

Science with CTA

The Cherenkov Telescope Array Status and Perspectives



Gernot Maier



The Cherenkov Telescope Array - Summary

- > future observatory for high-energetic gamma rays
 - astronomy & astroparticle physics with photons in the energy range 20 GeV to 300 TeV
- > huge improvements in all performance aspects
 - x10 better sensitivity; better field of view, angular and energy resolution; wider energy coverage; few km² collection area; flexible observations
- > user facility - guest observer driven
 - open observatory: data available after some proprietary period
- > international project ~400 M€ cost - fully online 2022-2024
 - involves ~90% of all gamma-ray astronomers + many more
- > large DESY project

Science Drivers for CTA

Implementation of CTA

Following the upcoming “Science for CTA”
publication - soon on the archive

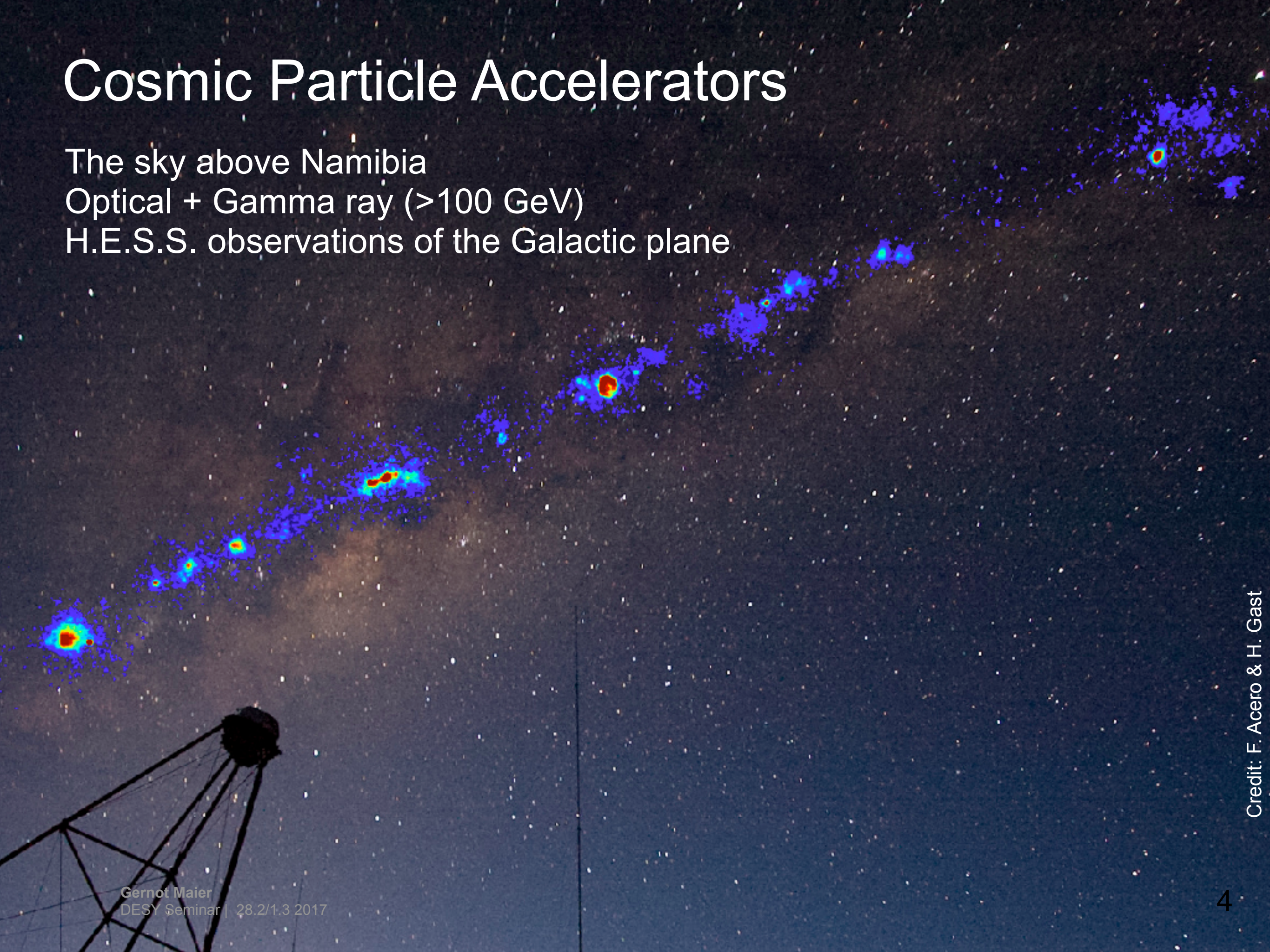


Cosmic Particle Accelerators

The sky above Namibia

Optical + Gamma ray (>100 GeV)

H.E.S.S. observations of the Galactic plane



Cosmic Particle Accelerators

The sky above Namibia

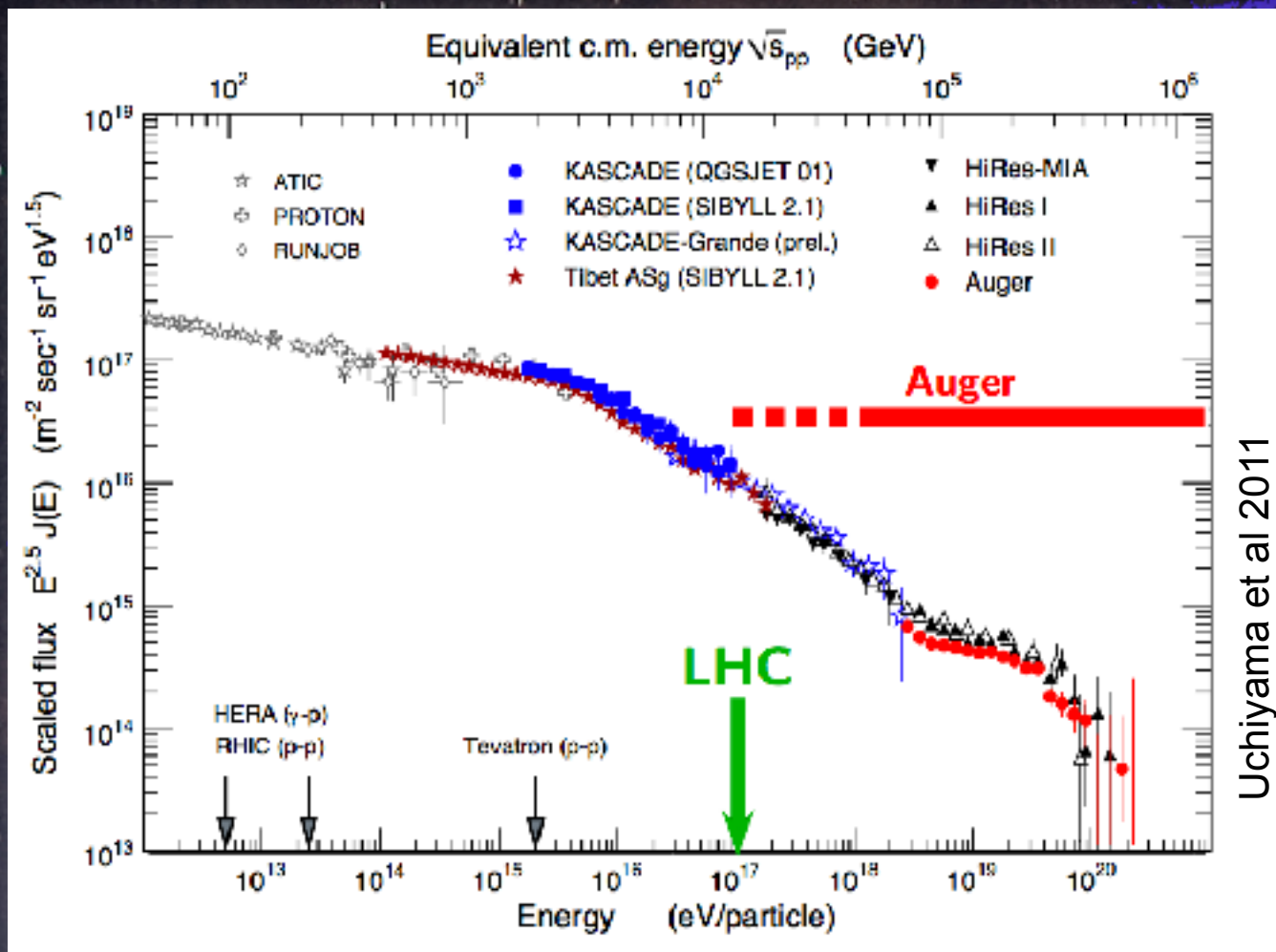
Optical + Gamma ray (>100 GeV)

H.E.S.S. observations of the Galactic plane

Multi-wavelength / multi-messenger image:
photons from radio to gamma rays
neutrinos
charged cosmic rays

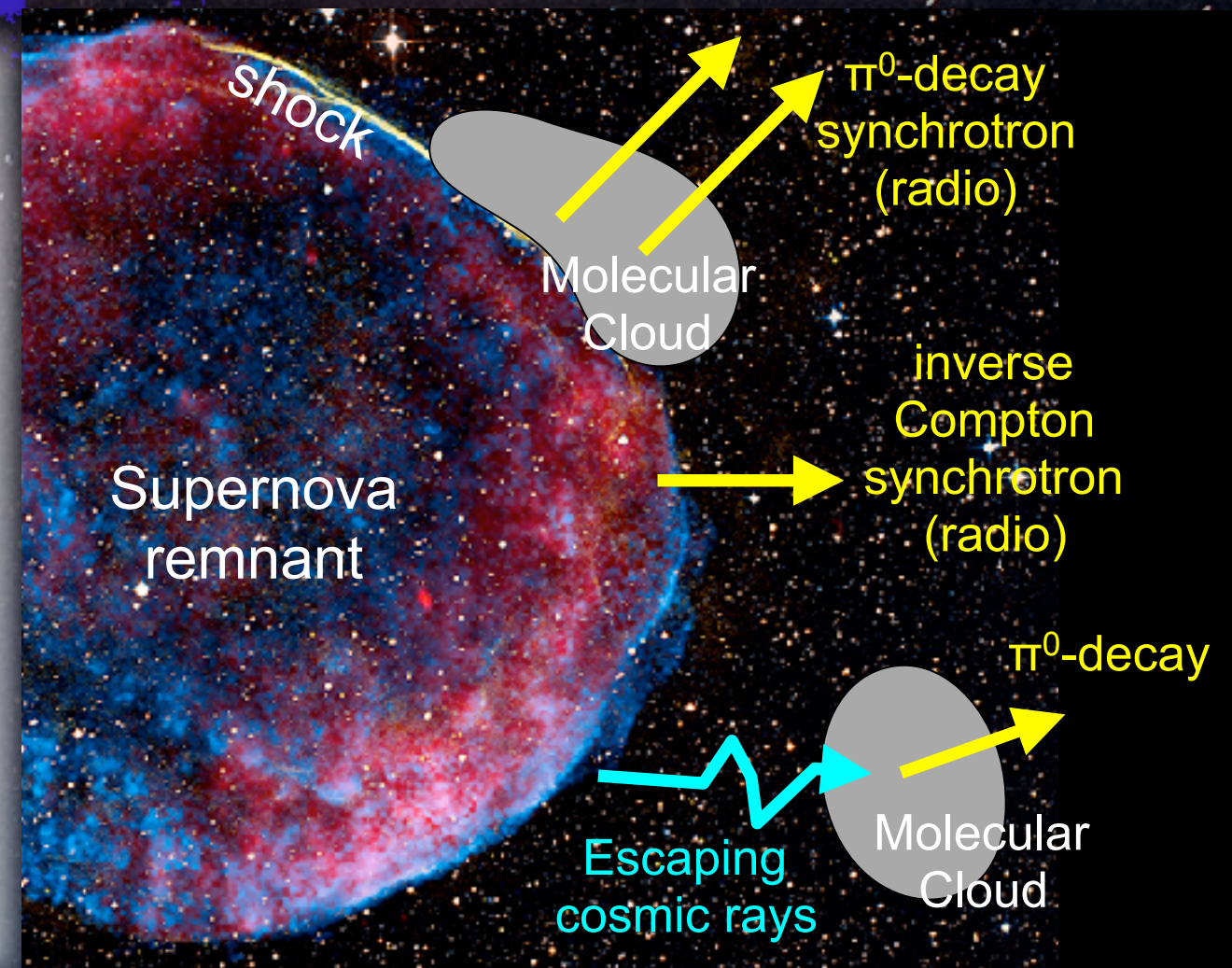
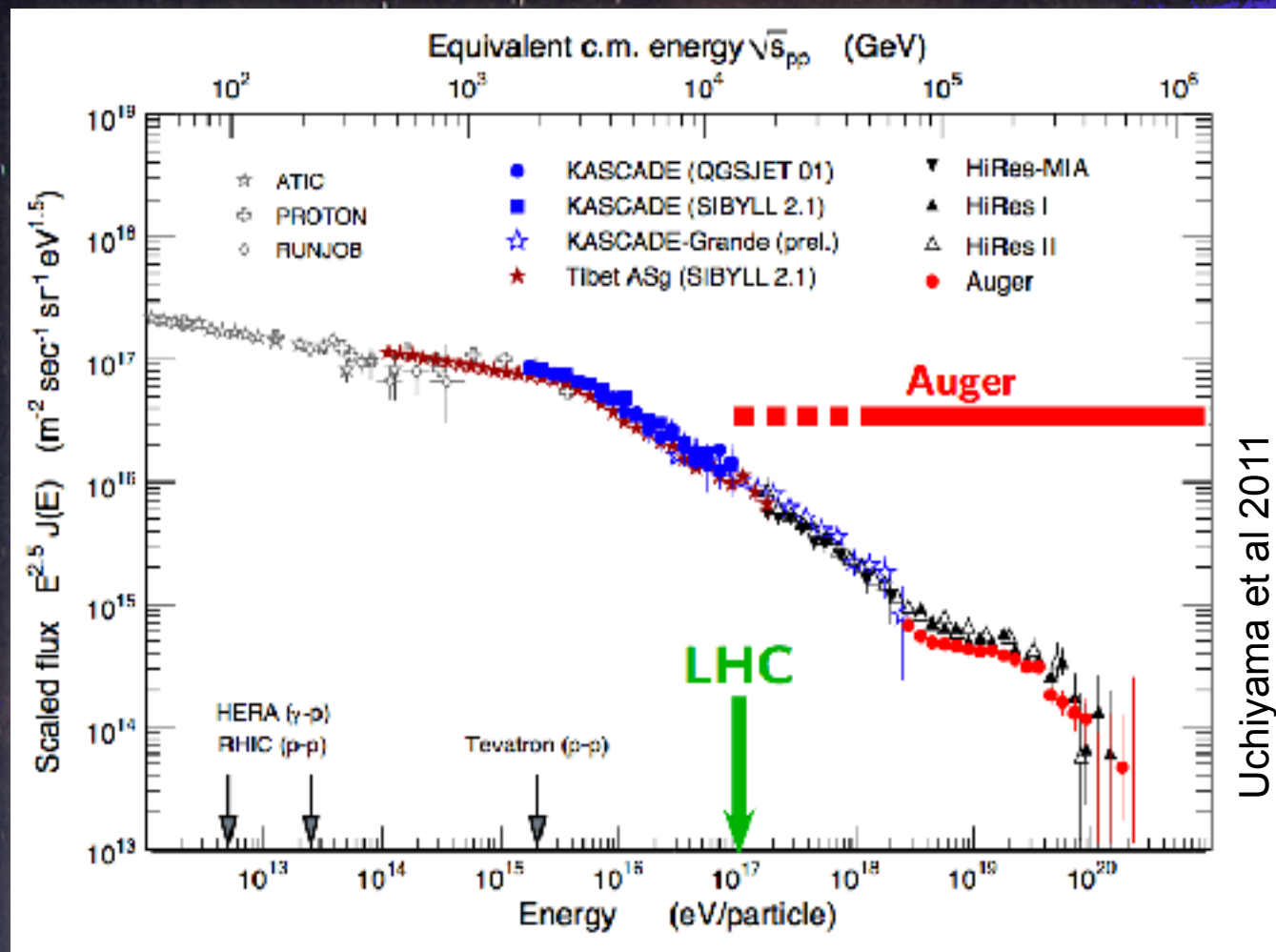
• Cosmic Particle Acceleration

- how and where are particles accelerated?
- how do they propagate?
- what is their impact on the environment?



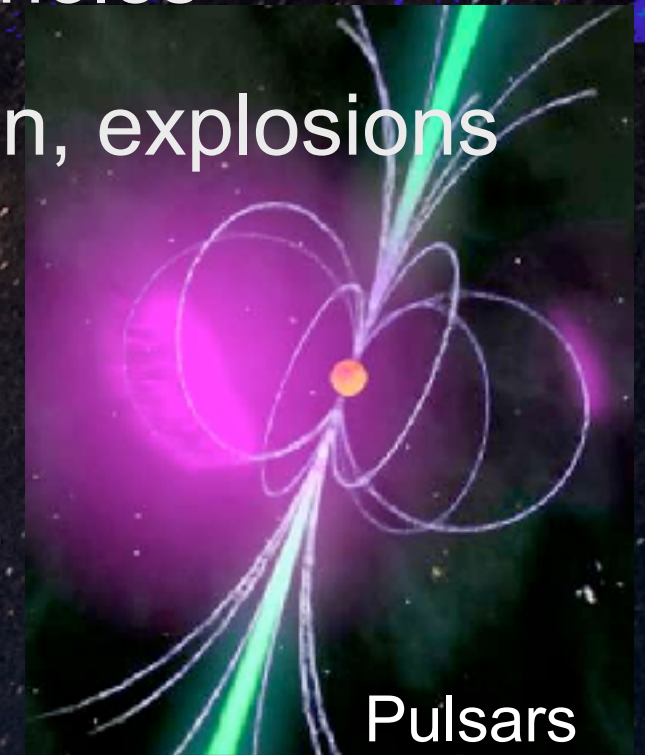
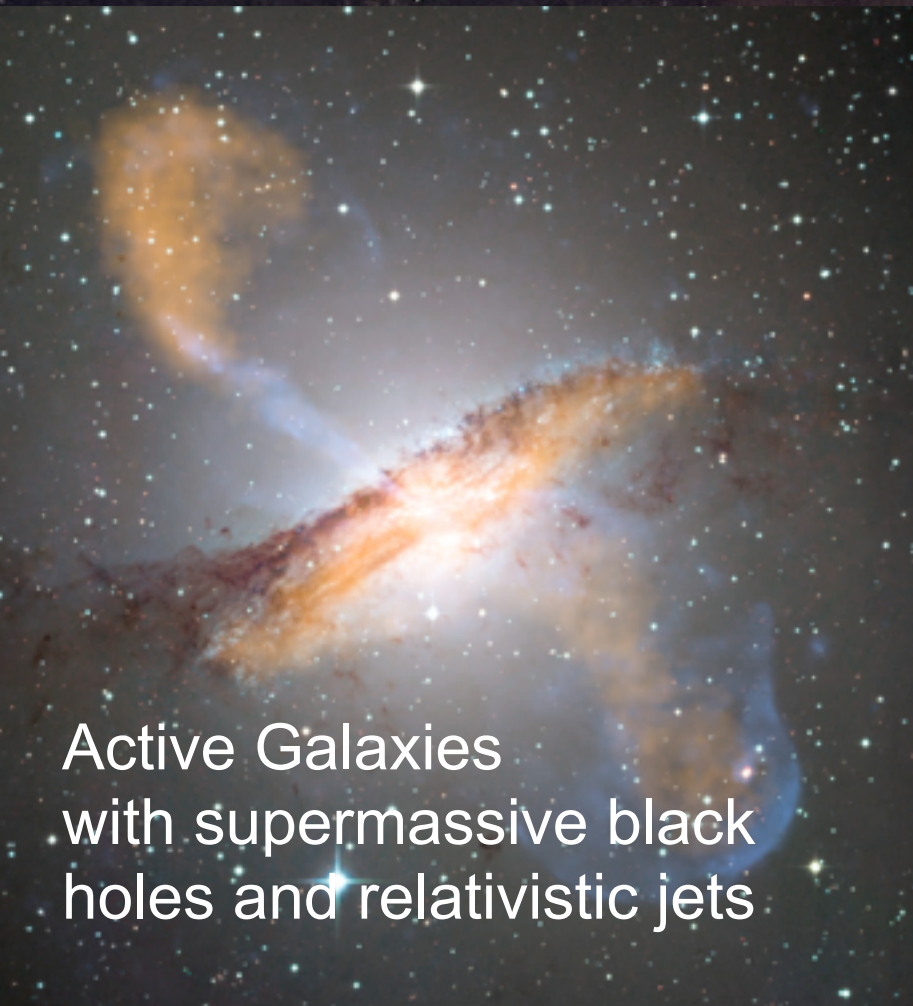
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• Probing Extreme Environments

- processes close to neutron stars and black holes
- processes in relativistic jets, winds, accretion, explosions
- cosmic voids

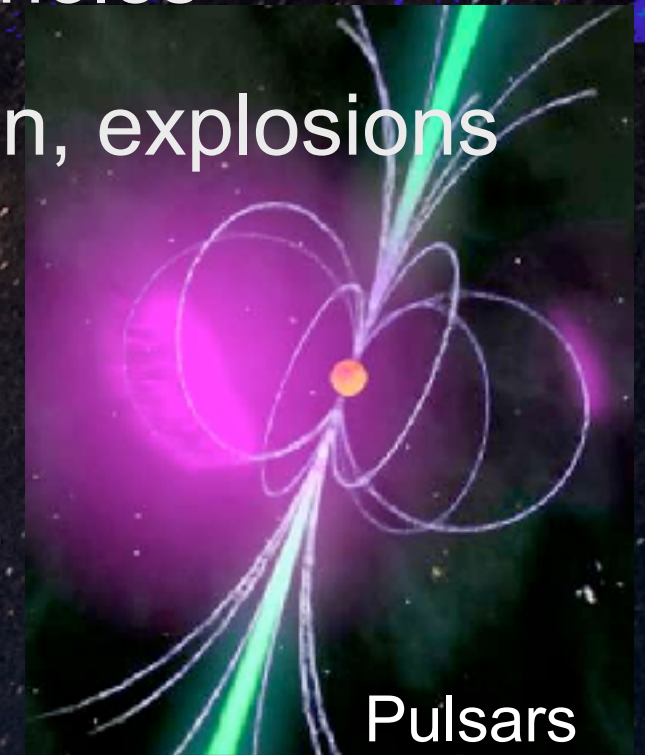


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Accreting source - binary systems



Pulsars

Active Galaxies
with supermassive black
holes and relativistic jets

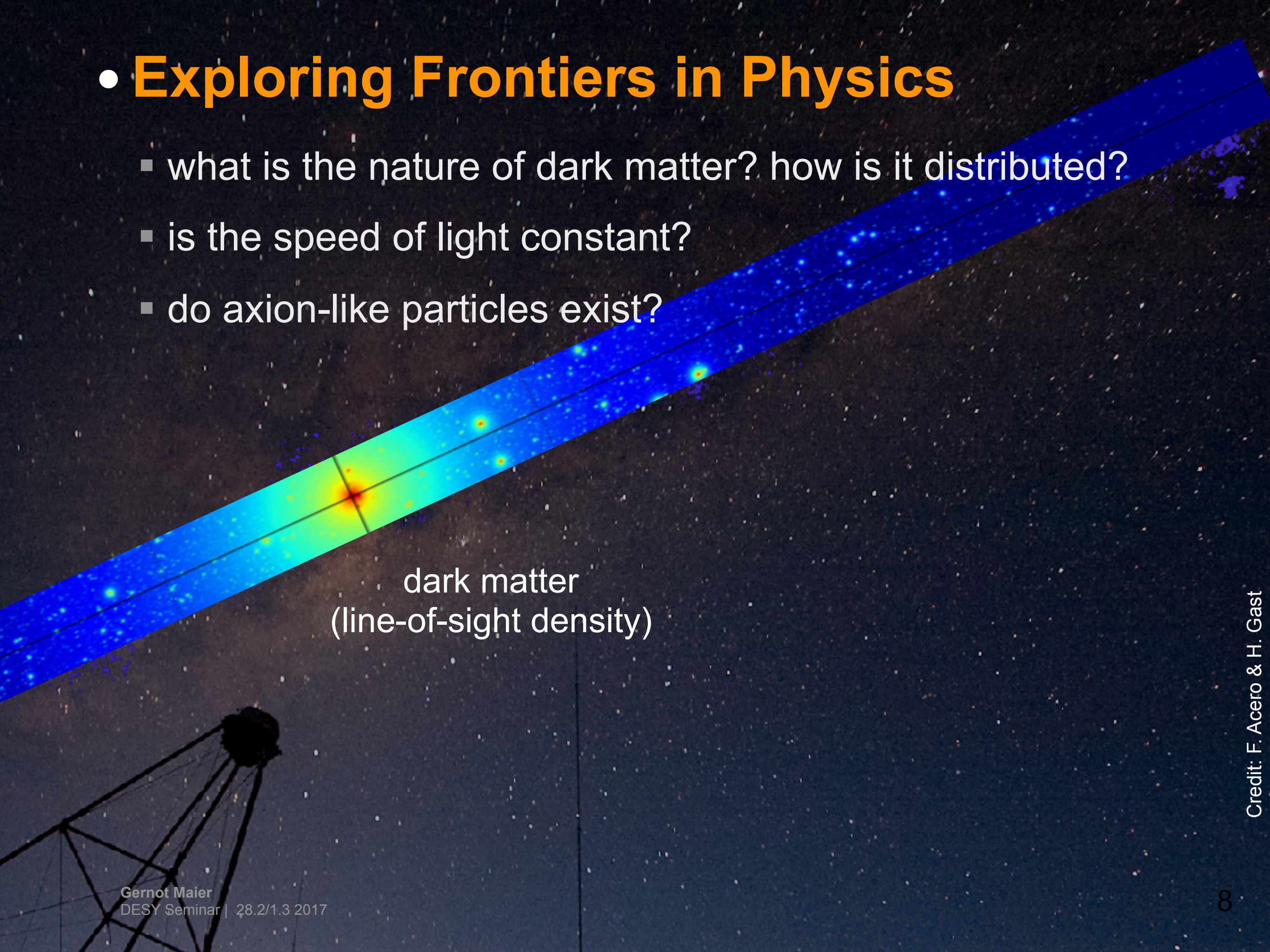
Particle acceleration in black hole systems:

- shocks in relativistic jets / outflow
- magnetospheric origin introduced by rotating black hole
-

• Exploring Frontiers in Physics

- what is the nature of dark matter? how is it distributed?
- is the speed of light constant?
- do axion-like particles exist?

dark matter
(line-of-sight density)



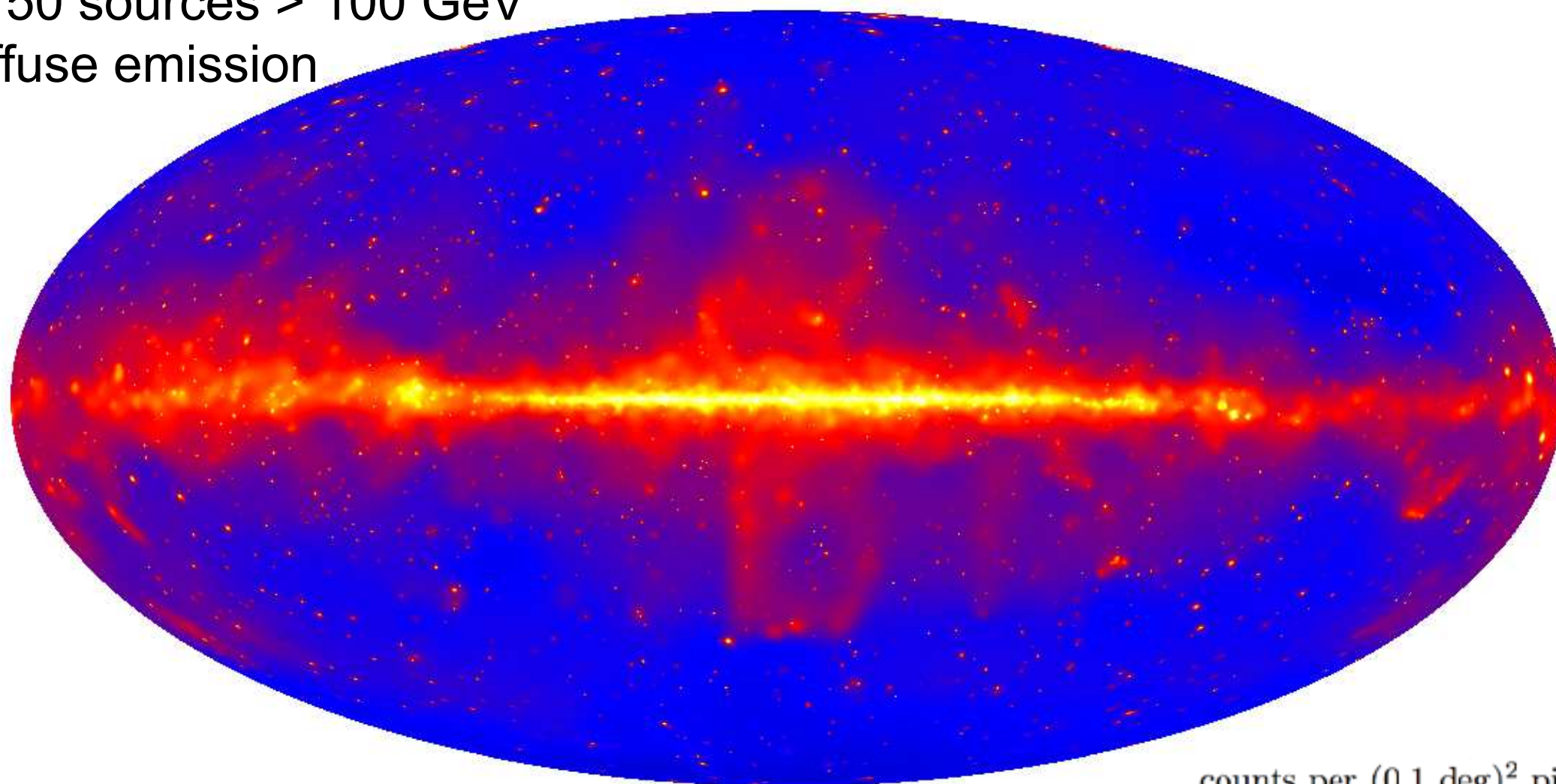
Gamma-rays from the Universe

Fermi LAT 7-years sky map (10 GeV - 2 TeV)

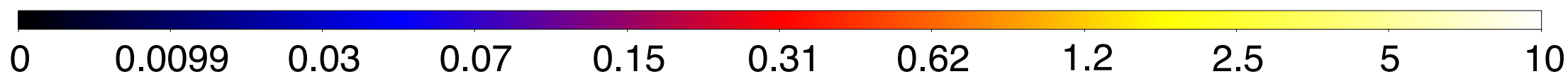
>1500 sources > 10 GeV

>150 sources > 100 GeV

diffuse emission



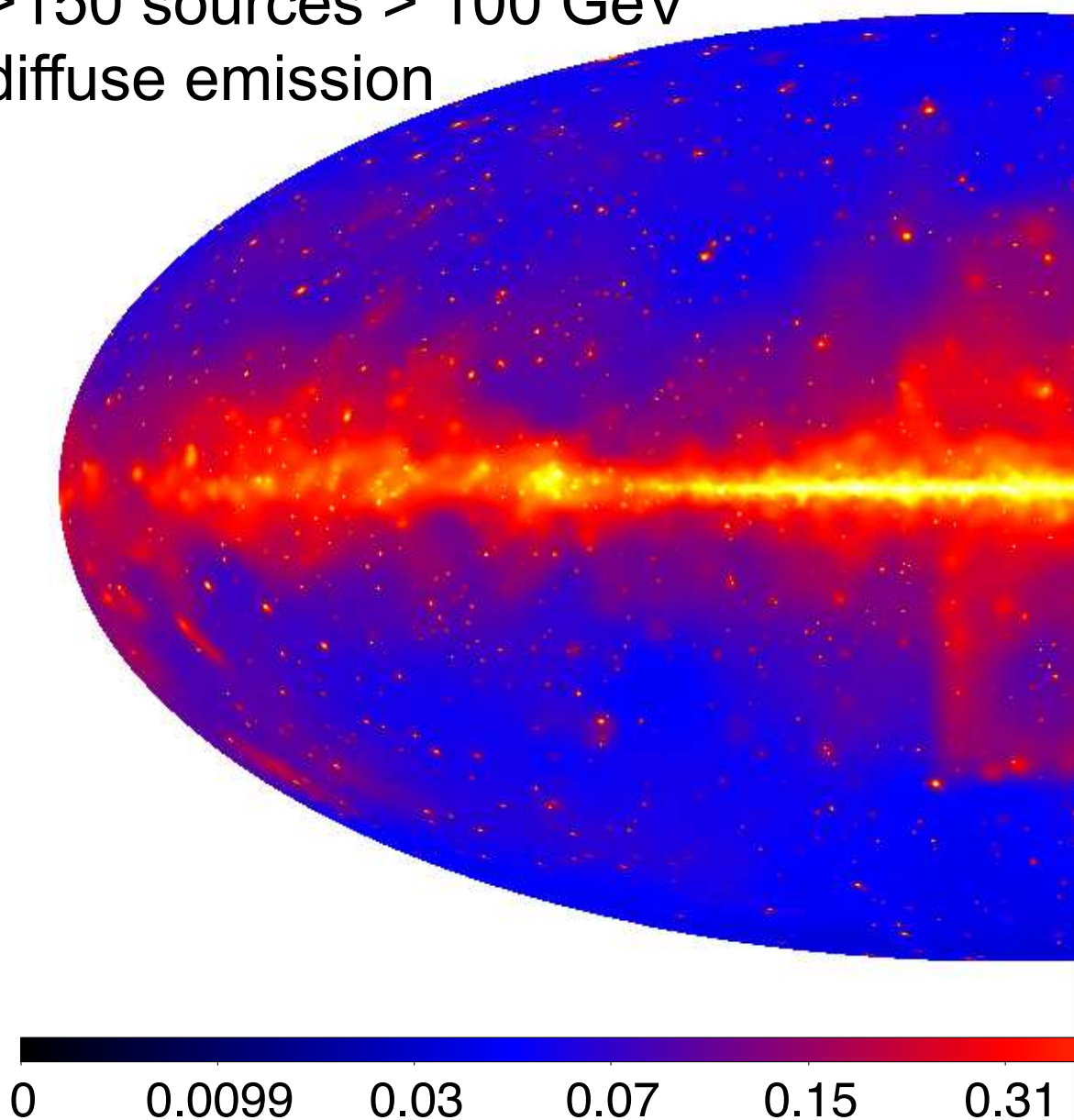
counts per $(0.1 \text{ deg})^2$ pixel



Gamma-rays from the Universe

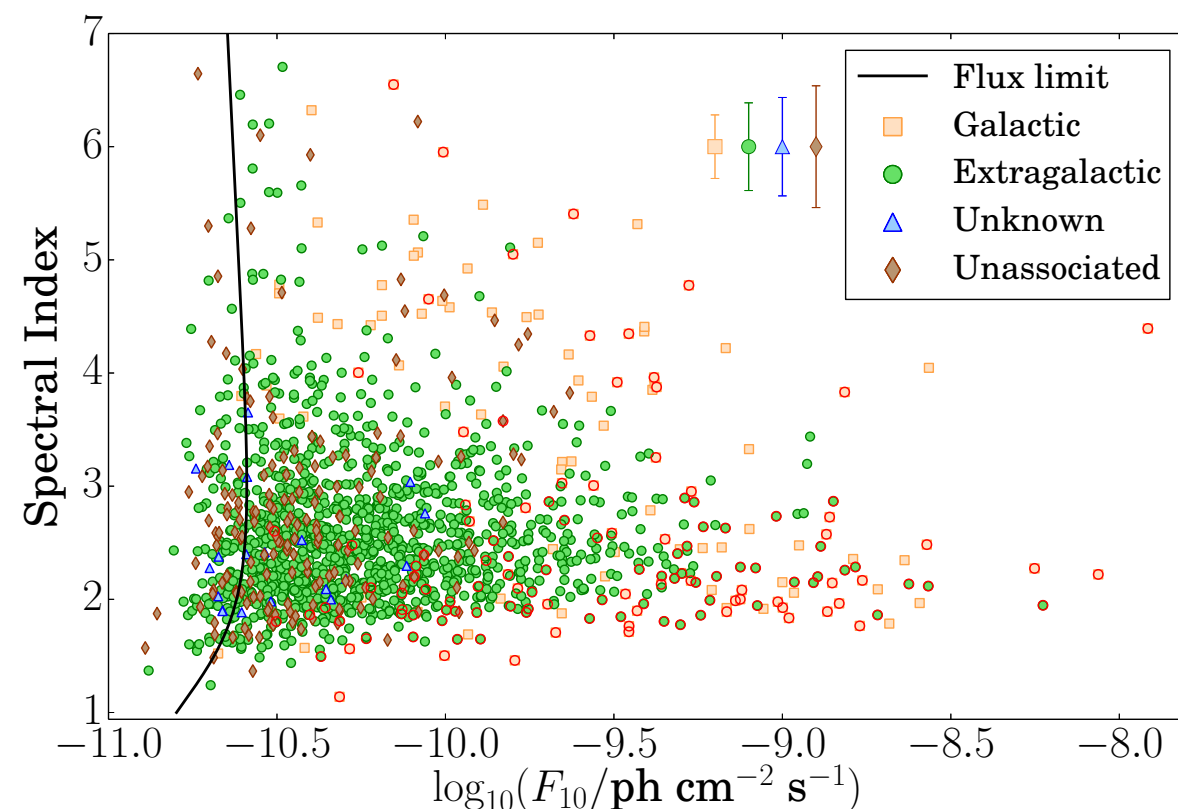
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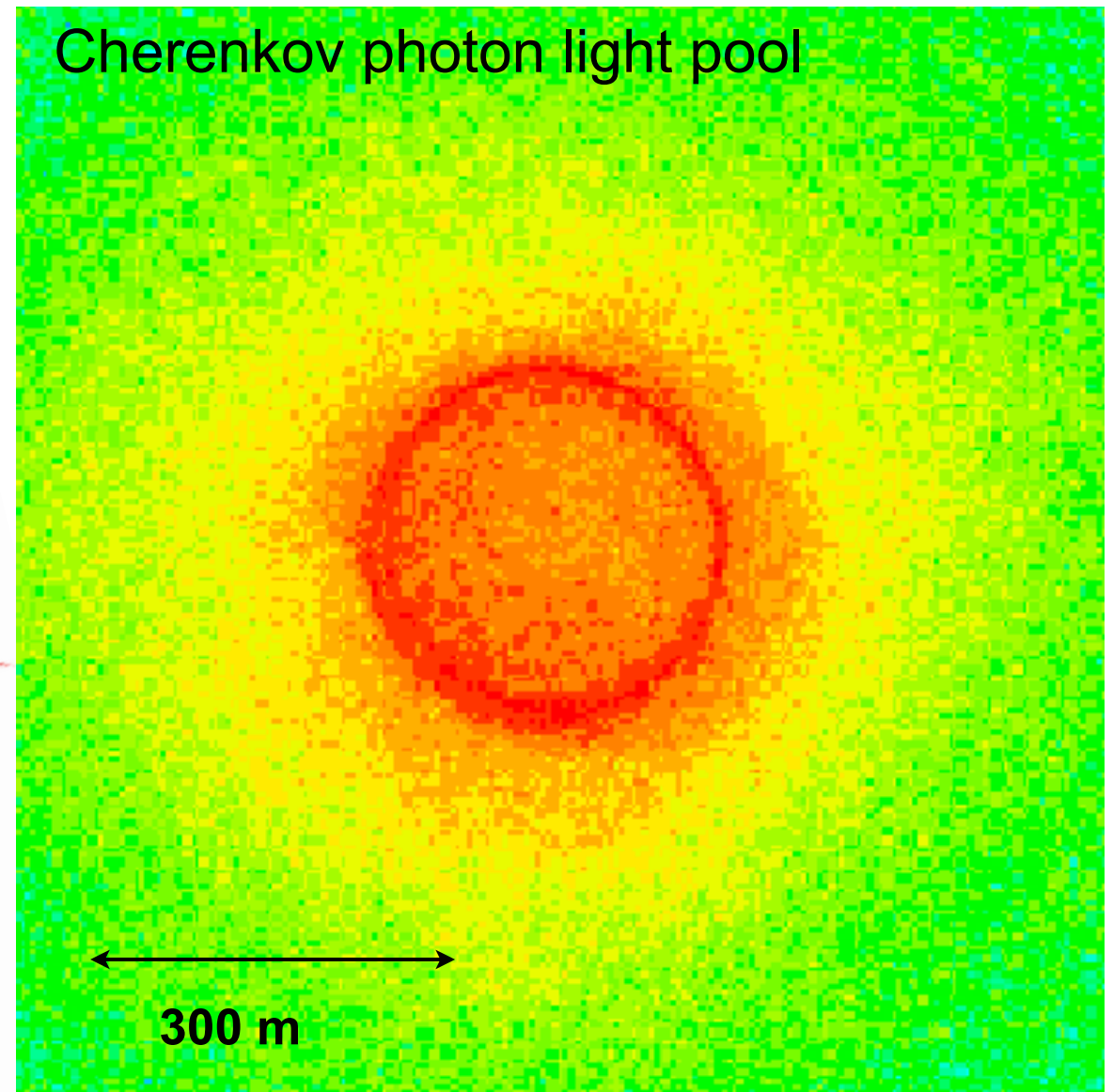
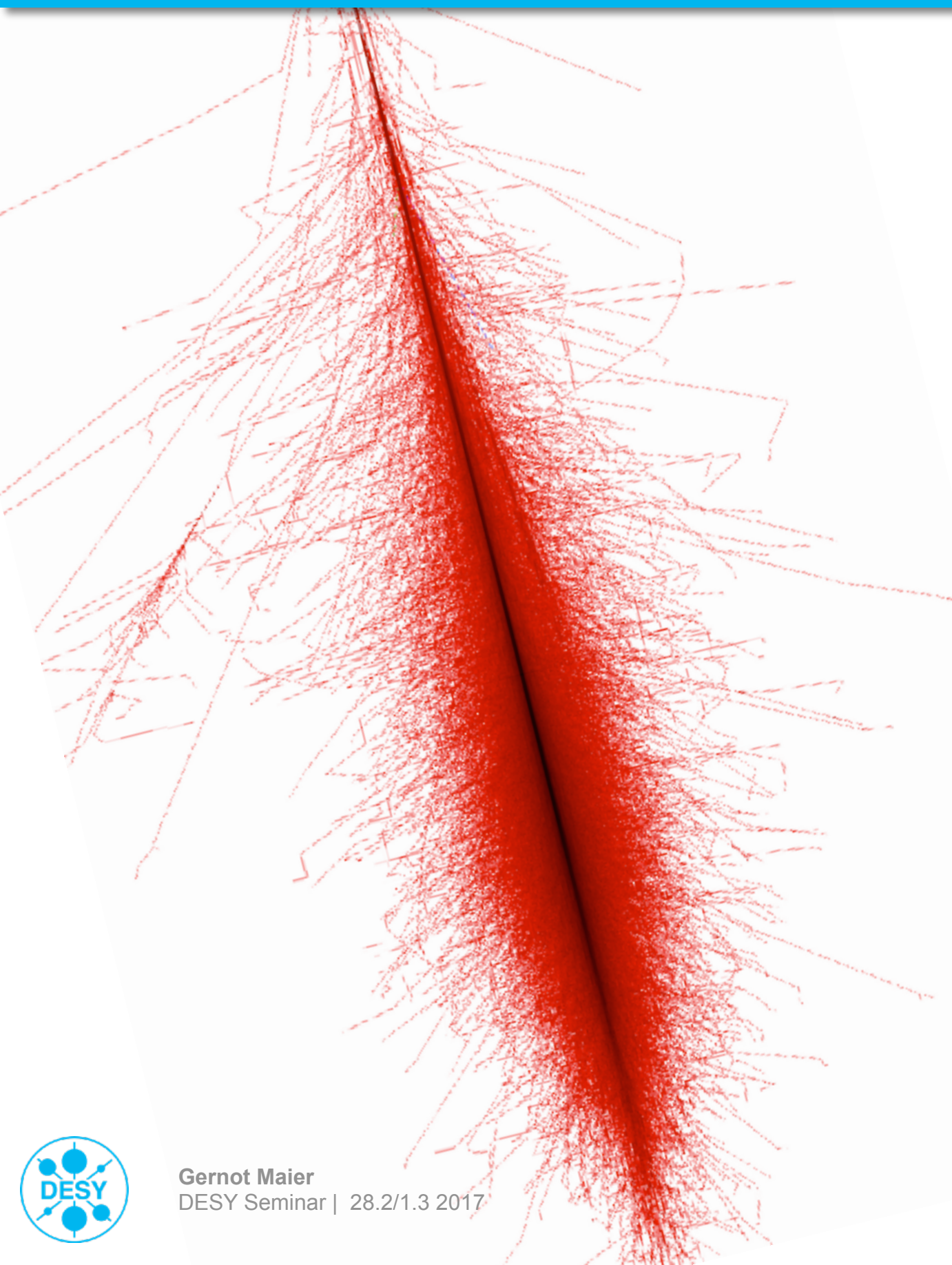


In general:

- weak sources (10^{-10} photons/cm²/s)
- spectra with power-law like shape

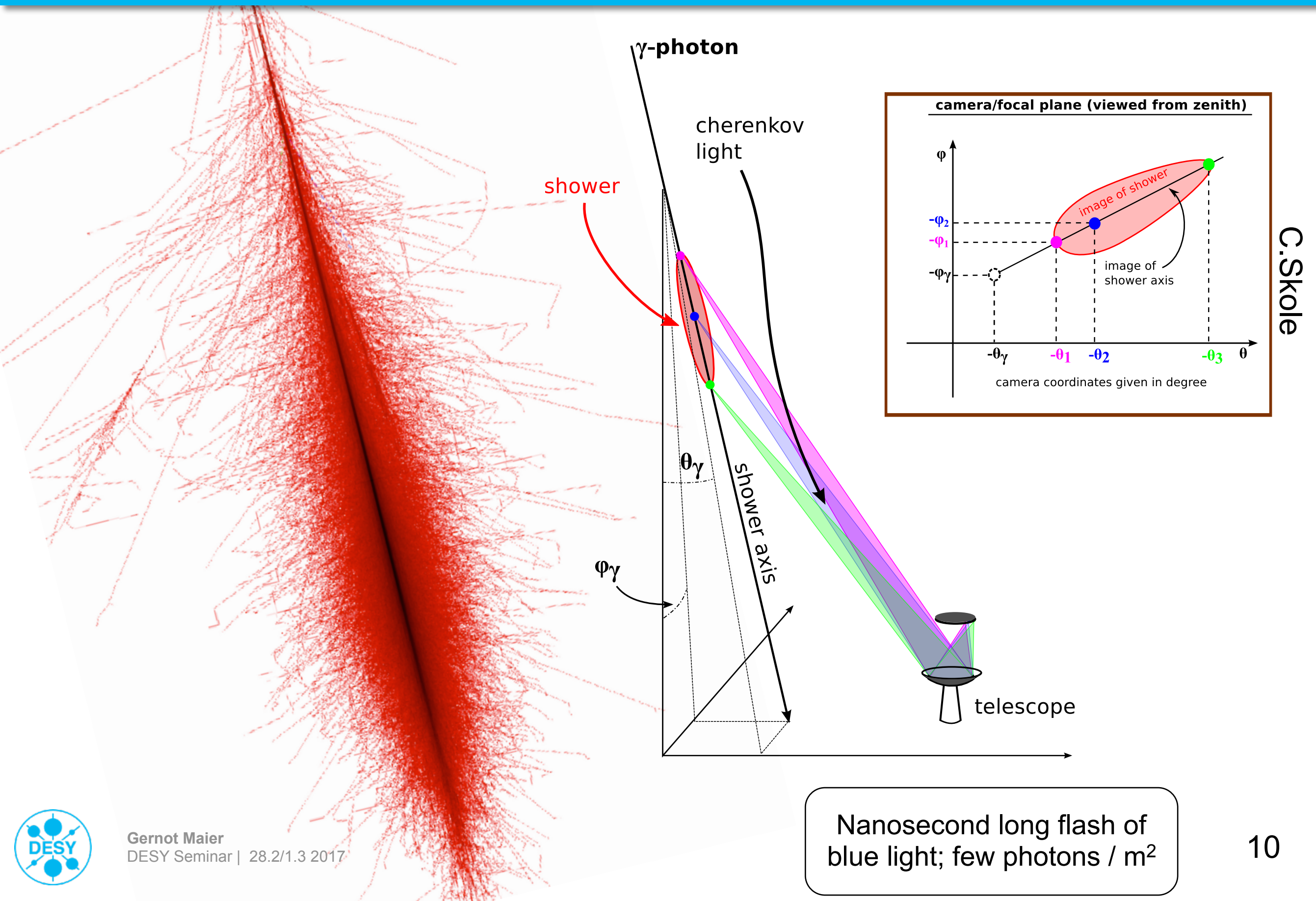


Measuring gamma-rays (20 GeV to 300 TeV)



Nanosecond long flash of
blue light; few photons / m²

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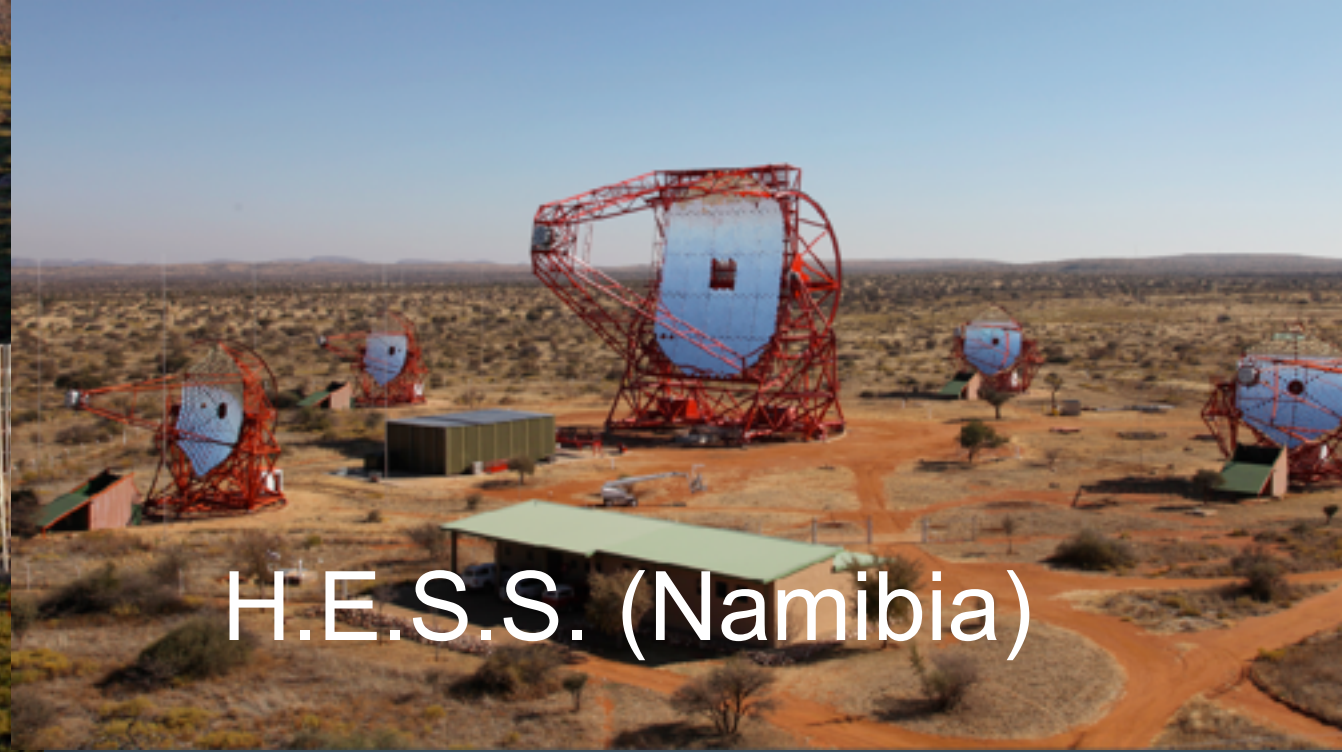
C.Skole

Nanosecond long flash of
blue light; few photons / m²

MAGIC (La Palma)



H.E.S.S. (Namibia)



VERITAS (Arizona)



Science drivers and requirements to the instrument

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> Probing Extreme Environments

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> Beyond the standard model

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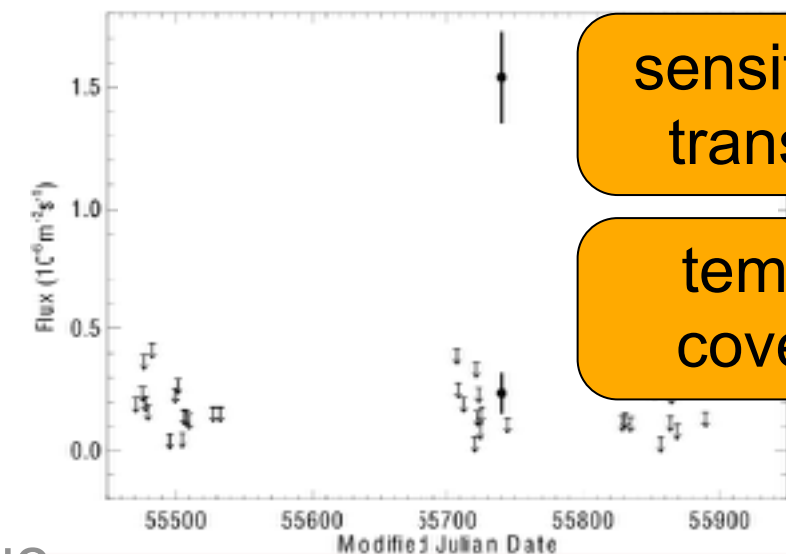
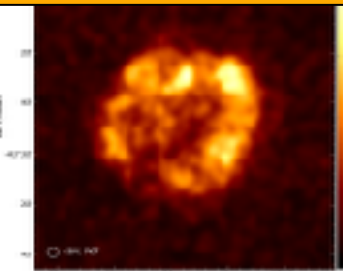
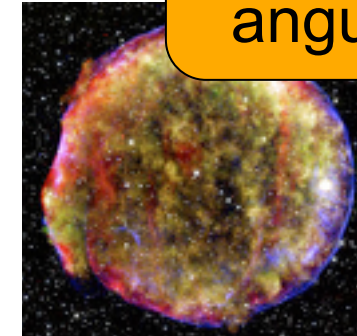
large field of view

all sky coverage

flux sensitivity

energy range

angular resolution



sensitivity to transients

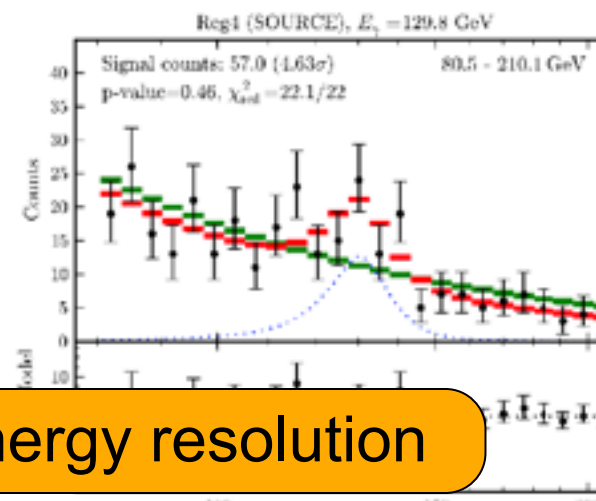
temporal coverage

rapid slewing

duty cycle

flexibility in operation

energy resolution

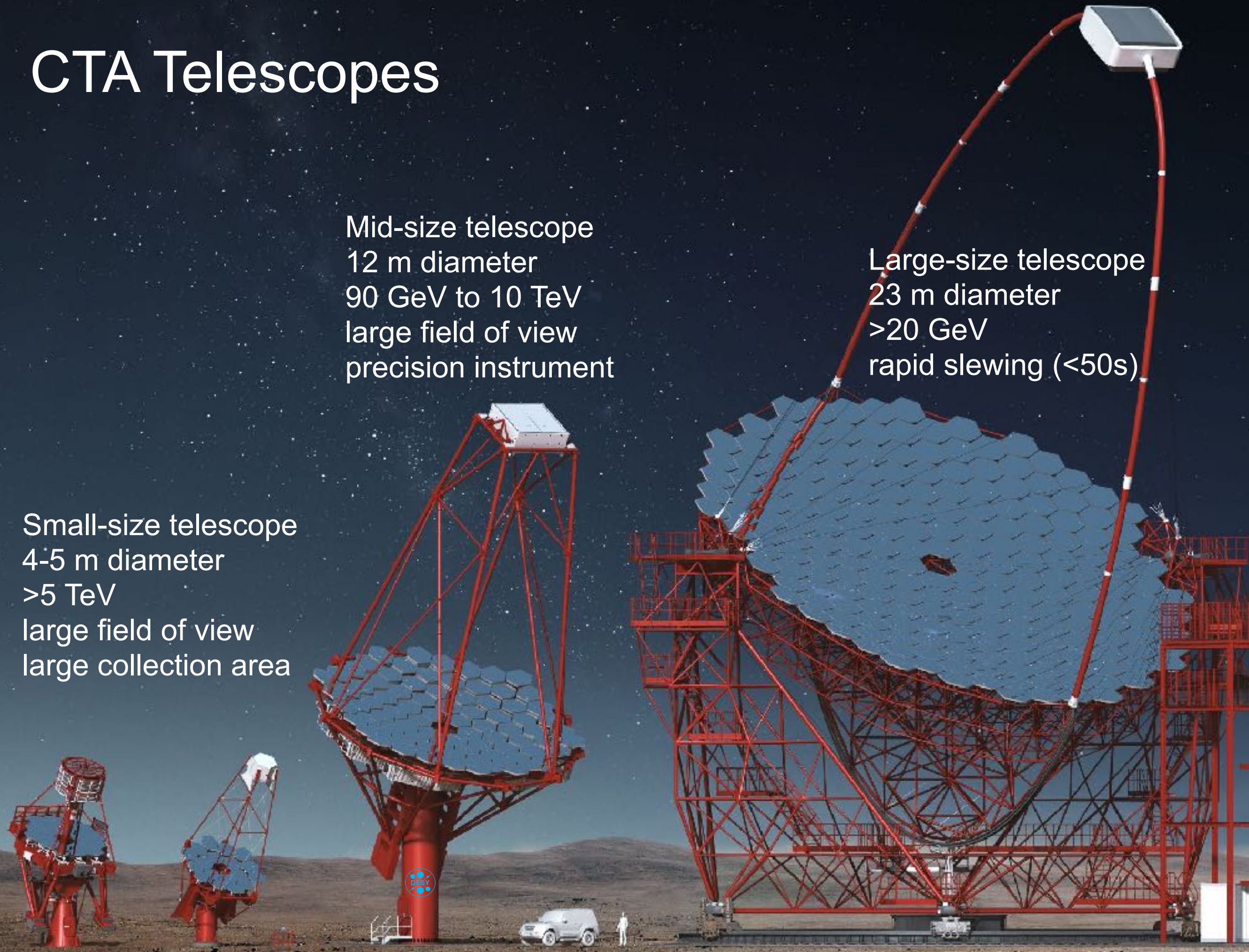


CTA Telescopes

Mid-size telescope
12 m diameter
90 GeV to 10 TeV
large field of view
precision instrument

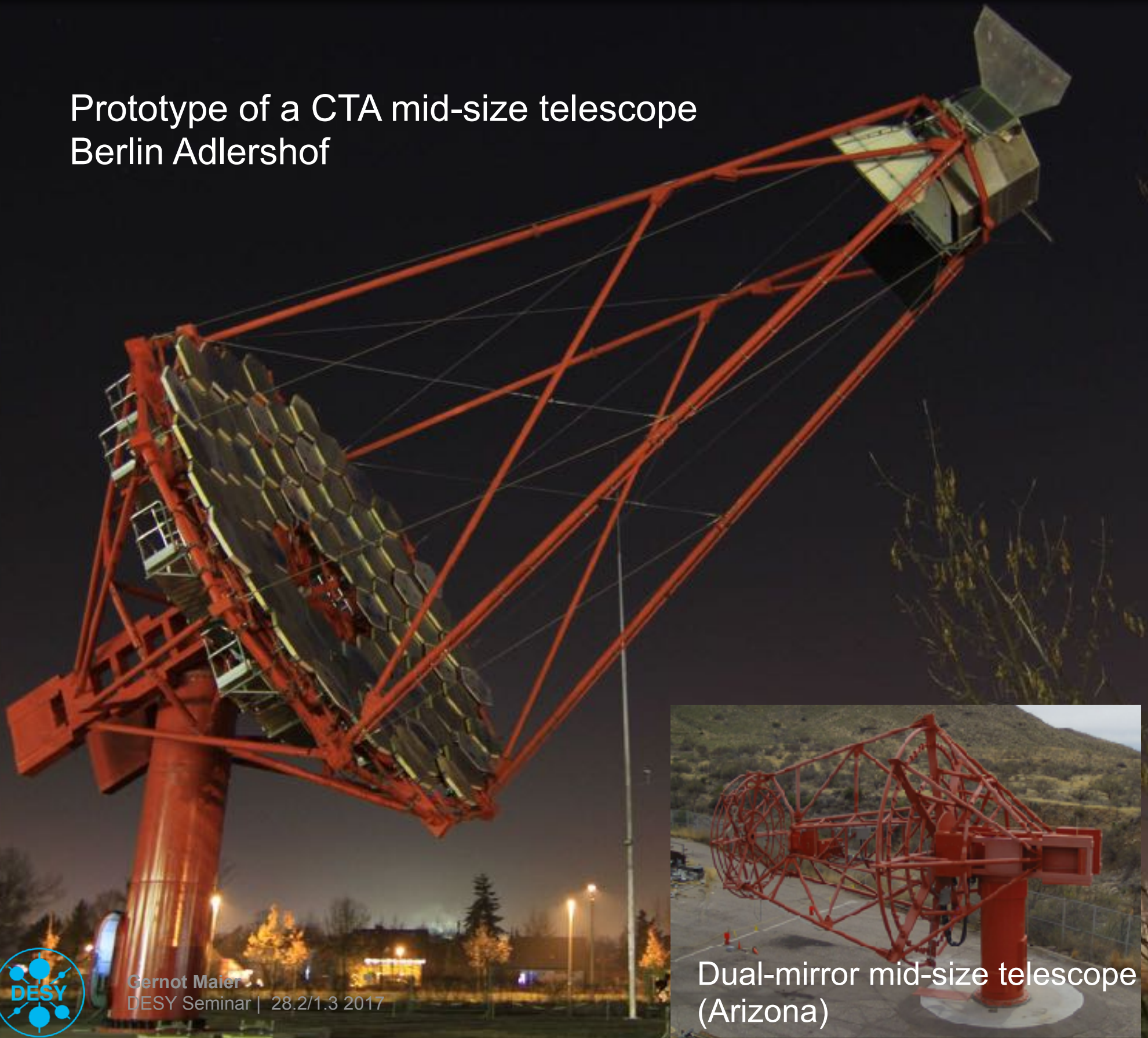
Large-size telescope
23 m diameter
>20 GeV
rapid slewing (<50s)

Small-size telescope
4-5 m diameter
>5 TeV
large field of view
large collection area



Prototypes

Prototype of a CTA mid-size telescope
Berlin Adlershof



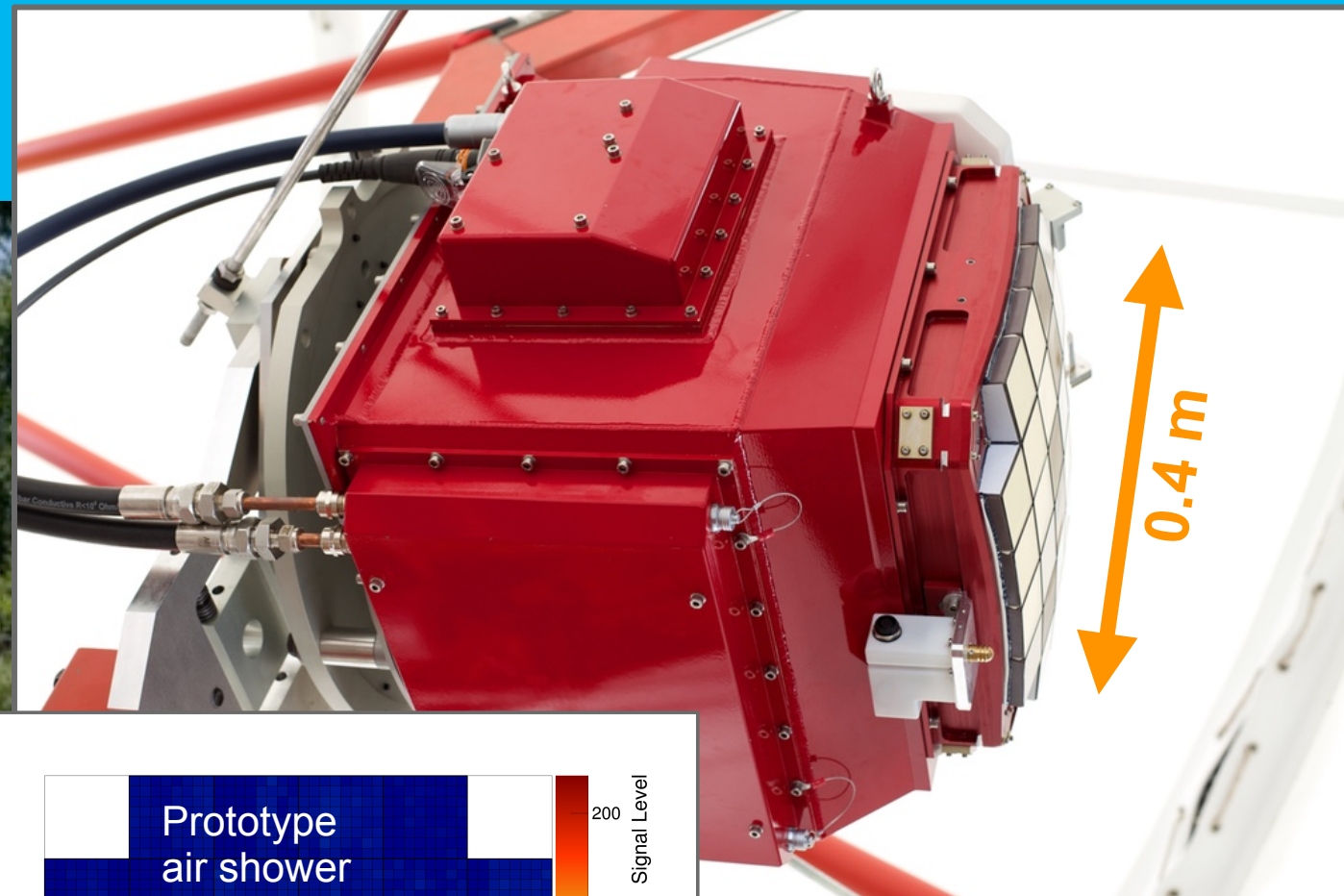
Dual-mirror mid-size telescope
(Arizona)



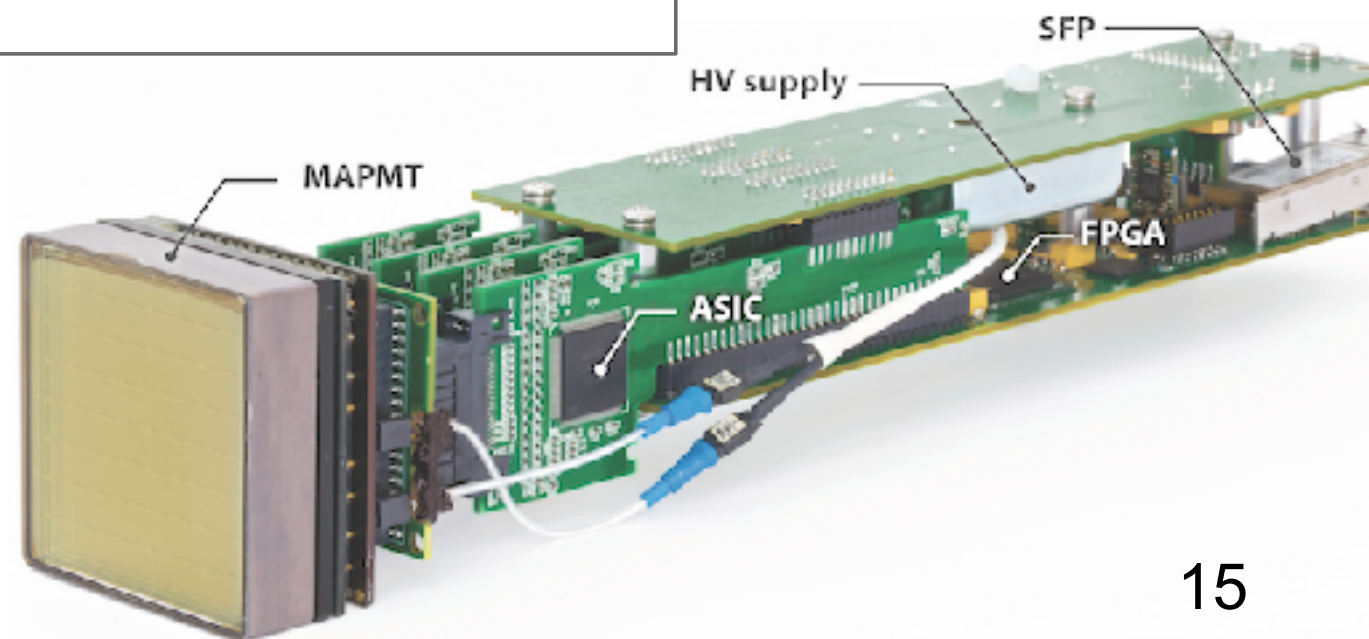
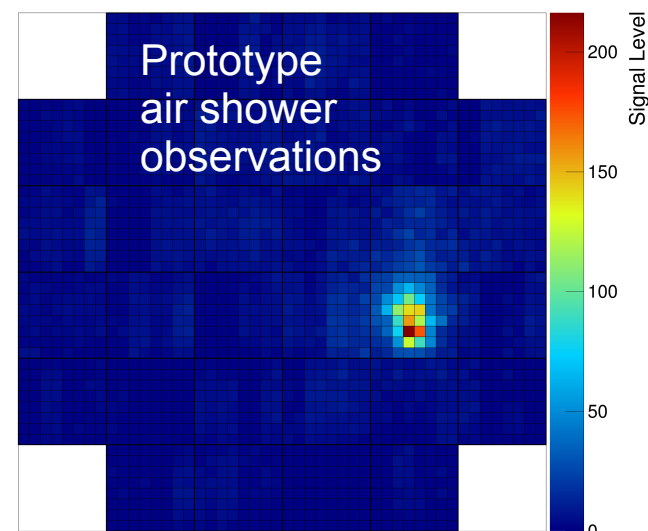
Prototype Cameras



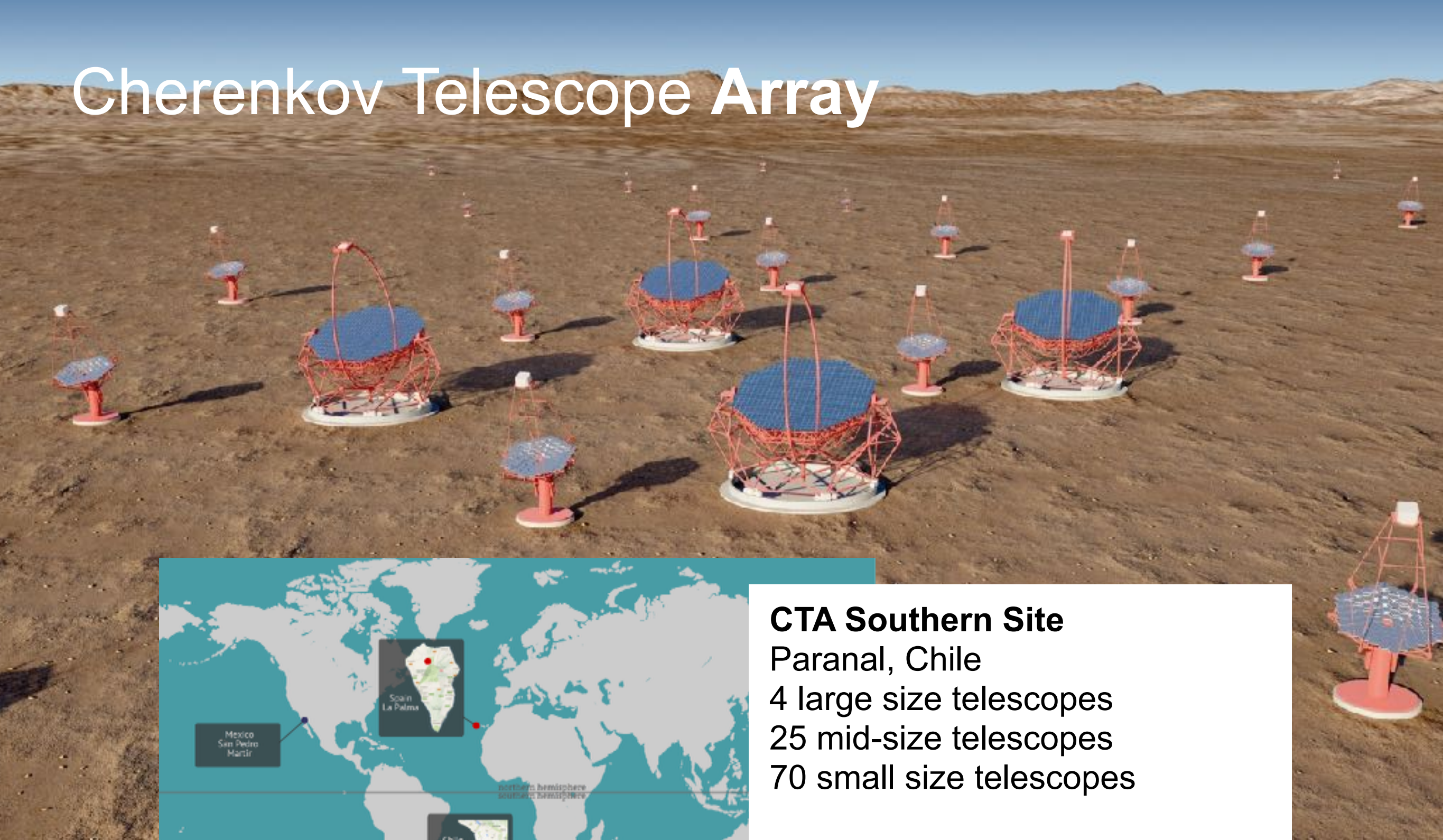
FlashCam camera for
mid-size telescopes



MAPM Camera
small-size telescope



Cherenkov Telescope Array



CTA Southern Site

Paranal, Chile

4 large size telescopes

25 mid-size telescopes

70 small size telescopes

CTA Northern Site

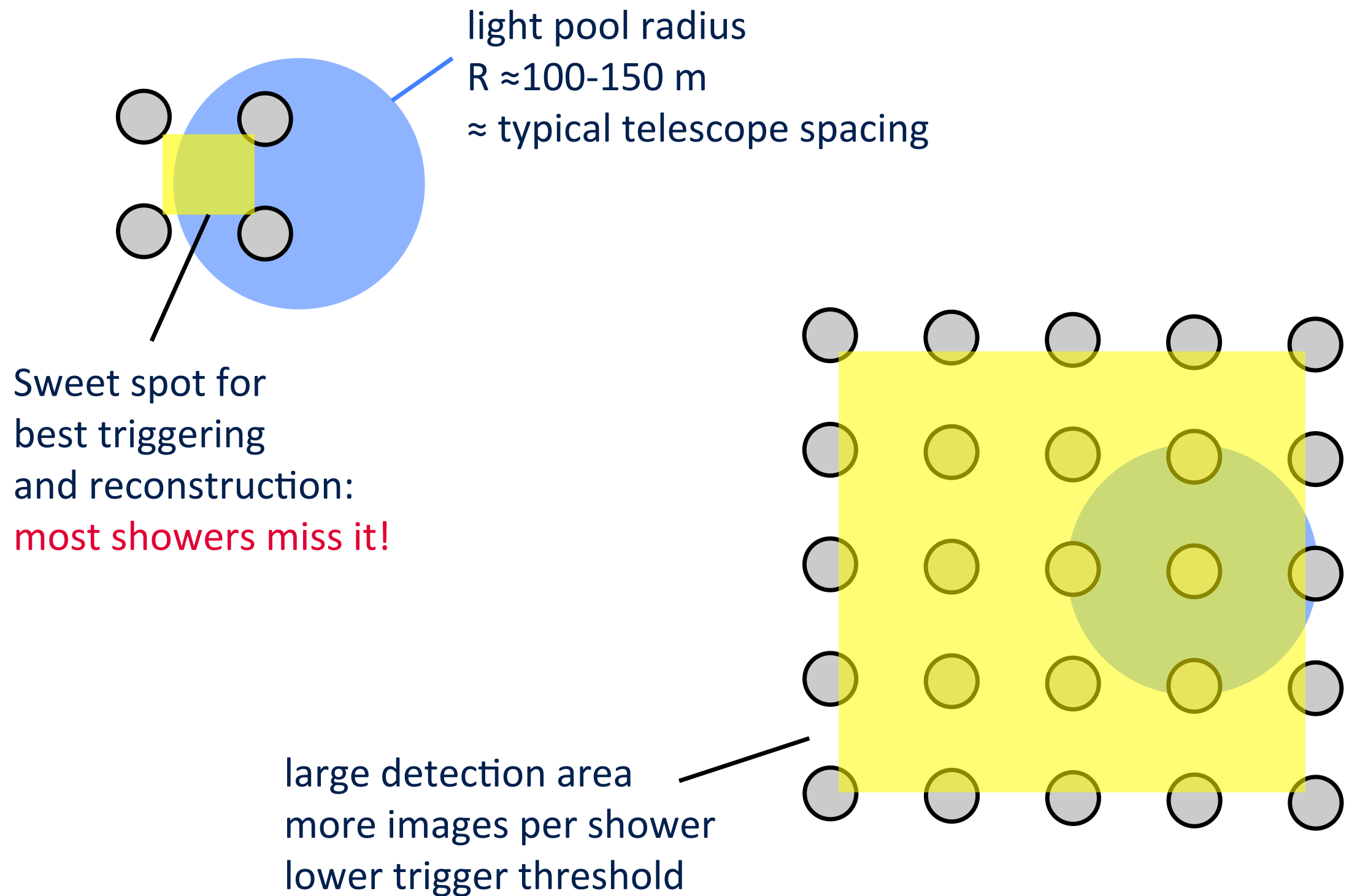
La Palma Island

4 large-size telescopes

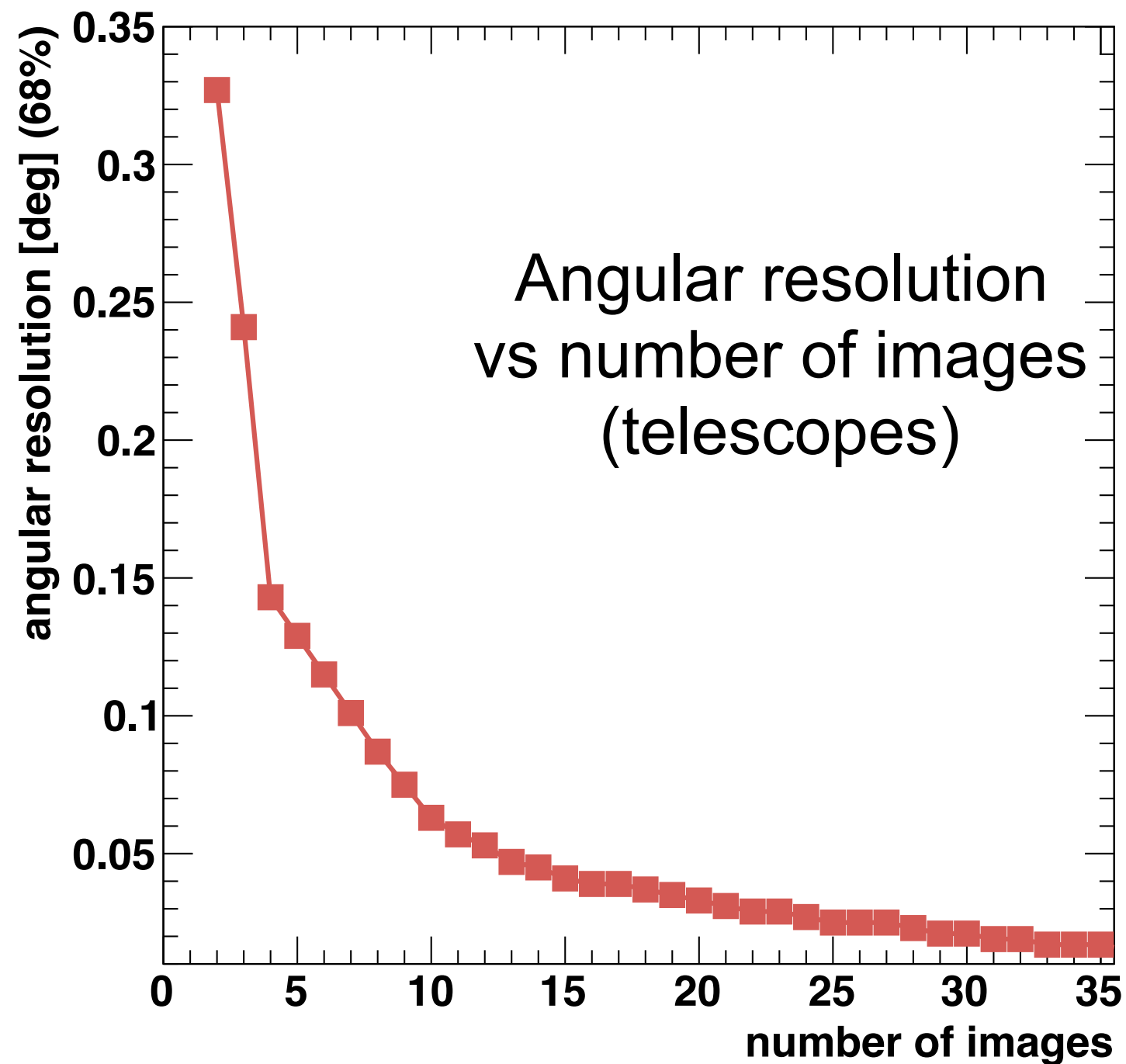
15 mid-size telescopes



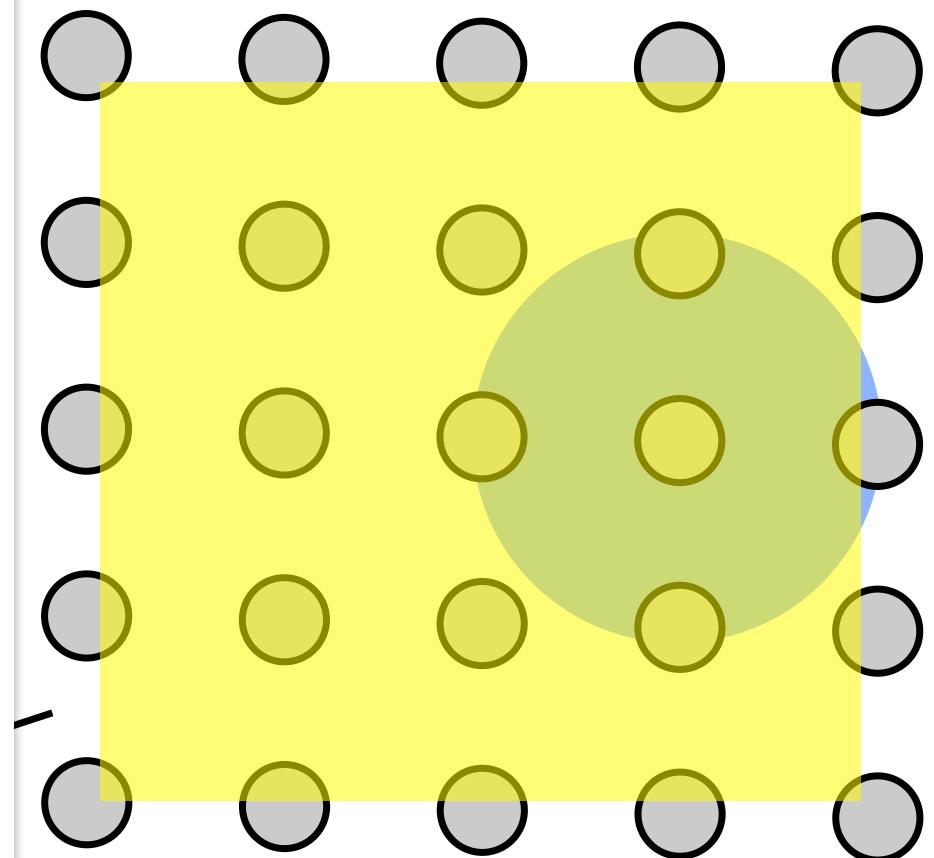
Large arrays of Cherenkov Telescopes



Large arrays of Cherenkov Telescopes



spacing



CTA SCHEDULING



Monitoring
4 telescopes



PeV Deep Field
using SSTs



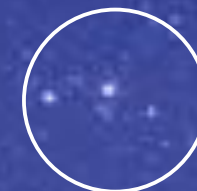
GeV observations
using LSTs



TeV
survey
using
MSTs



Large zenith angle
observations from
other hemisphere



Monitoring
1 telescope

CTA Site Paranal



Cerro Armazones
E-ELT



~~Proposed~~ Site for the
Cherenkov Telescope Array

Cerro Paranal
Very Large Telescope

CTA Site La Palma

Roque de los Muchachos Observatory, La Palma, Spain

Foundation of first
large-size telescope



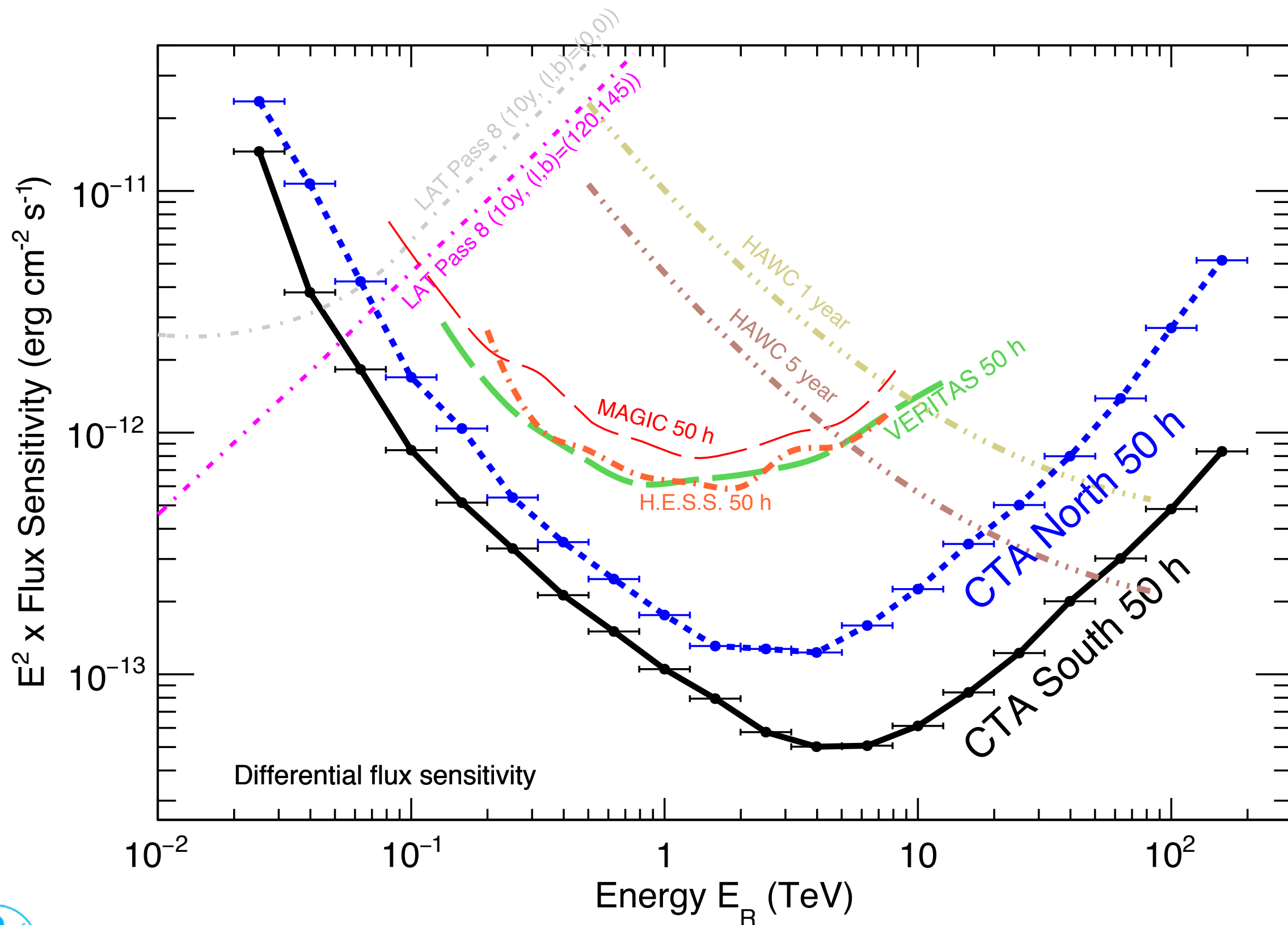
residencia

CTA-North site

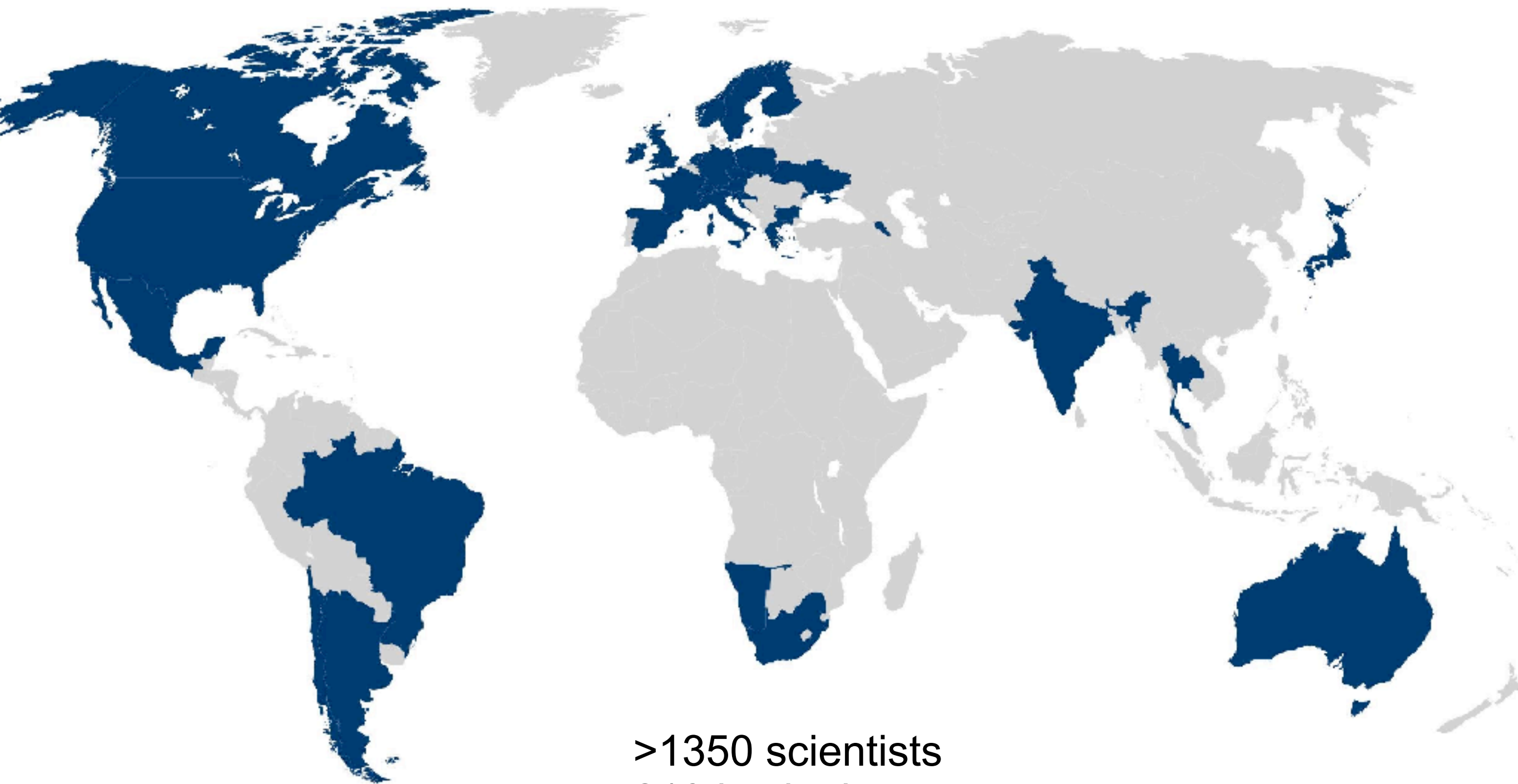
@Daniel Mazin

CTA Performance

10^6 m^2 effective area
close to arcmin angular resolution
less than 10% energy resolution



The CTA consortium



>1350 scientists
210 institutions
32 countries



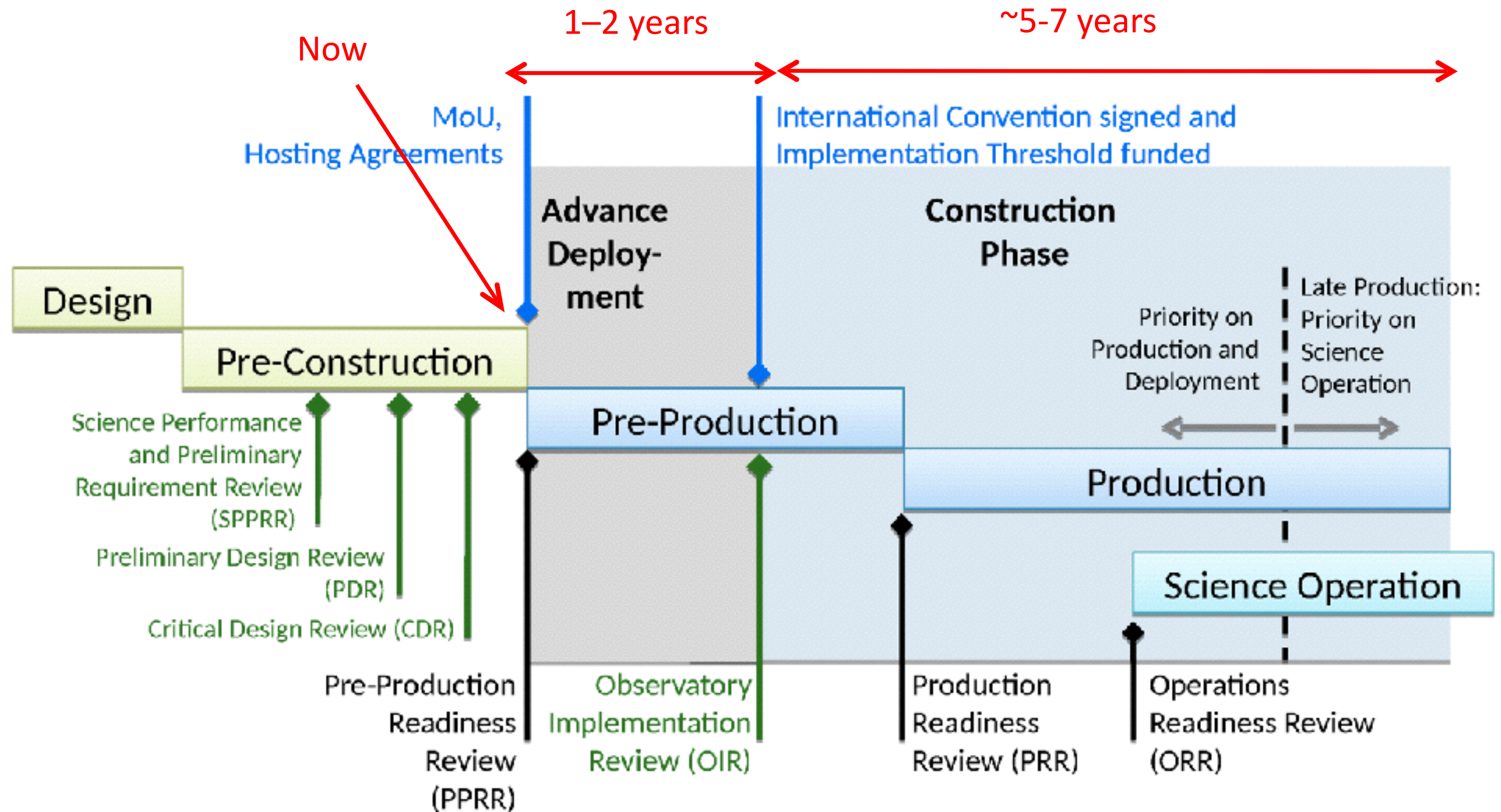
CTA Science Data Management Centre - DESY

Headquarters (CTA operation) in Bologna



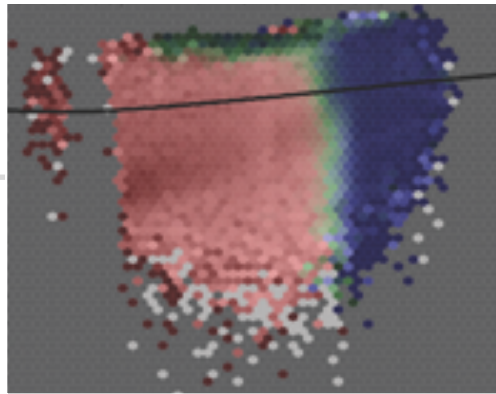
CTA Timeline

Release of official CTA Integrated Project Schedule in summer 2017

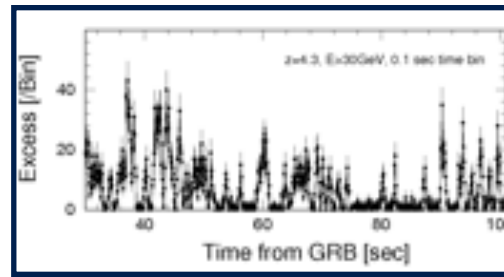


OIR is a global external gateway review

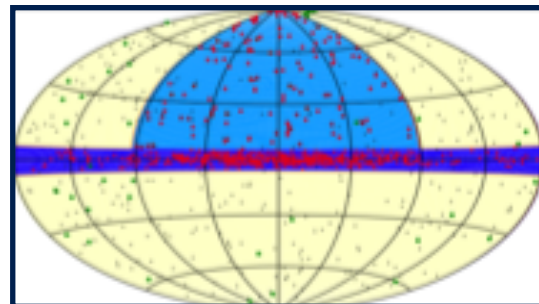
CTA Key Science Projects



Dark Matter Programme

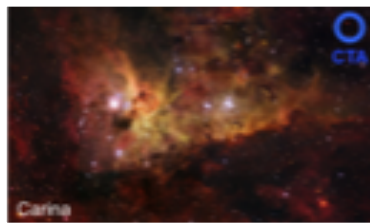
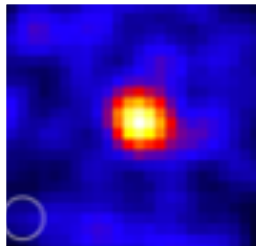


Transients



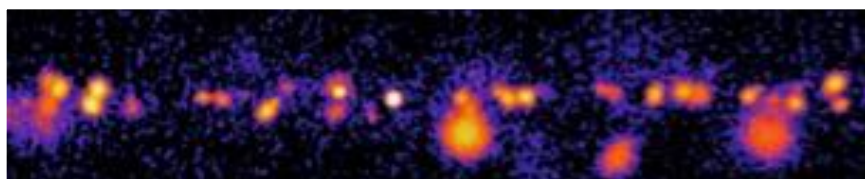
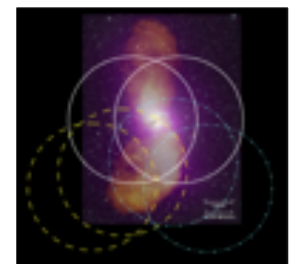
ExGal Survey

Galaxy Clusters



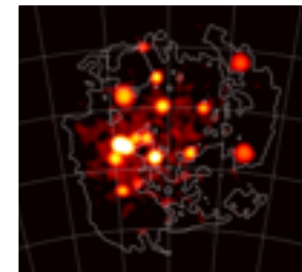
Star Forming Systems

AGN



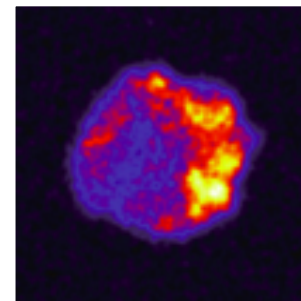
Galactic Plane Survey

LMC Survey

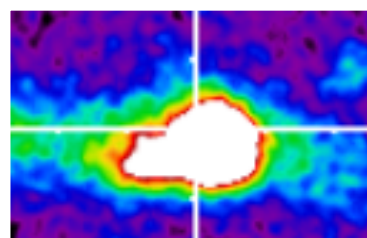


Galactic

PeVatrons



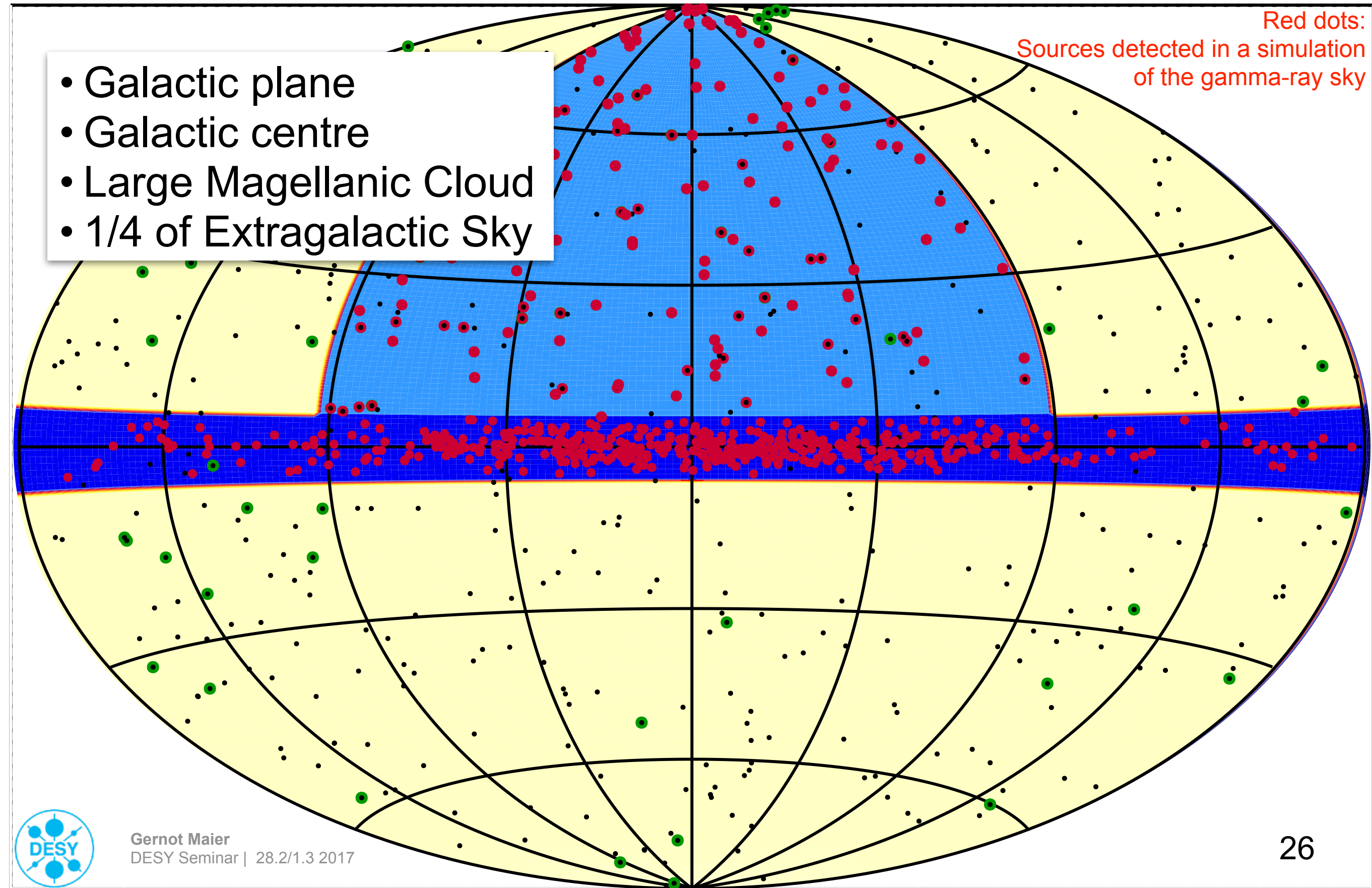
Galactic Centre



CTA Surveys - an unbiased census of particle acceleration

- Galactic plane
- Galactic centre
- Large Magellanic Cloud
- 1/4 of Extragalactic Sky

Red dots:
Sources detected in a simulation
of the gamma-ray sky



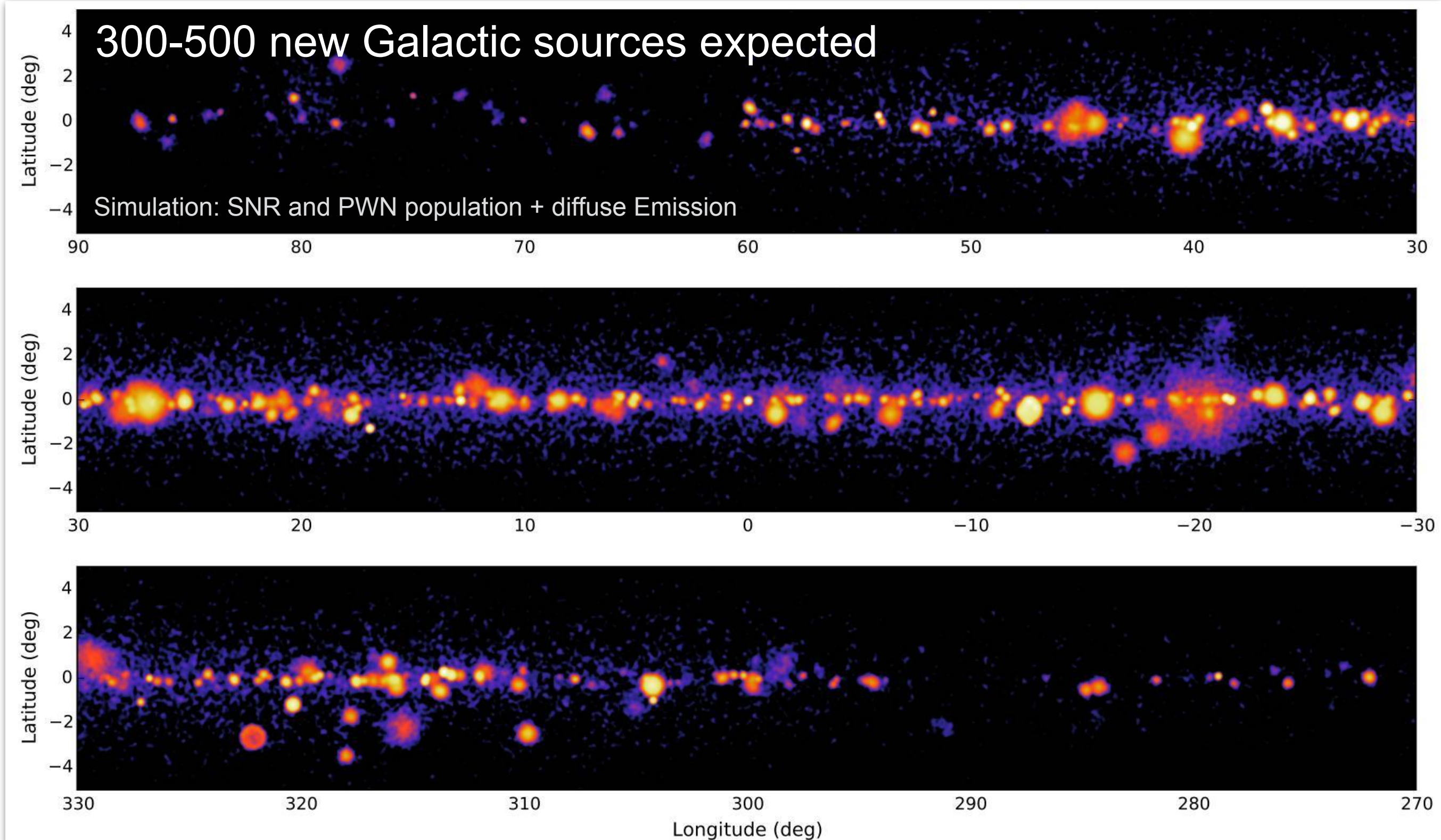
CTA Surveys - an unbiased census of particle acceleration

- Galactic plane
- Galactic centre
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Red dots:
Sources detected in a simulation
of the gamma-ray sky

- large-scale data sets
- systematic and complete census of objects
- galactic diffuse emission
- identification of list of promising objects
- discovery of the unexpected and new phenomena

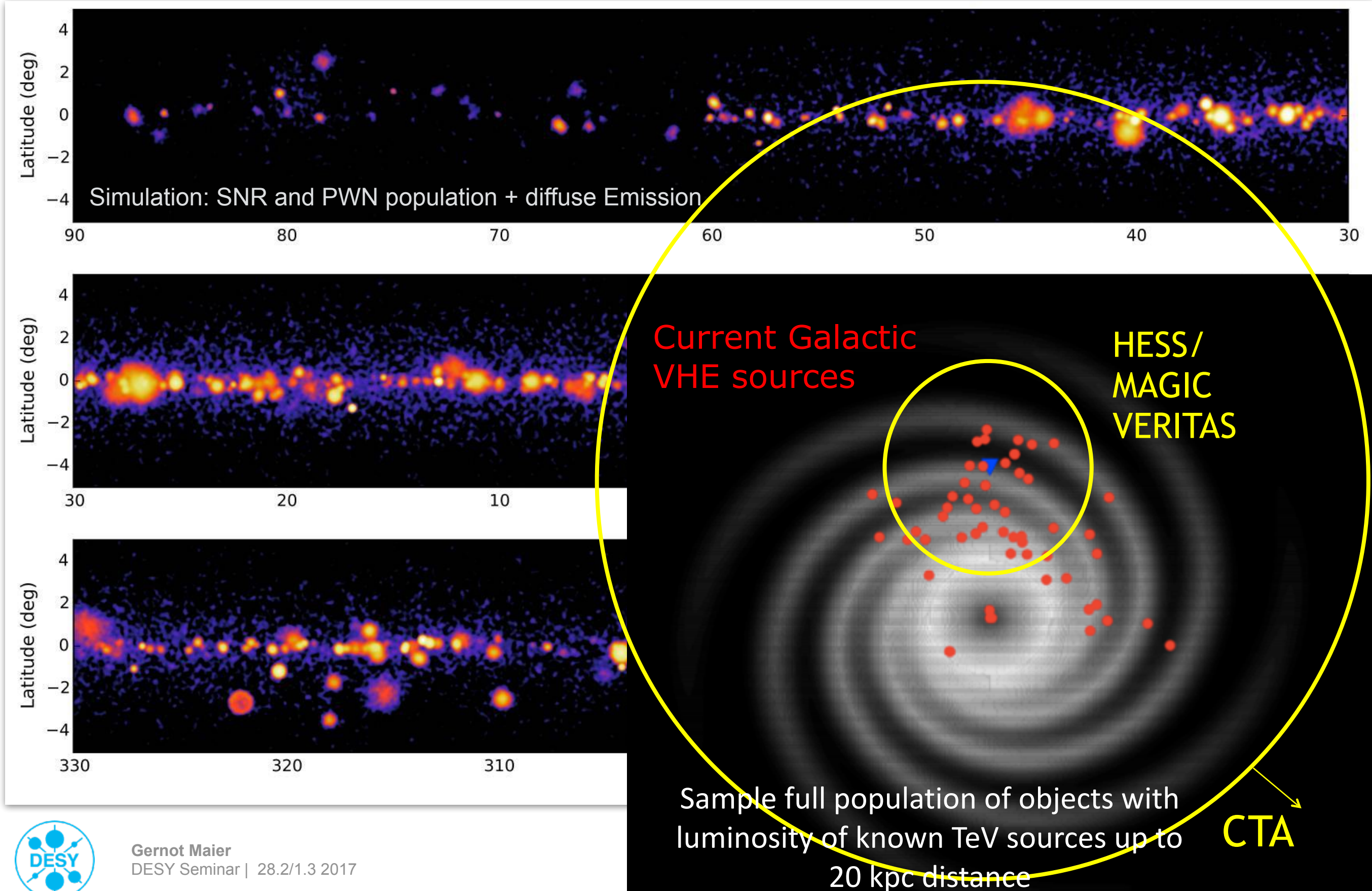
Deep Survey of the Galactic Plane



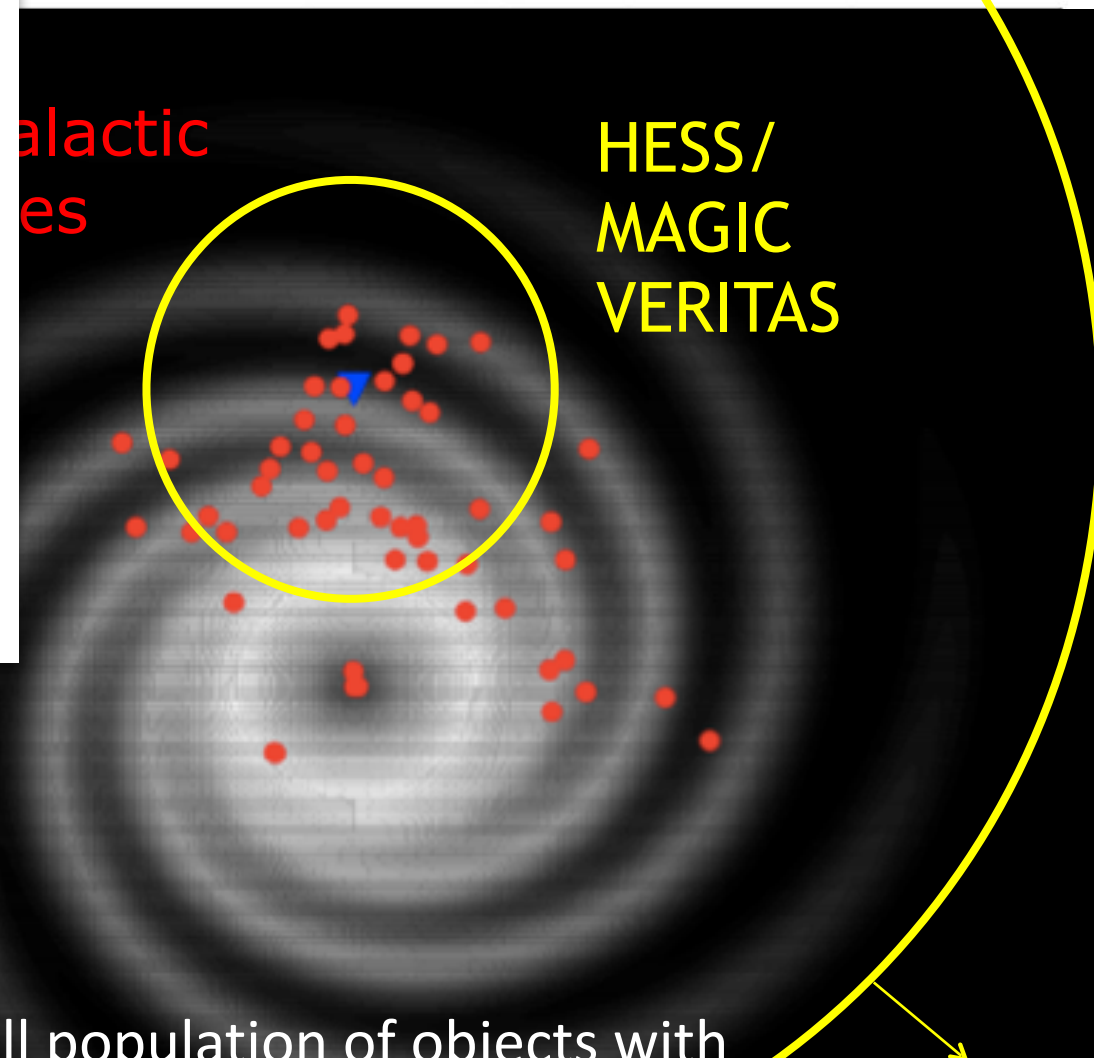
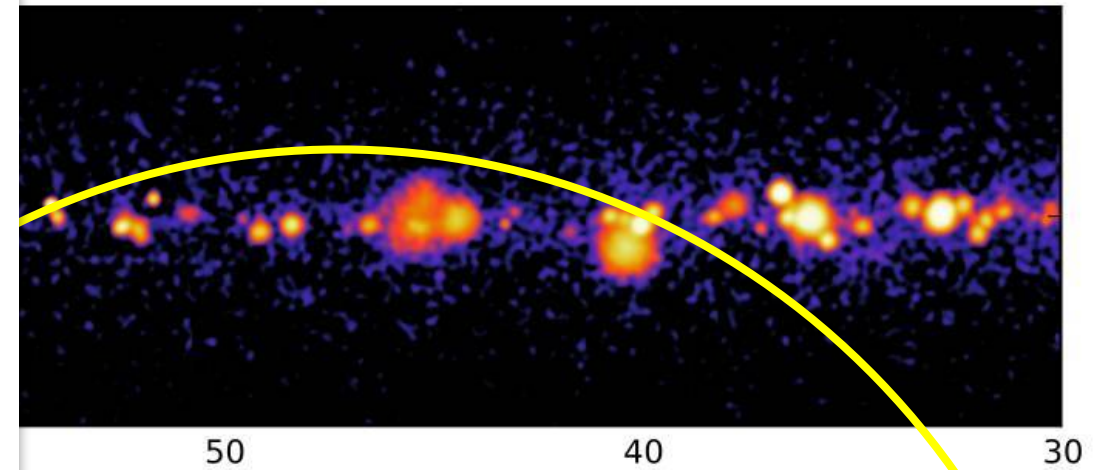
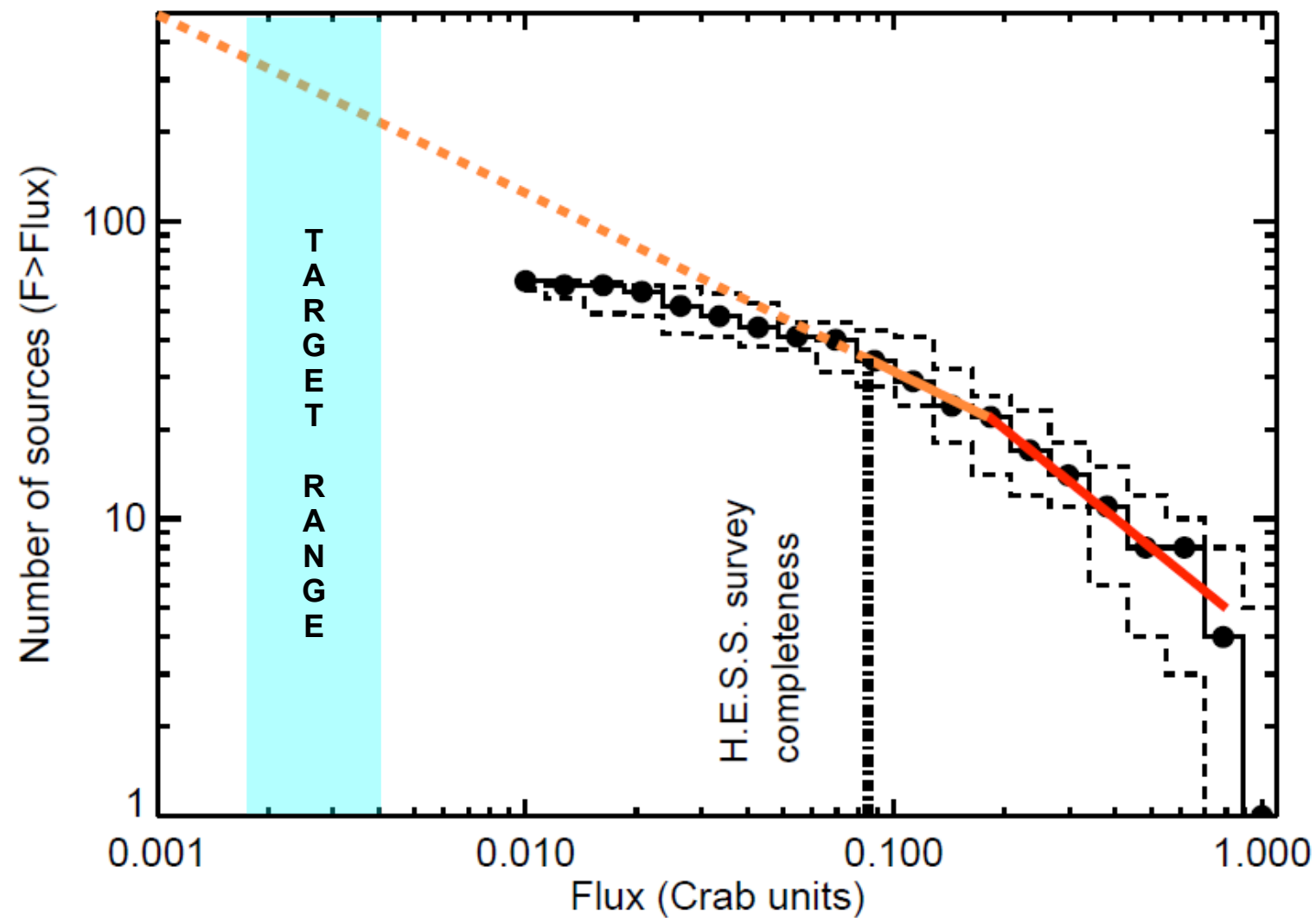
confusion limited!

Progress possible only due to the excellent
angular resolution of CTA

Deep Survey of the Galactic Plane



Deep Survey of the Galactic Plane



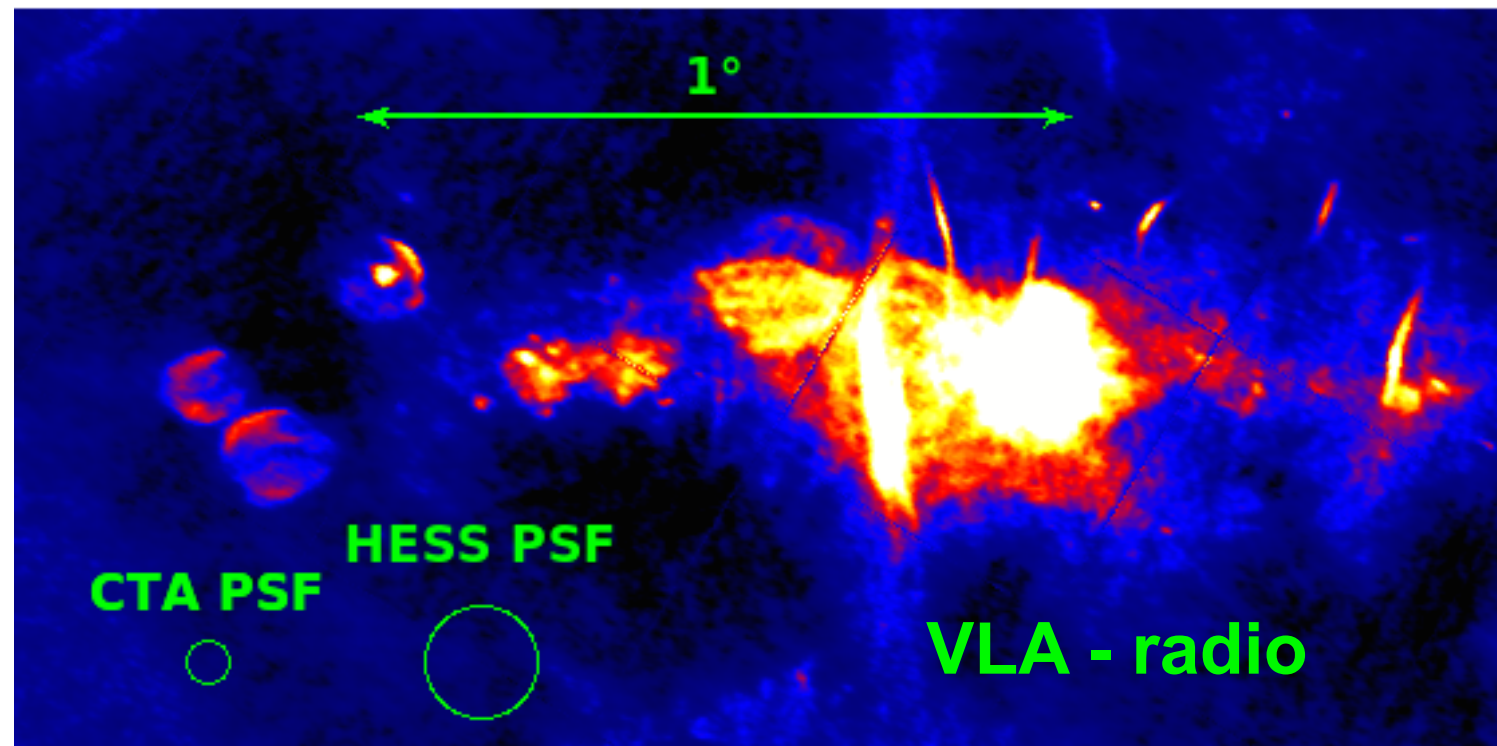
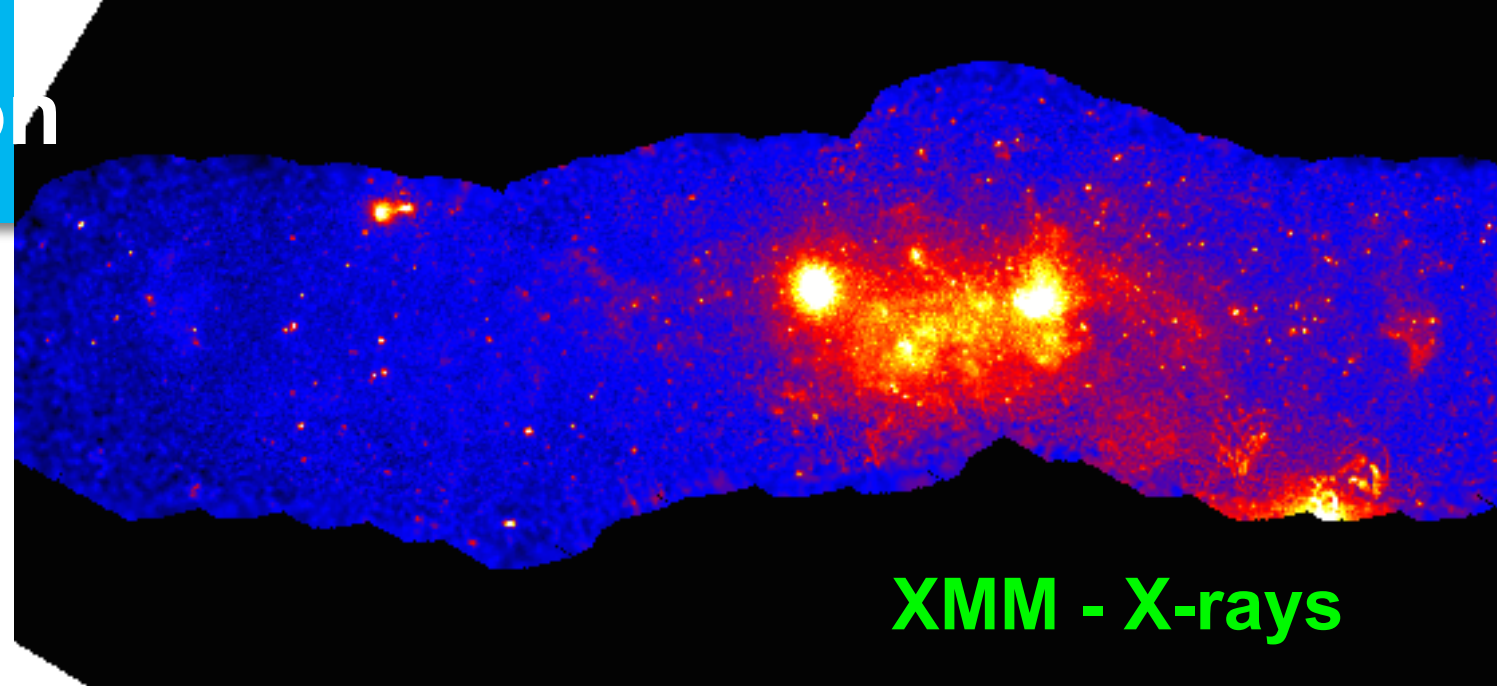
Sample full population of objects with
luminosity of known TeV sources up to
20 kpc distance

CTA

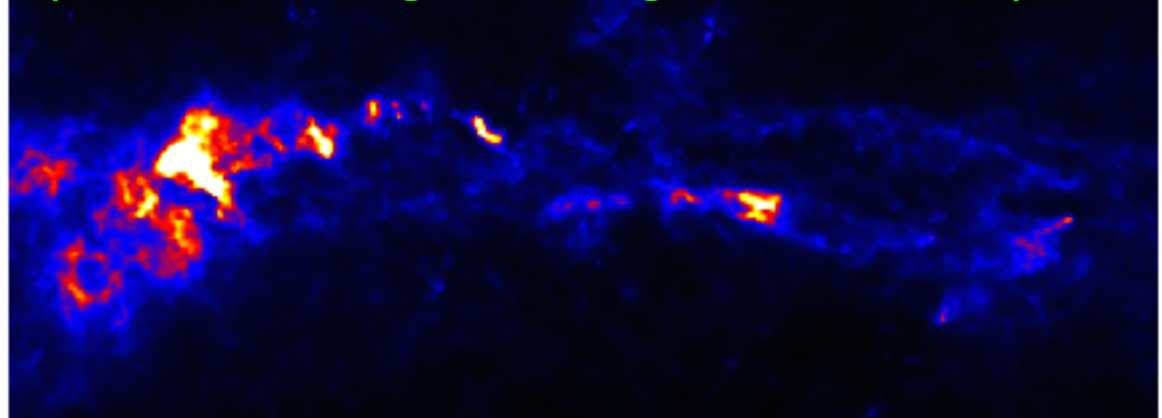


The Galactic Centre Region

- > closest supermassive black hole ($4 \times 10^6 M_{\odot}$)
 - low-luminosity active galactic nuclei
- > strong star-forming activity (10% of the activity of the whole Galaxy)
- > multiple supernova remnants and pulsar wind nebula
- > dense molecular clouds
- > large-scale outflows (Fermi bubbles)
- > largest dark matter line-of-sight density



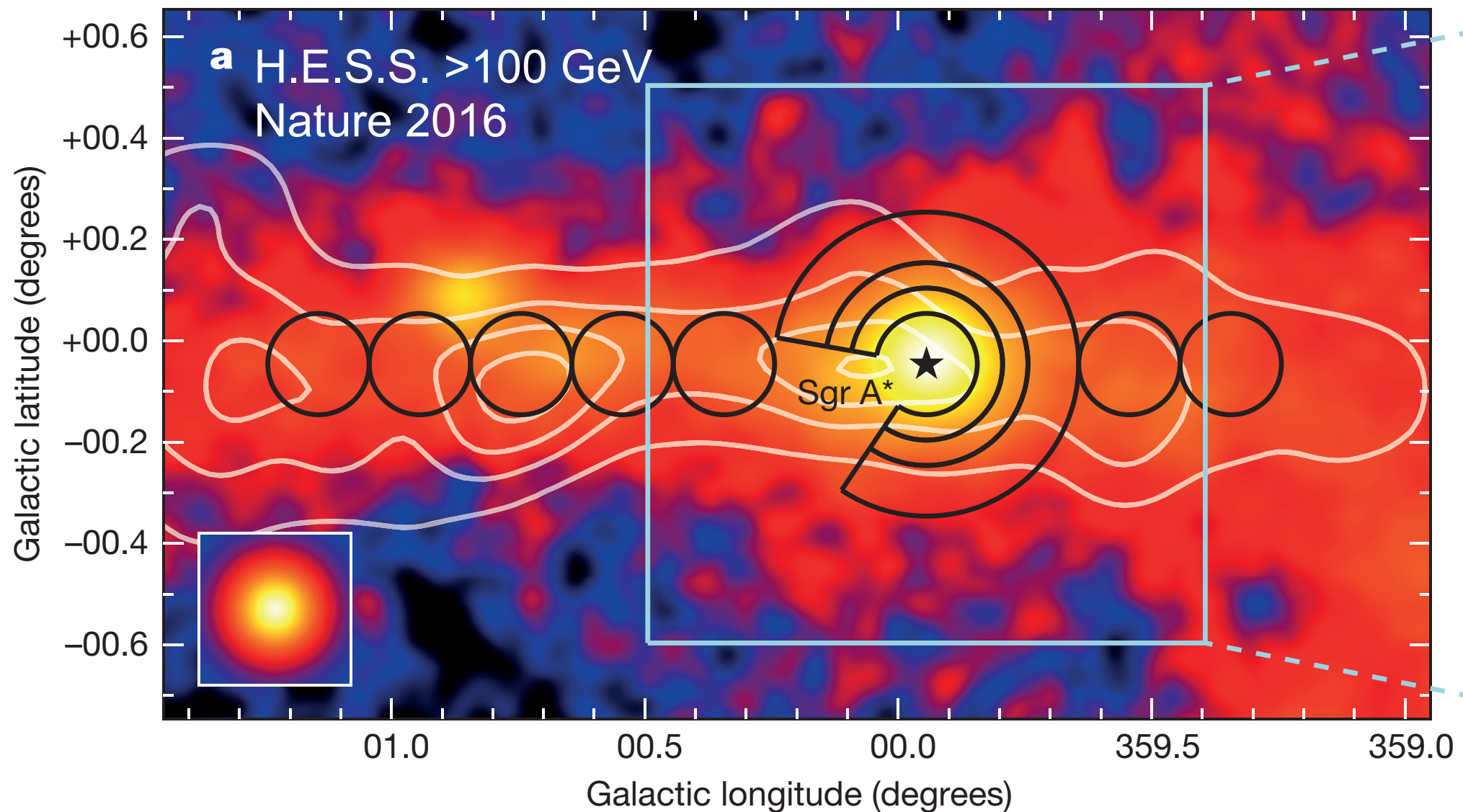
Herschel - infrared
(molecular gas, target material)



The Galactic Centre Region

- > close hole
- low-
- > strong (10% whole)
- > multi and
- > dense
- > large (Fermi)
- > large sight

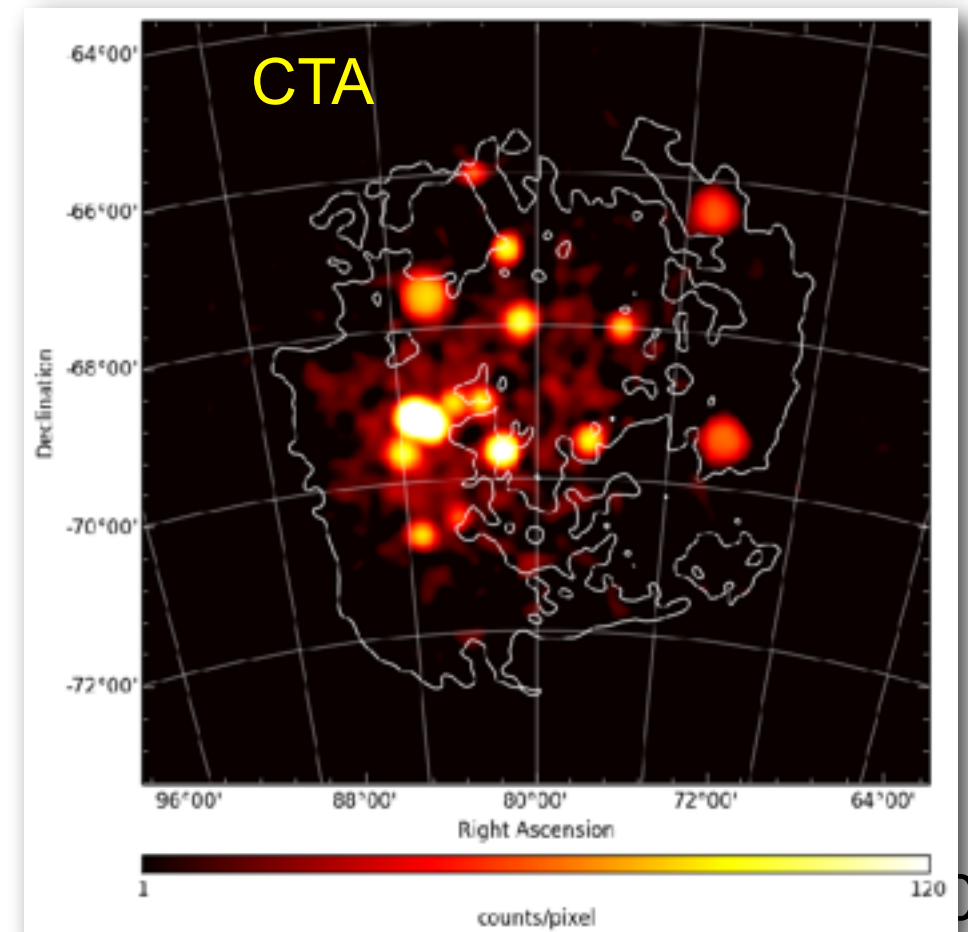
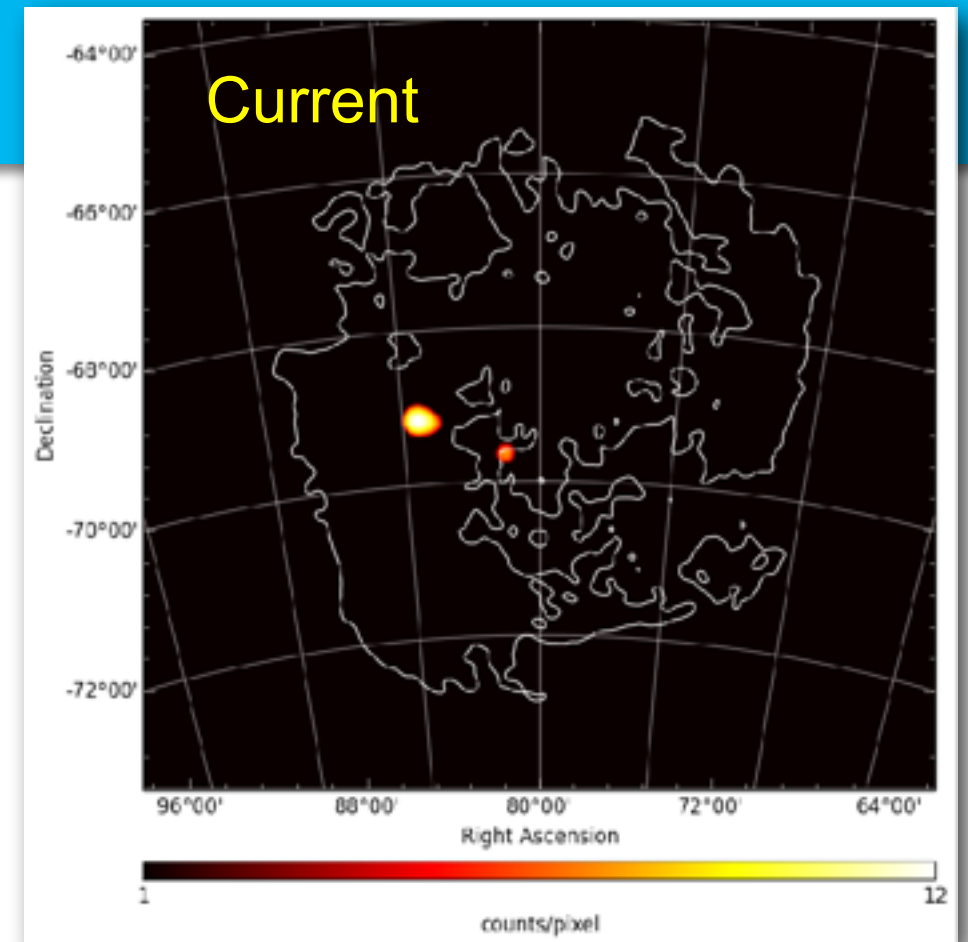
High-energy emission around the Galactic Centre



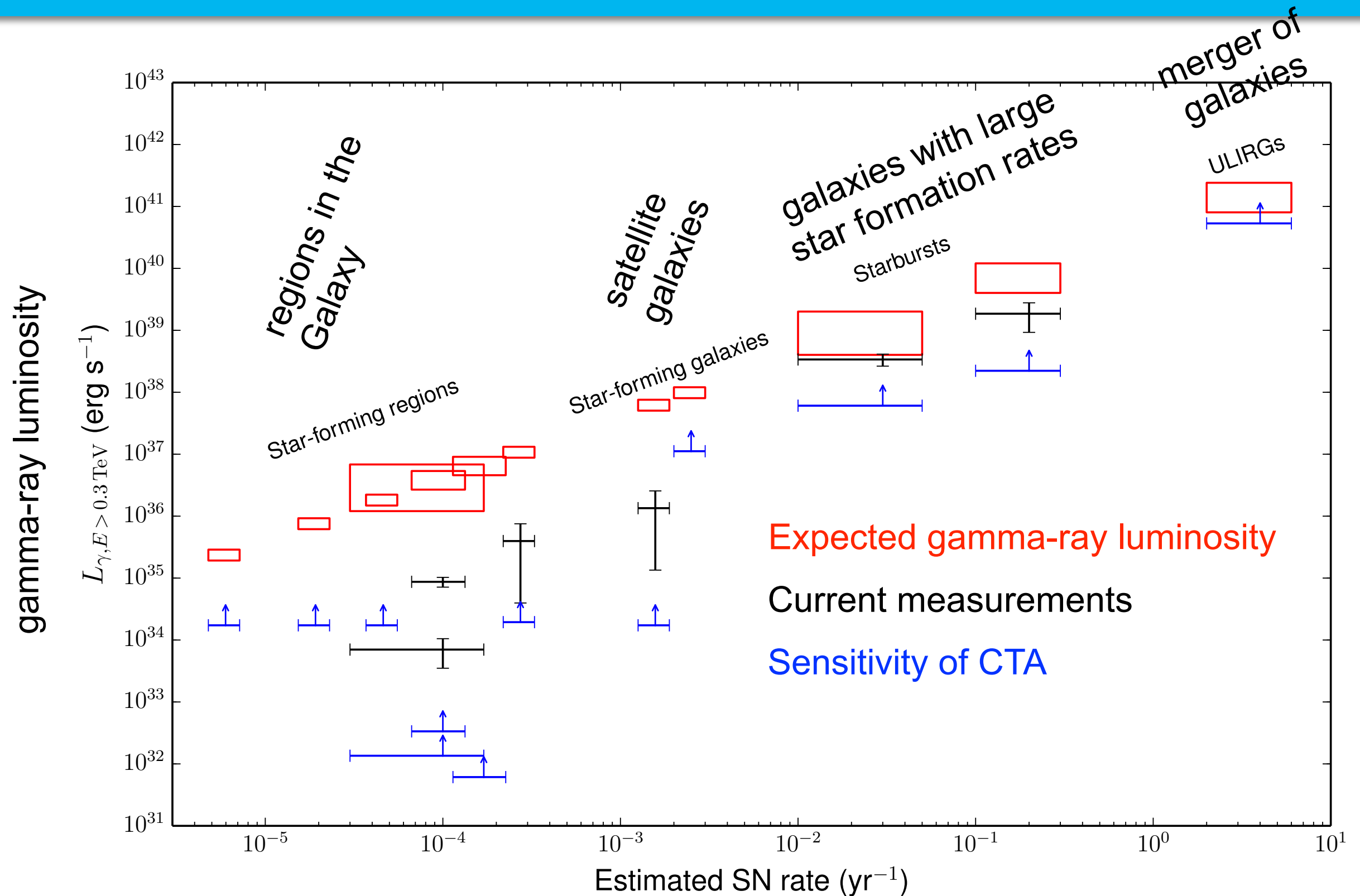
What is the source of gamma-rays in the Galactic Centre?
Does it point towards past high-accretion / outflow phases?
Is it the source of all cosmic rays in the Galaxy?
Emission due to a spike of dark-matter annihilation?

The Large Magellanic Cloud (LMC)

- > Milky Way is just one 'laboratory'
- > LMC: 10% of Milky Way star formation (2% volume only)
 - face on
 - well known distance (50 kpc)
- > deep CTA observations will reveal source population and diffuse emission
- > link of star formation to cosmic rays?
 - fundamentals of star forming not very well understood
 - impact of cosmic rays? (pressure + ionization)
- > SN 1987A
 - nearest naked eye Supernova since Kepler in 1604



Star forming regions and cosmic-ray acceleration



PeVatrons and Supernova remnants

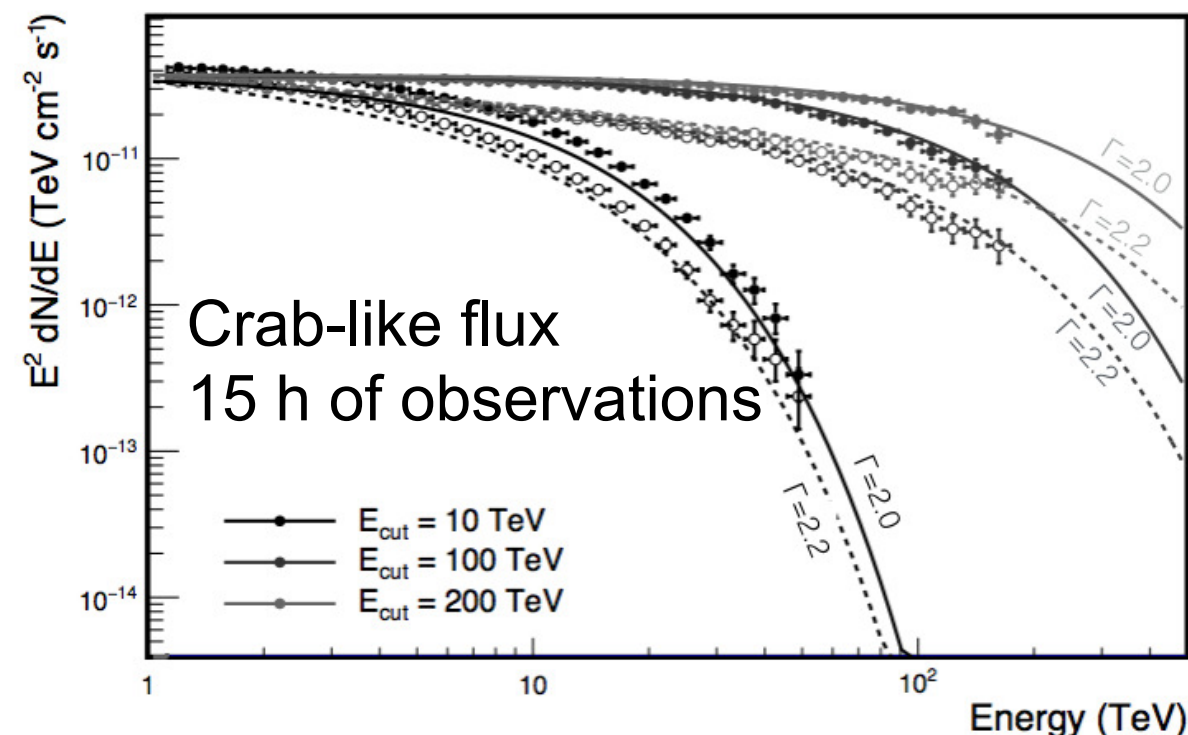
- > cosmic rays carry on average as much energy per unit volume as star light in the Galaxy
 - input of 10^{41} erg/s required to maintain cosmic ray intensity (~ 10 million years of confinement time)
- > flux largely dominated by protons up to PeV energies (knee)
- > what are the PeVatrons accelerating those particles?
 - Supernova remnants satisfy cosmic-ray energy requirements (10% conversion efficiency)
- > effective area, energy range and angular resolution



SN 1006 (X-ray, optical, radio)

PeVatrons and Supernova remnants

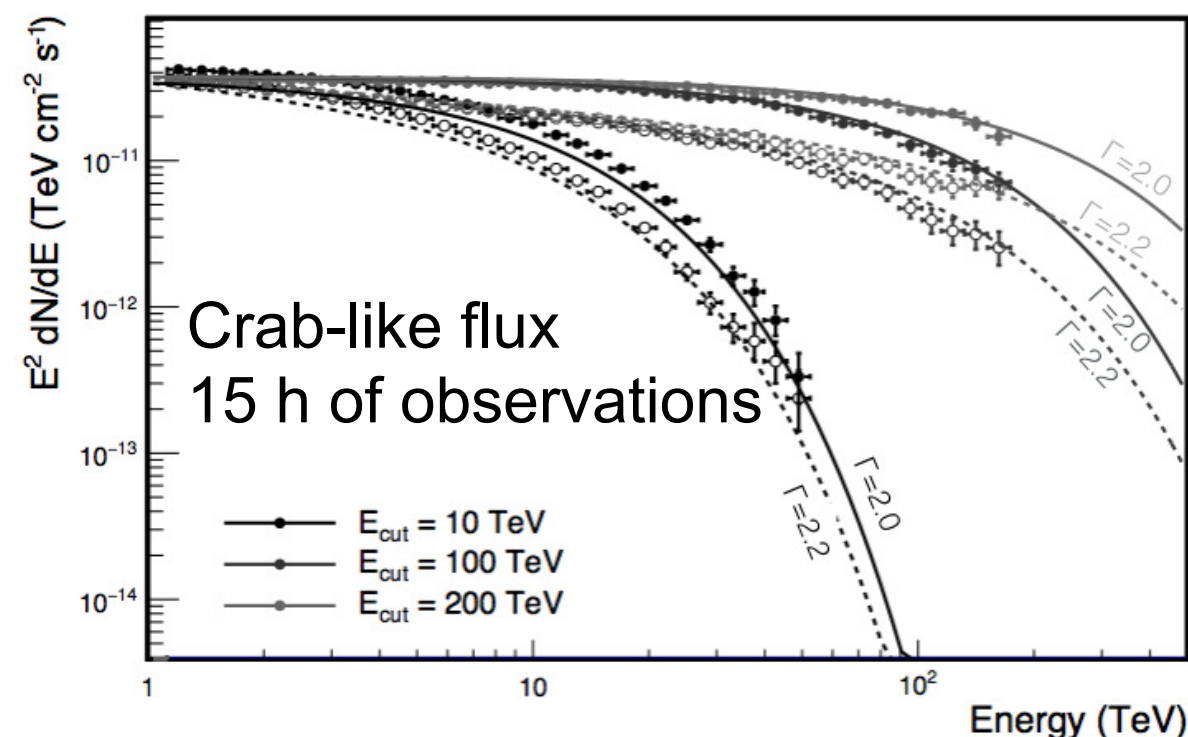
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Towards better than
1 arcmin angular
resolution

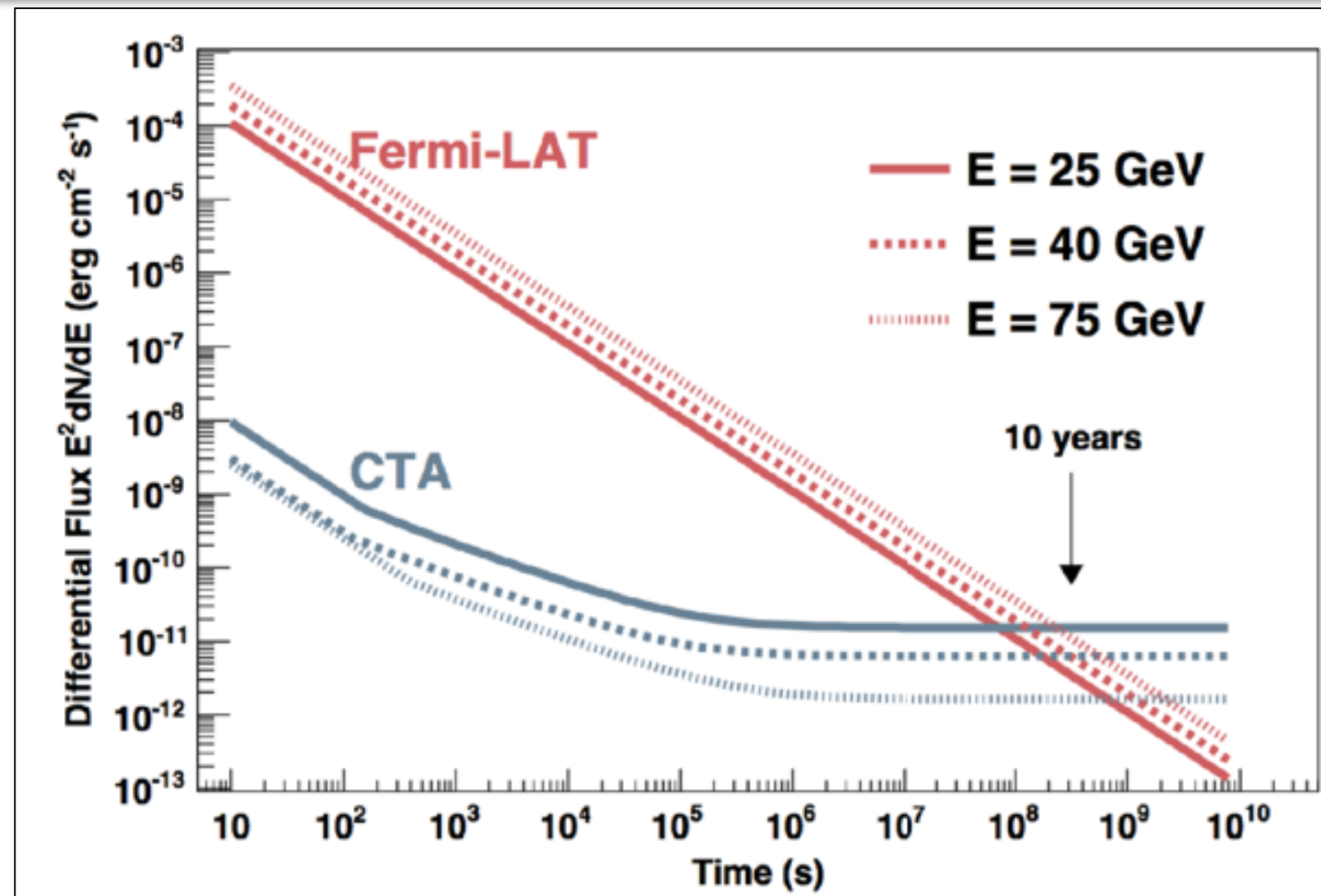
Imaging of shocks!

SN 1006
CTA resolution

SN 1006
H.E.S.S. resolution

Transients

- > dramatic outburst observed and expected in a wide range of objects
 - Gamma-ray bursts (GRBs)
 - binaries and pulsar wind nebulae
 - active galactic nuclei
 - PeV neutrino sources
 - gravitational waves
- > often associated with compact objects like neutron stars or black holes

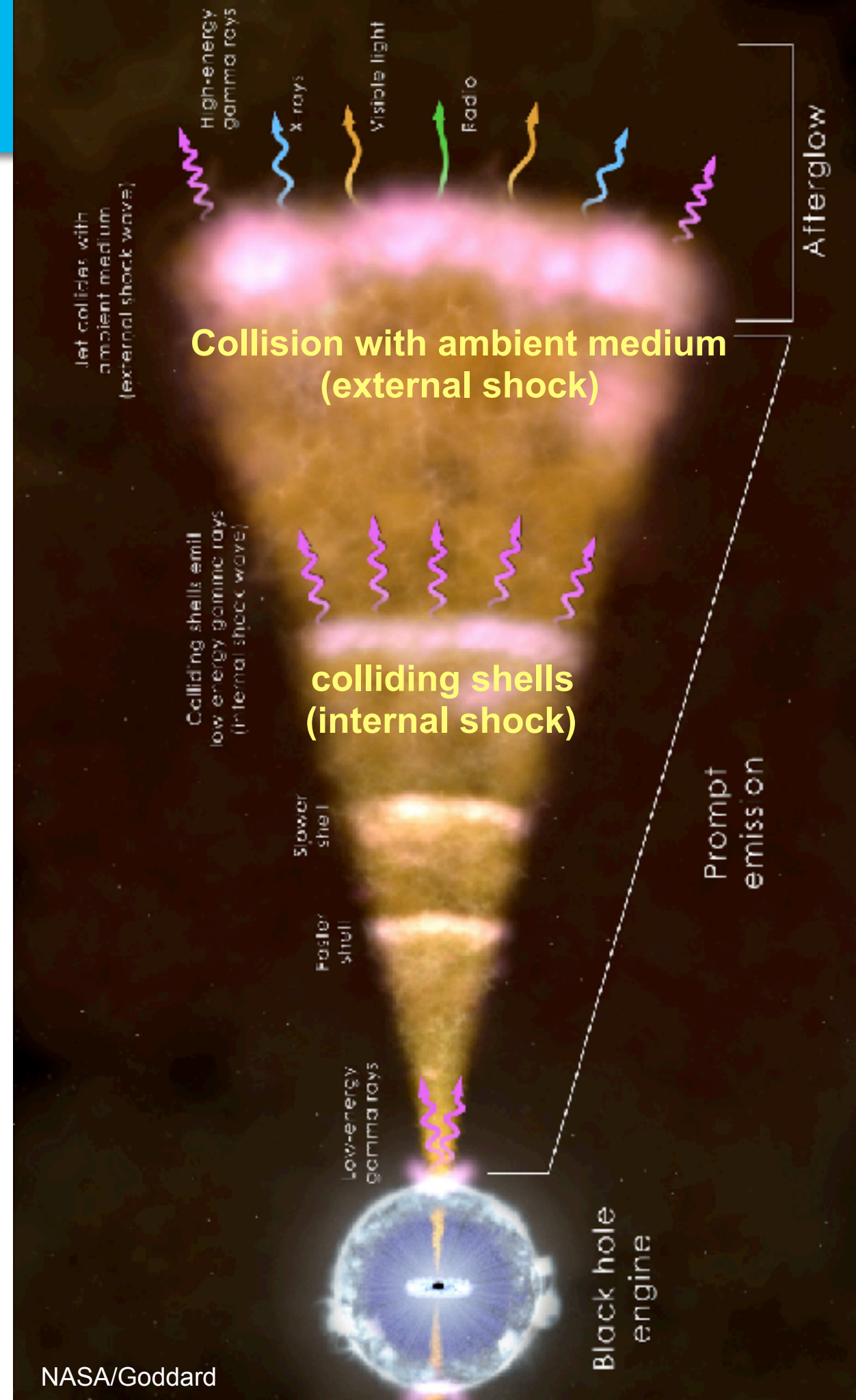


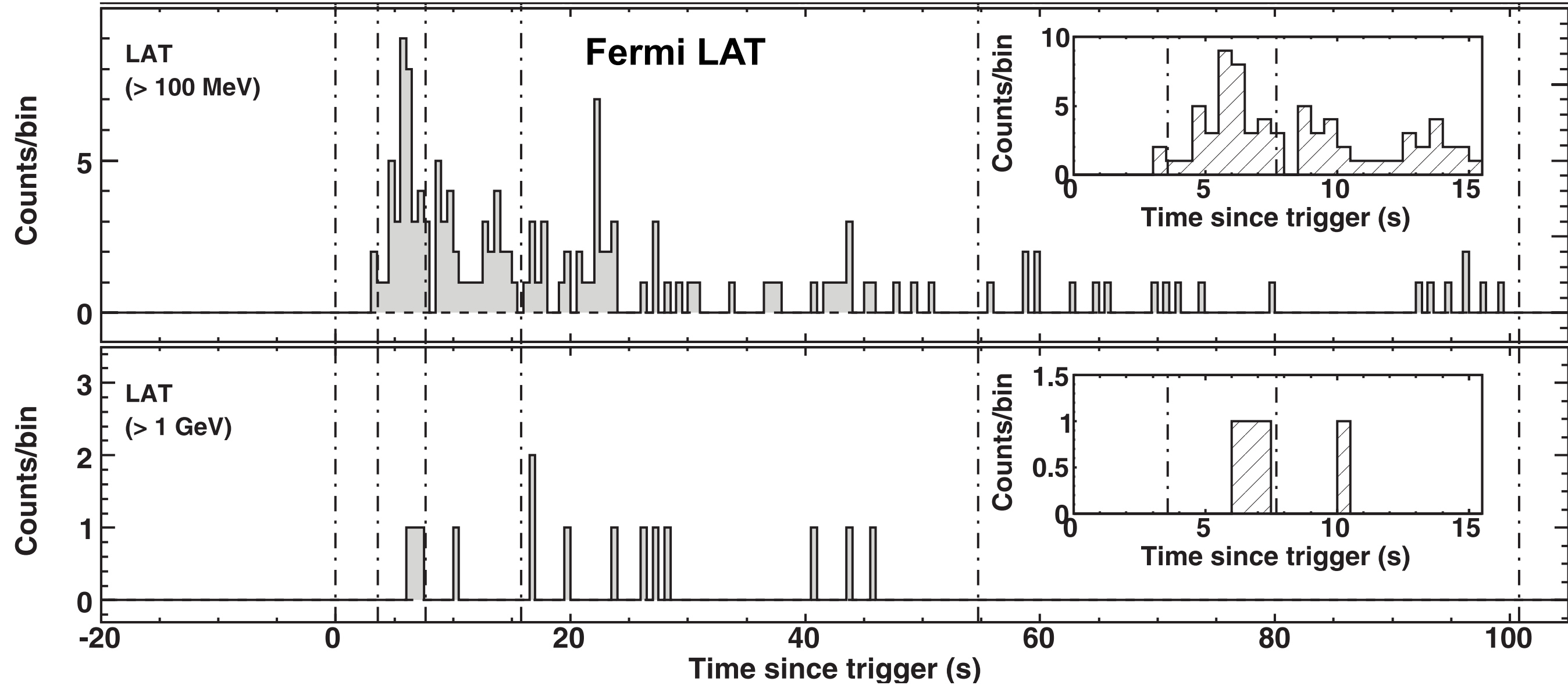
Four orders of magnitude better sensitivity for minute-scale phenomena.

Unexplored astronomical window!

Gamma-ray bursts

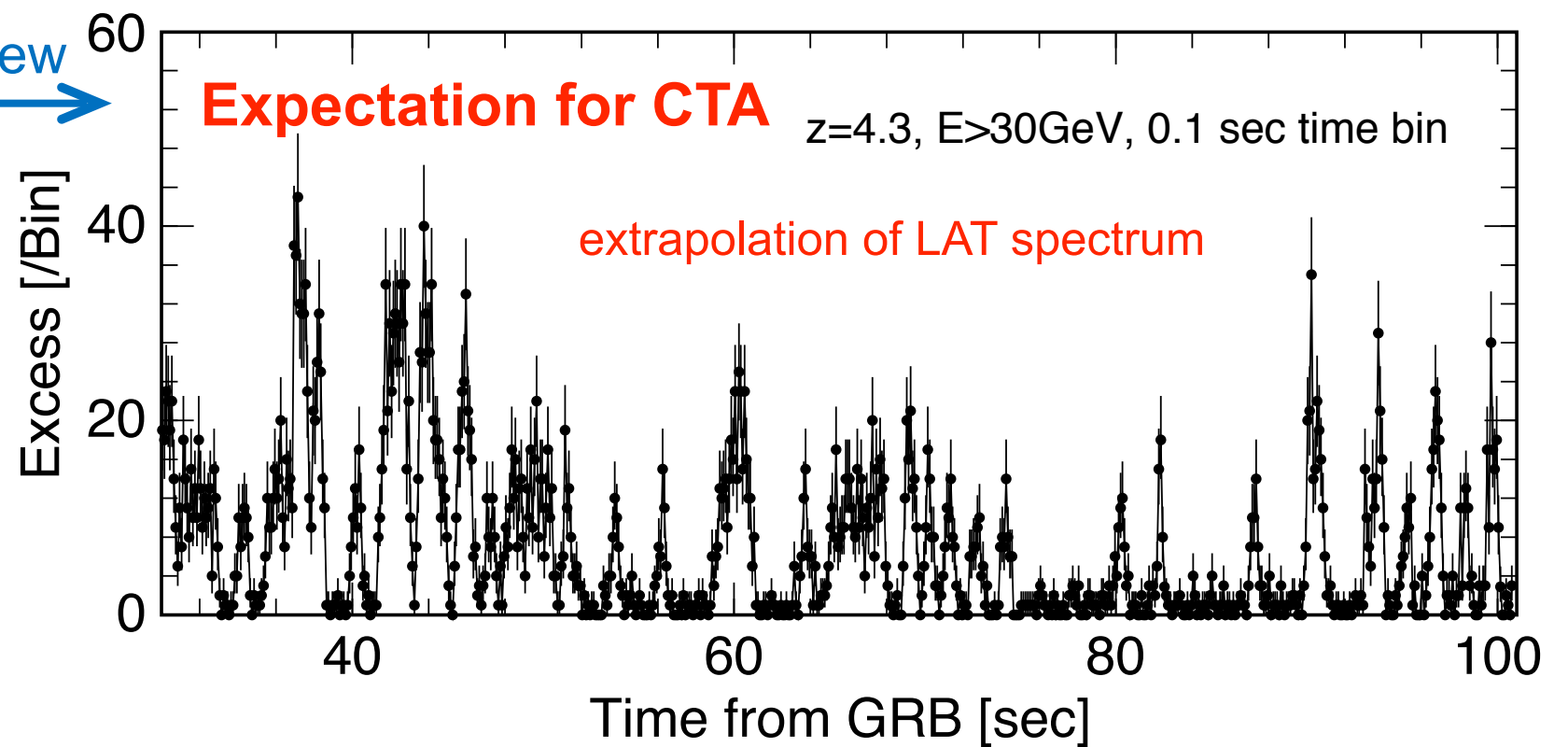
- > most luminous explosions in the Universe
 - 10^{52} - 10^{54} erg isotropic-equivalent energy release (primarily MeV band)
- > long GRBs: massive star collapse
- > short GRBs: neutron star or black hole mergers
- > cosmological distances
 - observed beyond $z=8$
- > basic aspects not well known
 - nature of central engine, jet formation, particle acceleration, prompt/afterglow emission
- > GRB origin of ultra-high energy cosmic rays ($E > 10^{18}$ eV)





GRB 080916C at $z=4.3$

20 - 50 s for slew



Active Galactic Nuclei

blue light:
synchrotron radiation
from HE electrons

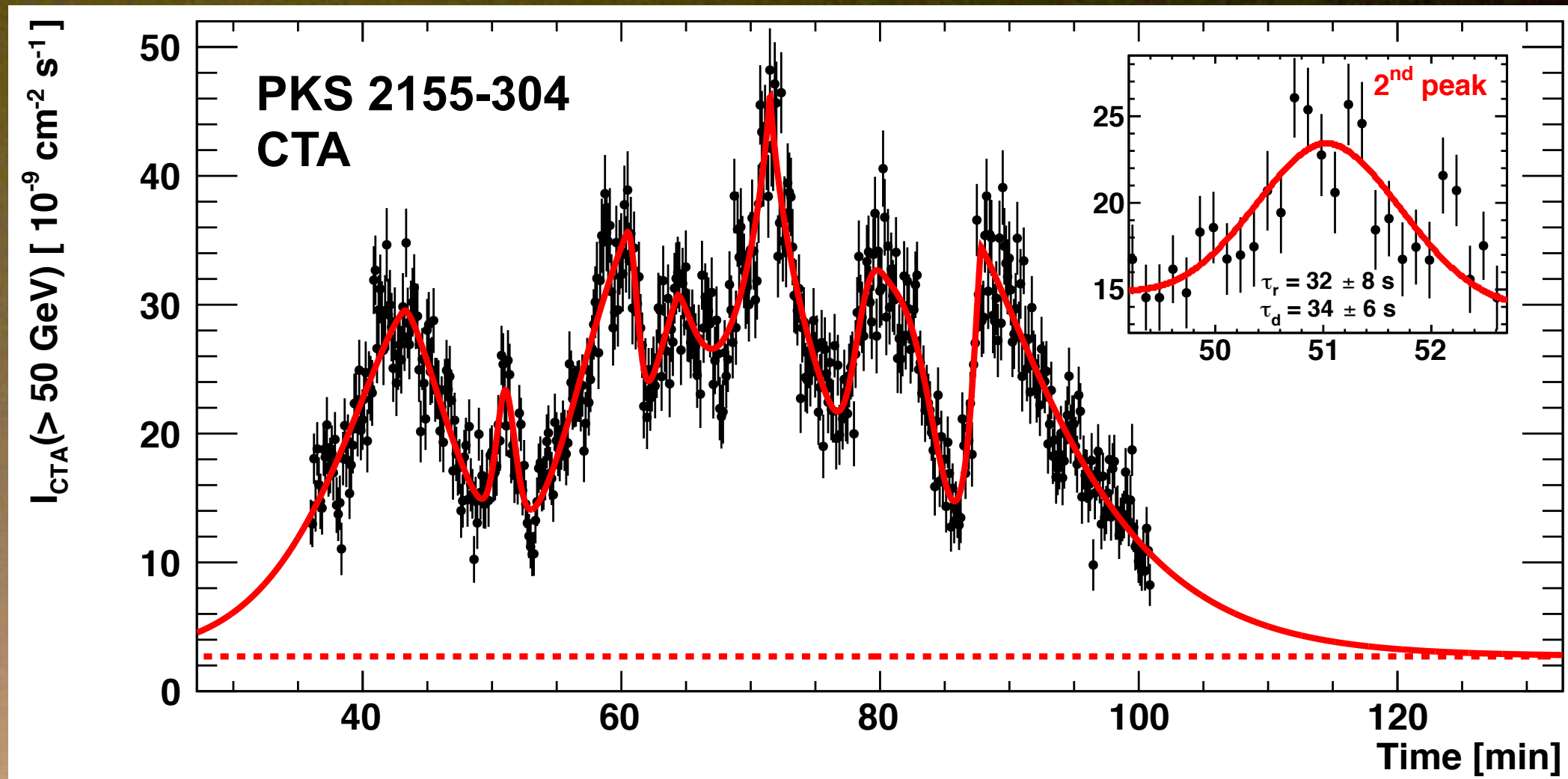
jet: relativistic hot,
magnetized plasma

5000 light years

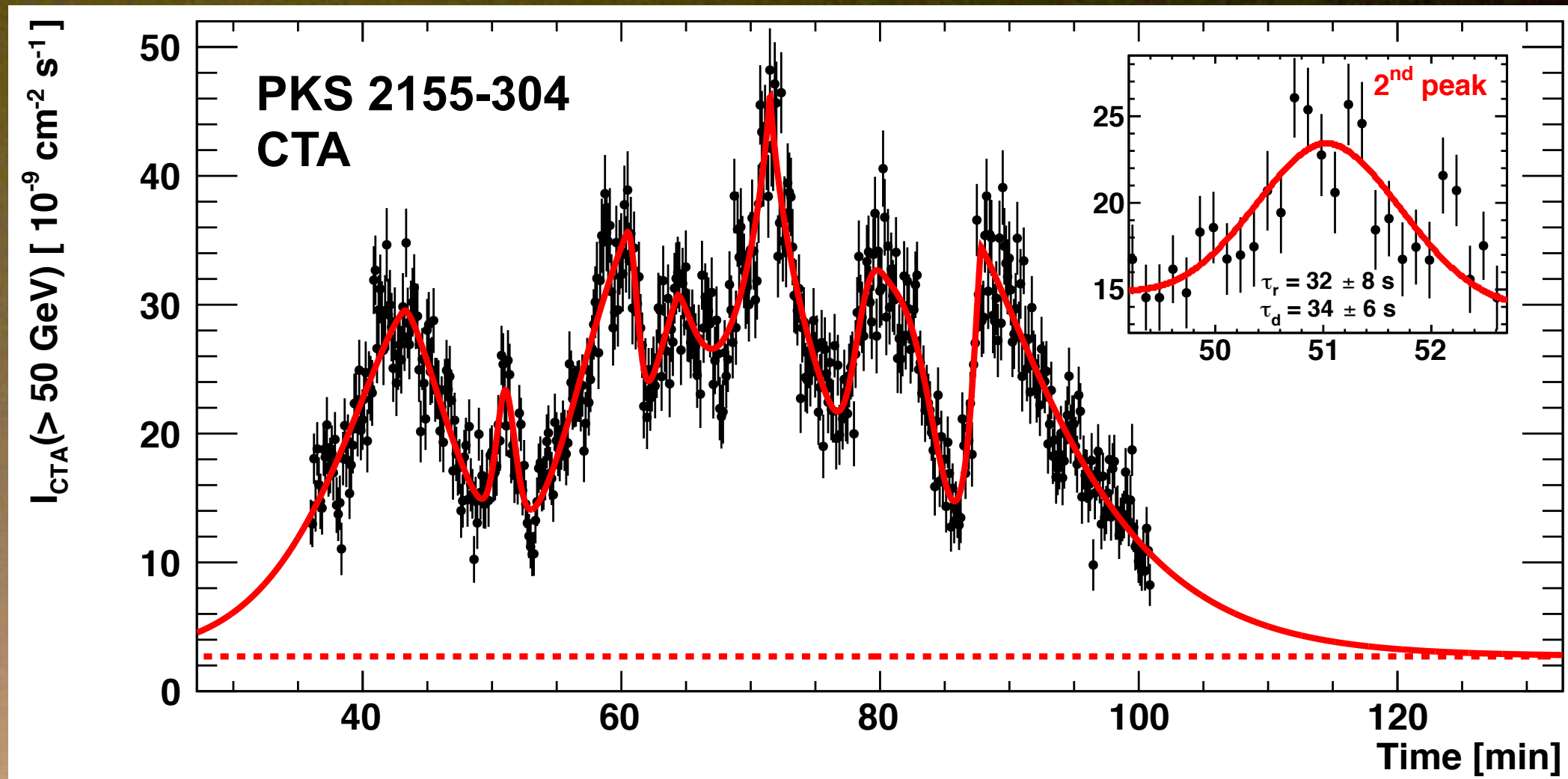
hot spots:
shocked jet
plasma

supermassive
black hole

Active Galactic Nuclei



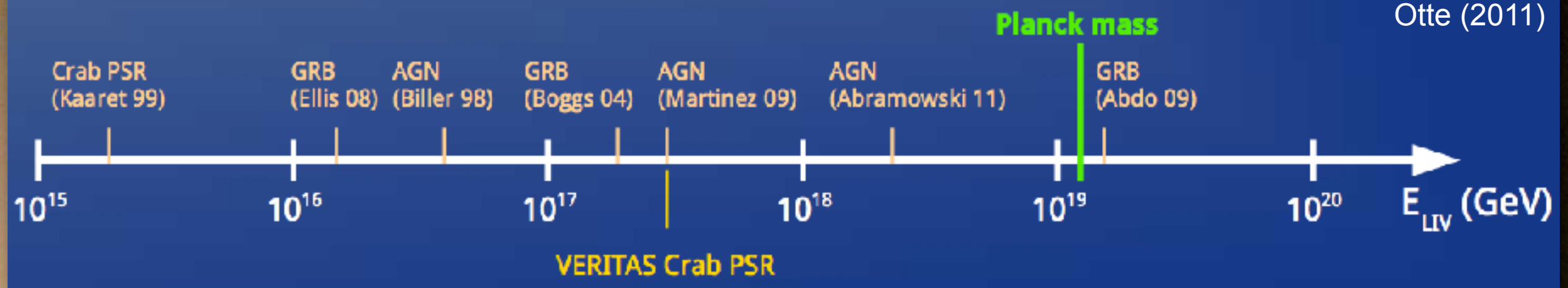
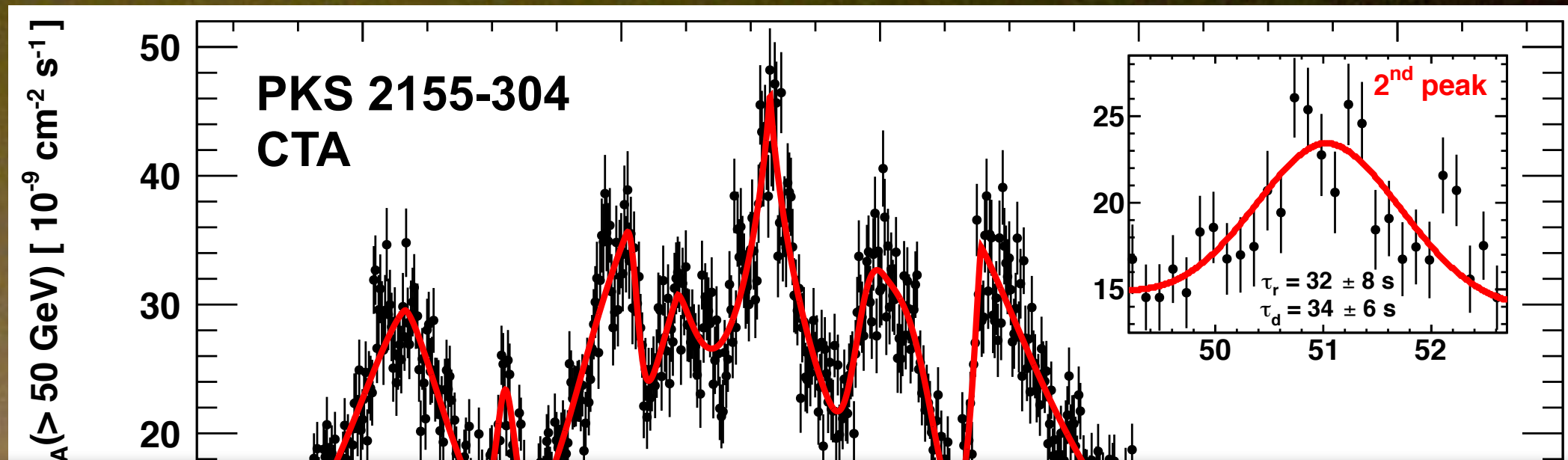
Active Galactic Nuclei & Lorentz invariance measurements



$$c^2 p^2 = E_\gamma^2 [1 \pm \xi_1 E_\gamma / E_{QG} \pm \xi_2 (E_\gamma^2 / E_{QG}^2) \pm \dots]$$

$$\delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_{Pl}} \right)^\alpha \frac{L}{c}$$

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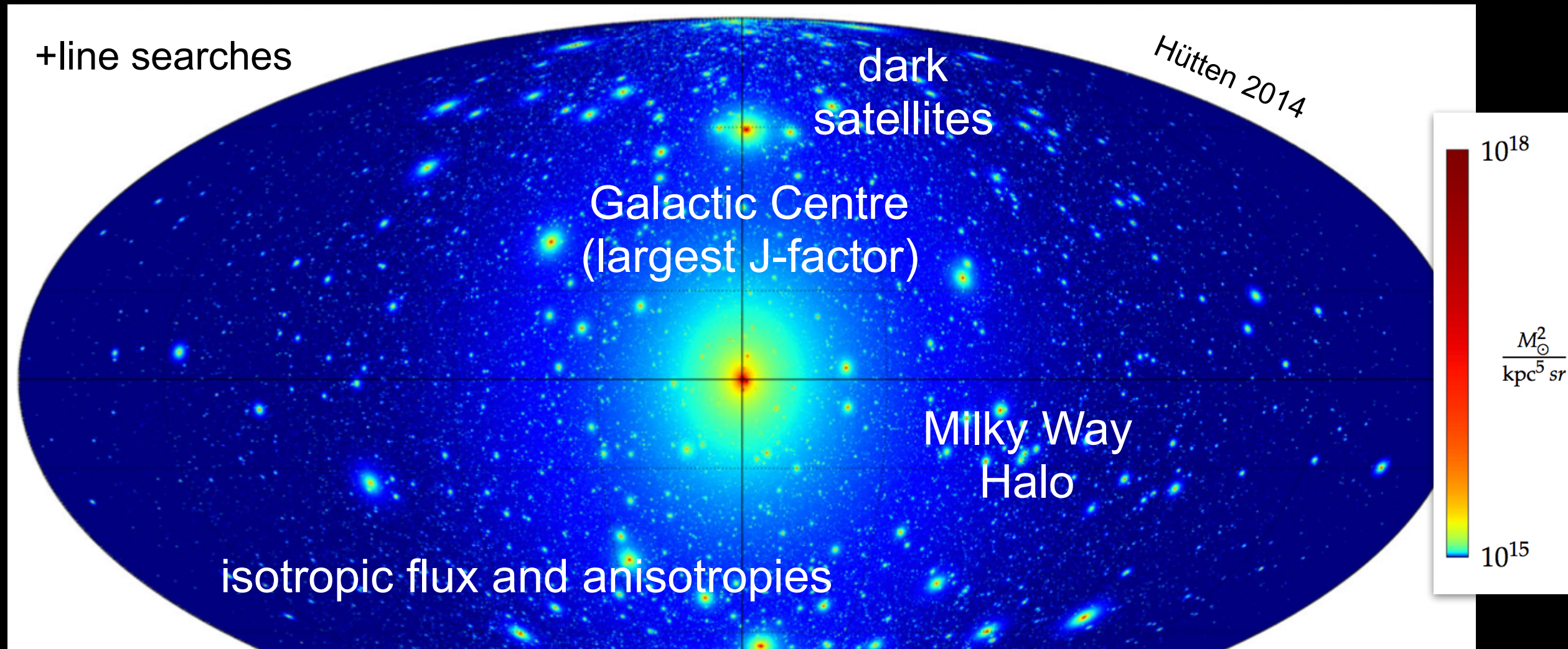
everything discussed until now is
background

(but necessary to understand if
we want to find physics beyond
the standard model)

Dark matter searches

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \underbrace{\frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{WIMP}}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f}_{\text{'Particle Physics'}} \times \overbrace{\int_{\Delta\Omega} d\Omega' \int_{\text{los}} \rho^2 r(l, \theta') dl(r, \theta')}^{\text{annihilation}} \underbrace{\hspace{10em}}_{\text{'Astrophysics' or } J(E)}$$

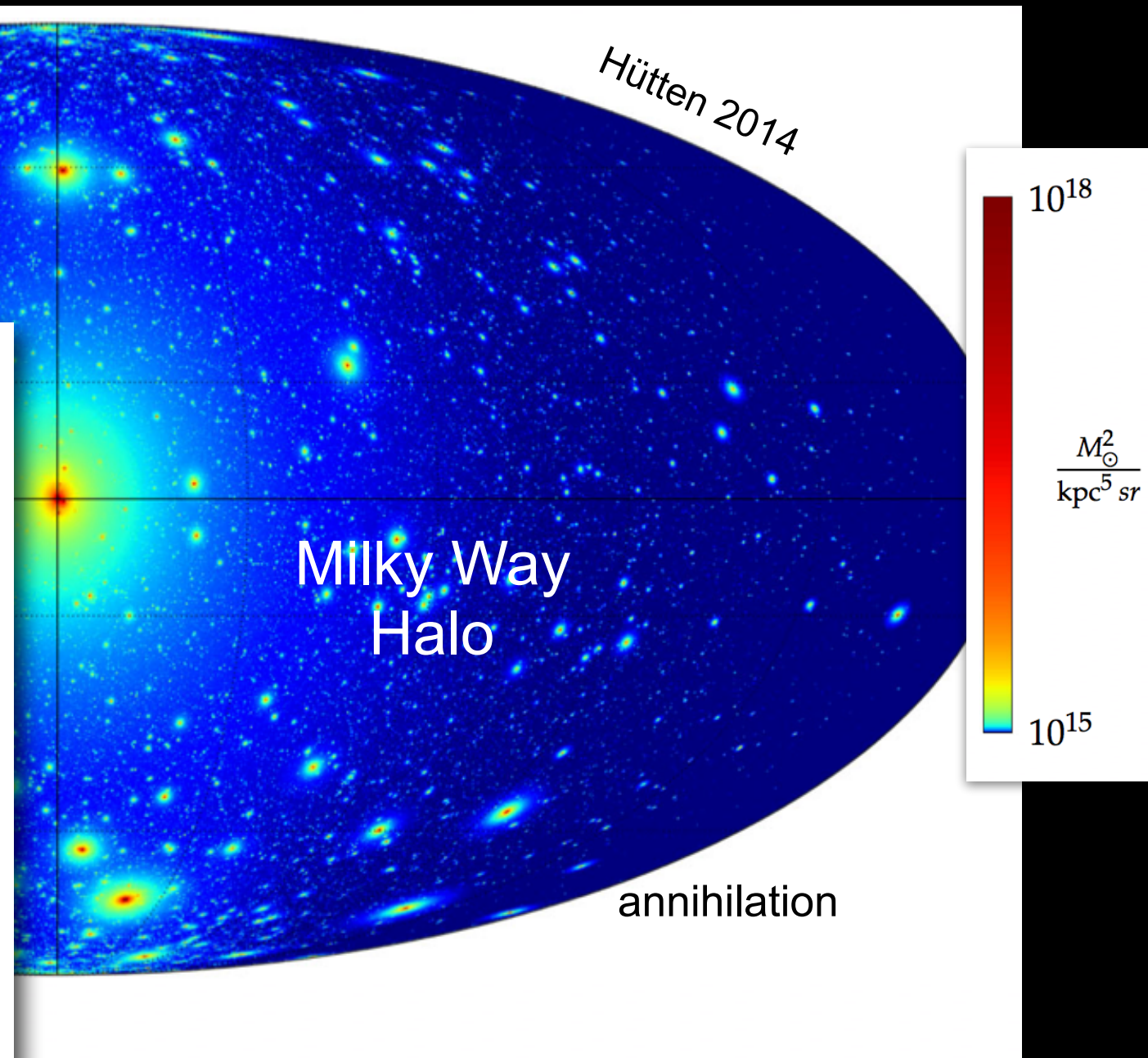
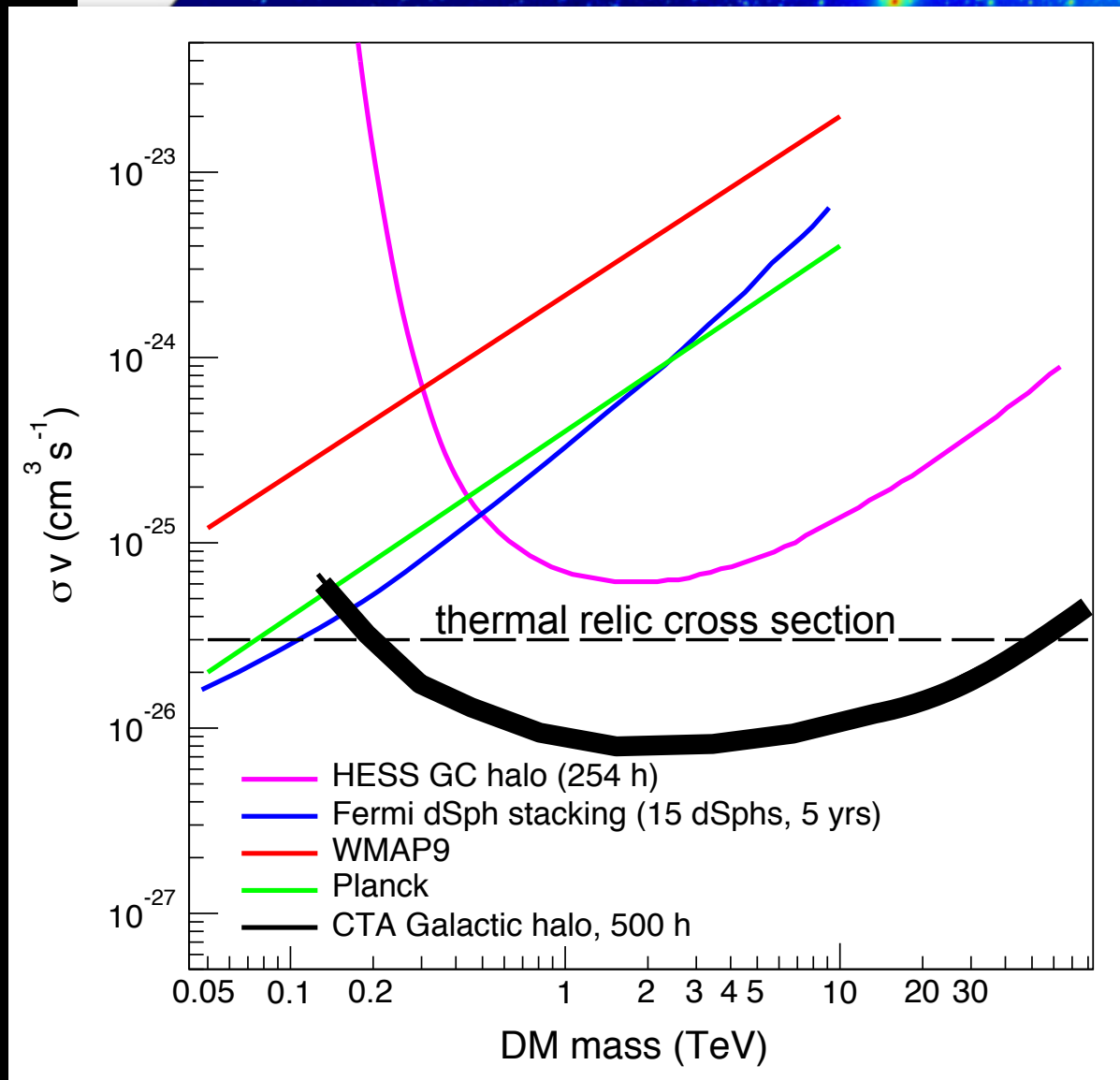
Dark matter searches



$$\frac{d\Phi_{\gamma}}{dE_{\gamma}} = \underbrace{\frac{1}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{WIMP}}^2} \sum_f \frac{dN_{\gamma}^f}{dE_{\gamma}} B_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} d\Omega' \int_{\text{los}} \rho^2 r(l, \theta') dl(r, \theta')}_{\text{'Astrophysics' or } J(E)} \quad \text{annihilation}$$

Dark matter searches

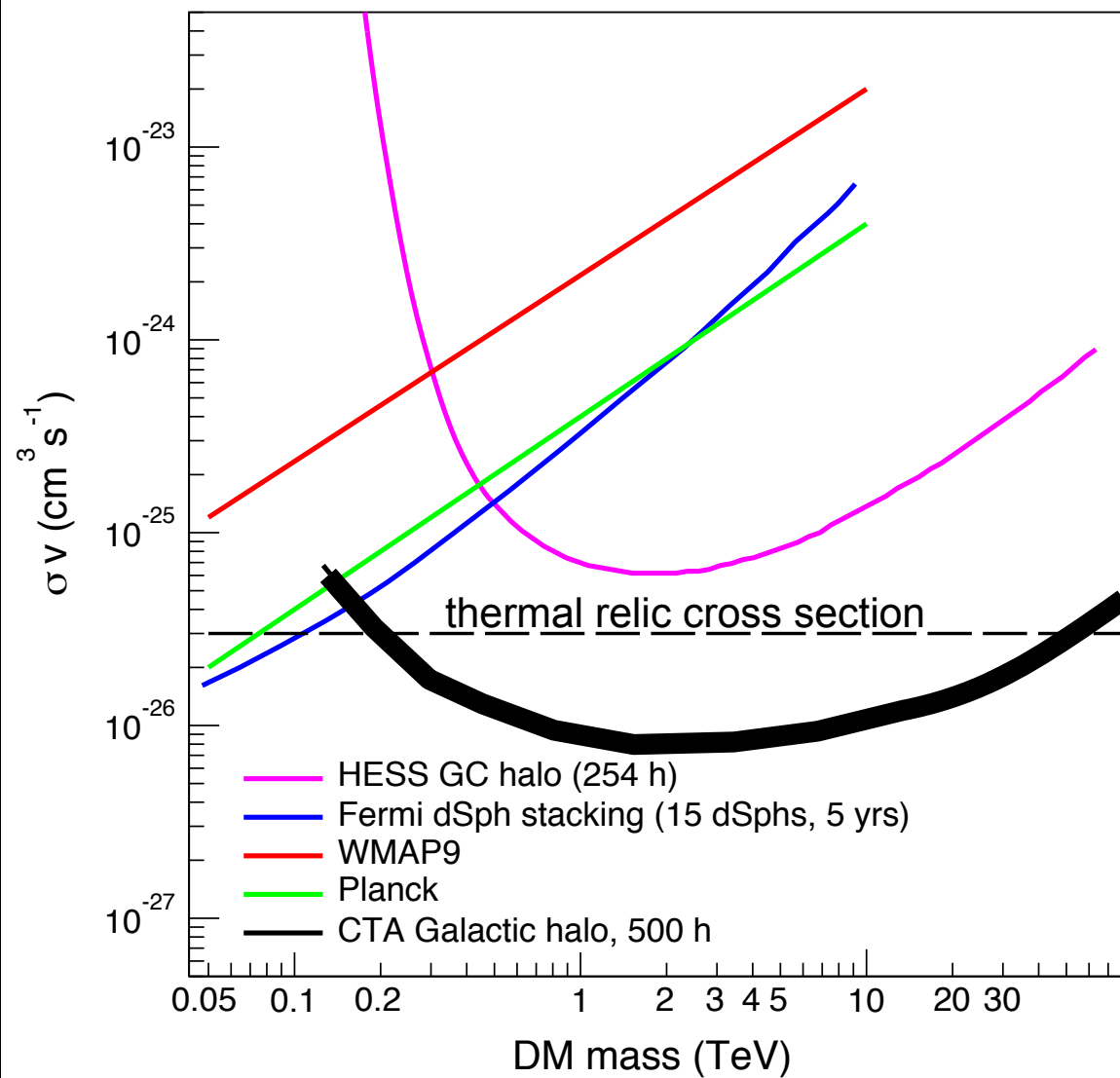
+line searches



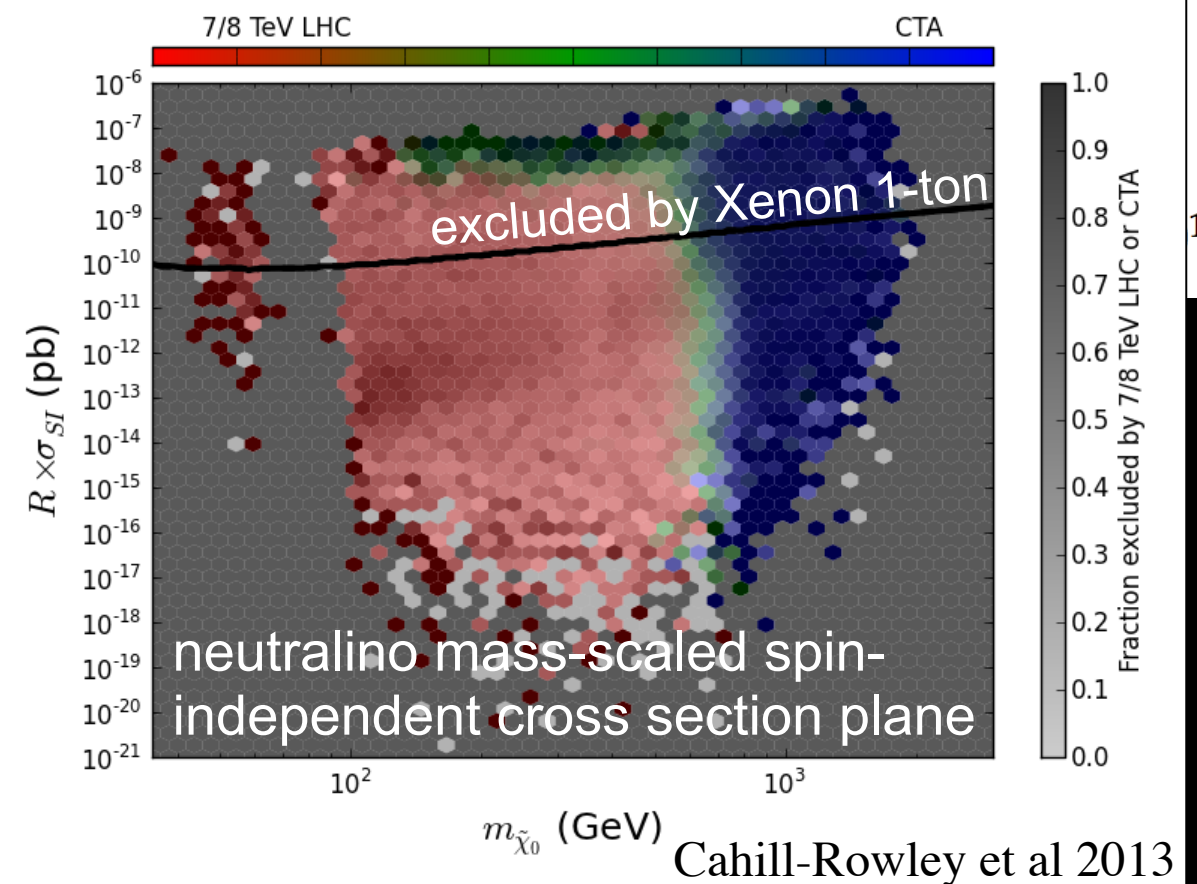
Dark matter searches

+line searches

Hütten 2014



Complementary of searches (PMSSM)

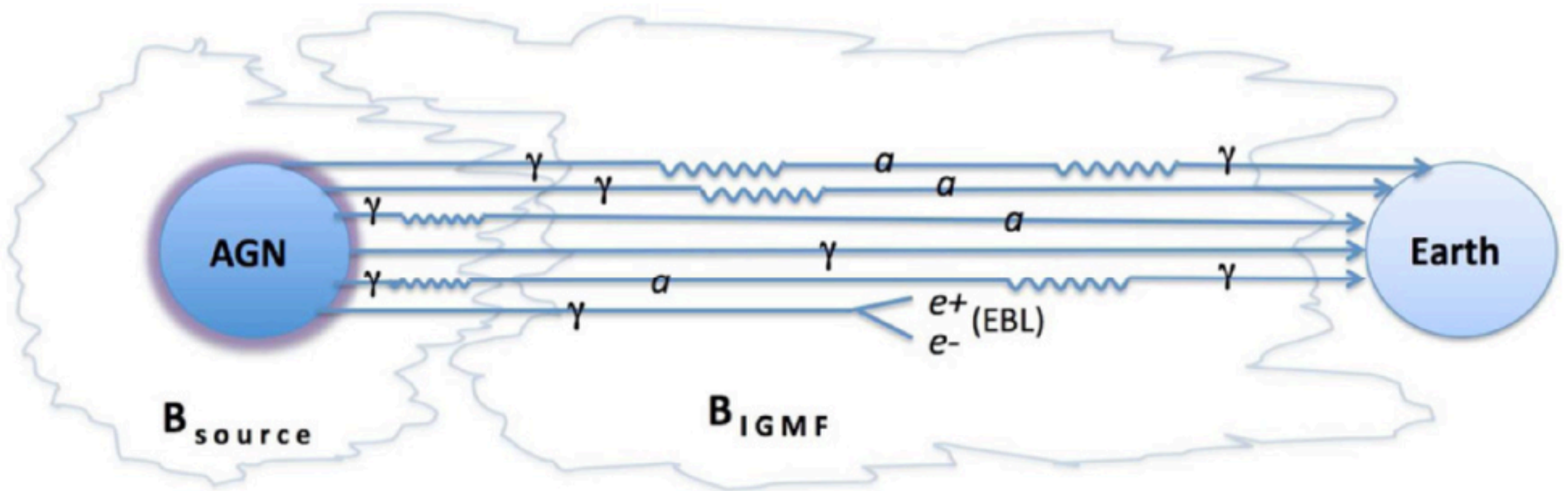


10^{18}

$\frac{M_\odot^2}{\text{pc}^5 \text{sr}}$

15

Axion-like particle searches



Doro et al (2013)

Coupling of photons to axion-like particles (ALPs):

$$\mathcal{L}_{\gamma a} = g_{\gamma a} \vec{E} \cdot \vec{B} a$$

ALPs: coupling strength and mass are independent parameters

Oscillations between ALPs and photons in external magnetic field for photons above critical energy:

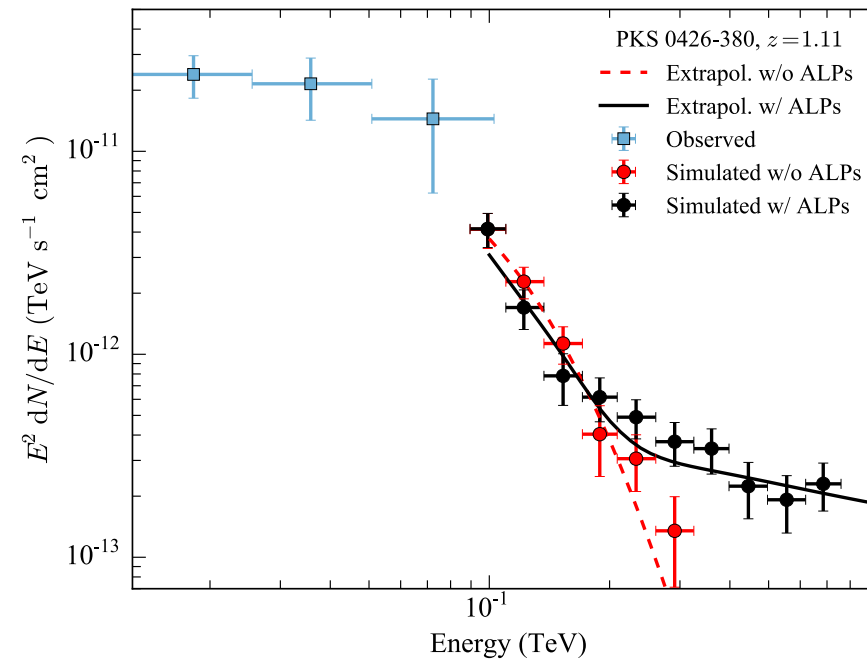
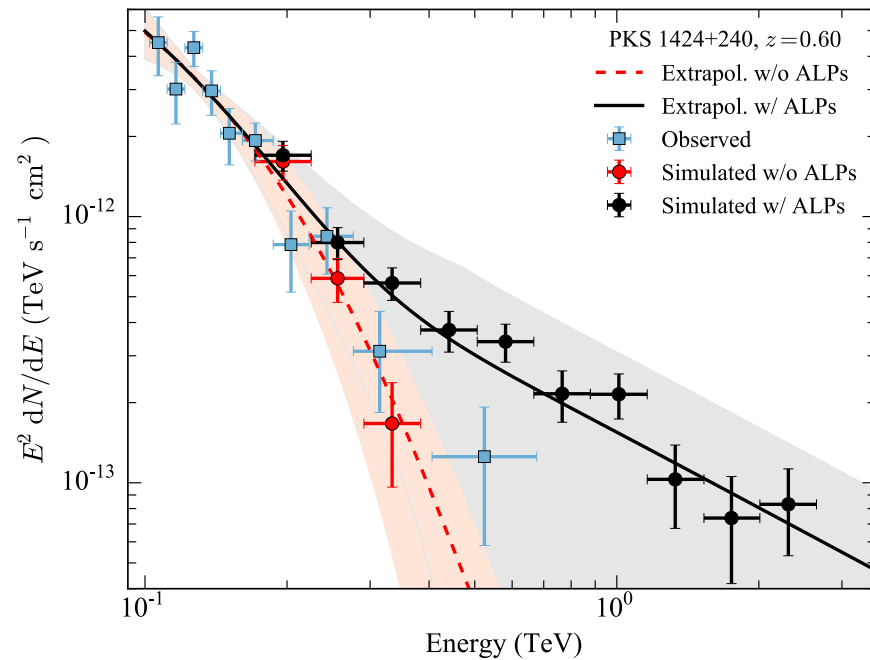
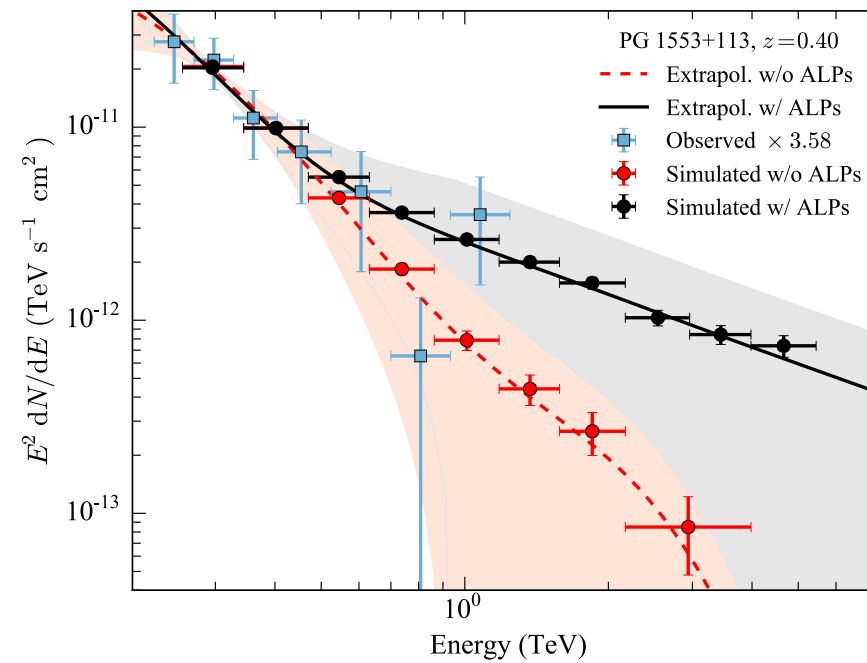
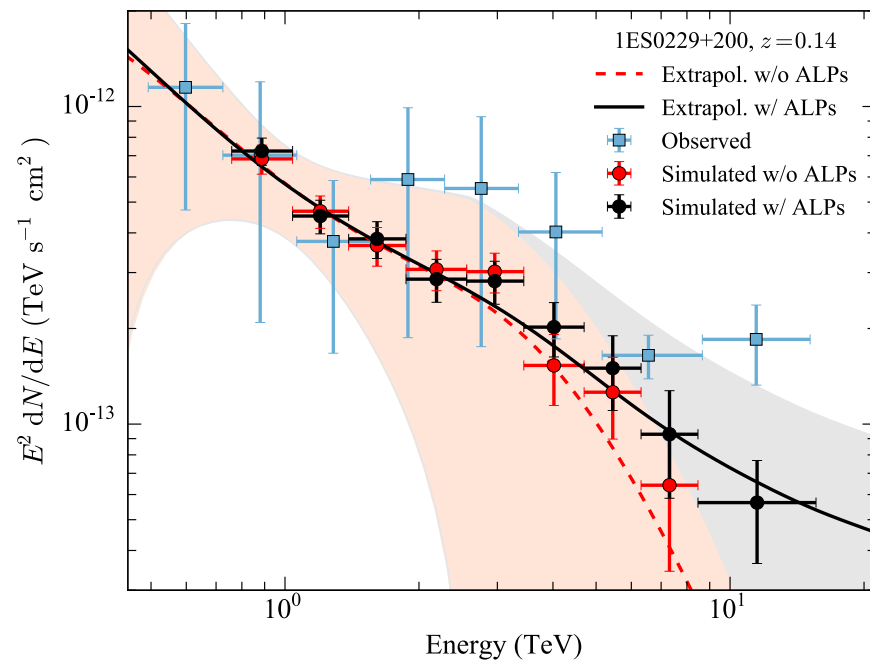
$$E_c = \frac{m^2}{2g_{\gamma a} B \sin \theta}$$

$$m = 20 \text{ neV}, g_{\gamma a} = 10^{-10} \text{ GeV}^{-1}: \\ E_c \sim 100 \text{ GeV}$$

(θ : angle between photon direction and magnetic field)

Axion-like particle searches with CTA

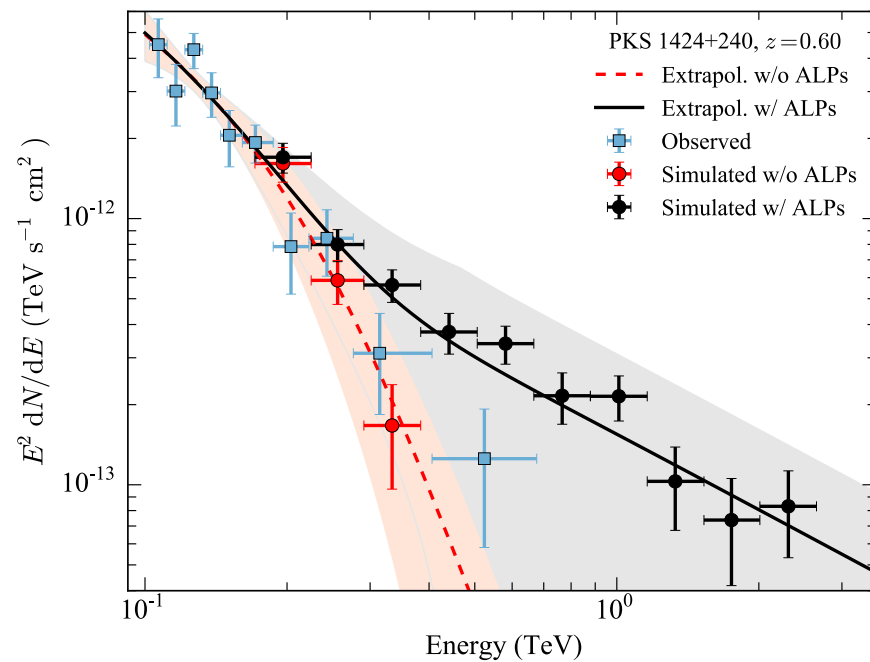
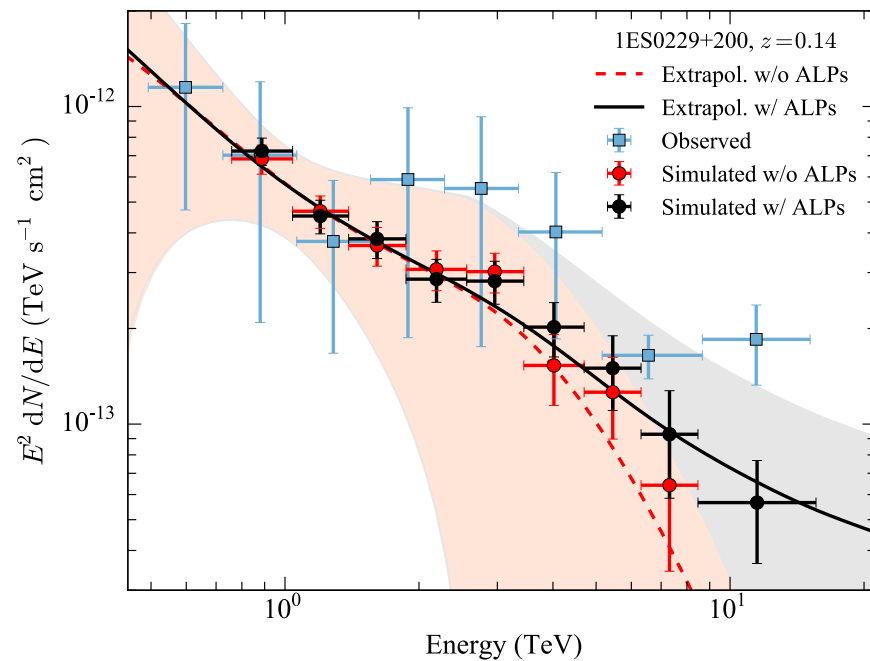
$$m_{\text{neV}} = 12.2, g_{11} = 4.3$$



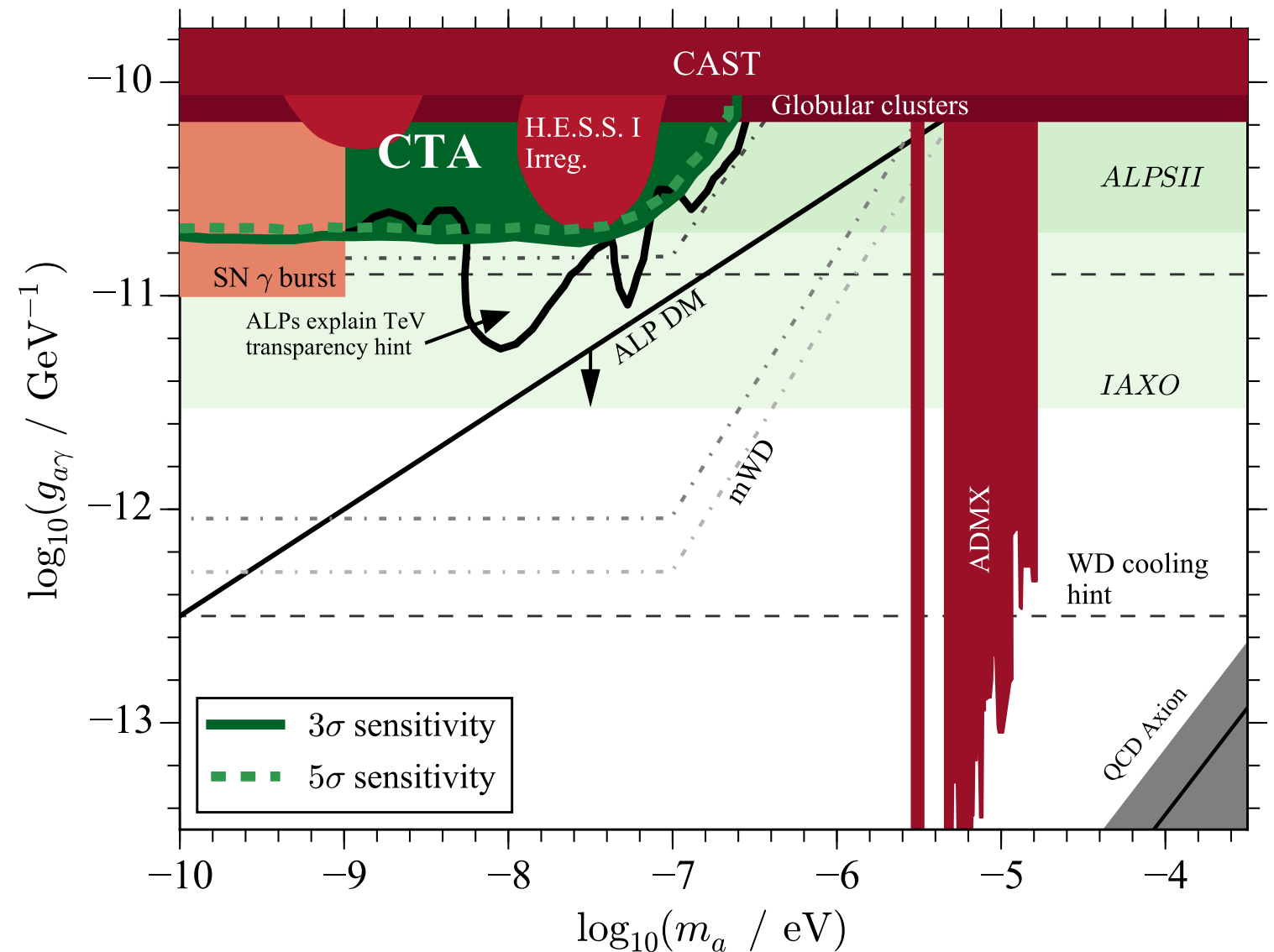
Current results
CTA (with ALPS)
CTA (without ALPS)

Axion-like particle searches with CTA

$$m_{\text{neV}} = 12.2, g_{11} = 4.3$$



Meyer & Conrad 2014



Note large uncertainties from unknown intrinsic source spectra and not well measured magnetic field properties

The Cherenkov Telescope Array

- Cosmic Particle Acceleration
- Probing Extreme Environments
- Beyond the standard model





