Gamma - Ray Astronomy in the 2020s

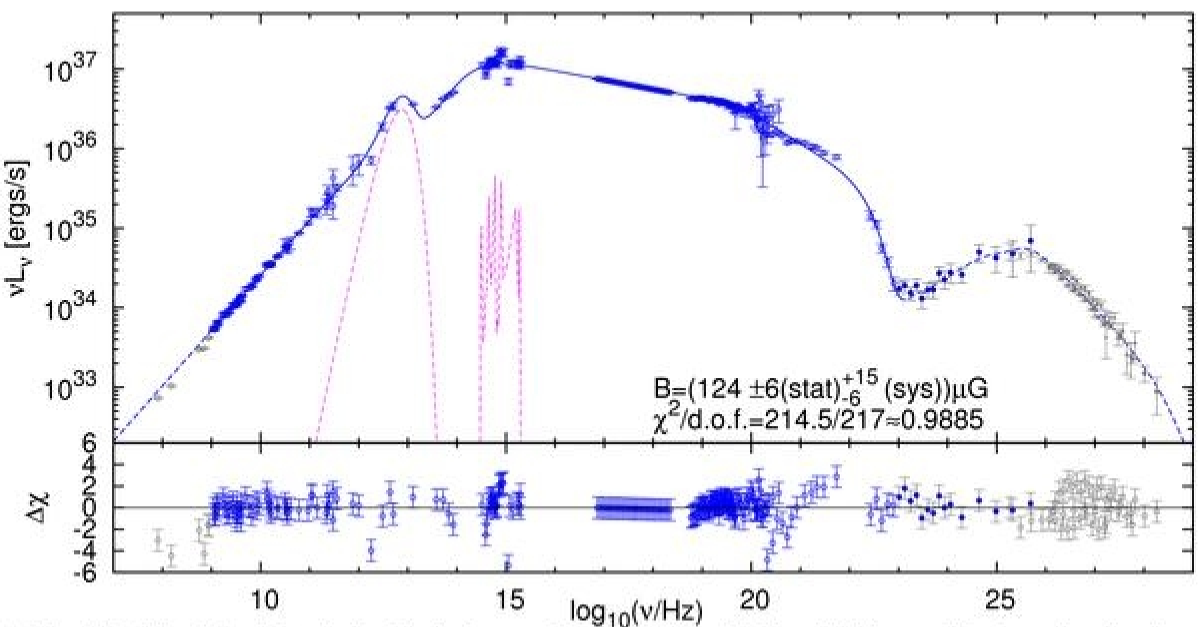
Stefan Wagner, LSW Heidelberg

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

γ – Ray Astronomy in the 2020s

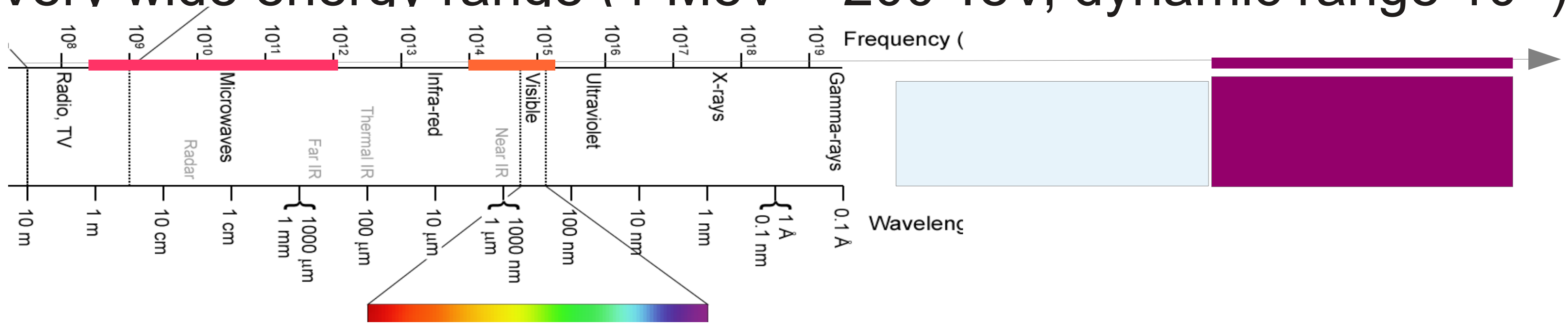
High – Energy Astrophysics: Relativistic Particles (1950s)
'High – Energy' Photons (1970s)
2015: Astronomy from <100 MHz to >100 TeV

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**

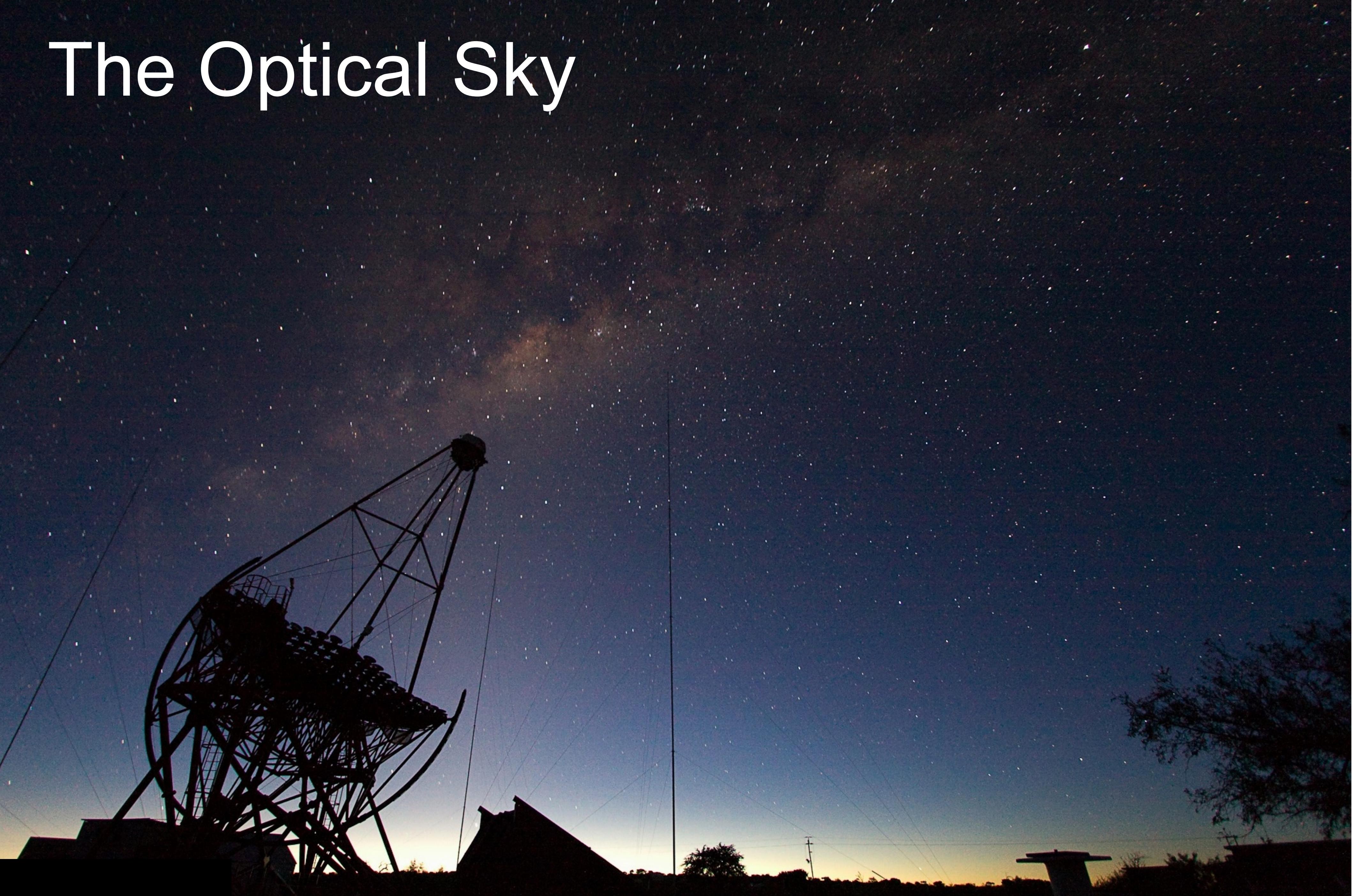
E > 20 GeV atmospheric Cerenkov
Enables large collection areas

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

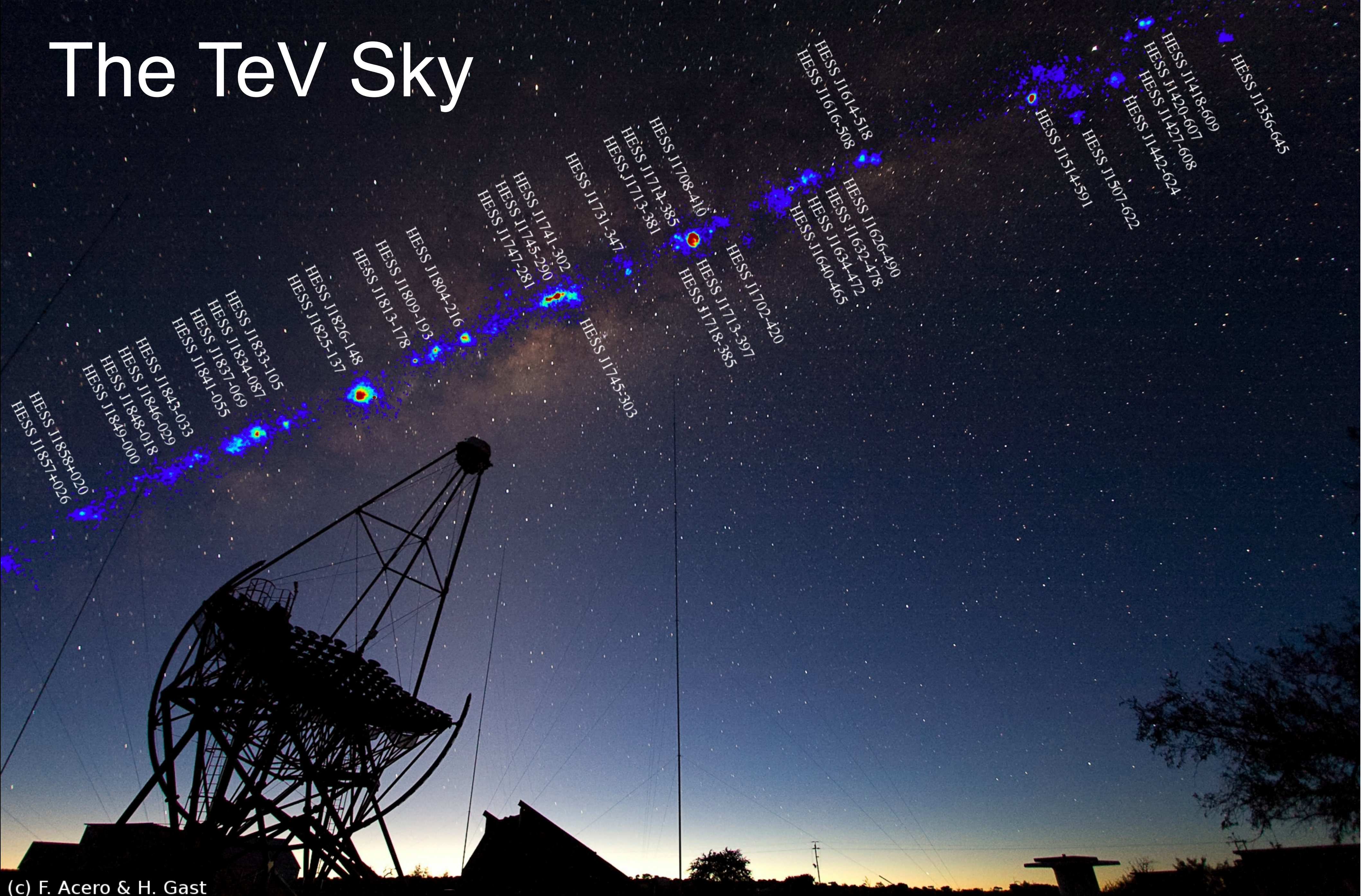
E > 10 TeV Water Cerenkov
Enables 24h, 2π sr observations

MILAGRO → **HAWK**

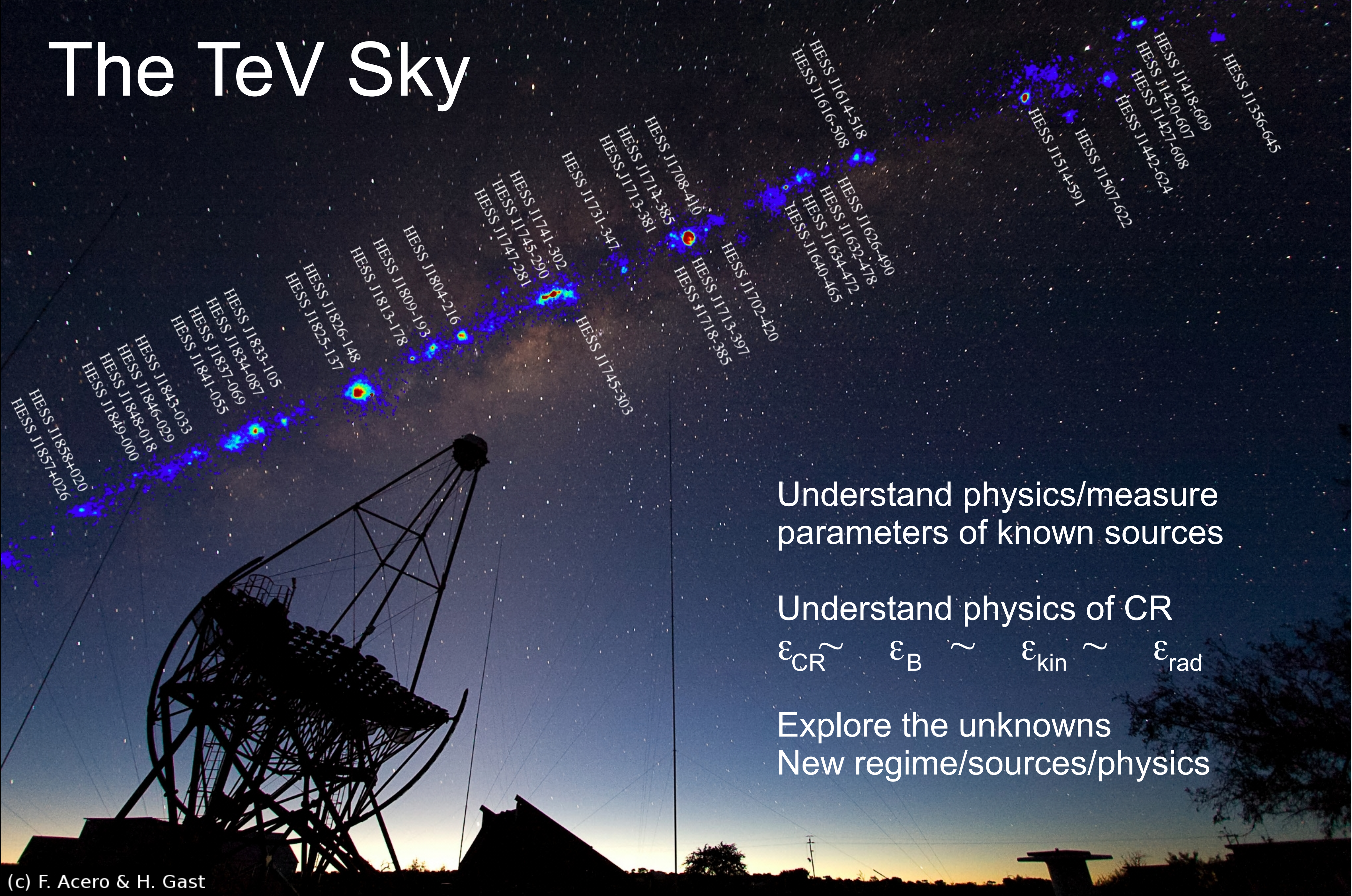
The Optical Sky



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 J1745-303
HESS J1731-347
HESS J1708-410
HESS J1714-385
HESS J1713-381
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
HESS J1507-622
HESS J1418-609
HESS J1420-607
HESS J1427-608
HESS J1442-624
HESS J1356-645

The TeV Sky



Understand physics/measure parameters of known sources

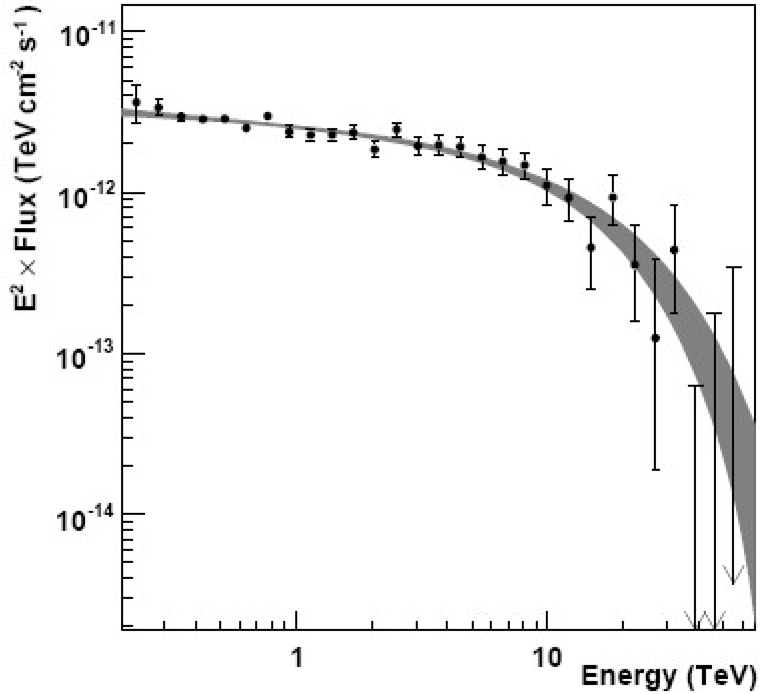
Understand physics of CR

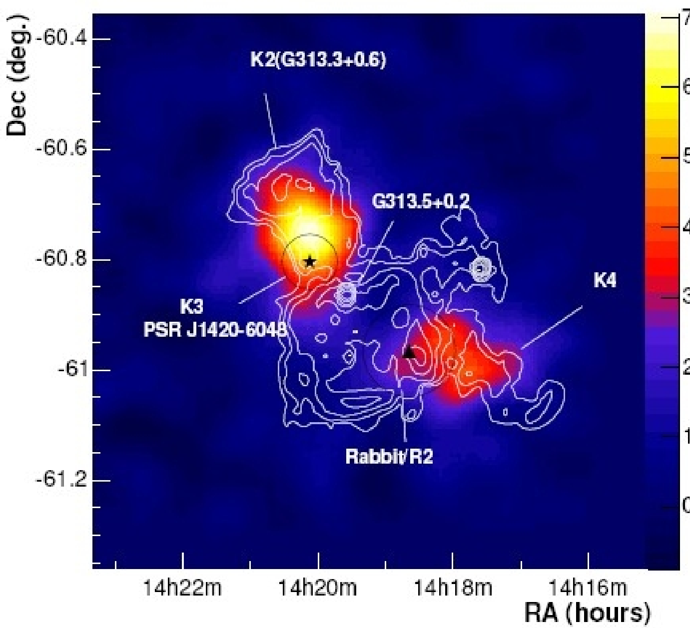
$\varepsilon_{CR} \sim \varepsilon_{B} \sim \varepsilon_{kin} \sim \varepsilon_{rad}$

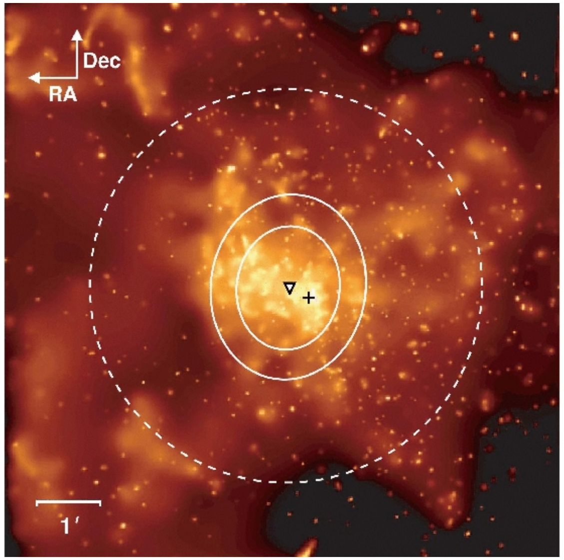
Explore the unknowns
New regime/sources/physics

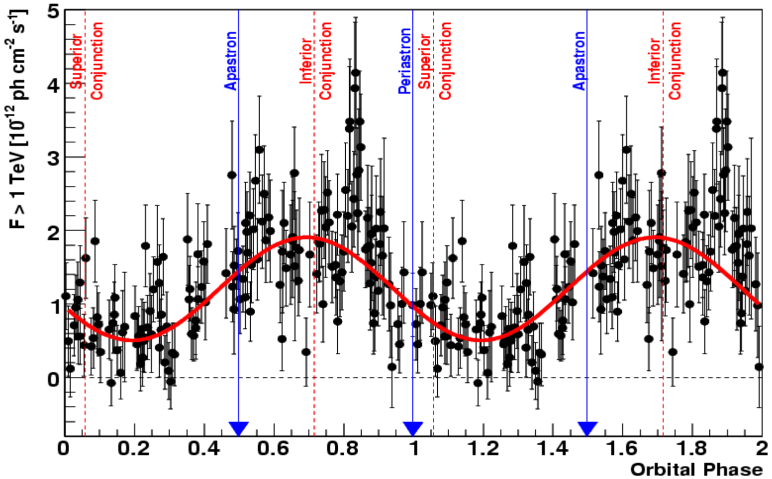
γ – ray Astronomy Today

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

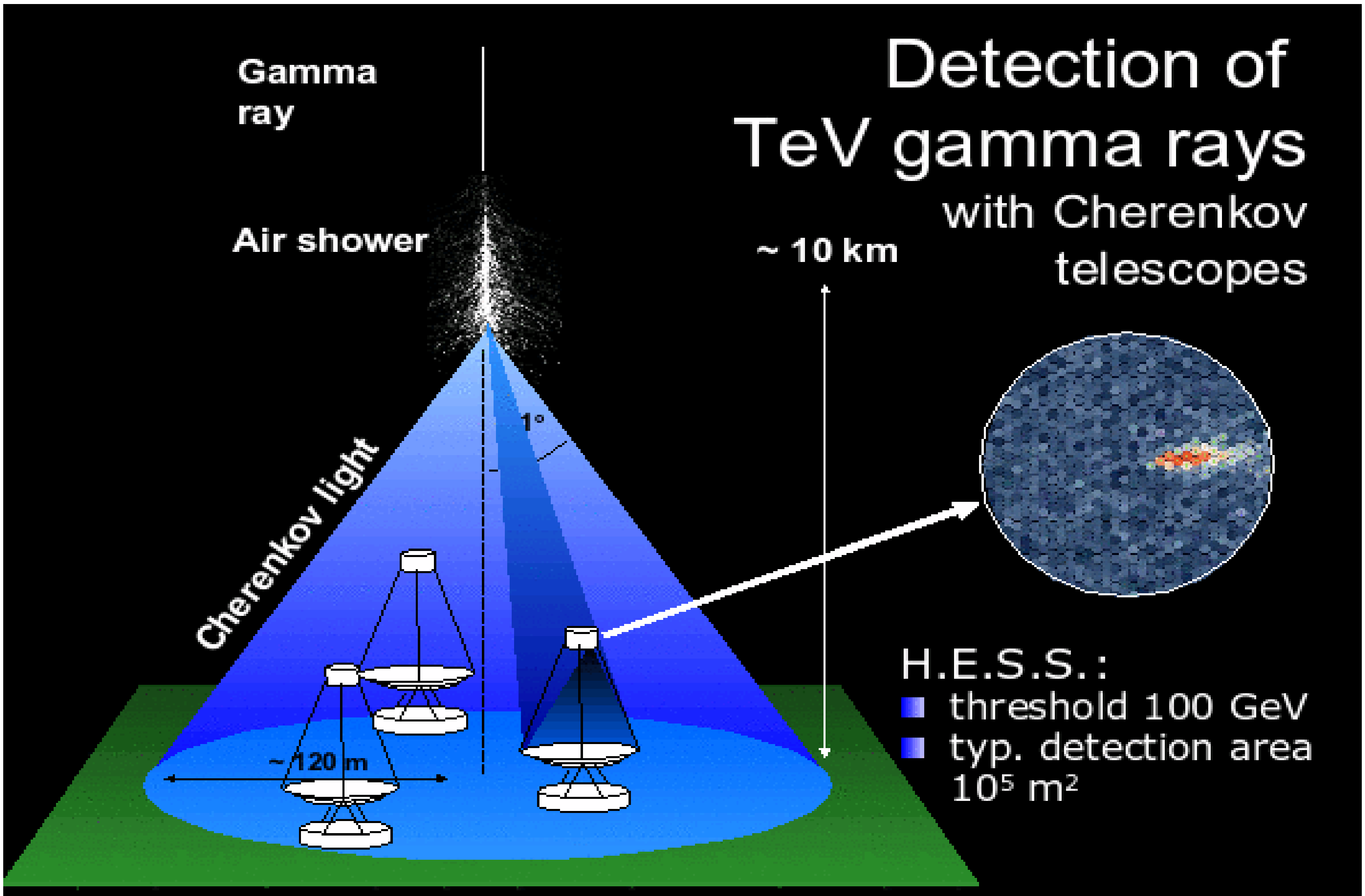






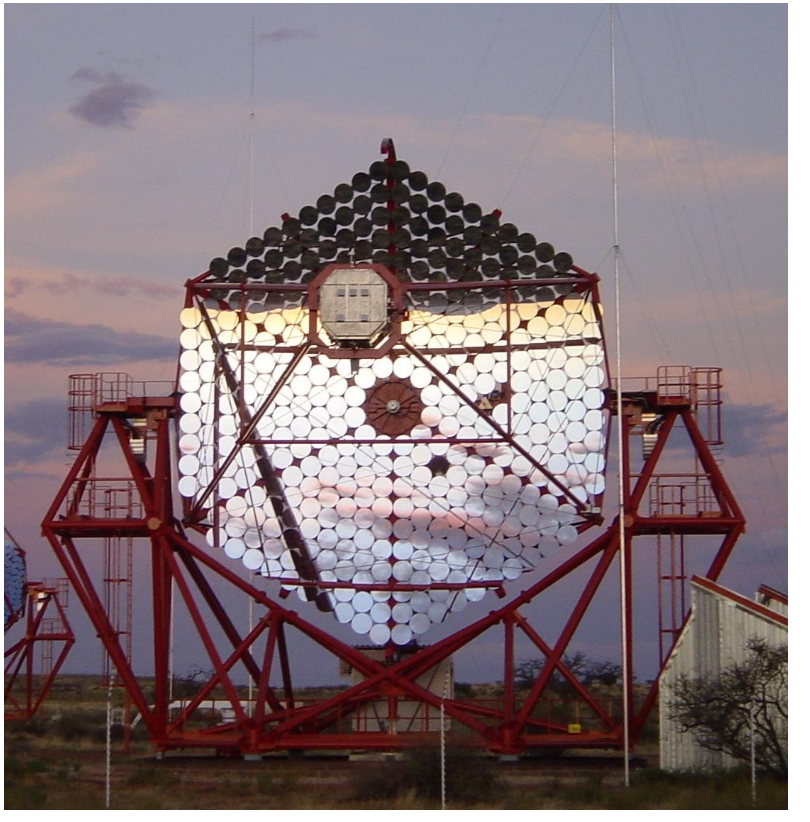


Stereoscopic Cherenkov imaging

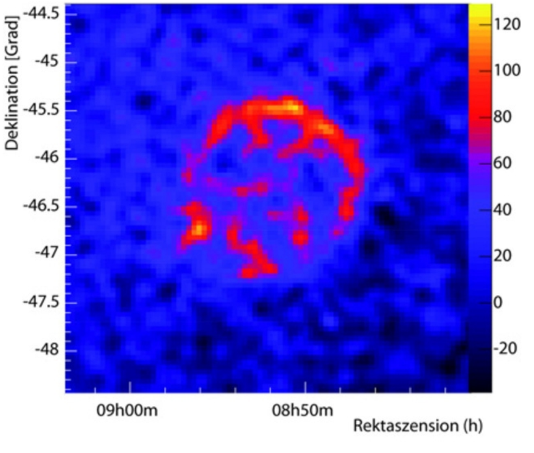


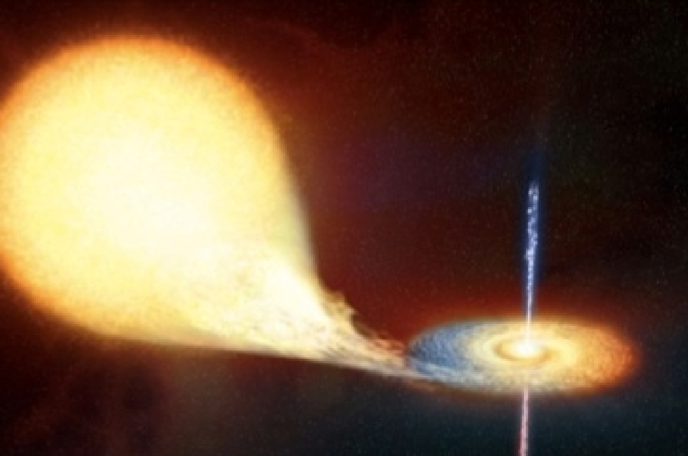
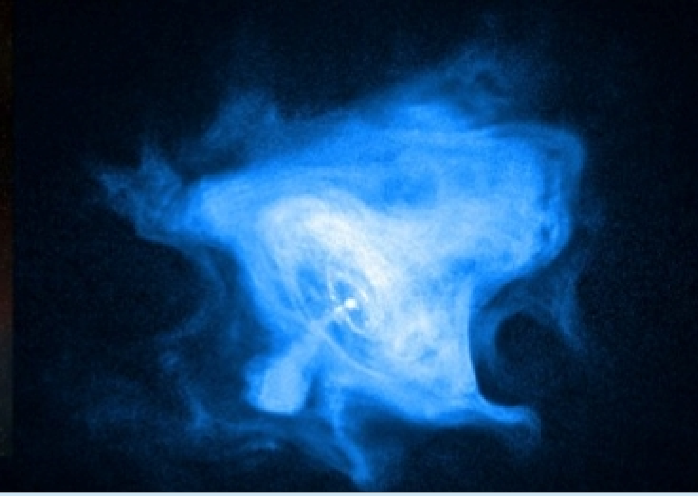
Imaging Cherenkov Astronomy

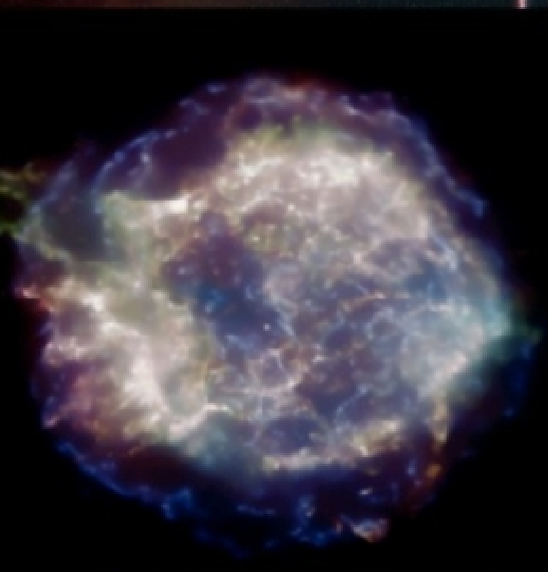
Sample camera pixels;
Identify shower;
Trigger other telescopes;
Record images;
Measure image parameters;
Discriminate photons;
Reconstruct shower
(energy, location, time);
→ Record **one** VHE photon
(every 100 sec)



integrate images:

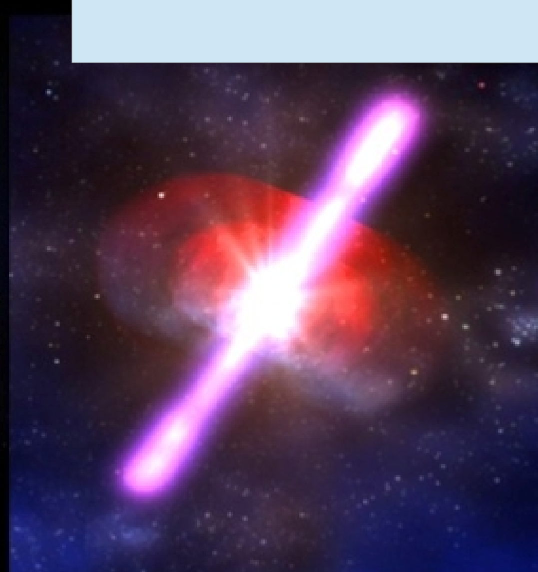


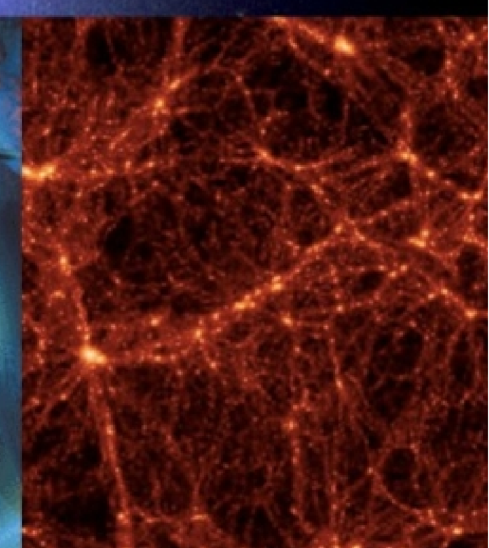





The Non-thermal Universe







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

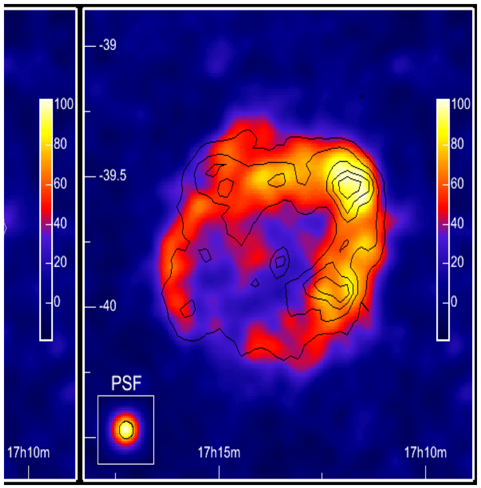
Physics Frontiers – beyond the SM

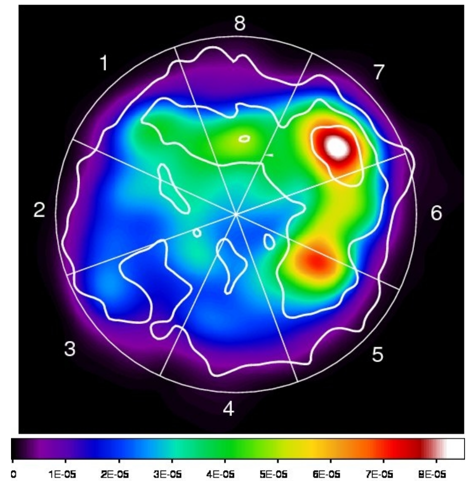
- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?

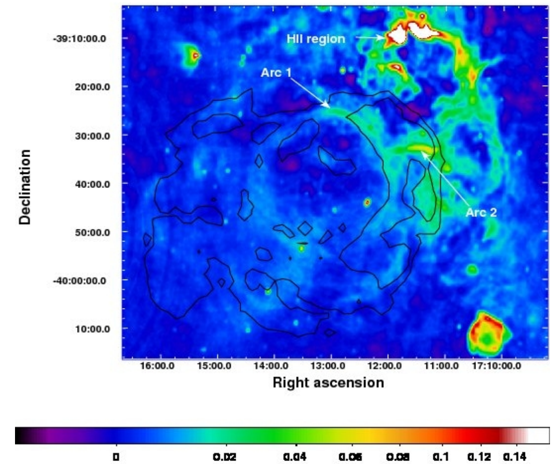
Cosmic Ray Acceleration

- 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?

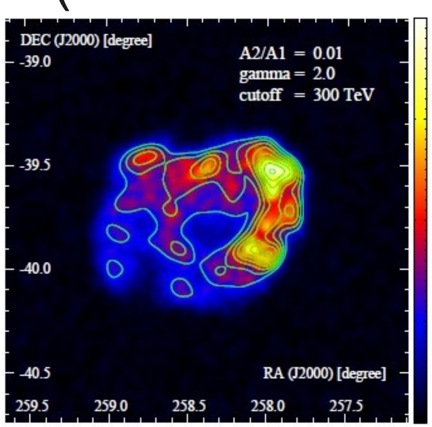
(Shell-type) Supernova Remnants

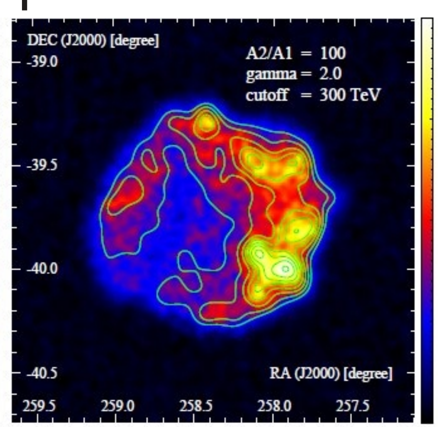


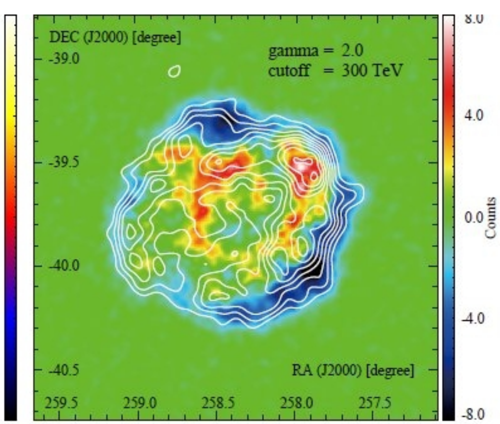




Global SED and close morphological match strongly support a hadronic origin of gamma emission of CR-ISM (pp) interaction.
Alternative leptonic explanation (IC emission) must contribute at some level (which can be quantified with future instrumentation).







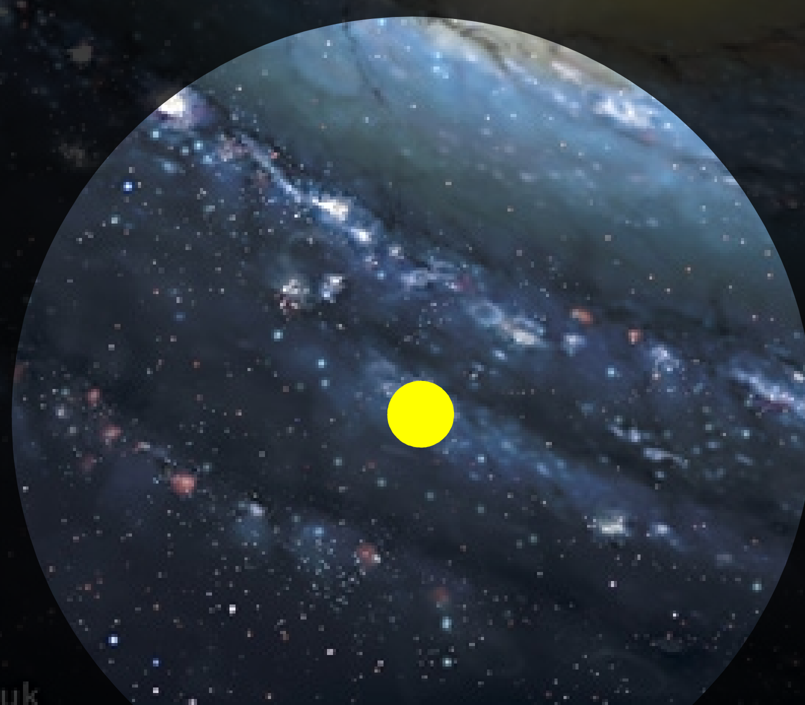
Cosmic Ray Origin

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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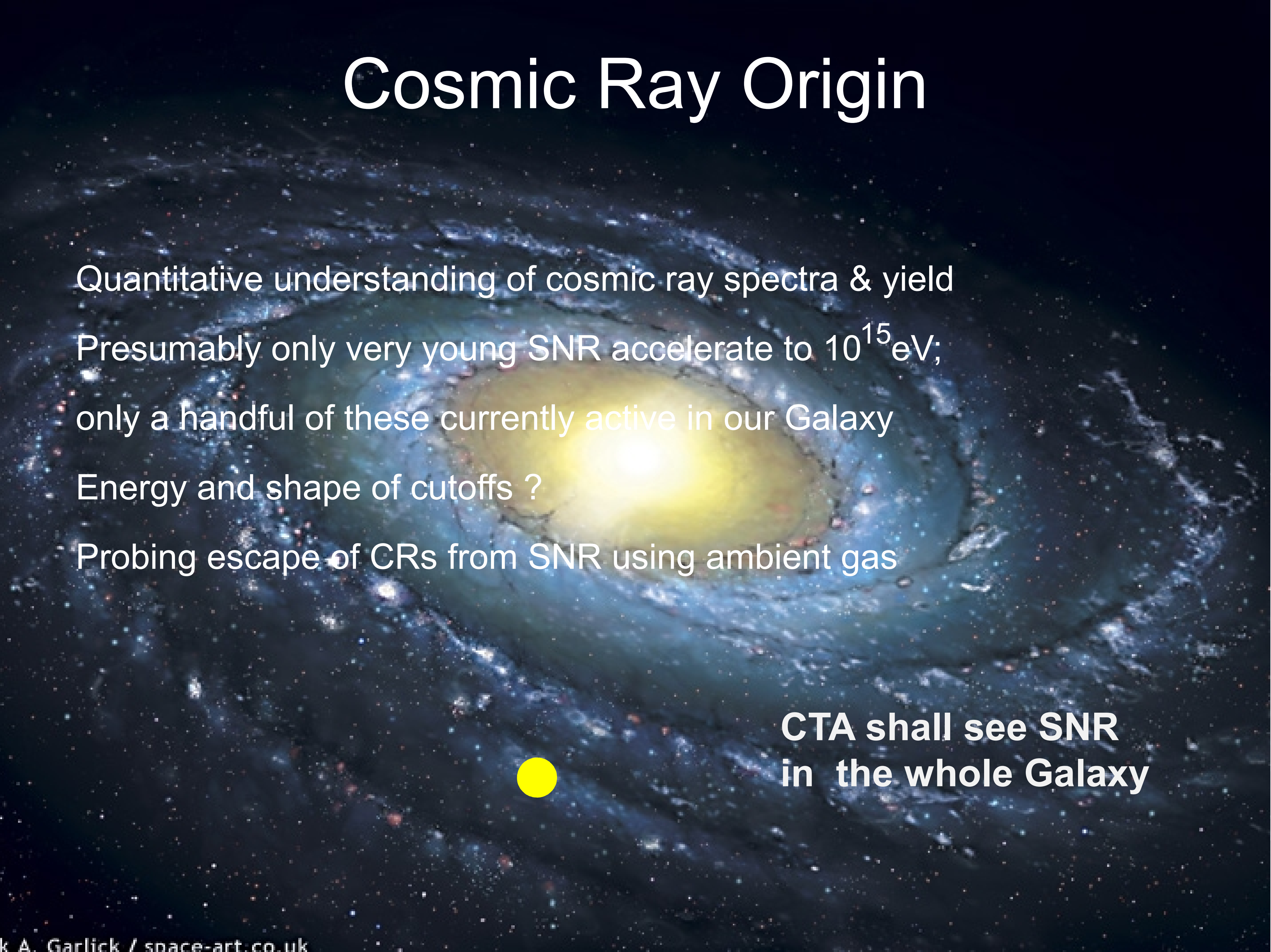
CTA shall see SNR in the whole Galaxy



Tracing Acceleration in the Cosmos

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

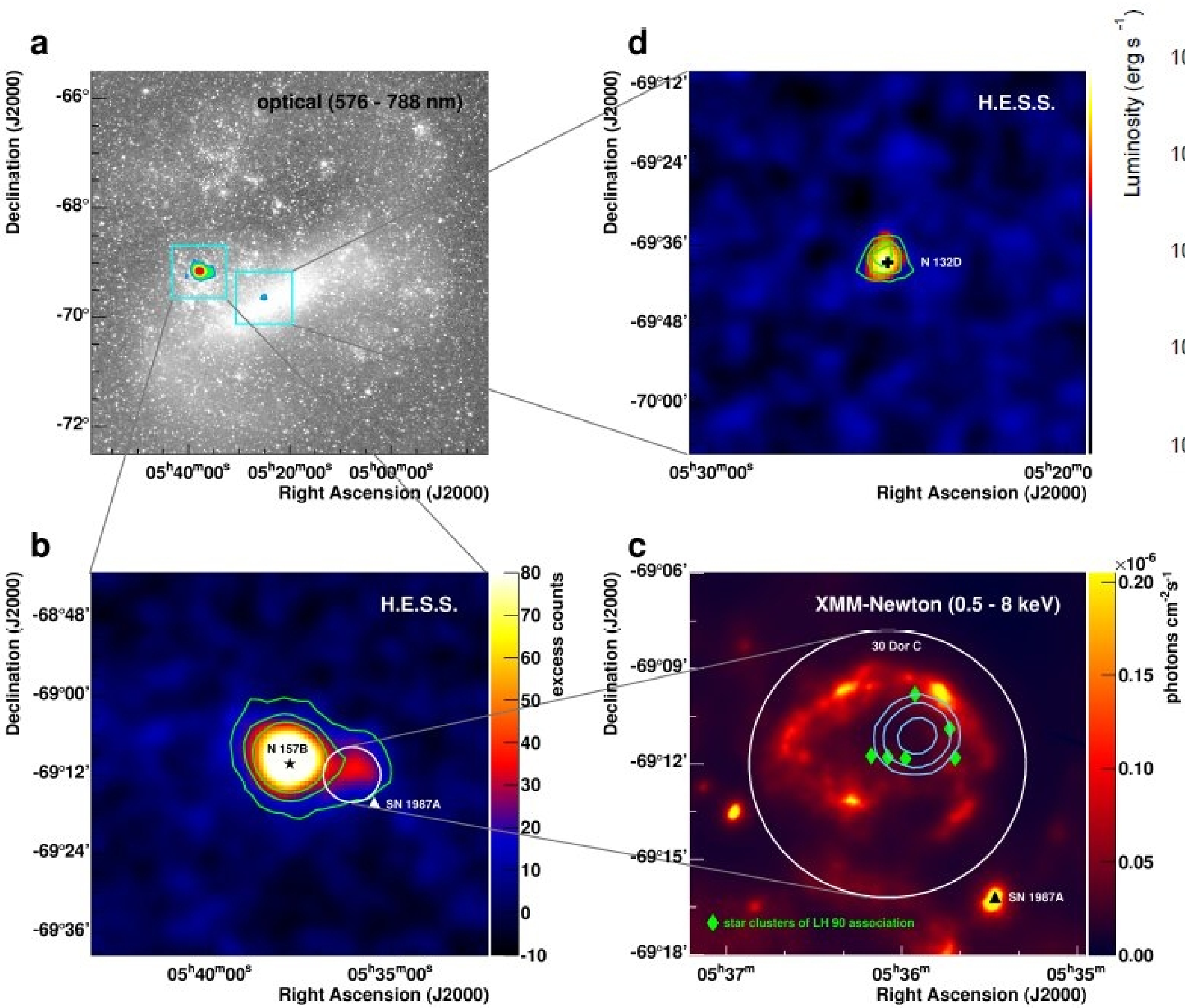
Nearby Galaxies – individual sources (other environments)

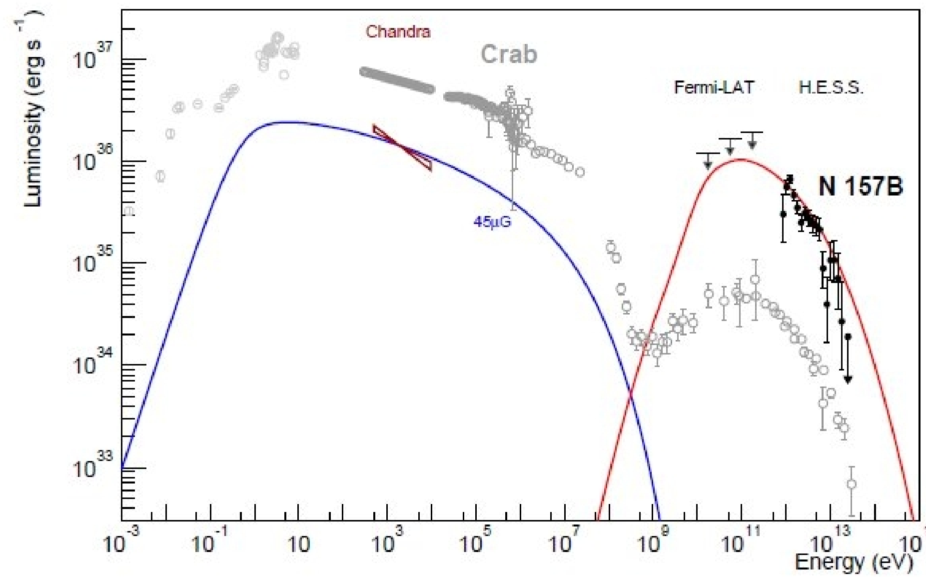
Starburst-Galaxies (effects on galaxy evolution?)

→ NGC 253, M82

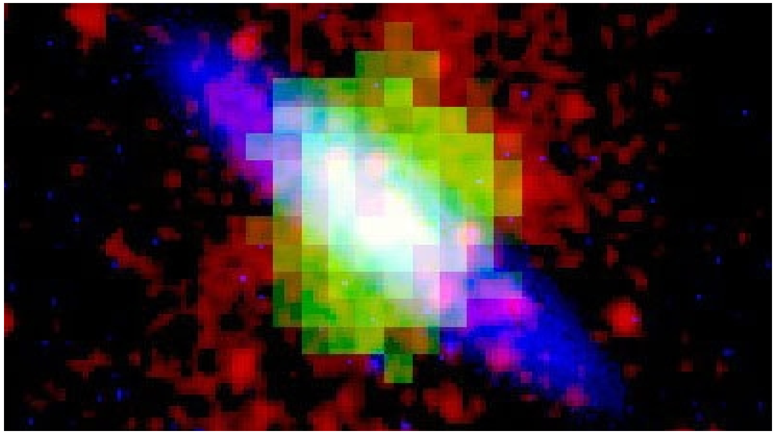
Shocks on larger scales (groups/clusters) ?

Tracing Acceleration in the Cosmos





NGC 253



Tracing Acceleration in the Cosmos

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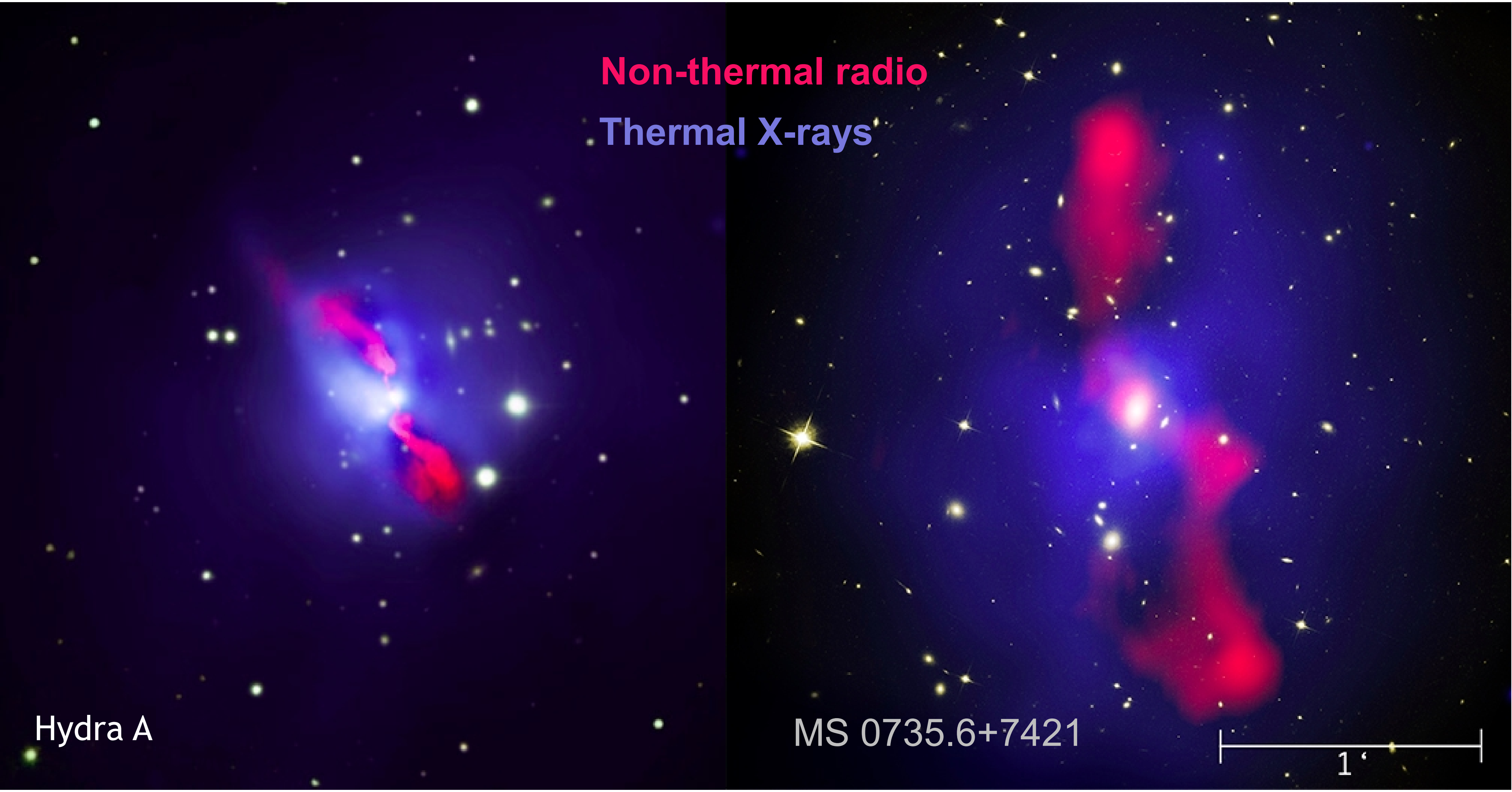
Nearby Galaxies – individual sources (other environments)
→ LMC (H.E.S.S. Collaboration, ***Science***, 22Jan2015)

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

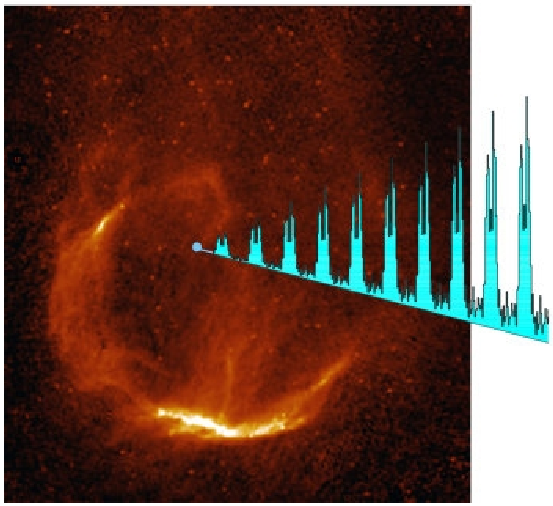
- **Processes in relativistic jets, winds and explosions?**

  - GRBs
  - AGN jets
  - Shocks

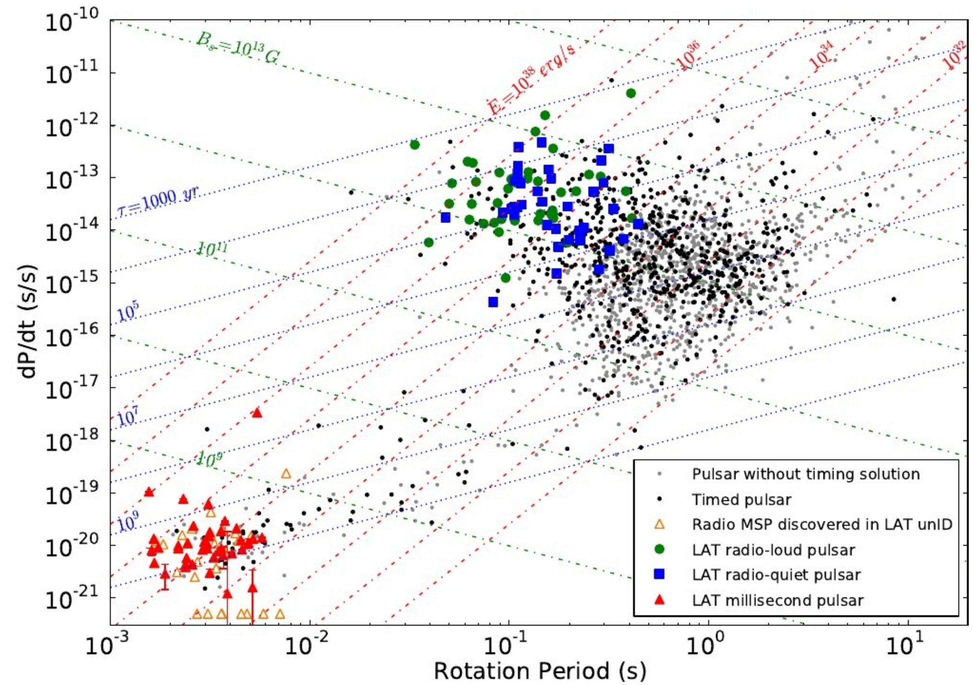
- **Exploring cosmic voids**

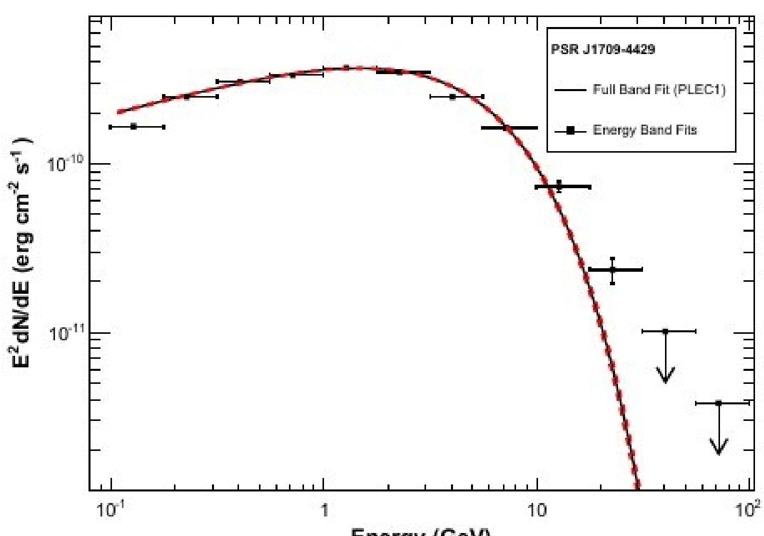
  - Contents
  - Evolution

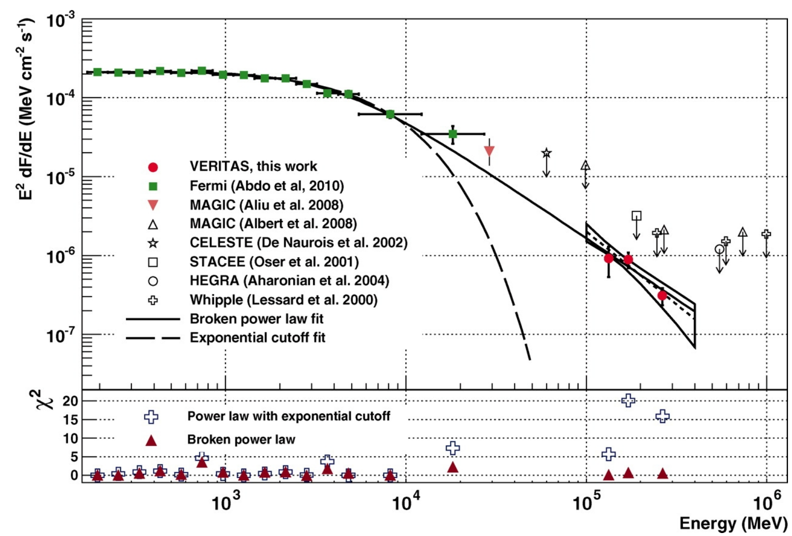
The stellar remnants



Fermi-LAT 2nd Pulsar catalog

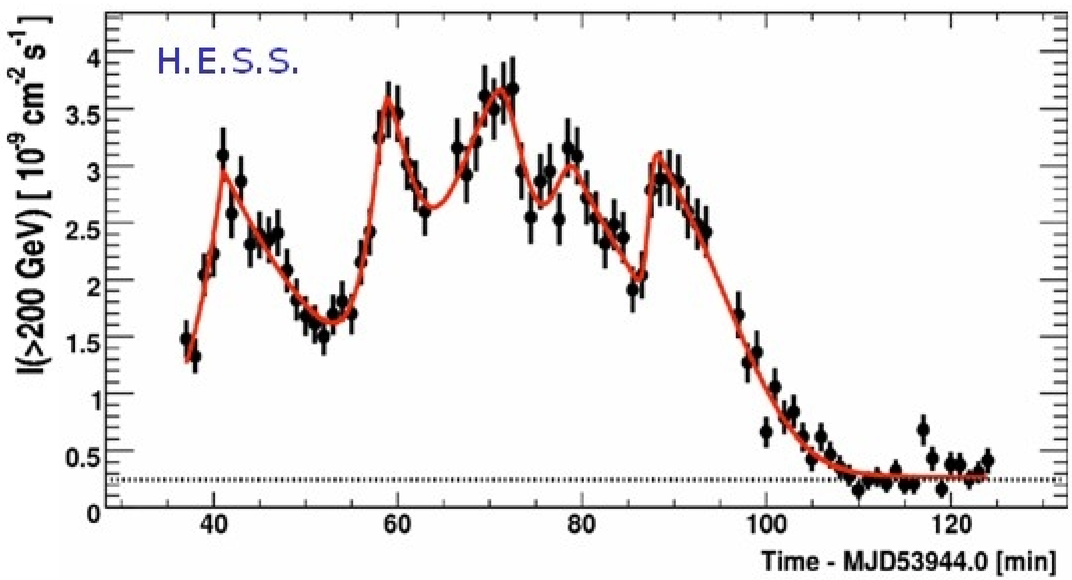






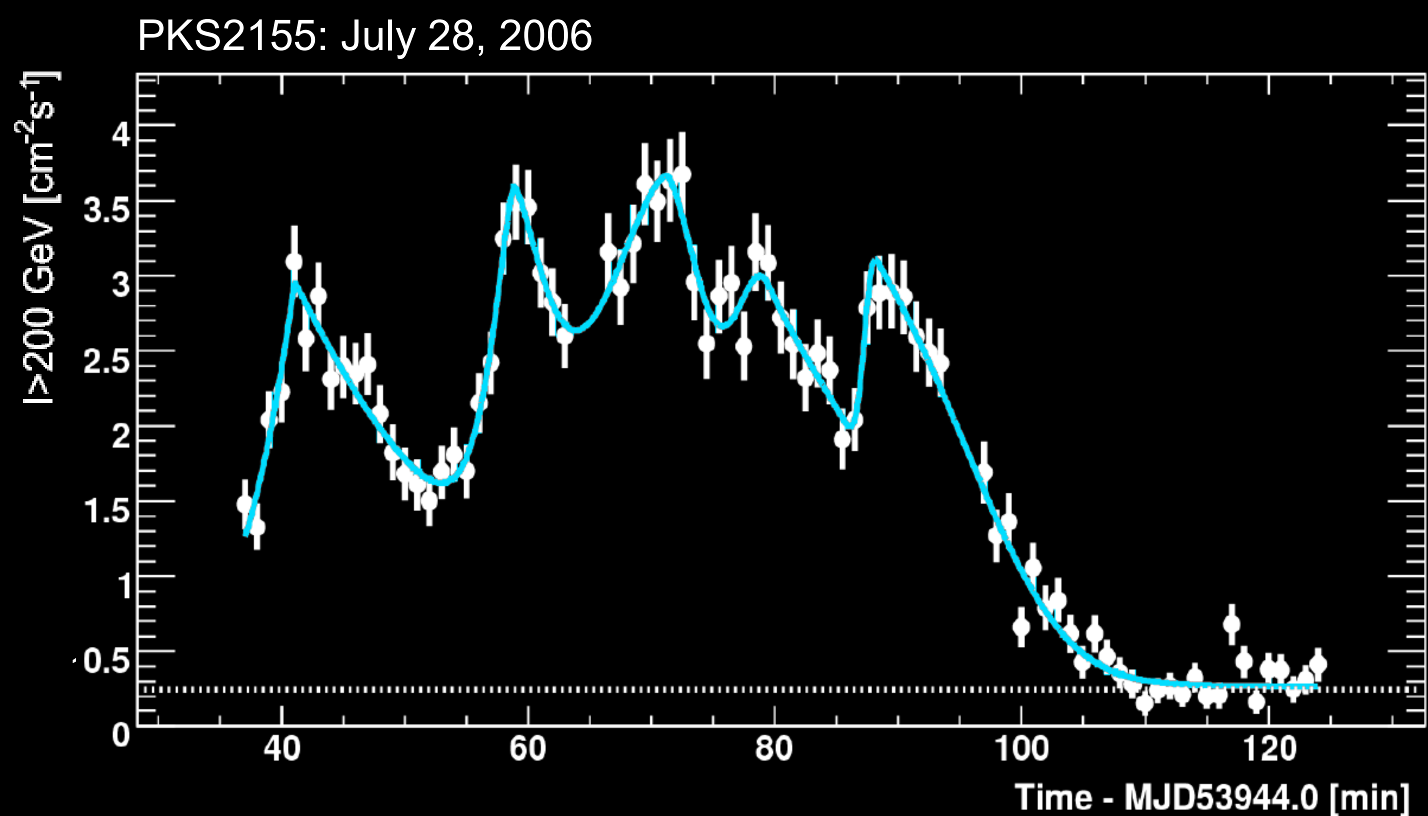
“Persistent GRBs”

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

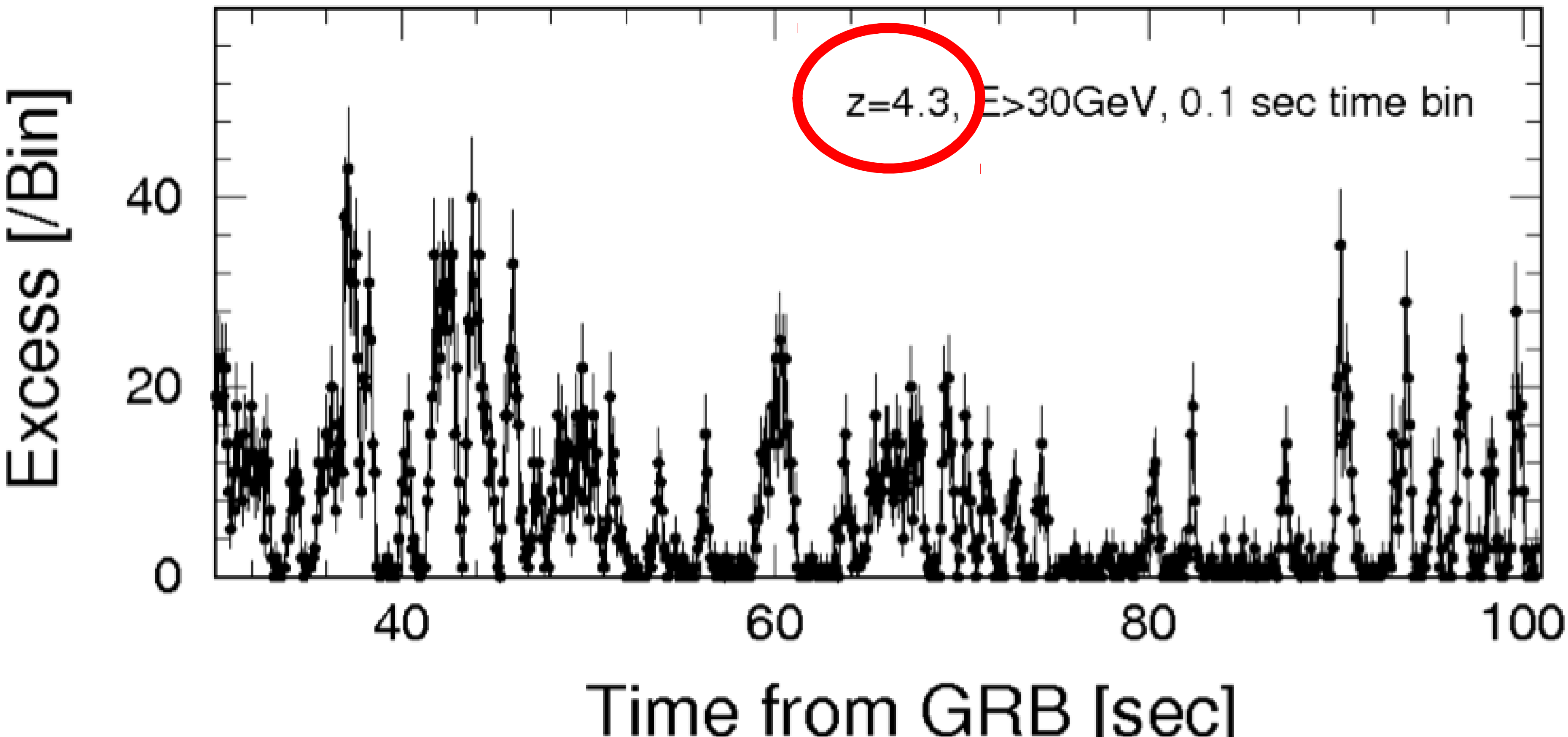
→ Doppler factors > 100 near SMBH

→ 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.

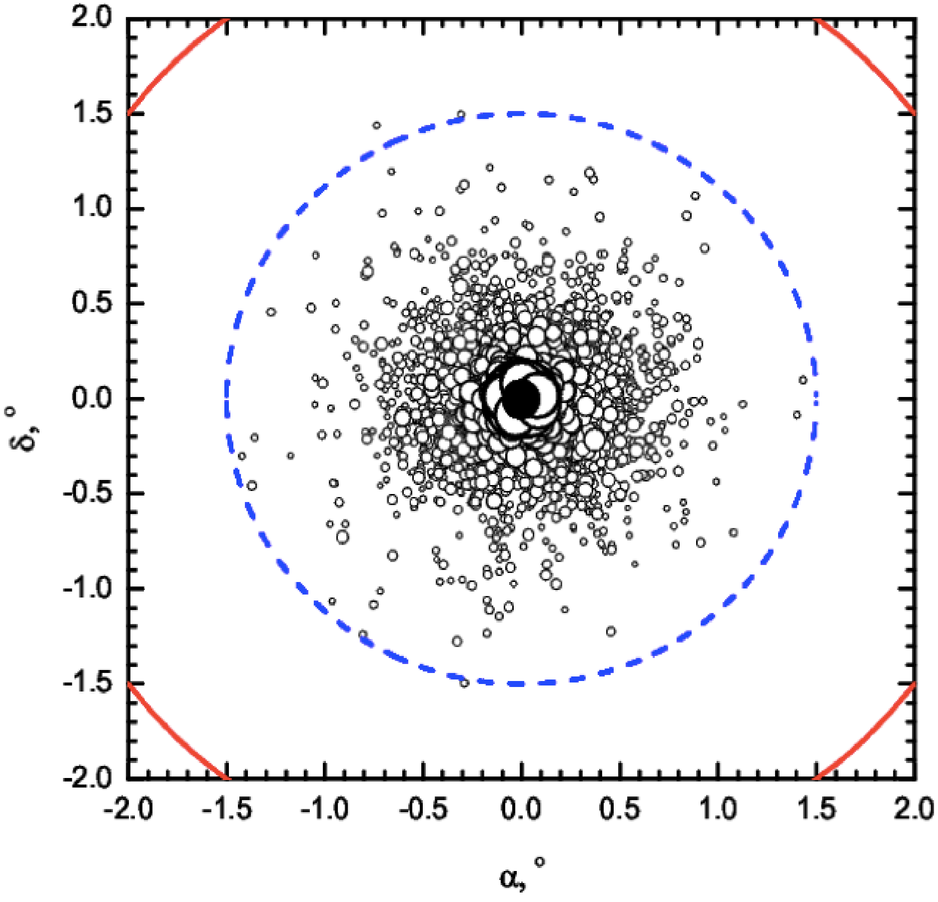
Do gamma-ray blazars impact voids?

Intergalactic Magnetic Fields

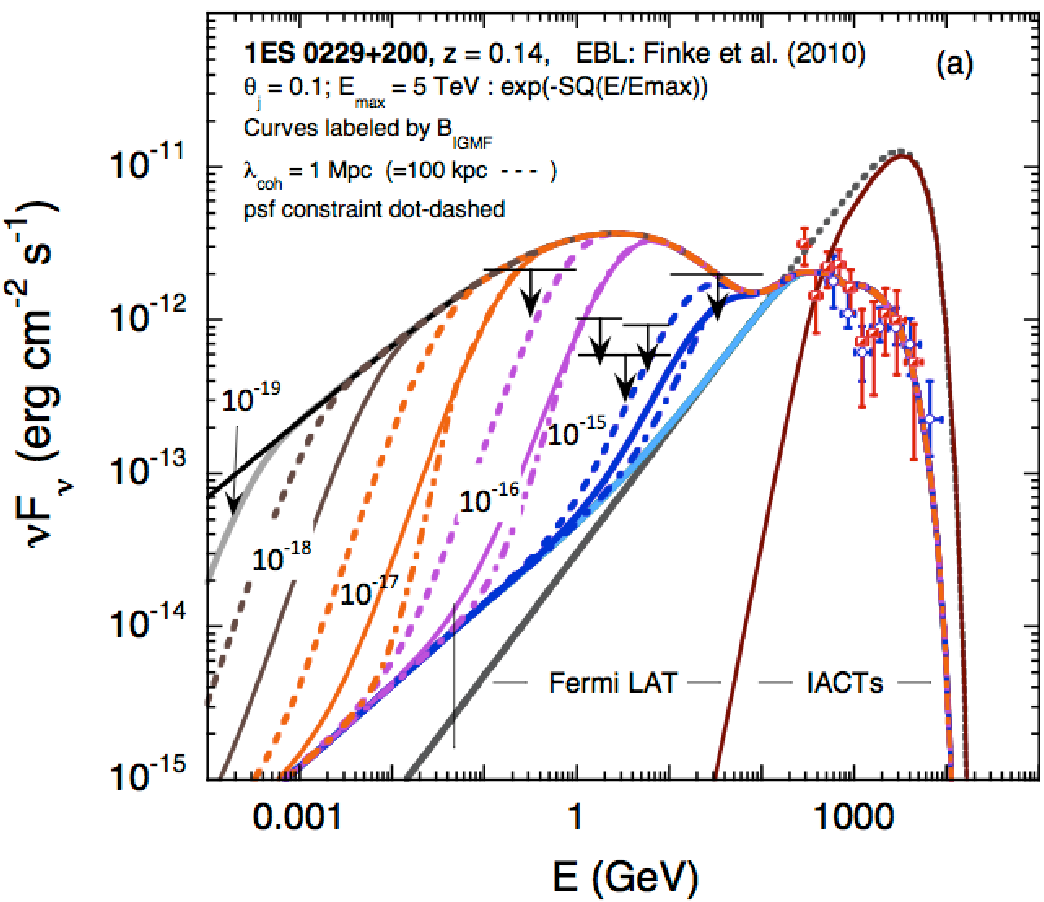
Imaging: Fields above 10^{-12}G give rise to detectable pair halos

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

Sol et al., arXiv:1304.3024

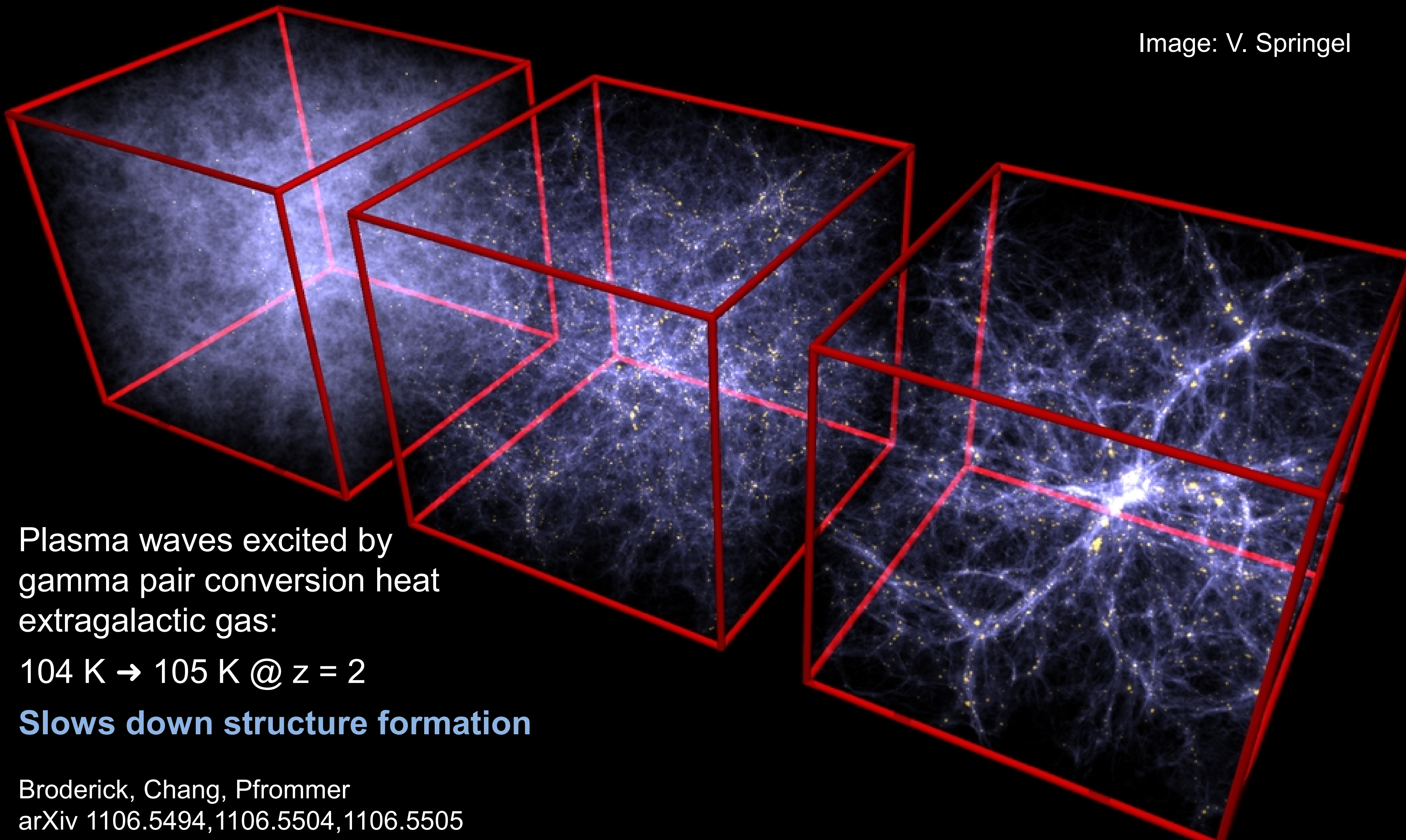


Dermer et al., arXiv:1011.6660



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

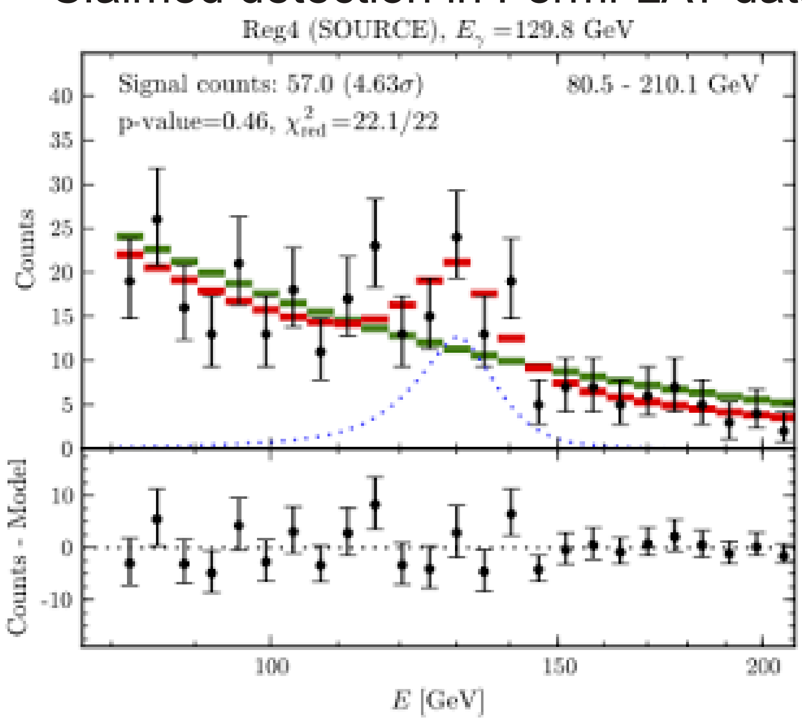
DM annihilation produced gamma-ray continuum and possibly lines

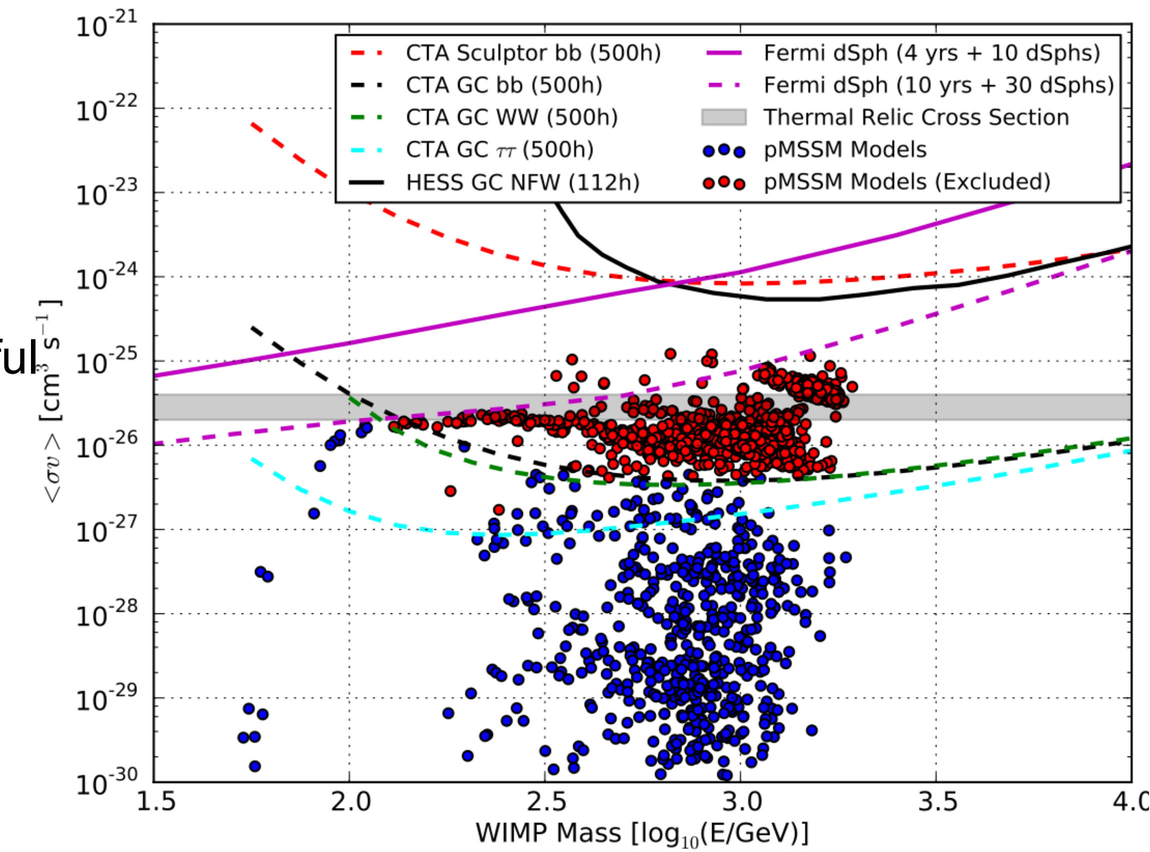
→ mass of DM particle

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

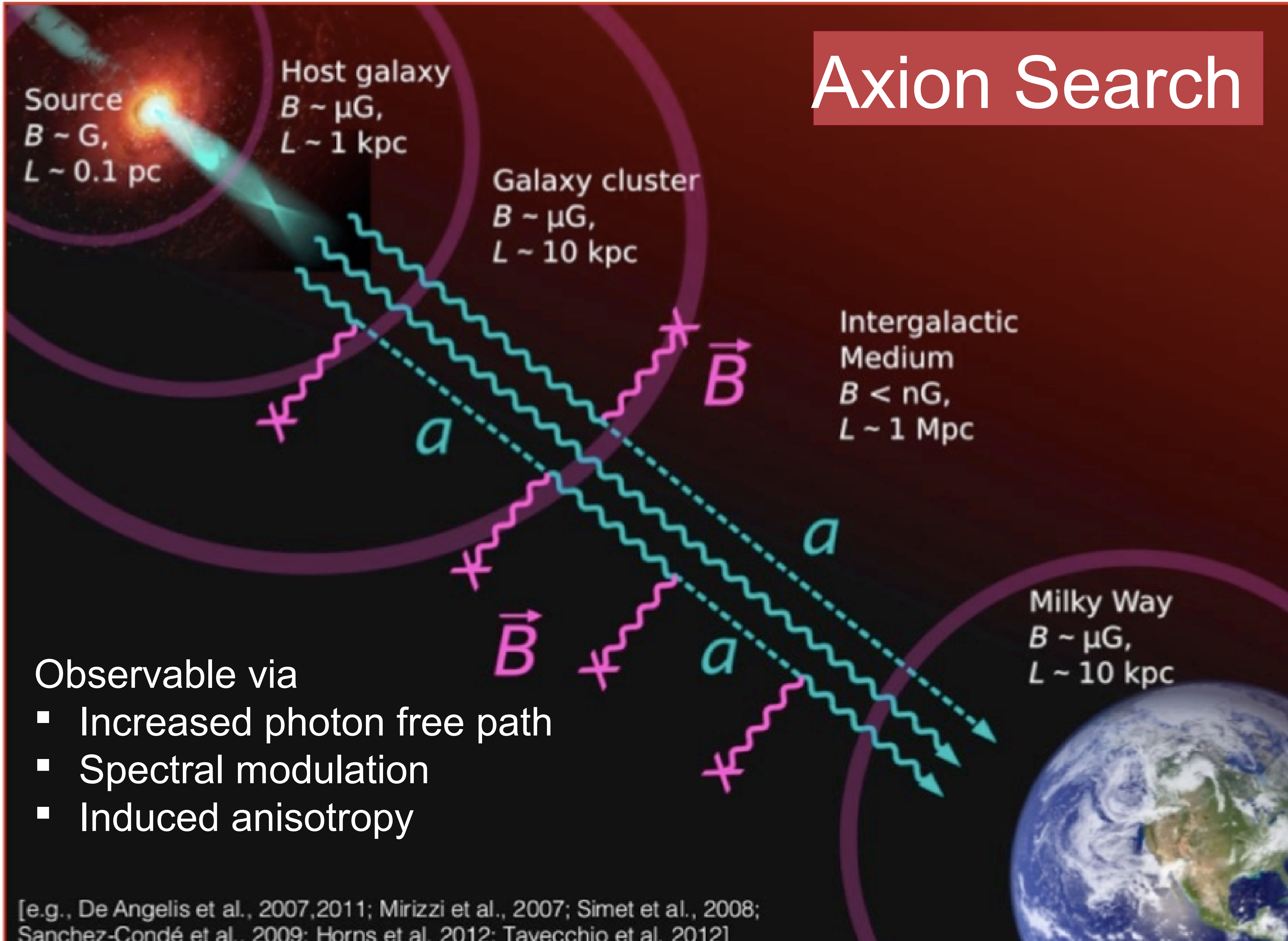




Complementarity between
CTA
Direct detection
LHC

M. Wood et al.
arXiv 1305.0302

Axion Search

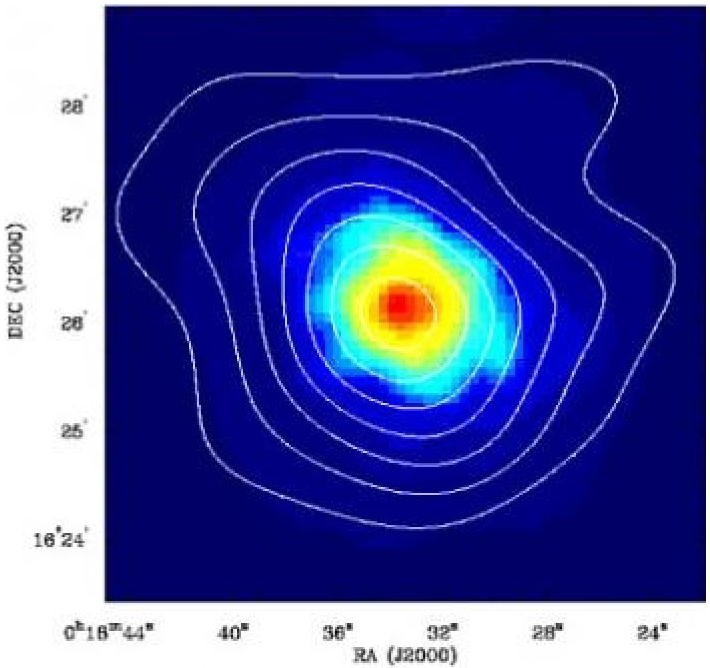


Observable via

- 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]

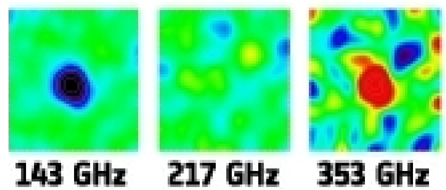
Sunyaev-Zel'dovich effect

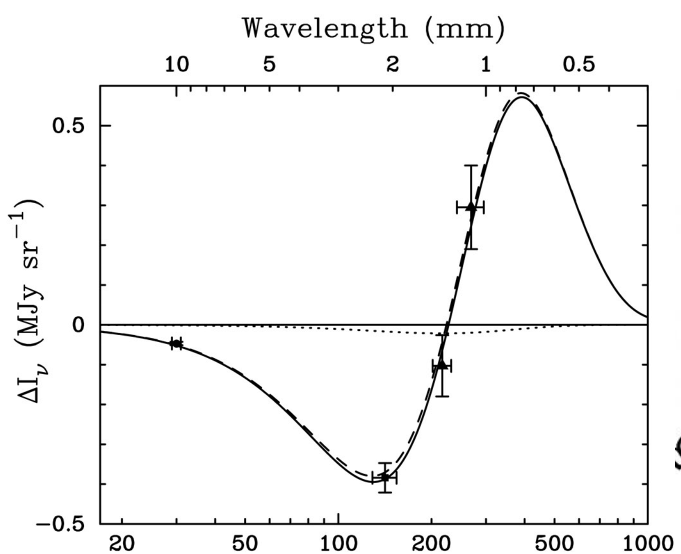


Low energies

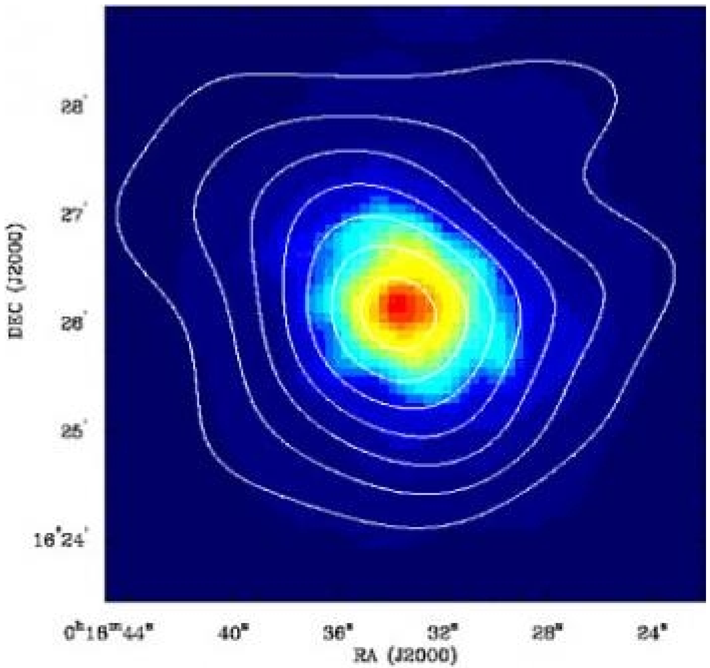
vs

High energies





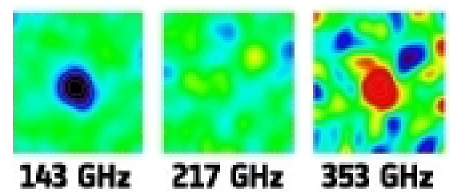
Sunyaev-Zel'dovich effect

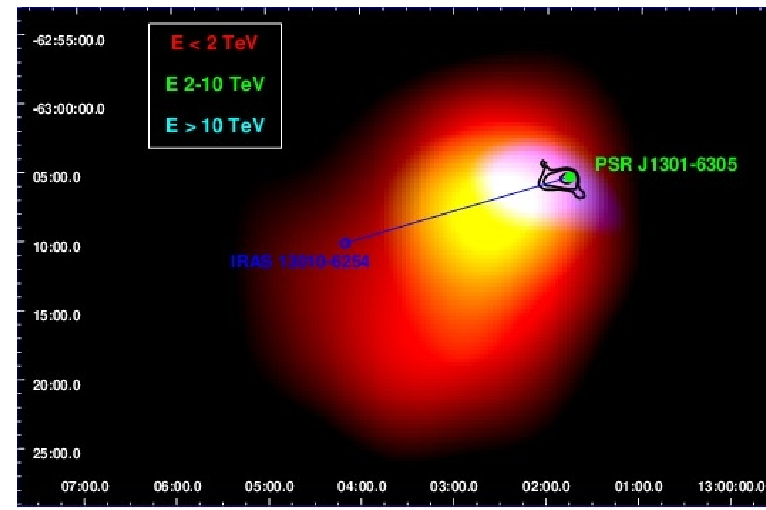


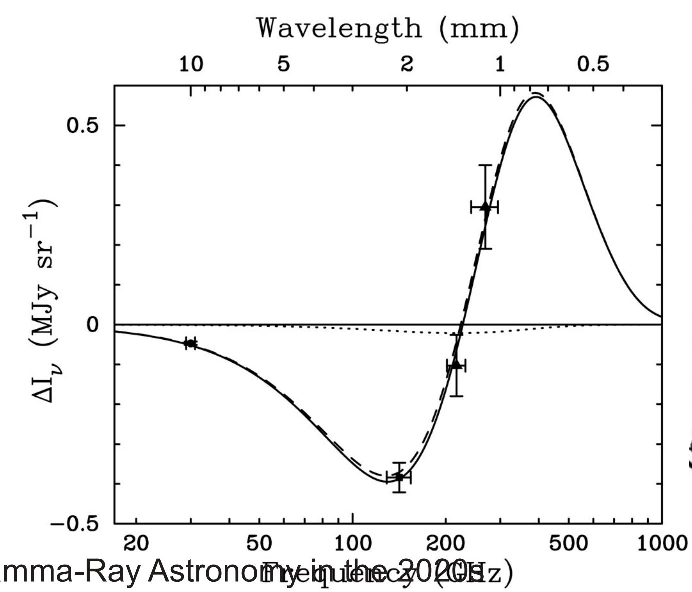
Low energies

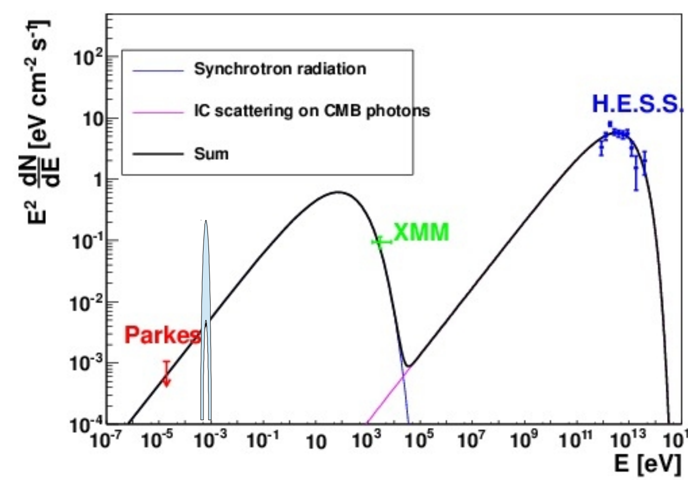
vs

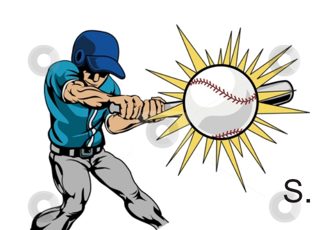
High energies



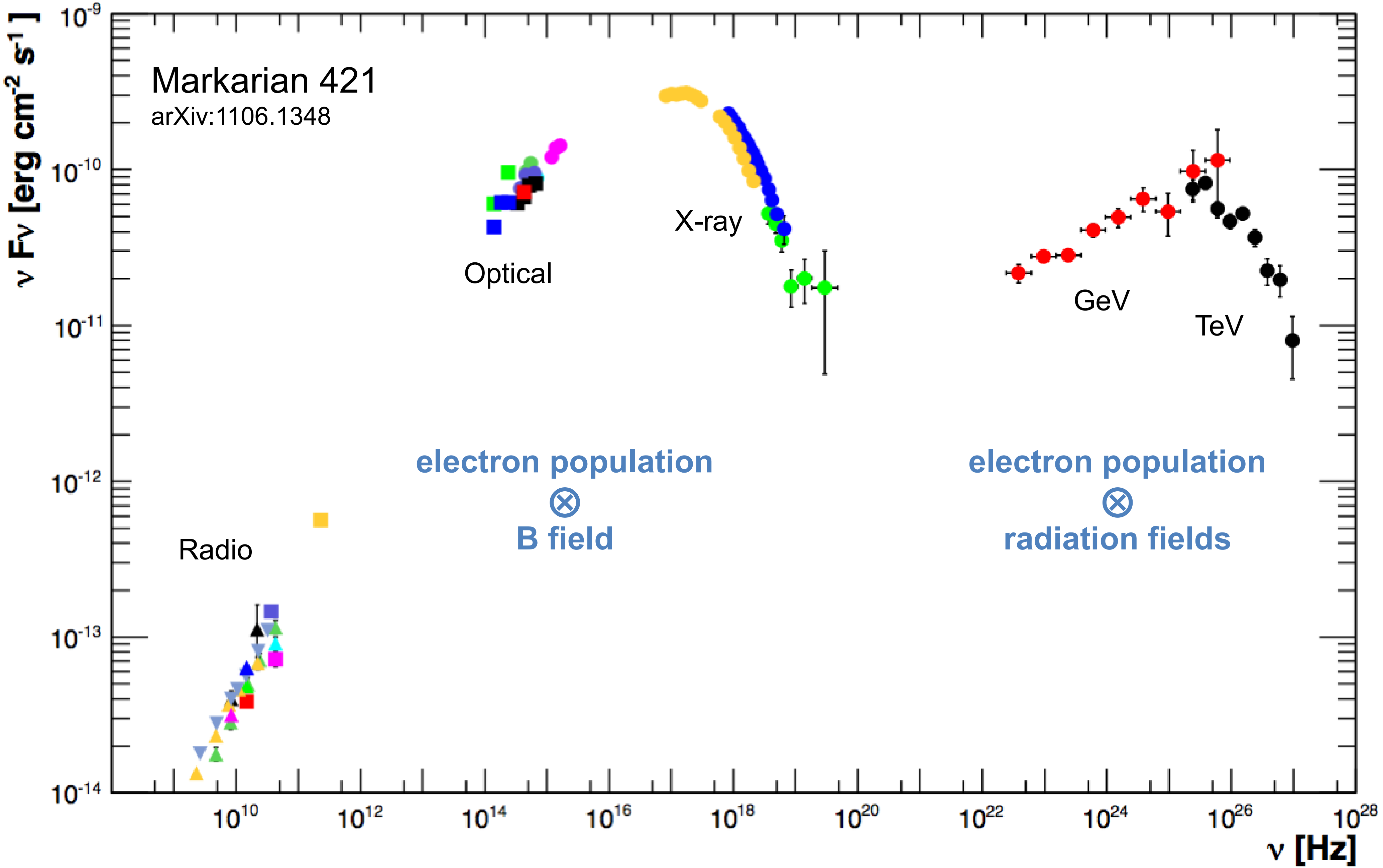








Multiwavelength aspects



Multiwavelength aspects

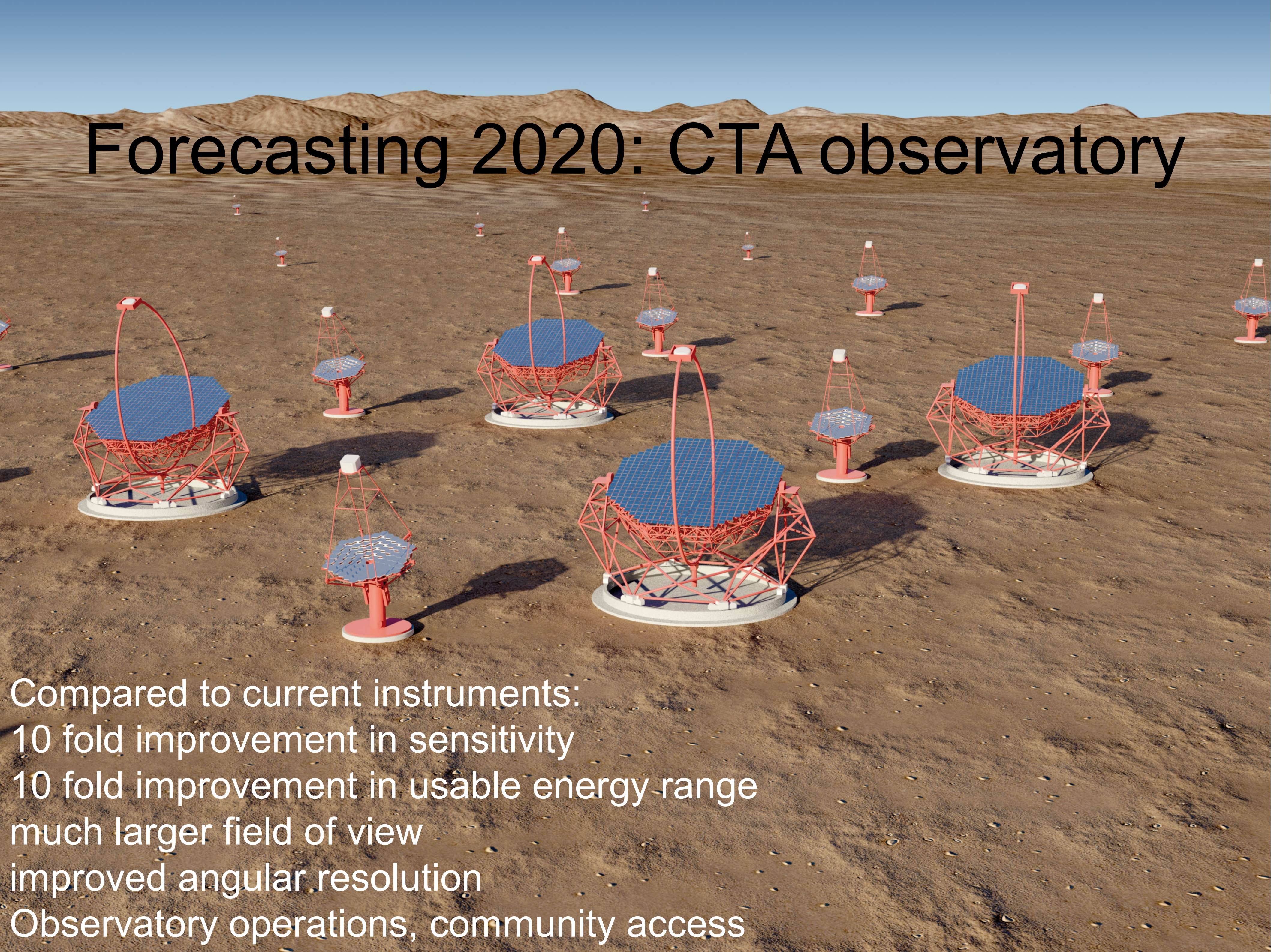
Gamma-ray studies provide new information about old friends. They provide measurements of otherwise inferred quantities.
Gamma-rays provide new probes of processes and interactions.

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

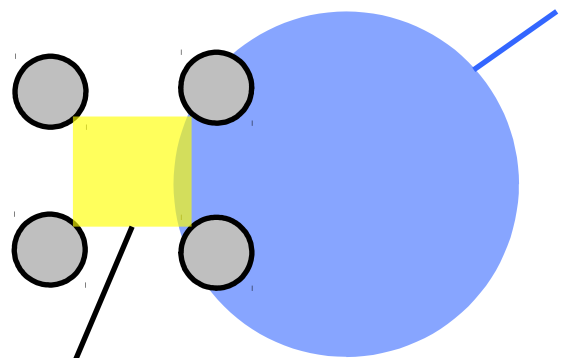
10 fold improvement in usable energy range

much larger field of view

improved angular resolution

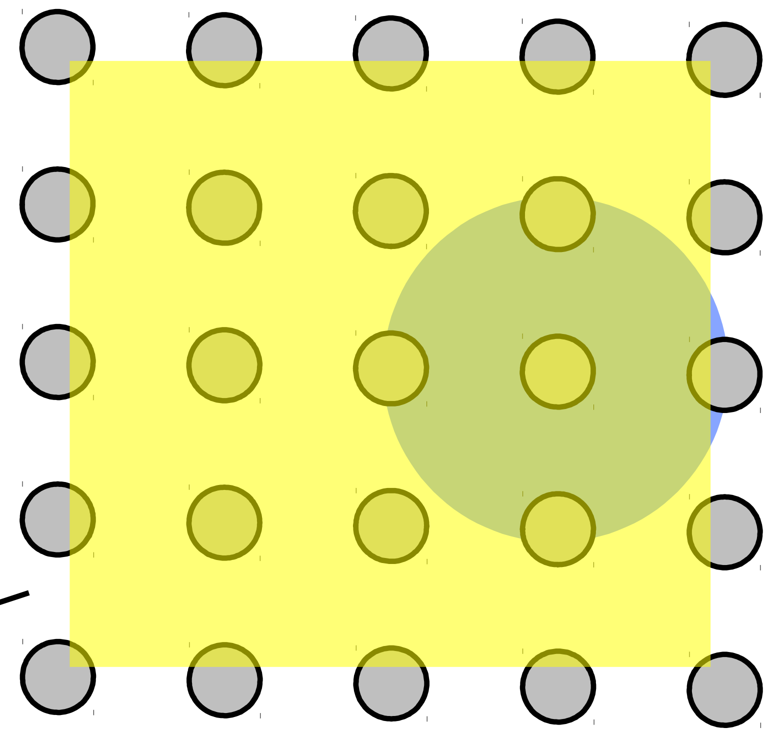
Observatory operations, community access

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!

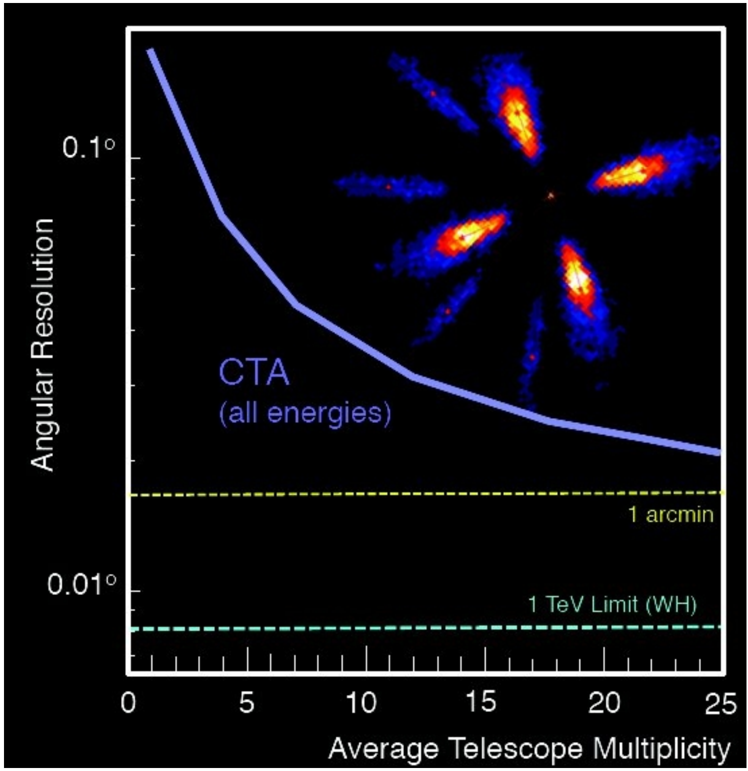


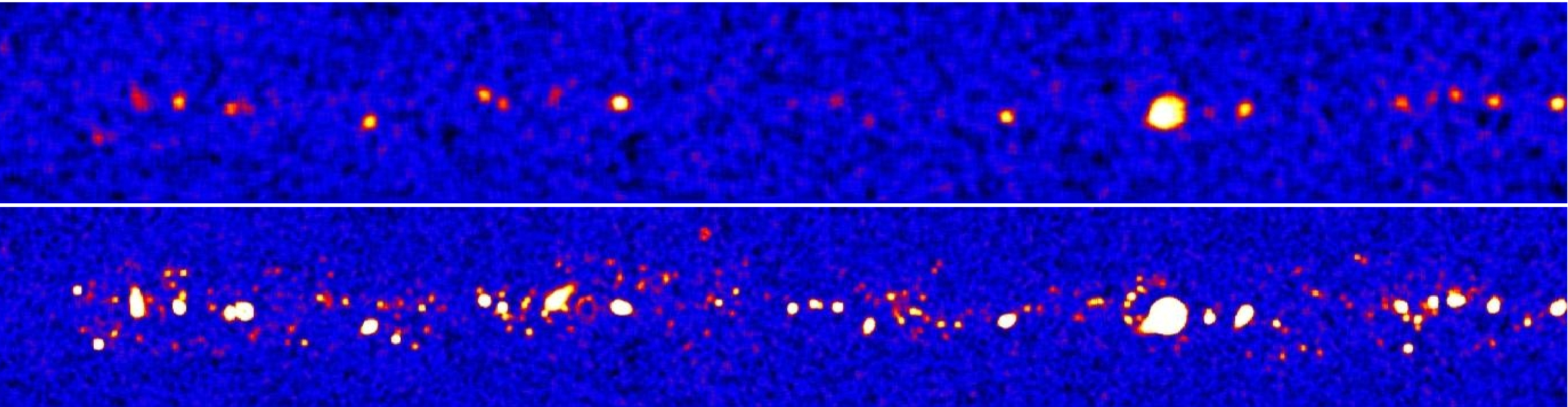
large detection area
more images per shower
lower trigger threshold

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)

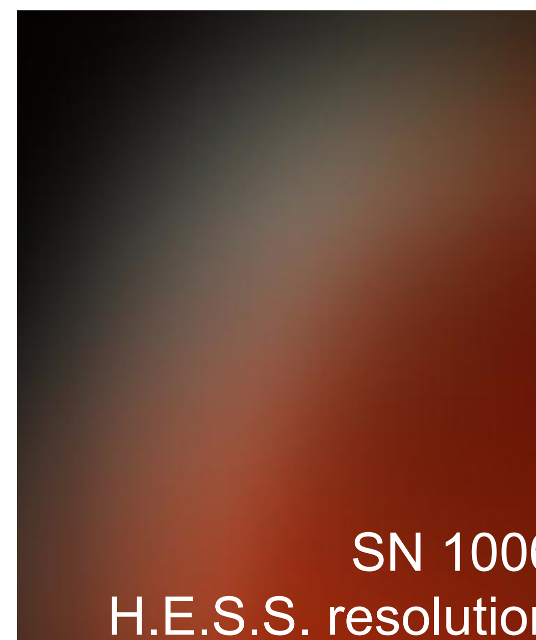




Resolving complex sources

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

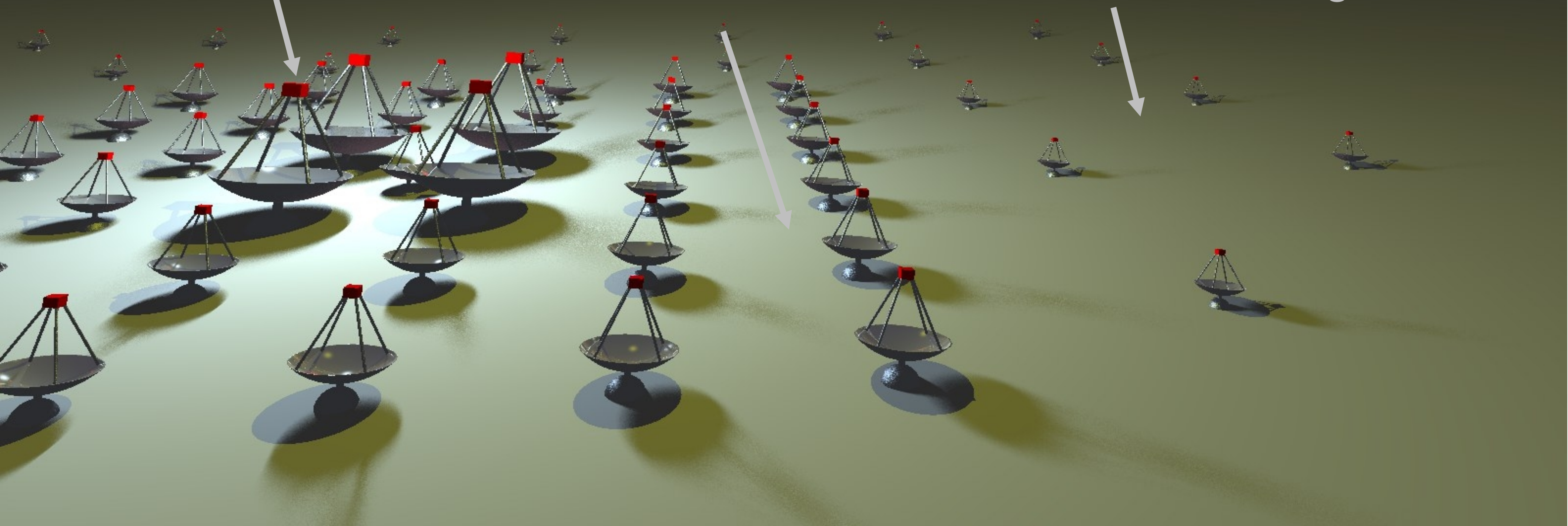
energy threshold of some 10 GeV

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

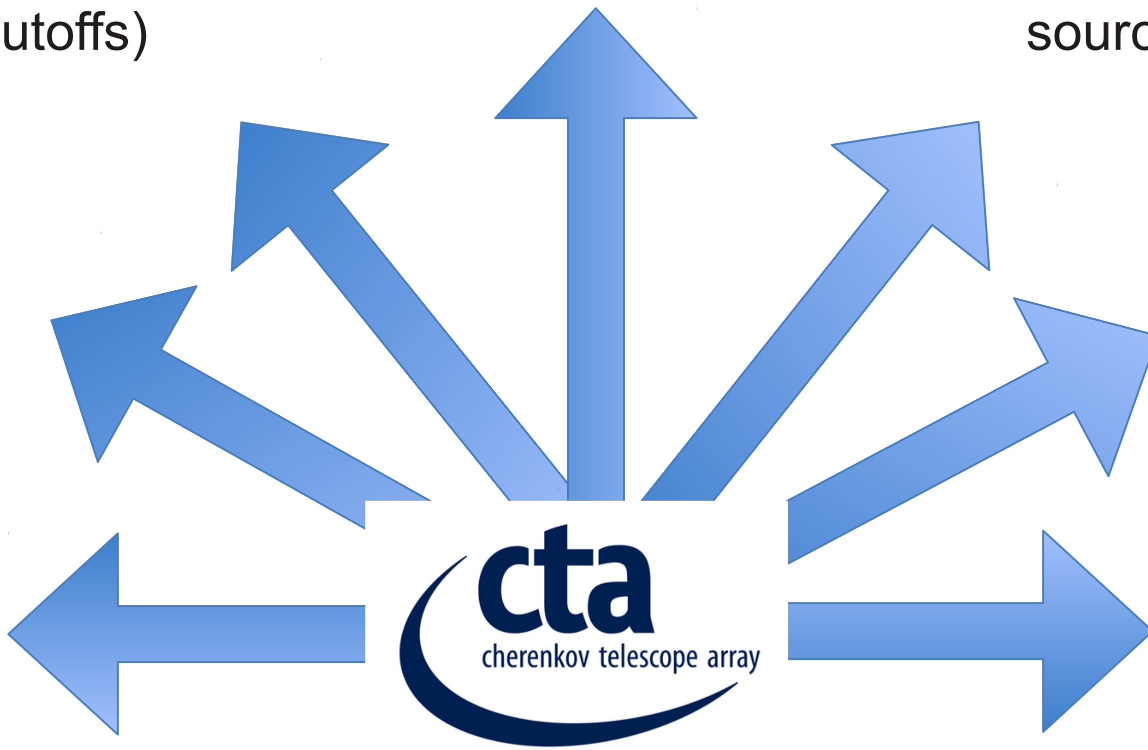
10 x Sensitivity
and collection area
(nearly every topic)

Good energy
resolution of ~10%
(lines, cutoffs)

Large field of view of 8o
(surveys, extended
sources, flares)

Rapid slewing
(20 s)
to catch flares

Improved angular
resolution of few ’
(source
morphology)



Energy coverage
down to 20 GeV
(AGN, cosmology)

Energy coverage
up to 300 TeV
(Pevatrons)

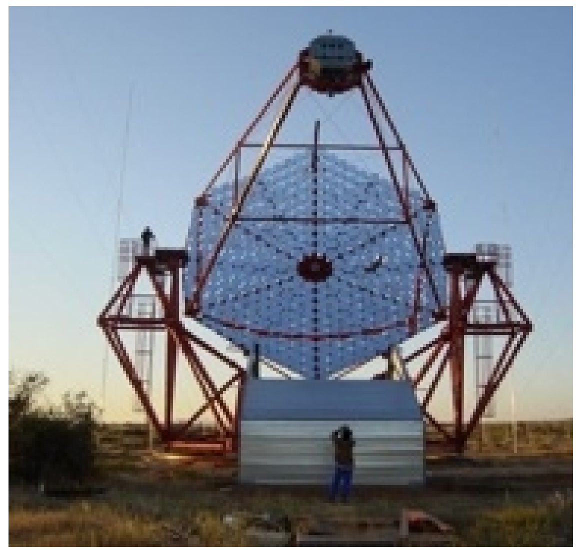
Comparison of Gamma Detectors

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

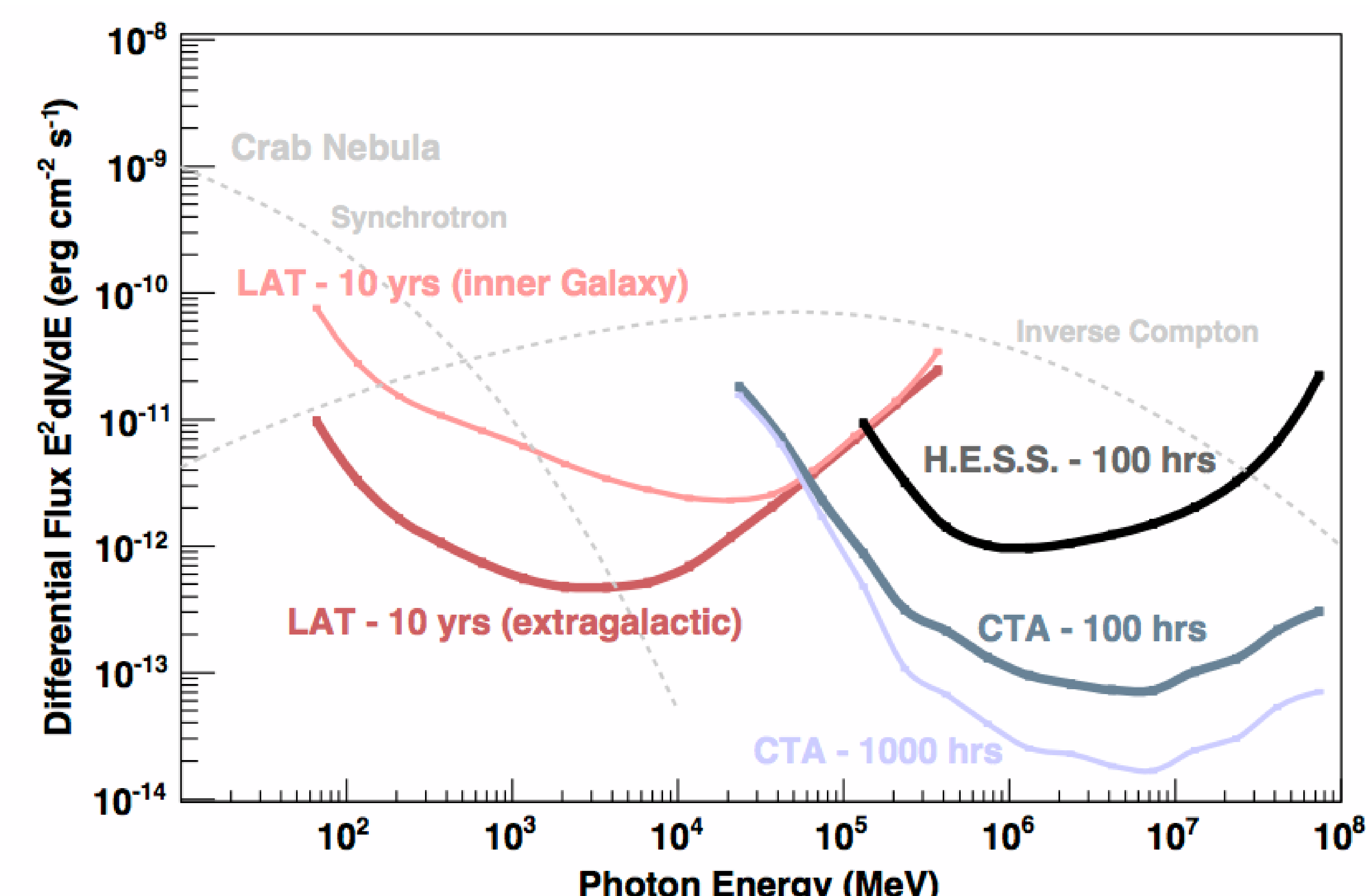
High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky at a time

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

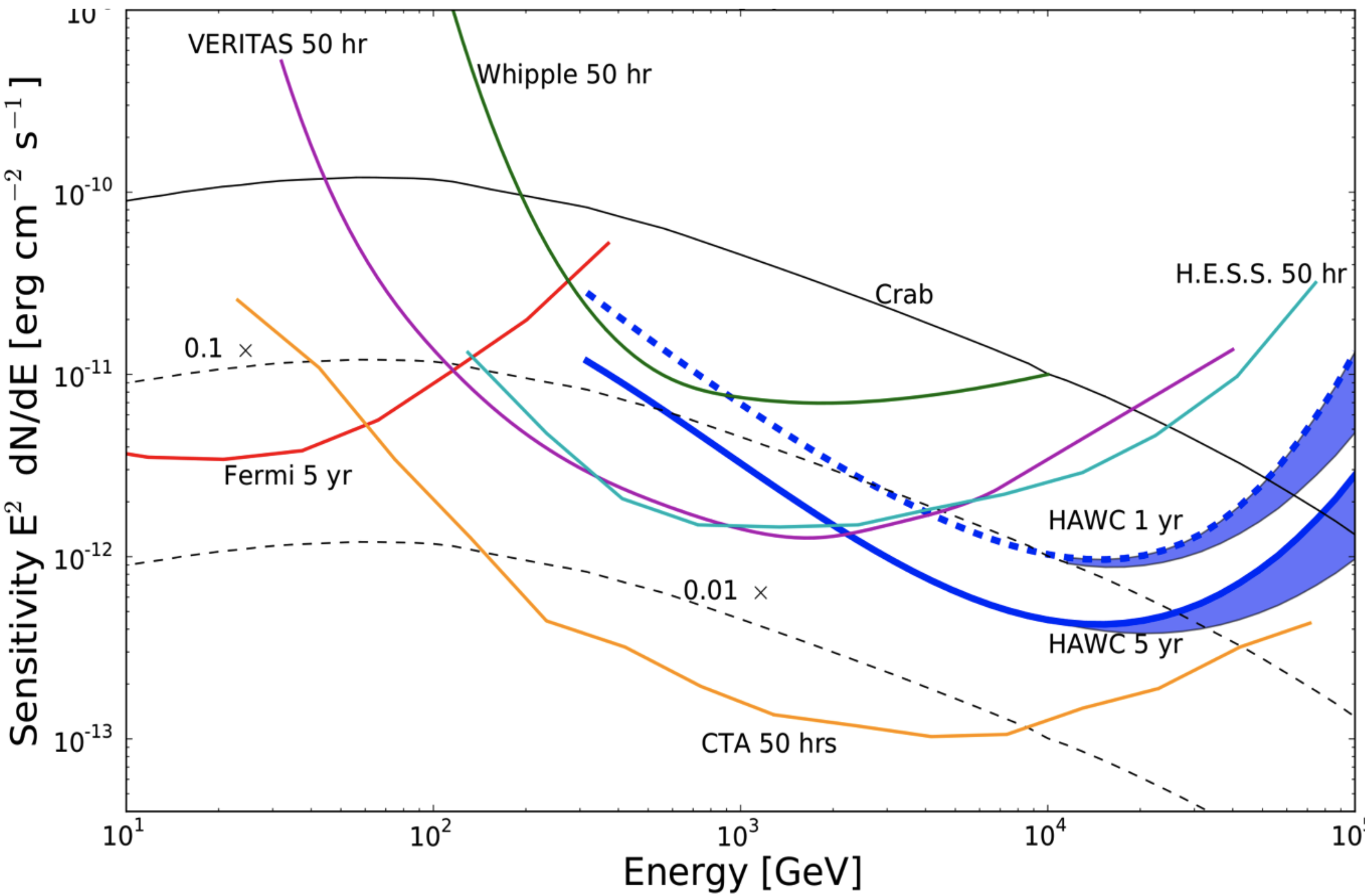
Moderate Area
Good Background Rejection
Large Duty Cycle/Large Aperture

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

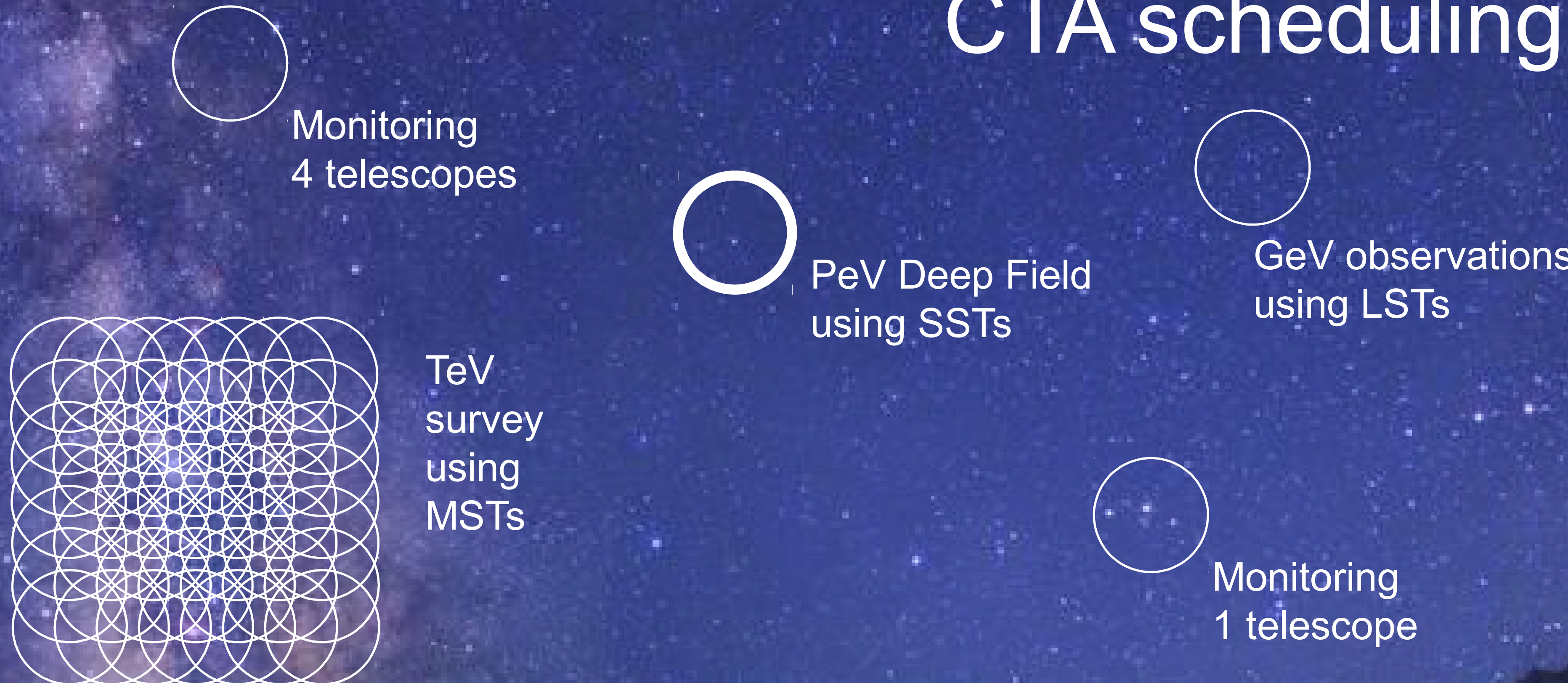
Differential Flux Sensitivity I



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.