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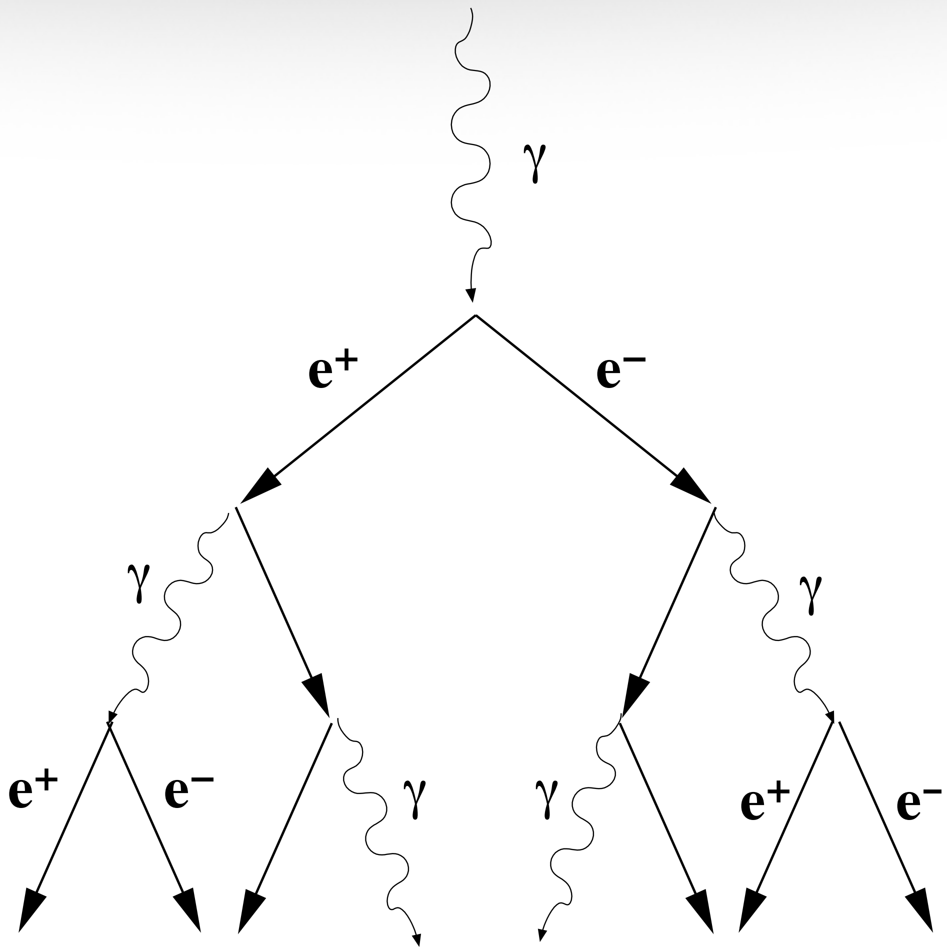

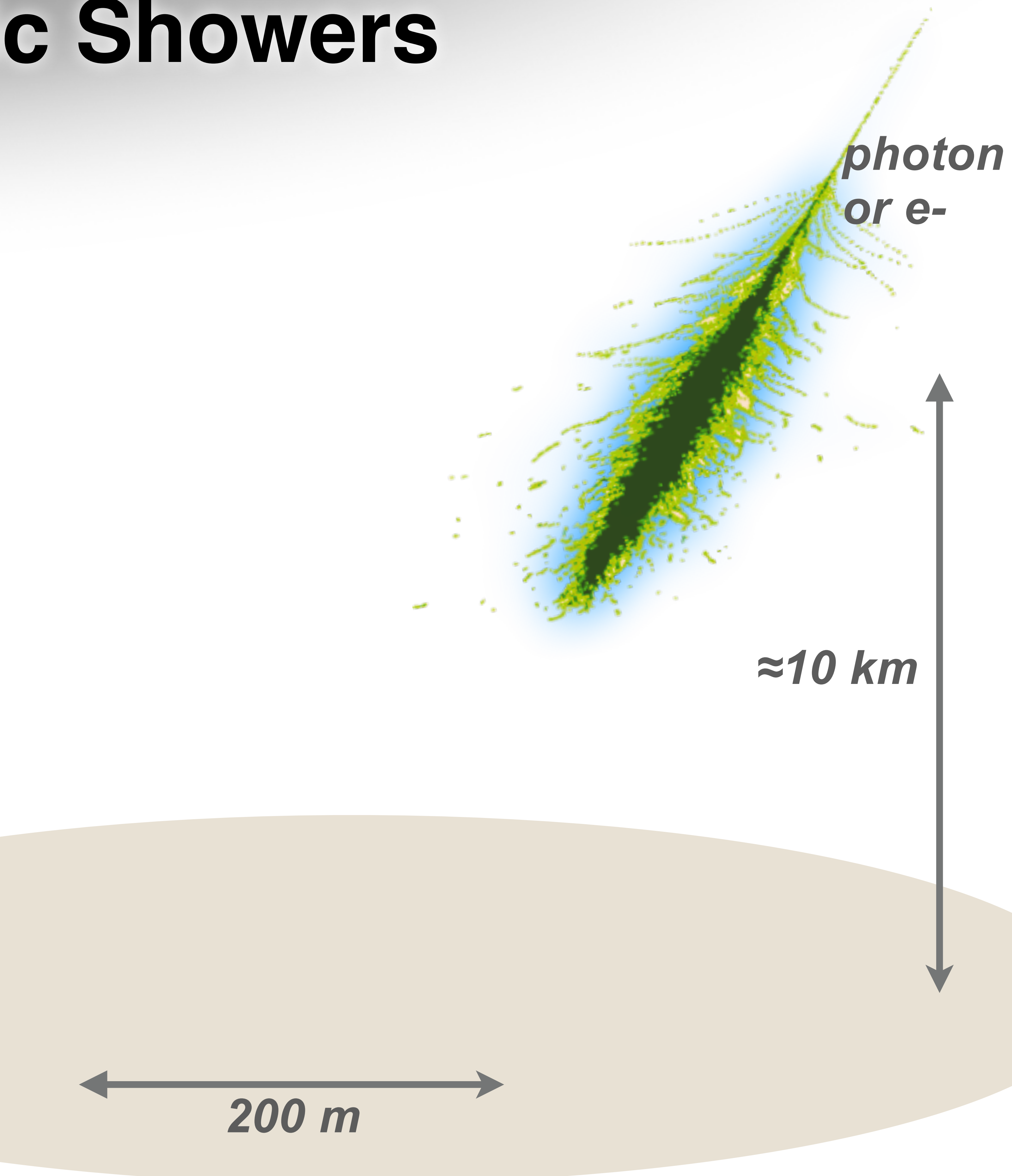

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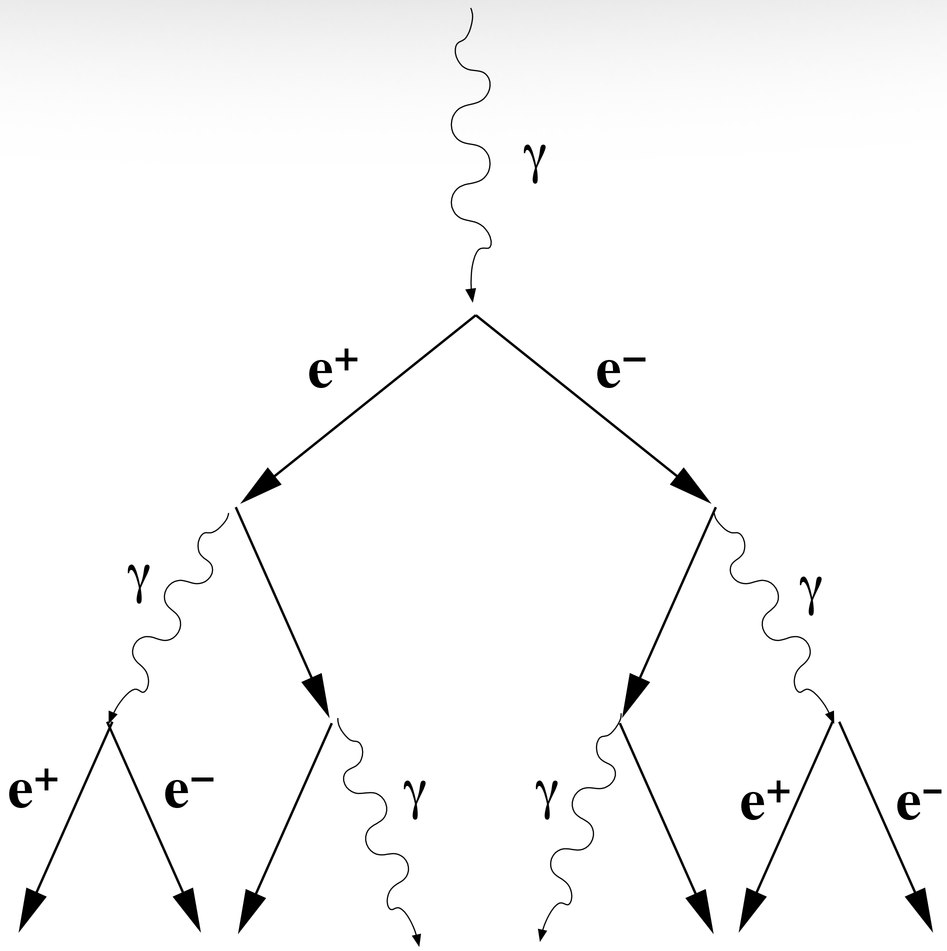

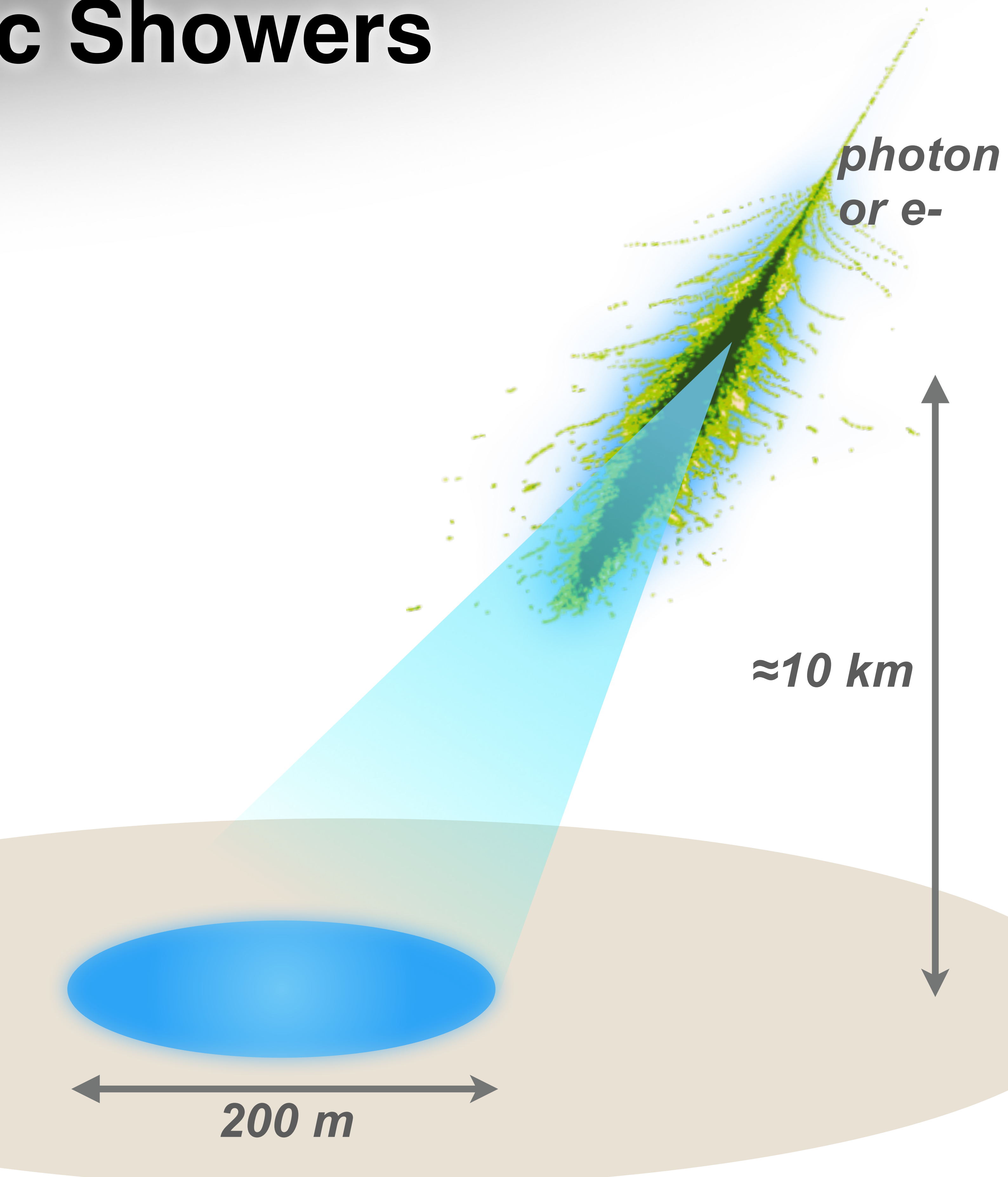

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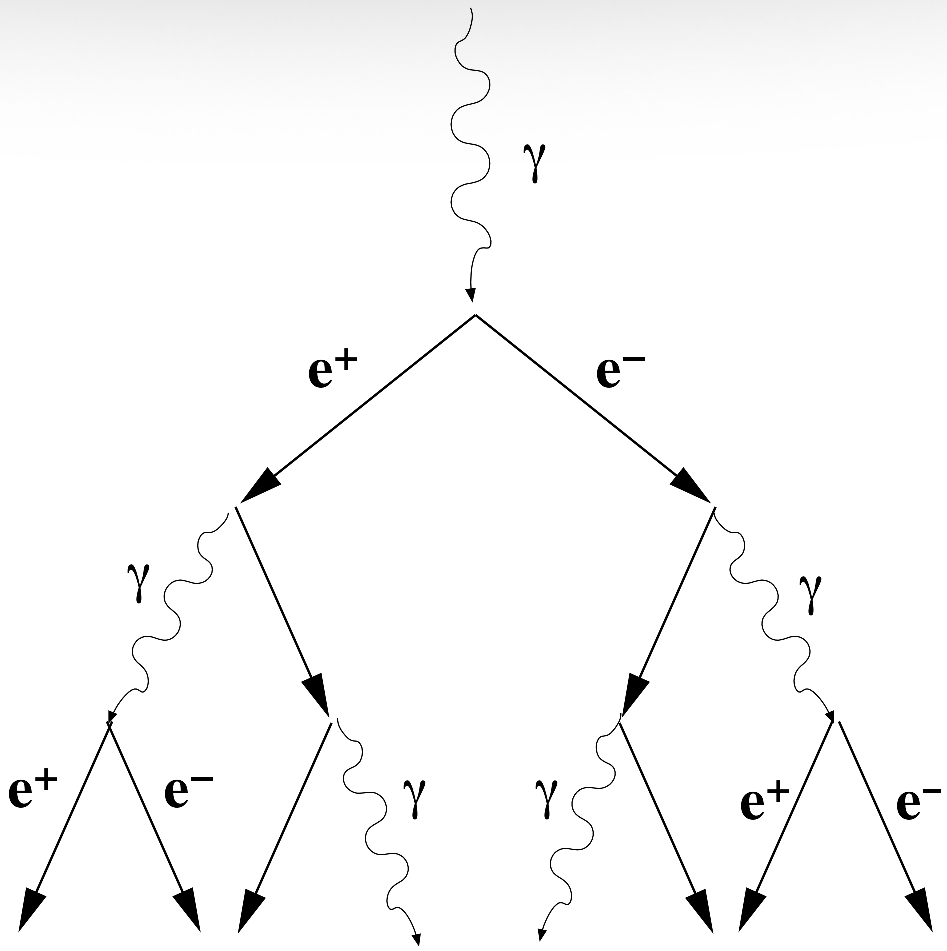
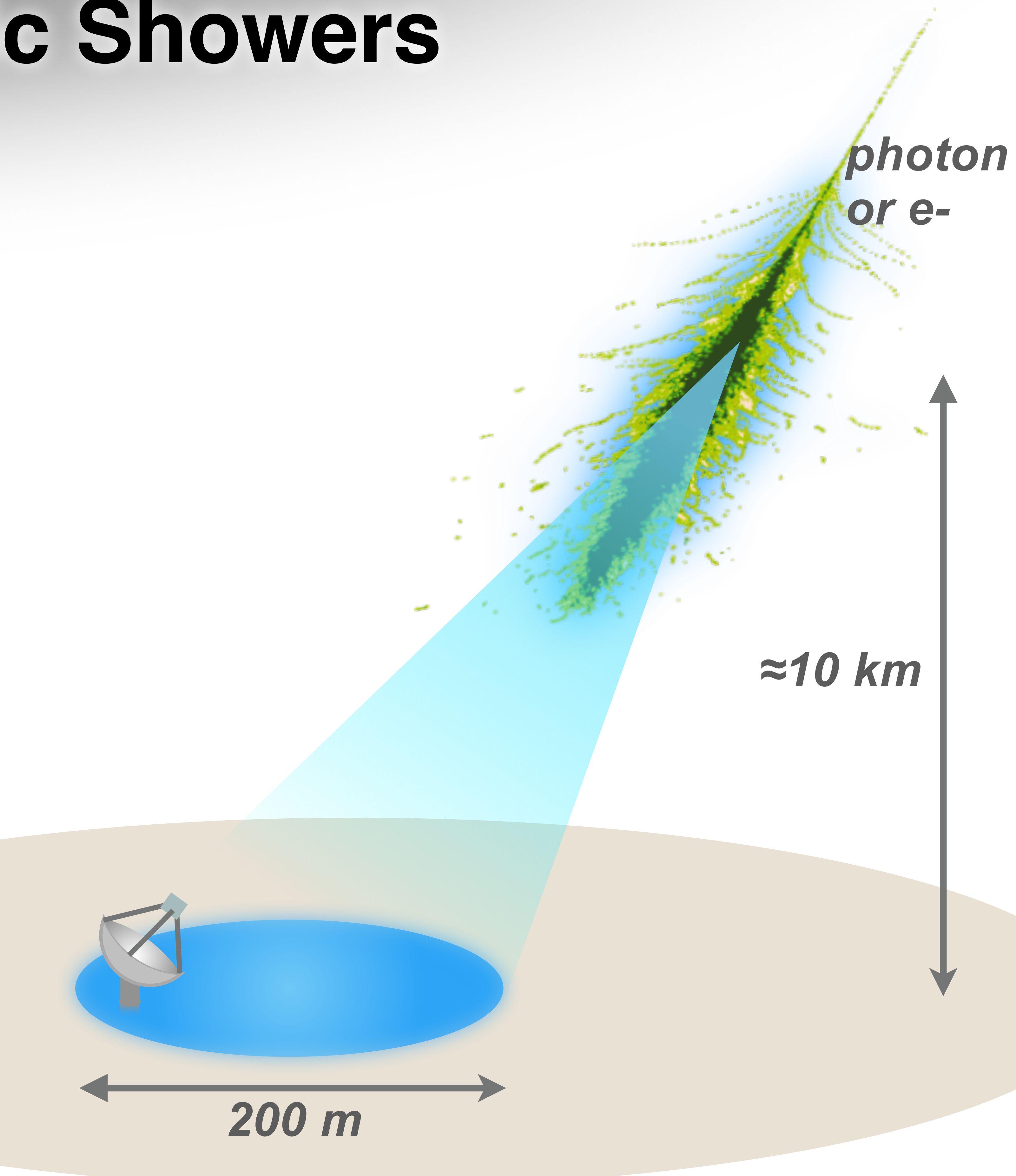
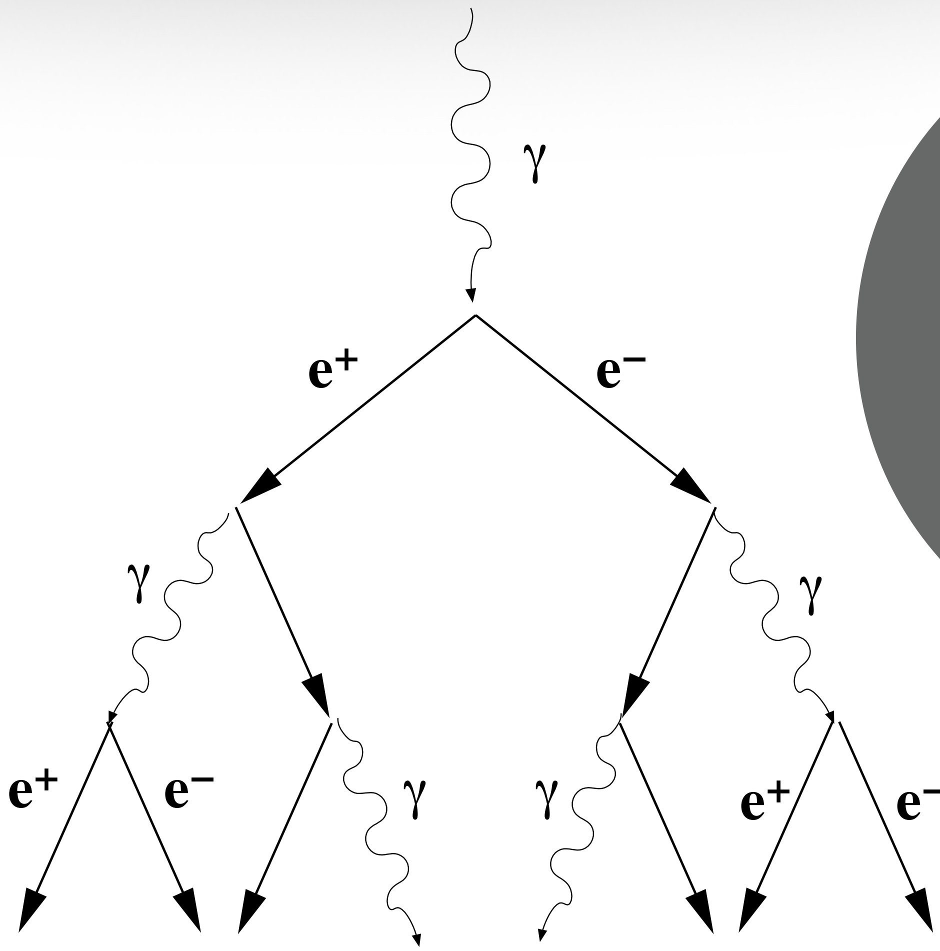
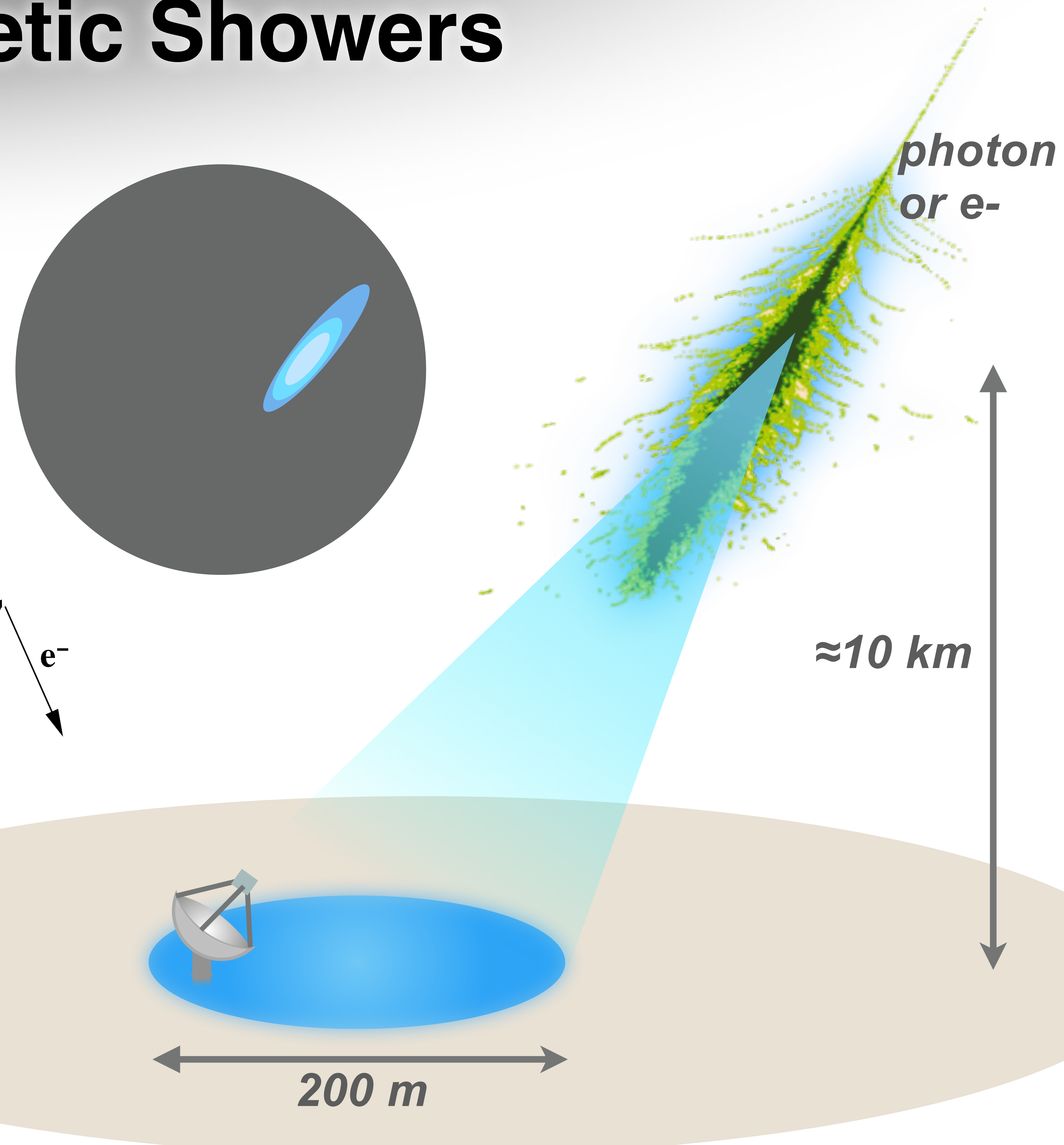




Electromagnetic Showers





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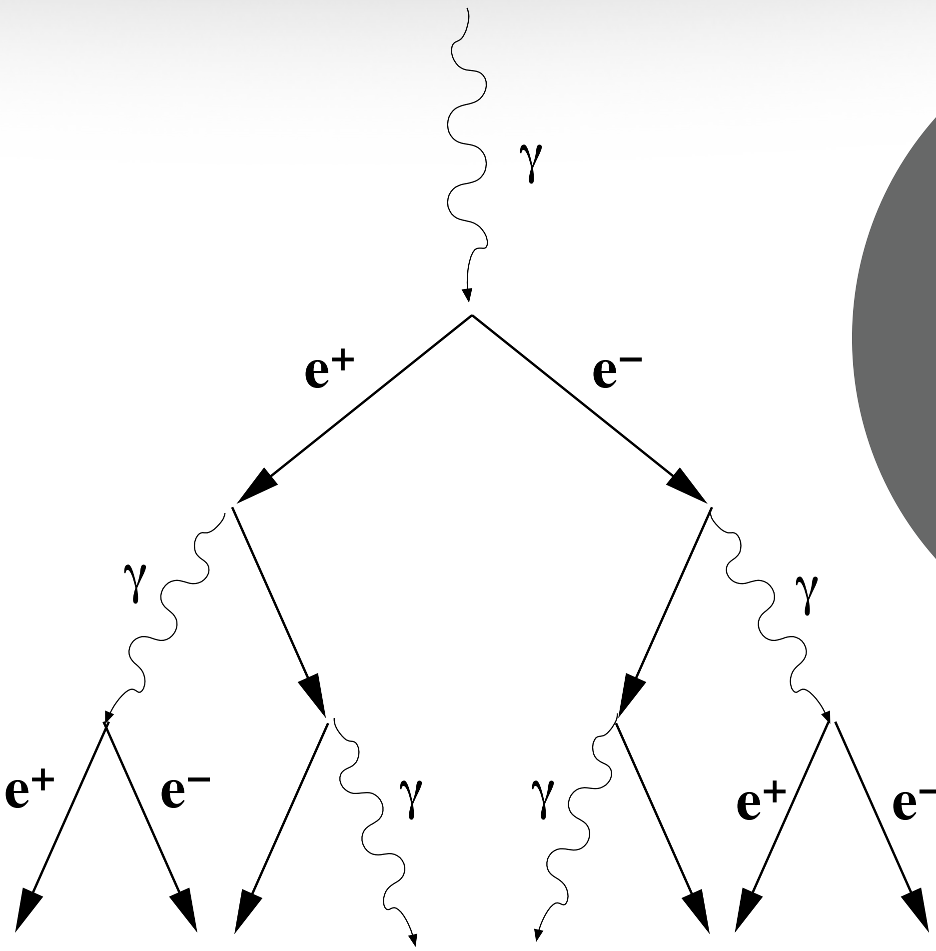
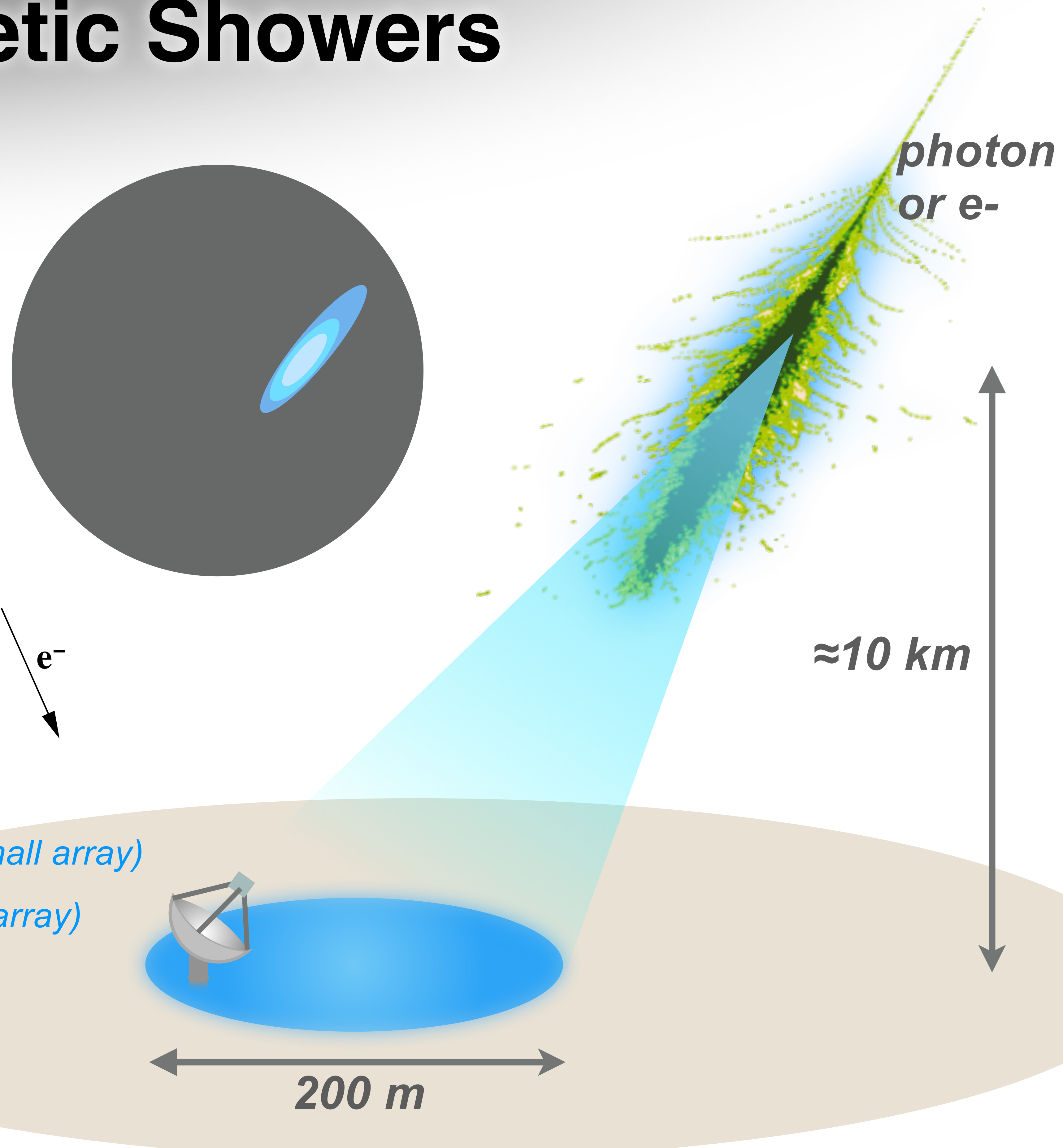




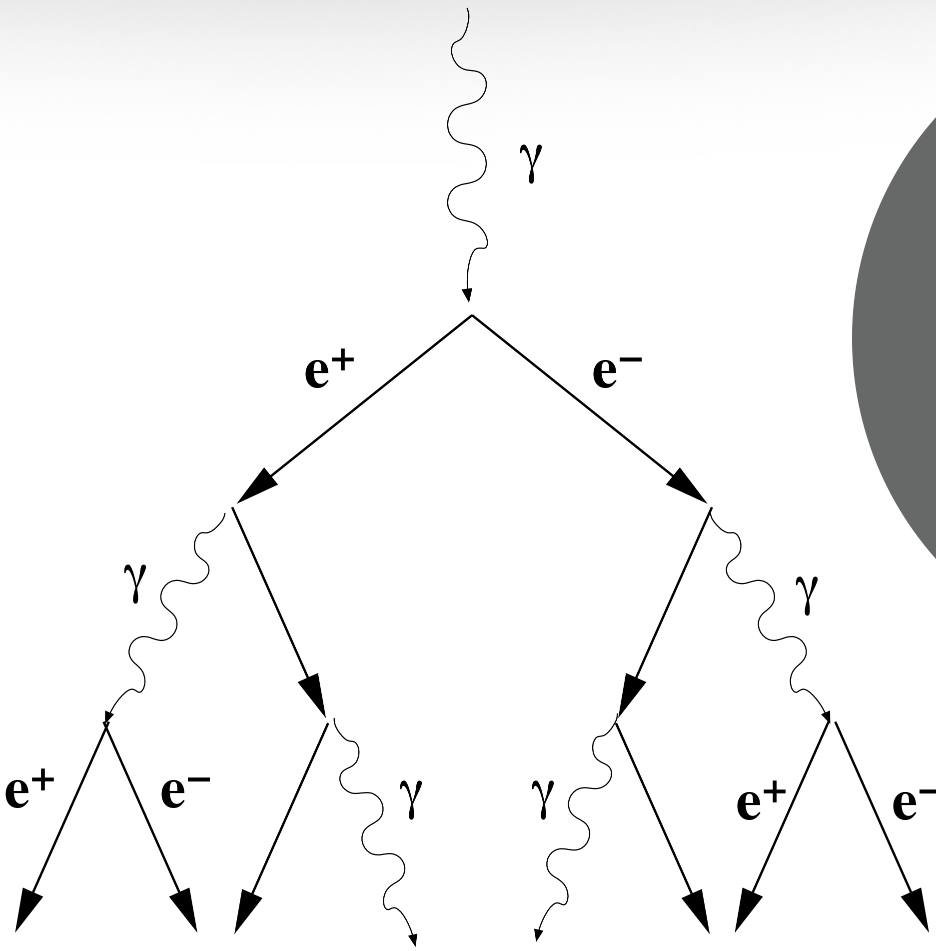
> 30k m2

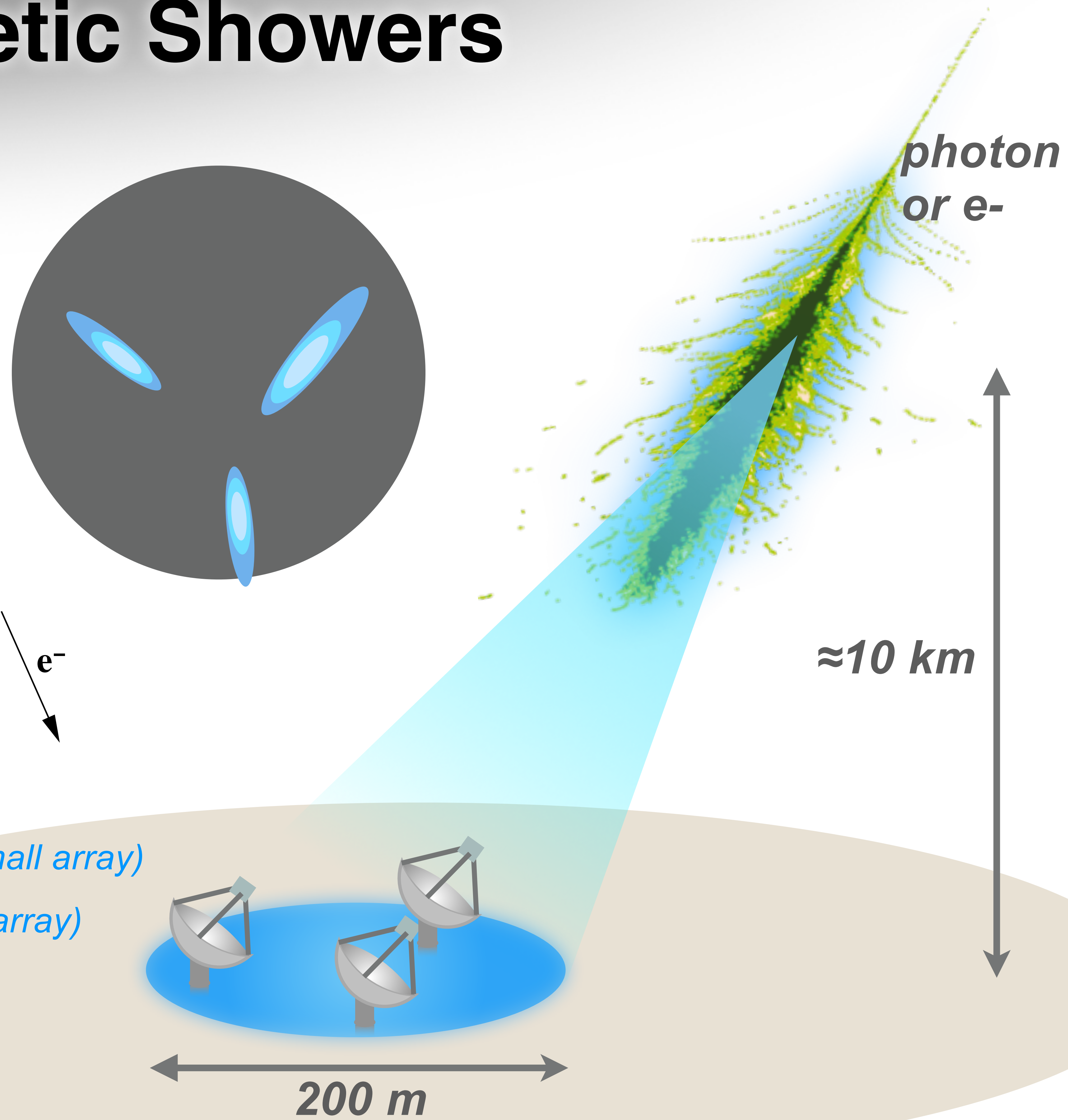
effective area *≈ size of light pool (small array)*

≈ size of array (large array)

Energy *prop to total intensity*

Electromagnetic Showers





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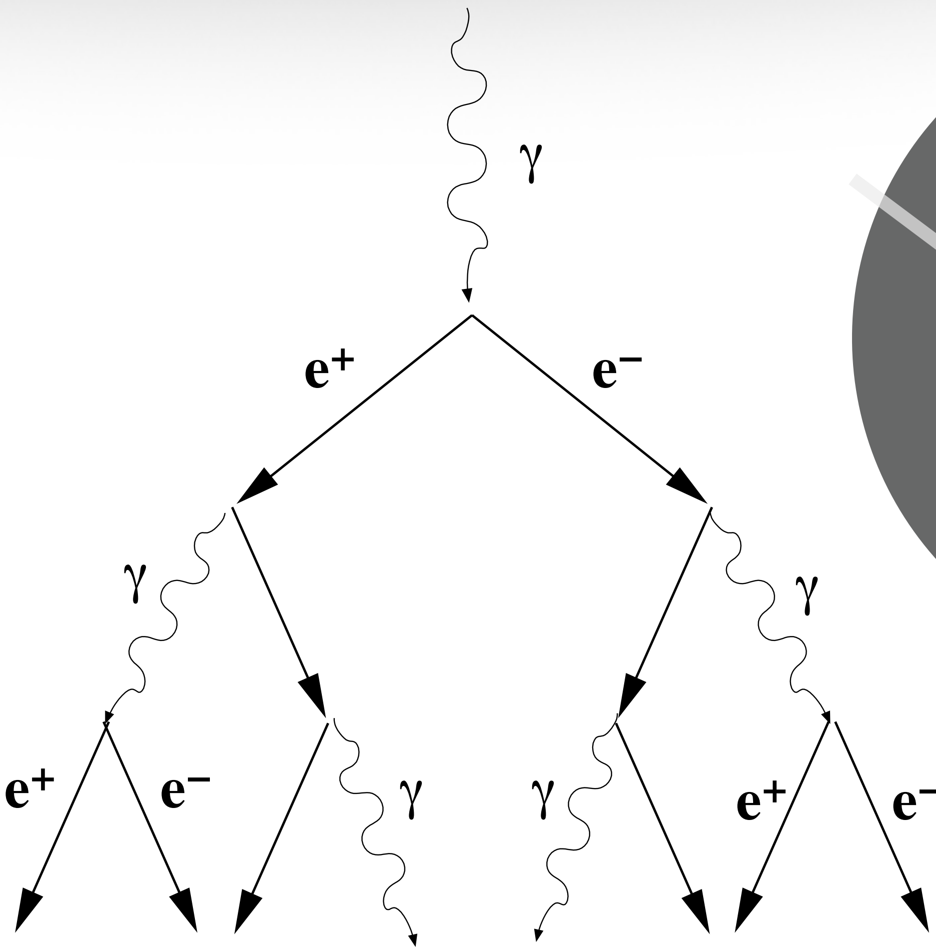

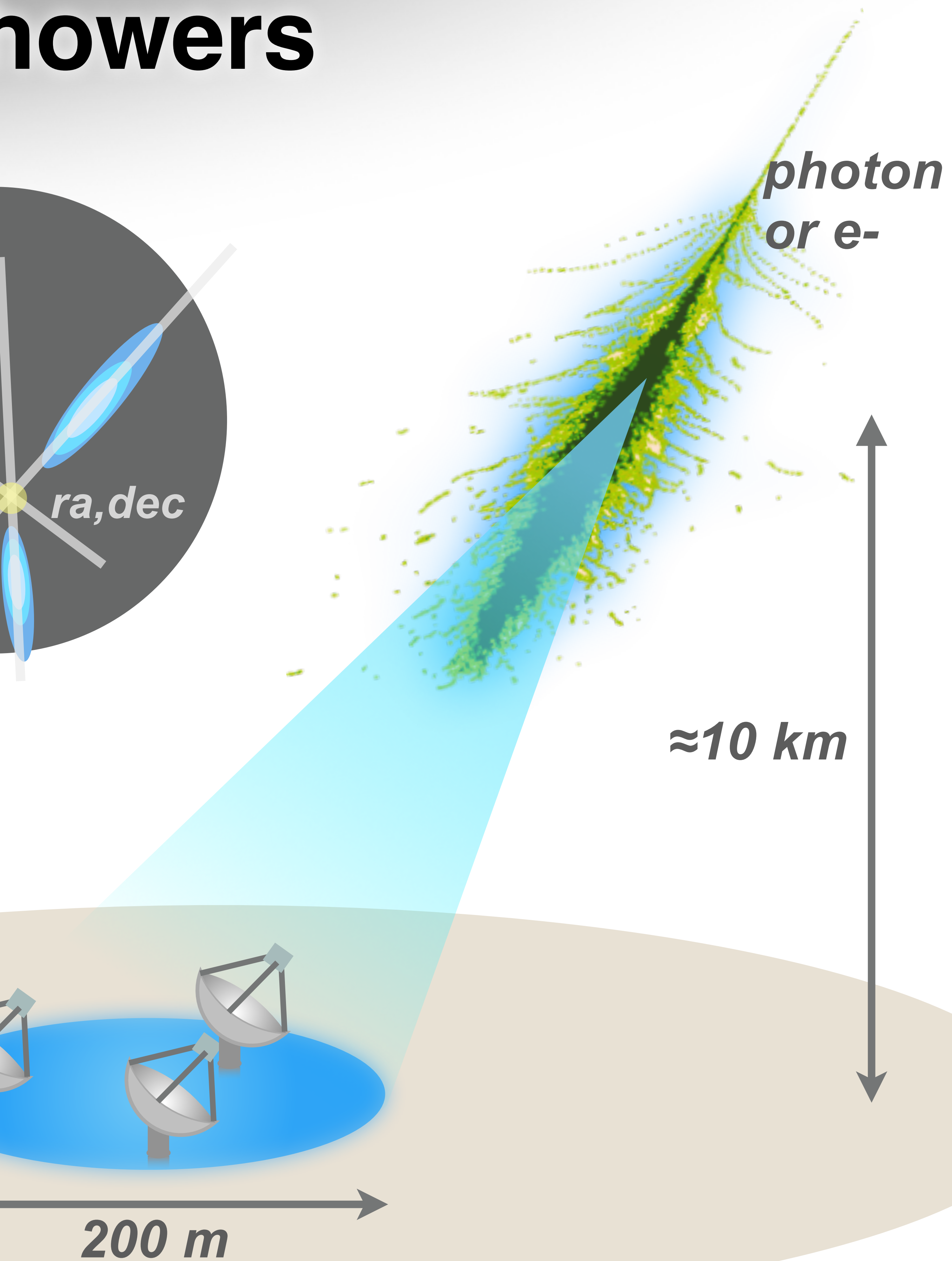

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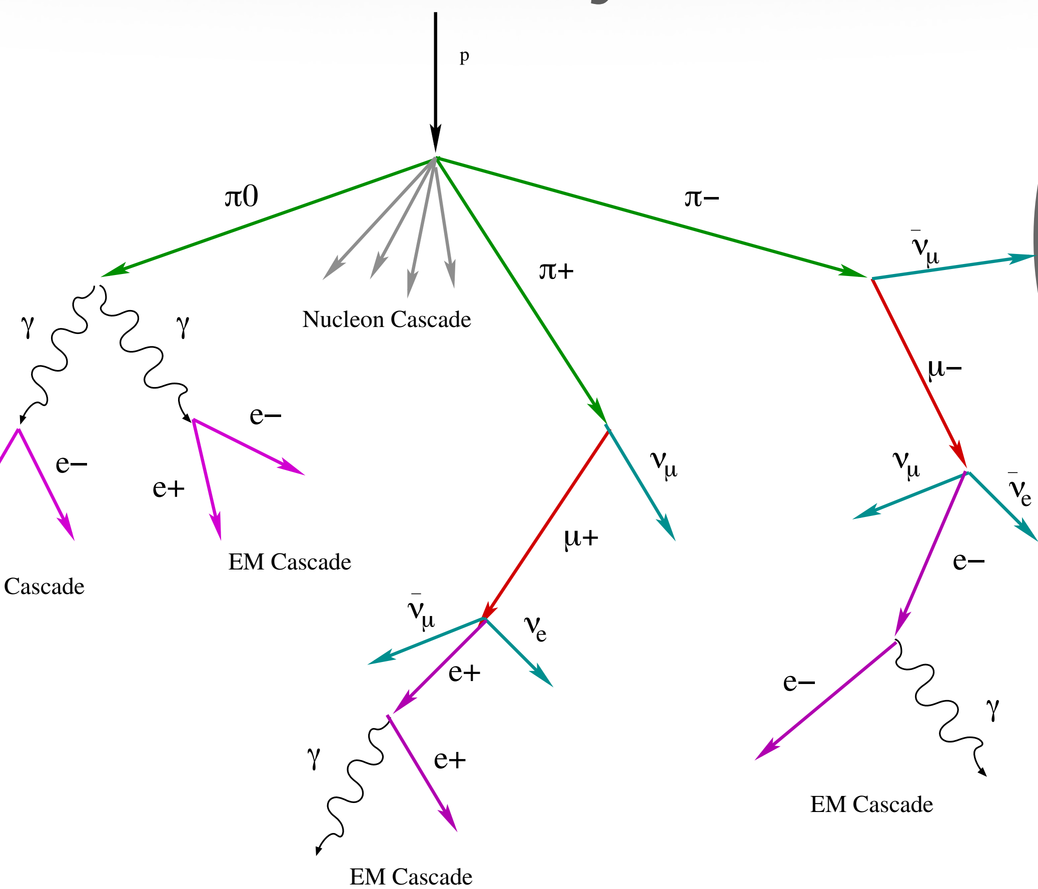
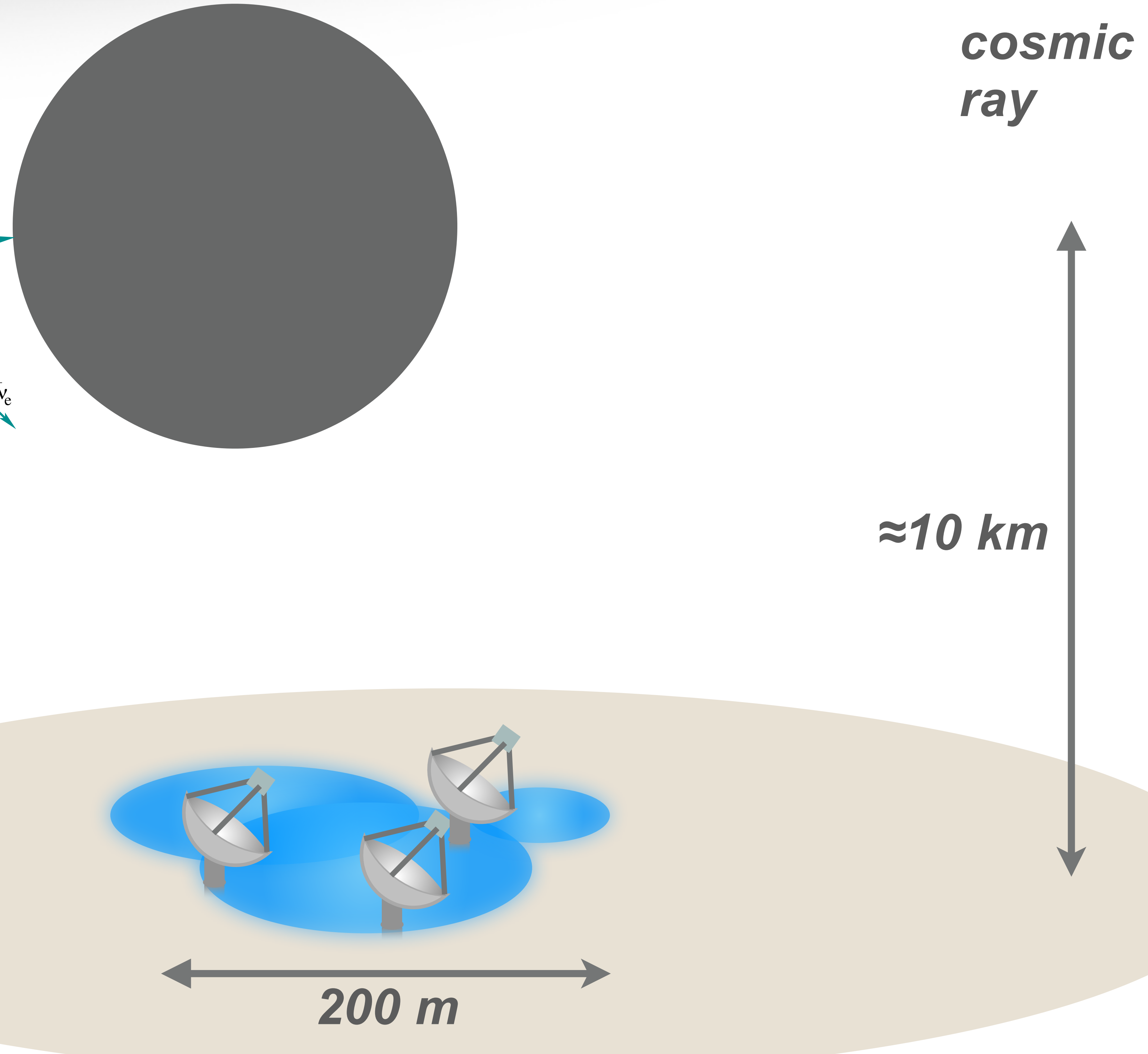
Hadronic Showers

Problem: 10^4-10^5 more Cosmic Rays than Gammas!

cosmic ray



EM sub-showers



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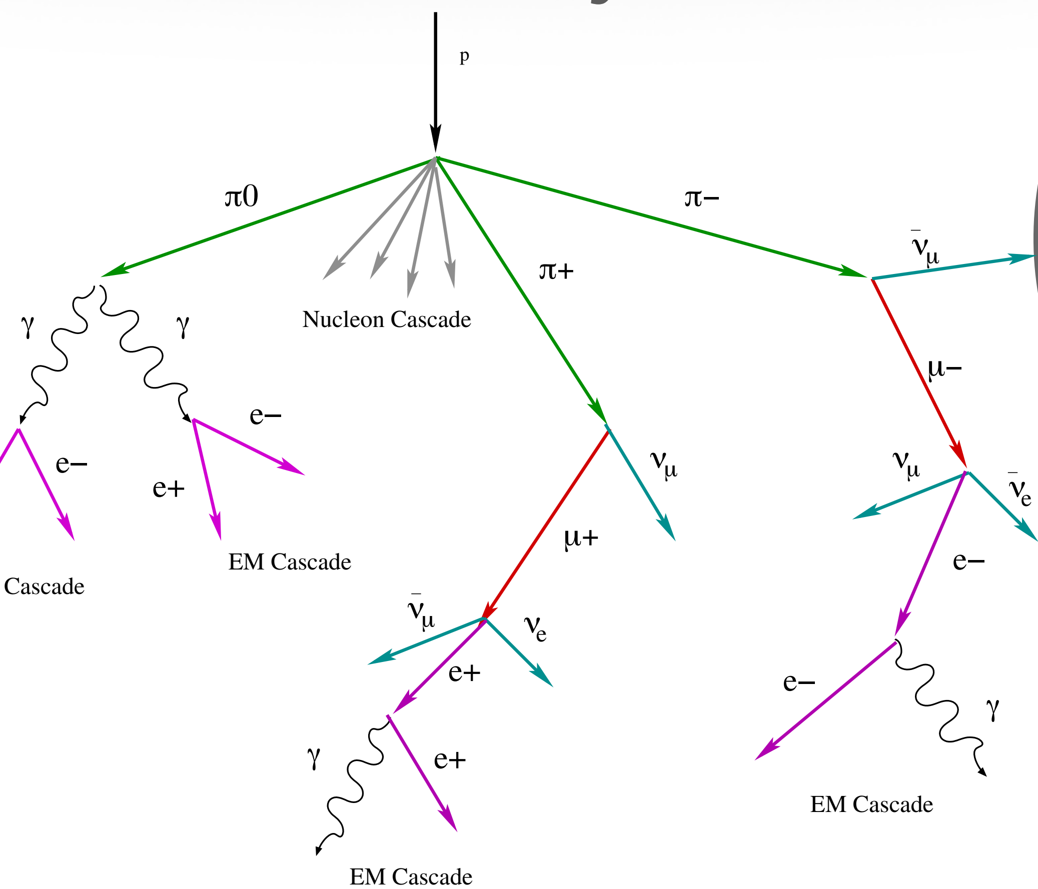

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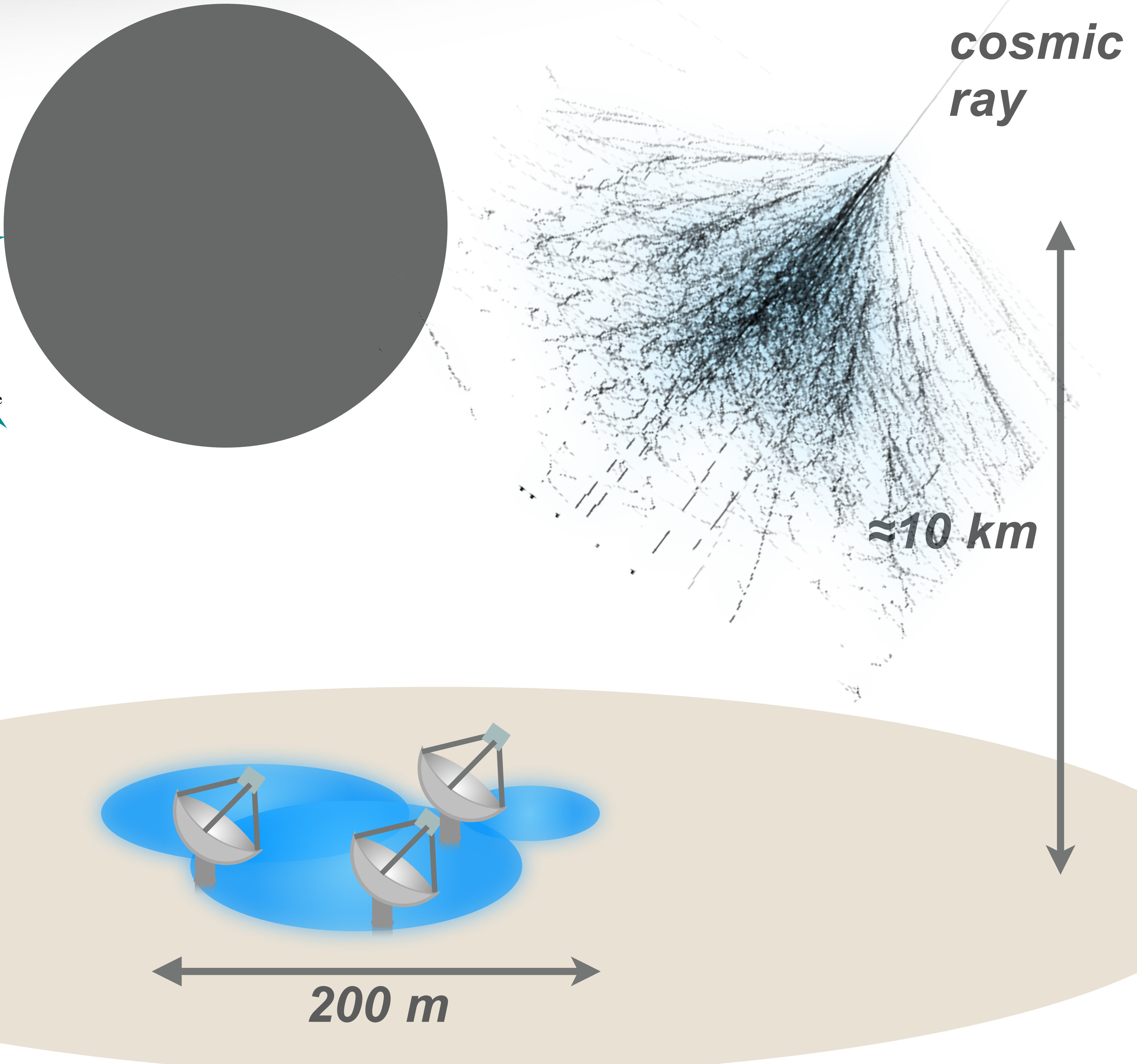

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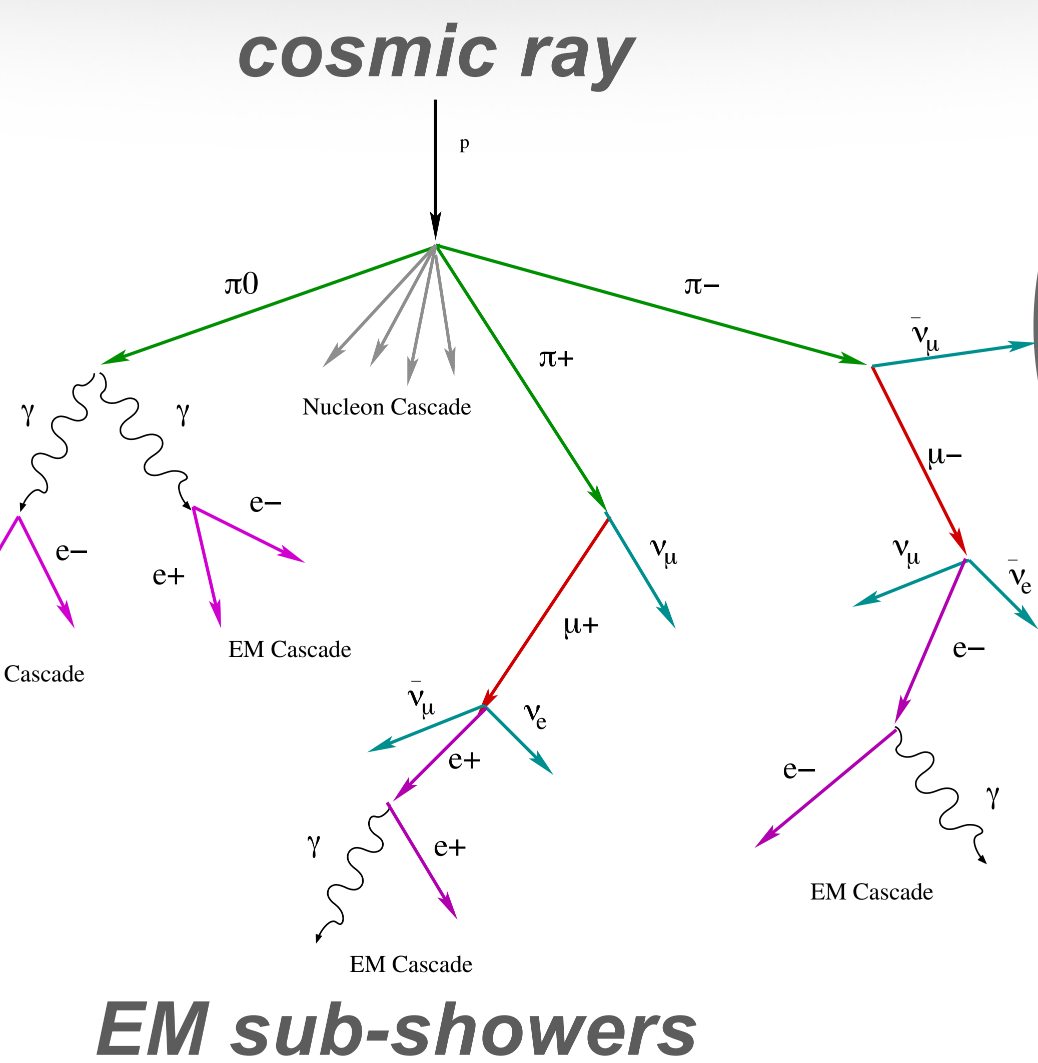

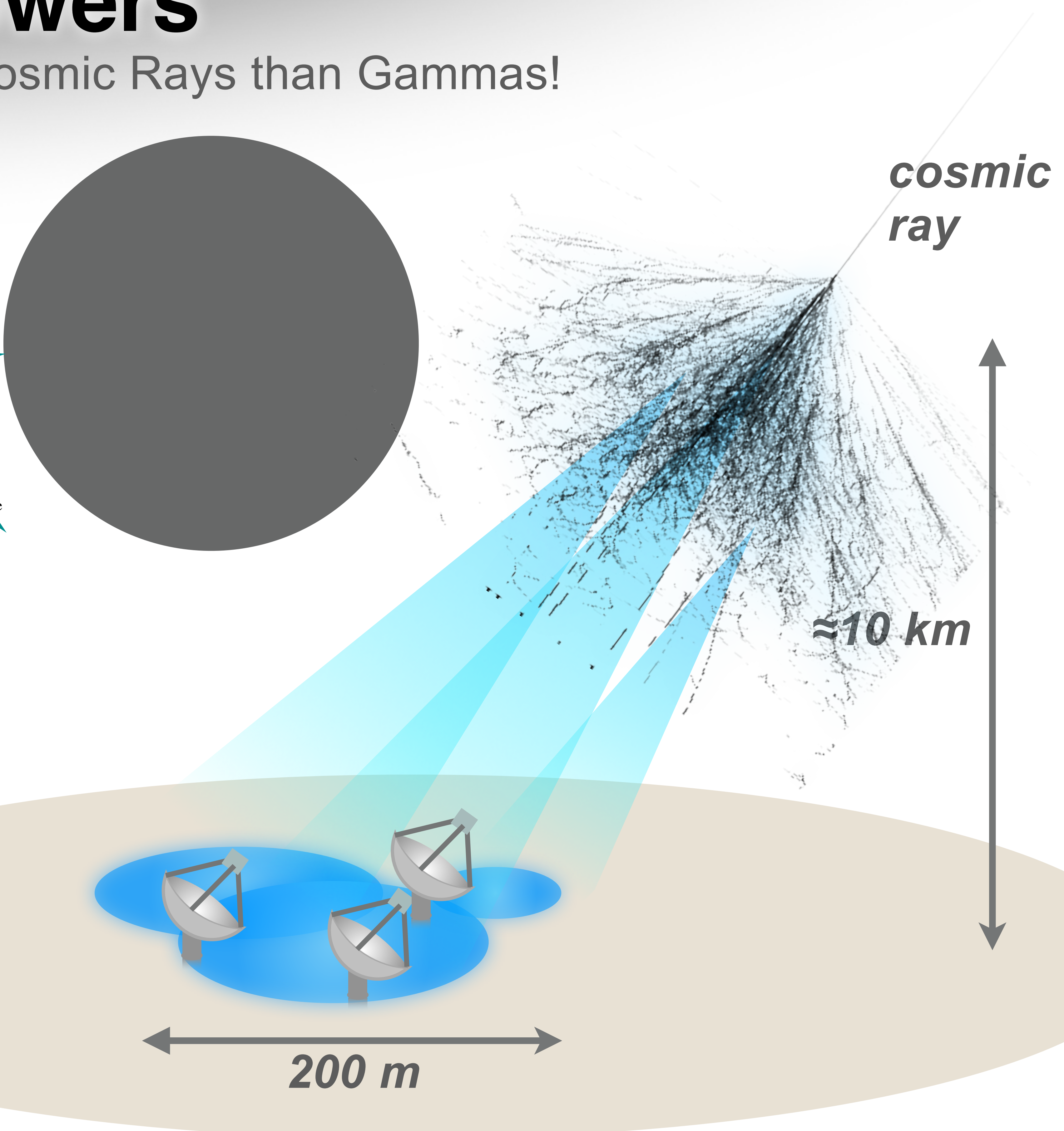

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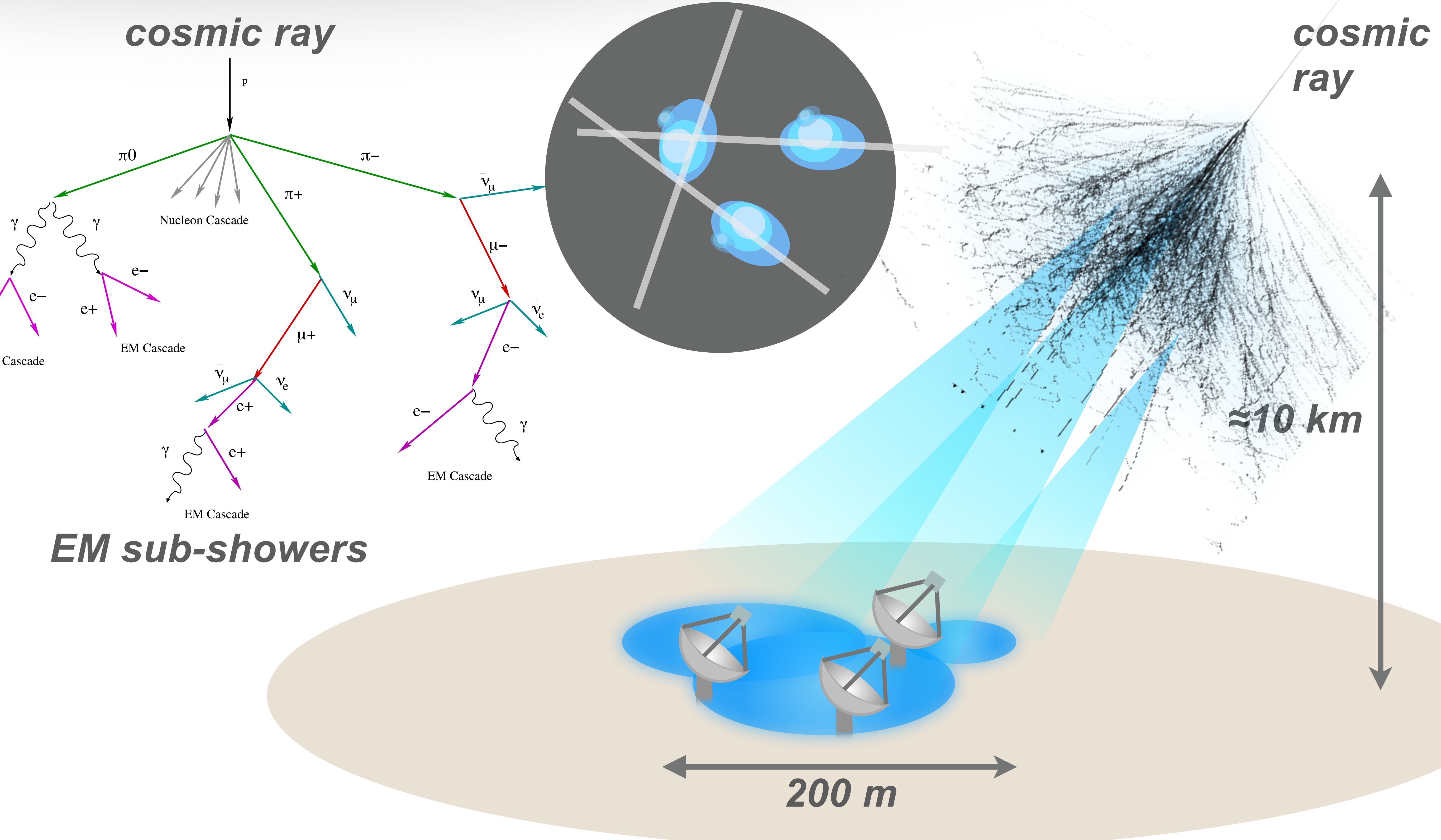


1 TeV Gamma
R: e⁺/e⁻
G: μ⁺/μ⁻
B: other
0.0 ns
100 m
[M. Nöthe]

1 TeV Gamma
R: e⁺/e⁻
G: μ⁺/μ⁻
B: other
0.0 ns
100 m
[M. Nöthe]


1 TeV Proton
R: e^+/e^-
G: μ^+/μ^-
B: other
0.1 ns
100 m
[M. Nöthe]


1 TeV Proton
R: e⁺/e⁻
G: μ⁺/μ⁻
B: other
0.1 ns
100 m
[M. Nöthe]

10 TeV Iron
R: e^+/e^-
G: μ^+/μ^-
B: p

0.0 ns

10 TeV Iron

R: e^+/e^-

G: μ^+/μ^-

B: p

0.0 ns


1 TeV Gamma
0.0 ns
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B: other
100 m
[M. Nöthe]


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0.1 ns
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10 TeV Iron
0.0 ns
R: e⁺/e⁻
G: μ⁺/μ⁻
B: p


1 TeV Gamma
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B: other
0.0 ns
100 m
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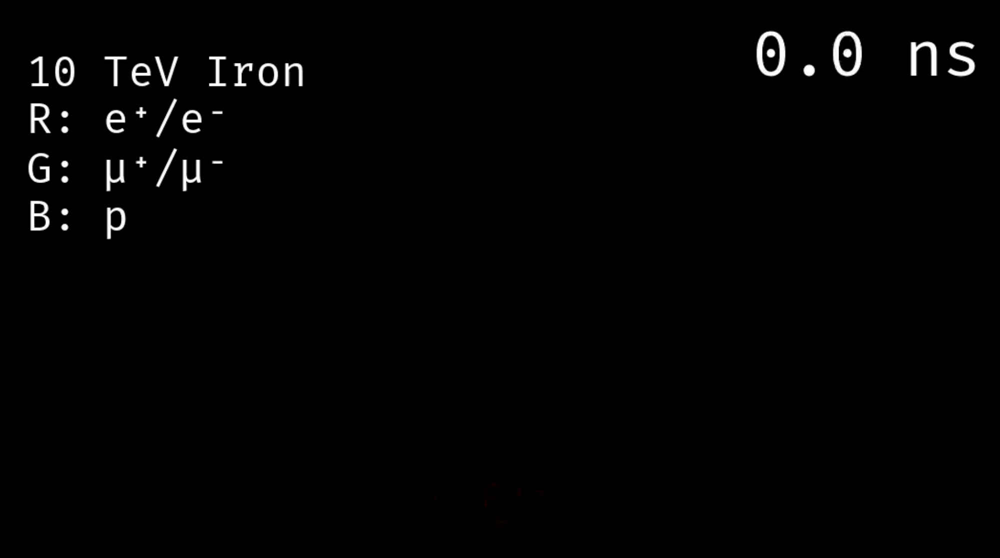
10 TeV Iron
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B: p
0.0 ns

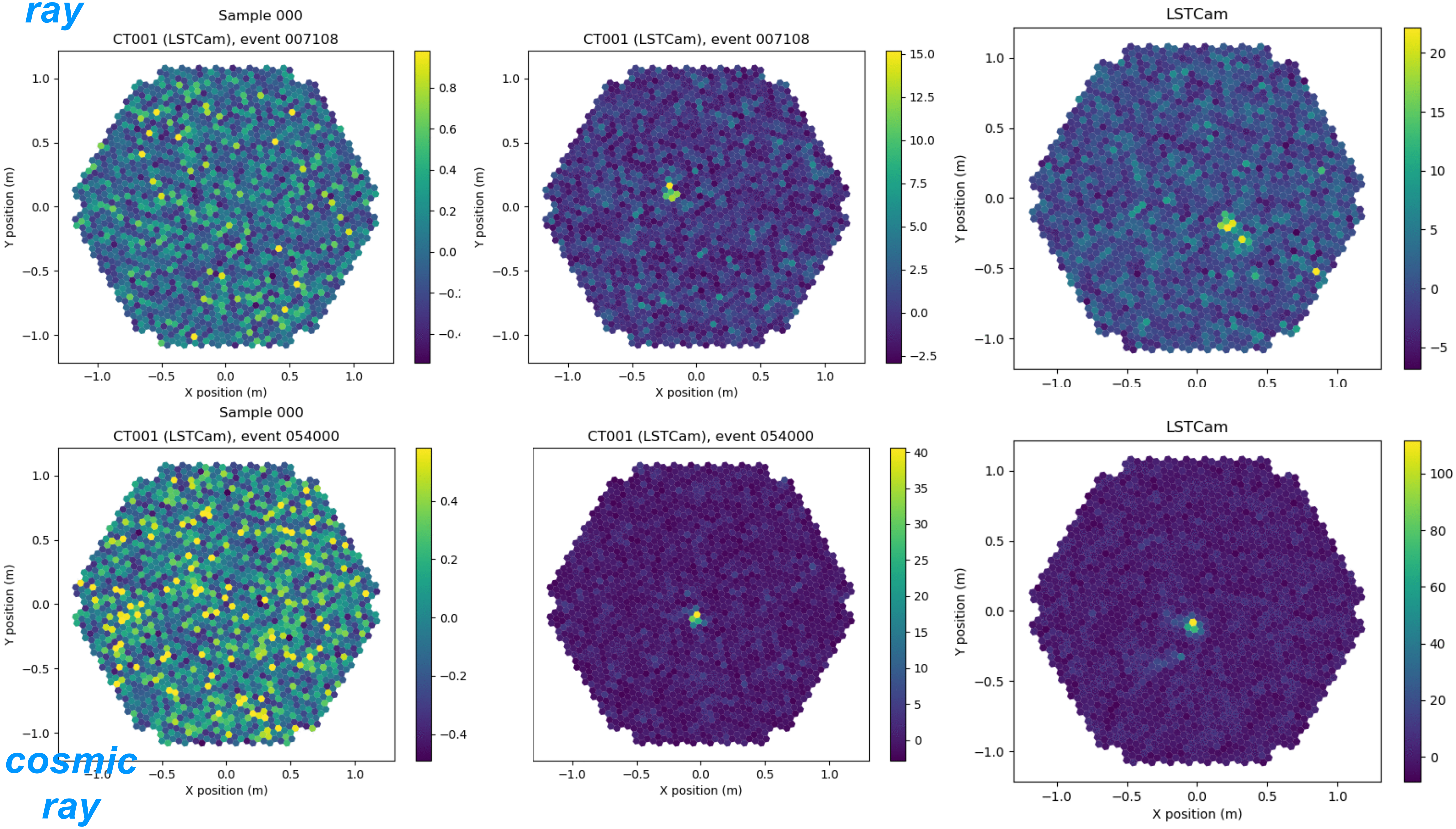
Single Telescope View

gamma ray

nanosecond frames

time-integrated

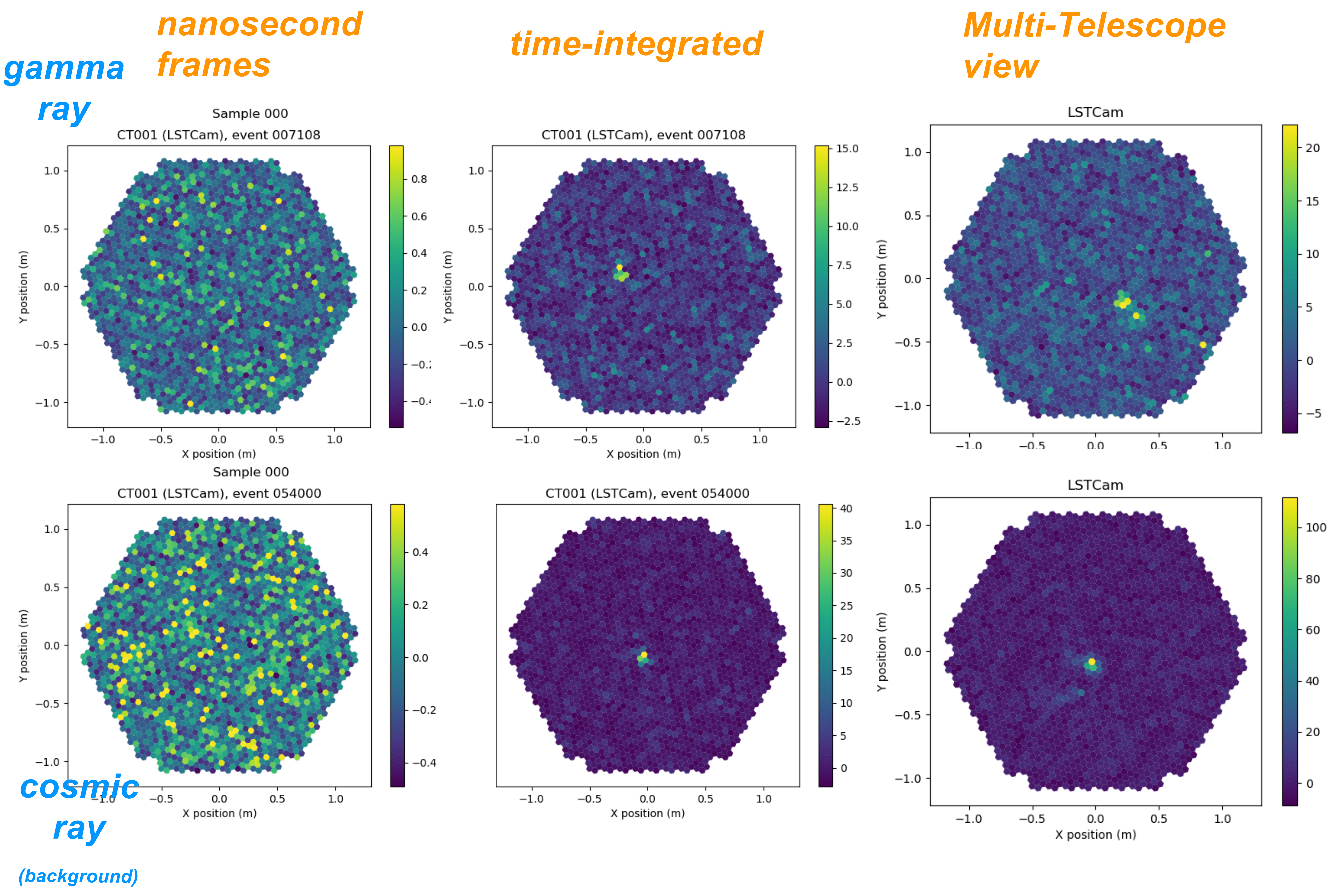
Multi-Telescope view



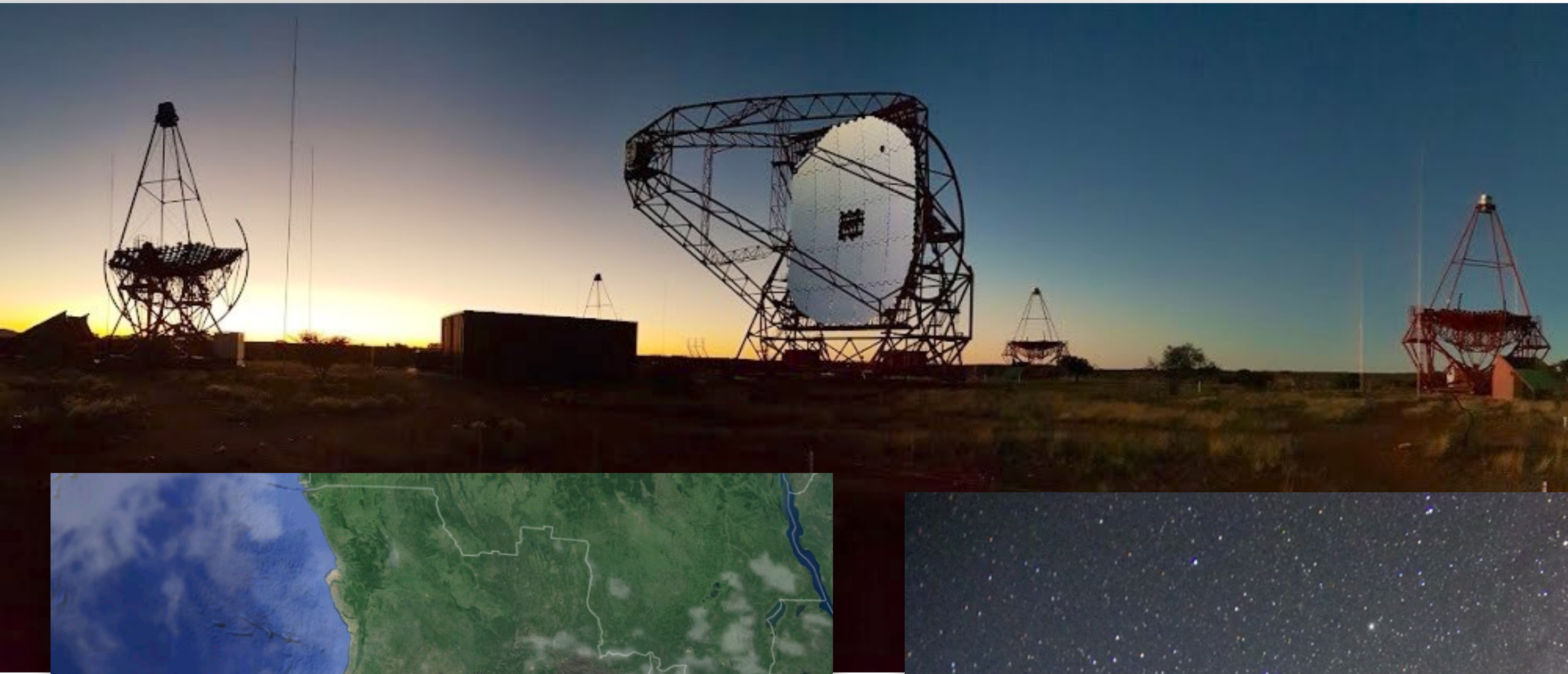
cosmic ray

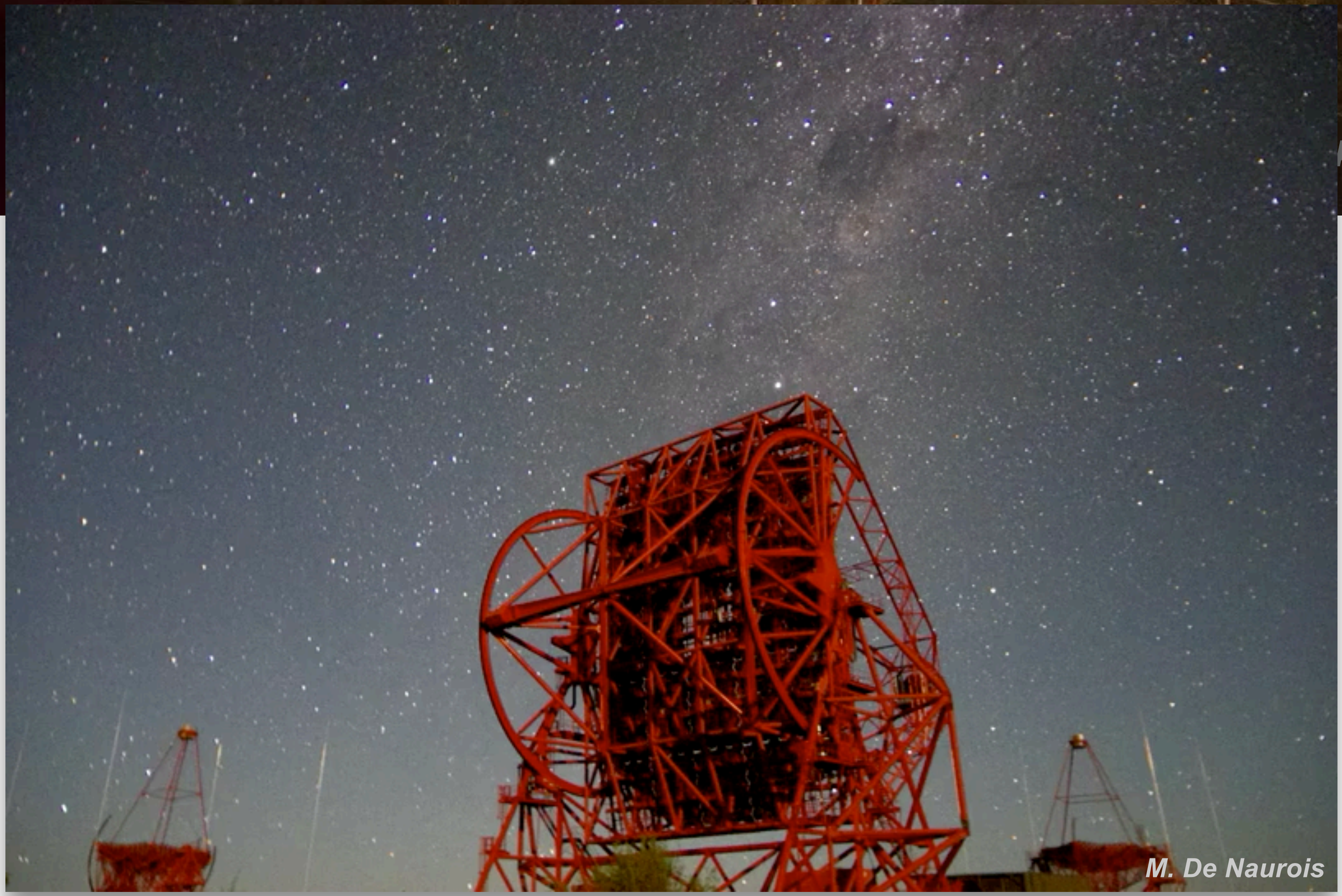
(background)

Single Telescope View



The HESS Telescope Array





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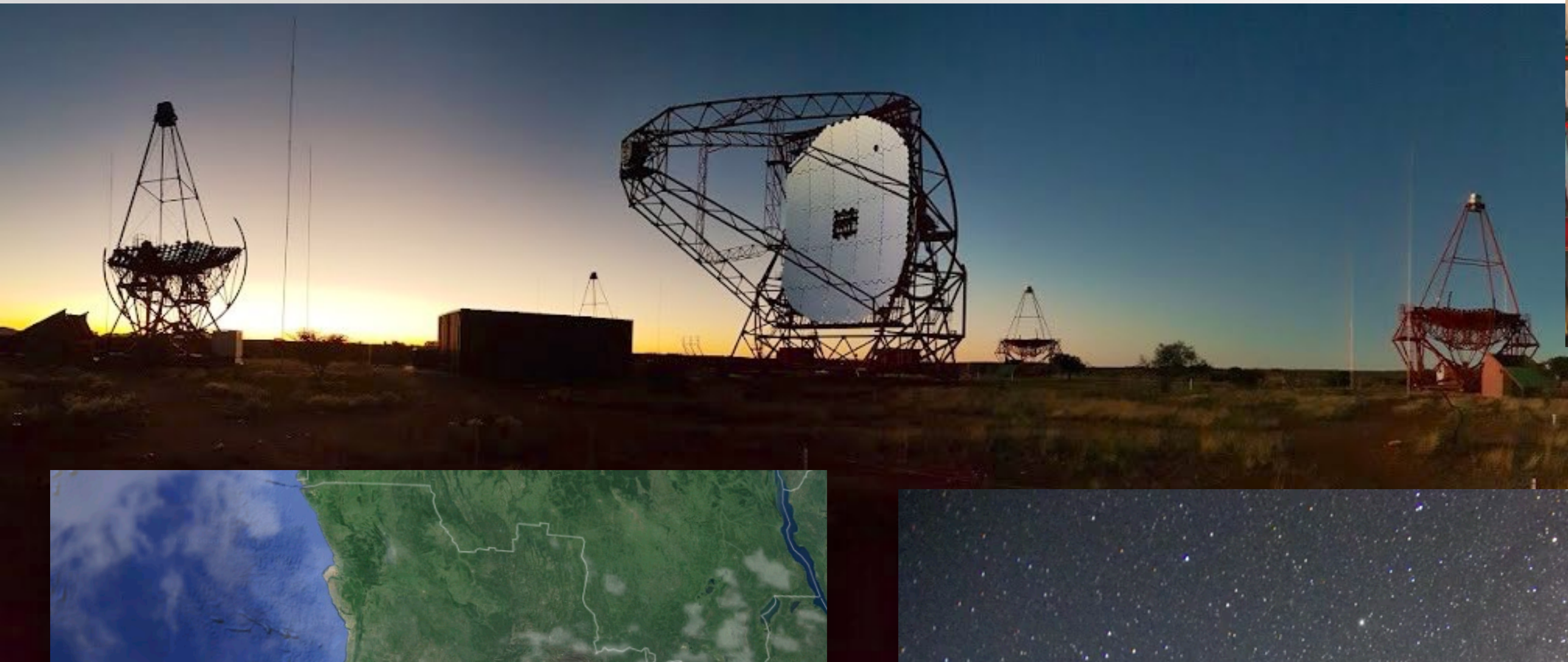
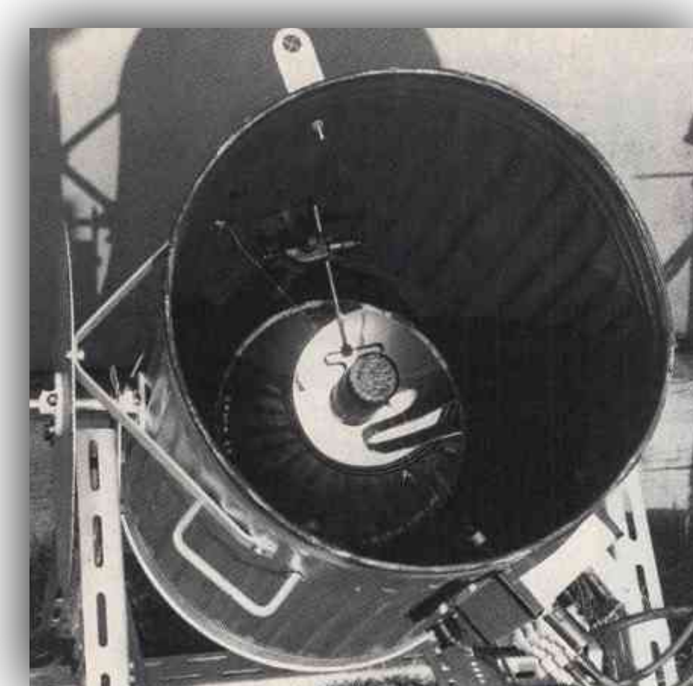


Early Gamma Ray Telescopes:
a look back



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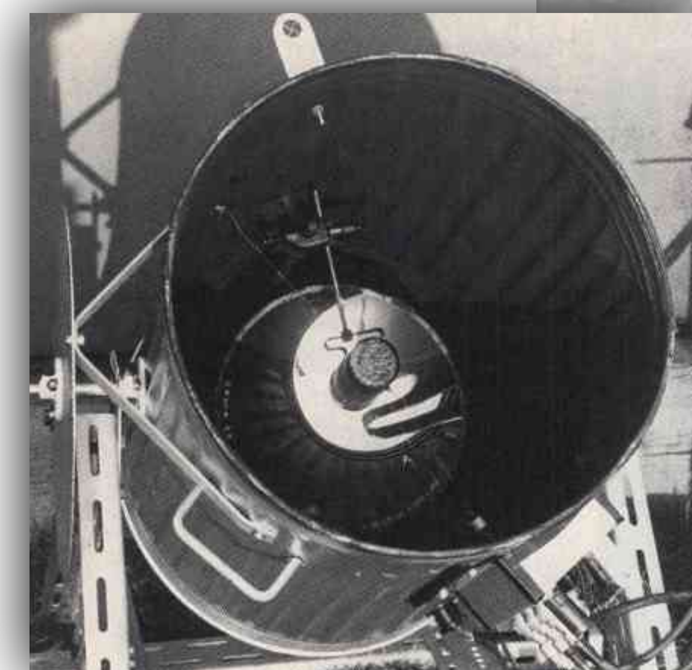
Weekes, 1967
“the early days”



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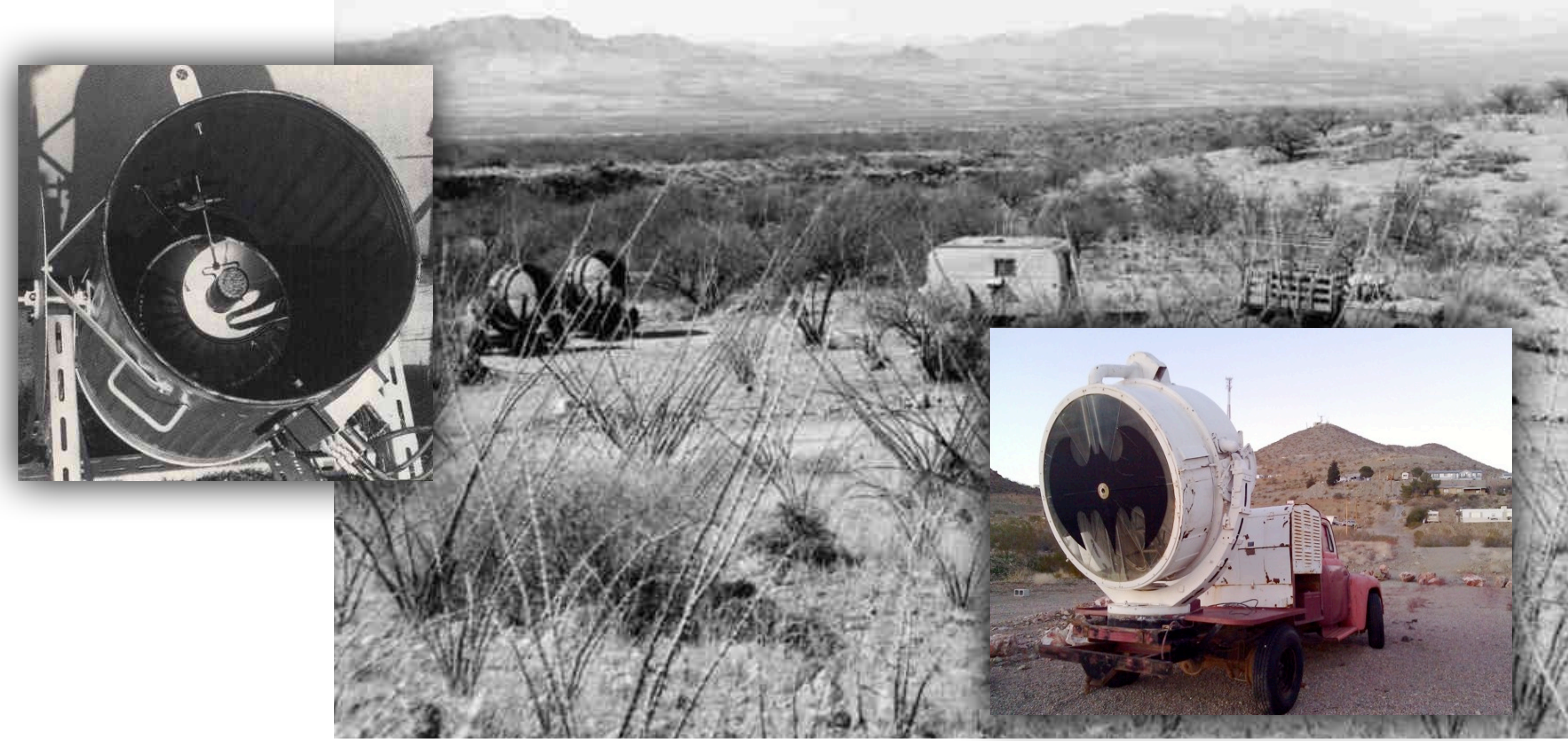


Some VHE History

The Whipple 10 m Telescope, 1968

Whipple 10m teleescope

- **1968:** Built, Single-pixel camera
- **Breakthrough**: multi-pixel camera: **Shower Imaging**
- **1989:** First detection of Crab Nebula (at 5 σ)

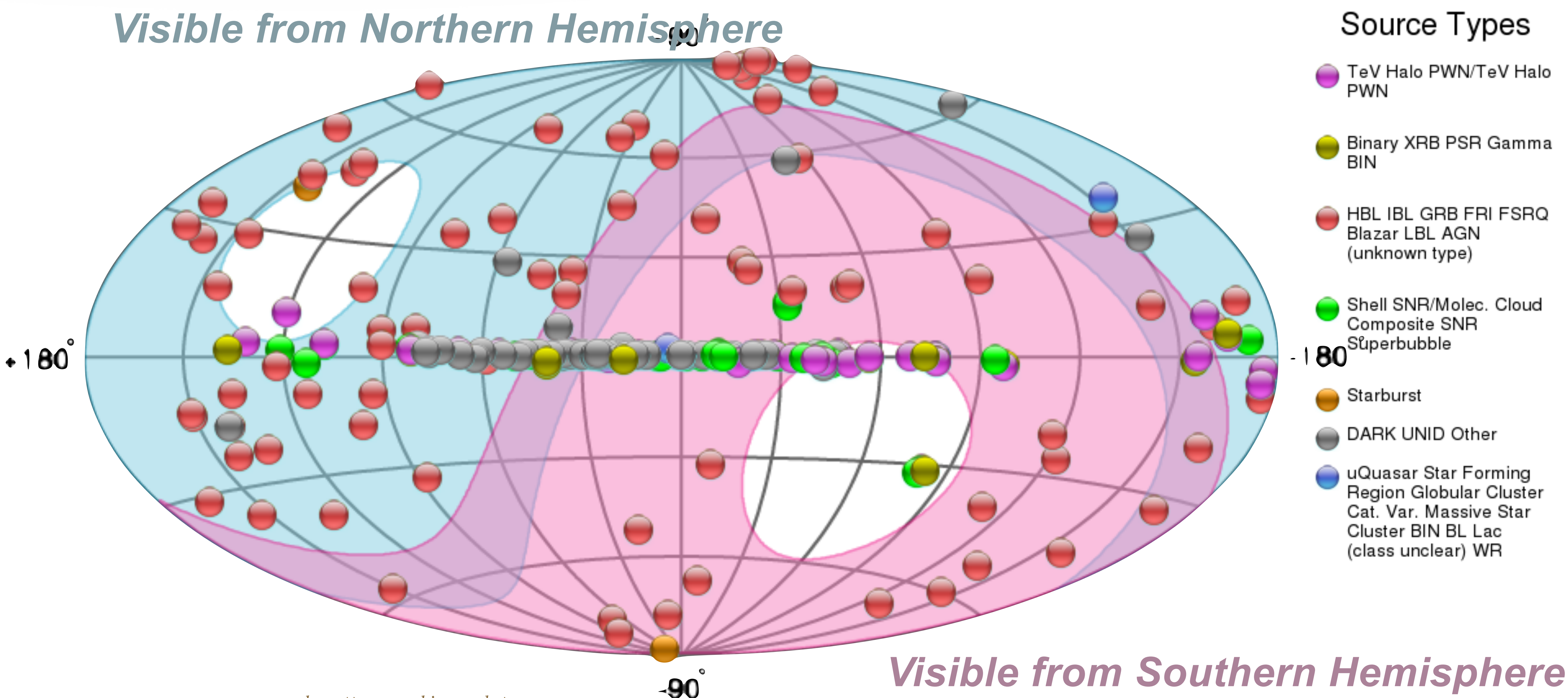
Many came in between:

- CAT (Pyrenees),
- Durham (Australia)
- HEGRA (Canaries)
- Grace (India)
- CANGAROO (Australia)

Current Atmospheric Cherenkov Telescopes

HESS, VERITAS, MAGIC

Ground-based Telescopes: **Visibility**



http://tevcat.uchicago.edu/

≈200 known gamma ray source

Characteristics of the Technique

Advantages:

- Spectra are easy!
  - ➤ Energy for each shower (prop to Cherenkov intensity)
  - ➤ Energy Resolution ≈10%
  - ➤ E = ≈50 GeV - 100 TeV
- Suited for morphology studies and large extended sources:
  - ➤ FOV is large (≈2-5° for current instruments)
  - ➤ Angular resolution is limited (> arcmin, <0.1°)

Drawbacks:

- Duty cycle is low (≈ **moonless nights** → ≈**1000 hours** out of 8760 h per year!)
- Pointed (FOV not *that* large → still have to slew)
- Background-dominated
  - ➤ residual gamma-like showers from electrons and protons
  - ➤ counts of **gamma-rays are only statistical** (excess events above background, don't know for an individual event if it is signal or background)

OVERVIEW

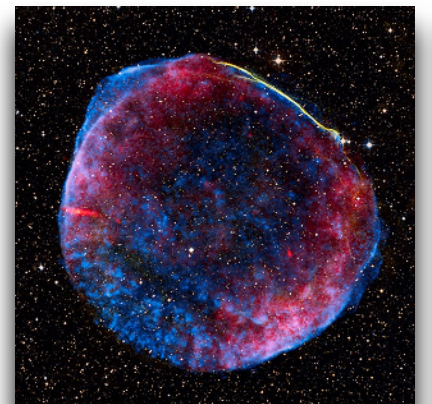
Introduction

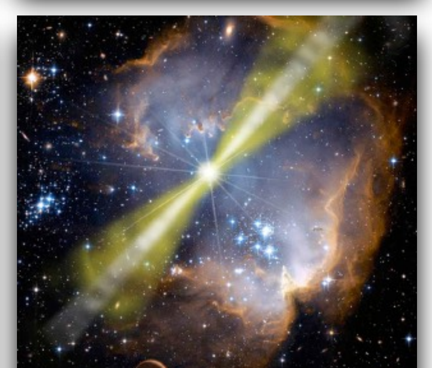
Detecting Gamma Rays

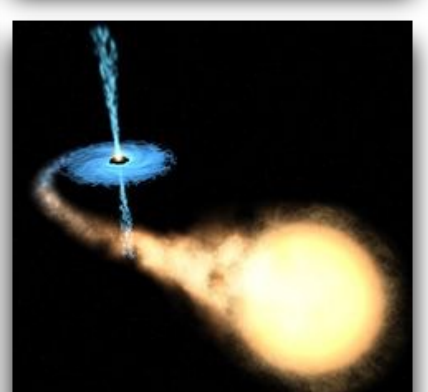
The Hunt for PeVatrons

Future Prospects

(Very) High Energy Gamma-Ray Astrophysics





The study of *non-thermal* phenomena in the universe

- black holes and neutron stars
- active galactic nuclei
- compact binary systems
- supernovae and remnants
- pulsars and PWNe
- gamma-ray bursts / hypernovae
- starburst regions and galaxies
- galaxy clusters
- *cosmic rays and their origin*
- dark matter

Accretion

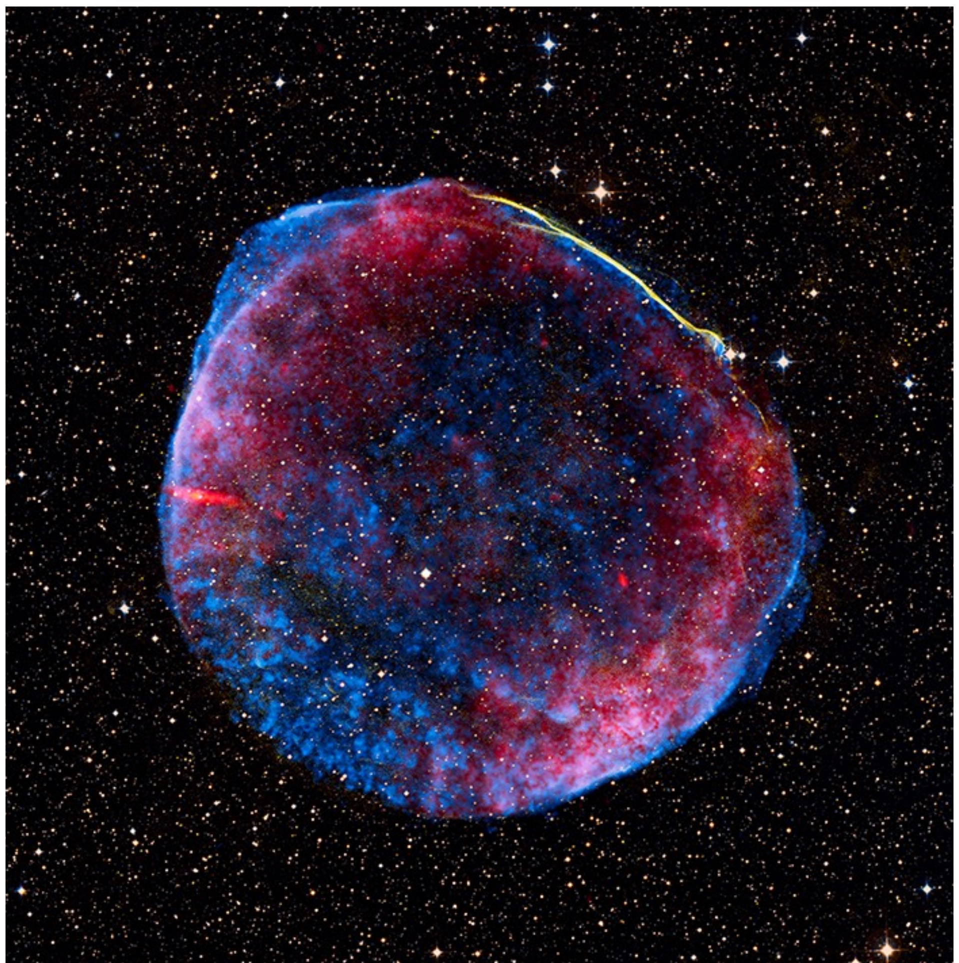
Jets

Winds

Shocks

Particle Acceleration

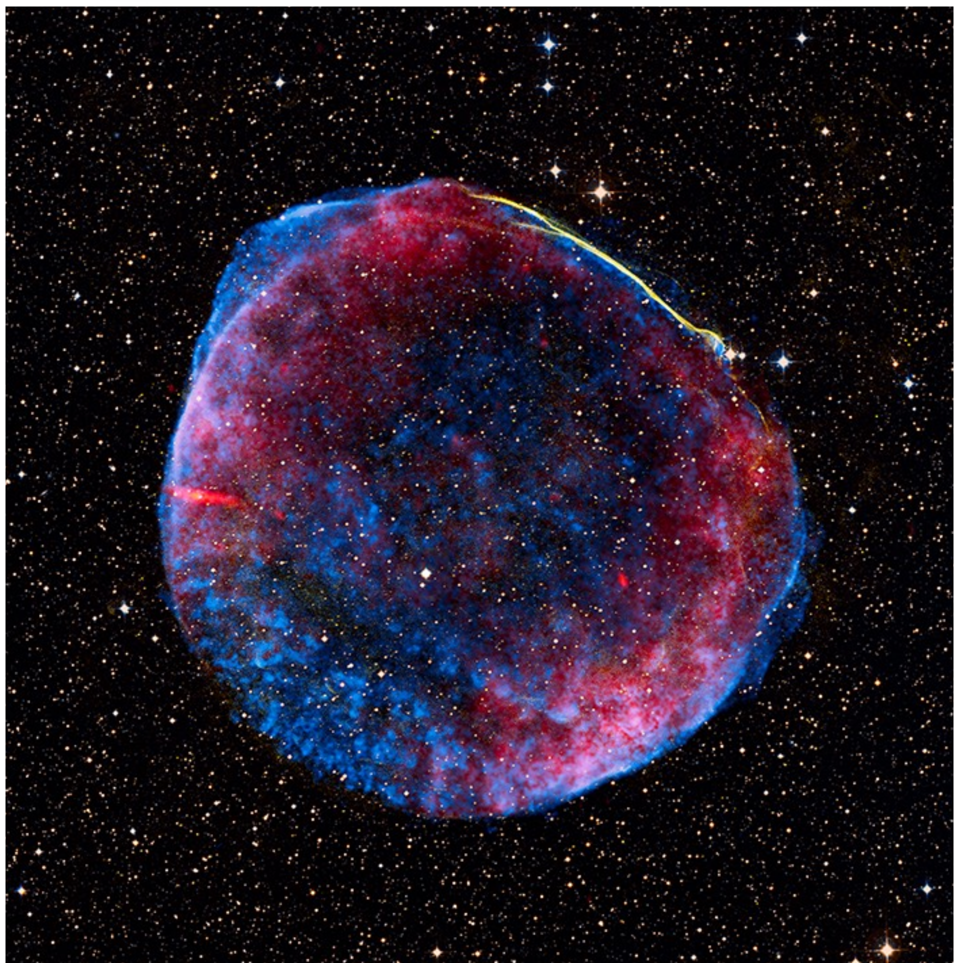
Supernova Remnants: an obvious choice



SN 1006 Supernova remnant in radio + optical + x-ray
(APOD 14/07/12)

Supernova Remnants: an obvious choice

Why are they a candidate?



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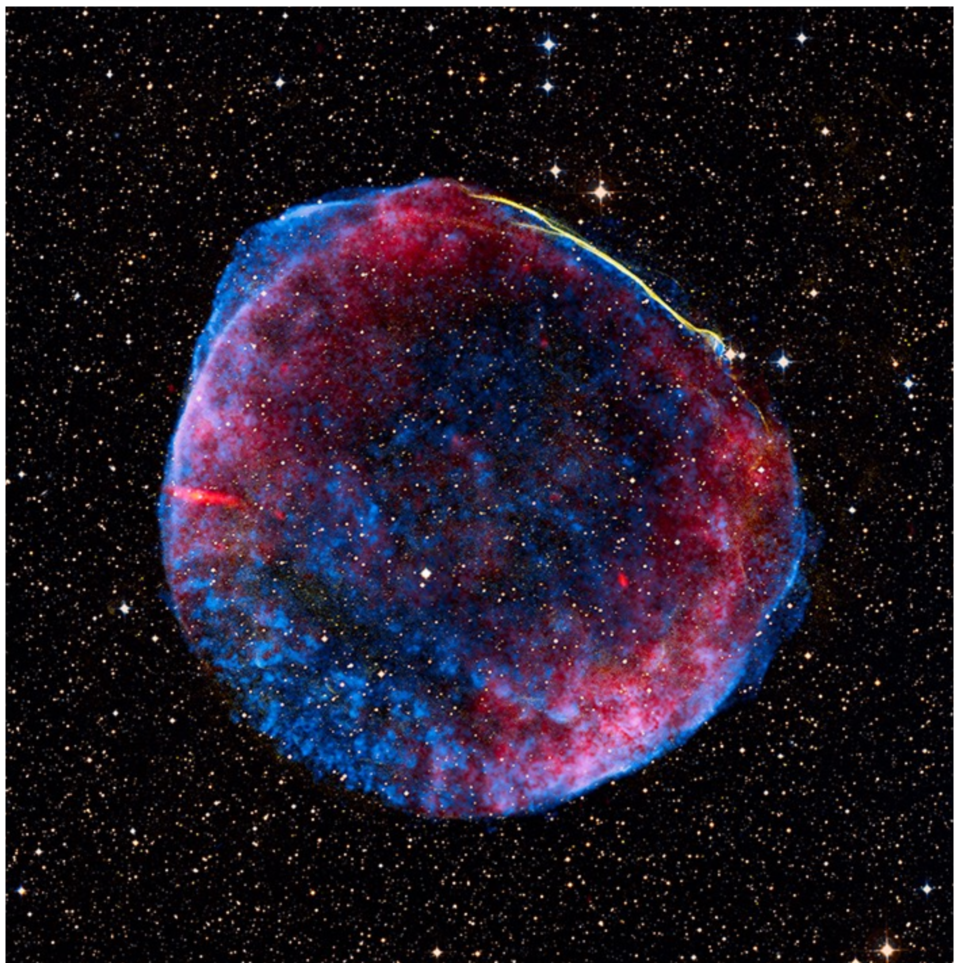

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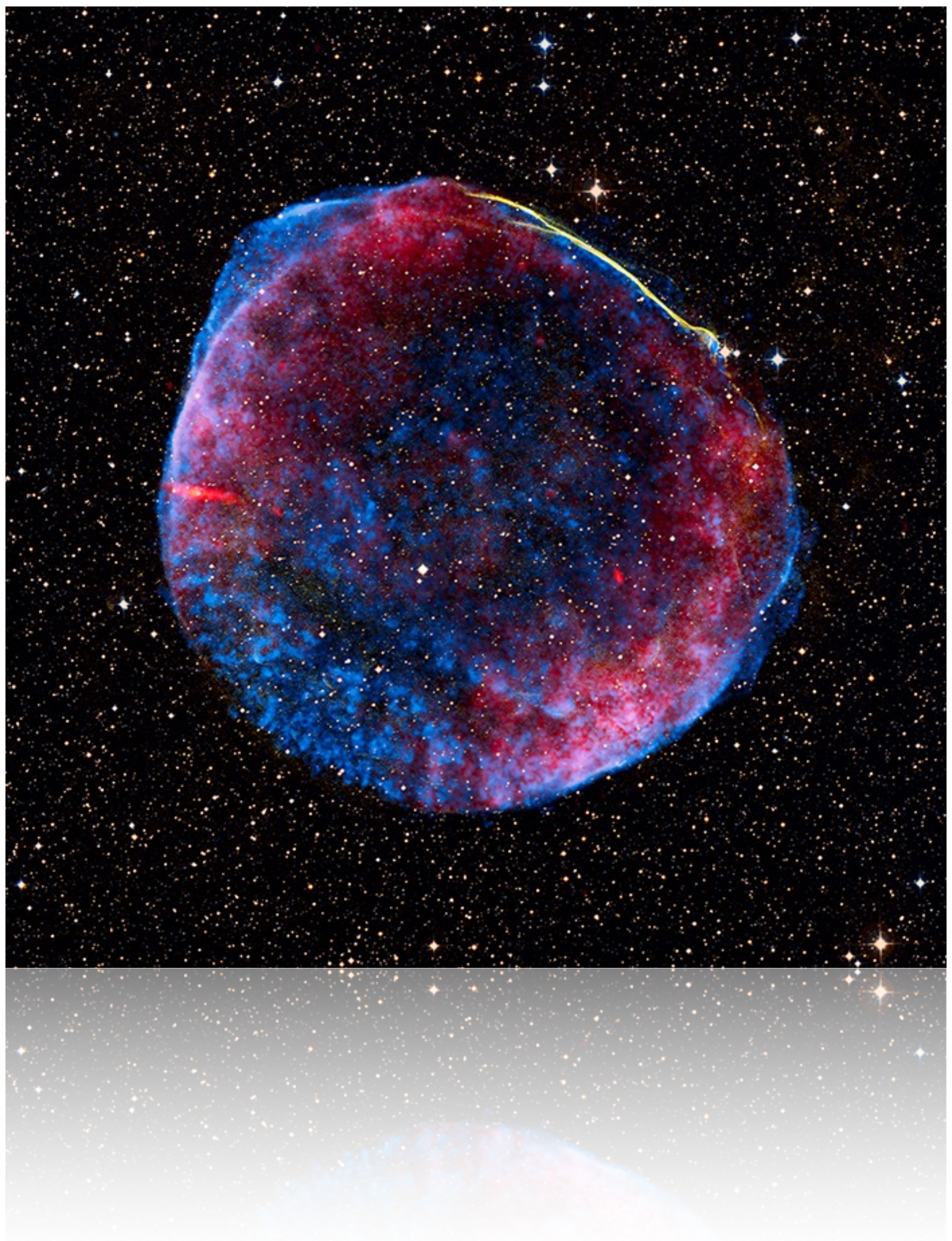

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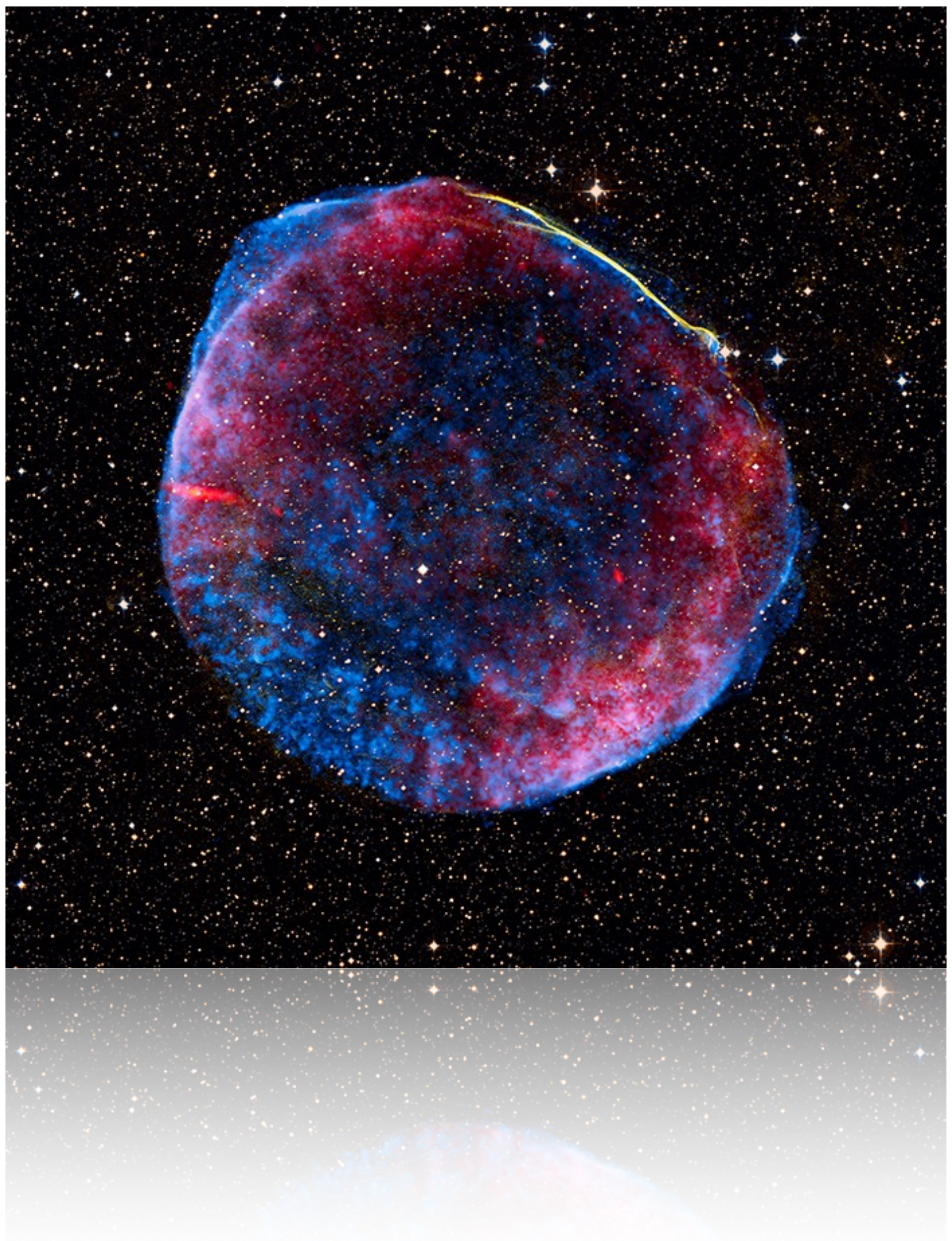

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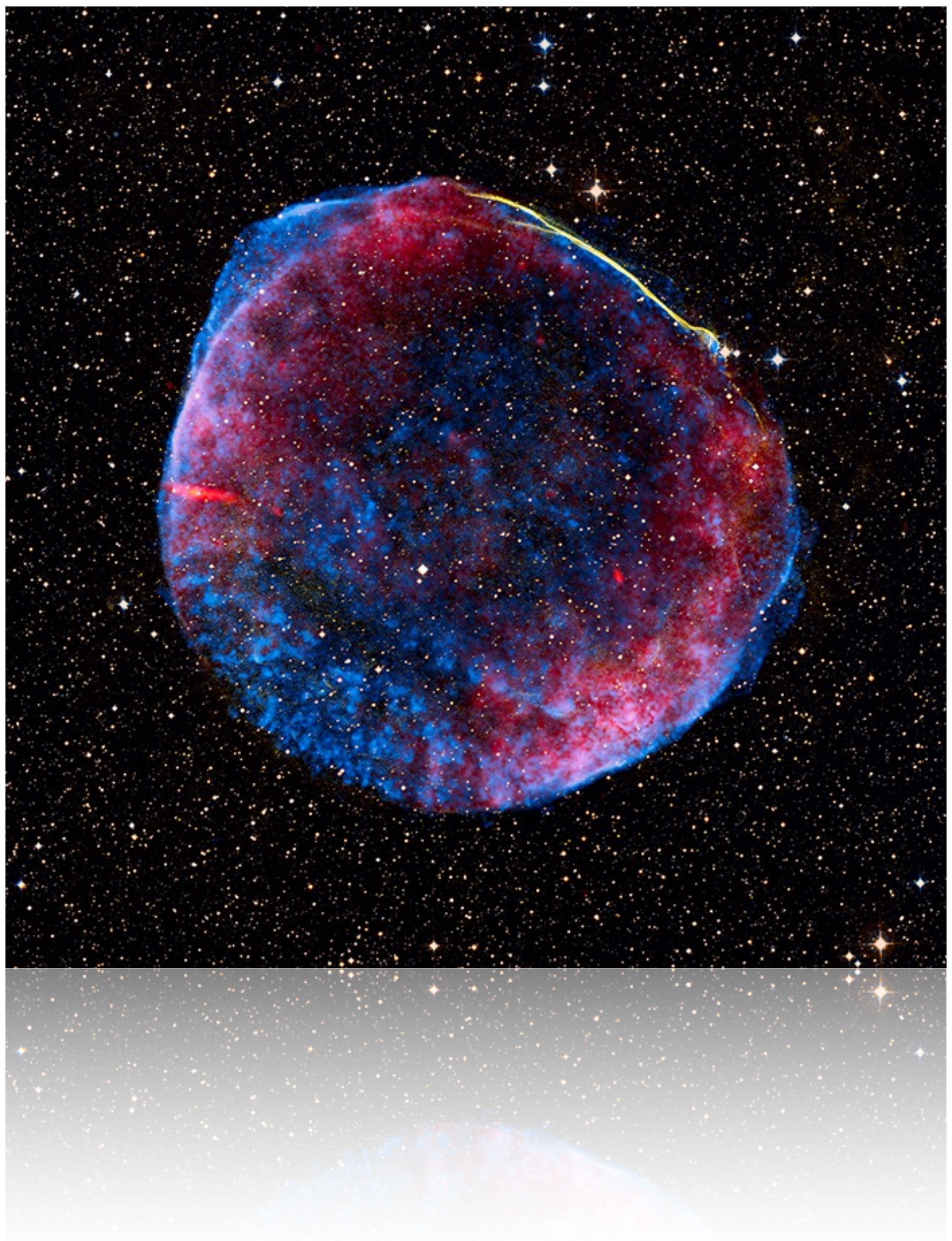

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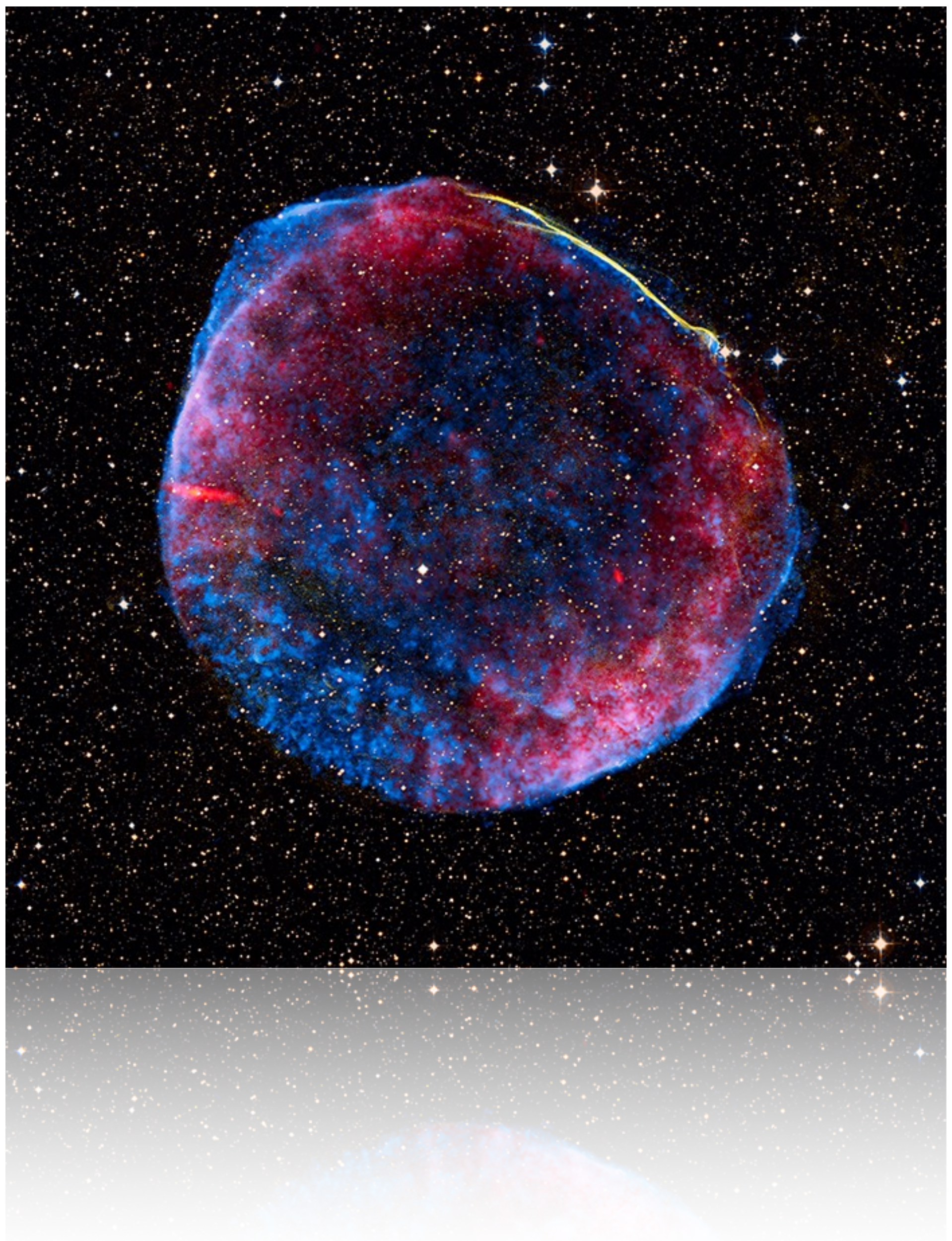

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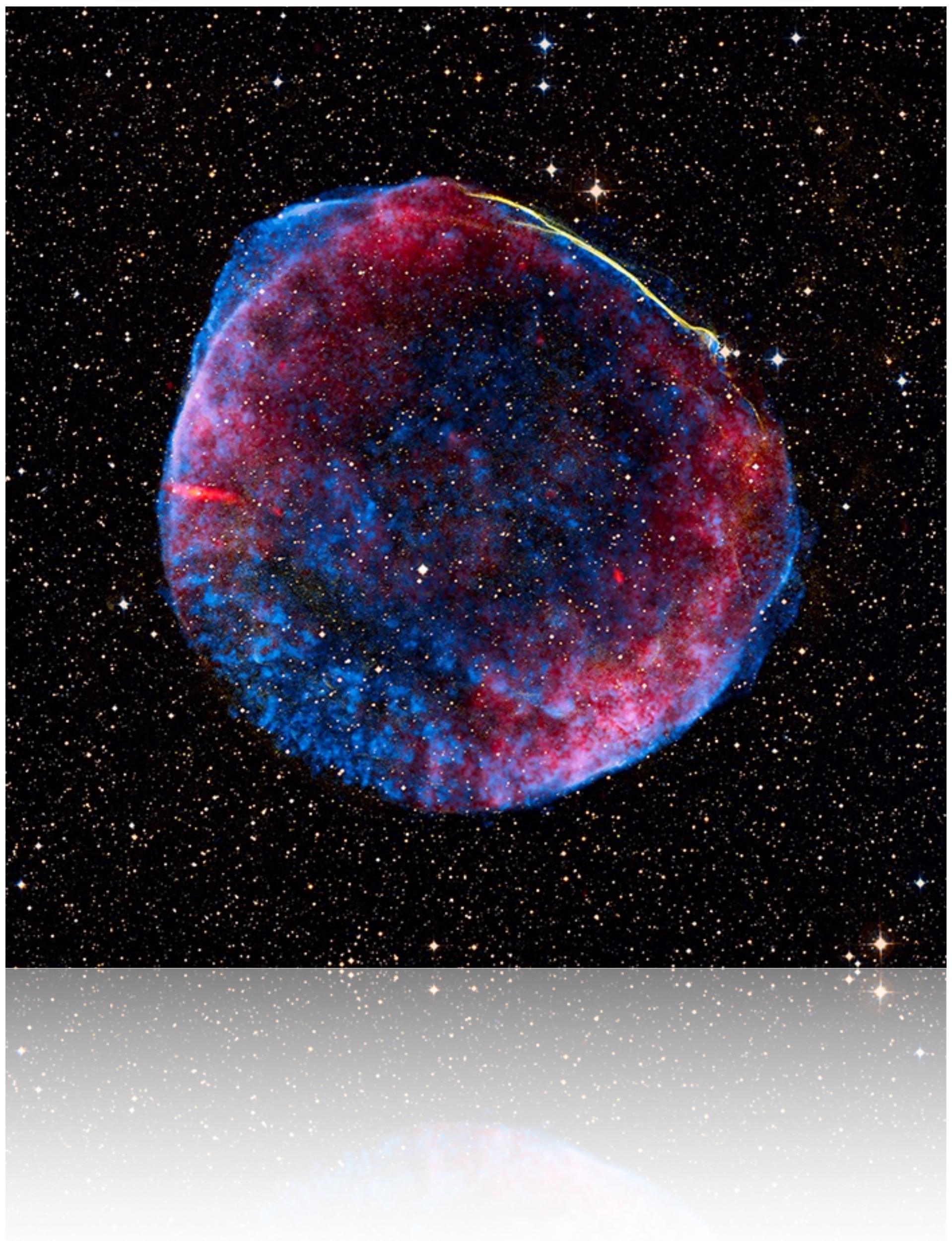

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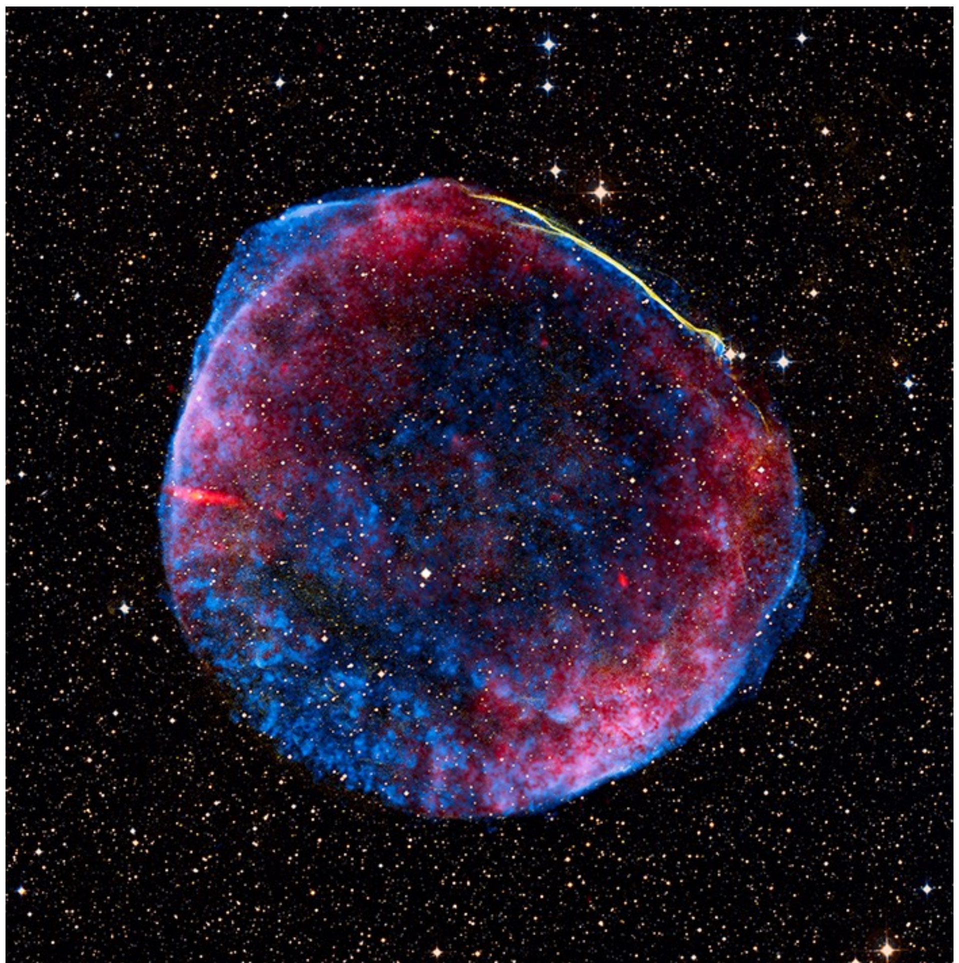

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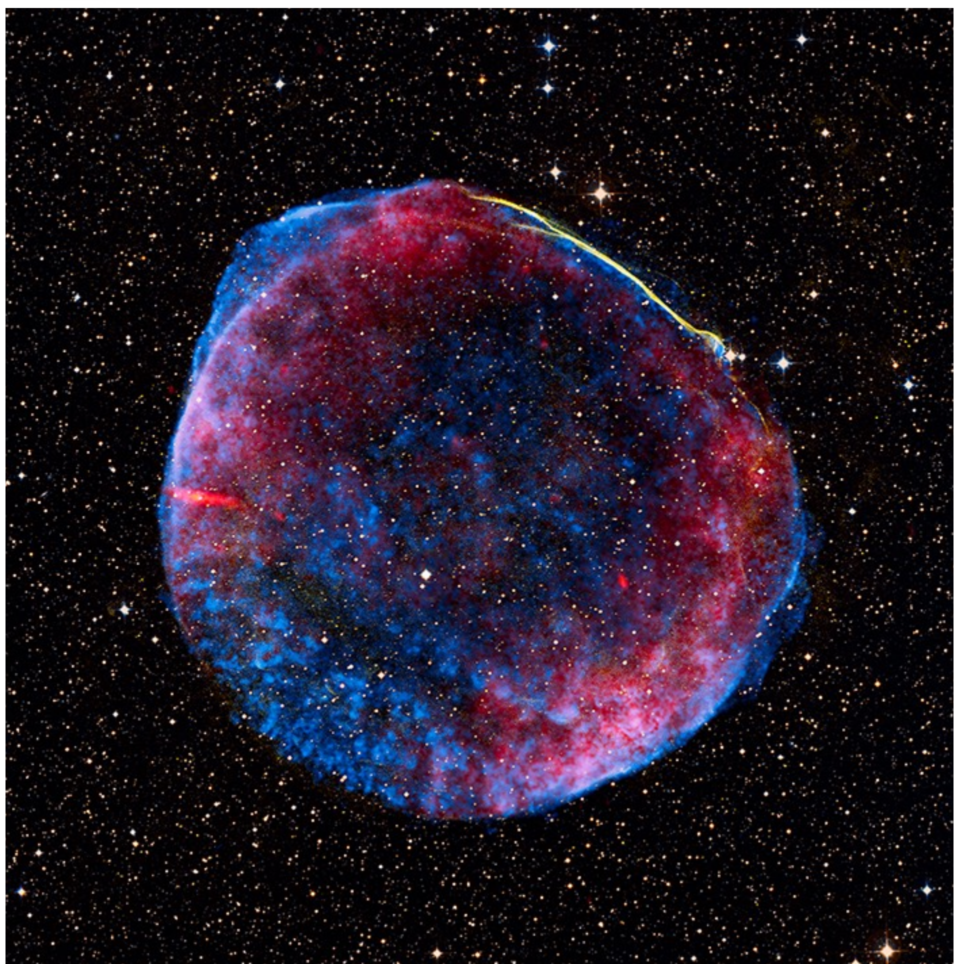

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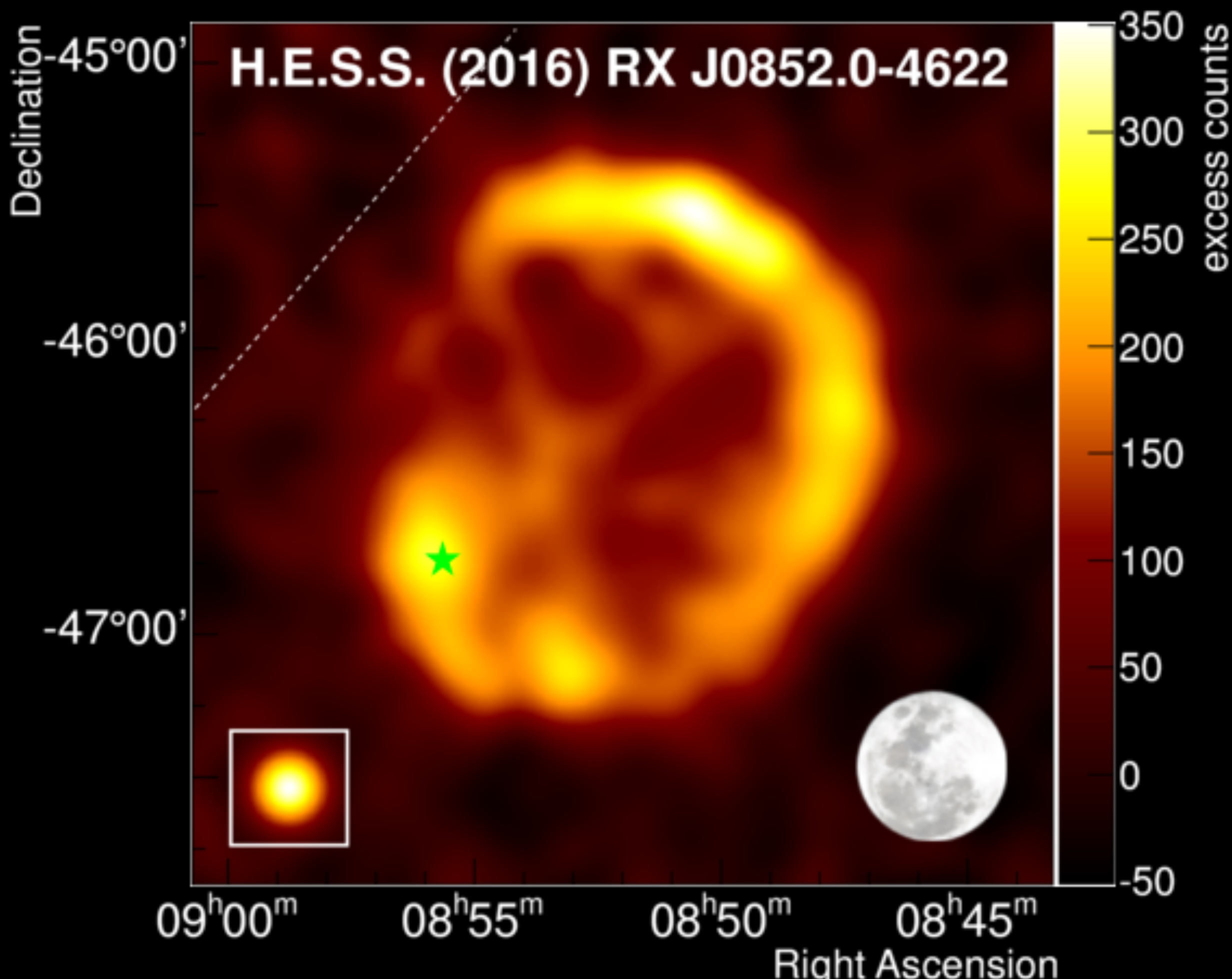
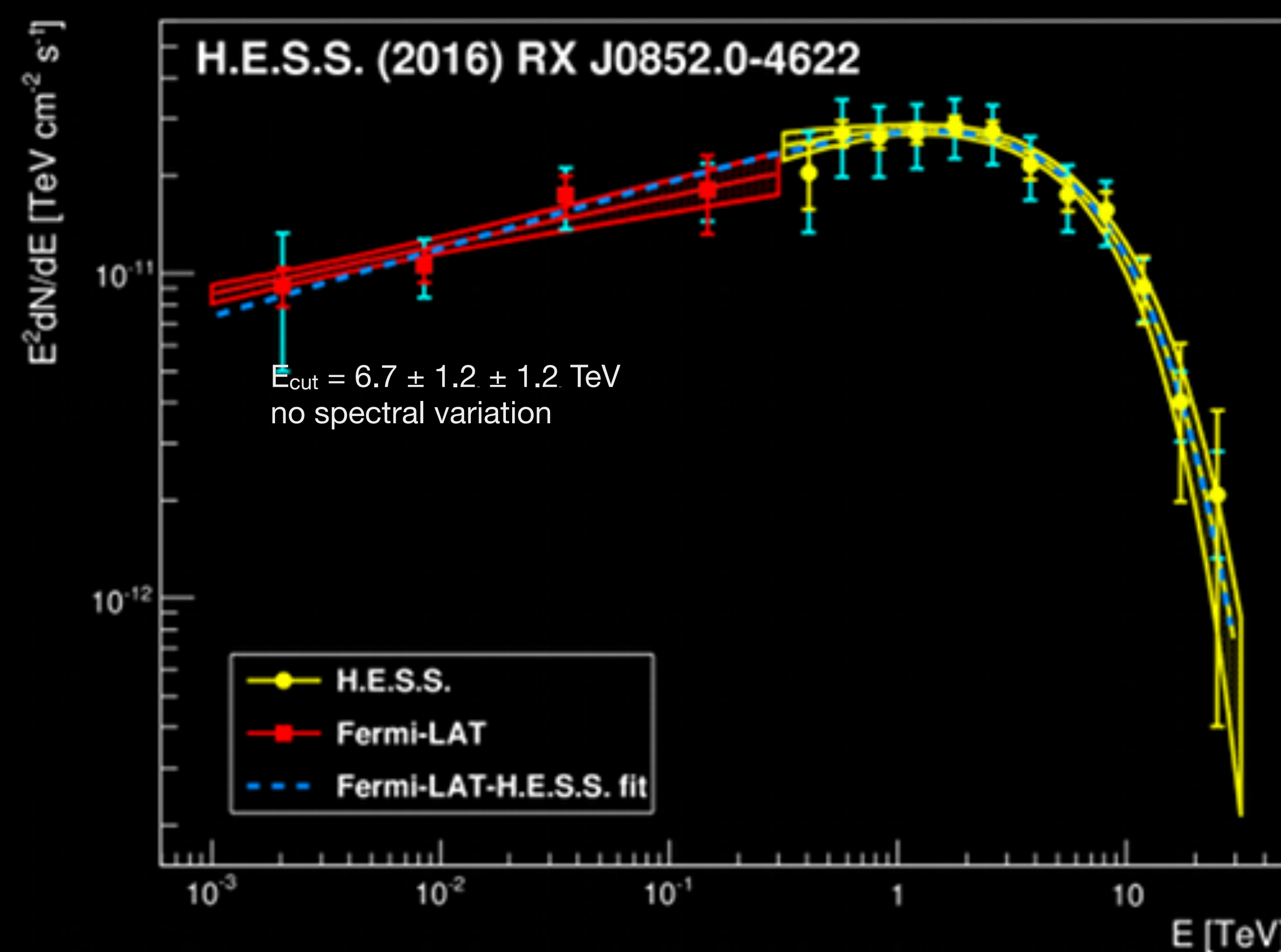
- During adiabatic-expansion / Sedov-Taylor phase, high shock speeds → CR acceleration
  - (but Emax decreases with time as SNR ages, so expect older SNRs don't accelerate)
- expand in to ISM (density n ≈ 0.1 cm^{-3}) → target for accelerated protons → gammas via pion decay

Gamma Rays from Young SNRs

Vela Jr *(also known as RX J0852.0-4622)*





HESS collaboration, A&A 2019

Leptonic and Hadronic models fit equally well

hadronic model →

$\varepsilon_{cr} \approx$100%! or very clumpy medium

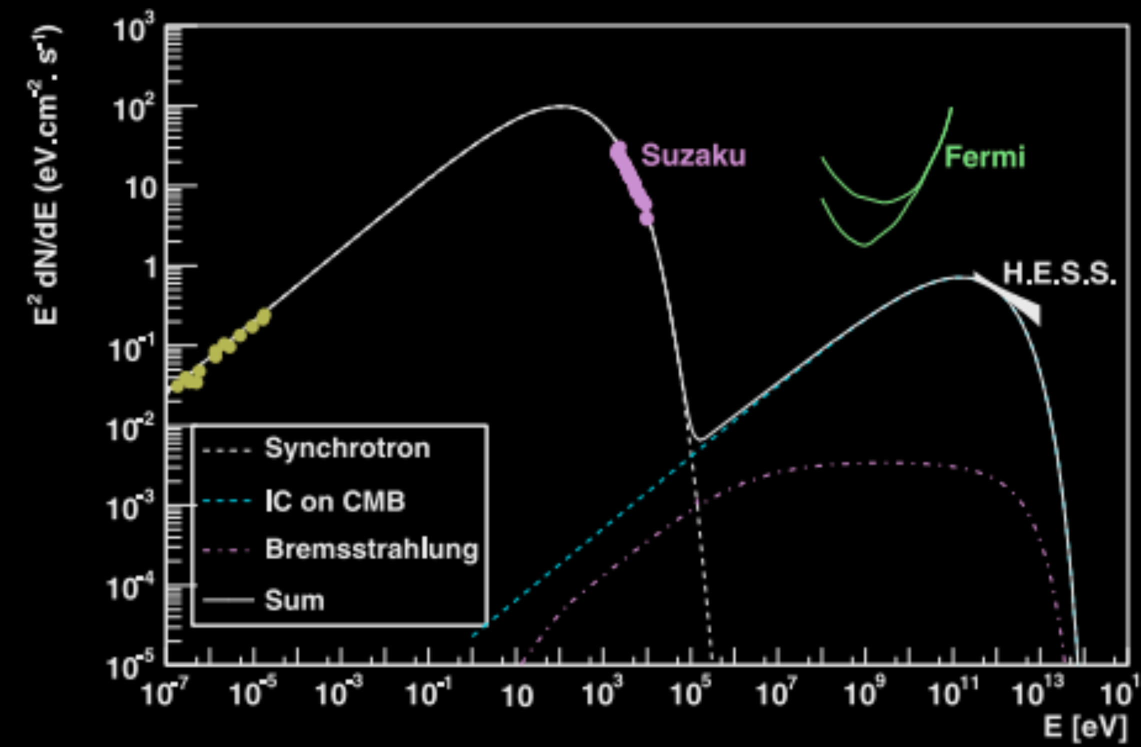
proton $E_{cut} \approx$ 55 TeV

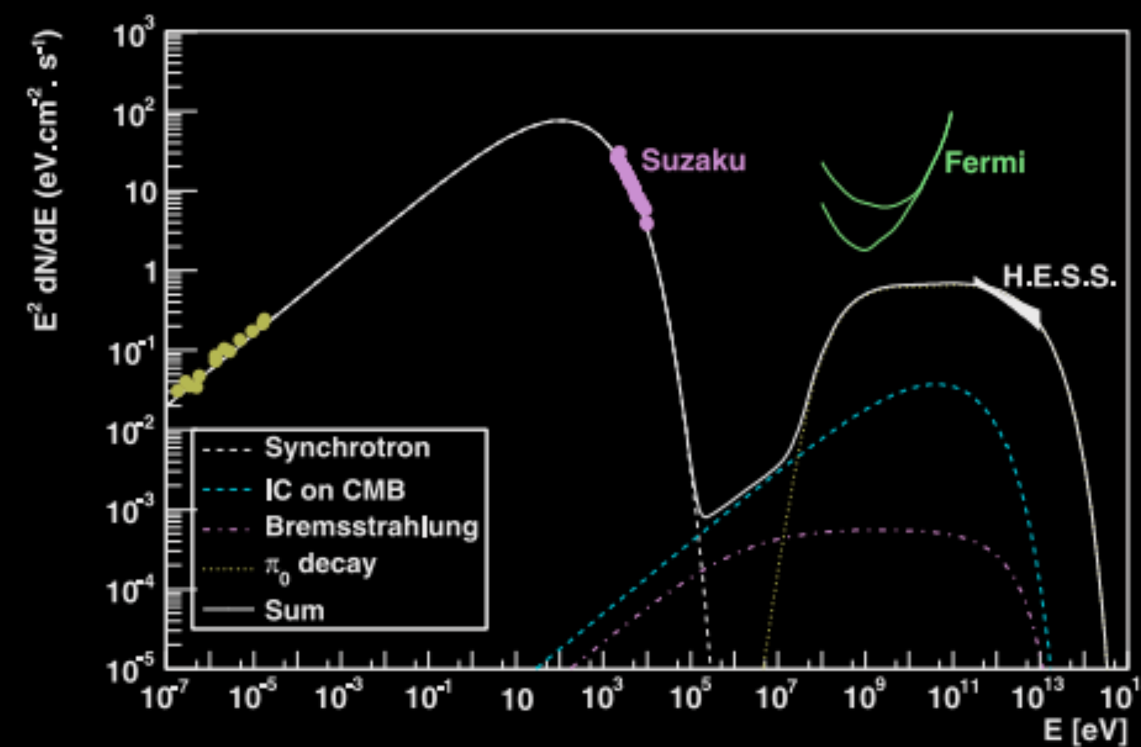
leptonic → B≈7μG

(Inoue et al. 2012; Gabici & Aharonian 2014)

Gamma Rays from Young SNRs

SN 1006





leptonic *→ B > 30μG (constrained by radio/X, but must not exceed VHE), VHE spectrum too hard!*

hadronic *→ $\varepsilon_{cr>}$ 30% (quite high required efficiency)*

combined lepto-hadronic model *→B≈45 μG proton* ***Ecut= 100 TeV***

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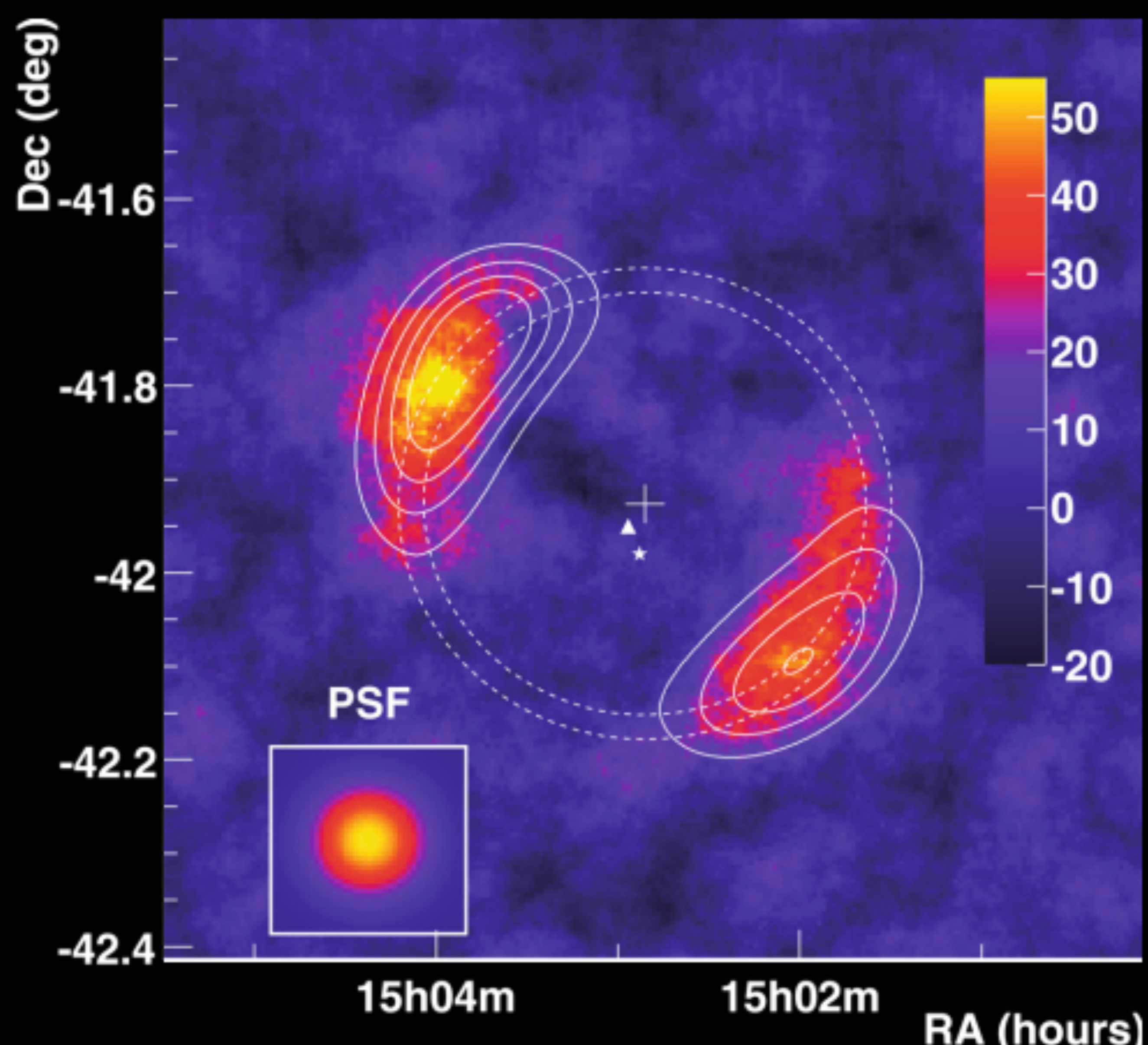
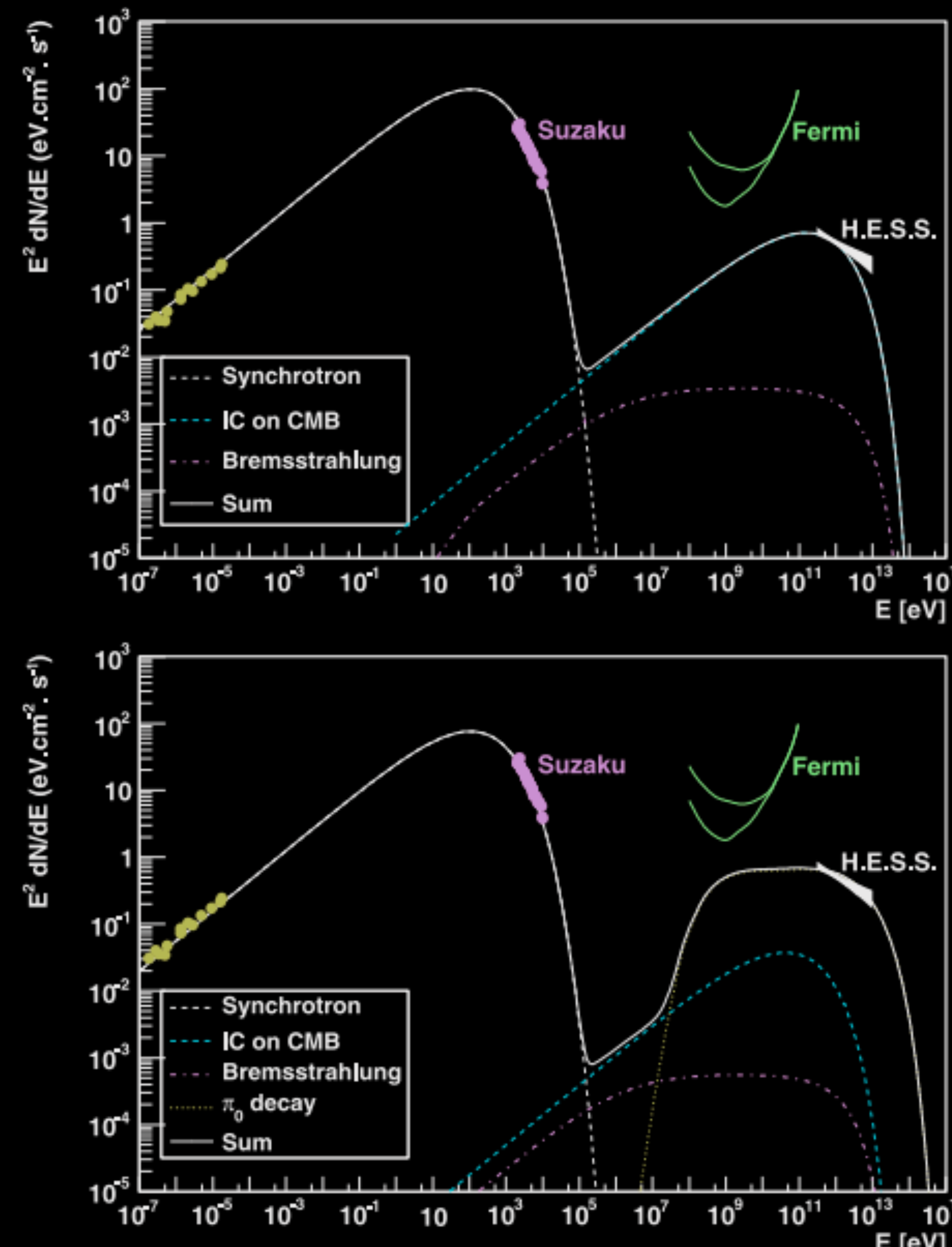
SN 1006





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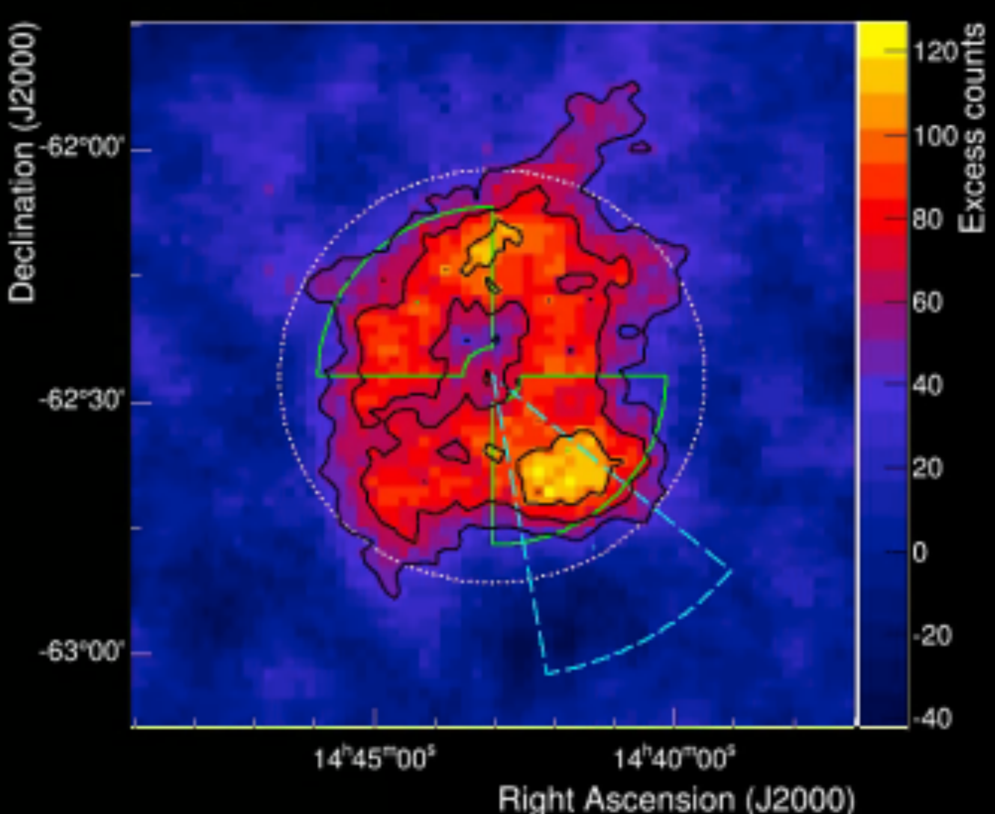
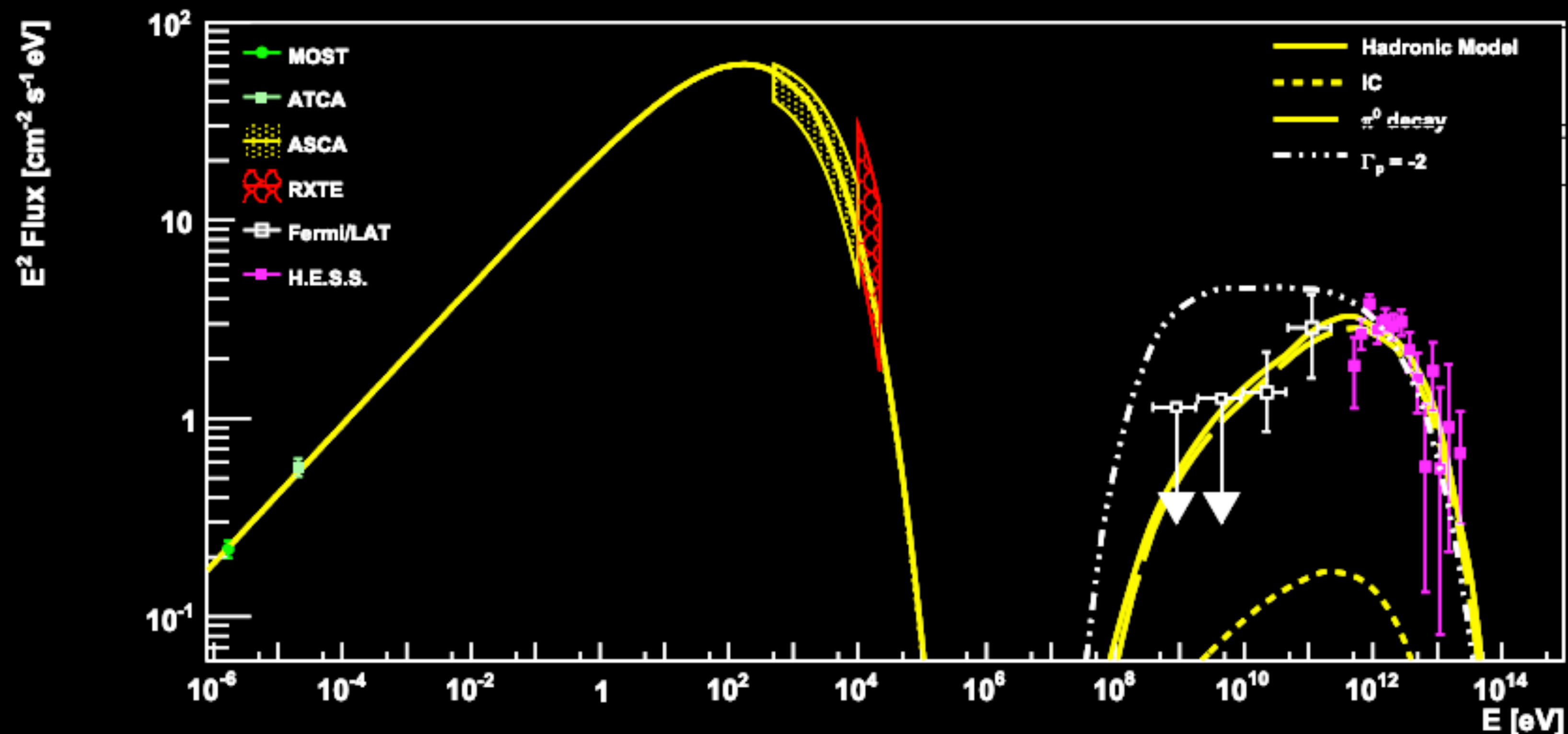
Gamma Rays from Young SNRs

RCW 86

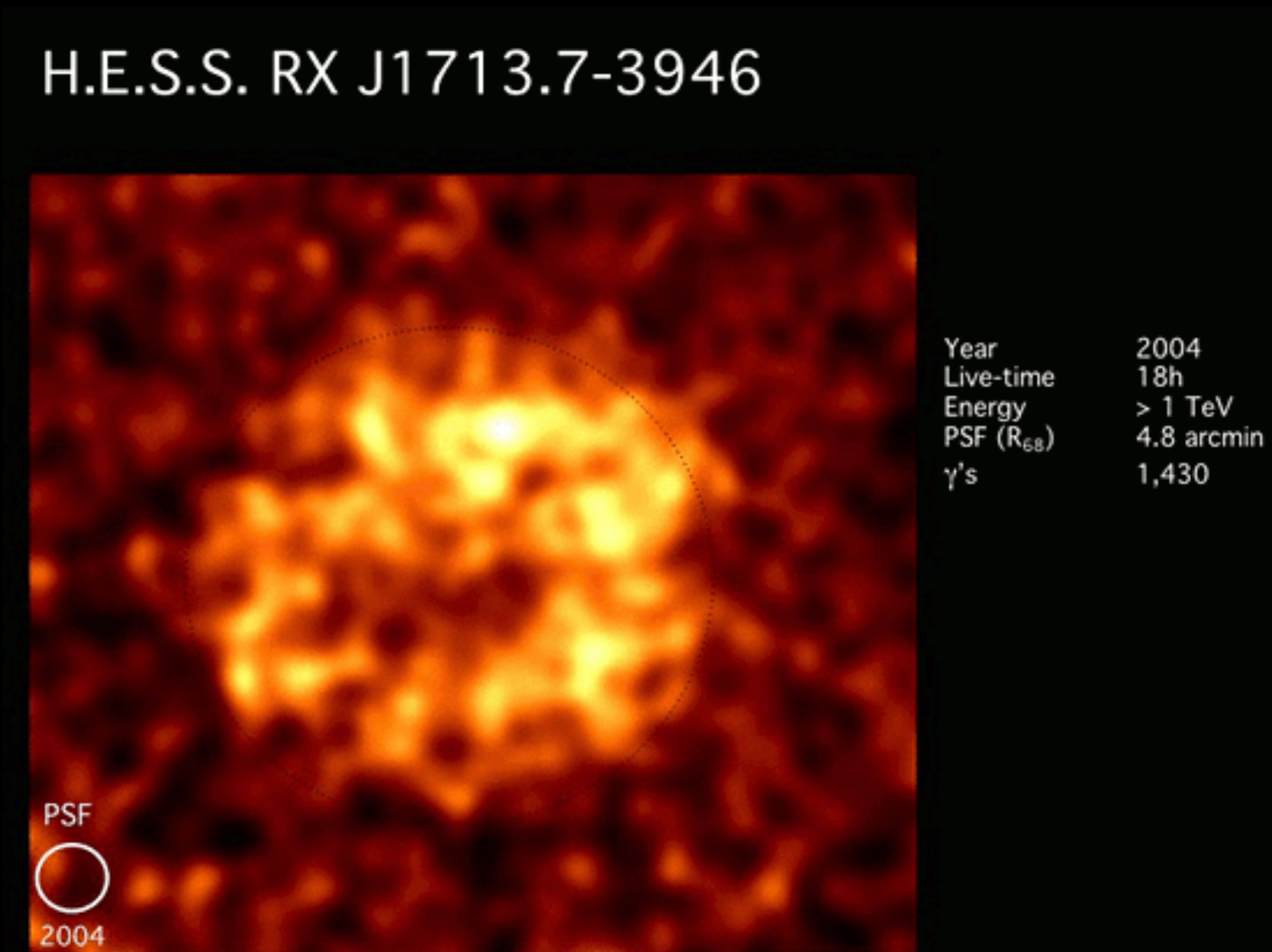


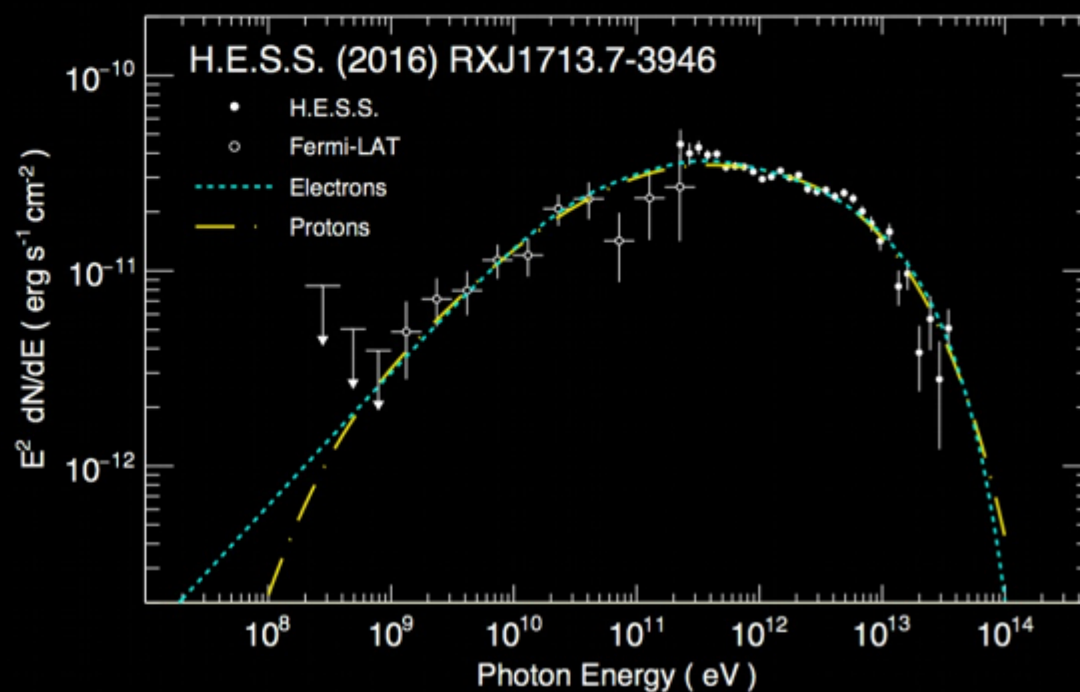


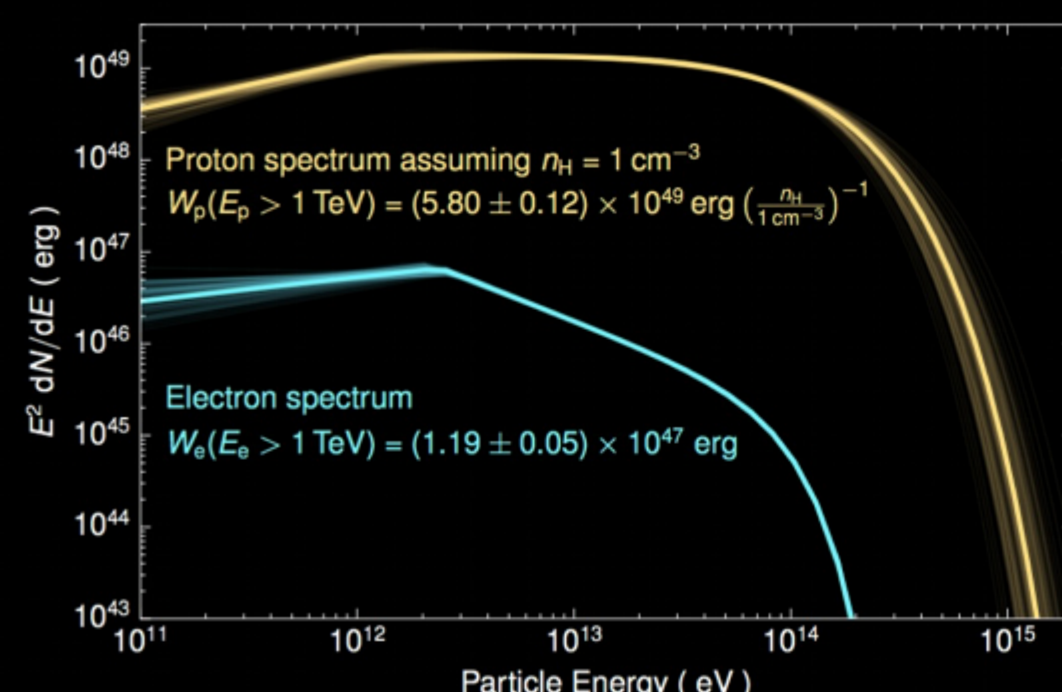
hadronic model ruled out by Fermi-LAT data

Gamma Rays from Young SNRs

RX J1713.7-3946







Leptonic and Hadronic models fit equally well

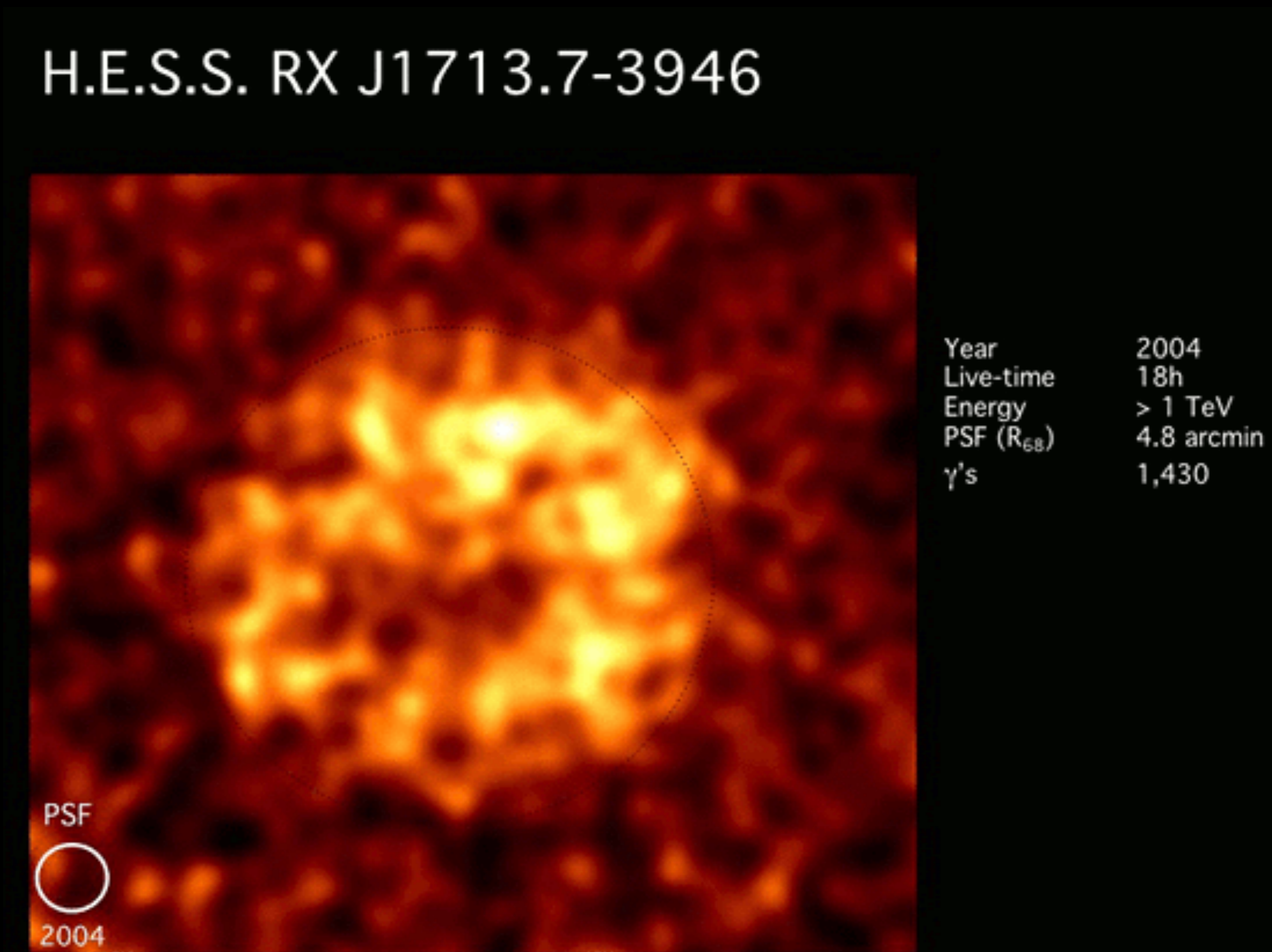
hadronic →

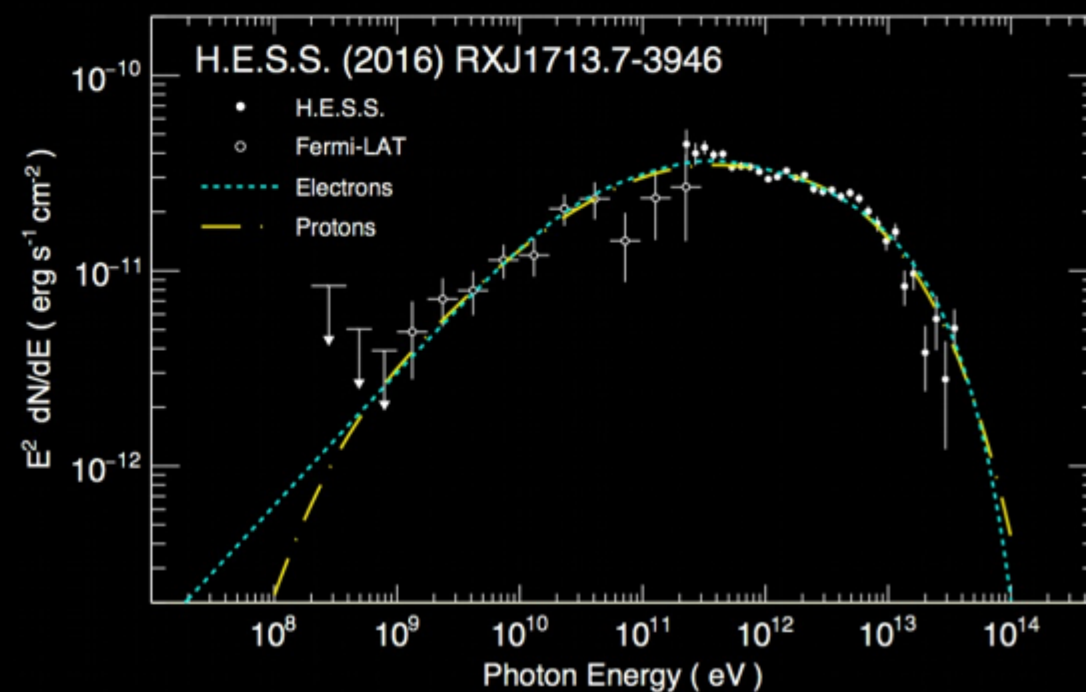
ε_{cr}<10%,
proton Ecut ≈ 150 TeV

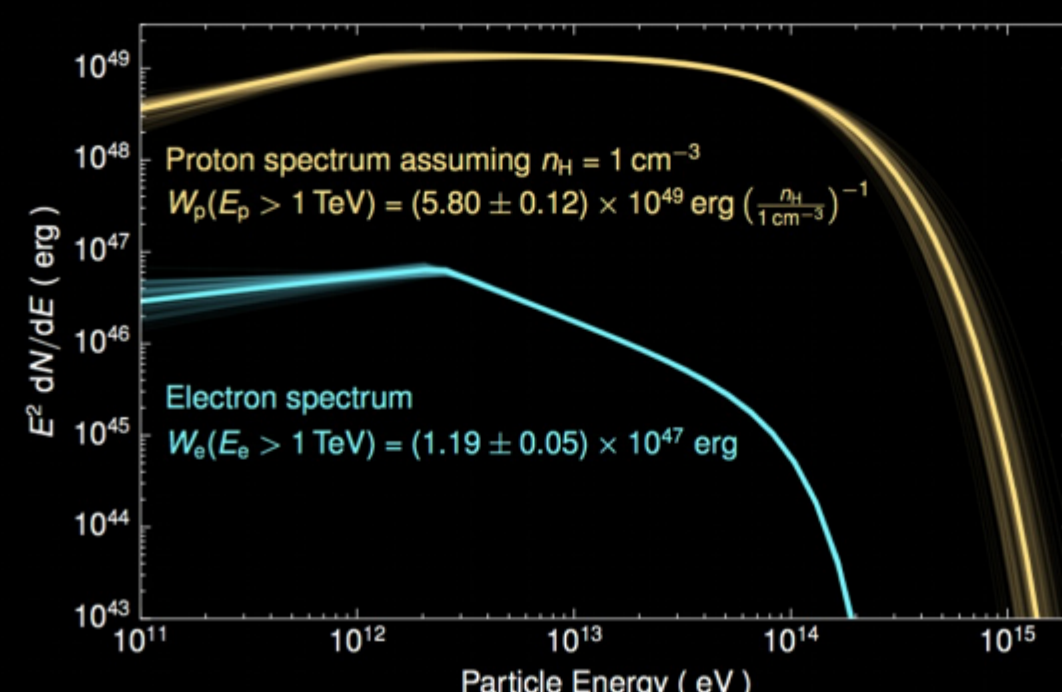
leptonic* → *B≈10μG

Gamma Rays from Young SNRs

RX J1713.7-3946







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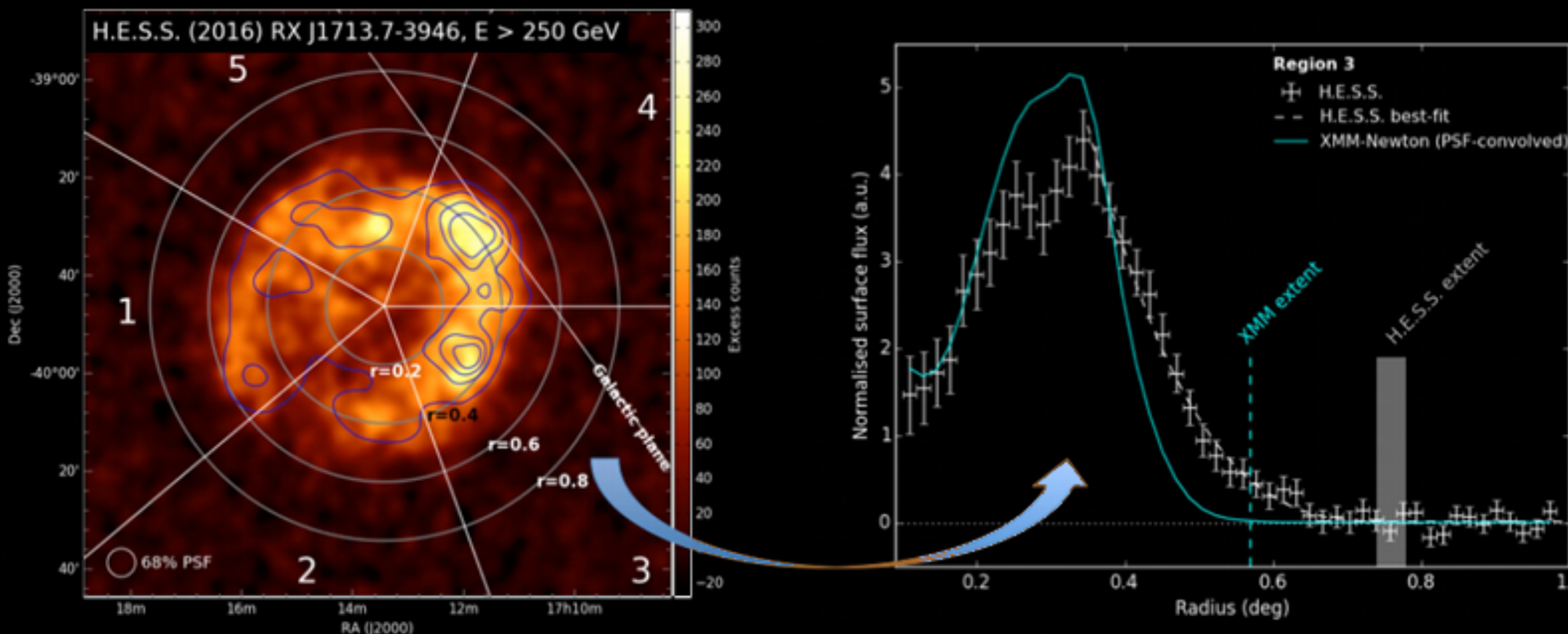
Gamma Rays from Young SNRs

Escaping Cosmic Rays? or particles in the forward shock?



Gamma Rays from Young SNRs

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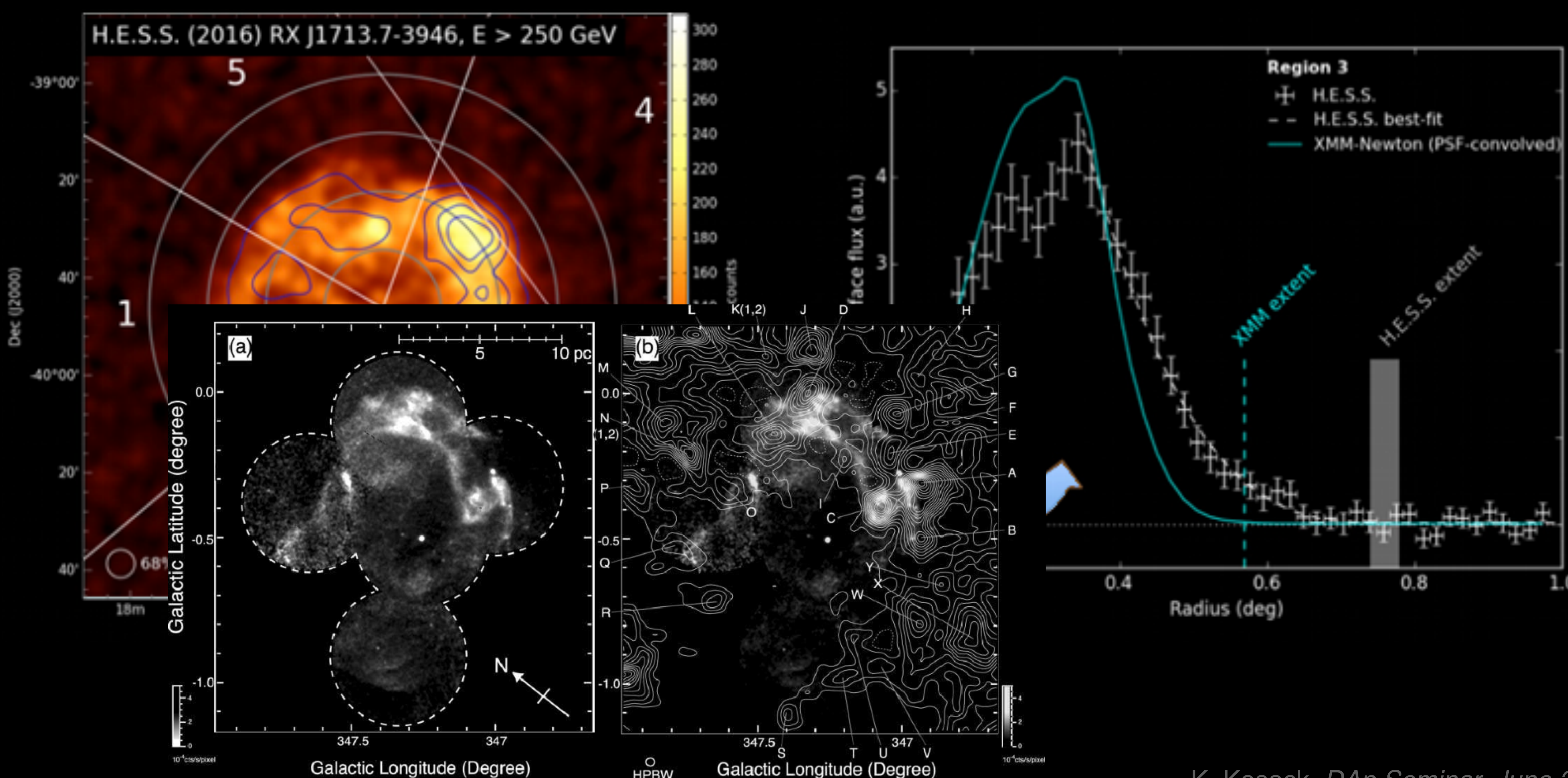
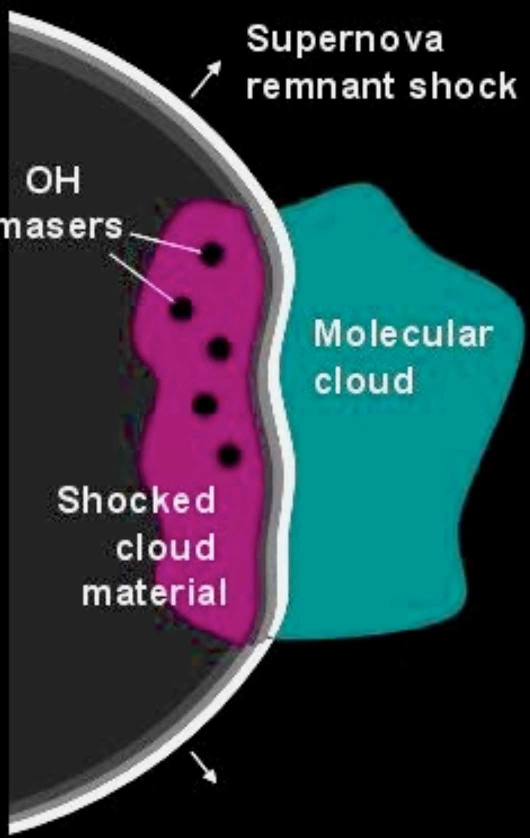


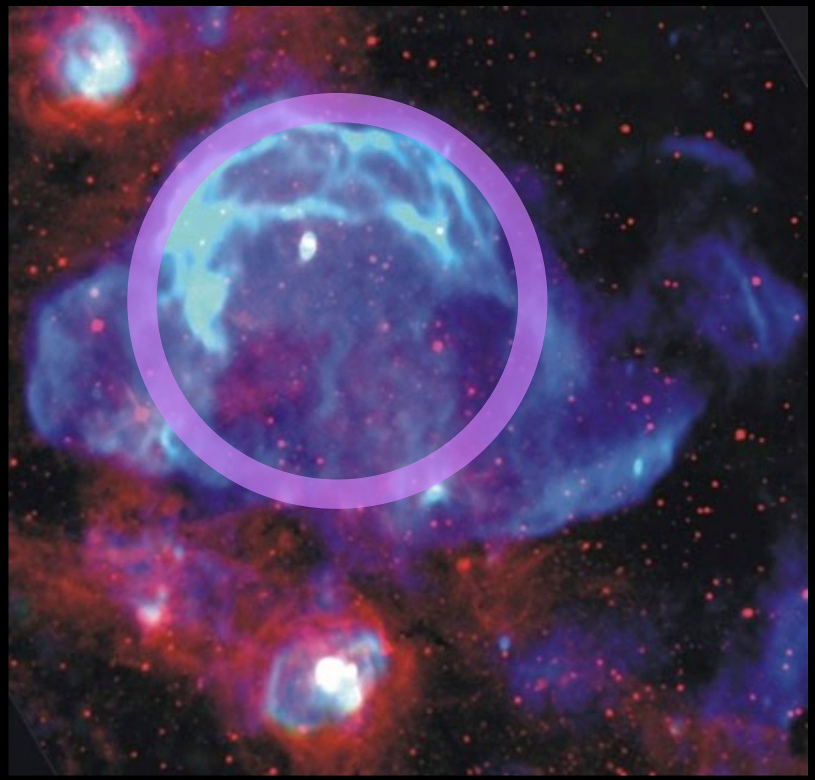
Cosmic Rays and Molecular Clouds

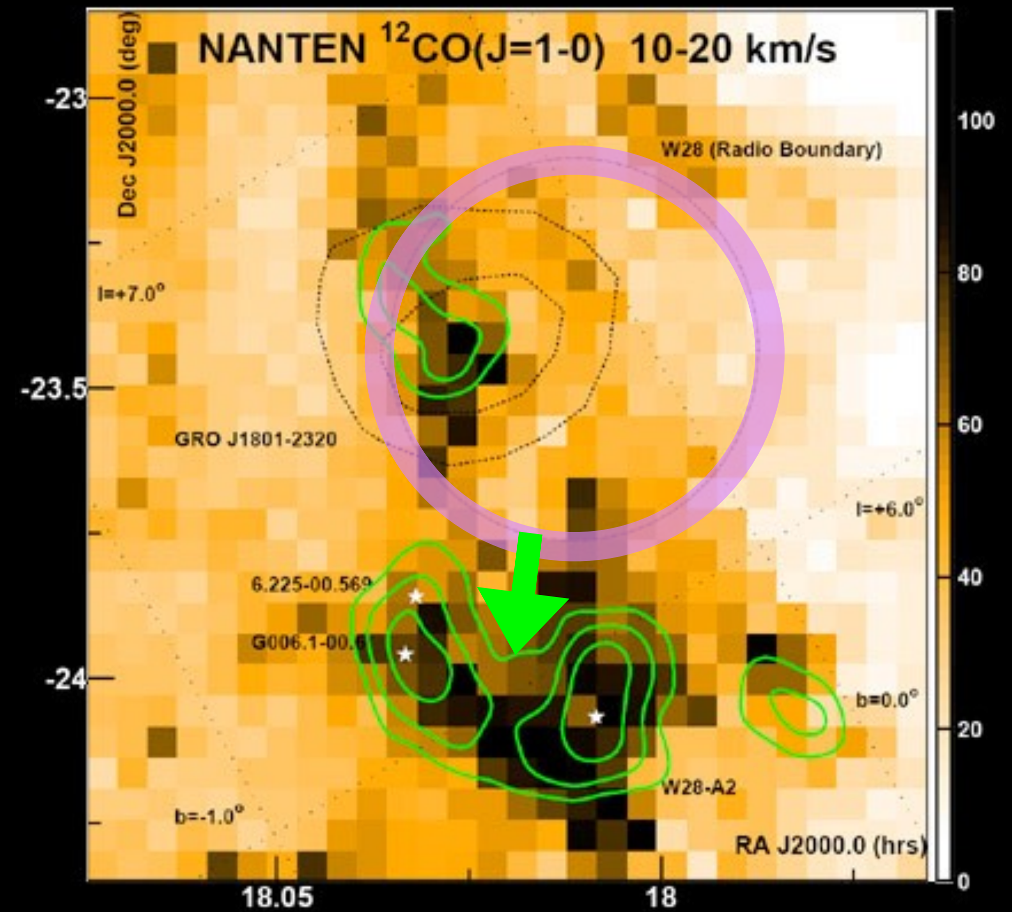
Target material for escaping Cosmic rays



- Another way to look for purely hadronic emission!

W28 region: An old SNR interacting with Clouds?

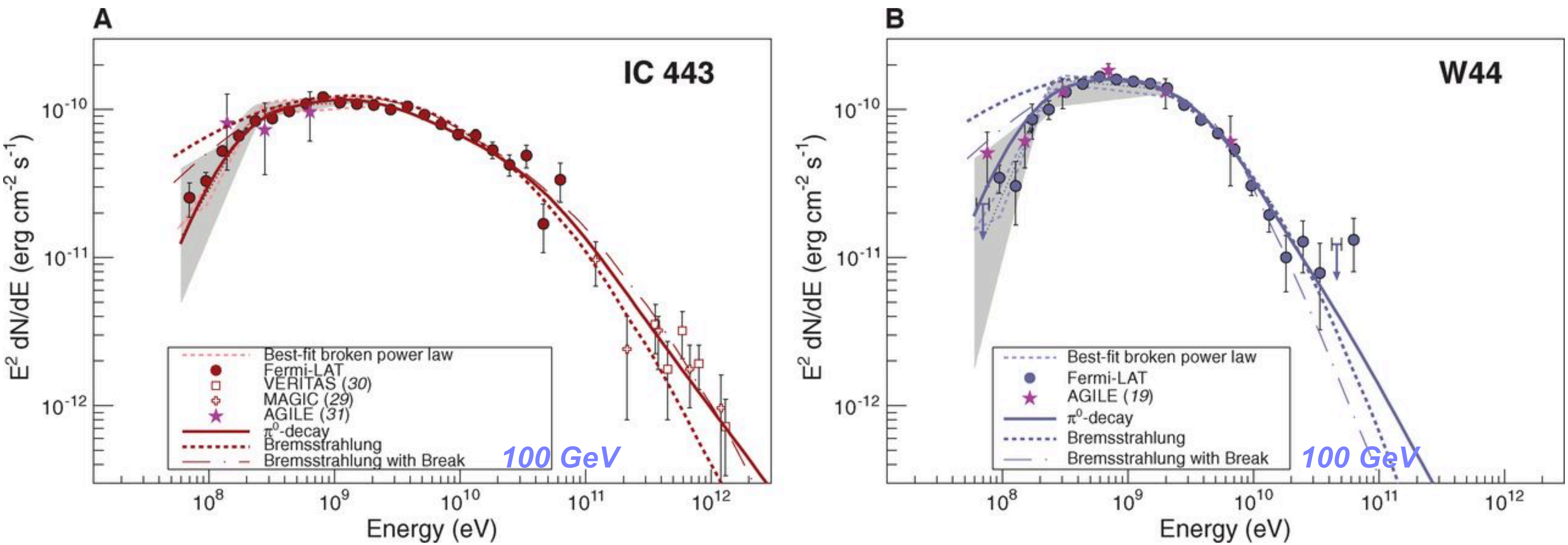




Detection of Pion Bumps!

Direct evidence that cosmic-ray protons are accelerated in SNRs!

Fermi Collaboration, Science 15 Feb 2013



But...

- $p_{br} \approx$ 240 GeV (IC 443)
- $p_{br} \approx$ 22 GeV (W44)

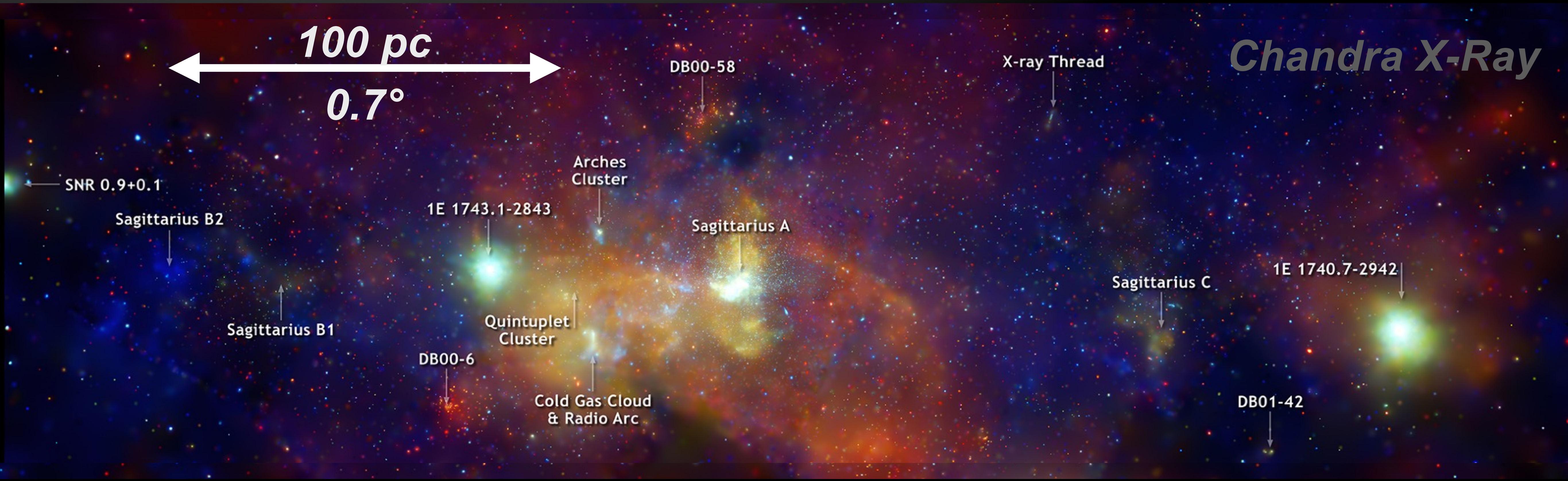
SNRs: Interim conclusion

- Young SNRs detected at VHE energies!
- Not always easy to rule out pure leptonic model for gamma-ray emission...
- But: evidence that SNRs do accelerate Cosmic Rays!
  - pion bump measurements
  - escaping protons interacting with nearby molecular clouds
  - not *currently* PeVatrons, but maybe were in their past… need more objects
  - Theory: SNRs should accelerate up to PeV only when shock speeds are **>10,000km/s** (early stage of evolution, only lasts a short time in typical case 10-100 years) [e.g. Bell+MNRAS 2013]

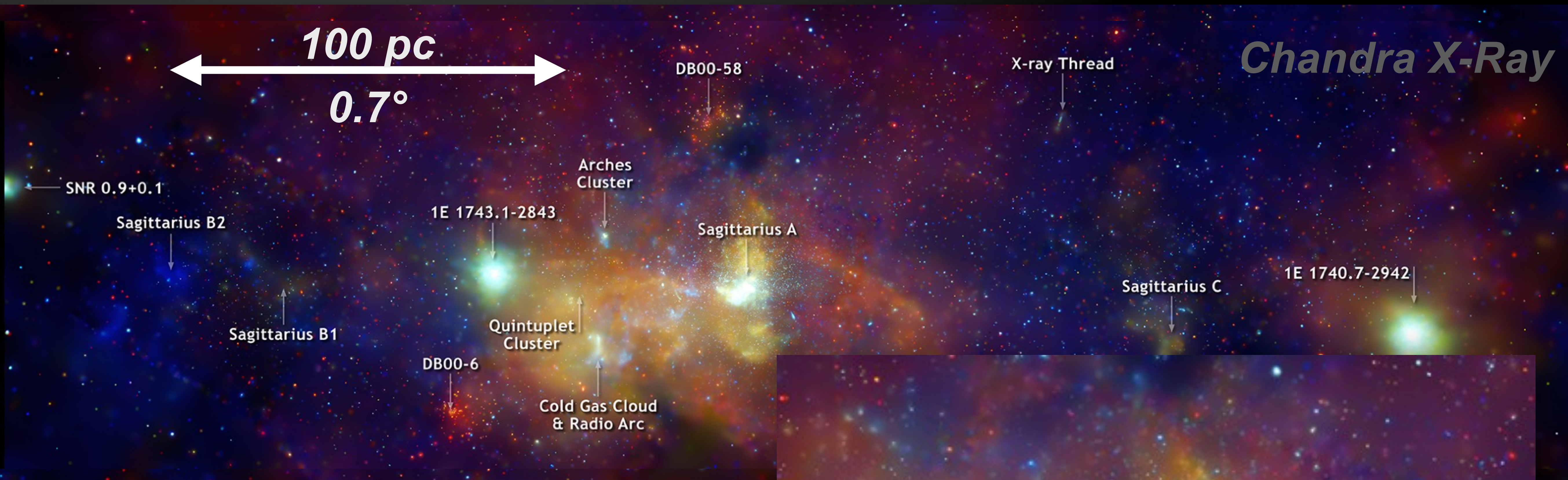
No smoking gun...

Jackpot (probably)! The Galactic Center...

Jackpot (probably)! The Galactic Center...



Jackpot (probably)! The Galactic Center...



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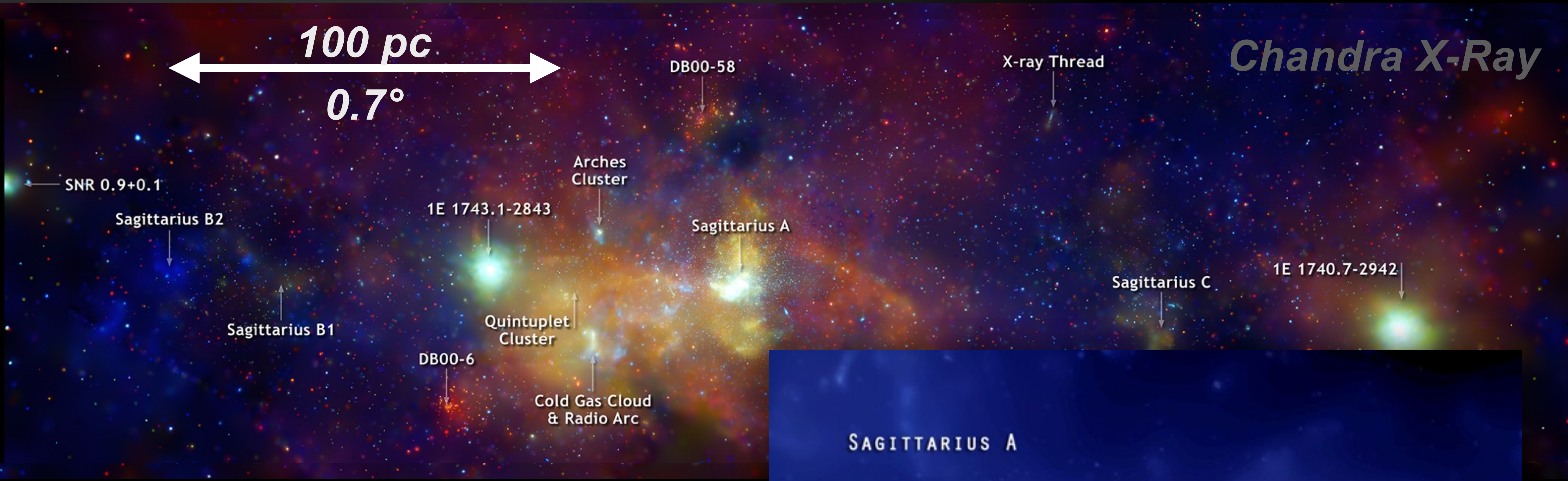

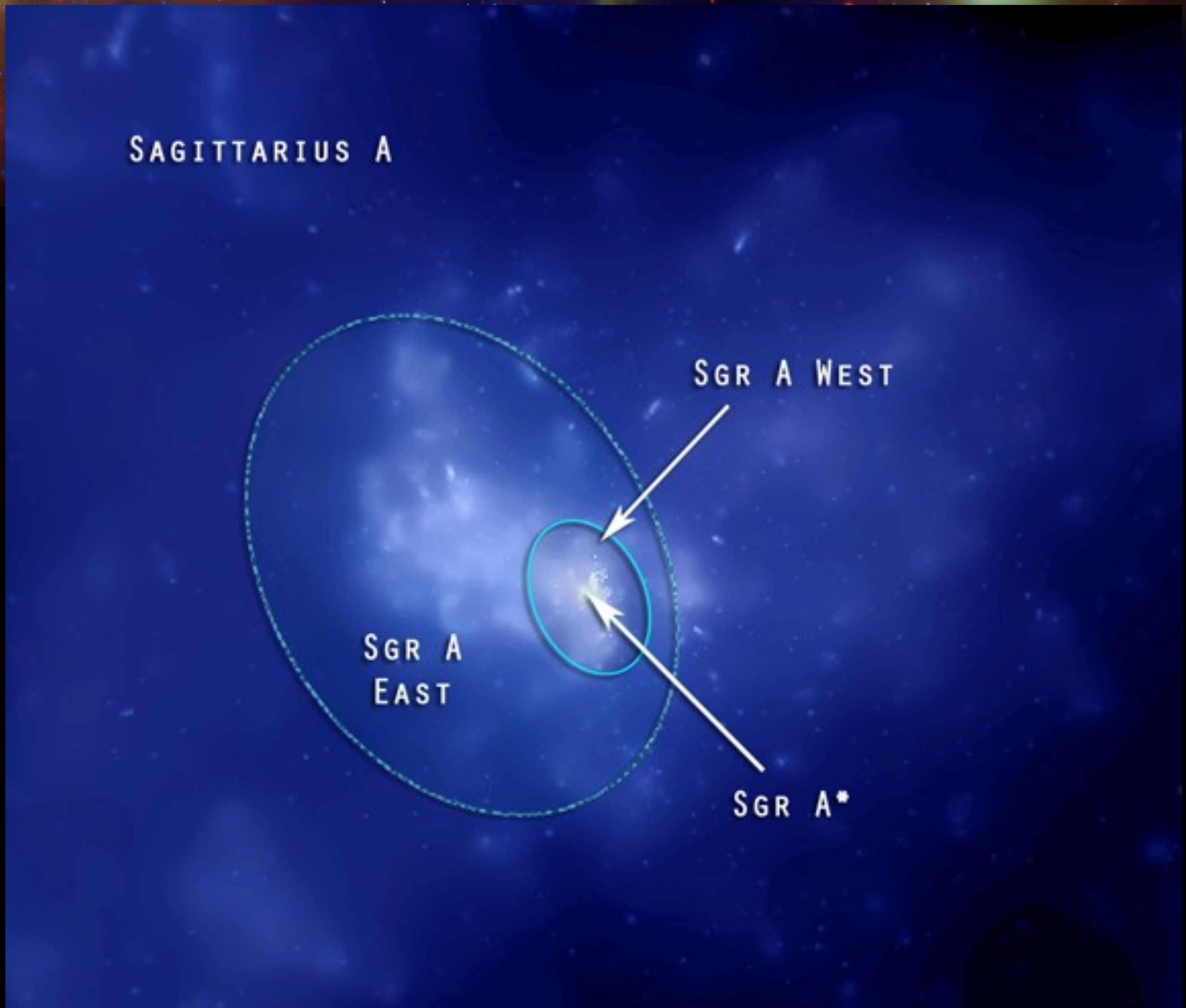

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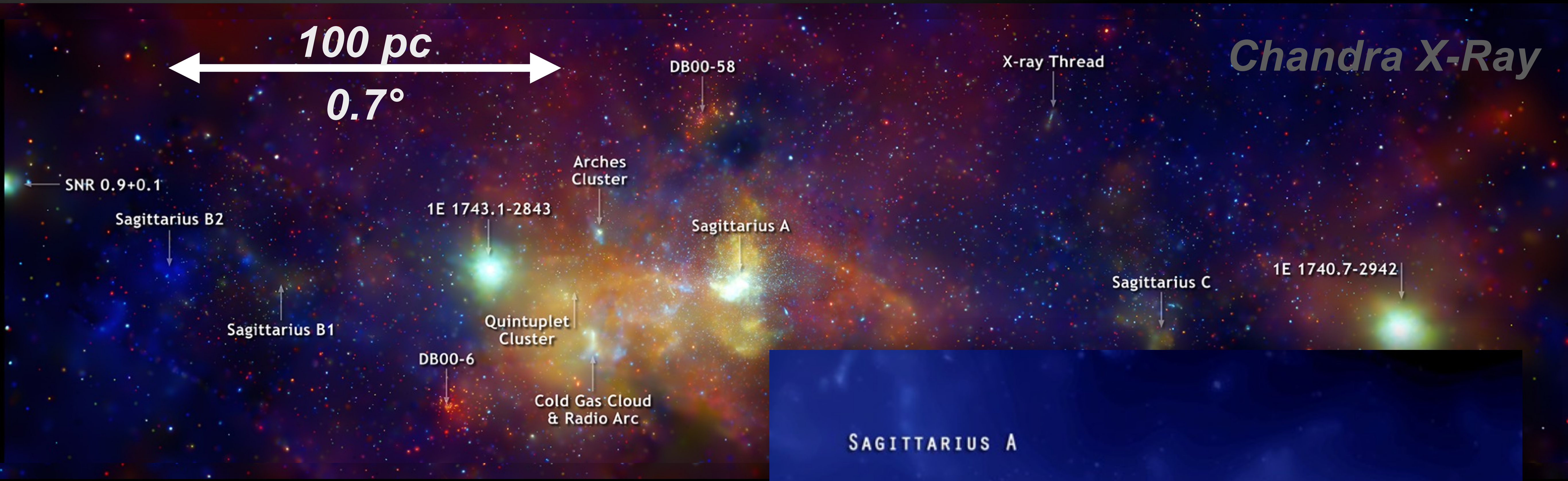
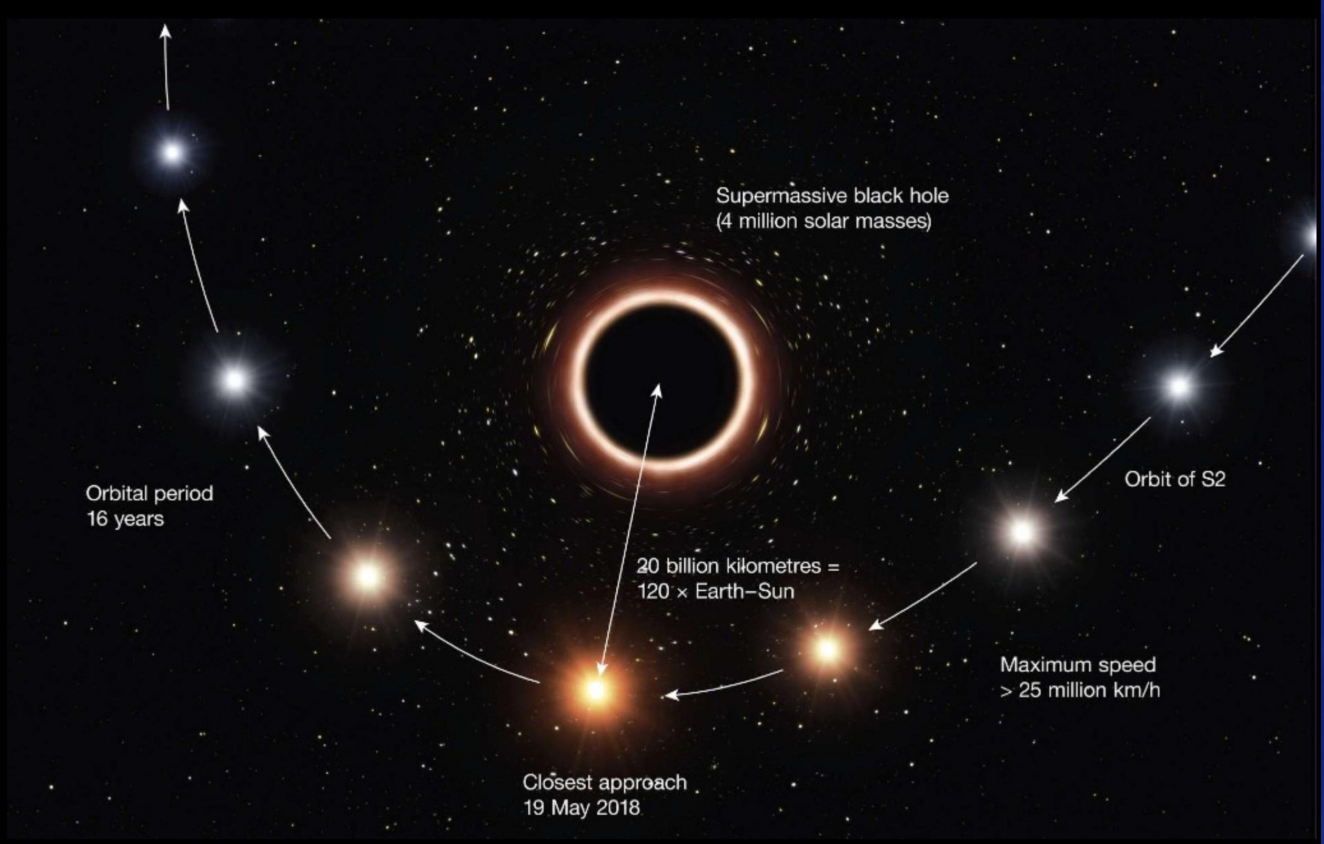
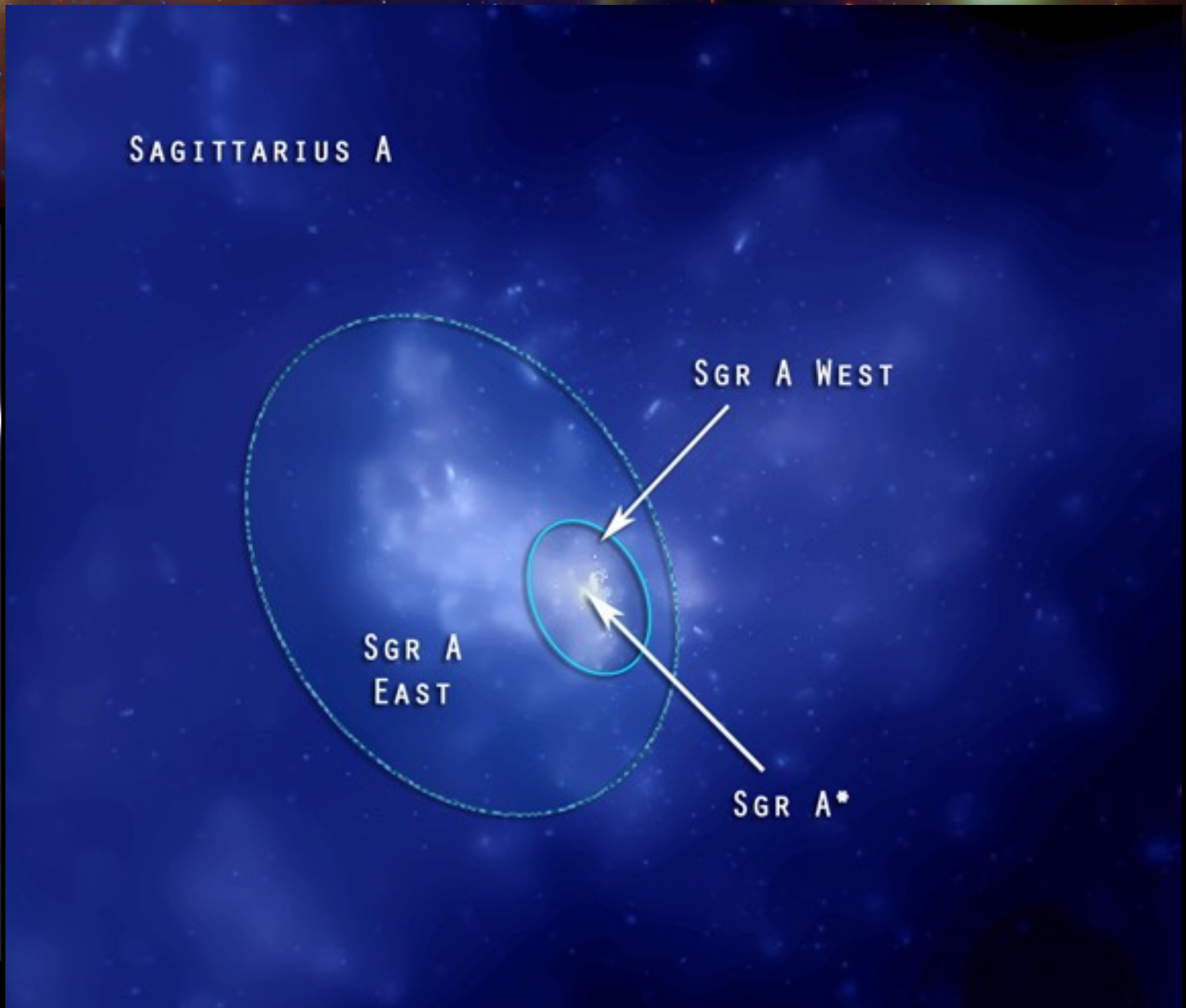
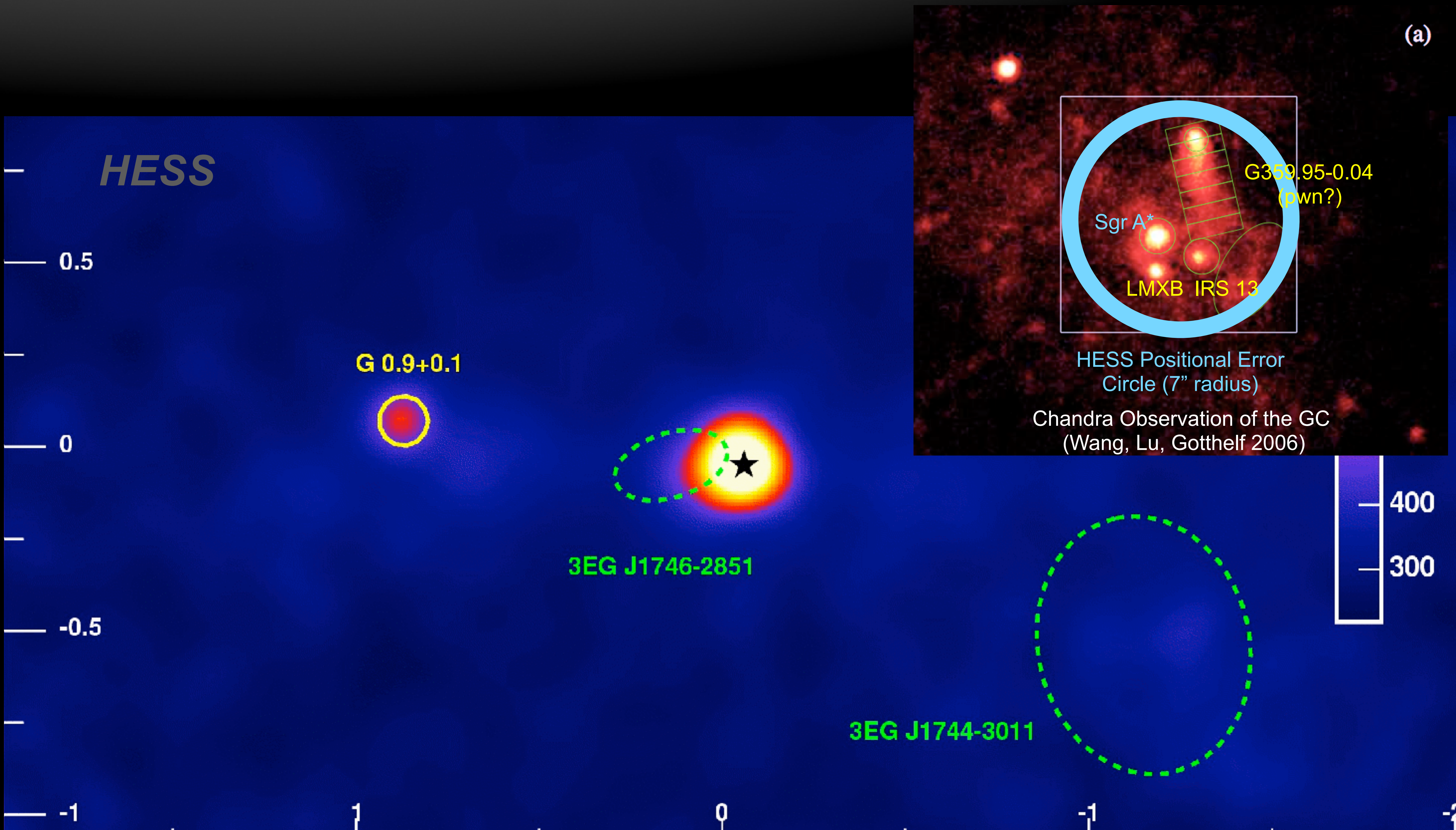




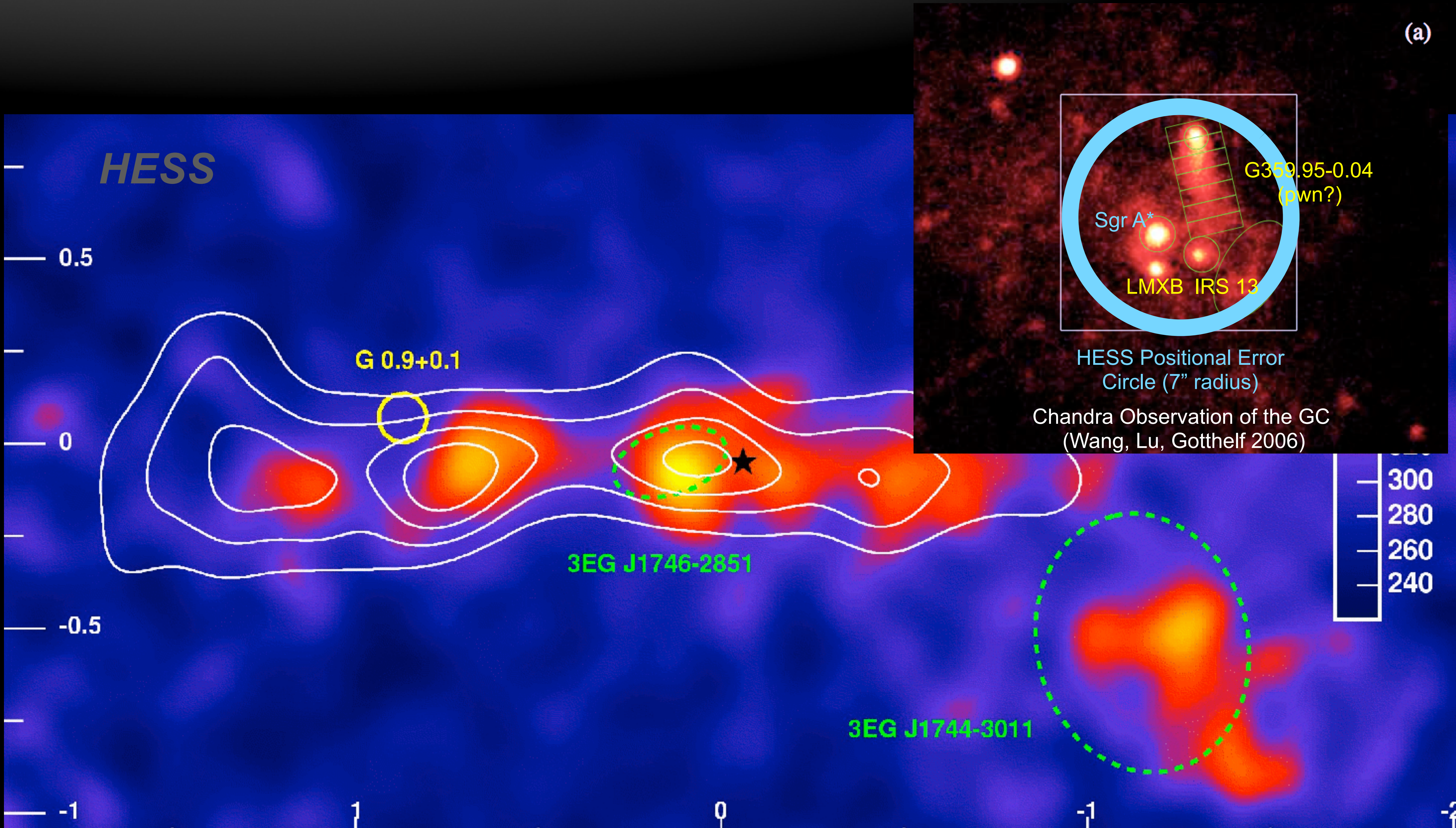


Galactic Center in Gamma Rays



Central source: *Kosack et al (Whipple 10m Collaboration) ApJ 2005*
Galactic Ridge: *HESS Collaboration, Nature 2006,*

Galactic Center in Gamma Rays



Central source: *Kosack et al (Whipple 10m Collaboration) ApJ 2005*
Galactic Ridge: *HESS Collaboration, Nature 2006,*

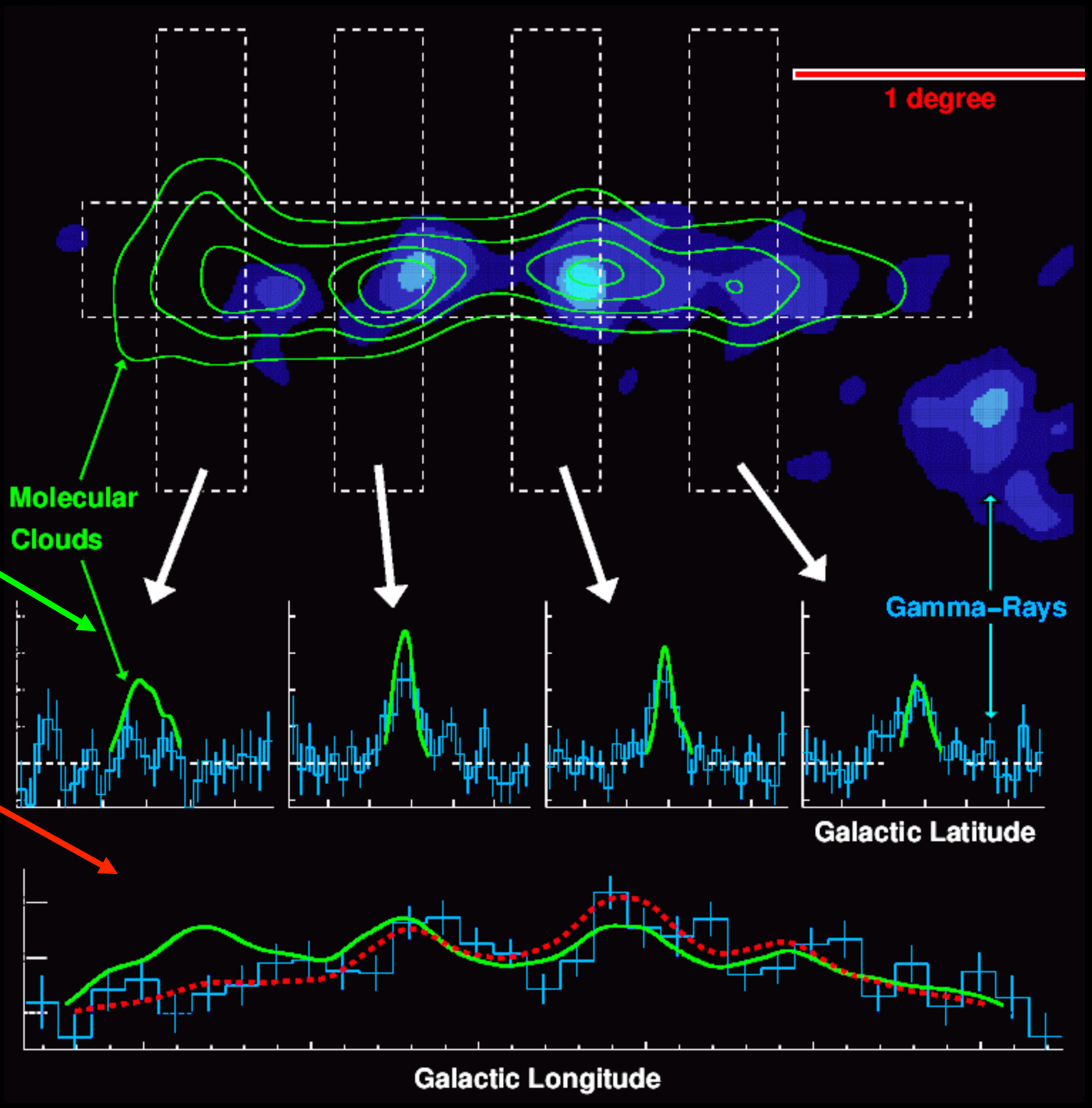
Galactic Center in Gamma-rays

close correlation between γ-rays and molecular clouds

deficit in
TeV γ-rays
source too young?

simulation
10^4 years old
source @ GC

GC accelerates
(nucleonic)
cosmic rates!

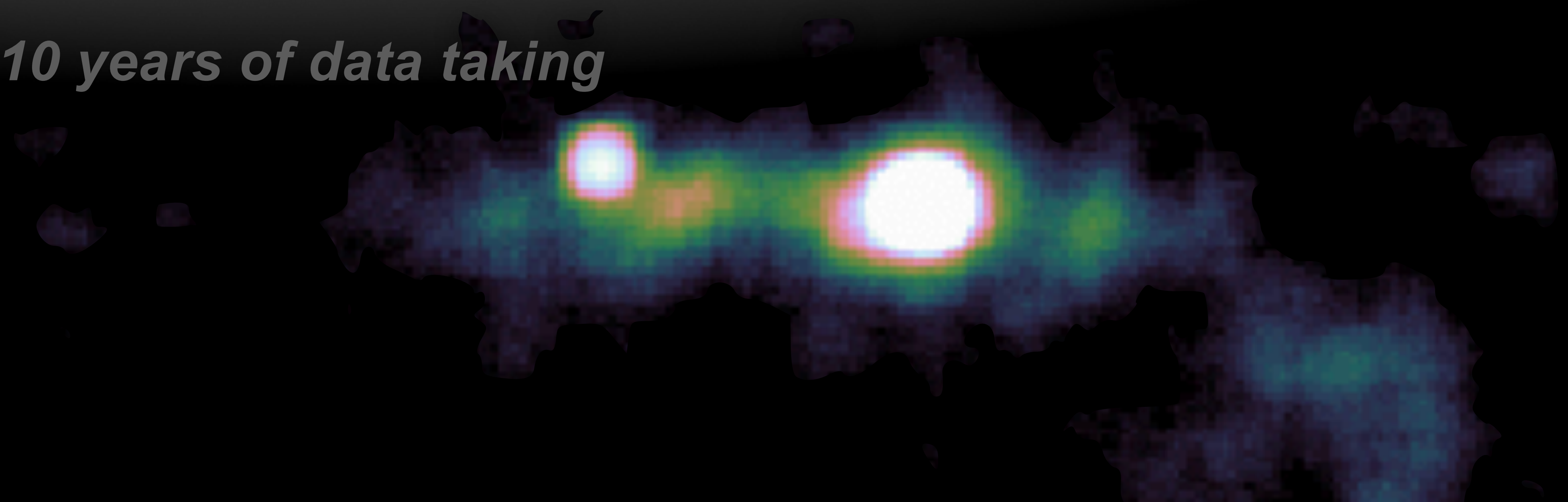


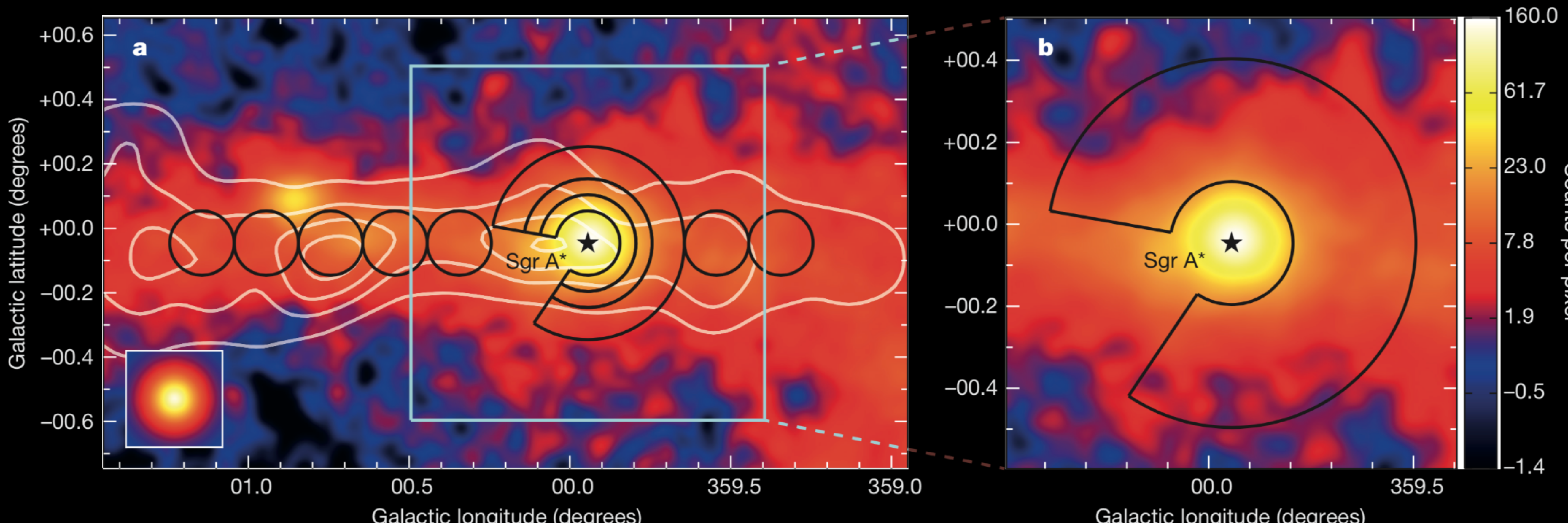
★ **Nature** 439 (2006)

Galactic Center: PeVatron?

Central Molecular Zone with HESS

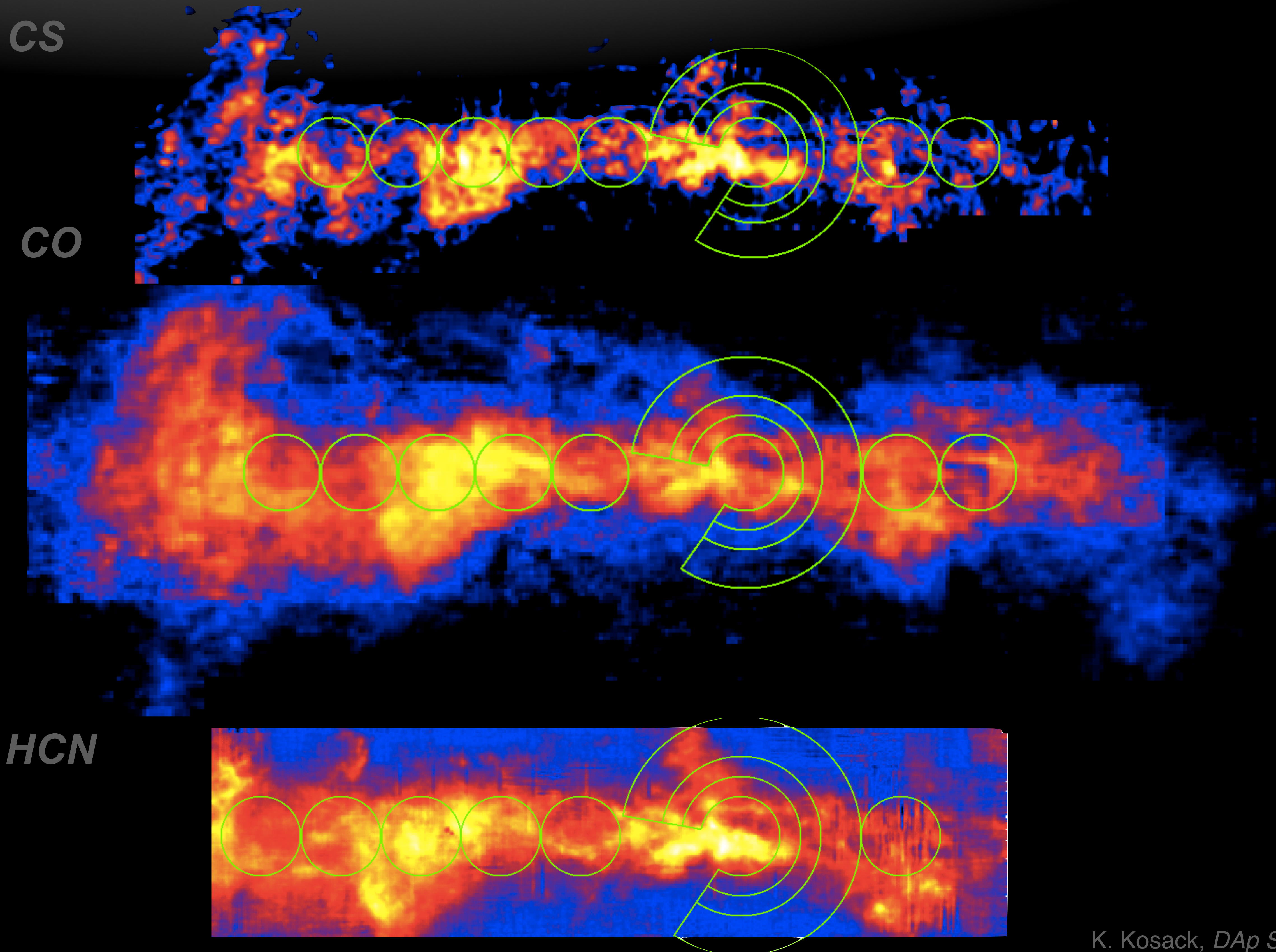
10 years of data taking



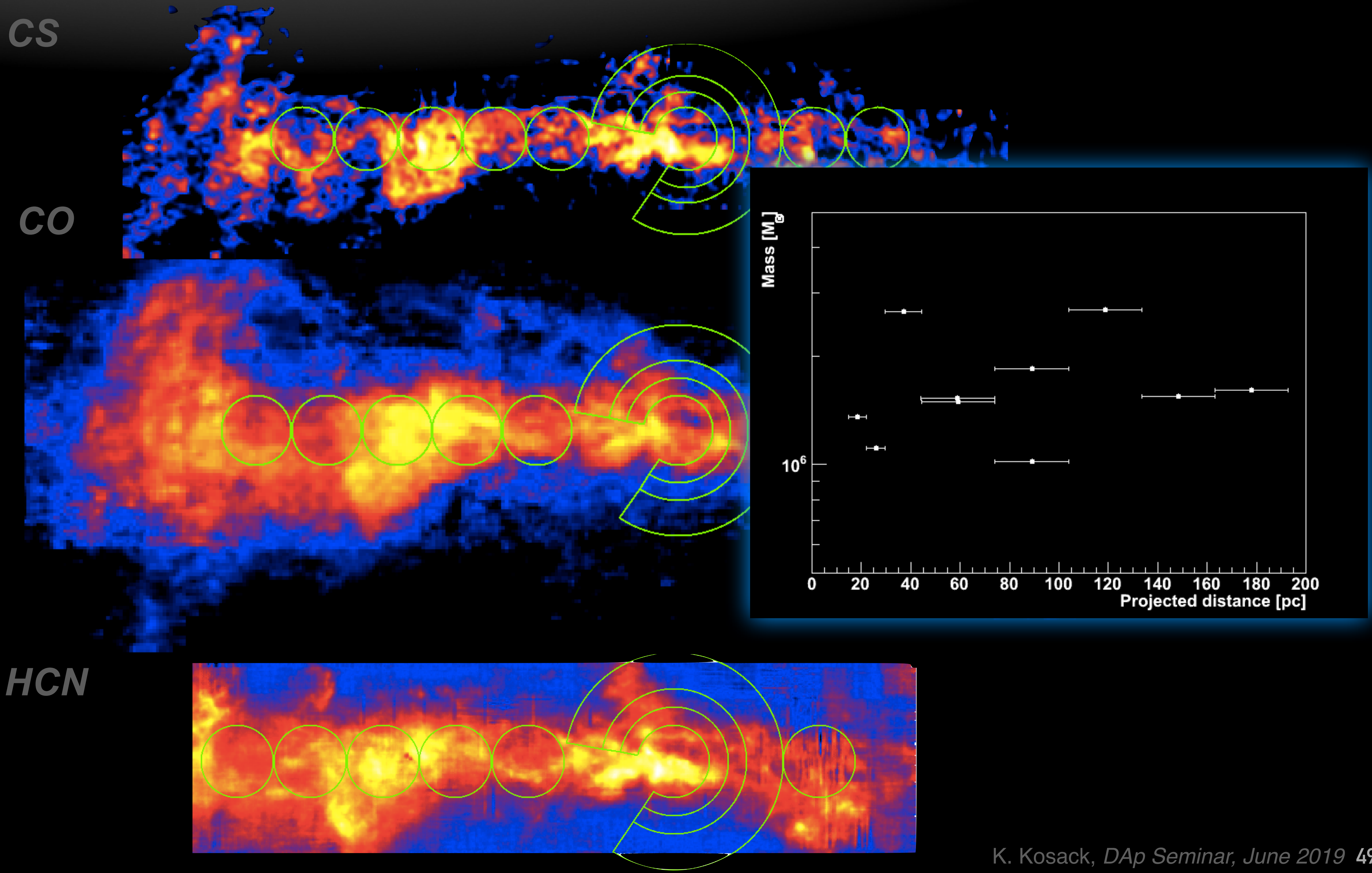


HESS Collaboration, Nature 2016

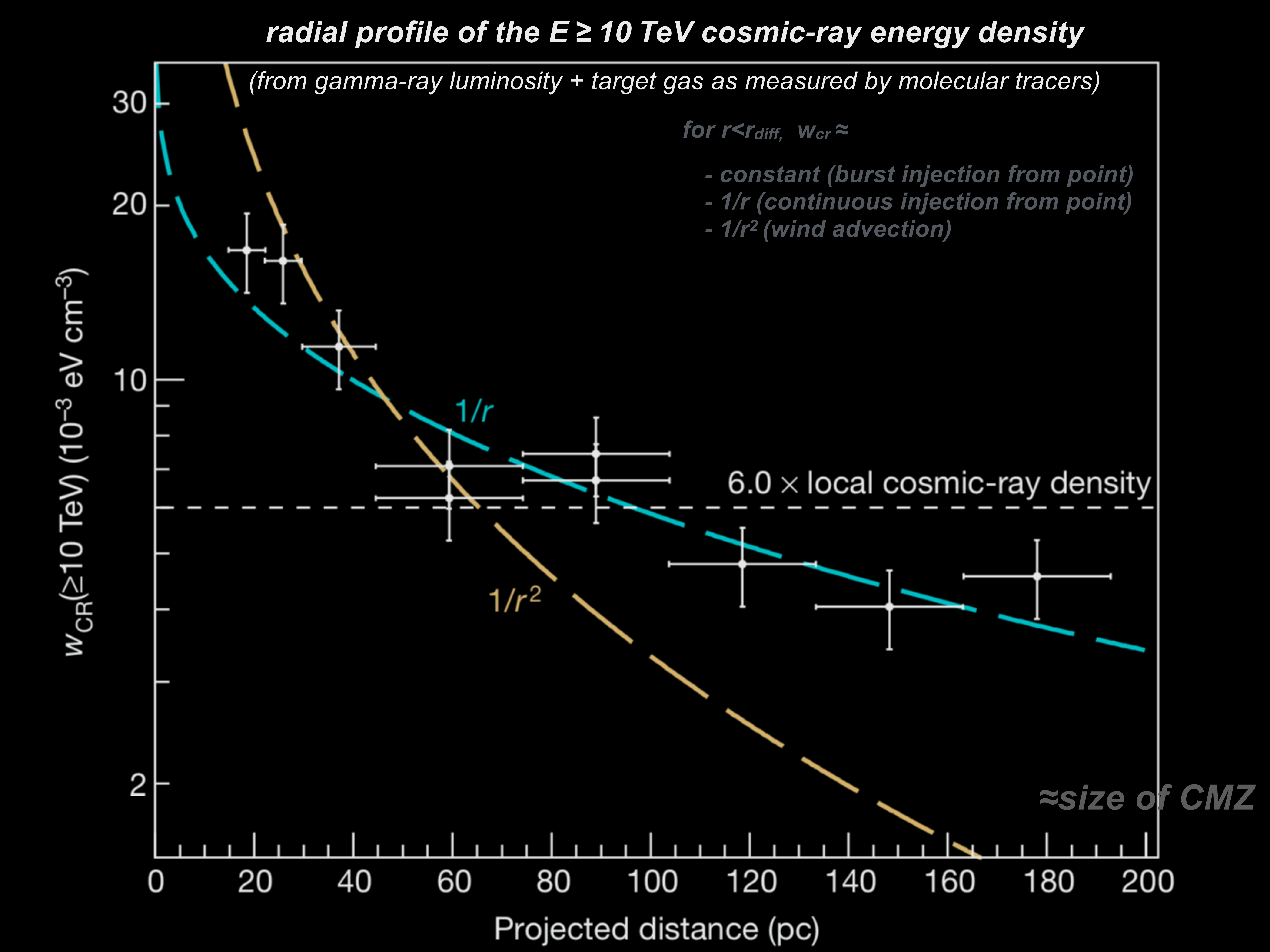
Gas Tracers



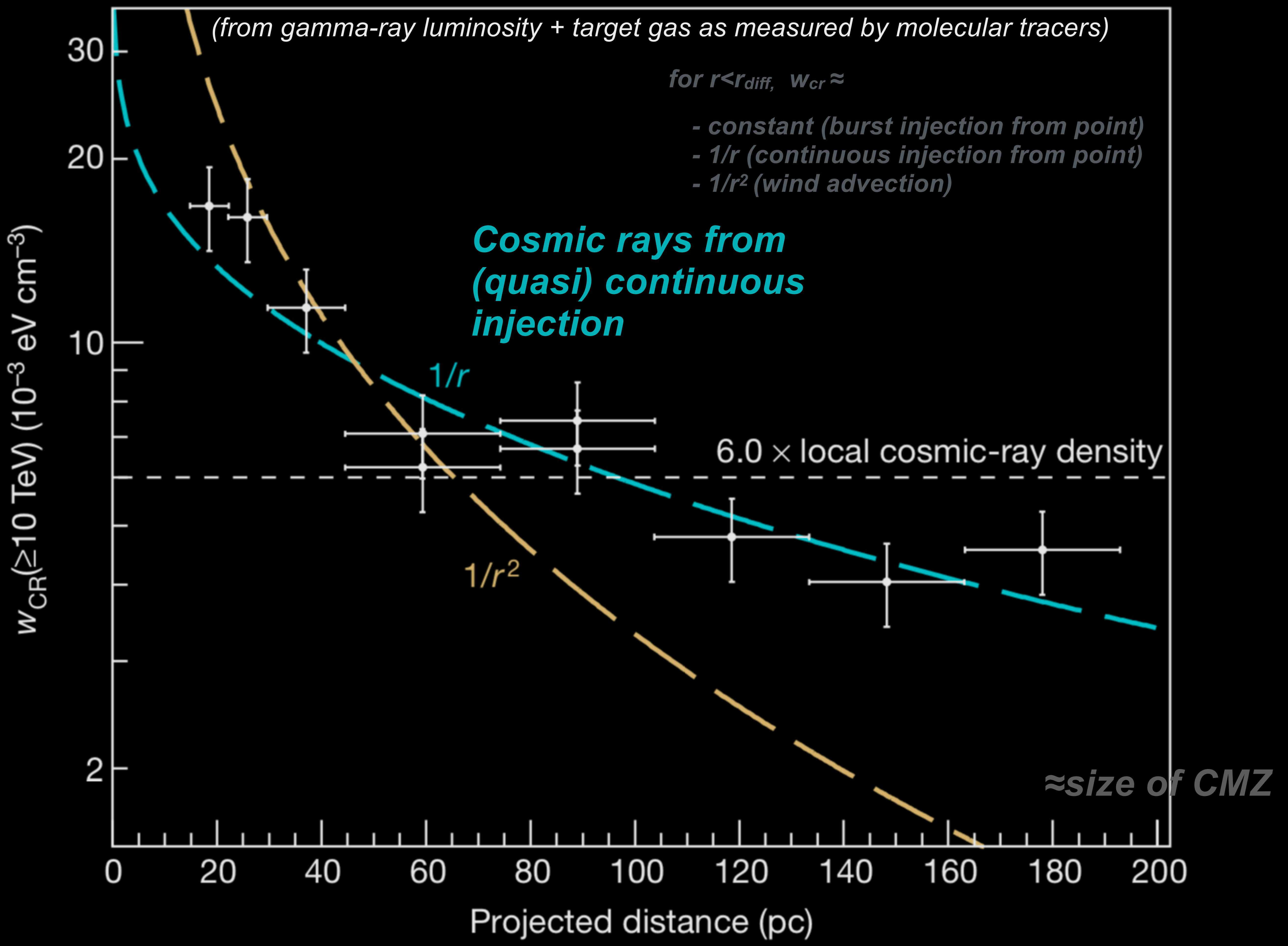
Gas Tracers

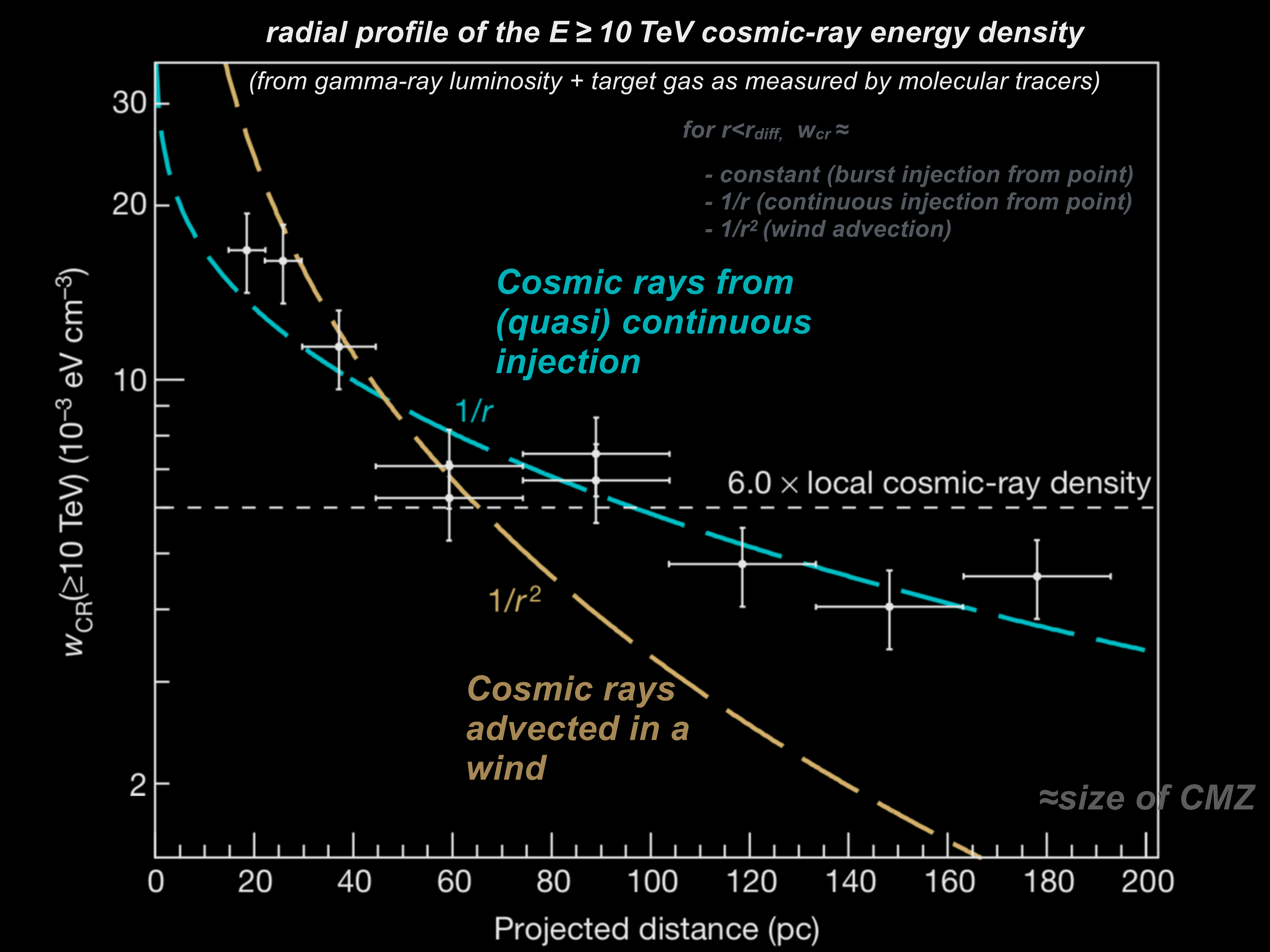


CS
CO
HCN
Mass [M$_\odot$]
10^6
0
20
40
60
80
100
120
140
160
180
200
Projected distance [pc]


radial profile of the E ≥ 10 TeV cosmic-ray energy density
(from gamma-ray luminosity + target gas as measured by molecular tracers)
for r<r_diff, w_cr ≈
- constant (burst injection from point)
- 1/r (continuous injection from point)
- 1/r² (wind advection)
1/r
1/r²
6.0 × local cosmic-ray density
≈size of CMZ
w_CR(≥10 TeV) (10⁻³ eV cm⁻³)
30
20
10
2
0
20
40
60
80
100
120
140
160
180
200
Projected distance (pc)

radial profile of the E ≥ 10 TeV cosmic-ray energy density





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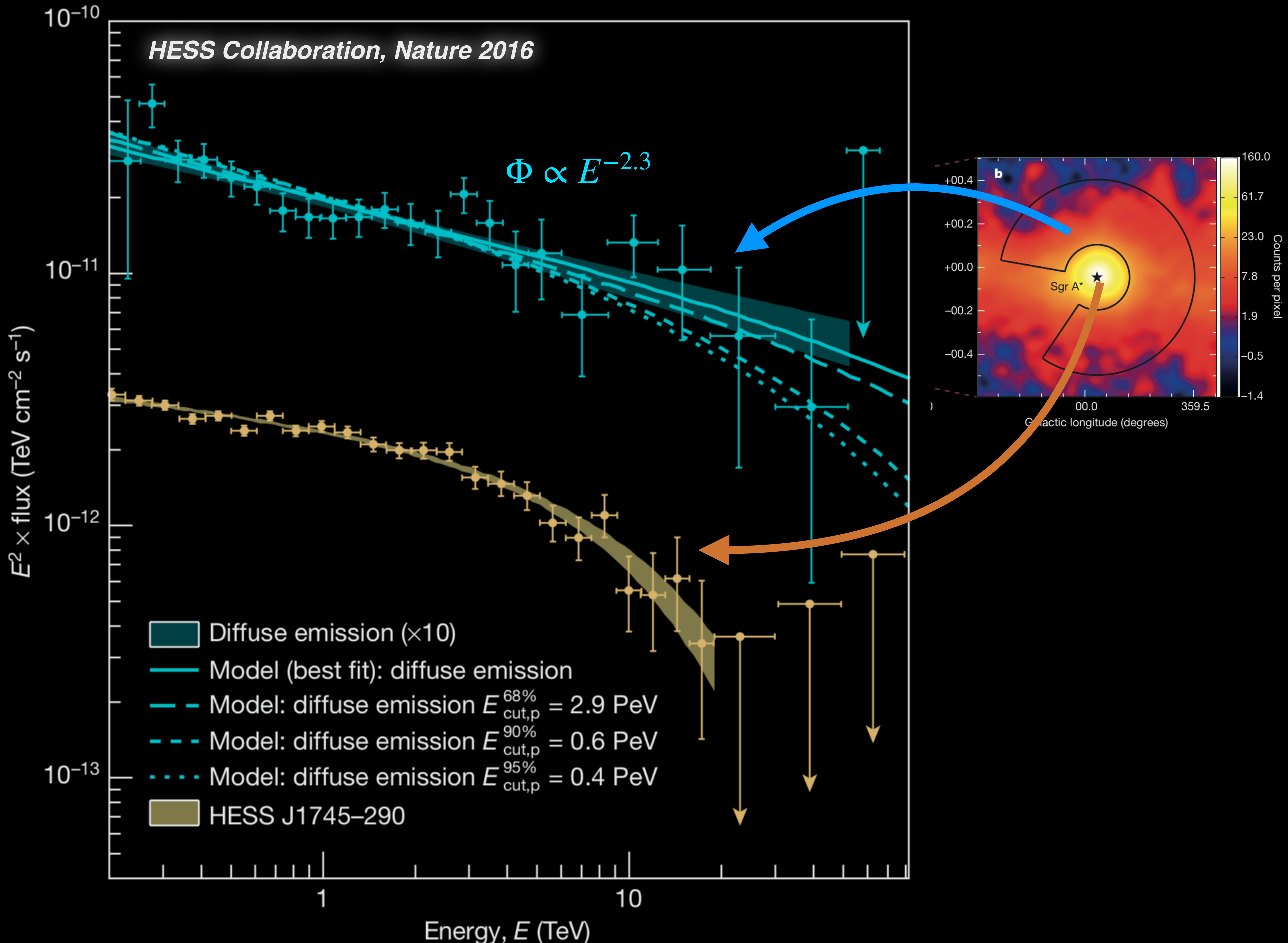
for $r<r_{diff}$, w_{cr} ≈
- constant (burst injection from point)
- 1/r (continuous injection from point)
- 1/r² (wind advection)
Cosmic rays from (quasi) continuous injection
1/r
6.0 × local cosmic-ray density
1/r²
Cosmic rays advected in a wind
≈size of CMZ
w_{CR}(≥10 TeV) (10^{-3} eV cm^{-3})
30
20
10
2
0
20
40
60
80
100
120
140
160
180
200
Projected distance (pc)



HESS Collaboration, Nature 2016
$\Phi \propto E^{-2.3}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$E^2 \times$ flux (TeV cm^{-2} s^{-1})
1
10
Energy, E (TeV)
Diffuse emission (×10)
Model (best fit): diffuse emission
Model: diffuse emission $E^{68\%}_{\mathrm{cut,p}}$ = 2.9 PeV
Model: diffuse emission $E^{90\%}_{\mathrm{cut,p}}$ = 0.6 PeV
Model: diffuse emission $E^{95\%}_{\mathrm{cut,p}}$ = 0.4 PeV
HESS J1745–290
b
+00.4
+00.2
+00.0
−00.2
−00.4
Sgr A*
00.0
359.5
Galactic longitude (degrees)
160.0
61.7
23.0
7.8
1.9
−0.5
−1.4
Counts per pixel

Implications

$$t_{\rm diff} \simeq 2 \times 10^3 (R/200\mathrm{pc})^2 (D/10^{30})\ \text{years}$$

leptonic gamma-ray emission scenario is unlikely

- e- radiative losses → size << central molecular zone
- to get to 100 TeV e-, need "Extreme accelerator", low B-field, and very high diffusion coefficient
- wouldn't show correlation between gamma-ray emission and gas cloud density

Hadronic model implies:

- Source is within 10 pc of Sgr A*
- Source injected cosmic rays *continuously* over ≈1000 yr timescale
- Source must accelerate particles above 1 PeV

What is the acceleration site?

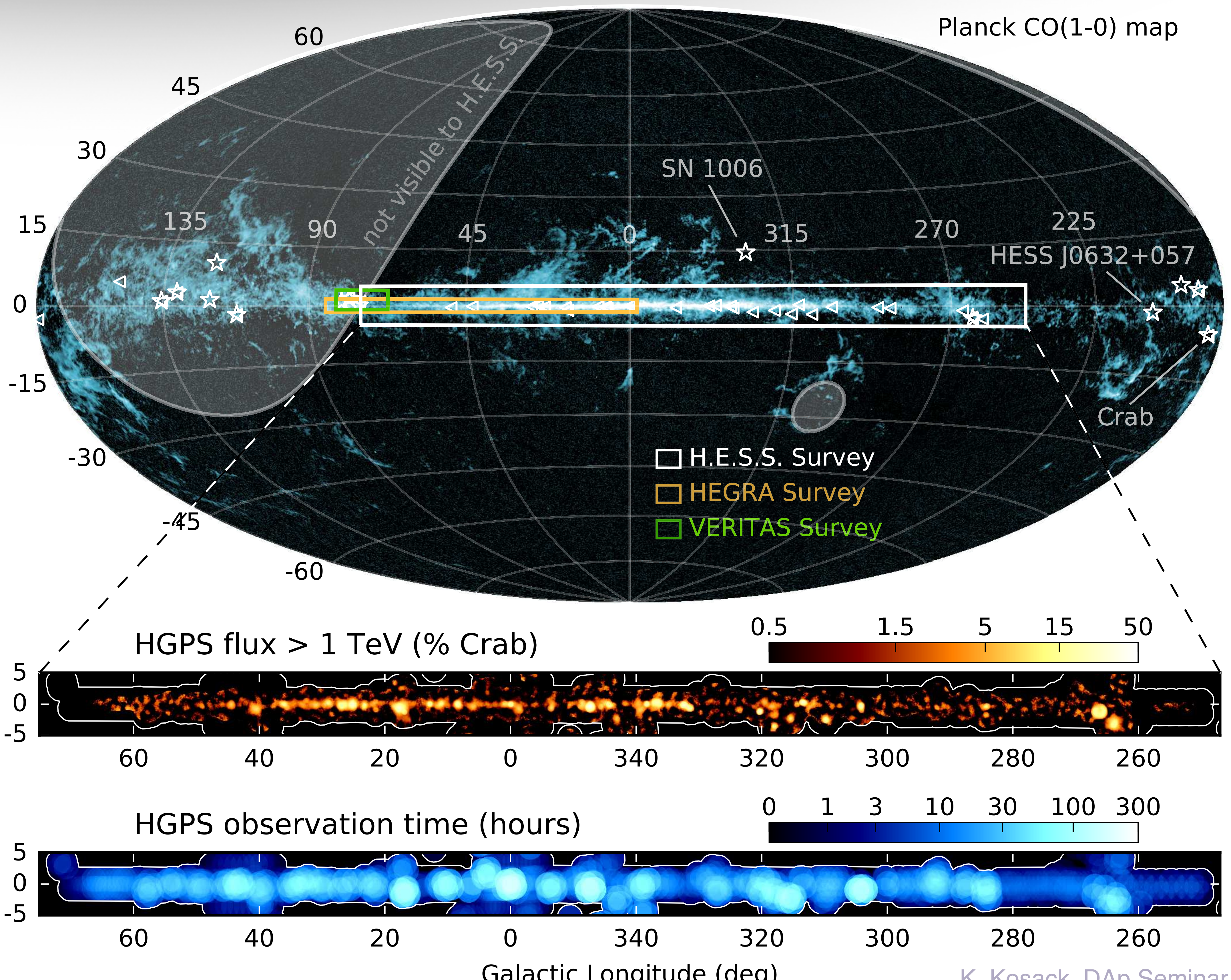
Sgr A*?

- bolometric luminosity is 100-1000x *too small* to explain this emission
- Perhaps past (higher) activity?
  - Need 10^6-10^7 years at 10^{39} erg/s acceleration to fully explain the CRs up to the "knee" → not ruled out!

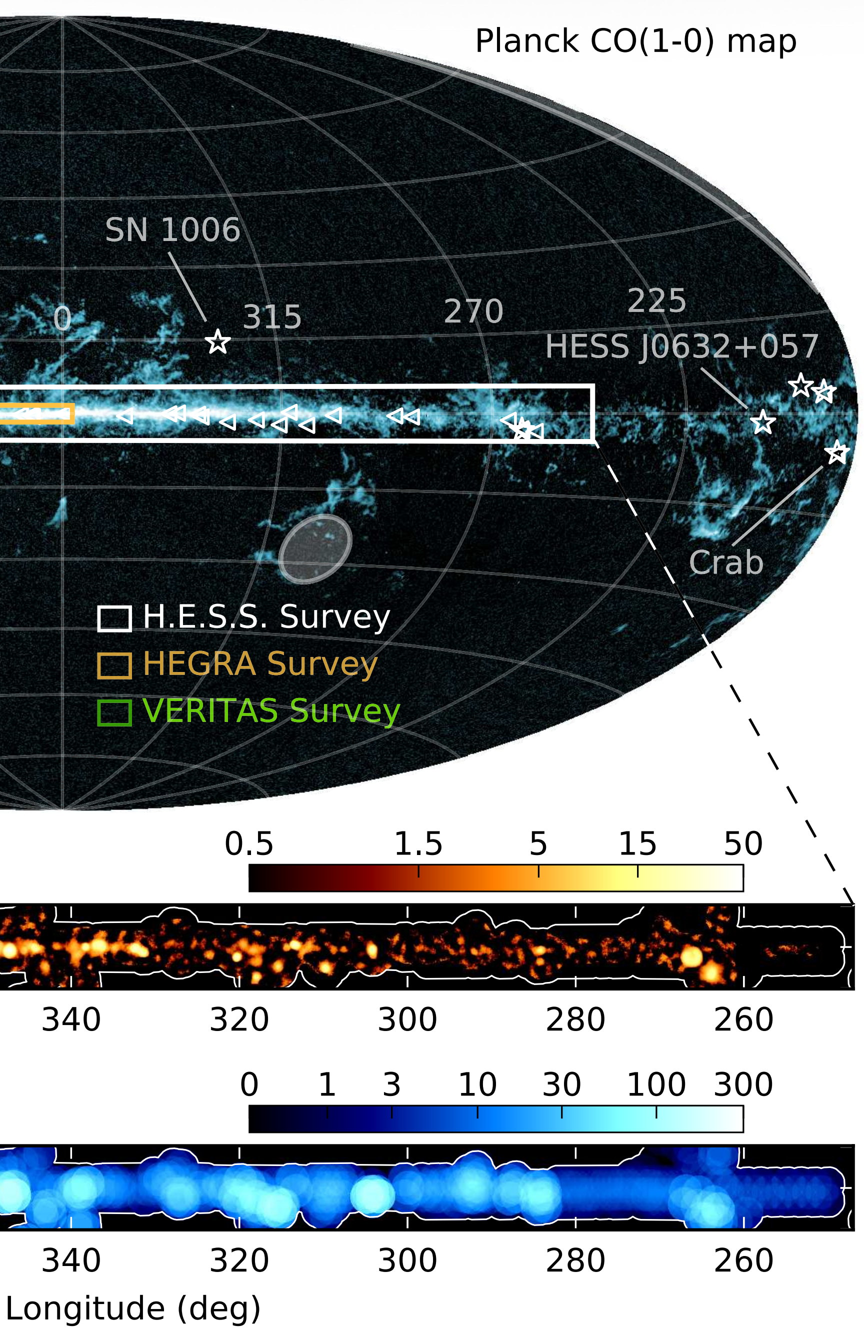
Other stuff in the Central Molecular Zone?

- unseen SNRs?
  - only accelerate for ≈10-100 years → would need 10s of them within 1000 years (quite high SNR rate...)
- Stellar Clusters (3 are in the region)
  - produce collective winds, but would need motion in excess of 10k m/s → SNRs
  - > 10pc from acceleration region
- Radio Filaments accelerating electrons via brehmsstrahlung?
  - Would follow distribution of filiments, not consistent with "centralized" source

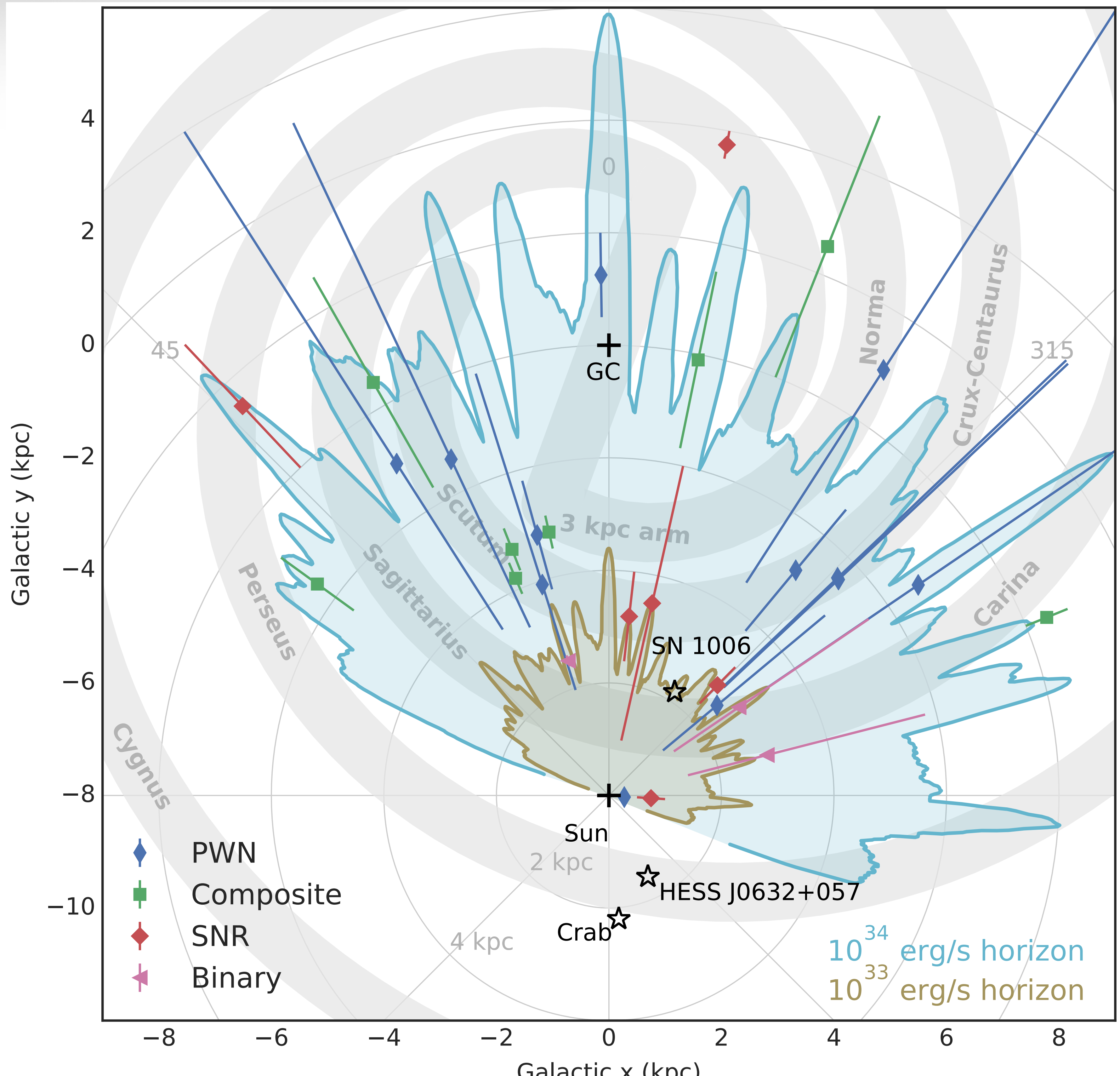
Where else to look? The HESS GPS



The HESS GPS

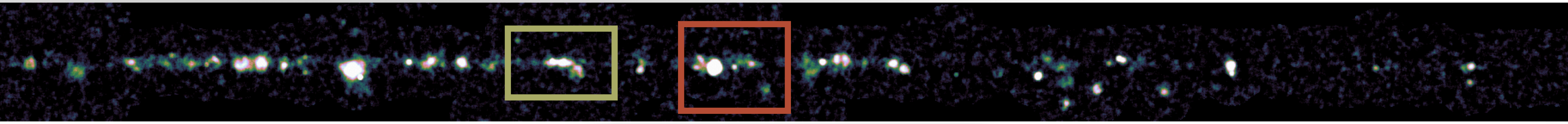


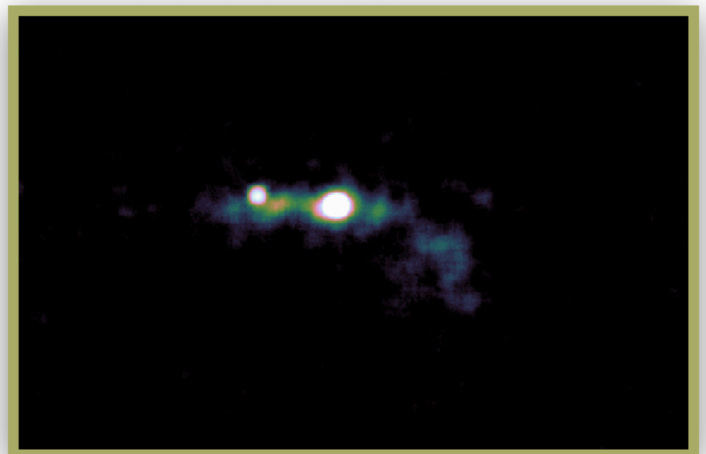
Planck CO(1-0) map
SN 1006
0
315
270
225
HESS J0632+057
Crab
H.E.S.S. Survey
HEGRA Survey
VERITAS Survey
0.5 1.5 5 15 50
340 320 300 280 260
0 1 3 10 30 100 300
340 320 300 280 260
Longitude (deg)

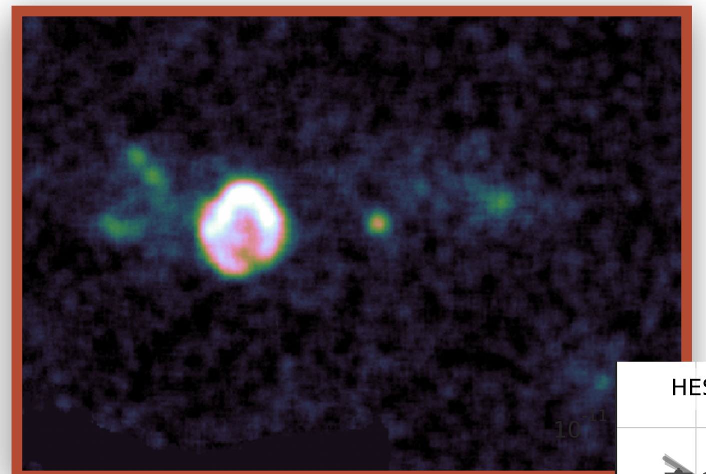


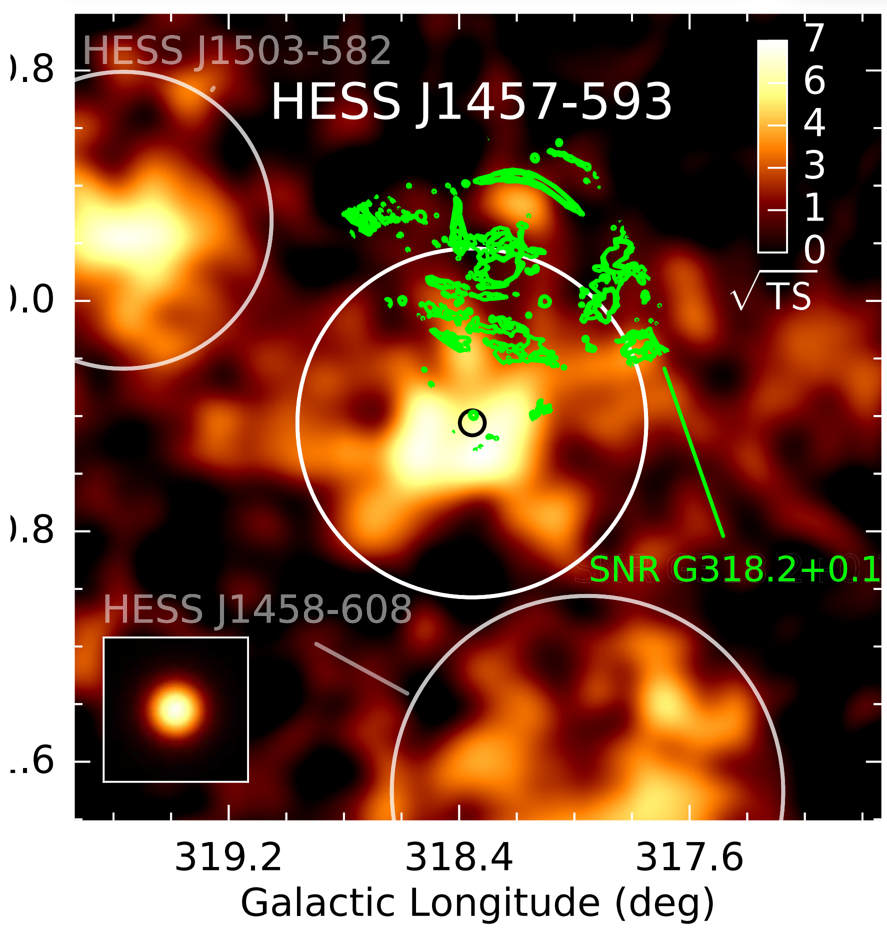
Galactic y (kpc)
Galactic x (kpc)
GC
Sun
SN 1006
HESS J0632+057
Crab
Norma
Crux-Centaurus
Carina
3 kpc arm
Scutum
Sagittarius
Perseus
Cygnus
45
0
315
2 kpc
4 kpc
PWN
Composite
SNR
Binary
10^34 erg/s horizon
10^33 erg/s horizon

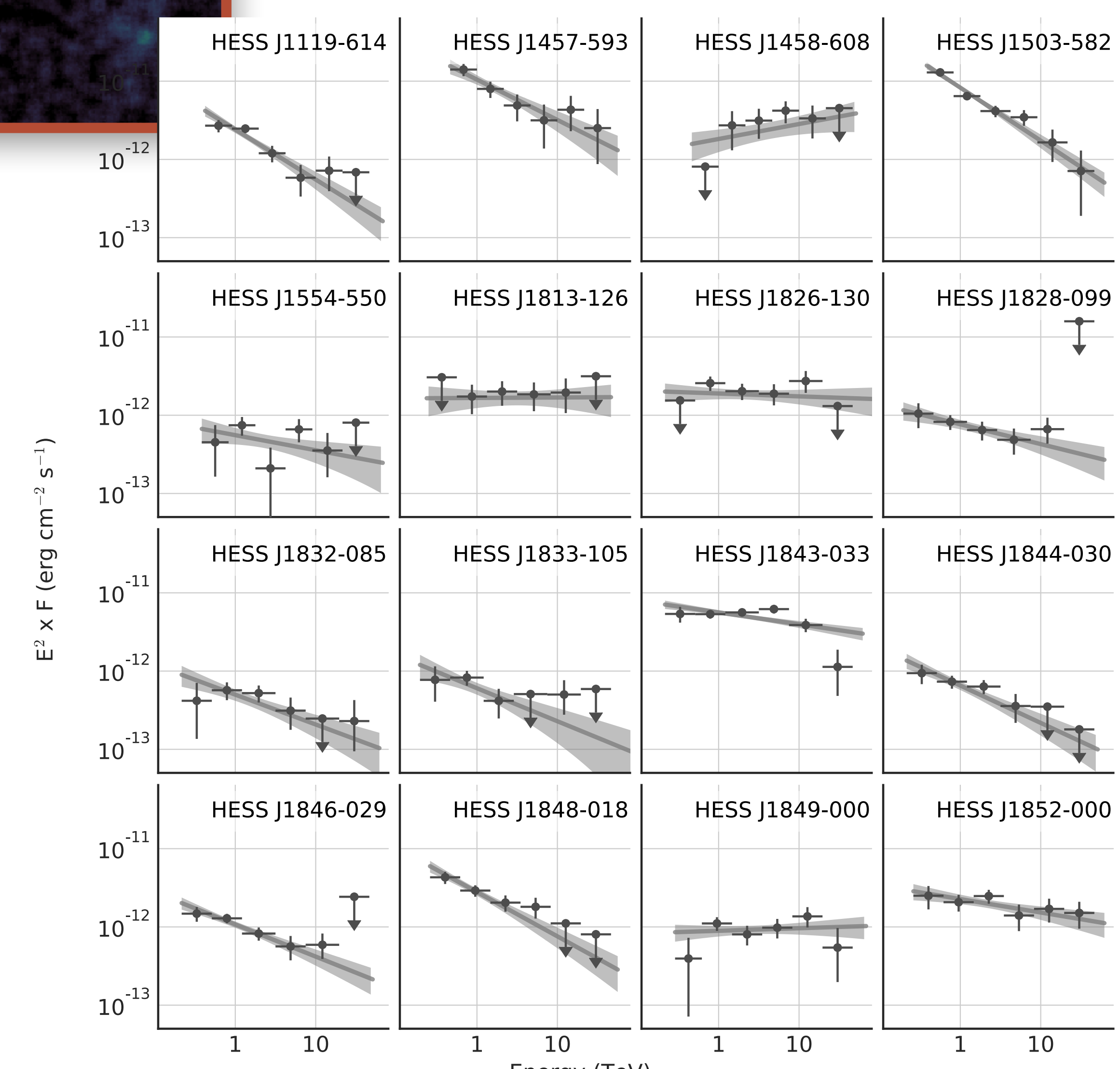
The HESS GPS





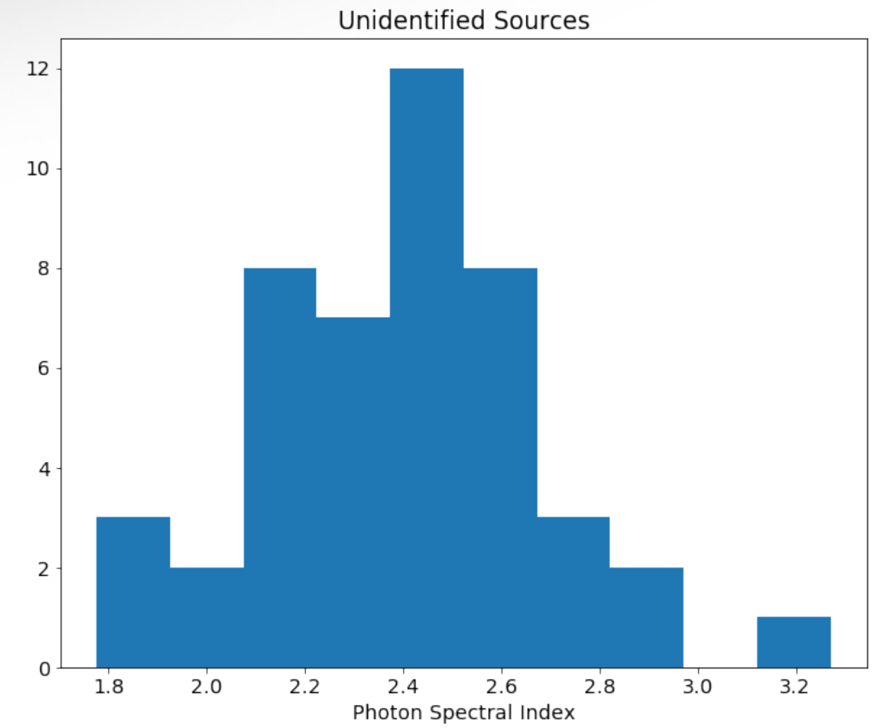


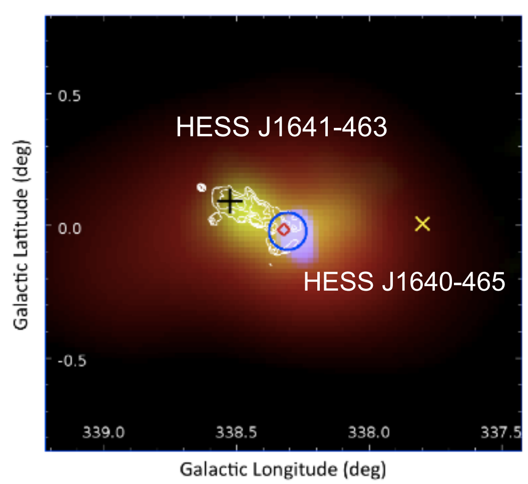

HESS J1503-582
HESS J1457-593
HESS J1458-608
SNR G318.2+0.1
7
6
4
3
1
0
√TS
319.2
318.4
317.6
Galactic Longitude (deg)

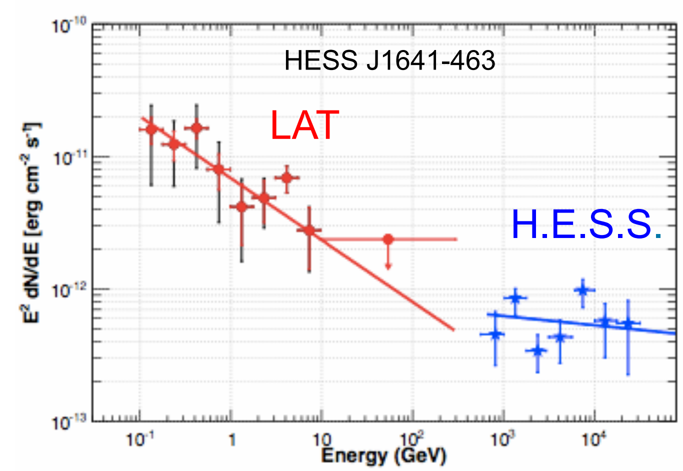

HESS J1119-614
HESS J1457-593
HESS J1458-608
HESS J1503-582
HESS J1554-550
HESS J1813-126
HESS J1826-130
HESS J1828-099
HESS J1832-085
HESS J1833-105
HESS J1843-033
HESS J1844-030
HESS J1846-029
HESS J1848-018
HESS J1849-000
HESS J1852-000
E² x F (erg cm⁻² s⁻¹)
Energy (TeV)

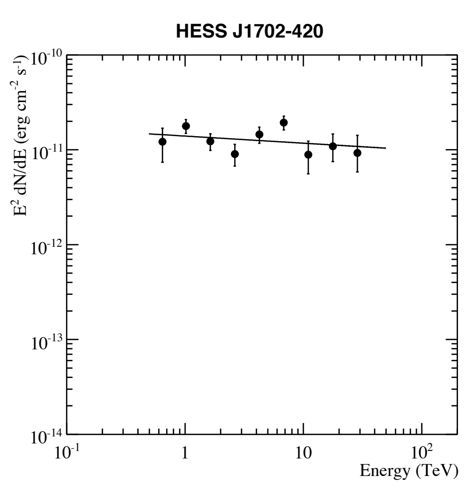
Unidentified VHE Sources

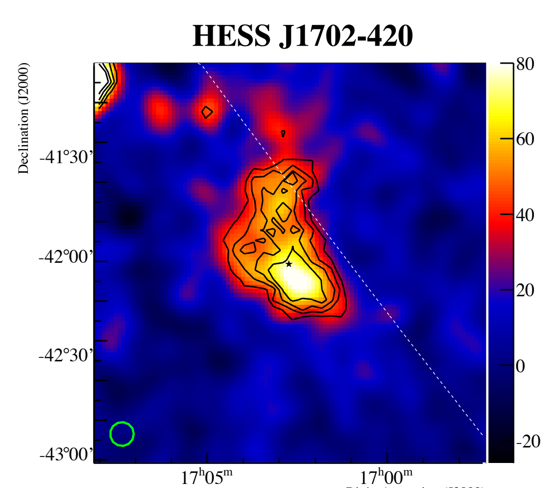
- 47 unidentified sources in the HESS catalog!
- Search for cutoff energy...
- Many have deeper observations since original publications
- HAWC also sees sources > 50 TeV (but with poor spectral resolution)

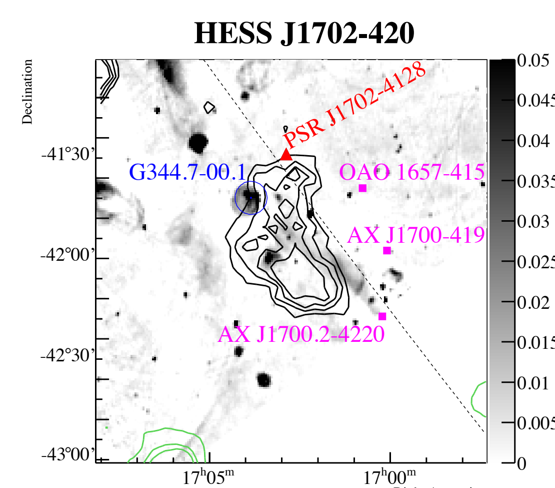












OVERVIEW

Introduction to
High Energy Astrophysics

Detecting Gamma Rays

The Hunt for PeVatrons

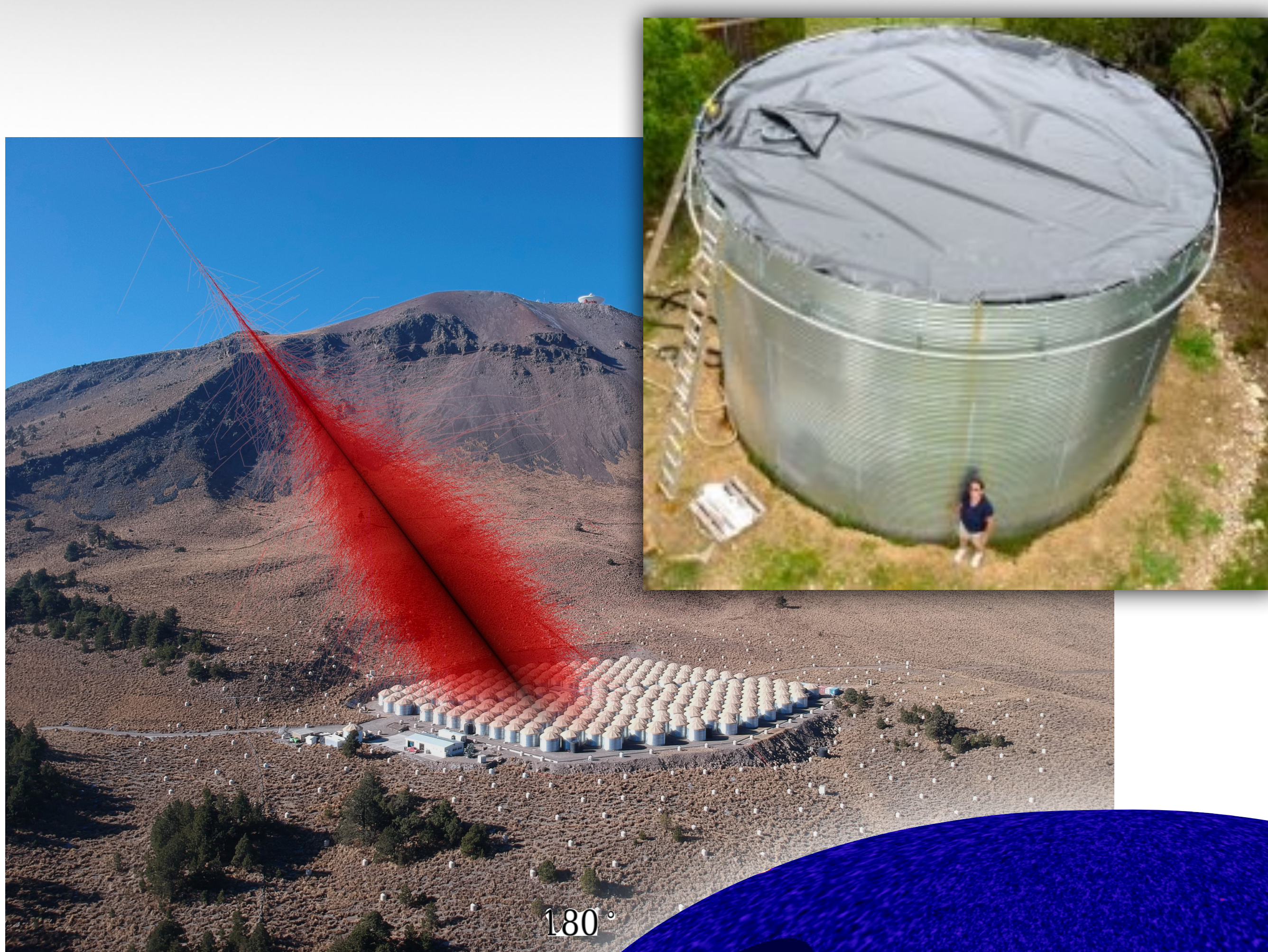
Future Prospects

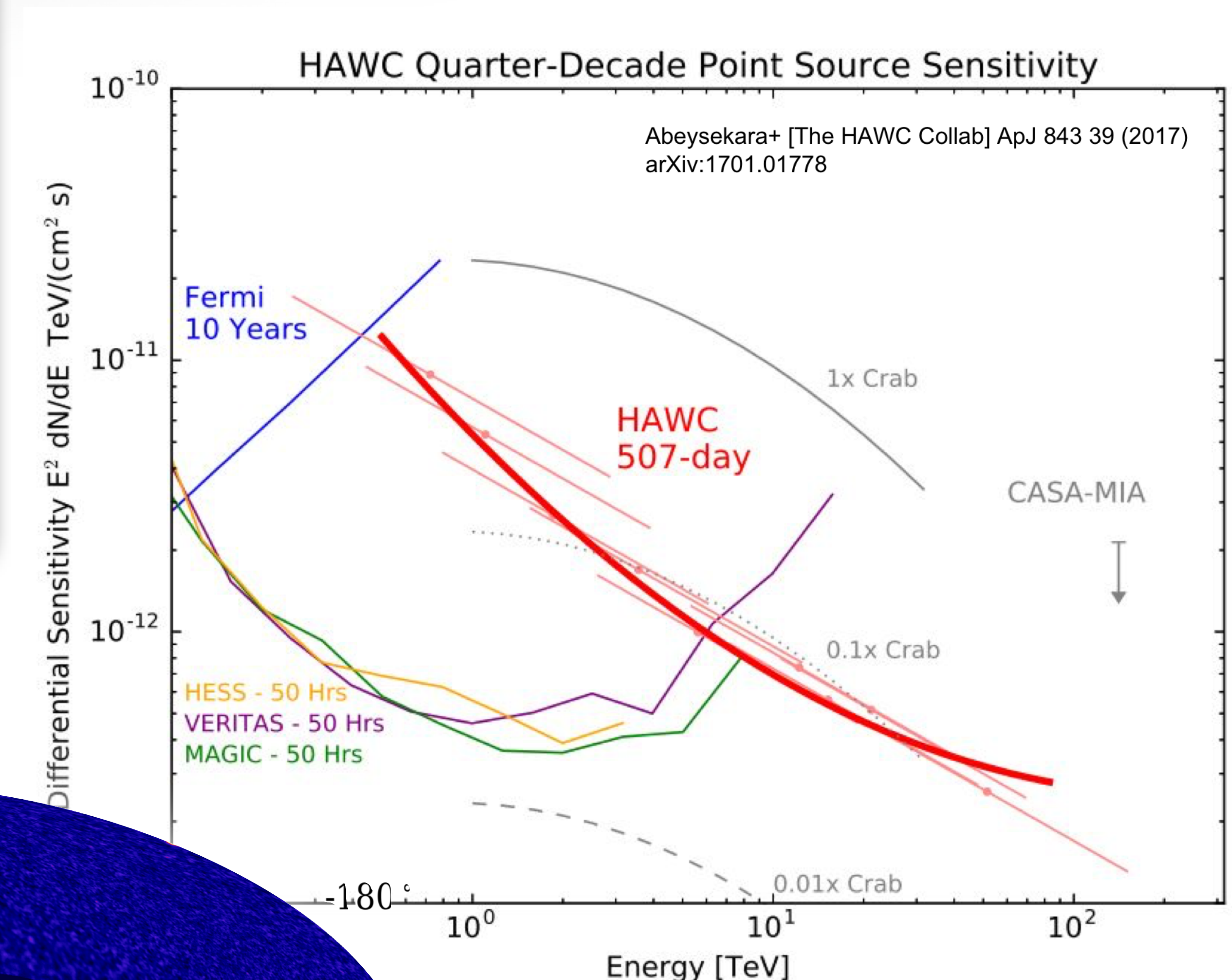
What could be improved?

- More sensitivity above 10 TeV
- Deeper observations
- Higher Angular Resolution to disentangle emission zones
- Southern Hemisphere for optimal coverage of the Galaxy

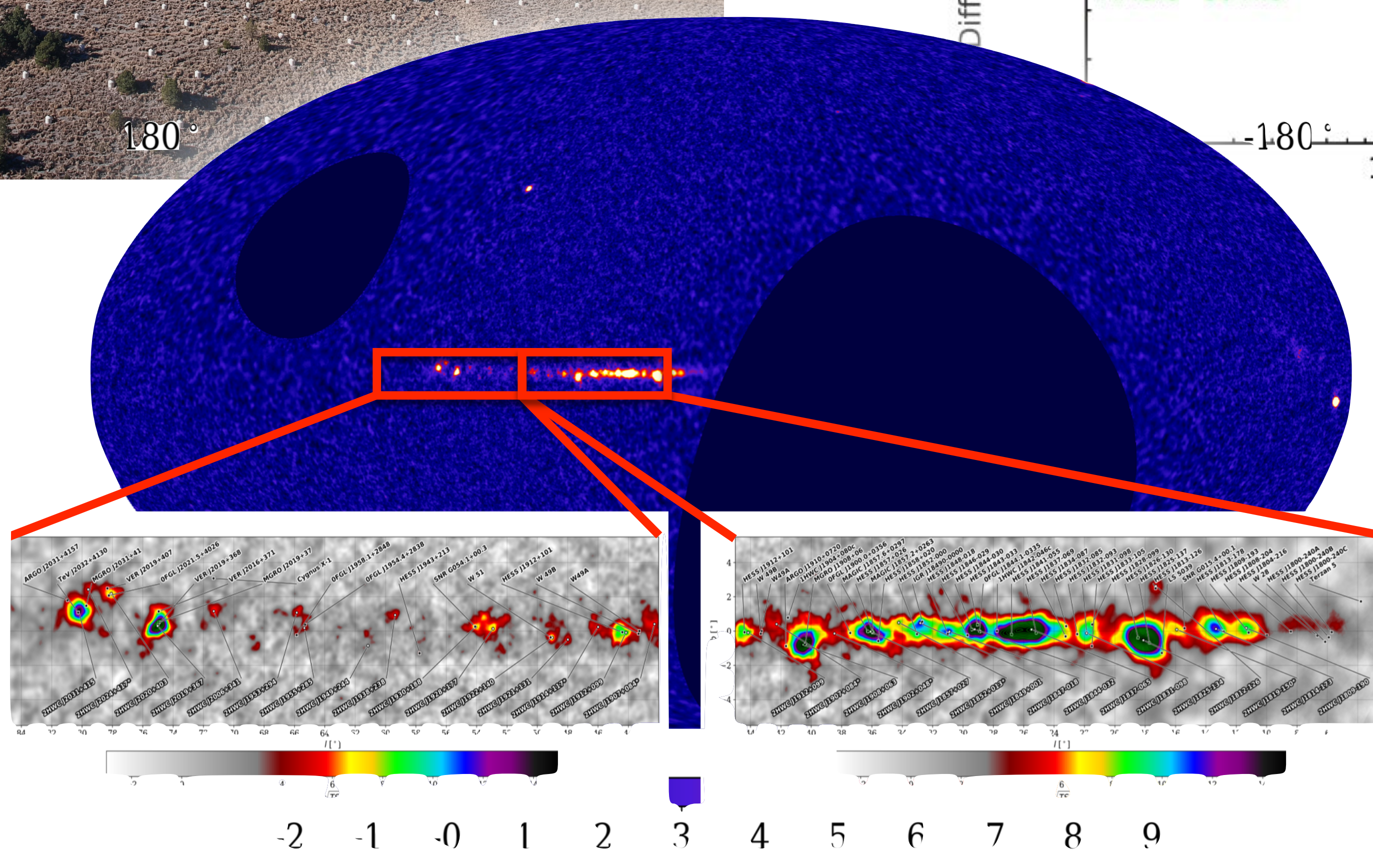
HAWC

High Energy Water-Cherenkov Observatory





In operation since 2015



Very high duty cycle!

Very large FOV

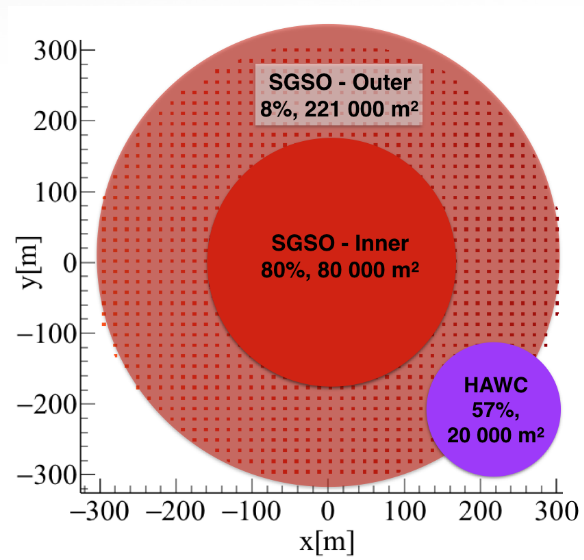
Poor Energy and angular resolution

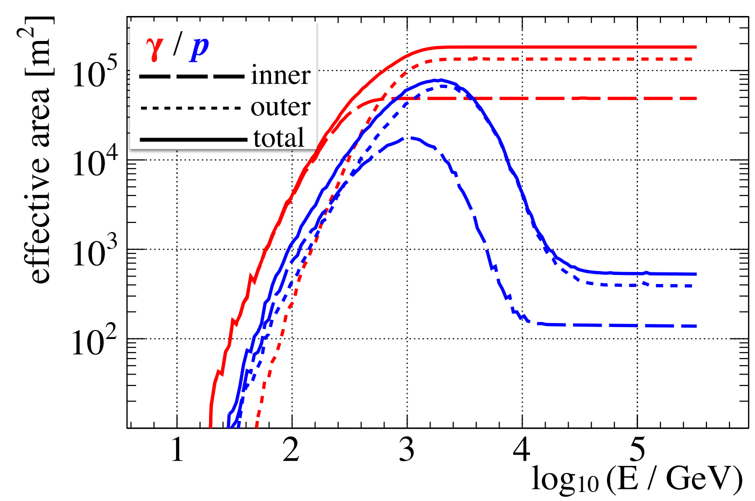
In the North...

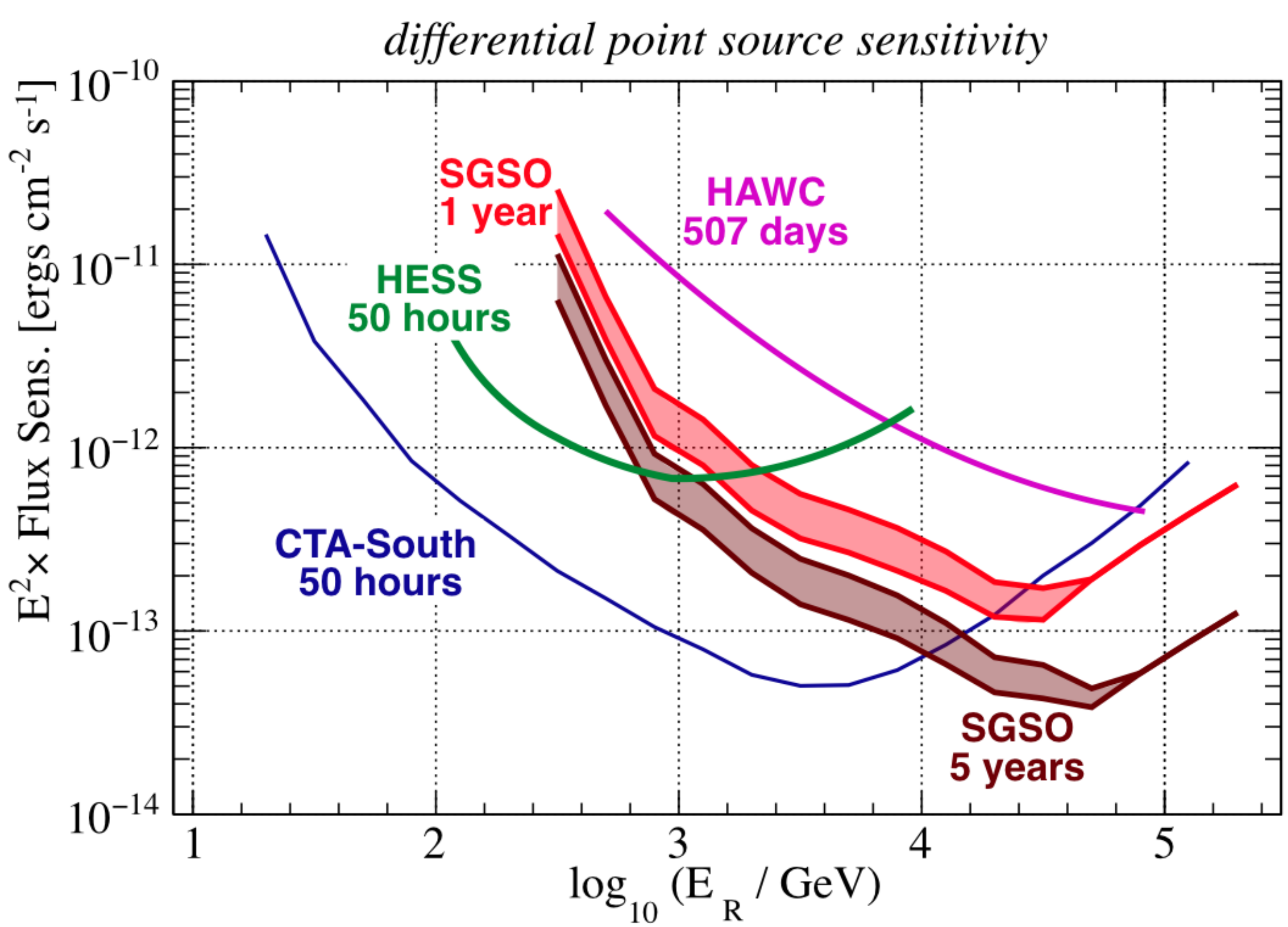
SGSO

Southern Gamma Ray Survey Observatory

Put a HAWC in the South!



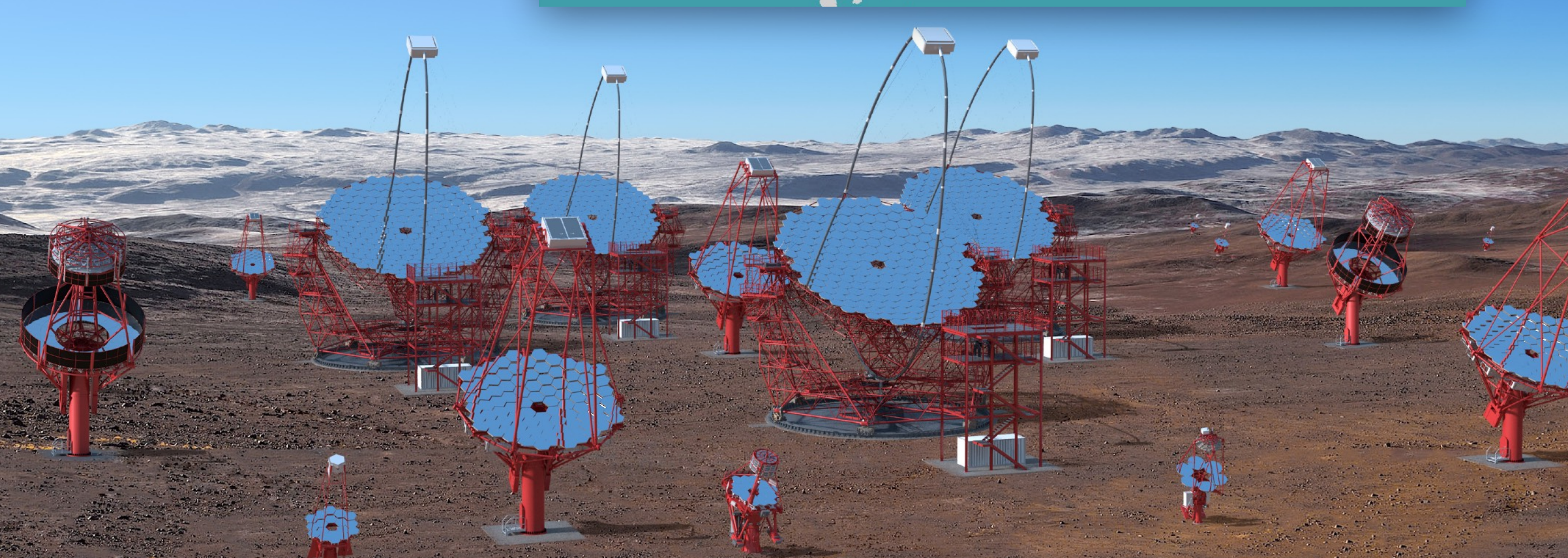


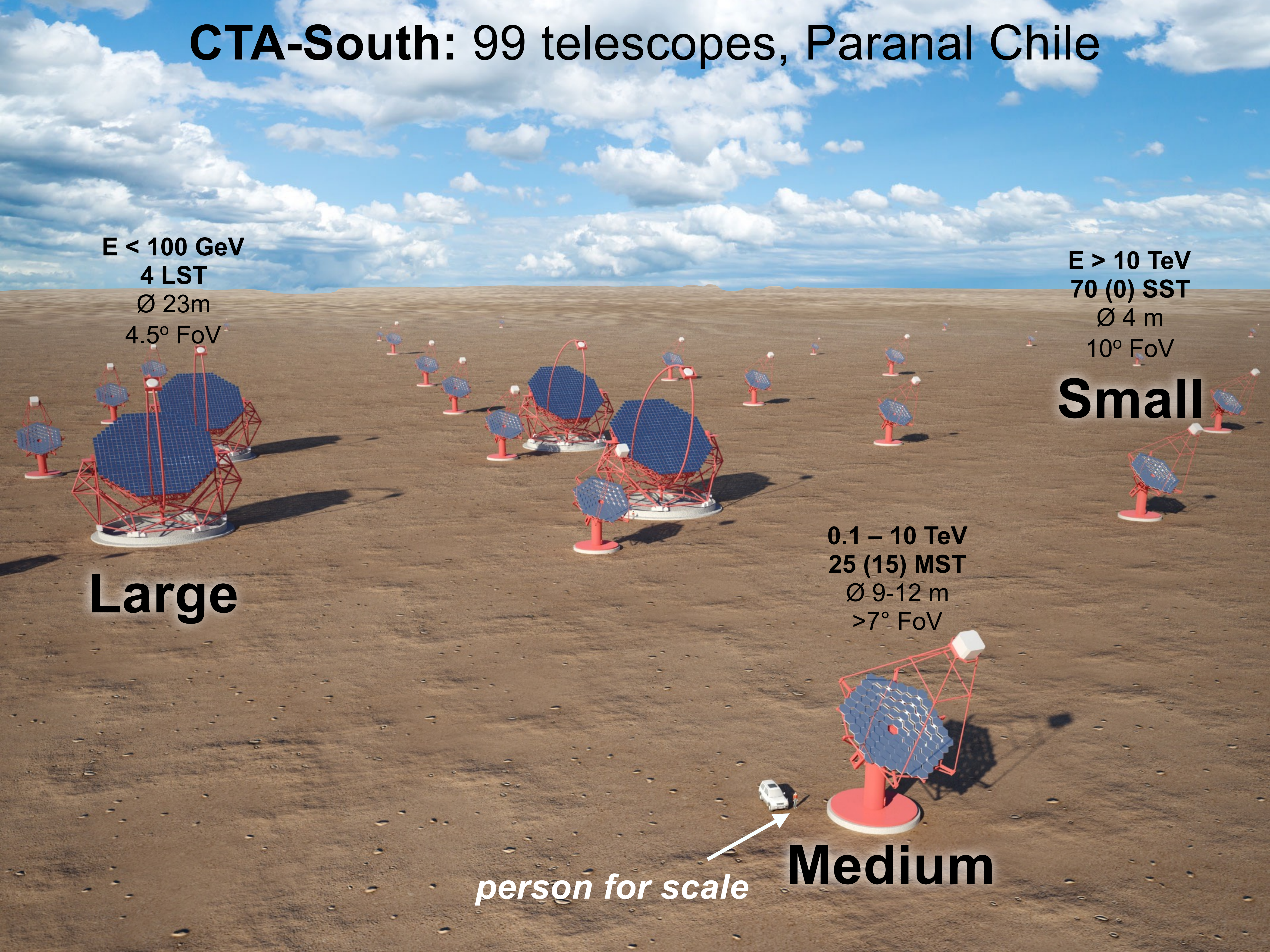


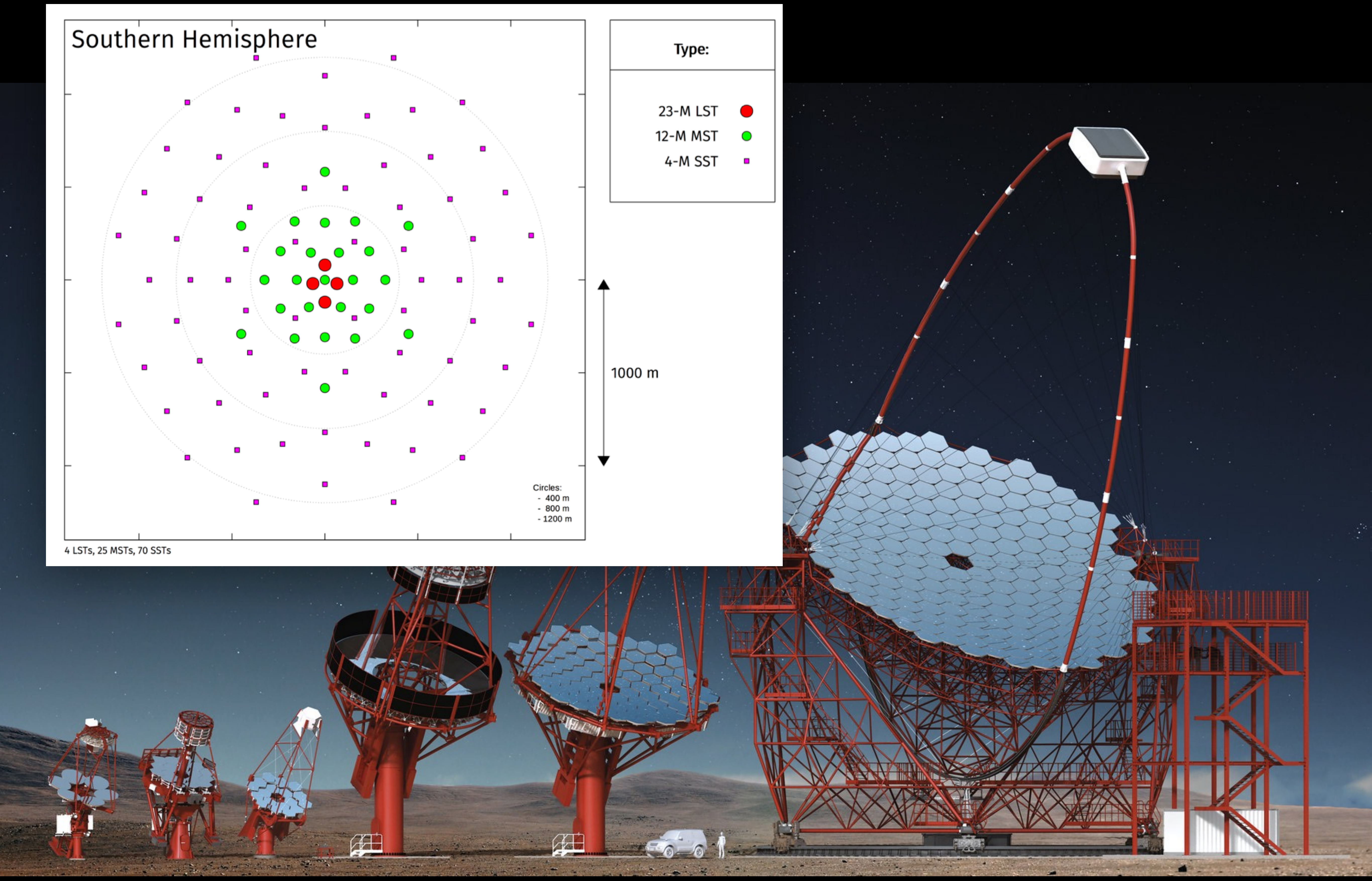
cta

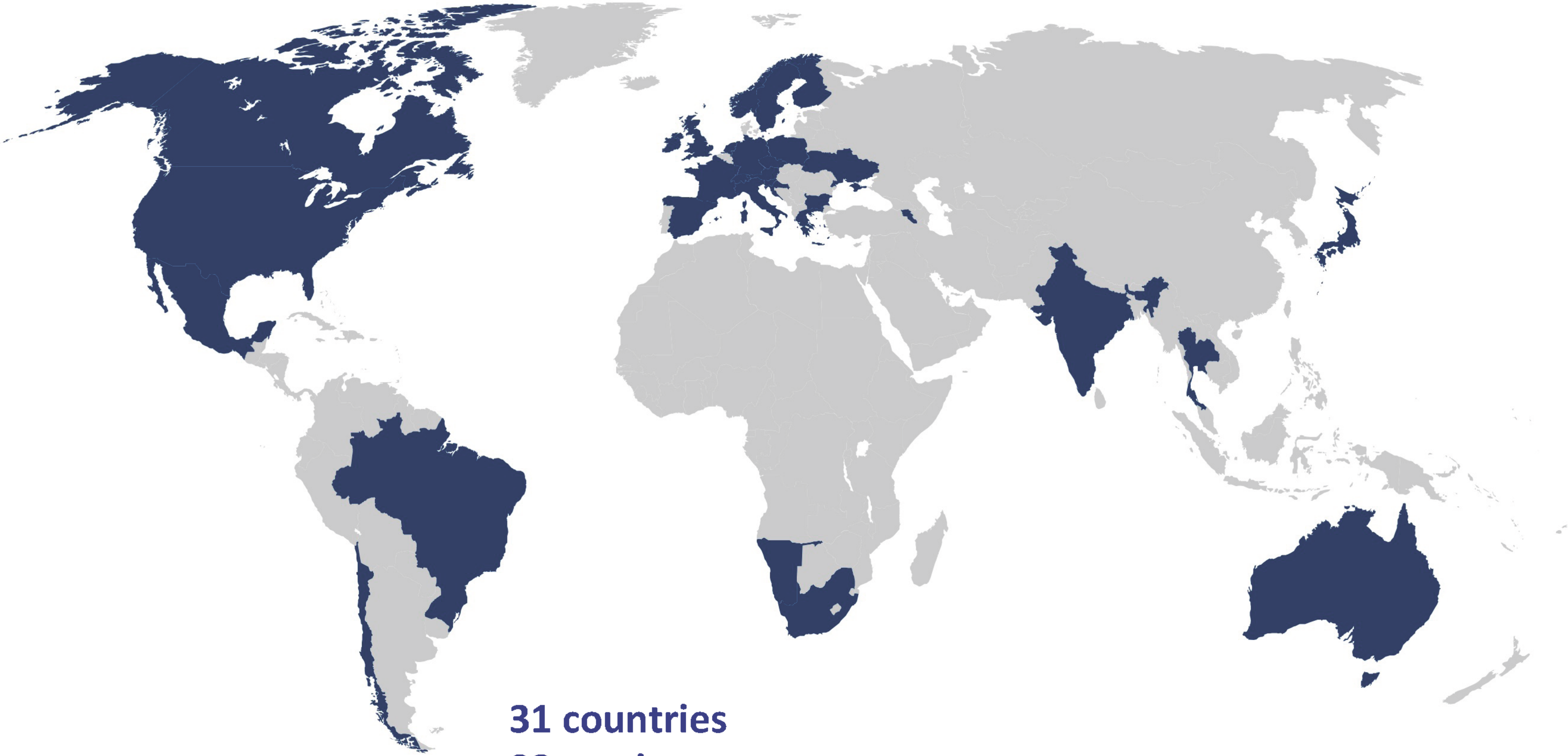
cherenkov telescope array

the observatory for
ground-based
gamma-ray astronomy




CTA-South: 99 telescopes, Paranal Chile
E < 100 GeV
4 LST
Ø 23m
4.5º FoV
Large
E > 10 TeV
70 (0) SST
Ø 4 m
10º FoV
Small
0.1 – 10 TeV
25 (15) MST
Ø 9-12 m
>7° FoV
Medium
person for scale

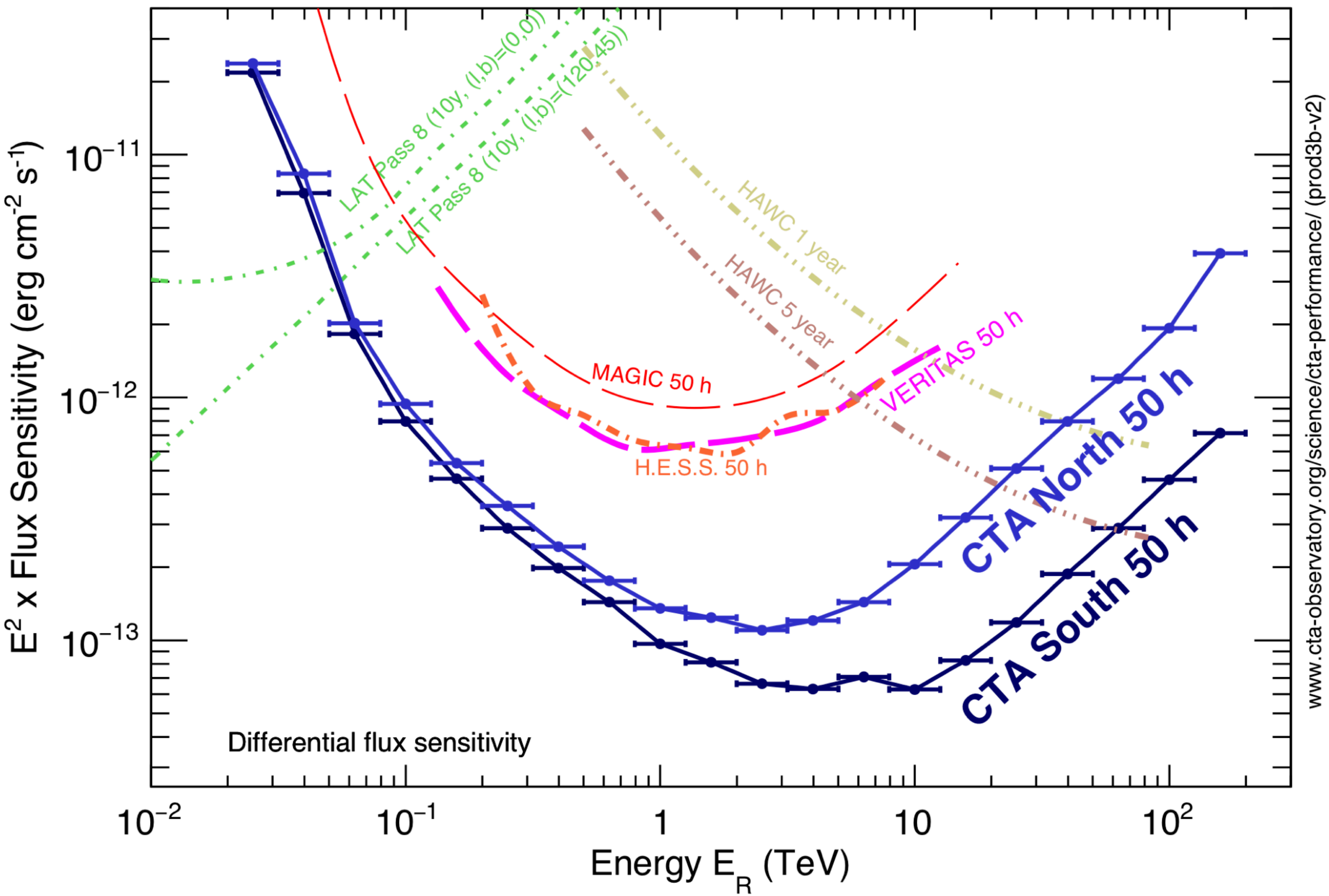

Southern Hemisphere
Type:
23-M LST
12-M MST
4-M SST
1000 m
Circles:
- 400 m
- 800 m
- 1200 m
4 LSTs, 25 MSTs, 70 SSTs



31 countries
92 parties
202 institutes
1451 members (508 FTE)

CTA group at DAp heavily involved!

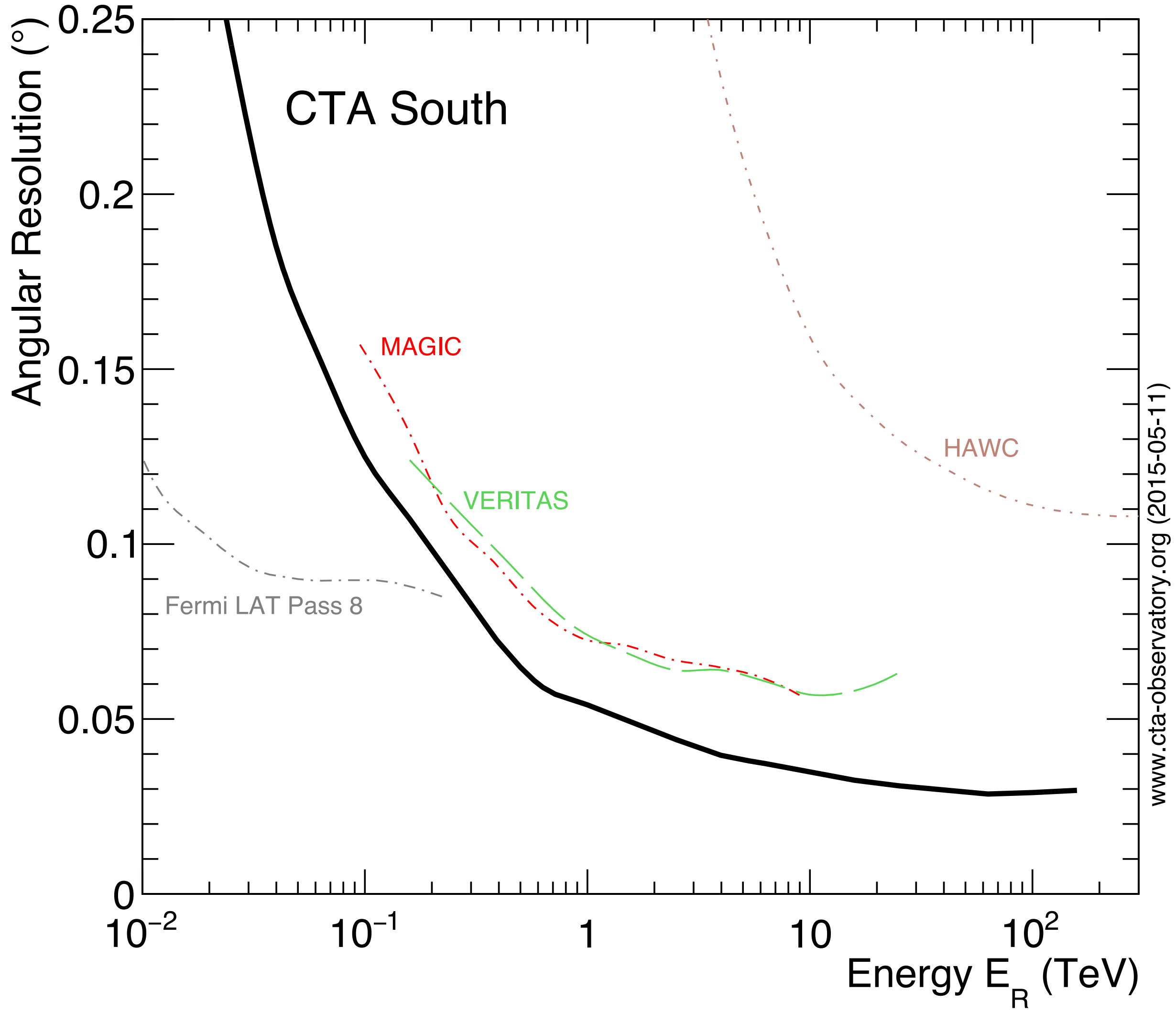
data processing pipeline + science!



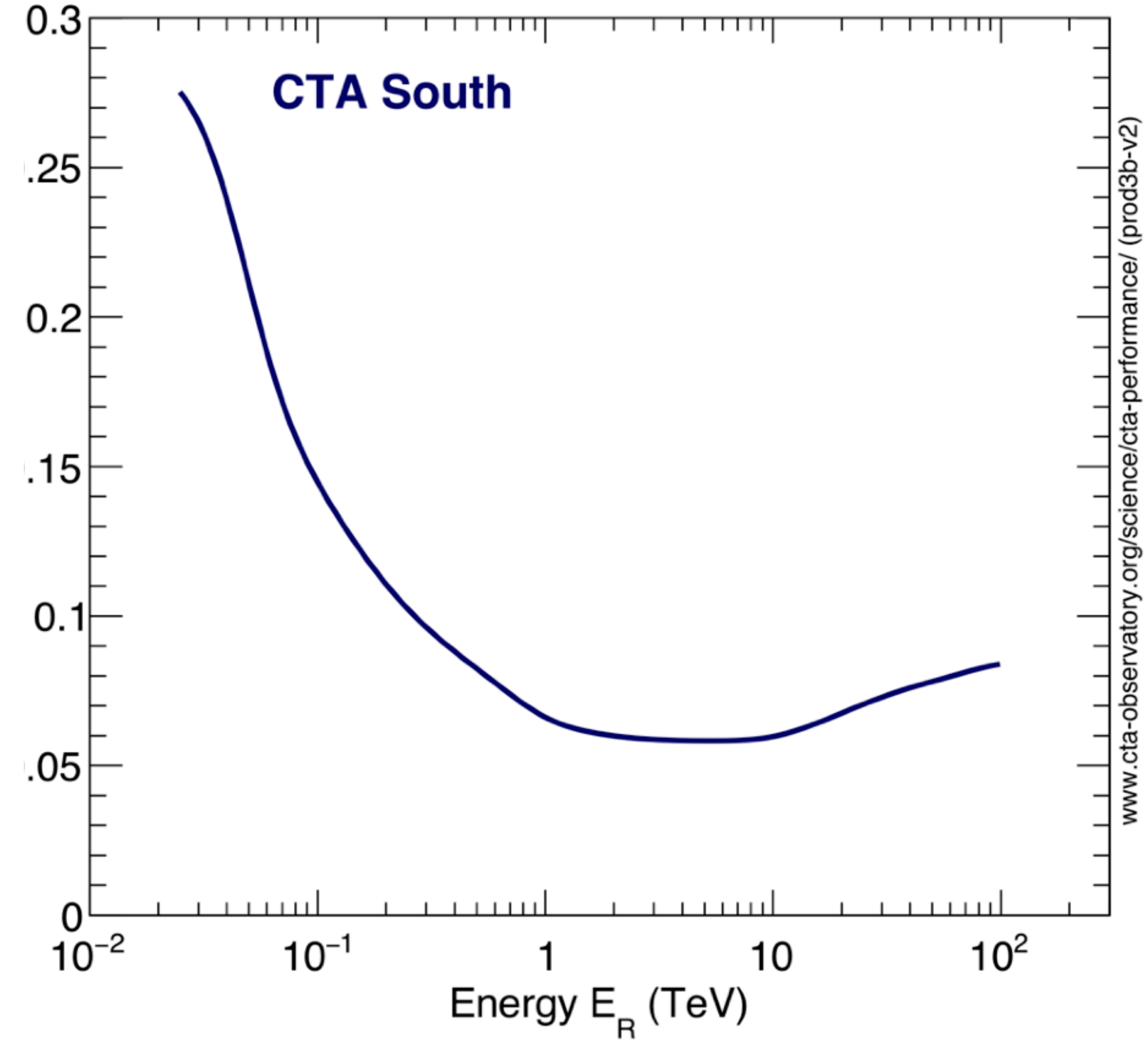
E² x Flux Sensitivity (erg cm⁻² s⁻¹)
Energy E_R (TeV)
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻²
10⁻¹
1
10
10²
LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
Differential flux sensitivity
www.cta-observatory.org/science/cta-performance/ (prod3b-v2)

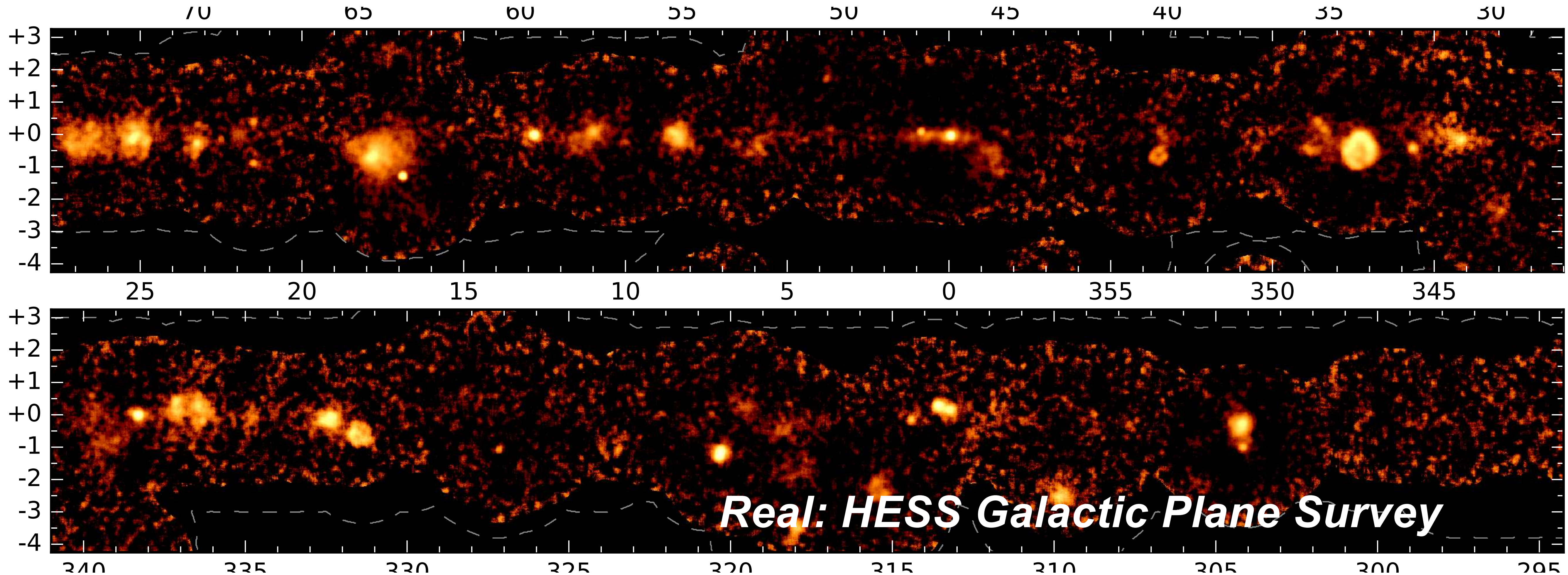
CTA Performance

Angular Resolution

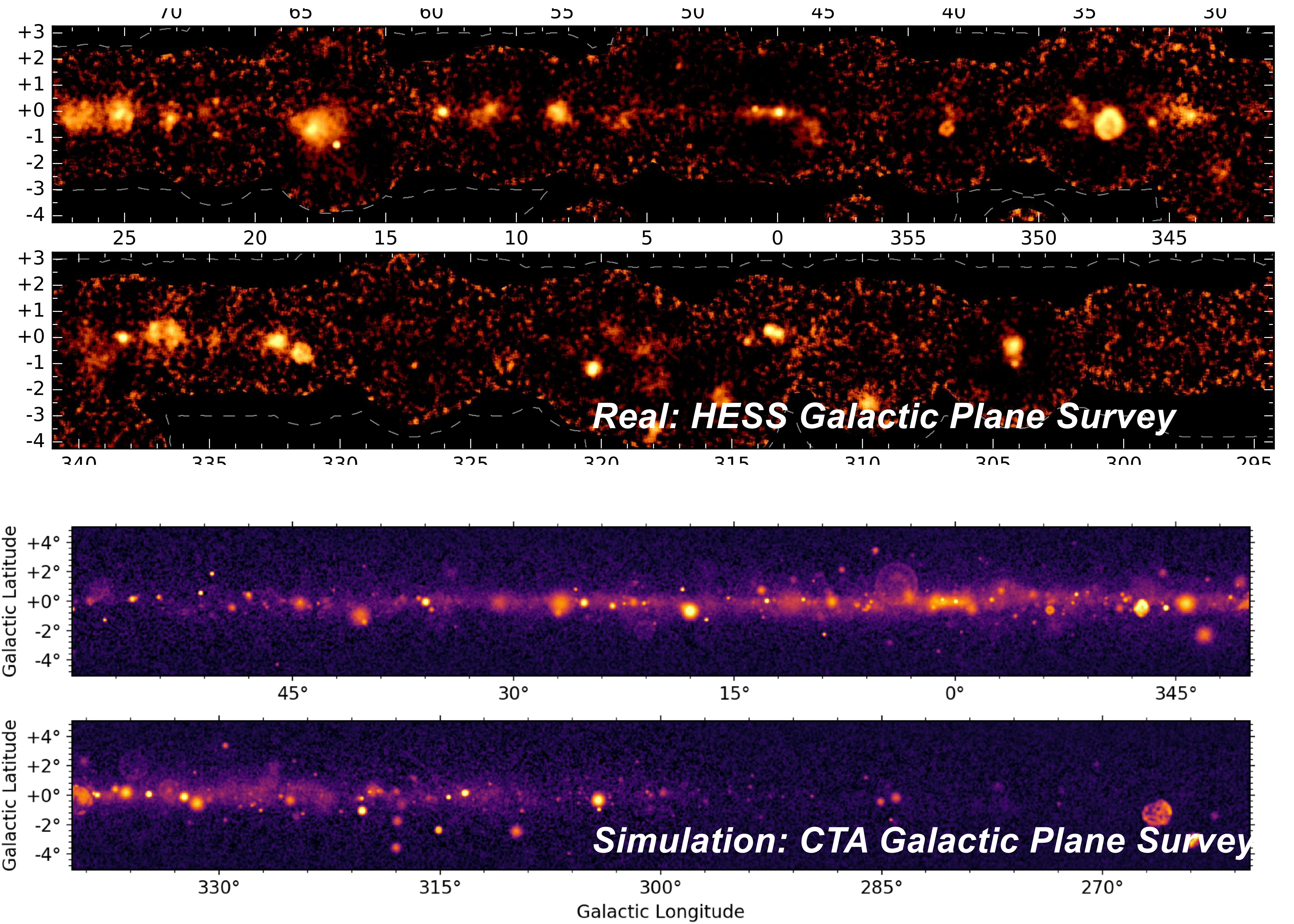


Spectral Resolution





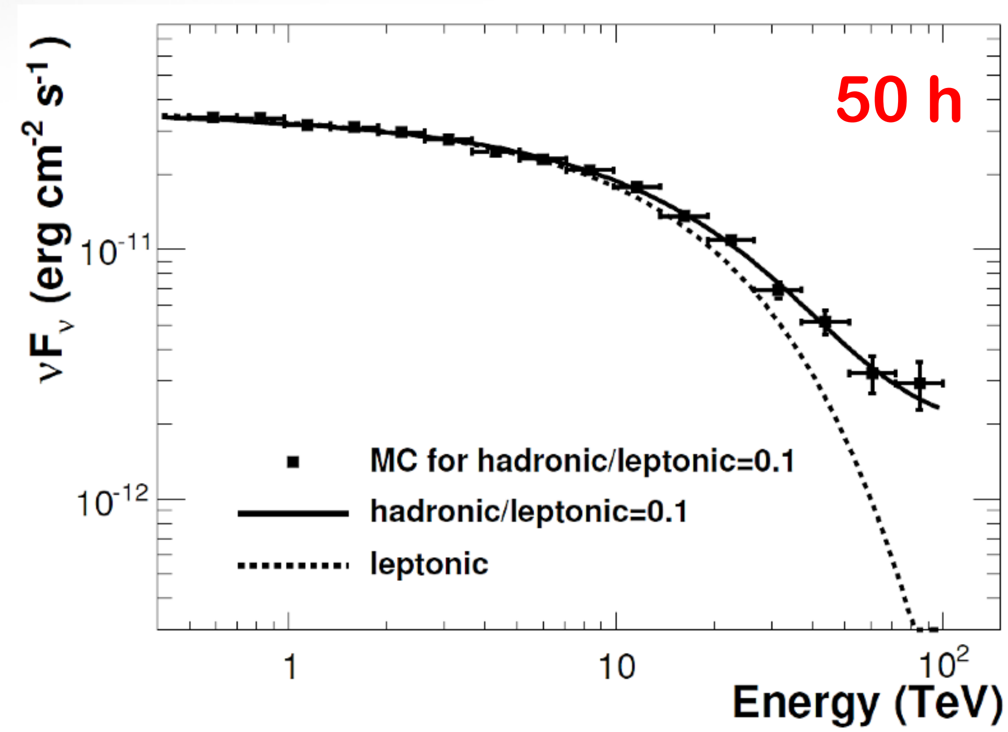
Real: HESS Galactic Plane Survey
+3 +2 +1 +0 -1 -2 -3 -4
25 20 15 10 5 0 355 350 345

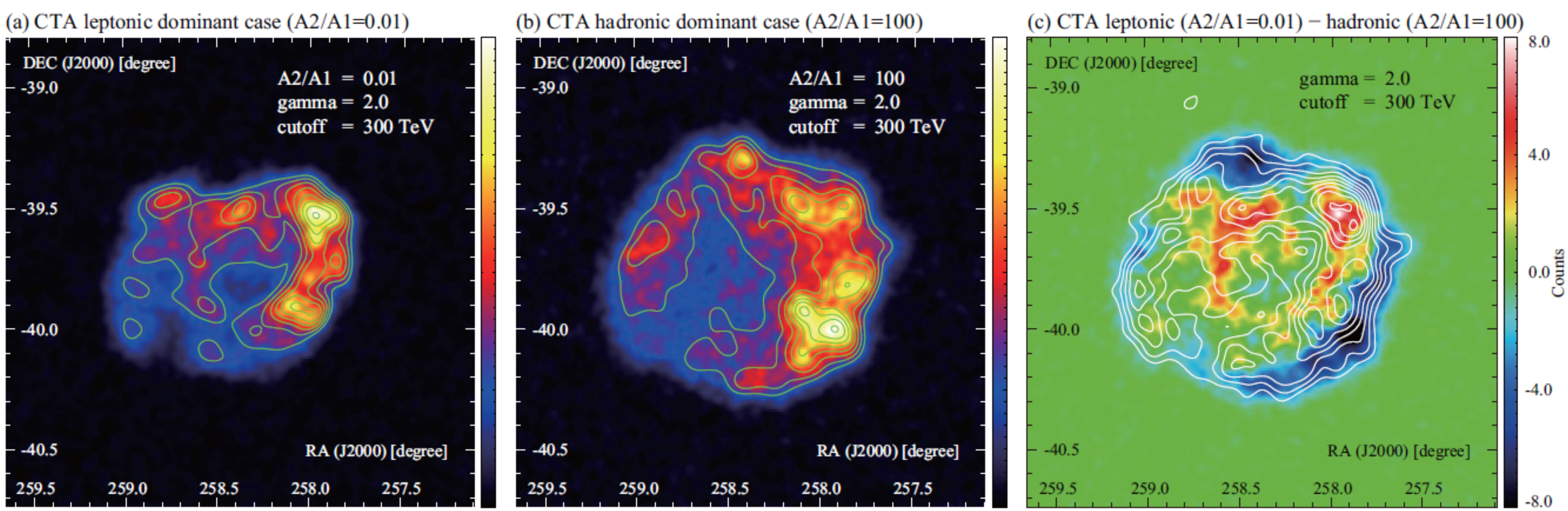

Real: HESS Galactic Plane Survey
Simulation: CTA Galactic Plane Survey
Galactic Latitude
Galactic Latitude
Galactic Longitude

PeVatrons with CTA

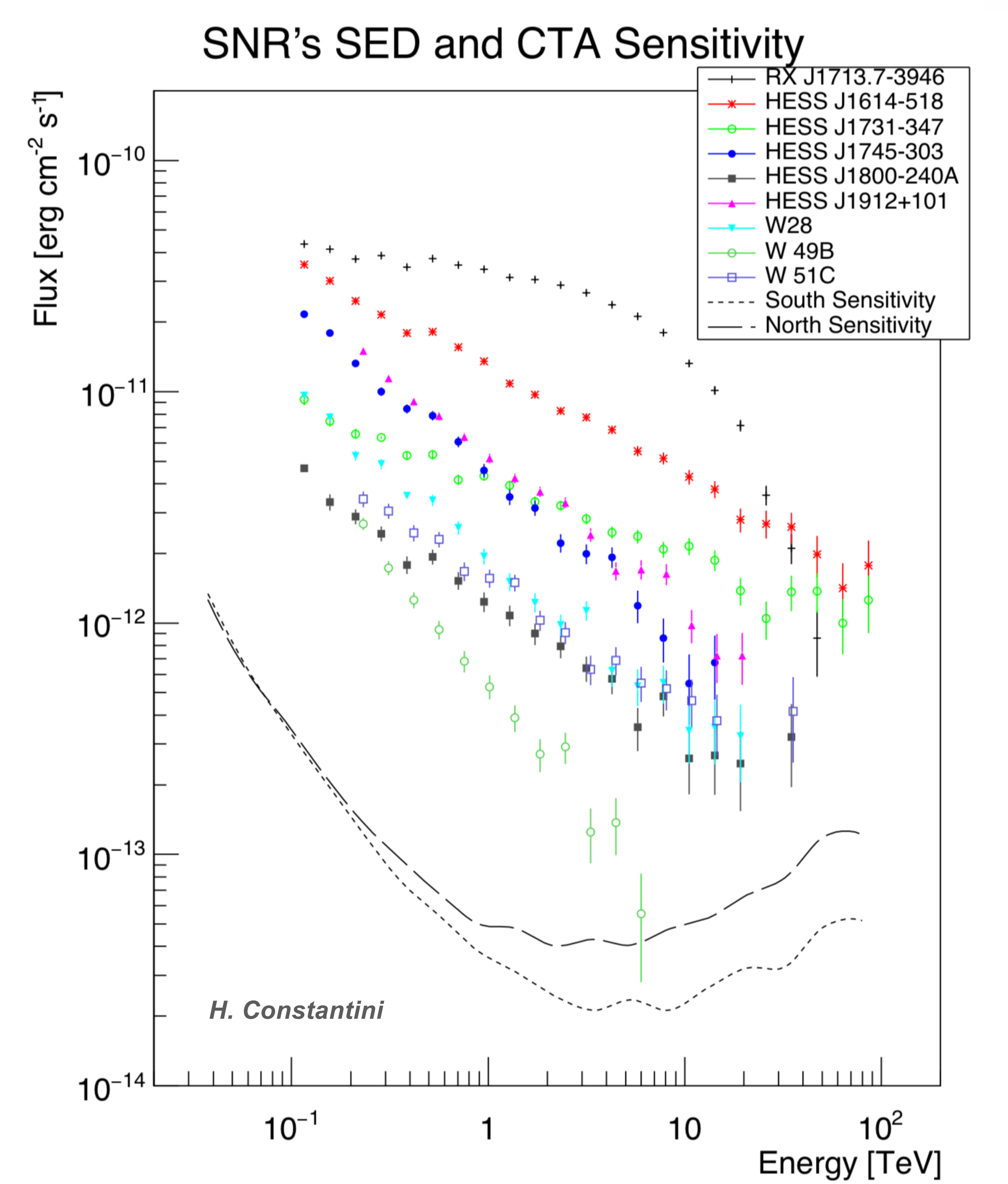
Supernova Remnants:

- Simulation of what CTA might see
  - ➤ XMM → Inv. Compton π°
  - ➤ HI + CO → π°γ's

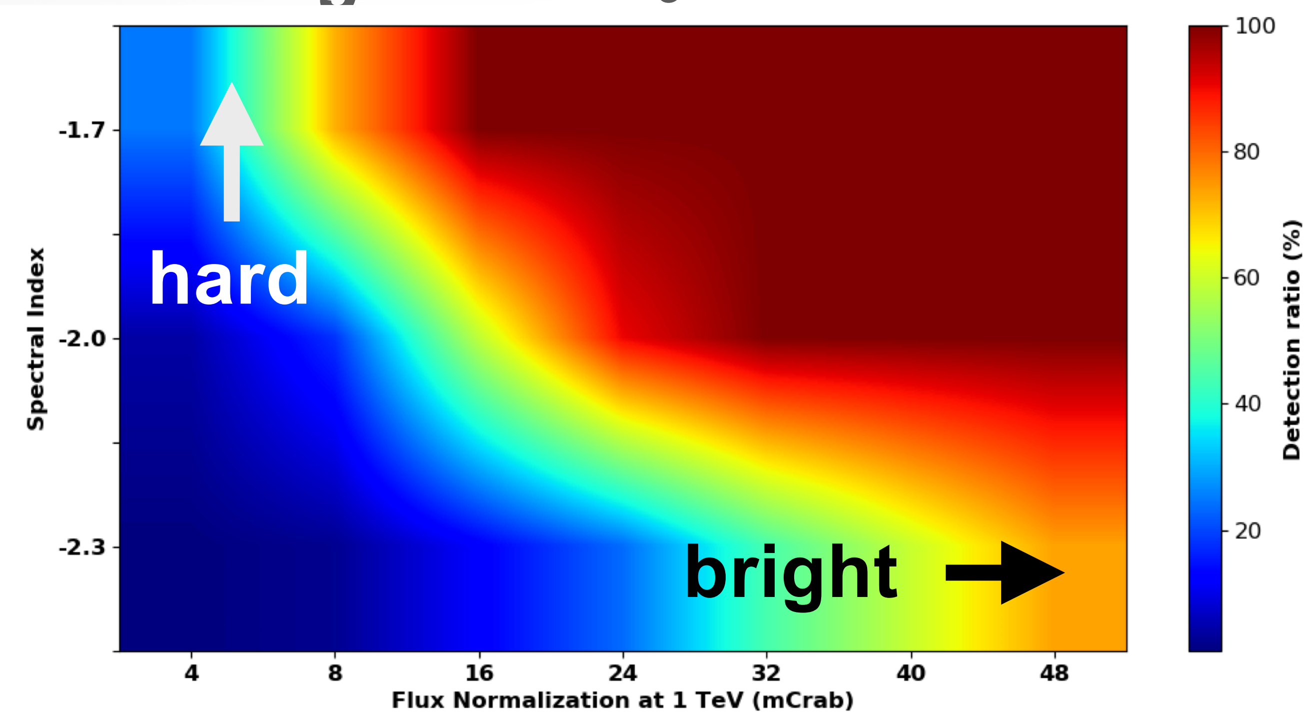




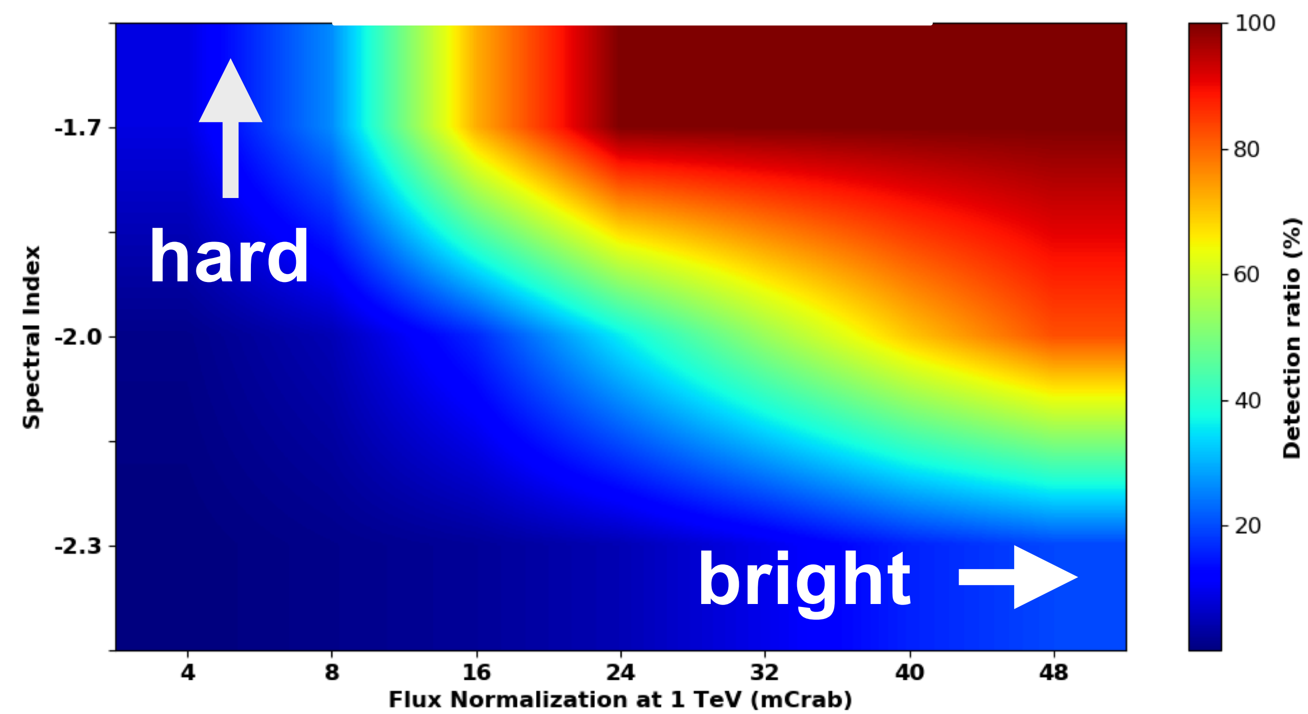
PeVatrons with CTA: *Supernova Remnants*



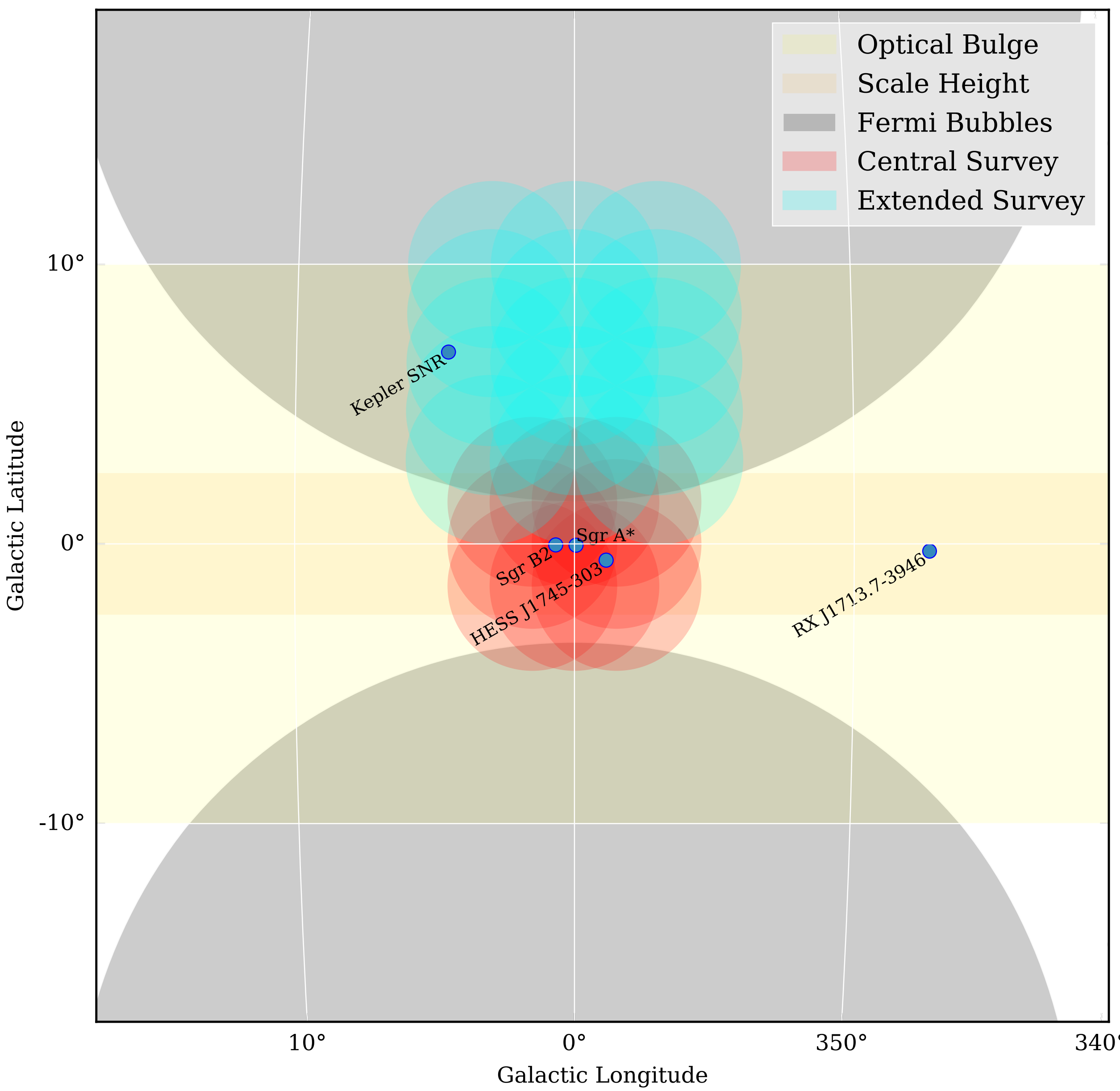
gamma E_c = 50 TeV

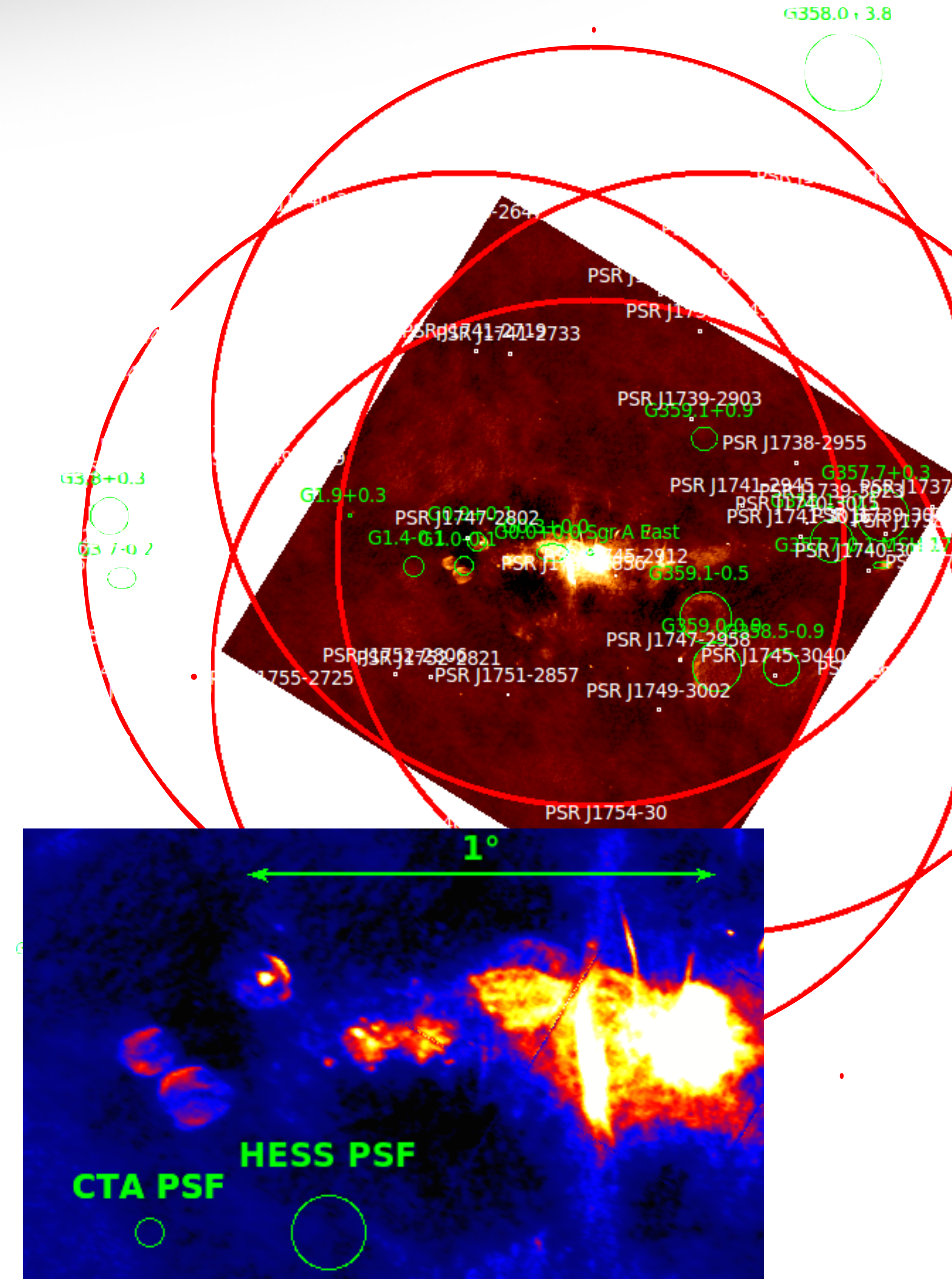


gamma E_c = 100 TeV



PeVatrons with CTA: *Galactic Center*





Bologna, Italy, 2019

Thank You!

CTA LST Prototype, La Palma, 2019
(not a time-lapse!)

Thank You!

CTA LST Prototype, La Palma, 2019
(not a time-lapse!)

HESS Galactic Plane Survey Data Release

- www.mpi-hd.mpg.de/hfm/HESS/hgps/
- Catalog as FITS table (includes spectra for each source)
- the only "true" catalog (all identical analysis methodology, single publication), so only exposure bias
- Image data (flux, etc) as FITS images

ASIDE:

THE HESS GPS AND YOU!