Gamma-rays / CTA

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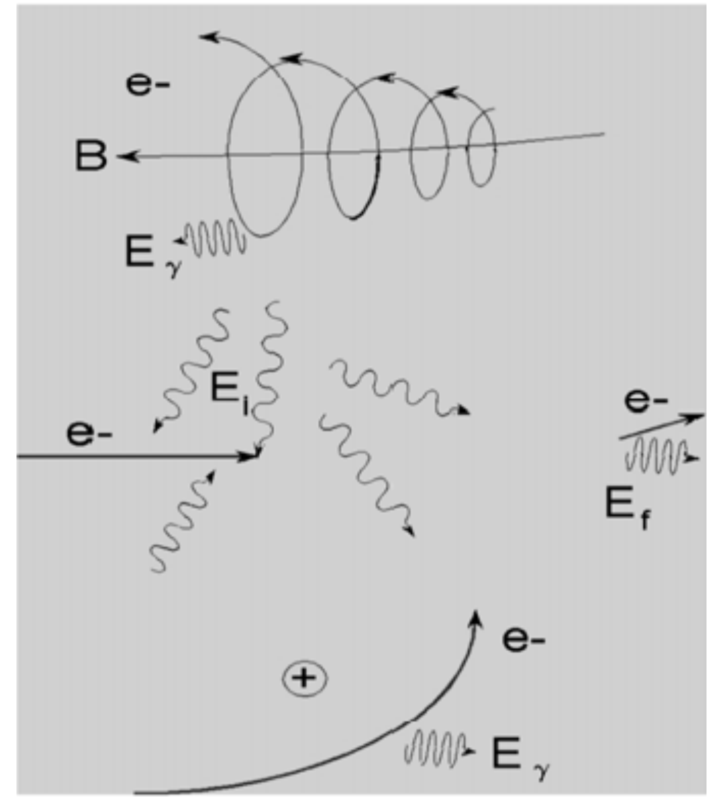
Outline

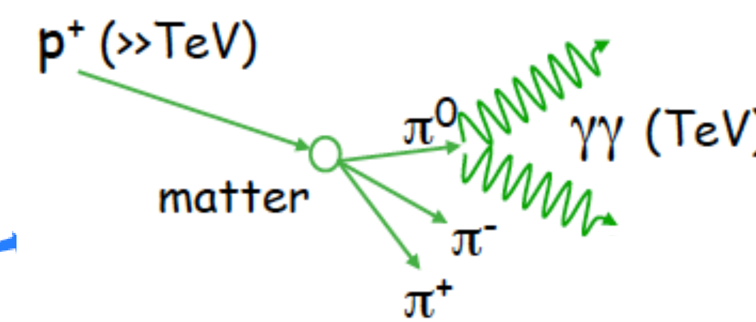
- Gamma rays in the Universe
- CTA
- CTA Core Science Program
  - Fundamental Physics
  - Galactic [Astro-]Physics
  - Extragalactic [Astro-]Physics
- Conclusions

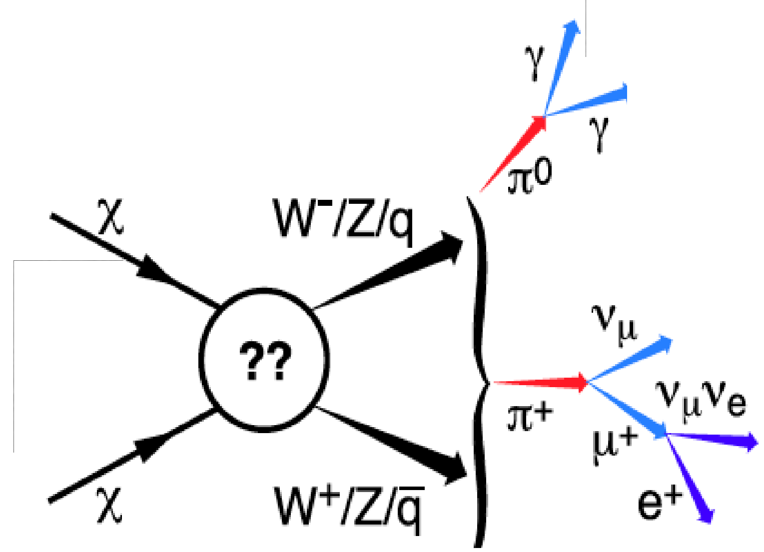
Gamma Rays in the Universe

Gamma-ray production mechanisms

- **By accelerated leptons**
  - Synchrotron
  - Inverse Compton scattering
  - Bremsstrahlung
- **By accelerated protons**
  - π^0 decay from pp interactions
- **By annihilation/decay of massive particles**



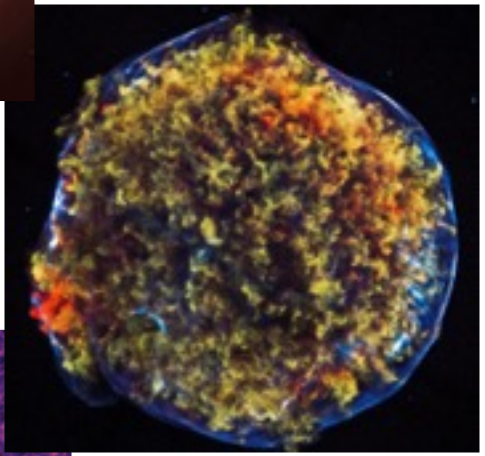
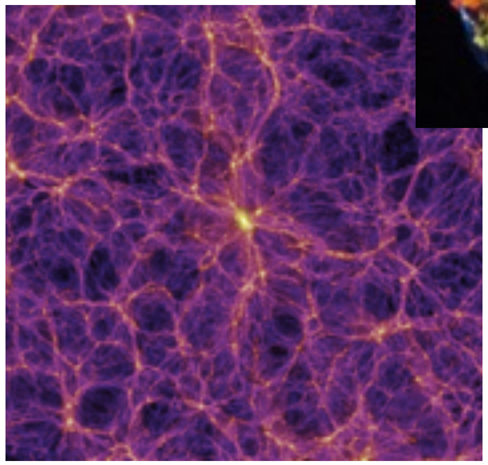




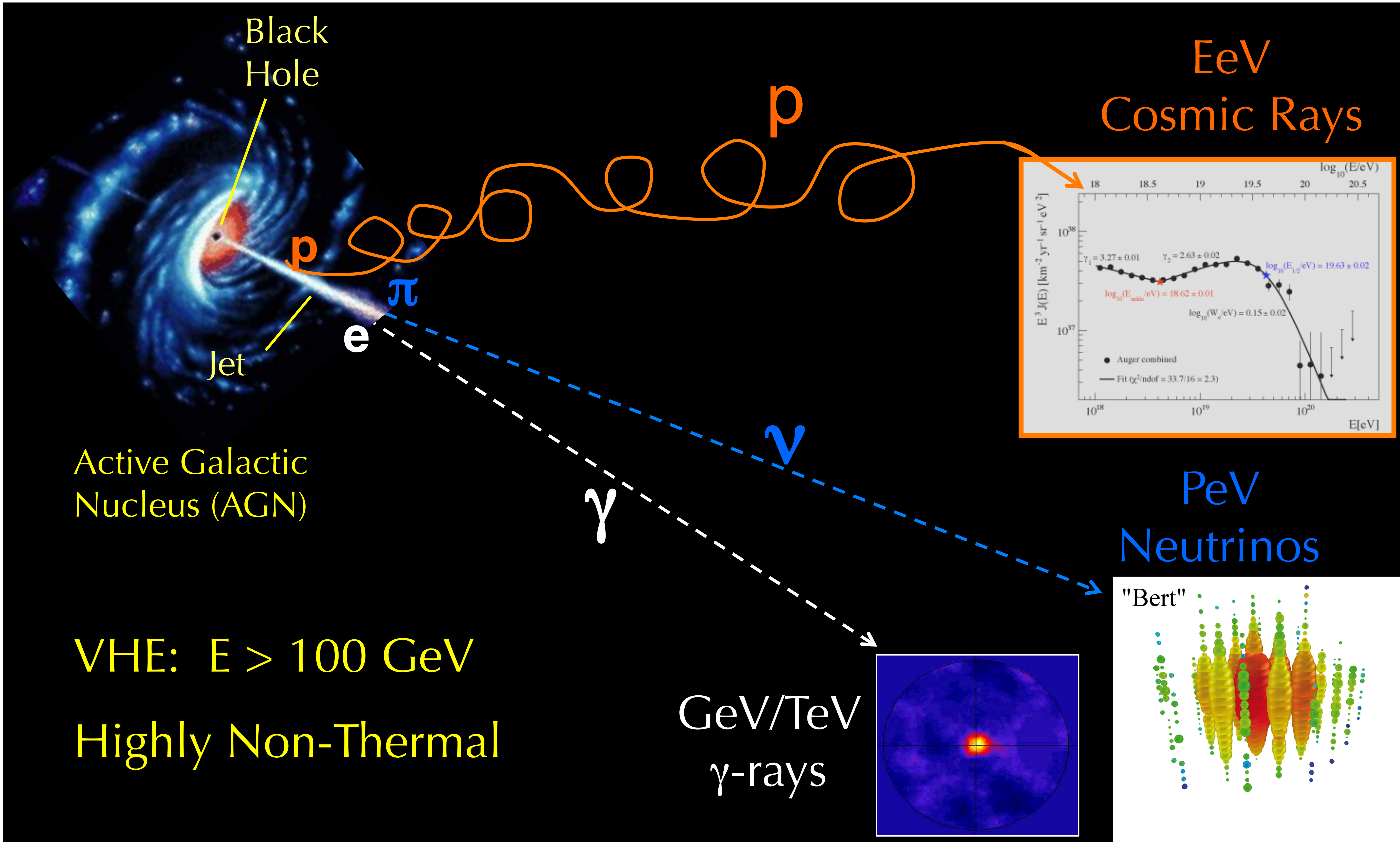
Particle acceleration

- **By electric fields**:
  - Pulsars
  - AGNs [?]
- **In shocks** (Fermi acceleration)
  - Supernova Remnants
  - Pulsar Wind Nebulae
  - Star forming regions
  - Relativistic jets (AGN, binary systems [?])
  - GRBs [?]
- **By annihilation/decay of massive particles**:
  - WIMPS



Multi-messenger synergies



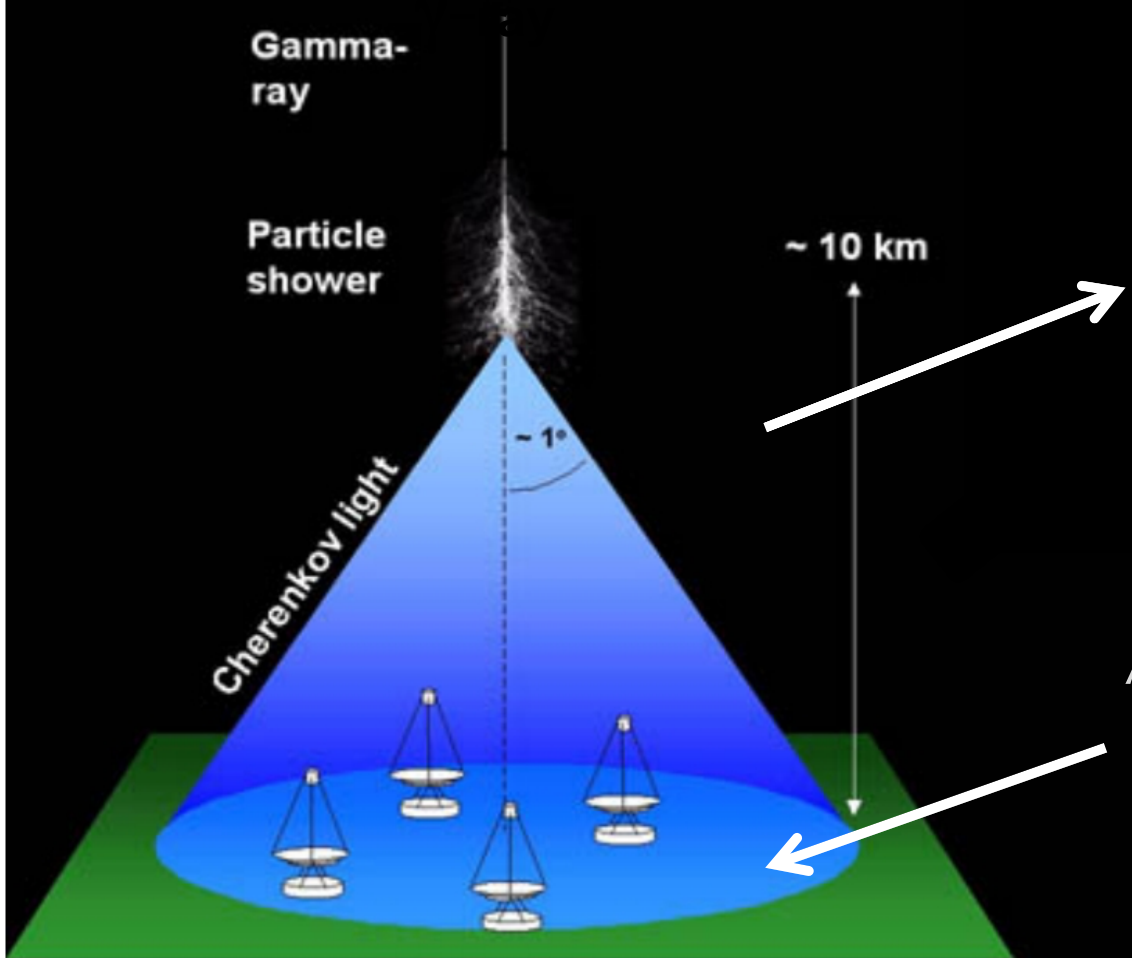
VHE: E > 100 GeV

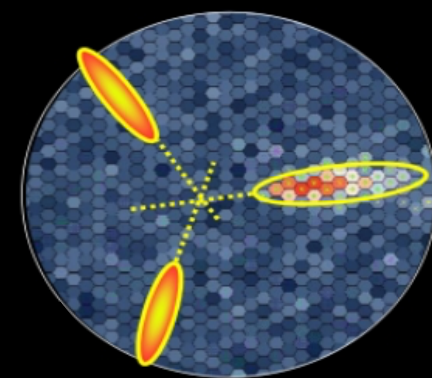
Highly Non-Thermal

Broad science themes

- **Understanding origin and role of cosmic rays (CRs)**
  - Find the CR acceleration sites
  - Understand mechanisms of CR acceleration
  - Understand role of accelerated particles in star formation and galaxy evolution
- **Probing extreme environments**
  - Understand physical processes near neutron star and black holes
  - How do relativistic jets, winds and explosions work
  - Measure radiation and magnetic fields in cosmic voids, and their evolution with time
- **Explore Physics frontiers**
  - What is the nature of dark matter and how it distributes
  - Search for quantum gravity effects on photon propagation
  - Search for axion-like particles

Imaging Cherenkov principle





γ-ray origin location on the camera focal plane (sky)

Area = $10^4 – 10^5$ m^2
~100 photons/m^2/TeV

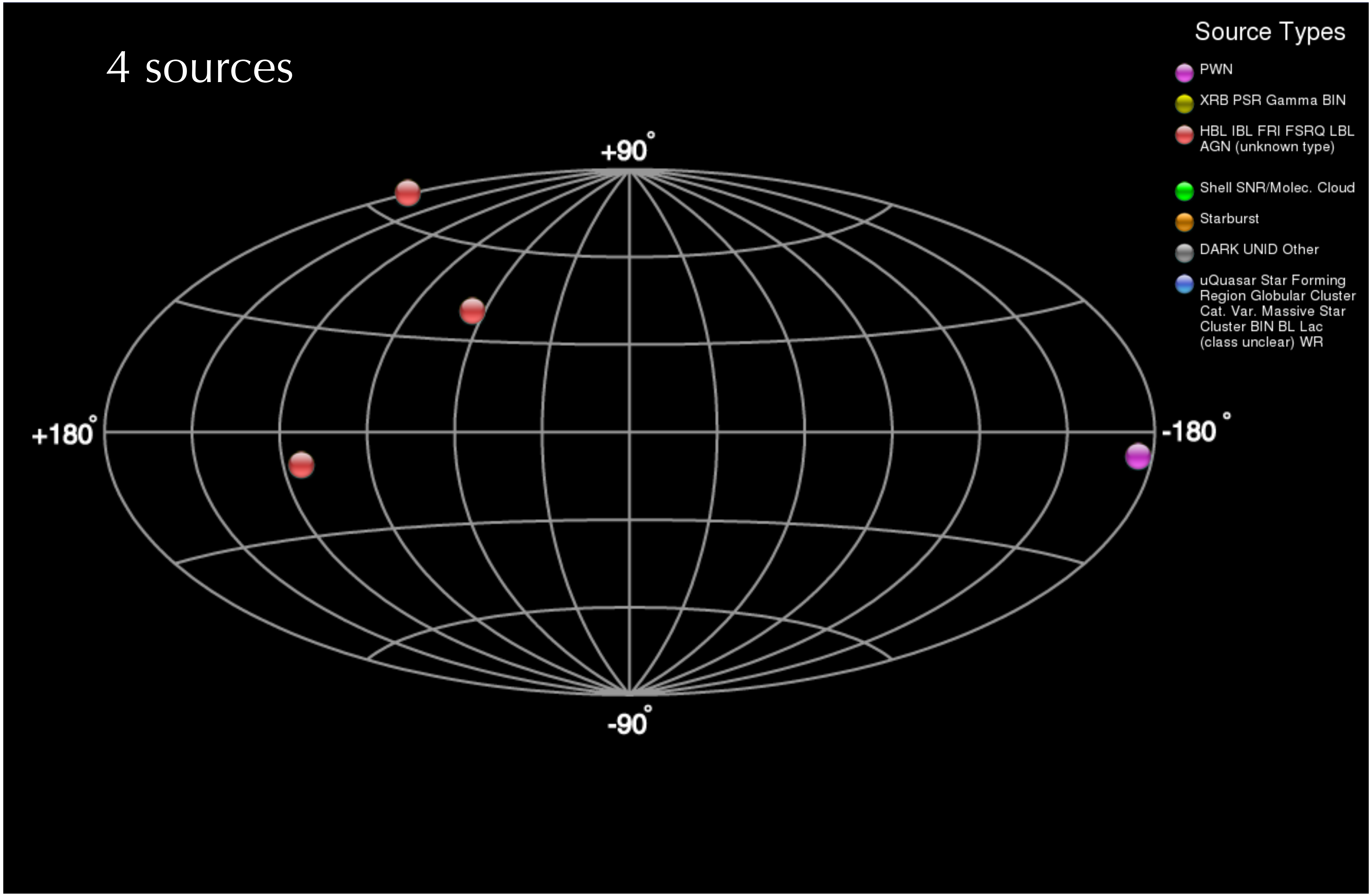
➔ Much larger effective area than space-based Fermi-LAT


VERITAS, Arizona

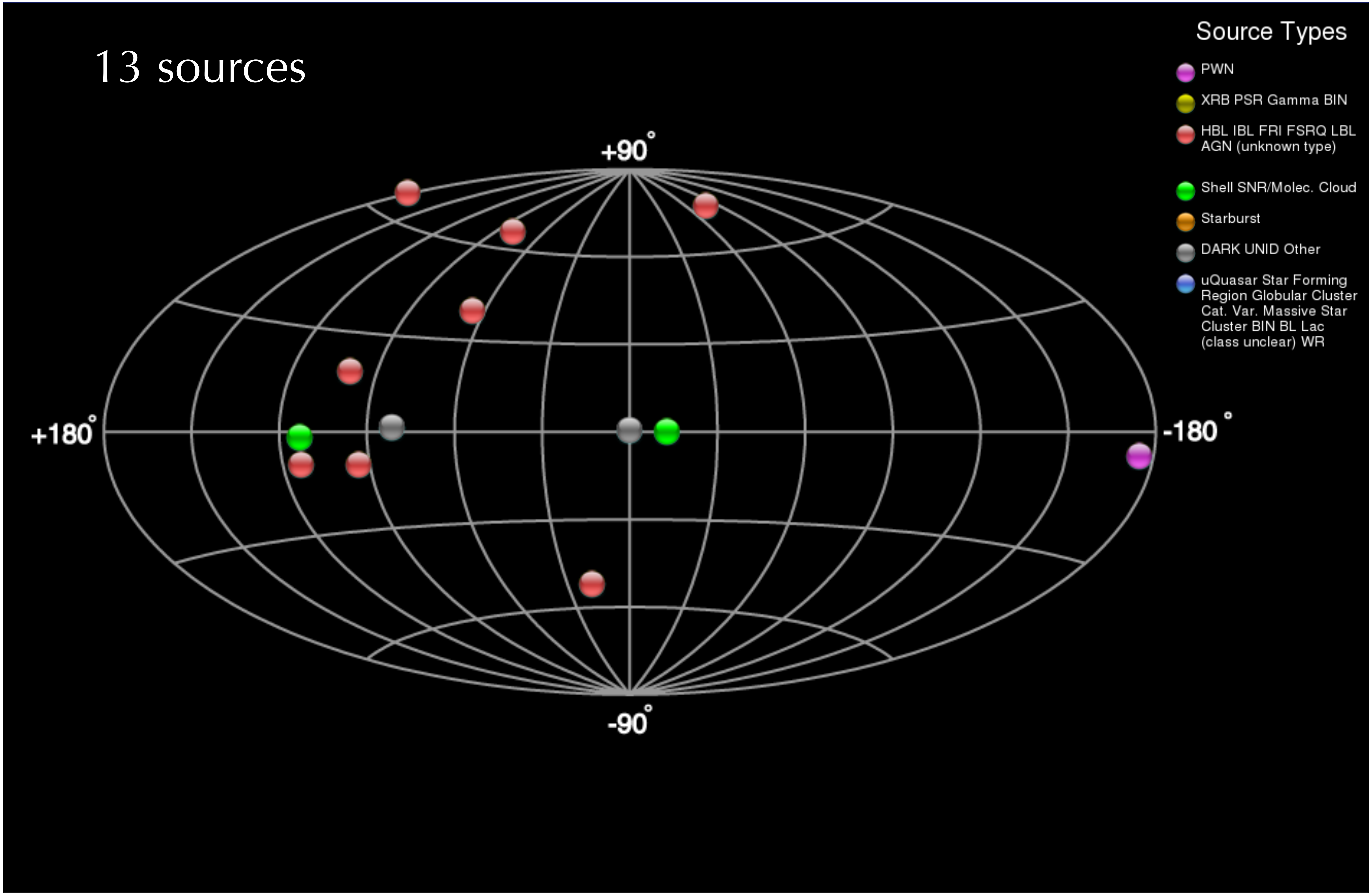

MAGIC, La Palma


HESS, Namibia

VHE γ-ray sky circa 1997

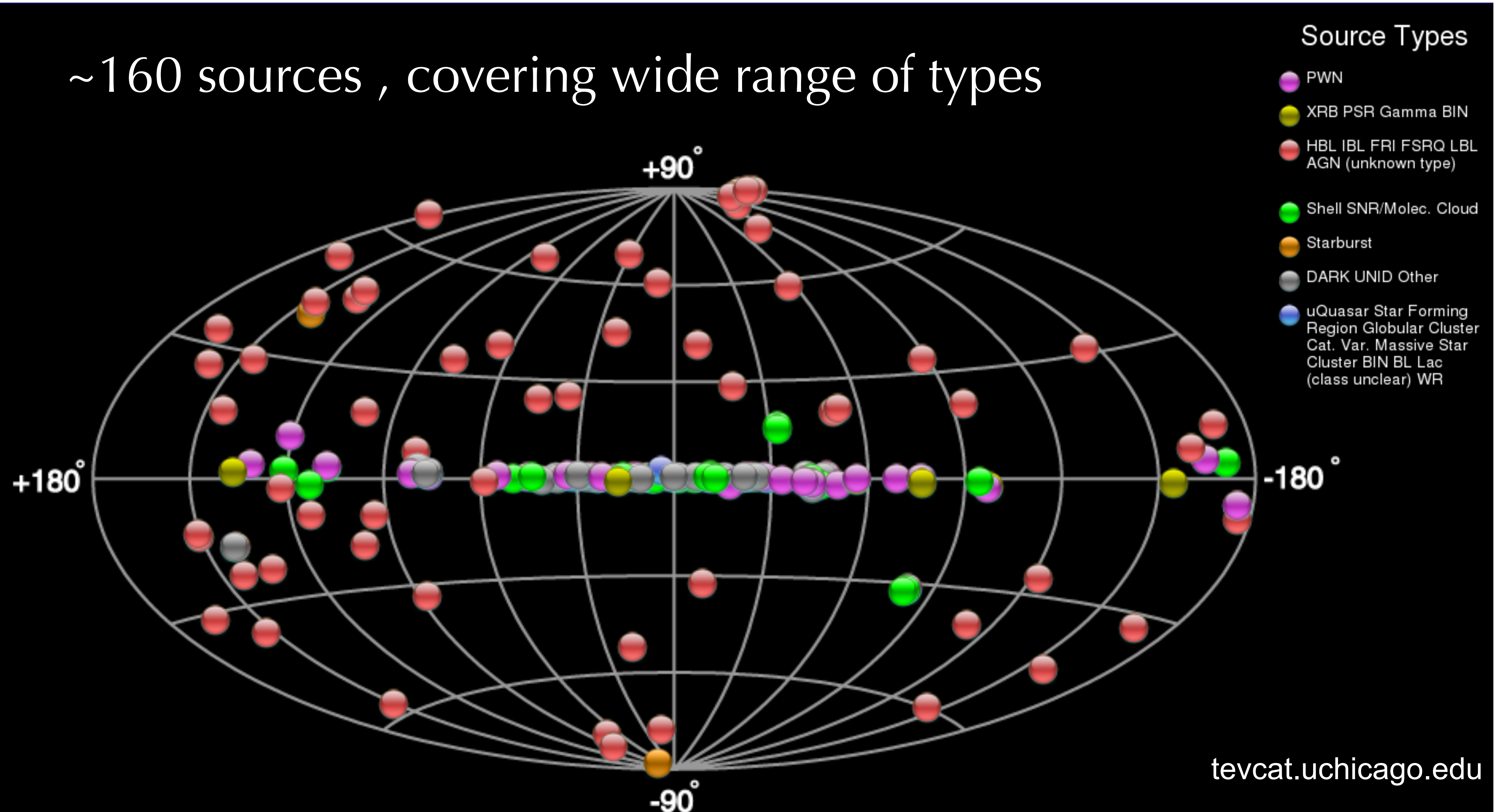


VHE γ-ray sky circa 2005



VHE γ-ray sky circa 1997

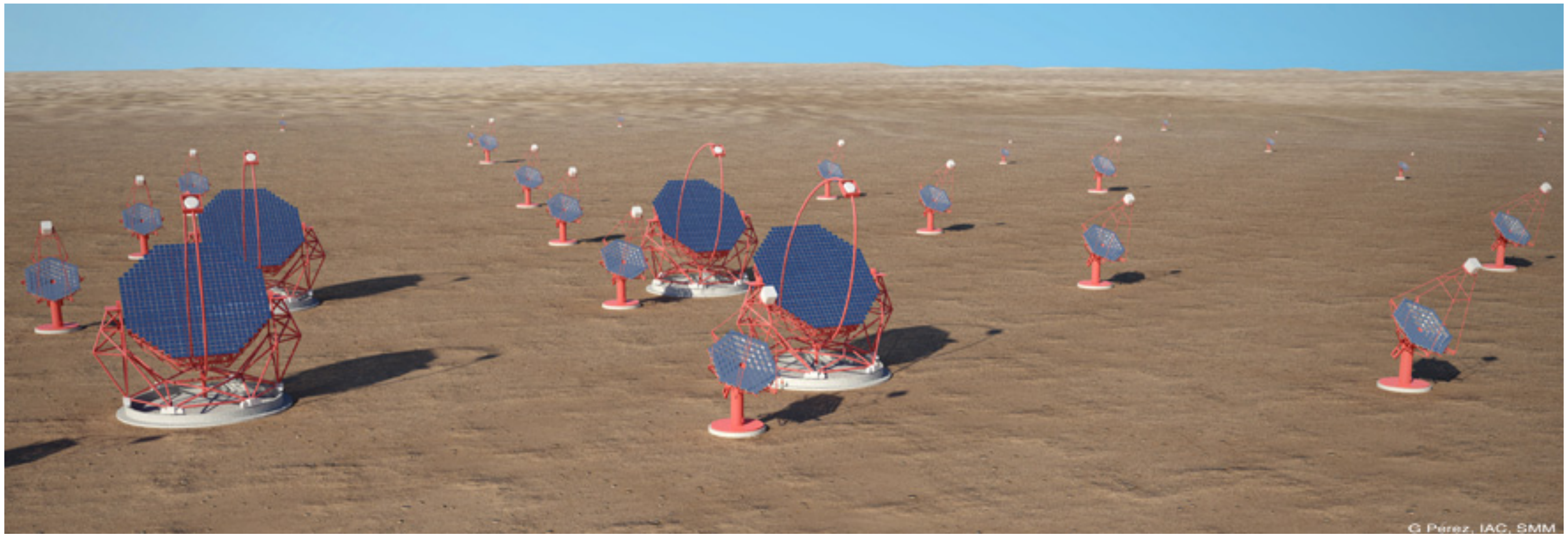
~160 sources , covering wide range of types



Detailed source information: Spectra, Images, Variability, MWL …

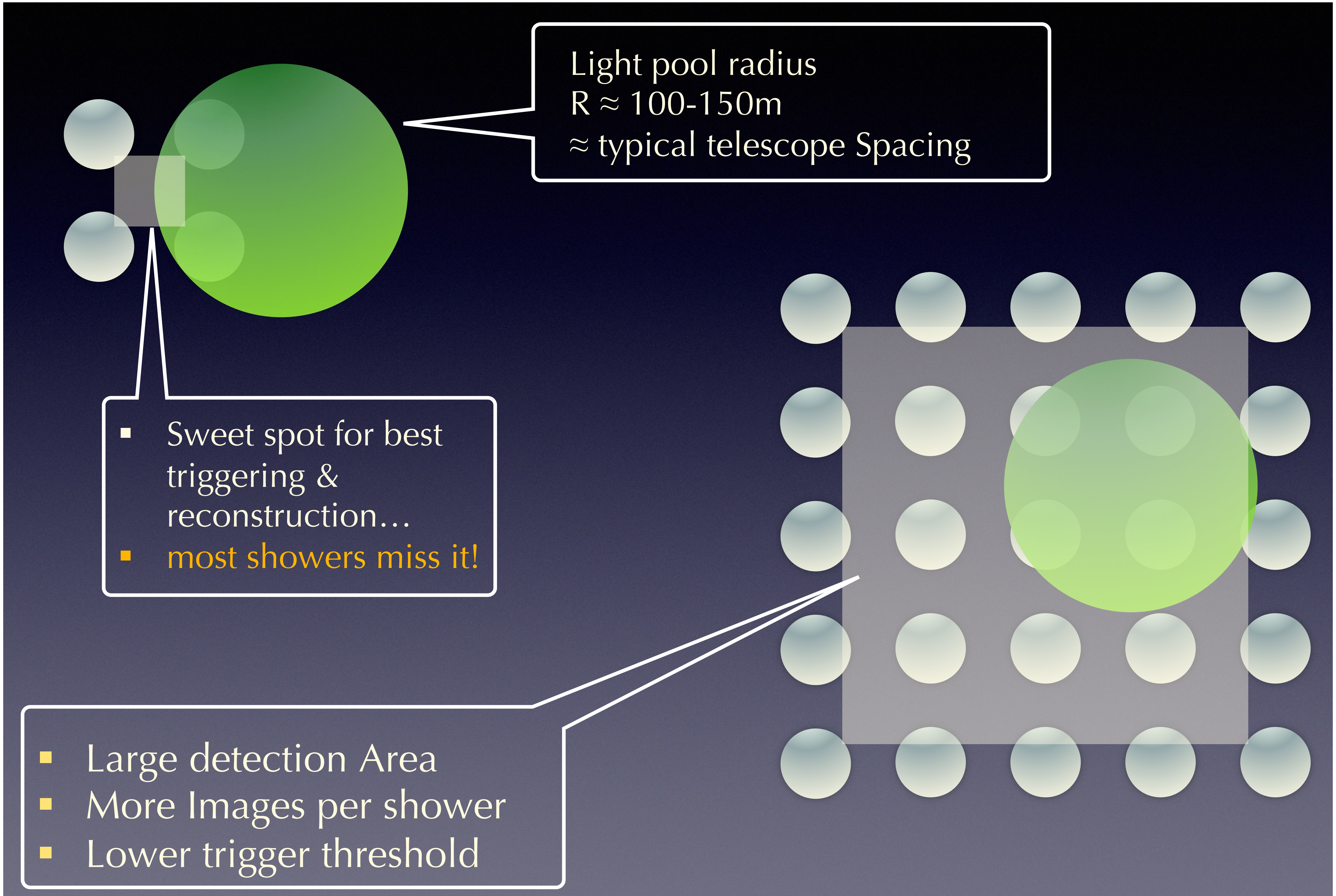
CTA

Cherenkov Telescope Array: CTA

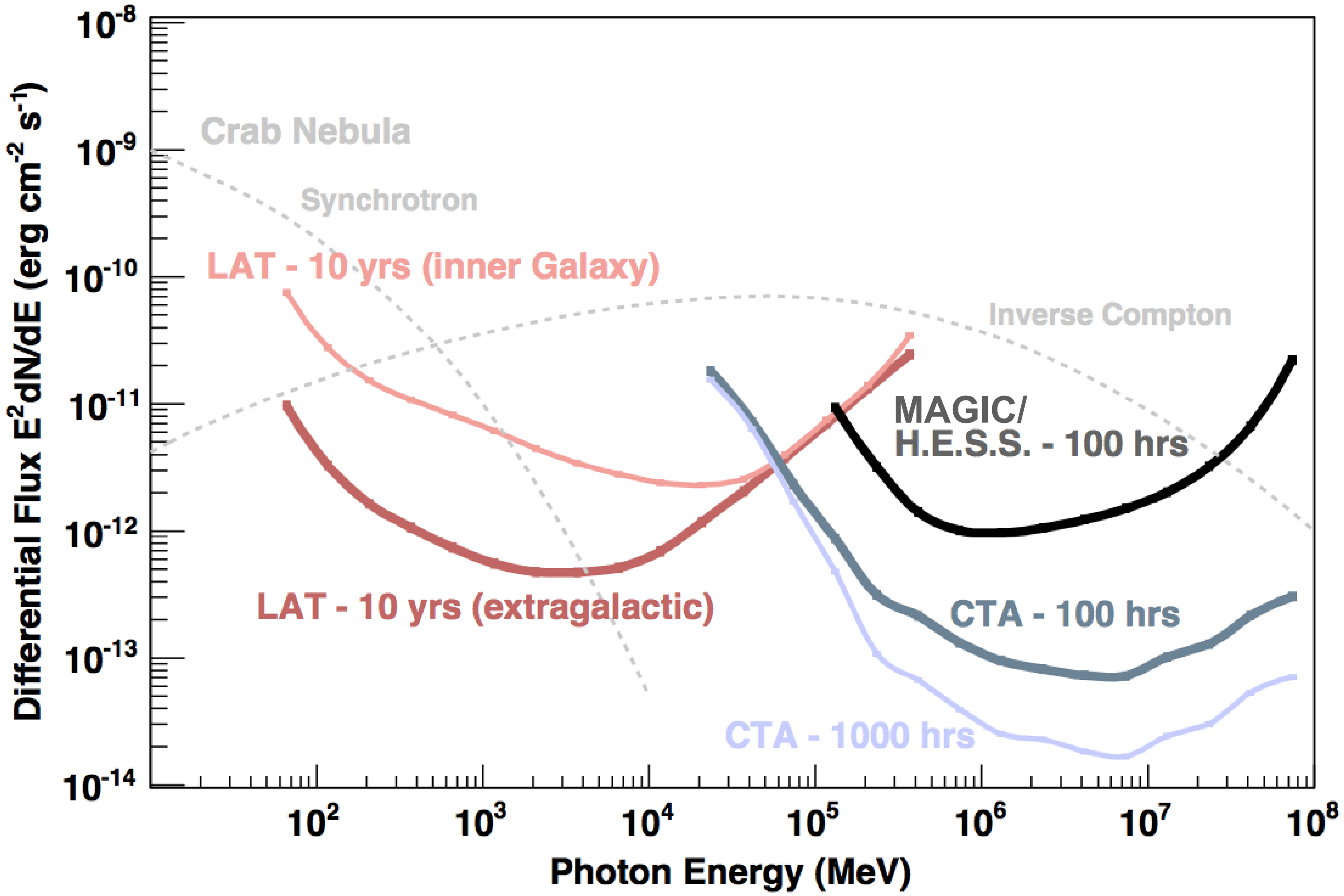


- **CTA: Full sky-coverage gamma-ray observatory**:
  - North: La Palma (Canary Islands, Spain), ~20 telescopes
  - South: Cerro Paranal (Atacama, Chile), ~100 telescopes
- **Multiple telescope size for energy coverage**:
  - Large Size Telescope (LST, 23m): 20-200 GeV
  - Medium Size Telescope (MST, 12m): 100 GeV-10 TeV
  - Small Size Telescope (SST, 4m): 5-300 TeV, South only
- **Construction**: 2016-2021 [?]

Present vs future

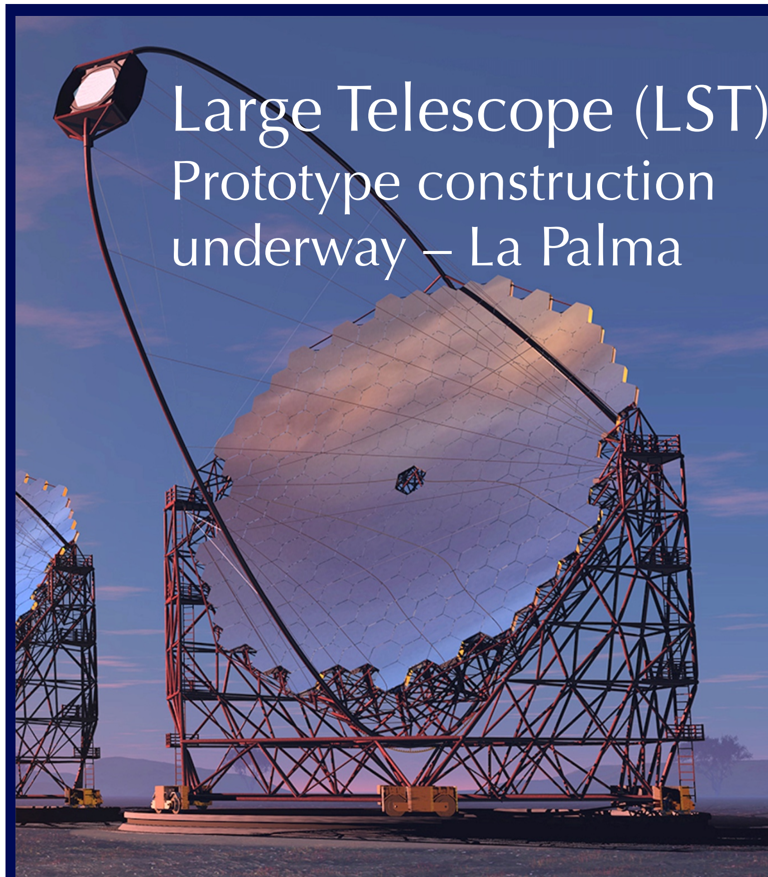


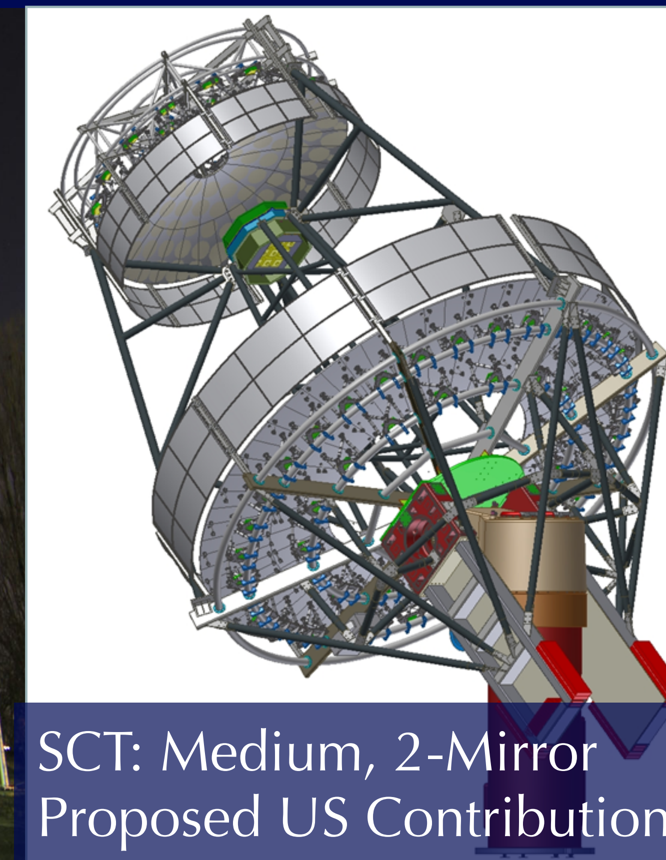
CTA Sensitivity



- ×10 sensitivity improvement
- Expanded energy range: 20 GeV - 300 GeV
- Better energy and angular resolution

Three telescope sizes

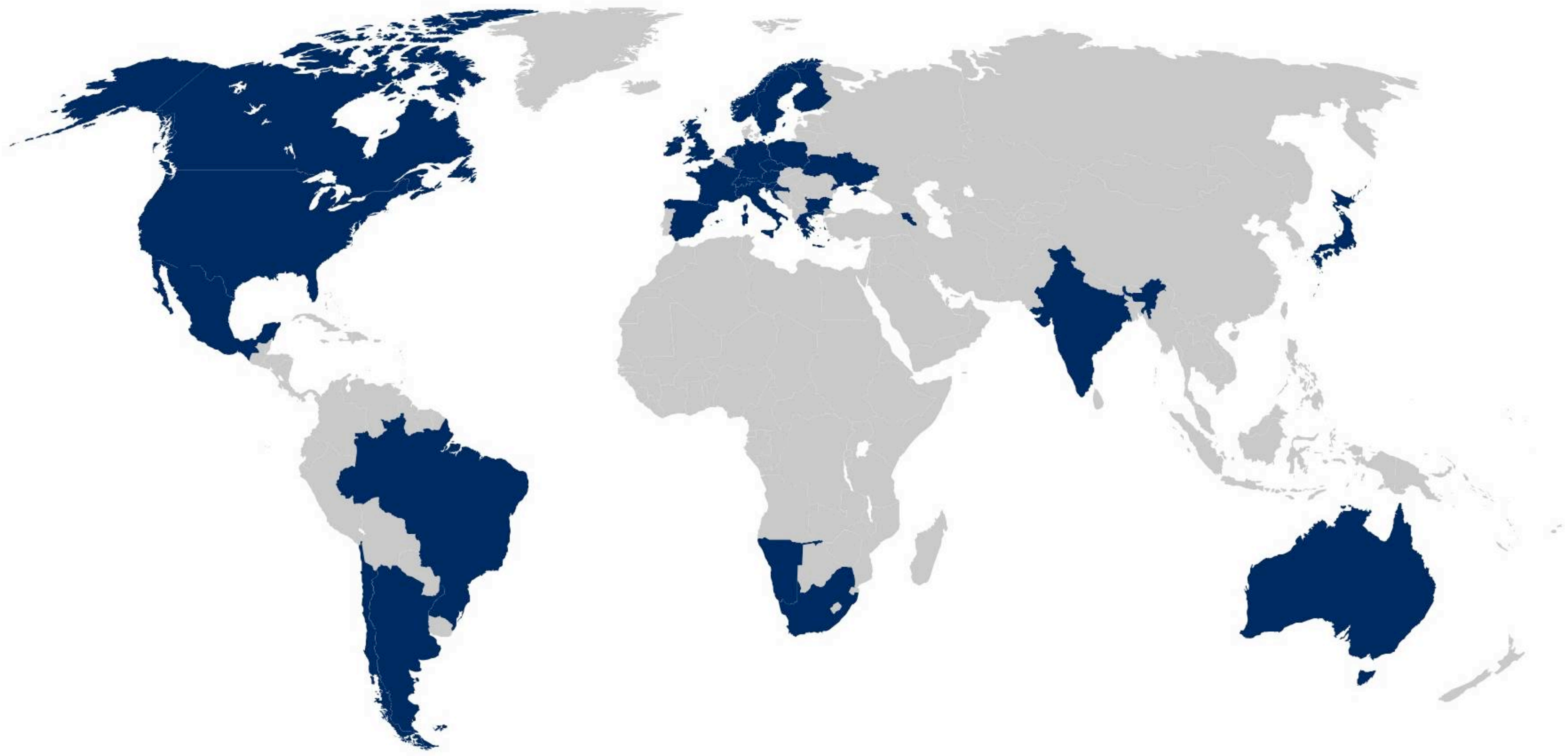




Small Telescope (SST):
3 different prototype designs

CTA: a World Wide effort

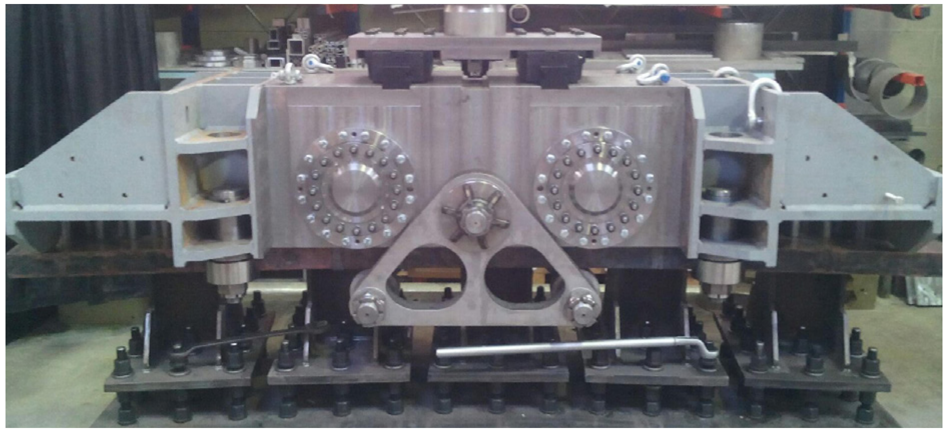
CTA is being developed by the CTA Consortium:

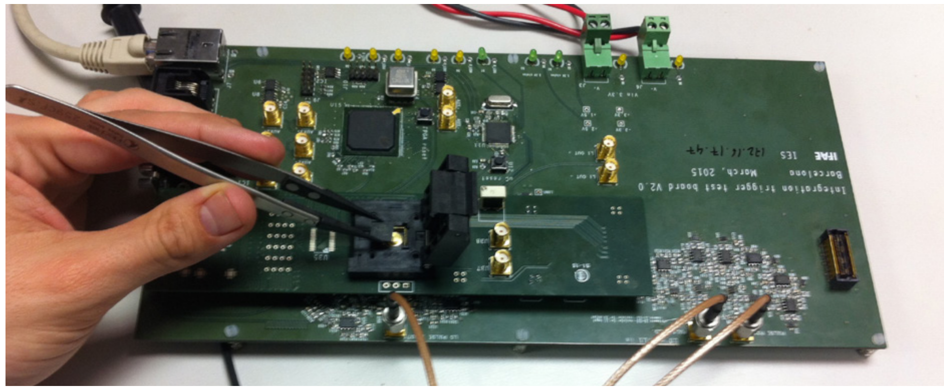


31 countries, ~1270 scientists, ~180 institutes, ~420 FTE

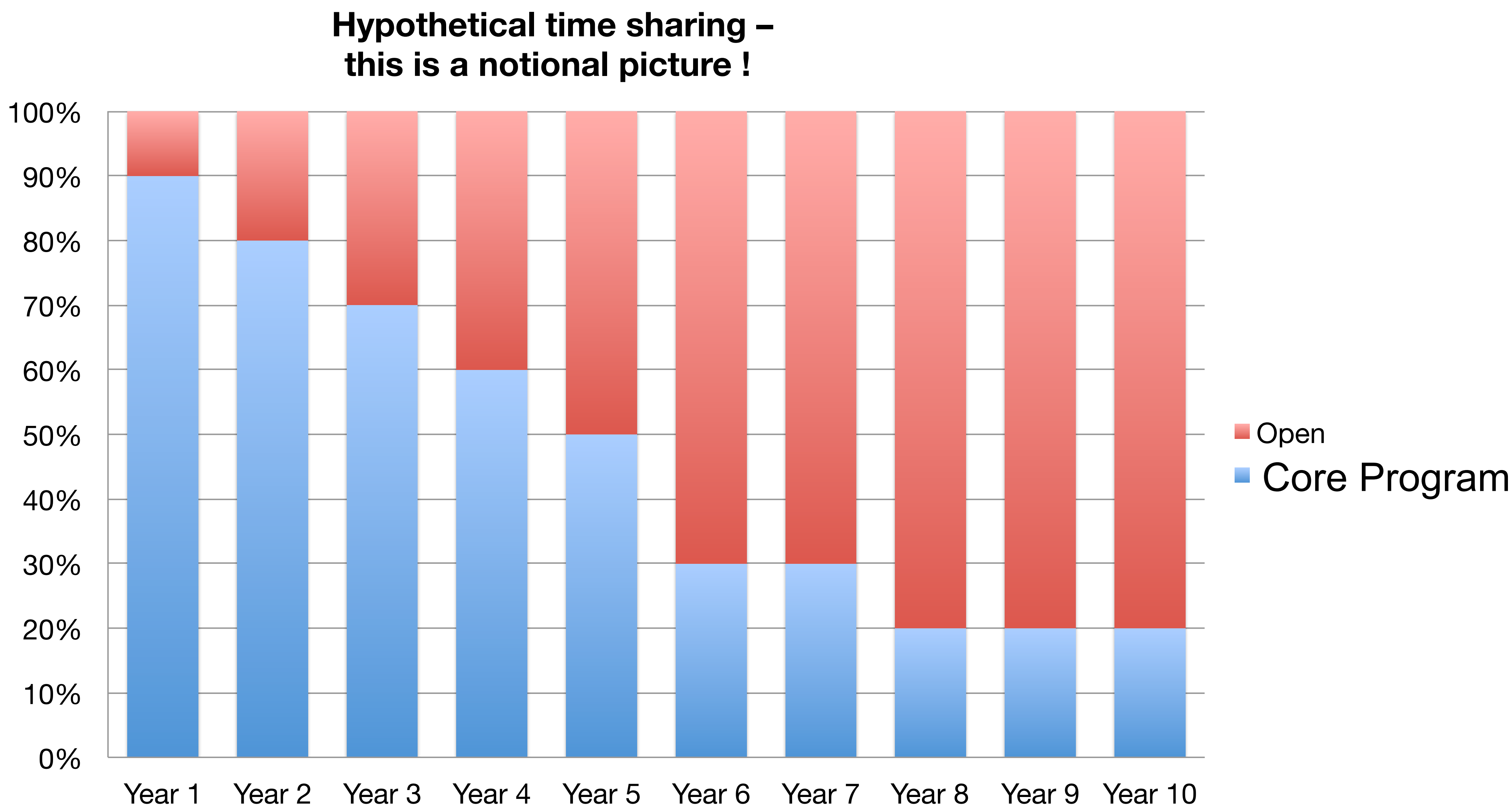
CTA-Spain

- Involved institutes: IFAE-BIST, IAC, Ciemat, UCM, ICC-UB, UAB, IEEC-CSIC, UJA (7-8% of CTA)
- MINECO strong support
- Major contributions:
  - CTA-N @ La Palma proposal
  - LSTs (prototype under construction):
    - Foundations
    - Under-carriage
    - Camera
    - Electronics
  - MSTs for CTA-N
  - Data management (Data Center?)
  - Simulations and Scientific exploitation



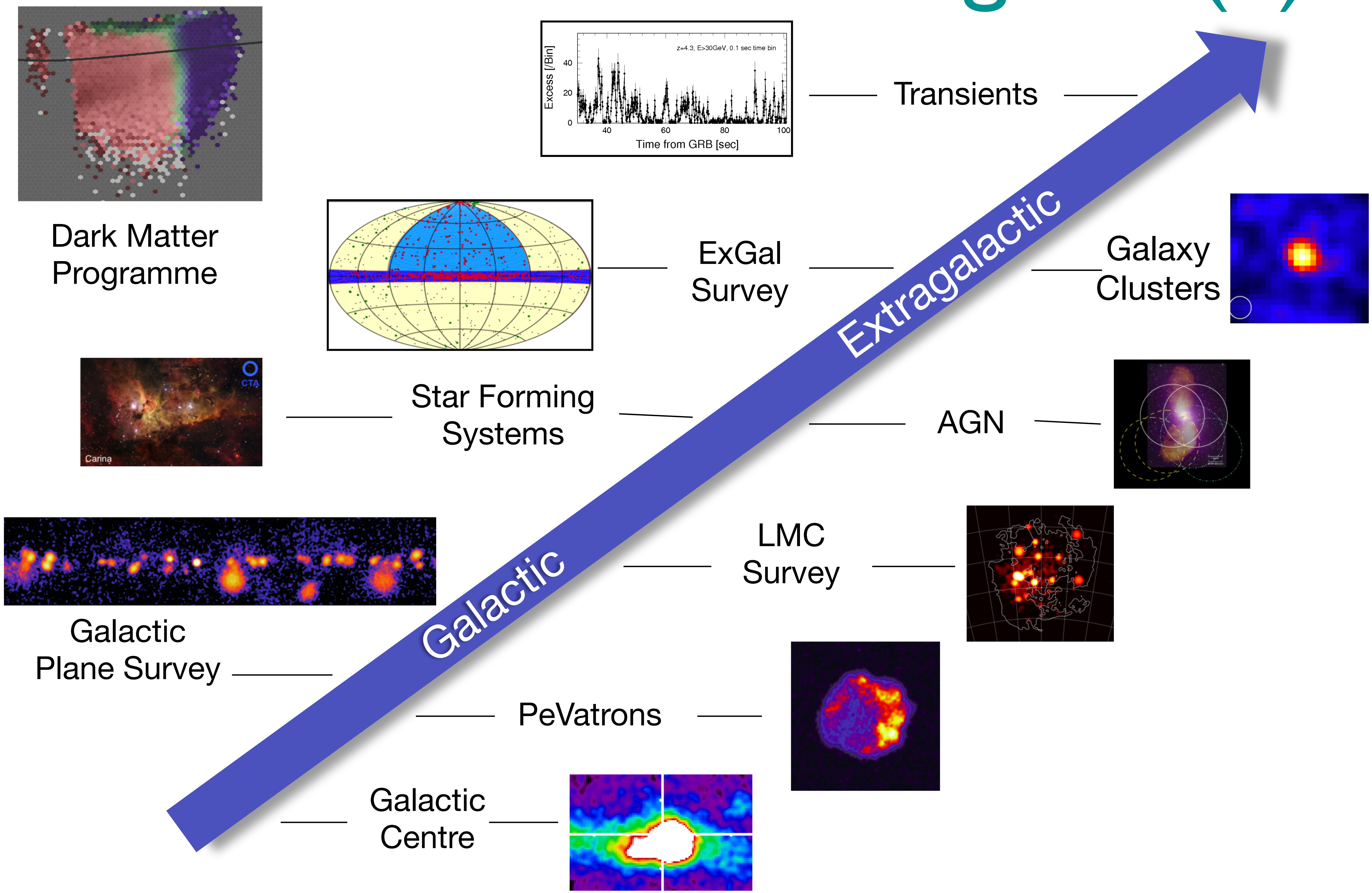


The CTA Core Program (I)



- ~50% of observation time
- Highly motivated scientific output
- Observatory legacy
- Input for guest observers
- 9 target-driven Key Observation Projects + Dark Matter program

The CTA Core Program (2)



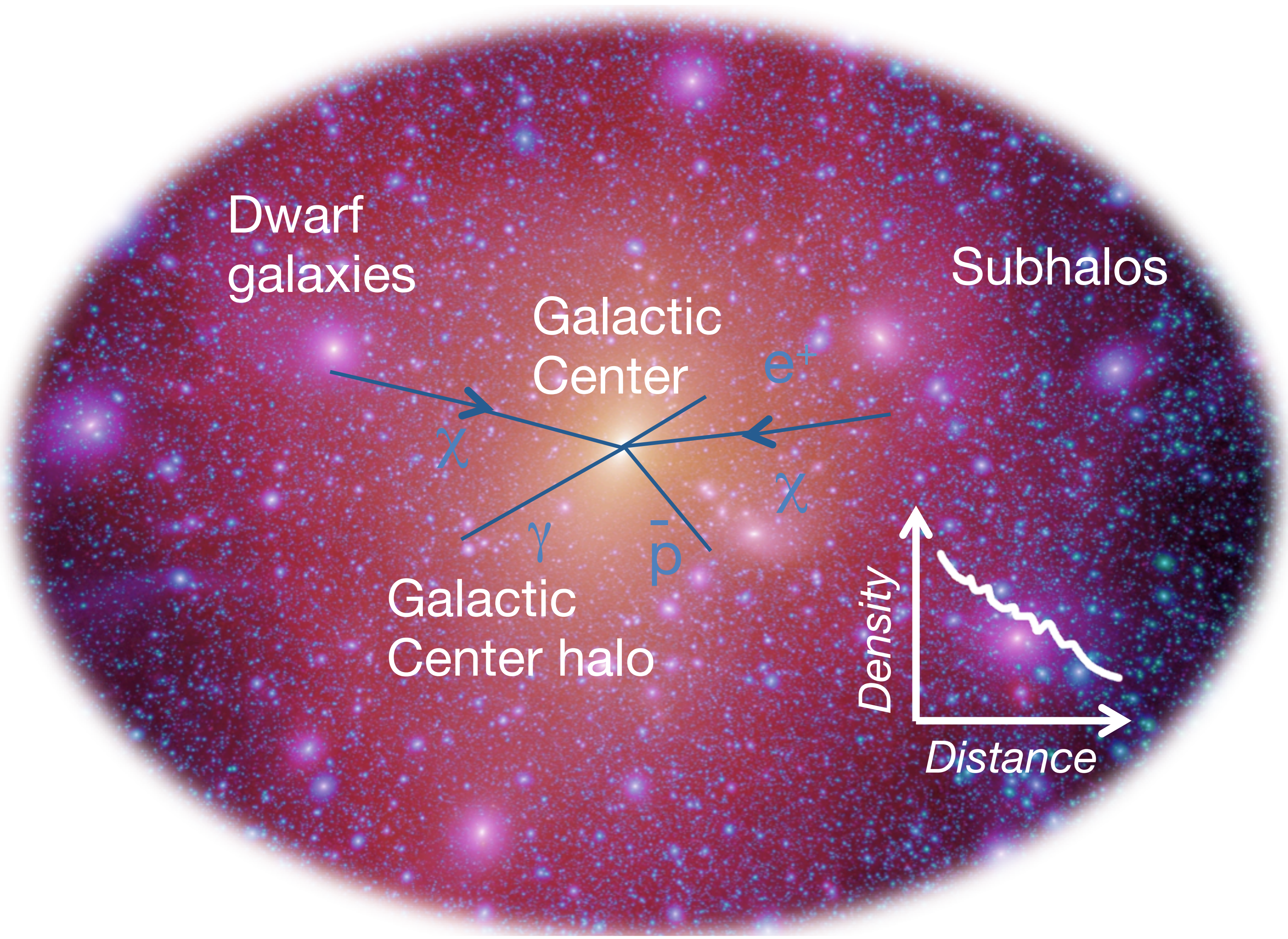
The CTA Core Program (3)

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

DM Surveys Source classes

Fundamental Physics

WIMP dark matter searches

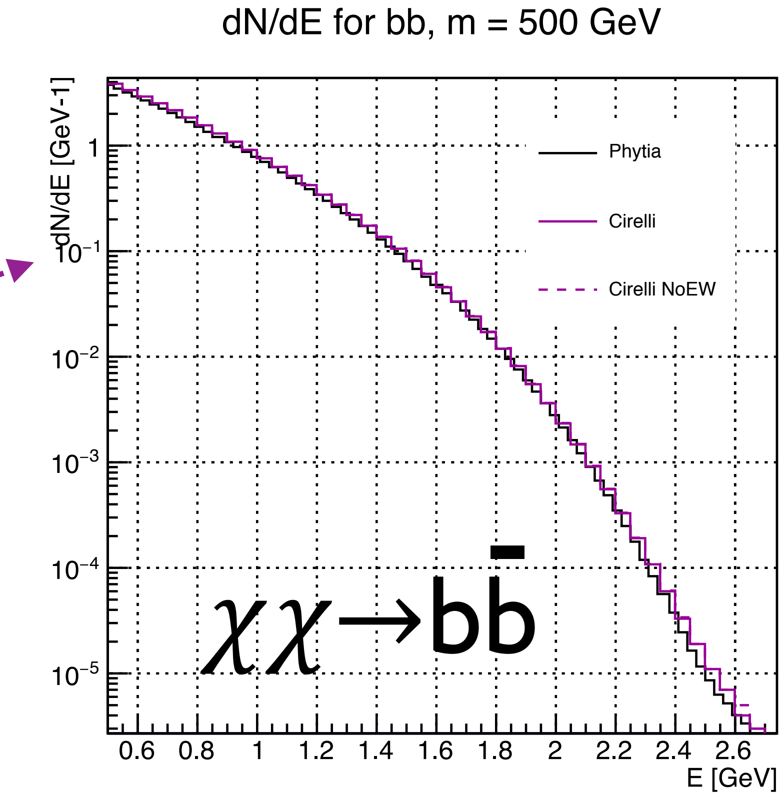


Gamma-ray fluxes

★ Expected differential gamma-ray flux:

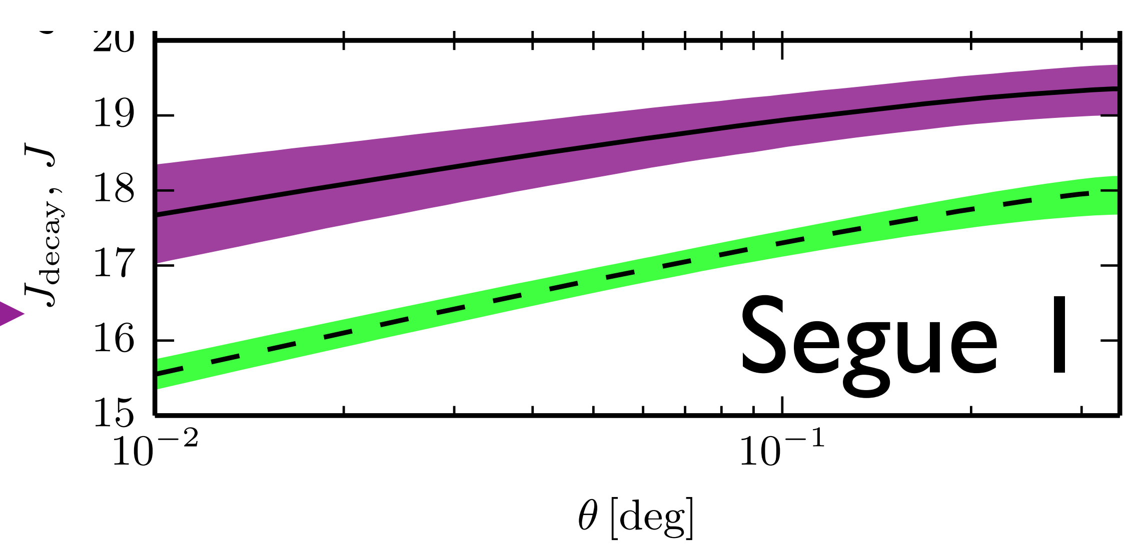
$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle\, J(\Delta\Omega)}{2m_{\rm DM}^2}\,\frac{dN}{dE}$$

Pythia



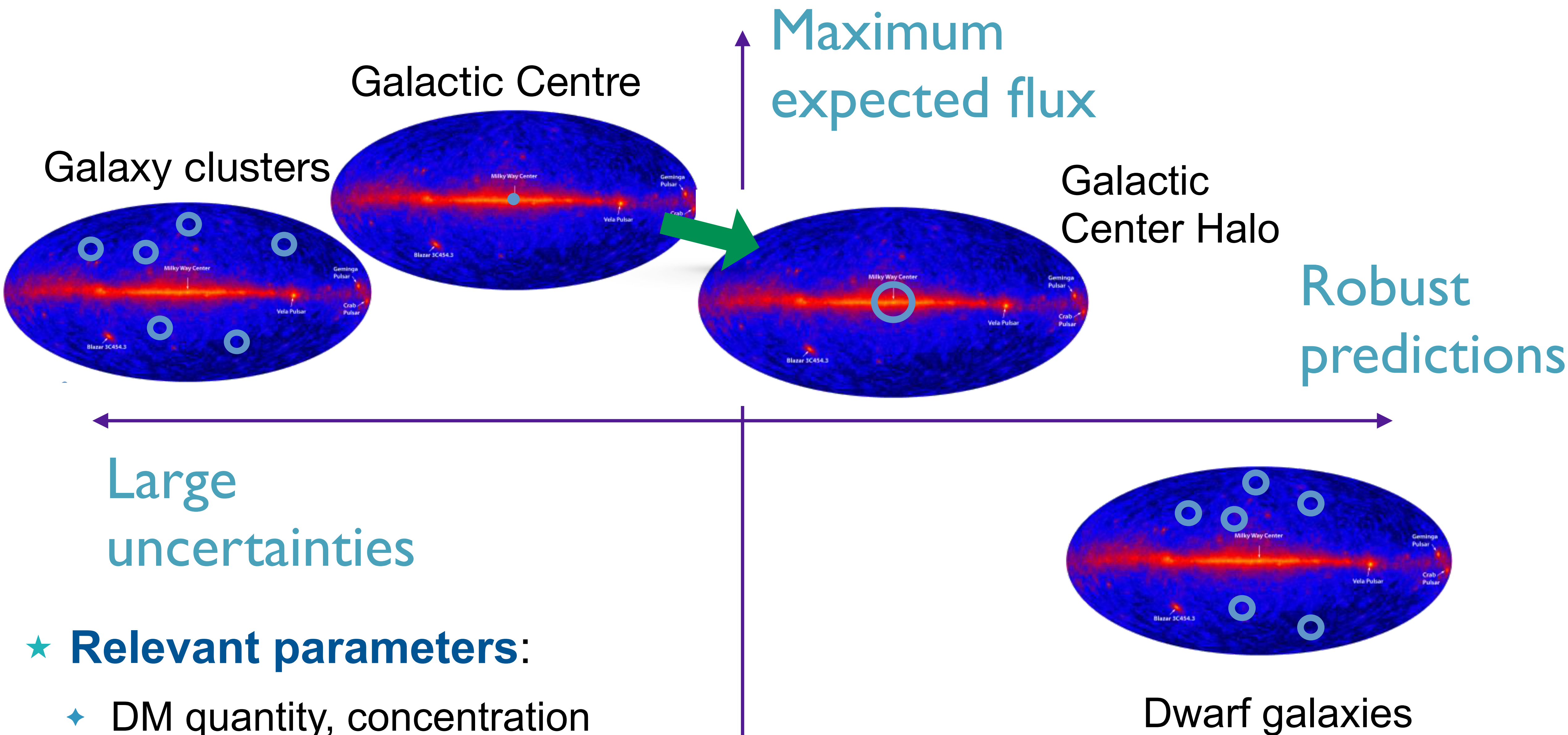
★ The astrophysical or J-factor depends on the DM distribution:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} dl\, \rho^2(l,\Omega)$$



Fit to stellar surface density and velocity dispersion profiles

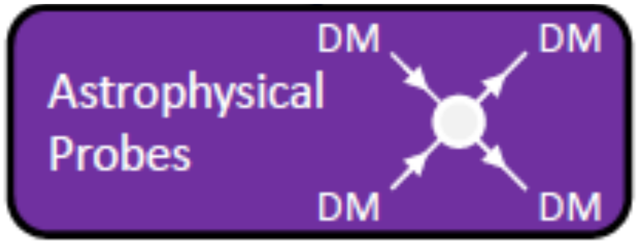
Targets for DM searches

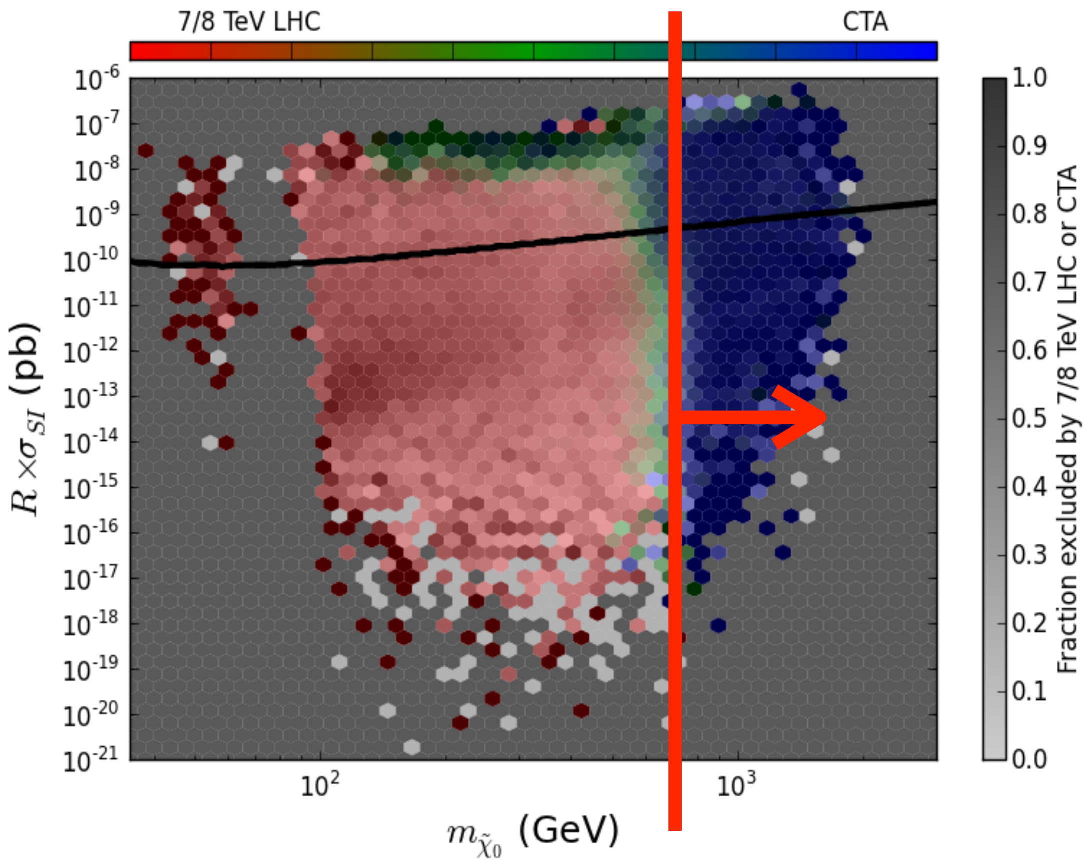


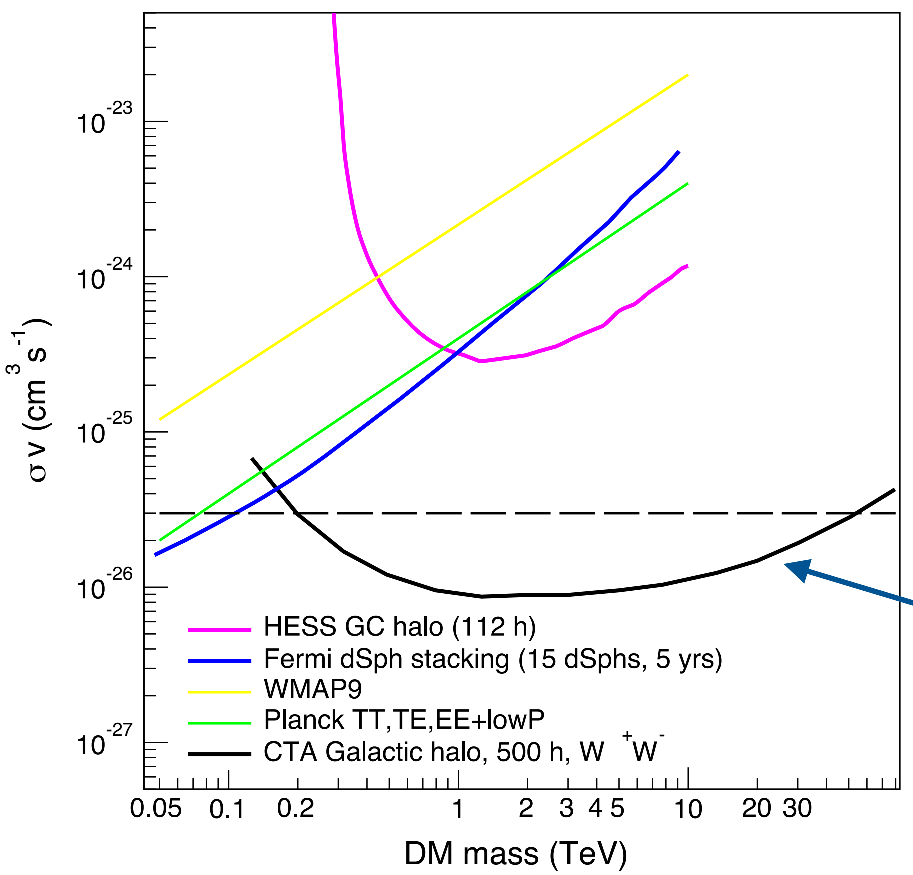
- **Relevant parameters**:
  - DM quantity, concentration and distance
  - Uncertainties
  - Astrophysical background

Complementary search

★ The identification of DM is a multi-faceted problem involving synergies of four complementary approaches

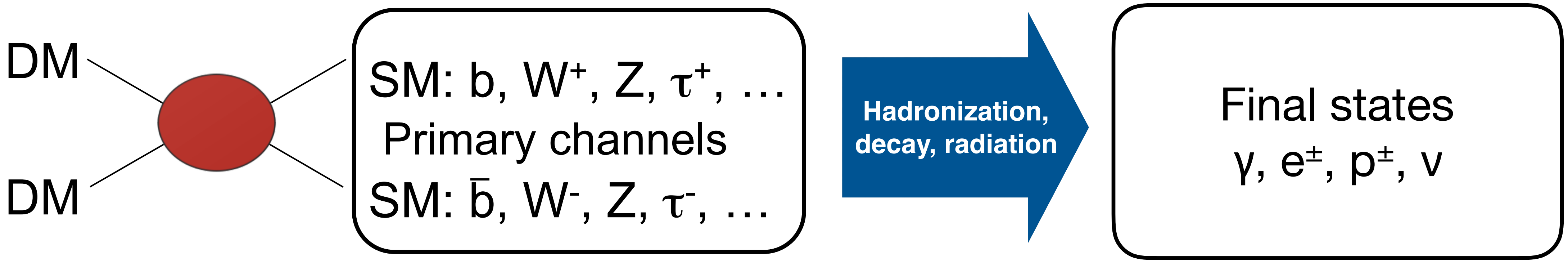




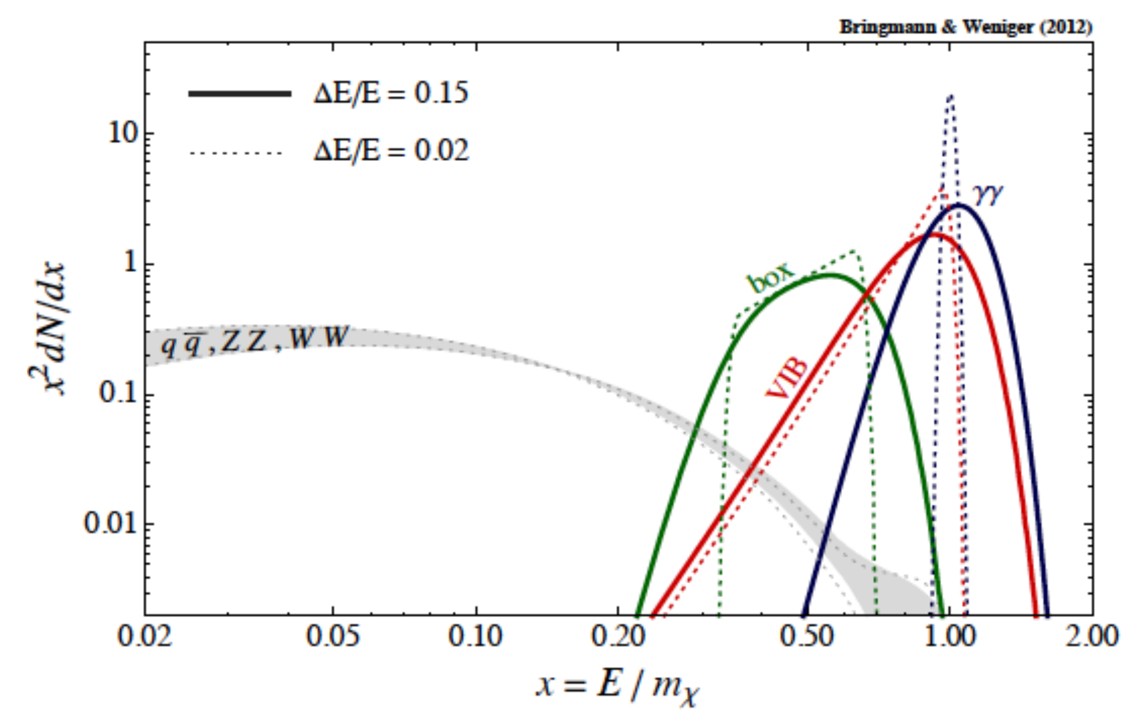


Mostly by LST in the South!

Pros of gamma-ray DM searches

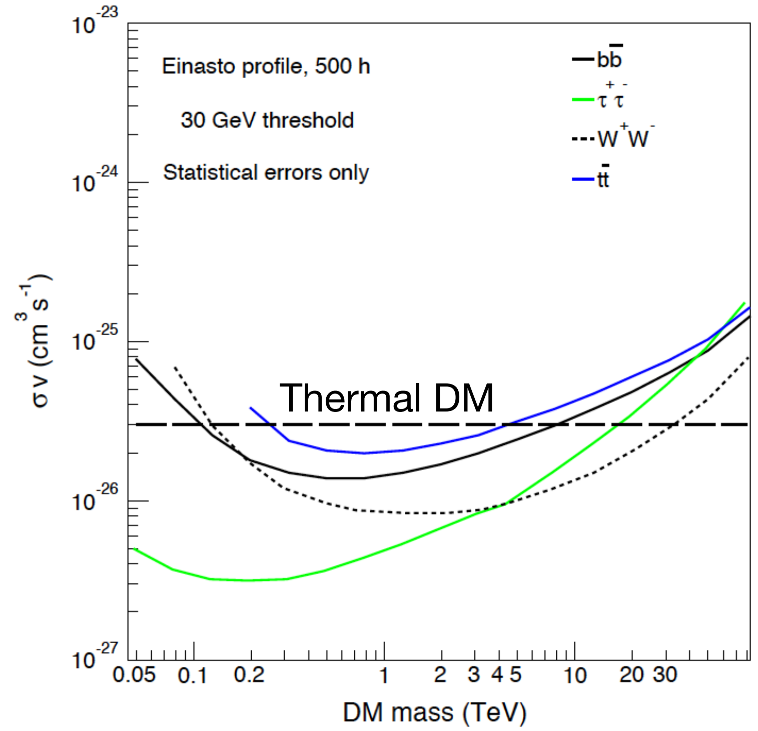


- **Do not suffer from propagation effects**:
  - Can determine DM abundance and distribution in the Universe
    → correlation with Astrophysical probes?
- **Can present characteristic spectral features**:
  - Good separation from background
  - Can measure basic physical properties: Mass, cross-section / lifetime

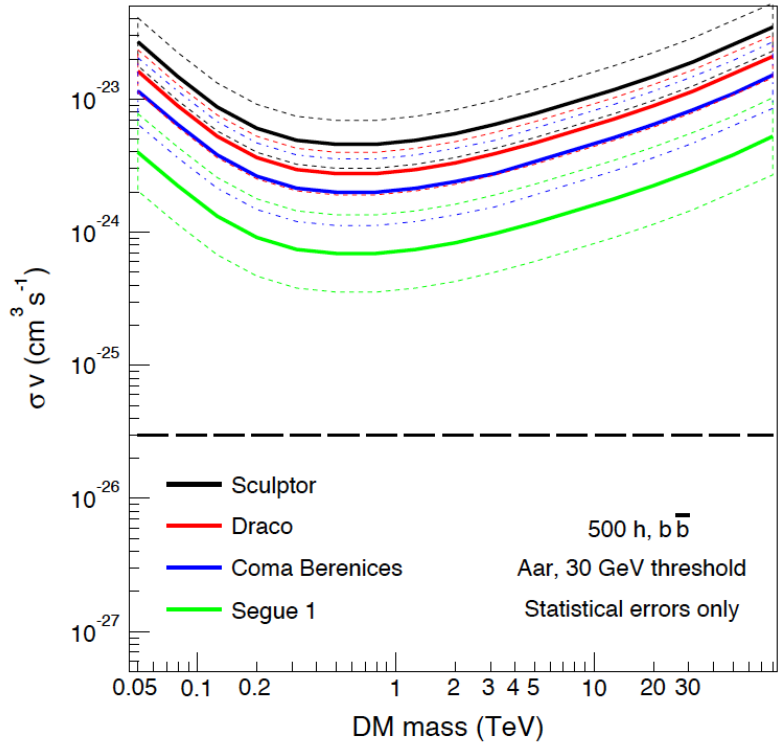


DM search strategy

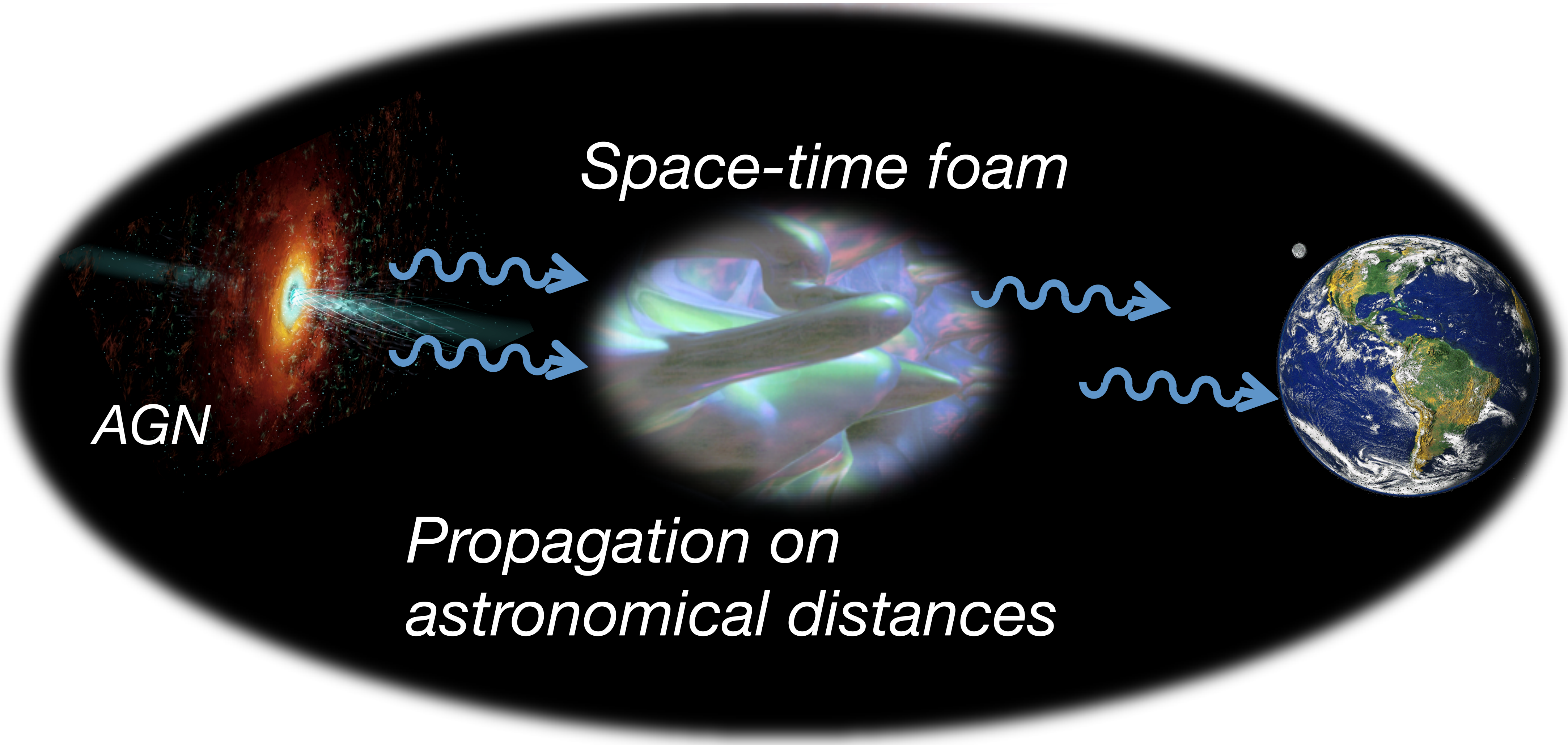
- ★ **High priority program for 10 years**
- ★ **First 3 years**:
  - Deep observations of the Galactic Center Halo (500 h)
  - Complemented by observations of best dSph (300 h)



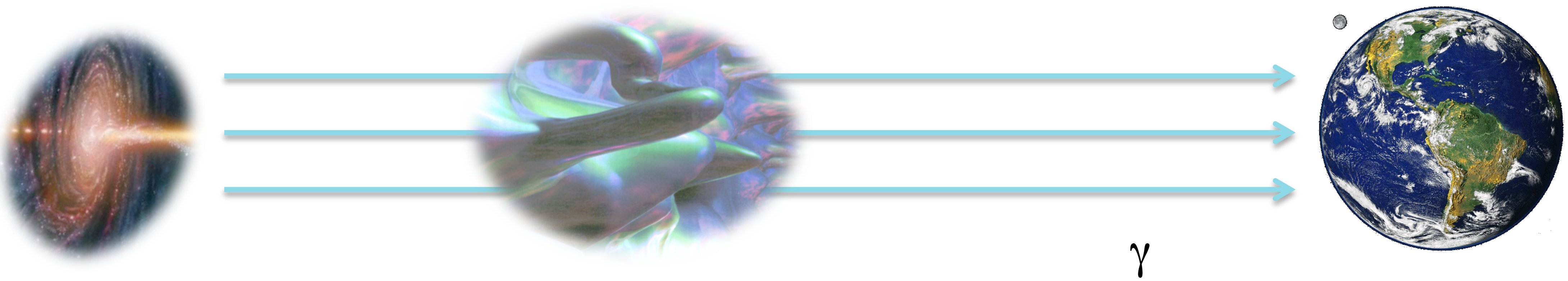
- ★ **Follow-up observations**:
  - In case of detection at GC halo:
    - <σv> high enough: check DM signal towards best dSph
    - otherwise deep observations of GC region
  - In case of no detection:
    - focus on best target to produce most robust limits



Test of Lorentz Invariance



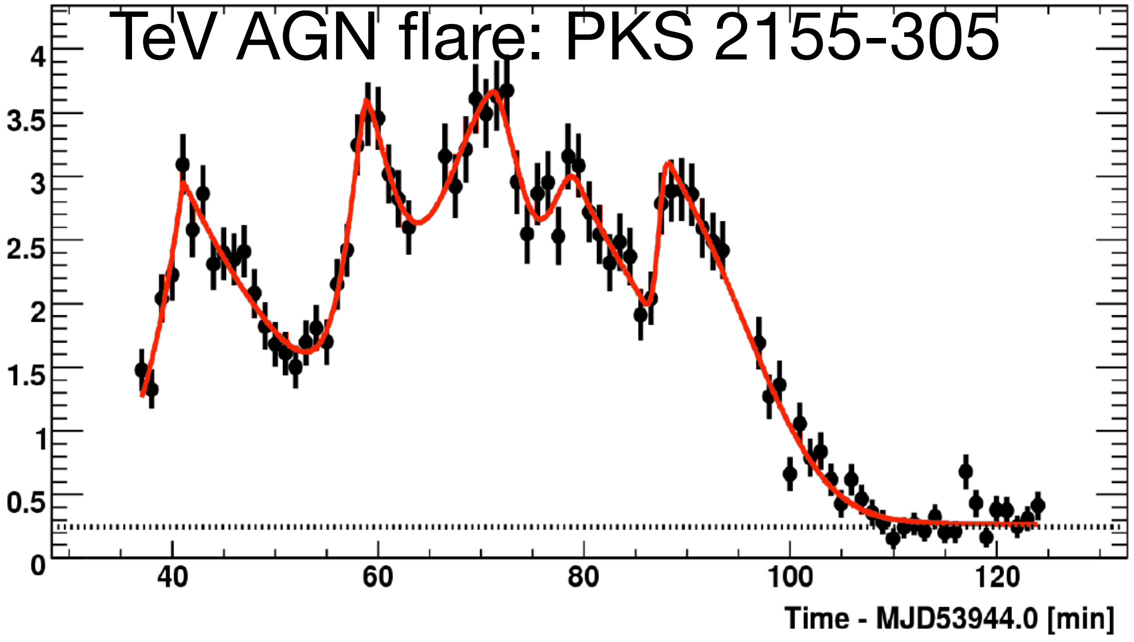
Tests of Lorenz Invariance



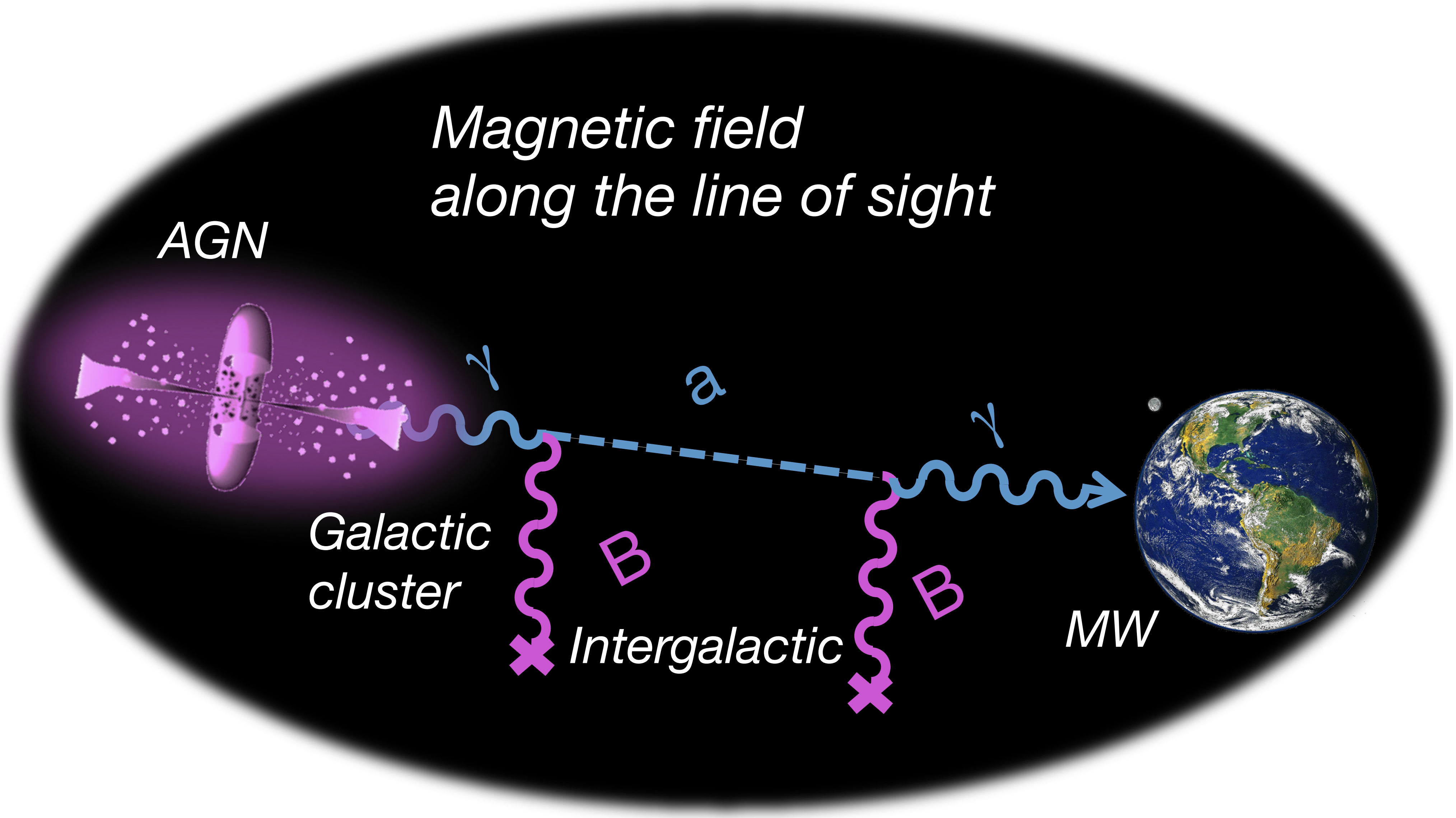
- Quantum Gravity theories predict **speed of light energy dependence**:

$$v = c\left(1 \pm \xi\left(\frac{E}{M_P}\right) \pm \zeta\left(\frac{E}{M_P}\right)^2 \pm \ldots\right)$$

- **Fast events** (GRB, AGN flares, pulsars) provide the t_0
- **Access to M_P** by large distances (results depend much on the kind of event)

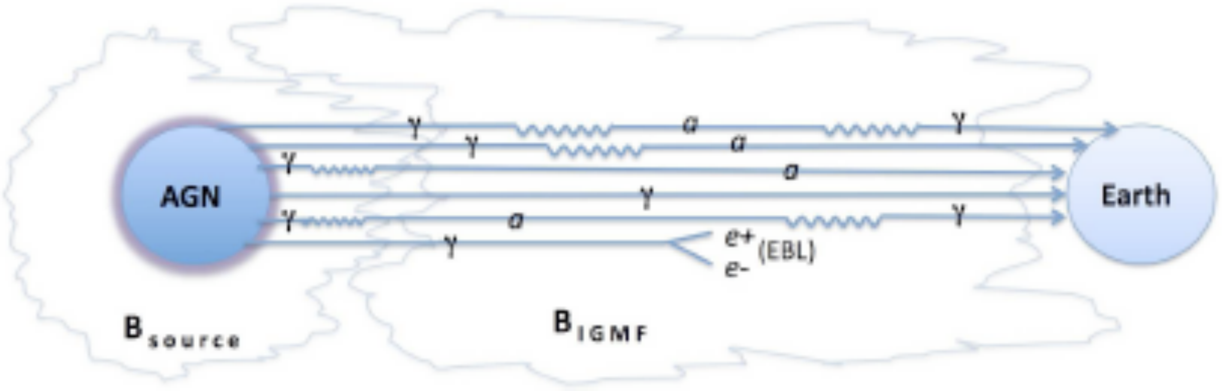


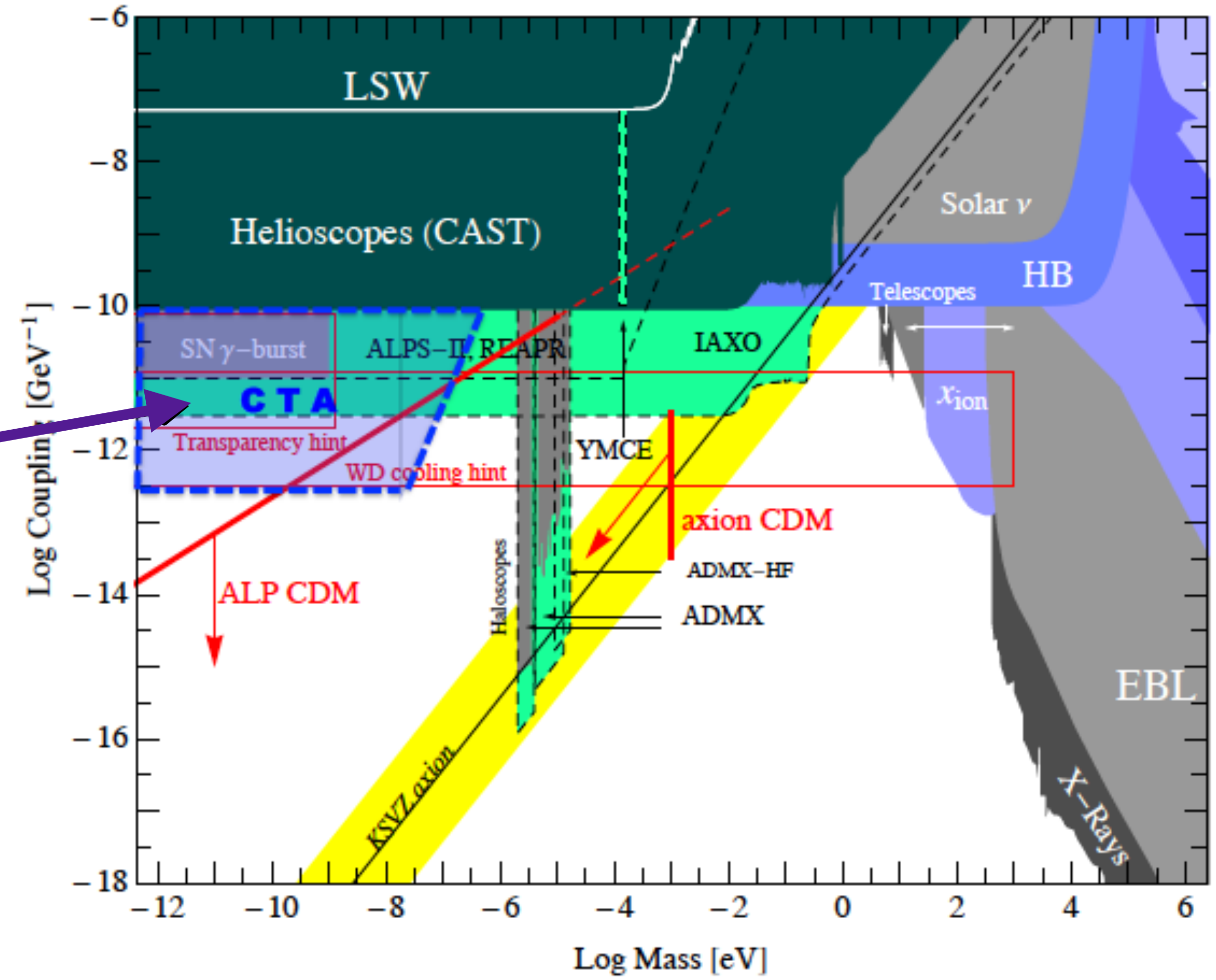
Search for axion-like particles



Search for axion like particles

- Gamma-rays may convert to/from ALPs in intergalactic B-fields
  - Spectral features
  - Universe becomes more transparent
- CTA probes ALP DM candidates:
  - m ~10^{-9} eV

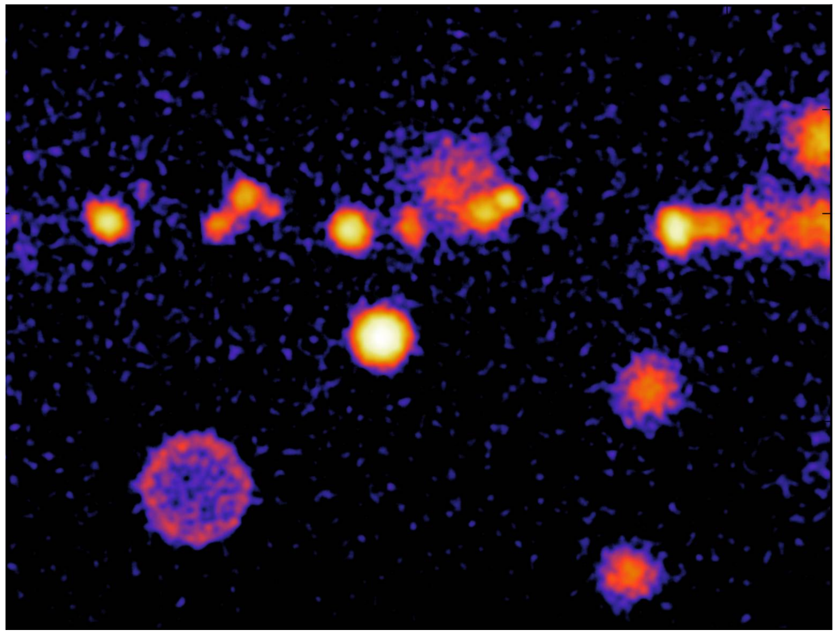


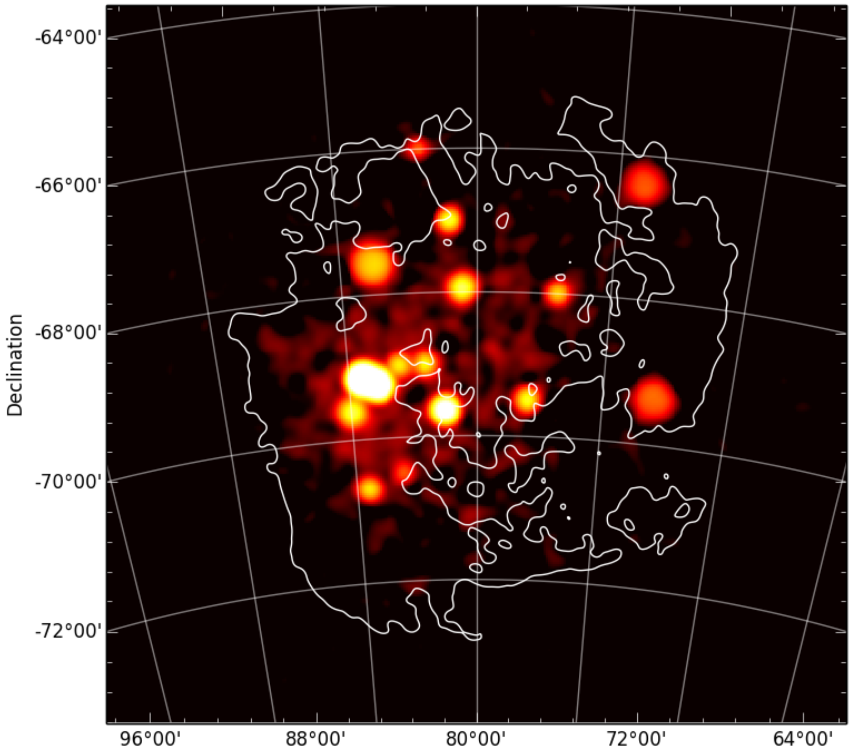


Galactic Key Science

Galactic Key Science Projects

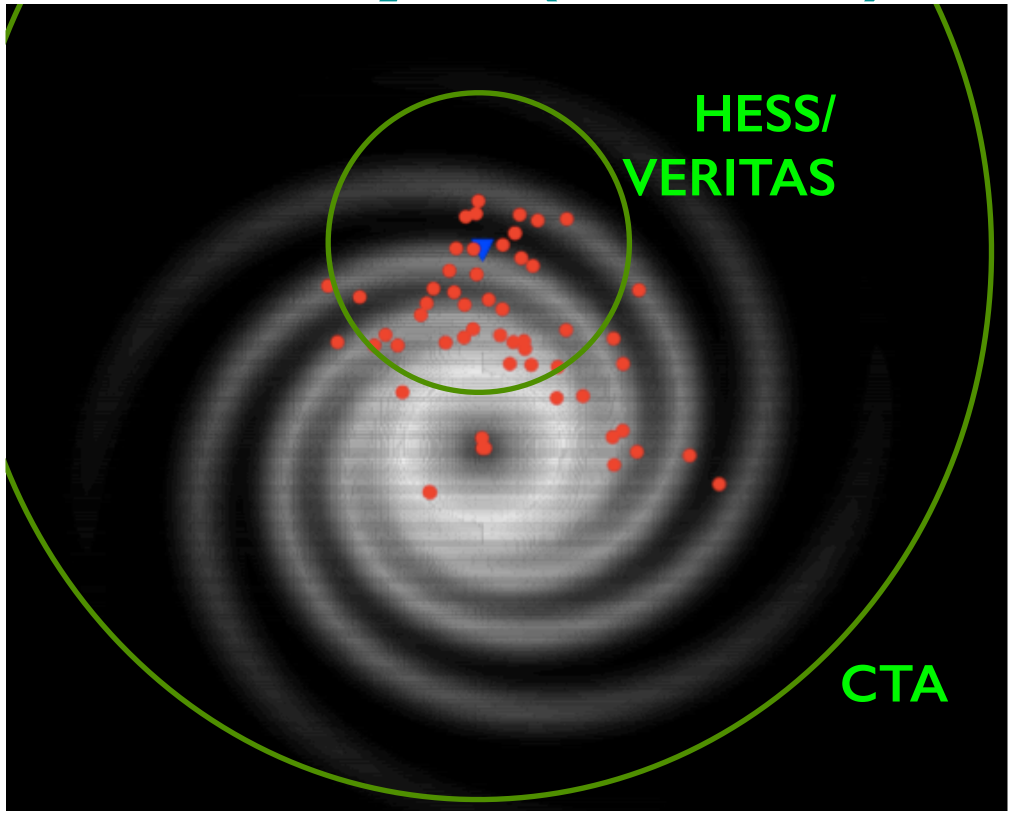
- **6 KSPs**:
  - Galactic Plane Survey, 1620h
  - Galactic Center,
    525 (center) + 300 (10º×10º) h
  - Large Magellanic Cloud, 340 h
  - PeVatrons (50h × 6 sources)
  - Star forming regions (270 h)
  - Transients (binaries, …?)
- **Early in CTA lifetime** →
  - produce legacy data set

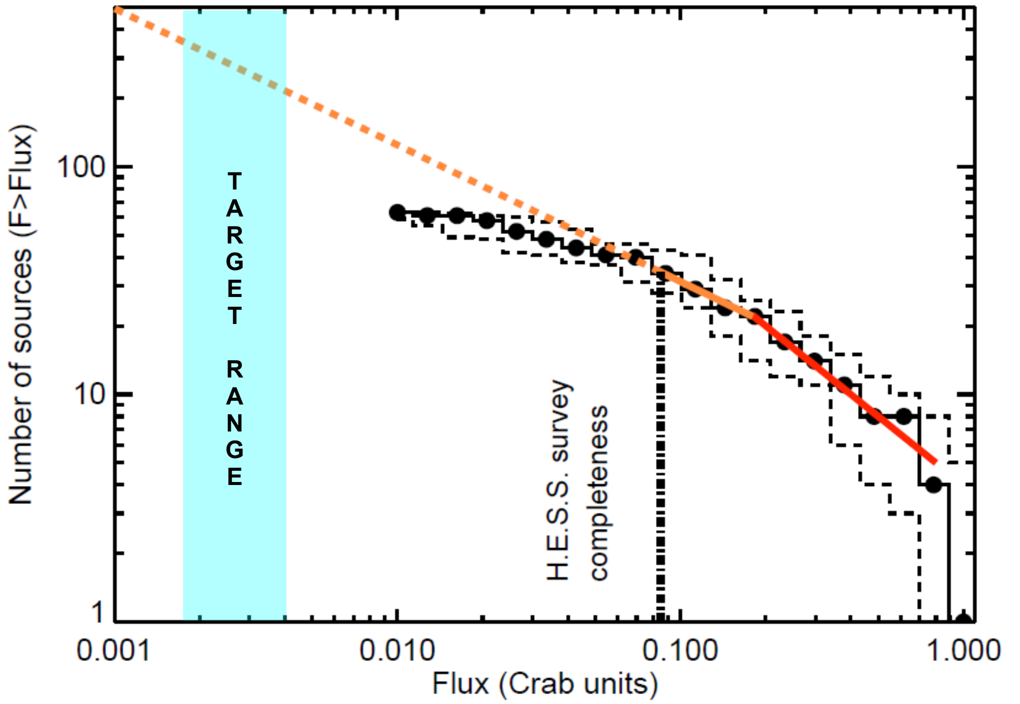




Galactic Plane Survey (GPS)

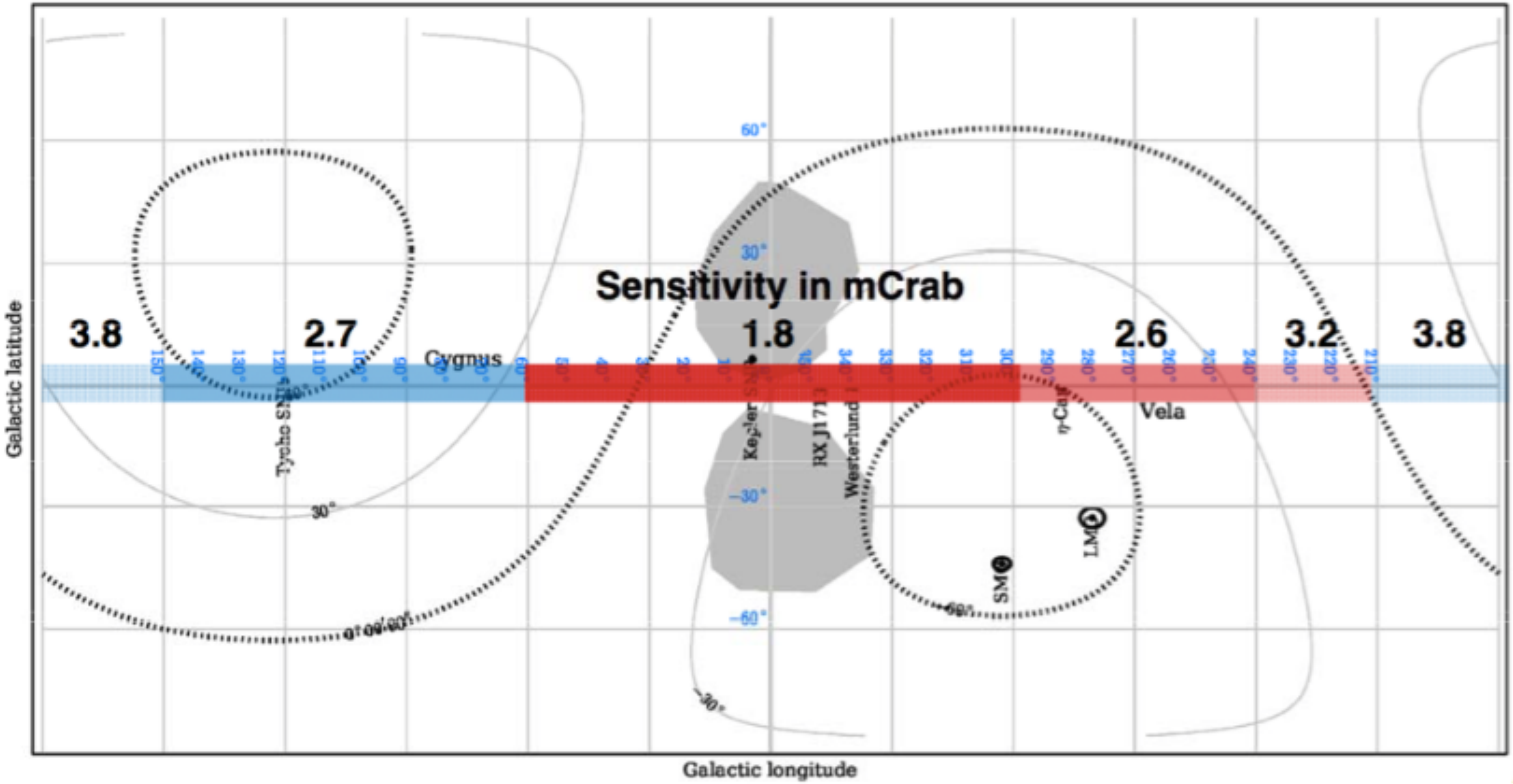
- ★ **Discover** new VHE source classes and unexpected phenomena
- ★ **Search** for Galactic PeVatrons
- ★ **Increase** population of known Galactic sources by factor ~5
- ★ **Detect** new binaries and other transients
- ★ **Measure** large-scale diffuse emission
- ★ **Provide** first-look science data to other KSPs
- ★ **Produce** a multi-purpose legacy dataset to MWL community





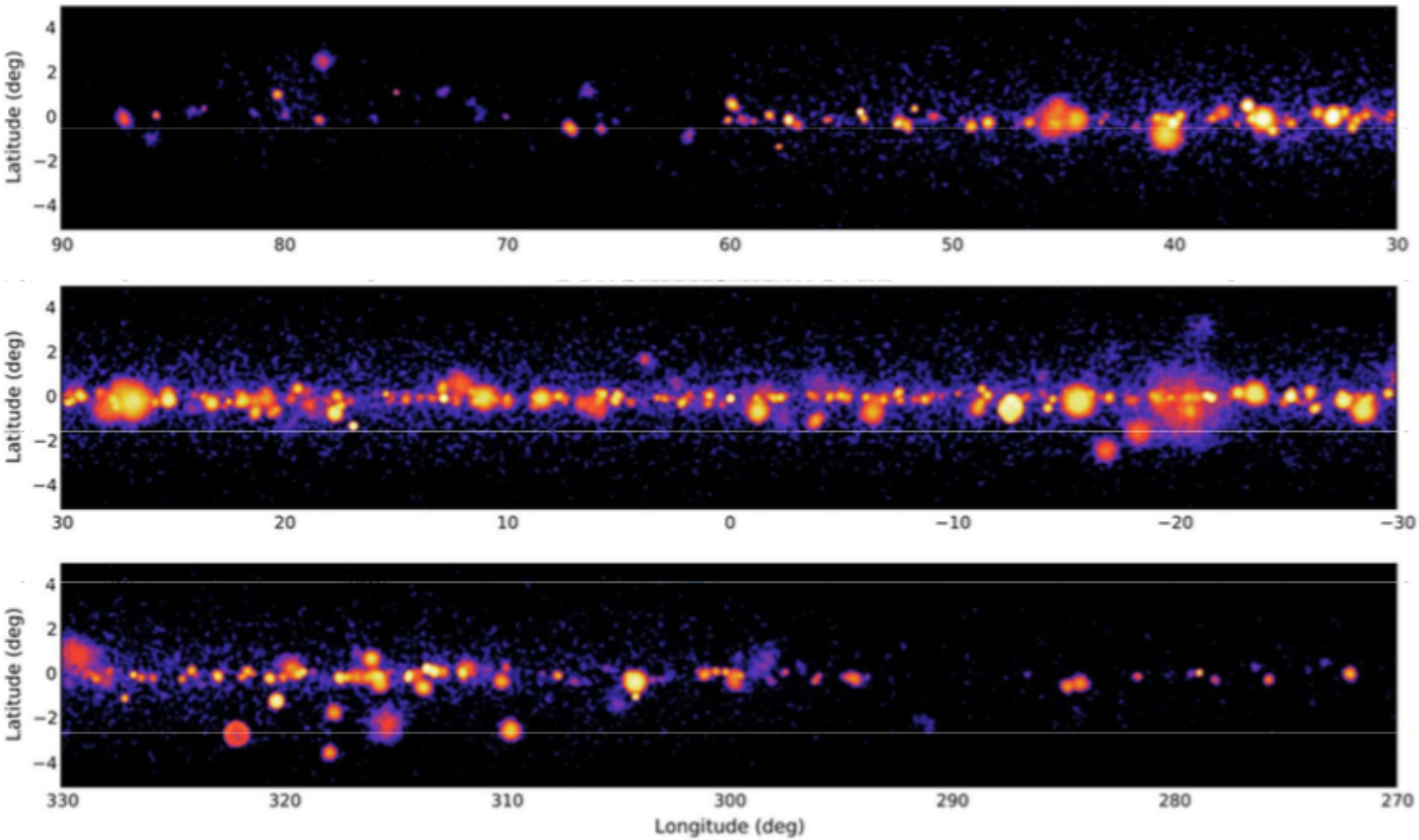
GPS sensitivity

Entire plane surveyed to < 3.8 mCrab - several 100's of sources



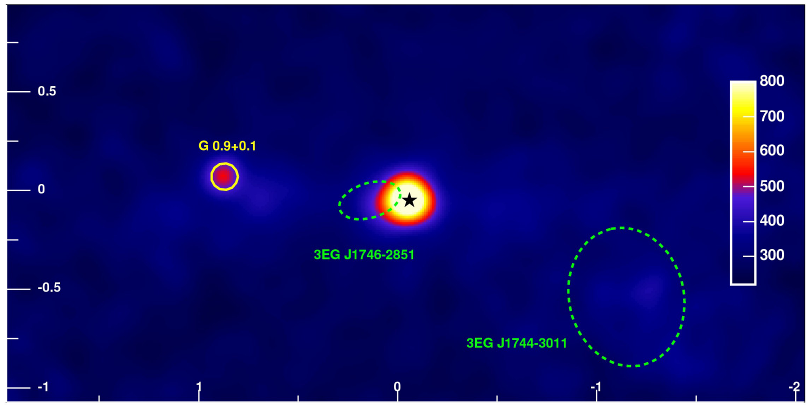
GPS expectations

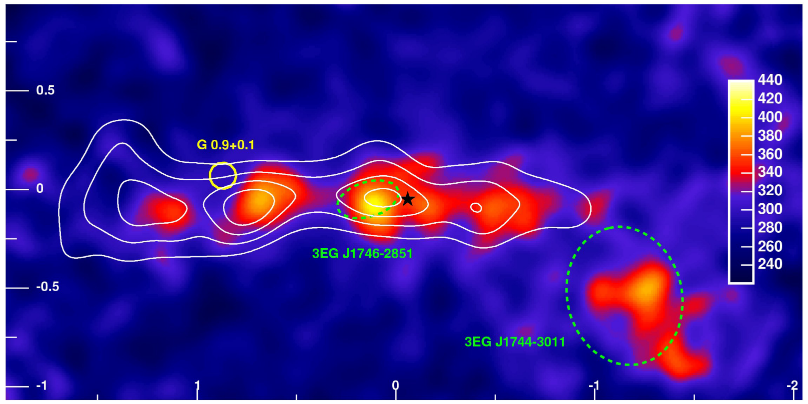
Entire plane surveyed to < 3.8 mCrab - several 100's of sources

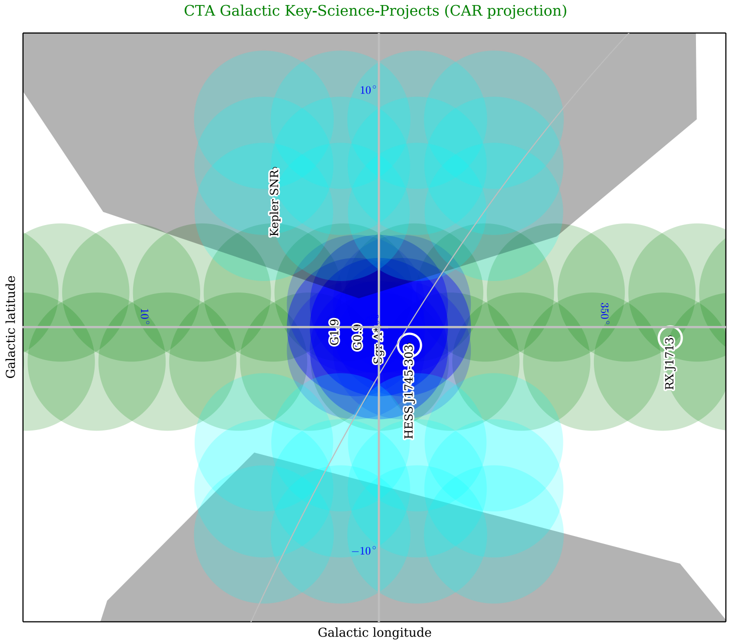


The Galactic Center

- Determine the nature of the central source
  - Sgr A* (SMBH), PWN,…?
- Detailed view of diffuse emission
  - What is illuminating the inner clouds?
- Resolving new, previously undetected sources
- Search for variability close to the central BH
- Study interaction of central source with neighboring clouds
- Fermi Bubbles
- Dark matter searches

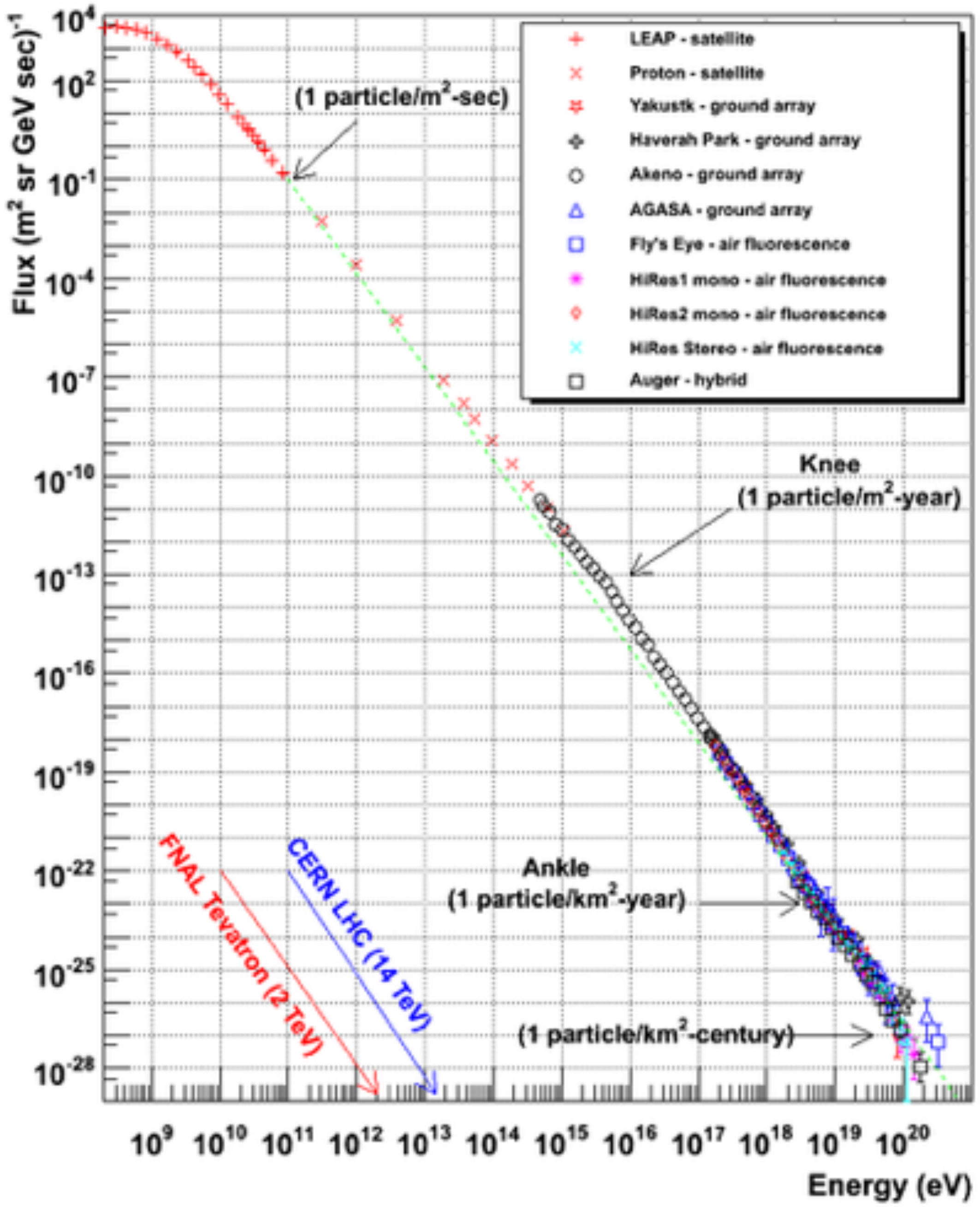






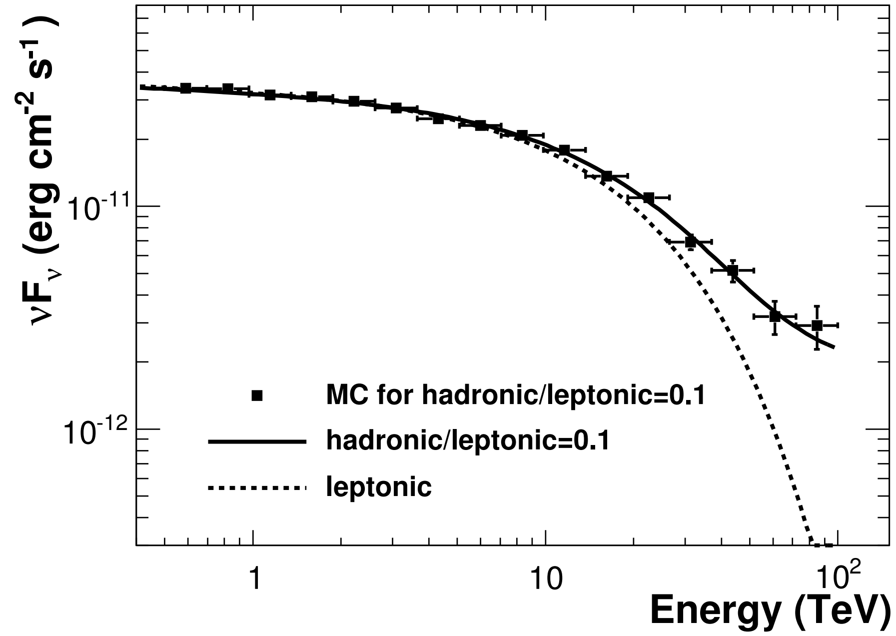
The quest for PeVatrons

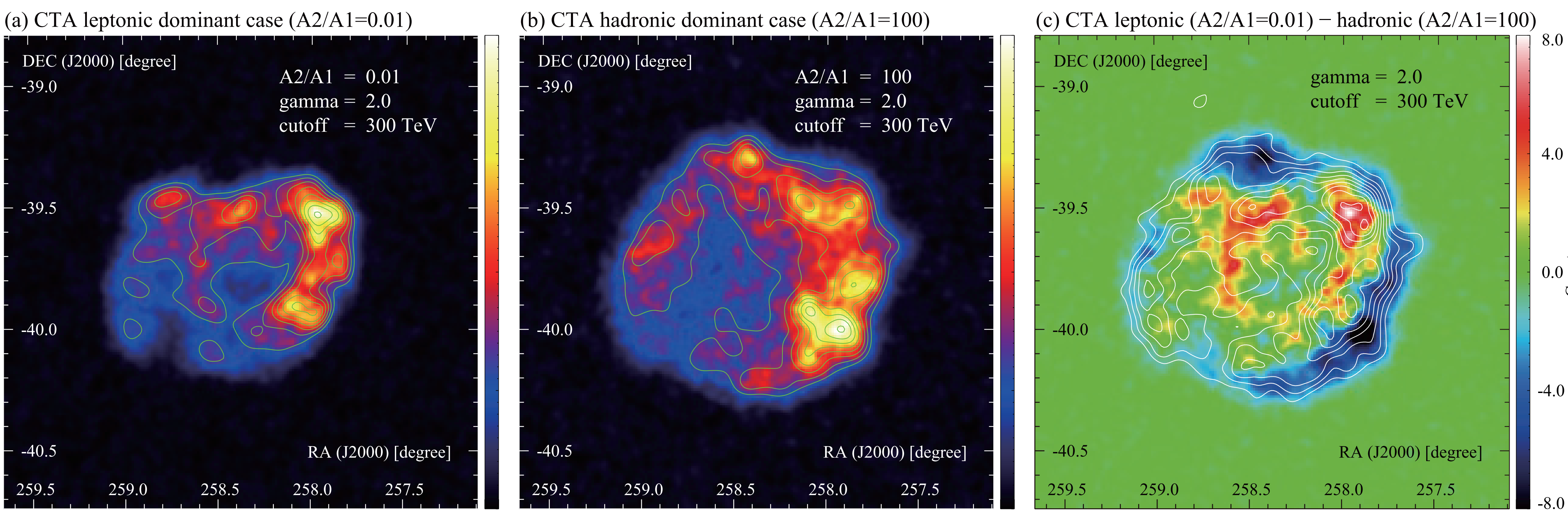
- **Origin of cosmic rays** $E \lesssim 10^{15}$ eV?
- **Usual suspects** are young SNRs:
  - Satisfy the CR energy budget
  - There are known mechanisms for p acceleration in shocks
  - π^0 kinematic cutoff observed for IC 443 and W44 (evolved SNR)
- **But**: no evidence for $E_\gamma > \sim 10^{13}$ eV
- **Approach**:
  - Measure emitters of $E_\gamma \sim 100$ TeV
  - Disentangle hadronic/leptonic contributions
  - Deep study RXJ1713 (50 h)
  - Find 5 candidates from GPS (5×50 h)



RXJ1713

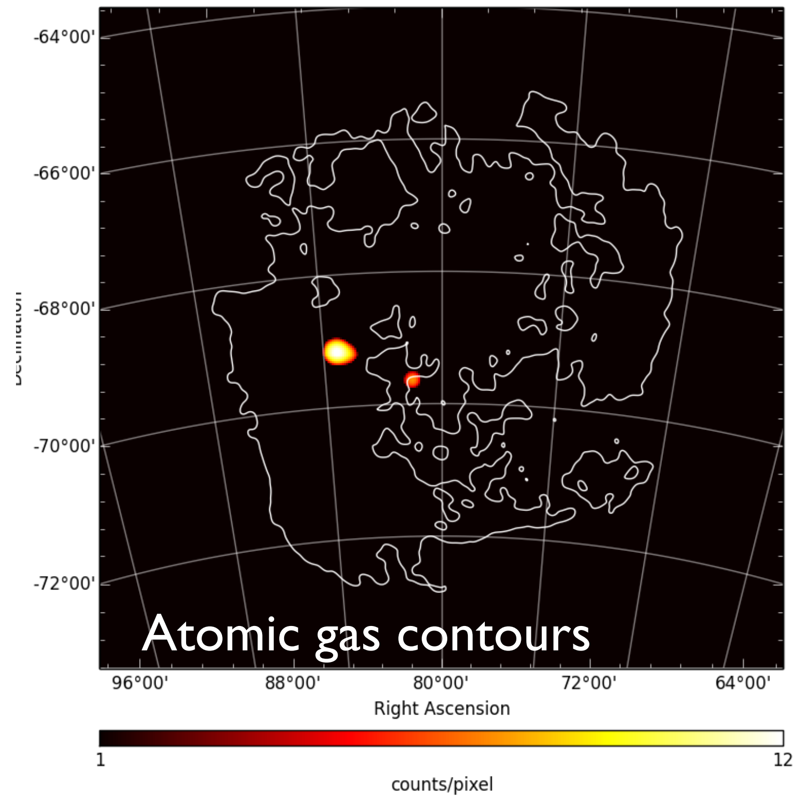
- **Brightest** SNR
- Spatially **resolved**
- **Lepton/hadron emission discriminated** by:
  - Shell morphology
  - Spectrum
  - Illumination of surrounding molecular environmer



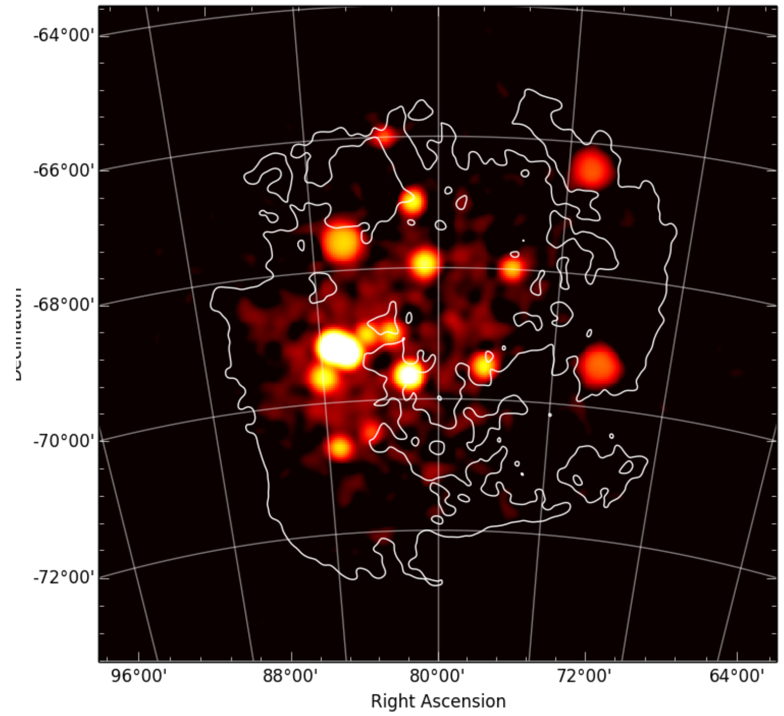


Large Magellanic Cloud Survey

- **A laboratory for CR production** and transport studies
- Approximately **face-on galaxy**:
  - No absorption, no source confusion, well known distance (49 kpc)
- **Very rich and active region**:
  - 10% of Milky Way star formation for 1% of its mass
  - largest SFR (30 Doradus), containing SN 1987A
  - most massive stars, densest stellar clusters, 20-60 SNRs, HII regions, super-bubbles, …
- Also considered as potentially good **target for DM searches**



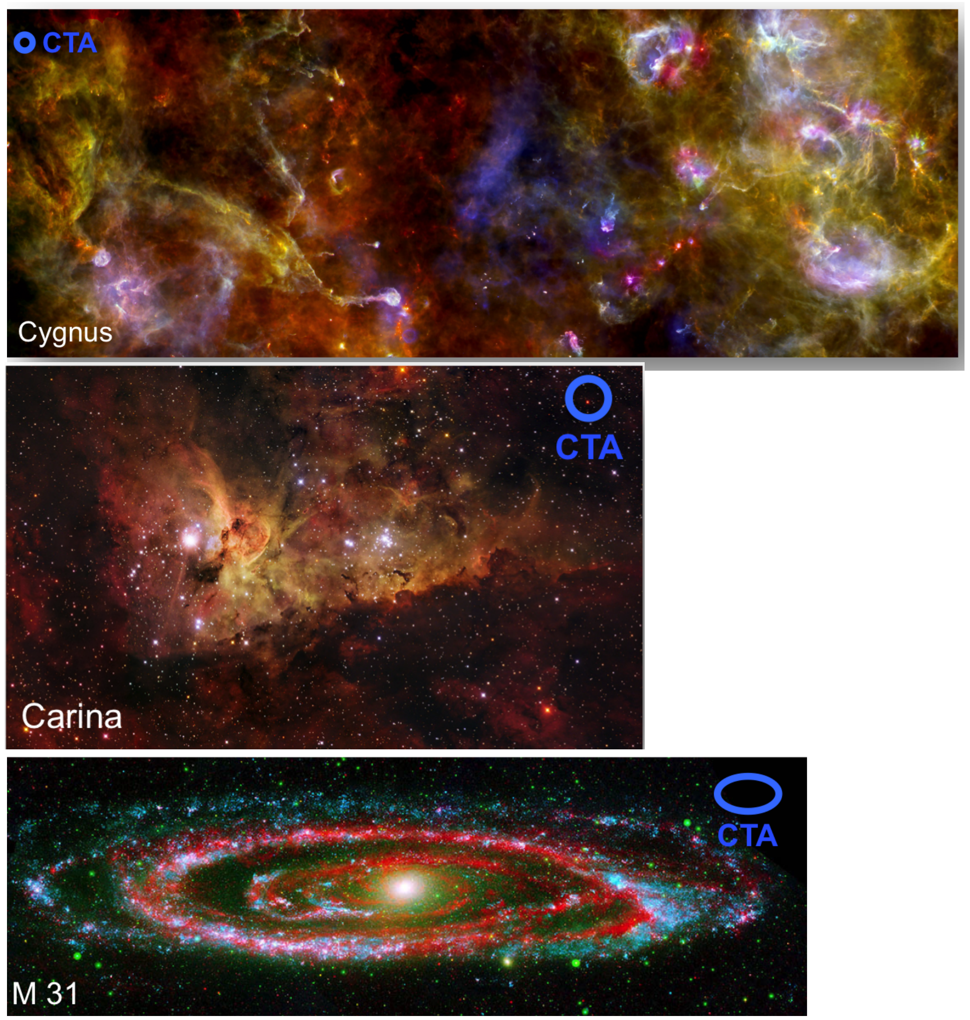
HESS
1 pointing, 16h
0.8-10 TeV

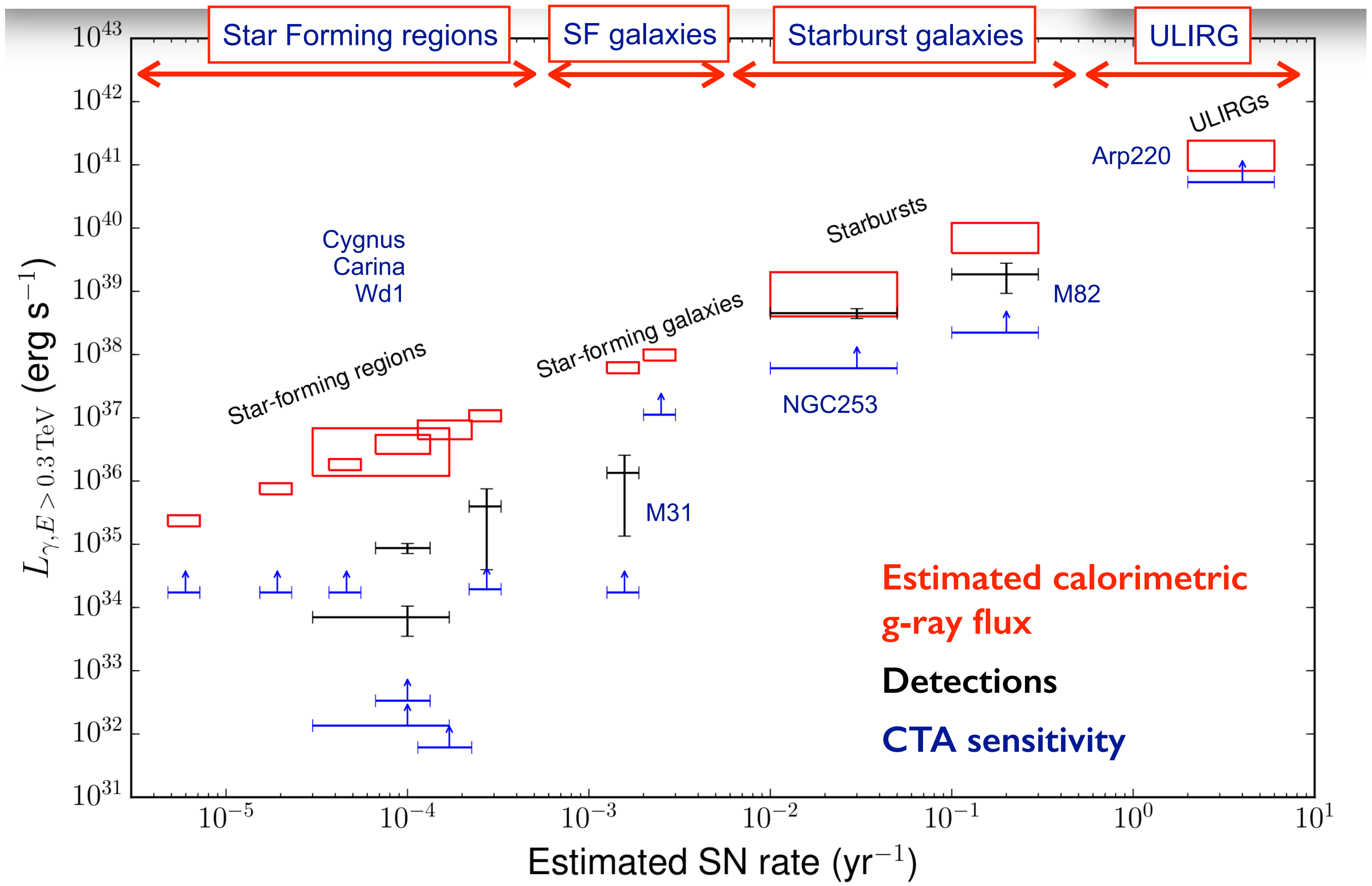


CTA
6 pointings, 340h
0.2-100 TeV

Star forming regions

- ★ Understand the impact of CRs on star formation process
- ★ How ISM influence CR acceleration and transport
- ★ 720 hours on galactic and extragalactic SF regions

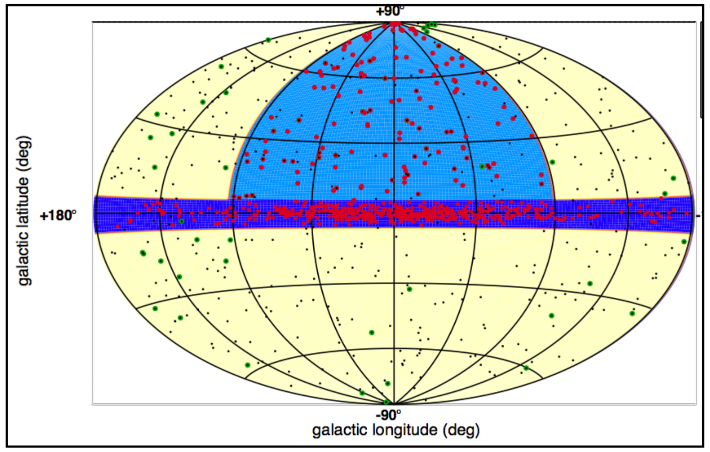


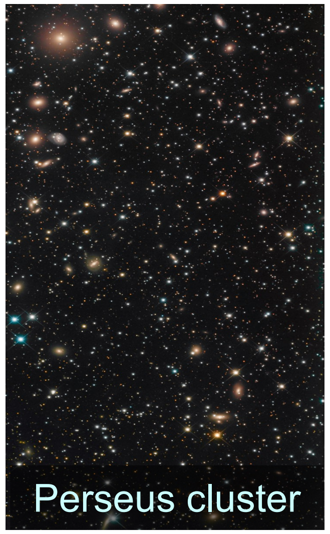


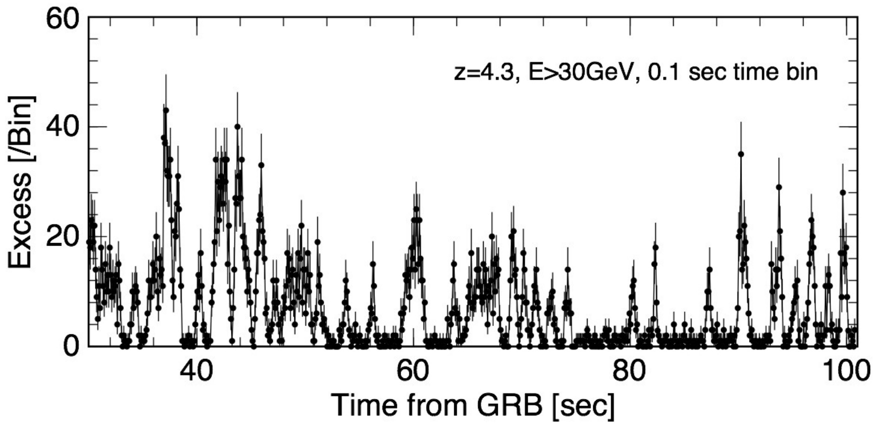
Extragalactic Key Science

Extragalactic Key Science Projects

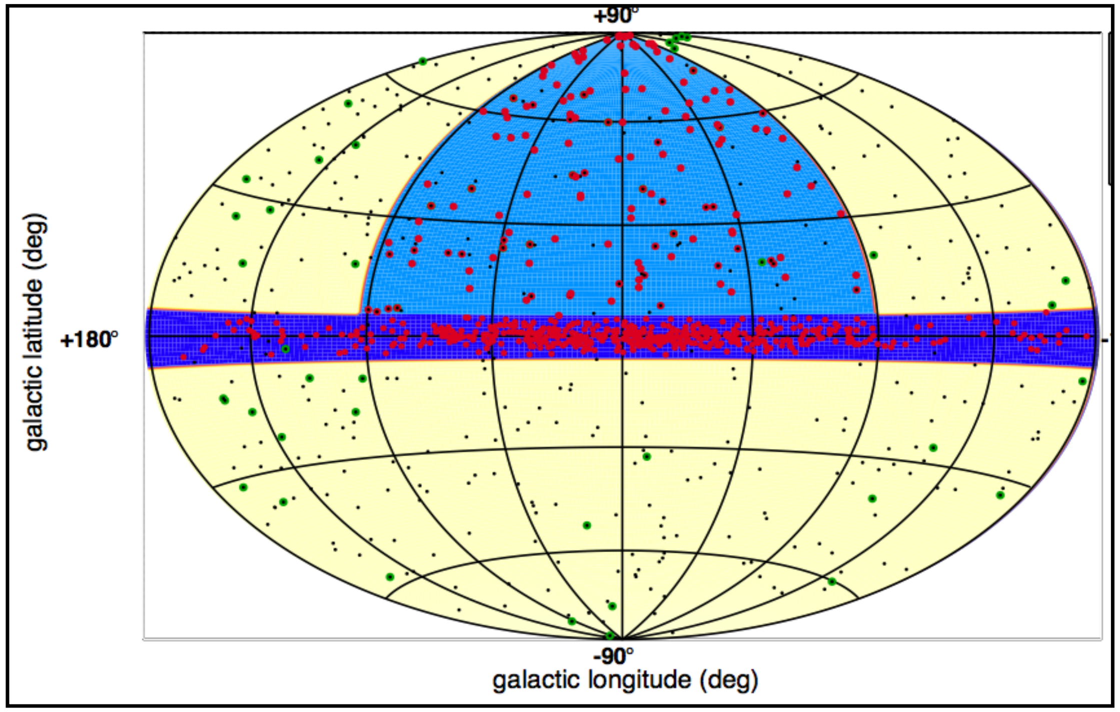
- **4 KSPs**:
  - Extragalactic Survey
  - AGNs
  - Transients (also Galactic)
  - Galaxy clusters
- **Scientific objectives**:
  - What are the relevant particle acceleration and emission mechanisms?
  - Are AGNs sources of UHECRs?
  - Why are there different types of blazars?
  - Are there other classes of gamma-ray emitting AGNs?
  - What are GRBs and up to which energies accelerate particles?
  - How cosmic rays influence the evolution of galaxy clusters?
  - What is the spectrum of EBL and how does evolve with redshift?
  - What is the strength of IGMF?
  - What can we say about Lorentz Invariance violation?

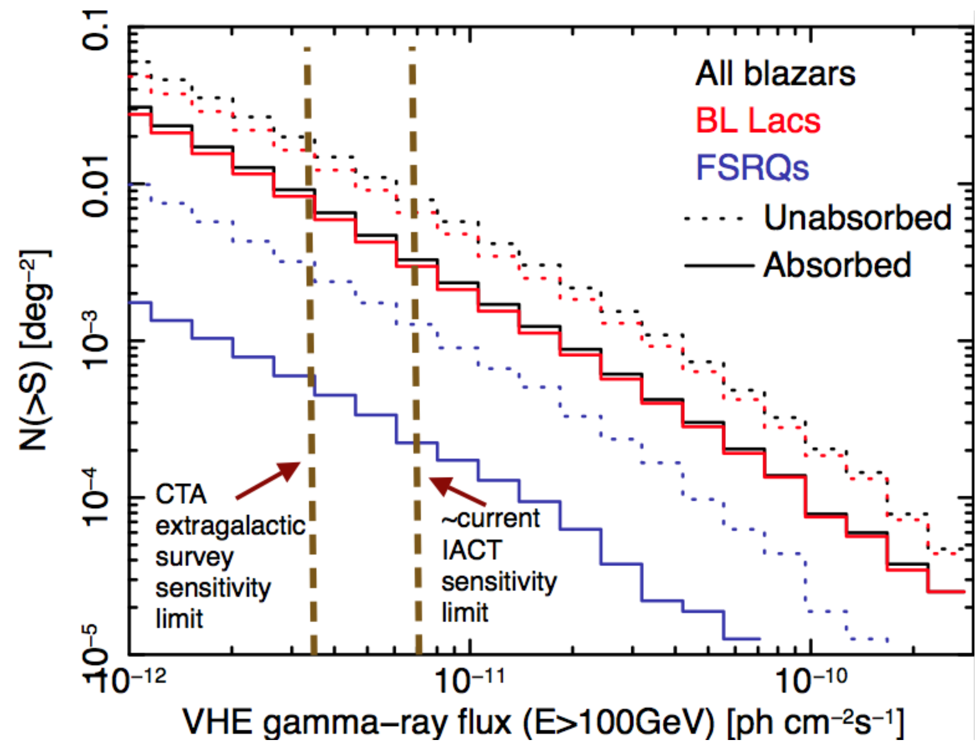






Extragalactic Survey

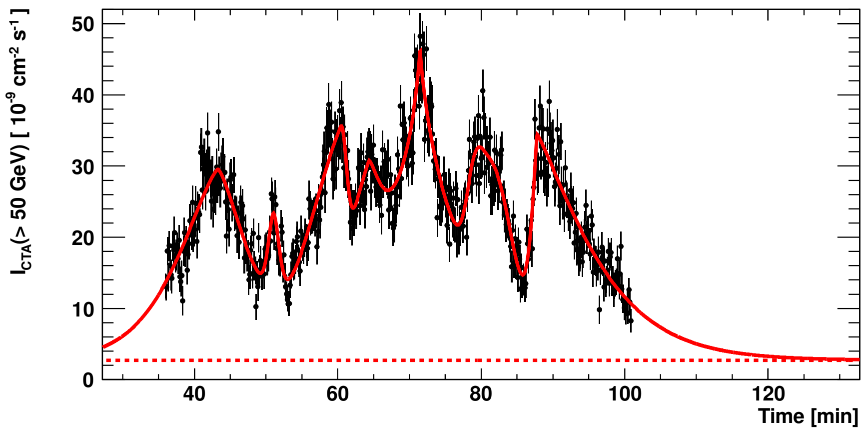


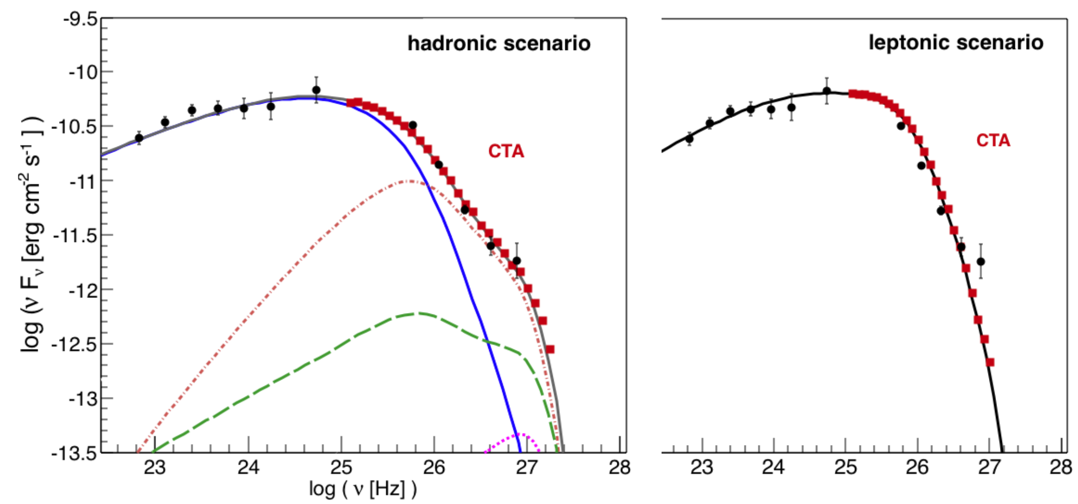


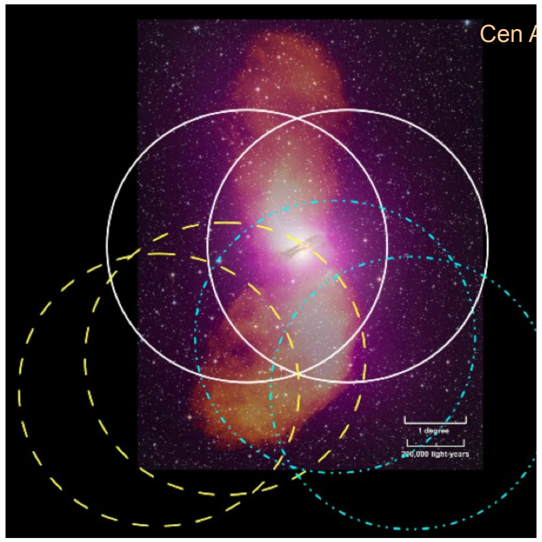
- First **unbiased view** of the extragalactic VHE sky (100 GeV-100 TeV, ~6 mCrab)
  - Possible thanks to CTA large field of view
- **1/4 of the extragalactic sky**
  - Expected ~150 detections based on Fermi + flares
  - Opportunity for serendipitous discoveries
- Measure **luminosity function** for VHE blazars
- Measure **diffuse extragalactic gamma-ray background** → look for anisotropies caused by e.g. DM
- Provide **triggers** for the transients KOP

AGNs

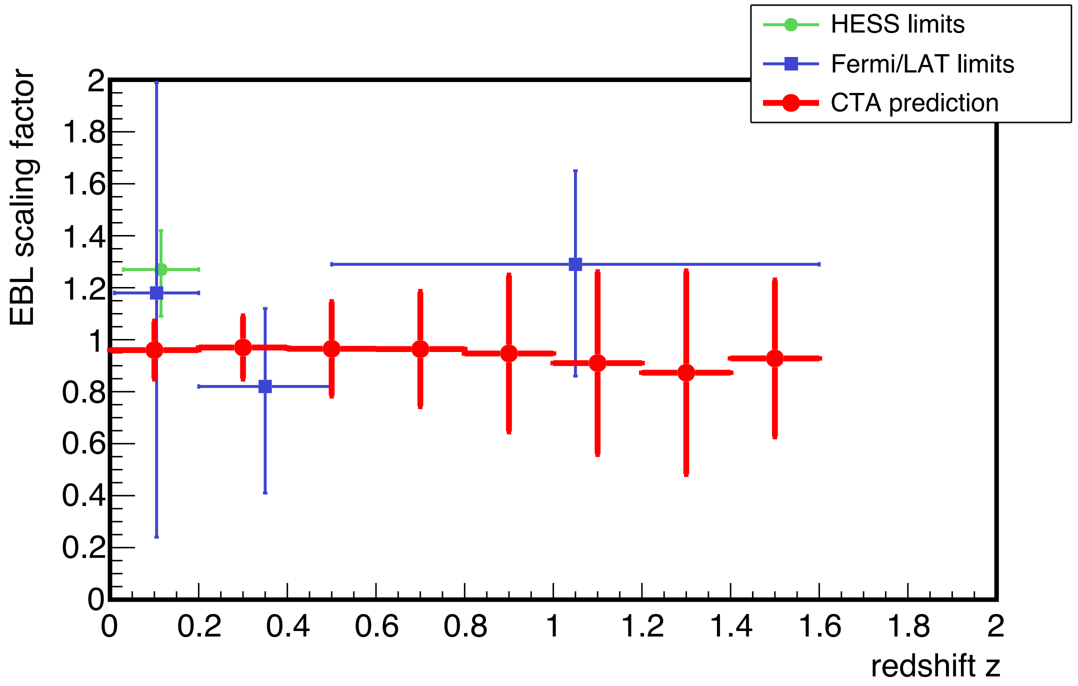
- **Variability**
  - Long term:
    - Duty cycle
    - Periodicity
  - Short Term:
    - Size and location of emitter
    - Acceleration and cooling mechanisms
    - LIV studies
- **Spectrum**
  - Leptonic/hadronic emission
  - EBL studies with source/propagation discrimination
- **Spatial information** (radio galaxies)
  - Where emission is coming from?
  - What is the link with blazars?

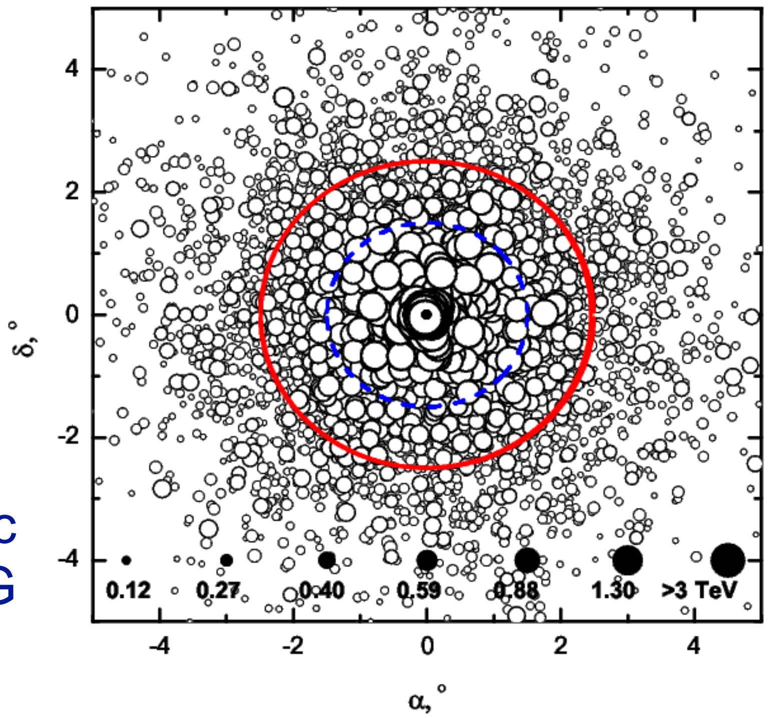






Probing the universe with AGNs





d = 120 Mpc
IGMF =10^{-14} G

- **Extra-galactic background light**:
  - Spectrum from mid UV to far IR
  - 20% precision
  - Evolution up to redshift z>1
  - Measure the cosmic γ-ray horizon
  - Measure the Hubble constant
- **Inter-galactic magnetic field**:
  - Lower limit or detection
  - Imaging analysis: "pair halos" (IGMF > 10^{-16} G)
  - Time resolved spectra: "pair echoes" (IGMF < 10^{-16} G)

Conclusions

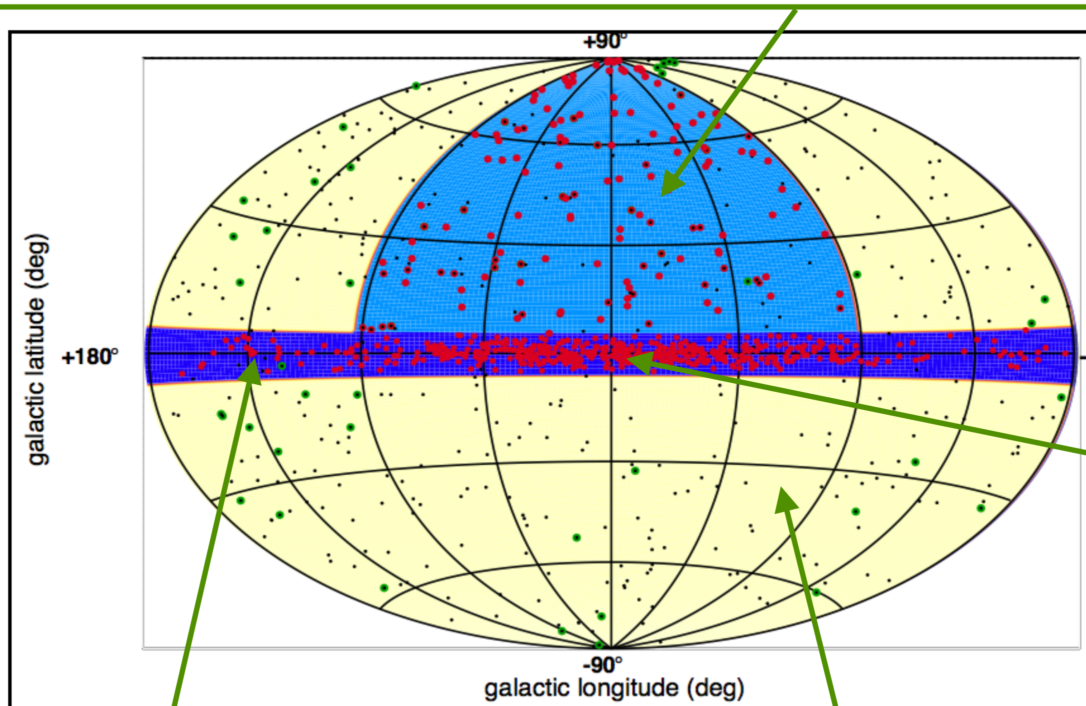
Conclusions

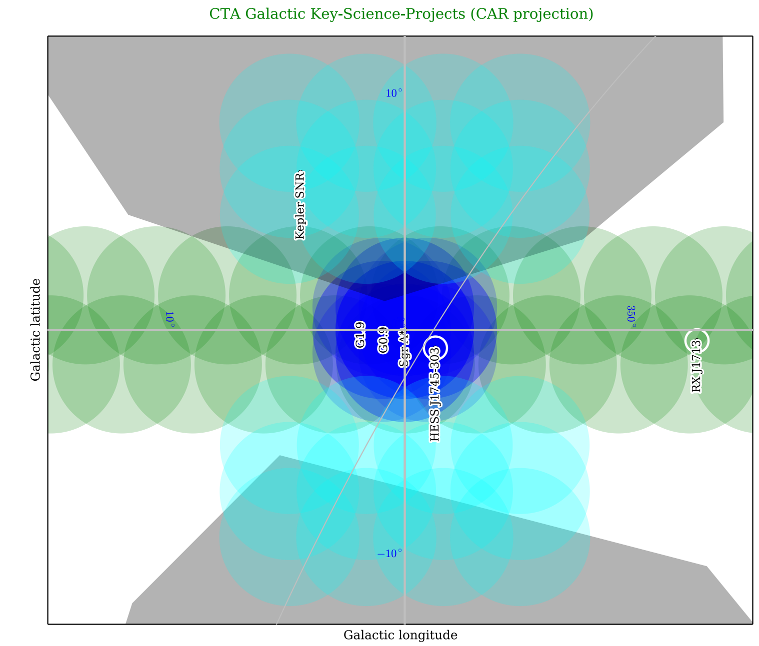
- Next decades gamma-ray astronomy to be dominated by CTA
- The Core Science Program will be developed by the CTA Consortium
  - 9 KSPs + DM program
- Big progress is expected in several science topics:
  - Cosmic rays: origin and role
  - Cosmic particle accelerators
  - Search for Dark Matter (WIMPs and ALPs) + LIV

Backup slides

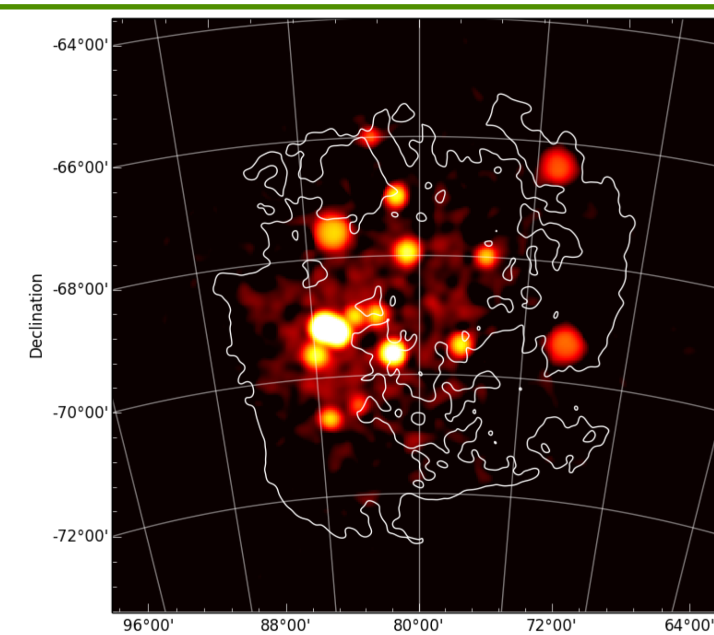
CTA Survey Key Science Projects

- ★ Extragalactic Survey:
  - ✦ 1/4 of sky at ~6 mCrab (1000 h)



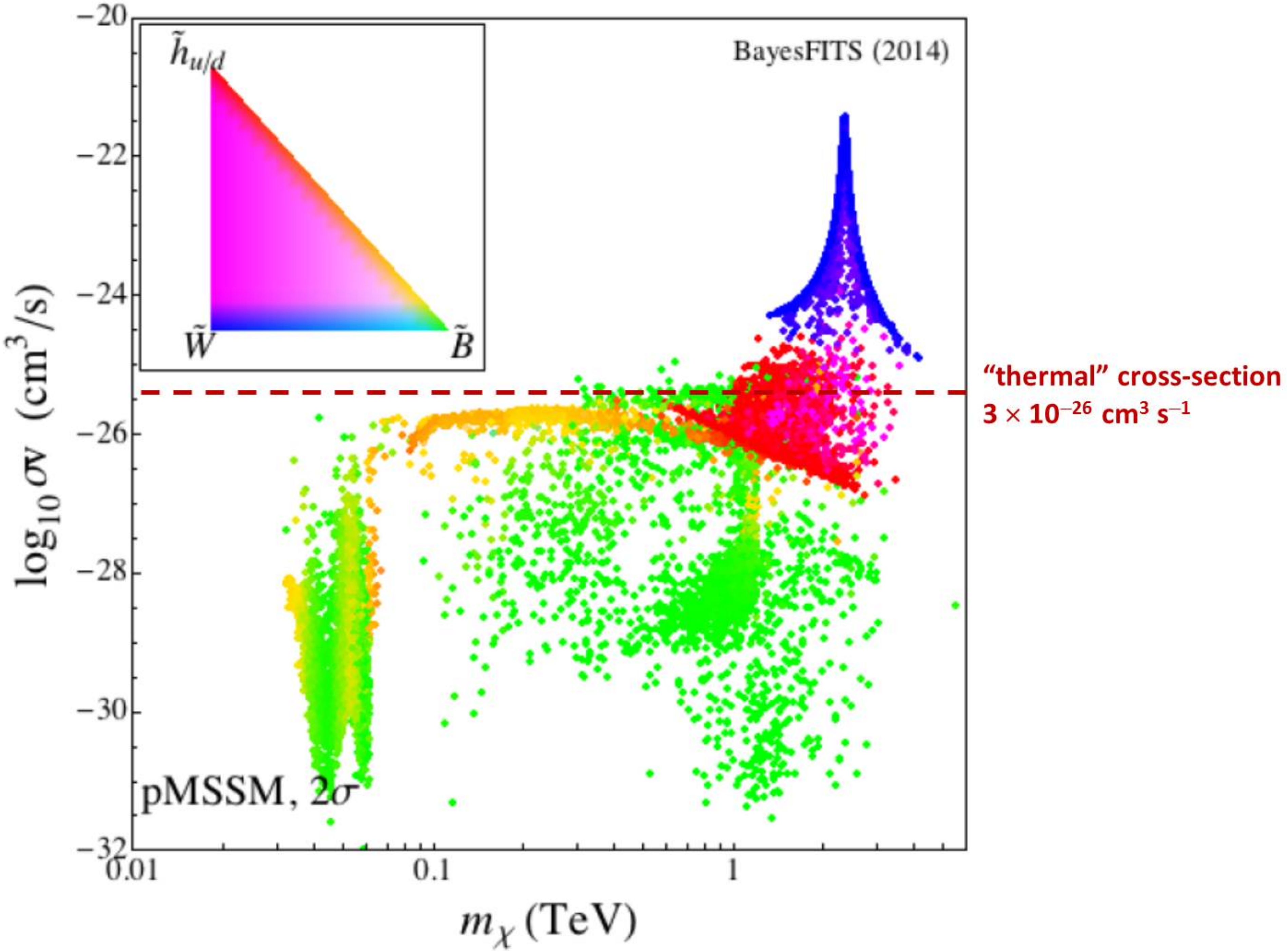


- ★ Galactic Center Survey:
  - ✦ 525 (center) + 300 (10^o×10^o) h



- ★ Galactic Plane Survey:
  - ✦ Entire plane at ~2 mCrab (1620 h)
- ★ Large Magellanic Cloud
  - ✦ 340 h in six pointings

pMSSM scan [Roszkowski et al. 2014]



Galactic Center Halo: DM uncertainties