Gamma-ray astronomy with Imaging Air Cherenkov Telescopes

Lecture 3

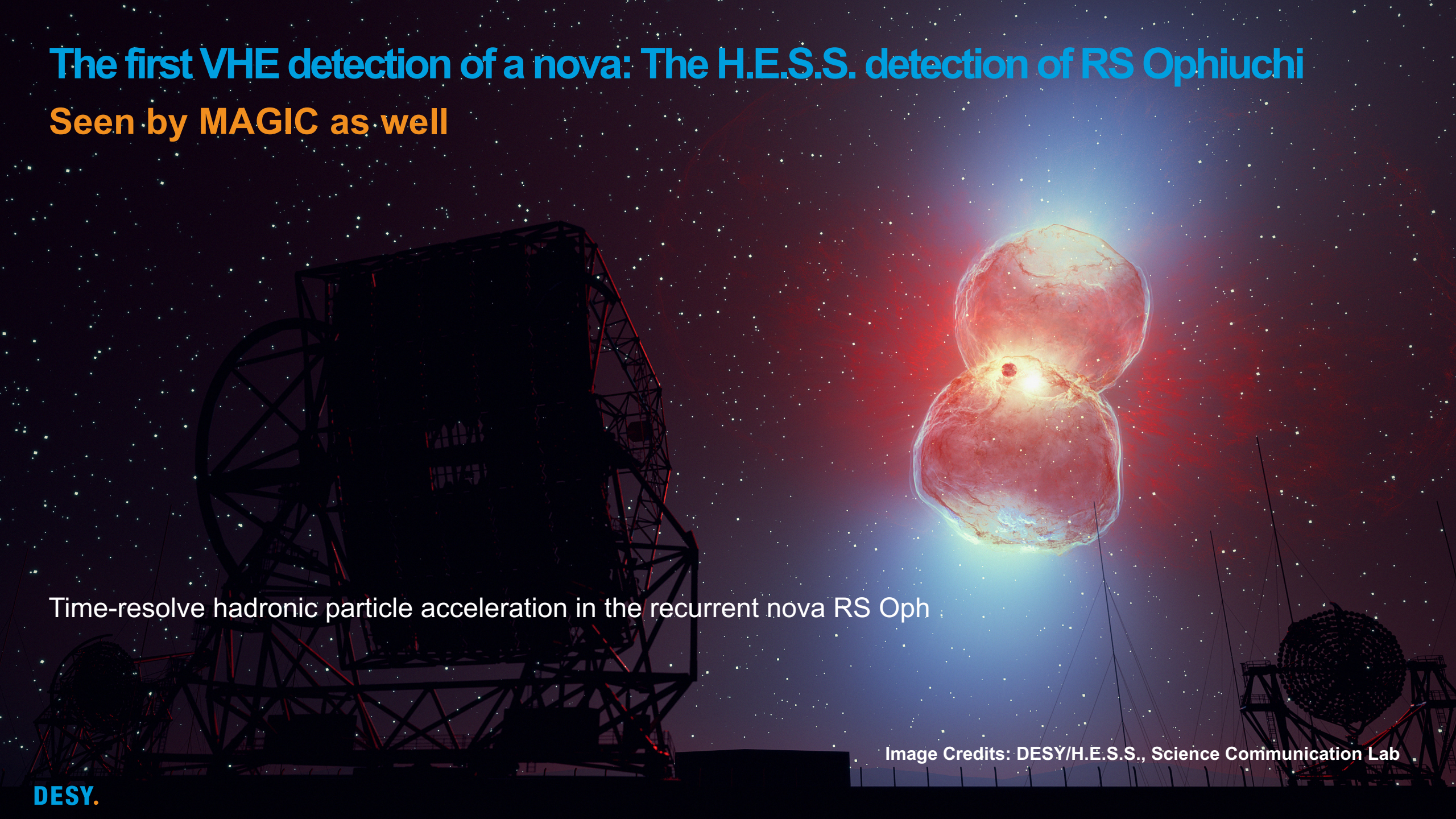
Christian Stegmann
International School of Cosmic Ray Astrophysics
Erice, July, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

The first VHE detection of a nova: The H.E.S.S. detection of RS Ophiuchi

Seen by MAGIC as well



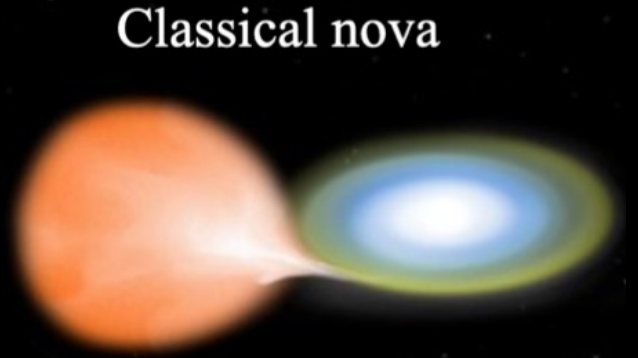
Time-resolve hadronic particle acceleration in the recurrent nova RS Oph

Image Credits: DESY/H.E.S.S., Science Communication Lab

DESY.

Novae

Classification



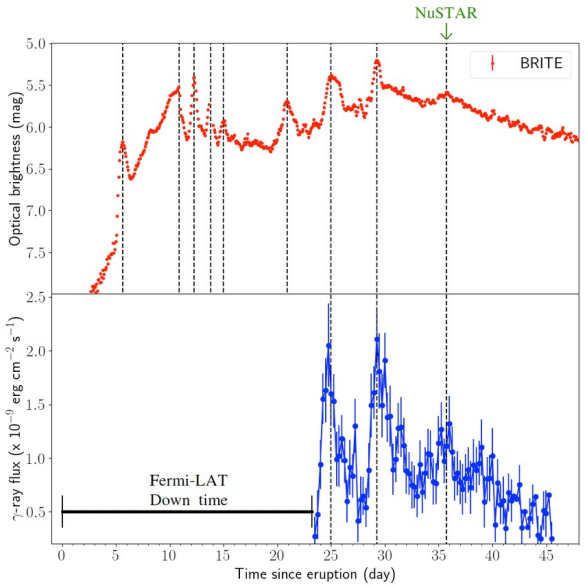
- White dwarf + main sequence (MS) companion
- Short period (~days), slow recurrence (10^4-10^5 yrs)
- Low-density, fast wind from MS companion

- White dwarf + red giant (RG) companion
- Long period (~1 year), fast recurrence (~100 yrs)
- High-density, slow wind from RG

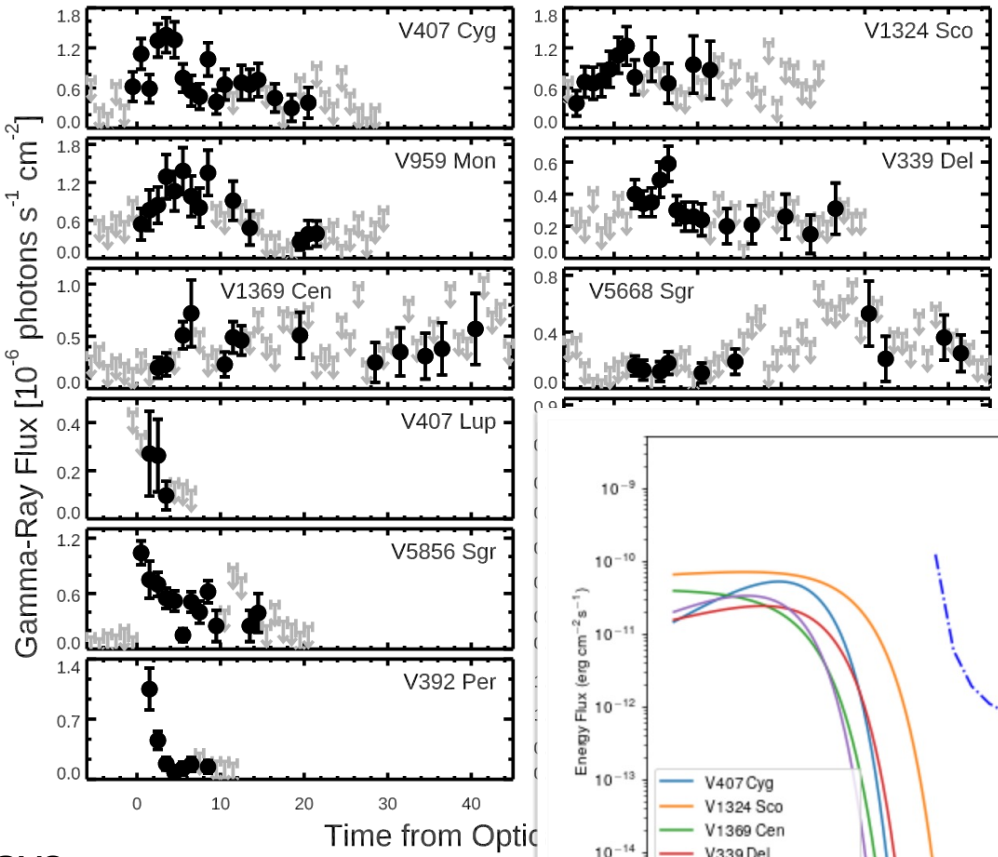
Novae phenomenology

Shocks

- internal and external shocks are expected
- Observational evidences:
  - GeV emission from a dozens of novae
    $L_{GeV} = 10^{34}$-10^{36} erg/s
  - Shocks seem energetically important



Aydi et al, 2020



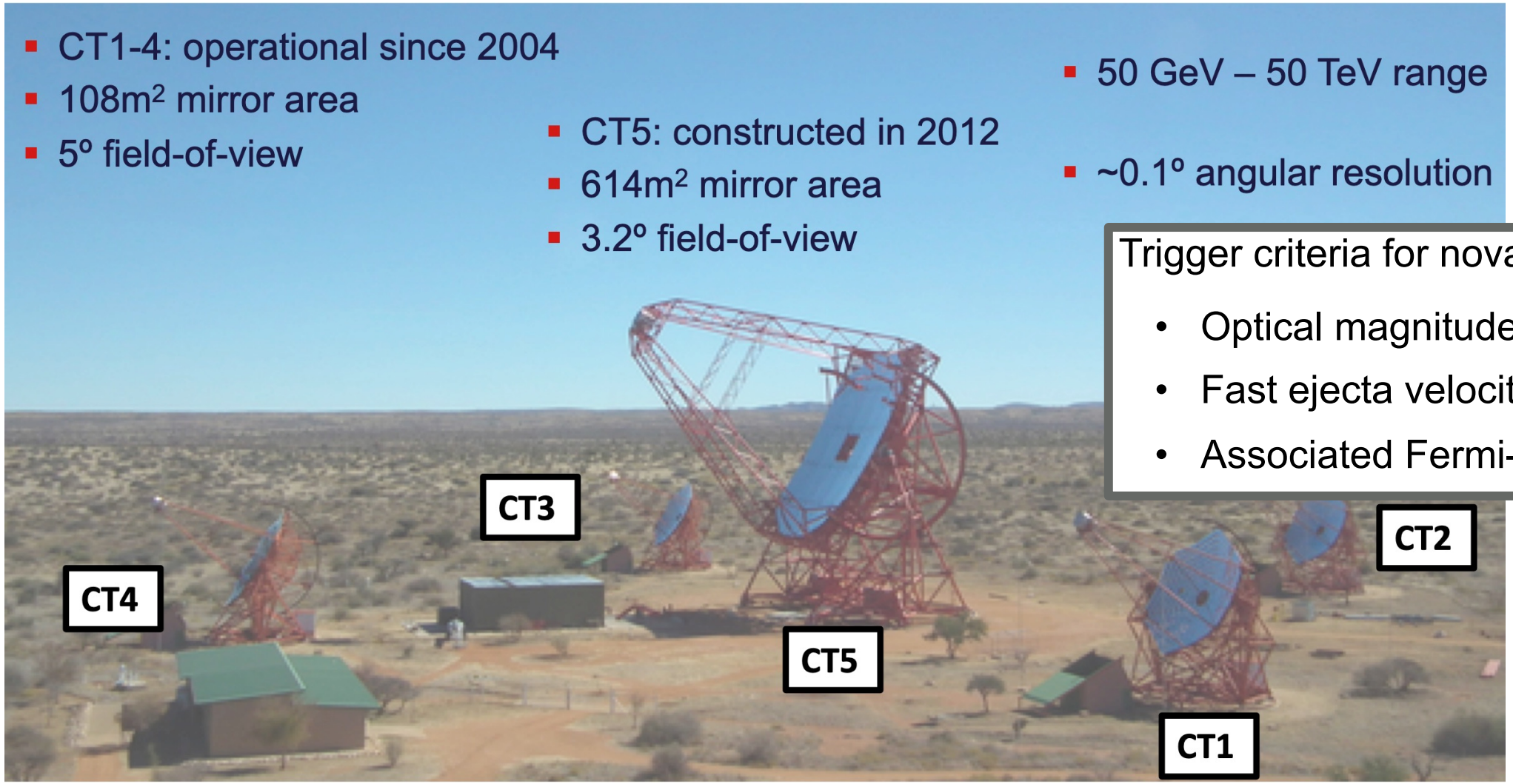
Correlation between
optical and gamma-rays
=> a portion of the optical luminosity
reprocessed shock power?

The H.E.S.S. Telescope System

- CT1-4: operational since 2004
- 108m² mirror area
- 5º field-of-view

- CT5: constructed in 2012
- 614m² mirror area
- 3.2º field-of-view

- 50 GeV – 50 TeV range
- ~0.1º angular resolution



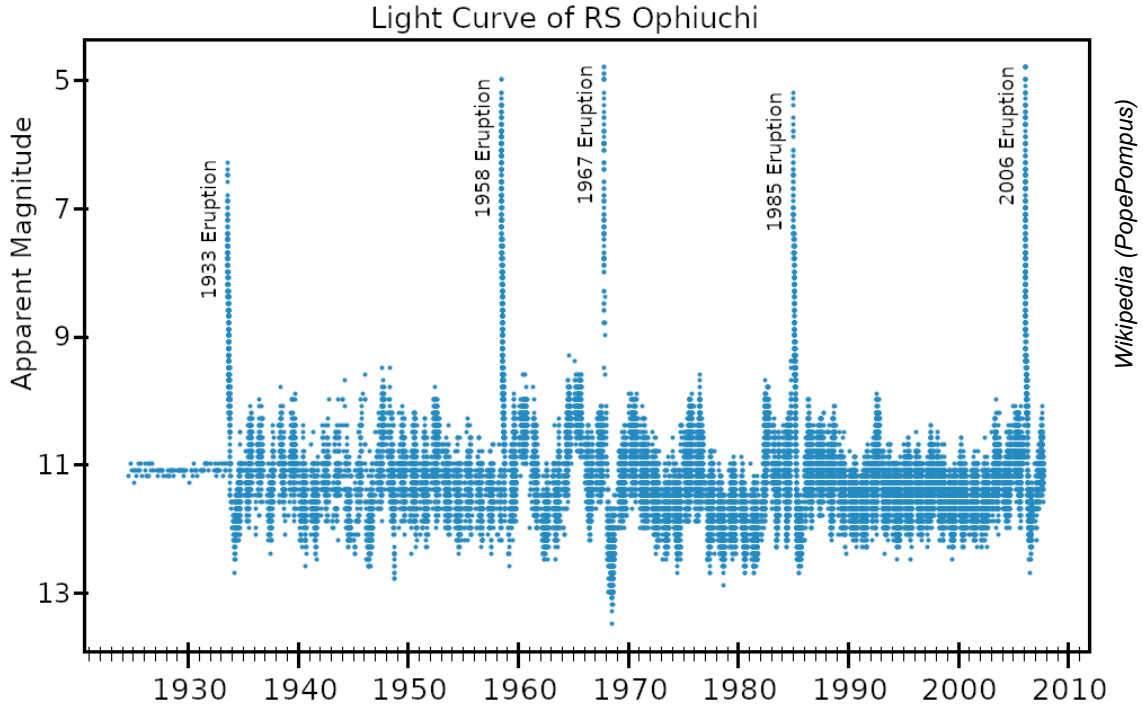
Trigger criteria for novae:

- Optical magnitude, $m_V \lesssim 9$
- Fast ejecta velocity $\gtrsim$ 1500 km/s
- Associated Fermi-LAT detection

RS Ophiuchi

VHE Observations

- Symbiotic nova d ~ 1.4 (2.45) kpc
- Orbital period ~450 days, m_v<9
- Post-2006: asymmetric expansion at 5.5 days from infrared interferometric observations
- **Outburst on 8th – 9th August 2021**
  - 6σ in Fermi LAT data
  - $v_{ej} \gtrsim 2600$ km/s
  - m_v ~ 5.0



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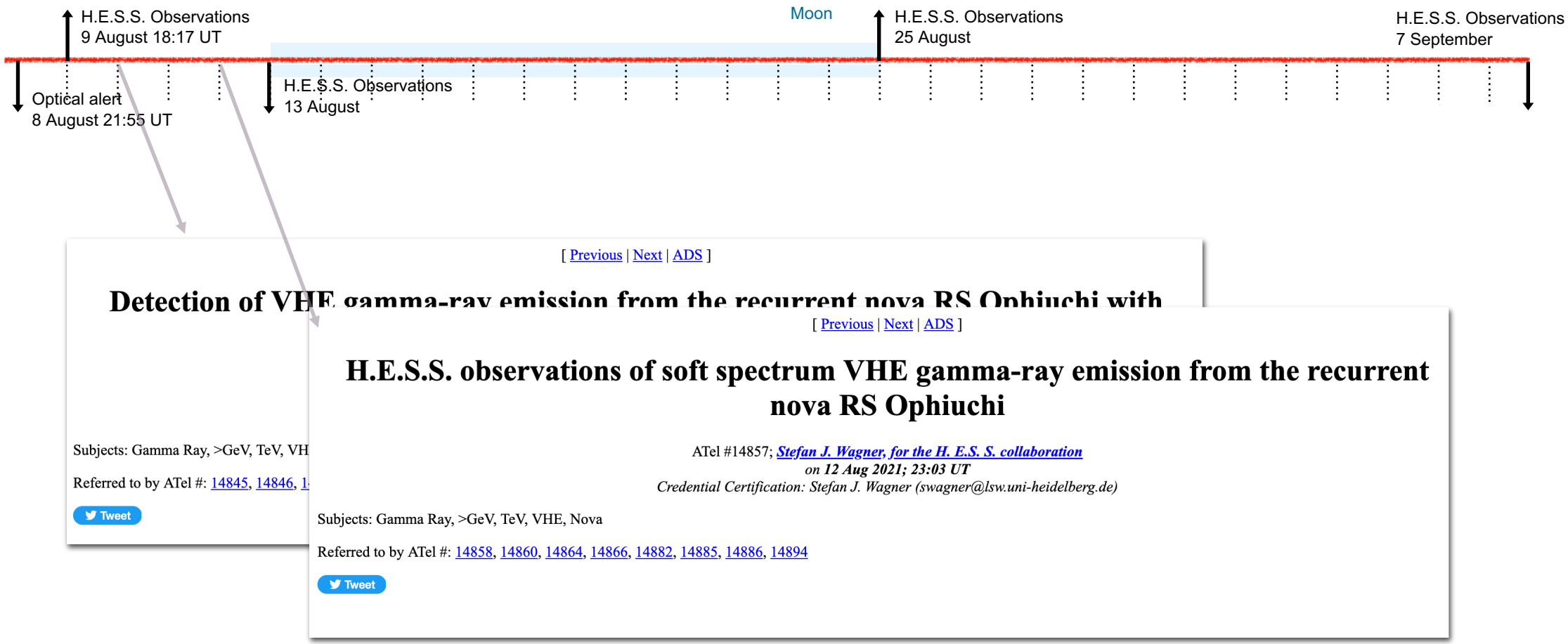
VHE Observations

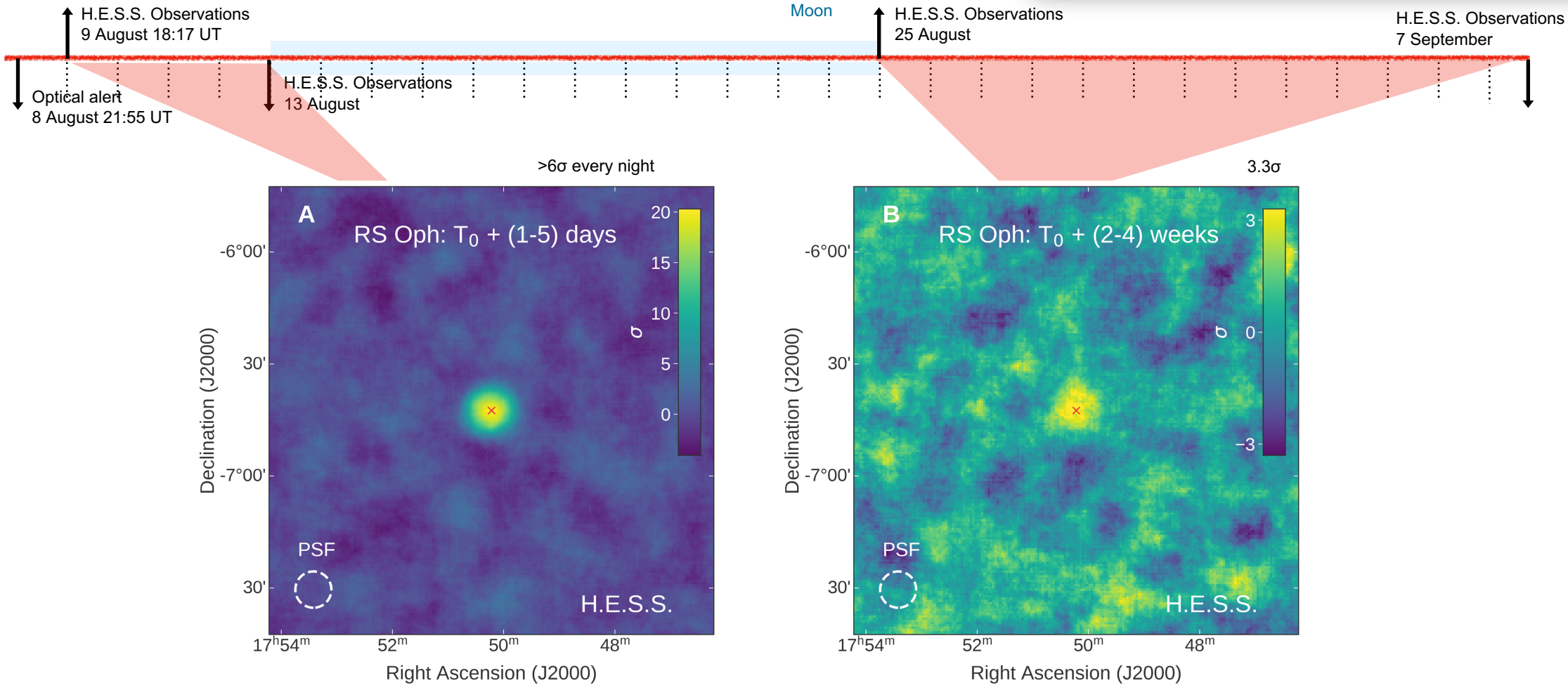


+ > 40 ATel related to follow-up observations

RS Ophiuchi

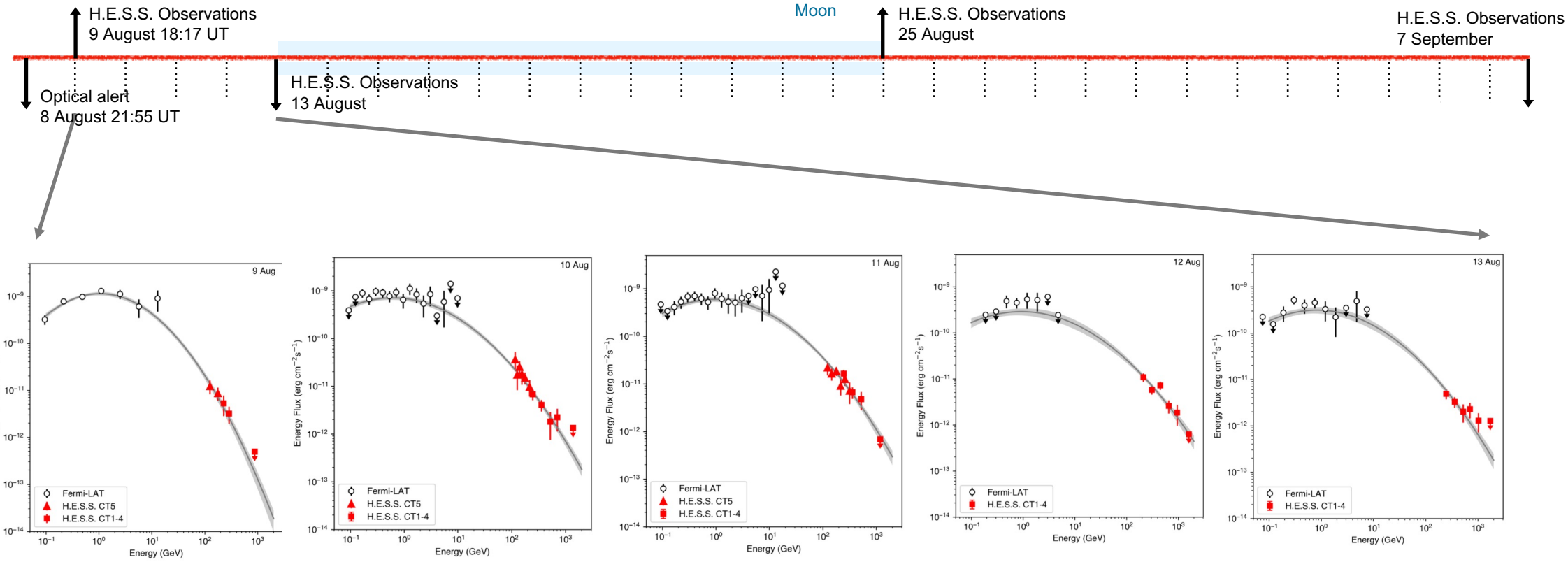
VHE Observations

Night	T_{obs} (UTC)	Livetime (hours)	Significance (σ)
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)
12 Aug. 2021	18:17:12	2.3	13.6
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)
25 Aug. – 07 Sep. 2021	17:48:03; 19:47:31	14.6 (13.4)	3.3 (2.3)



RS Ophiuchi

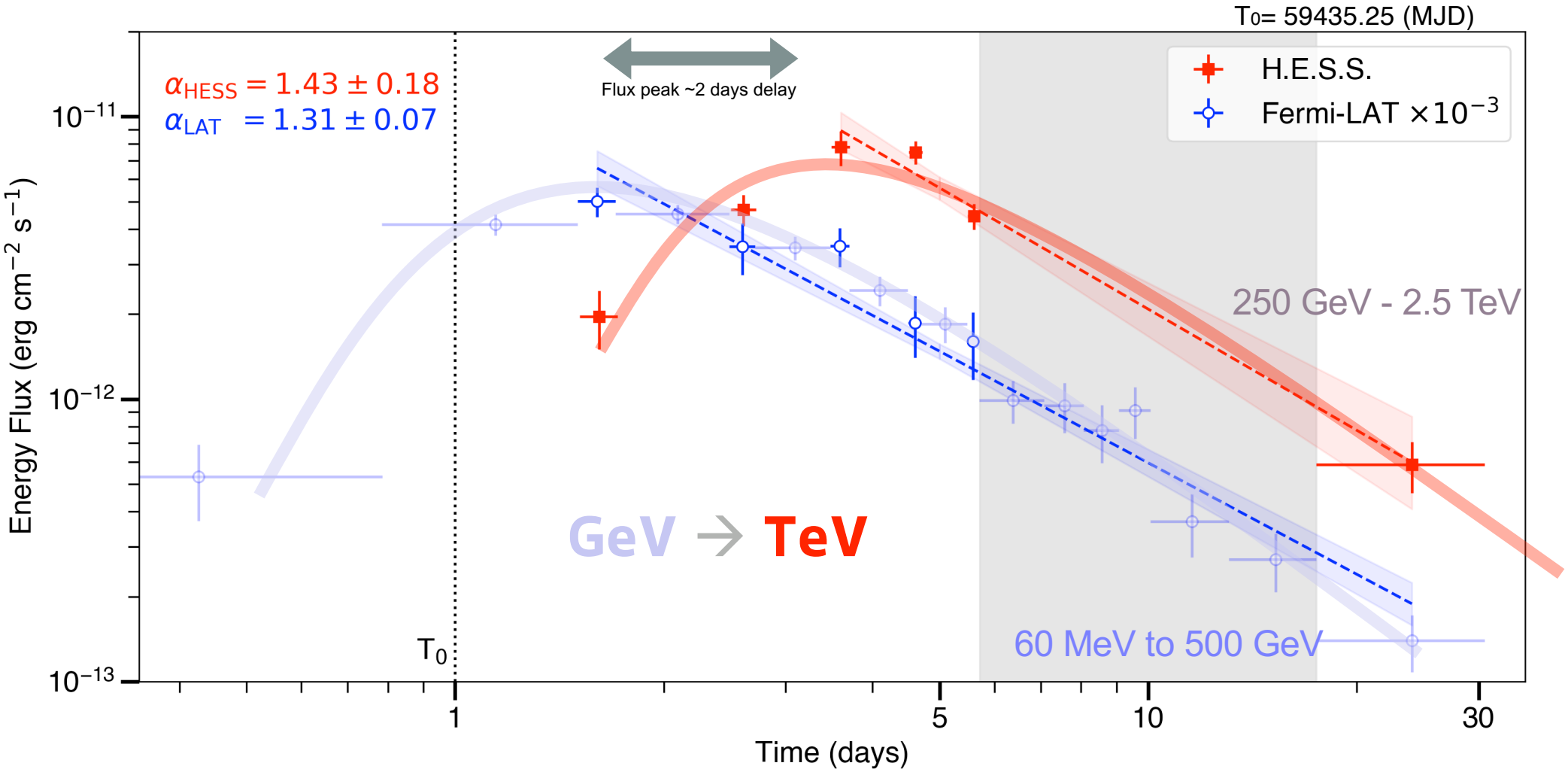
GeV Observations



Fit with a log-parabola function LAT + HESS (CT5 + CT1-4)

RS Ophiuchi

Light curve



RS Ophiuchi

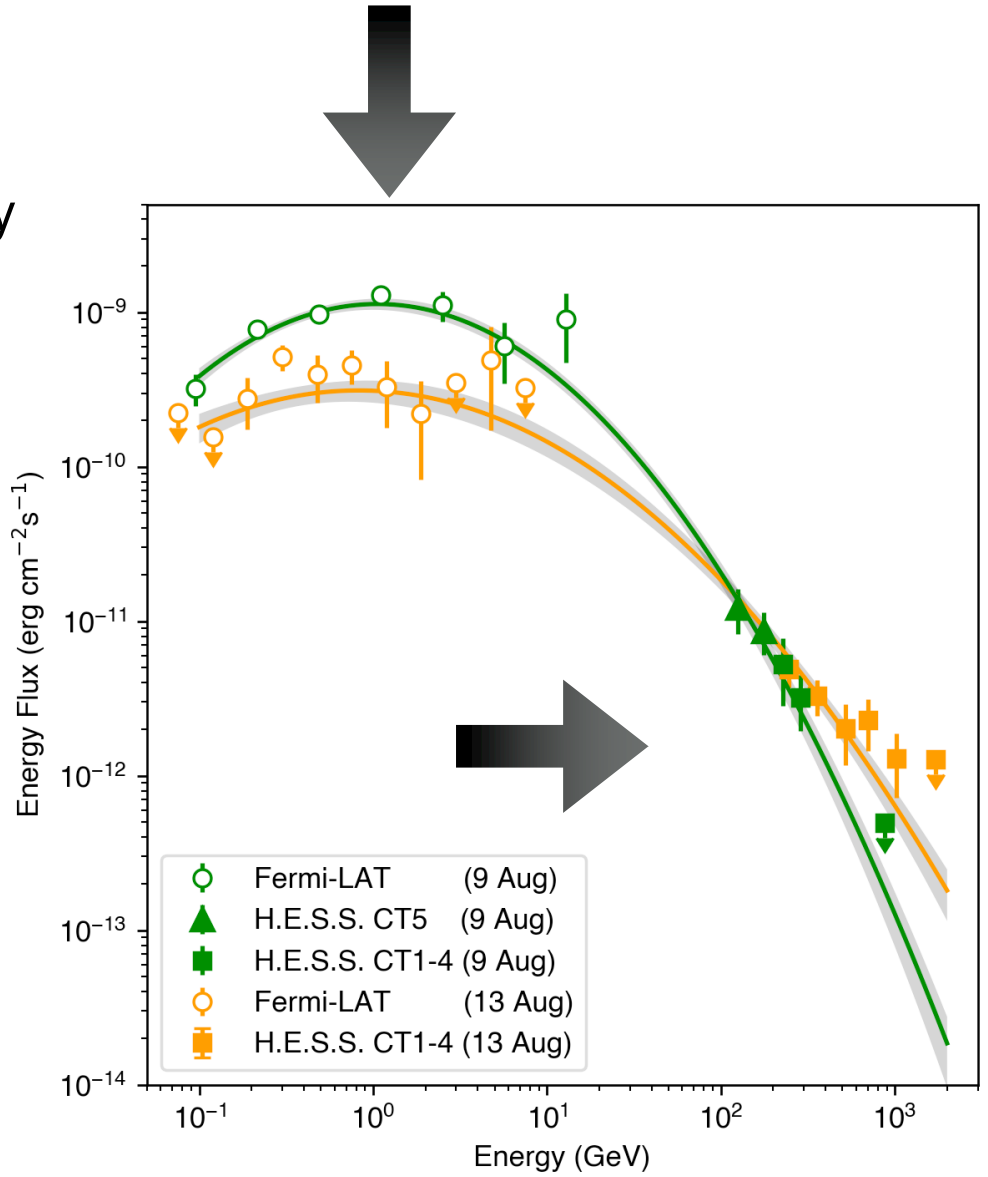
Spectral evolution

- H.E.S.S. spectrum becomes harder and extends to very high energies **E_{max} ~ 1 TeV**
- Maximum attainable particle energy depends on:
  - Confinement for protons:

$$E_{\max} = 1.5|Z| \left(\frac{\xi_{\rm esc}}{0.01}\right) \left(\frac{\dot{M}/v_{\rm wind}}{10^{11}{\rm kgm^{-1}}}\right)^{1/2} \left(\frac{u_{\rm sh}}{5000{\rm kms^{-1}}}\right) {\rm TeV}$$

  - Cooling for electrons:

$$E_{\max} = 10 \left(\frac{u_{\rm sh}}{5000{\rm km/s}}\right) \left(\frac{R_{\rm sh}}{\rm au}\right) \left(\frac{B_\star}{1{\rm G}}\right) {\rm TeV}$$



RS Ophiuchi

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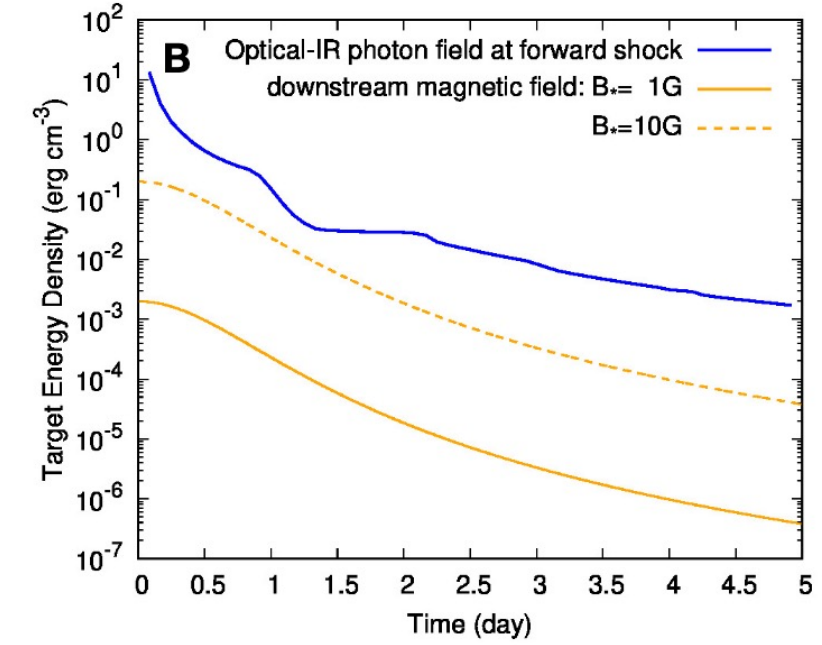
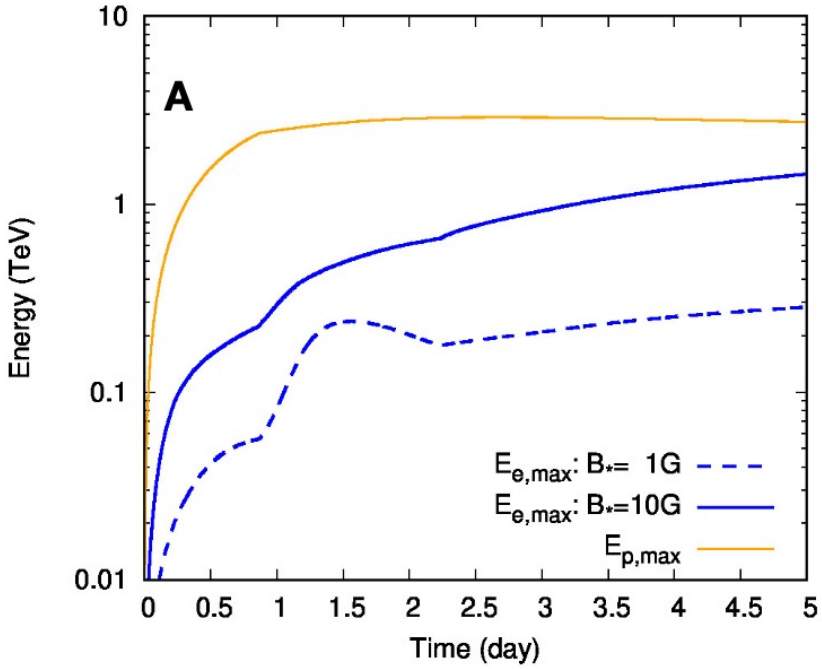
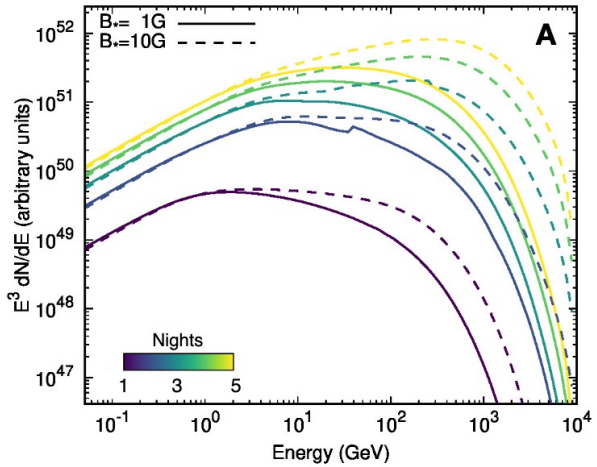




RS Ophiuchi

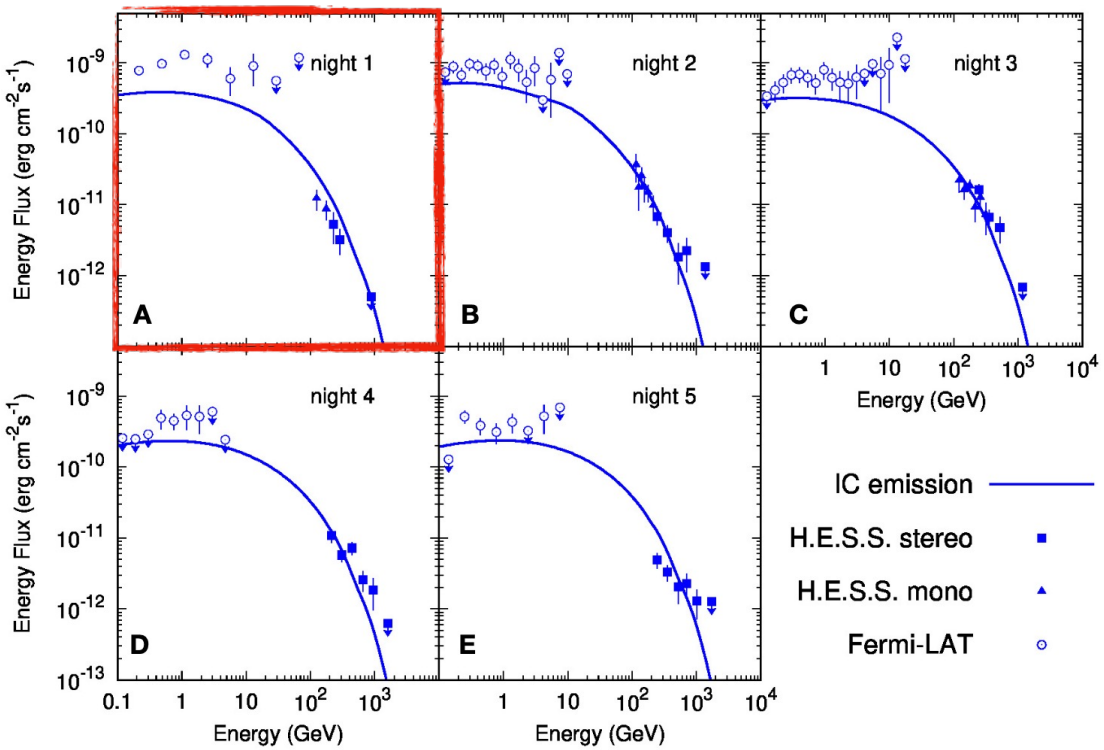
Inverse Compton

- Accelerate electrons at external shock, IC scatter in time-dependent radiation field of the nova
- In principle works, **but**
  - Fraction of energy of shock transferred to non-thermal emission >1% => inconsistent with DSA theory
  - Acceleration close to Bohm limit, requiring strong self-generated B-fields, requiring protons => p-p
  - 1st night very hard to explain



$$\frac{dE}{dt} = \frac{dE}{dt}\Big|_{\text{acc}} + \frac{dE}{dt}\Big|_{\text{losses}}$$

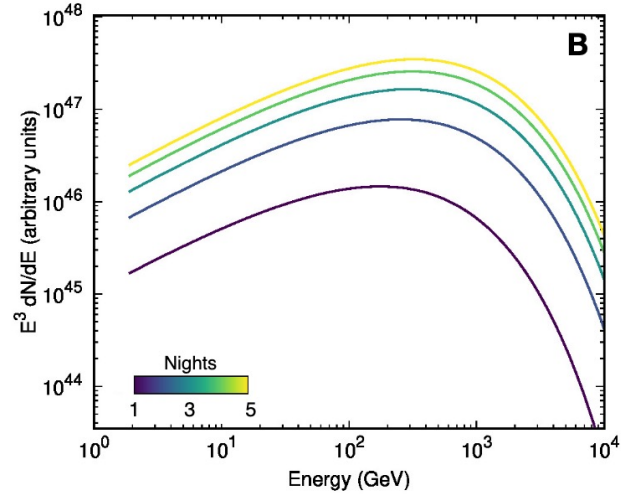
$$\frac{dE}{dt}\Big|_{\text{acc}} = \frac{qB_{sh}u_{sh}^2}{\eta c}$$

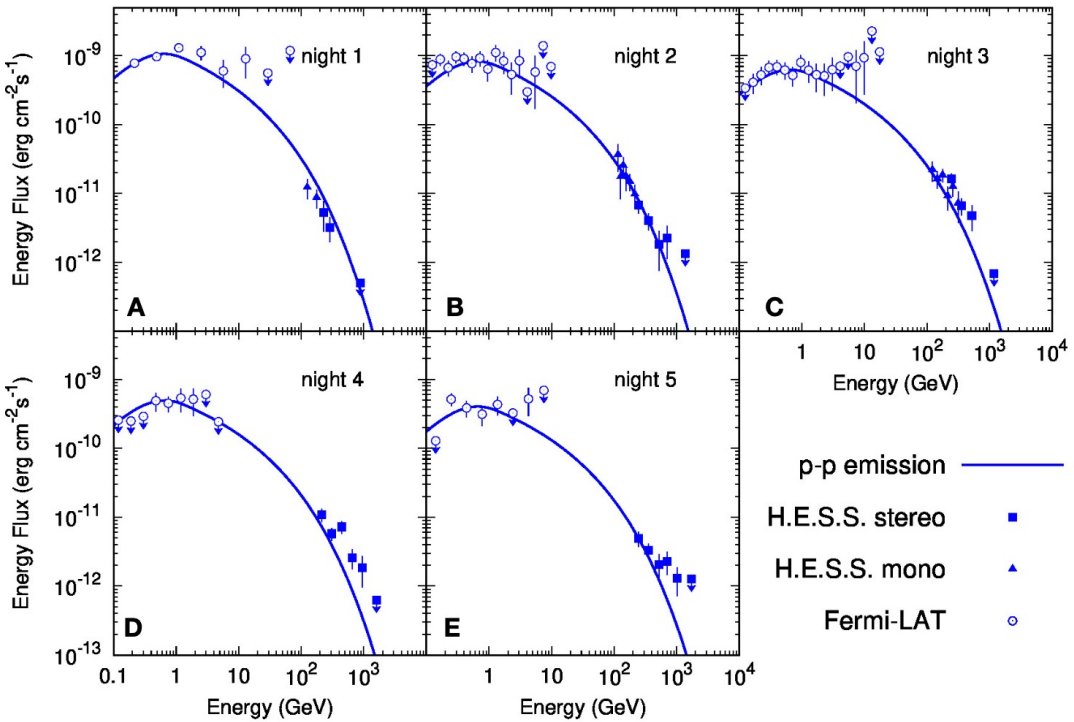


RS Ophiuchi

Proton-proton

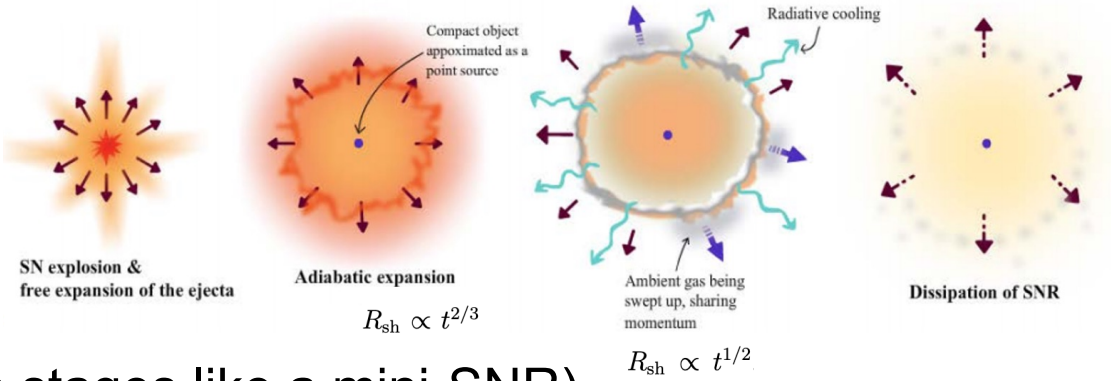
- Accelerate protons at external shock, proton-proton interaction with RG wind particles
- Hadronic model **strongly favoured**
  - Fraction of energy of shock transferred to non-thermal protons ~10% => consistent with DSA
  - E_{max} consistent with DSA, at theoretical limit!
  - Drop in LAT flux due to decreasing wind density
  - Increase in TeV flux consistent with build-up of high-energy proton population
  - Consistent with previous findings of other nova gamma detections





RS Ophiuchi

Modeling



- Dense medium => external shock (~evolution stages like a mini-SNR)
- Timescale evolution is ruled by $M_{\rm ej}^{3/2} v_{\rm wind} / E^{1/2} \dot{M}_{\rm wind}$ <= ratio ~10^{-5}

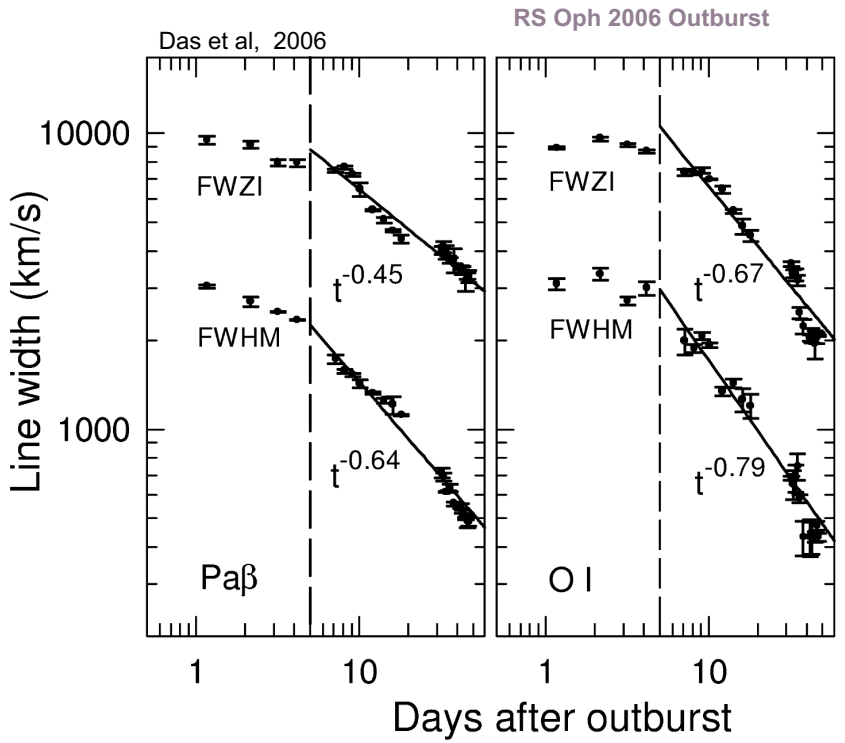
RS Oph

$\dot{M}_{\rm wind} = 3\times10^{-6} M_\odot {\rm yr}^{-1}$
$v_{\rm wind} = (10-30){\rm km/s}$
$E = 10^{43}{\rm erg}$
$M_{\rm ej} = 10^{-6} M_\odot$

SNR

$\dot{M}_{\rm wind} = 10^{-5} M_\odot {\rm yr}^{-1}$
$v_{\rm wind} = 10{\rm km/s}$
$E = 10^{51}{\rm erg}$
$M_{\rm ej} = 10 M_\odot$

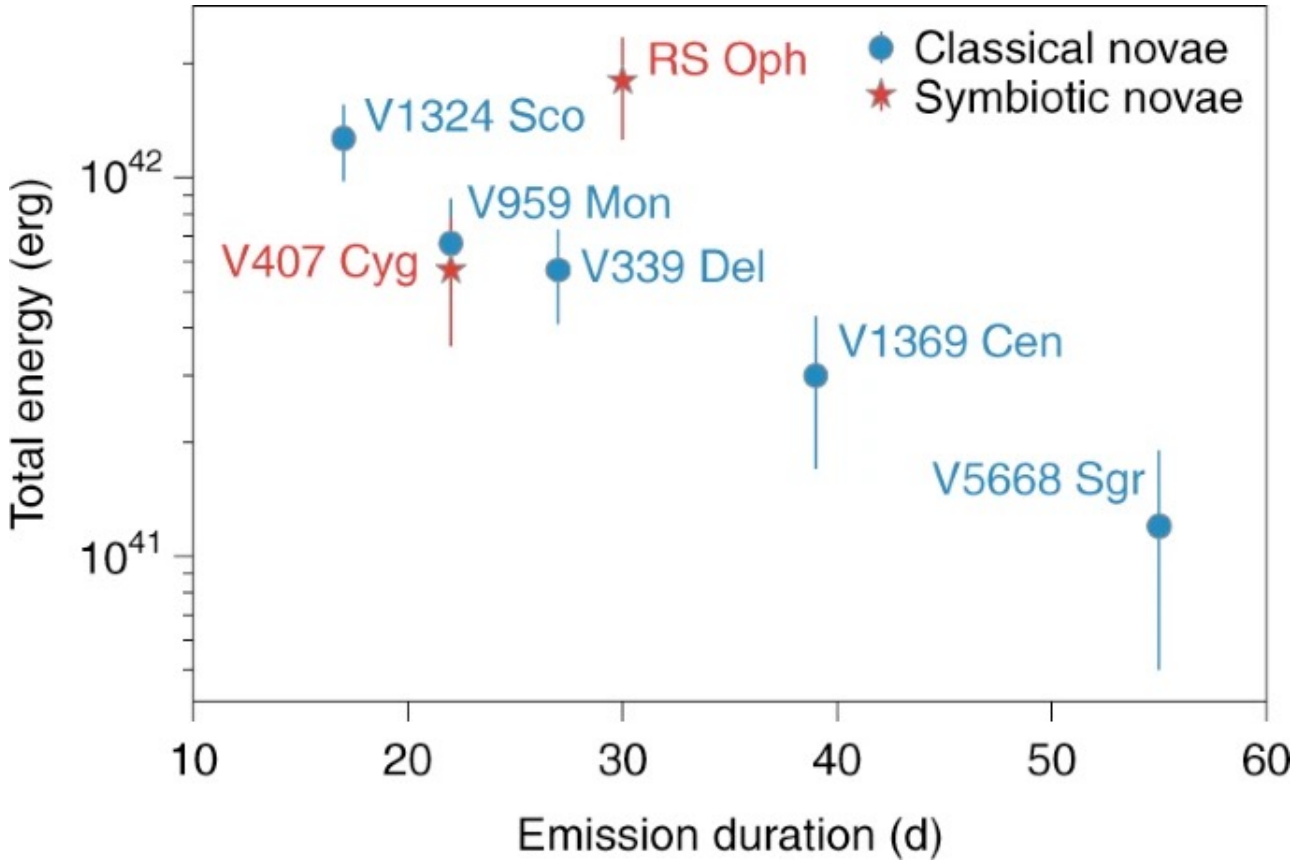
First ~5 days => ejecta dominated v~(2-4)x10^3 km/s

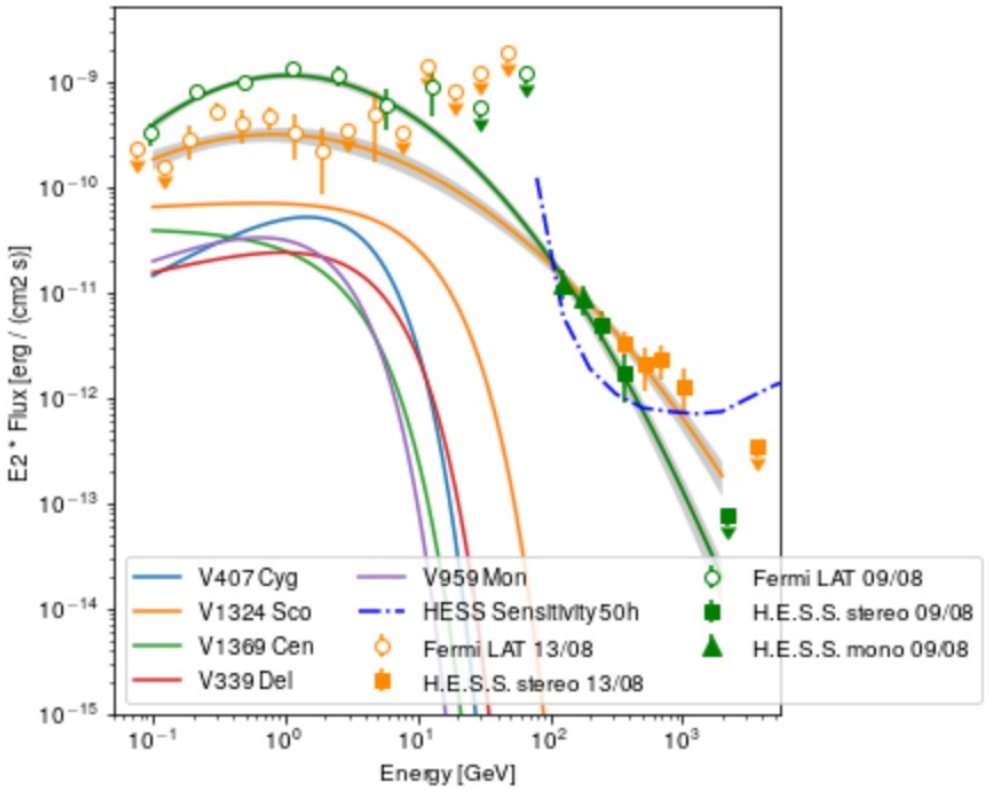


Relevance of H.E.S.S. & MAGIC detection

- This discovery is not just "yet another new source class", but
  - We witnessed CR acceleration and gamma-ray production in **real-time** outside the solar system for 1st time => "movies" instead of “snapshots"
  - Were able to study DSA in ~controlled environment in time-dependent fashion
  - DSA at (predicted) theoretical limit works
  - Proofs particle acceleration in dense stellar winds is highly effective => relevance for PeV CR acceleration?!

Comparison with previous Novae



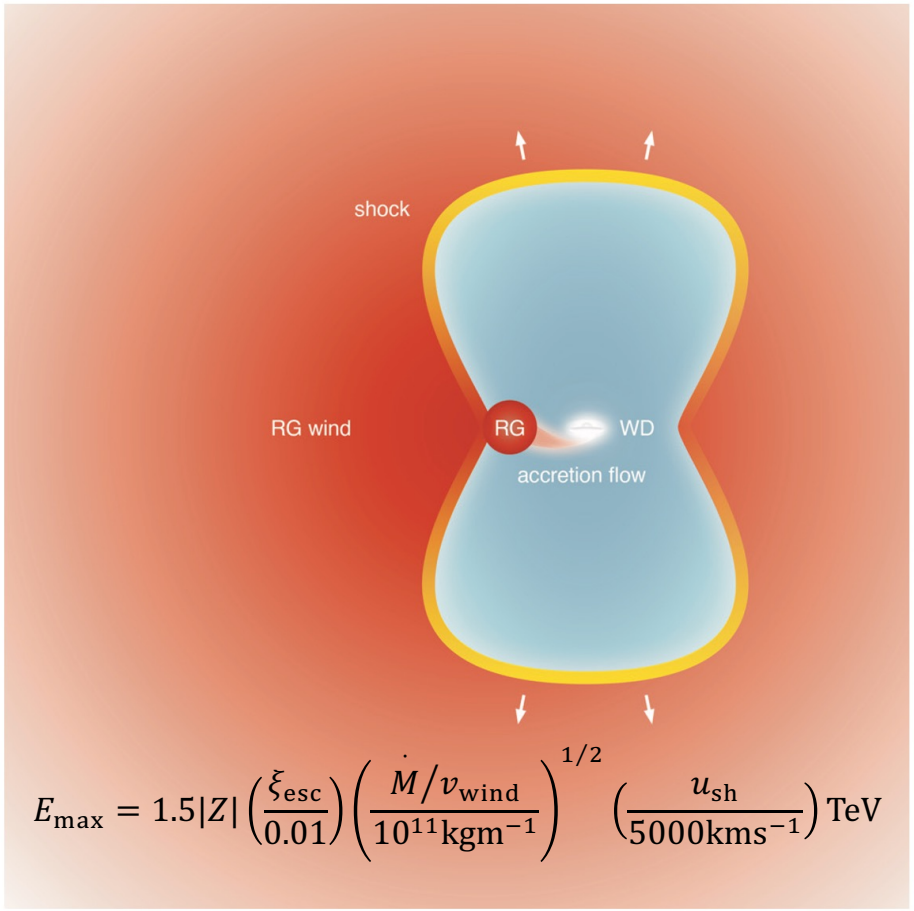


- Go back to archive and look into previous follow-ups, adapt follow-up strategy
- Longer duration, more observation time needed for CTA

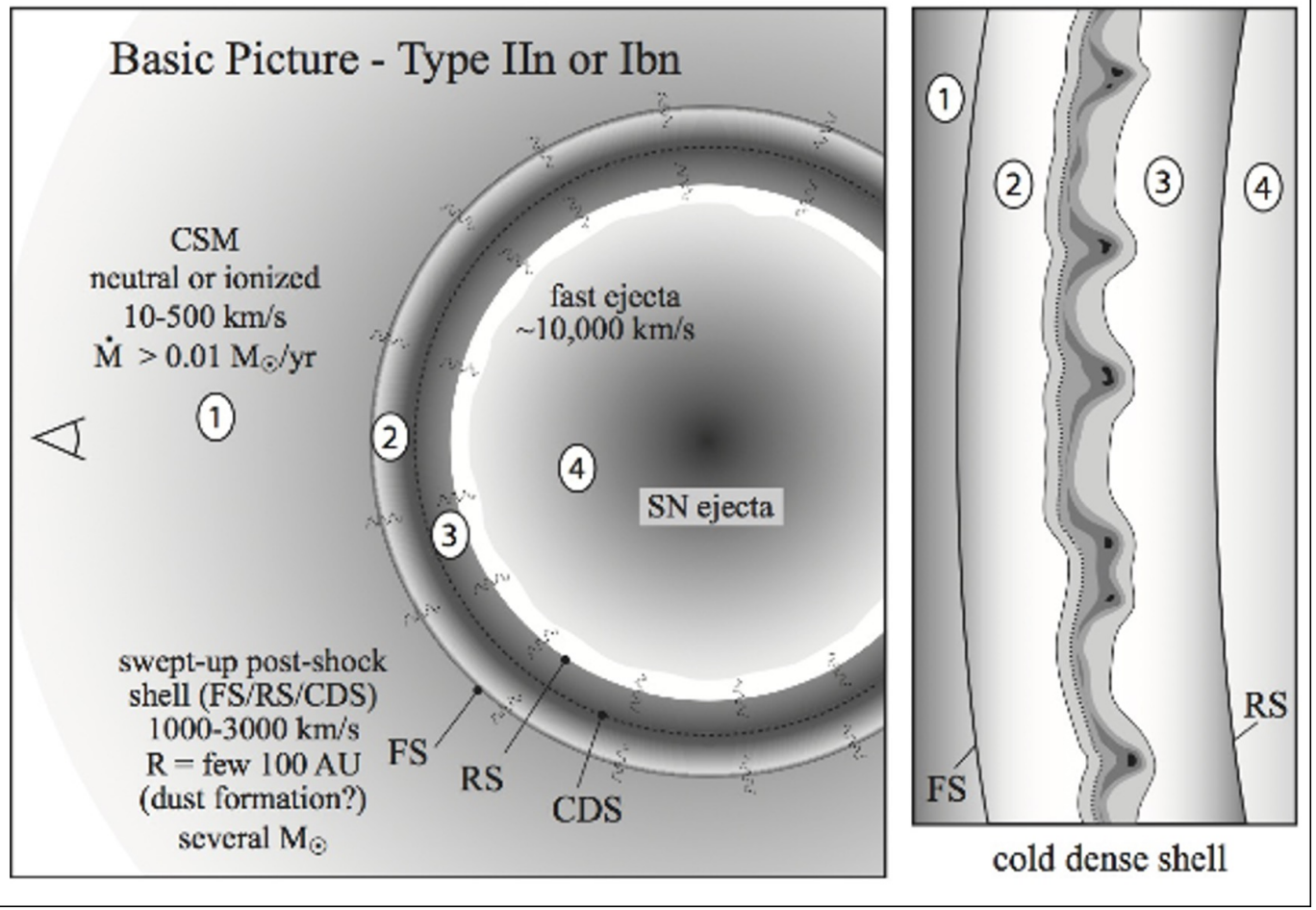
From novae to supernovae

More energy + faster shocks + dense & structued (?) CSM

Recurrent novae



Interaction-powered SNe



Recurrent nova RS Ophiuchi

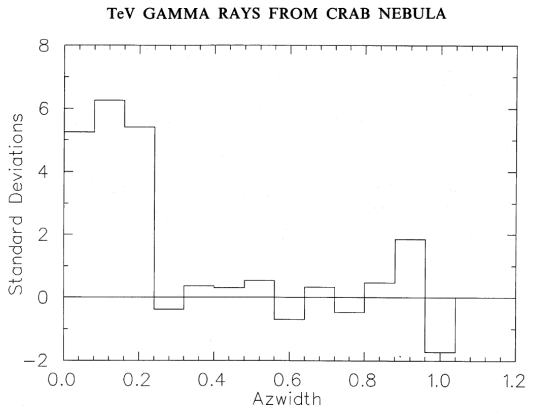
Image Credits: DESY/H.E.S.S., Science Communication Lab

Time Domain Astronomy

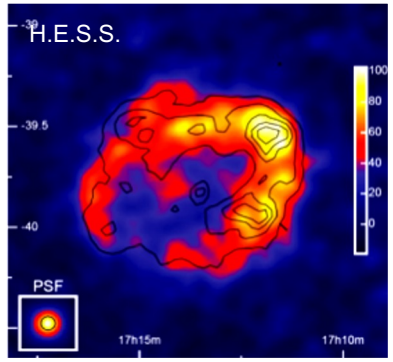
- Increasingly important field to study the dynamics of astrophysical processes on short time scales
- Flares of Active Galactic Nuclei
- Gravitational Wave Events
- Gamma-Ray Bursts (GRBs)
- Novae
- …

Data Quality

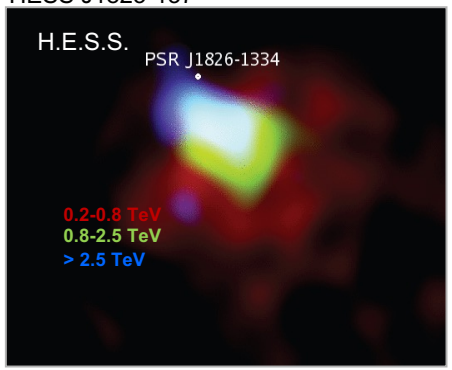
- Morphologies
  - spacial
  - energy-dependent
- Periodicities/Variability
  - from ms to years
- Energy-coverage
  - over several decades
- Source positions and extensions
  - on the arc-second level



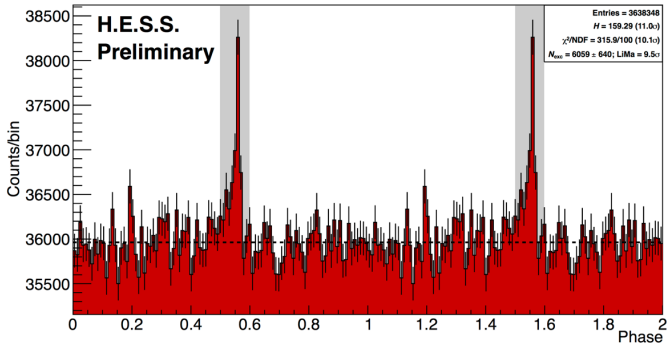
RX J1713-3946



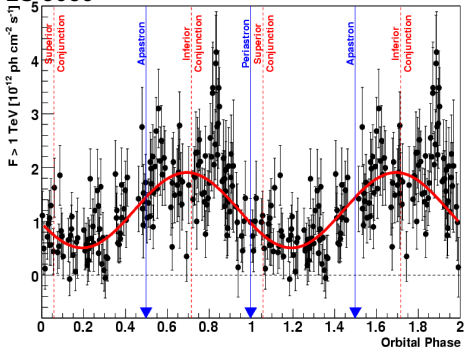
HESS J1825-137



Vela pulsar



LS 5039



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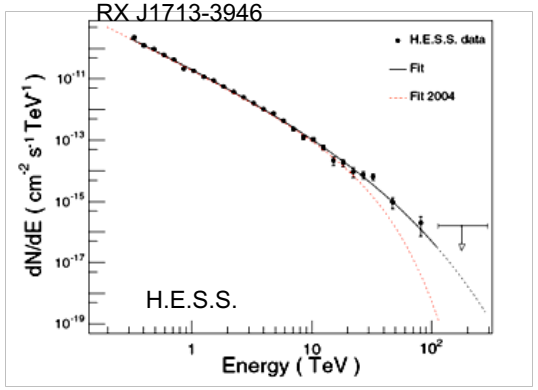
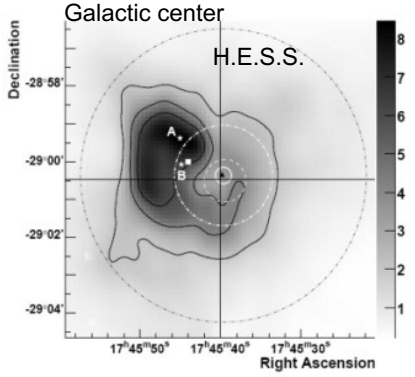


Galactic center



How to do better?

- More events
  - more photons = better spectra, images, fainter sources

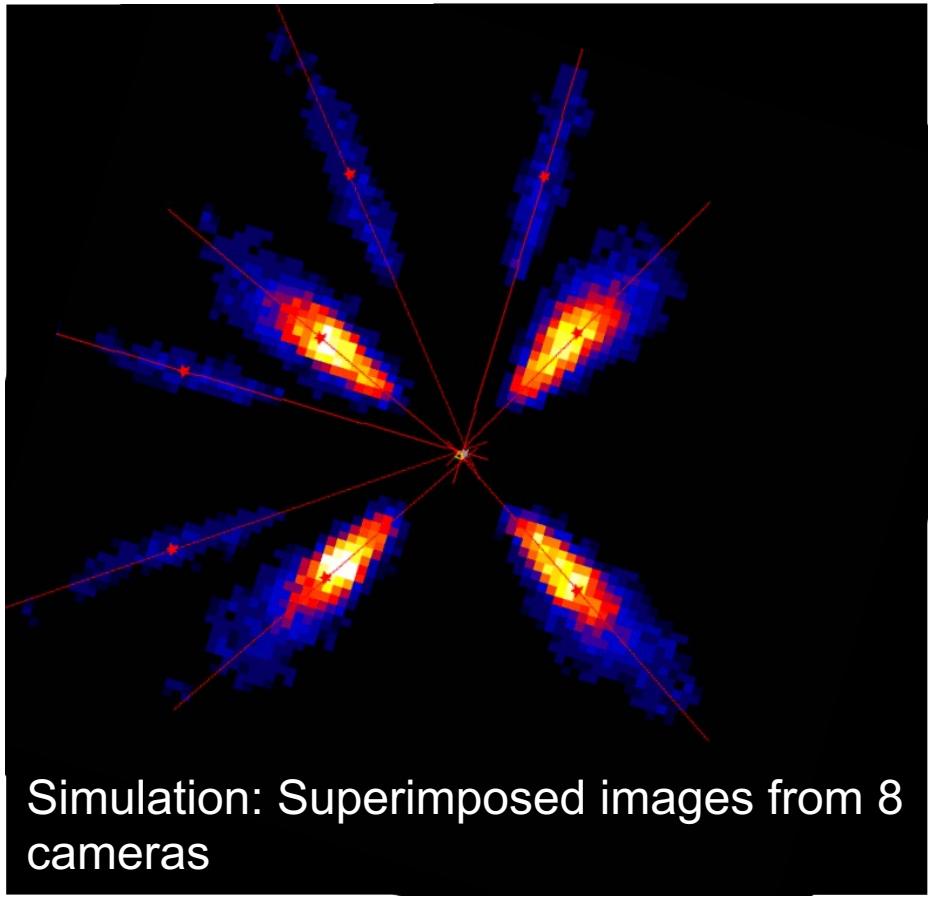
  → **larger collection area for gamma-rays**

- Better events
  - more precise measurements of atmospheric cascades and hence primary gammas

  → **improved angular resolution**

  → **improved background rejection power**

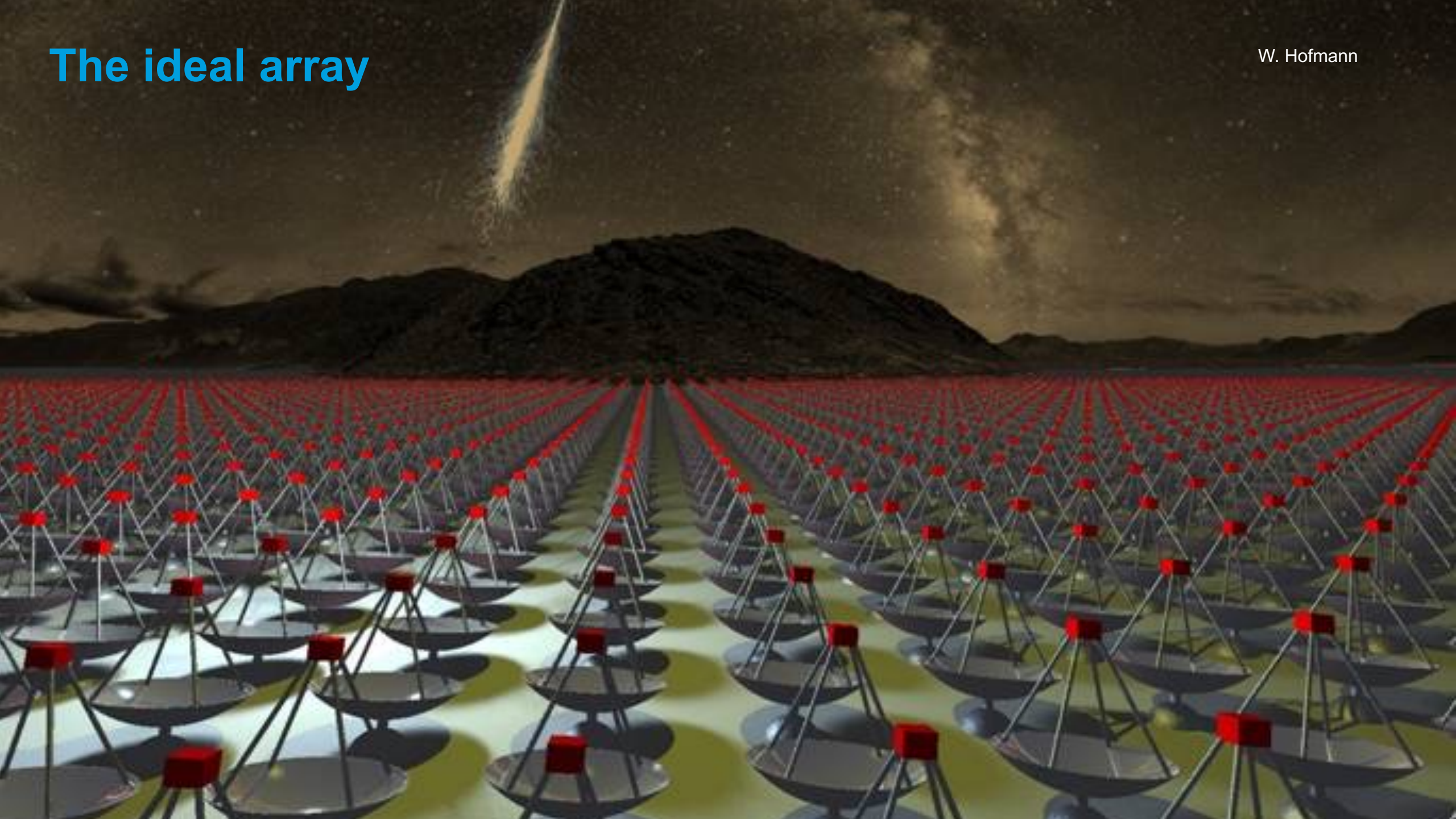
→ **More telescopes!**



Simulation: Superimposed images from 8 cameras

A project with more than 1200 scientists, over 70 insitutes around the world

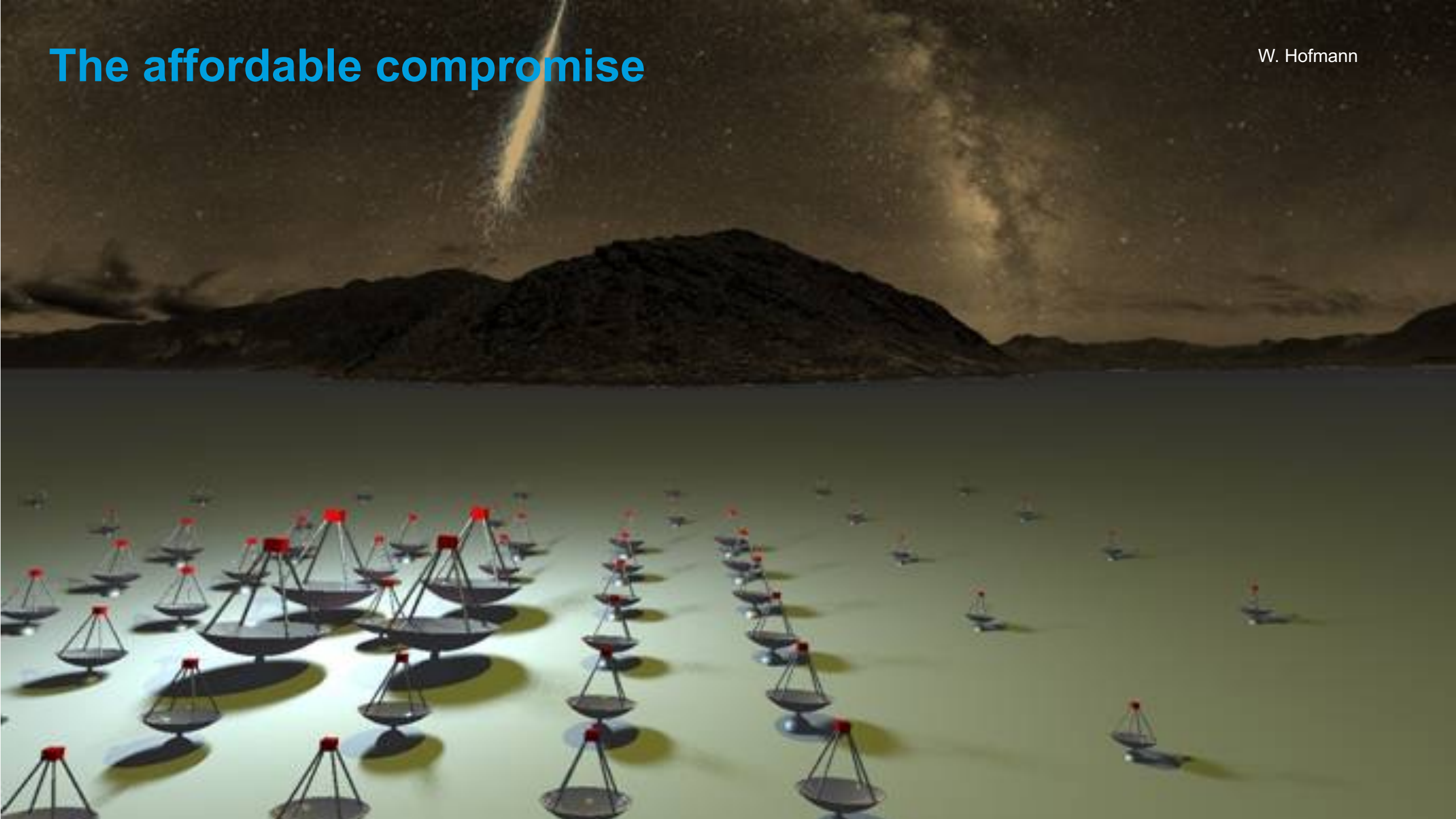
The ideal array



W. Hofmann

The affordable compromise

W. Hofmann



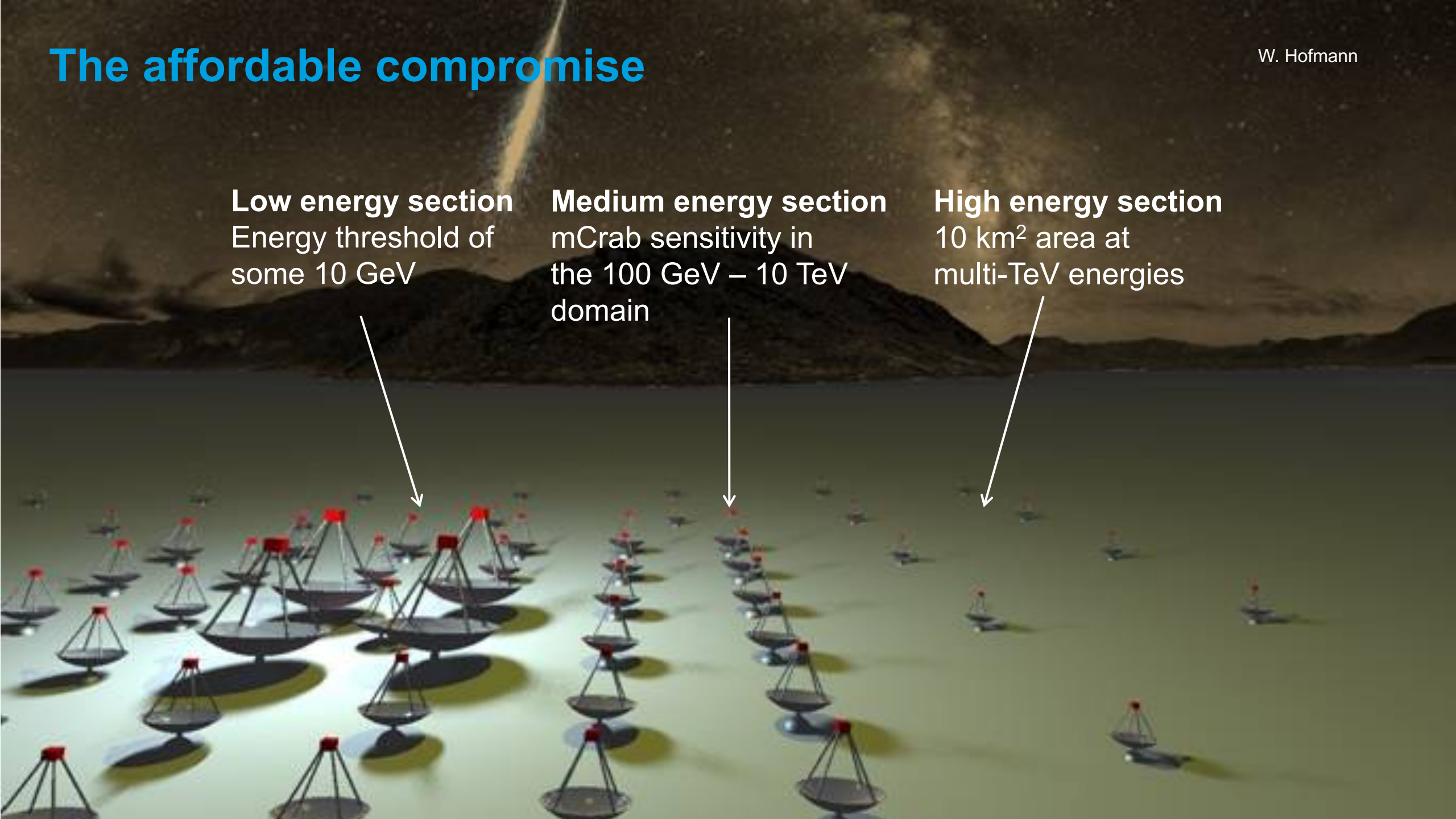
The affordable compromise

W. Hofmann

Low energy section
Energy threshold of some 10 GeV

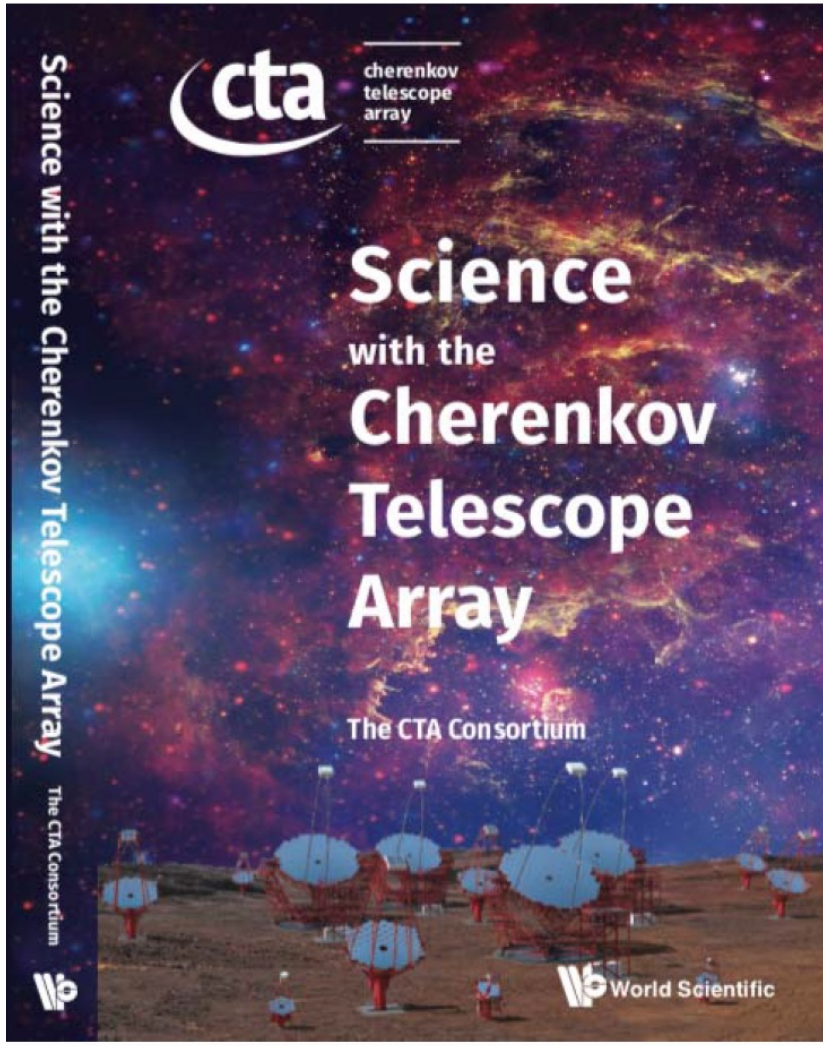
Medium energy section
mCrab sensitivity in the 100 GeV – 10 TeV domain

High energy section
10 km^2 area at multi-TeV energies

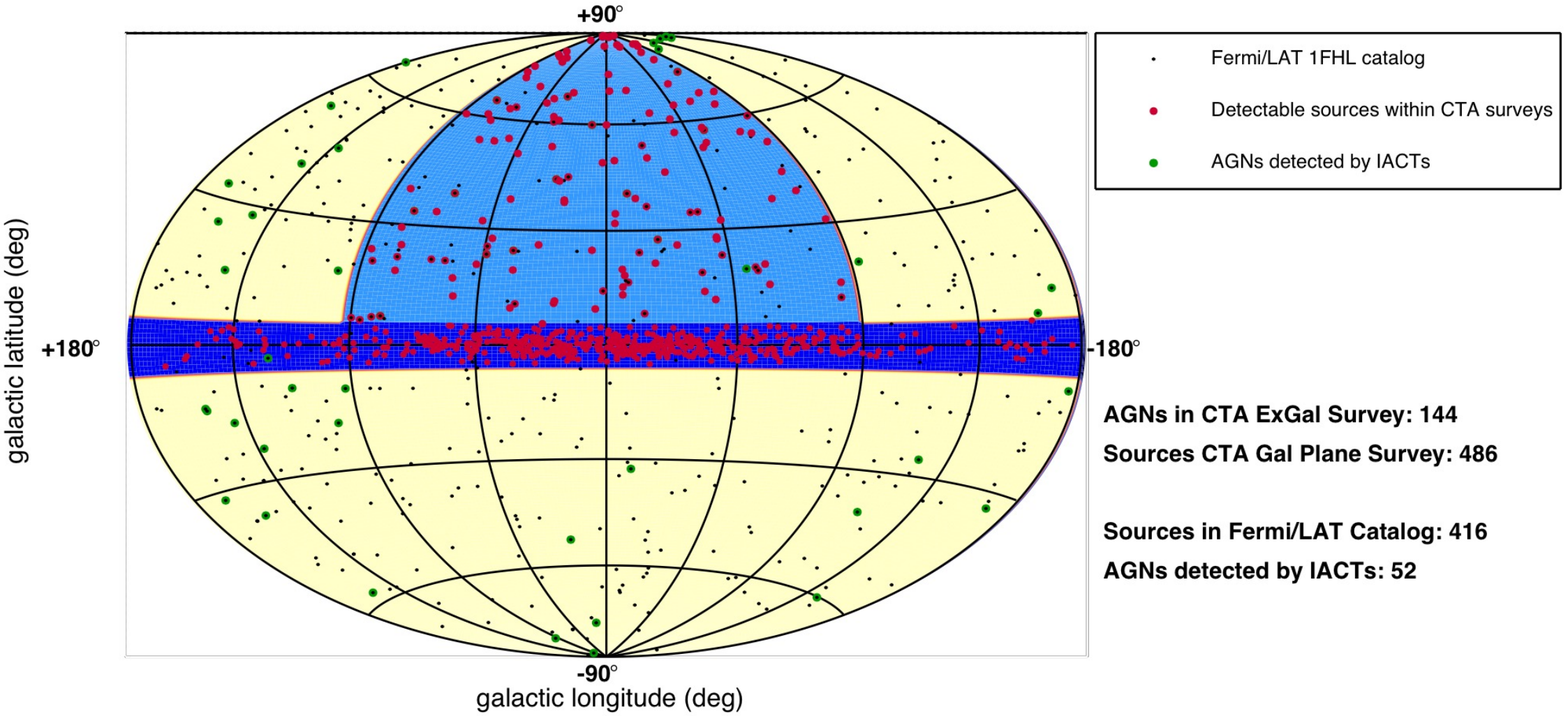


Science drivers for CTA

- **Theme 1: Cosmic Particle Acceleration**
  - How and where are particles accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- **Theme 2: Probing Extreme Environments**
  - Processes close to neutron stars and black holes?
  - Processes in relativistic jets, winds and explosions?
  - Exploring cosmic voids
- **Theme 3: Physics Frontiers – beyond the SM**
  - What is the nature of Dark Matter? How it is distributed?
  - Is the speed of light a constant for high energy particles?
  - Do axion-like particles exist?



Survey Sensitivity



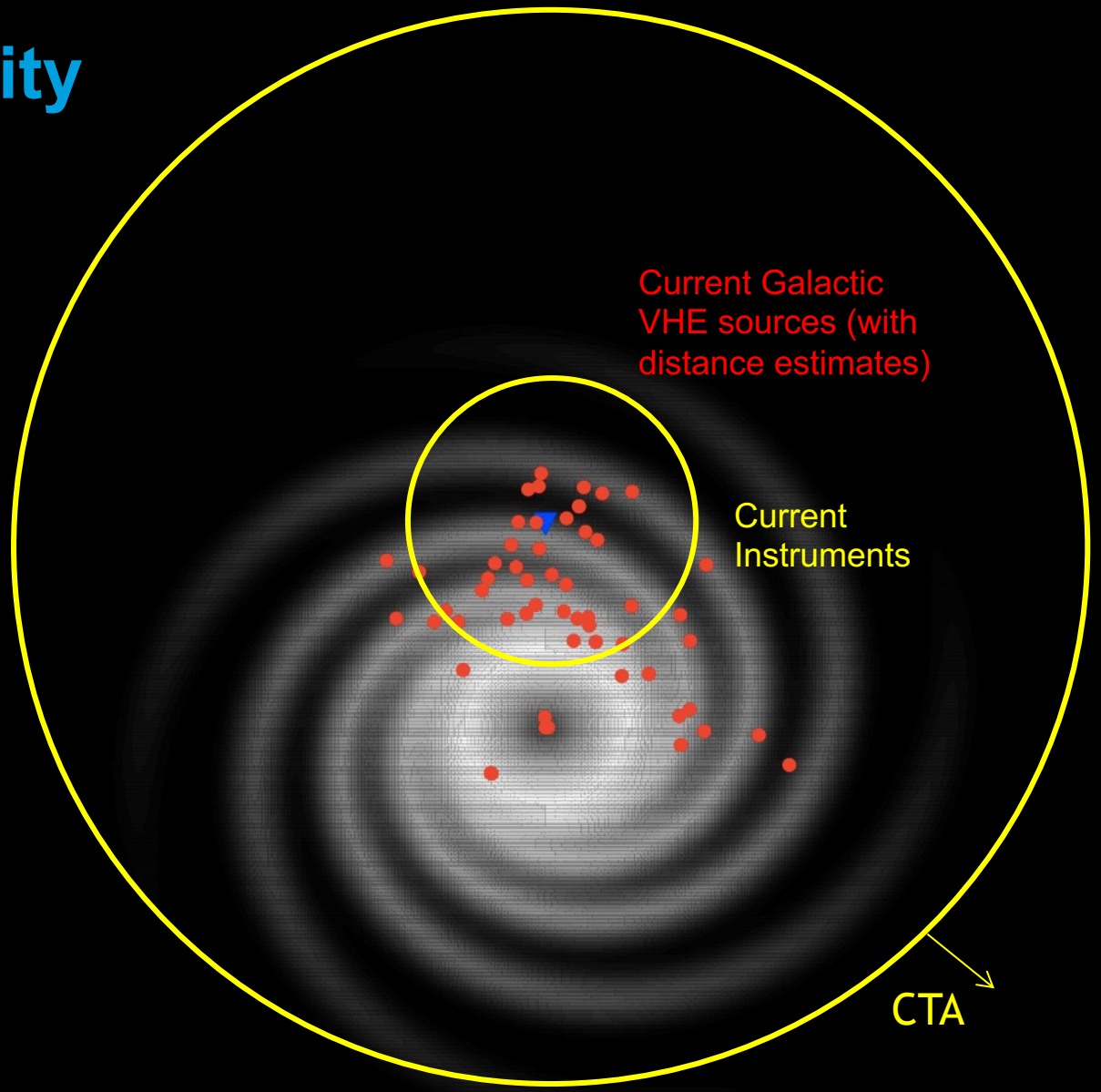
AGNs in CTA ExGal Survey: 144

Sources CTA Gal Plane Survey: 486

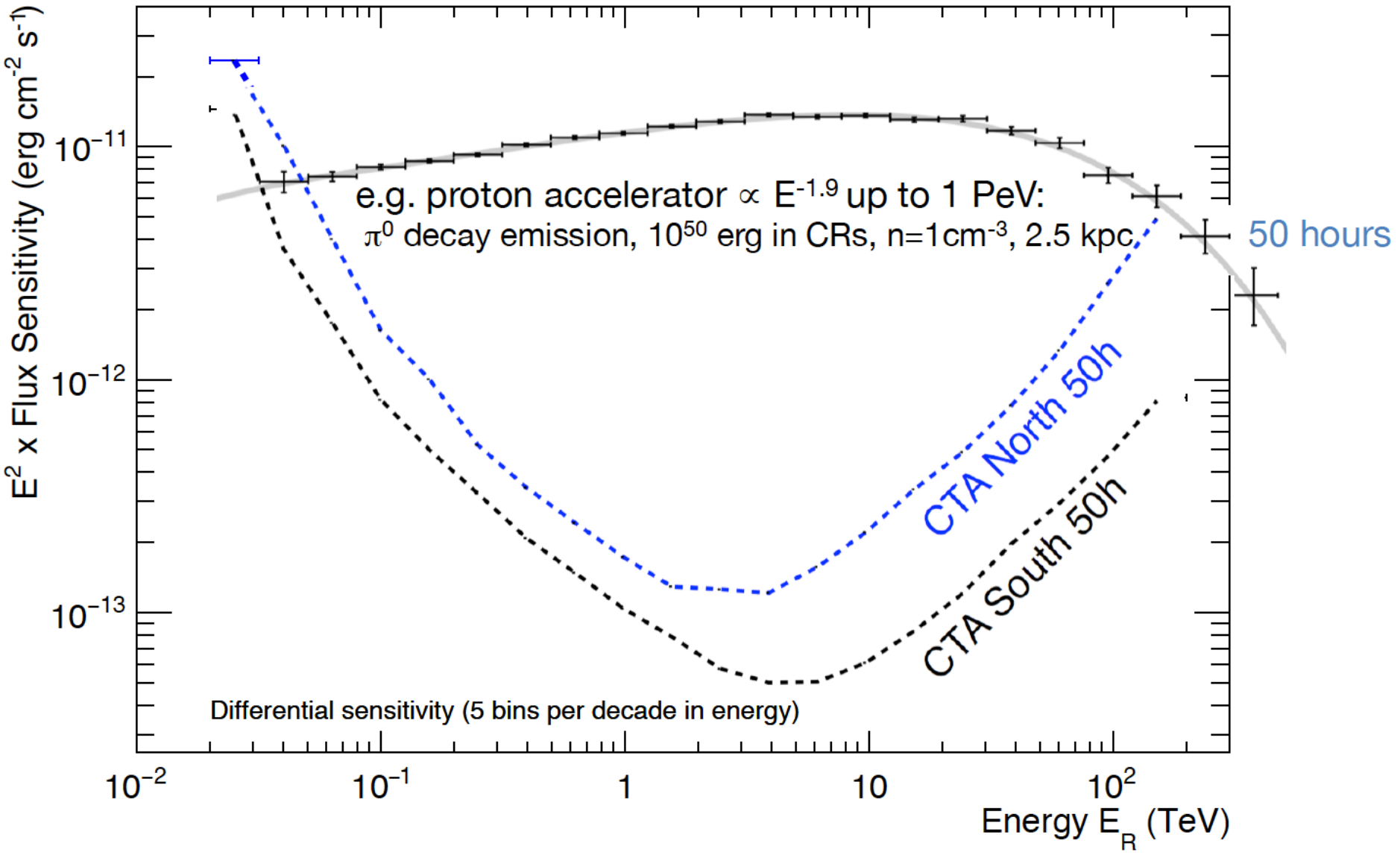
Sources in Fermi/LAT Catalog: 416

AGNs detected by IACTs: 52

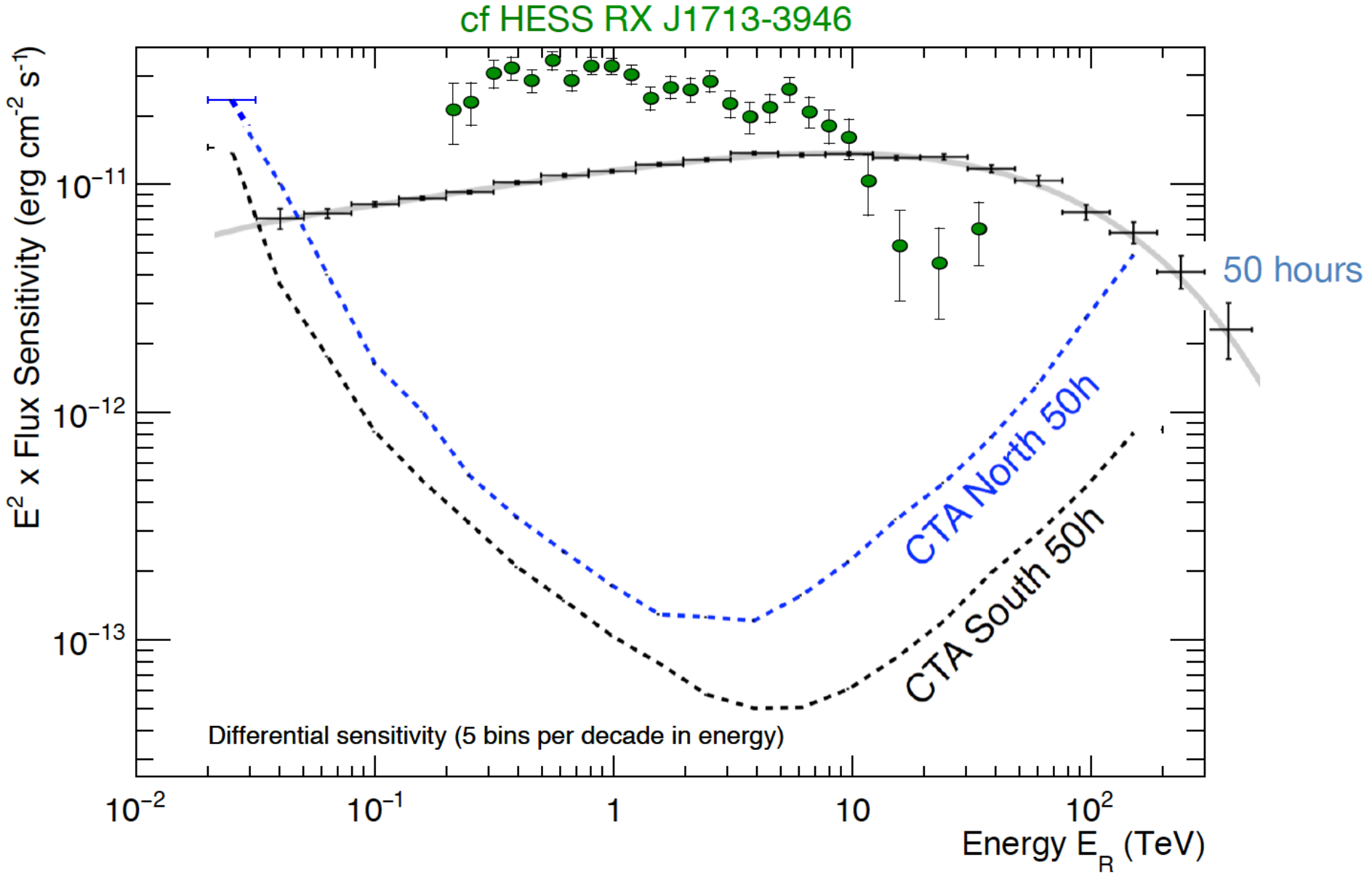
mCrab Sensitivity



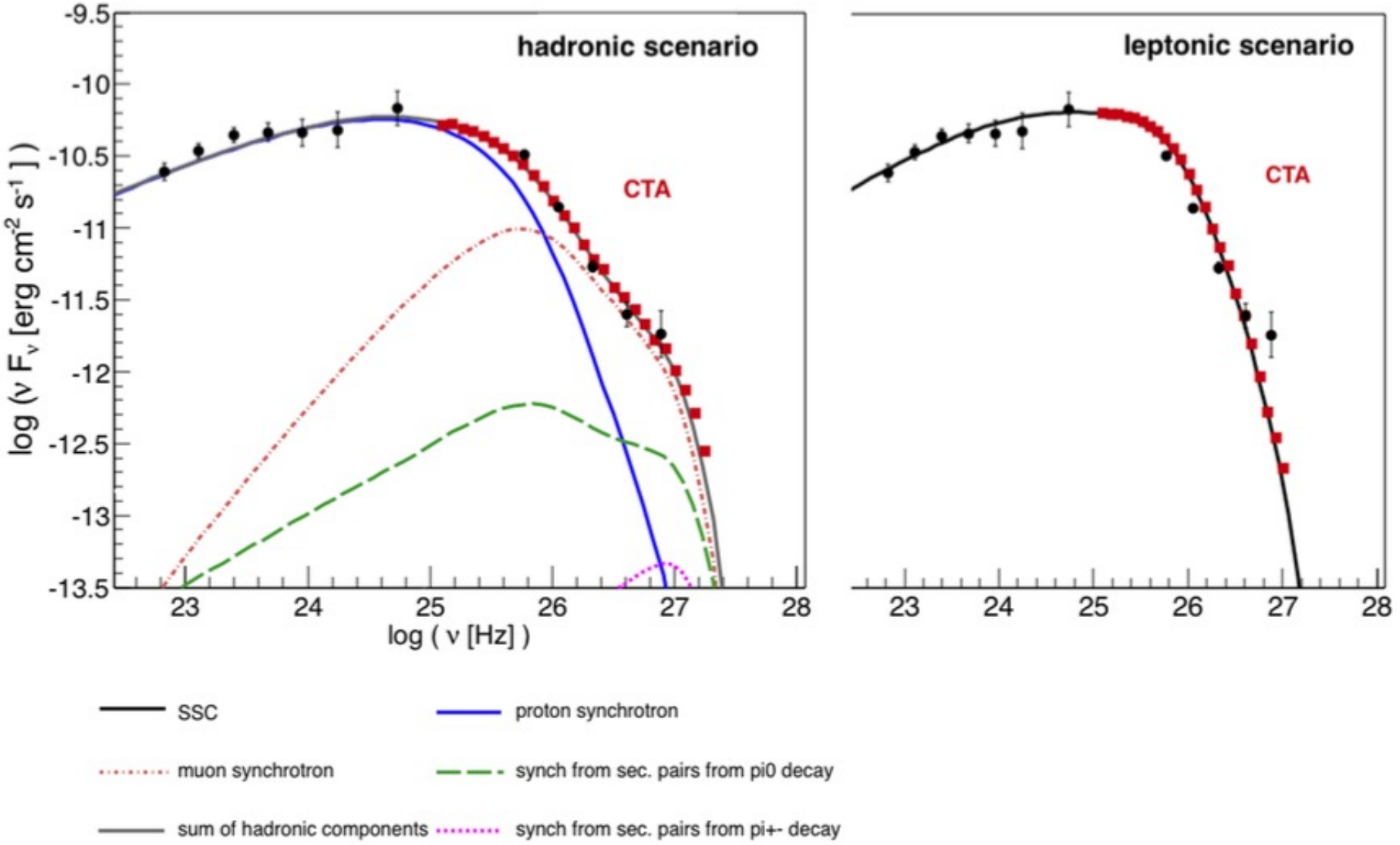
Galactic PeVatrons



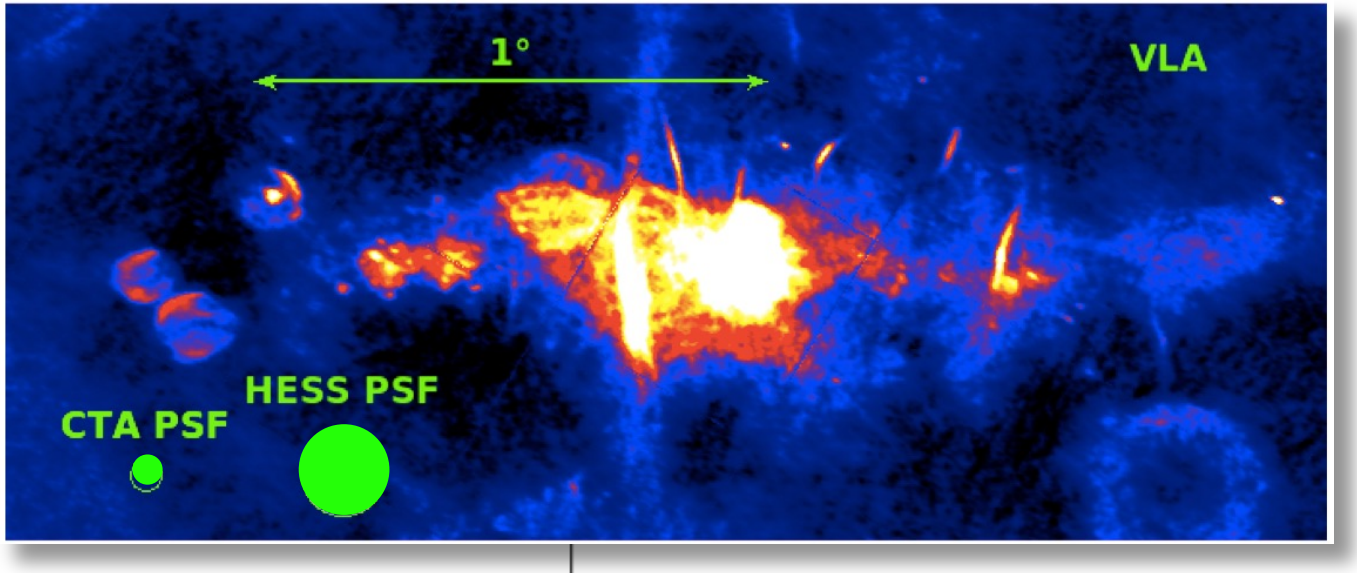
Galactic PeVatrons

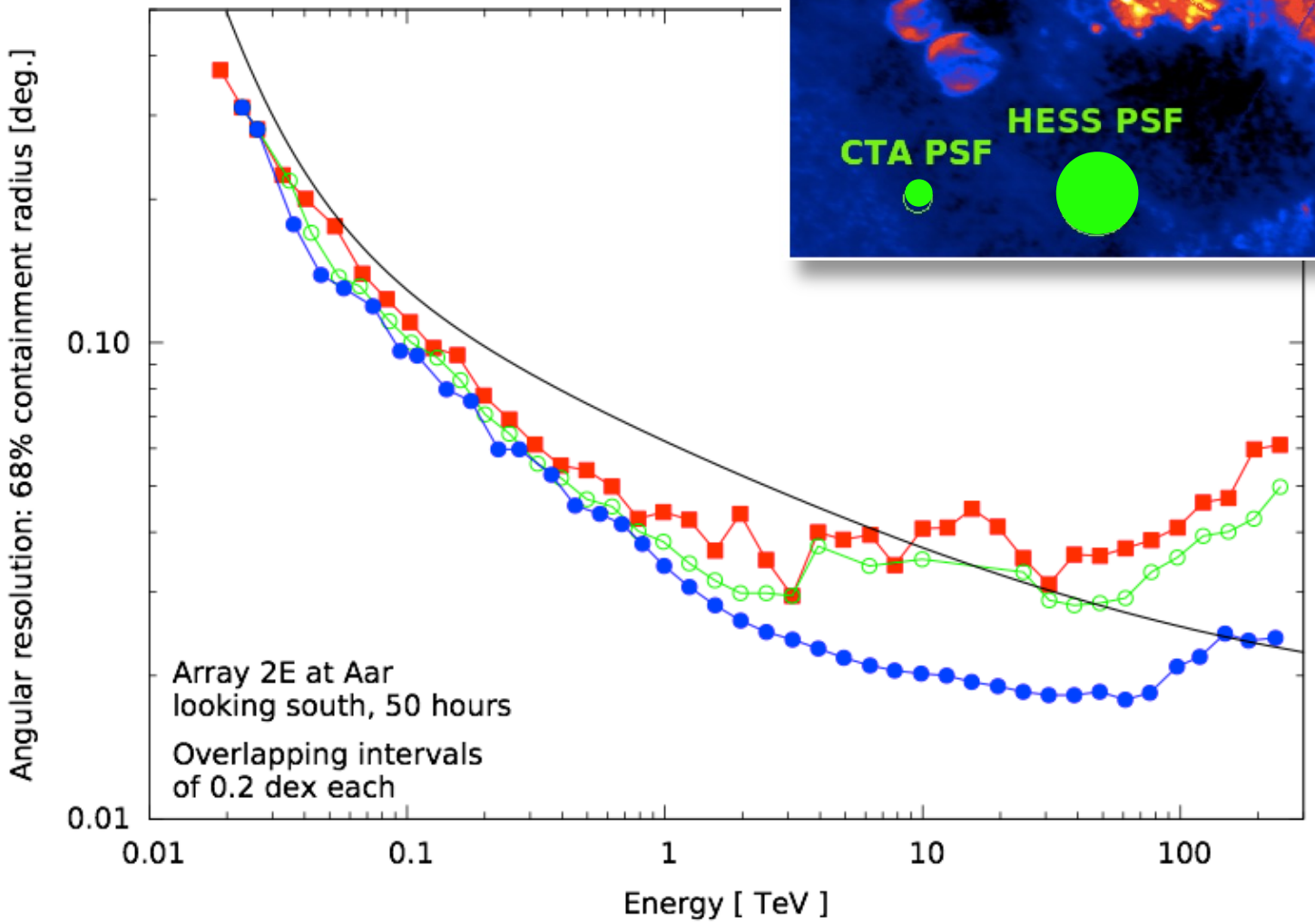


Acceleration mechanisms



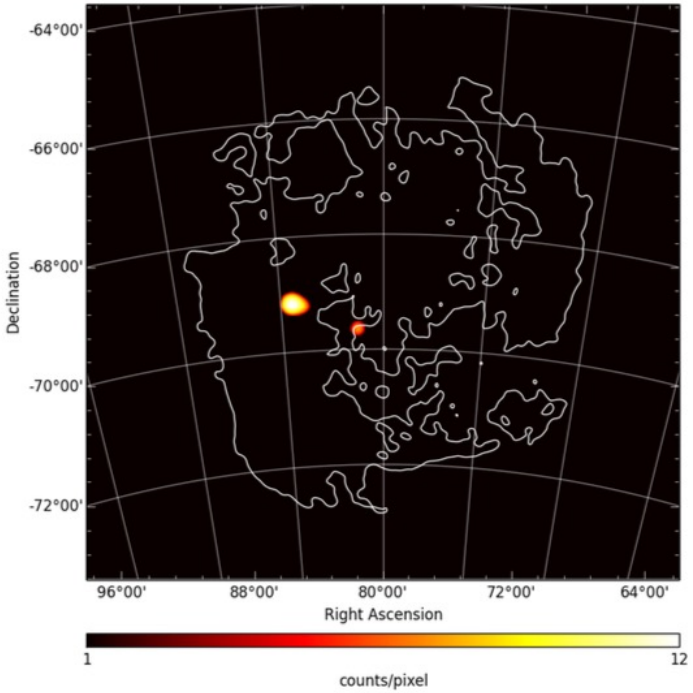
Angular Resolution

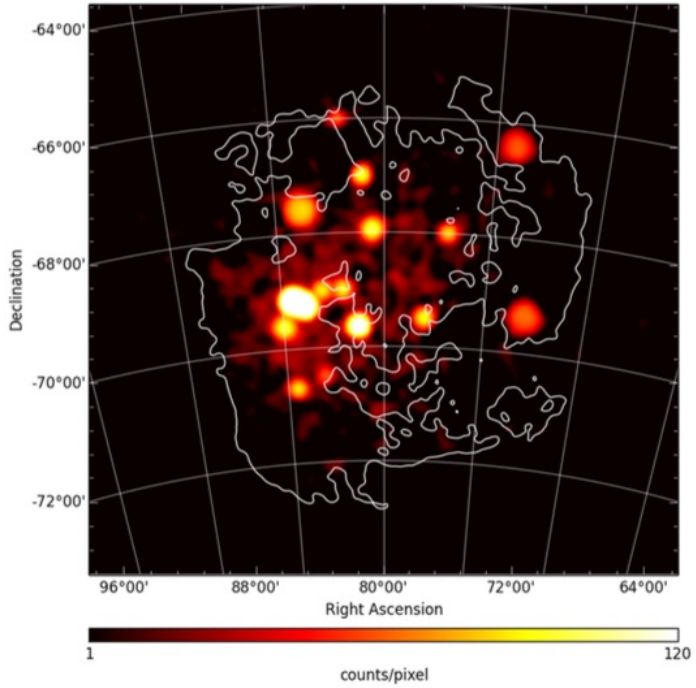




LMC Survey

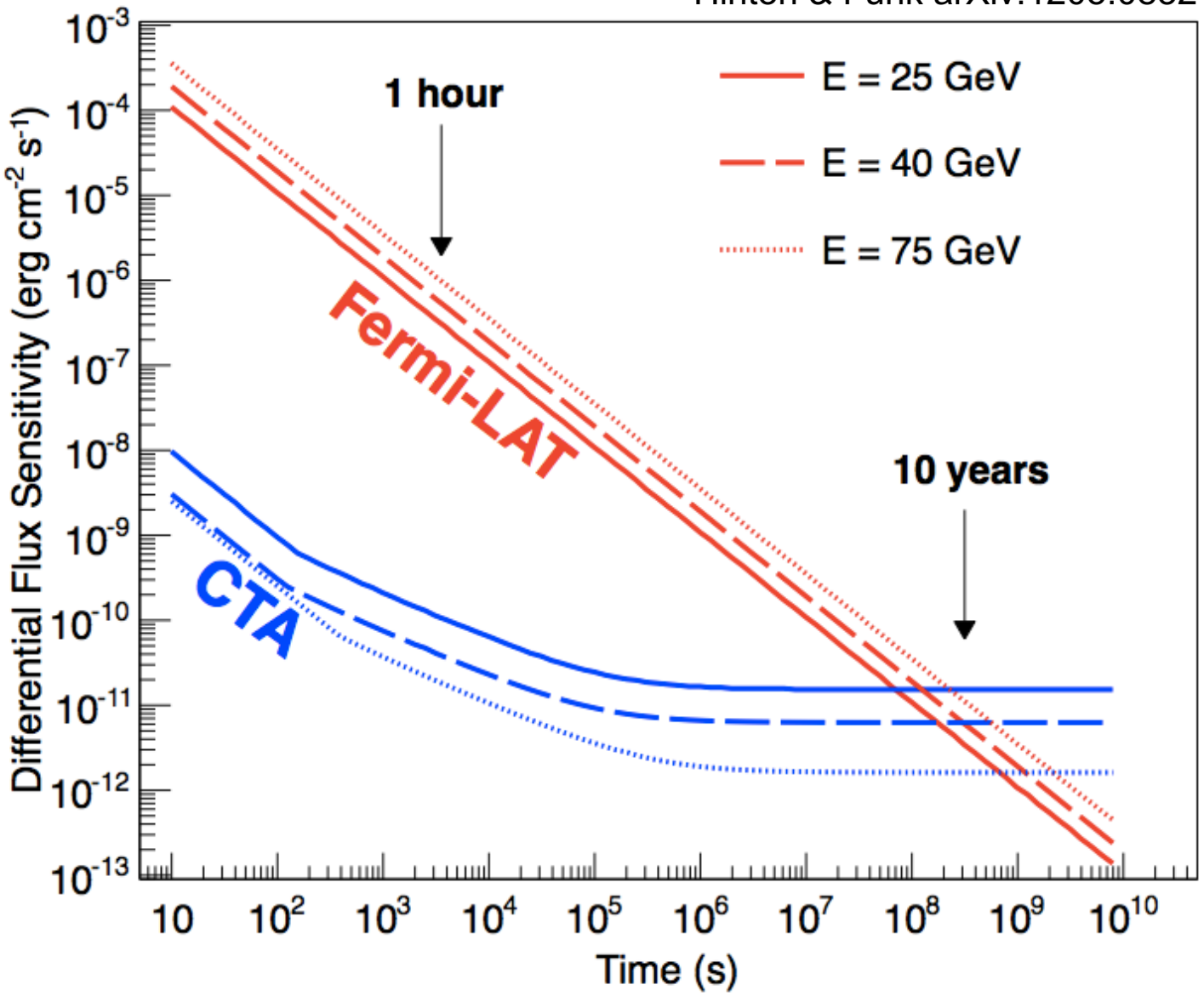
- The Large Magellanic Cloud
  - 10% of MW star formation (2% vol.)
  - hosts extreme accelertors (HESS Coll. 2015, Science 347, 406)
  - Approximately face on and well known distance of 50kpc
- Deep CTA observations will reveal source population and diffuse emission



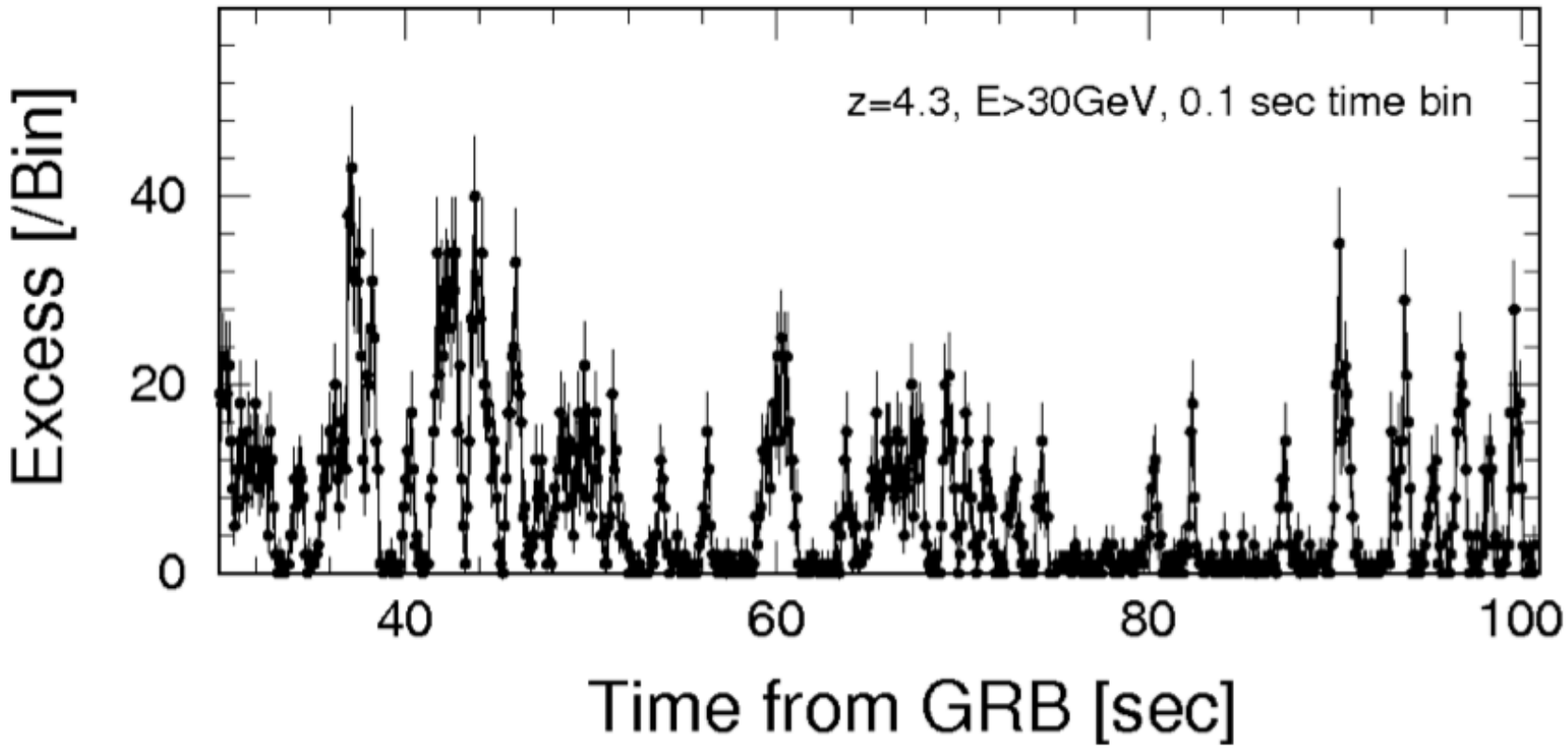


Transients with CTA

Hinton & Funk arXiv:1205.0832



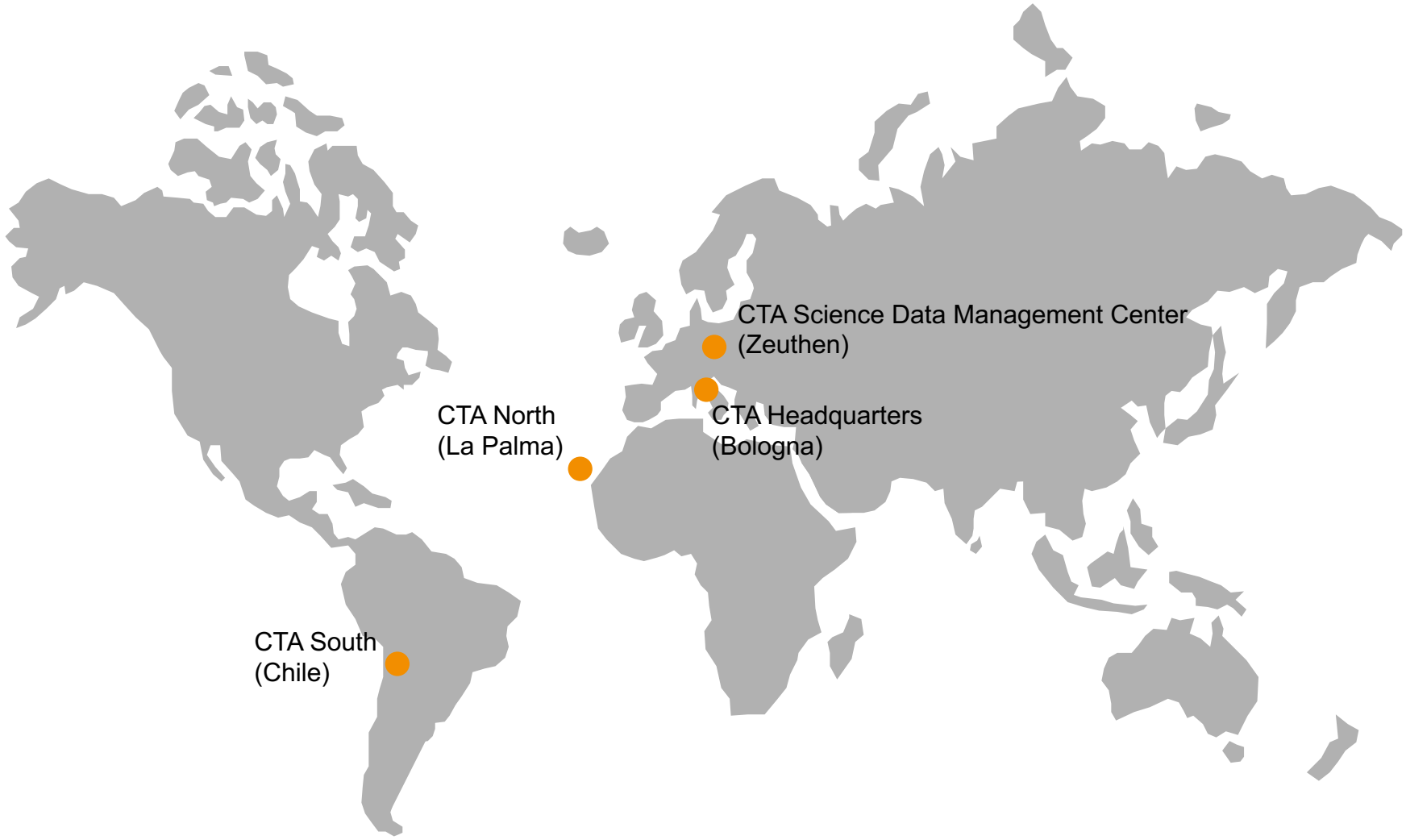
Gamma Ray Bursts (E>30 GeV)



From Gamma-Ray Burst Science in the Era of Cherenkov Telescope Array
(Astroparticle Physics special issue article)
Susumu Inoue et al., arXiv:1301.3014

Status CTA

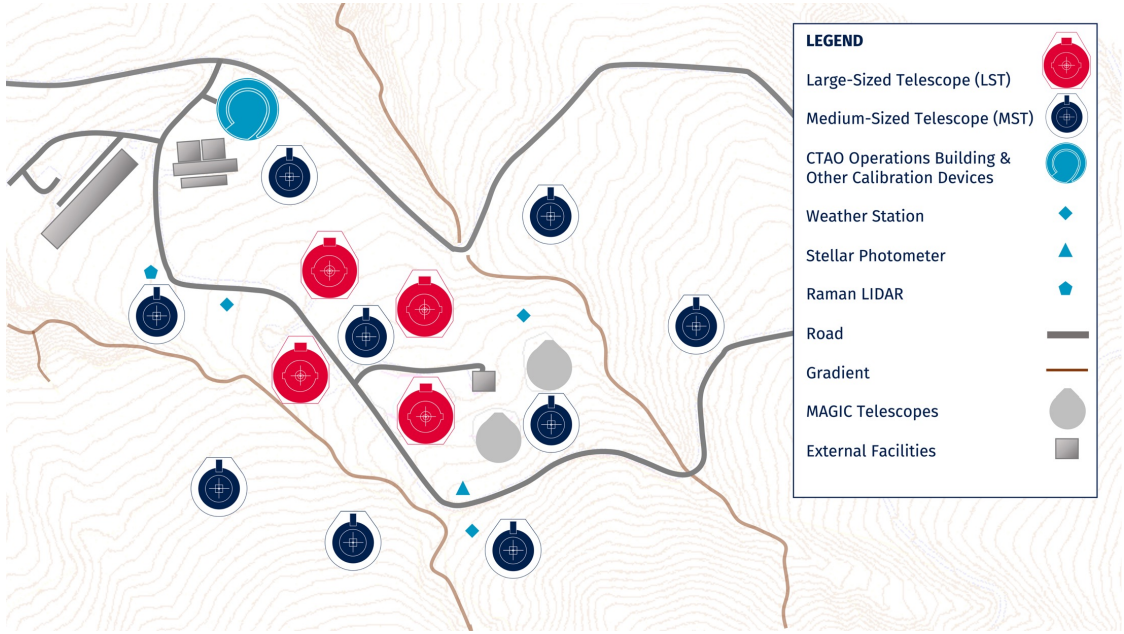
CTA Sites


CTA Science Data Management Center
(Zeuthen)
CTA Headquarters
(Bologna)
CTA North
(La Palma)
CTA South
(Chile)

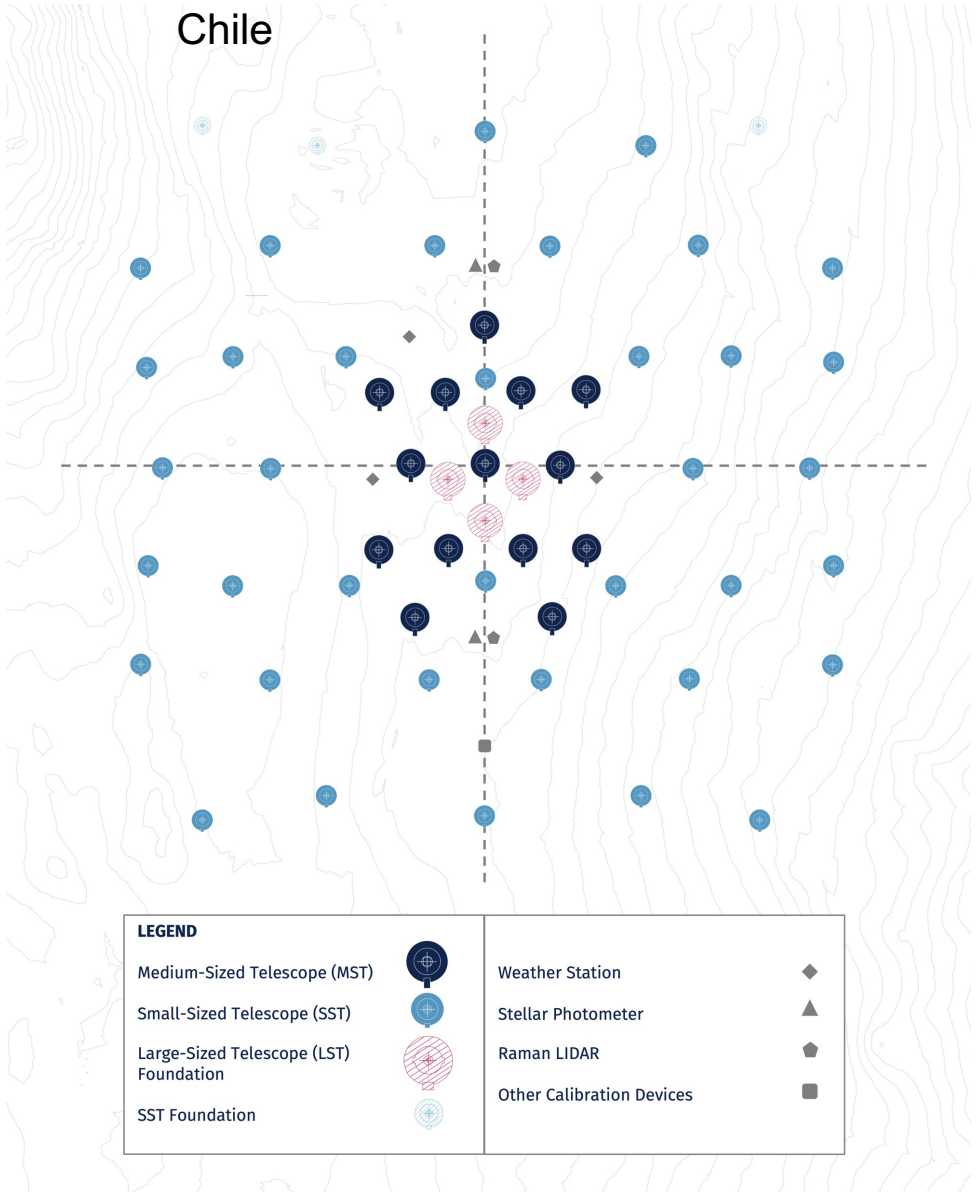
Array layouts

- La Palma: 4 LST, 9 MST
- Chile: 14 MST, 37 SST

La Palma



Chile



CTA

1st LST on La Palma

May 2022: Foundation stone ceremony of the CTA SDMC

A sign of open and international science just a few days after the launch of the brutal Russian attack on Ukraine

The SDMC in Zeuthen

https://bau-zeuthen.desy.de/cta_sdmc/

CTA

Chile, the southern site

CTAO South Access Road Construction

Preparation of gravel base layer, which will be covered by the asphaltic “Cape seal”

Road construction machinery

CTAO South Access Road Construction

Terminated base layer, ready to receive Asphalt

CTAO South Access Road Construction

Preparation Km 0,0 to 2,1

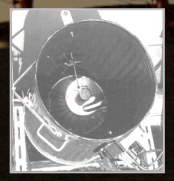
CTAO South Access Road Construction

View from Km 2,5 to the East

CTA – the Cherenkov Telescope Array

- A huge improvement in all aspects of performance
  - A factor ~10 in sensitivity, much wider energy coverage, much better resolution, field-of-view, full sky, …
- A user facility / proposal-driven observatory
  - With two sites with a total of >100 telescopes
- A 29 nation investment project
- Construction started

This is the future of ground-based gamma-ray astronomy with Air Cherenkov Telescopes and an important partner in multimessenger astronomy



The end