CTA KEY SCIENCE PROJECTS

RENE ONG

FOR THE CTA CONSORTIUM

OUTLINE

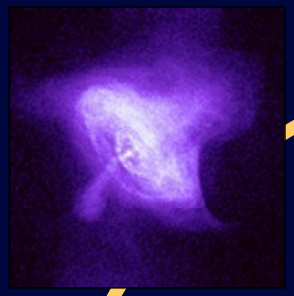
- Brief introduction to VHE γ-rays and CTA
- CTA Science: Core programme, GO programme
- Introduction to CTA Key Science Projects (KSPs)
  - **The Surveys**
  - **Galactic KSPs**
  - **Extragalactic KSPs**
  - **Summary of time allocations; scheduling the KSPs**
- Conclusions

(note: DM/Fund Physics covered in separate talk)

Exploring the non-thermal Universe

Pulsars/PWN

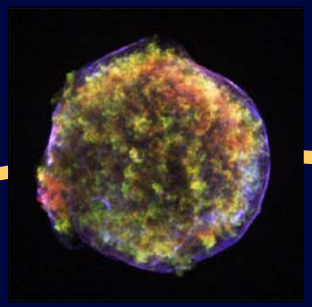
NS dynamo winds



Binaries

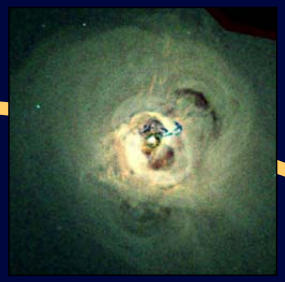
Jets, winds

SNRs



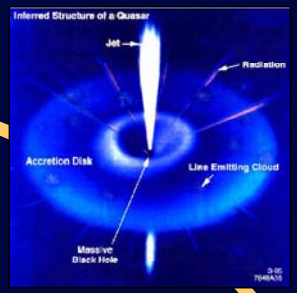
Shocks Fermi Mech.

Starbursts



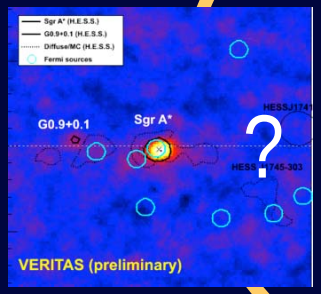
SN activity Cosmic rays

AGN



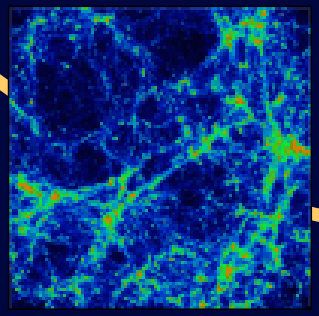
SMBH accretion, jets

GRBs

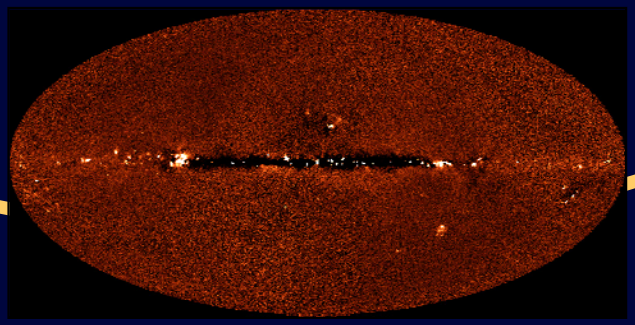


Unknowns (Gal Center)

VHE γ-rays



Dark Matter

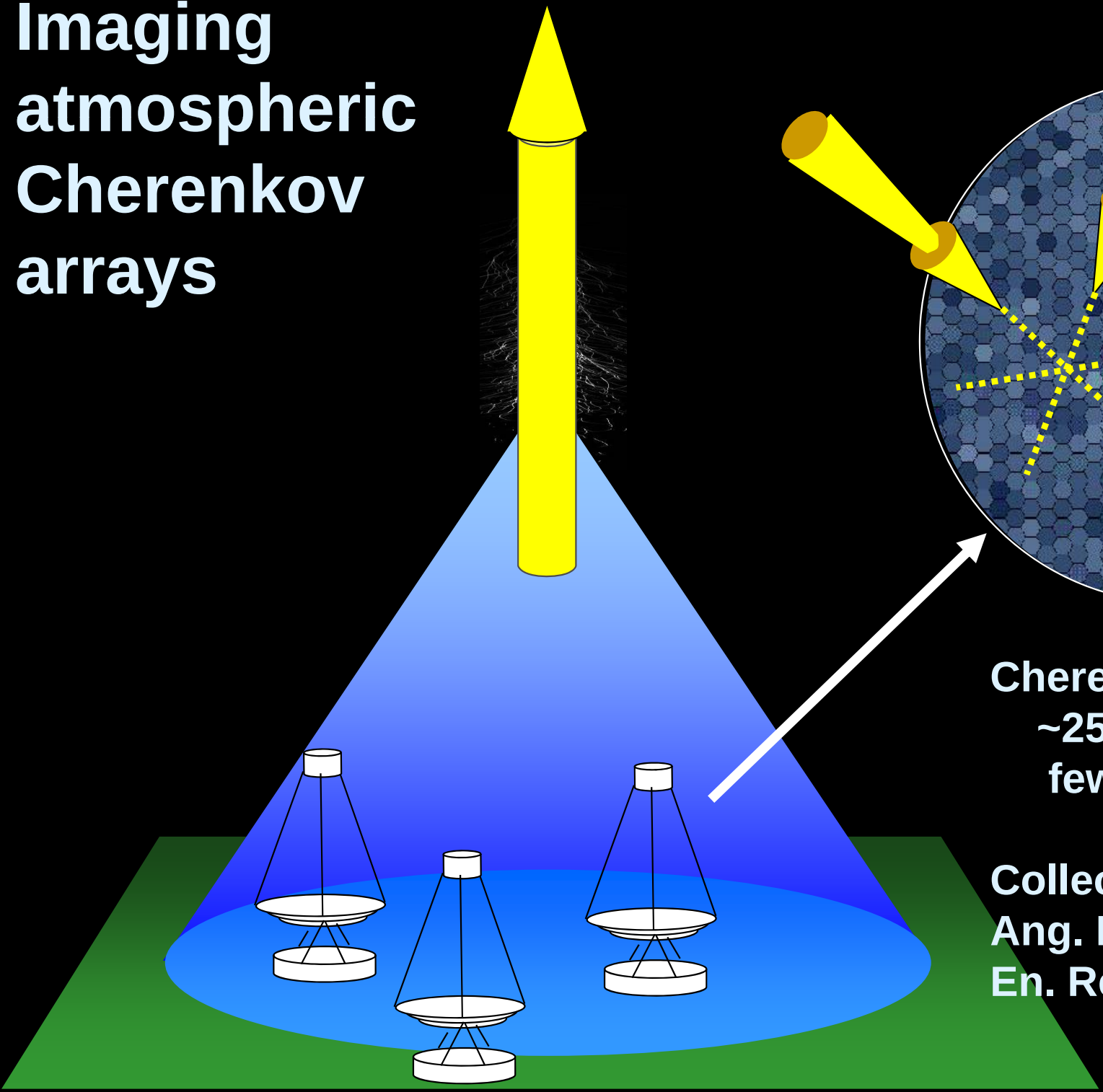


Cosmological Fields

PBHs, QGr

Probing New Physics at GeV/TeV scale

Imaging atmospheric Cherenkov arrays



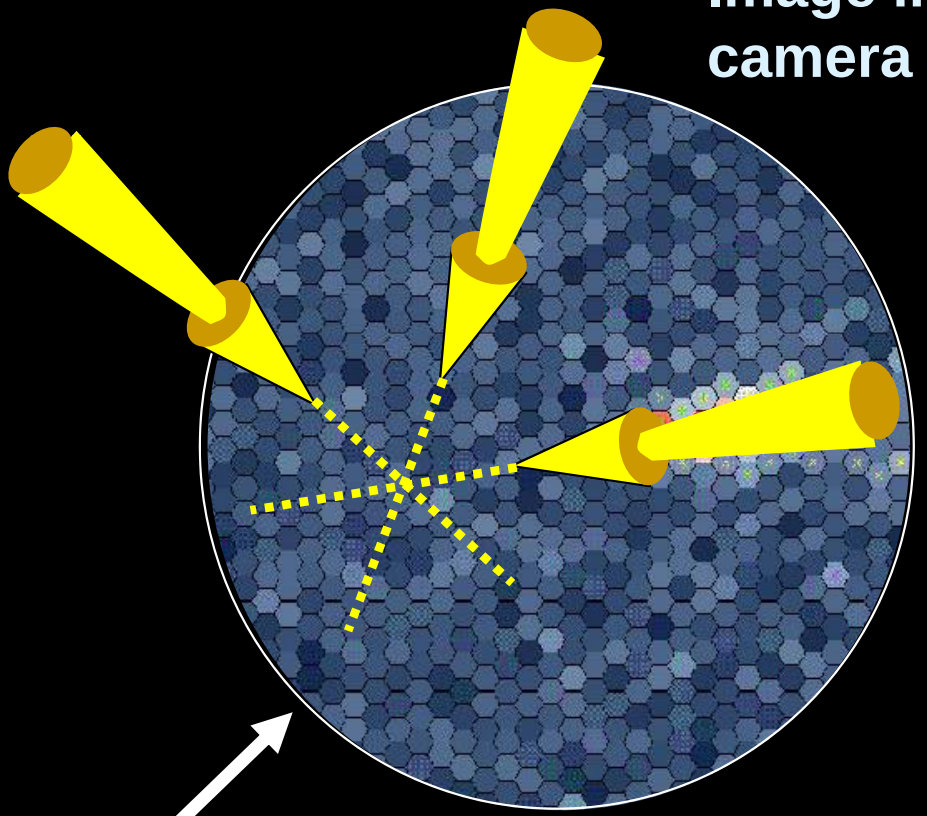


Image in camera

Cherenkov light pool:
~250 m diameter
few ns duration

Collection area ~ > 10^5 m^2
Ang. Res ~ few arc-mins
En. Res ~ 10%


cta
cherenkov telescope array

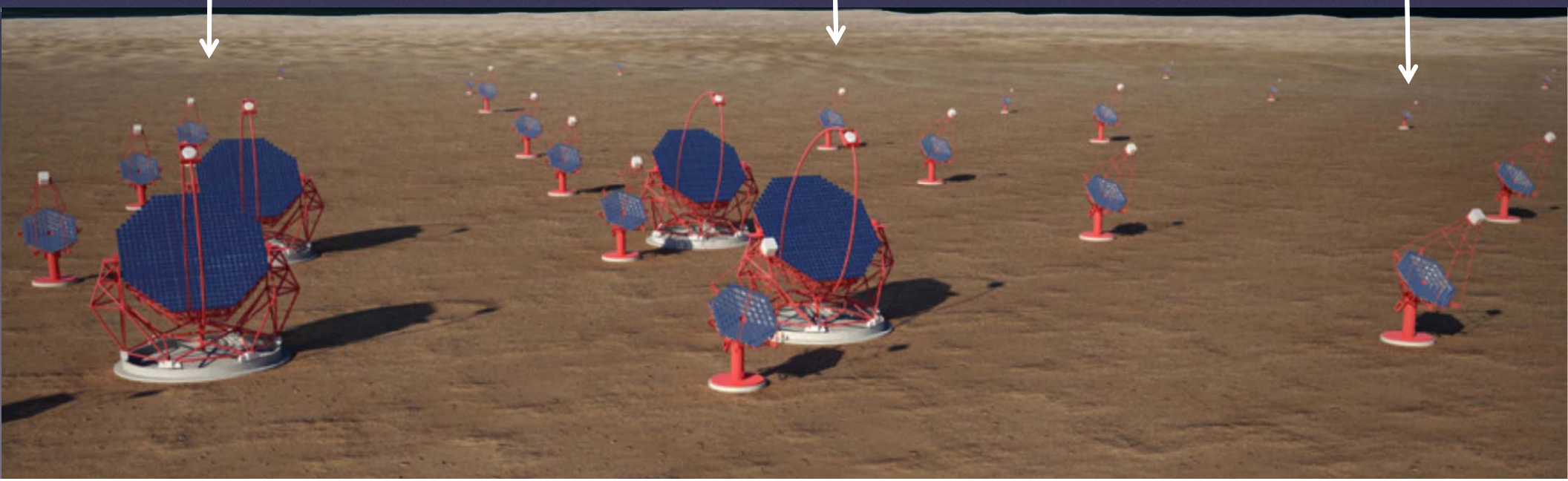
CTA Design (S array)

Science Optimization under budget constraints

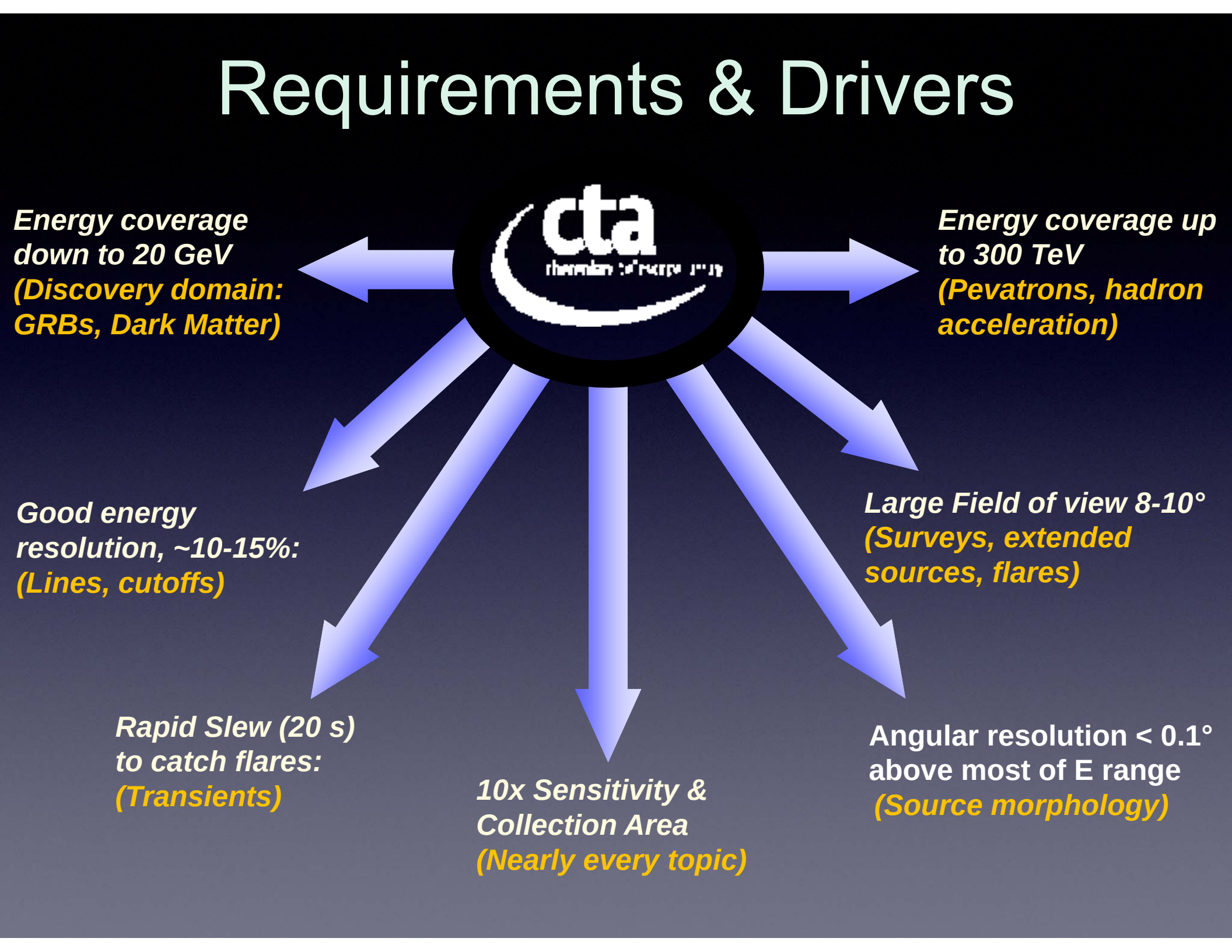
Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LST's)

Medium energies
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
(MST's/SCTs)

High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SST's)

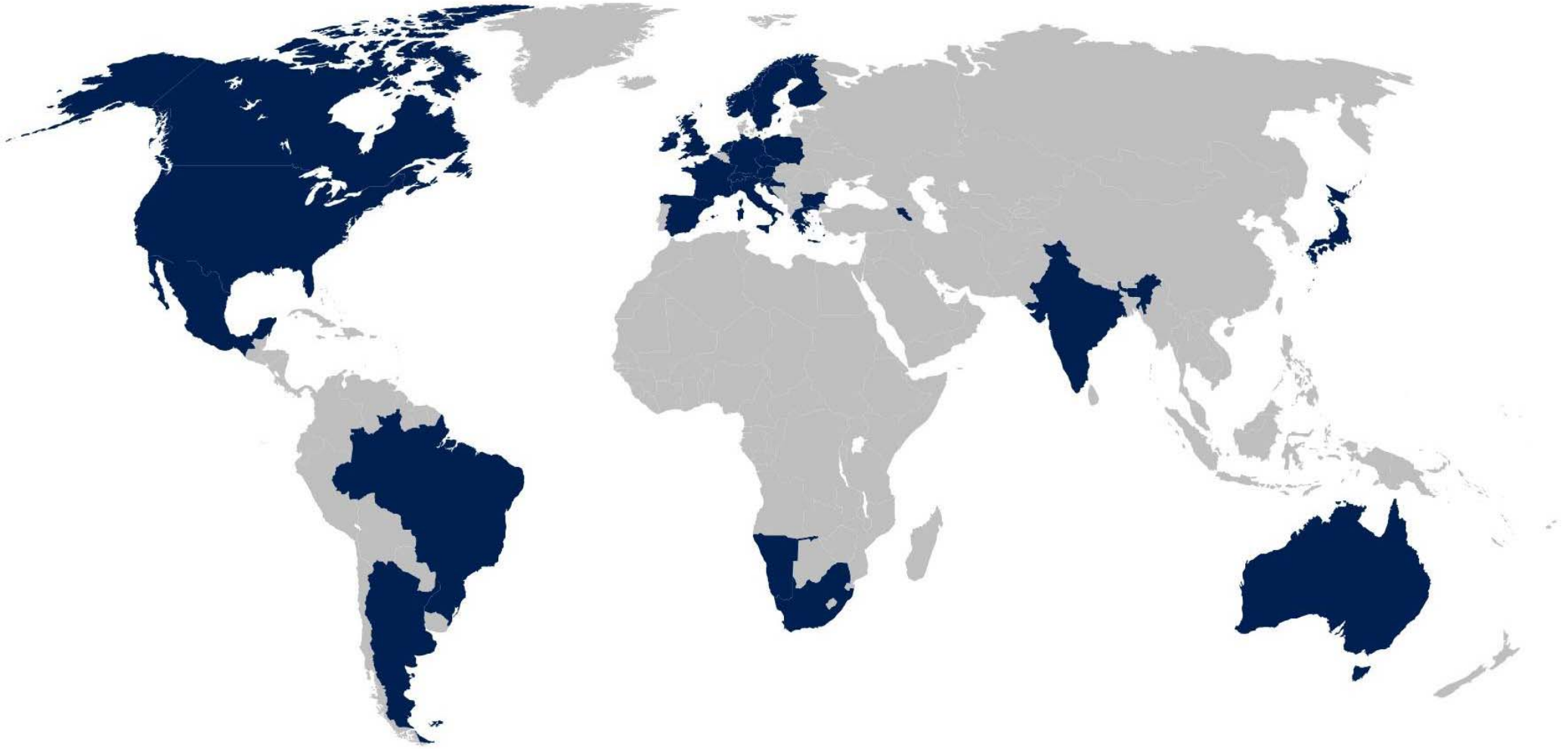


Requirements & Drivers



CTA Consortium

CTA is being developed by the CTA Consortium:



31 countries, ~1200 participants, ~180 institutes, ~400 FTE

THE CTA SCIENCE PROGRAMME

(INCLUDING MATERIAL FROM JIM HINTON & ANDREAS ZECH)

Science Themes

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

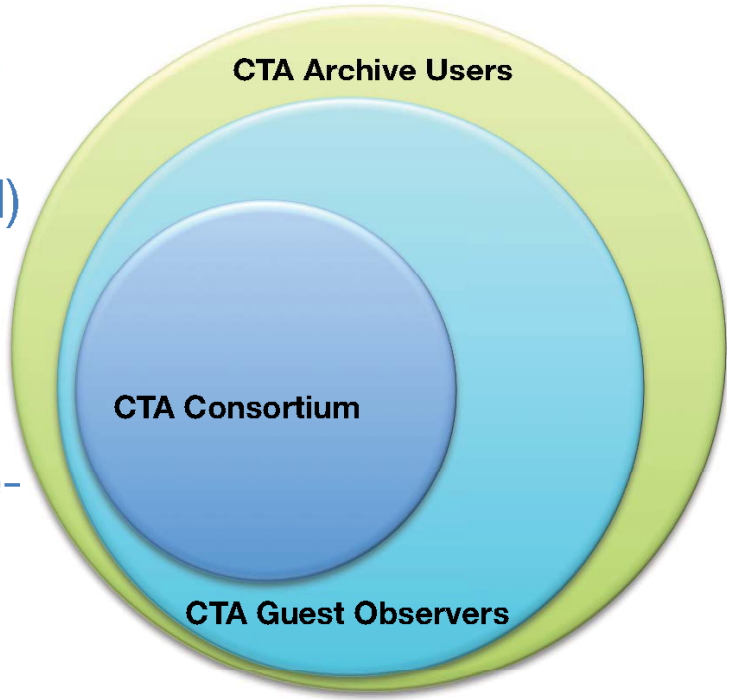
OBSERVATORY PROGRAMME

- Baseline scenario for the first 10 years after completion
  - 40-50% Core Programme conducted by Consortium
  - 50-60% Open time for guest observers (+host country)
  - Consortium time ramping down over first few years – some scenarios being considered:
    - A) 100% years 1&2 then 30% [first AO is late]
    - B) 45% for 10 years [a long time to complete surveys]
    - C) 100% year 1 then 40% [reasonable compromise?]

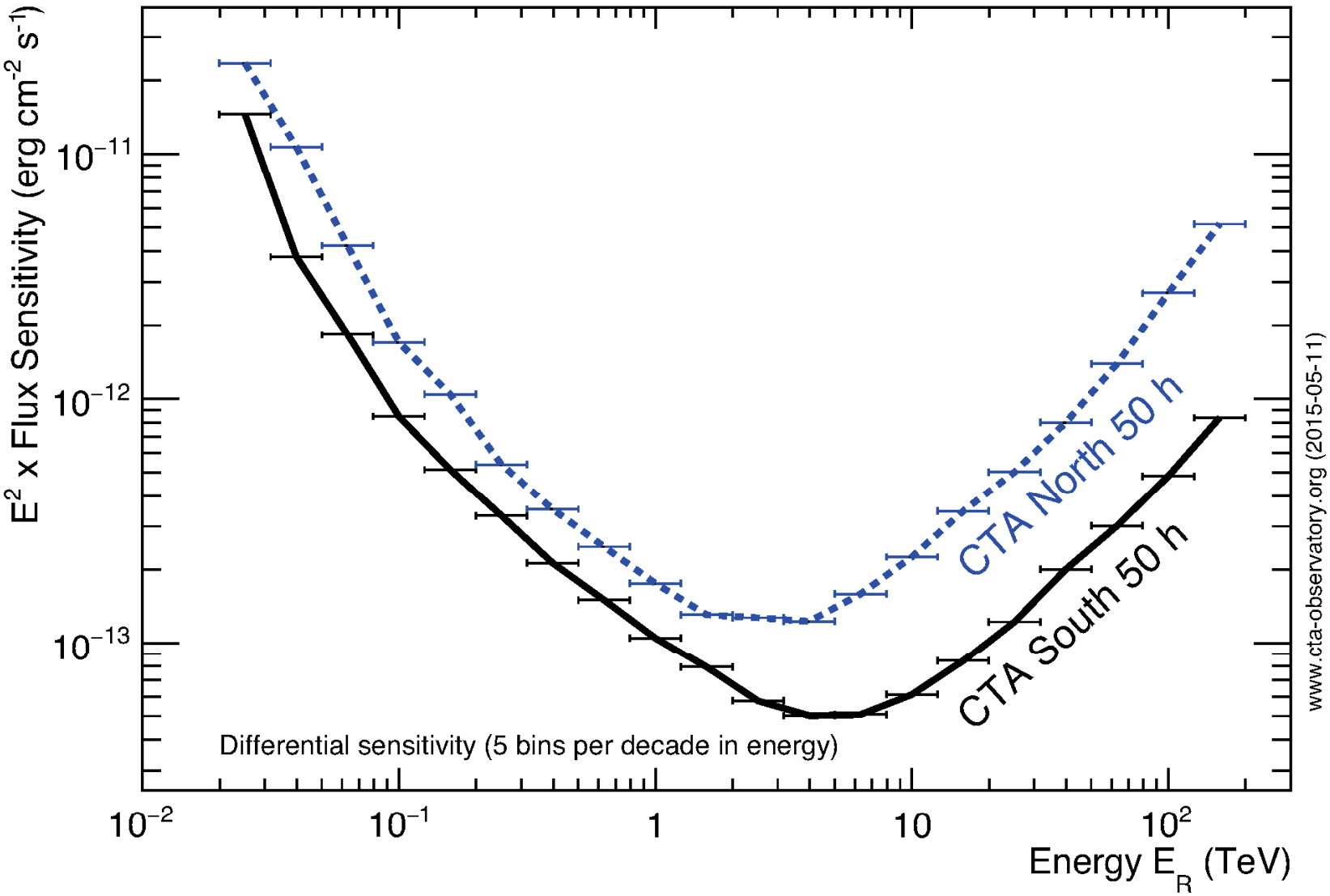
- Proposed Core Programme is selective
  - Most time invested in surveys and population studies rather than important individual targets
    - e.g. targets a single galaxy cluster and a single SNR, and no targeted observations of pulsars, pulsar winds or gamma-ray binaries
  - Huge potential for guest observer proposals – also building on / triggered by results from KSP surveys

USER COMMUNITY

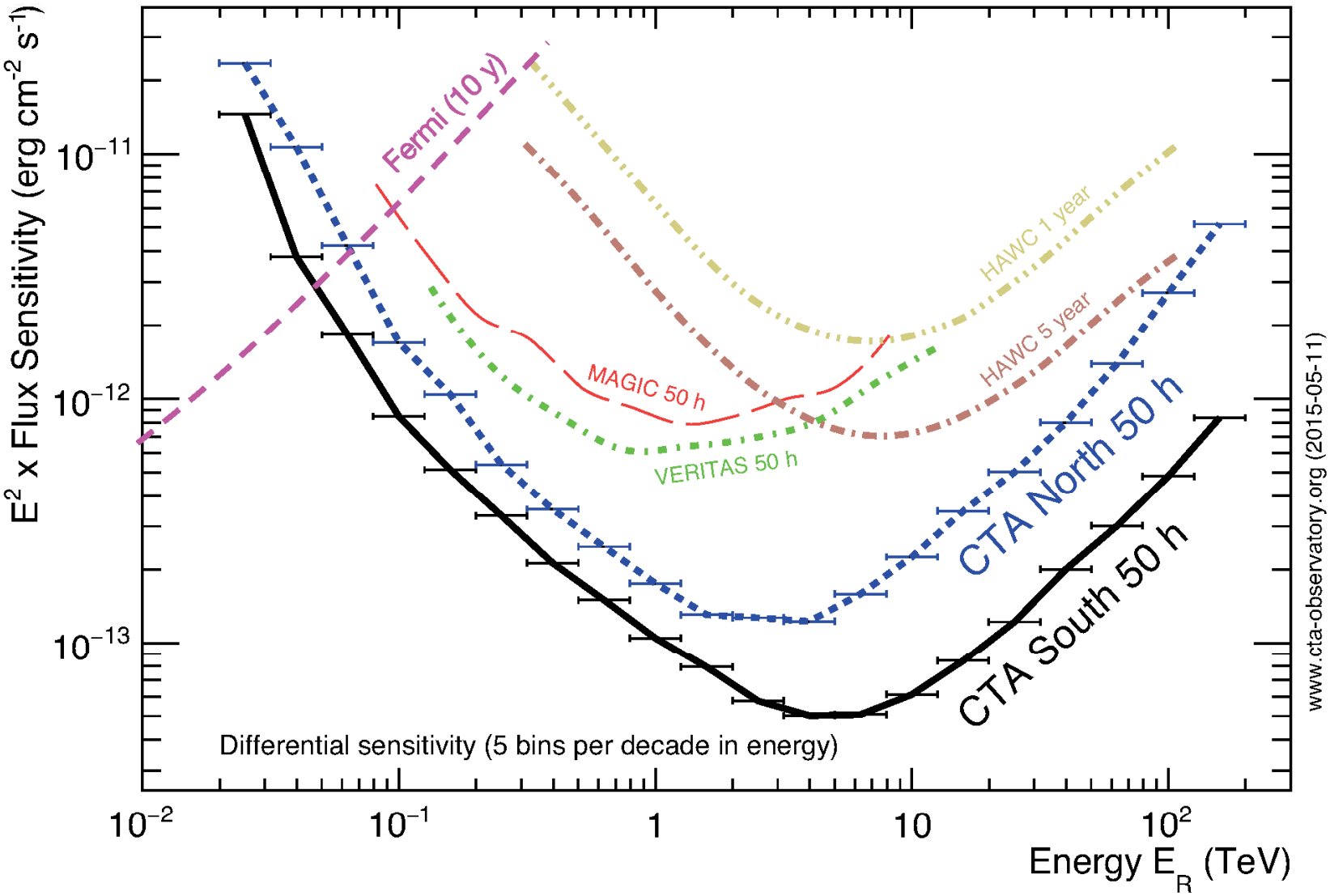
- CTA is the first true open observatory for VHE gamma-ray astronomy
  - Annual AOs for guest observer proposals
    - With PI from participating country
  - Anticipate public archive for all (high-level) data after one year proprietary period
- Community Size?
  - Consortium 1000, Estimated Co-Is of GO proposals O(5000), Co-authors of archive-based publications O(10000)
- Series of workshops held to engage with a wider community
  - Particle Physics, X-ray, Cosmic ray (+several more general)



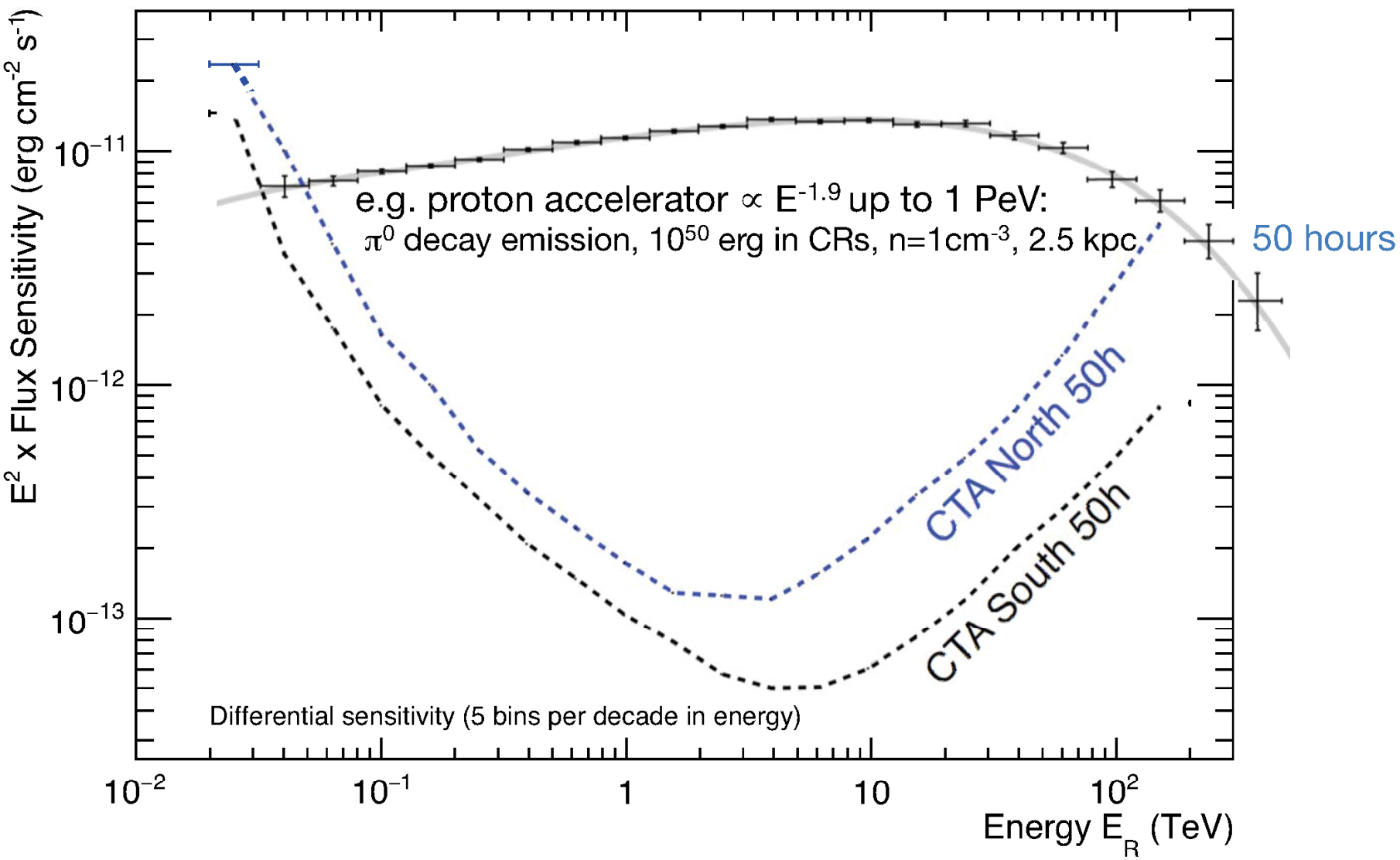
SENSITIVITY



SENSITIVITY

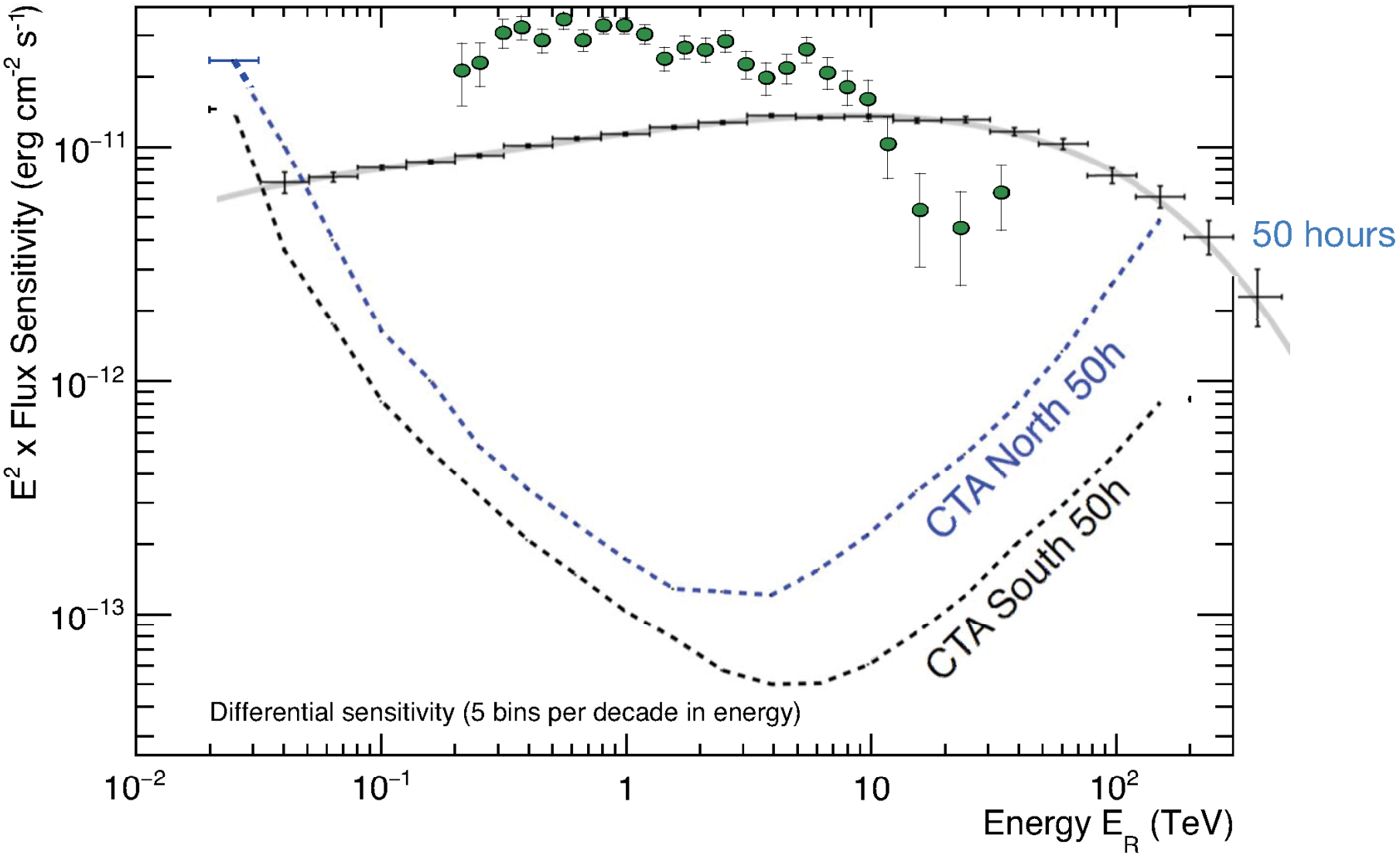


SENSITIVITY

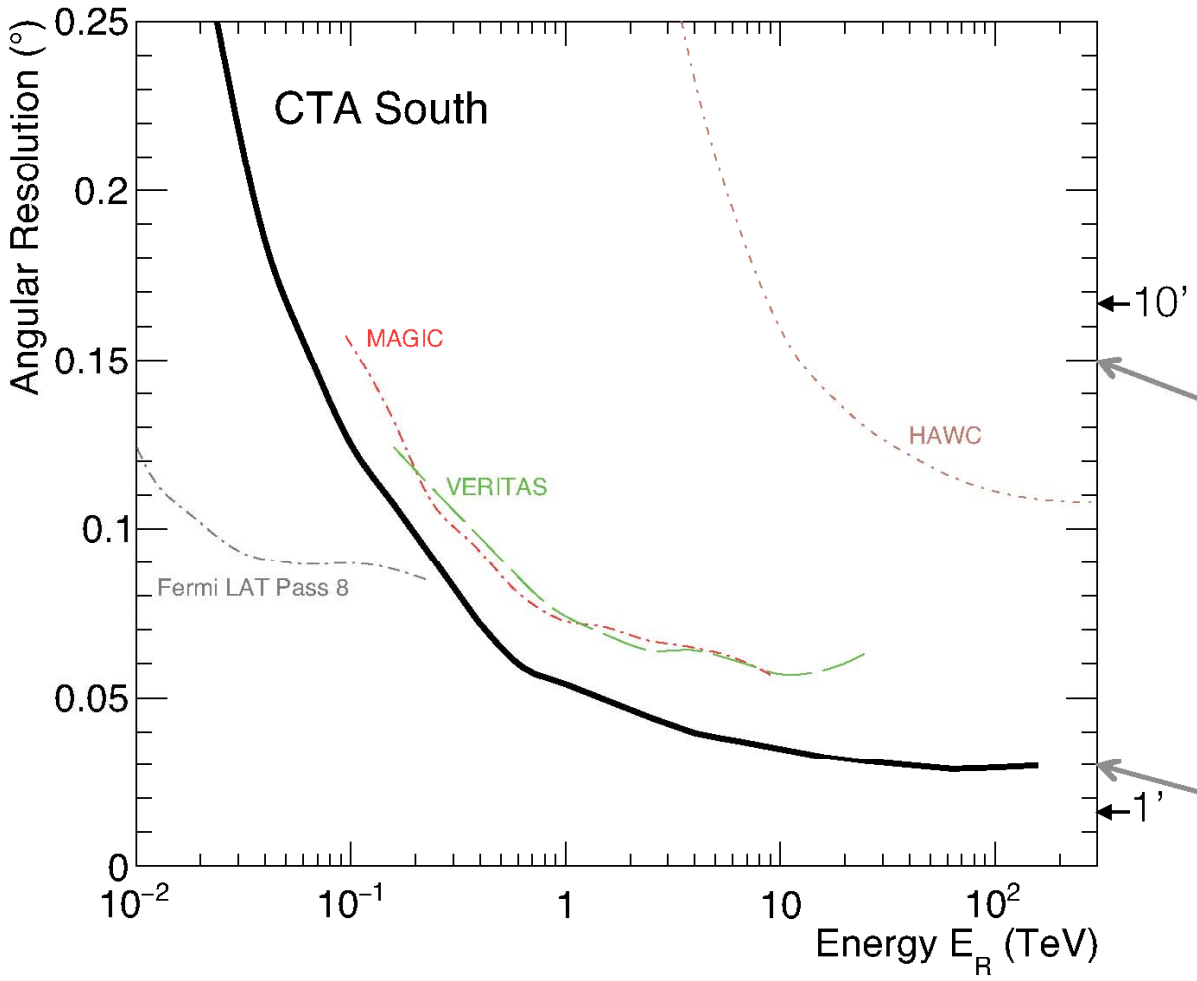


SENSITIVITY

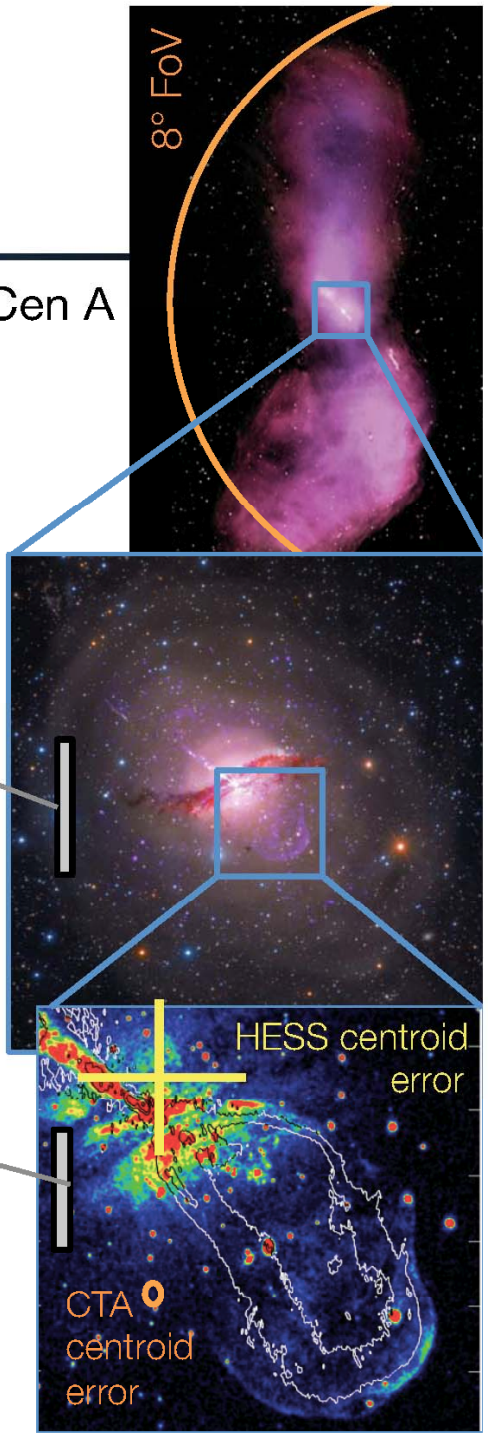
cf HESS RX J1713-3946



ANGULAR RESOLUTION



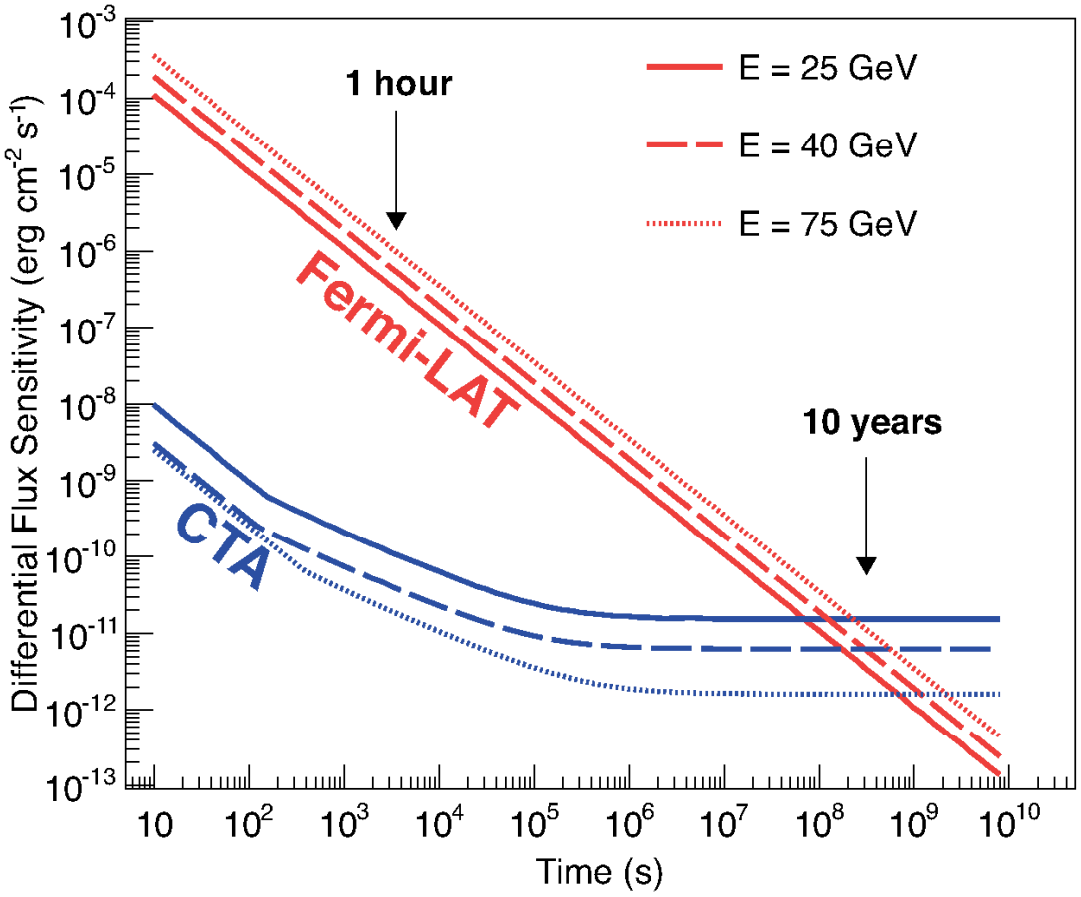
e.g. Cen A



*Event selection optimised for point-source sensitivity not resolution, significantly better resolution possible at the expense of collection area

VARIABILITY & TRANSIENTS

- Huge advantage over Fermi in energy range of overlap for ~second to ~week timescale phenomena
  - e.g. Explosive transients, AGN flares, binary systems
- Disadvantage
  - Slewing time O(1 min) and limited (cf Fermi) Field of View
  - External triggers critical

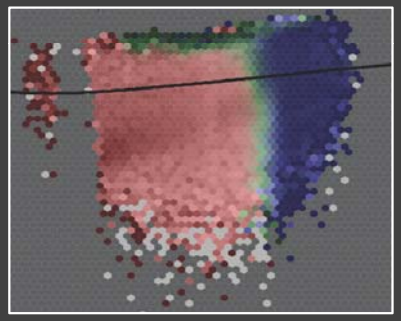


KEY SCIENCE PROJECTS

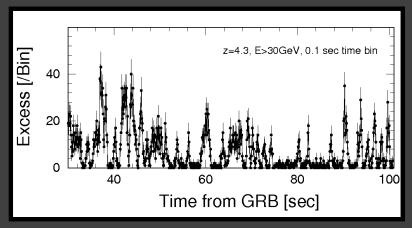
KEY SCIENCE PROJECTS (KSPS)

- The CTA KSPs are:
  - to ensure that important science questions for CTA are addressed, in a coherent fashion and with a well-defined strategy,
  - planned, proposed, and carried out by the CTA Consortium under guaranteed time,
  - typically hard to carry out in the Guest Observer program,
  - conceived to provide legacy data sets for the entire community and
  - proposed to use 40-50% of CTA observation time in first ten years.
- Key point:
  - We expect that the KSPs will be reviewed (and adjusted accordingly) on a regular basis before, and during, the operational phase.

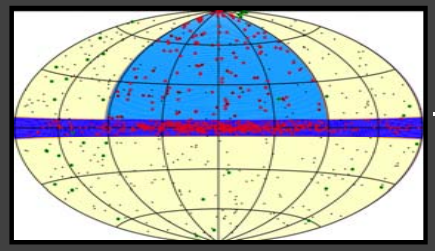
CTA KEY SCIENCE



Dark Matter Programme

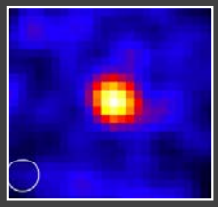


Transients



ExGal Survey

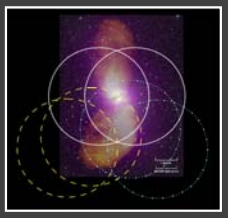
Extragalactic

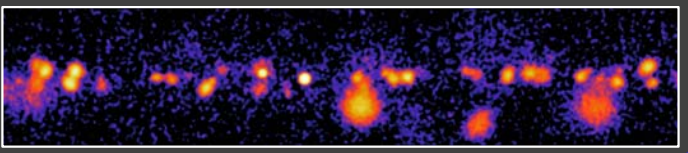


Galaxy Clusters

Star Forming Systems

AGN

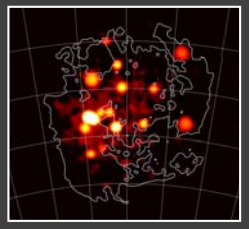


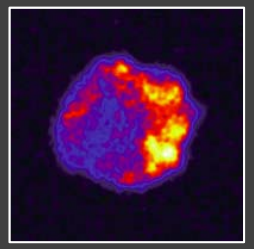


Galactic Plane Survey

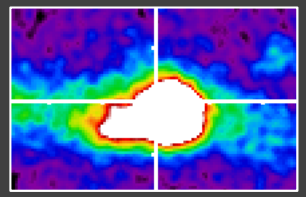
Galactic

LMC Survey





PeVatrons



Galactic Centre

cta
cherenkov telescope array

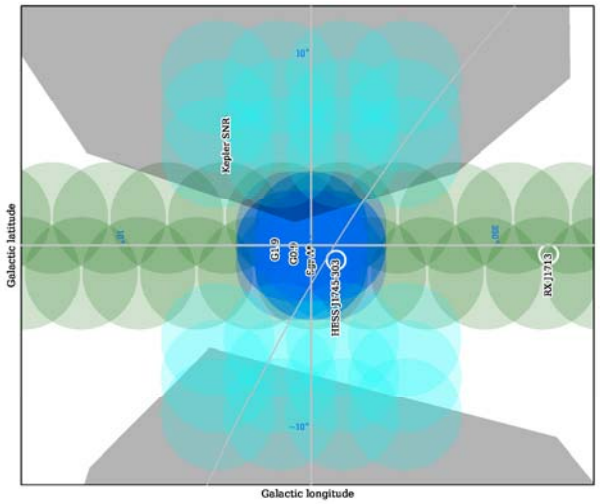
MAPPING SCIENCE → OBSERVATIONS

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
1 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?		✔		✔				✔✔	✔	✔
2 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?					✔	✔			✔✔	
3 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?					✔	✔			✔✔	

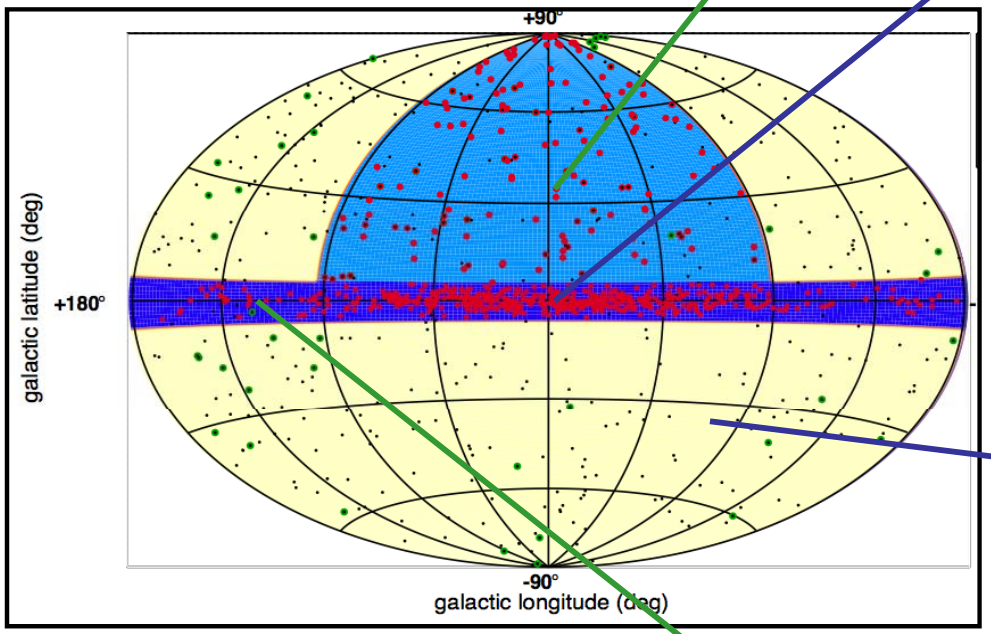
DM ← KSPs →

- Nine KSPs and one DM Programme are proposed
- DM was discussed in detail on Tuesday

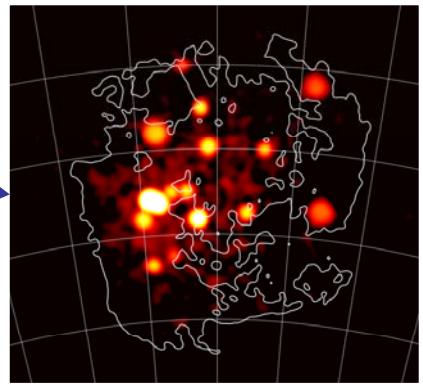
THE SURVEY KSPS



Extragalactic Survey:
Unbiased survey of ¼ sky to ~6 mCrab
VHE population study, duty cycle
New, unknown sources; 1000 h



Galactic Centre Survey:
ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search
Central exposure: 525 h, 10^ox10^o : 300 h



Galactic Plane Survey:
Survey of entire plane to ~2 mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, 1620 h

Large Magellanic Cloud Survey:
Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; 340 h in six pointings

GALACTIC KSPS

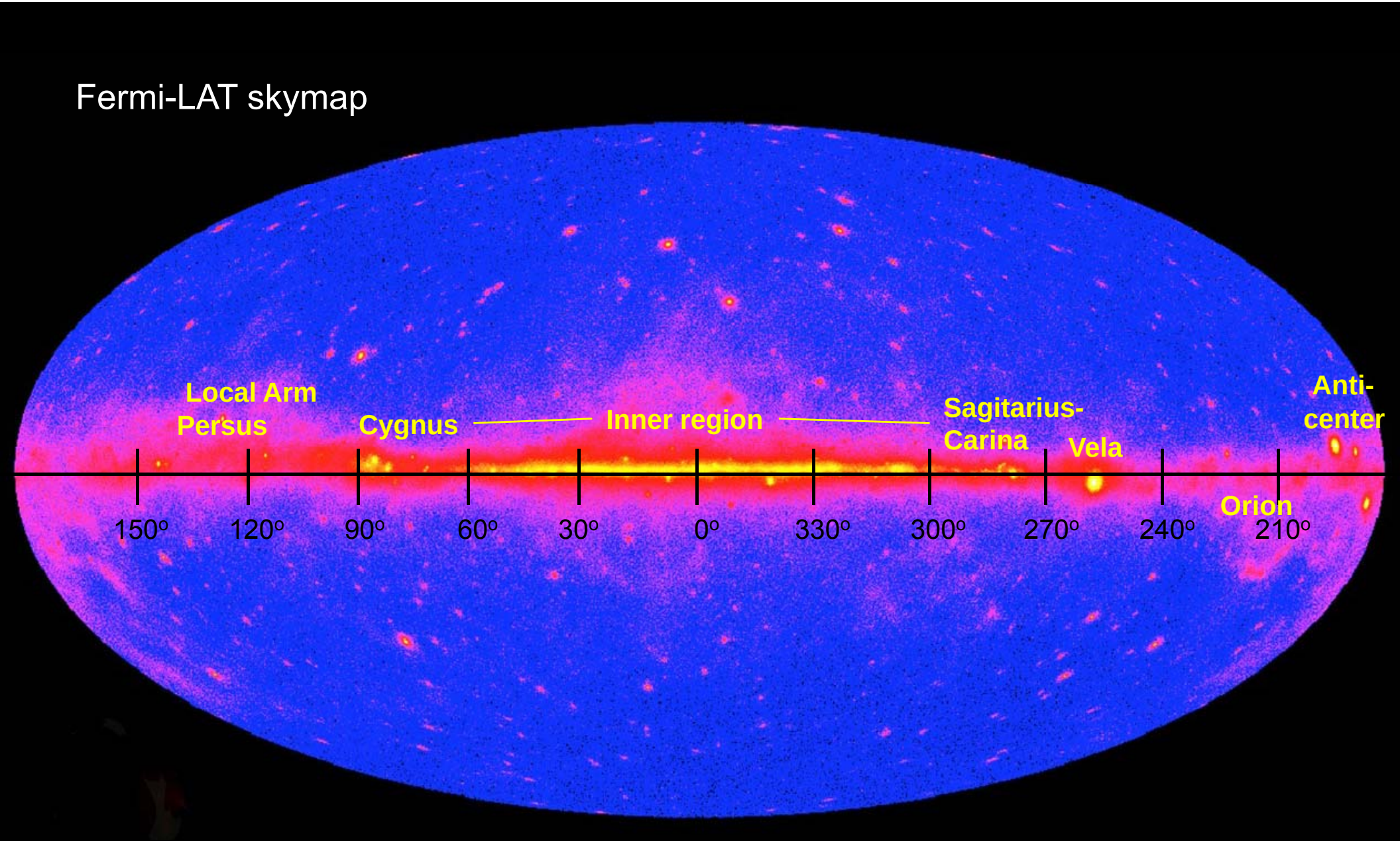
GALACTIC KSPS

- Galactic Plane Survey (GPS), 1620 h
  - Unbiased survey of Galactic plane: provides basis for all Galactic science programs and will be a major legacy of CTA
- Targeted KSPs
  - **Galactic Centre KSP (525 h + 300 h):** determining the VHE astrophysics of the GC region, deep DM search
  - **PeVatron KSP (50 h per source):** identifying sources of CR's up to the knee in spectrum; follow-up of five candidates from GPS
  - **Star Forming Systems KSP (270 h Cygnus, Carina, Wd 1):** impact of SFR & CRs on VHE particle acceleration at all scales
  - **Transients KSP**: follow up of Galactic transient sources

GALACTIC PLANE SURVEY KSP

- Scientific objectives
  - Discover new VHE source classes and new phenomena
  - Survey entire galaxy → complete census of Galactic population
  - Increase population of known Galactic sources (PWNe, SNRs) by factor of ~5, enabling better population studies
  - Search for Galactic cosmic ray PeVatrons
  - Detect new gamma-ray binaries and other Galactic transients
  - Unveil cosmic ray injection into the ISM the propagation of cosmic rays through large-scale diffuse emission mapping
  - Provide first-look science data to other KSPs and GO Programme
  - Produce a major multi-purpose legacy dataset

GALACTIC PLANE REGIONS



VHE GALACTIC SURVEYS

- Previous Surveys

Experiment	Hemisphere	Galactic Plane Coverage	Energy (GeV)	Sensitivity (mCrab)
H.E.S.S.-I	S	$-70° < l < 60°$, $\|b\| < 2°$	$>\sim 300$	10 – 30
VERITAS	N	$67° < l < 83°$, $-1° < b < 4°$	$>\sim 300$	20 – 30
ARGO-YBJ	N	Northern Sky	> 300	240 – 1000
HEGRA	N	$-2° < l < 85°$, $\|b\| < 1°$	> 600	150 – 250
Milagro	N	Northern Sky	$> 10,000$	300 – 500

- Present/future Surveys

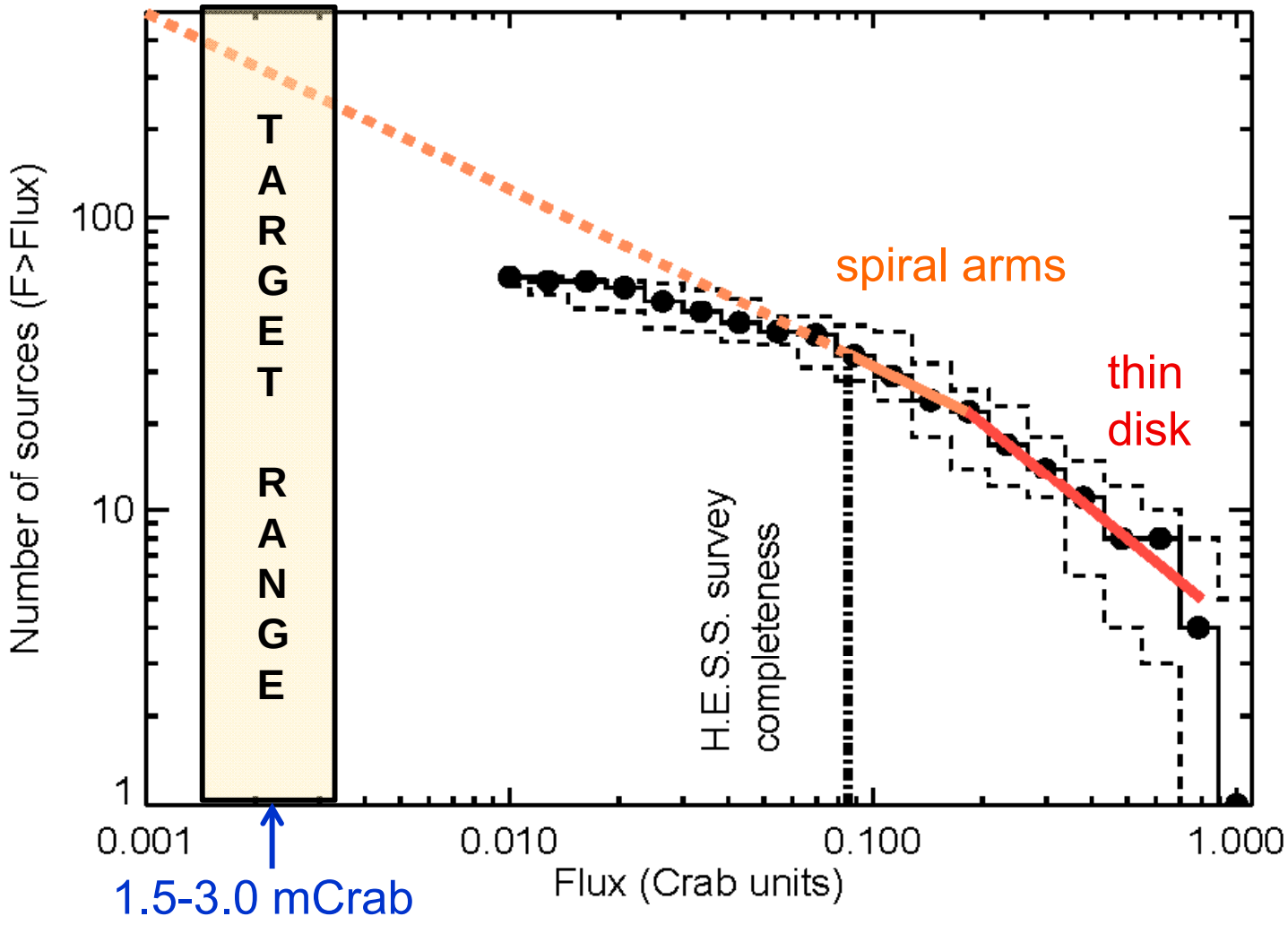
Observatory	Hemisphere	Energy Threshold	Angular Resolution	Pt. Source Sensitivity
CTA	N, S	125 GeV	$\sim 0.10°$ at 300 GeV	2 – 4 mCrab
HAWC	N	2 TeV	0.30°	20 mCrab

CTA GPS: **Full-plane survey with graded exposure**
Wide energy range and unprecedented angular resolution
Order of magnitude improvement in sensitivity

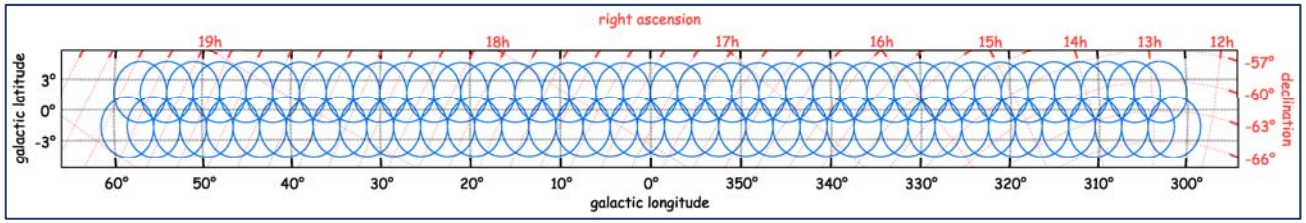
GALACTIC SOURCE POPULATION

log N – log S from existing population (mostly PWNe)
→ expect several hundreds of sources

Renaud, 2009



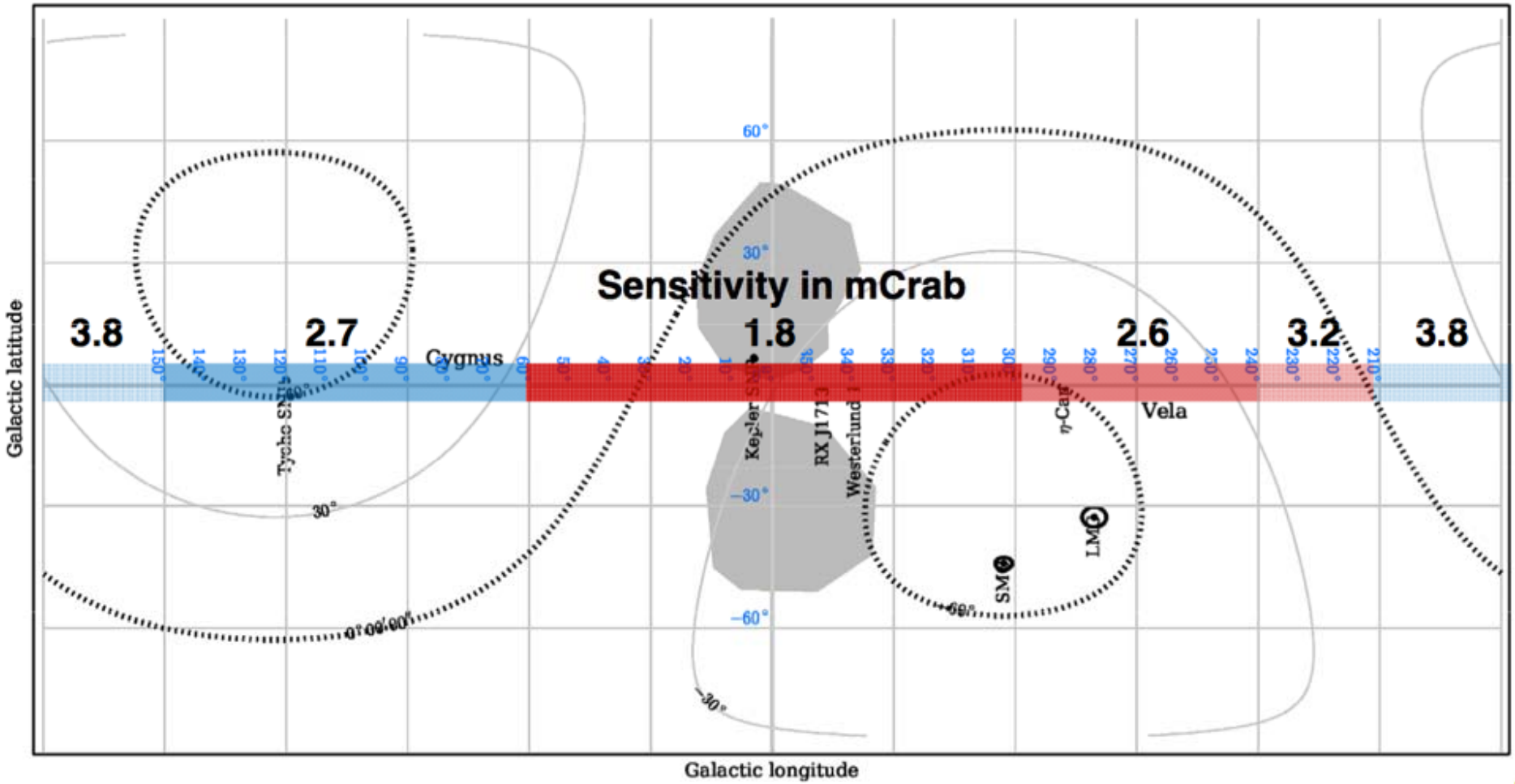
GPS IMPLEMENTATION



- Strategy
  - Both CTA-S and CTA-N
  - Dark time, full arrays, zenith < 45^{o}
  - Double-row pointing scheme with 3^{o} spacing; LST participation still under study
  - Sensitivity-graded with deepest exposure in the inner, Cygnus and Carina regions
  - Carried out over ten years, but with significant exposure in Years 1-2 to provide early bright-source list (Year 2) and first catalog (Year 3)
  - Transients detected are followed-up in context of Transients KSP
  - Total time: 1020 h (S), 600 h (N)

GPS SENSITIVITY

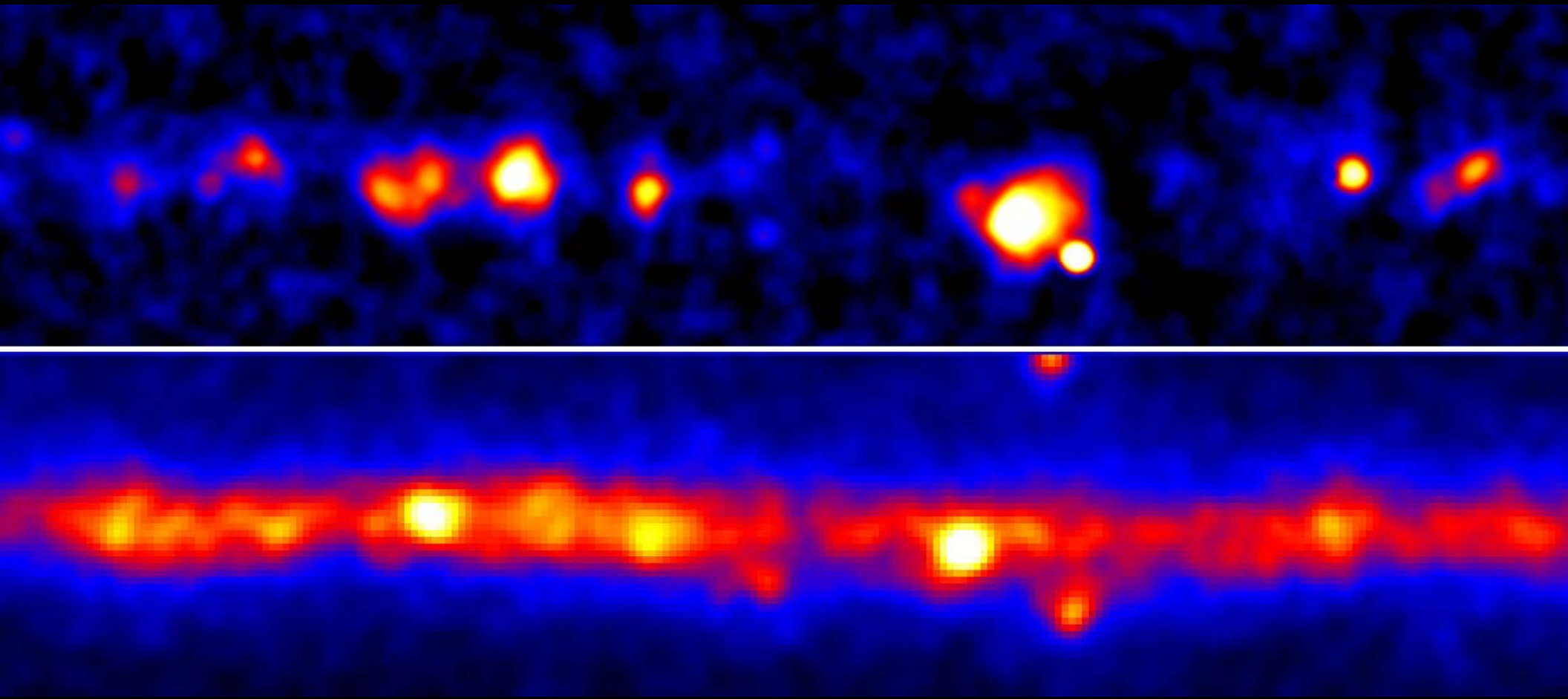
Entire plane surveyed to < 3.8 mCrab - several 100's of sources



The HE Milky Way (2015)

Extended sources, size typically few 0.1^{o}
few 10 pc

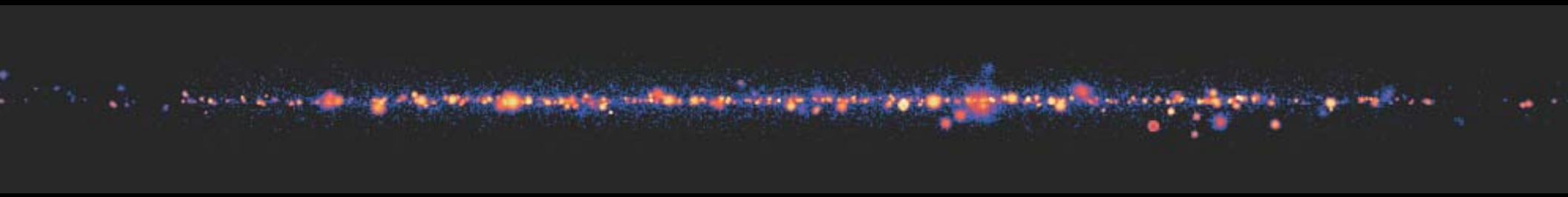
H.E.S.S. (TeV)



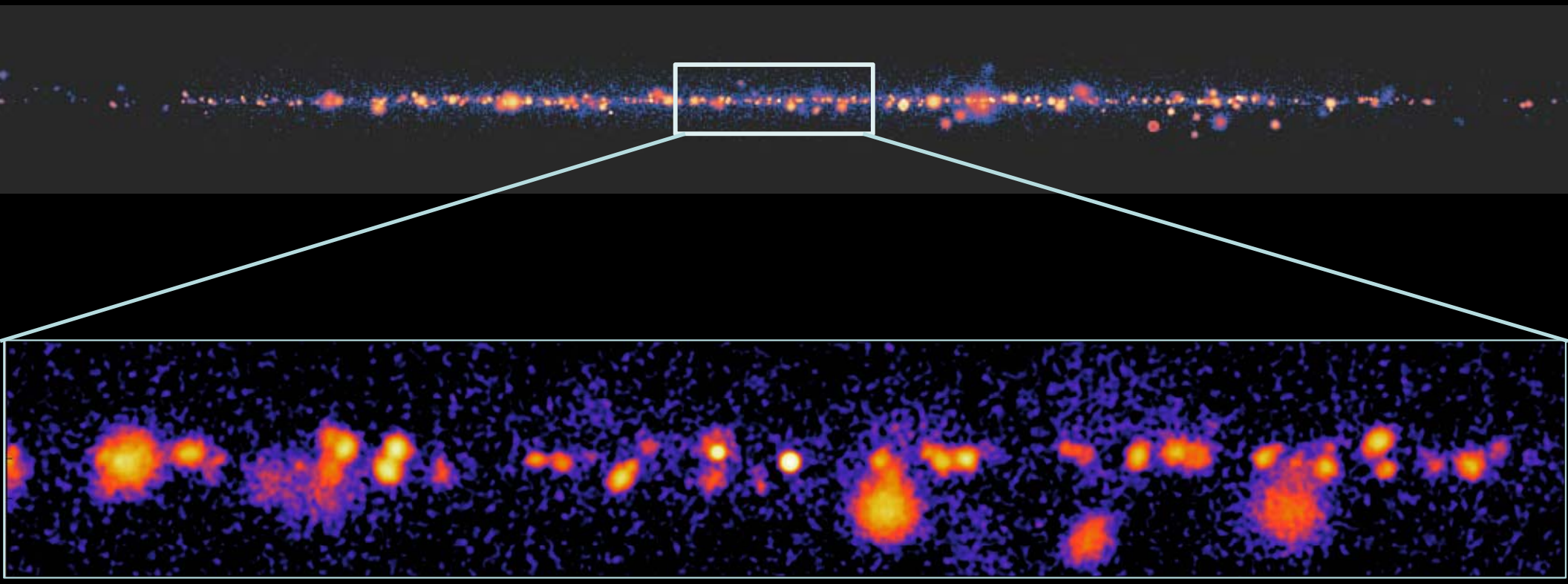
Fermi-LAT (GeV)

W. Hofmann

CTA Galactic Plane Survey

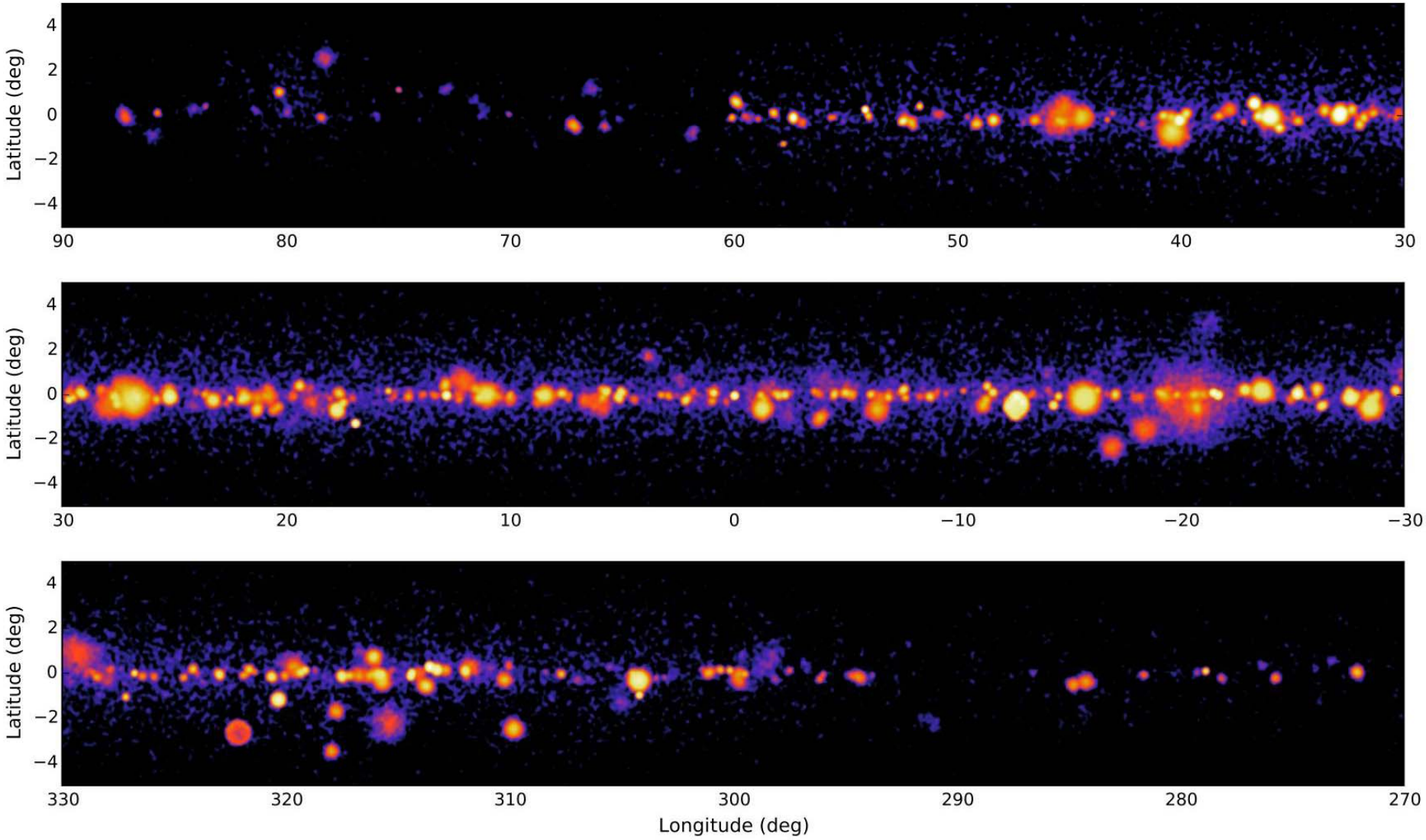


CTA Galactic Plane Survey



GPS EXPECTATIONS

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



COSMIC RAY PEVATRONS KSP

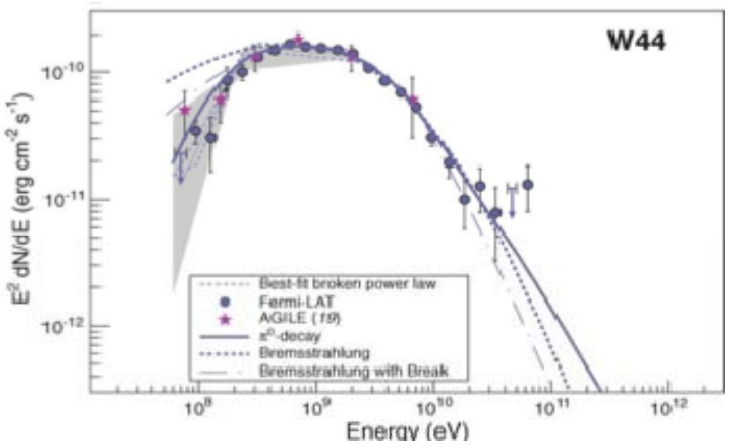
- Objectives & Strategy
  - Origin of cosmic rays (CRs) is a century old problem; SNRs can satisfy CR energy budget; several SNRs now provide good evidence for CR acceleration – both in evolved SNRs (IC 443, W44) and in young SNRs (Tycho, Cas A)

    → **but no evidence at E ~20 TeV and above**

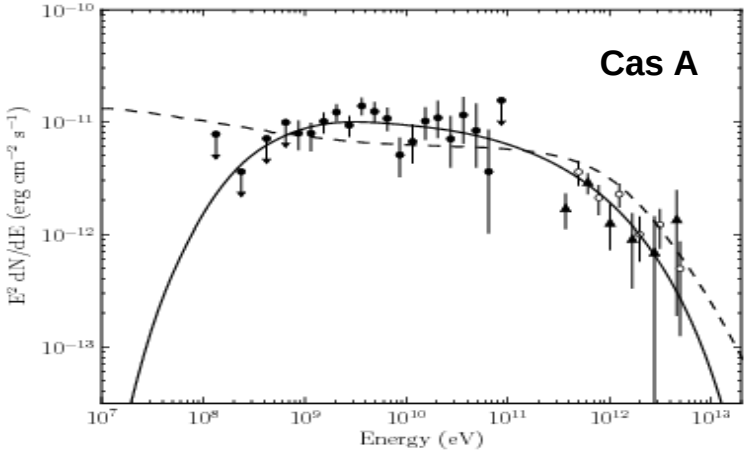
  - This KSP aims to identify PeVatrons – sources that accelerate CRs to PeV energies;
  - Hypothesize that young SNRs may accelerate CRs to PeV energies at beginning of Sedov phase when shock speed is high – it is likely that only a small handful of these exist in the Galaxy;
  - Target *RX J1713.7-3946* and up to *five candidates* detected in GPS for deep observations (50 h each).

EXISTING CR ACCELERATORS

Abdo et al (Fermi Coll.) 2010



Abdo et al (Fermi Coll.) 2010



Evolved SNRs:

- Hadronic accelerators
- Bright at GeV, faint at TeV
- Not PeVatron accelerators (at least now)

Young SNRs:

- Hadronic accelerators
- Energy cutoff at a few TeV
- Not PeVatron accelerators (at least now)

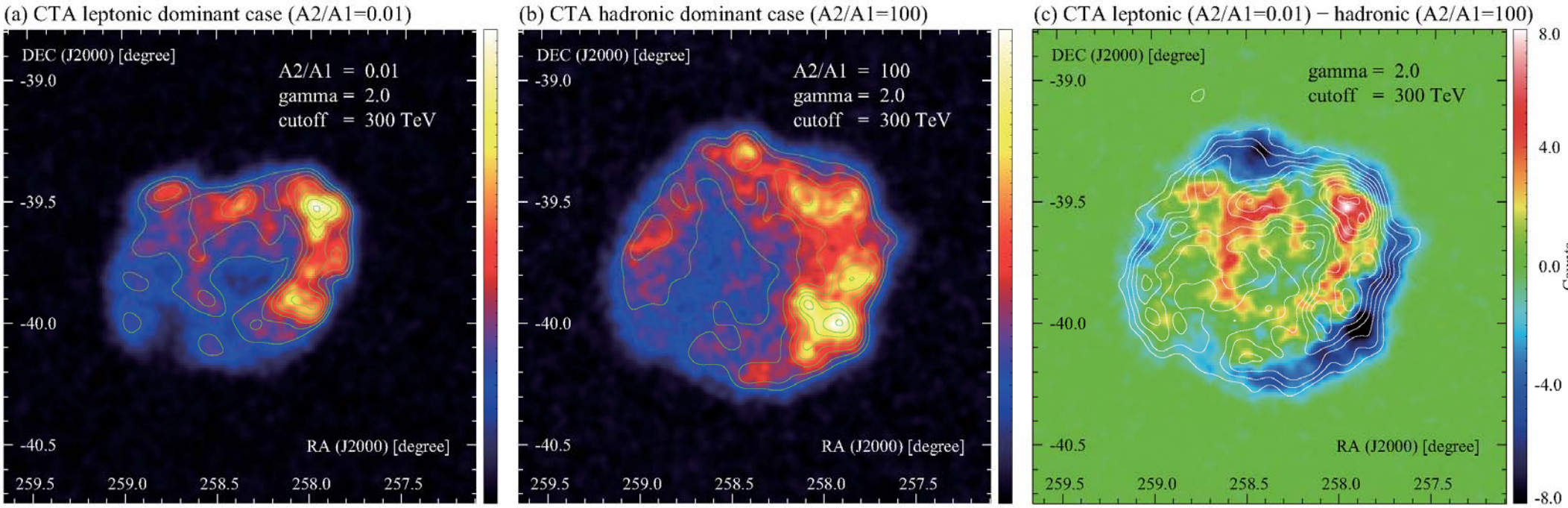
PeV particles might be accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high ($E_{max}=V_{sh}*Rsh*B$)

Look deeper at the surroundings of the SNR for very-high-energy run-away particles

⇒ Deep observations (50 h) of RX J1713.7-3946

⇒ Deep observations of up to five PeVatron candidates found in GPS

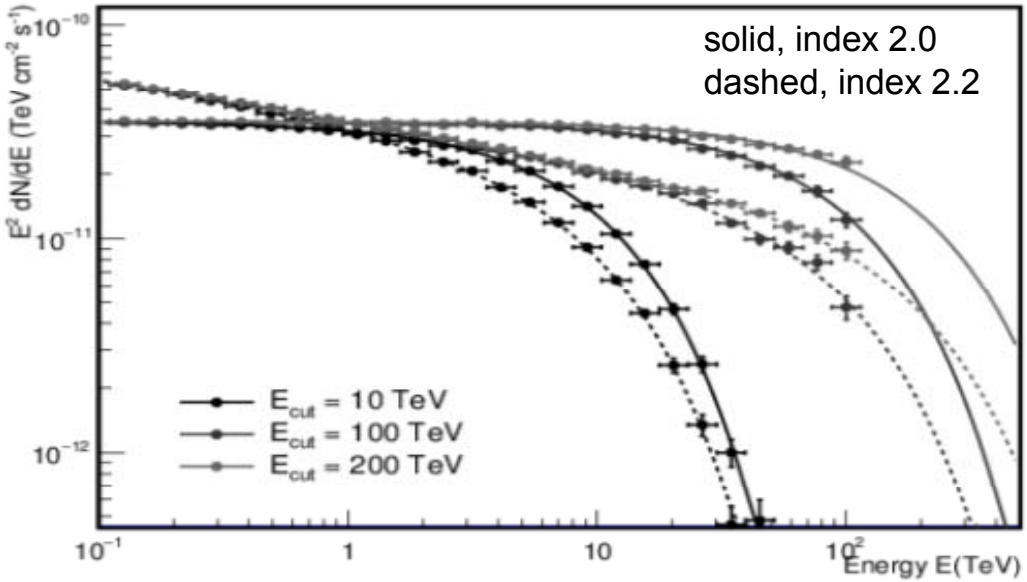
RX J1713.7-3946



- CTA can disentangle hadronic/leptonic contributions
  - Excellent angular resolution
  - Unprecedented sensitivity

CR PEVATRON CANDIDATES

- Strategy
  - GPS will identify candidate PeVatrons (hard power-law spectra with 3σ detection above 50 TeV)
  - Deep observations of 50 h each (MST+SST required)
  - Measure spectrum extension, localization of source and measurement of source size → MWL counterpart to pinpoint the PeVatron



Reconstructed spectra for various cut-off energies

In 50 h, the spectrum above 60 TeV of a PeVatron flux ~10^{-12} ph/TeV/cm^2/s will be reconstructed with an error <10%

EXTRAGALACTIC KSPS

EXTRAGALACTIC KSPS

AGN KSP

1. long-term monitoring
2. high-quality spectra
3. AGN flare programme

-> AGN physics at VHE
-> γ-ray cosmology
-> UHECRs & fundamental physics

EGAL Survey KSP

blind survey of 1/4 sky

-> VHE population studies & duty cycle

-> new VHE sources / source classes

Transients KSP

follow-up of external or internal triggers

-> GRB physics at VHE

-> Galactic Transients at VHE

Galaxy Clusters KSP

deep observations of a galaxy cluster

-> probing cosmic rays in clusters

-> multi-purpose field of view

AGN KSP - STRATEGY

long-term monitoring programme

- regular full-array observations of 15 archetypal γ-loud AGN of different classes

- ~30 min / week for each target

-> long-term light curves over at least 10 years

-> time-resolved spectra

AGN flare programme

- ~25 flare alerts / year from external triggers (Fermi, Swift, HAWC...), ~ half followed up

- regular bi-weekly **snapshots** with CTA subarrays for ~80 AGN of different classes , different z

  -> about 20 flares / year / site

AGN KSP - FOCUS ON VARIABILITY

from the longest variations ...

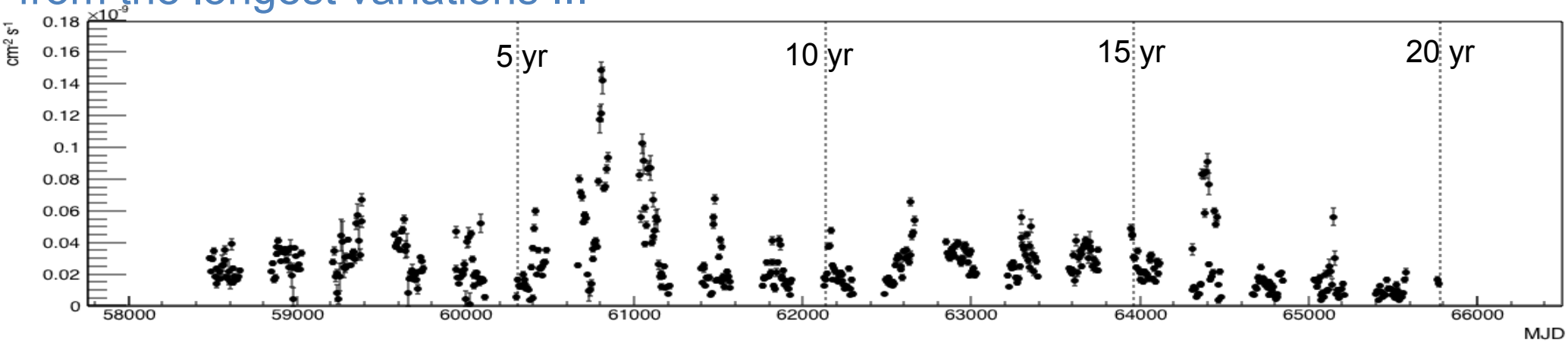
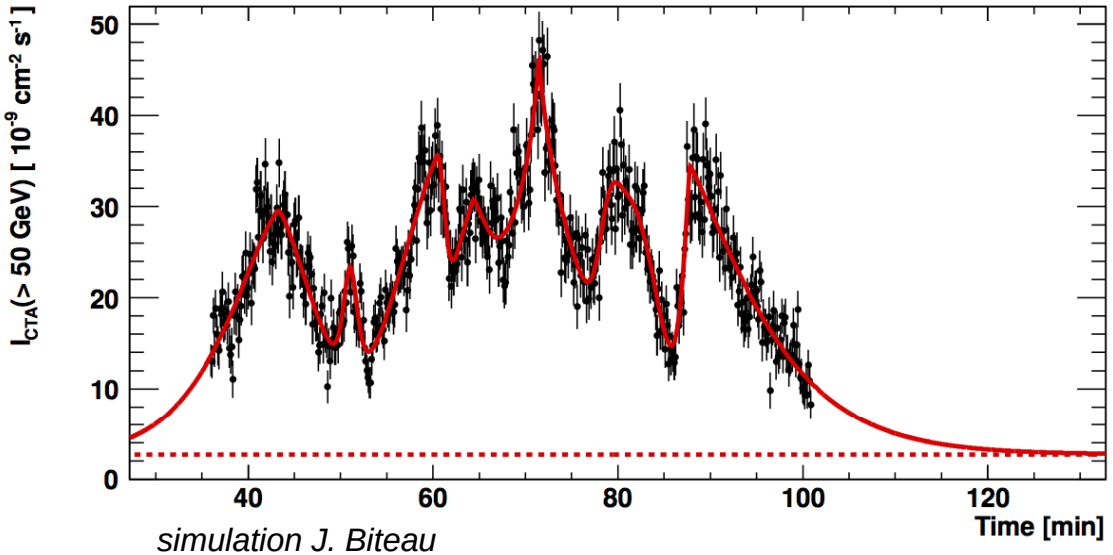


illustration AZ

- duty cycle ?
- (quasi) periodicities ?
- breaks in the power spectra ?

... to the shortest flares



simulation J. Biteau
(H. Sol, AZ, C. Boisson et al. 2013)

- size (location, nature) of the emission region ?

- acceleration and cooling mechanisms ?

AGN KSP - STRATEGY

high quality spectra programme

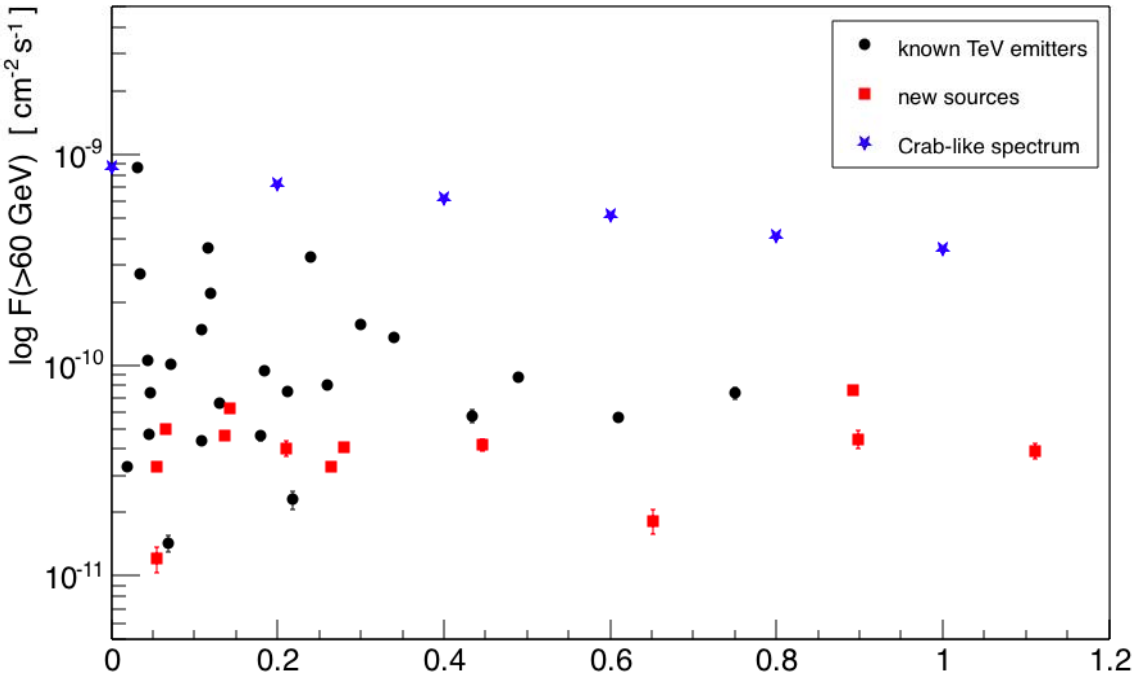
~ 40 AGN of different classes
at 0.02 < z < 1.11

(*small subset of "detectable" Fermi sources - others covered by GO*)

-> uniform set of high-quality spectra

deep observations of two radio-galaxies: M87 , Cen A

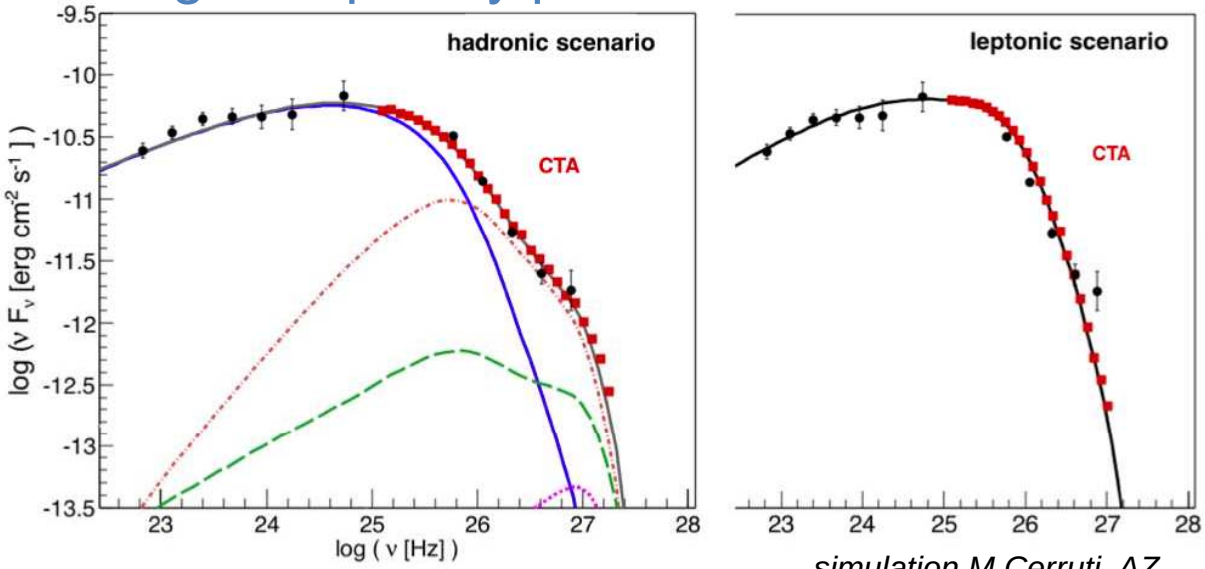
-> spectra, extended emission ?



simulation
D.Mazin, AZ

AGN KSP - FOCUS ON EMISSION PROCESSES

from high-frequency peaked blazars...



simulation M.Cerruti, AZ

- Signatures for leptonic / hadronic origin of VHE emission ?

- Signatures of γ-ray interaction with photon fields ?

wide energy range, different AGN classes / redshifts
-> Separation of intrinsic spectral features from propagation-induced effects.

... to radio galaxies

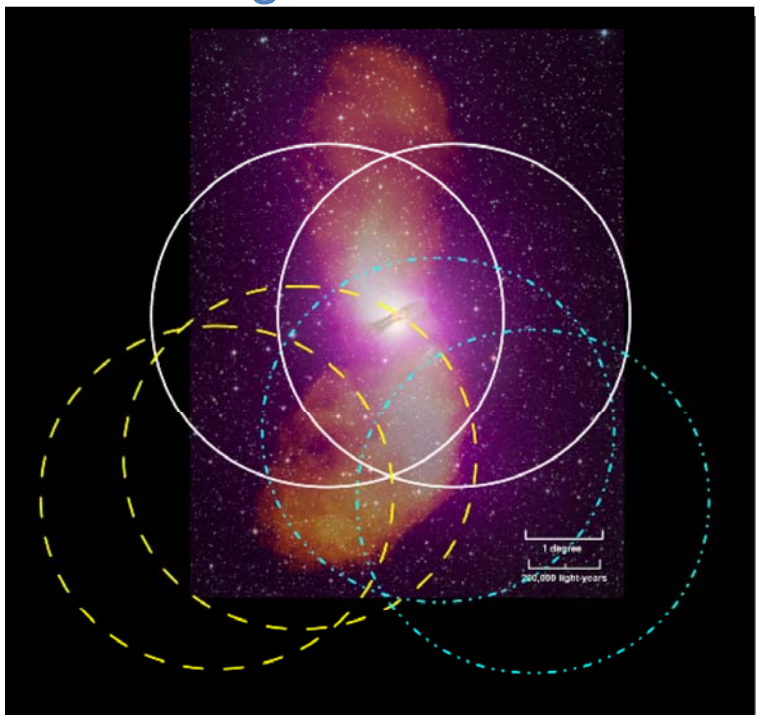
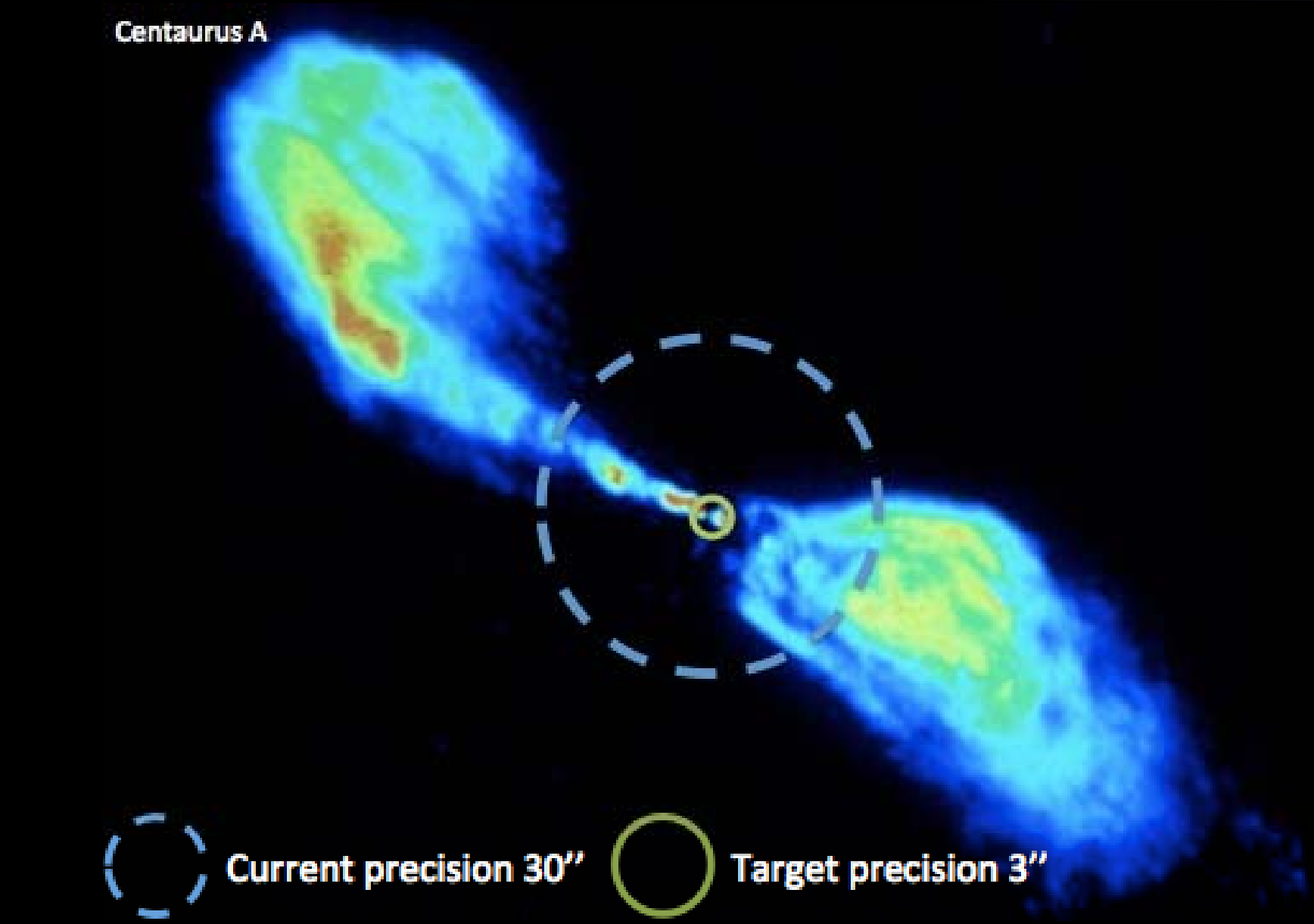


illustration with image from NASA/DOE/Fermi LAT, Capella et al.

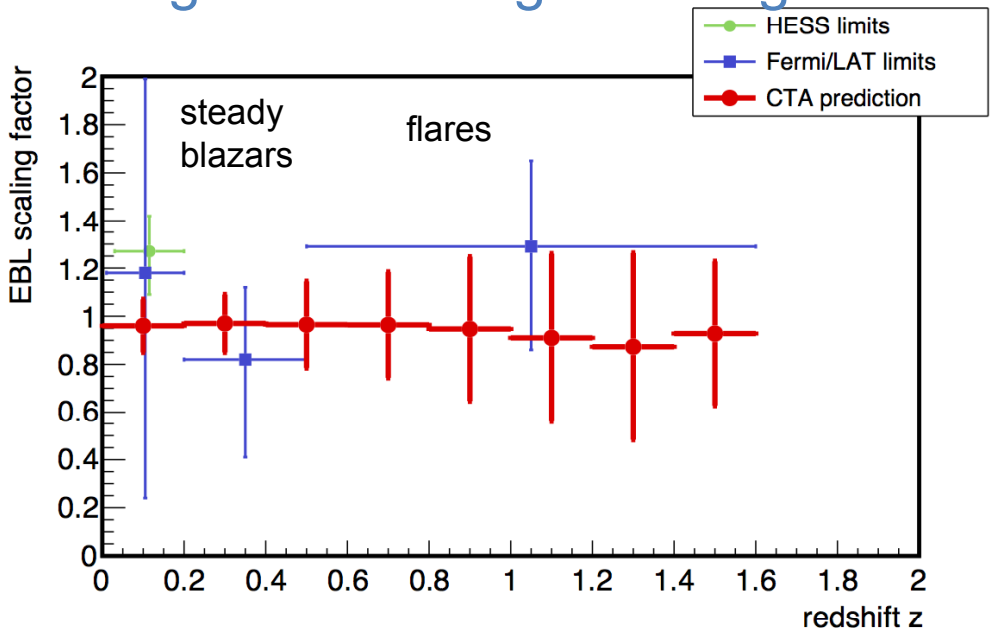
- Origin of VHE emission in radio galaxies ?
- Link to VHE blazars ?

The importance of pointing precision



AGN KSP - EBL & IGMF

Extragalactic Background Light

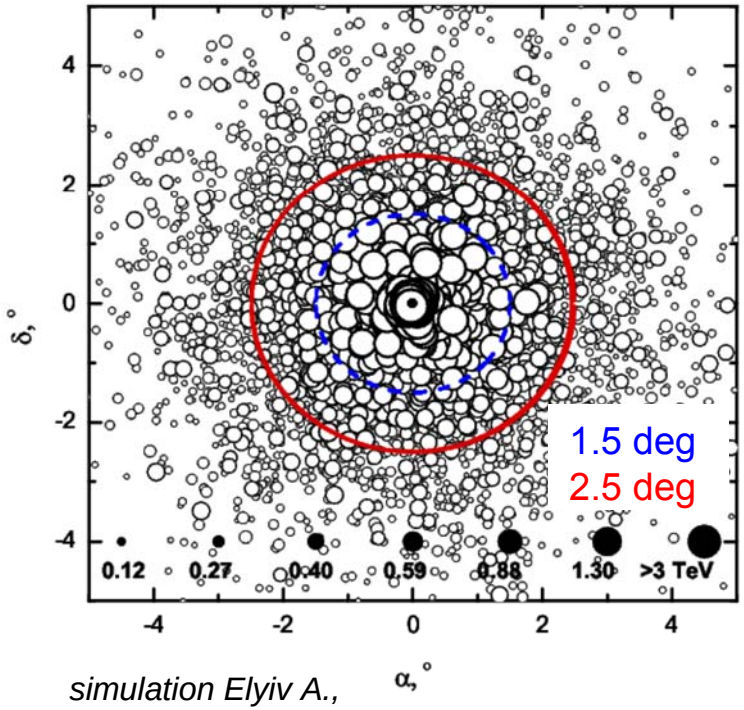


simulation D. Mazin

- measurement of the EBL at z~0 from mid UV to far IR with a precision of +/-10%

- characterize its evolution up to z > 1

InterGalactic Magnetic Field



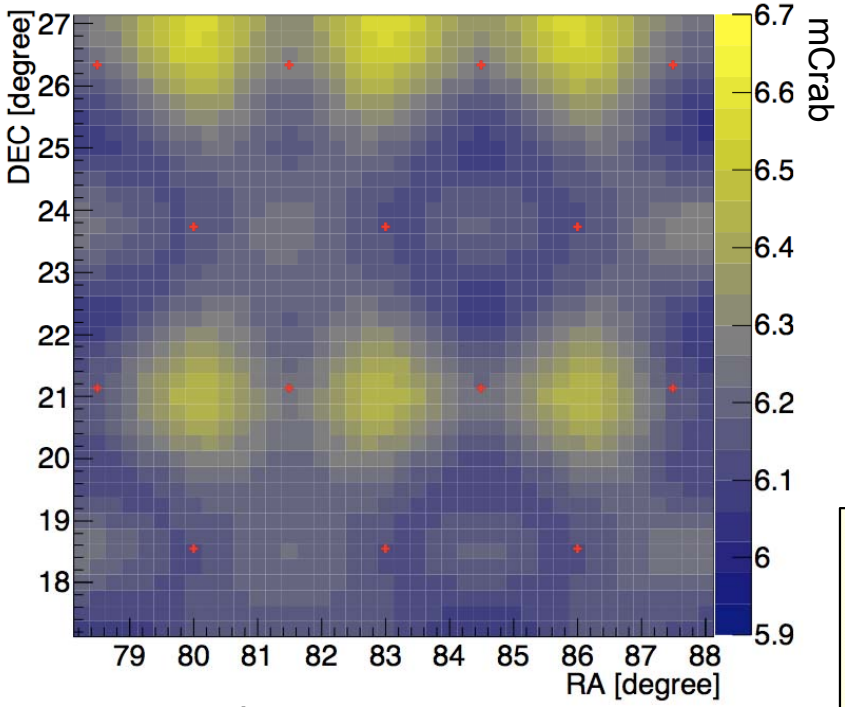
simulation Elyiv A., Neronov A. & Semikoz 2009

Detection of the IGMF ?

- imaging analysis : "pair halos" for IGMF $\gtrsim 10^{-16}$ G
- time-resolved spectra : "pair echoes" if smaller IGMF

EGAL SURVEY KSP - STRATEGY

pointing strategy (baseline)



simulation L. Gérard

blind survey of 25% (10,000 deg^2) of the egal. sky

- uniform exposure at ~6 mCrab

- observe each FoV with several pointings, spread over two years

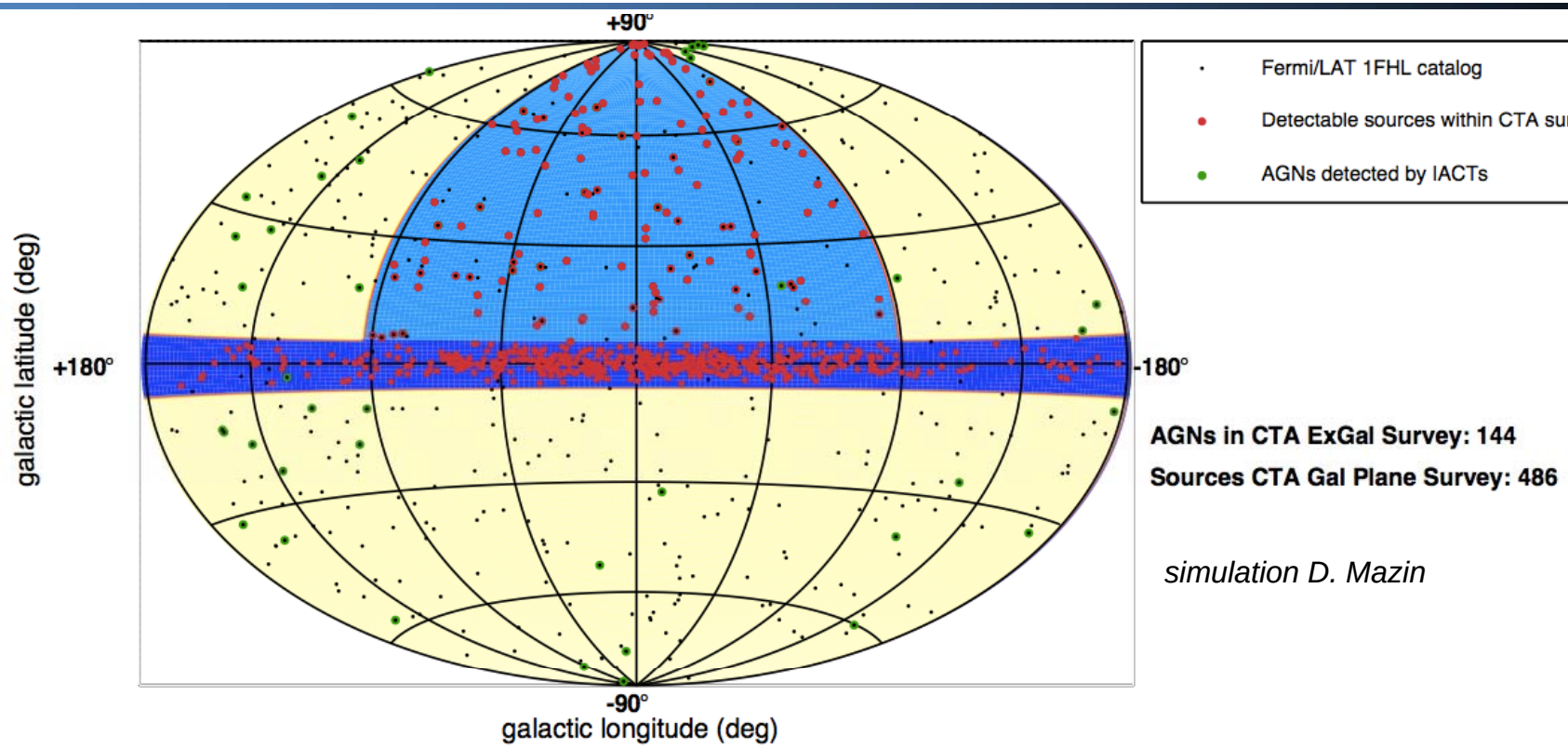
  -> average over source activity states

divergent pointing ?

preliminary estimates: FoV ~200 deg^2 possible for ~ factor 2 degradation in angular and energy resolution

-> gain in sensitivity by factor ~1.5 for same obs. time
-> very interesting for transient searches (catch long and short GRBs from their onset ?)

EGAL Survey KSP - expected results

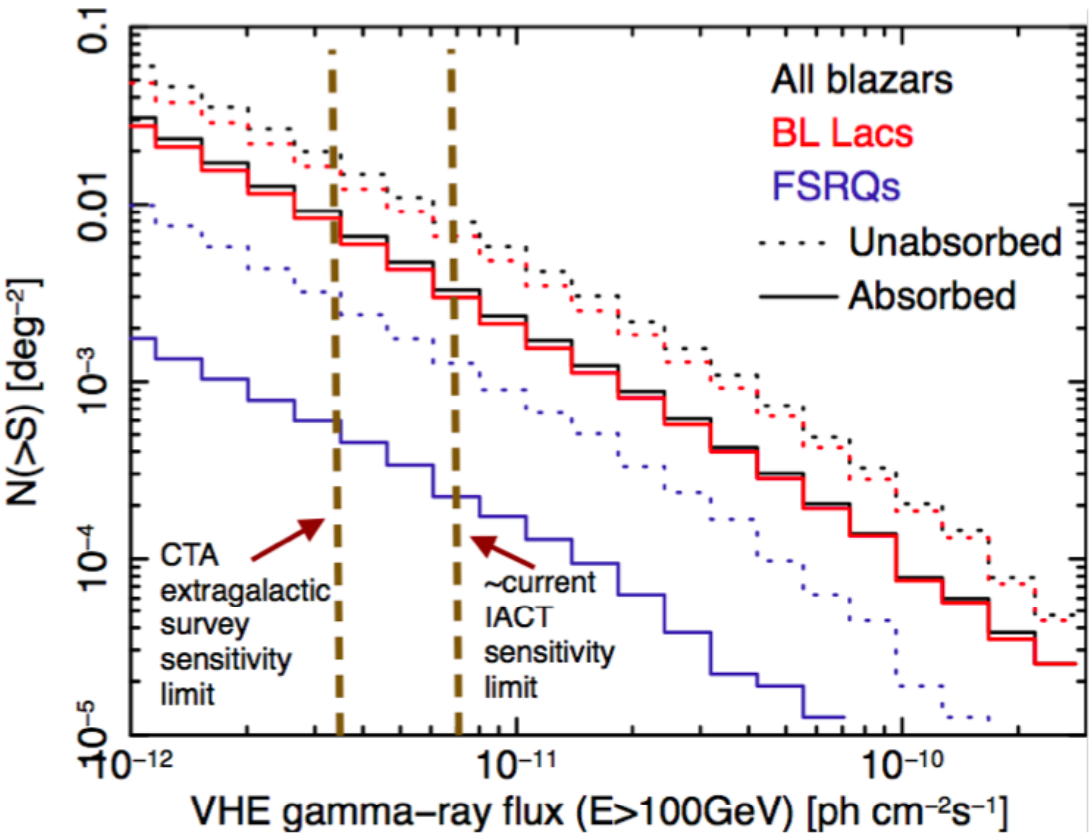


- expect at least 30 - 40 detections based solely on Fermi (1FHL) spectra + flares
- expect up to ~150 detections from current estimates

- first unbiased view of the egal. VHE sky with unique sensitivity between 100 GeV and 10 TeV

-> measurement of the luminosity function for nearby VHE blazars
-> estimate of diffuse γ-ray background

EGAL SURVEY KSP - DISCOVERY POTENTIAL



simulation P. Padovani & P. Giommi 2014

The EGAL Survey is an essential tool for VHE discoveries.

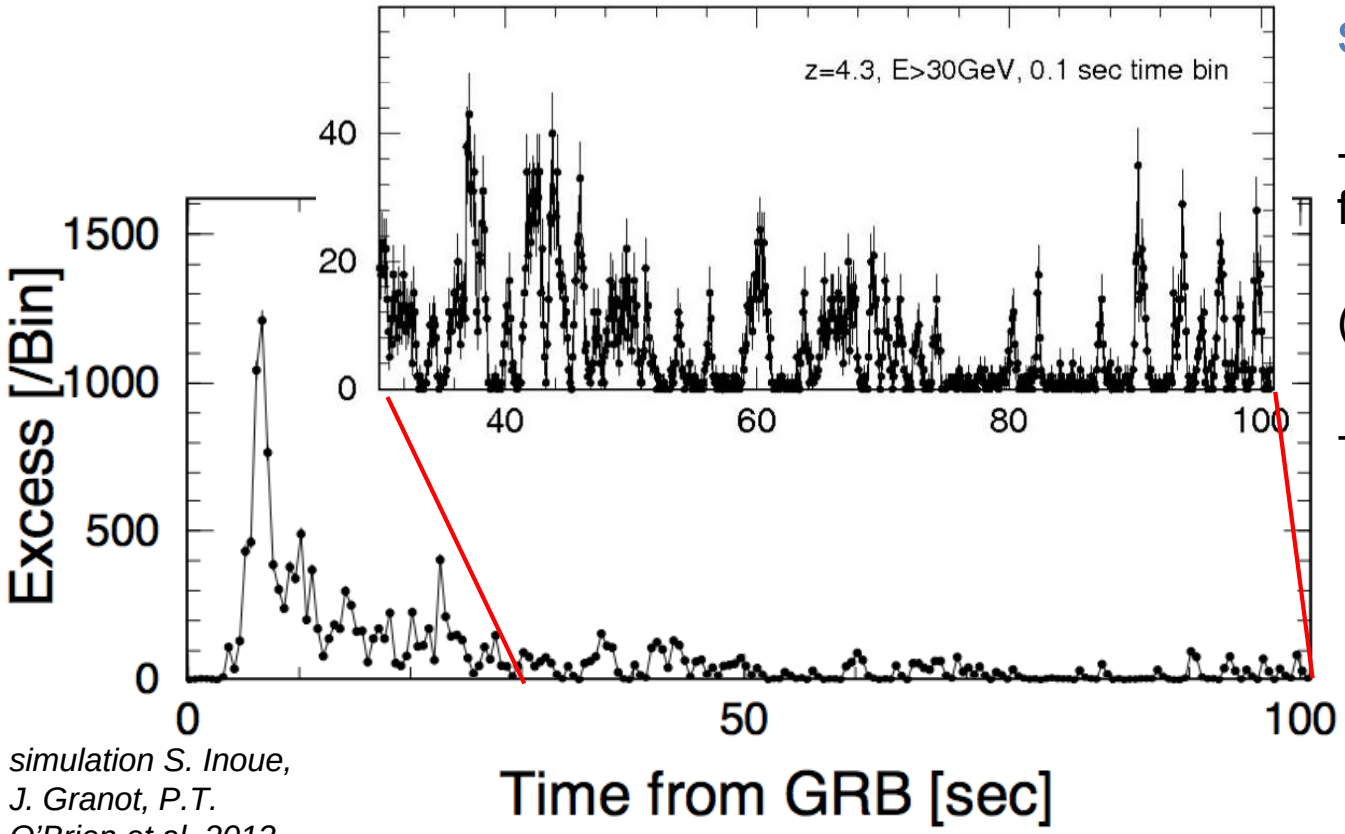
- discovery of new VHE emitters, including "extreme" blazars

- discovery of fast-flaring sources ?

- discovery of new VHE classes (Seyferts, ULIRGs, "dark sources"...) ?

-> *rich target list for GO proposals*

TRANSIENTS KSP - FOCUS ON GRBS



simulation S. Inoue, J. Granot, P.T. O'Brien et al. 2013

strategy:

- all GRB alerts in accessible FoV followed up with LSTs for 2 hr

(LST repositioning time < 20 s !)

- if detection
  -> observe with full array

We expect far superior photon statistics compared to Fermi-LAT statistics above a few GeV.

objectives:

- jet velocity and emission site from intrinsic γγ absorption & rapid variability
- probe particle acceleration and radiation for prompt emission & afterglow
- probe EBL, IGMF, LIV

MWL SUPPORT

MultiWaveLength / MultiMessenger support organized by dedicated working group:

- **MWL campaigns** to follow up on transients, AGN flares/ active states

- regular **MWL coverage** of long-term monitoring targets and complete coverage of EGal Survey (at least optical)

- MWL coverage, including **VLBI,** of radio-galaxy scans

- agreements / MoUs for **MWL & MM alerts**

- link to **redshift campaigns** for blazars

dedicated optical telescopes (photometry / polarimetry)

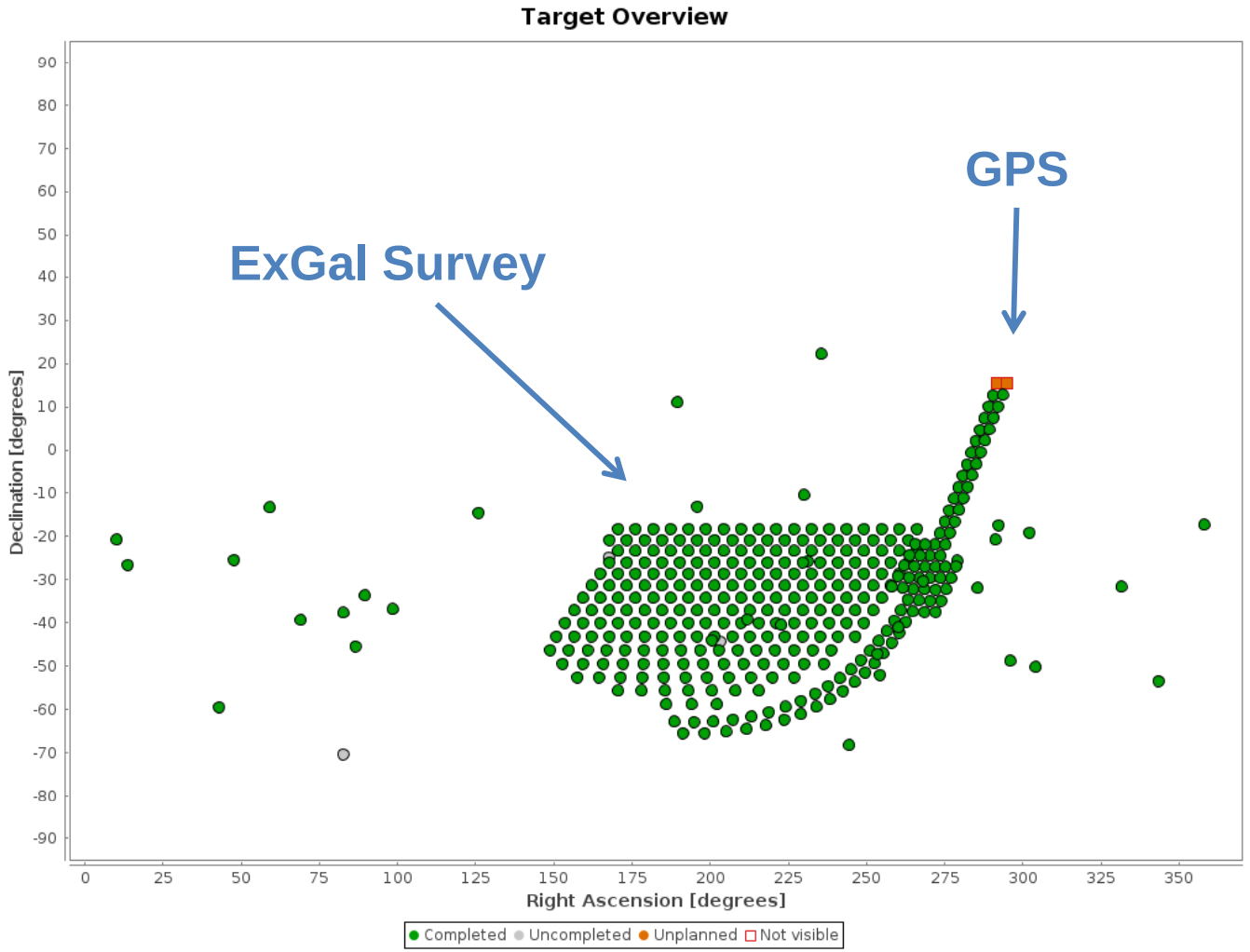
- systematic optical coverage of CTA targets

- AGN monitoring for high optical states & polarimetry swings

SCHEDULE FOR KSPS

- KSP scheduling studied for first three years → viability exercise
- Successful completion of KSP program using assumed KSP allocation

Target map for CTA-S array:

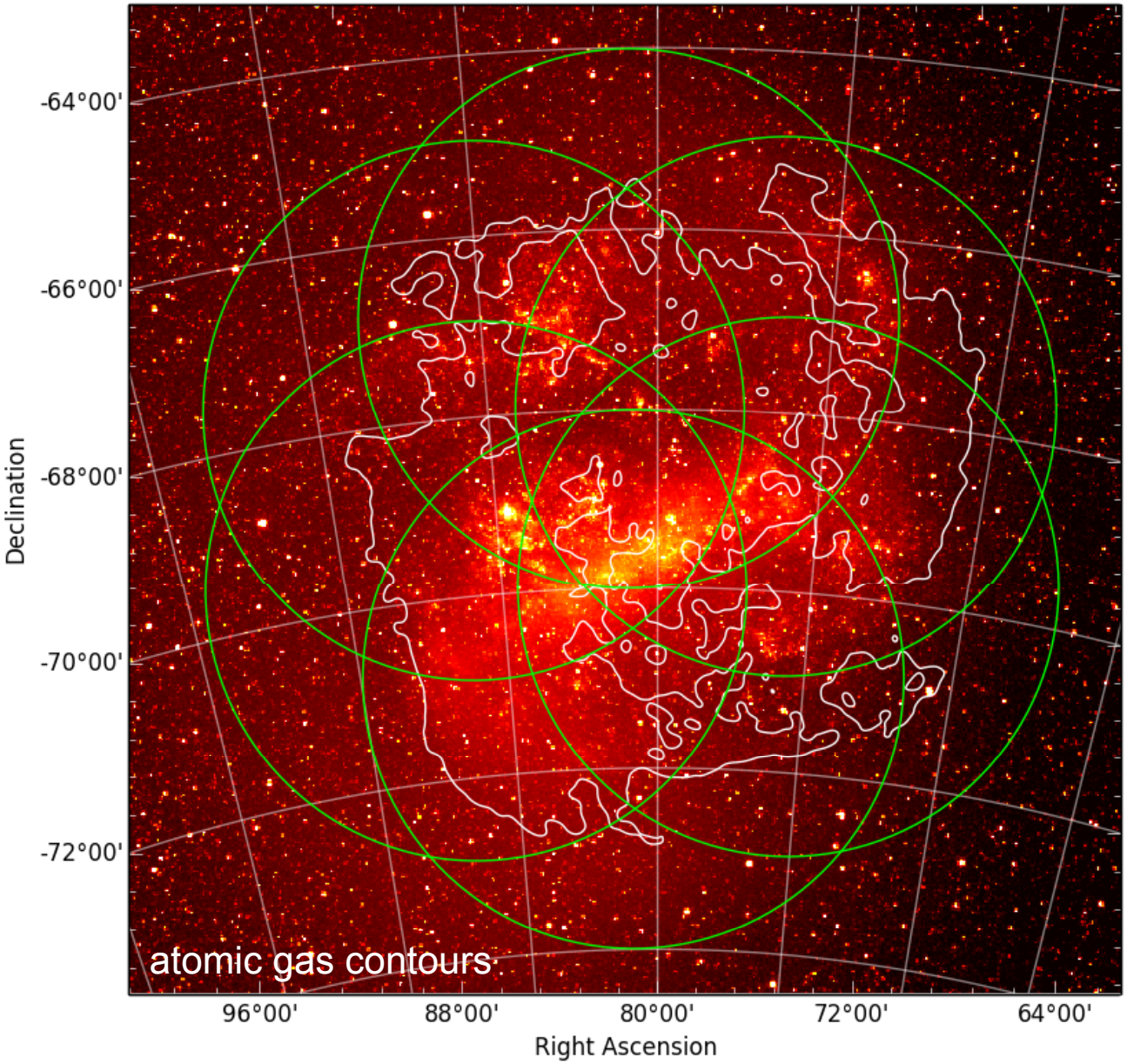


CONCLUSIONS

- The CTA KSPs cover a range of science topics and are designed to explore important CTA science in a coherent fashion.
- Both the Galactic and extragalactic programs will be rich and cover a variety of exciting science topics and sources.
- *Key point*: for the KSP science listed here, there is as much, or more, science in the GO program – e.g. most iconic HE/VHE sources are not part of the KSPs.
- Data products are specified for all KSPs; data releases will occur with an eye to inform the community promptly – and, at a minimum, by one year after the calibrated data are delivered.
- Flexibility is built into the system – regular reviews of the KSPs are expected before, and during, the CTA operational period.

BACKUP SLIDES

LMC KSP



A unique target to study extreme Galactic-type VHE Sources & diffuse emission (CRs)

Face-on satellite galaxy:
- No source confusion
- Relatively nearby, and no distance ambiguity

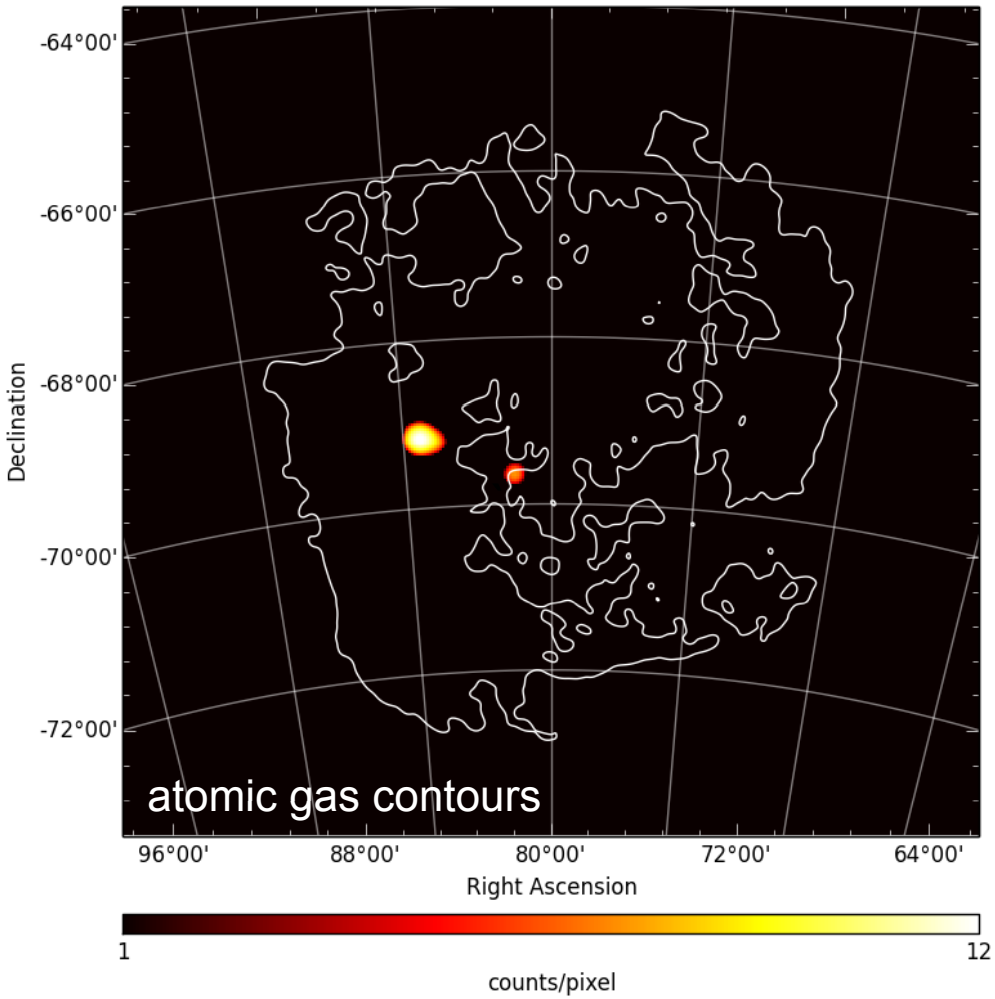
Very active:
- Only 1% mass of the Milky Way
- Yet 10% the SFR

Potential pointing pattern overlaid on starry sky image

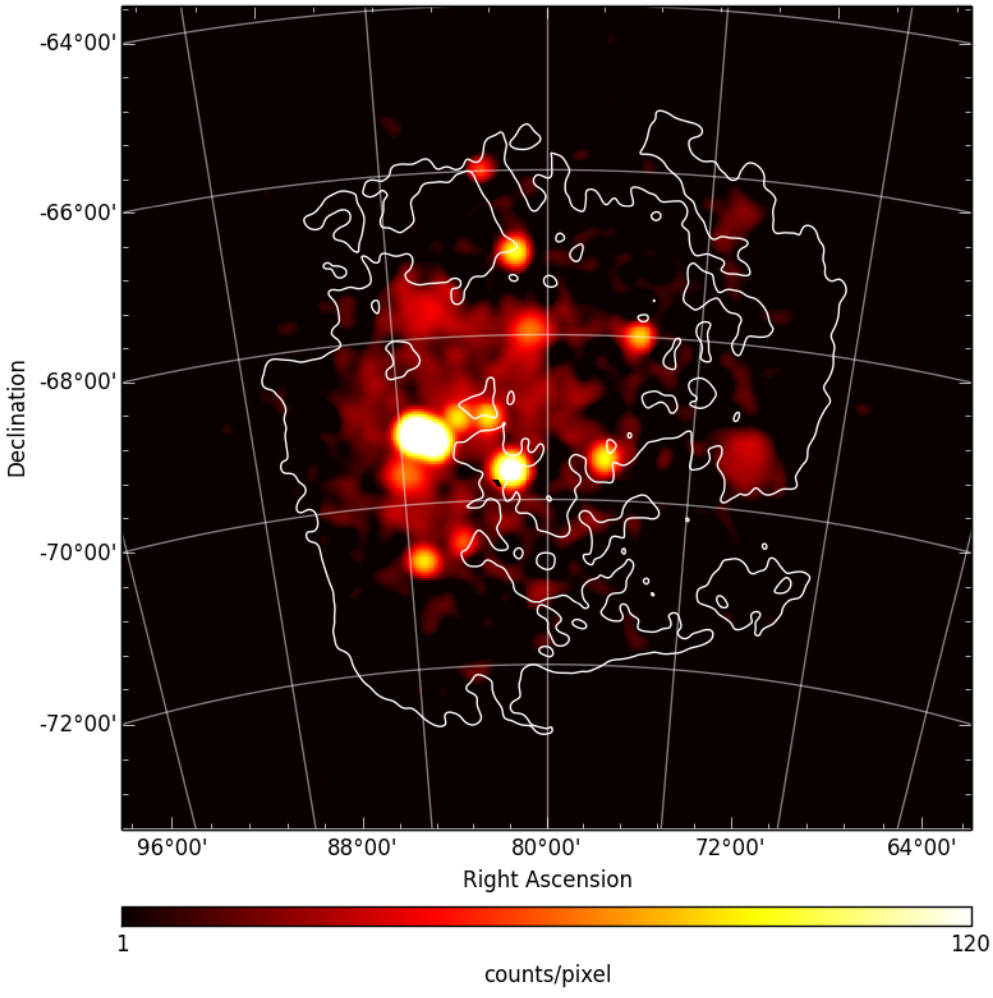
LMC KSP - SIMULATIONS

- Includes known sources (N 157B, 30 Dor C, N 132D), luminous point-like sources, CR-enriched regions, & SN 1987A

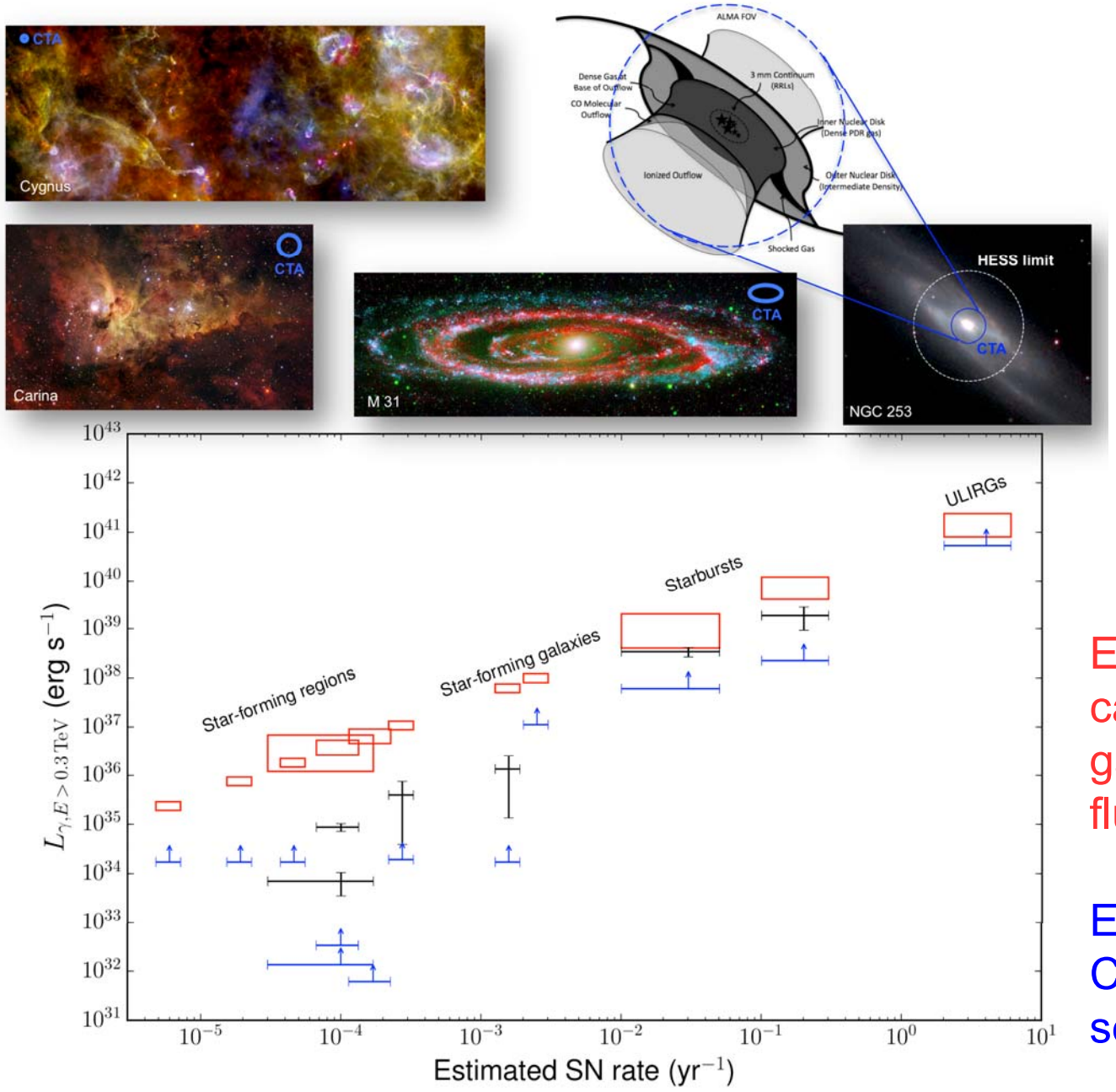
H.E.S.S.-like performance
1 pointing, 16 h, 0.8-100 TeV



CTA performance
6 pointings, 340 h, 0.2-100 TeV



SFS KSP:
CONNECTING CR'S AND STAR FORMATION



Estimated calorimetric gamma-ray flux

Estimated CTA sensitivity