Gamma - Ray Astronomy in the 2020s

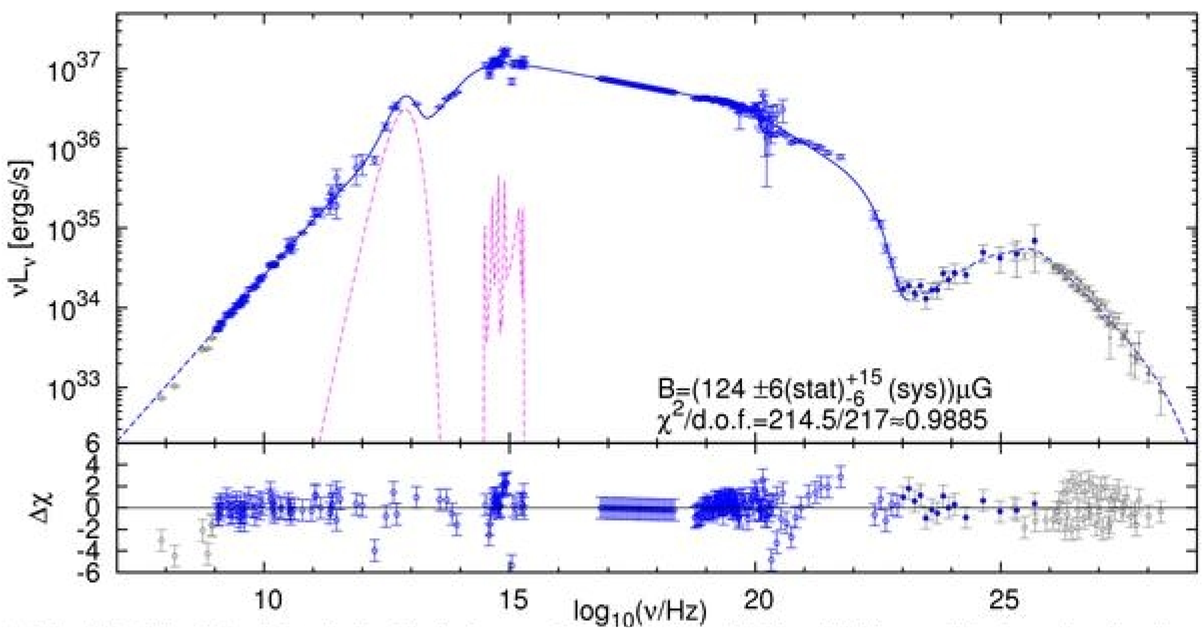
Stefan Wagner, LSW Heidelberg

Gamma-Ray Astronomy Today
The non-thermal universe
Forecasting 2020 (CTA)
Multiwavelength Context

γ – Ray Astronomy in the 2020s

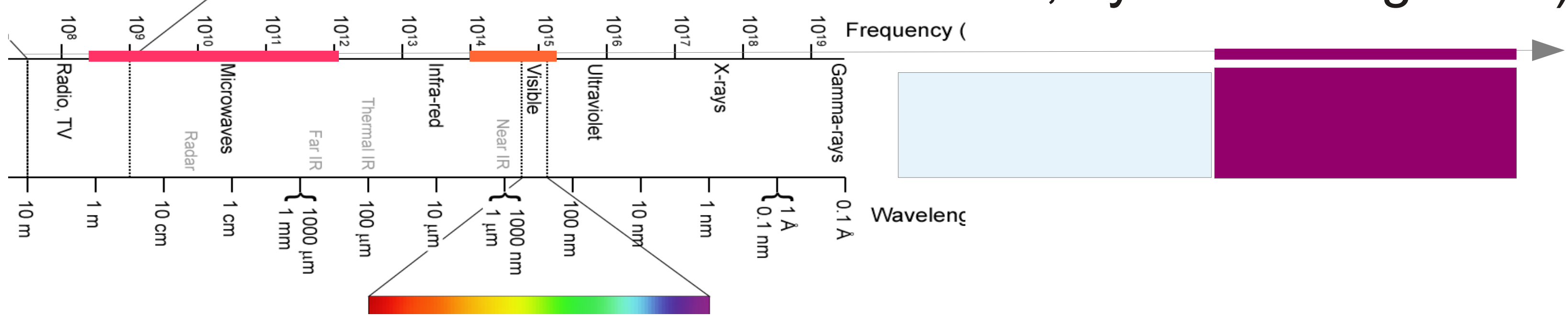
High – Energy Astrophysics: Relativistic Particles (1950s)
'High – Energy' Photons (1970s)
2015: Astronomy from <100 MHz to >100 TeV

Some object are detected throughout this range
→ >20 orders of magnitude in frequency/energy
but (approximately) 40 orders of magnitude in photon density (!)



Gamma-ray Astronomy Today

Very wide energy range (1 MeV – 200 TeV, dynamic range 10^8)



Different techniques: E < 20 GeV - γ absorbed in atmosphere

Only space-borne (mostly pair conversion)

COMTEL, EGRET → **Fermi**

E > 20 GeV atmospheric Cerenkov

Enables large collection areas

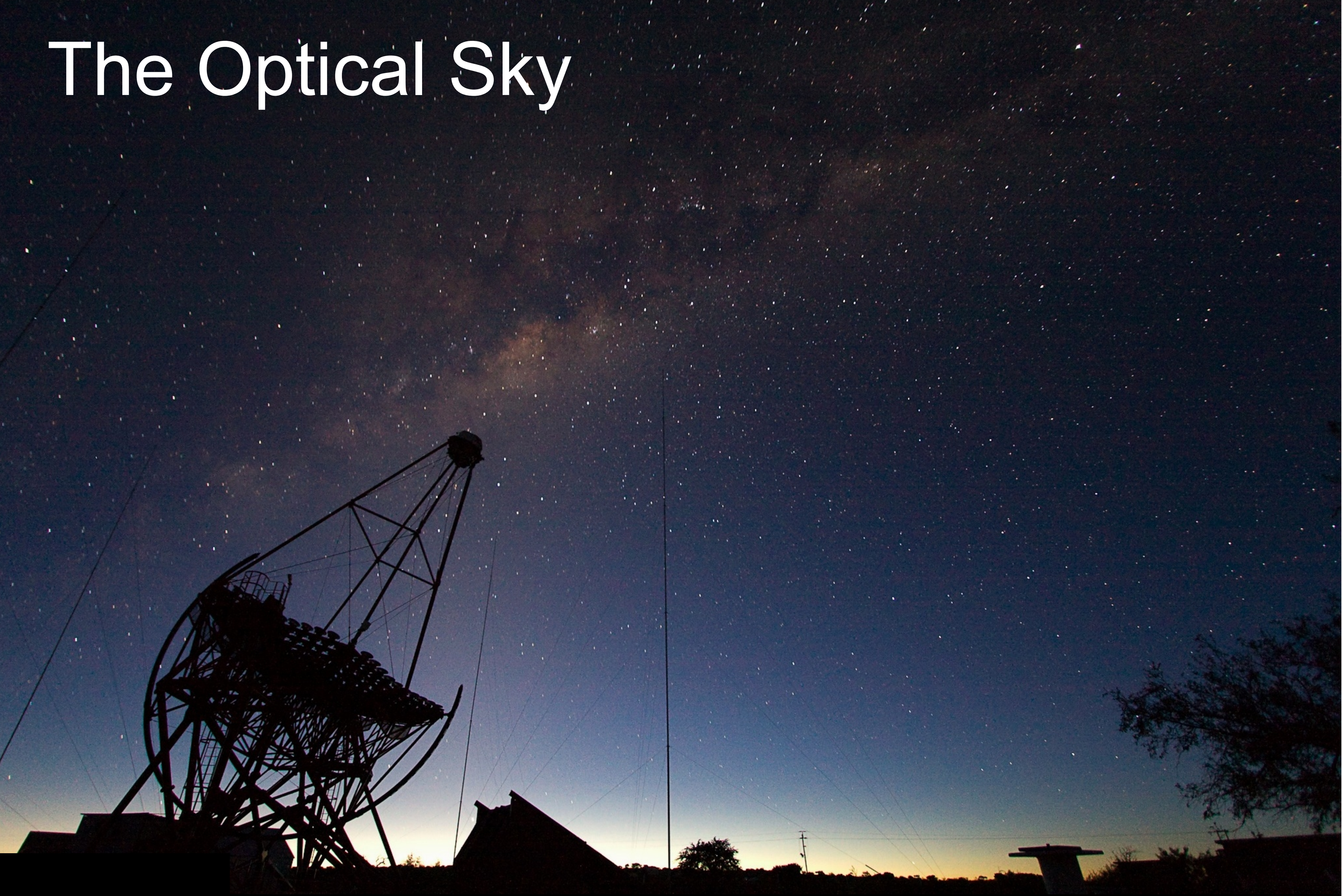
Whipple → **HESS, MAGIC, VERITAS** → **CTA**

E > 10 TeV Water Cerenkov

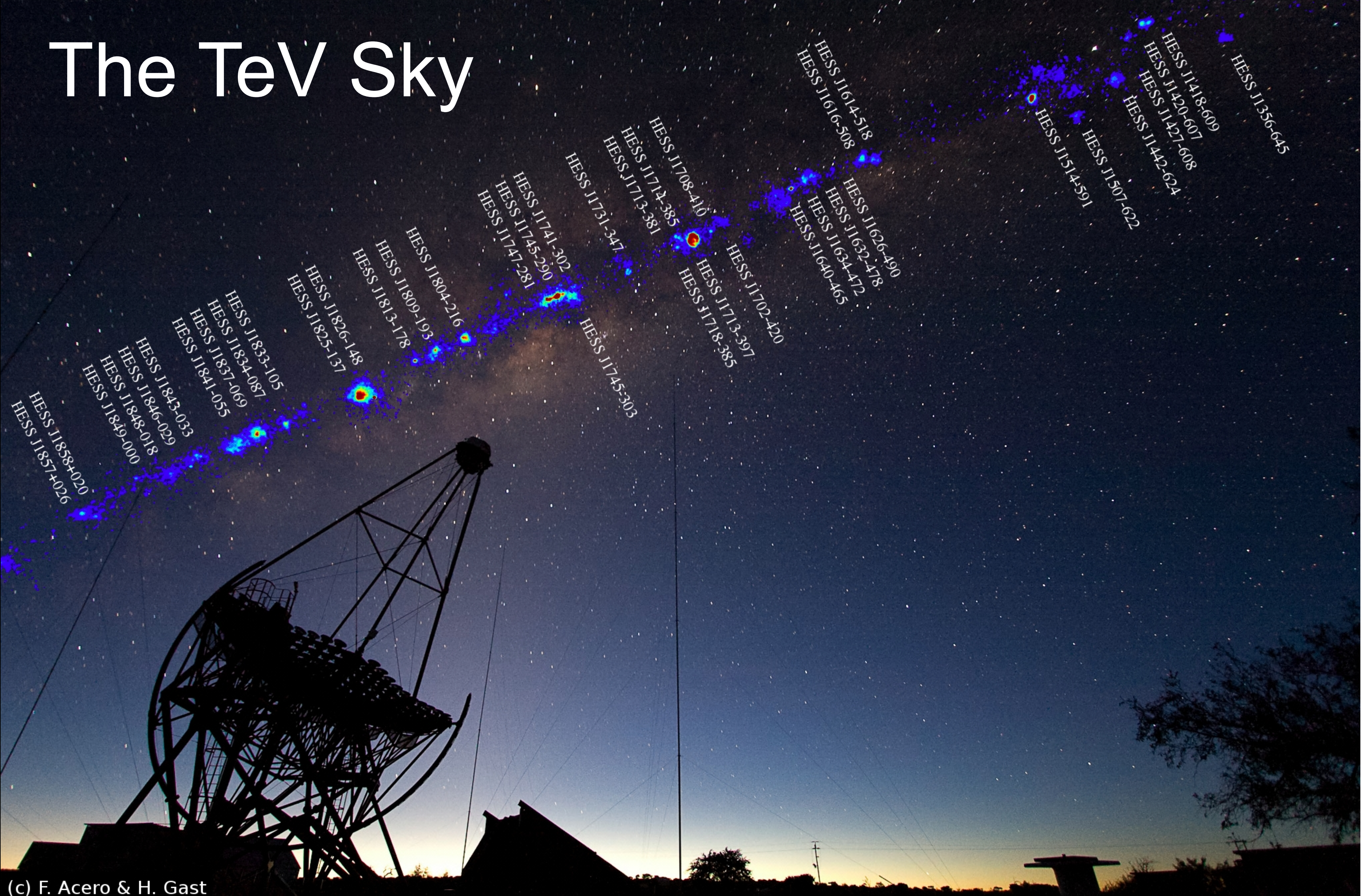
Enables 24h, 2π sr observations

MILAGRO → **HAWK**

The Optical Sky



The TeV Sky


HESS J1858+020
HESS J1857+026
HESS J1843-033
HESS J1846-029
HESS J1848-018
HESS J1849-000
HESS J1833-105
HESS J1834-087
HESS J1837-069
HESS J1841-055
HESS J1826-148
HESS J1825-137
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1731-347
HESS J1708-410
HESS J1714-385
HESS J1713-381
HESS J1745-303
HESS J1702-420
HESS J1713-397
HESS J1718-385
HESS J1614-518
HESS J1616-508
HESS J1626-490
HESS J1632-478
HESS J1634-472
HESS J1640-465
HESS J1514-591
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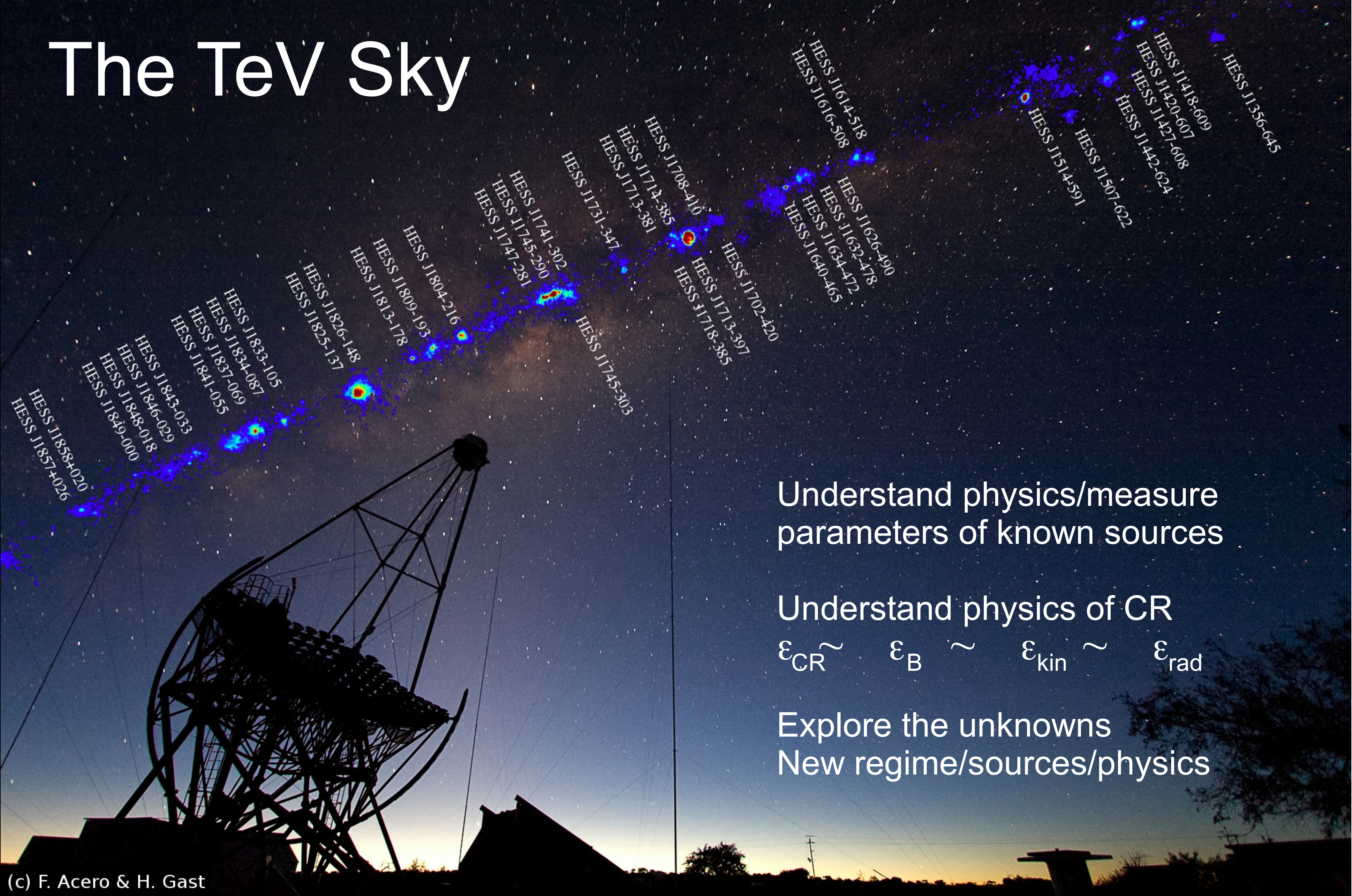
HESS J1427-608
HESS J1442-624
HESS J1356-645

The TeV Sky



Understand physics/measure parameters of known sources

Understand physics of CR

$\varepsilon_{CR} \sim \varepsilon_B \sim \varepsilon_{kin} \sim \varepsilon_{rad}$

Explore the unknowns
New regime/sources/physics

γ – ray Astronomy Today

In the last decade the field joined mainstream astrophysics:

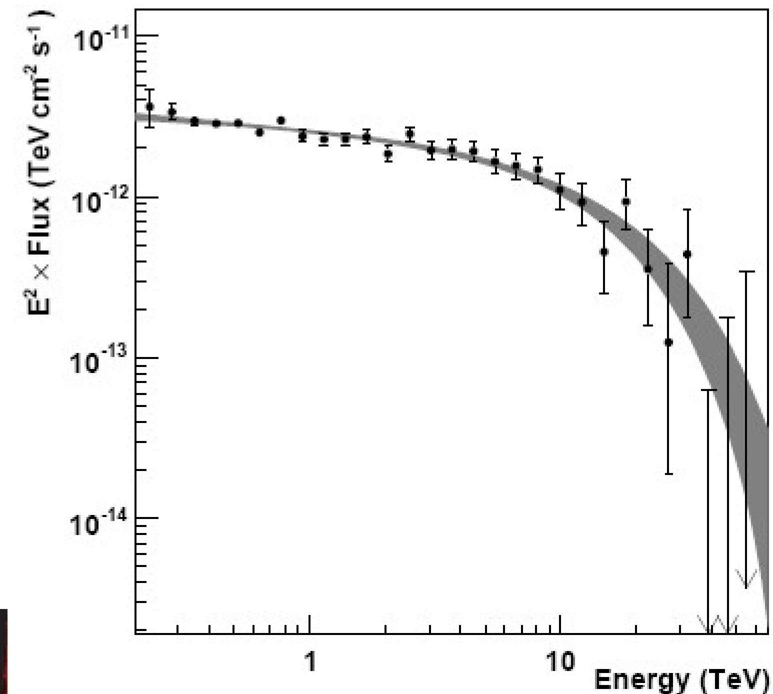
Images: Morphology, Astrometry

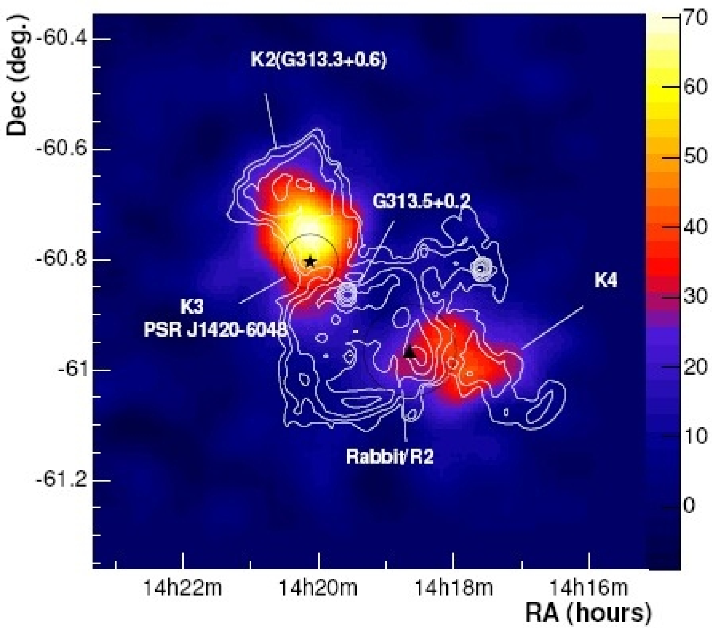
Spectra, Broad-band Coverage

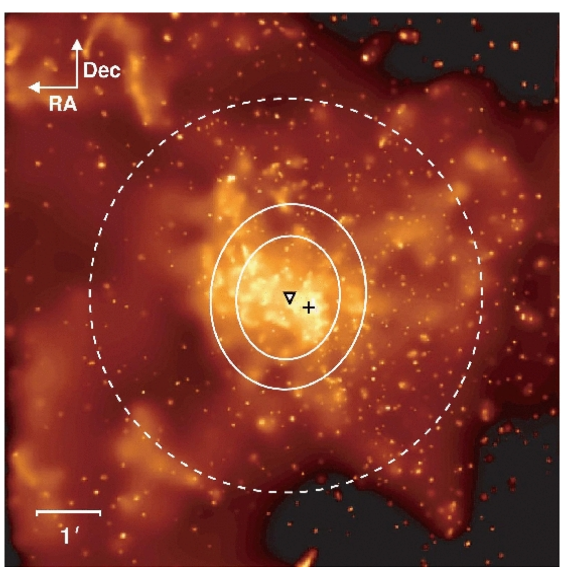
Lightcurves (msec - years)

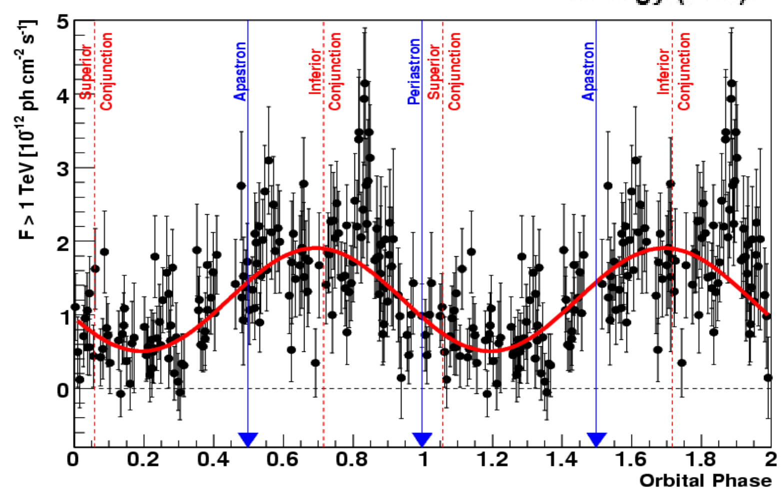
Surveys, Populations, Catalogs

VHE-dominated sources

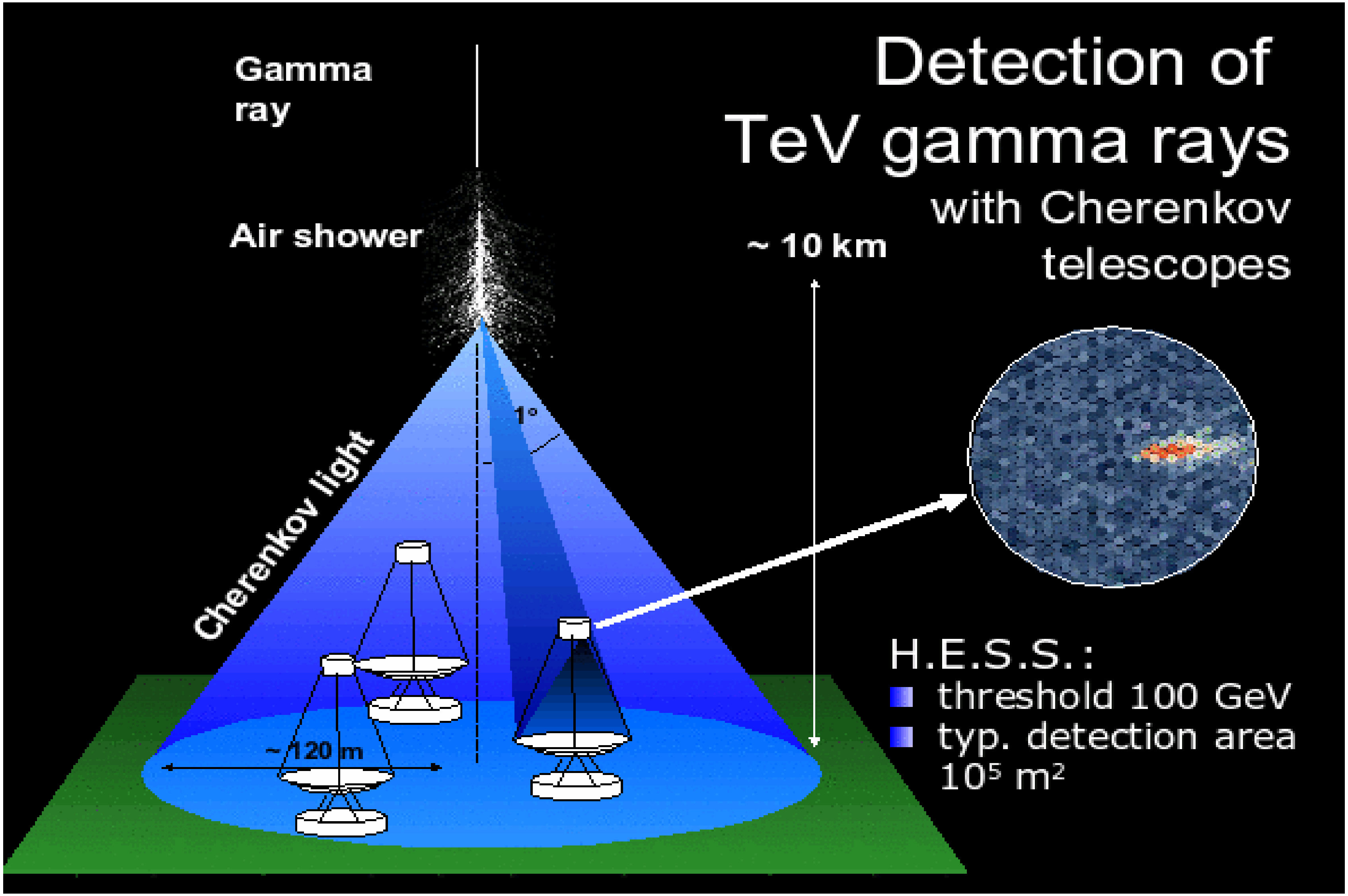






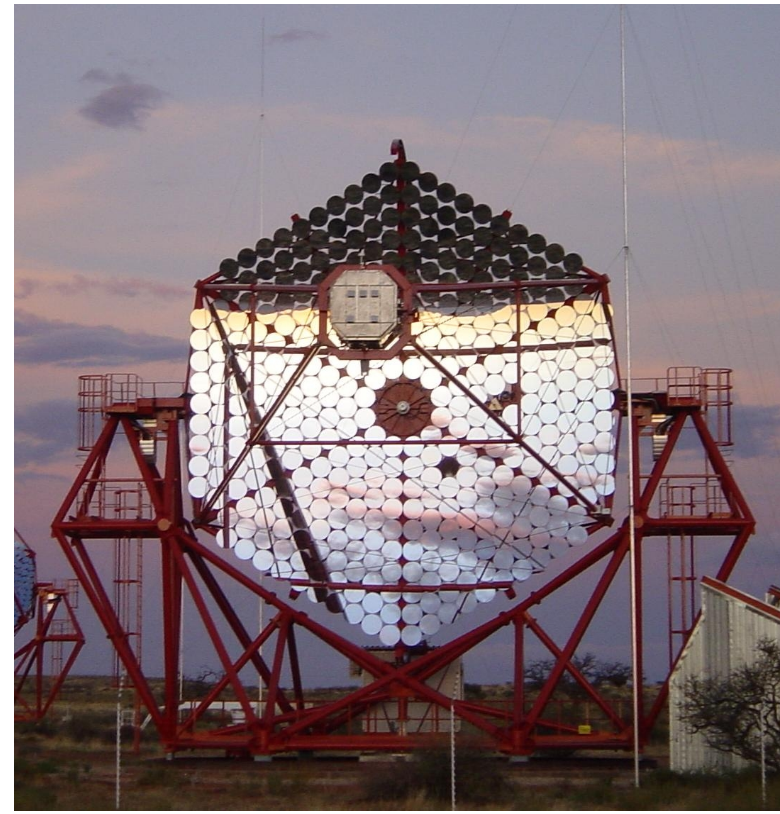


Stereoscopic Cherenkov imaging

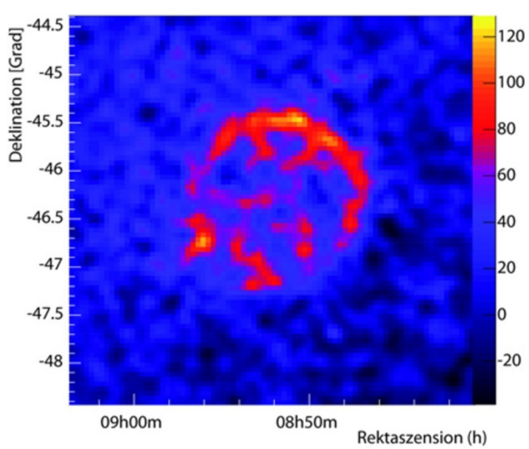


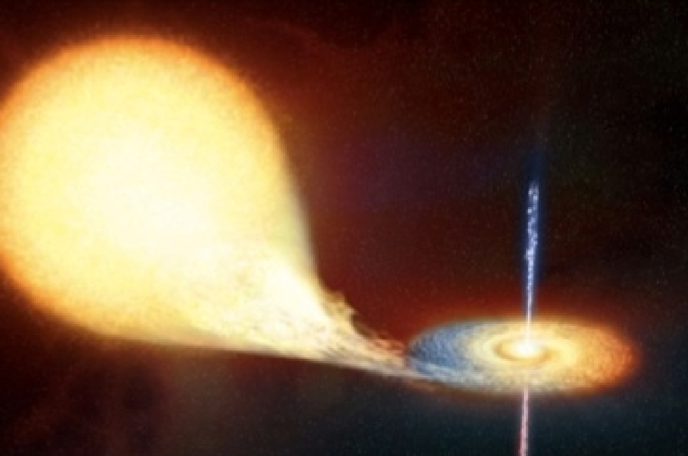
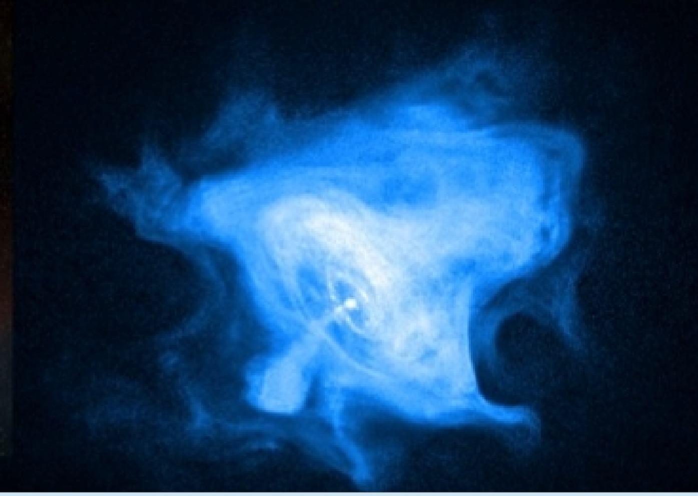
Imaging Cherenkov Astronomy

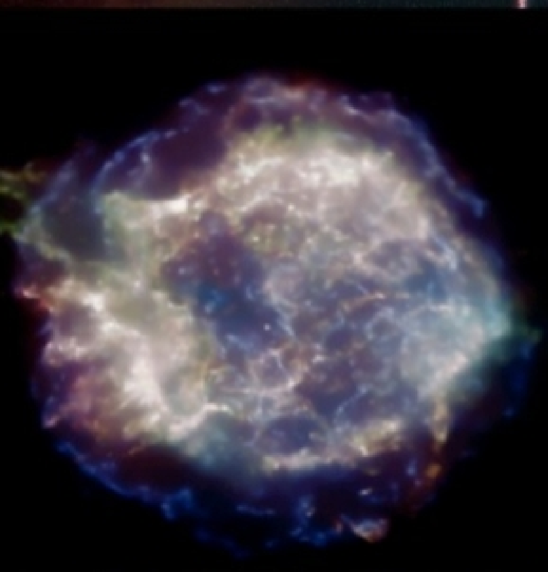
Sample camera pixels;
Identify shower;
Trigger other telescopes;
Record images;
Measure image parameters;
Discriminate photons;
Reconstruct shower
(energy, location, time);
→ Record **one** VHE photon
(every 100 sec)



integrate images:

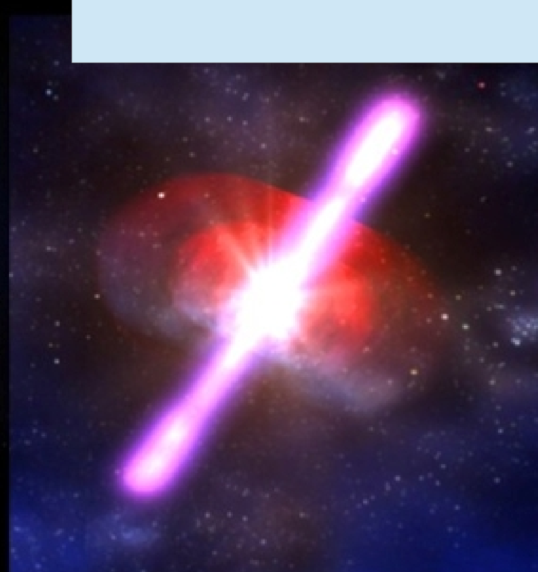
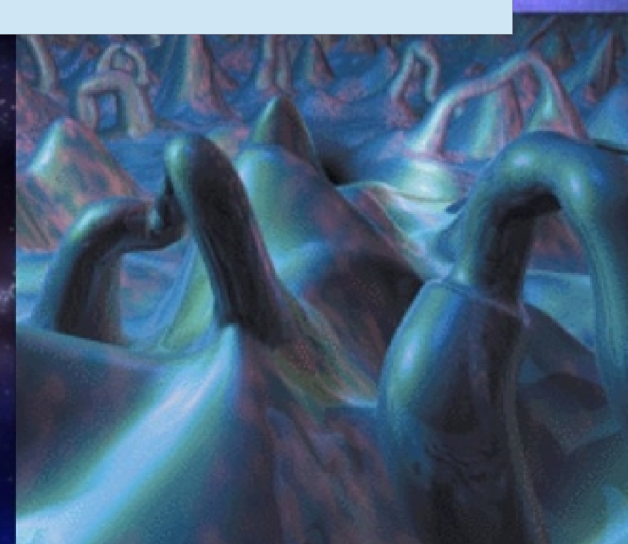
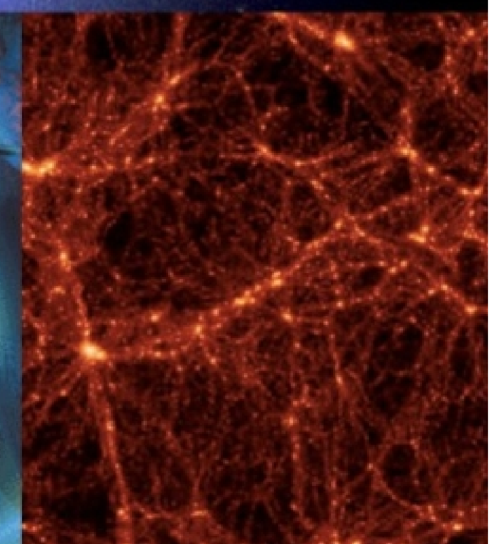




The Non-thermal Universe



The Non-thermal Universe

Cosmic Ray 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 and explosions?
- Exploring cosmic voids

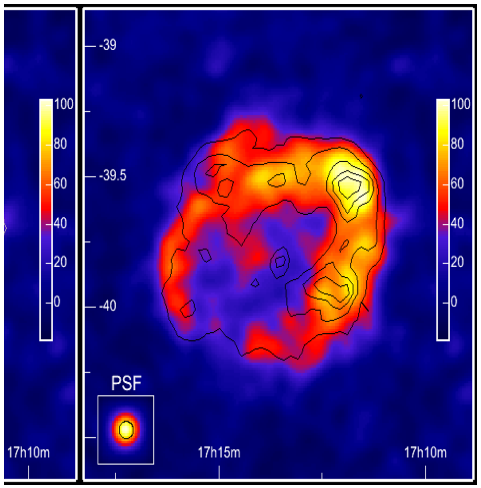
Physics Frontiers – beyond the SM

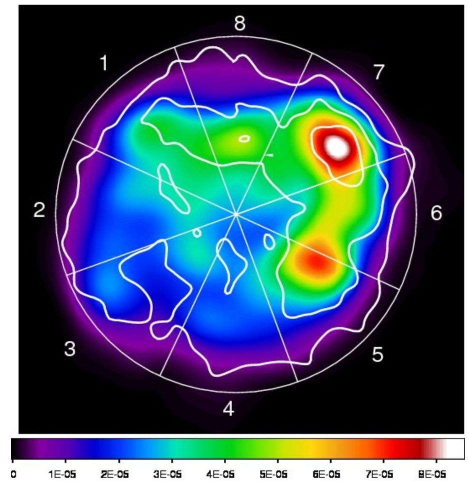
- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?

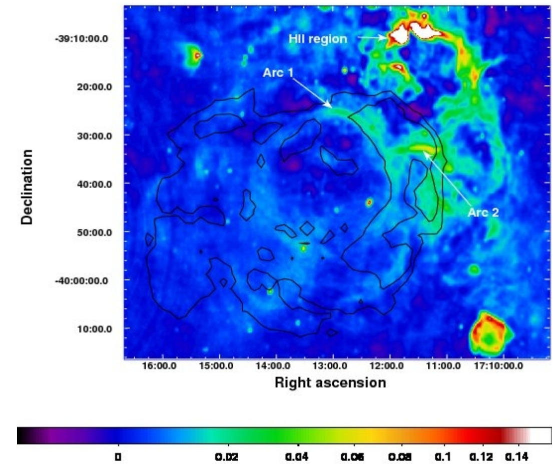
Cosmic Ray Acceleration

- What are the sites of particle acceleration in the Milky Way? (origin of Galactic Cosmic Rays)
- What are the sites of acceleration in jets and lobes of AGN?
- Where do UHECRs originate from?
- What are the mechanisms of CR acceleration?
- How do they propagate?
- What is their impact on the environment?

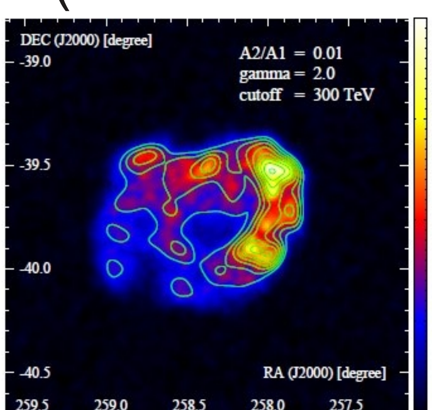
(Shell-type) Supernova Remnants

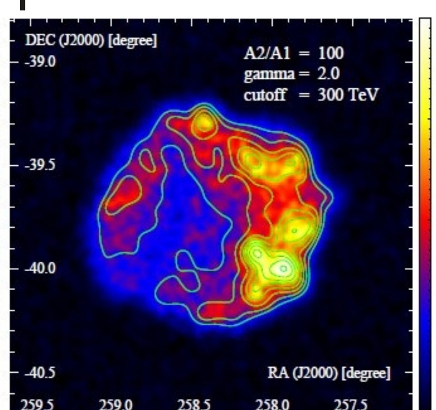


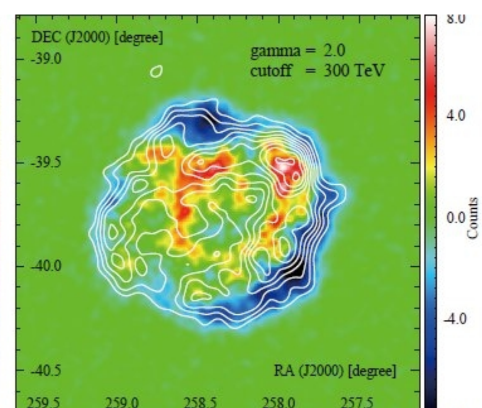




Global SED and close morphological match strongly support a hadronic origin of gamma emission of CR-ISM (pp) interaction.
Alternative leptonic explanation (IC emission) must contribute at some level (which can be quantified with future instrumentation).







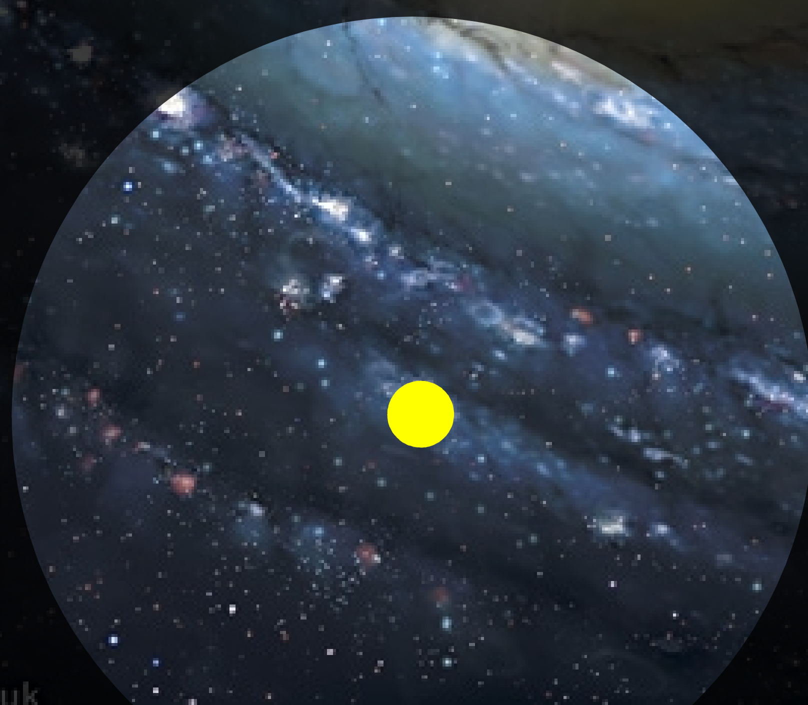
Cosmic Ray Origin

Quantitative understanding of cosmic ray spectra & yield

Presumably only very young SNR accelerate to 10^{15}eV; only a handful of these currently active in our Galaxy

Energy and shape of cutoffs ?

Probing escape of CRs from SNR using ambient gas



current instruments probe SNR only up to few kpc

Cosmic Ray Origin

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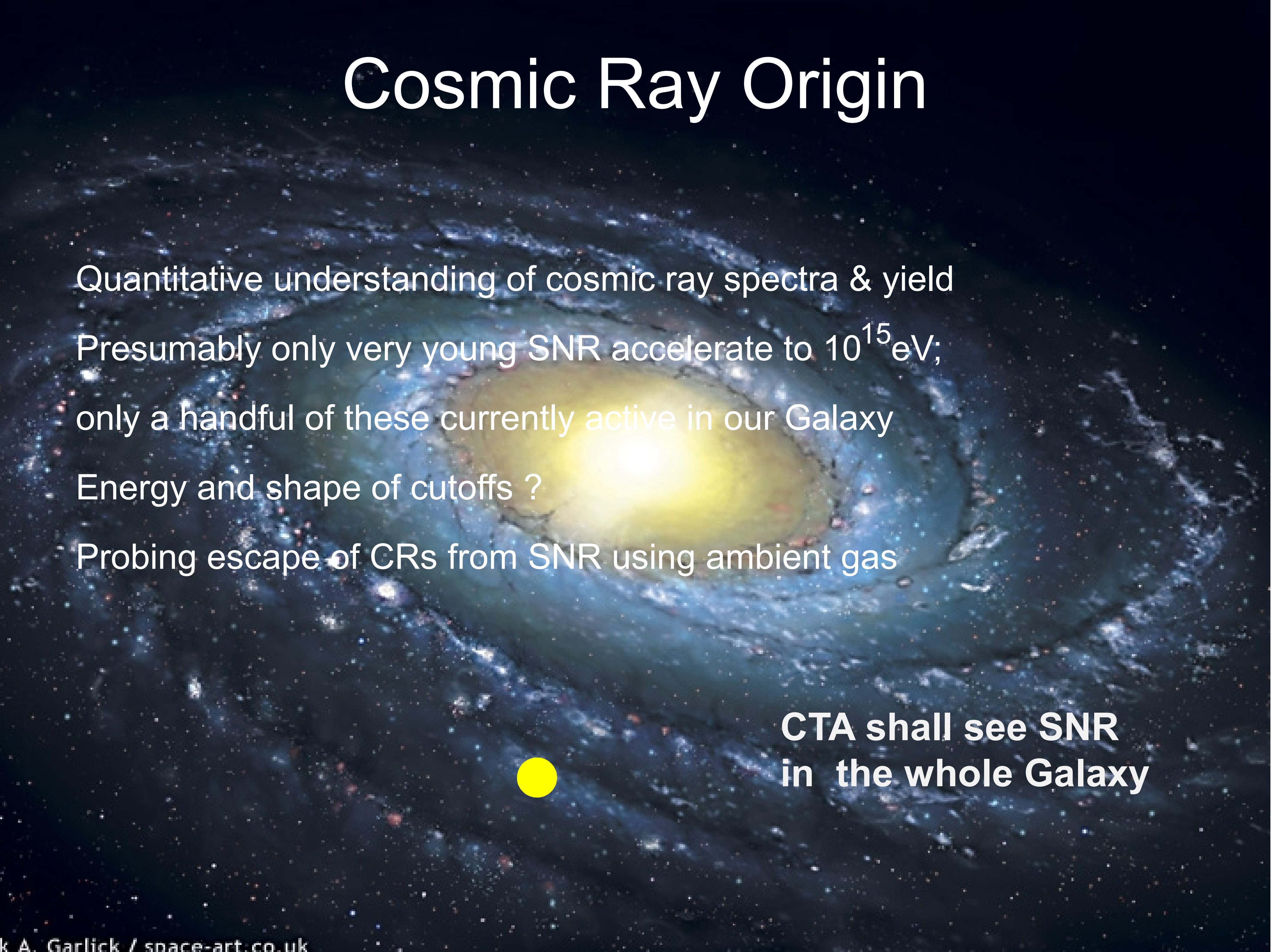


Tracing Acceleration in the Cosmos

(Local) Milky Way –
Stellar Winds, Shocks (massive stars and their leftovers)

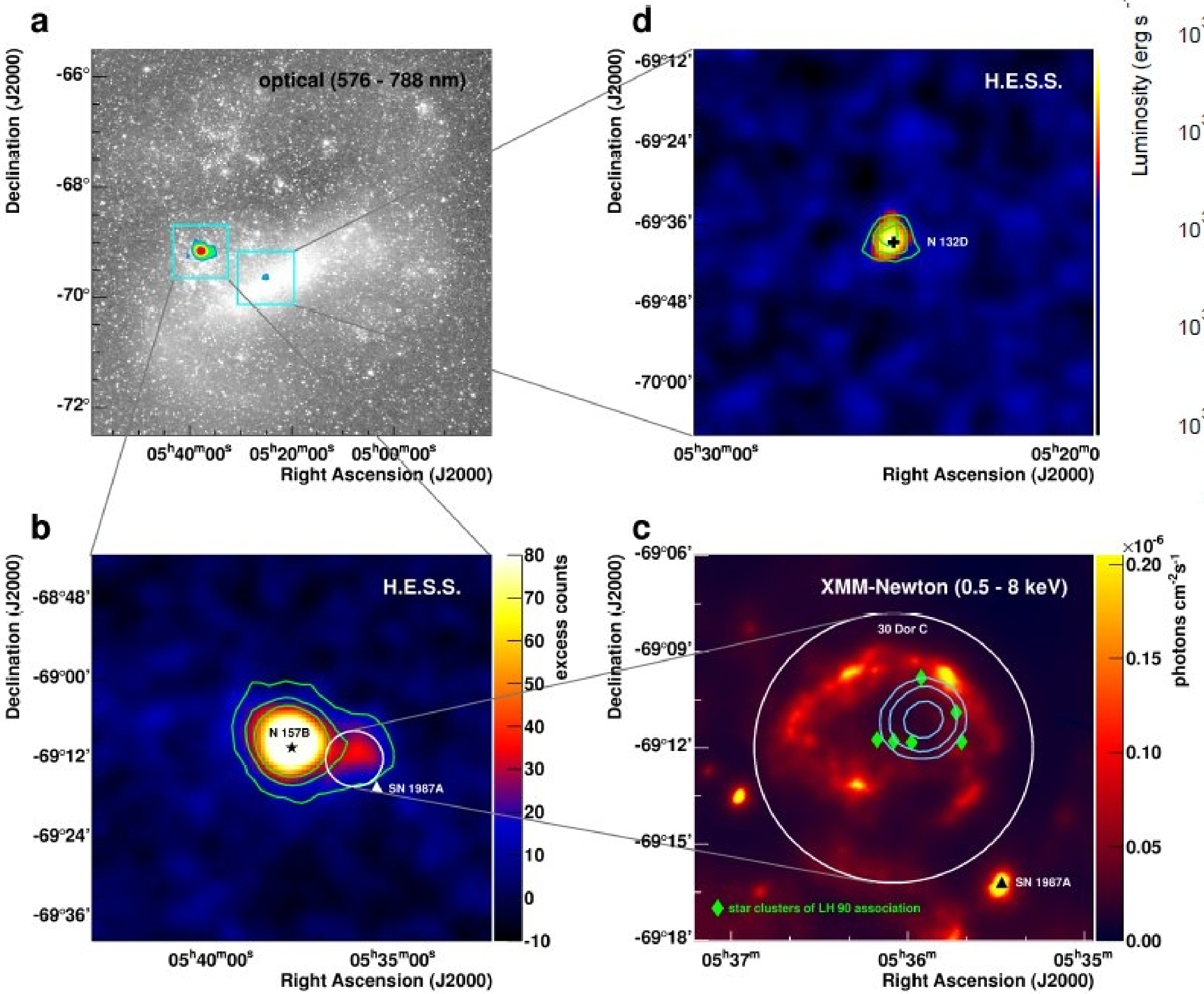
Nearby Galaxies – individual sources (other environments)

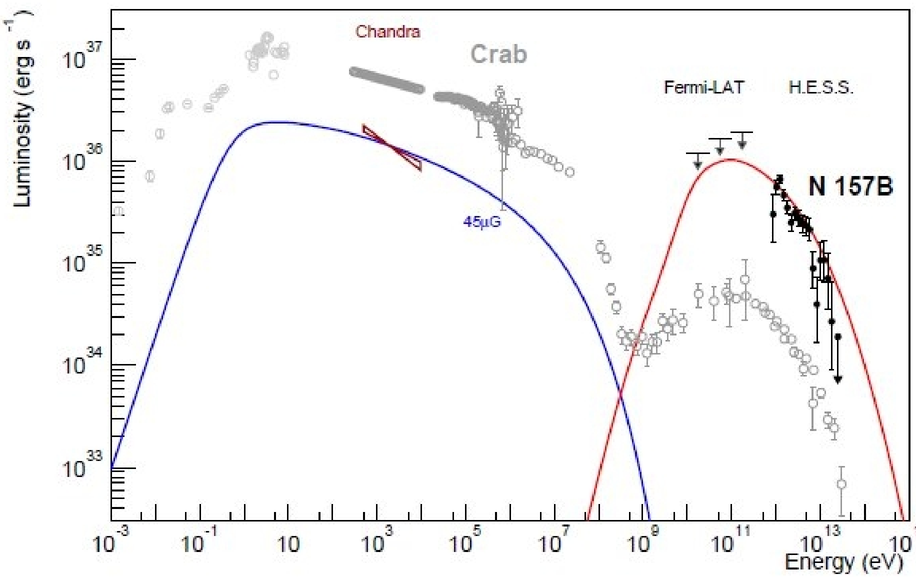
Starburst-Galaxies (effects on galaxy evolution?)

→ NGC 253, M82

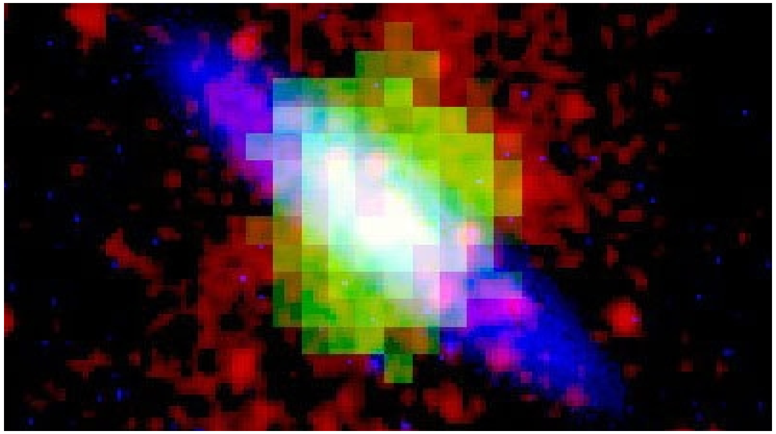
Shocks on larger scales (groups/clusters) ?

Tracing Acceleration in the Cosmos





NGC 253



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(Local) Milky Way –
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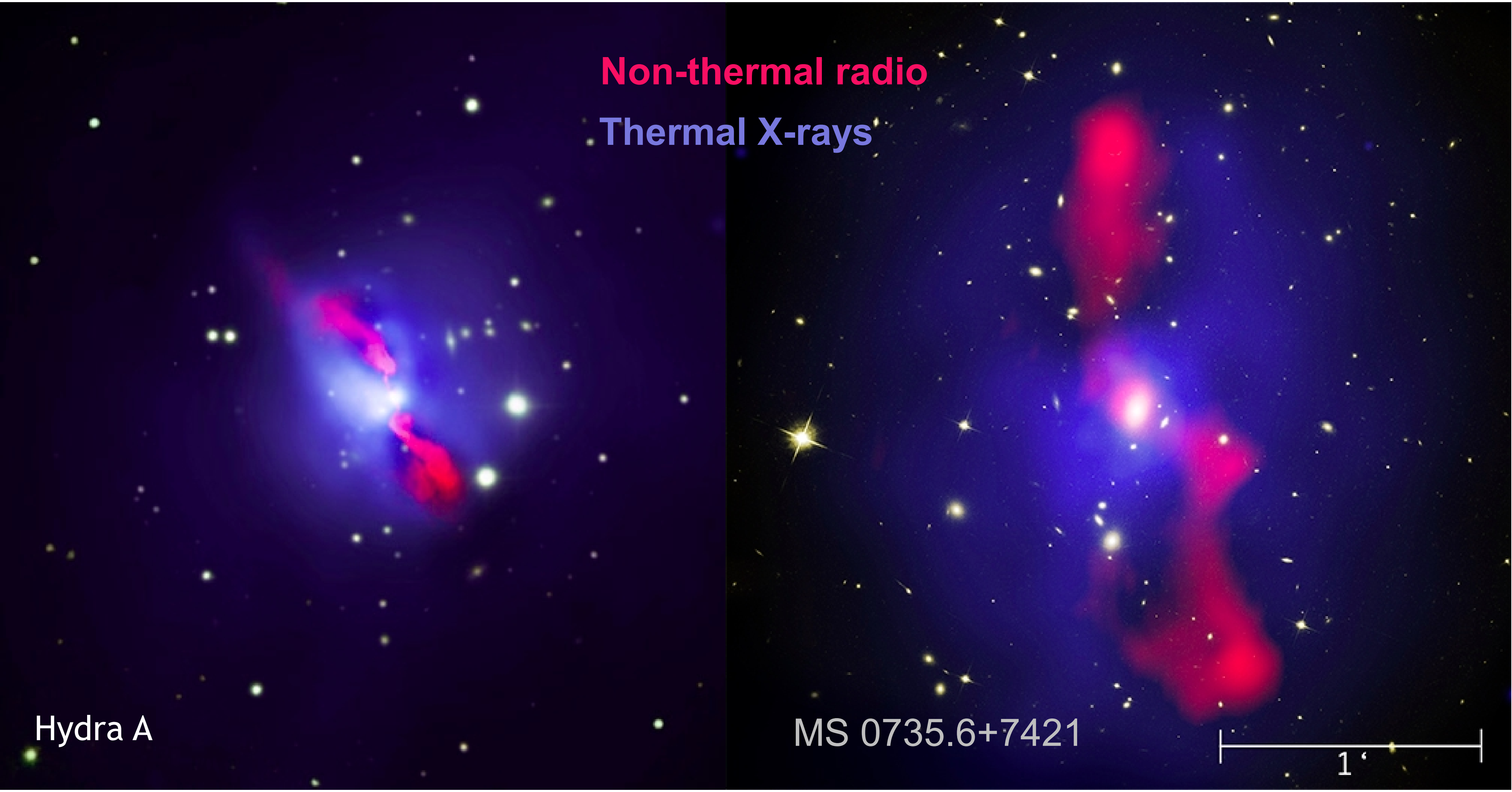
Nearby Galaxies – individual sources (other environments)
→ LMC (H.E.S.S. Collaboration, ***Science***, 22Jan2015)

Starburst-Galaxies (effects on galaxy evolution?)
→ NGC 253, M82

Shocks on larger scales (groups/clusters) ?

The biggest bubbles



Probing Extreme Environments

- **Processes close to neutron stars and black holes?**

  - Pulsed emission from Neutron Stars
  - SMBH ergospheres

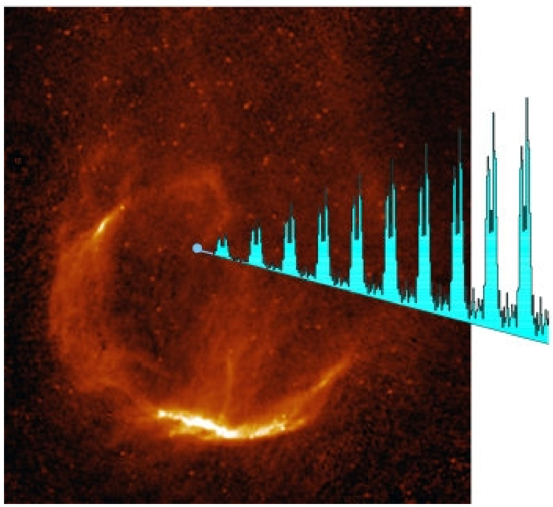
- **Processes in relativistic jets, winds and explosions?**

  - GRBs
  - AGN jets
  - Shocks

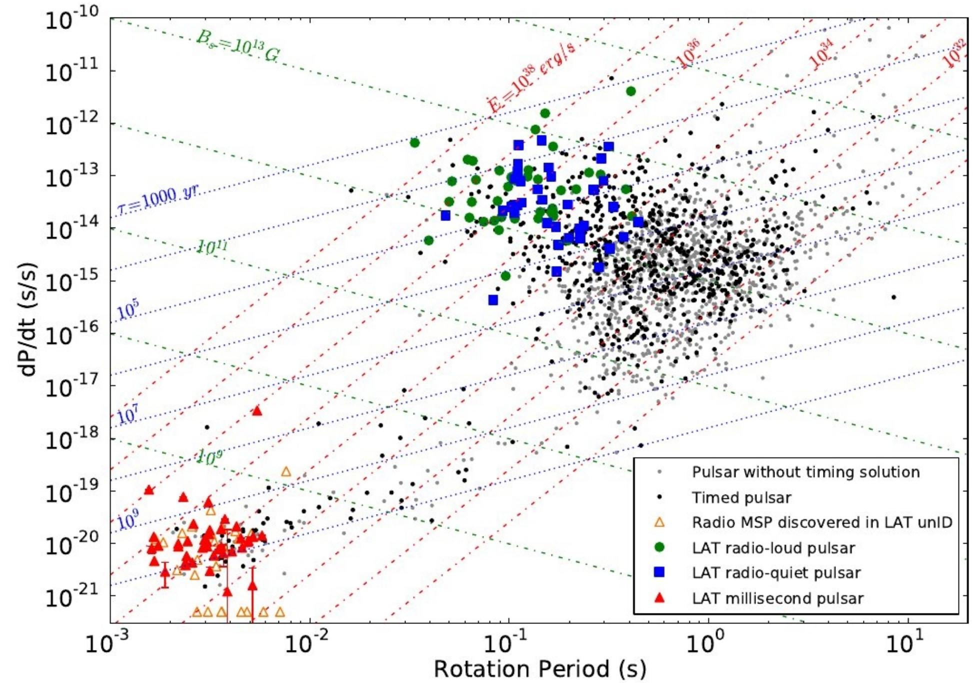
- **Exploring cosmic voids**

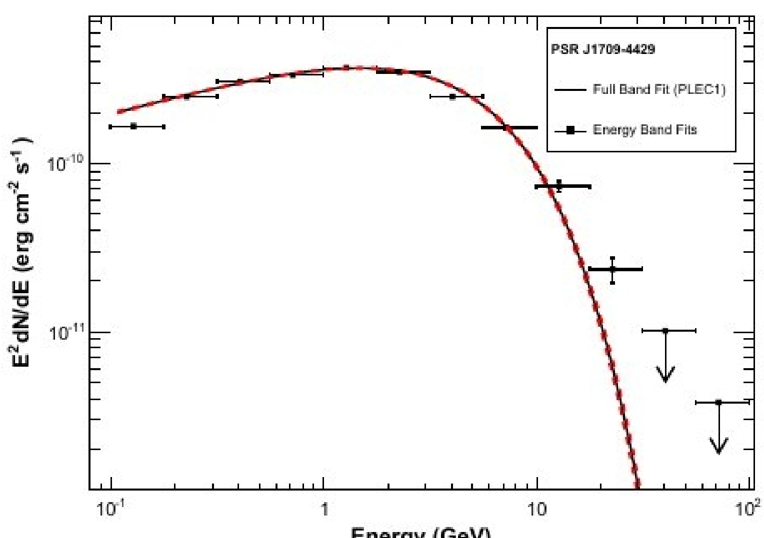
  - Contents
  - Evolution

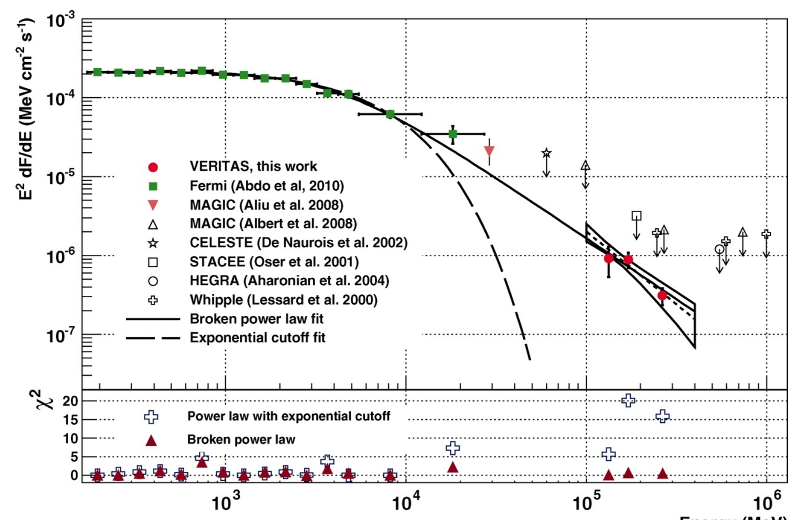
The stellar remnants



Fermi-LAT 2nd Pulsar catalog

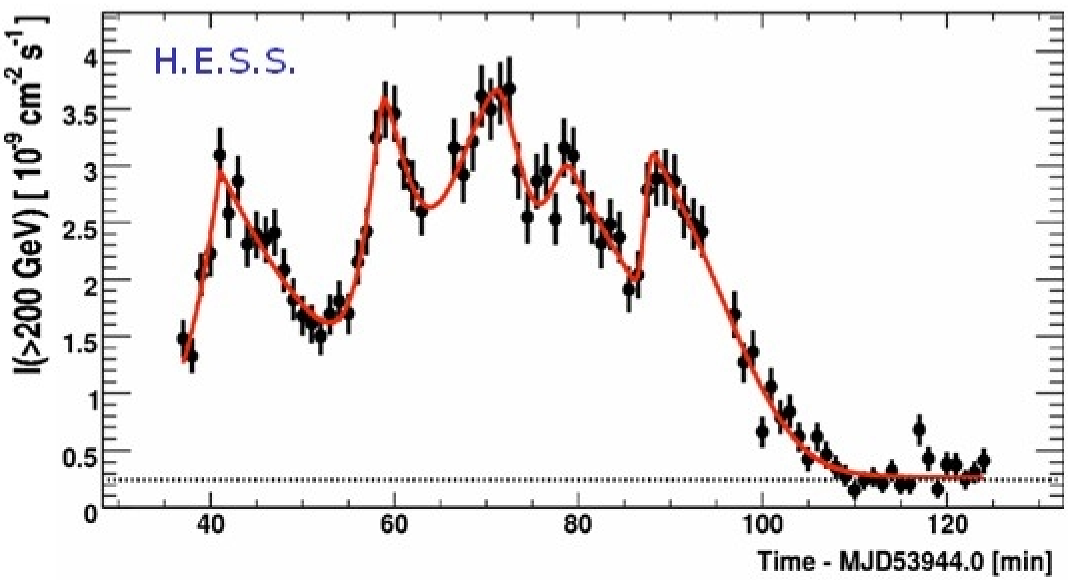






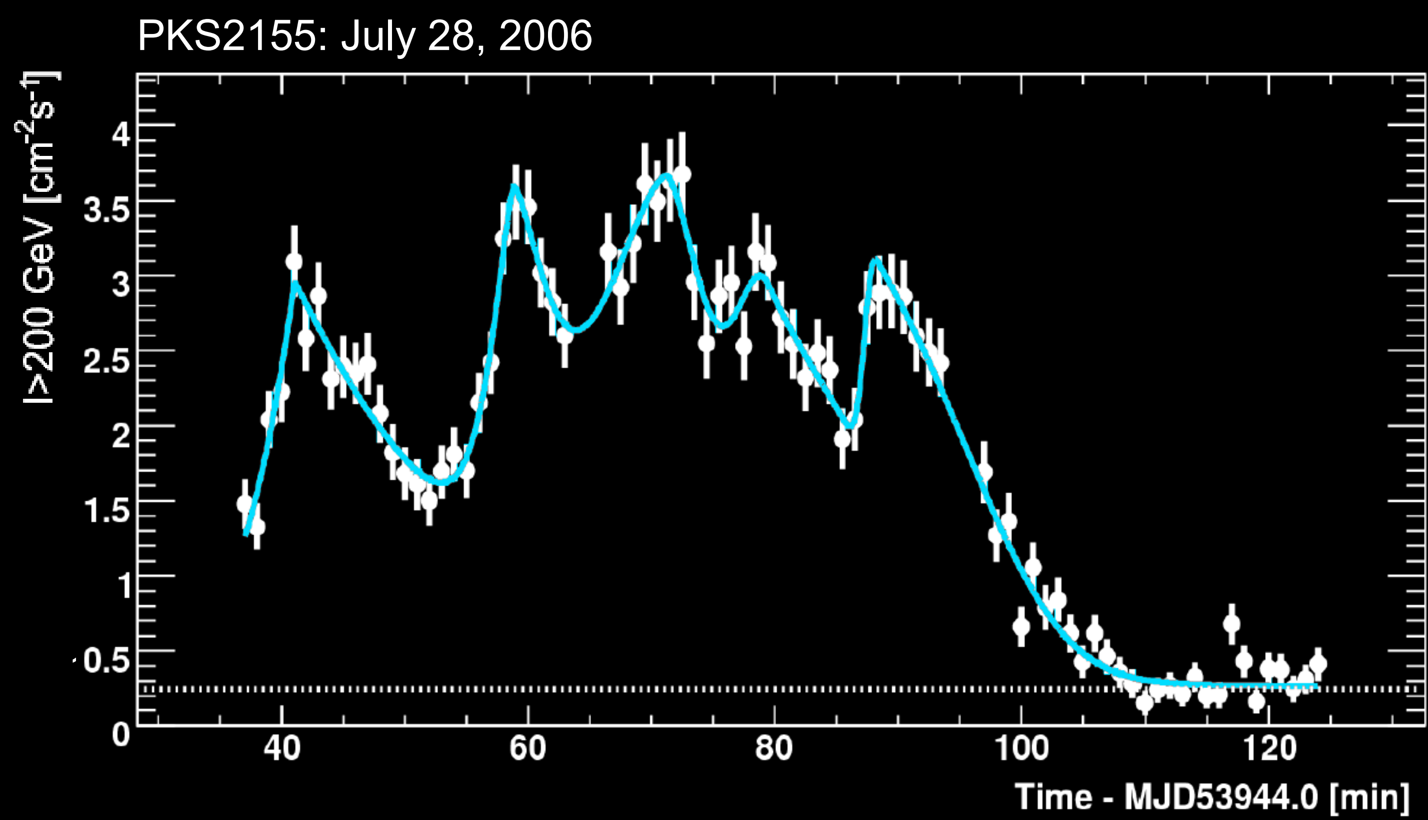
“Persistent GRBs”

Flares by factors > 100 on time-scales of minutes
(PKS 2155-304, HESS; Mrk 501, MAGIC; Mrk 421, VERITAS)



Variability time-scales and BH mass: 300 nano-sec per solar mass
Causality-inferred diameter ~ 100 million km, ie < 1 AU <<< 1 pc

Grazing the horizon?



→ Timescale x c << R_S

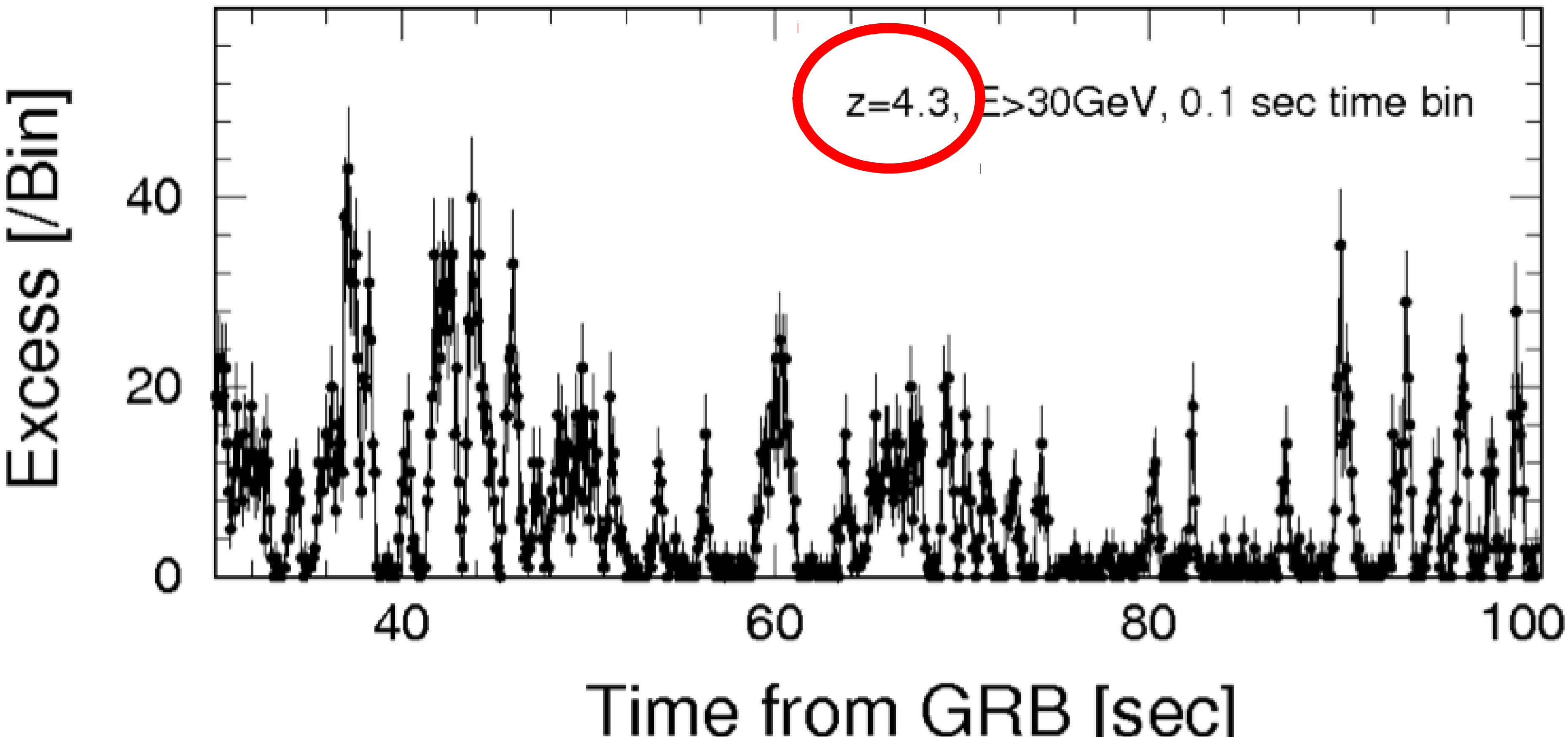
→ Doppler factors > 100 near SMBH

→ Jet acceleration

→ Statistics, Isotropy

→ Opacity problem

Gamma – ray bursts (E > 30 GeV)



from
GRB Science in the Era of CTA
(Astroparticle Physics special issue article)
Susumu Inoue et al., arXiv:1301.3014

Probing Intergalactic Voids

Gamma-Rays interact with background photon field (EBL), reflecting integrated emission from stars. Used to make integrated 'in-situ' measurements of the EBL density.

$$\gamma\gamma \longleftrightarrow e^+ e^- \quad (1\ \text{TeV} \sim 1\ \mu\text{m})$$

Pairs upscatter CMB, enabling measurements of magnetic fields.

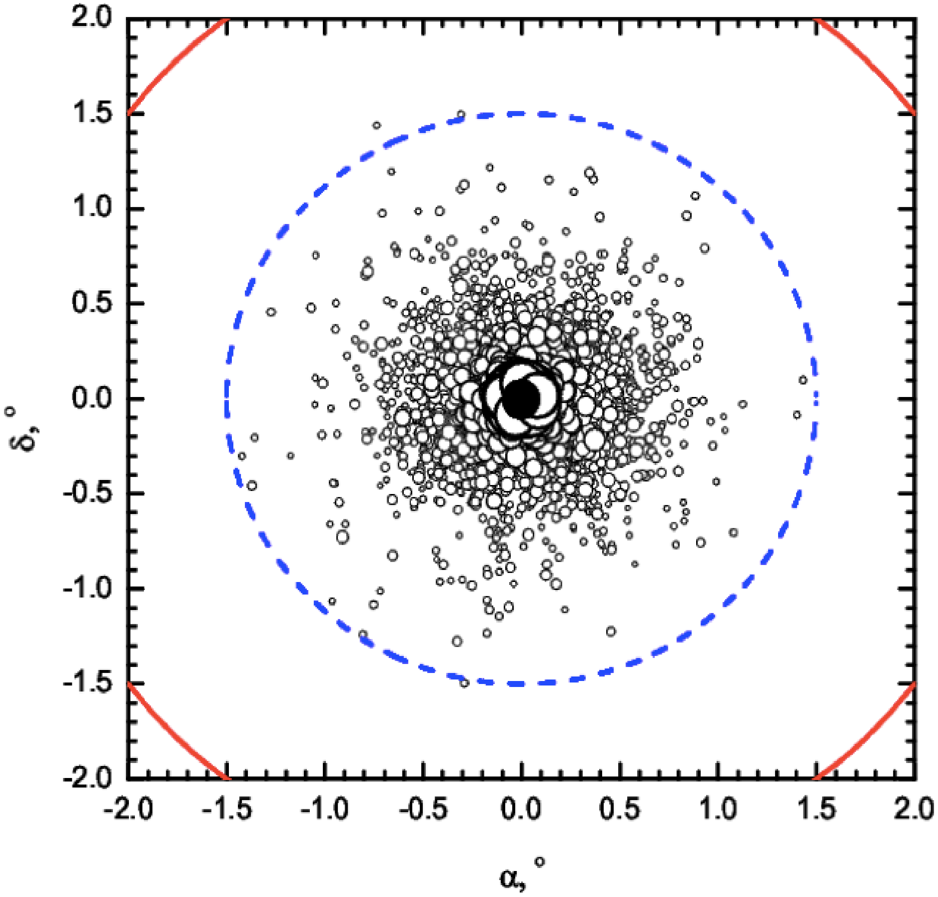
Do gamma-ray blazars impact voids?

Intergalactic Magnetic Fields

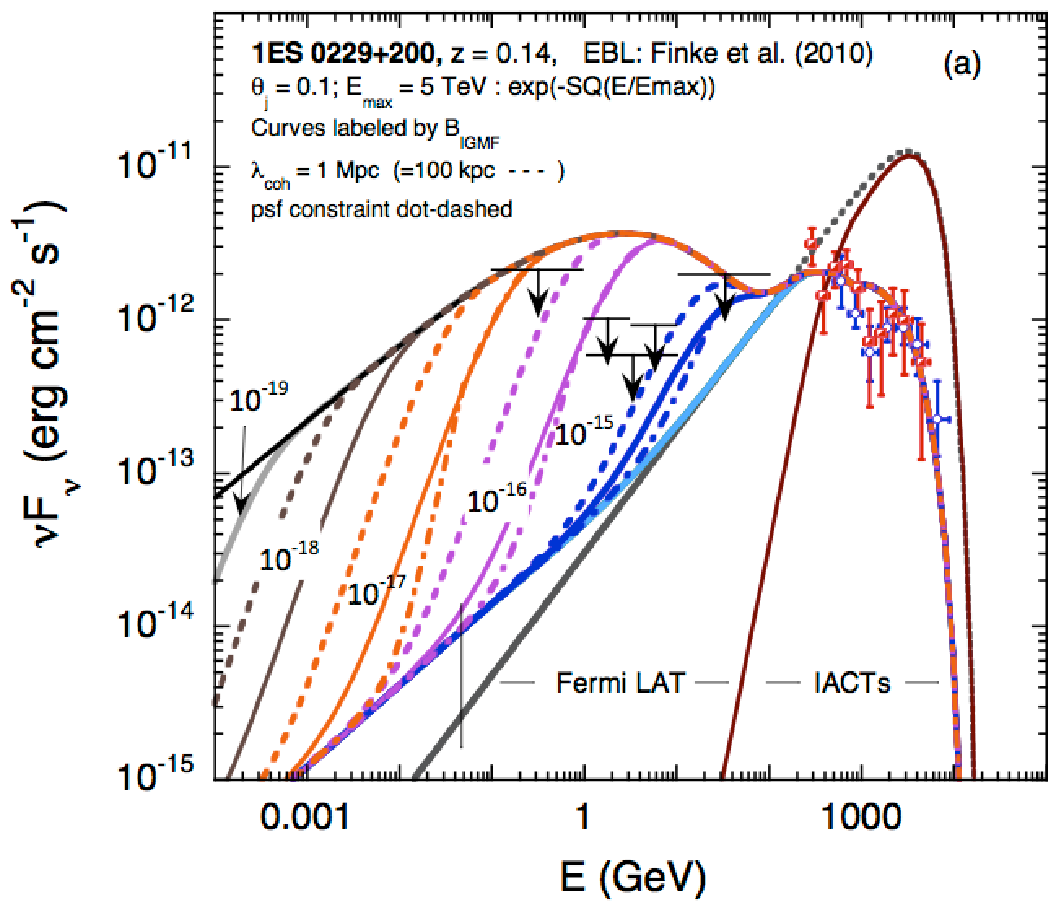
Imaging: Fields above 10^{-12}G give rise to detectable pair halos

Spectra/Timing: Fields below 10^{-15}G give rise to detectable cascades

Sol et al., arXiv:1304.3024



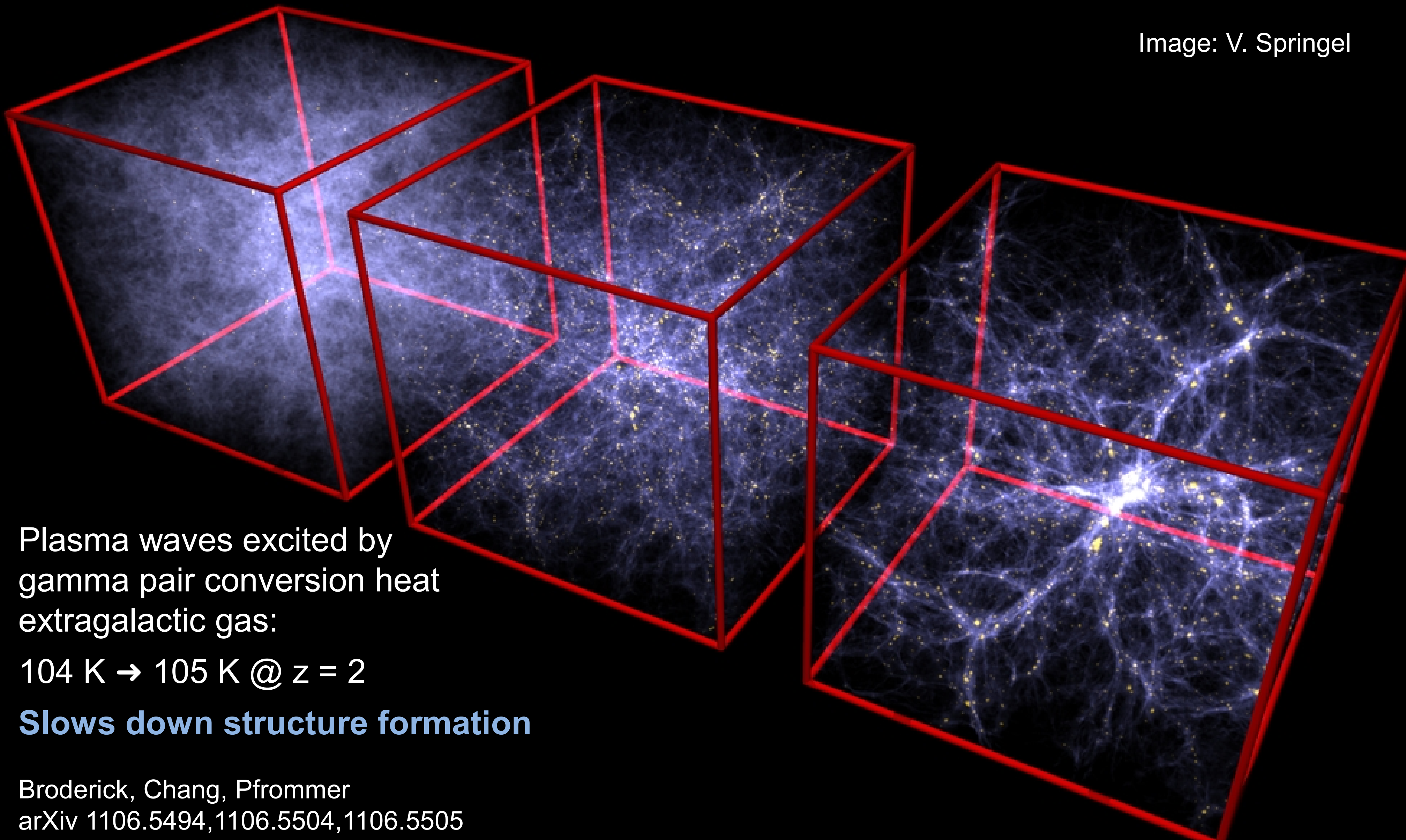
Dermer et al., arXiv:1011.6660



02

Blazar-Heating of the IGM?

Image: V. Springel



Plasma waves excited by gamma pair conversion heat extragalactic gas:

104 K ➜ 105 K @ z = 2

Slows down structure formation

Broderick, Chang, Pfrommer
arXiv 1106.5494,1106.5504,1106.5505

Frontiers beyond the SM

- What is the nature of Dark Matter?
- What is the mass of the DM particle?
- How is it distributed?
- Is the speed of light constant for high energy photons?
  (Search for violation of Lorentz invariance)
  Some models of QG predict non-vanishing dispersion for high E.
- Do axion-like particles exist?

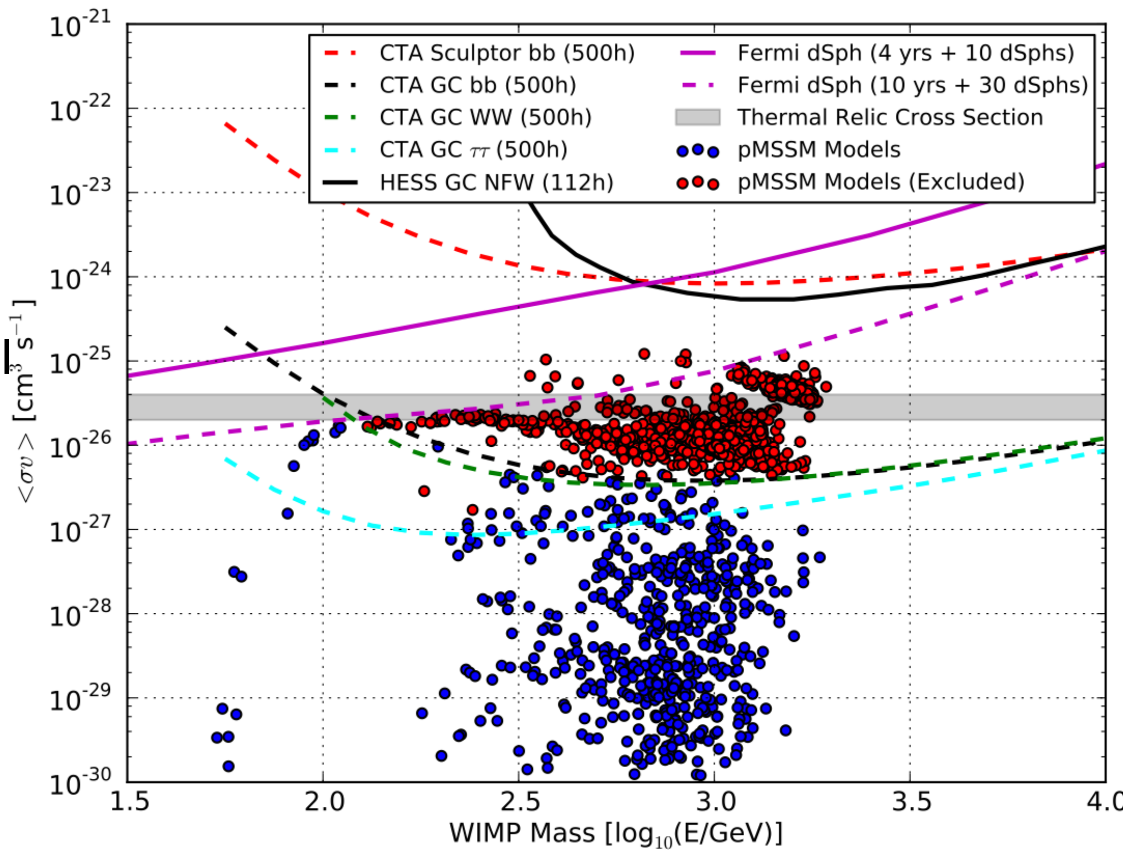
Dark matter annihilation

DM annihilation produced gamma-ray continuum and possibly lines

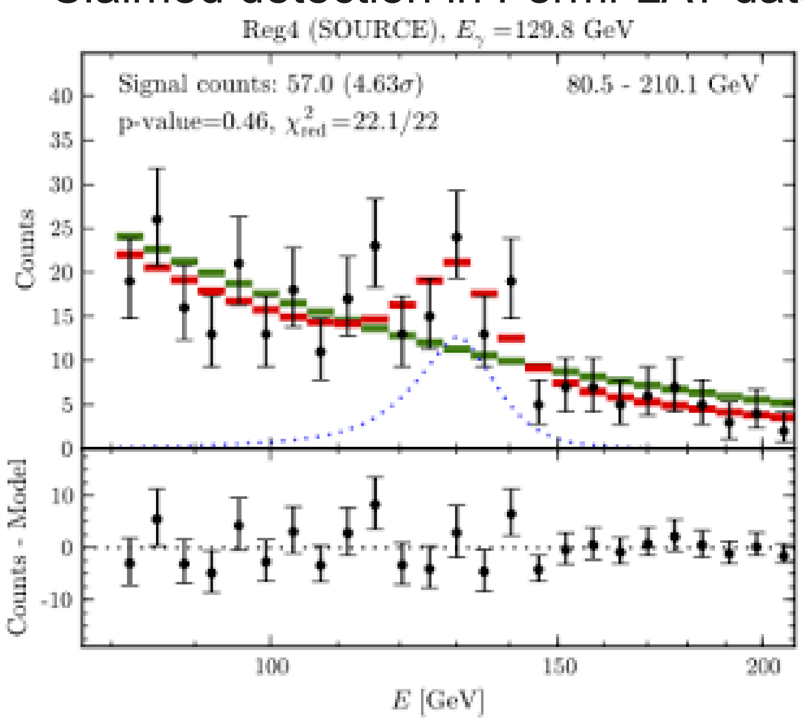
→ mass of DM particle

Upper limits on GC and dwarf galaxies

CTA will for the first time reach meaningful sensitivity in the TeV range



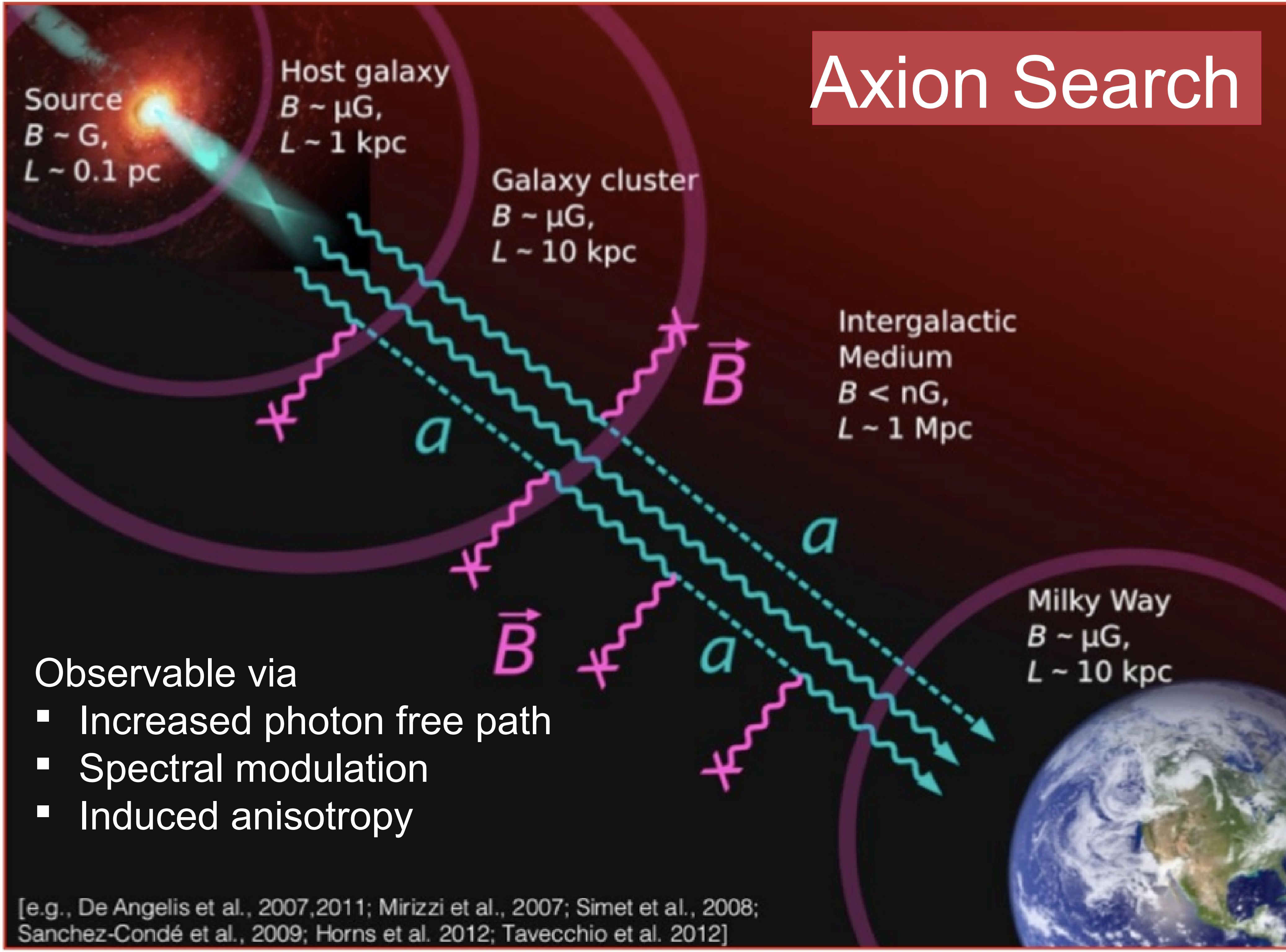
Claimed detection in Fermi-LAT data



Complementarity between
CTA
Direct detection
LHC

M. Wood et al.
arXiv 1305.0302

Axion Search

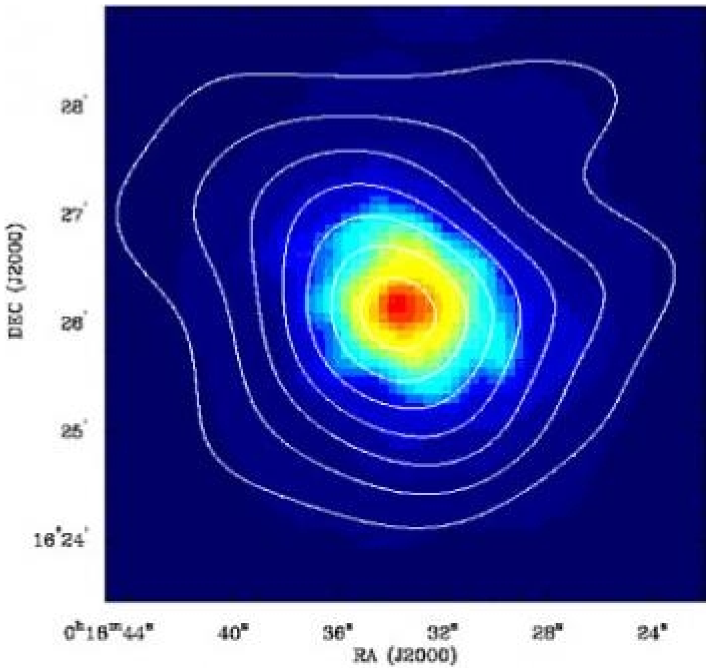


Observable via

- Increased photon free path
- Spectral modulation
- Induced anisotropy

[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]

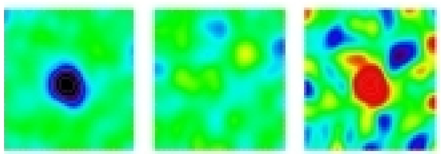
Sunyaev-Zel'dovich effect

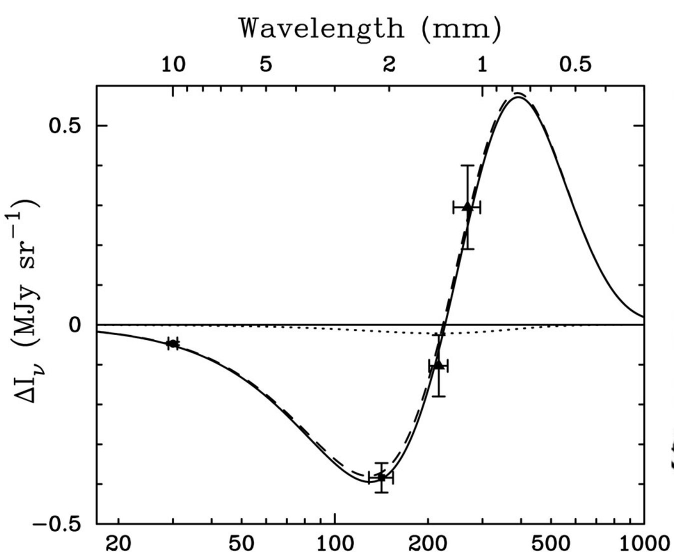


Low energies

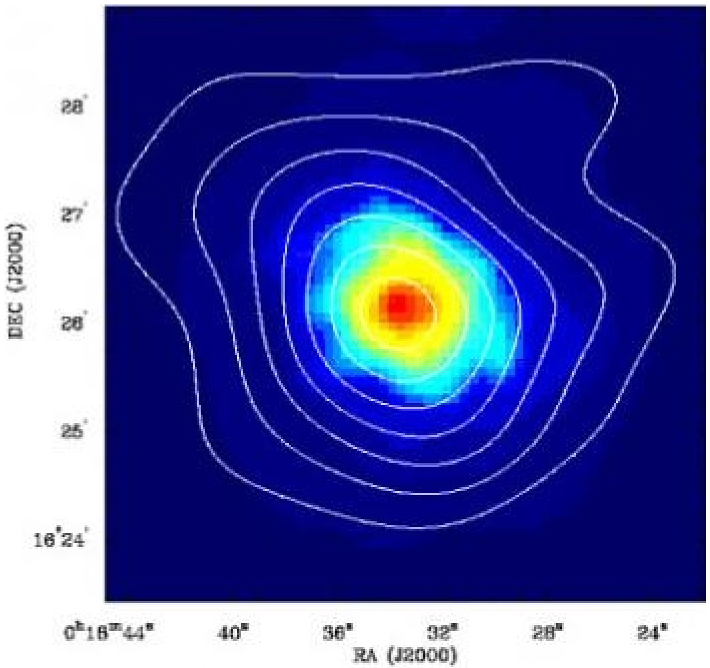
vs

High energies





Sunyaev-Zel'dovich effect



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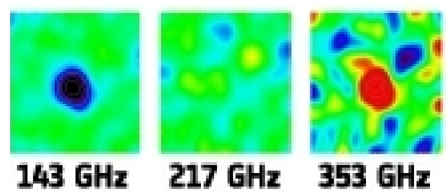
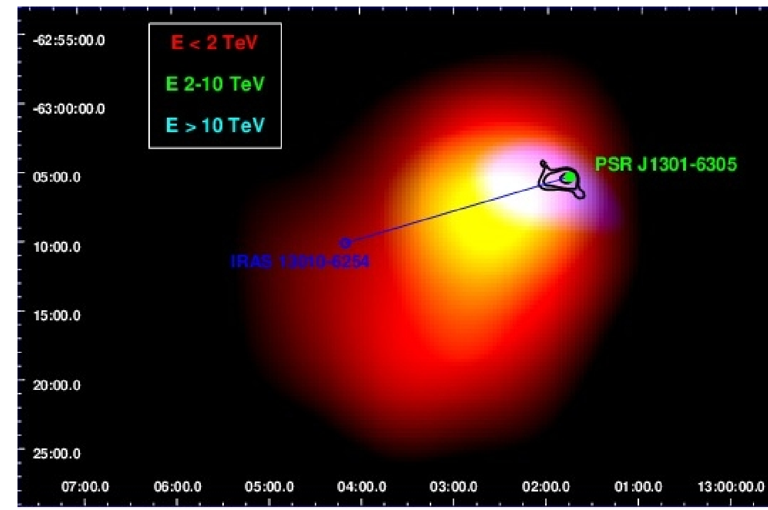
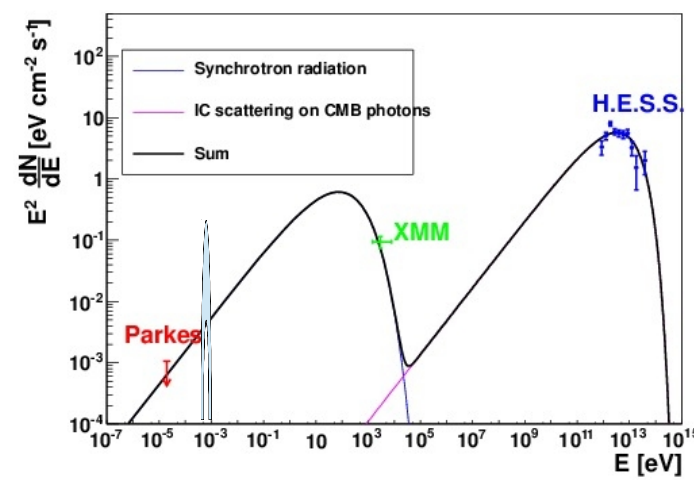
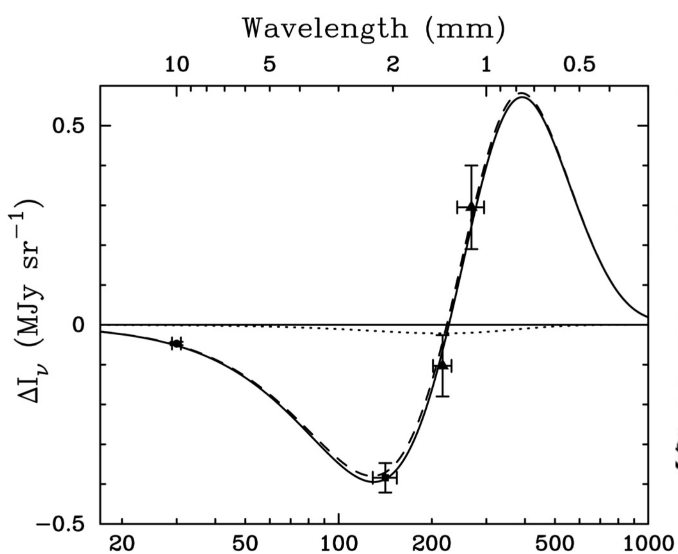
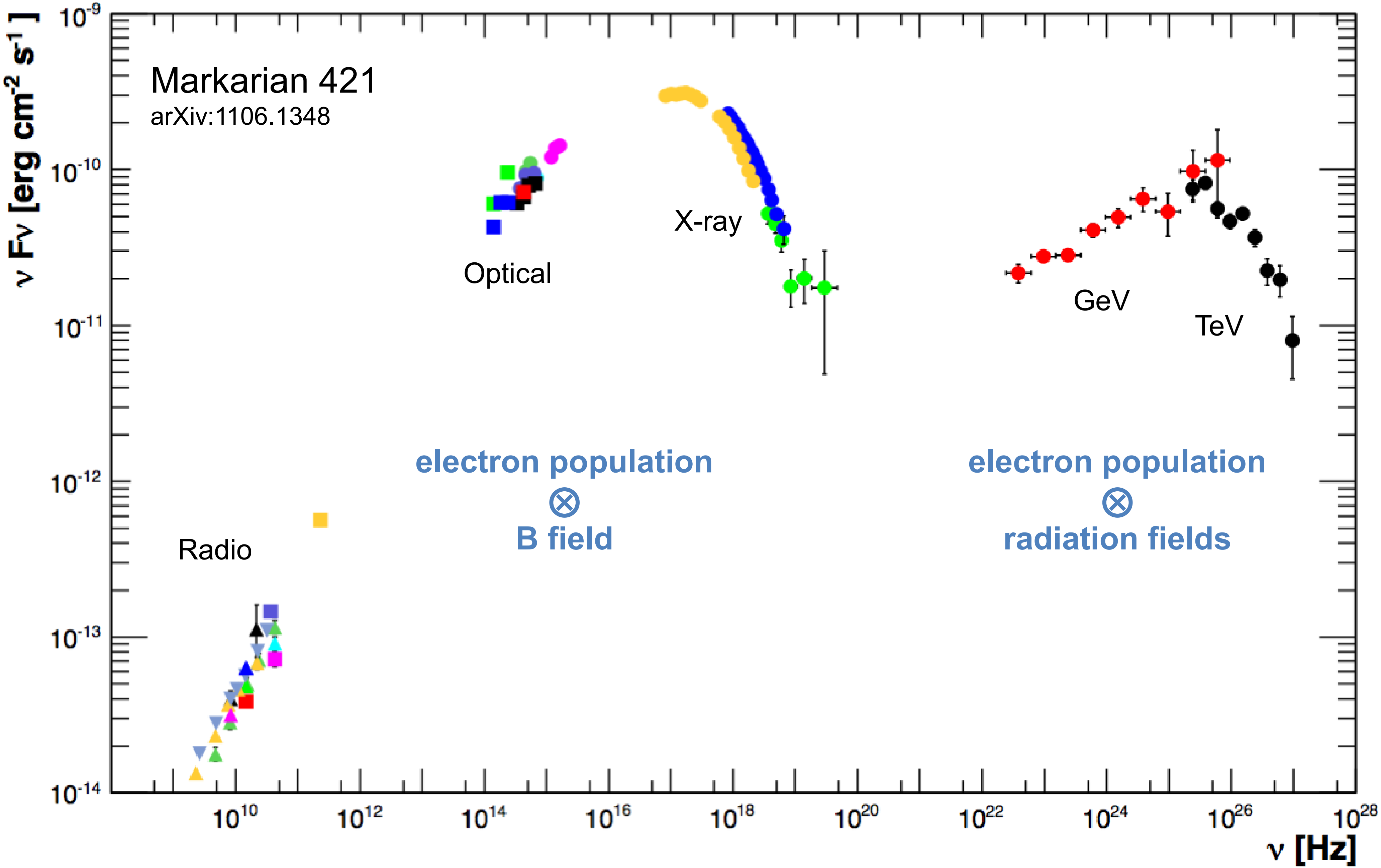








Multiwavelength aspects



Multiwavelength aspects

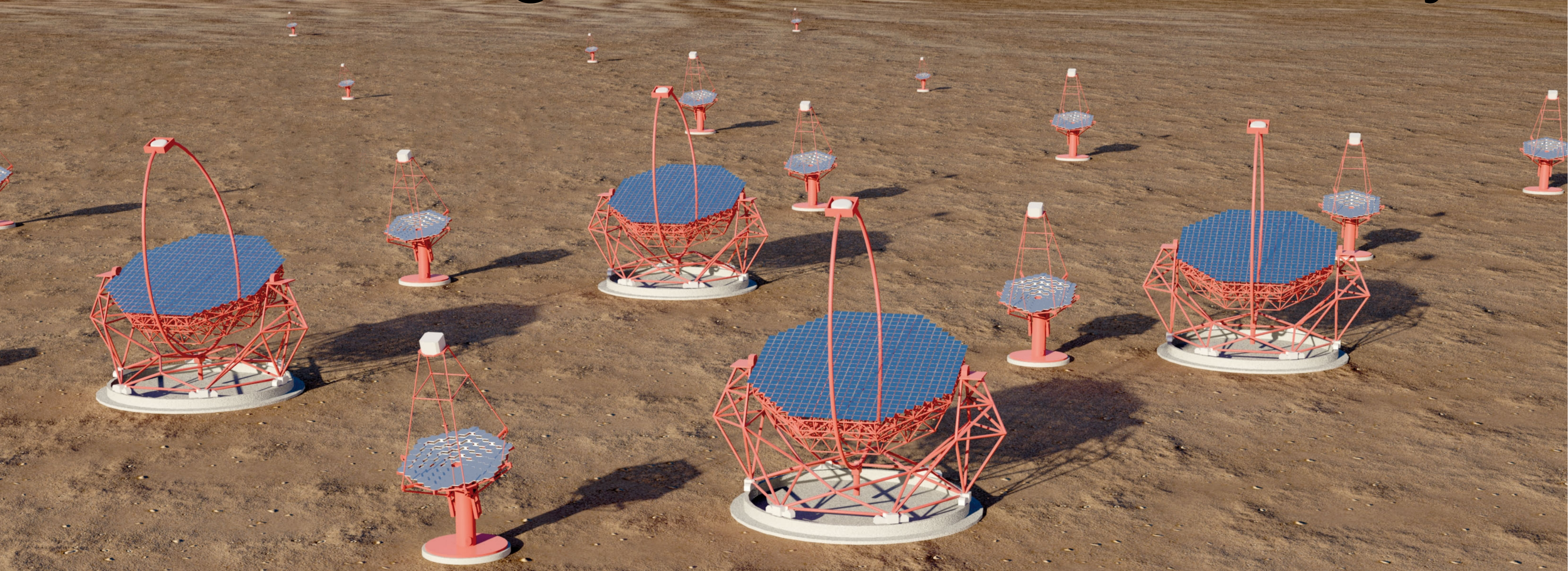
Gamma-ray studies provide new information about old friends. They provide measurements of otherwise inferred quantities.
Gamma-rays provide new probes of processes and interactions.

Many sources are not identified.
Identification via multiwavelength studies.
Many sources are variable (a curse and a blessing).

Interpretation needs quantitative information about otherwise inferred quantities (e.g. sizes, densities, velocities, distances).

I refrain from listing specific capabilities/instrumentation
(CTA themes not aligned to 'big questions' but require versatile, multipurpose instrumentation on different telescopes.)

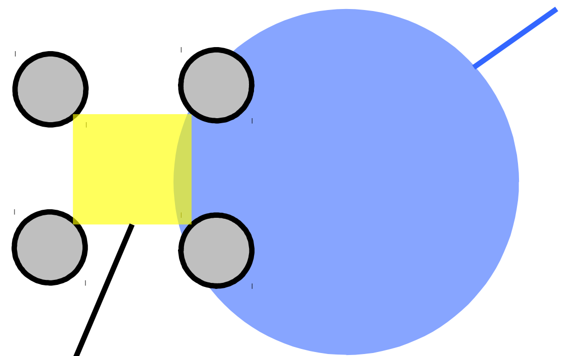
Forecasting 2020: CTA observatory



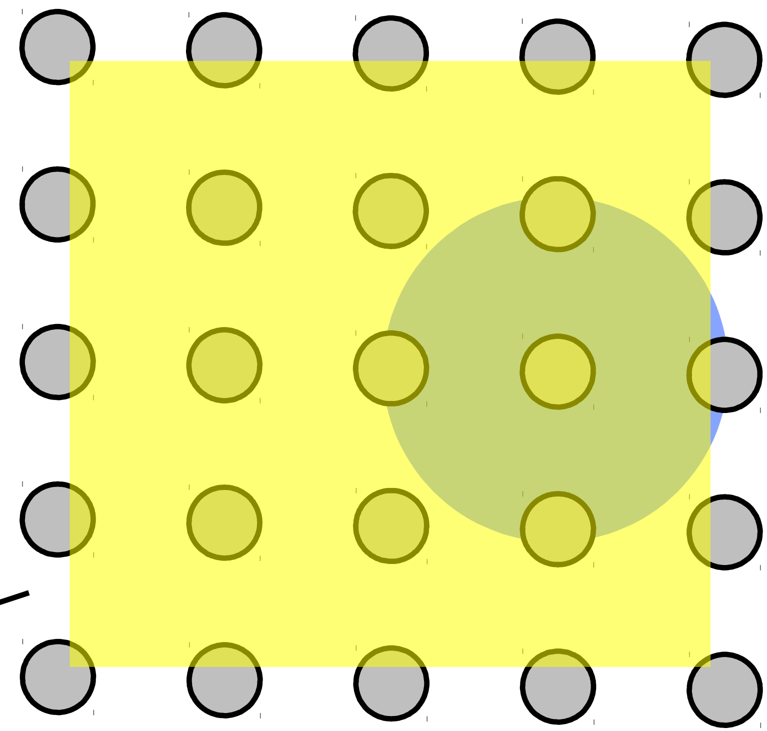
Compared to current instruments:
- 10 fold improvement in sensitivity
- 10 fold improvement in usable energy range
- much larger field of view
- improved angular resolution
- Observatory operations, community access

From current arrays to CTA

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



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

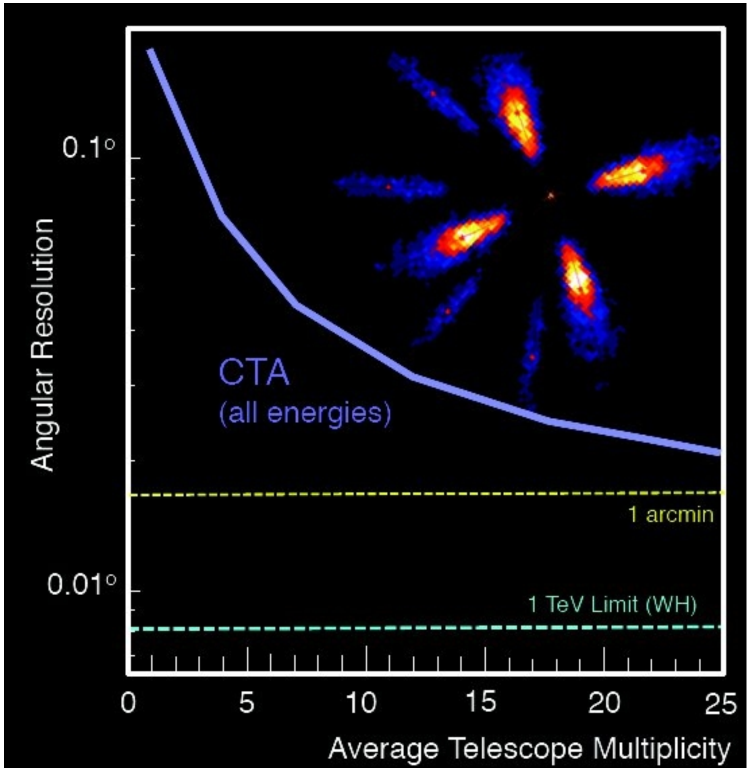


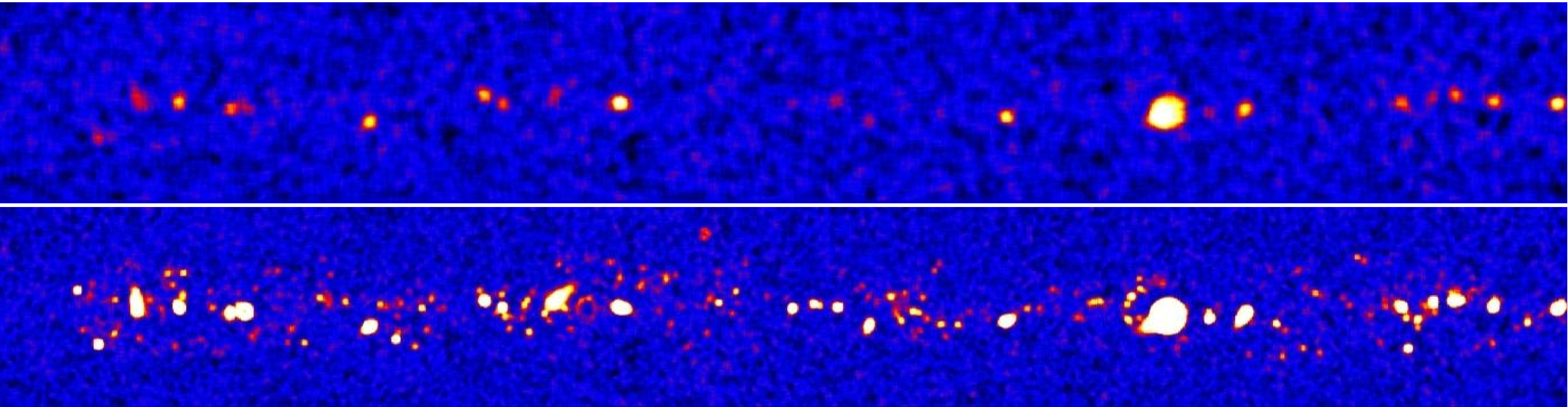
large detection area
more images per shower
lower trigger threshold

What to expect?

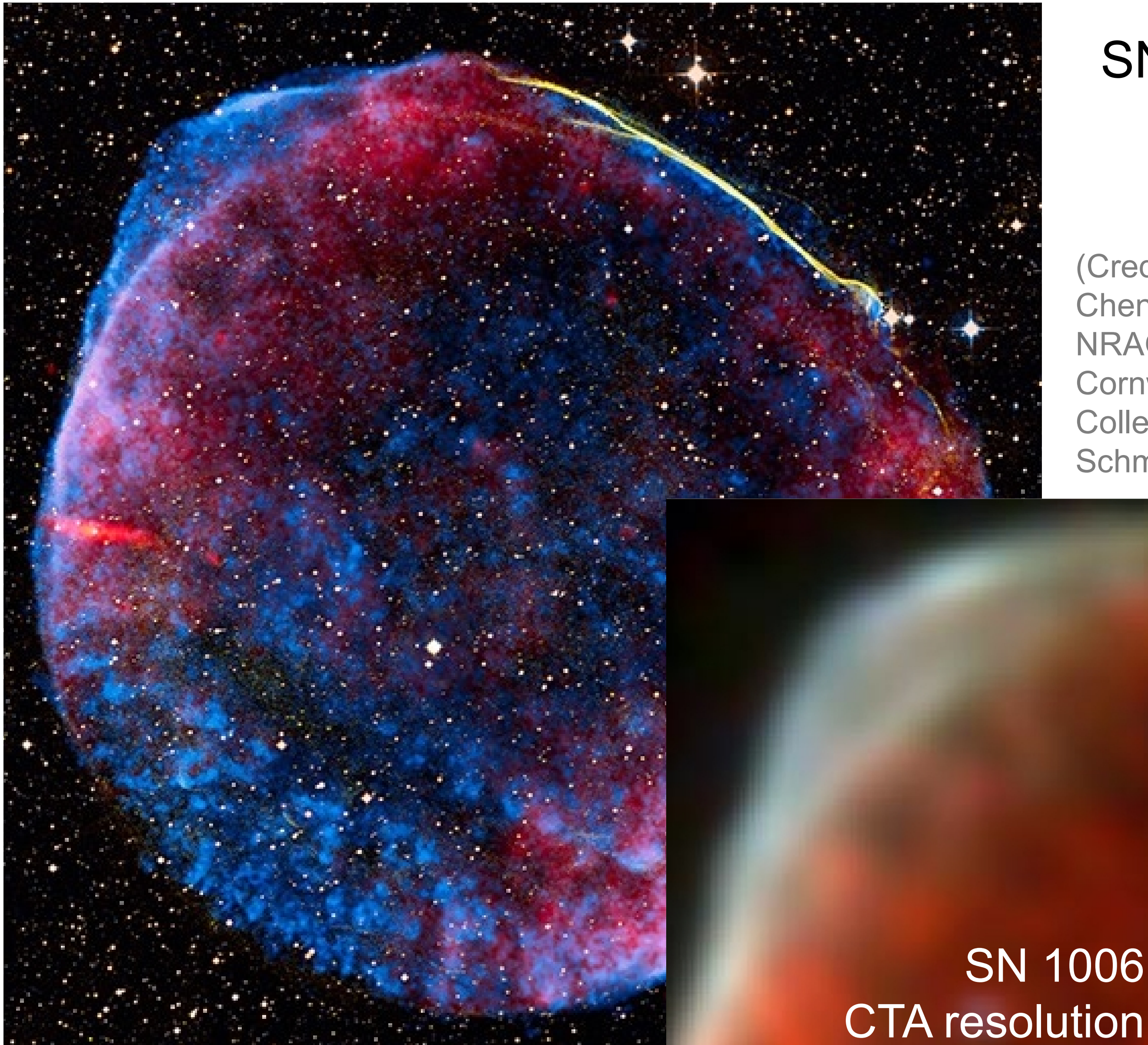
Performance goals:

Improved sensitivity (> factor 10)
Increased Energy range (0.03 - 100 TeV)
Improved Energy Resolution
Improved Angular Resolution
Larger Field-of-view (Survey)



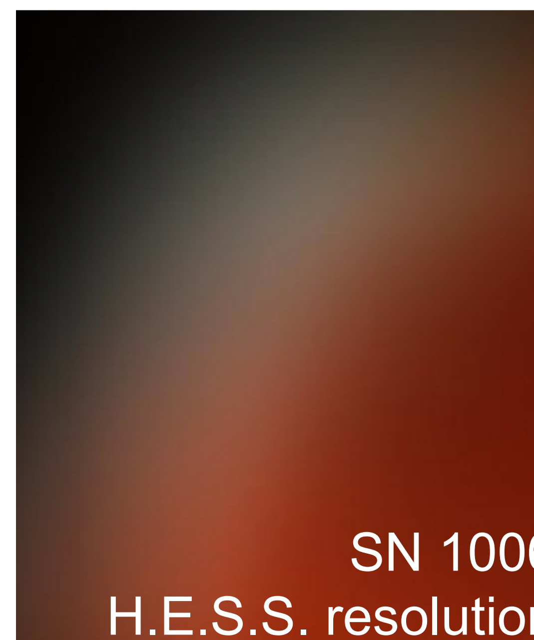


Resolving complex sources



SN 1006

(Credit:X-ray: NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS)



Possible Configuration

Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- FOV: 4-5 degrees

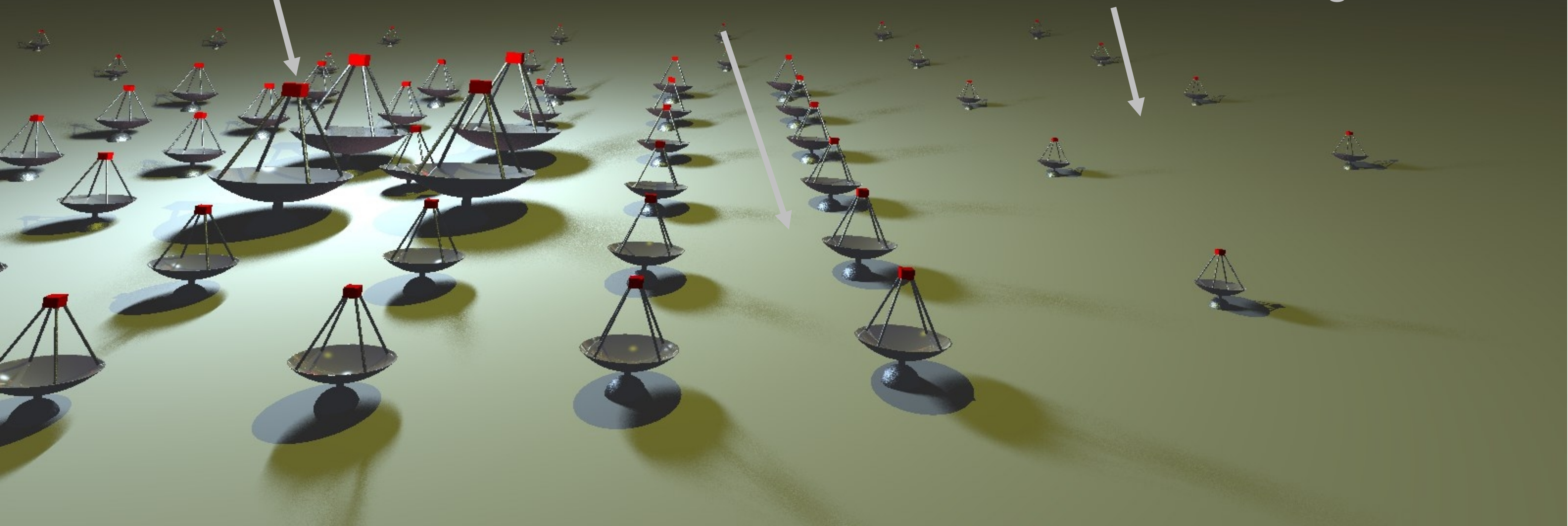
energy threshold of some 10 GeV

Core-energy array:
24 x 12 m tel. (MST)
- Davies-Cotton reflector
- FOV: 7-8 degrees

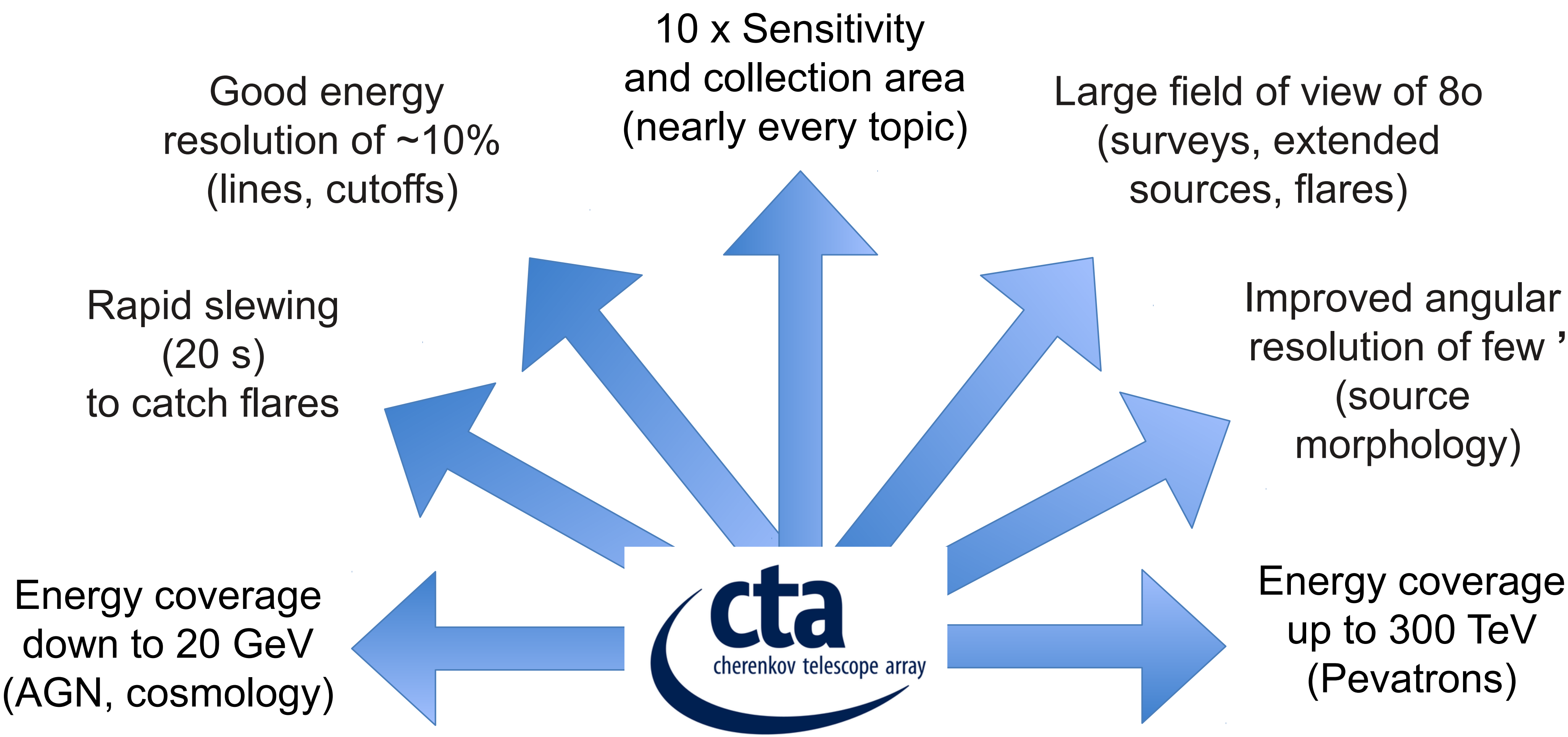
mCrab sensitivity in the 100 GeV–10 TeV domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- Davies-Cotton reflector (or Dual Mirror design)
- FOV: ~10 degrees

10 sq.km area at multi-TeV energies



Requirements & drivers



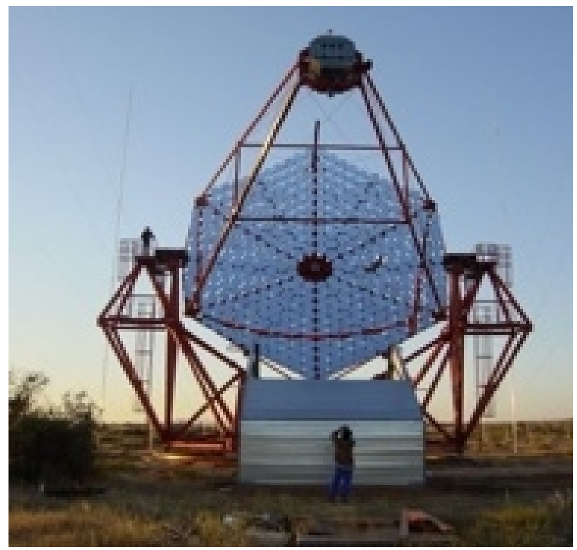
Comparison of Gamma Detectors

Low Energy Threshold
EGRET/Fermi

Space-based (Small Area)
"Background Free"
Large Duty Cycle/Large Aperture

Sky Survey (< 10 GeV)
AGN Physics
Transients (GRBs) < 100 GeV

High Sensitivity
HESS, MAGIC, VERITAS, CTA



Large Effective Area
Excellent Background Rejection
Low Duty Cycle/Small Aperture

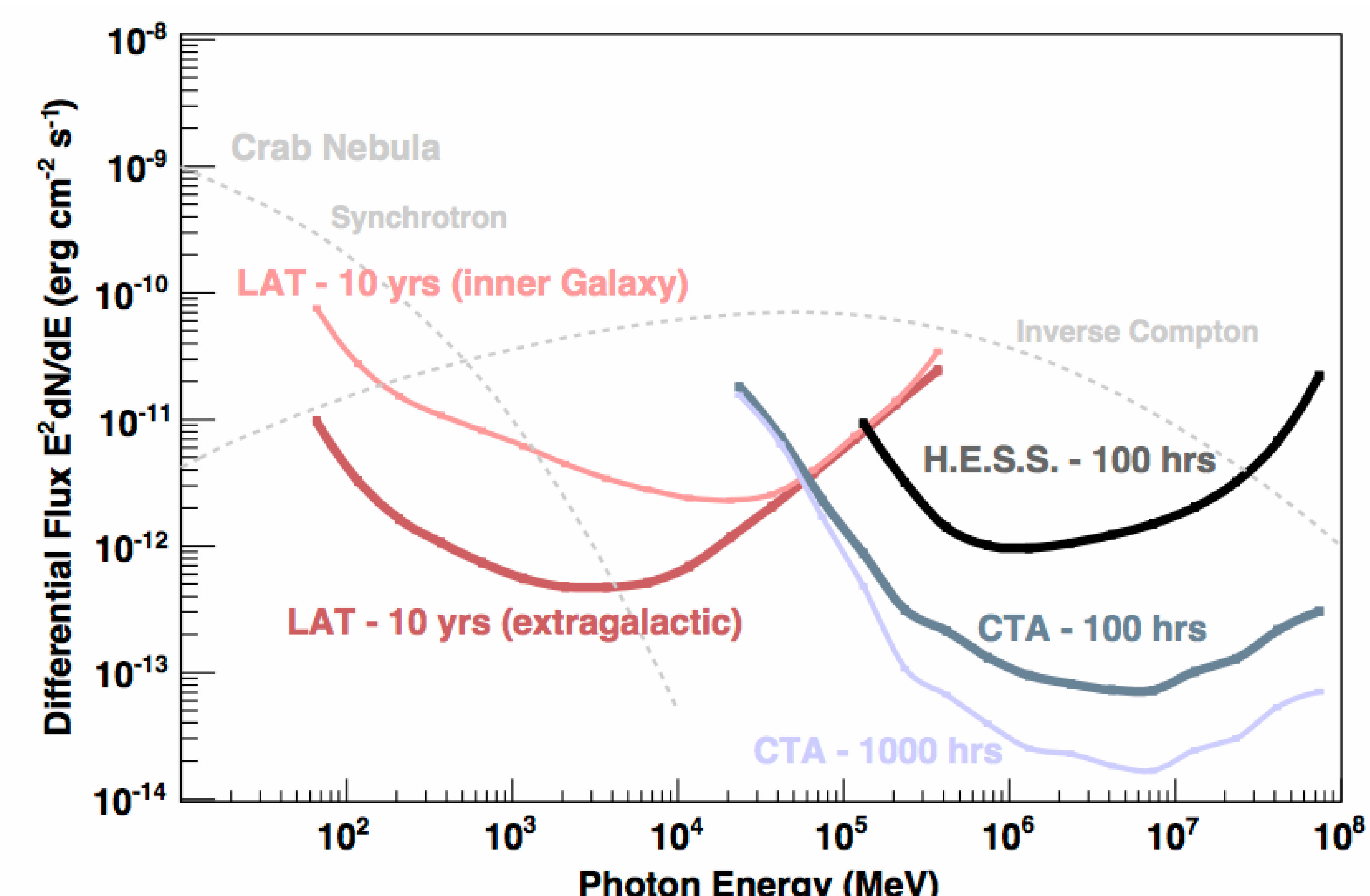
High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky at a time

Large Aperture/High Duty Cycle
Milagro, Tibet, ARGO, HAWC

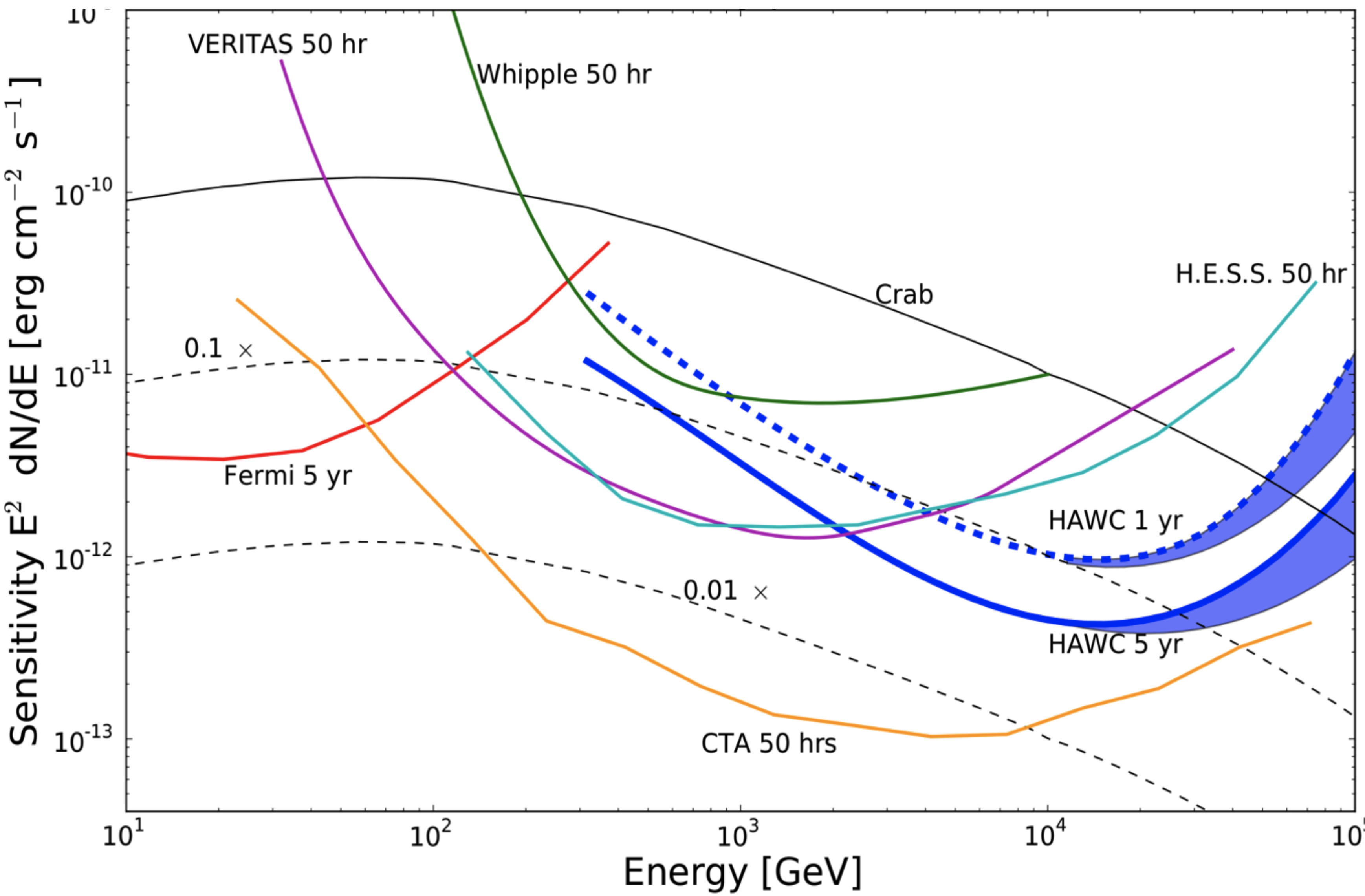
Moderate Area
Good Background Rejection
Large Duty Cycle/Large Aperture

Unbiased Sky Survey
Extended sources
Transients (GRB's)
Solar physics/space weather

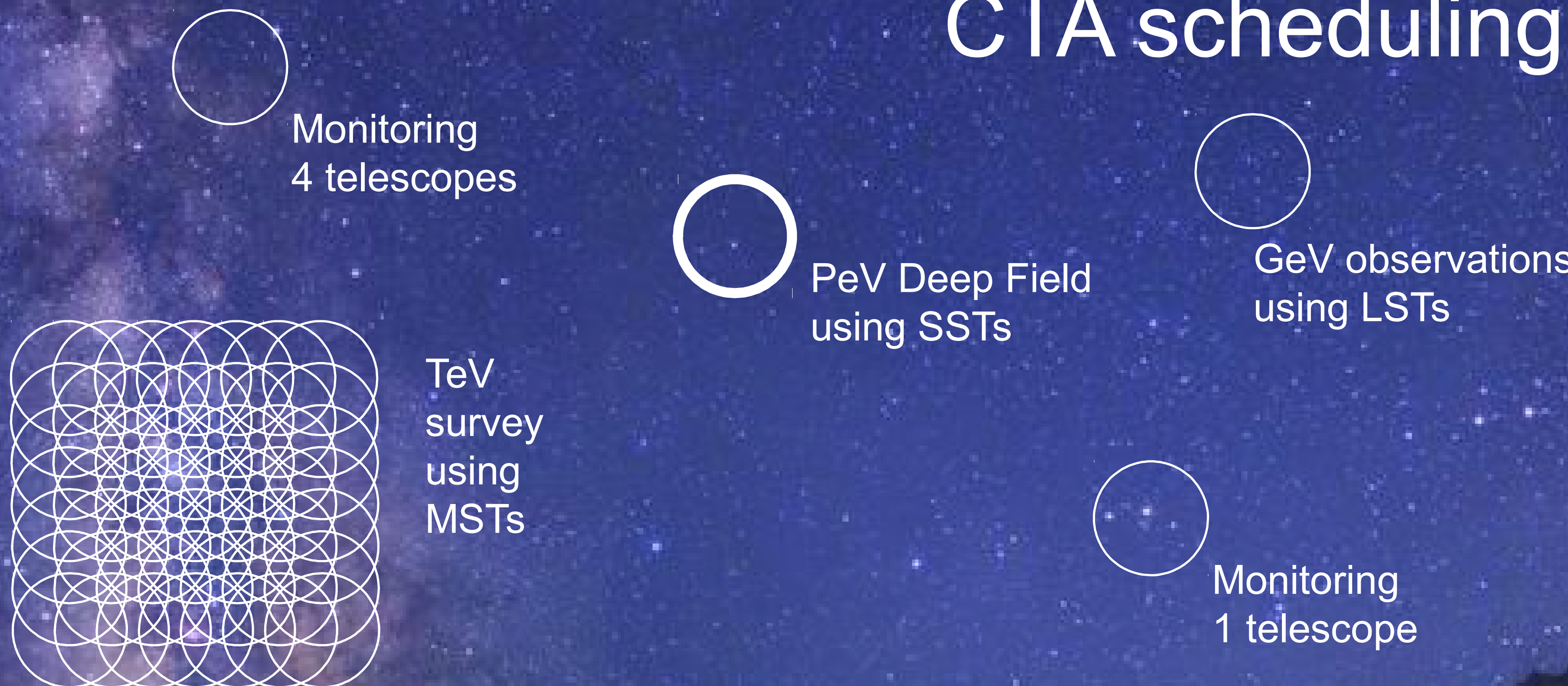
Differential Flux Sensitivity I



Differential Flux Sensitivity II



CTA scheduling



- Queue mode scheduler taking into account actual sky conditions, sub-arrays & conditions requested in proposal, TOOs
- Typical time per pointing ~20 min, up to few h per night on given target (energy threshold increases rapidly for larger zenith angles)

Summary

High-Energy Astrophysics has been pushed to 100 TeV.
Astronomical sources are studied in detail at high energies.
Gamma-data reveal new insights into old questions.
Gamma-rays allow exploration of new phenomena.

New opportunities for everybody:

High-impact Fermi results come from the general community.
Ground based gamma-ray science with new observatory.
The CTA observatory is proposed as a new infrastructure.
It shall provide access based on peer-reviewed proposals
and an open access to archival data.

CTA has completed its preparatory phase, a legal entity has been founded and operates the project office (Heidelberg), preparing for a founding agreement for the observatory.