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 km^2 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

Credit: F. Acero & H. Gast

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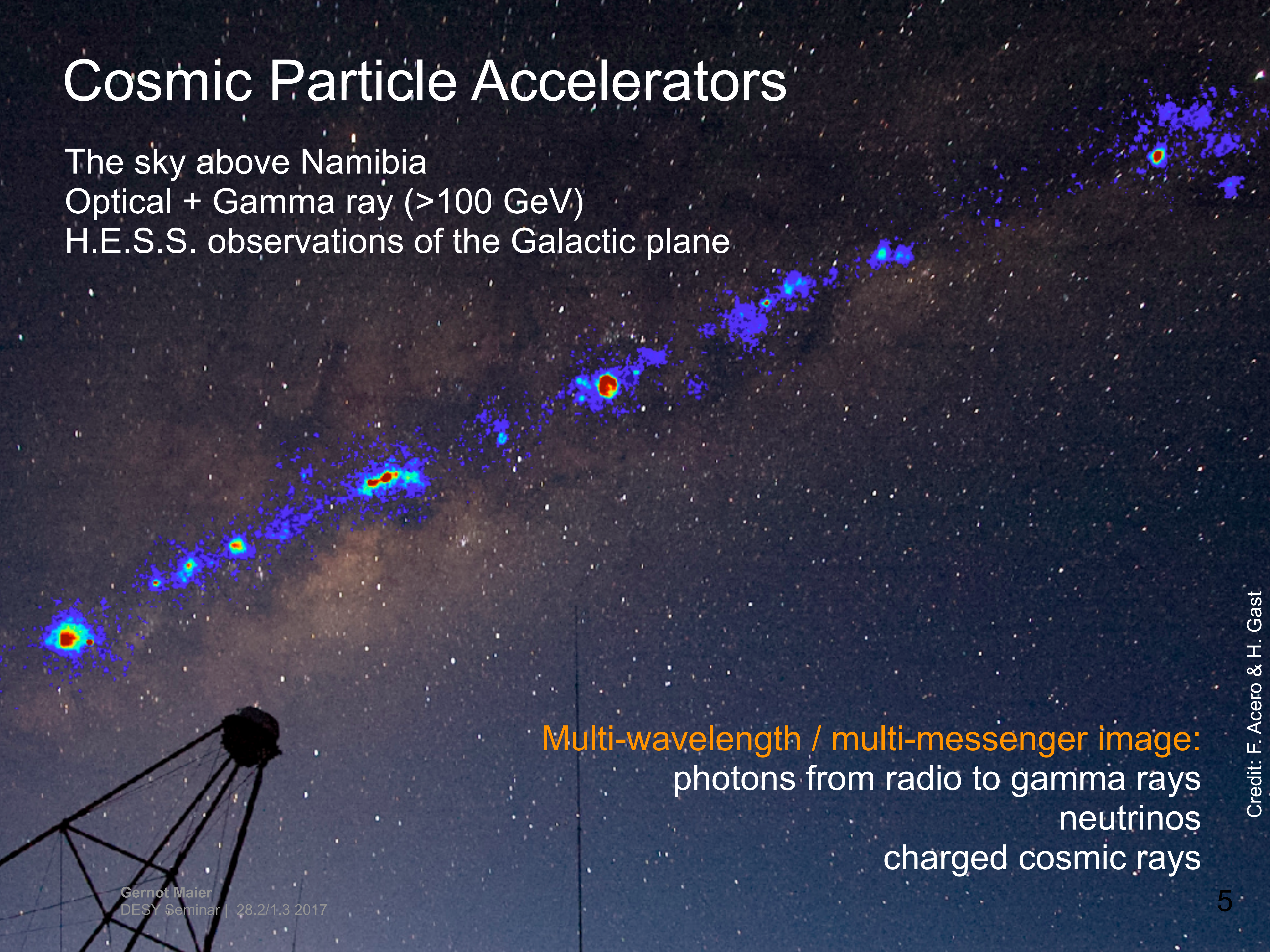
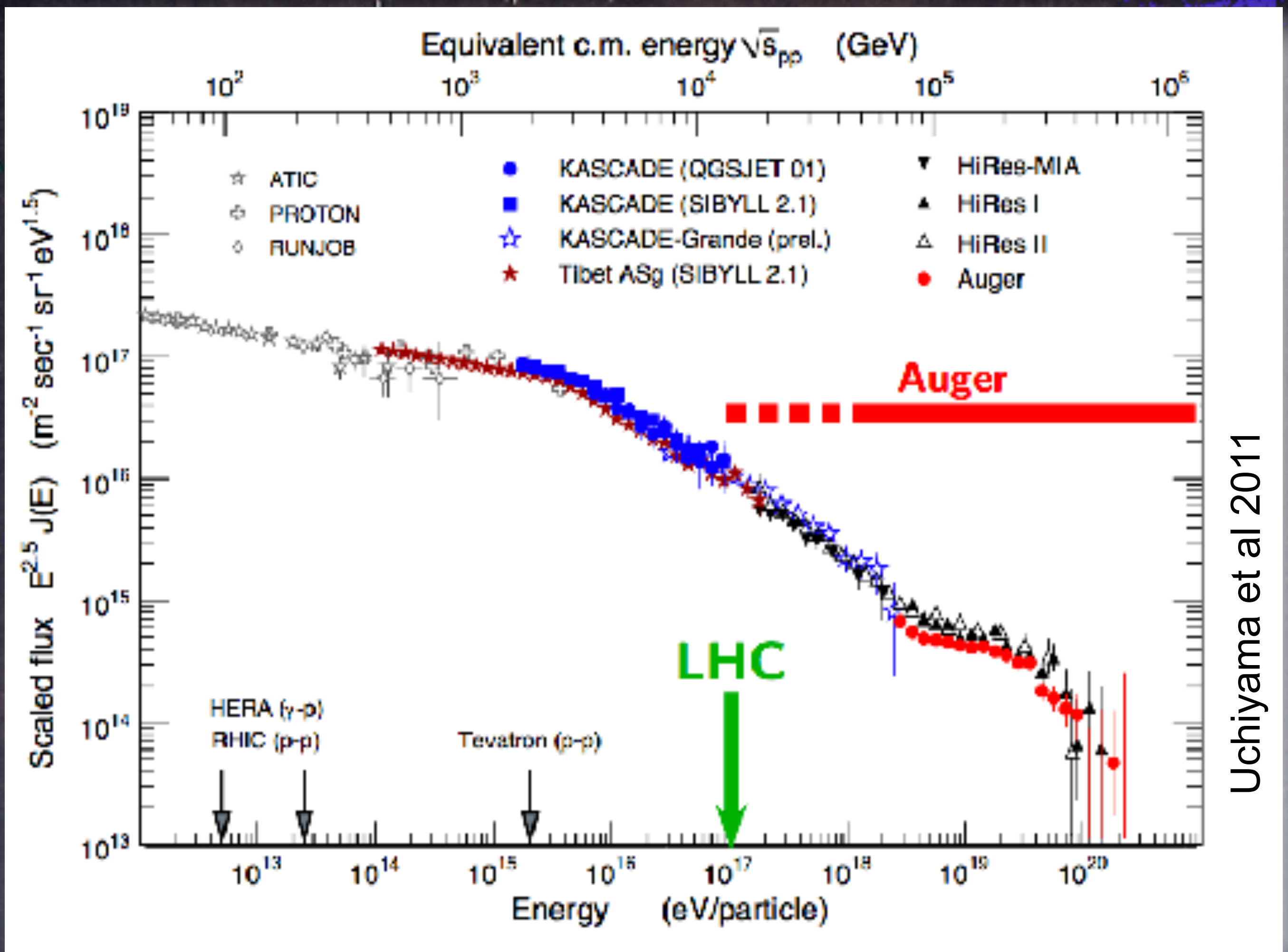


Credit: F. Acero & H. Gast

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?



Uchiyama et al 2011

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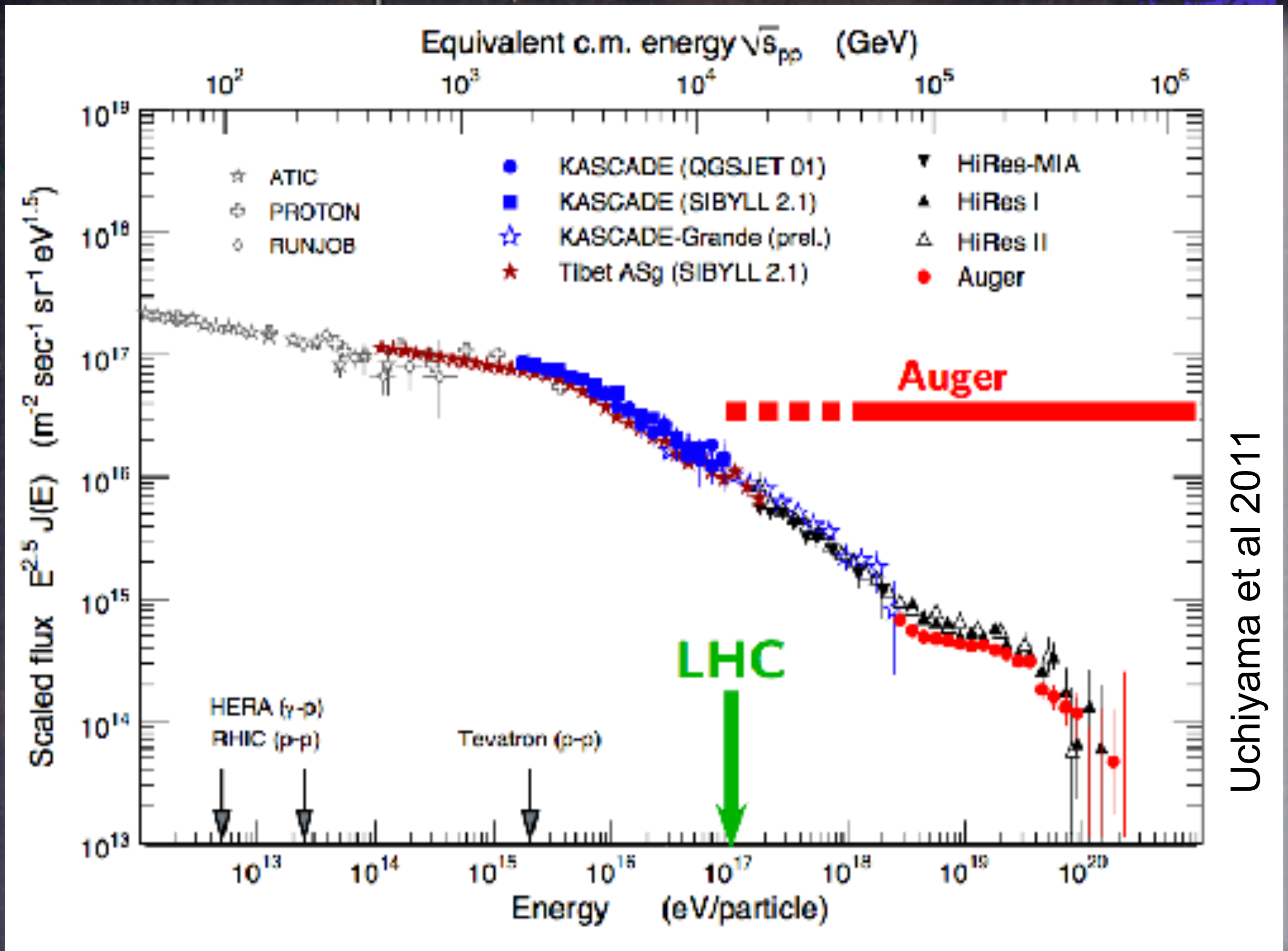
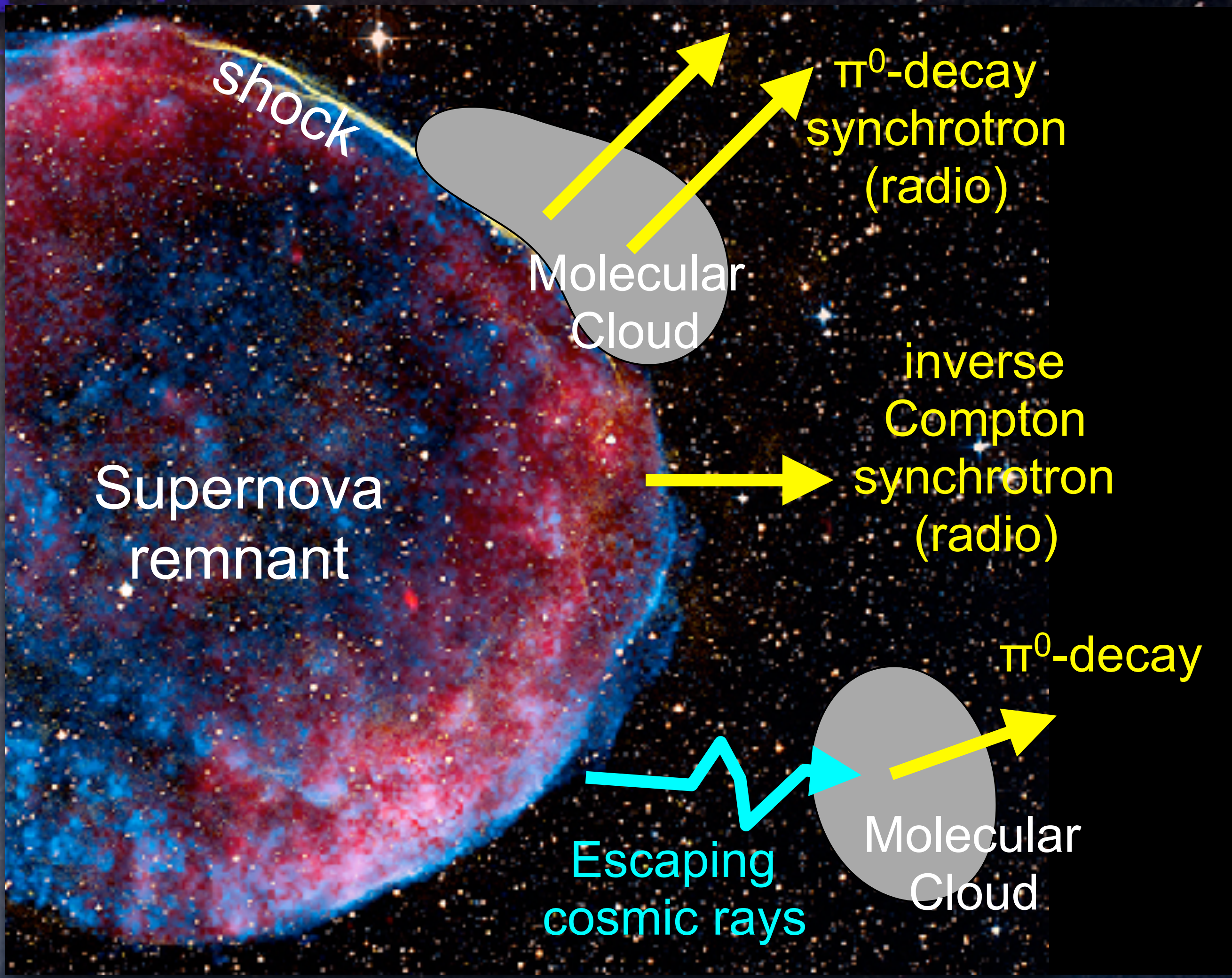
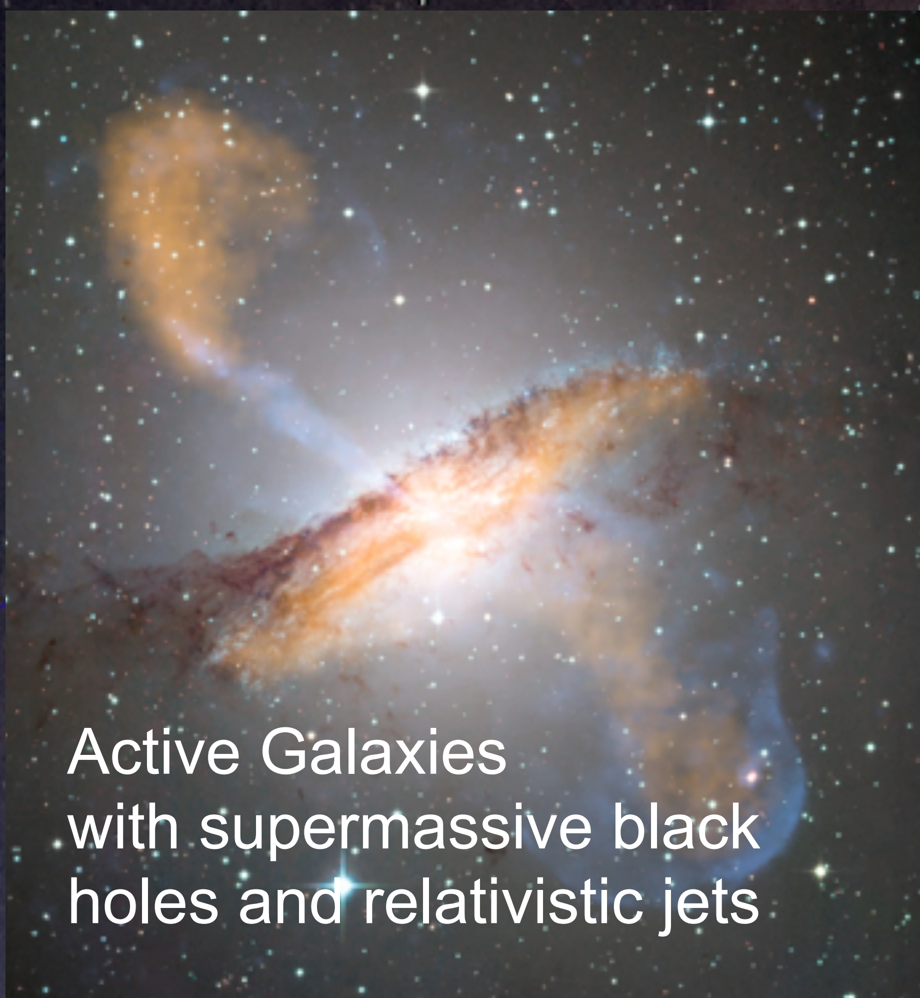




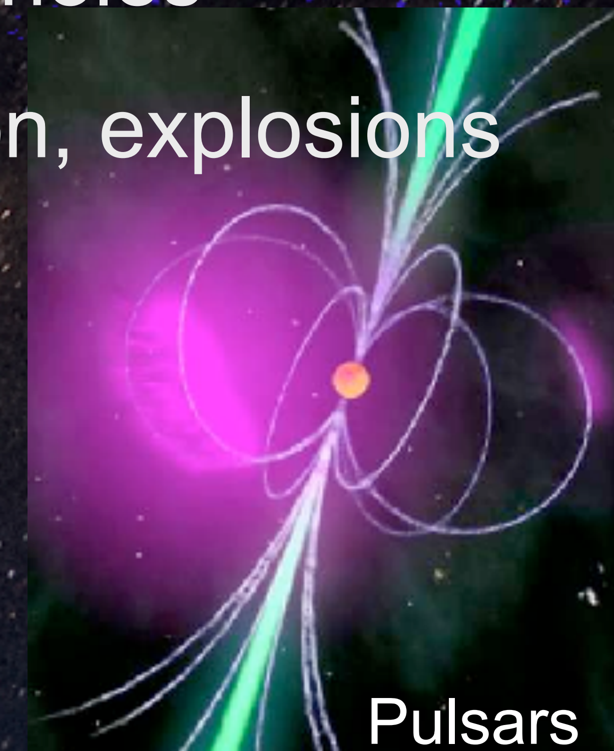
Uchiyama et al 2011

Probing Extreme Environments

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


Active Galaxies
with supermassive black
holes and relativistic jets


Accreting source - binary systems


Pulsars

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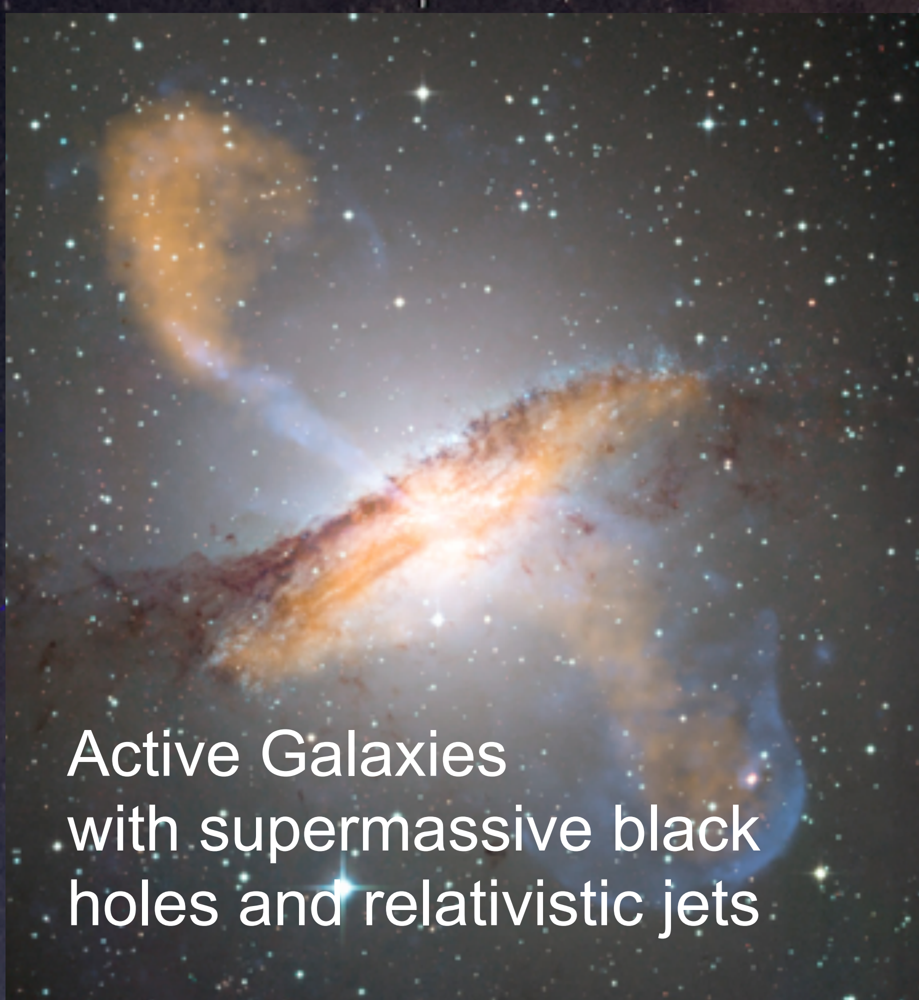
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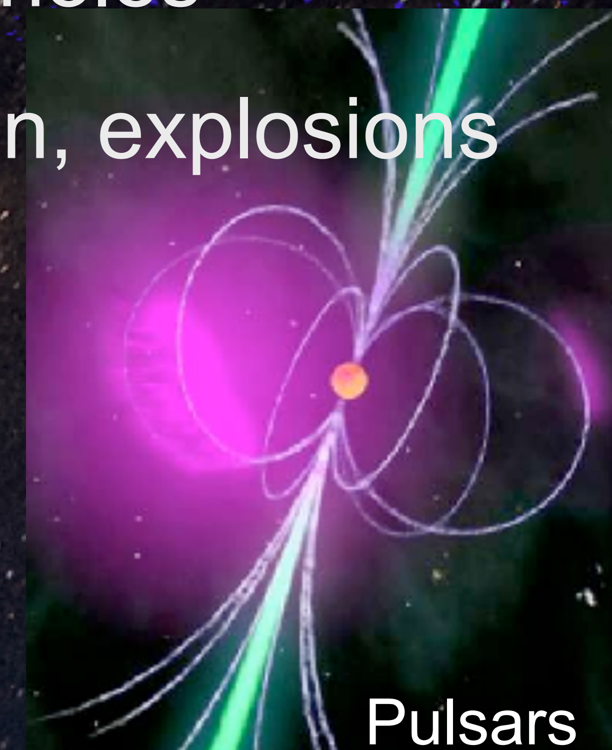
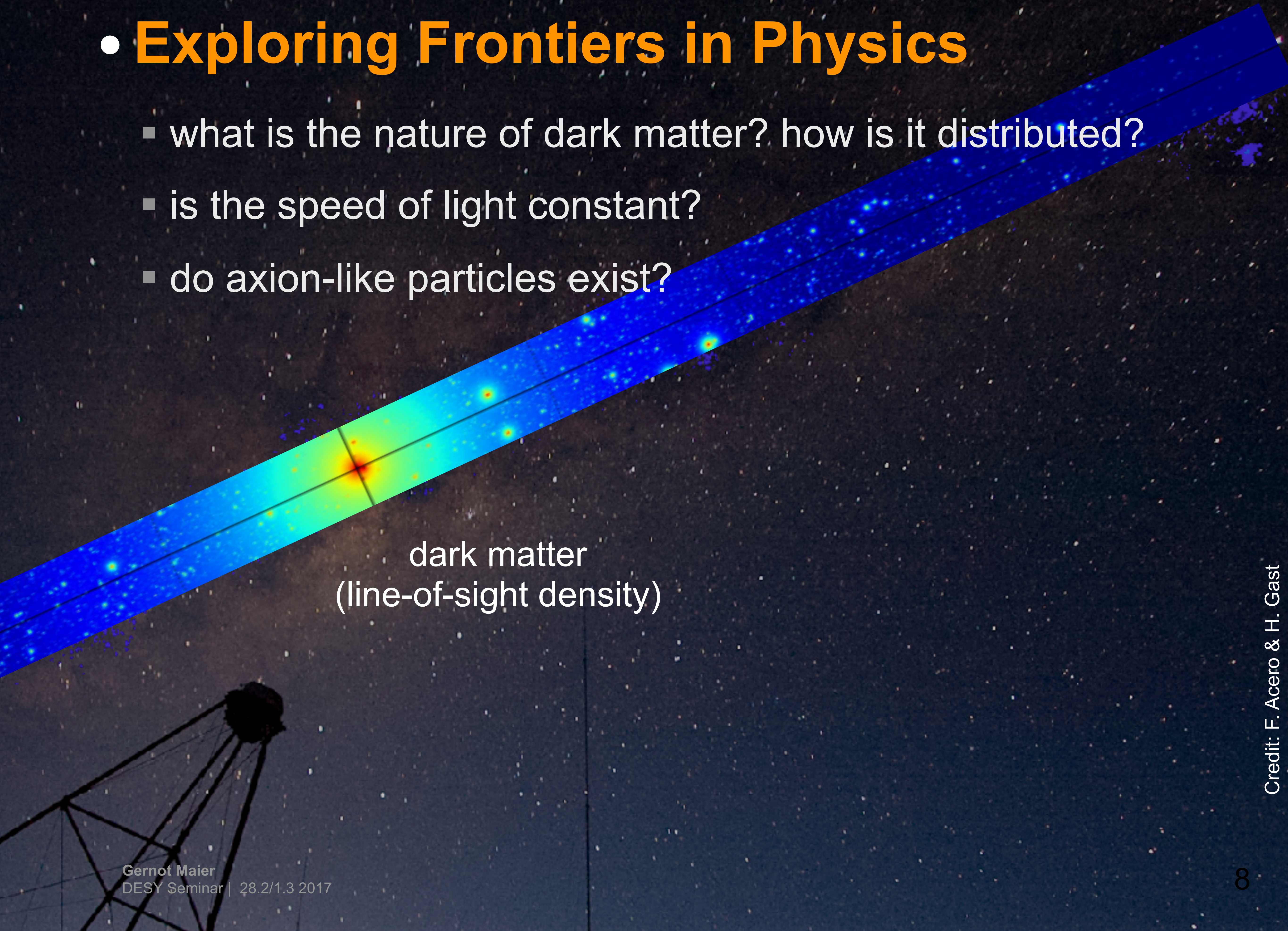

Pulsars

Particle acceleration in black hole systems:

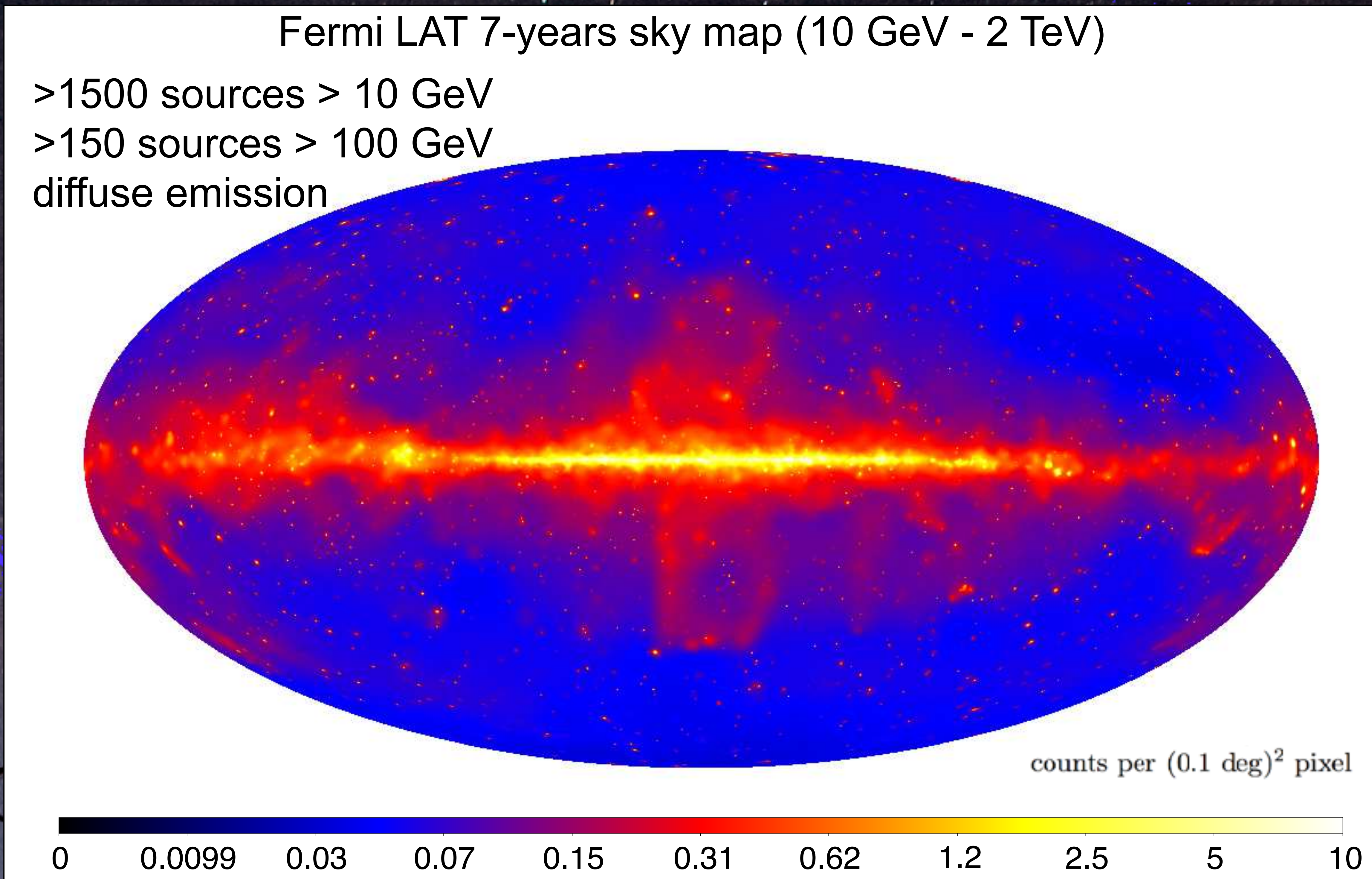
- shocks in relativistic jets / outflow
- magnetospheric origin introduced by rotating black hole
- ….

Credit: F. Acero & H. Gast

- **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?



Gamma-rays from the Universe

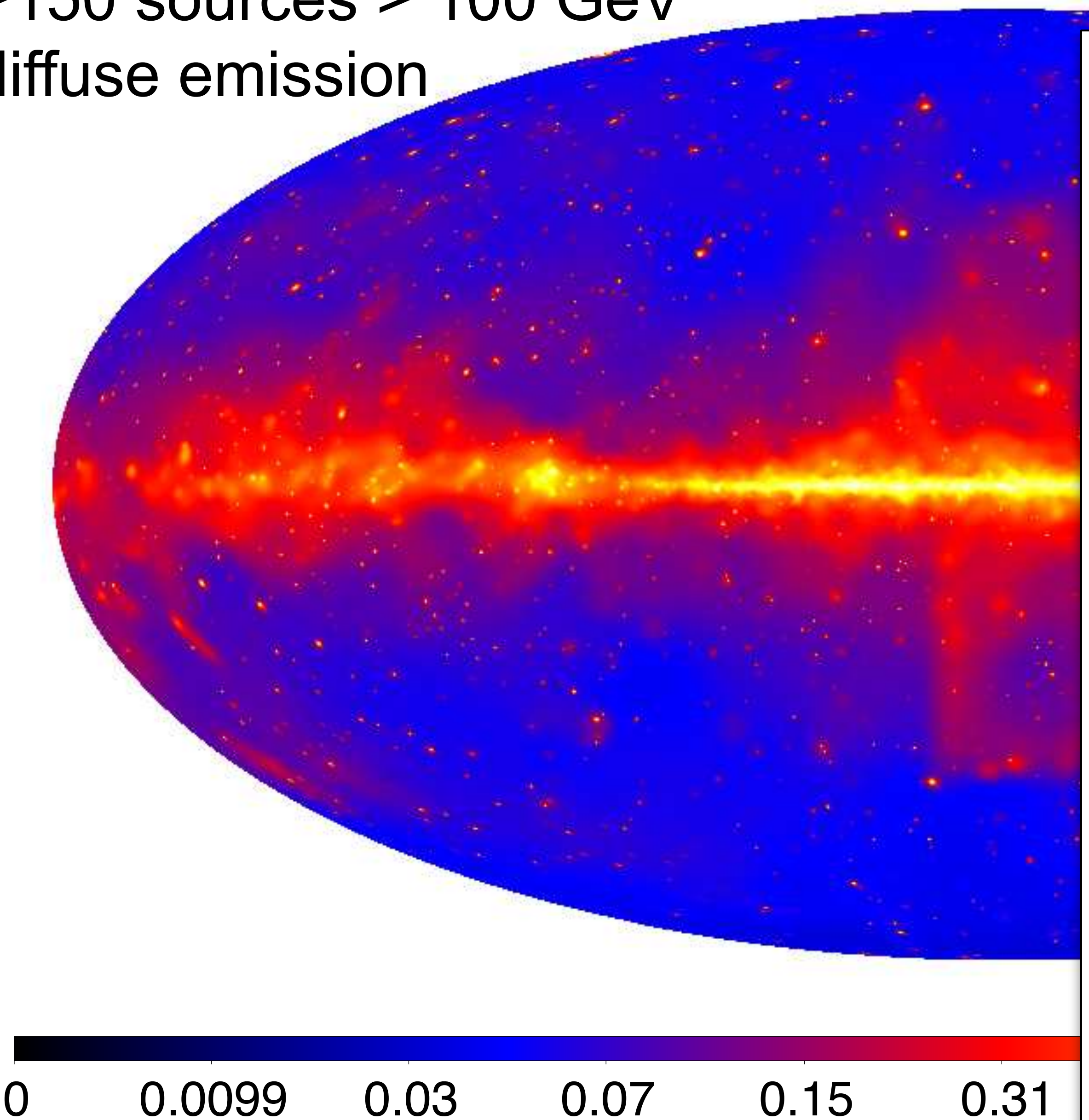


Credit: F. Acero & H. Gast

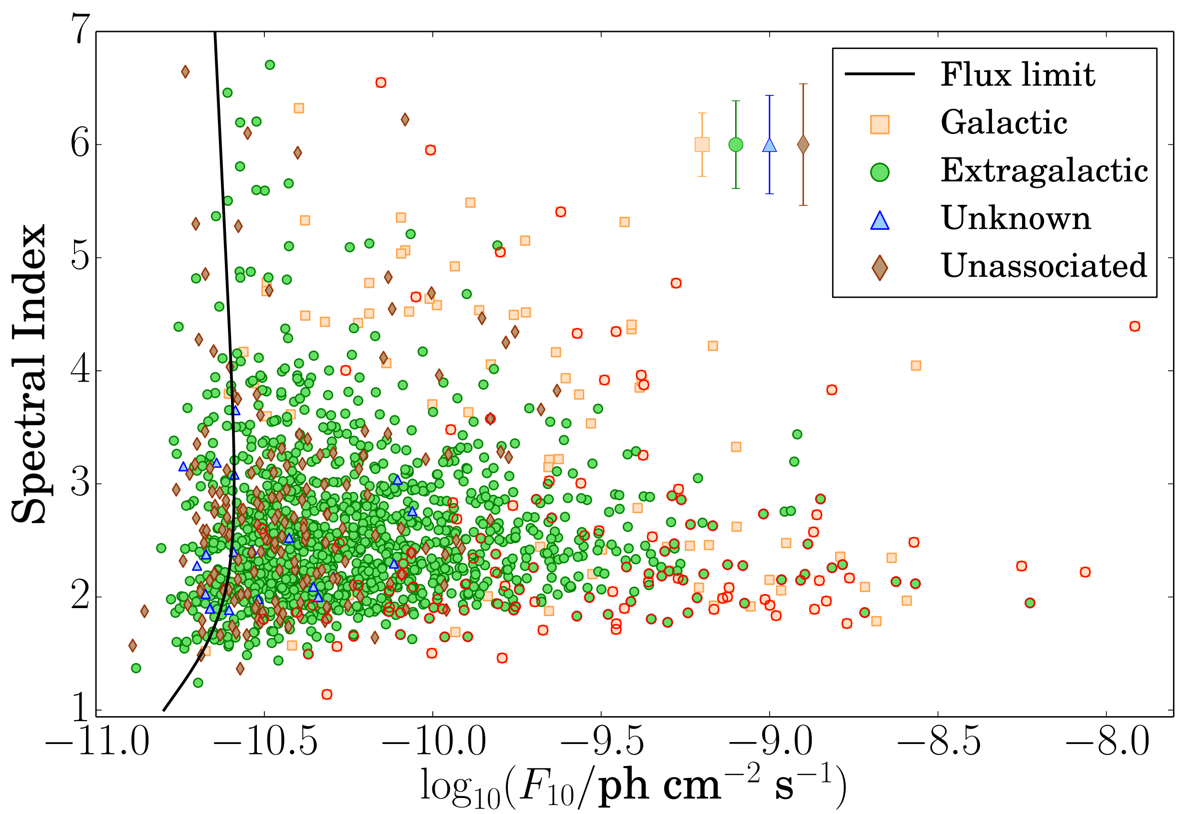
Gamma-rays from the Universe

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

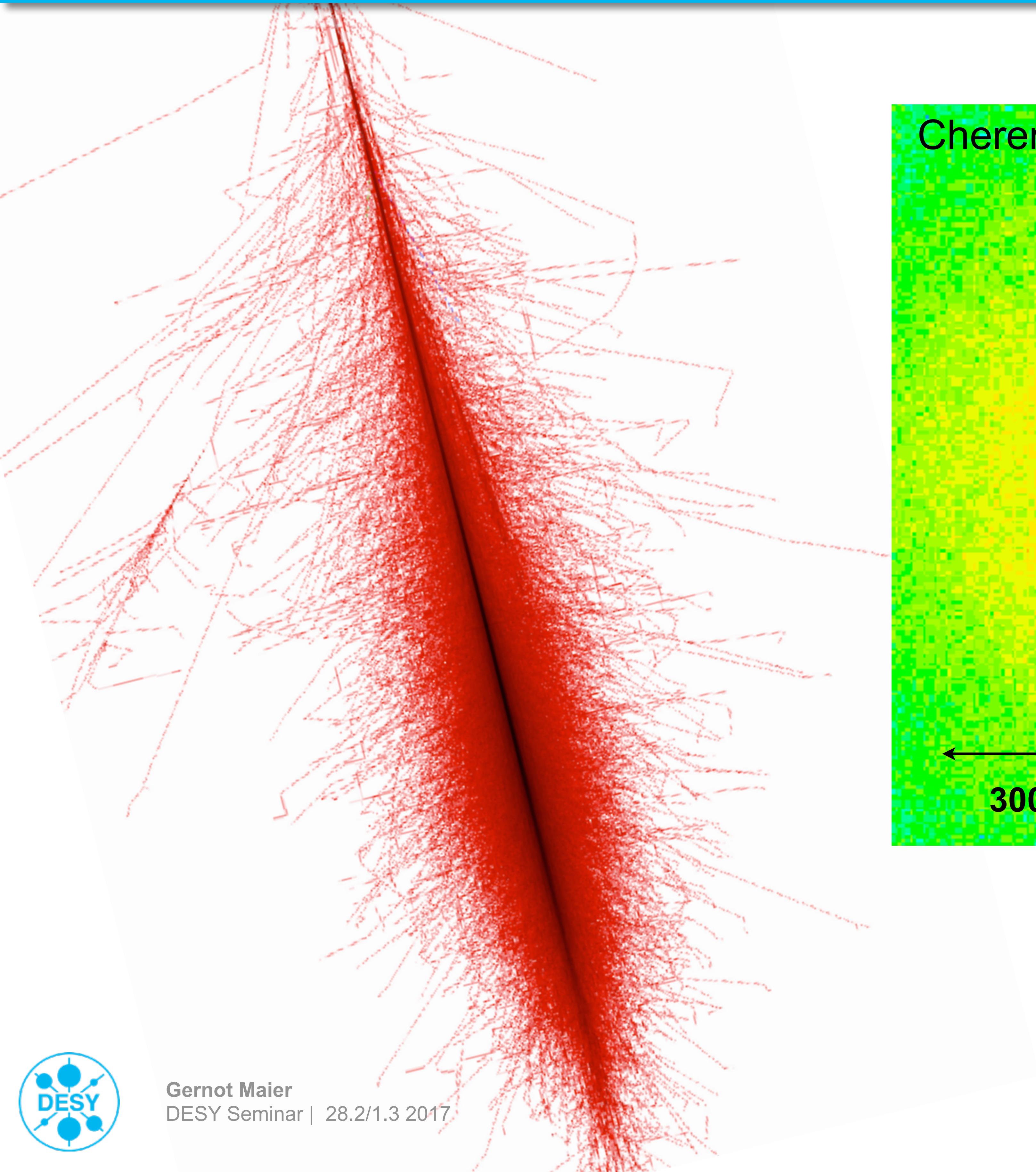
>1500 sources > 10 GeV
>150 sources > 100 GeV
diffuse emission

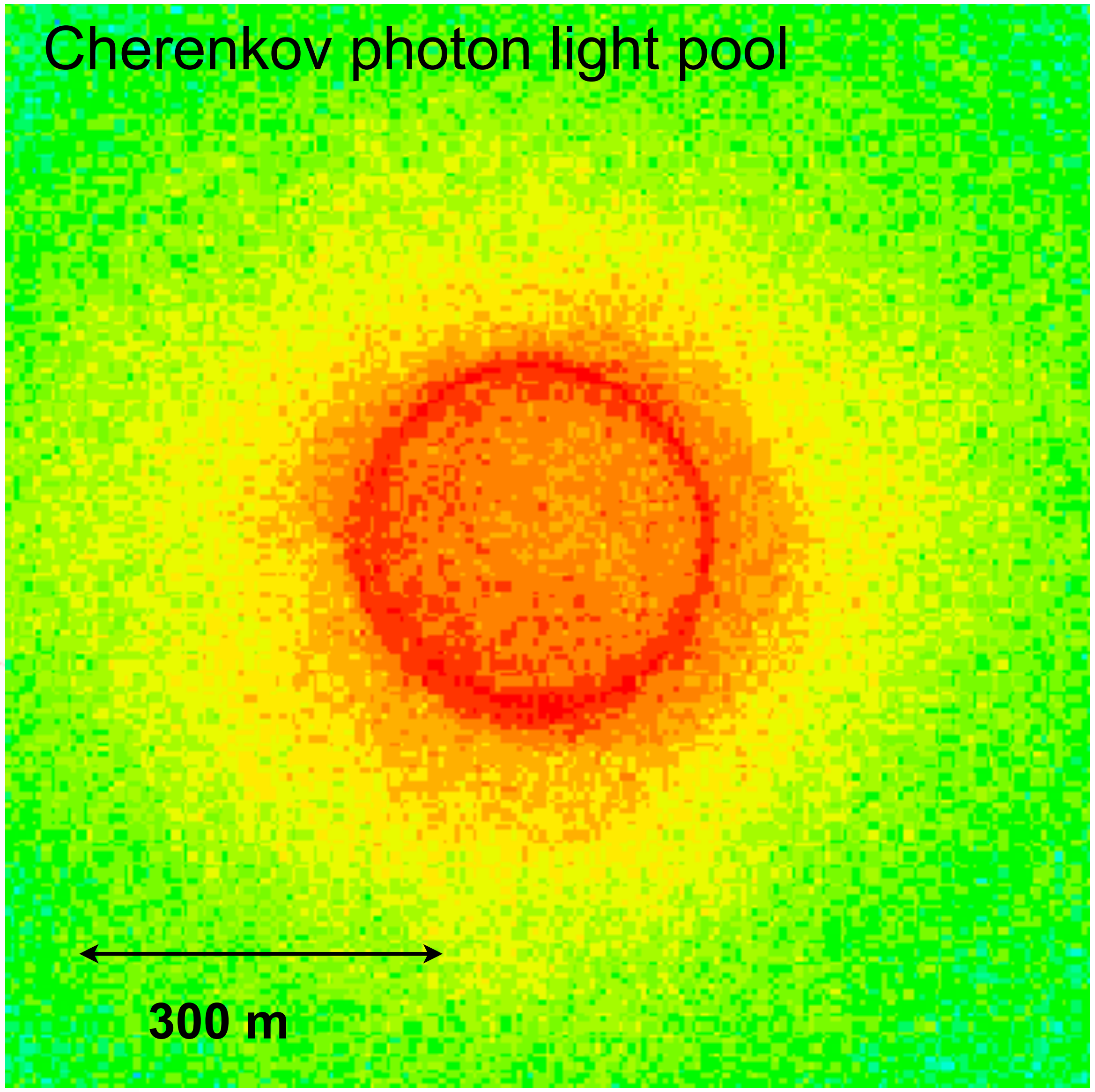


In general:
- weak sources (10^{-10} photons/cm^2/s)
- spectra with power-law like shape



Measuring gamma-rays (20 GeV to 300 TeV)





Nanosecond long flash of blue light; few photons / m^2

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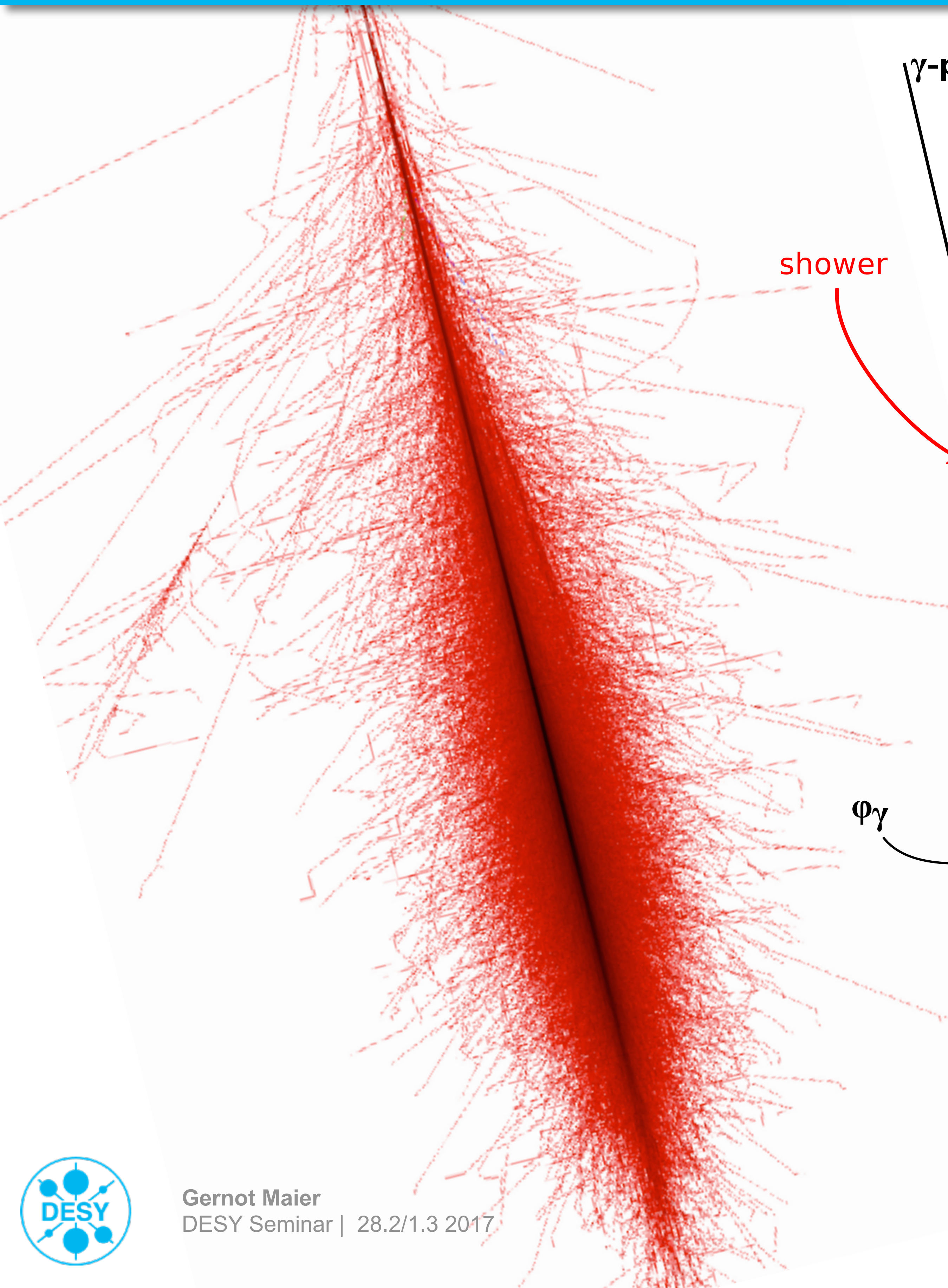
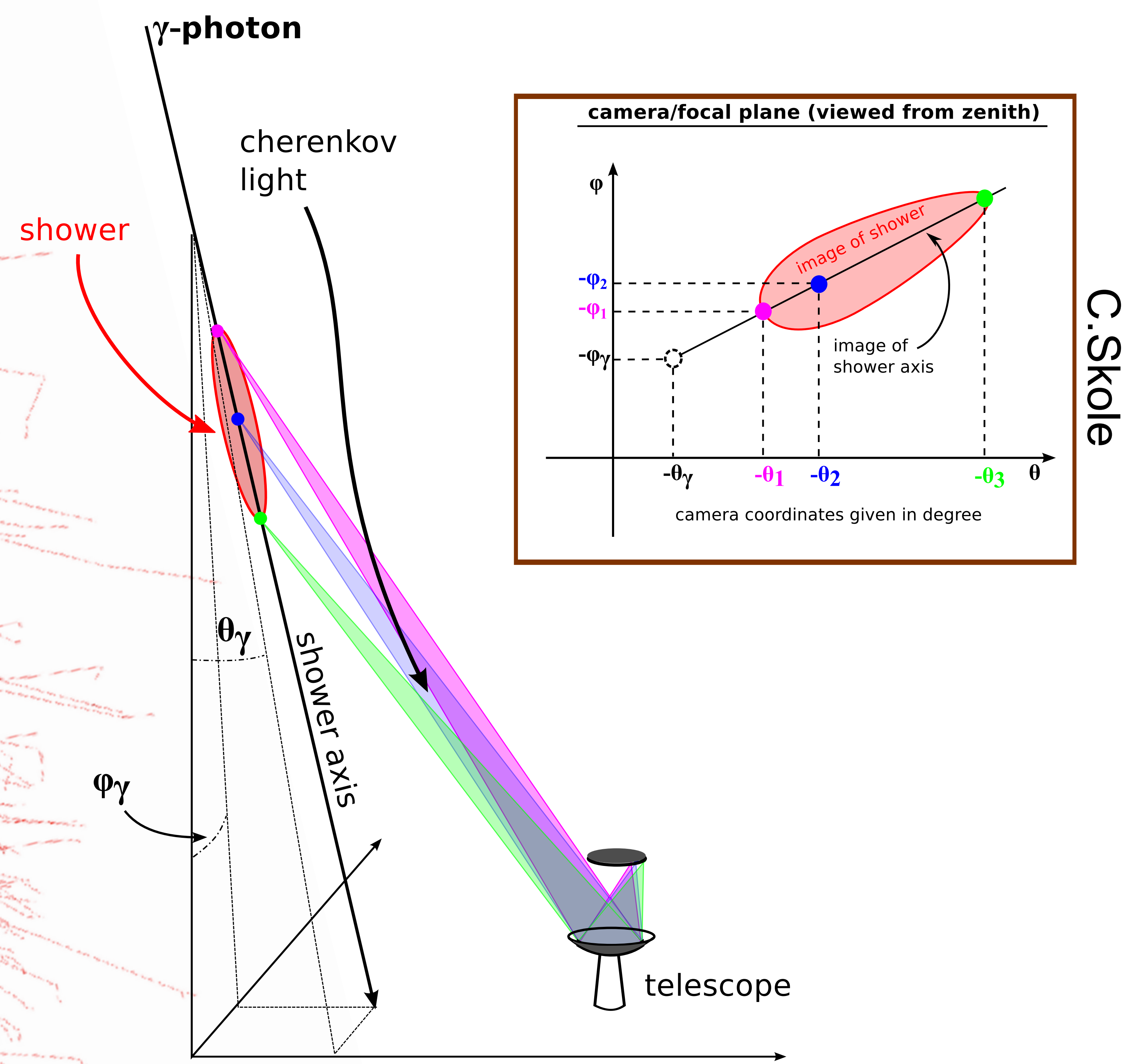
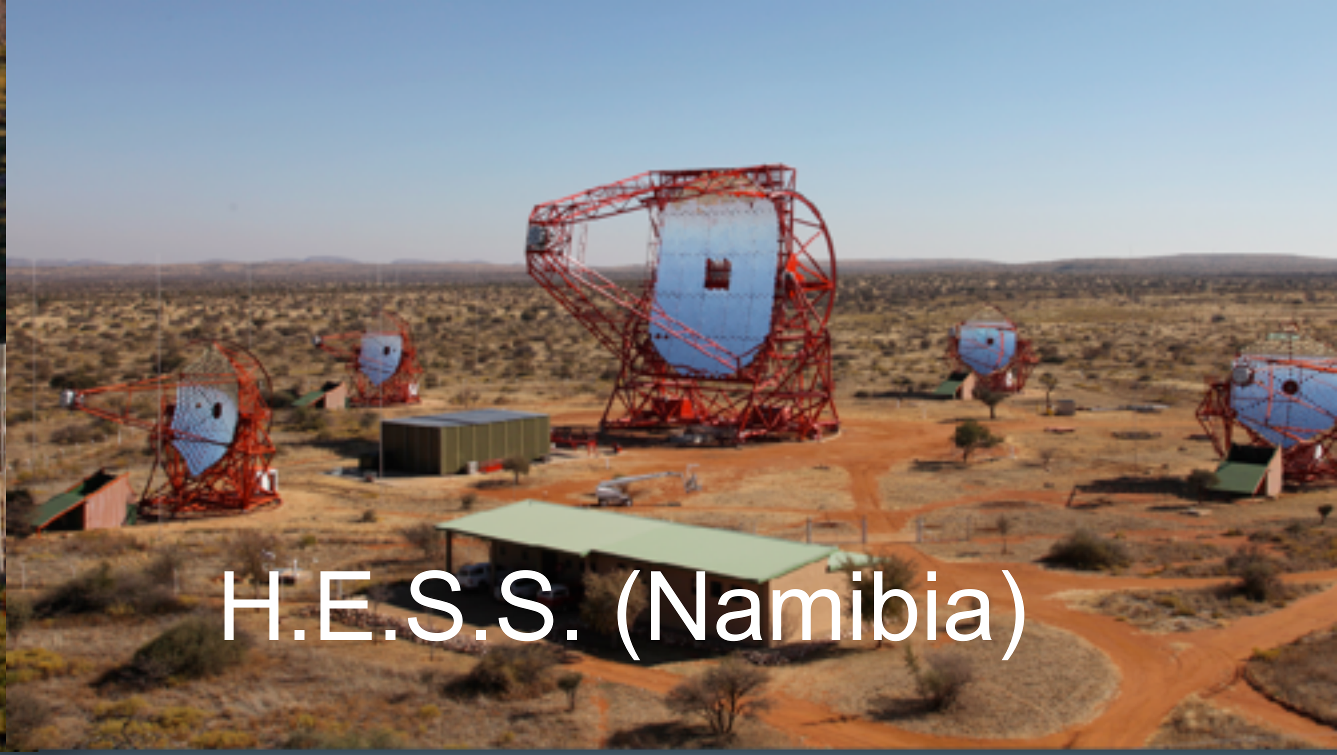




Nanosecond long flash of blue light; few photons / m²


MAGIC (La Palma)


H.E.S.S. (Namibia)


VERITAS (Arizona)

Science drivers and requirements to the instrument

> Cosmic Particle Acceleration

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

> Probing Extreme Environments

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

> Beyond the standard model

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

Science drivers and requirements to the instrument

large field of view

all sky coverage

flux sensitivity

energy range

angular resolution

- **>** Cosmic Particle Acceleration
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  - how do they propagate?
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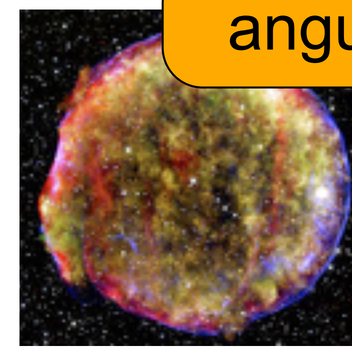

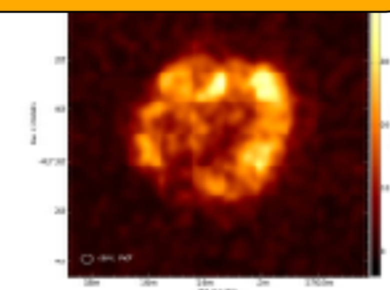

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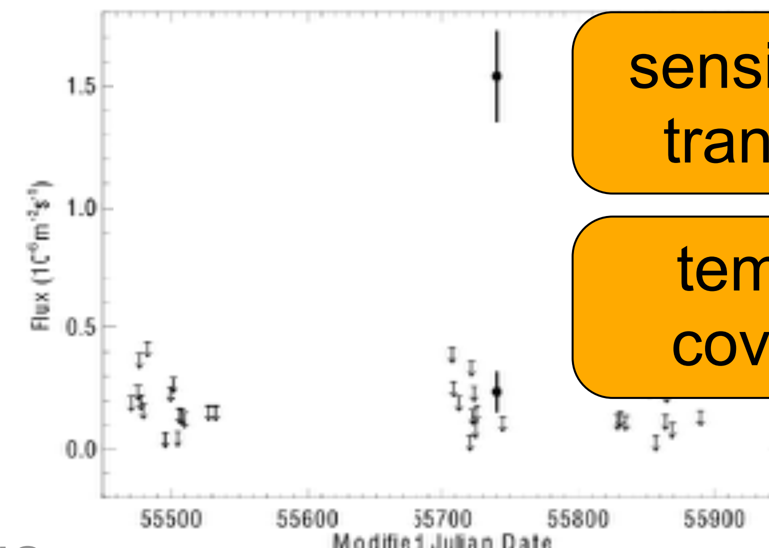

sensitivity to transients

temporal coverage

- **>** Beyond the standard model
  - what is the nature of dark matter? how is it distributed?
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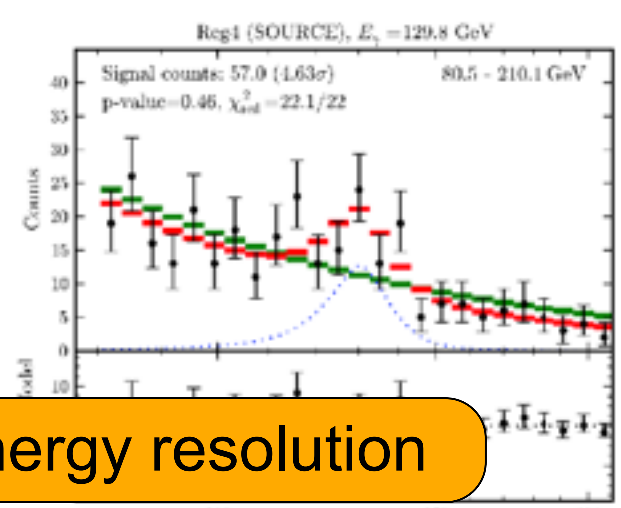
rapid slewing

duty cycle



energy resolution

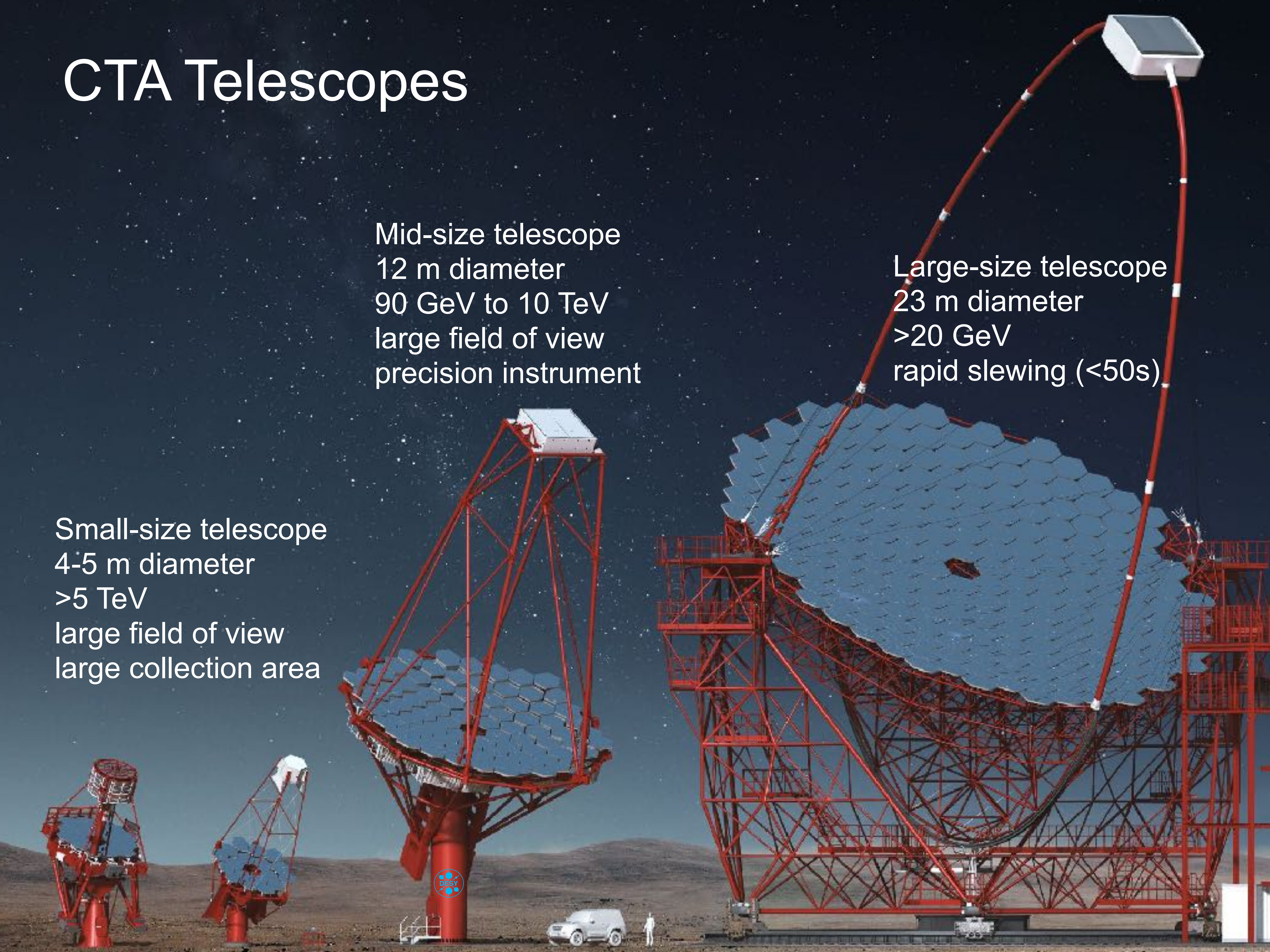
flexibility in operation

CTA Telescopes

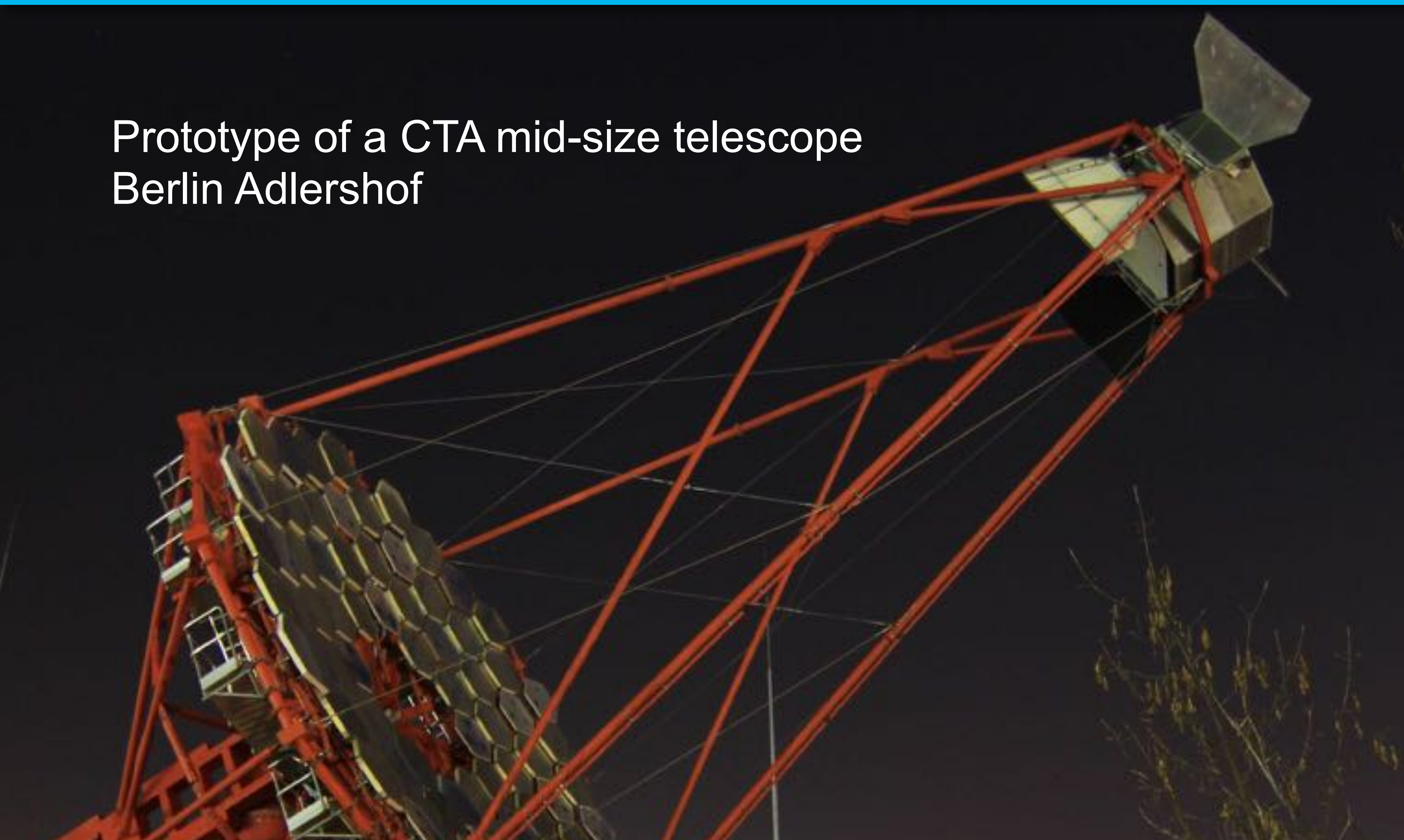
Mid-size telescope
12 m diameter
90 GeV to 10 TeV
large field of view
precision instrument

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)

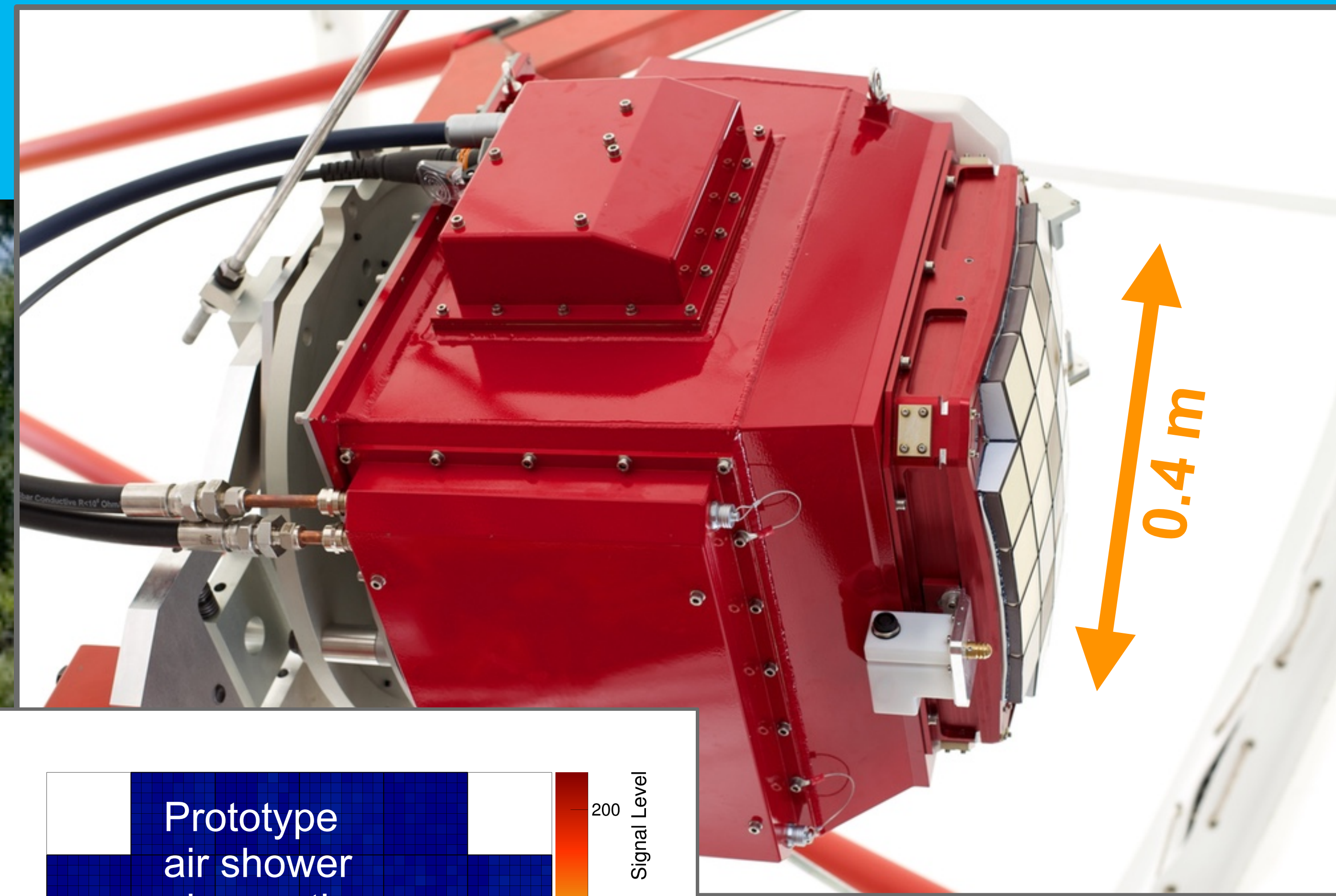
Small-size telescope
(Meudon)

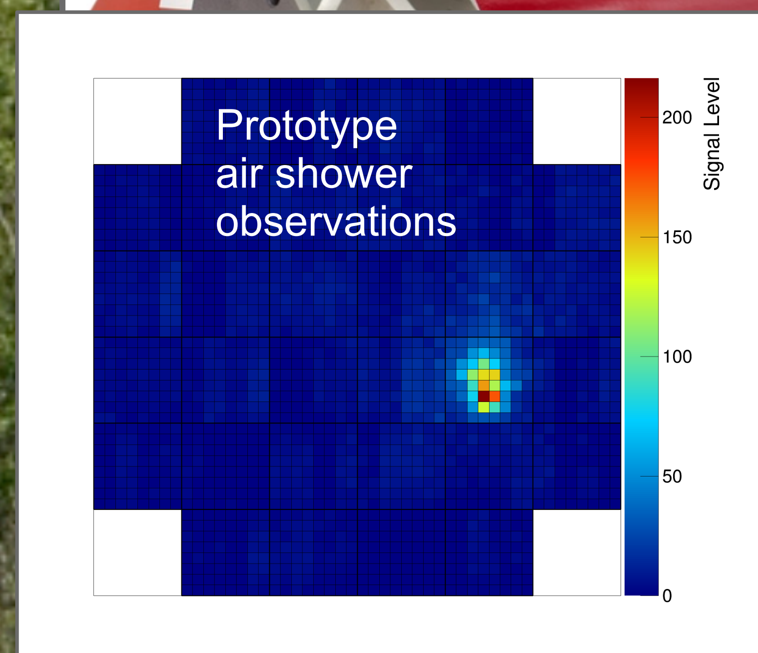
Small-size telescope
(Krakow)

Small-size telescope
(Sicily)

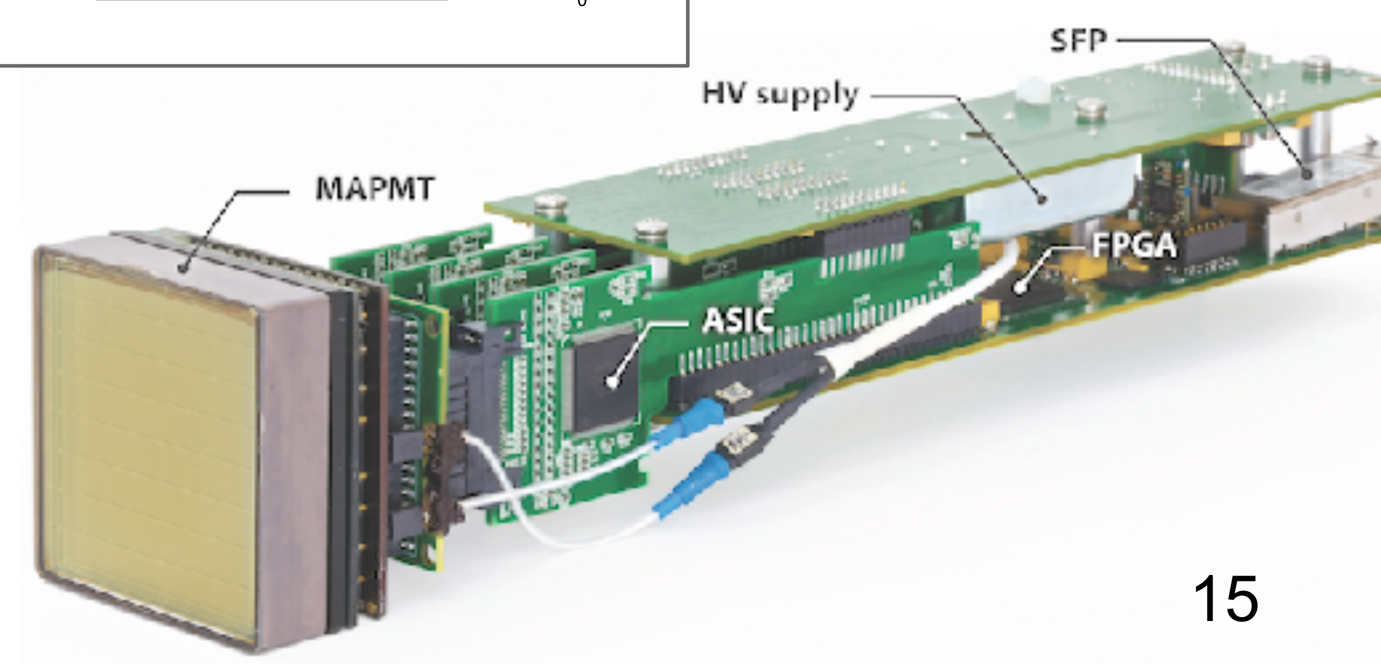
Prototype Cameras

FlashCam camera for mid-size telescopes

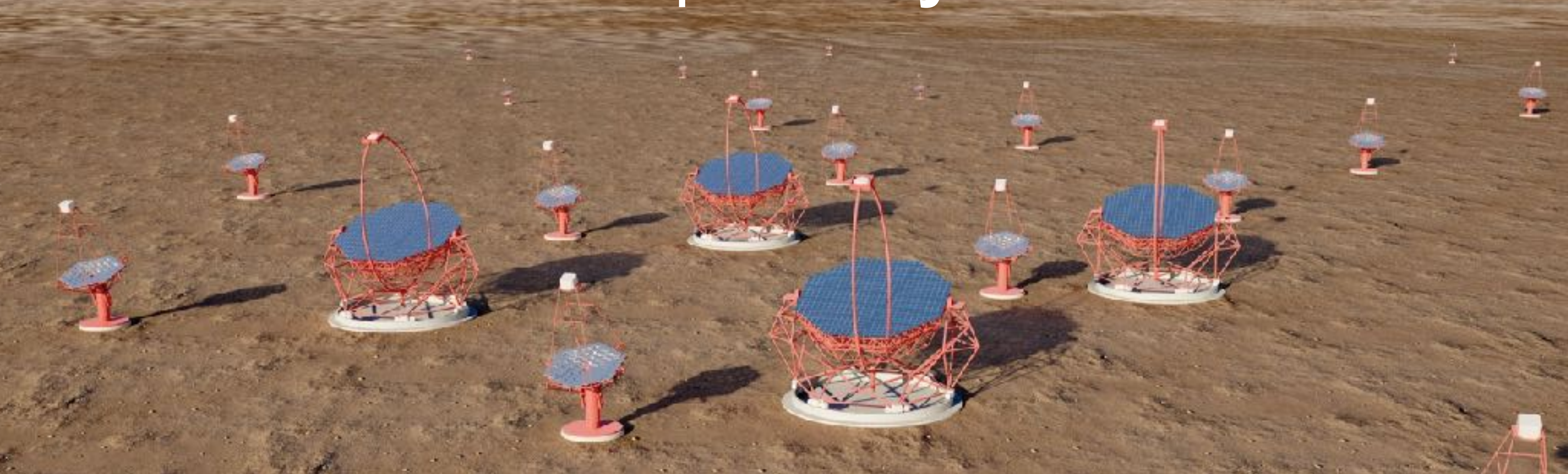




MAPM Camera small-size telescope



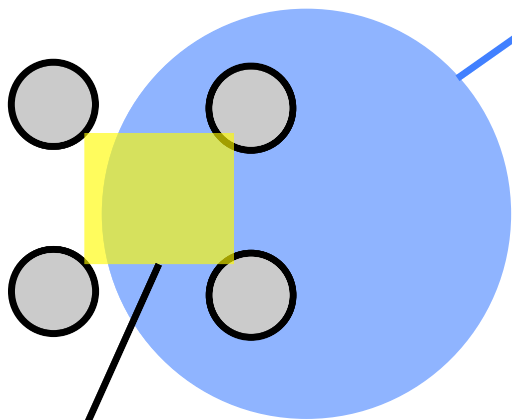
Cherenkov Telescope **Array**



CTA Southern Site
Paranal, Chile
4 large size telescopes
25 mid-size telescopes
70 small size telescopes

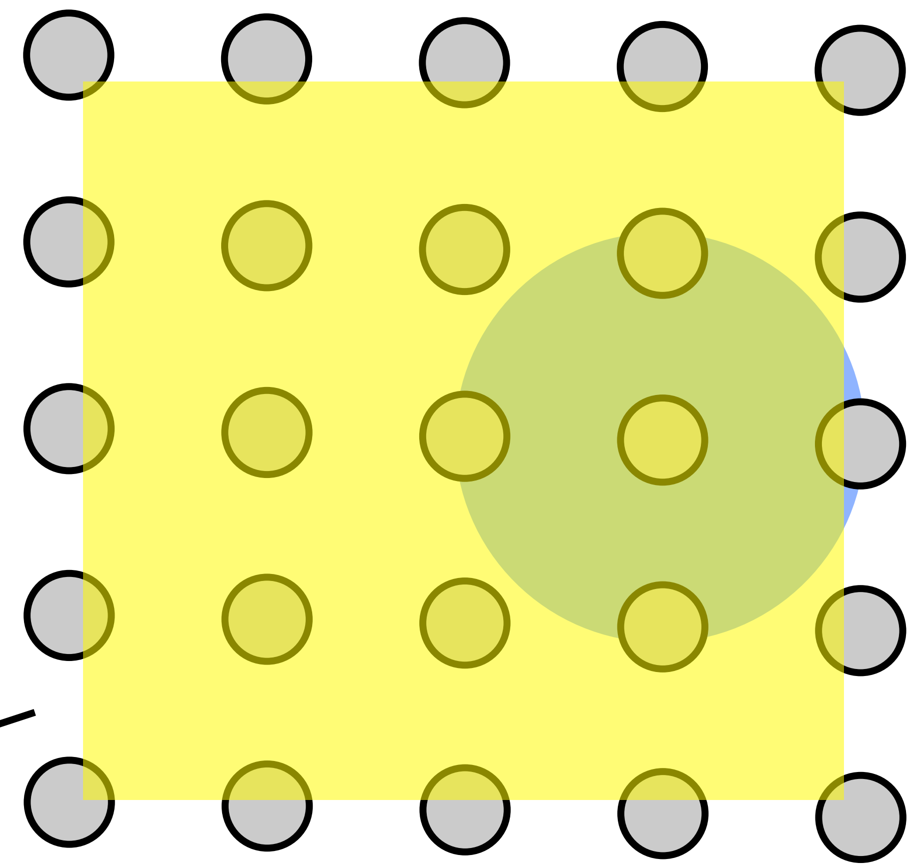
CTA Northern Site
La Palma Island
4 large-size telescopes
15 mid-size telescopes

Large arrays of Cherenkov Telescopes



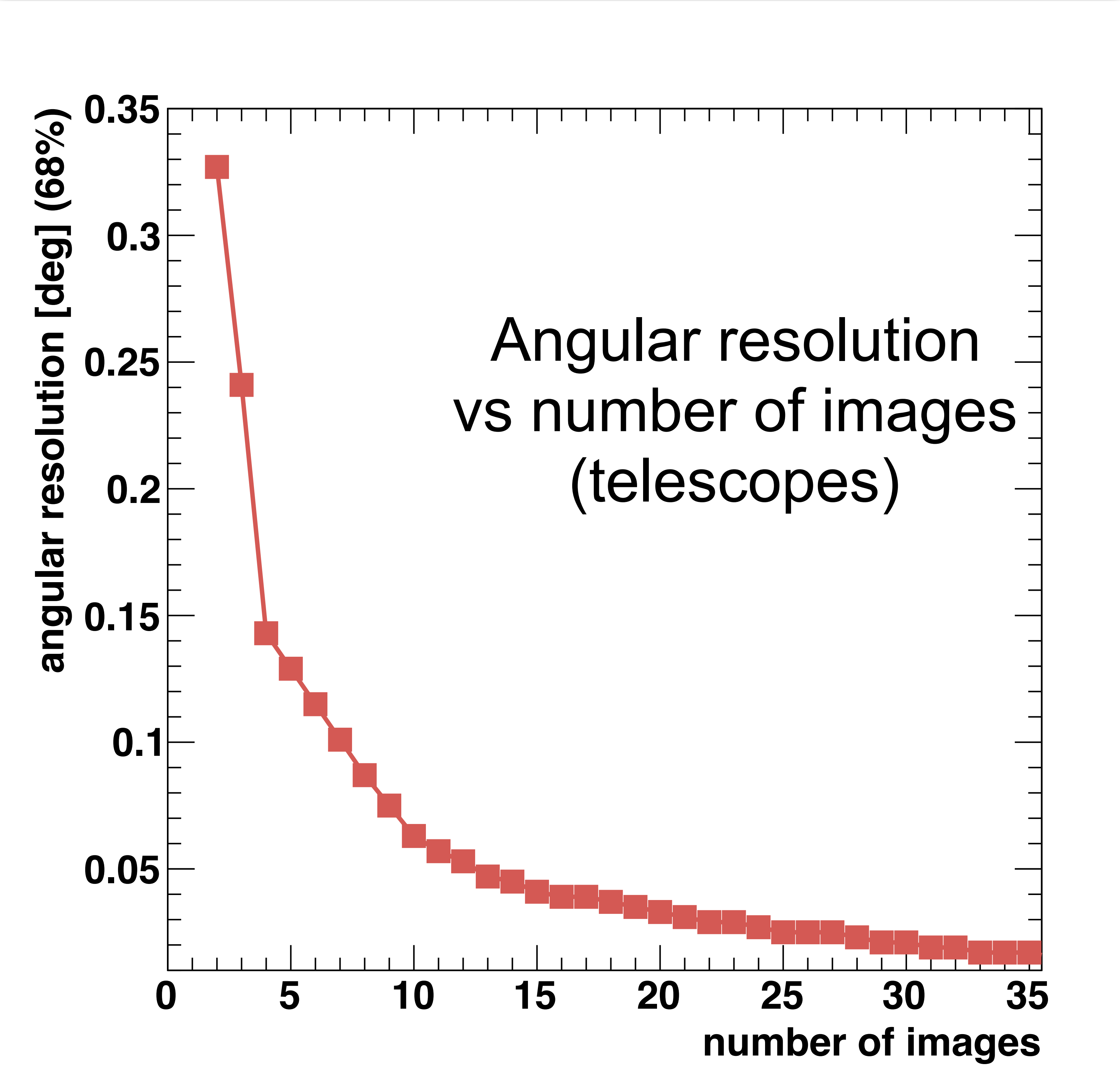
light pool radius
R ≈100-150 m
≈ typical telescope spacing

Sweet spot for
best triggering
and reconstruction:
most showers miss it!

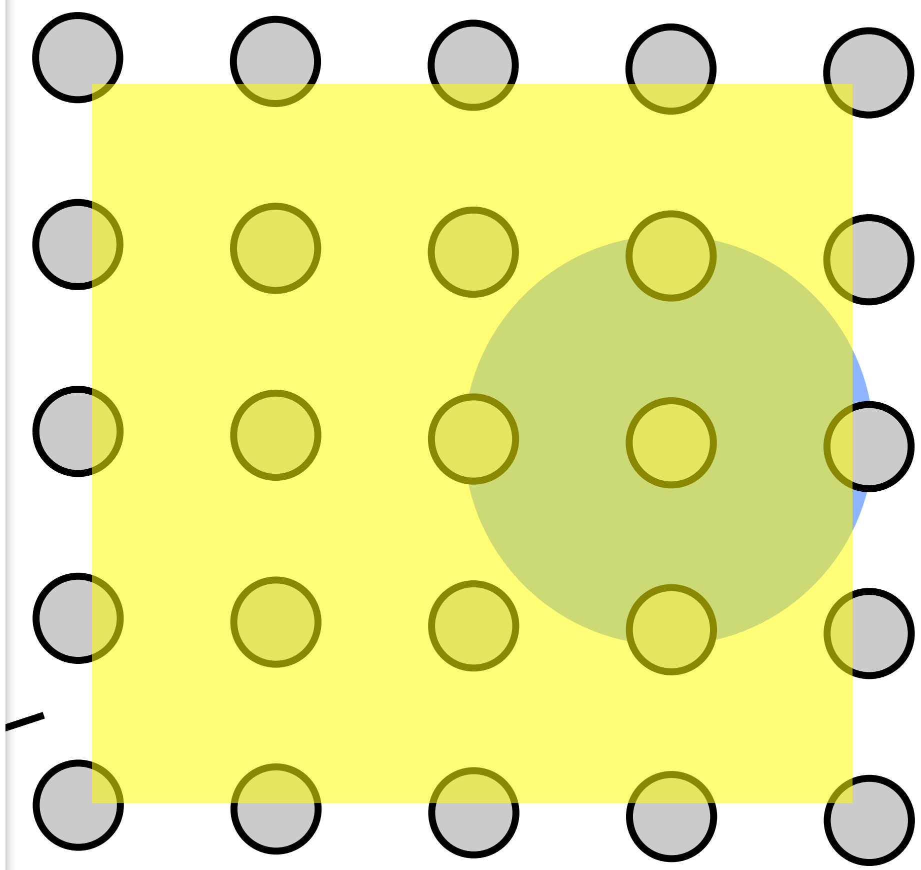


large detection area
more images per shower
lower trigger threshold

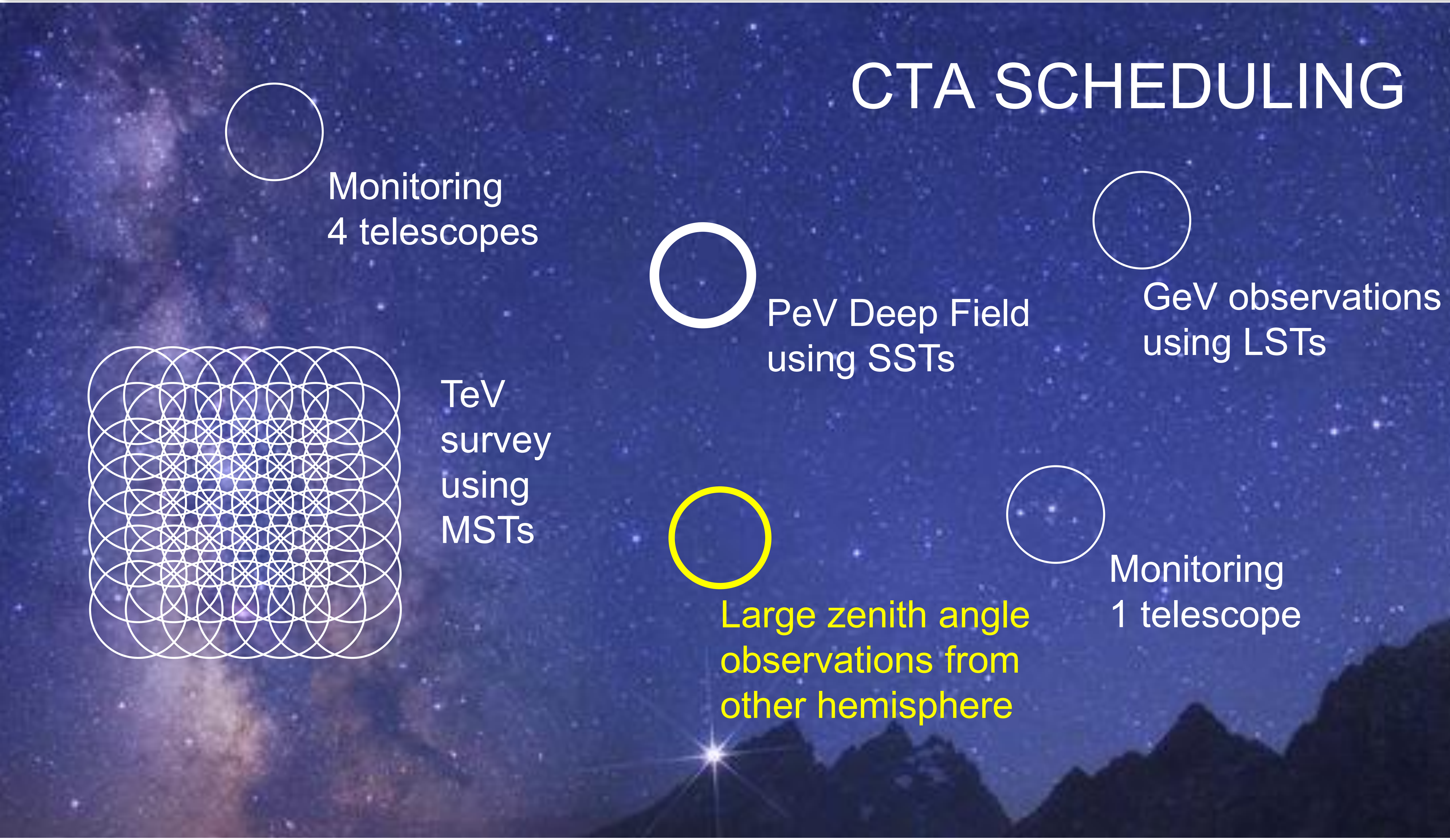
Large arrays of Cherenkov Telescopes



spacing



Flexibility: Surveys and Monitoring



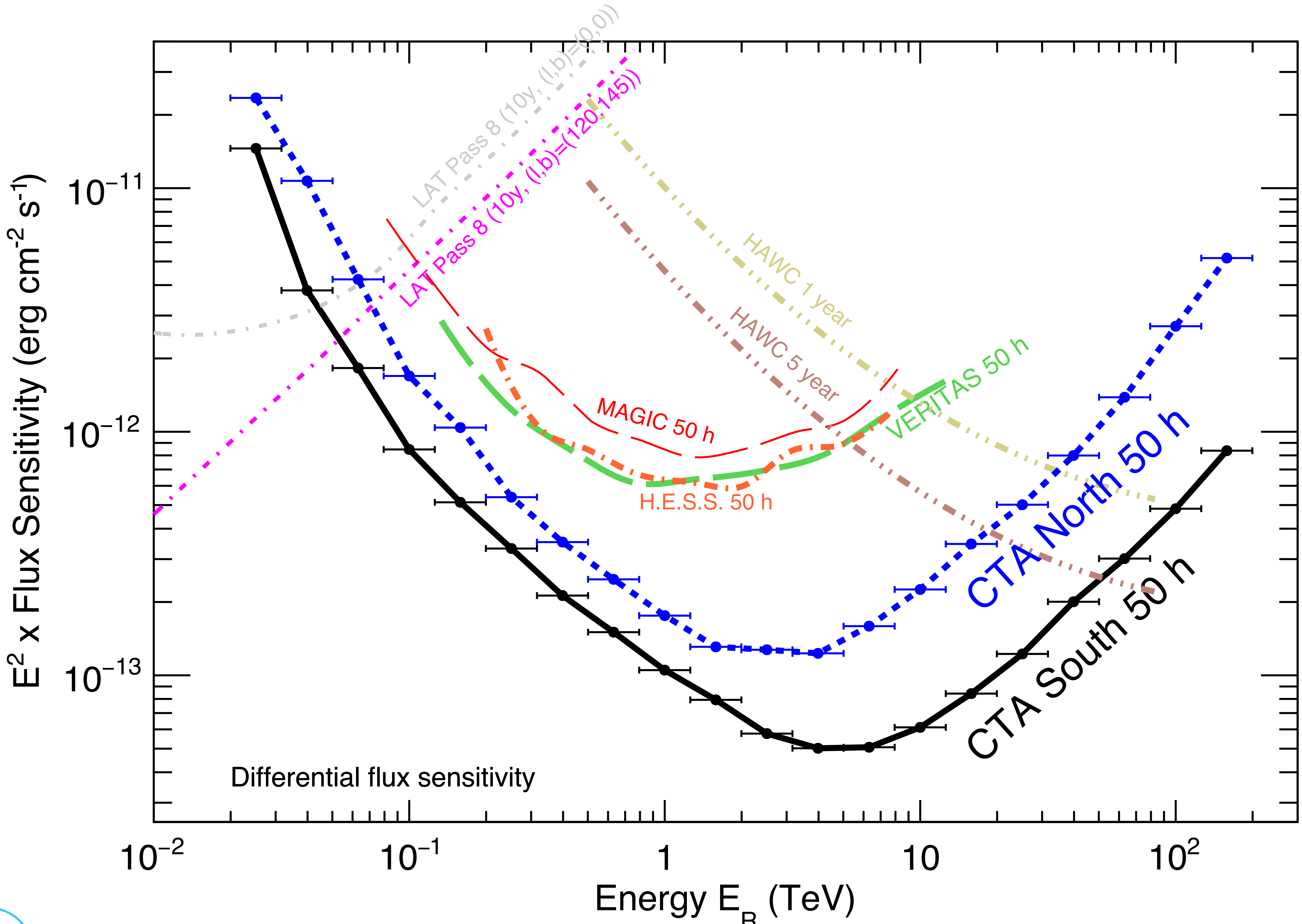
CTA Site Paranal

CTA Site La Palma

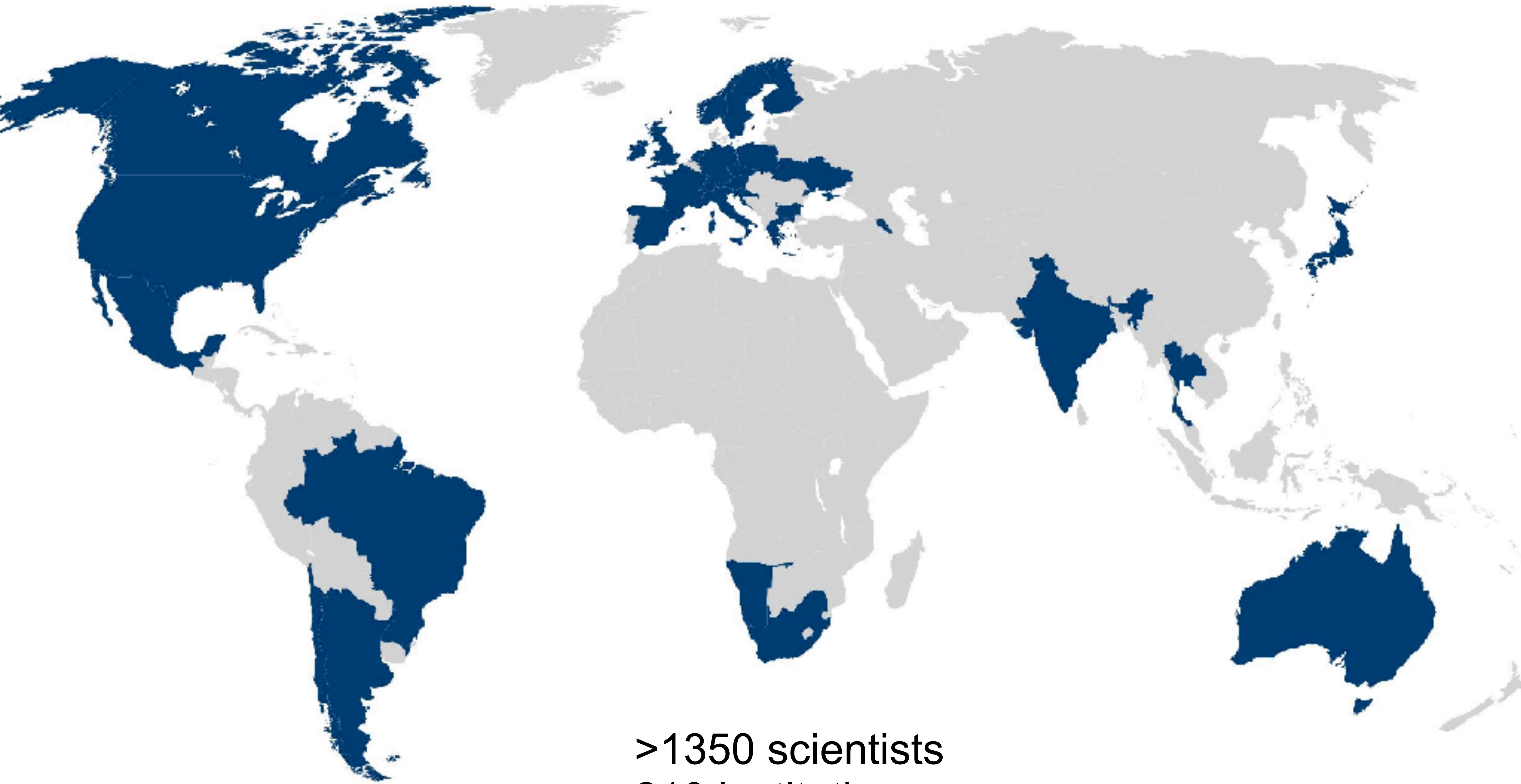
Roque de los Muchachos Observatory, La Palma, Spain

CTA Performance

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



The CTA consortium



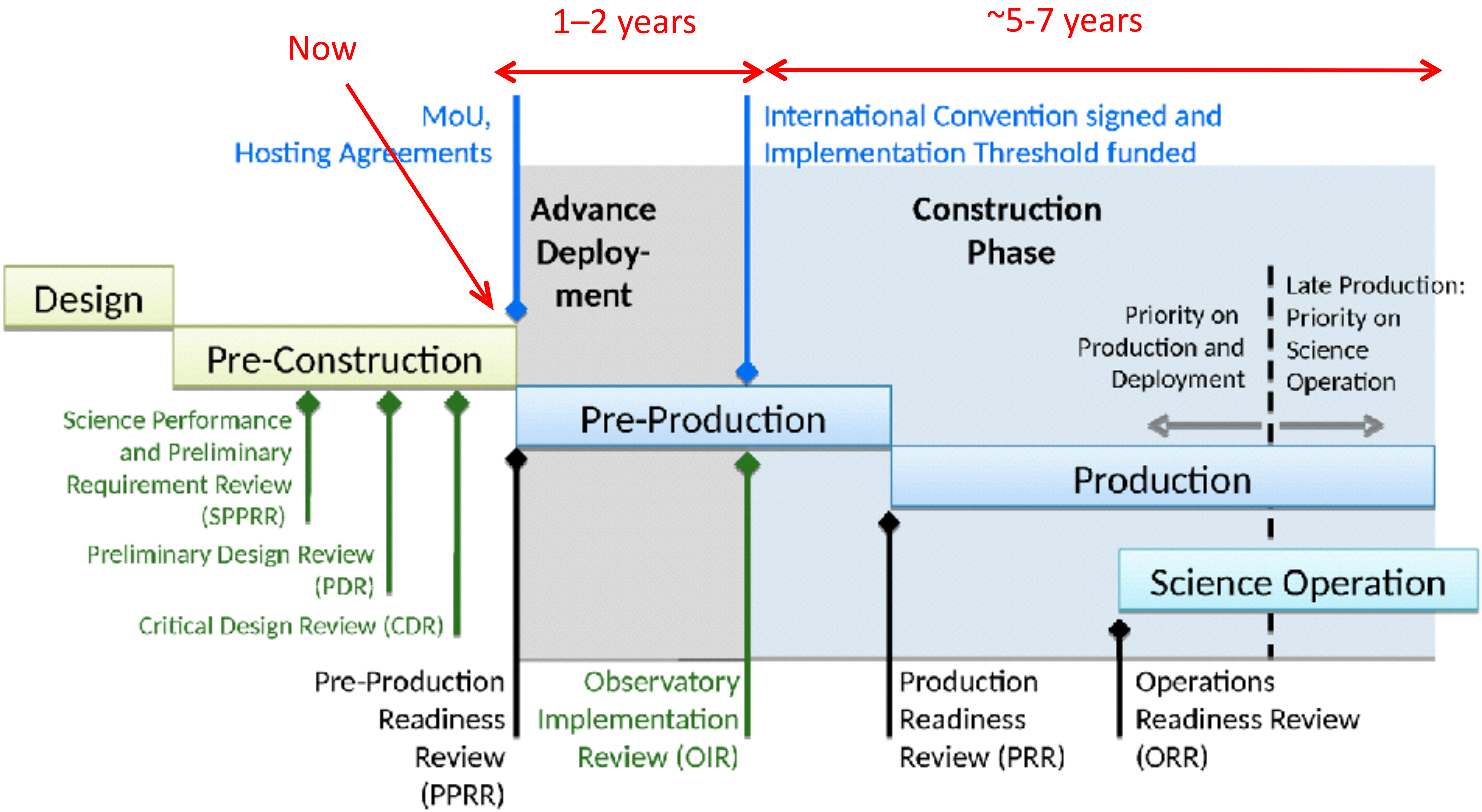
>1350 scientists
210 institutions
32 countries

CTA Science Data Management Centre - DESY

Headquarters (CTA operation) in Bologna

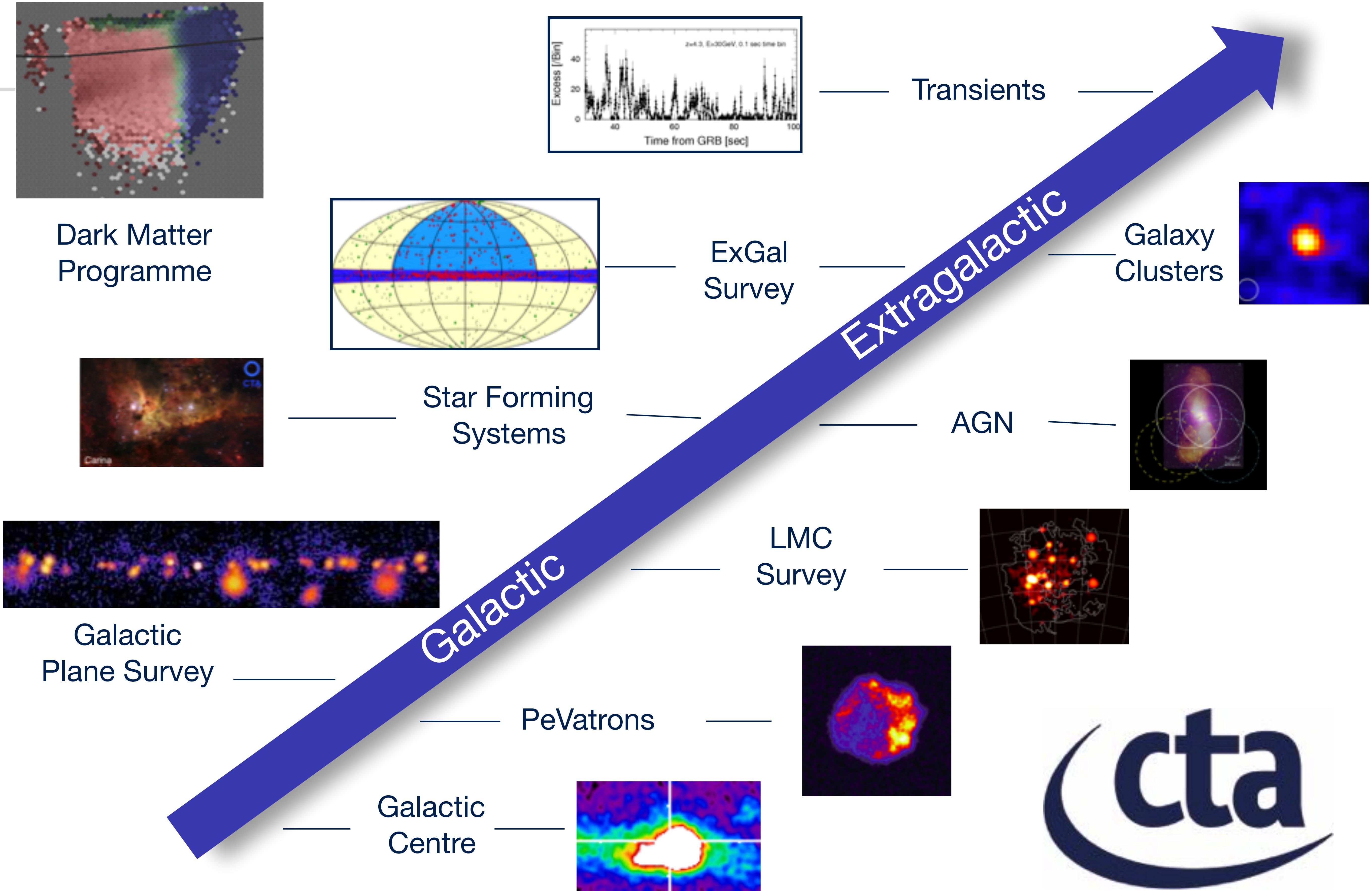
CTA Timeline

Release of official CTA Integrated Project Schedule in summer 2017

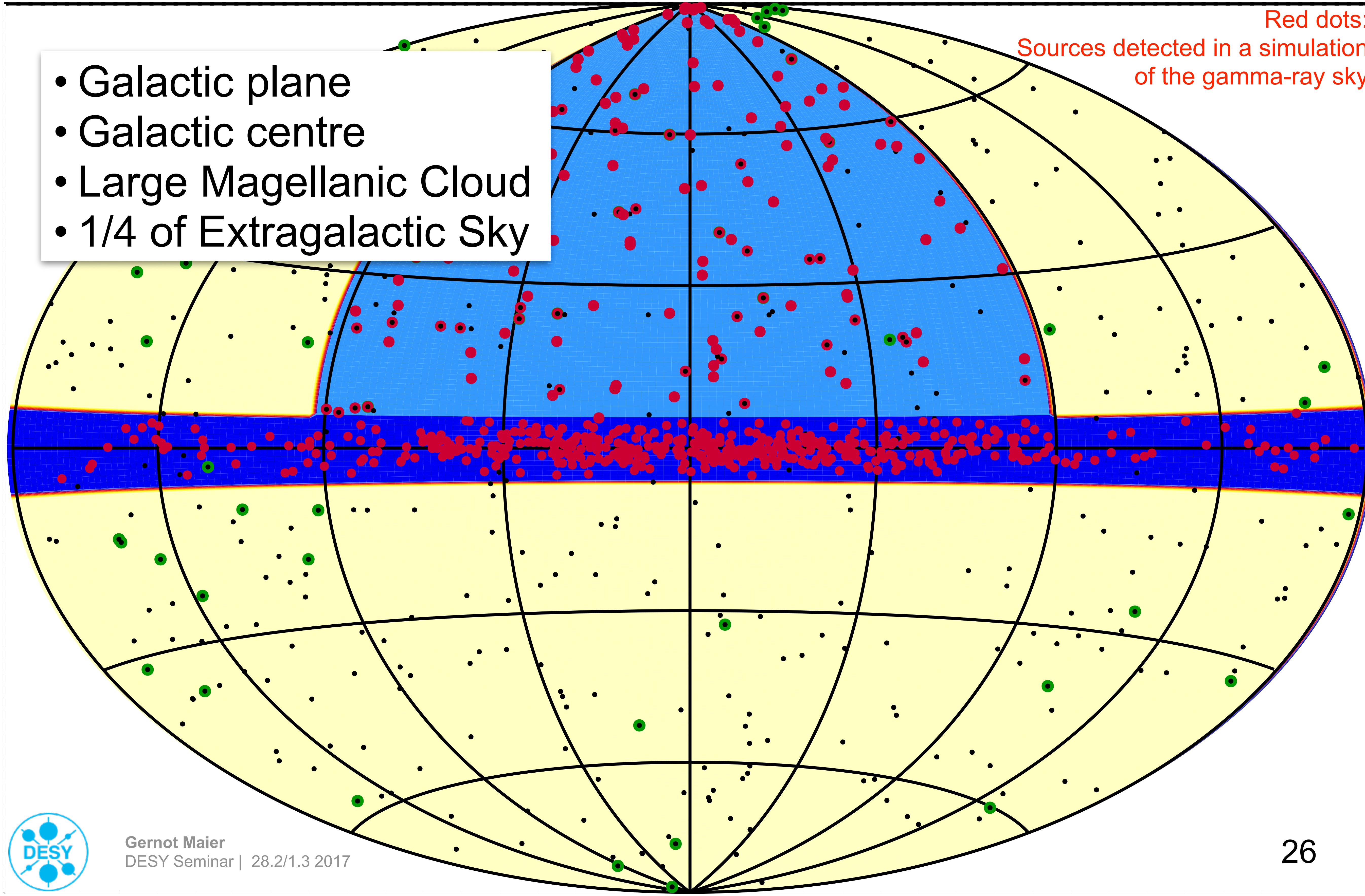


OIR is a global
external gateway
review

CTA Key Science Projects



CTA Surveys - an unbiased census of particle acceleration



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

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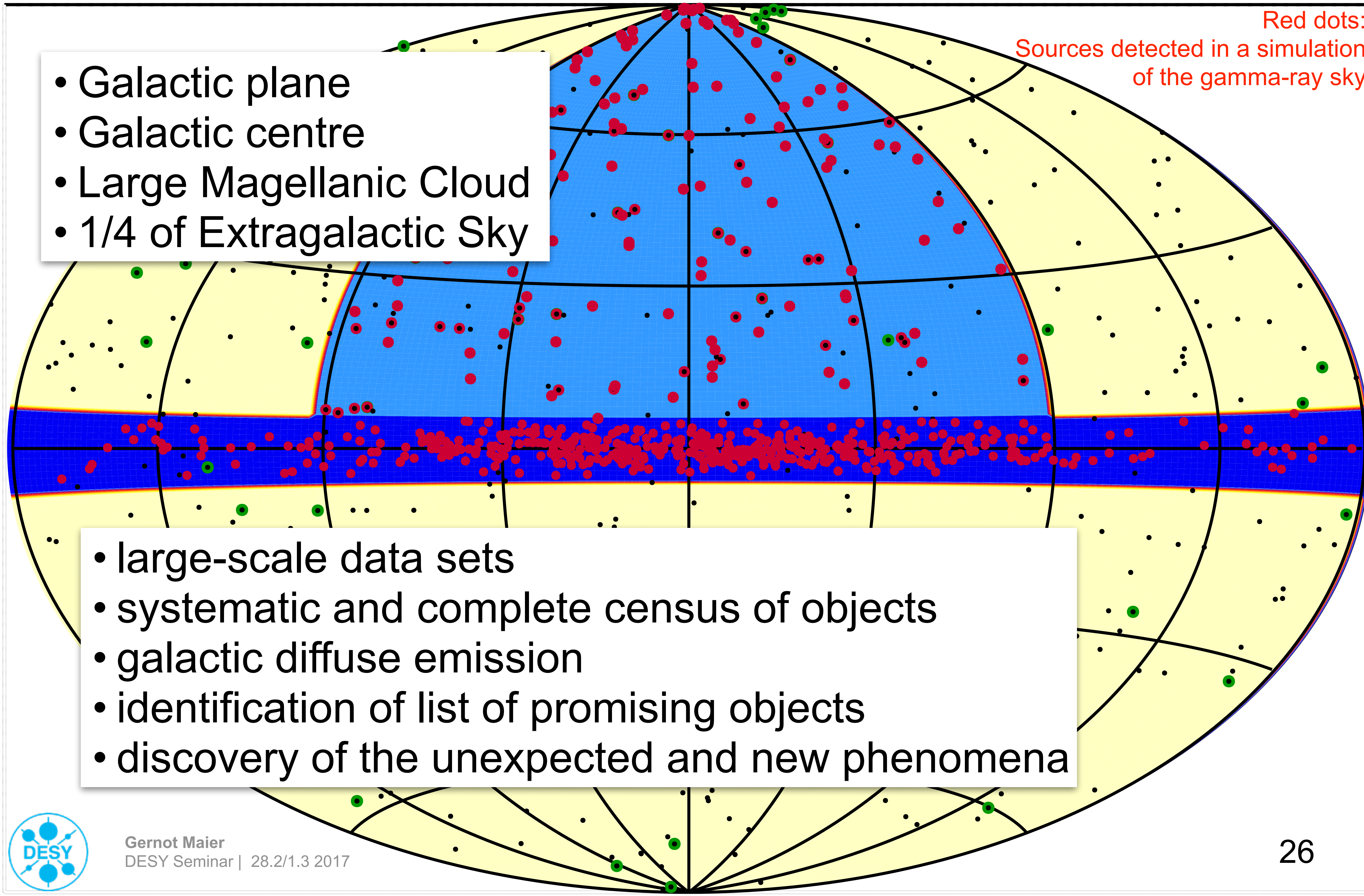
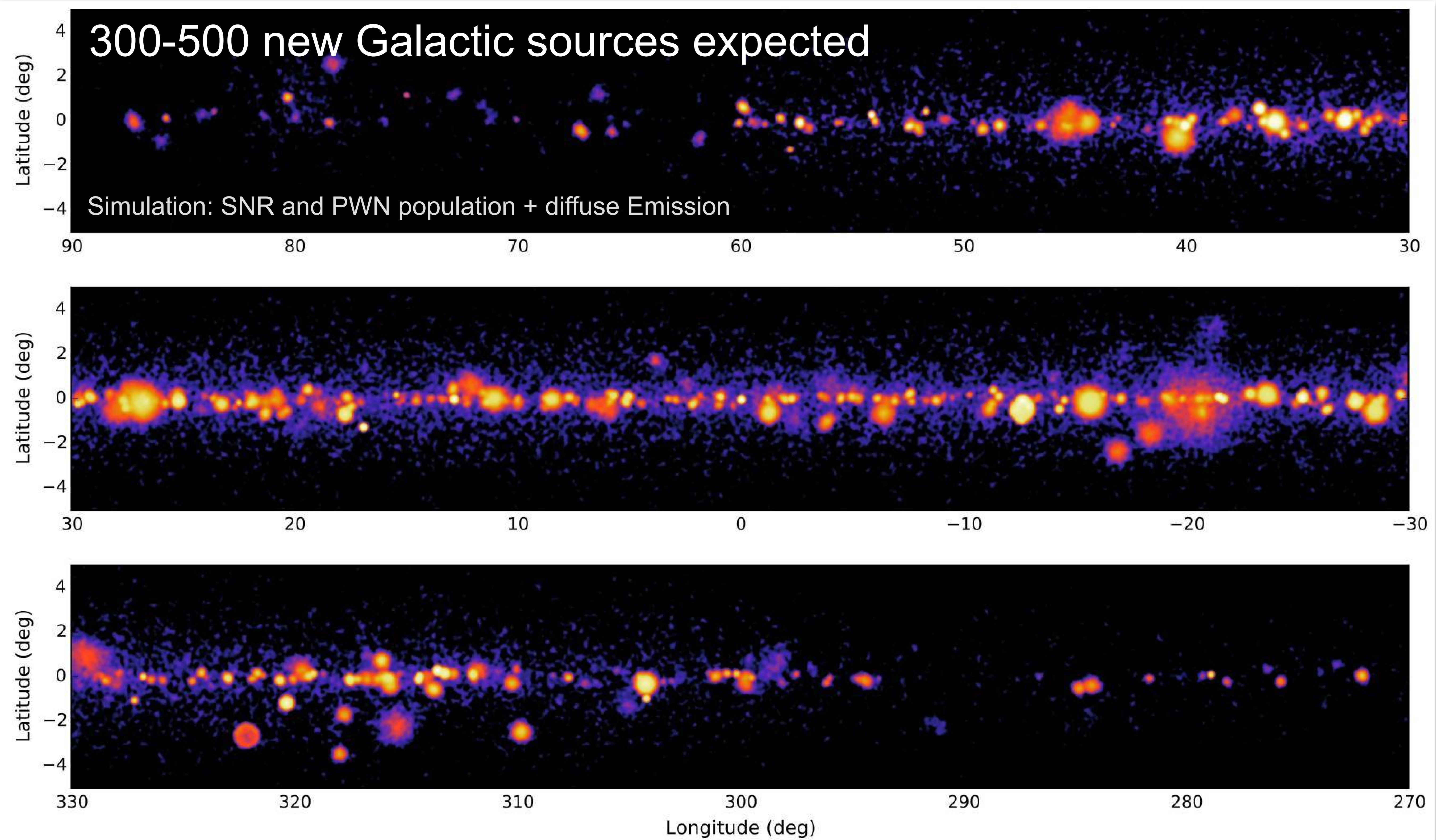


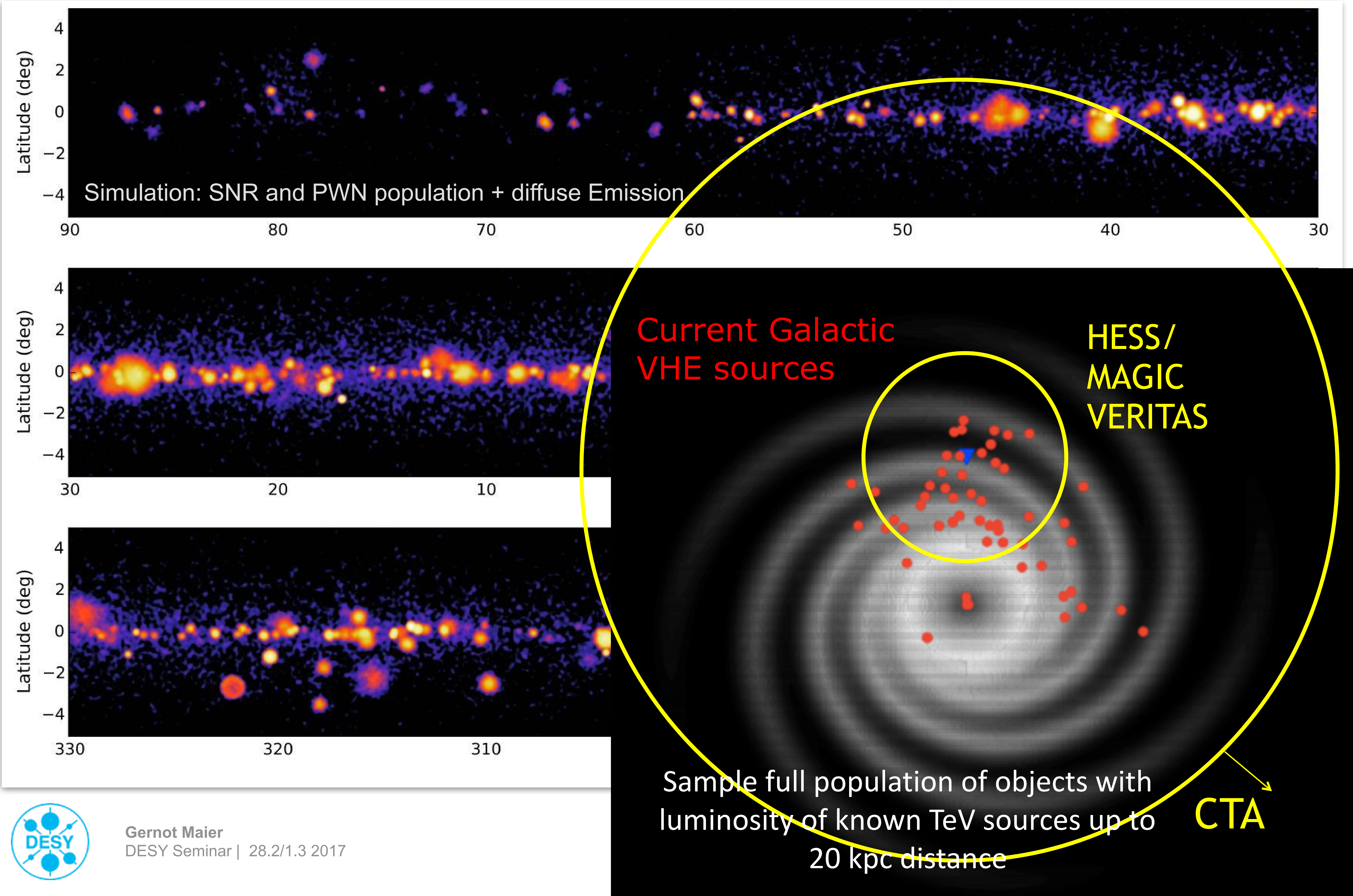
- large-scale data sets
- systematic and complete census of objects
- galactic diffuse emission
- identification of list of promising objects
- discovery of the unexpected and new phenomena

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



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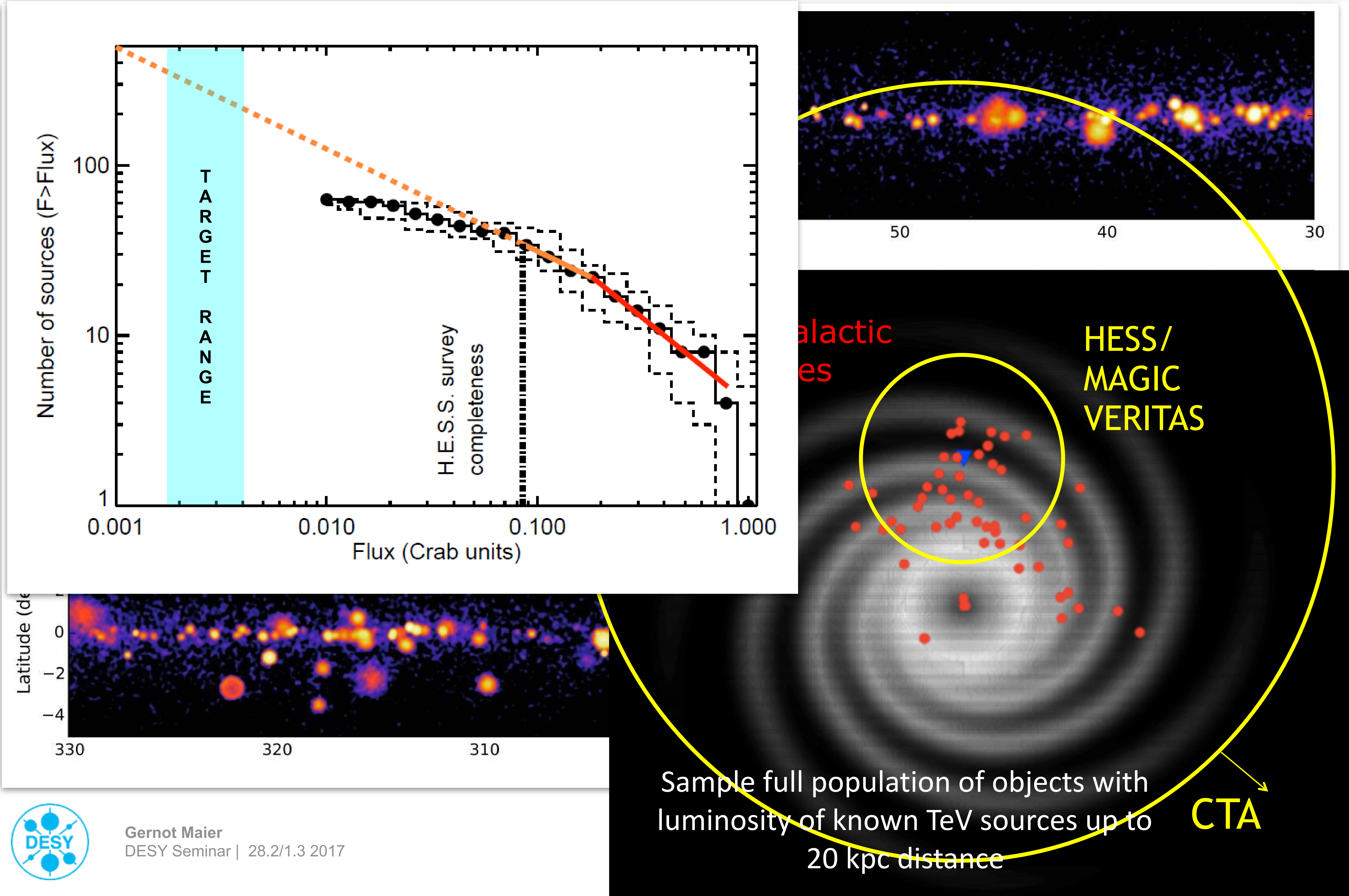
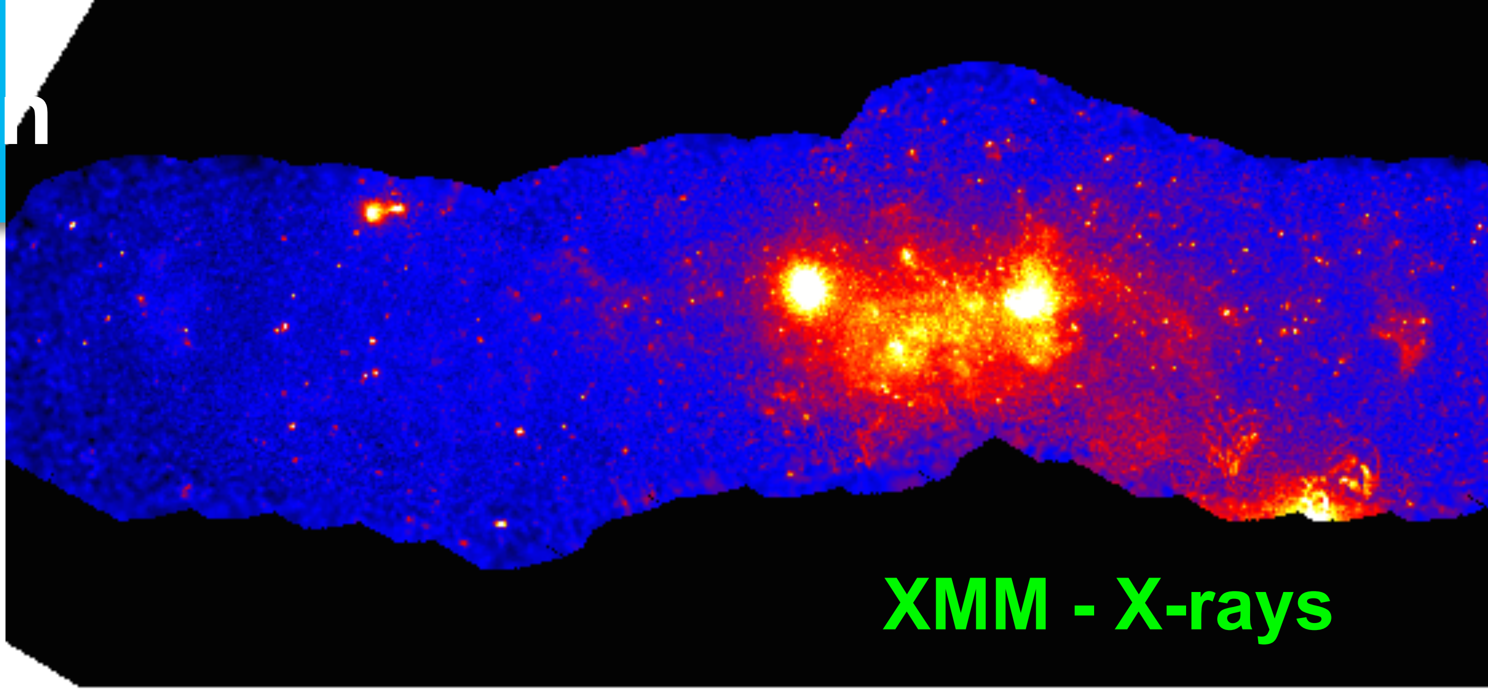
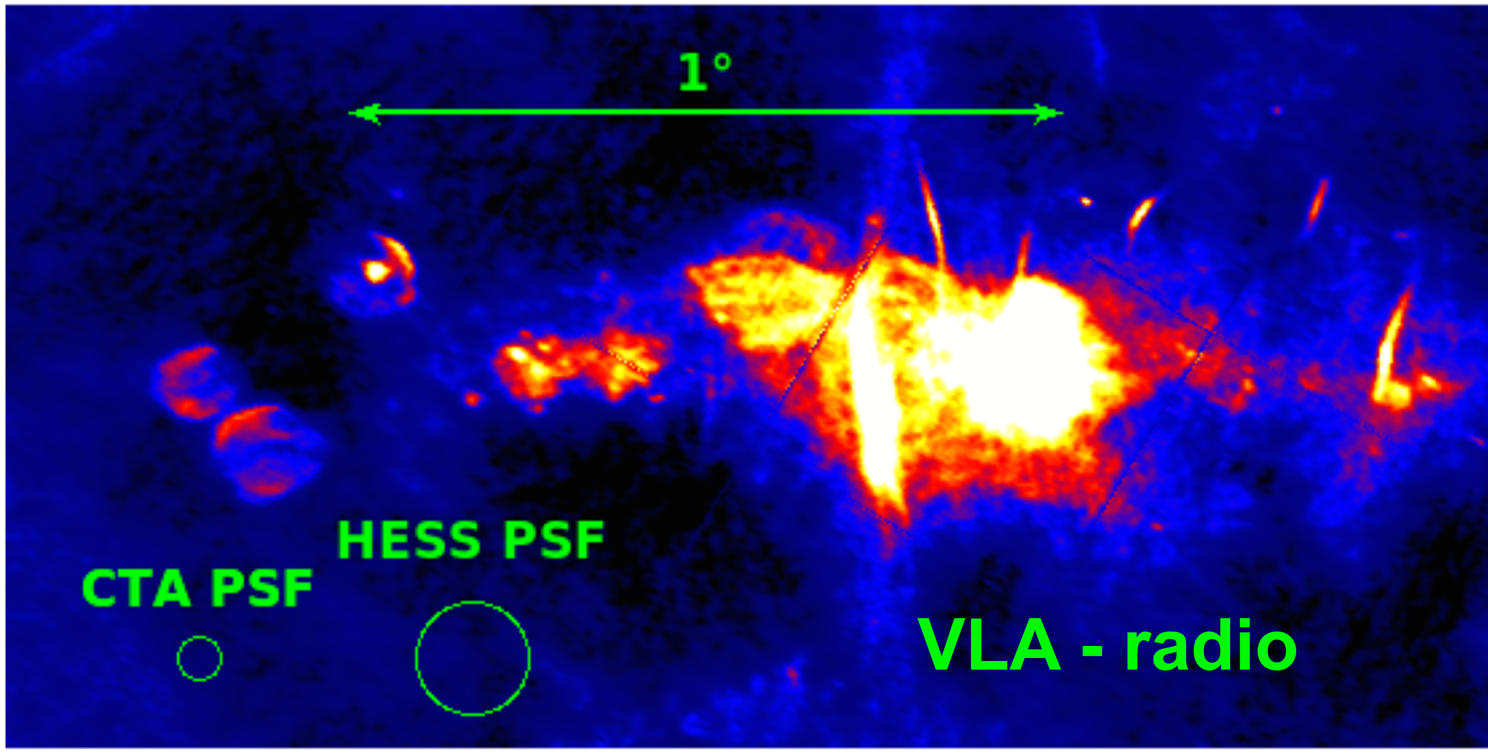
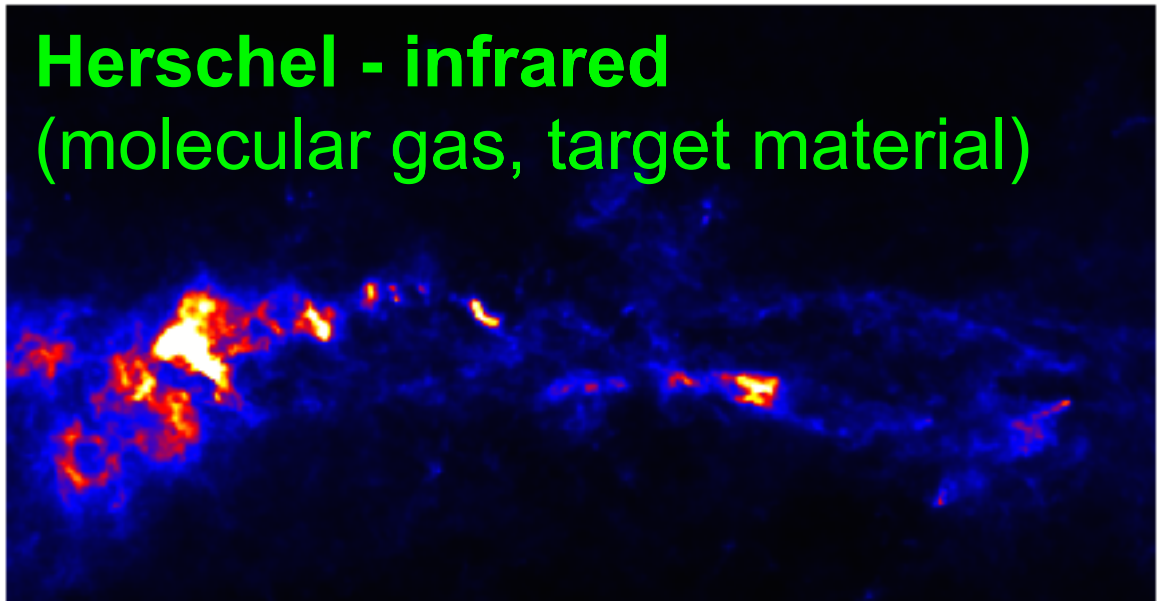


The Galactic Centre Region

- closest supermassive black hole ($4x10^6$ $M_\odot$)
  - 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







The Galactic Centre Region

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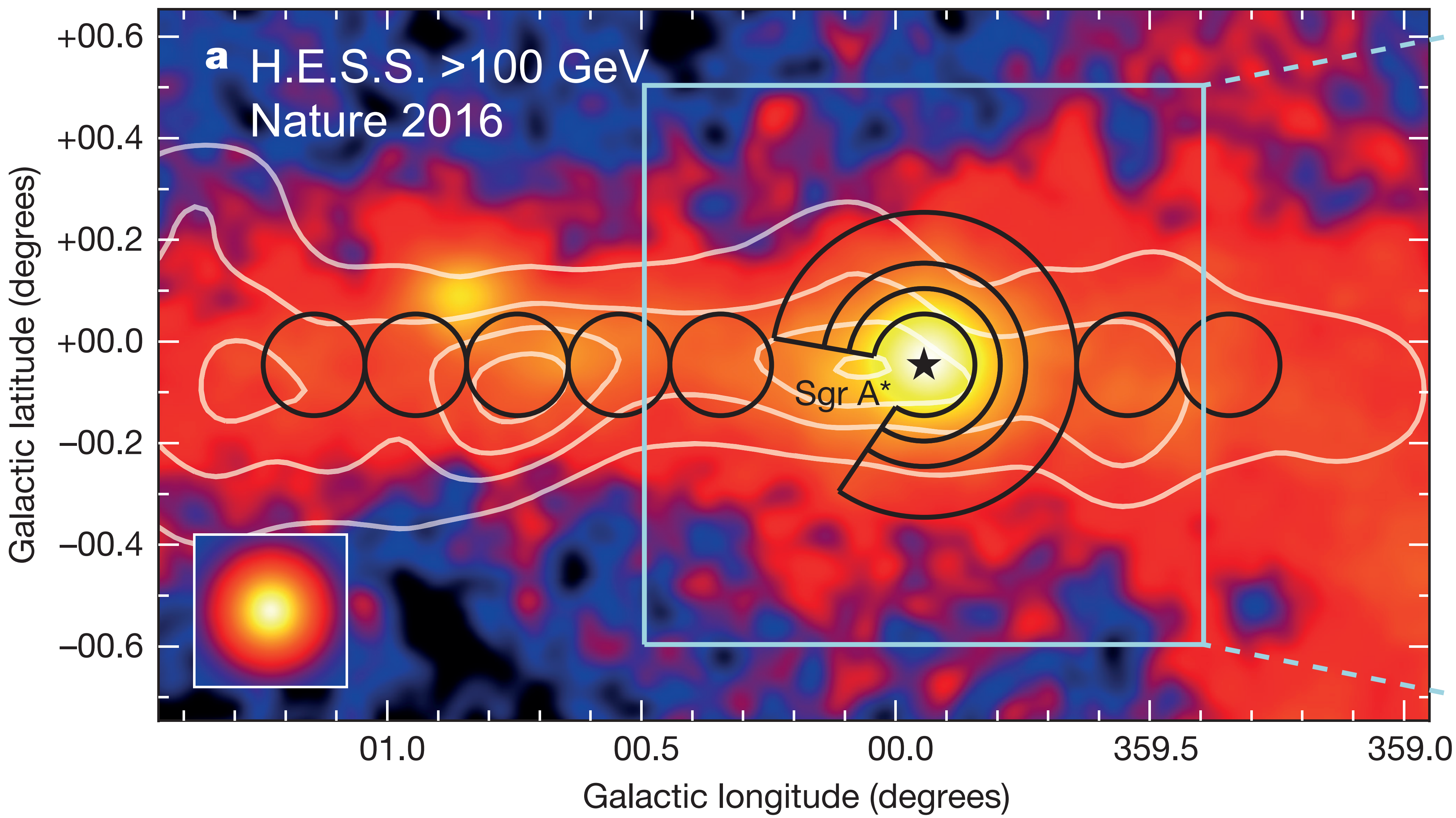
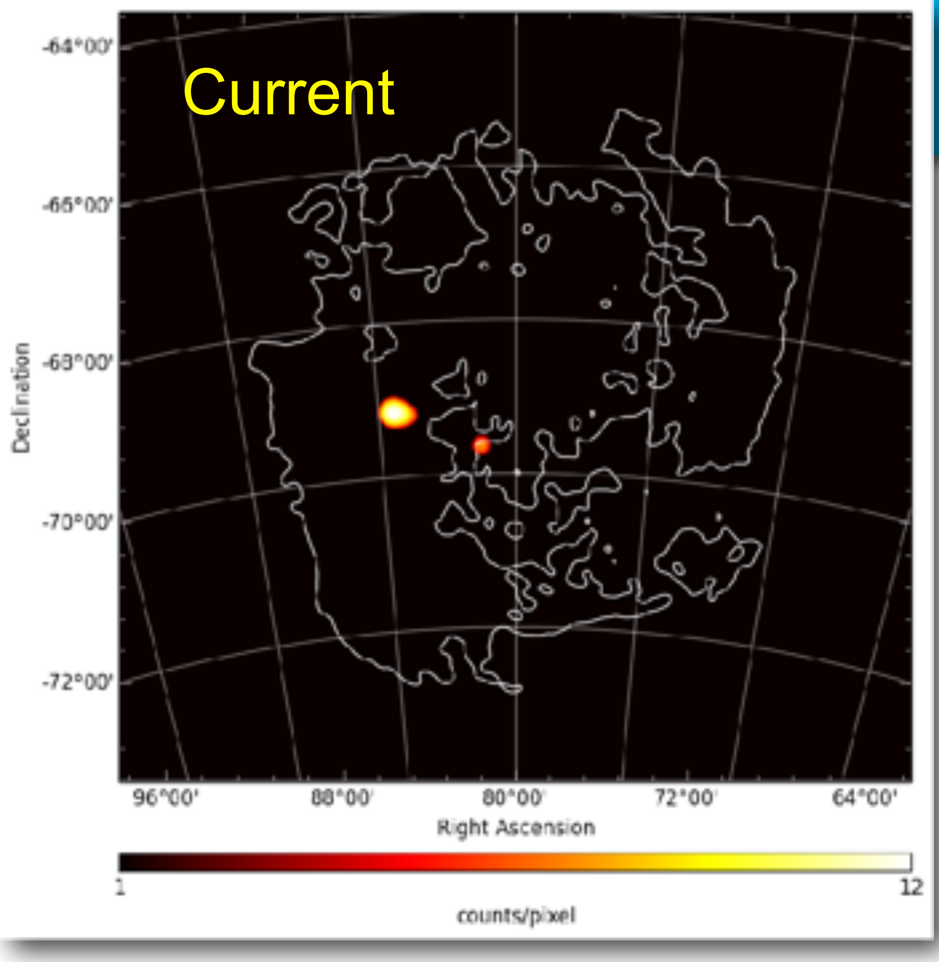
High-energy emission around the Galactic Centre

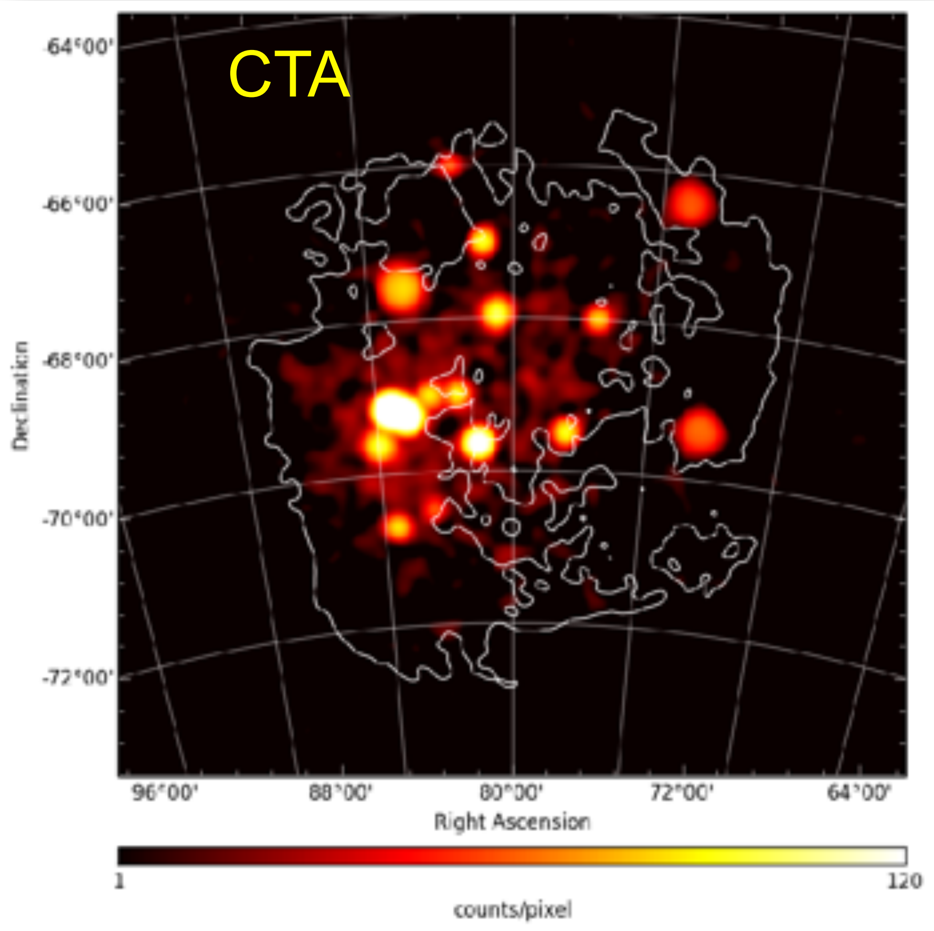


What is the source of gamma-rays in the Galactic Centre?
Does it point towards past high-accretion / outflow phases?
Is it the source of all cosmic rays in the Galaxy?
Emission due to a spike of dark-matter annihilation?

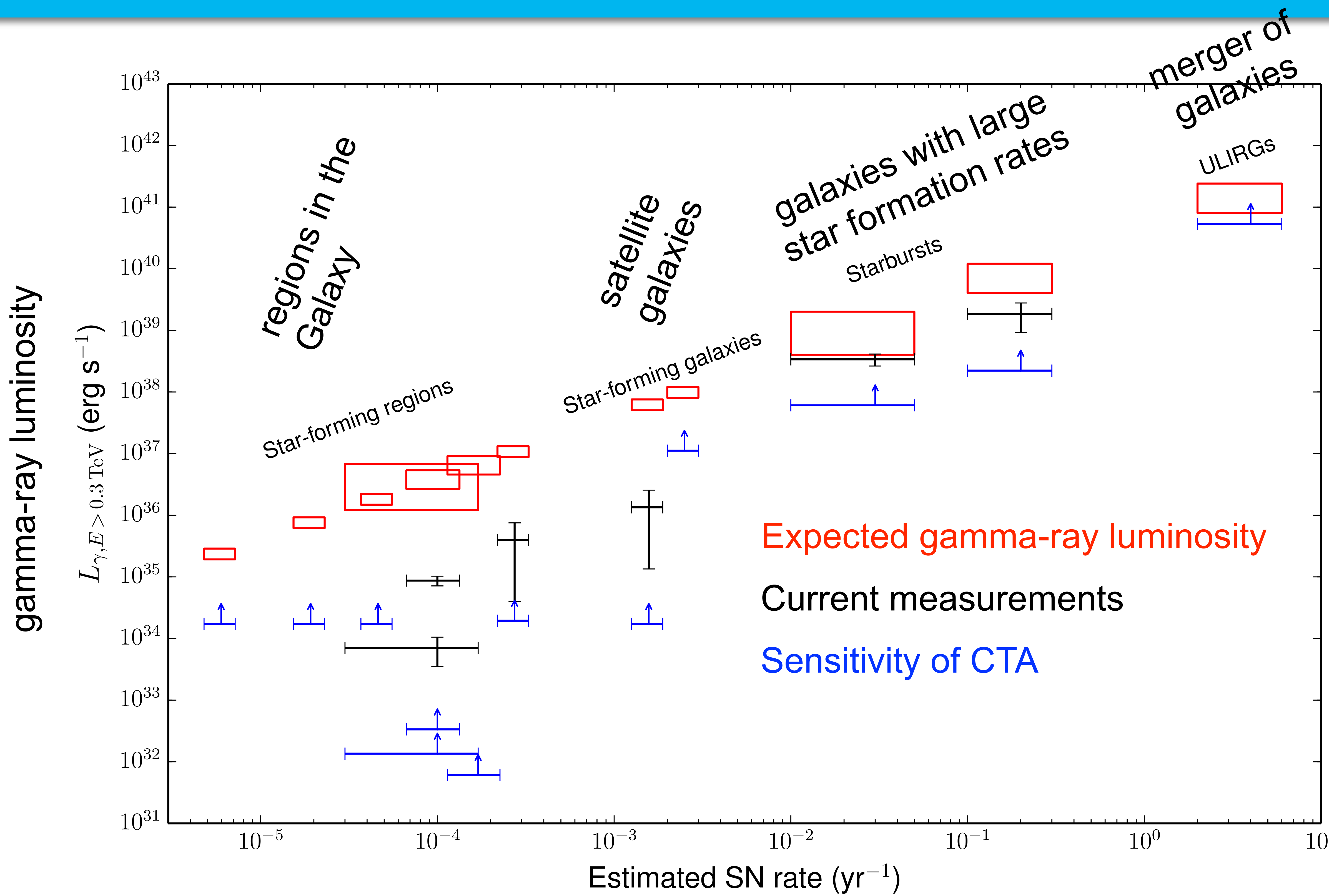
The Large Magellanic Cloud (LMC)

- 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)

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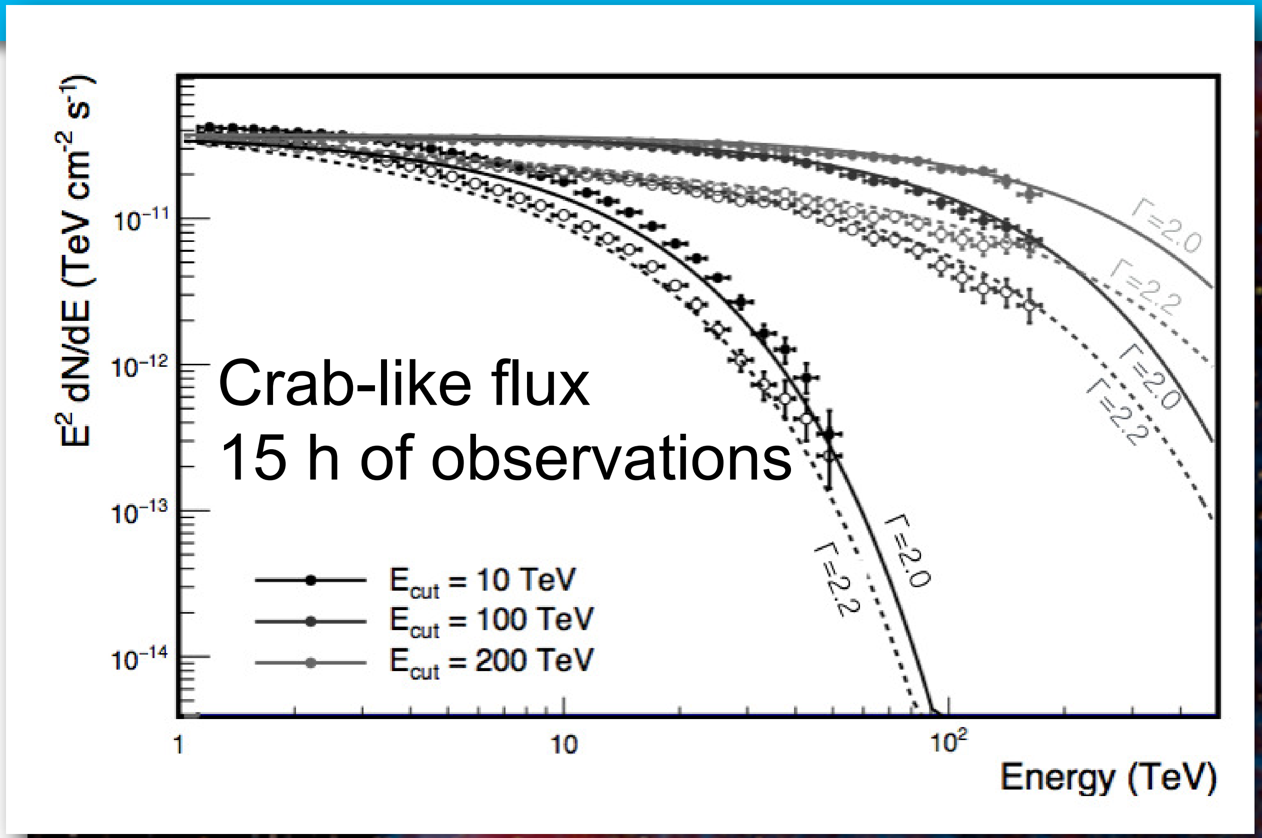

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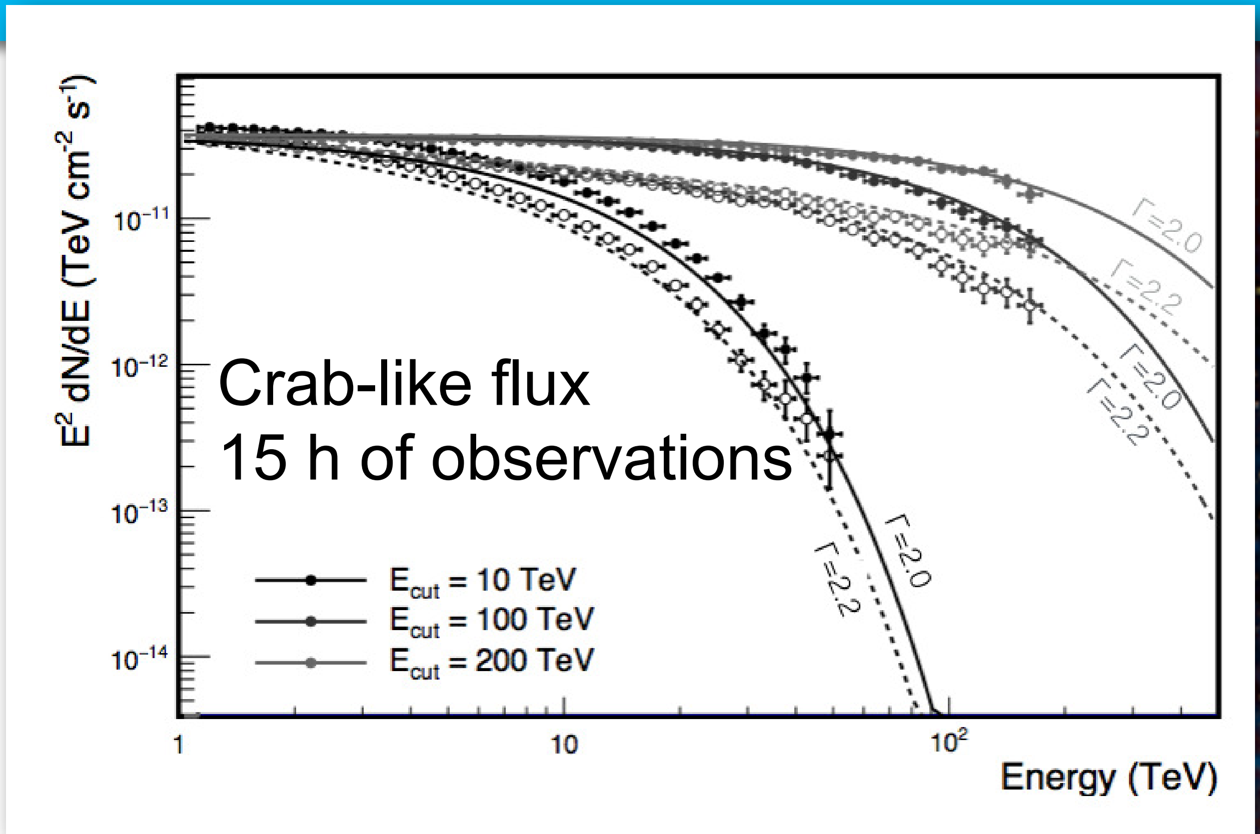
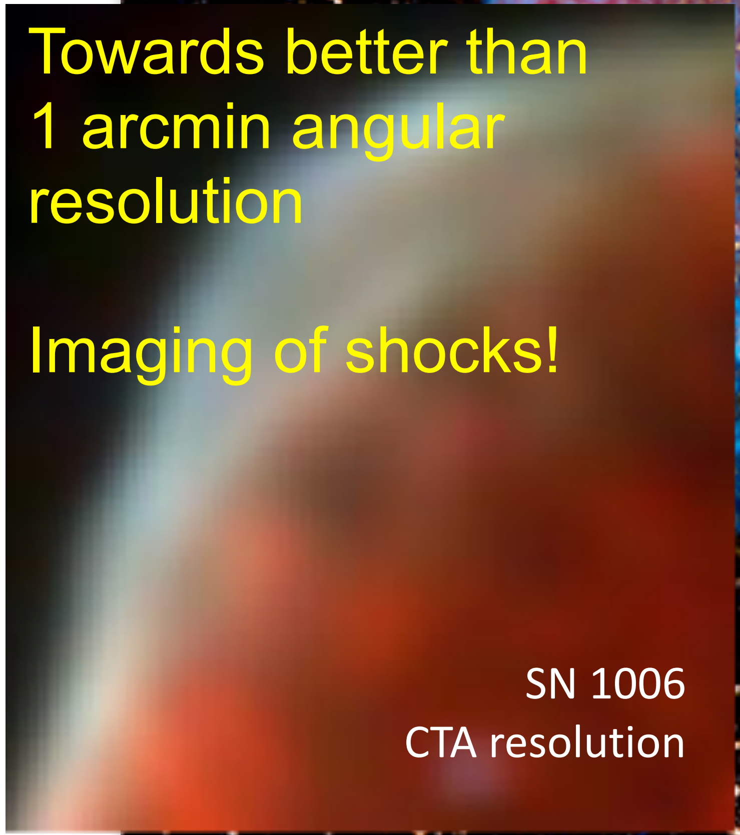
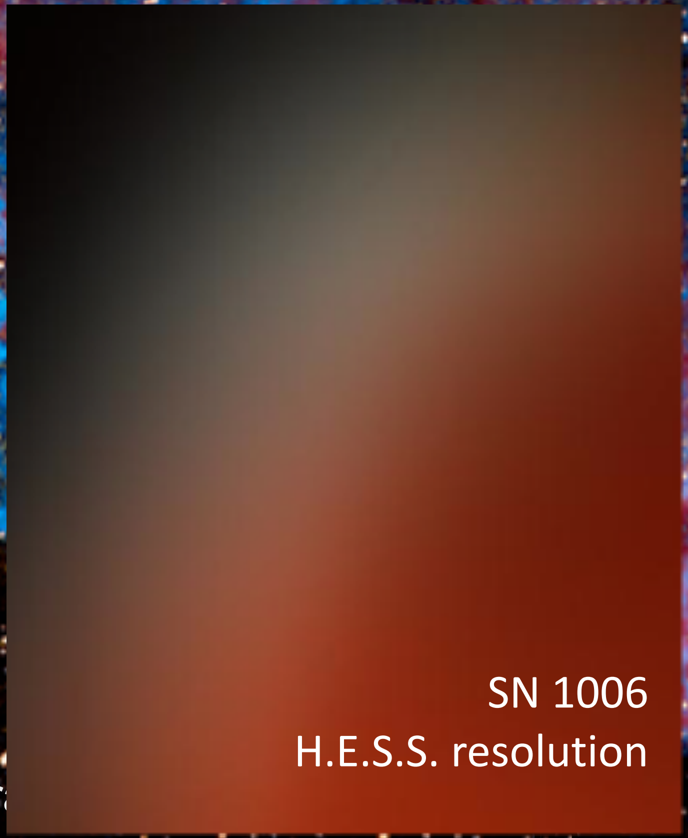
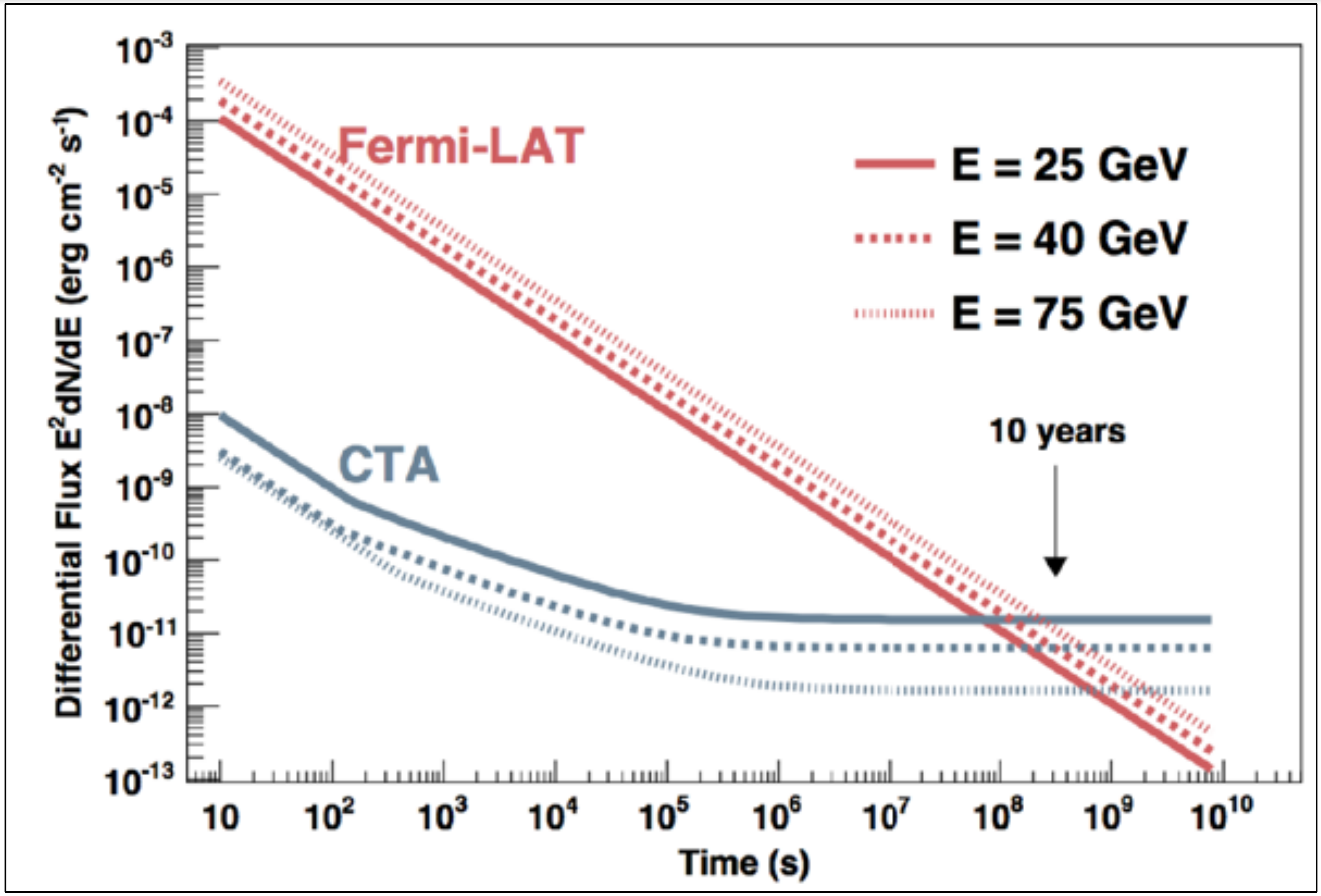






Transients

- 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

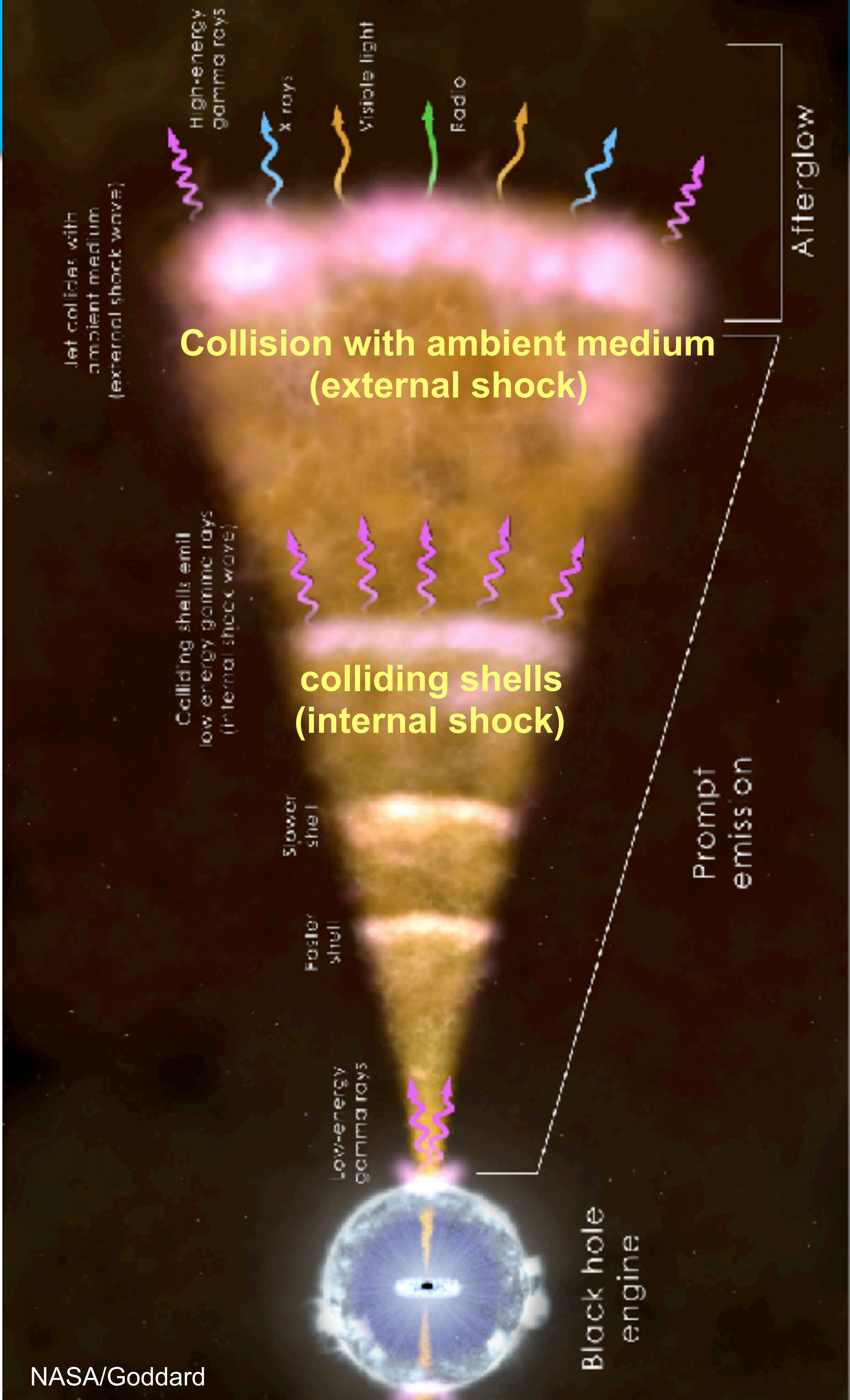


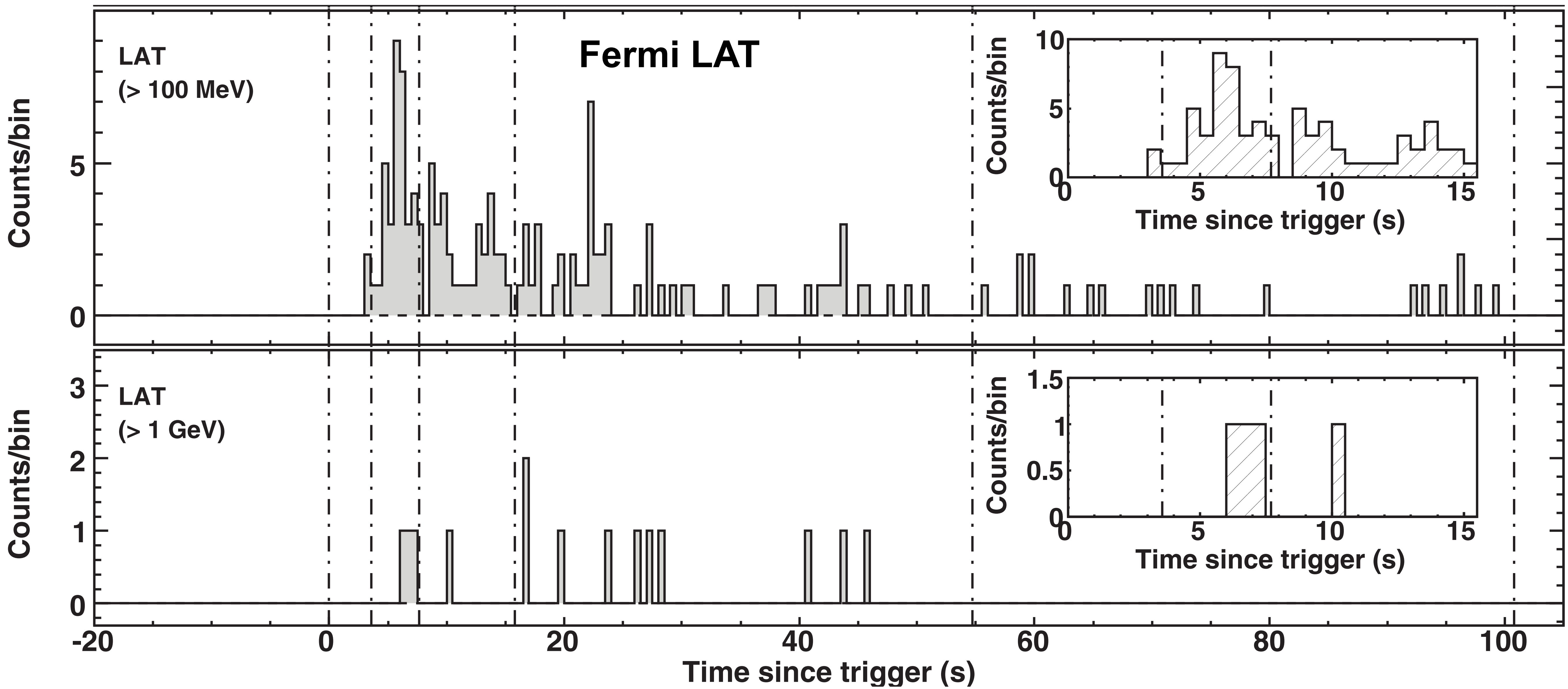
Four orders of magnitude better sensitivity for minute-scale phenomena.

Unexplored astronomical window!

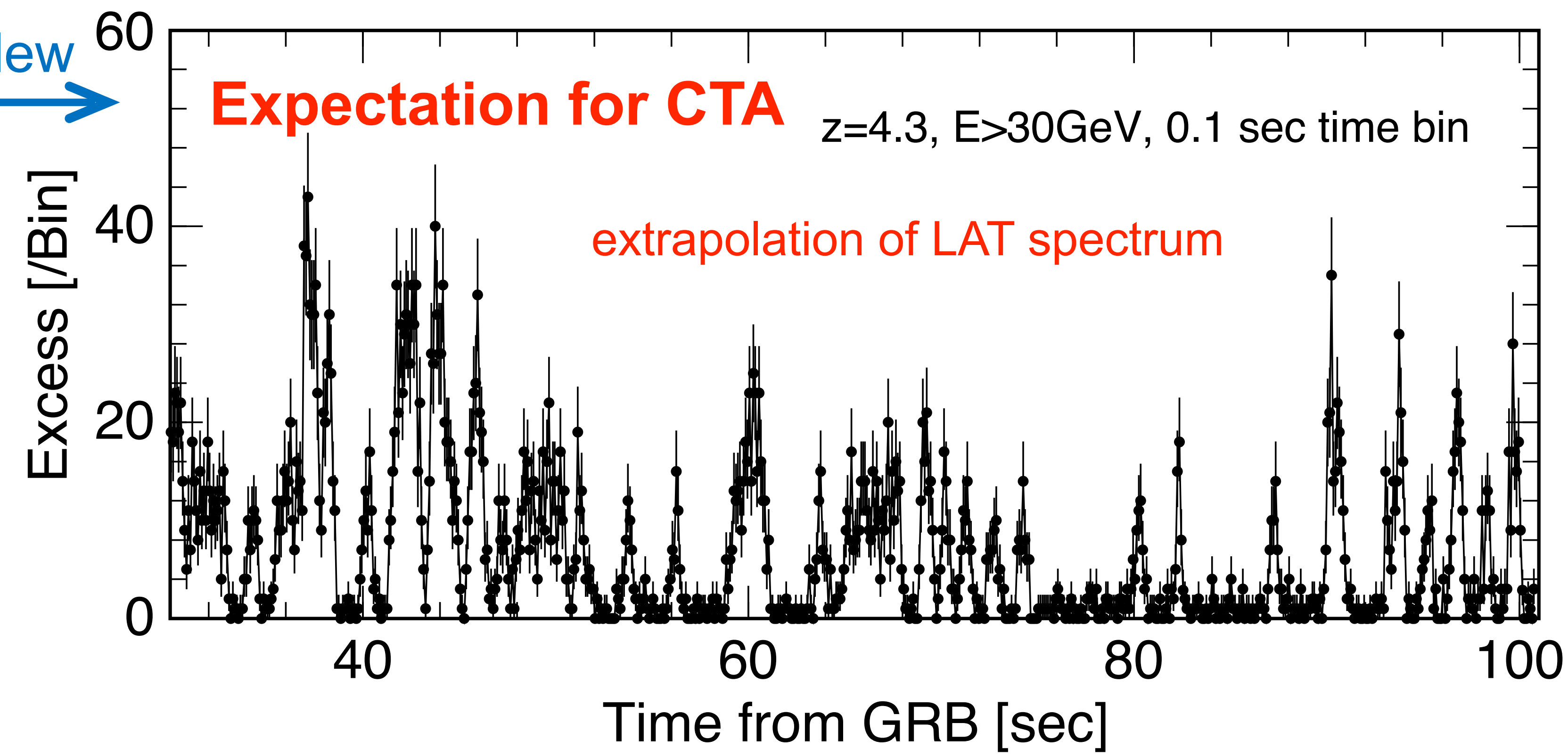
Gamma-ray bursts

- 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)



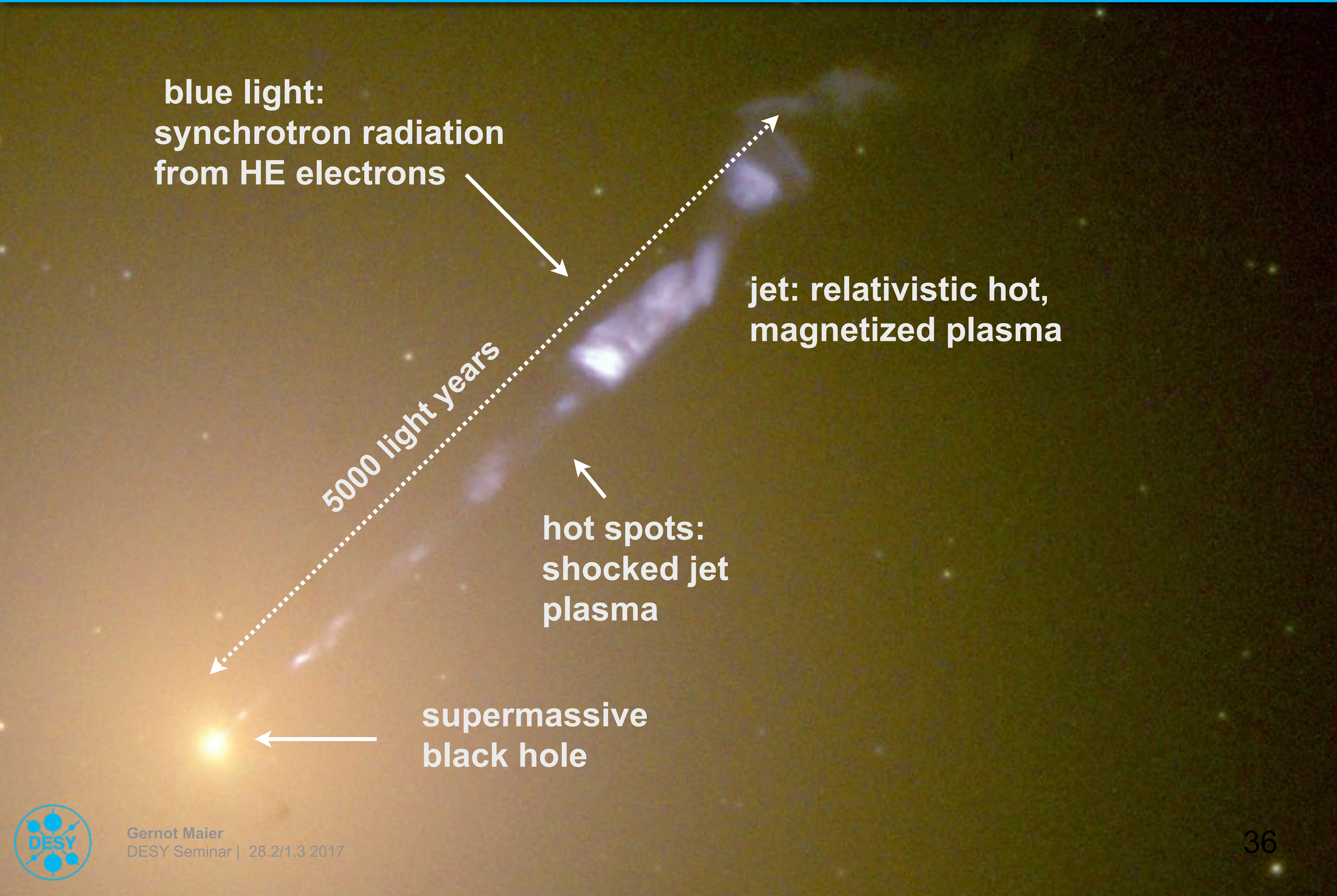


20 - 50 s for slew

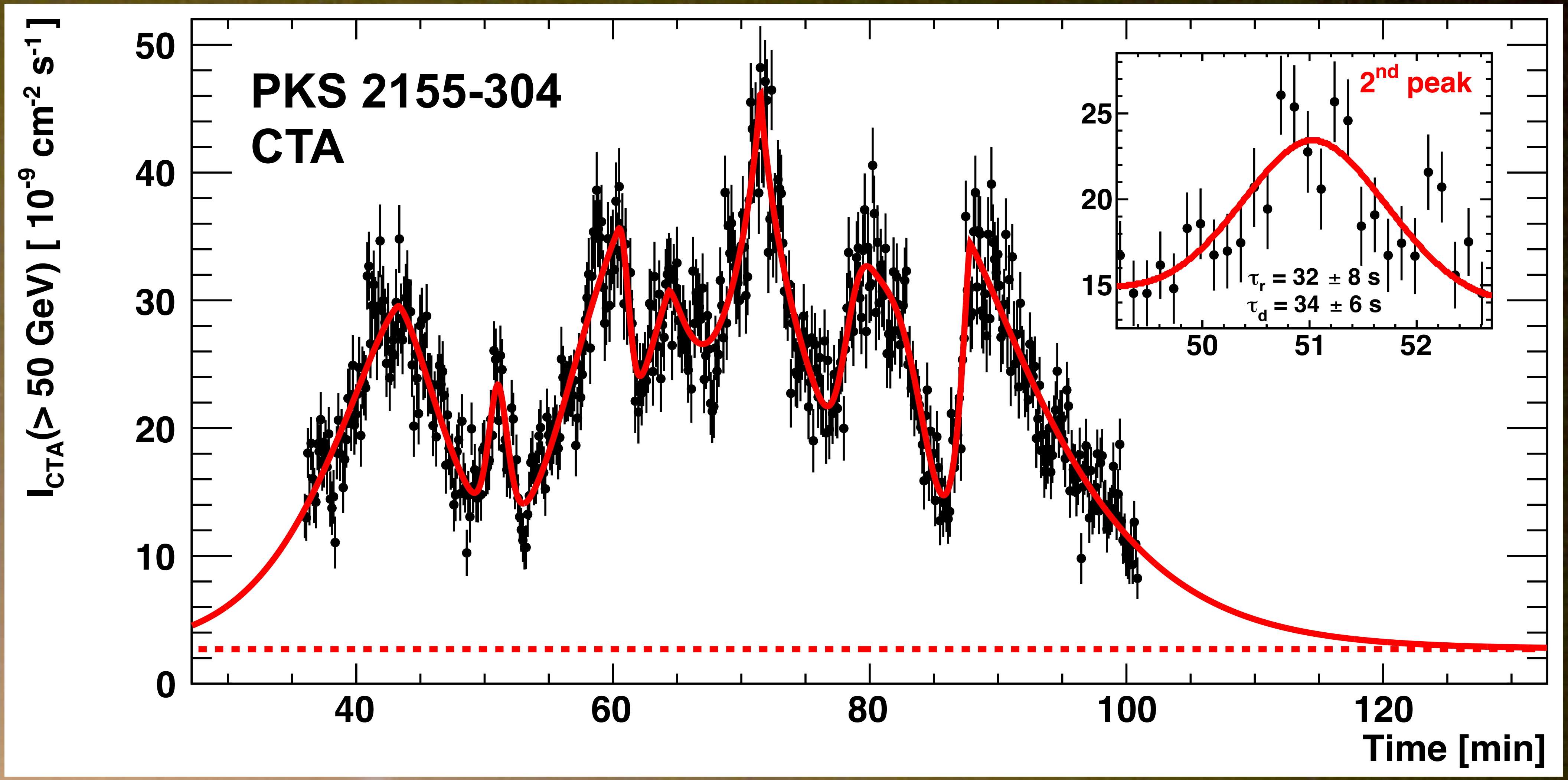


GRB 080916C at z=4.3

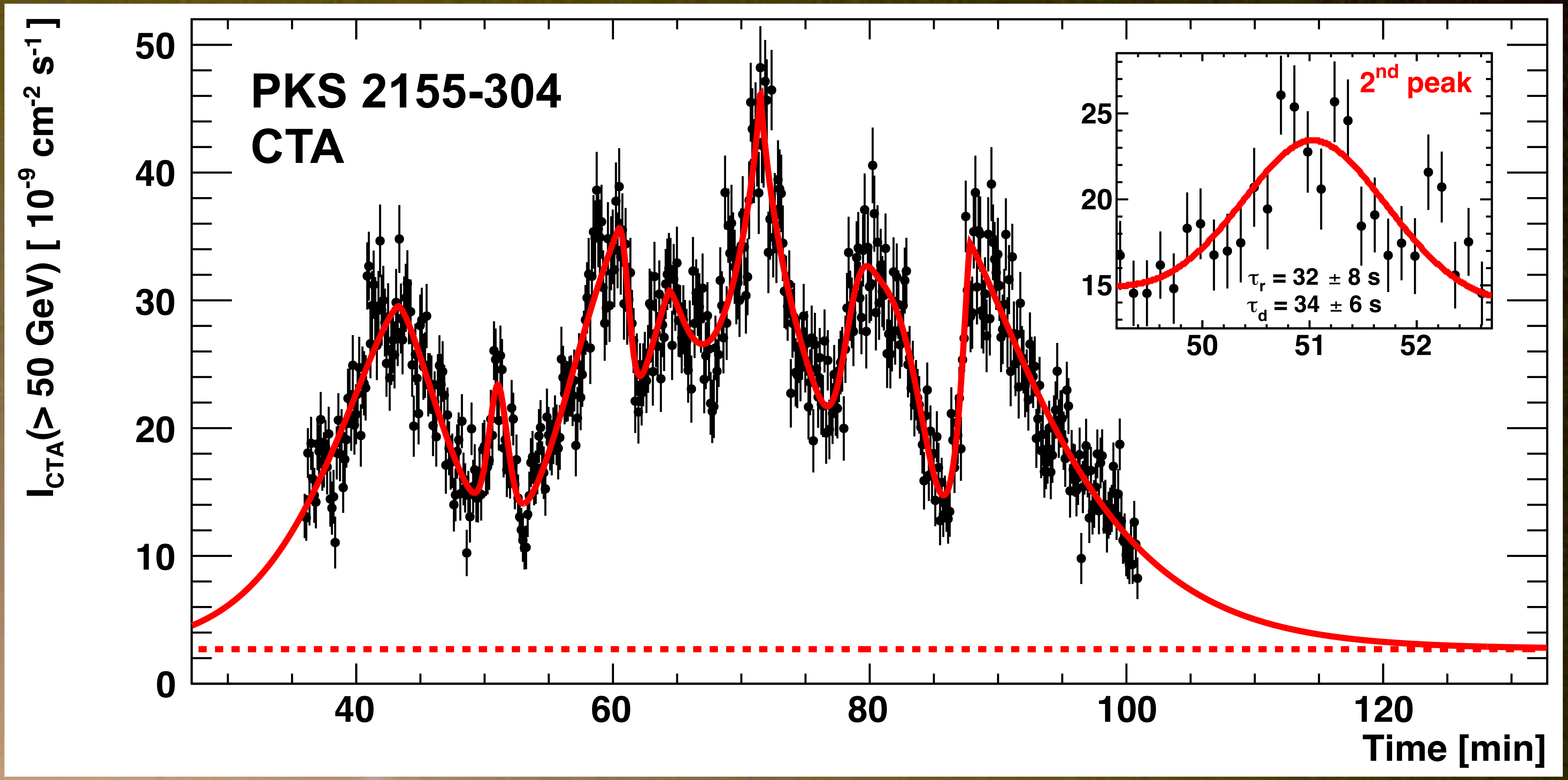
Active Galactic Nuclei



Active Galactic Nuclei



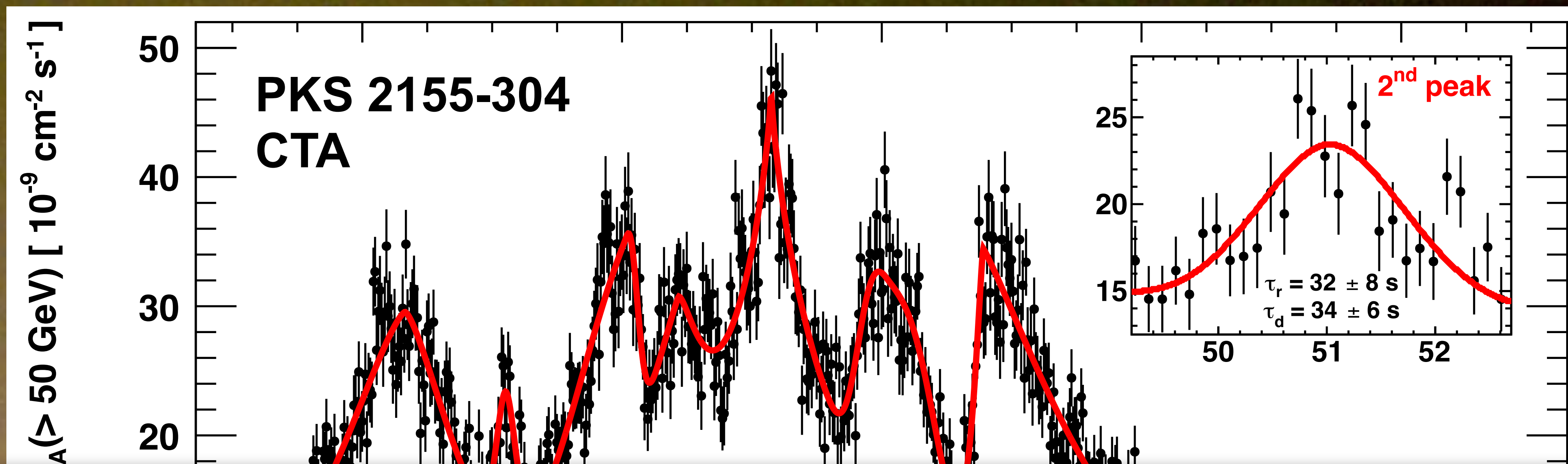
Active Galactic Nuclei & Lorentz invariance measurements

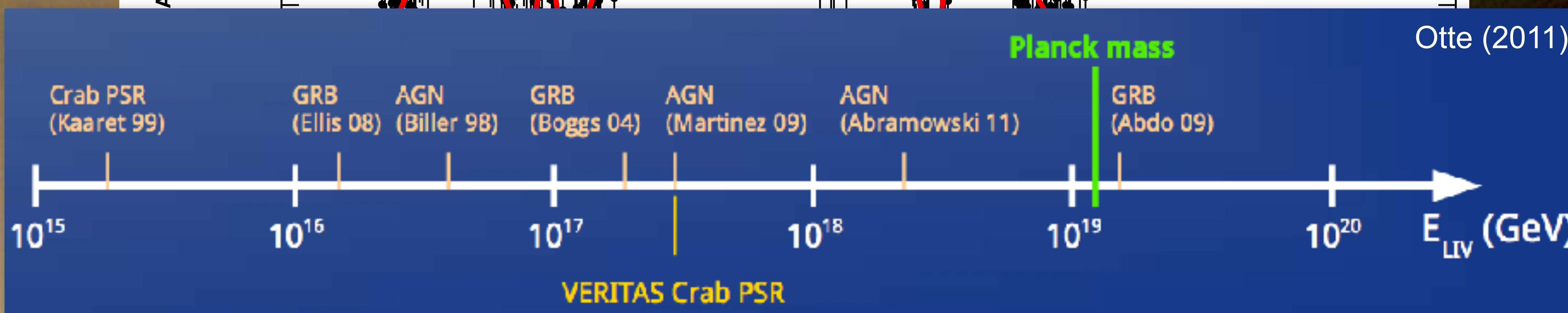


$$c^2 p^2 = E_\gamma^2 [1 \pm \xi_1 E_\gamma / E_{QG} \pm \xi_2 (E_\gamma^2 / E_{QG}{}^2) \pm \ldots]$$

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

Active Galactic Nuclei & Lorentz invariance measurements





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

Beyond the standard model (of astro & particle physics)

everything discussed until now is background

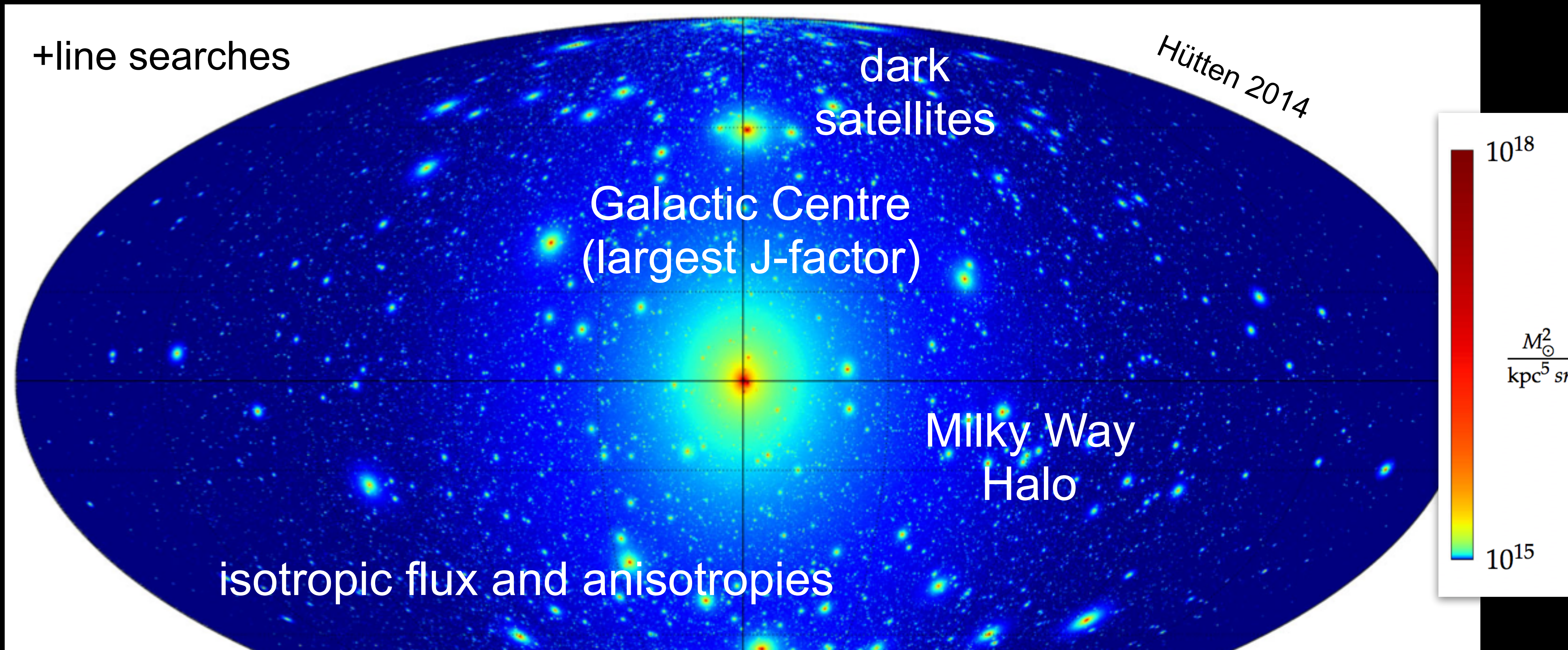
(but necessary to understand if we want to find physics beyond the standard model)

Dark matter searches

annihilation

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{dE}_\gamma} = \frac{1}{4\pi} \underbrace{\frac{<\sigma_{\mathrm{ann}} v>}{2\mathrm{m}^2_{\mathrm{WIMP}}} \sum_f \frac{\mathrm{dN}^f_\gamma}{\mathrm{dE}_\gamma} \mathrm{B}_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} \mathrm{d}\Omega' \int_{\mathrm{los}} \rho^2 r(l, \theta') \mathrm{d}l(r, \theta')}_{\text{'Astrophysics' or } J(E)}$$

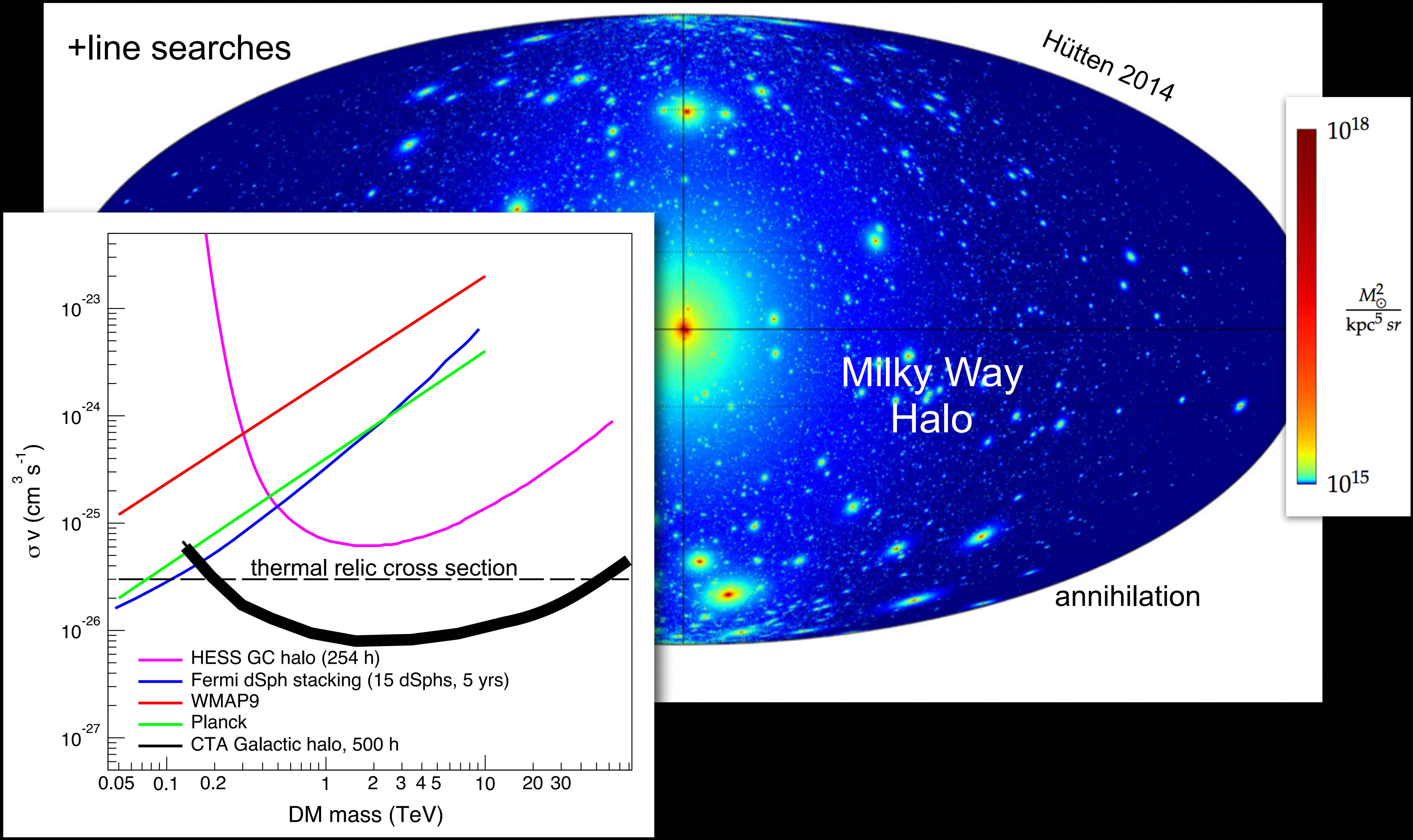
Dark matter searches



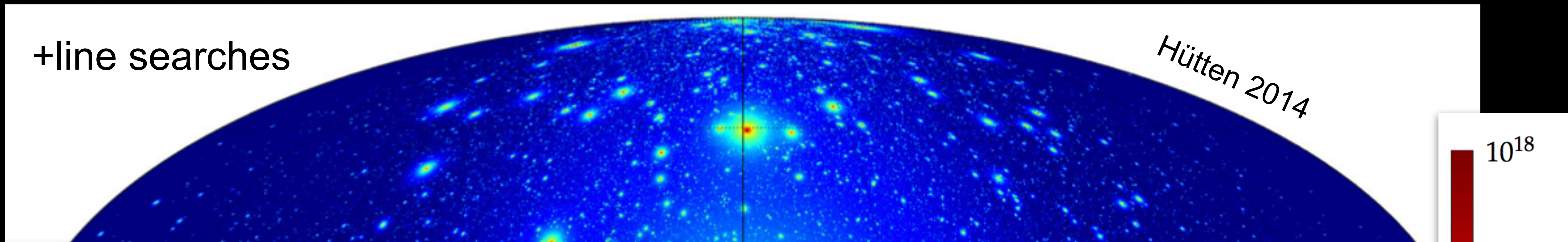
annihilation

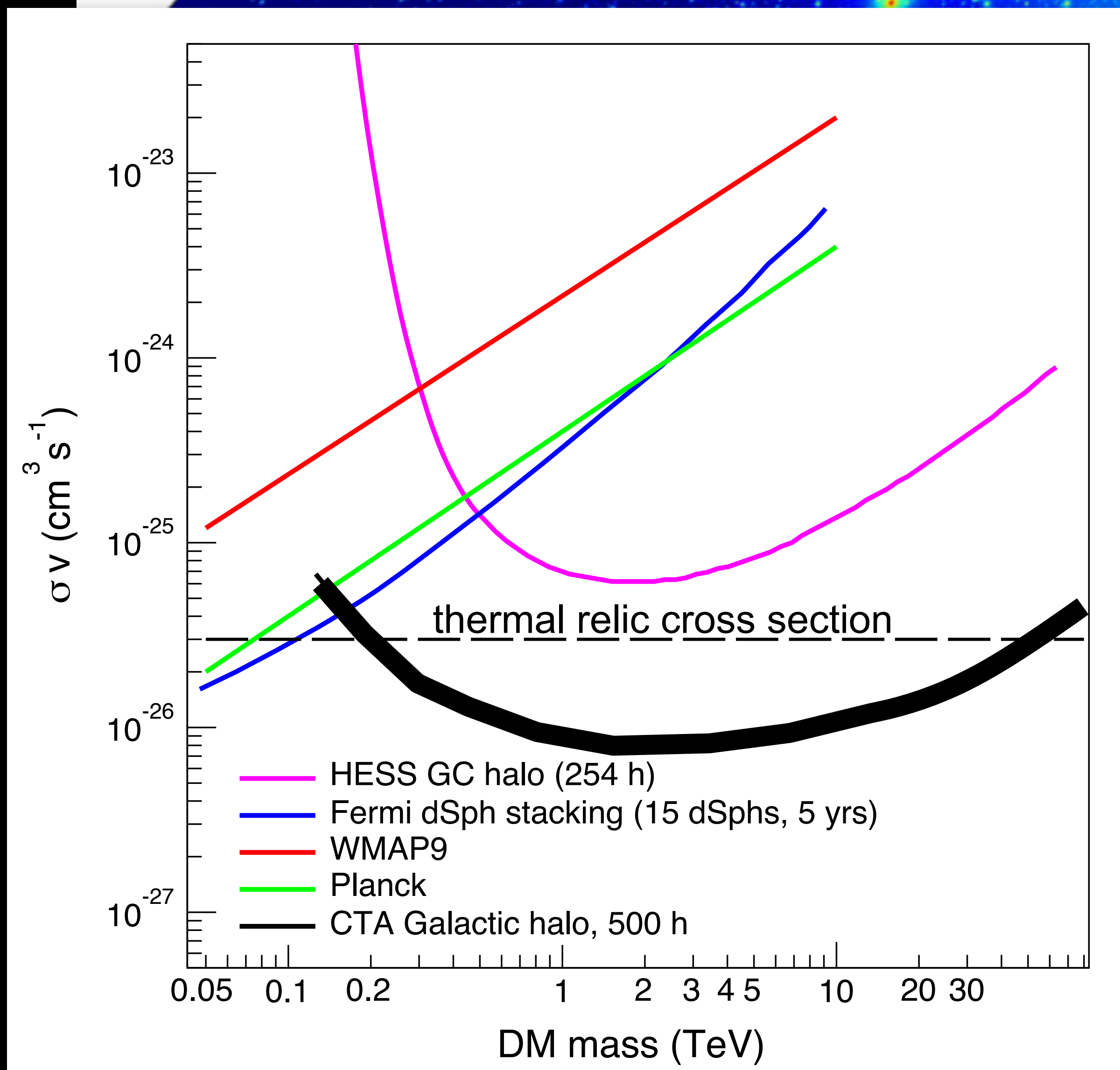
$$\frac{d\Phi_\gamma}{dE_\gamma} = \underbrace{\frac{1}{4\pi} \frac{<\sigma_{\mathrm{ann}} v>}{2 m_{\mathrm{WIMP}}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} d\Omega' \int_{\mathrm{los}} \rho^2 r(l,\theta') dl(r,\theta')}_{\text{'Astrophysics'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

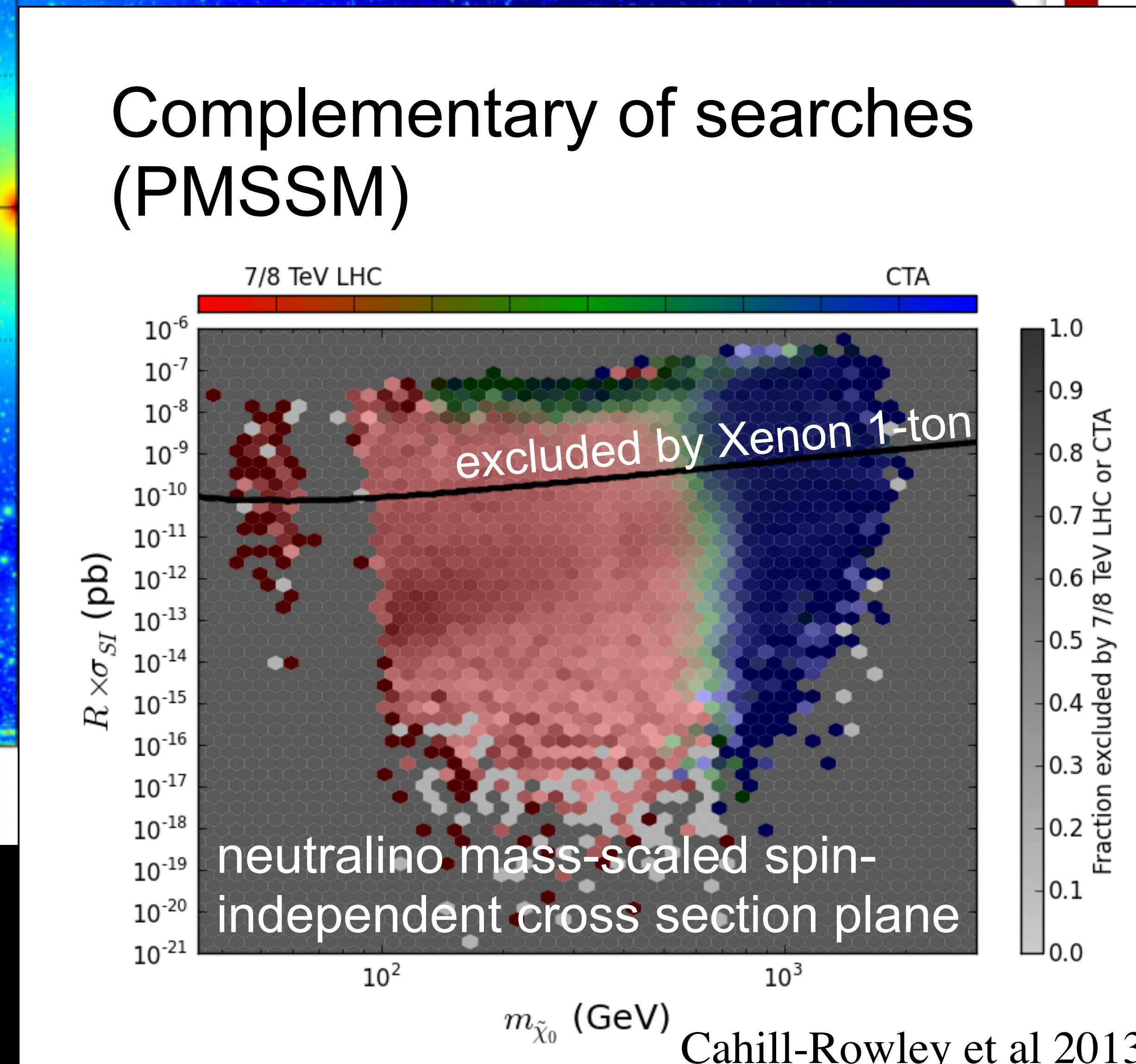
Dark matter searches



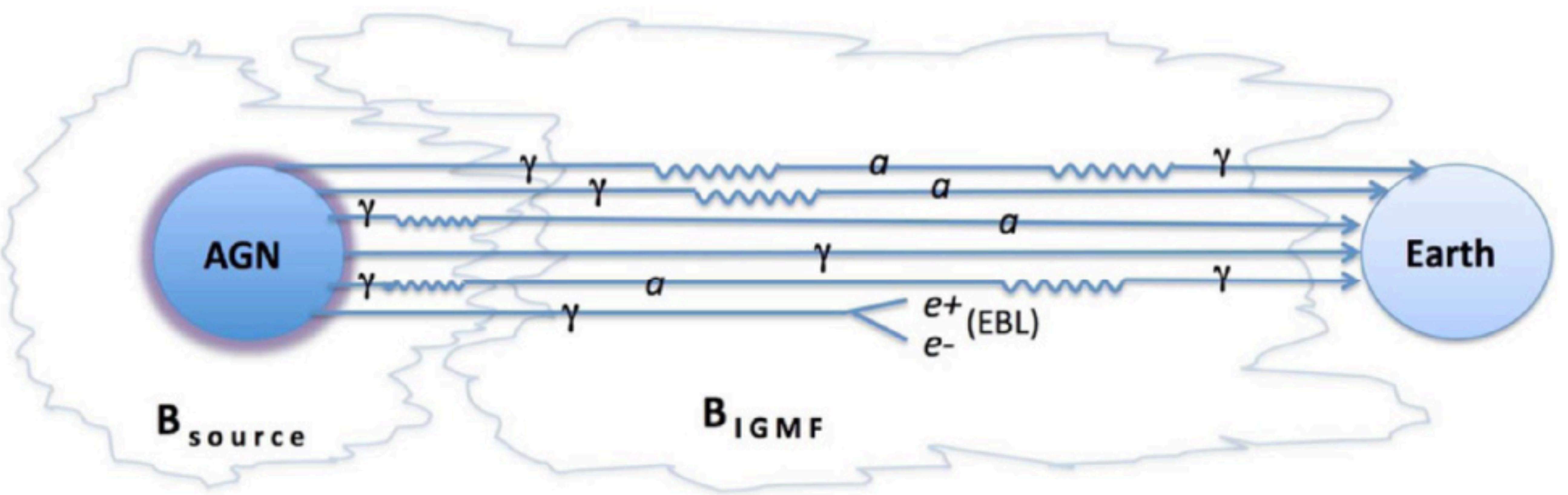
Dark matter searches







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:

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

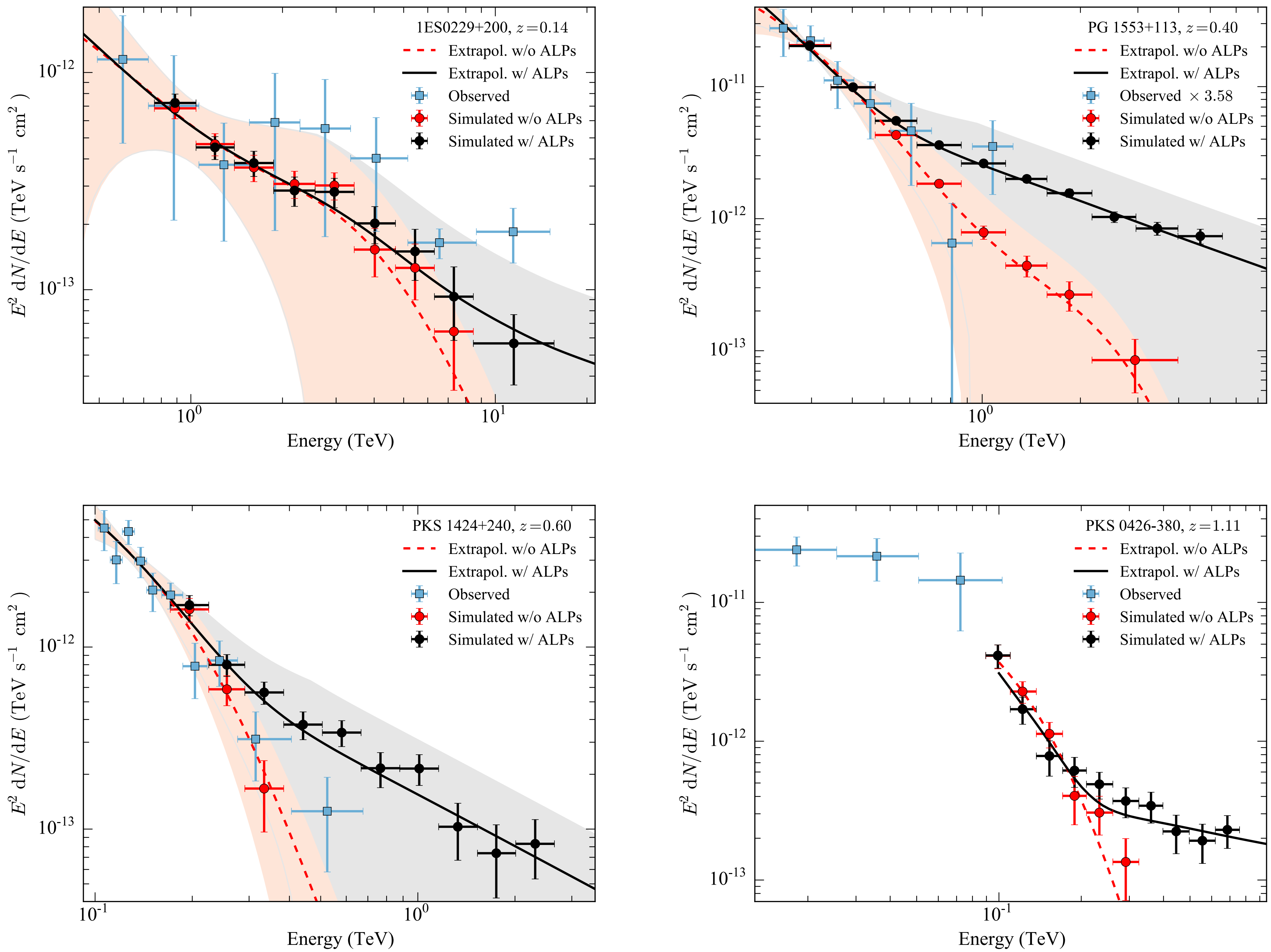
m = 20 neV, $g_{\gamma\alpha} = 10^{-10}$ GeV^{-1}:
E_C ~ 100 GeV

(Θ: angle between photon direction and magnetic field)

Axion-like particle searches with CTA

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

Meyer & Conrad 2014



Current results

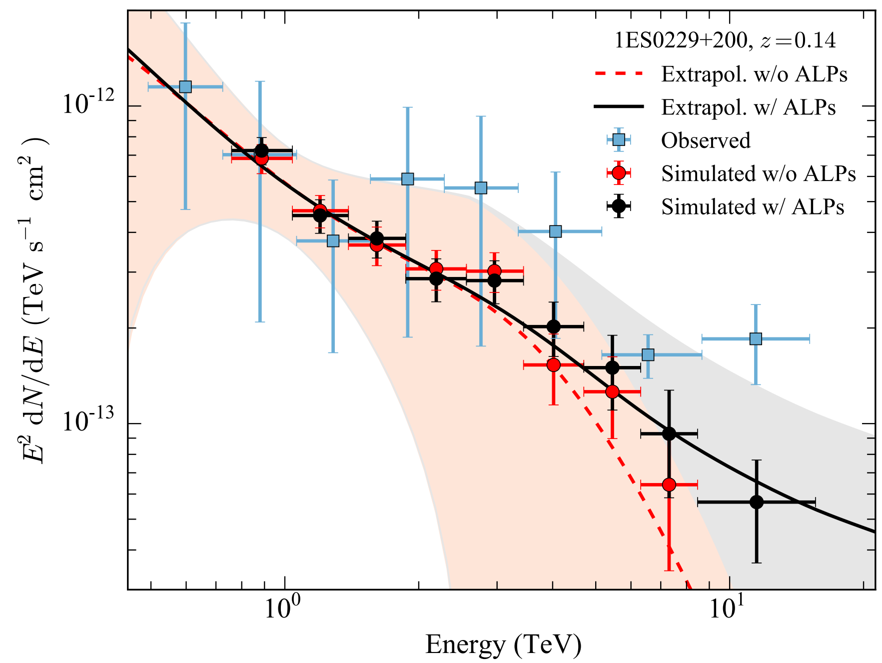
CTA (with ALPS)

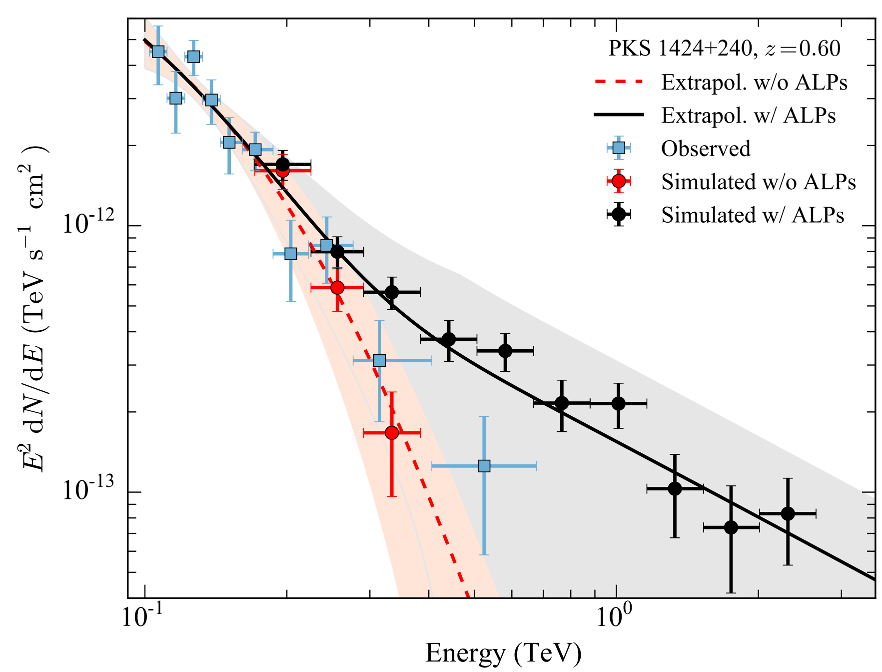
CTA (without ALPS)

Axion-like particle searches with CTA

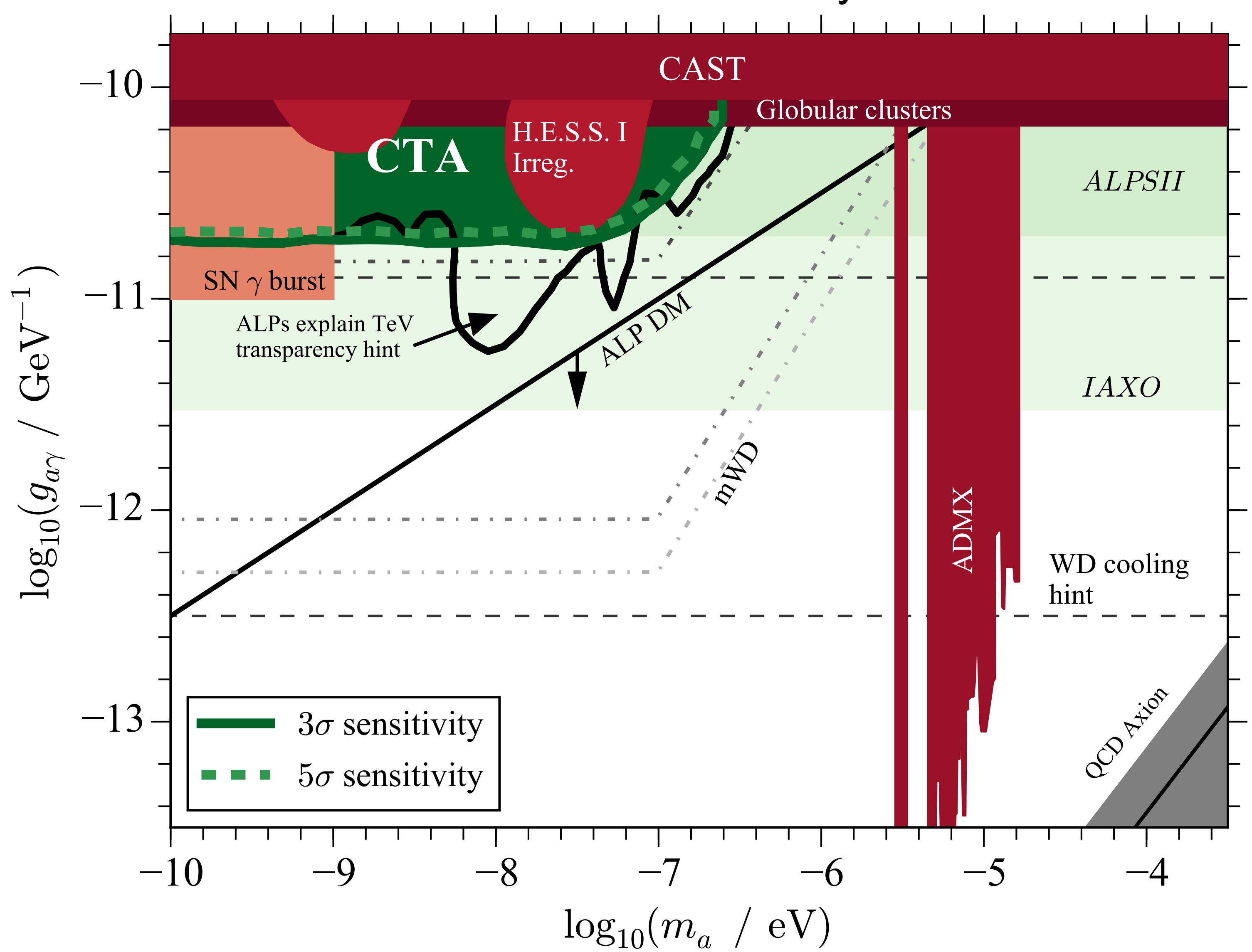
$m_{\mathrm{neV}} = 12.2,\ g_{11} = 4.3$

Meyer & Conrad 2014





Meyer & Conrad 2014

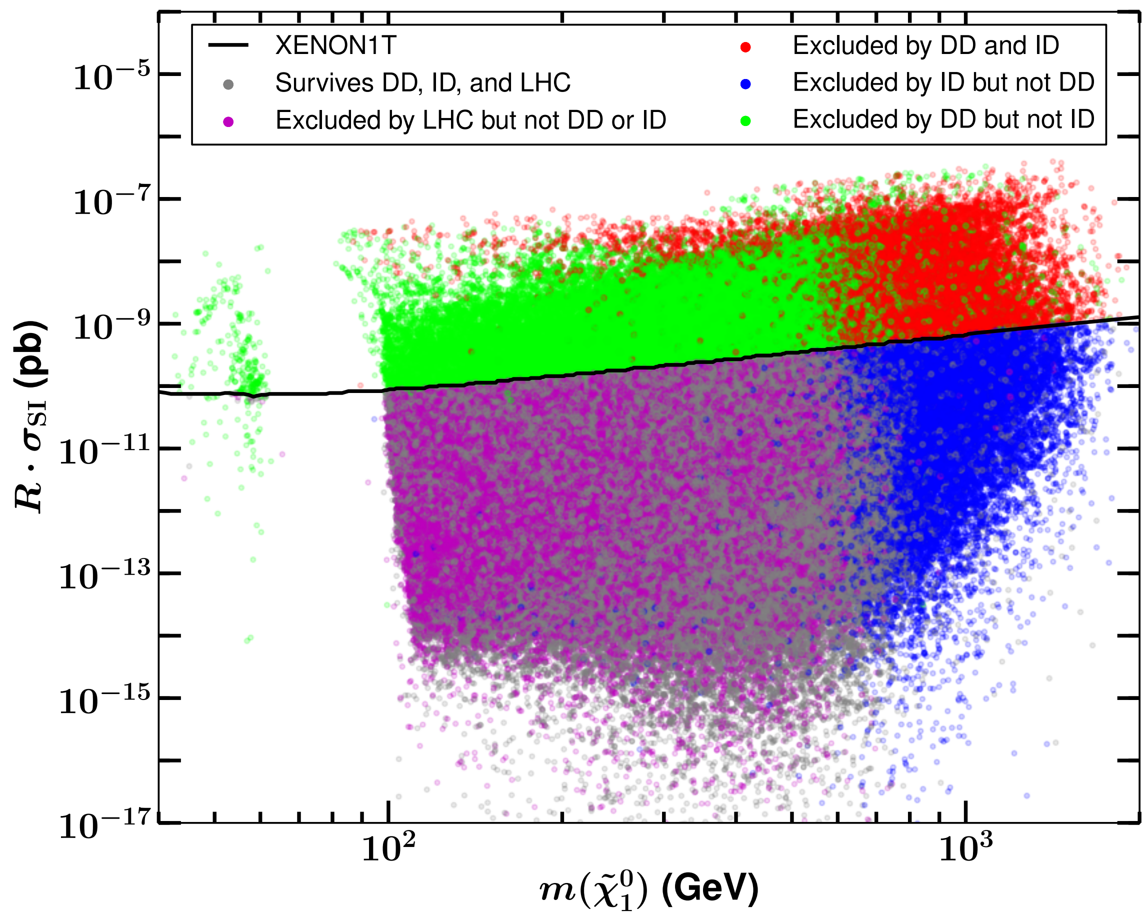


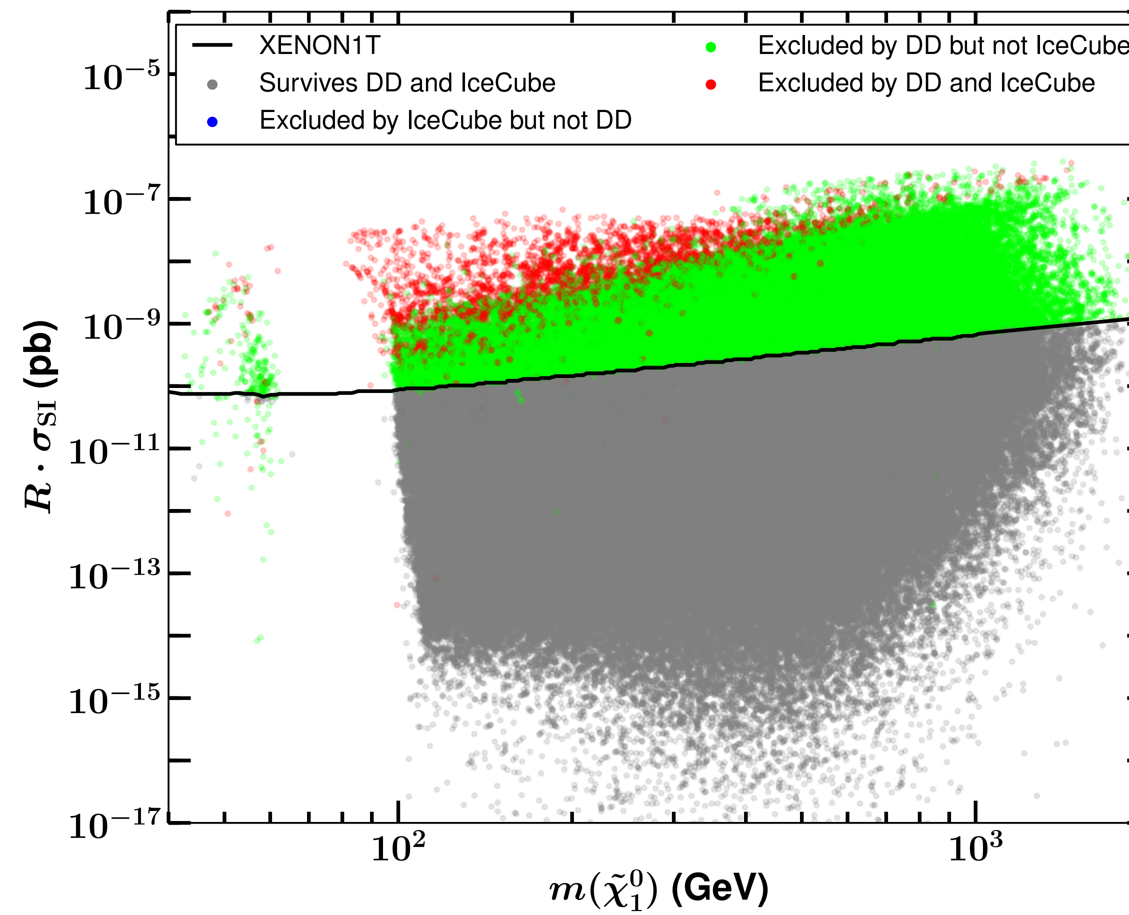
Note large uncertainties from unknown intrinsic source spectra and not well measured magnetic field properties

The Cherenkov Telescope Array

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

Very exciting years ahead!





Cahill-Rowley et al 2013