Experiment
Cherenkov Telescope Array

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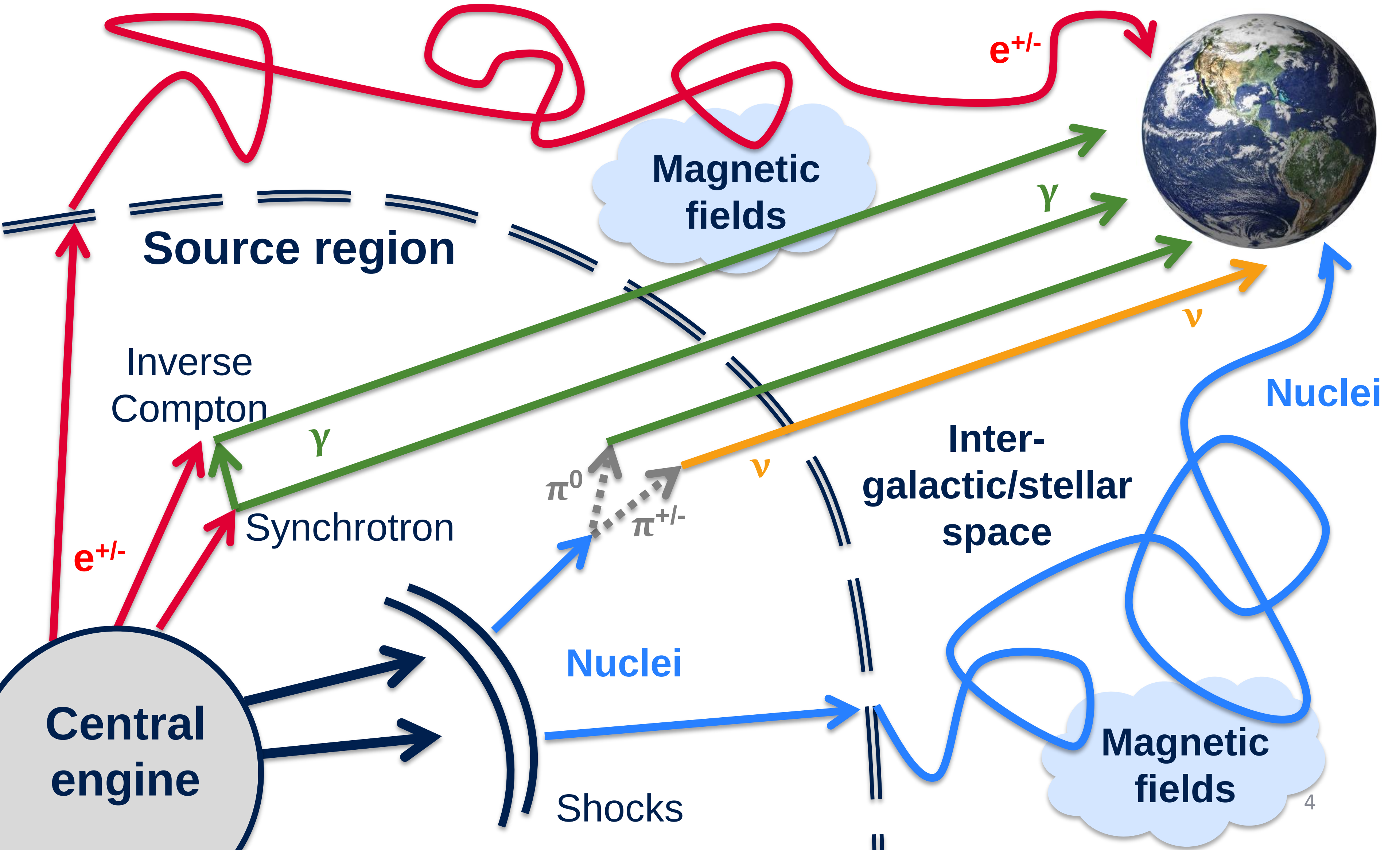
Outline

A (very) general introduction into γ-ray astronomy:

- Role of γ-rays in astrophysics
- Science Cases
- Imaging Atmospheric Cherenkov Telescopes
- Cherenkov Telescope Array

Role of γ-rays in astrophysics

Multi-messenger astrophysics



Gamma ray window

High Energy (HE) regime:
- high photon fluxes
- small effective areas needed
- direct detection in space

↔

Very High Energy (VHE) regime:
- low photon fluxes
- large effective areas needed
- ground-based detection
- Earth's atmosphere opaque to γ-rays
- indirect detection

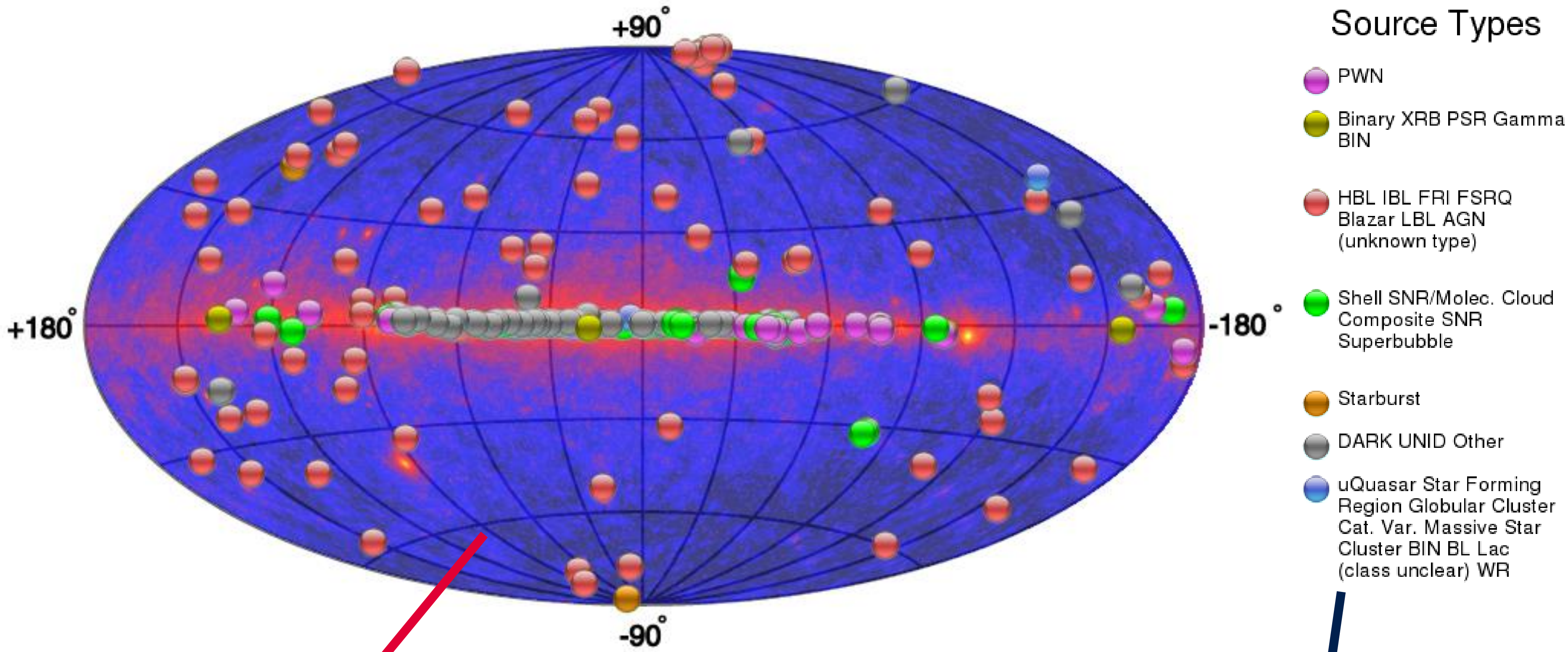
100 MeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

Satellites

Cherenkov telescopes

Water Cherenkov detectors

Detection of sources



Fermi-LAT (satellite) sky:
> 3000 sources

VHE sources detected by Cherenkov telescopes:
~ 160

Science Cases for the Cherenkov Telescope Array

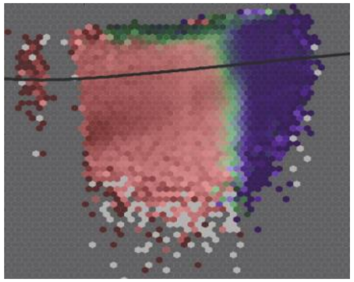
Fields of study

- **Origin and role of relativistic cosmic particles**
  - sites of acceleration of cosmic rays
  - mechanisms of acceleration
  - interactions of cosmic rays inside and outside the Galaxy

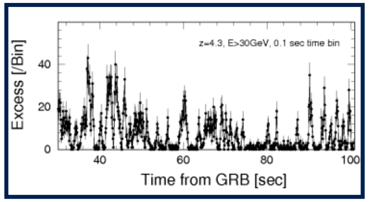
- **Extreme environments**
  - processes in the vicinity of neutron stars, black holes, relativistic jets, winds, explosions
  - extragalactic radiation and magnetic fields

- **Beyond the Standard Model**
  - dark matter
  - axion-like particles
  - Lorentz invariance violation

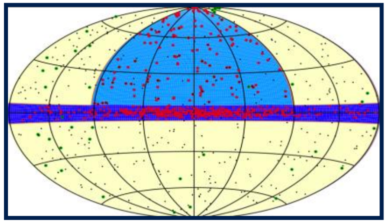
Key targets



Dark Matter Programme

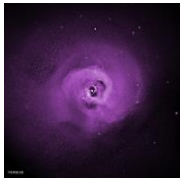


Transients



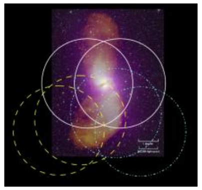
ExGal Survey

Galaxy Clusters



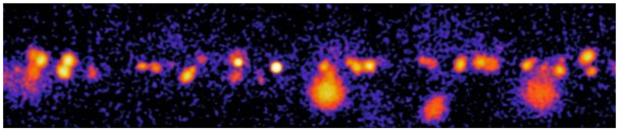
Star Forming Systems

AGN



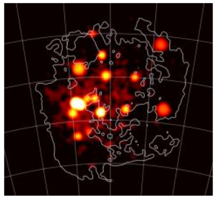
Extragalactic

Galactic

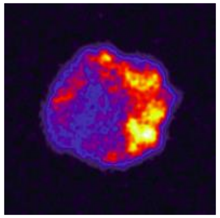


Galactic Plane Survey

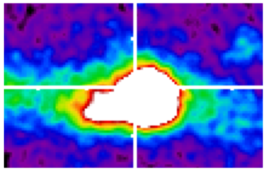
LMC Survey



PeVatrons

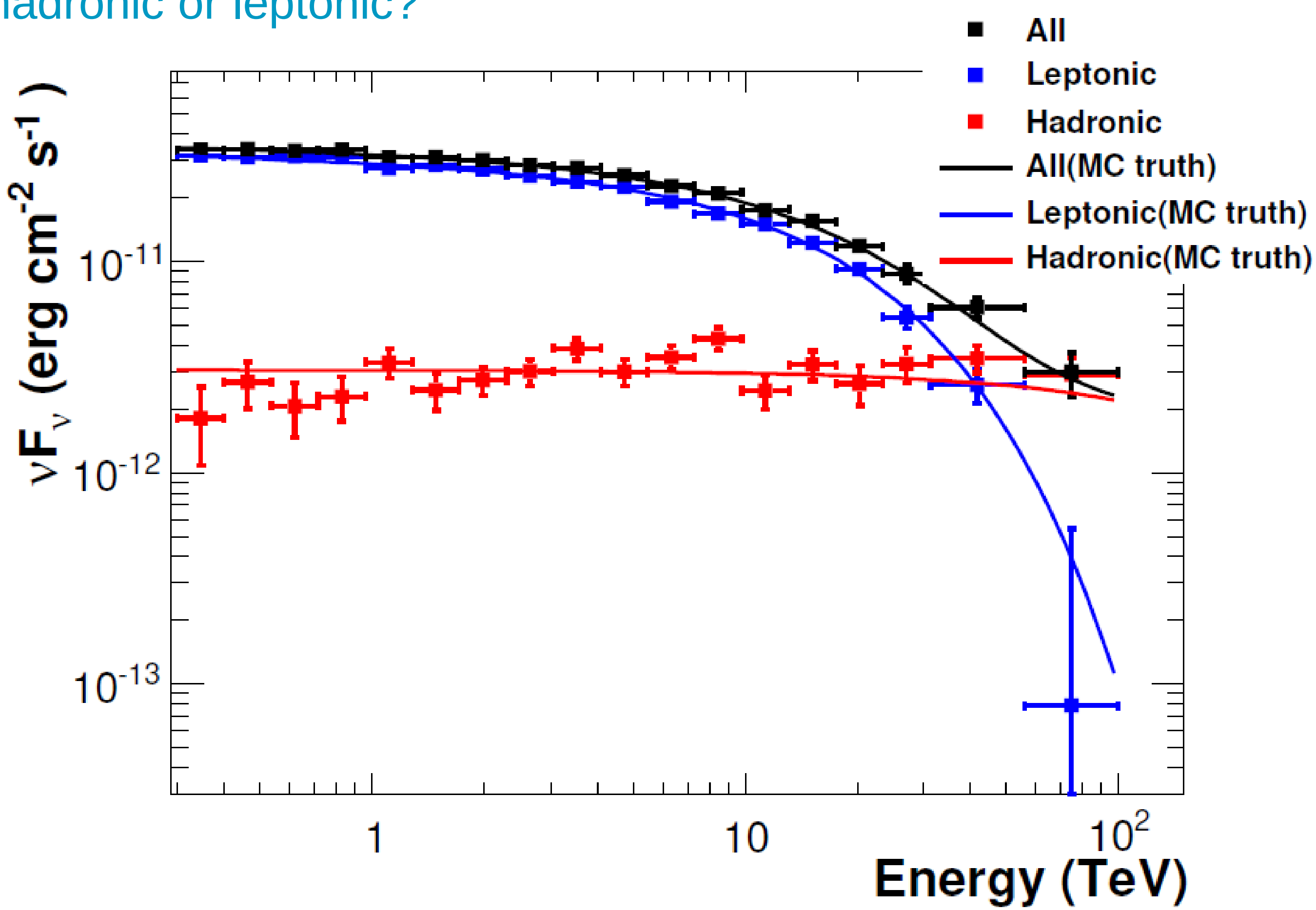


Galactic Centre



Acceleration mechanisms in galactic sources

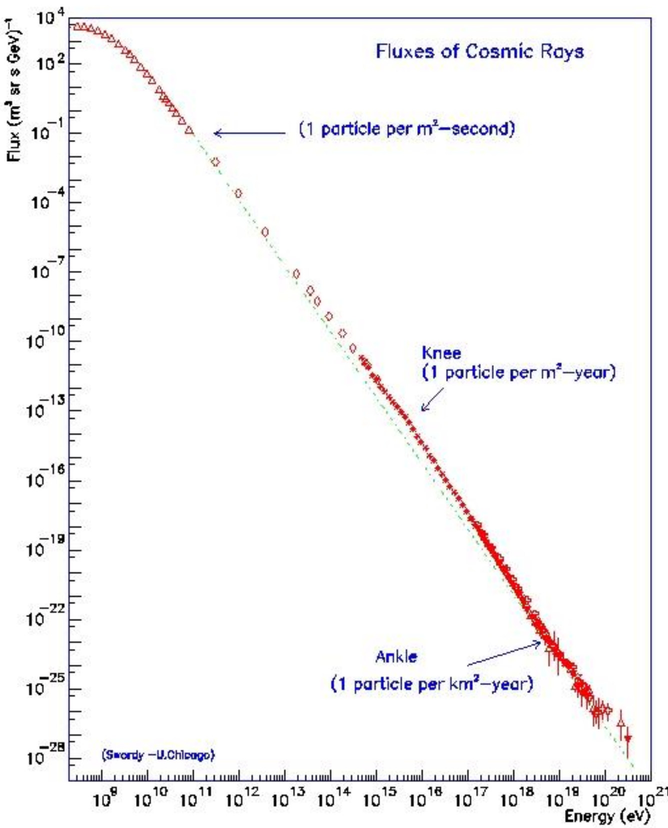
- disentangle between γ-ray production models
  - hadronic or leptonic?

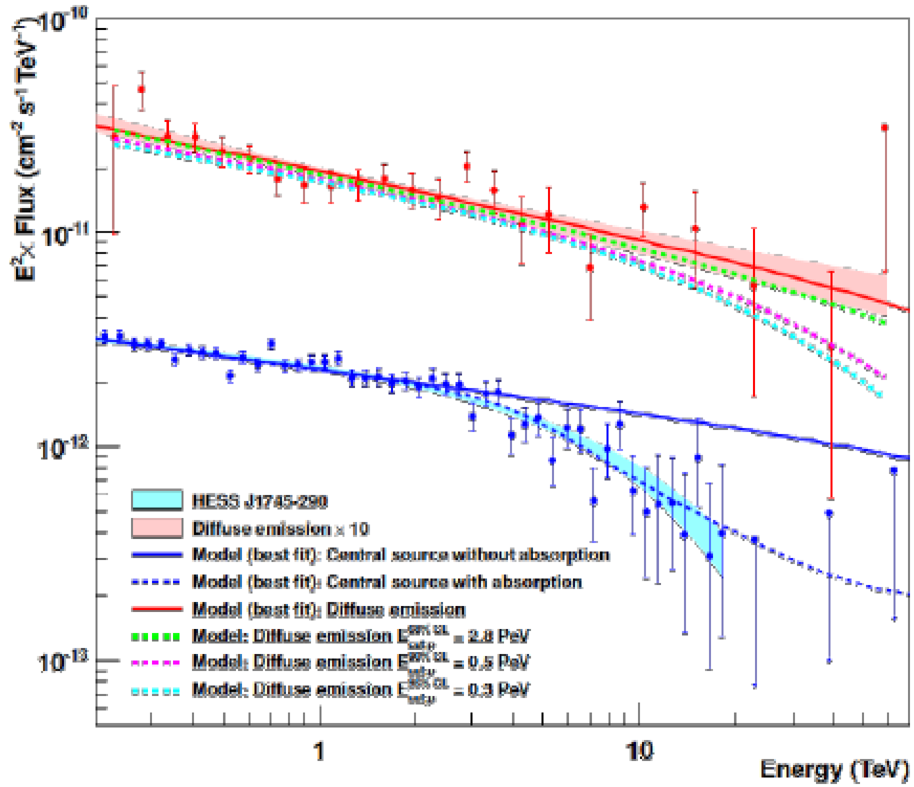


prospects for supernova remnant RX J1713.7-3946

Cosmic ray PeVatrons

- energy spectrum of cosmic rays up to ~ PeV = ‘knee’
- which galactic sources accelerate particles up to PeV?
  - measurement of γ-ray spectrum up to ~ tens of TeV necessary

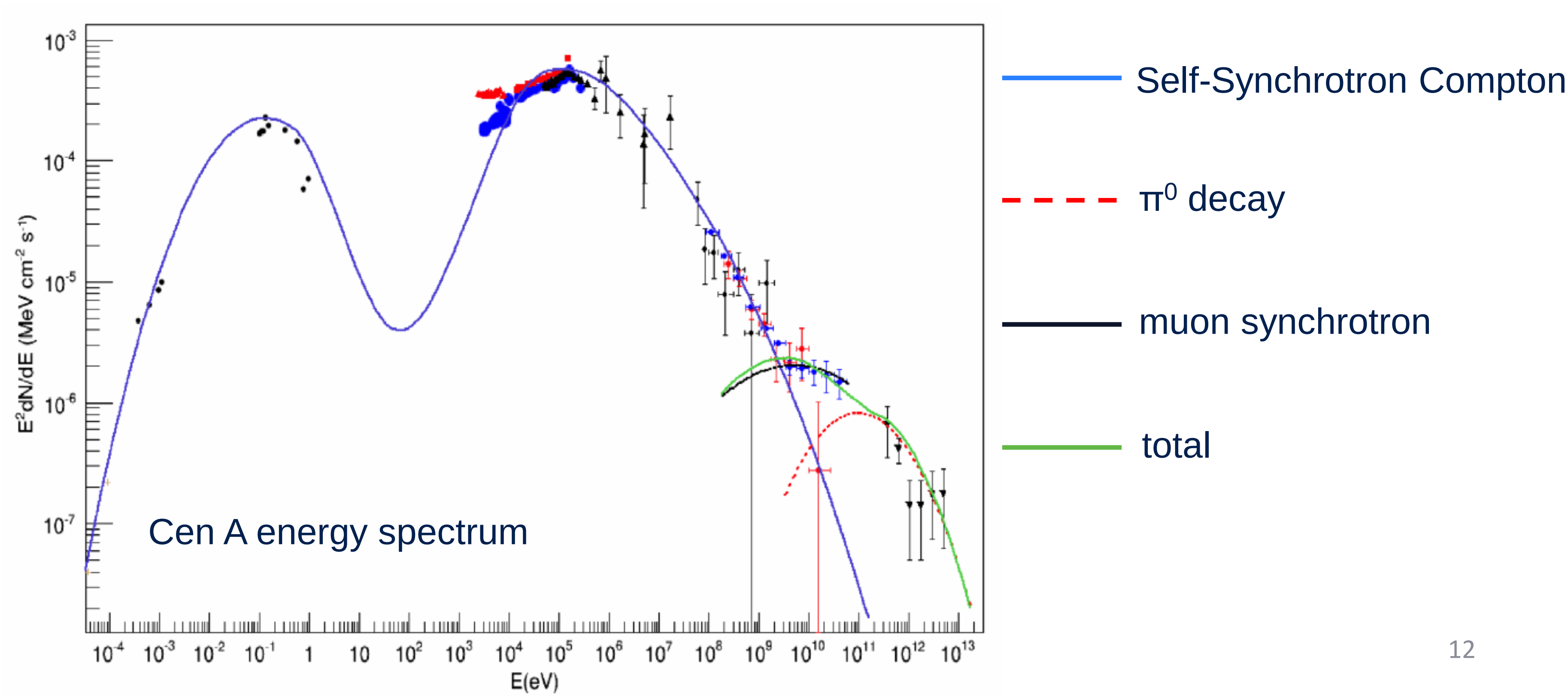




- the only confirmed PeVatron – Galactic Centre

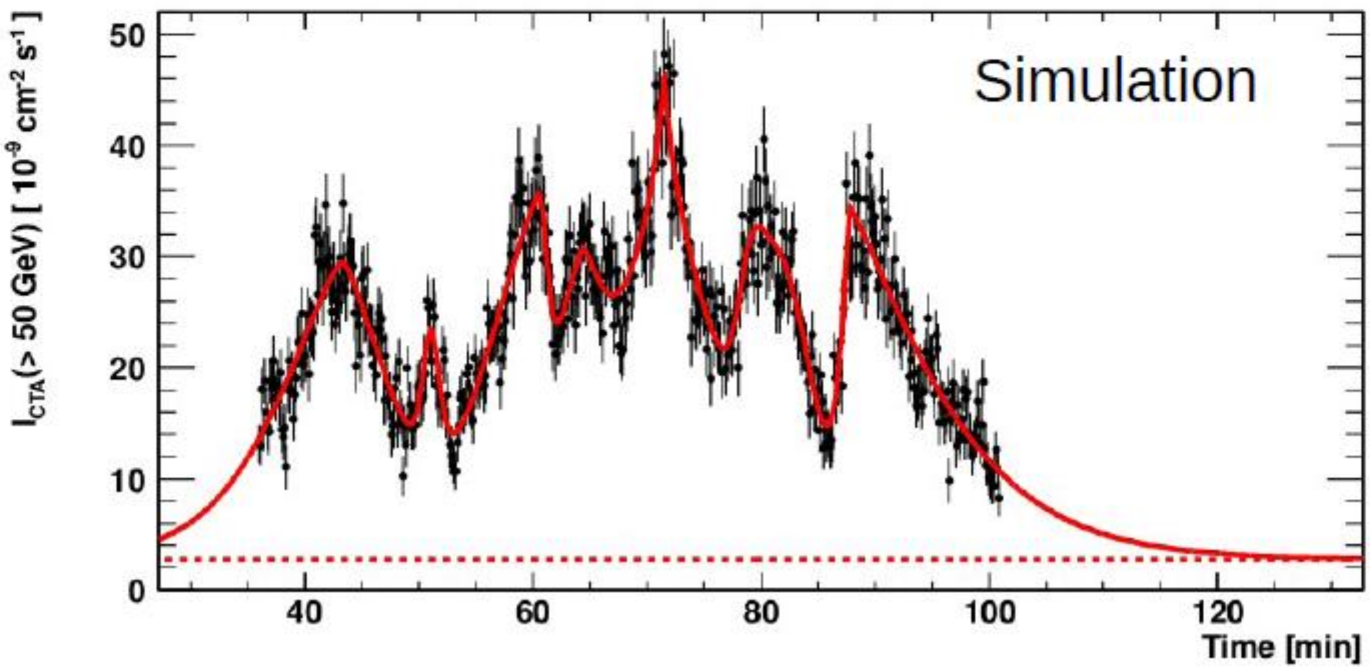
Acceleration & emission mechanisms in AGN

- active galactic nuclei:
  - the most populous sort of VHE γ-ray sources
  - likely to harbor particles of the highest energies
  - in-depth observations of individual objects (e.g. Cen A)
    + population study (extragalactic survey)

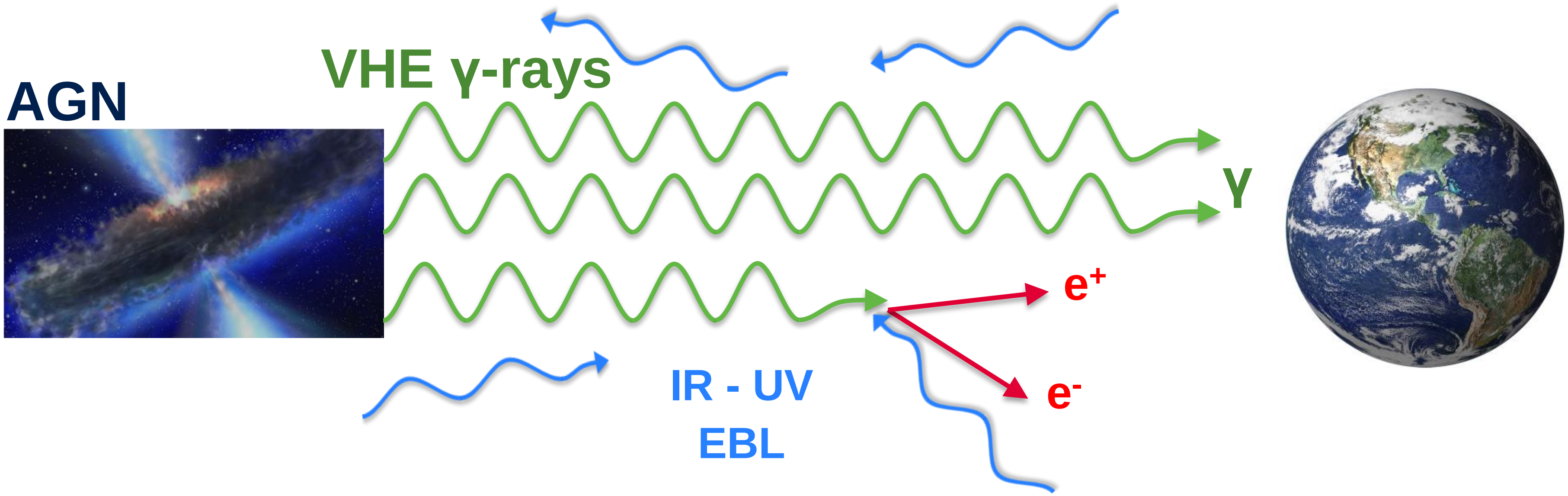


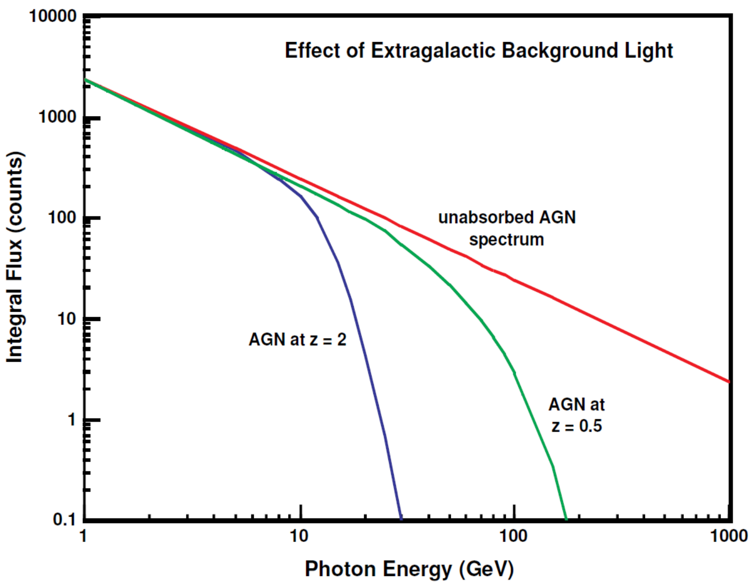
Time variability

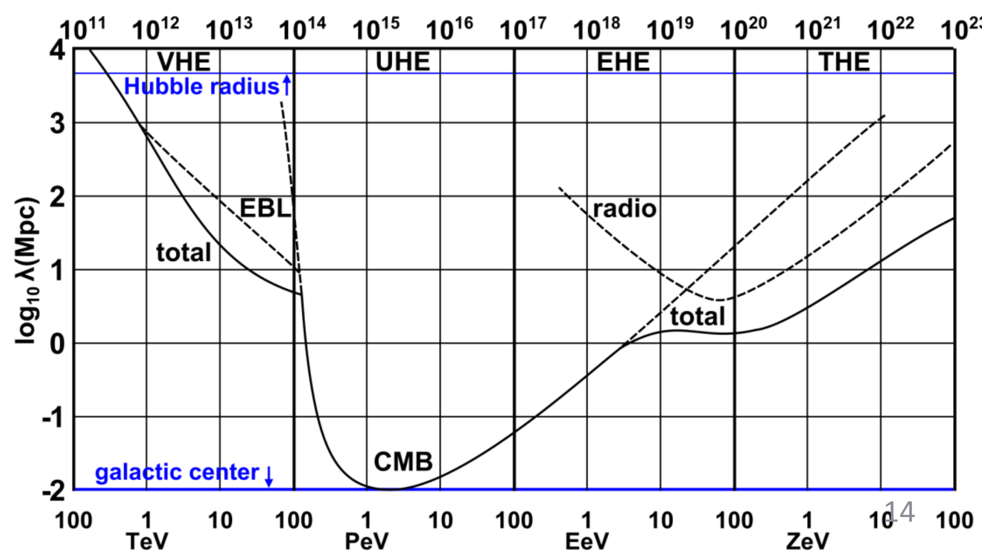
- AGN exhibit variability of their γ-ray flux
  - constraint on the size of emitting region: $R \leqslant Dct_{\rm var}/(1+z)$
  - study of particle acceleration
  - important in ‘exotic’ physics studies



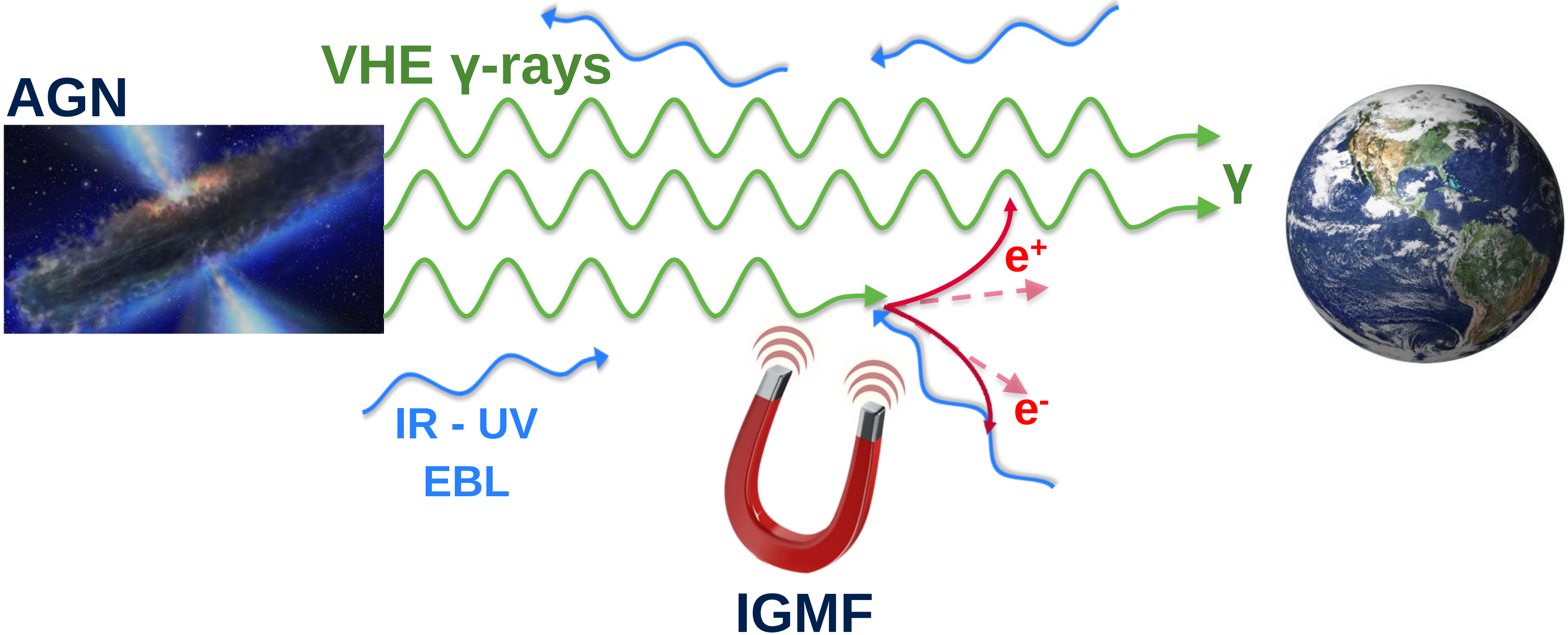
Extragalactic background light





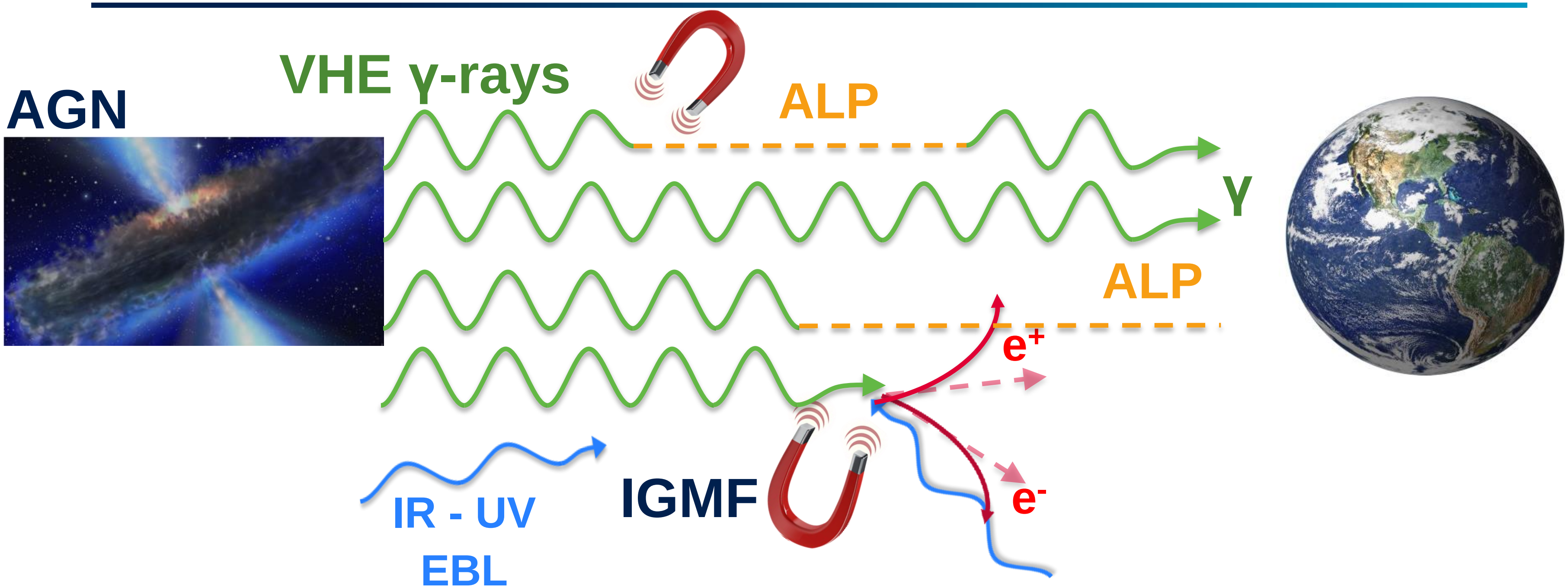


Intergalactic Magnetic Field



- deflection of $e^{+/-}$:
  - search for extended emission around point-like AGN images
  - good angular resolution & wide FoV necessary

Axion-like particles

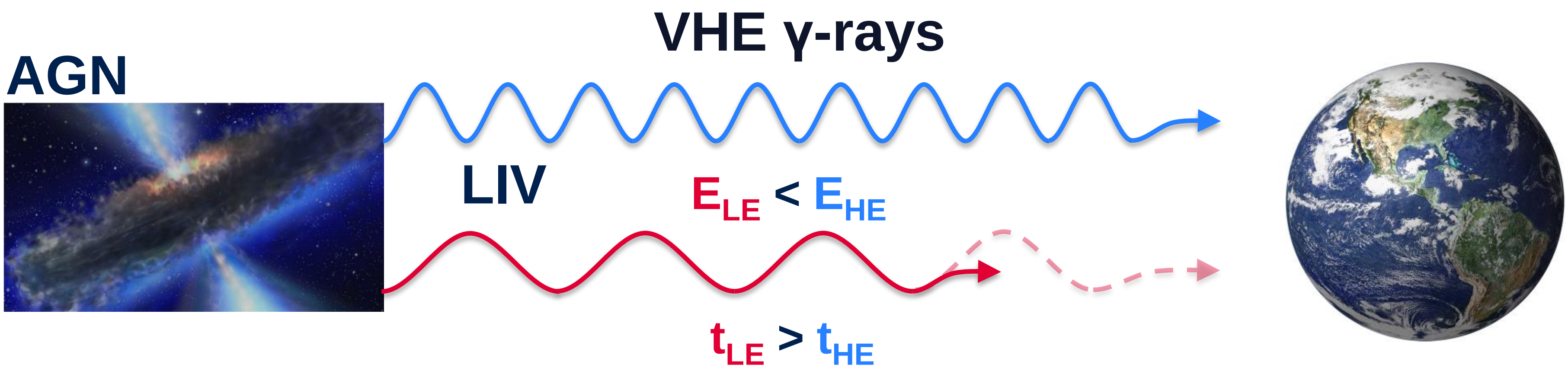


$$P_0 = \frac{1}{1+(E_{crit}/E_\gamma)^2}\ \sin^2\left[\frac{B\,s}{2\,M}\sqrt{1+\left(\frac{E_{crit}}{E_\gamma}\right)^2}\right]$$

$$E_{crit}(GeV) \equiv \frac{m_{\mu eV}^2\, M_{11}}{0.4\ B_G}$$

- photon to axion oscillations in the presence of magnetic field
  - universe more transparent to VHE γ-rays (no interaction of ALP and EBL)
  - modulation of energy spectra

Lorentz Invariance Violation



- LIV might arise in the theory of Quantum Gravity
  - residual effects at GeV-TeV: anomalous photon velocity dispersion in vacuum

$$c^2 p^2 = E^2 \left[1 \pm \xi_1 (E/E_{\rm Pl}) \pm \xi_2 (E/E_{\rm Pl})^2 \pm \ldots \right]$$

  - small time delays detectable at cosmological distances $\Delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_{\rm Pl}} \right)^\alpha \frac{L}{c}$
  - Active Galactic Nuclei (high E / small z), Gamma Ray Bursts (small E / high z)

Indirect dark matter searches

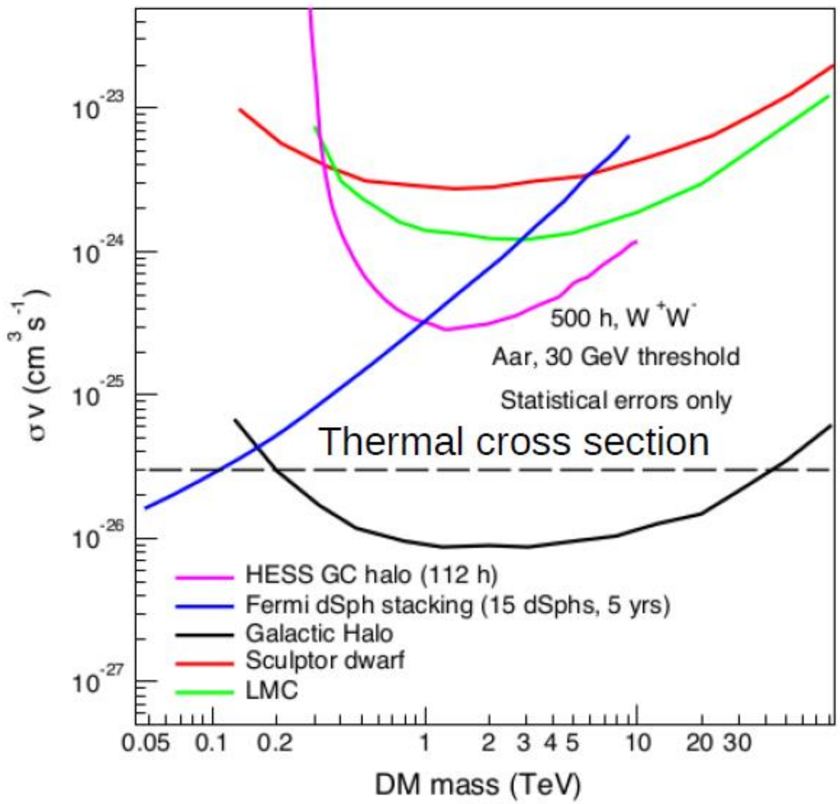
Astrophysics

spectrum

$$\frac{d\Phi(b,\ell)}{dE_\gamma} = \frac{\langle\sigma v\rangle_{b\bar{b}}}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \int_{\text{los}} dx\, \rho^2\left(r_{\text{gal}}(b,\ell,x)\right)$$

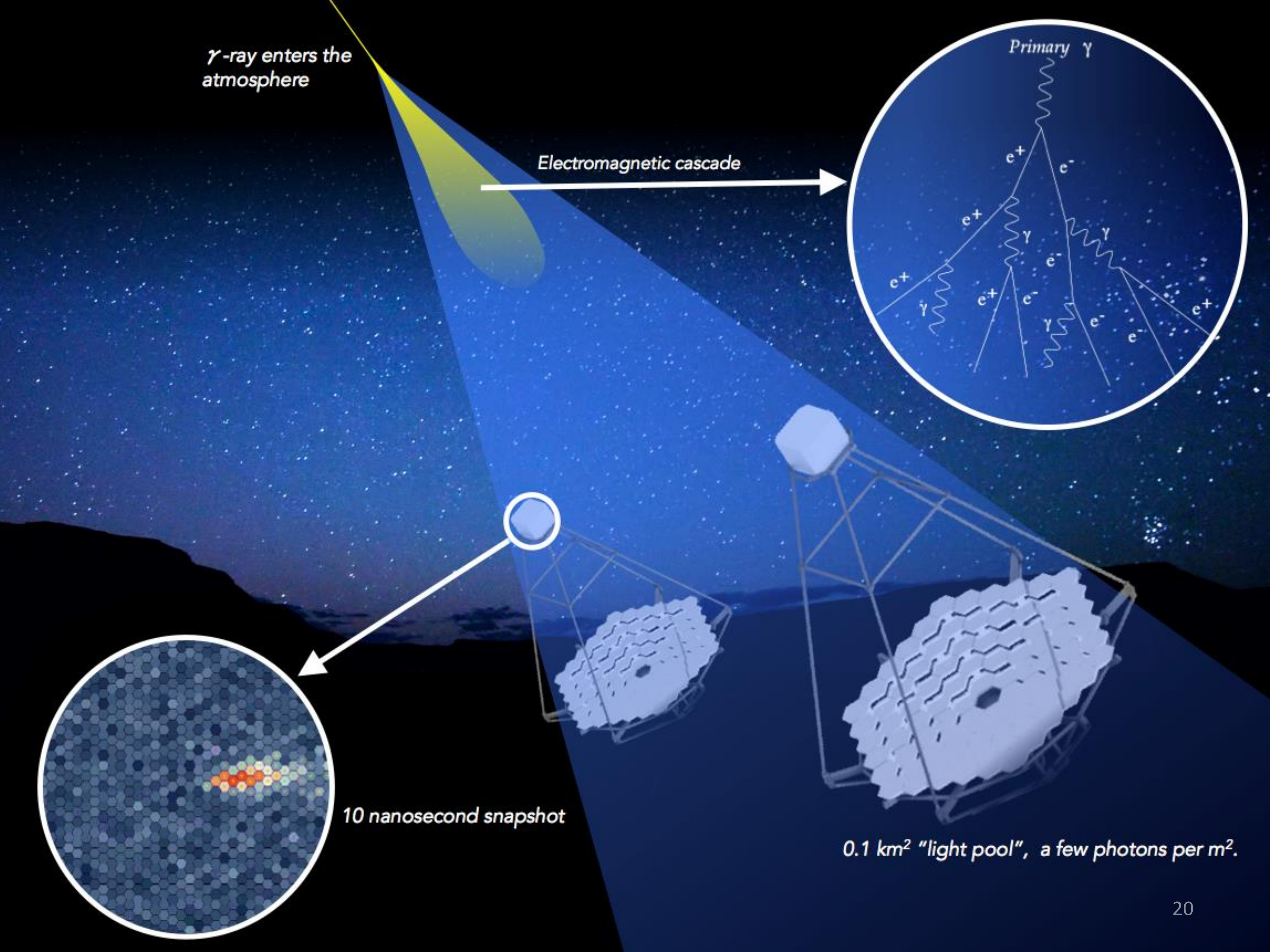
Particle Physics

- Galactic Halo
  - \+ large DM statistics
  - – diffuse astrophysical background
  - – astrophysical source confusion
- Dwarf Spheroidal Galaxies
  - \+ low astrophysical background
  - – low DM statistics
- Spectral lines
  - \+ no background
  - – very low DM statistics



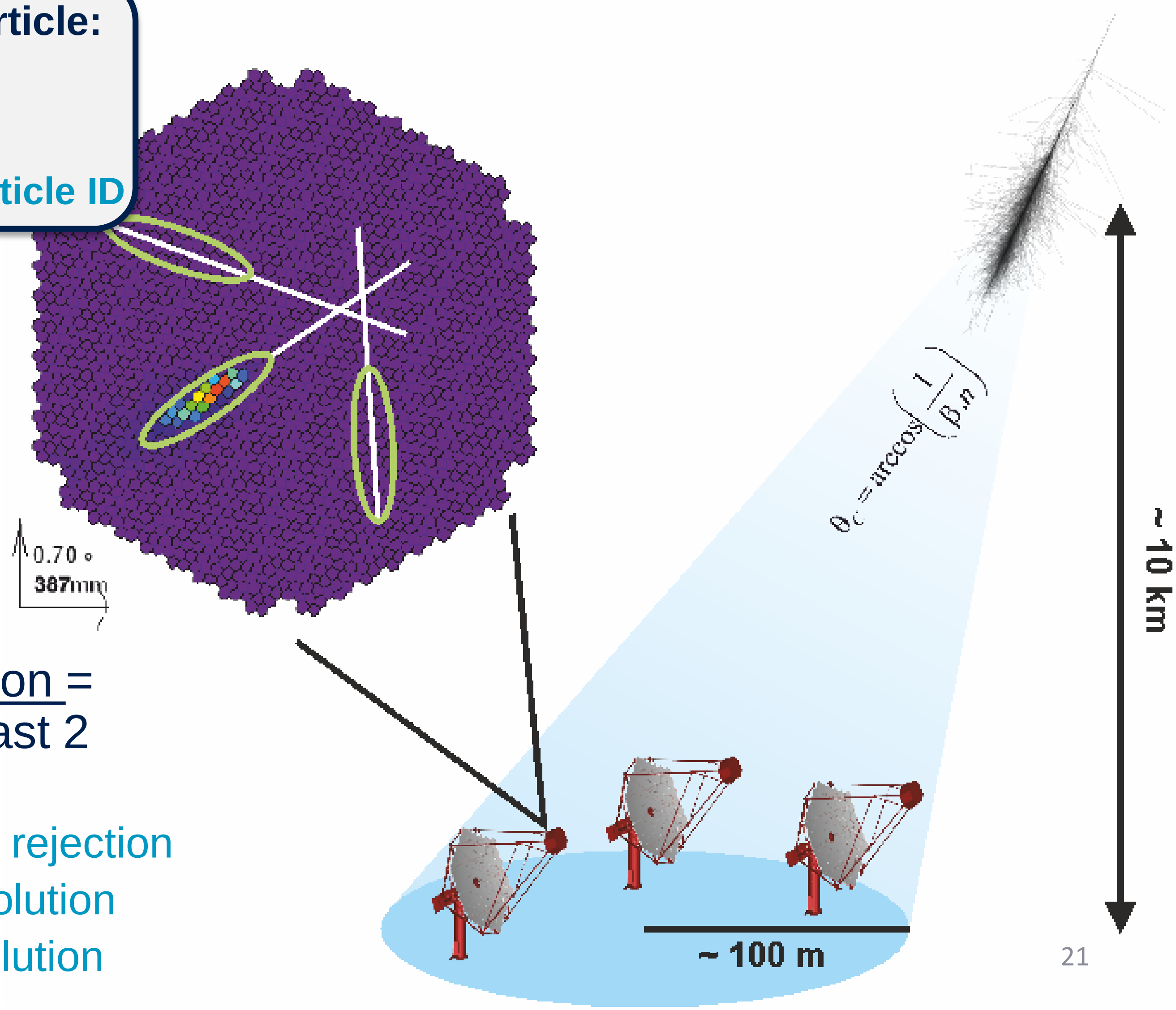
- DM searches with CTA

Imaging Atmospheric Cherenkov Telescopes


γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².

Imaging Atmospheric Cherenkov Technique

Image:	Gamma/Particle:
Intensity →	Energy
Orientation →	Direction
Shape →	Primary particle ID



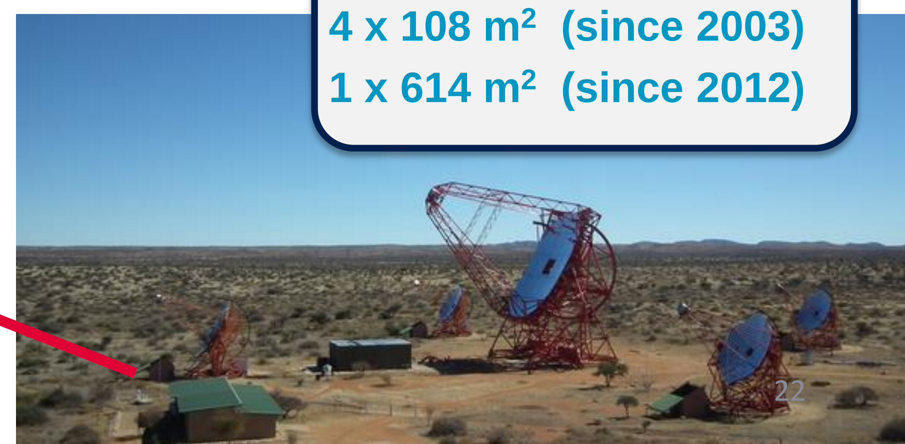
- stereoscopic detection = coincidence of at least 2 telescopes:
  - better background rejection
  - better angular resolution
  - better energy resolution

Current experiments

VERITAS (Arizona)
4 x 110 m^2 (since 2007)

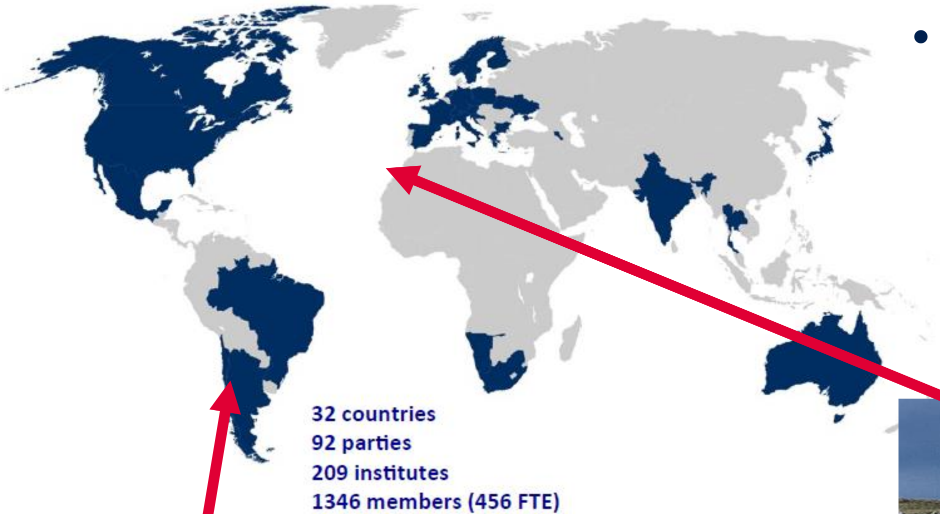
MAGIC (La Palma)
2 x 236 m^2 (2003/2009)

H.E.S.S. (Namibia)
4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)

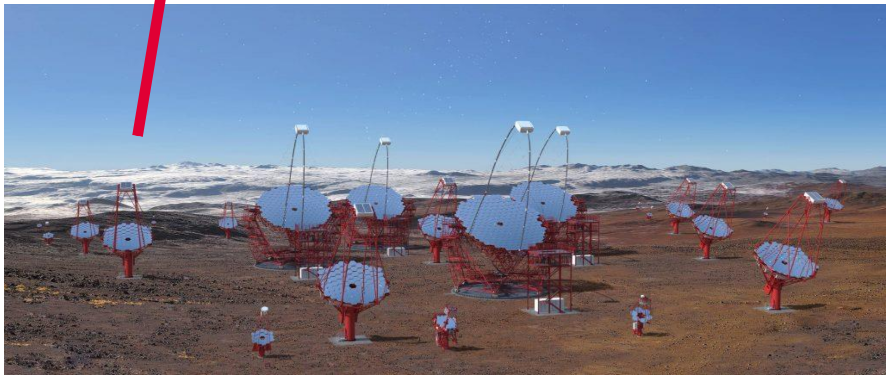


Cherenkov Telescope Array

CTA sites & layouts

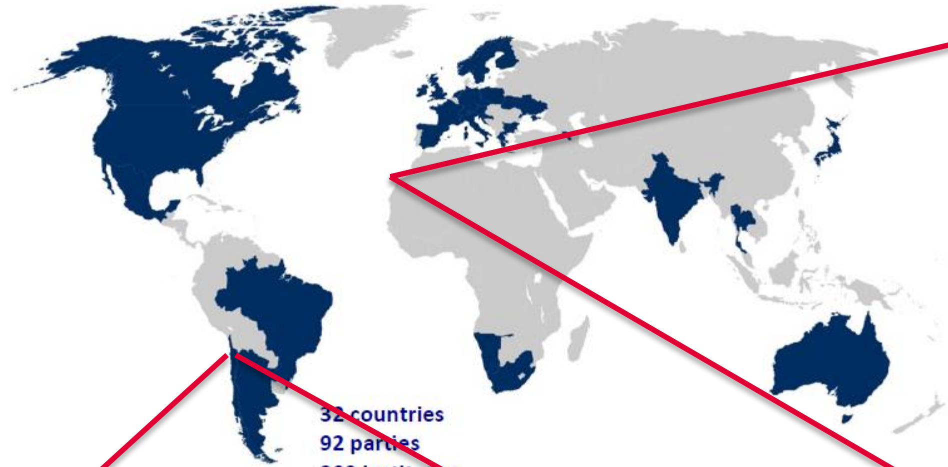


- **CTA-North:**
  - La Palma, Spain
  - Roque de los Muchachos Observatory (MAGIC site)
  - 2200 m a.s.l.

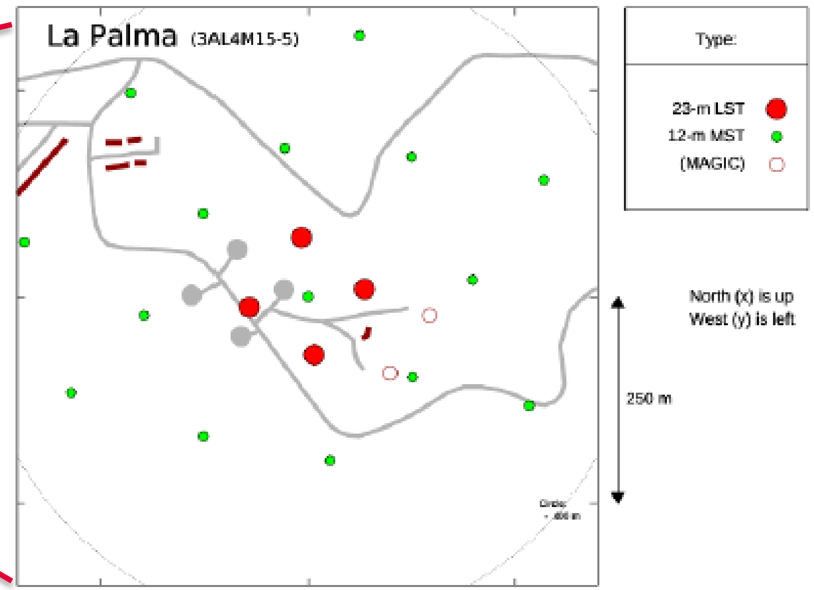


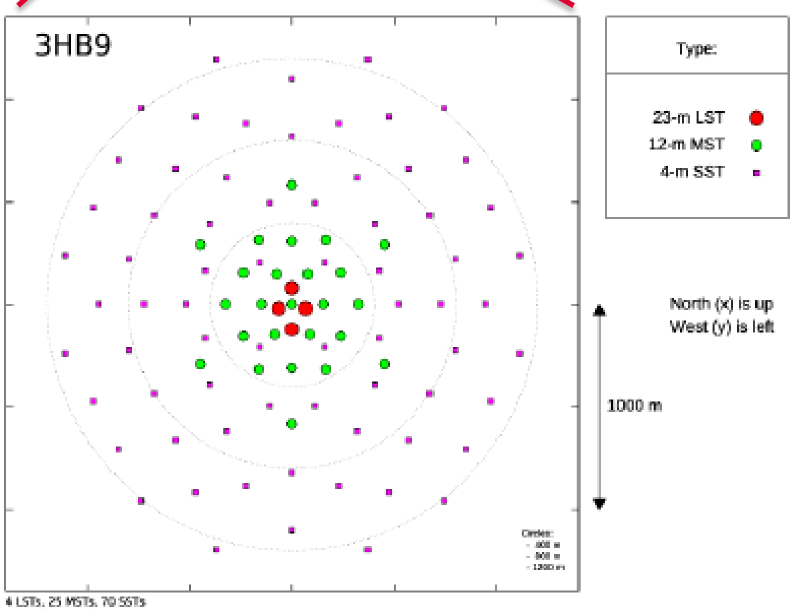
- **CTA-South:**
  - Atacama Desert, Chile
  - ESO site Paranal
  - 2635 m a.s.l.

CTA sites & layouts



32 countries
92 parties
209 institutes
1346 members (456 FTE)

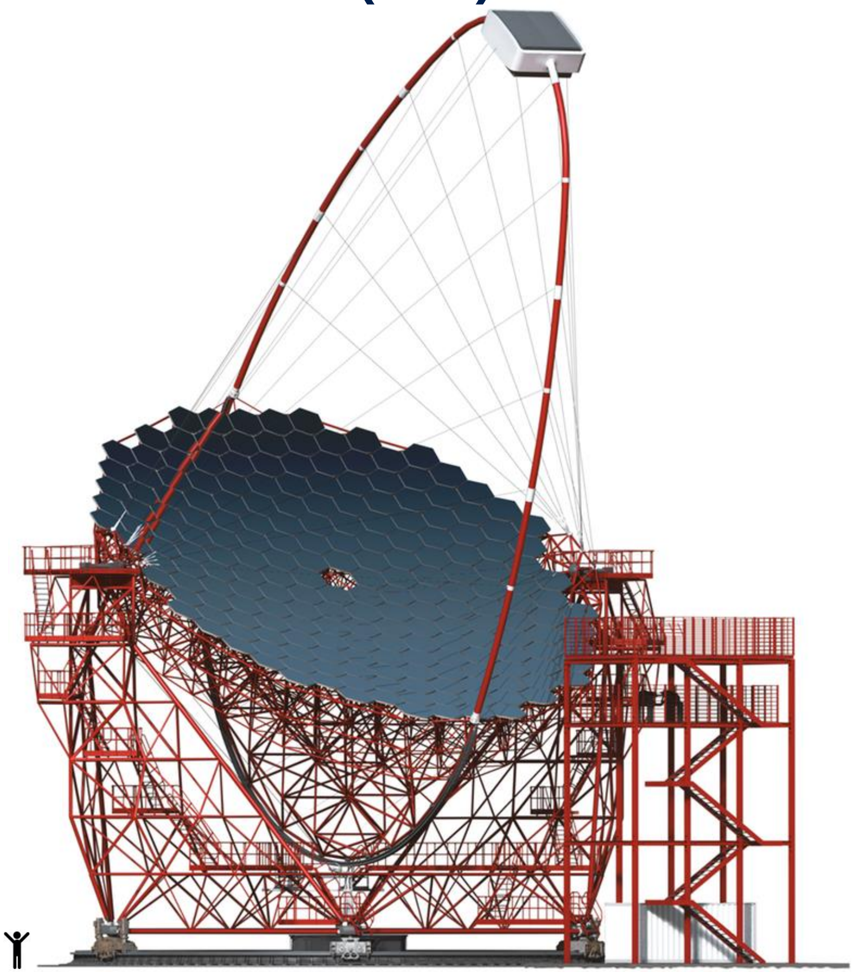




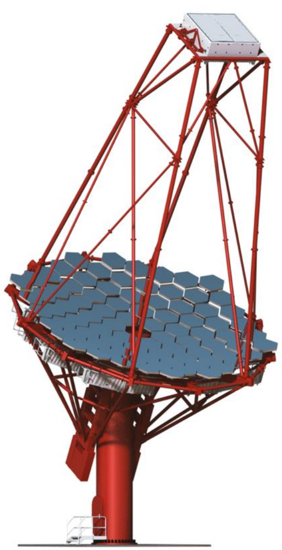
Site	Telescopes	Threshold Array	Baseline Array	Energy range [TeV]
North	LST	4	4	0.02 – 1
	MST	5	15	0.2 – 10
South	LST	0	4	0.02 – 1
	MST	15	25	0.2 – 10
	SST	50	70	5 – 300

CTA telescopes

Large-Size Telescope (LST)

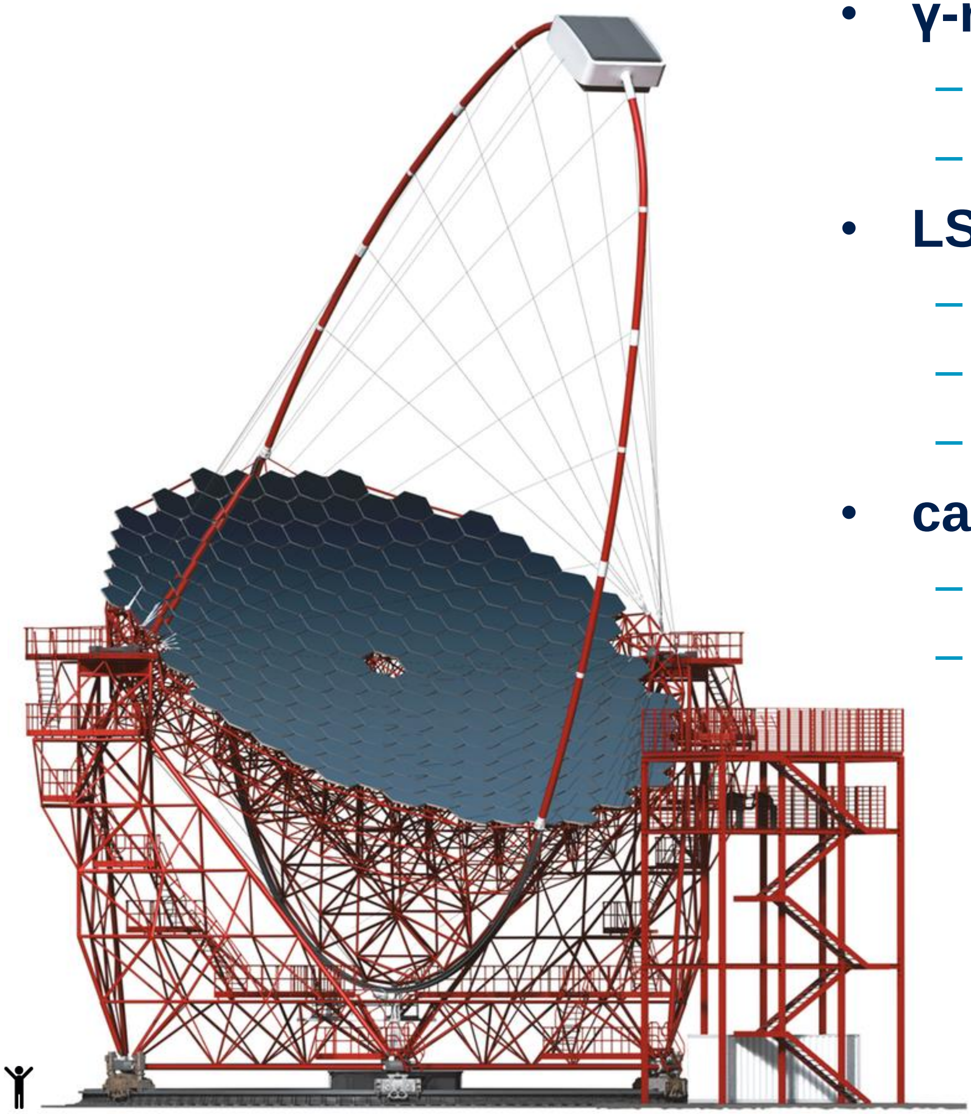


Medium-Size Telescope (MST)



Small-Size Telescope (SST)

Large-Size Telescope



- **γ-rays at low energies (20 - 200 GeV):**
  - few Cherenkov photons from air showers
  - large mirrors needed
- **LST:**
  - mirror: parabolic, 23 m diameter
  - height 45 m, 100 tonnes
  - re-positioning: < 20 s
- **camera:**
  - 1855 PMTs in 265 modules
  - field of view 4.5°

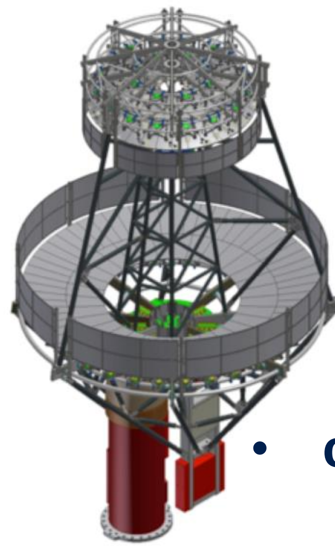
Key science targets:
- transient phenomena in our Galaxy
- high-redshift active galactic nuclei
- gamma ray bursts

Medium-Size Telescopes

- **γ-rays at core energy range (10 GeV - 10 TeV)**

MST:

- **optical system:**
  - Davies-Cotton design
  - 1 spherical mirror
  - 12 m diameter
- **camera:**
  - 2 designs
  - PMT based
  - field of view 8°



SCT:

- **optical system:**
  - Schwarzschild-Couder design
  - 2 mirrors
  - 9.7 m (primary), 5.4 m (secondary)
  - cancel aberrations, improved point spread function
- **camera:**
  - SiPM based
  - field of view 8°

Key science targets:
- all targets + quick surveys

Small-Size Telescopes

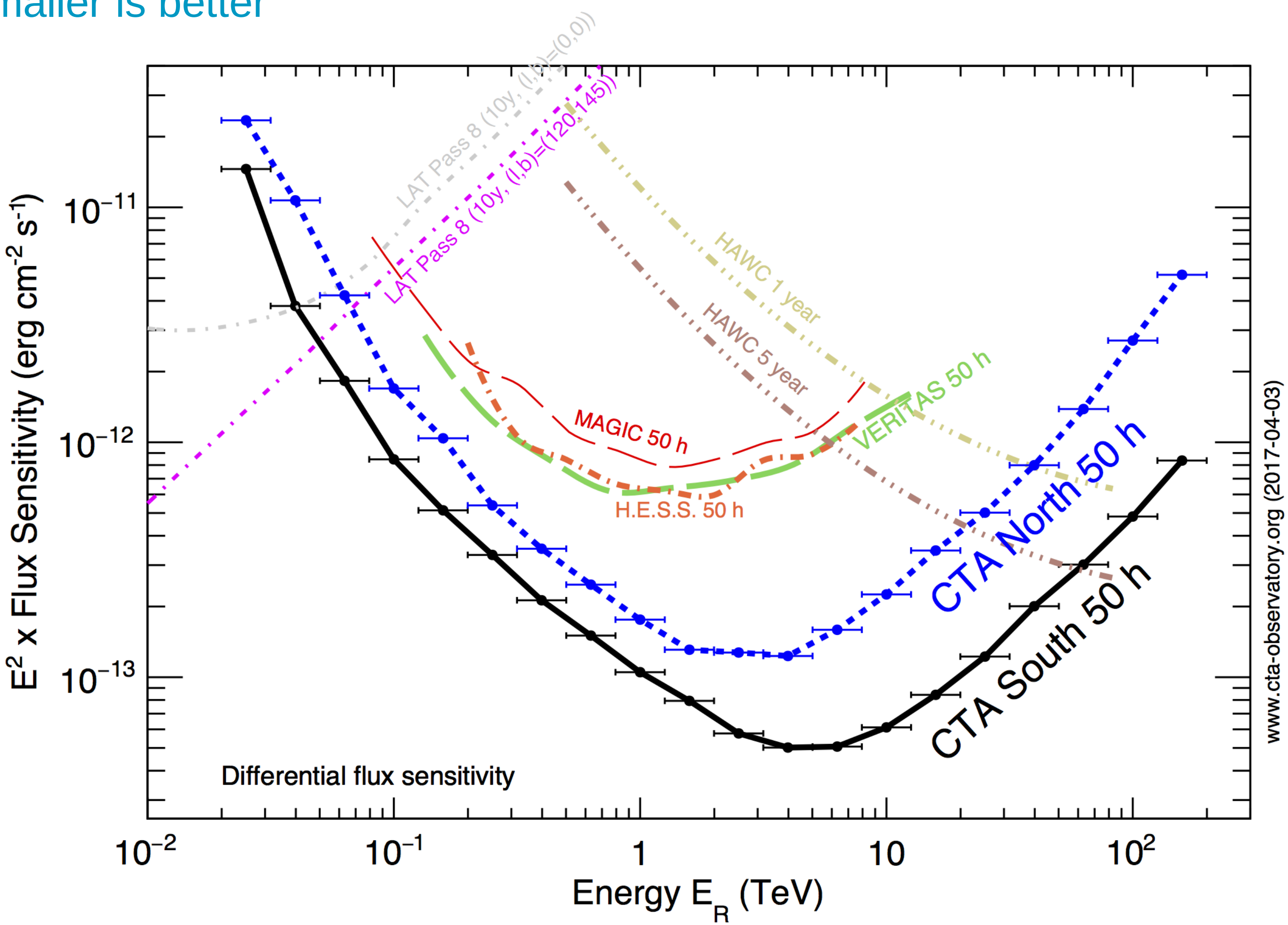
- **γ-rays at high energies (5 TeV - 300 TeV):**
  - plenty of Cherenkov light from air showers across large area
  - small mirrors sufficient
  - large spacing between telescopes (>~ 200 m)
- 1 DC design, 2 SC designs
- ~ 4 m diameter (primary) mirrors
- all cameras SiPM based

Key science targets:
- highest energetic sources from our Galaxy
  → SSTs only at CTA-South

SST-2M GCT SST-2M ASTRI SST-1M

CTA sensitivity

- differential energy flux sensitivity
  - smaller is better

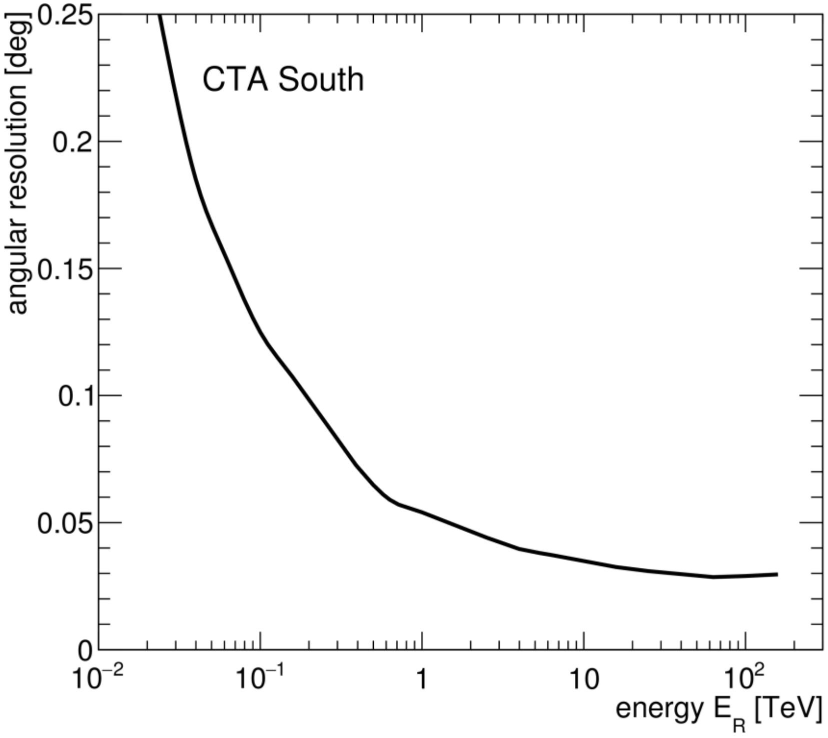


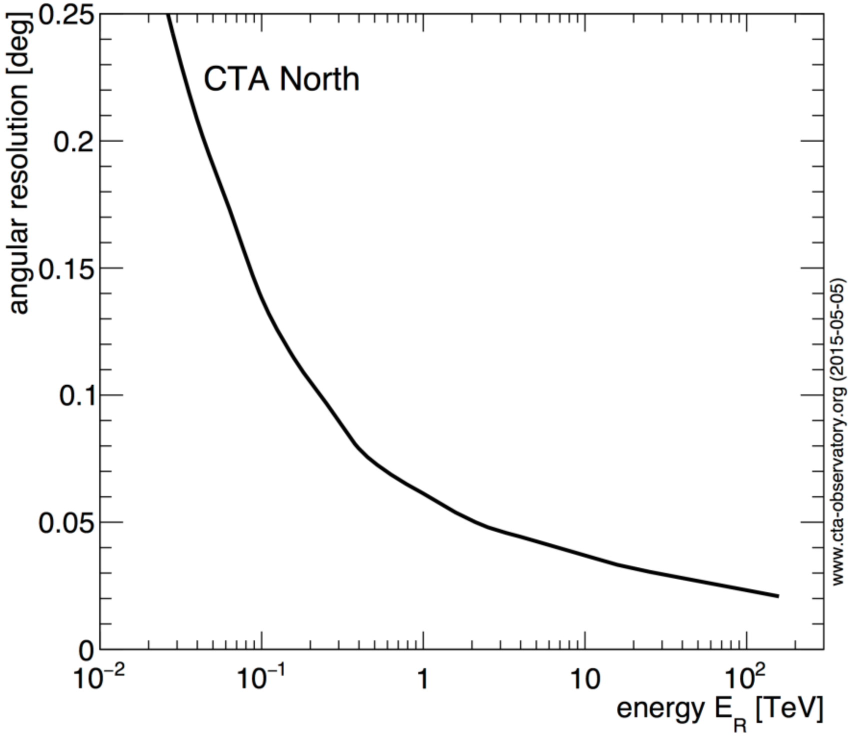
Thank you!

Backup

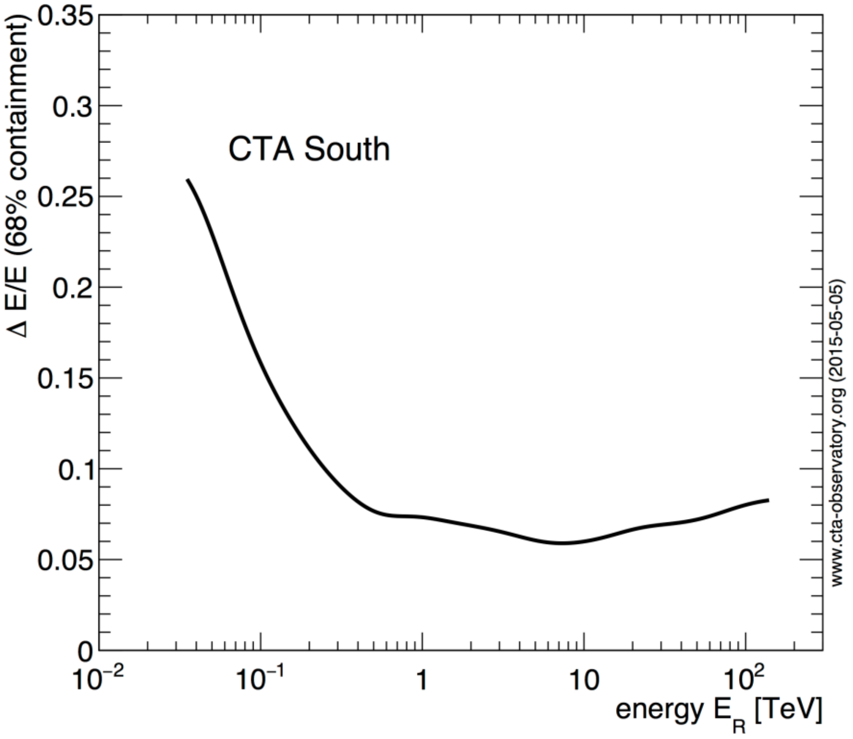
CTA angular resolution

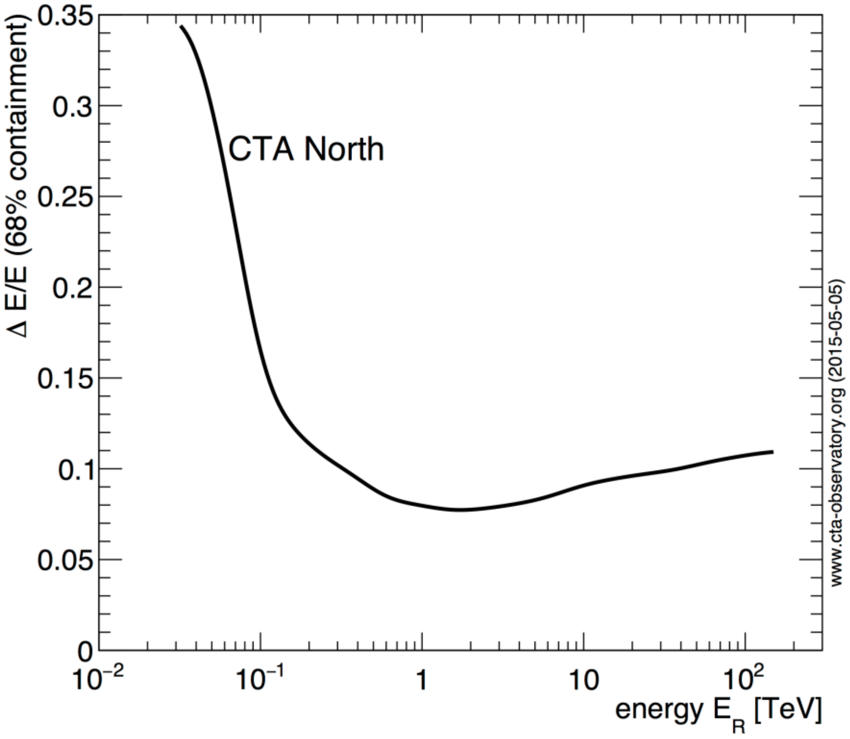
- 68% containment angle of reconstructed γ-rays
  - smaller is better





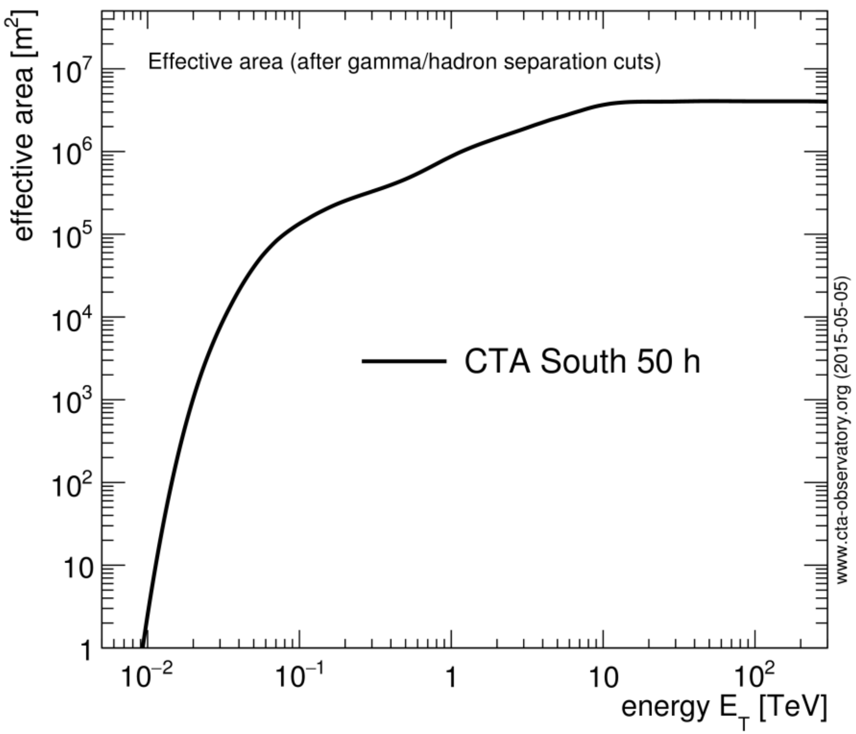
CTA energy resolution

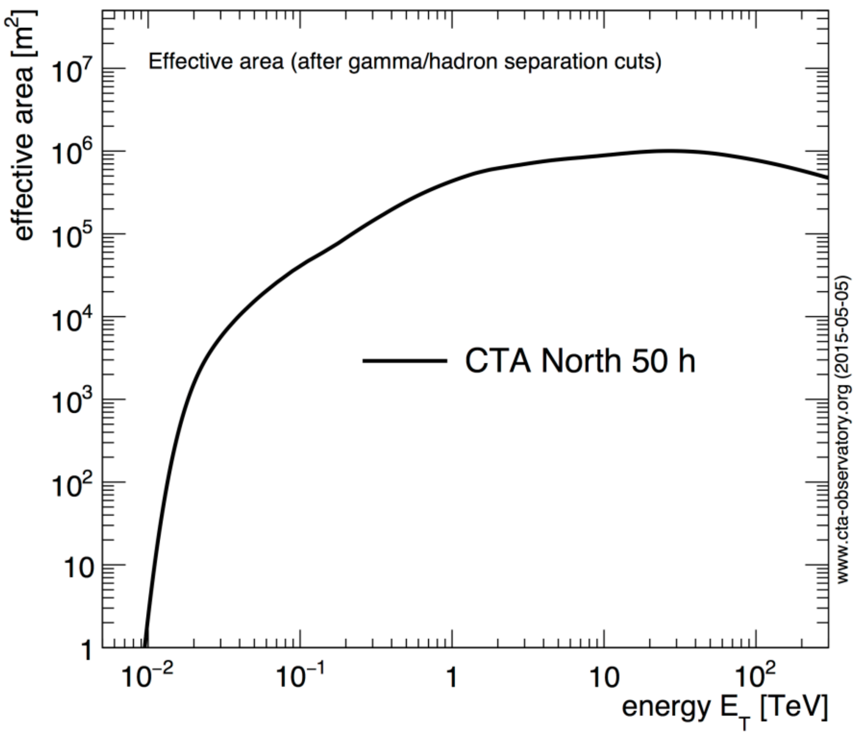




CTA effective area

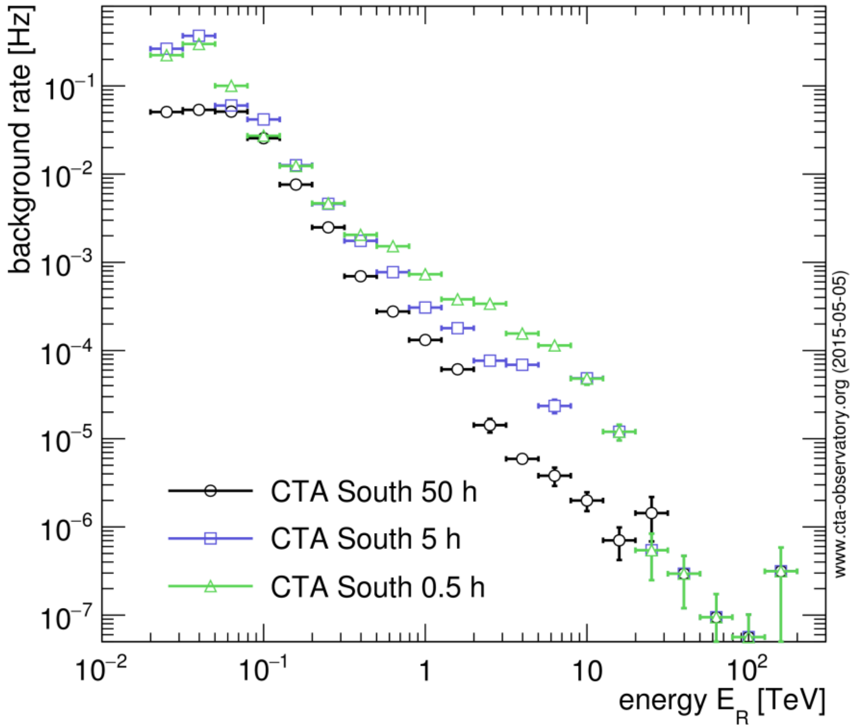
- effective collection area
  - larger is better

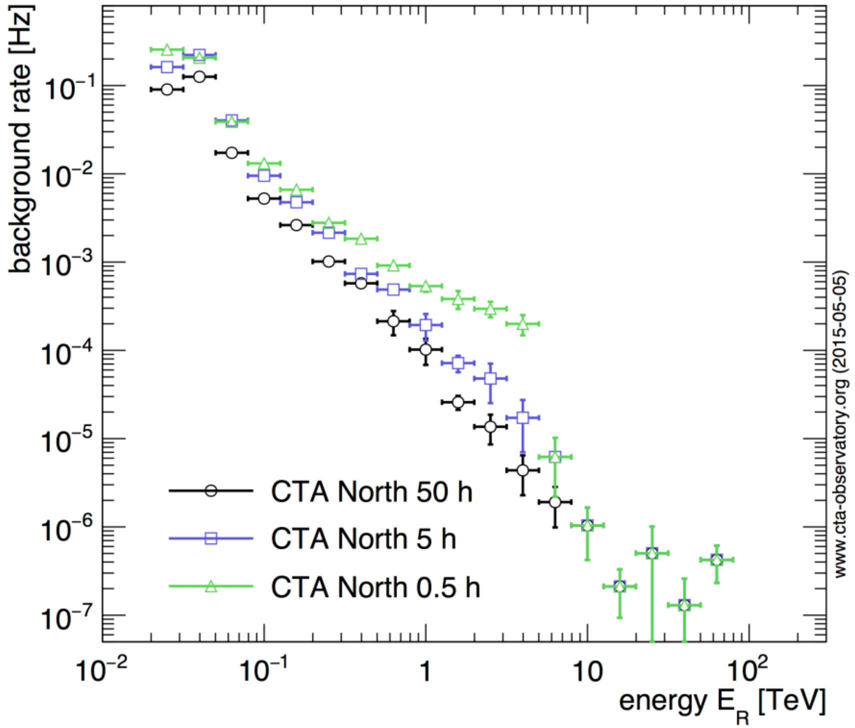




CTA background rate

- cosmic-ray background rate after gamma-hadron separation cuts





LST parameters

LST Main Parameters		
Optical Parameters		
Reflector type	1-mirror, parabolic	
Focal length	28 m	
Dish diameter	23 m	
f/D	1.2	
Mirror area	396 m^2	w/o shadowing
Mirror effective area	368 m^2	Including shadowing
Preliminary on-axis PSF	0.05°	
Preliminary off-axis PSF	0.11°	at 1° off-axis
Preliminary tracking accuracy	20 arcsec	RMS, online precision
Pointing accuracy	14 arcsec	RMS, post-calibration precision
Camera Parameters		
Camera dimensions (LxHxW)	2.8 m x 2.9 m x 1.15 m	
Weight	$<$ 2000 kg	
Number of pixels	1855	
Pixel linear size	1.5 inch	2 inch including light concentrator
Pixel field of view	0.1°	
Camera field of view	4.5°	
Trigger region field of view	4.5°	
Sampling speed	1 GS/s	
Analogue buffer length	4 μs	for hardware stereo trigger
Readout rate	7.5 kHz (target), 15 kHz (goal)	
Dead time	5% at 7.5 kHz	
Mechanical parameters		
Total weight	103 tons	all moving parts
Repositioning speed	20 s	for 180° in azimuth
Elevation drive range	-70° to 100°	
Azimuth drive range	408°	
Inertia elevation	$\sim$6000 tons·m^2	
Inertia azimuth	$\sim$12000 tons·m^2	
Park position	zenith angle 95°	locked at the camera tower
Height at Camera Access	13 m above ground	In the parking position

MST parameters

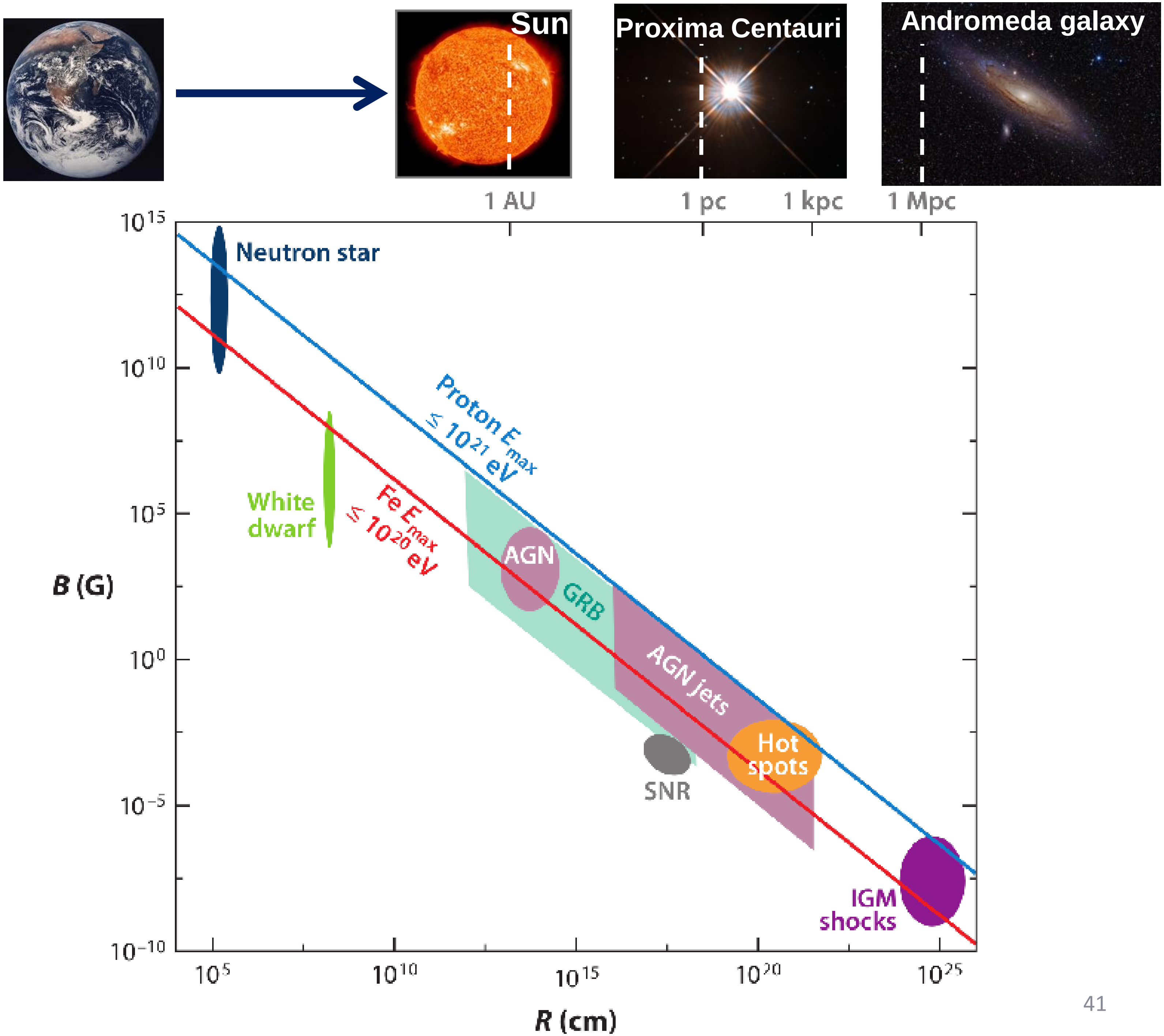
Parameter	Requirement
Effective mirror area (corrected for shadowing)	> 88 m^2 corresponding dish diameter D ~12 m
Camera FoV	> 7° resulting camera weight ~2 tons
RMS optical time spread (over 80% of the required camera FoV)	< 0.8 ns hexagonal facets, 1.2 m flat-to-flat
Mirror focal length (F)	>1.3 × D (realised with F = 16 m)
Mirror shape	spherical hexagonal facets, 1.2 m flat-to-flat
Average specular reflectivity of the reflector at all wavelengths from 300 – 550 nm	> 85%
Average efficiency of the focal plane detectors (weighted by the Cherenkov spectrum in the range 300 – 550 nm)	> 13%
Fractional RMS charge resolution per pixel	~0.45 / ~0.12 at 10/1000 photoelectrons
Optical PSF for 80% light containment over 80% of the camera FoV	< 0.18°
Dish radius of curvature	1.2 × F (realised with 19.2 m)
Angular pixel size	< 0.18°
Slewing speed to any point on the sky > 30∘ in elevation	90 s
Positioning range in elevation	−20 … 91°
Tracking range in elevation	< 89.2°
Tracking precision	< 0.1° in each axis
RMS post-calibration pointing precision in space	< 7″

SCT parameters

SCT main parameters		
Optical properties		
Focal length	5.5863 m	
f/D	0.5781	
Dish diameter (primary)	9.6638 m	
Mirror area	50.31 m^2	
Mirror effective area	40 m^2	Including mirror reflectivity and shadowing
Largest mirror facet (diagonal)	1.75 m	Mirror panels are segments of an annulus
On-axis PSF real optical parameters, 2 x max (RMS_x,RMS_y)	3.5'	
PSF 3.5° off-axis real optical parameters, 2 x max (RMS_x,RMS_y)	4.4'	
Time Spread RMS	negligible	Schwarzschild-Couder optics are isochronous
Camera Characteristics		
Camera housing width	1.45 m	Flat to flat on an octagon
Camera housing depth	1.07 m	
Total pixel number	11,328	
Pixel linear size	6.2 mm	Prototype size; may differ slightly in production
Pixel angular size	3.8'	Prototype size; may differ slightly in production
FoV	8.3°	Prototype size; may differ slightly in production
Photosensors PDE at 500 nm peak	38 %	Prototype device; higher expected for production
Sampling frequency	1 GSa/s	
Readout rate	≤10 kHz	Expect to operate at ≤2.5 kHz
Mechanical Properties: telescope structure		
Telescope height pointing horizontally	11.51 m	
Telescope height pointing vertically	17.94 m	
Telescope length pointing horizontally	17.22 m	
Telescope width	10.52 m	
Foundation above ground (radius)	3 m	
Mechaical Properties: drives		
Elevation range	-5° – 92°	<89.2° for tracking
Azimuth range	±270°	From stow
Maximum time to acquire target at elevation >30°	90 s	
Tracking precision	<0.1°	Each axis
Total telescope weight	51 tons	

SST parameters

SST parameters			
	ASTRI	GCT	SST-1M
Effective collecting area (m^2)	6	6	6.47
Focal lengh (m)	2.15	2.28	5.6
Field of view	9.6°	9.2°	9.1°
On axis PSF (spot diameter 80% photon inclusion)	0.17°	0.1°	0.08°
Pixel size (mm) and shape	6.1 (square)	7 (square)	6 (hexagon side)
Dish diameter (m)	4	4	4
Camera number of channels	1984	2048	1296
Camera diameter (m)	0.4	0.35	0.88
Camera mass (kg)	55	45	186
Max. power consumption of camera inc. cooling (W)	400 + 400 cooling	450 + 450 cooling	1640 + 1250 cooling
Data rate at 600 Hz (Gb/s)	0.046	3	0.187 for 80 ns readout window
Readout window length (ns)	12.5…100	96	20…2000
Telescope mass (tons)	20	7.8	8.6
Typical power consumption in 24 hrs (kWh)	41	30.1	57.8
Investment cost in production phase (€)	600 743	520 516	472 630


Sun
Proxima Centauri
Andromeda galaxy
1 AU
1 pc
1 kpc
1 Mpc
Neutron star
Proton E_{max} $\lesssim 10^{21}$ eV
White dwarf
Fe E_{max} $\lesssim 10^{20}$ eV
AGN
GRB
AGN jets
Hot spots
SNR
IGM shocks
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
B (G)
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
R (cm)

Milky Way galaxy