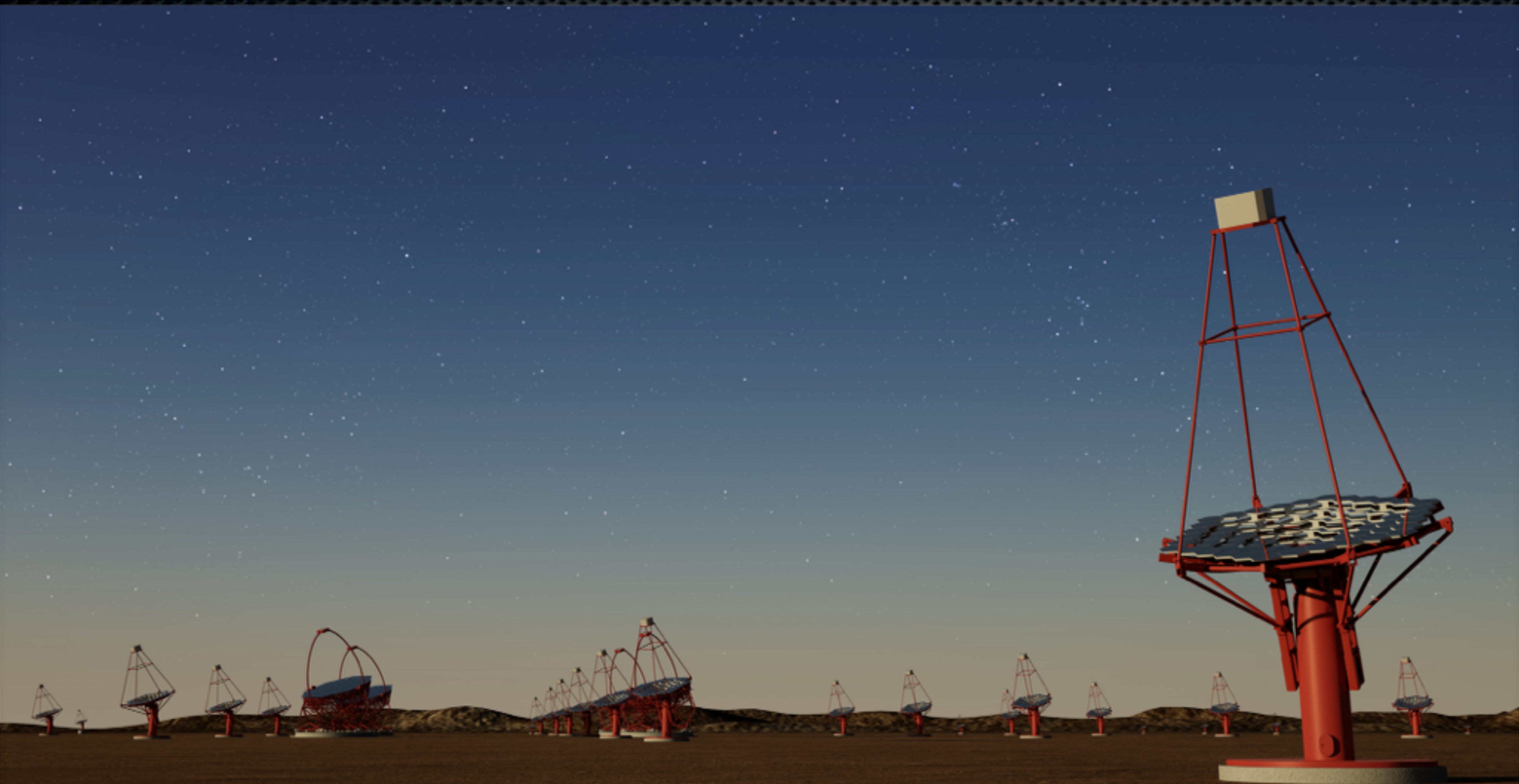
LOFAR + Gamma-ray Astronomy:

Synergy and strategy with the Cherenkov Telescope Array



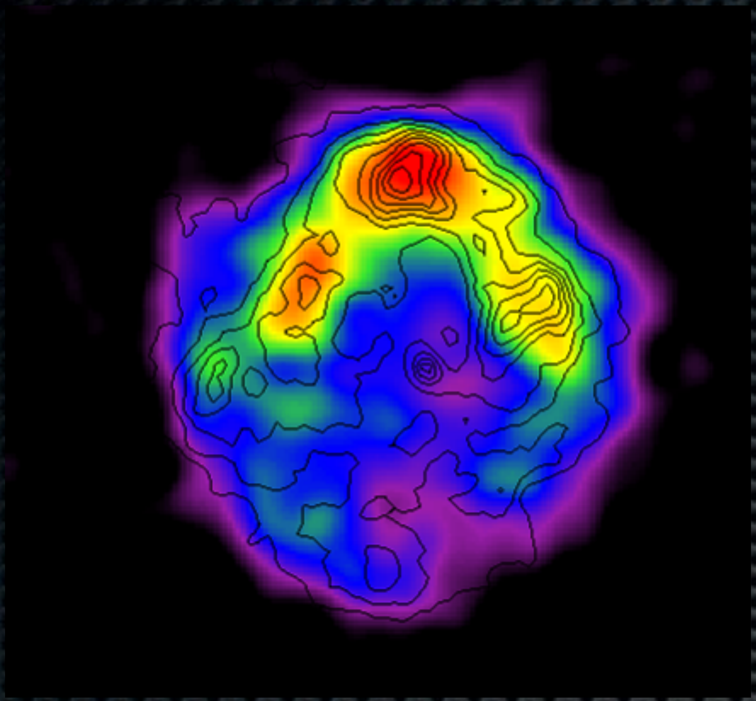
Sera Markoff (UvA) ⊂ CTA-NL (vd Berg, Berge, Hörandel, Stuik, Venema, Vink)


Optical
© Fabio Acero

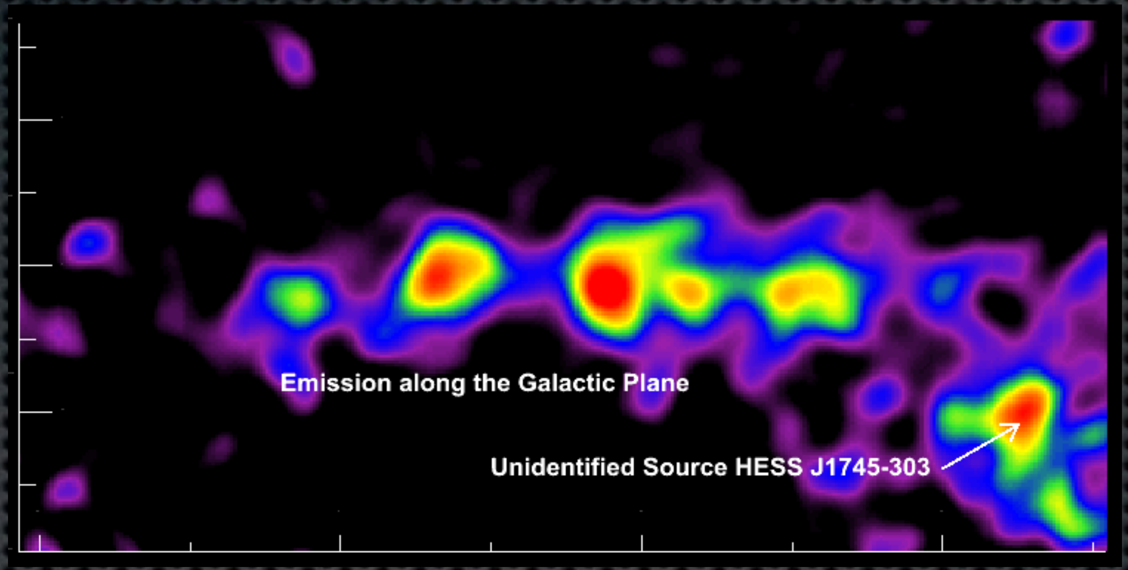

Optical
+TeV
(c) F. Acero & H. Gast

Key science interests w/obvious LOFAR synergy

Supernova remnants

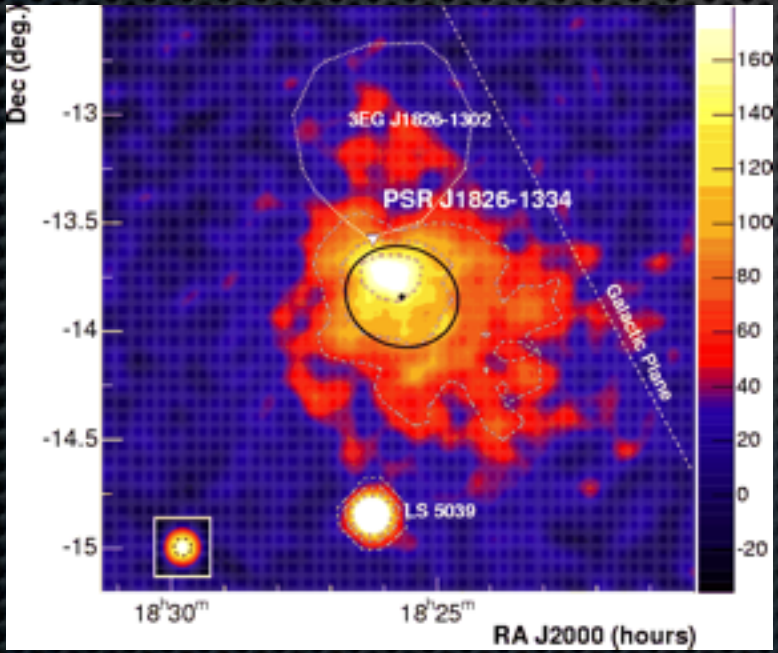


CR interactions in diffuse gas/Galactic Center

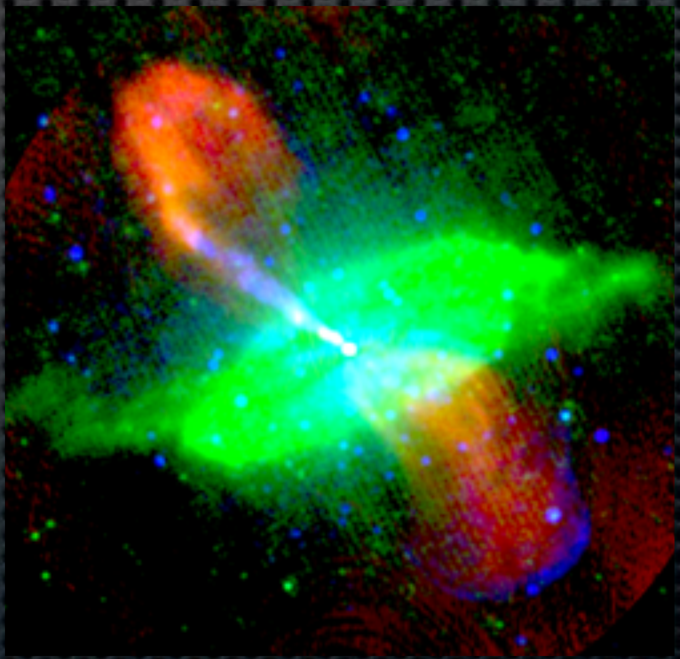


GRBs/Transients

Pulsar Wind Nebulae



SMBH/AGN Jets



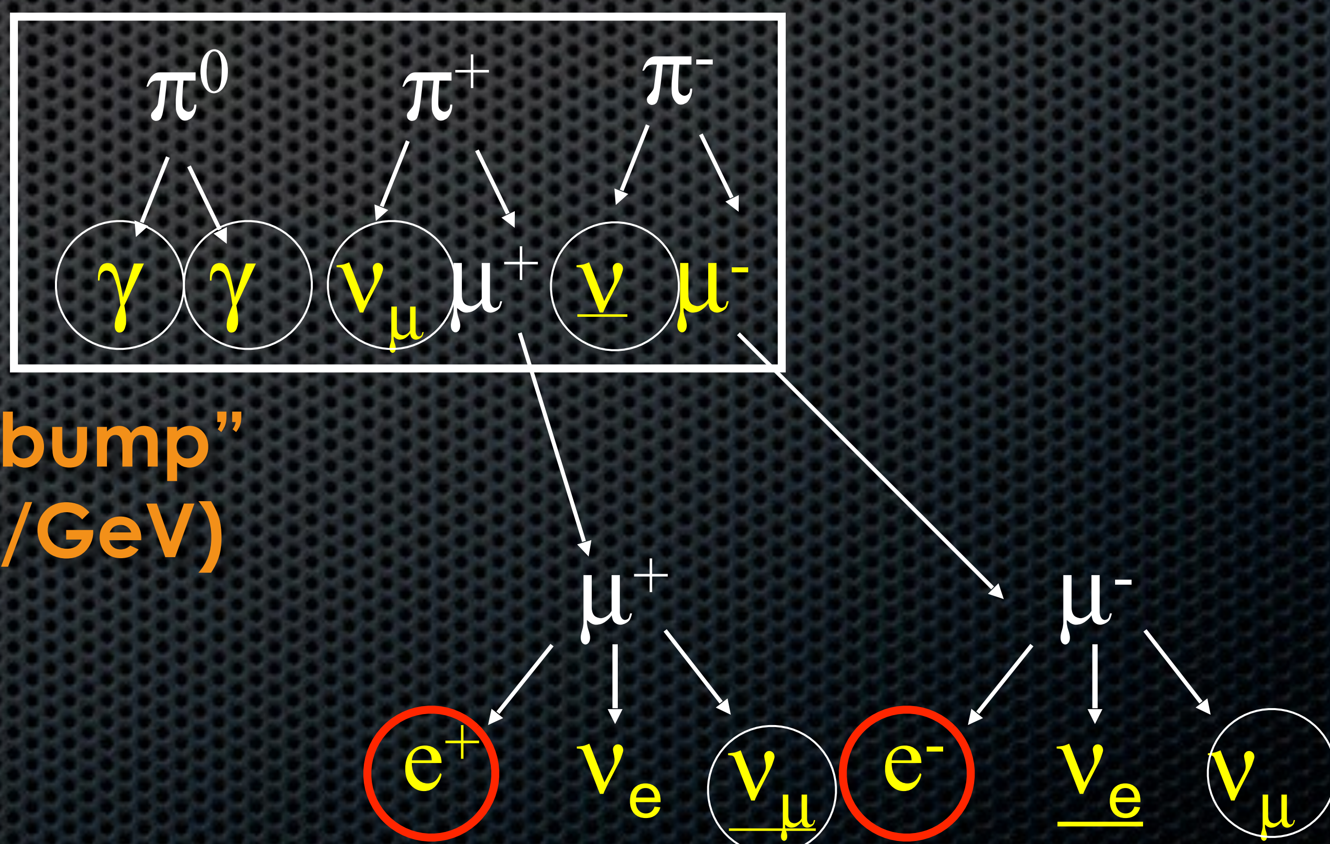
Clusters of Galaxies

γ-rays trace HE particle acceleration and/or interactions

Particles (e+e- pairs and/or e-p/ions) **+** B field (or ∇V) **+** shock (or turbulence, reconnection, waves)

⇒ accelerated particles (CRs: e+e-,p's, ions)

Hadronic CR + (γ or ion) $\longrightarrow$ CR's + N(π^0,π^+,π^-)



"pion bump"
(MeV/GeV)

γ-rays trace HE particle acceleration and/or interactions

Particles (e+e- pairs and/or e-p/ions) **+** B field (or ∇V) **+** shock (or turbulence, reconnection, waves)

➠ accelerated particles (CRs: e+e-,p's, ions) **+** secondary (higher energy) leptons

synchrotron ➠ synchrotron self-Compton (SSC)

γ-rays trace HE particle acceleration and/or interactions

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➠ accelerated particles (CRs: e+e-,p's, ions) **+** secondary (higher energy) leptons

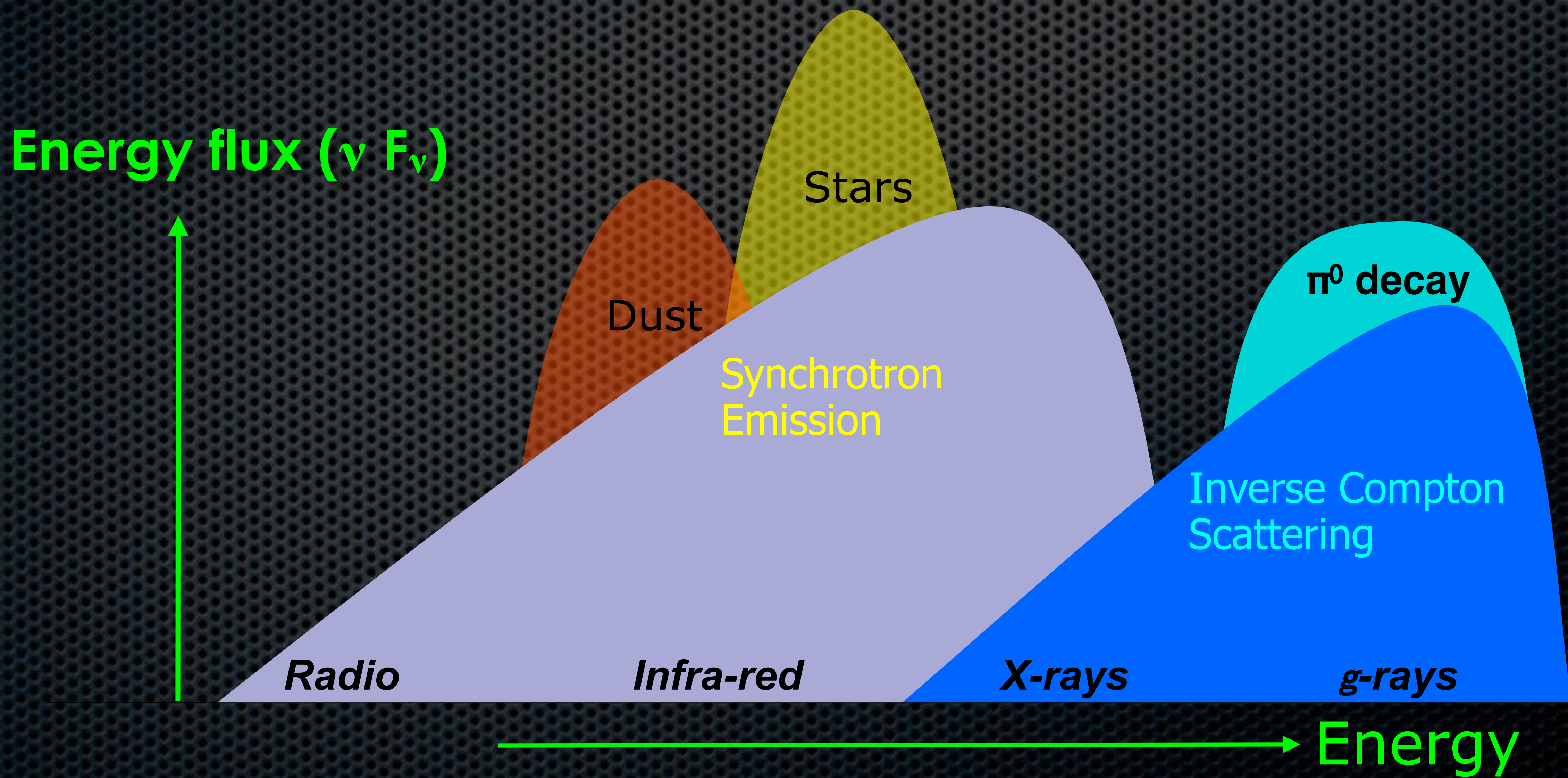
synchrotron ➠ synchrotron self-Compton (SSC)

+ background γ's (CMBR/ EBL) ➠ inverse Compton (IC)

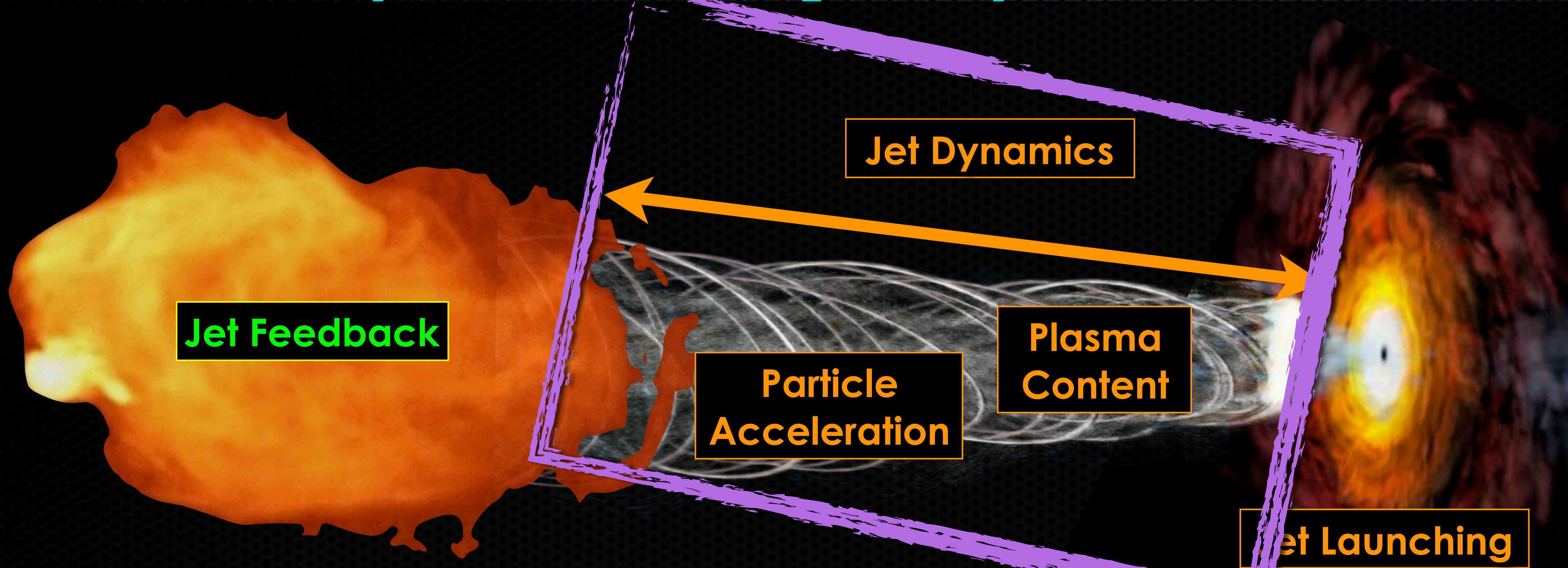
γ-rays trace HE particle acceleration and/or interactions

Particles (e+e- pairs and/or e-p/ions) **+** B field (or ∇V) **+** shock (or turbulence, reconnection, waves)

= accelerated particles (CRs: e+e-,p’s, ions) **+** secondary (higher energy) leptons

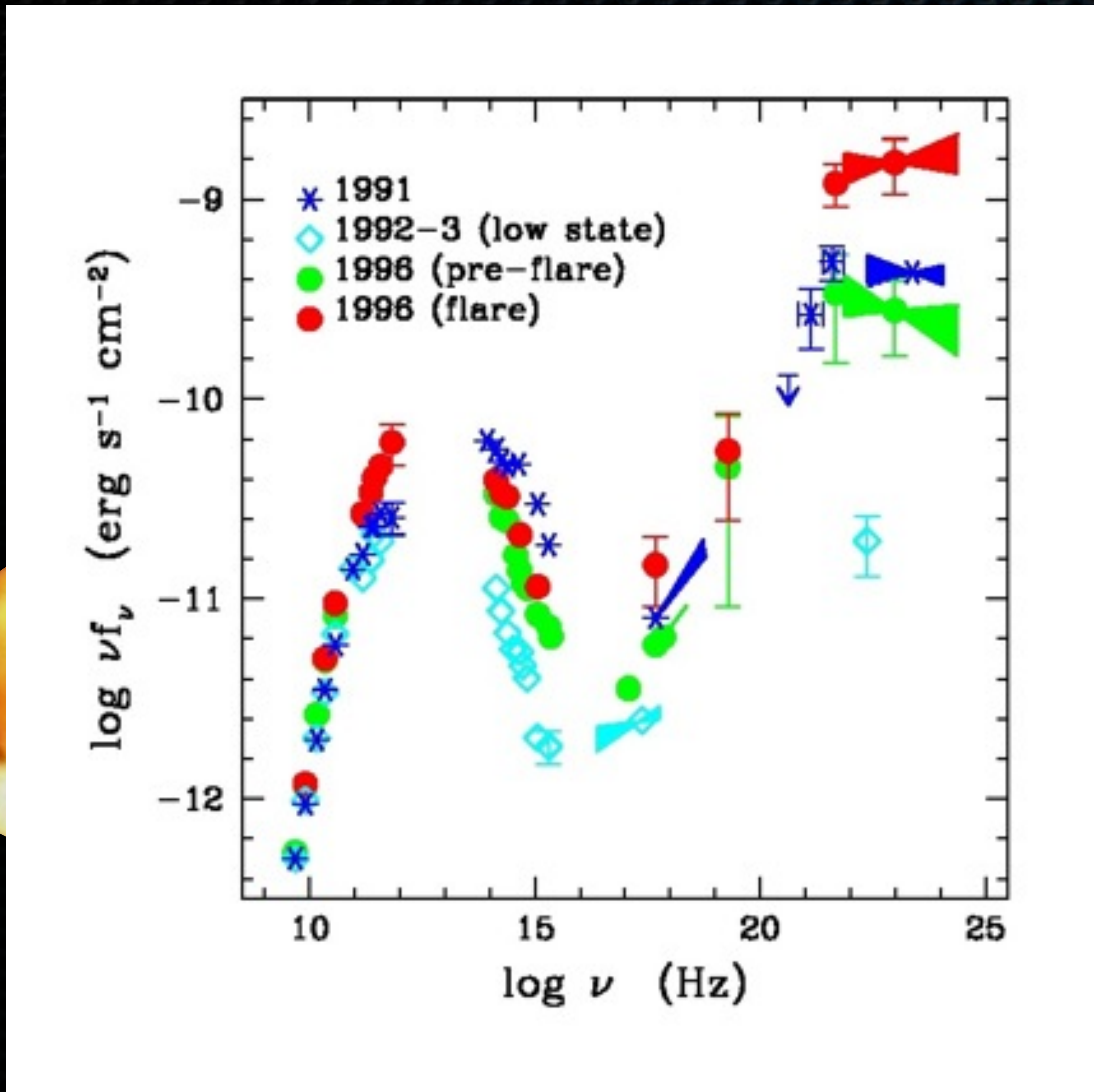


Too many unknowns = degeneracy in the theories

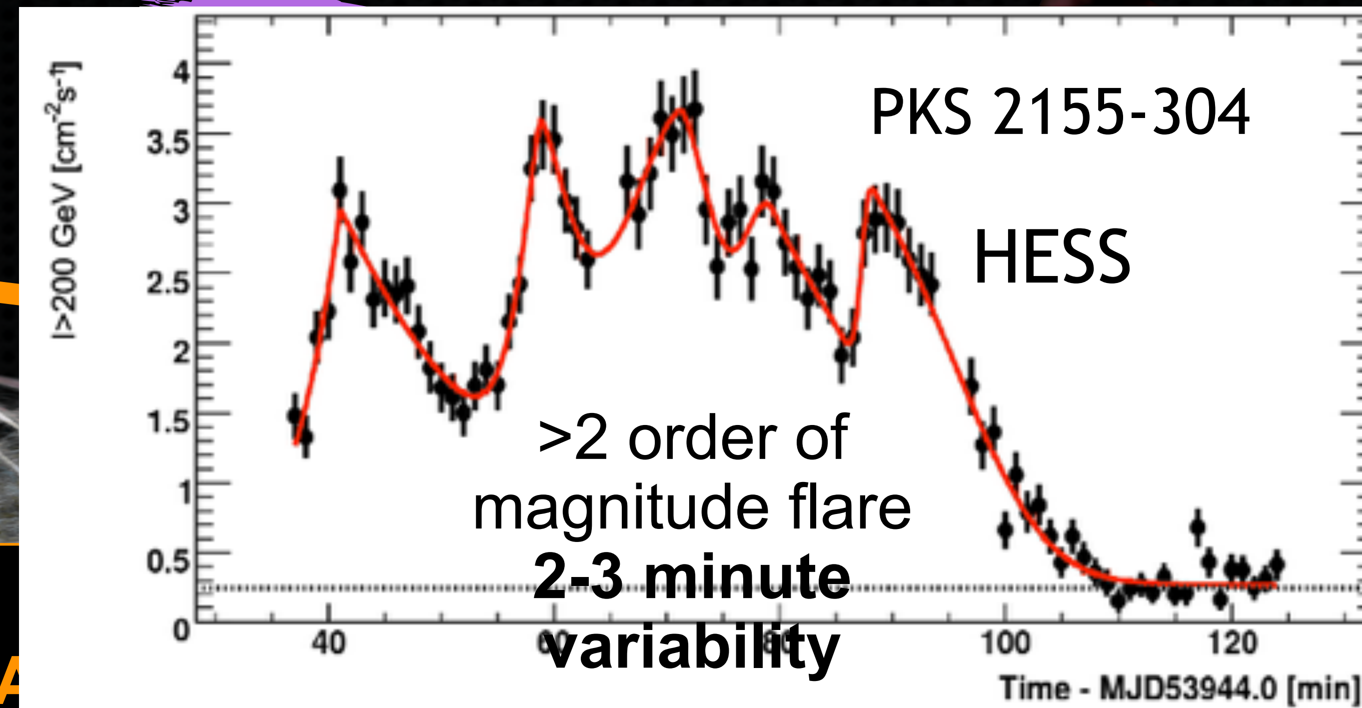


TeV observations can help address several key outstanding questions:

- Constraining particle content (hadron/lepton): *places limits on jet launching scenarios (accretion flow vs black hole ergosphere)*
- Constraining ratio of synchrotron vs inverse Compton processe: *constrains internal plasma conditions (magnetic vs thermal vs nonthermal)*
- Constraining particle acceleration process and efficiency: *helps track conversion of magnetic to kinetic energy, localises acceleration sites*



= degeneracy in the theories



et Launching

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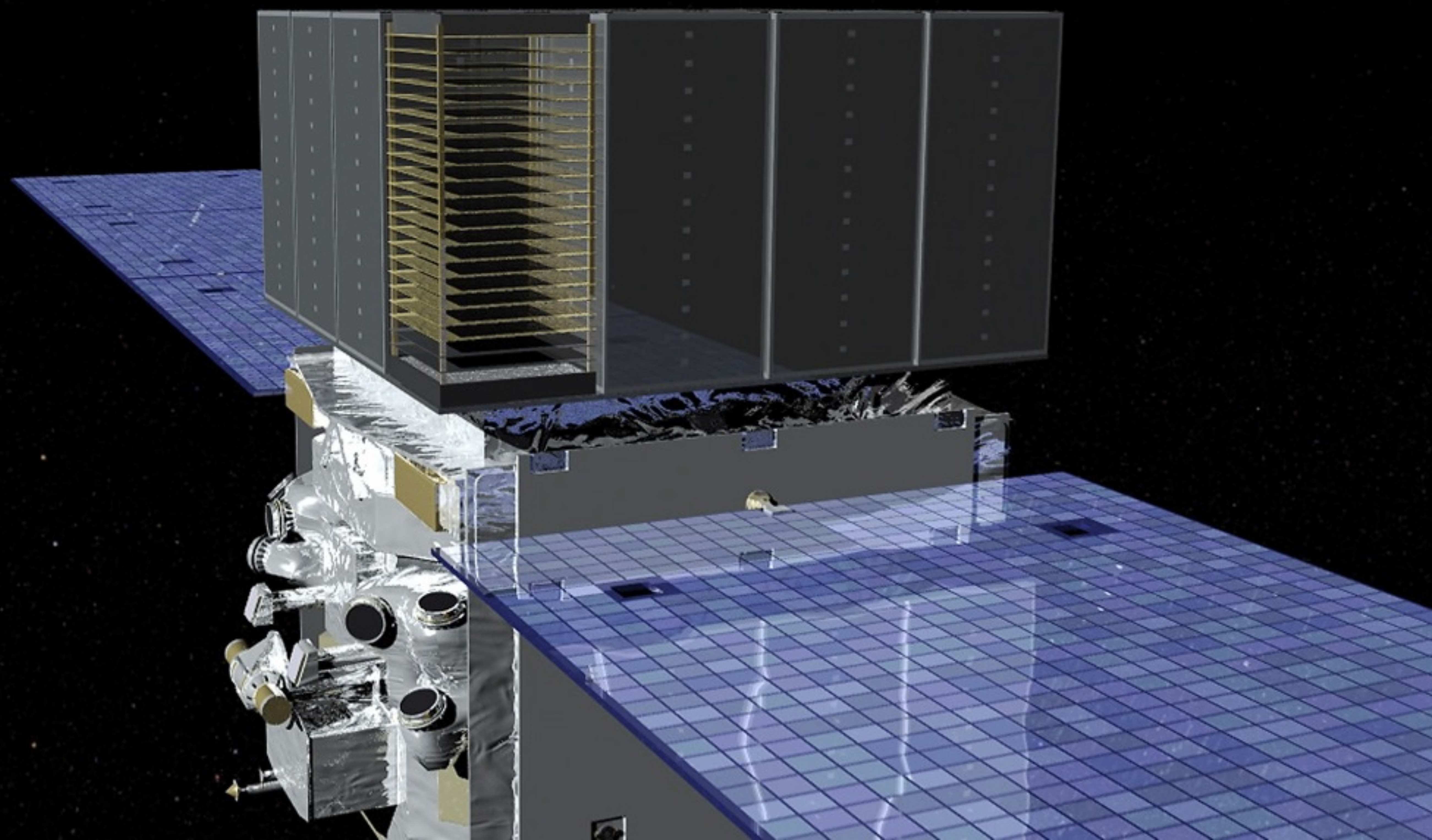
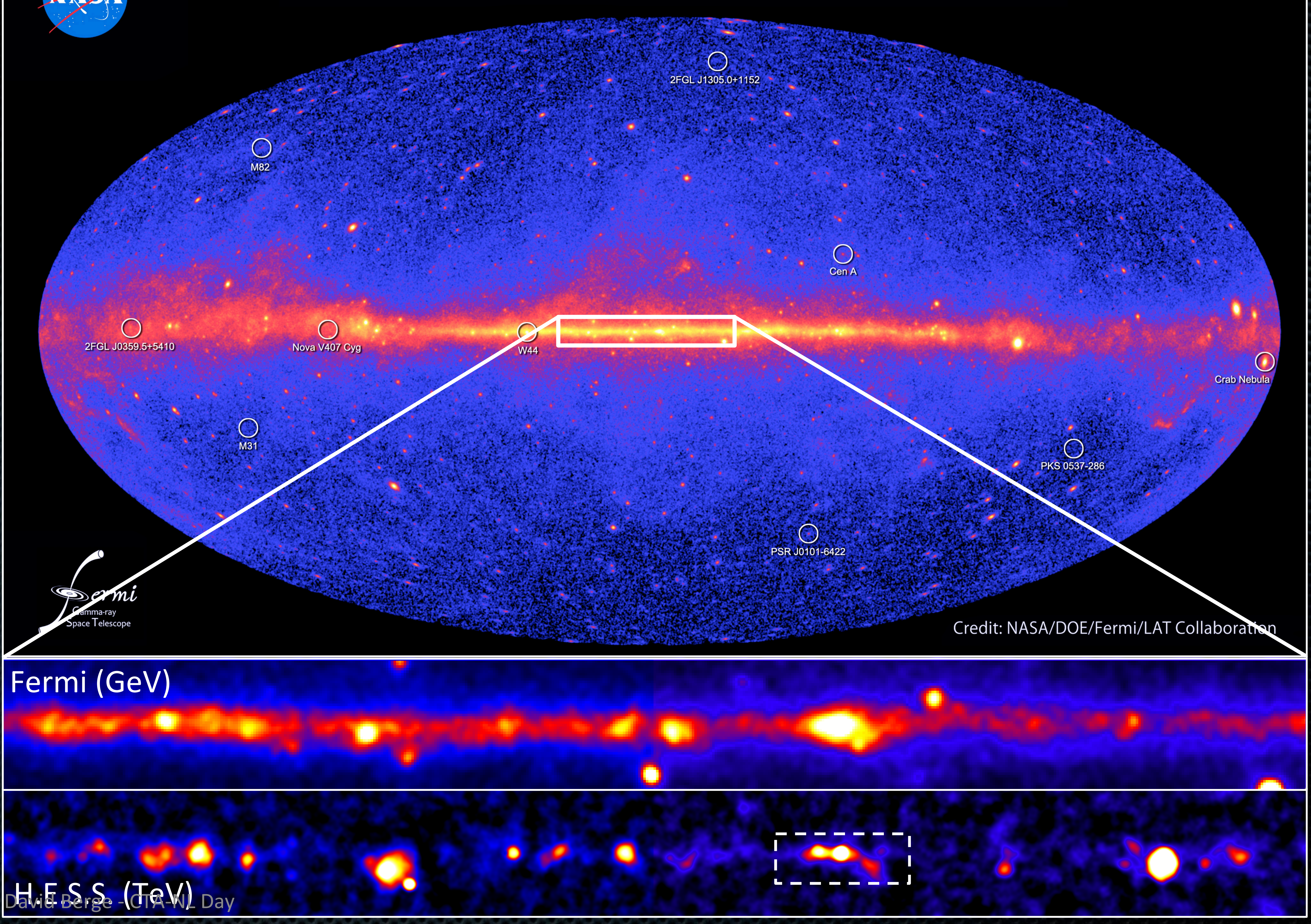
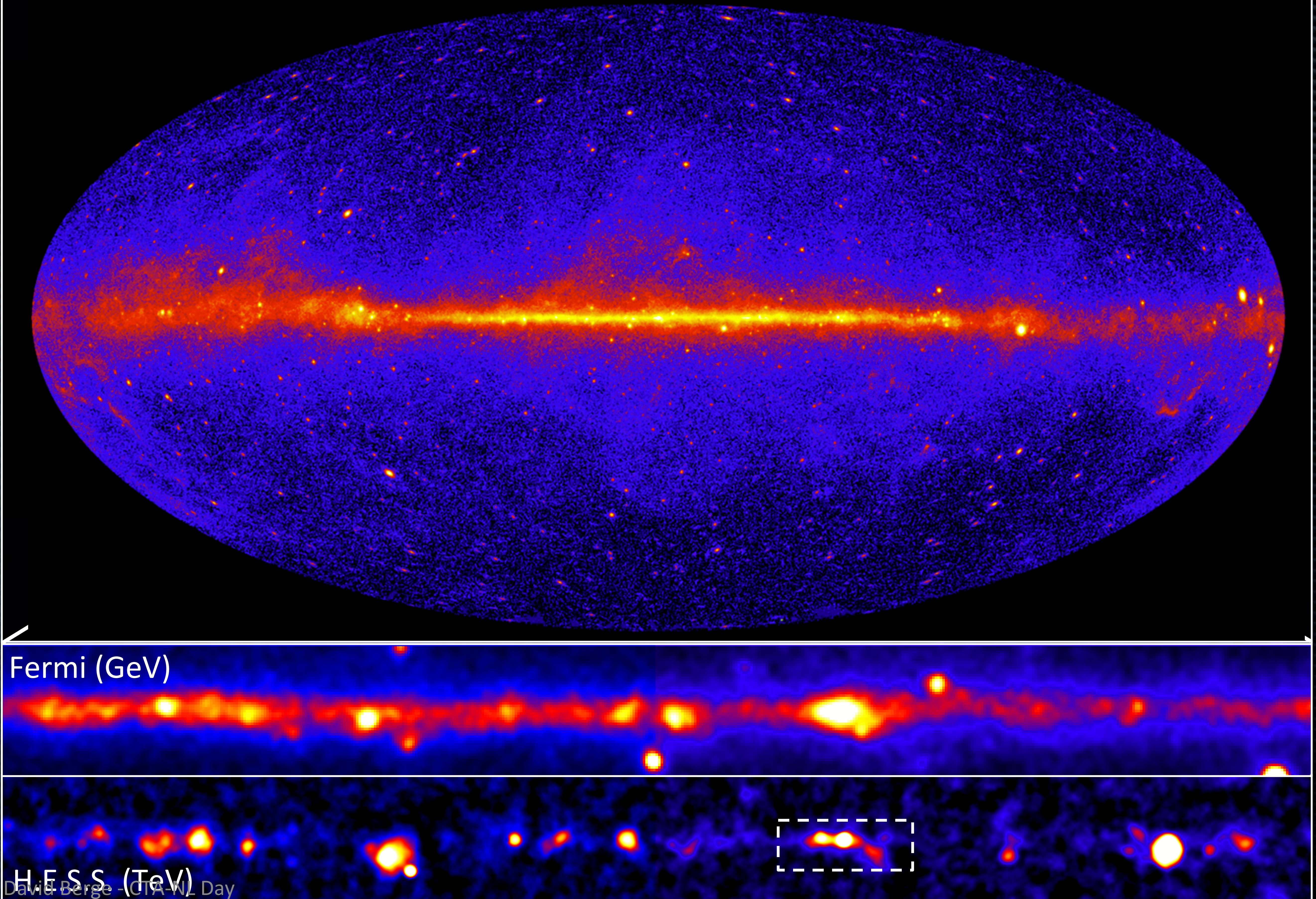
MeV/GeV state-of-the-art: Fermi Telescope



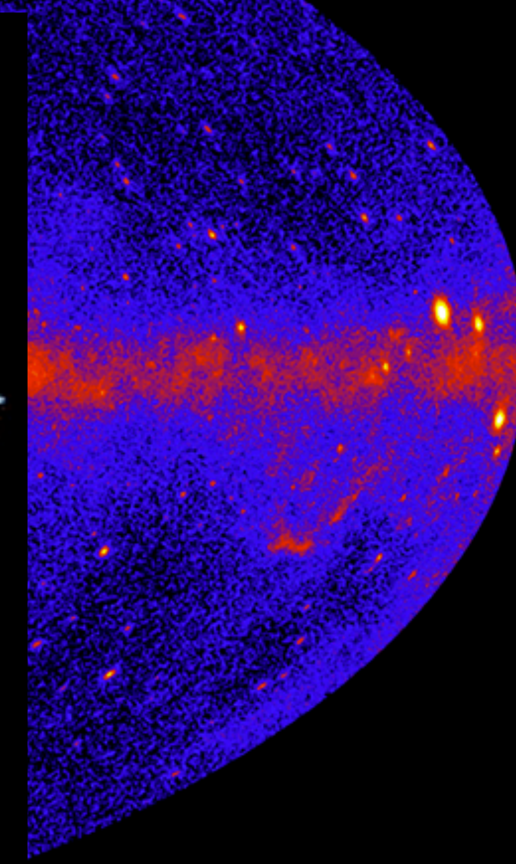
Fermi two-year all-sky map



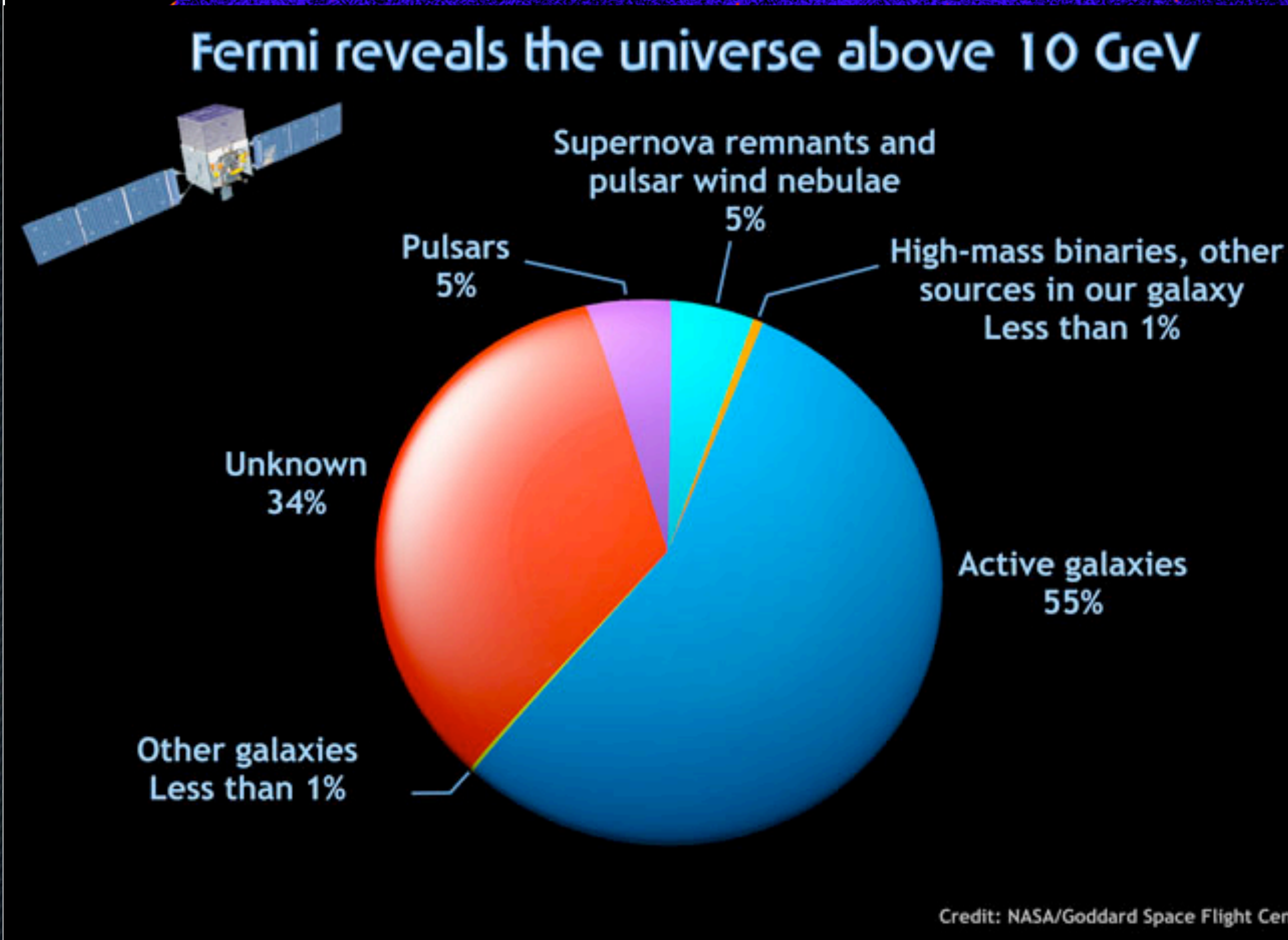
Fermi Three year all-sky map

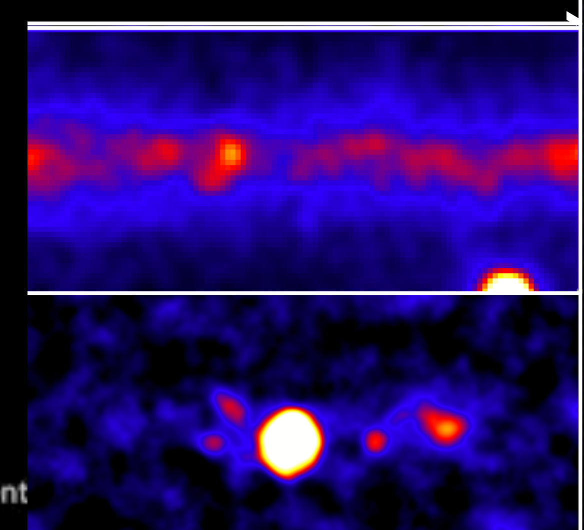


Fermi Three year all-sky map

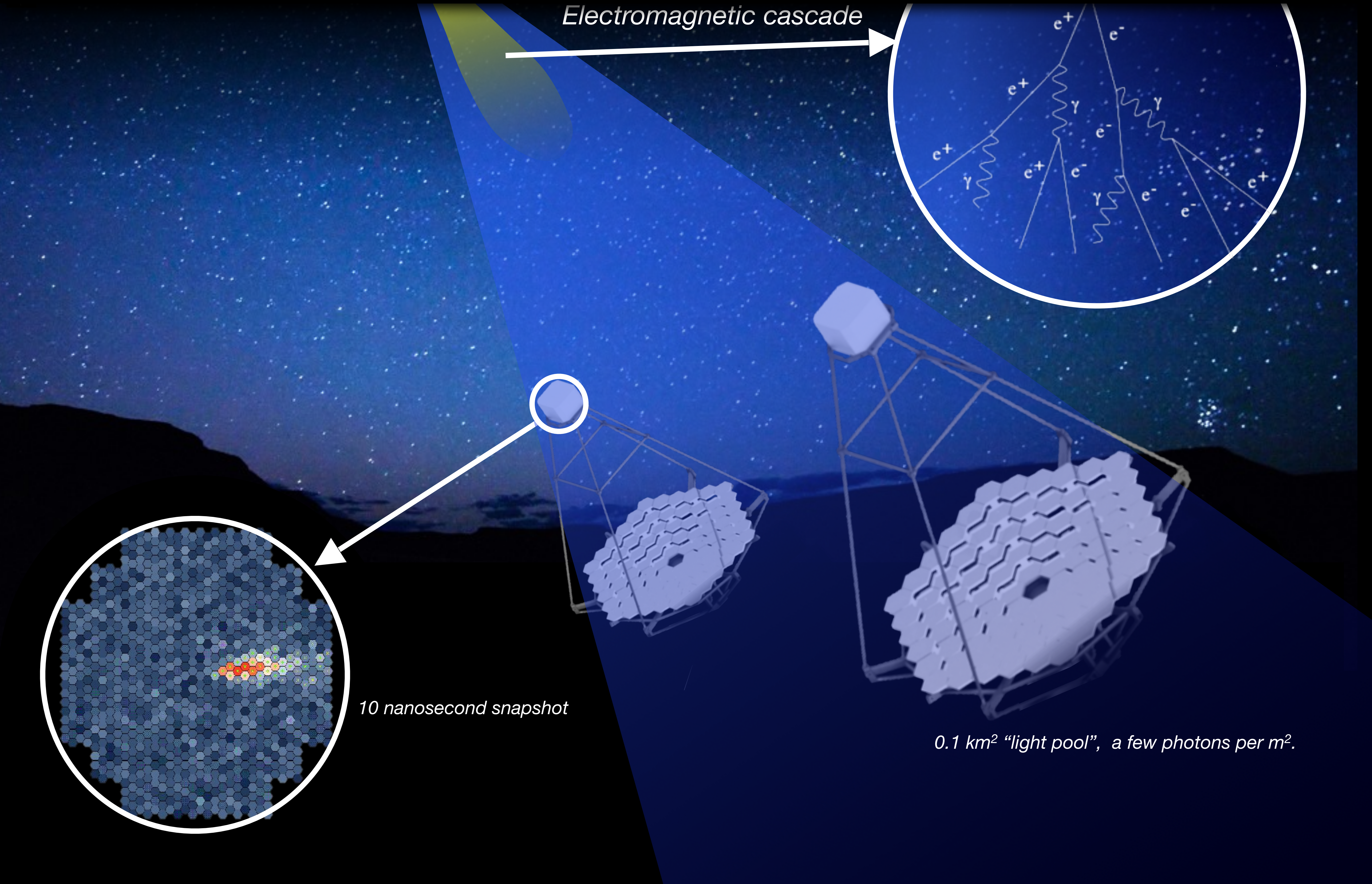


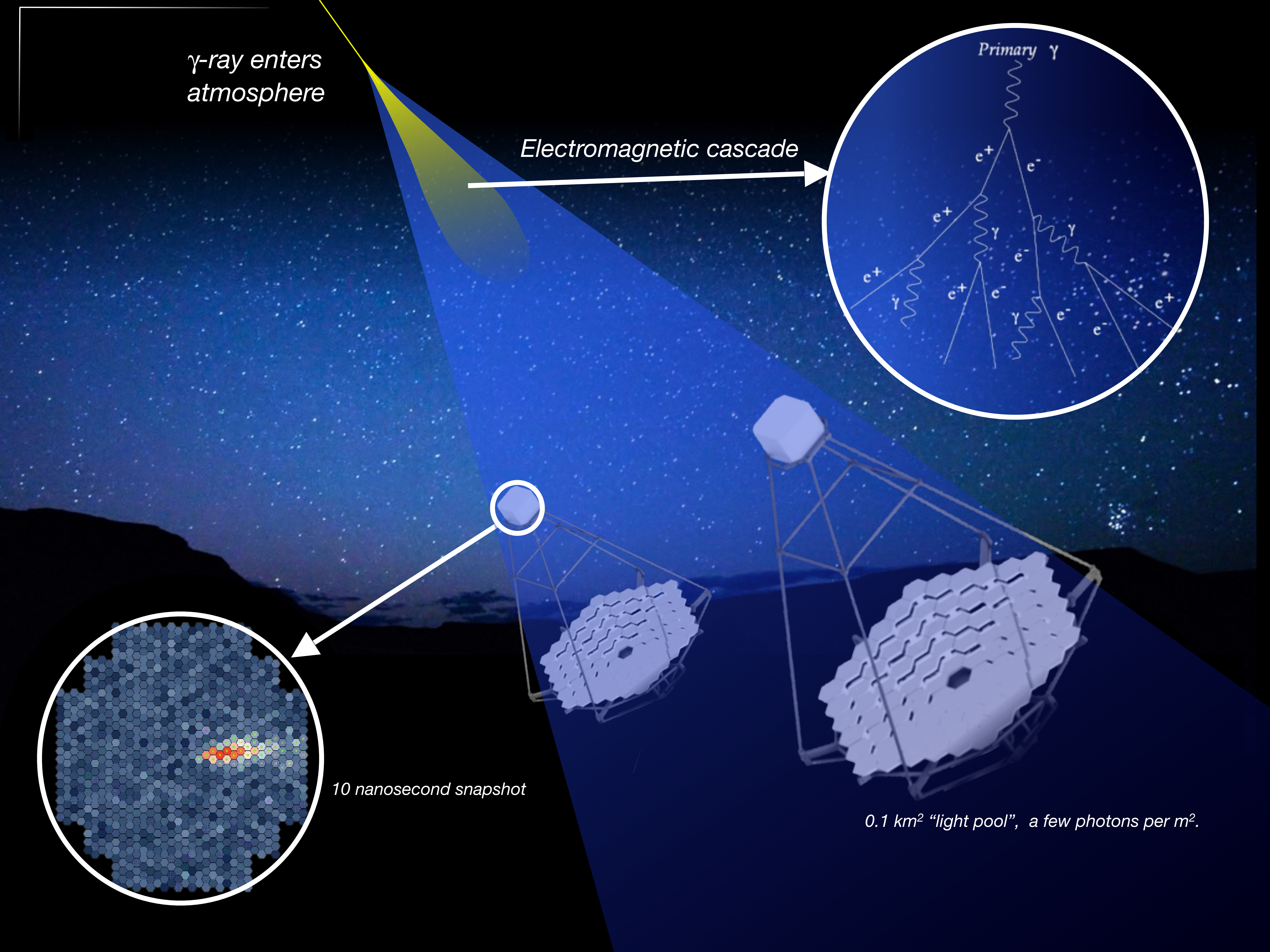
>2500 sources at MeV-GeV
>500 sources > 10 GeV
>150 sources > 100 GeV

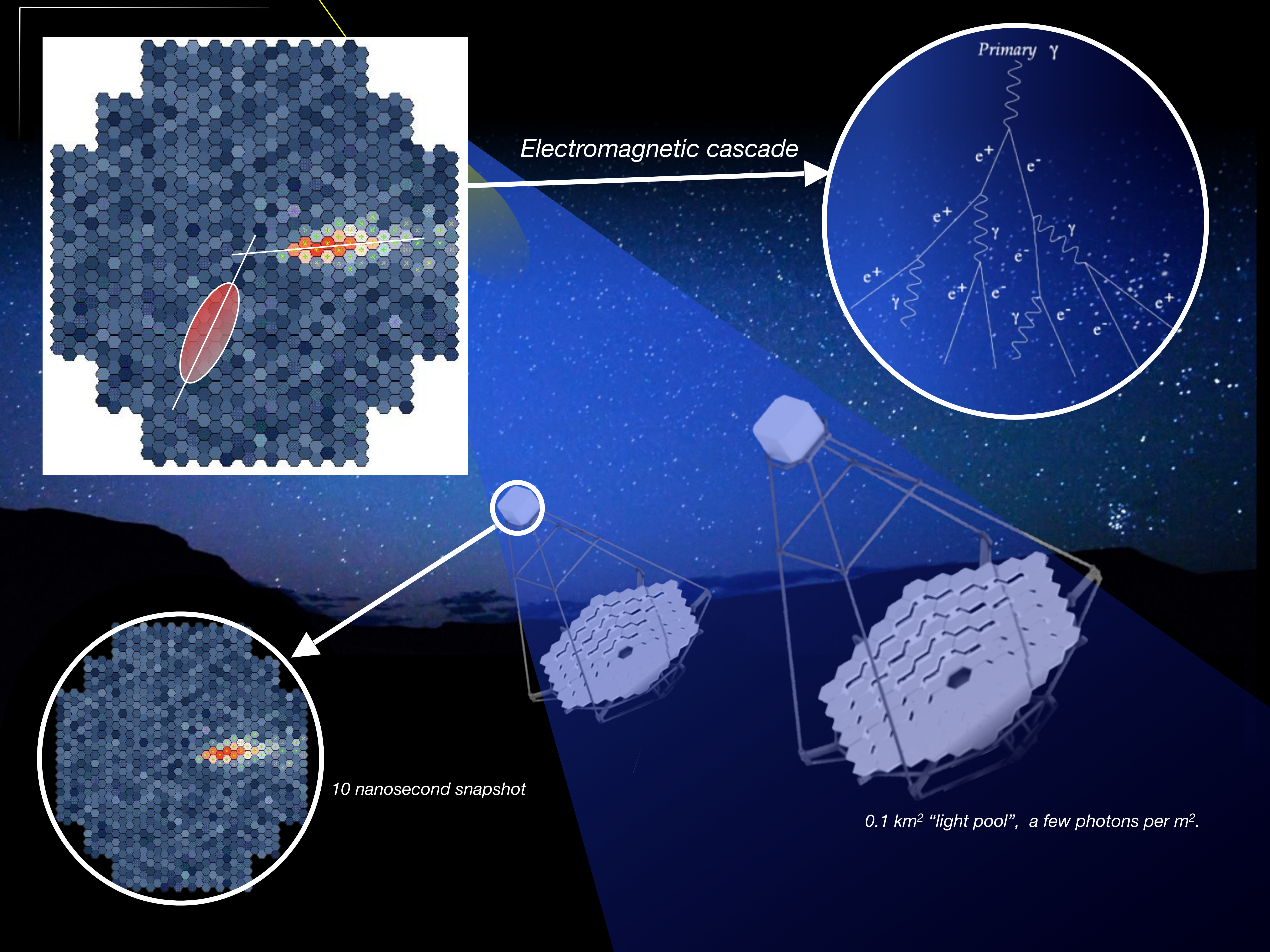




Ground based: Imaging Atmospheric (or Air) Cherenkov Telescope

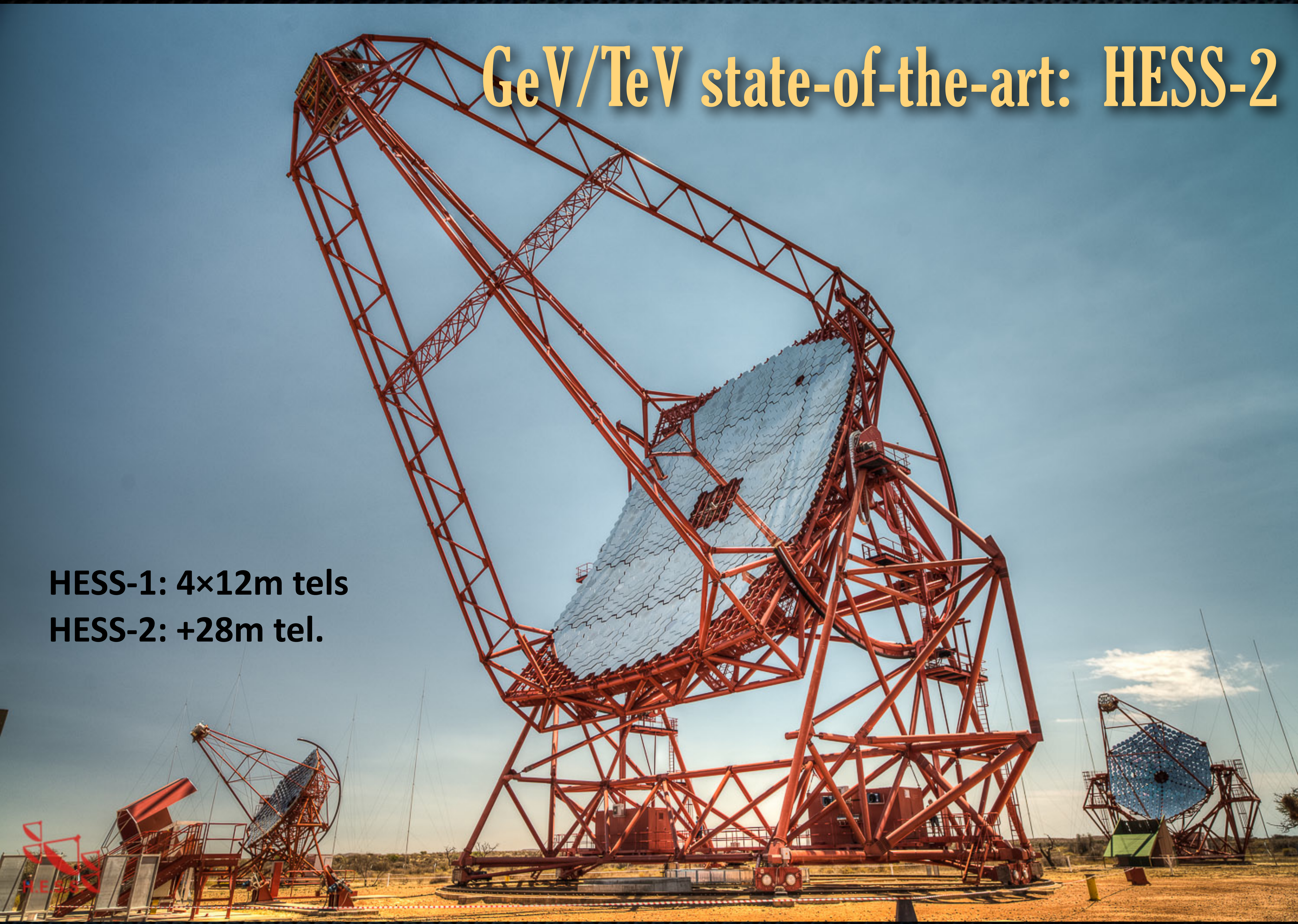



γ-ray enters atmosphere
Electromagnetic cascade
Primary γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².



Primary γ
Electromagnetic cascade
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².

GeV/TeV state-of-the-art: HESS-2



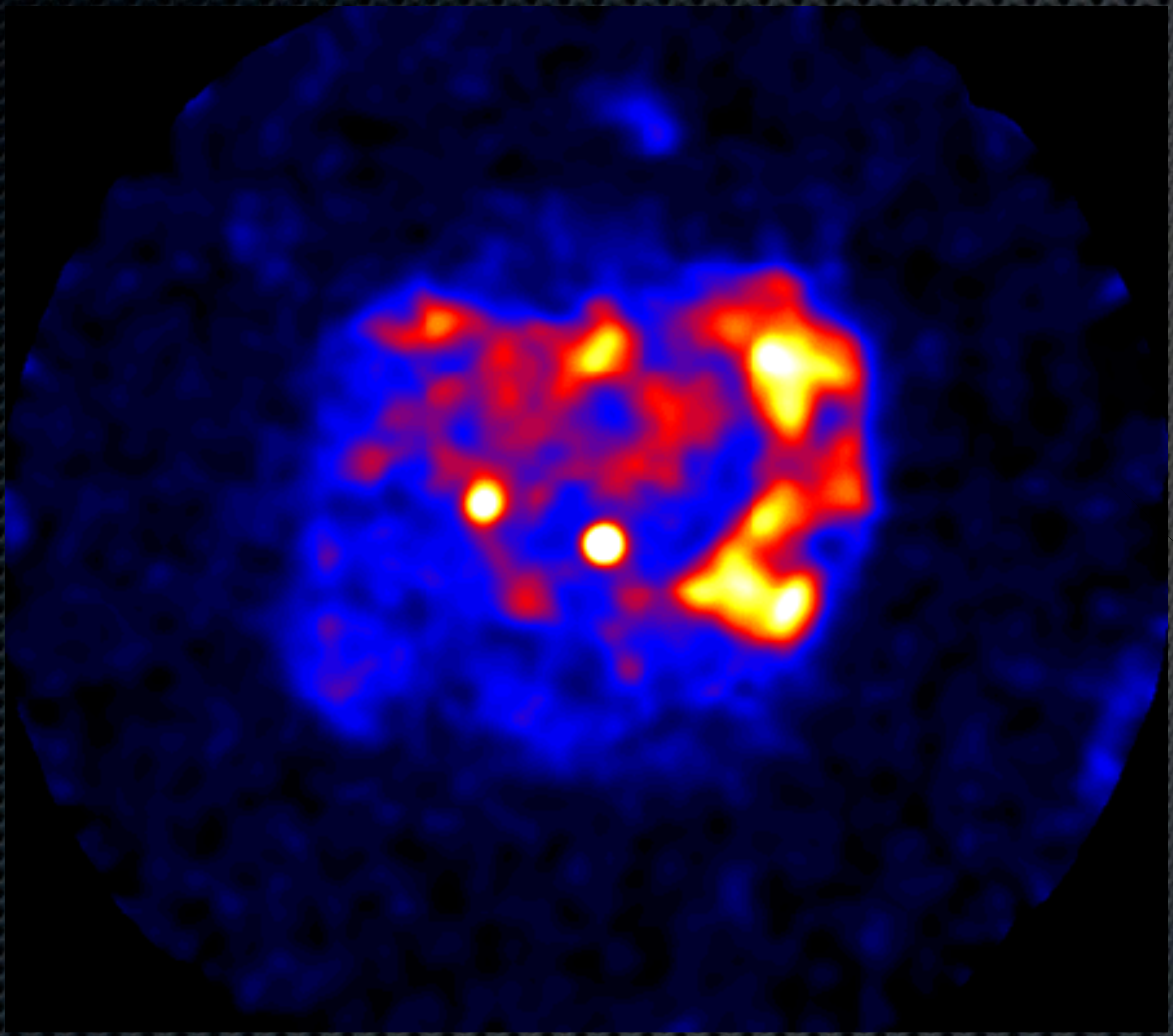
HESS-1: 4×12m tels
HESS-2: +28m tel.

GeV/TeV state-of-the-art: HESS-2

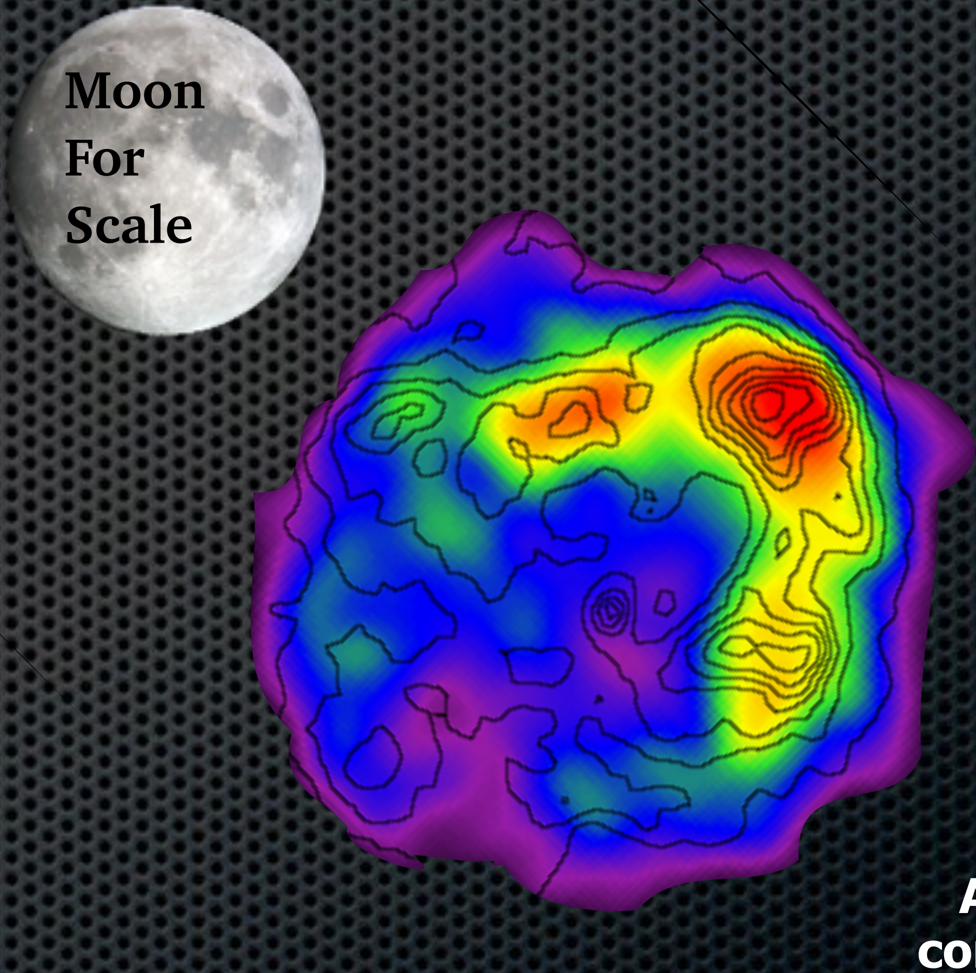
GeV/TeV state-of-the-art: HESS-2

First TeV detection of supernova shell: RX J1713.7-3946

ROSAT – X-ray

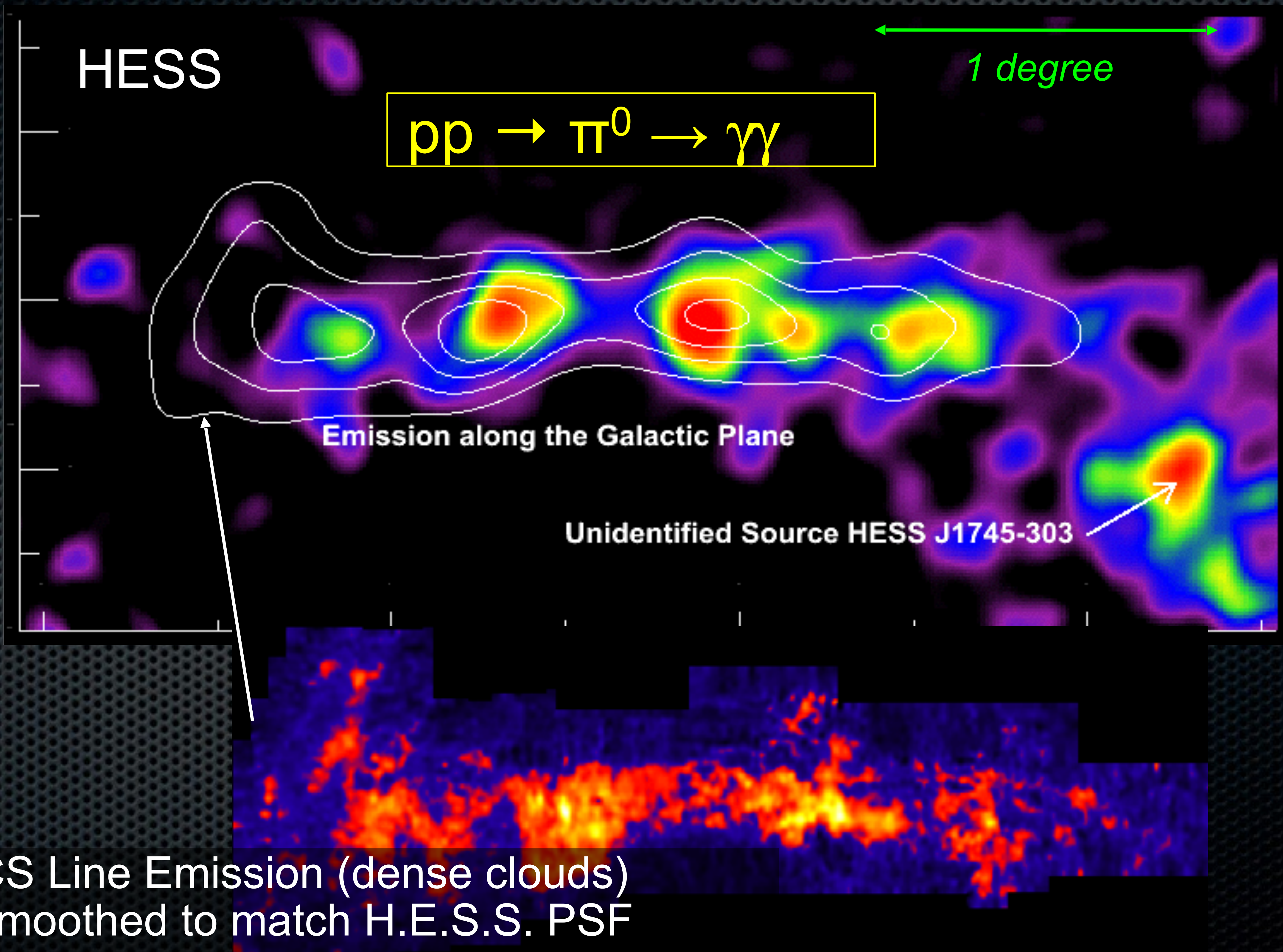


HESS – TeV γ-ray



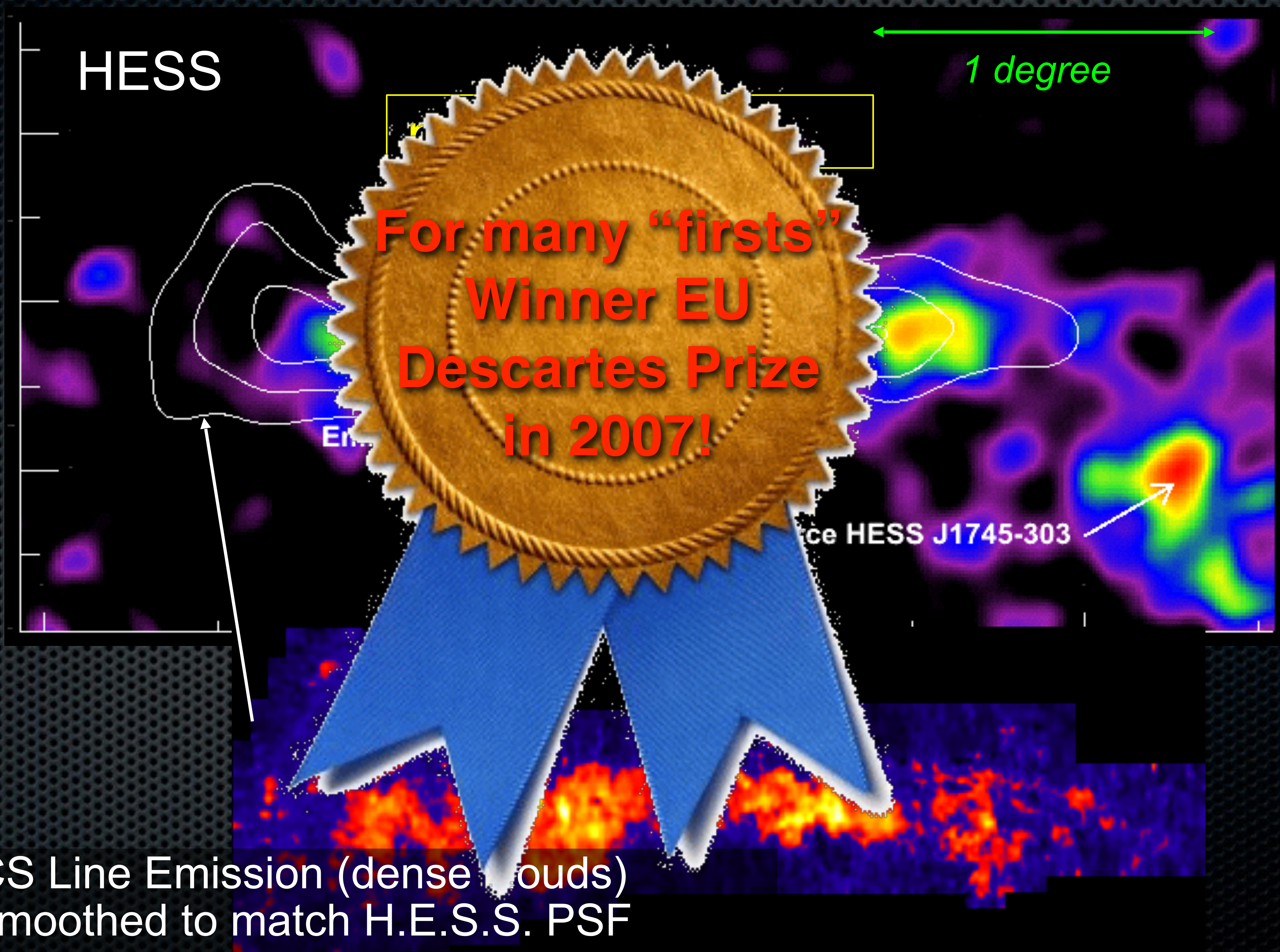
- Purely non-thermal X-ray source
- First TeV gamma-ray SNR (and first image, Nature 432, 75)
- Closely correlated keV/TeV and radio morphology…

Diffuse Emission from CRs in molecular gas



CS Line Emission (dense clouds)
smoothed to match H.E.S.S. PSF

Diffuse Emission from CRs in molecular gas

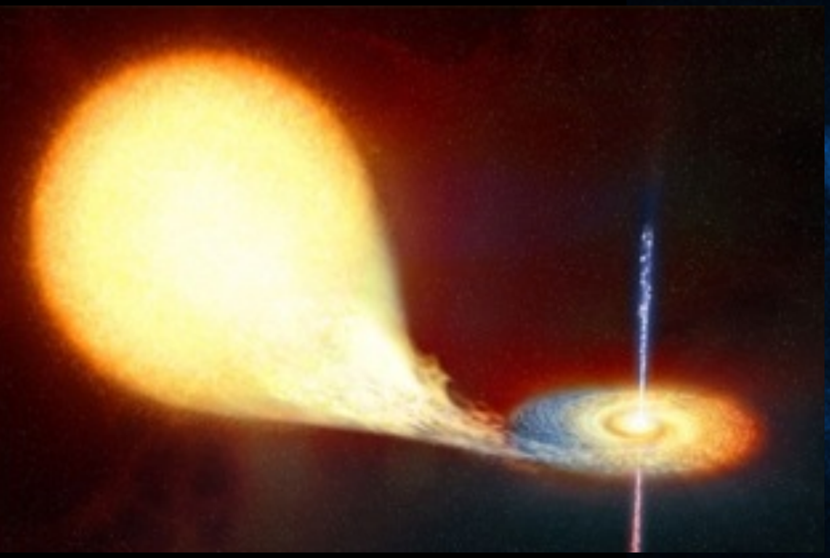
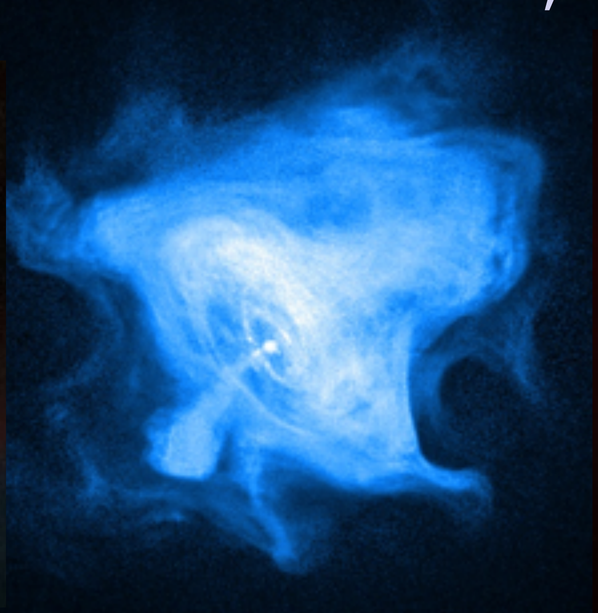


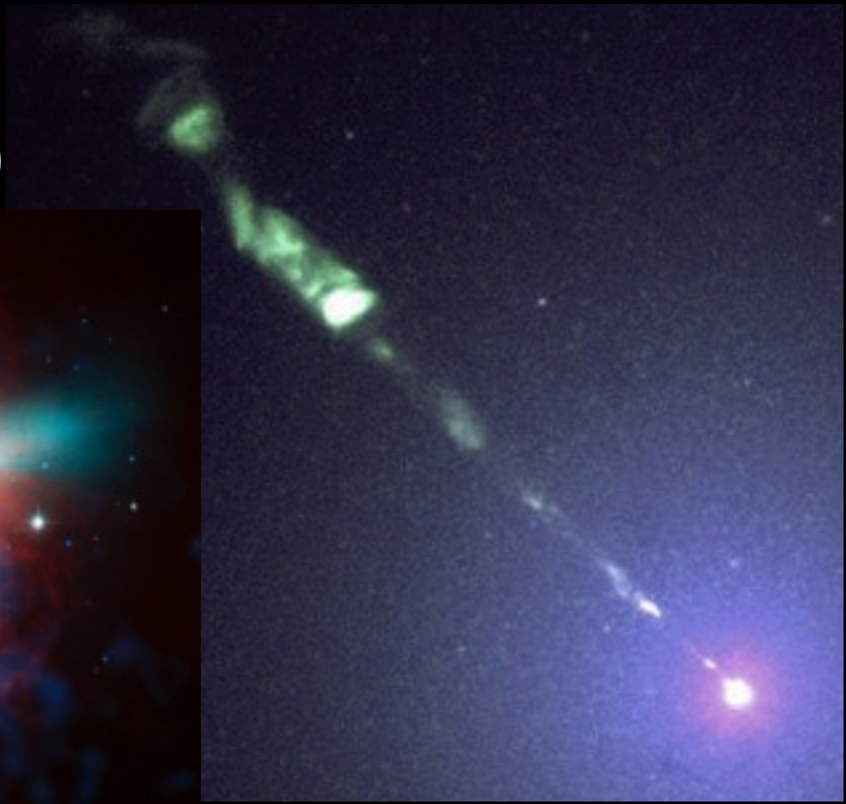
CS Line Emission (dense ouds)
smoothed to match H.E.S.S. PSF

TeV Highlights

Results from **HESS**, **MAGIC** and **VERITAS**

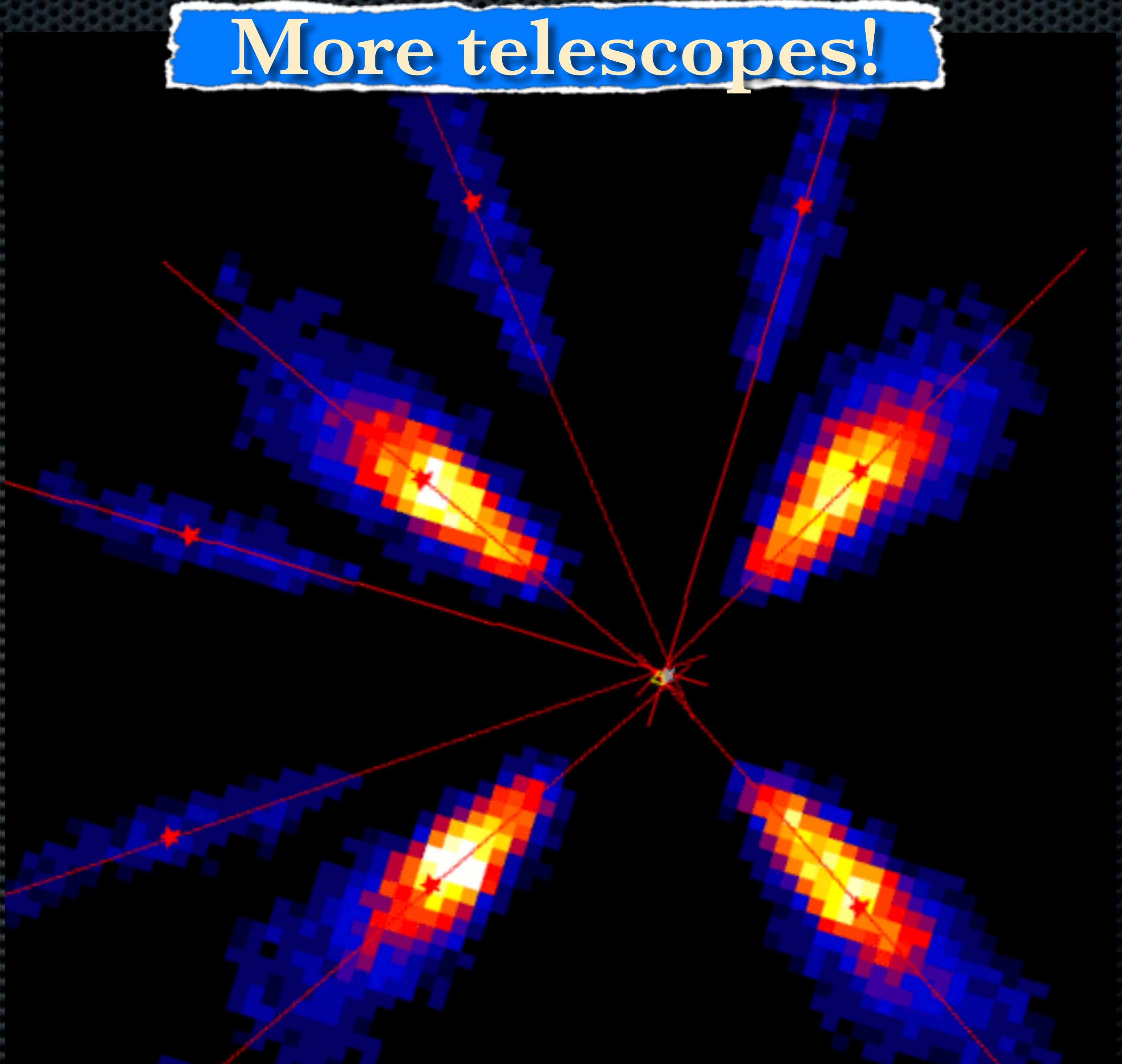
- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars:* Science 322, 1221 (2008), Science 334, 69 (2011)
- *Supernova Remnants:* Nature 432, 75 (2004)
- *The Galactic Centre:* Nature 439, 695 (2006)
- *Galactic Survey:* Science 307, 1839 (2005)
- *Starbursts:* Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN:* Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL:* Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark Matter:* PRL 96, 221102 (2006), PRL 106, 161301 (2011)
- *Lorentz Invariance:* PRL 101, 170402 (2008)
- *Cosmic Ray Electrons:* PRL 101, 261104 (2009)

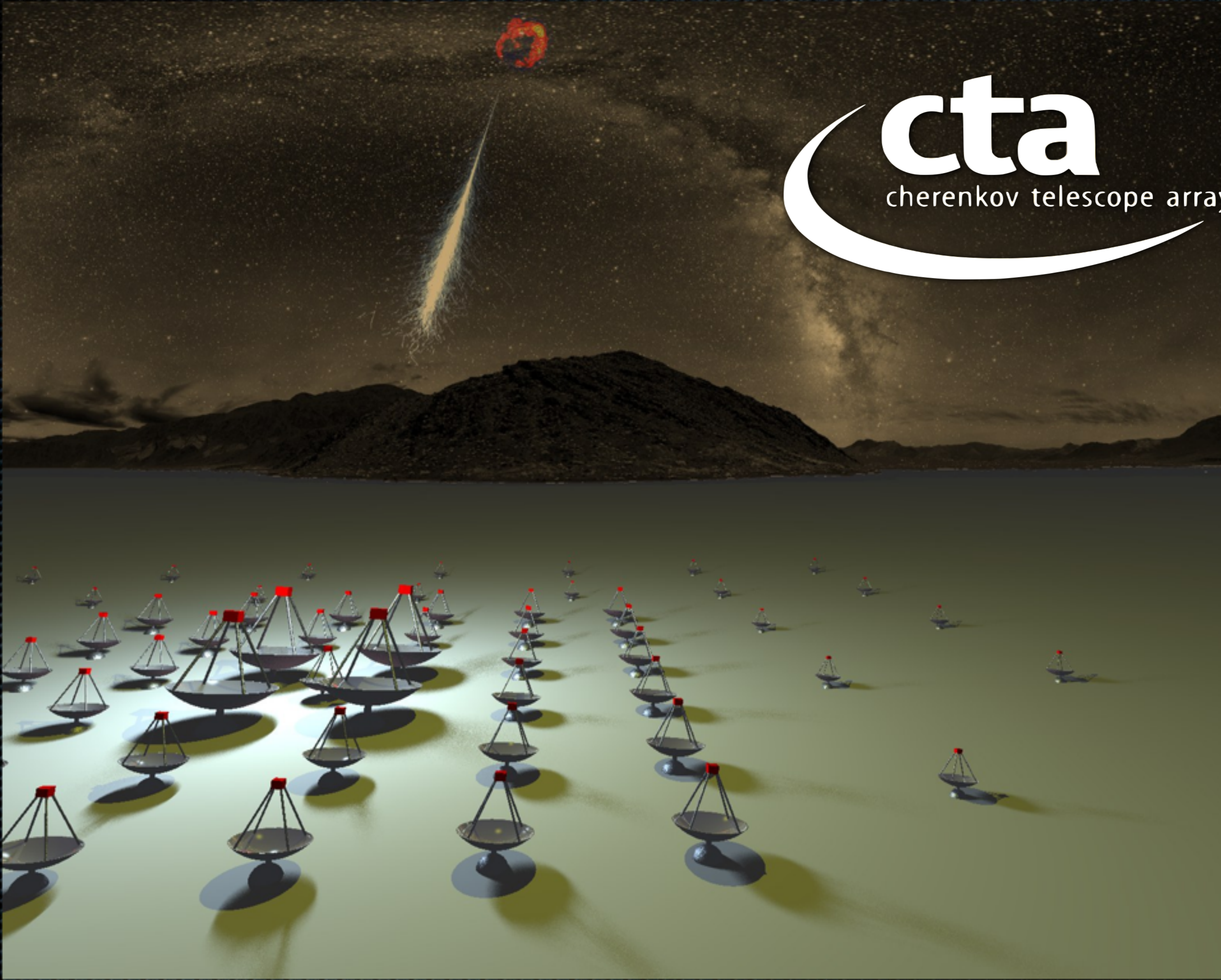


How to improve sensitivity, resolution, localisation:

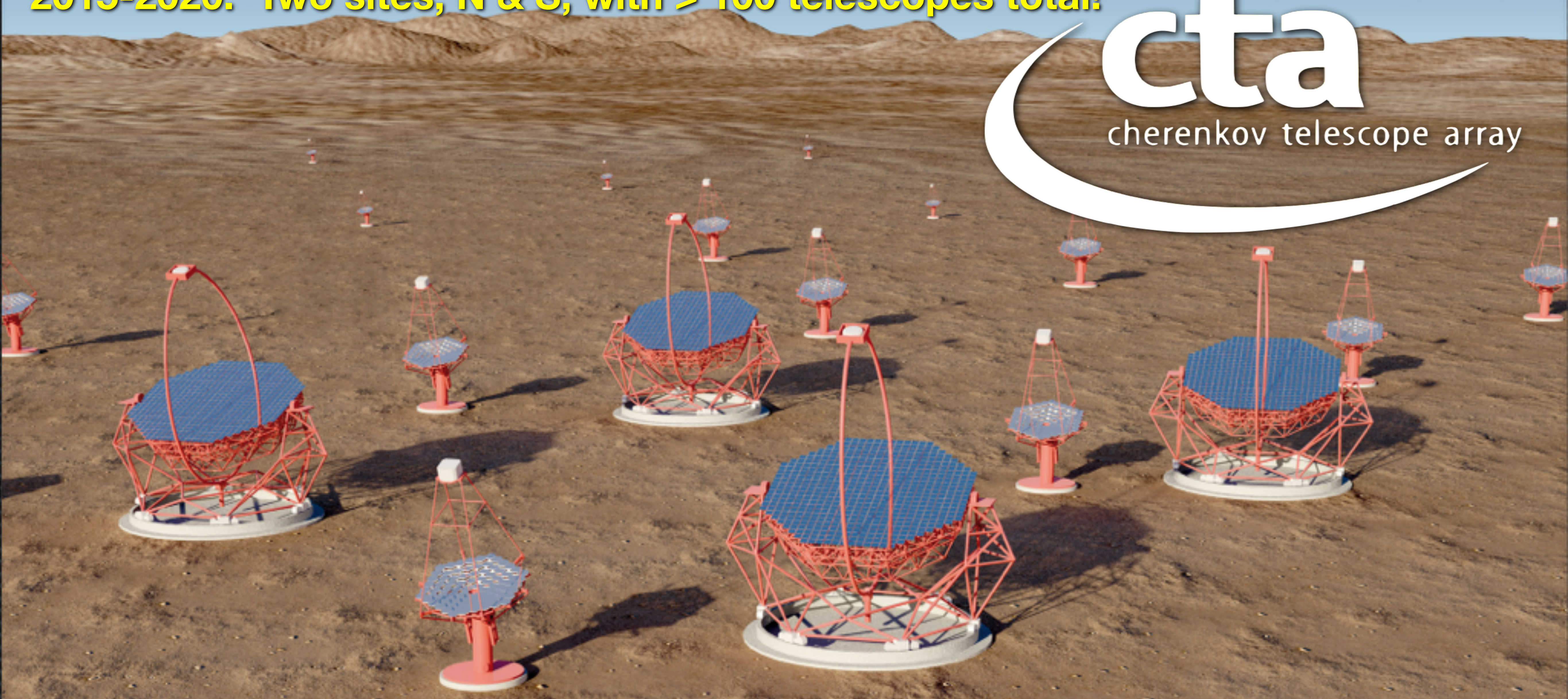
- More telescopes = larger collecting area
- More photons ➠ better spectra, images, increased sensitivity
- More trajectories to trace back ➠ better source localisation
- Improved background rejection



Simulation:
Superimposed images from 8 cameras


cta
cherenkov telescope array

28 countries, >1000 members, ~200M€ investment, construction planned for 2015-2020. Two sites, N & S, with > 100 telescopes total!

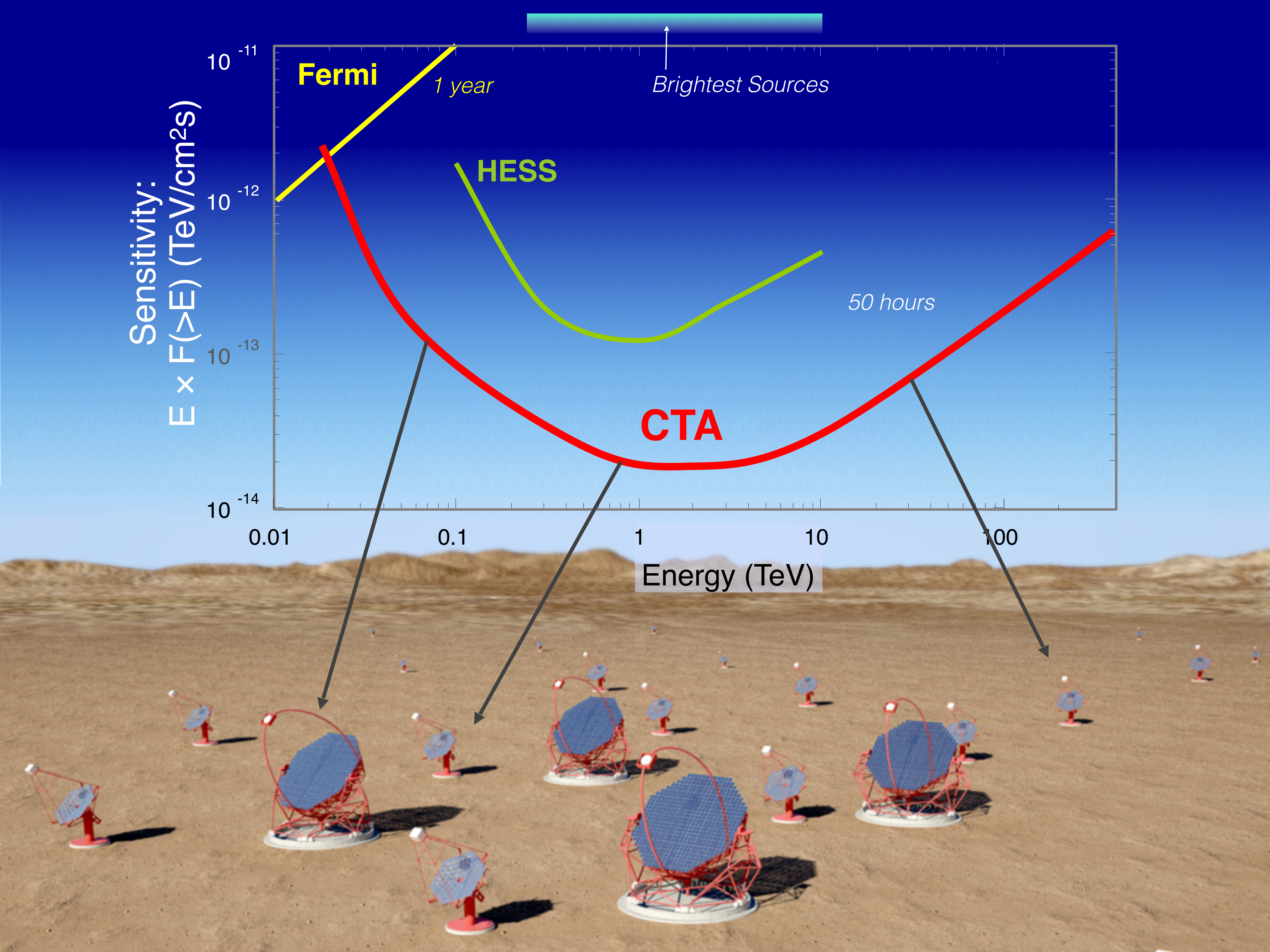


Key design goals:

- Range overlapping Fermi: 20 GeV-200+ TeV
- 10x better sensitivity at TeV energies and 10x better effective energy coverage
- Larger field of view for surveys
- Improved angular resolution
- Improved pointing accuracy
- Full sky coverage: one array per hemisphere

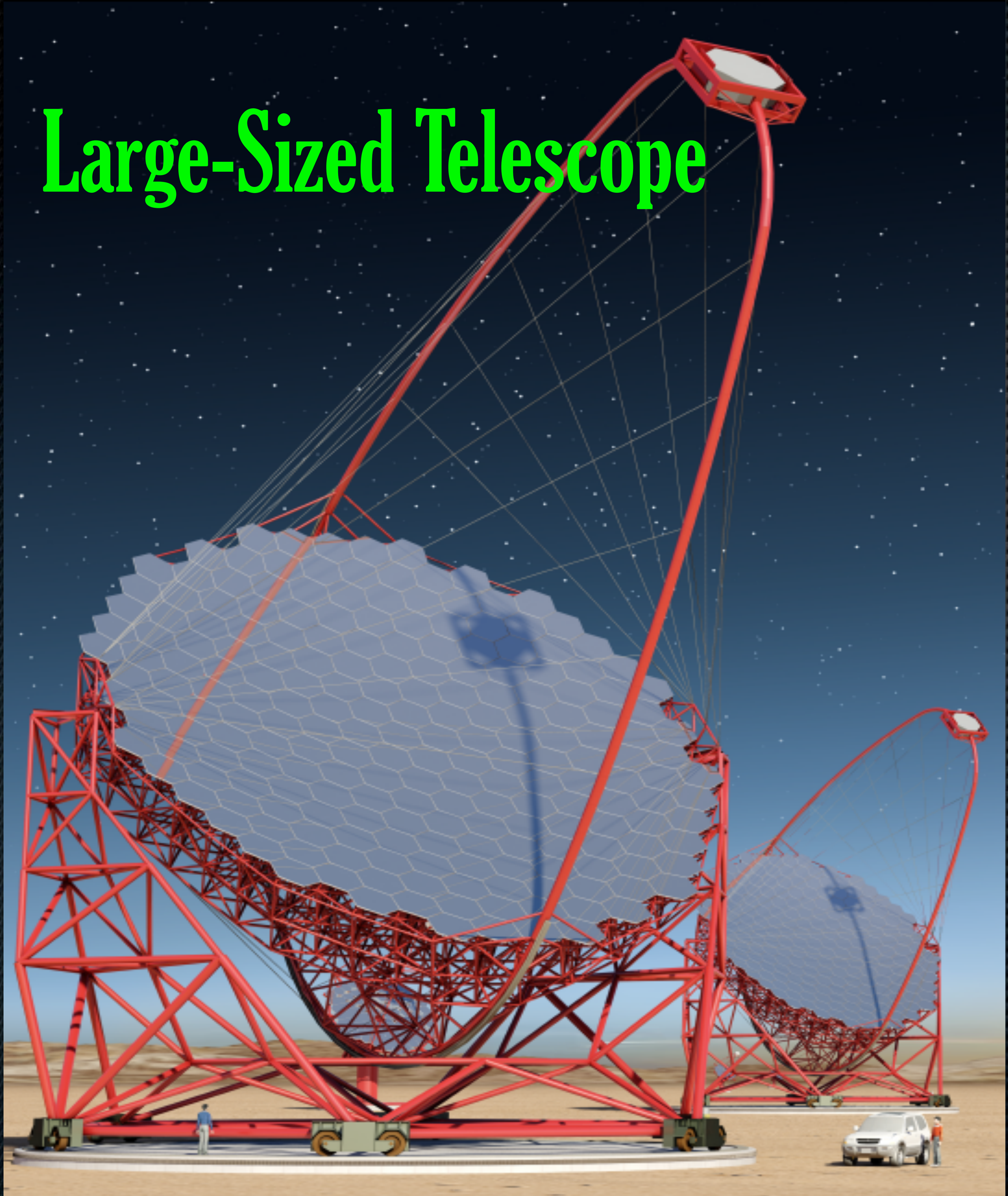
CTA Timeline

- **Design Study**
  - Design development 2006-9
  - CTA appears on key roadmaps
- **Preparatory Phase**
  - EU FP7 funded activity 2010-14
  - Preliminary Design Review 2013
  - Site Selection during 2014
  - Critical Design Rev. early 2015
- **Construction Phase**
  - Site development and first telescopes on site 2015/16 ("seed array")
  - First science 2016/17
  - Completion ~2020



Brightest Sources
Fermi
1 year
HESS
50 hours
CTA
Sensitivity:
E × F(>E) (TeV/cm2s)
10 -11
10 -12
10 -13
10 -14
0.01
0.1
1
10
100
Energy (TeV)

Large-Sized Telescope



23 m diameter
389 m^2 dish area
28 m focal length
1.5 m mirror facets

4.5^o field of view
0.1^o pixels

Carbon-fibre structure
for 20 s positioning

Active mirror control

4 LSTs on South site
4 LSTs on North site

Medium-Sized Telescope

~12m diameter
$100\ m^2$ dish area
16 m focal length
1.2 m mirror facets

7.5^o field of view
~2000 x 0.18^o pixels

25 MSTs on South site
15 MSTs on North site

Berlin
MST prototype

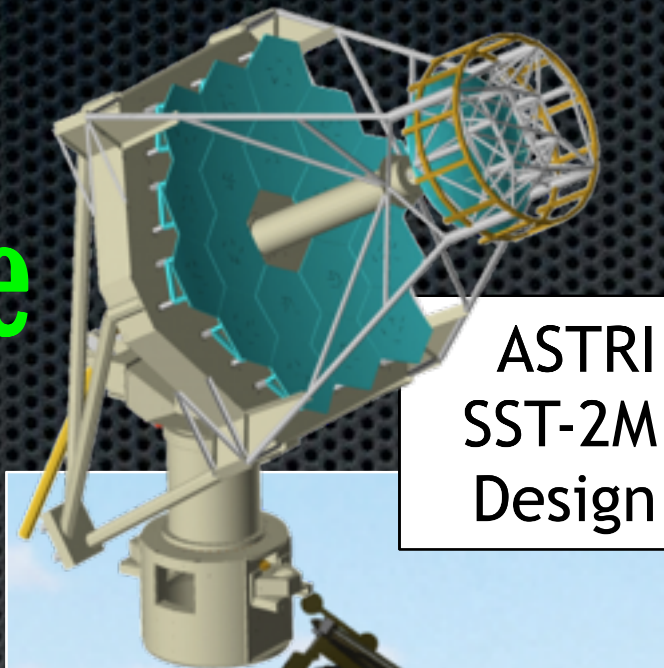
Small-Sized Telescope

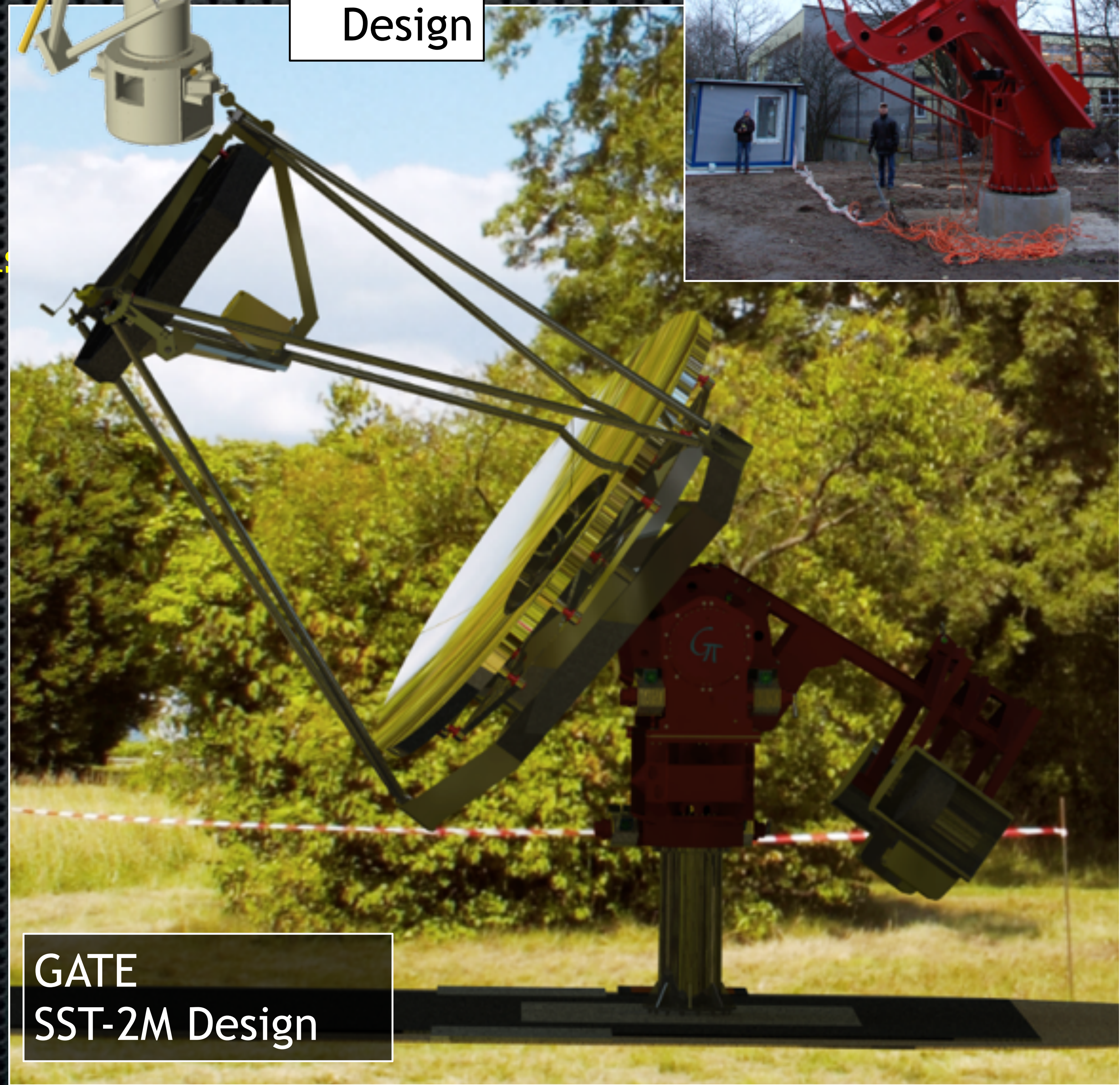
~4-7 m diameter
~8 m^2 dish area
Dual and single mirror options
SST-1M
SST-2M

~9^o field of view
0.17-0.24^o pixels

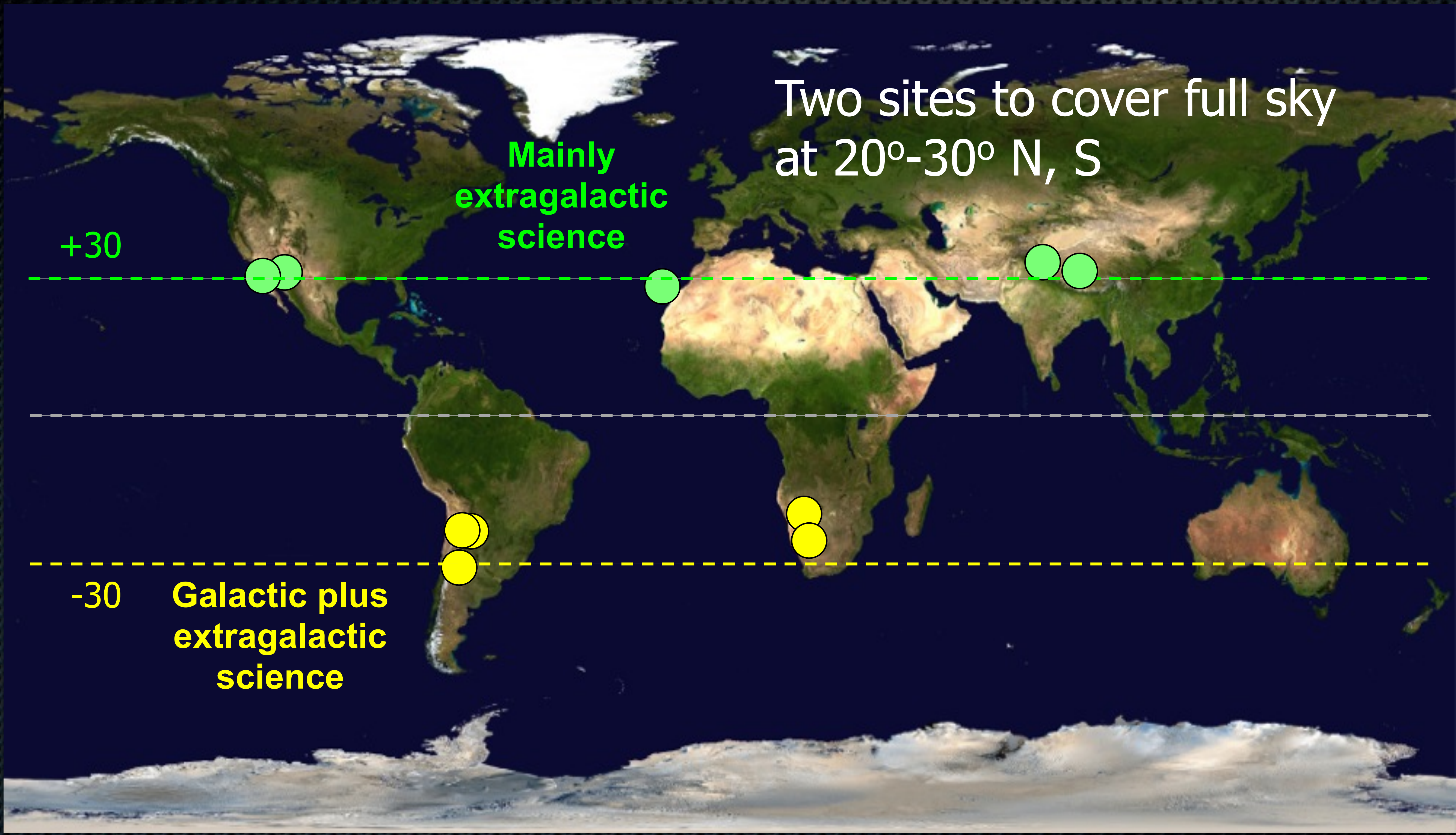
70 SSTs on South site

Require low cost and high reliability
~4-7 km^2 collection area

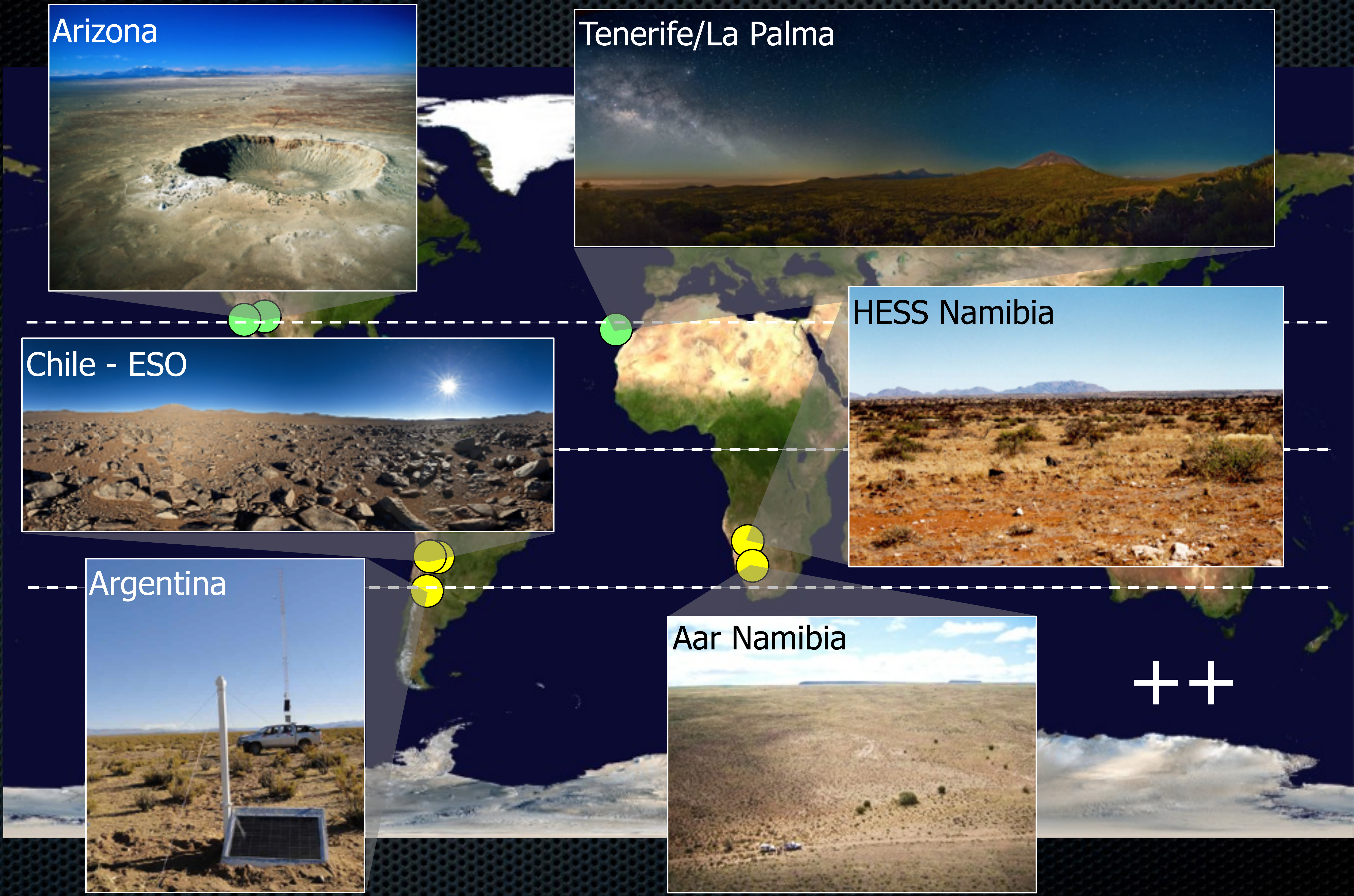




CTA Sites

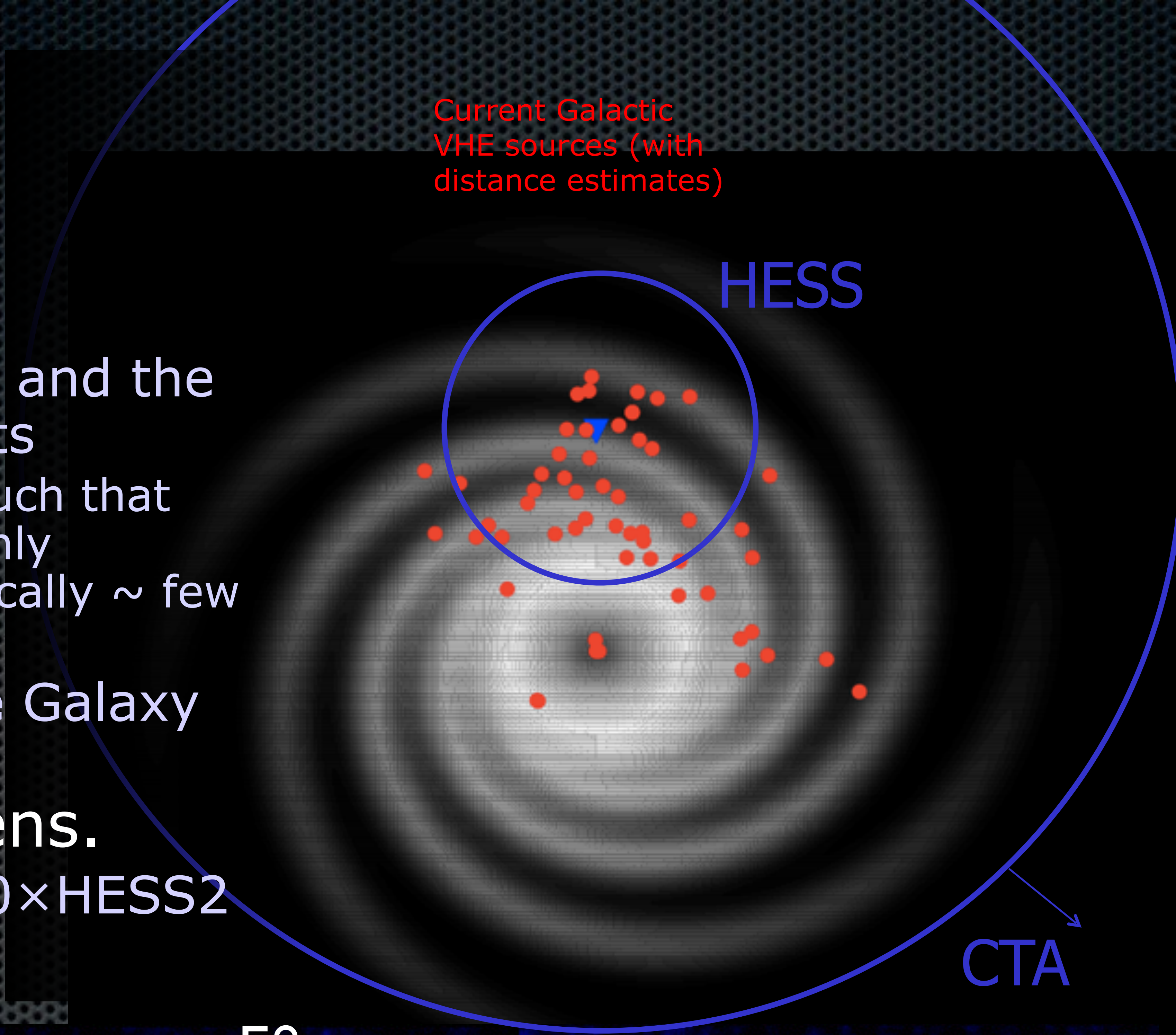

Two sites to cover full sky at 20º-30º N, S
Mainly extragalactic science
+30
-30
Galactic plus extragalactic science

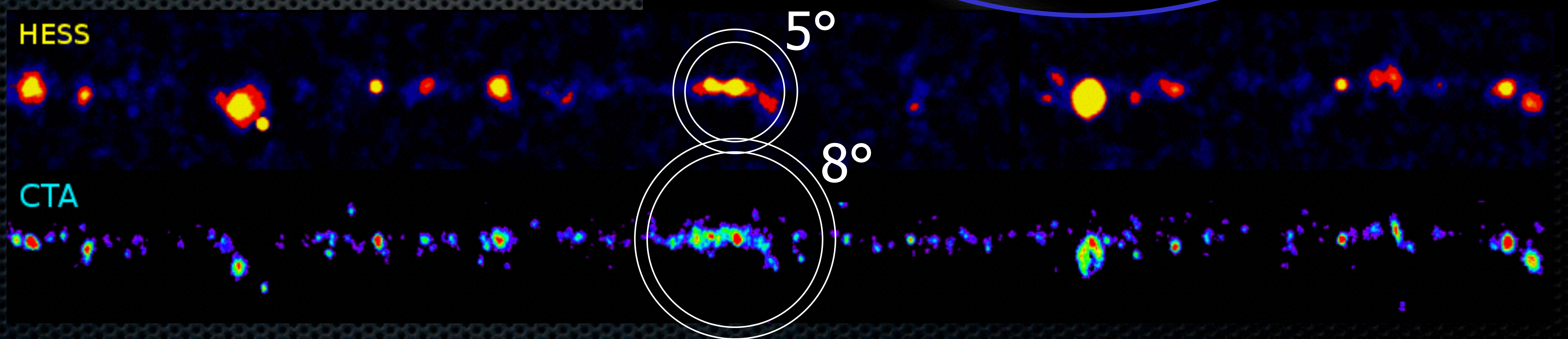
Sites: Candidates



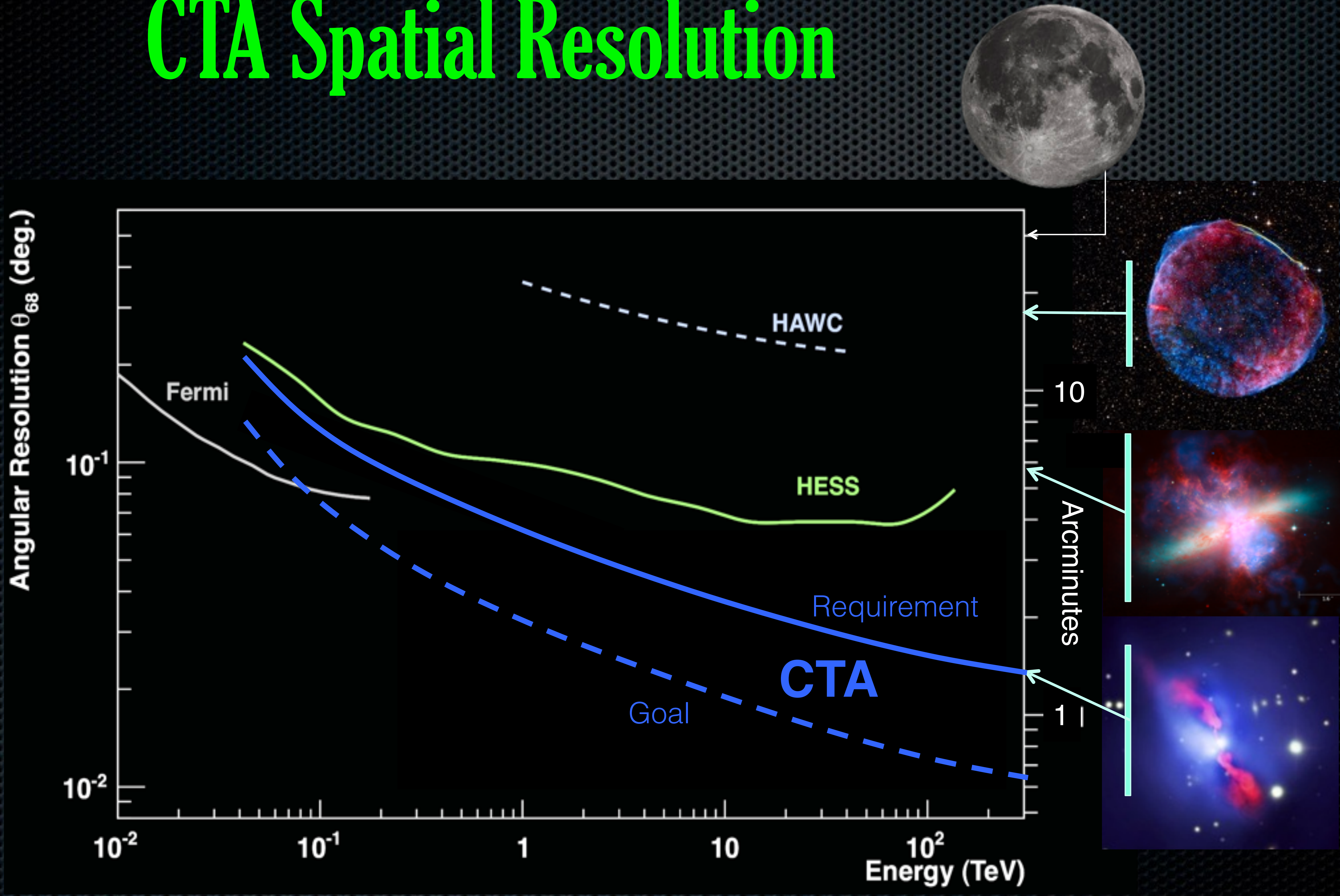
CTA capabilities

- Galactic objects
  - Newly born pulsars and the supernova remnants
    - typical brightness such that HESS etc can see only relatively local (typically ~ few kpc) objects
  - CTA will see **whole** Galaxy
- Field of view + sens.
  - Survey speed ~200×HESS2



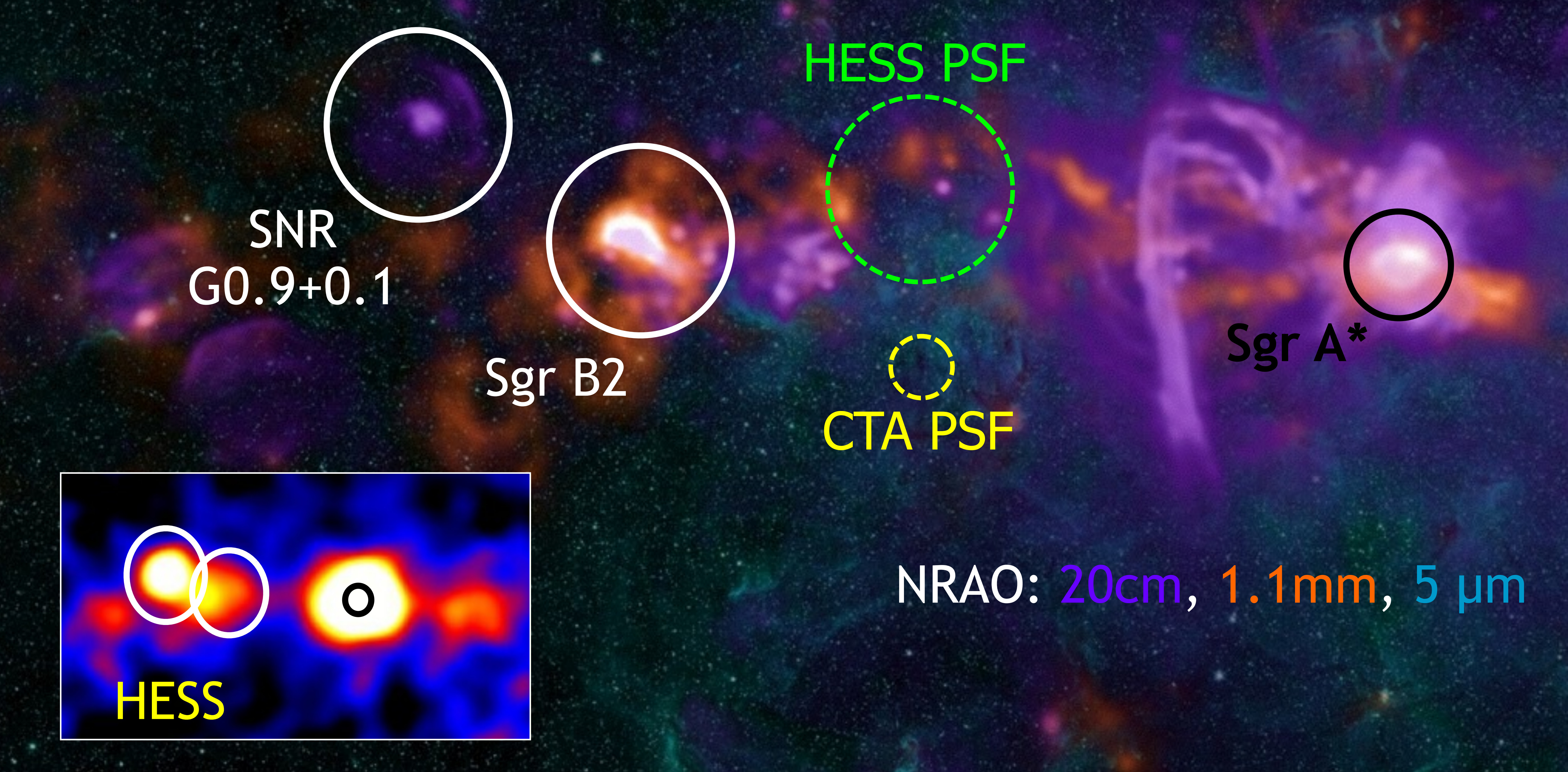


CTA Spatial Resolution

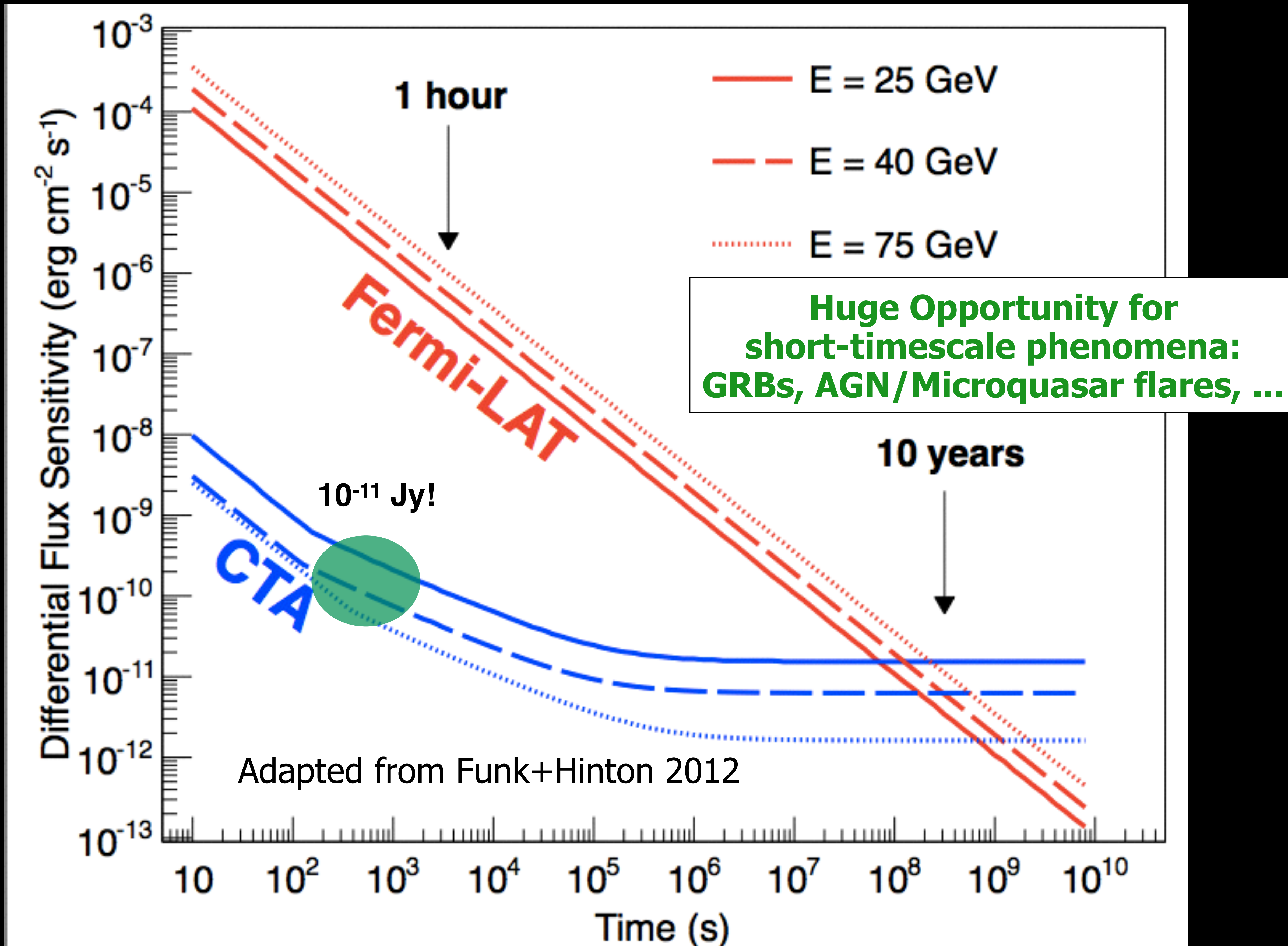


e.g. The Galactic Centre

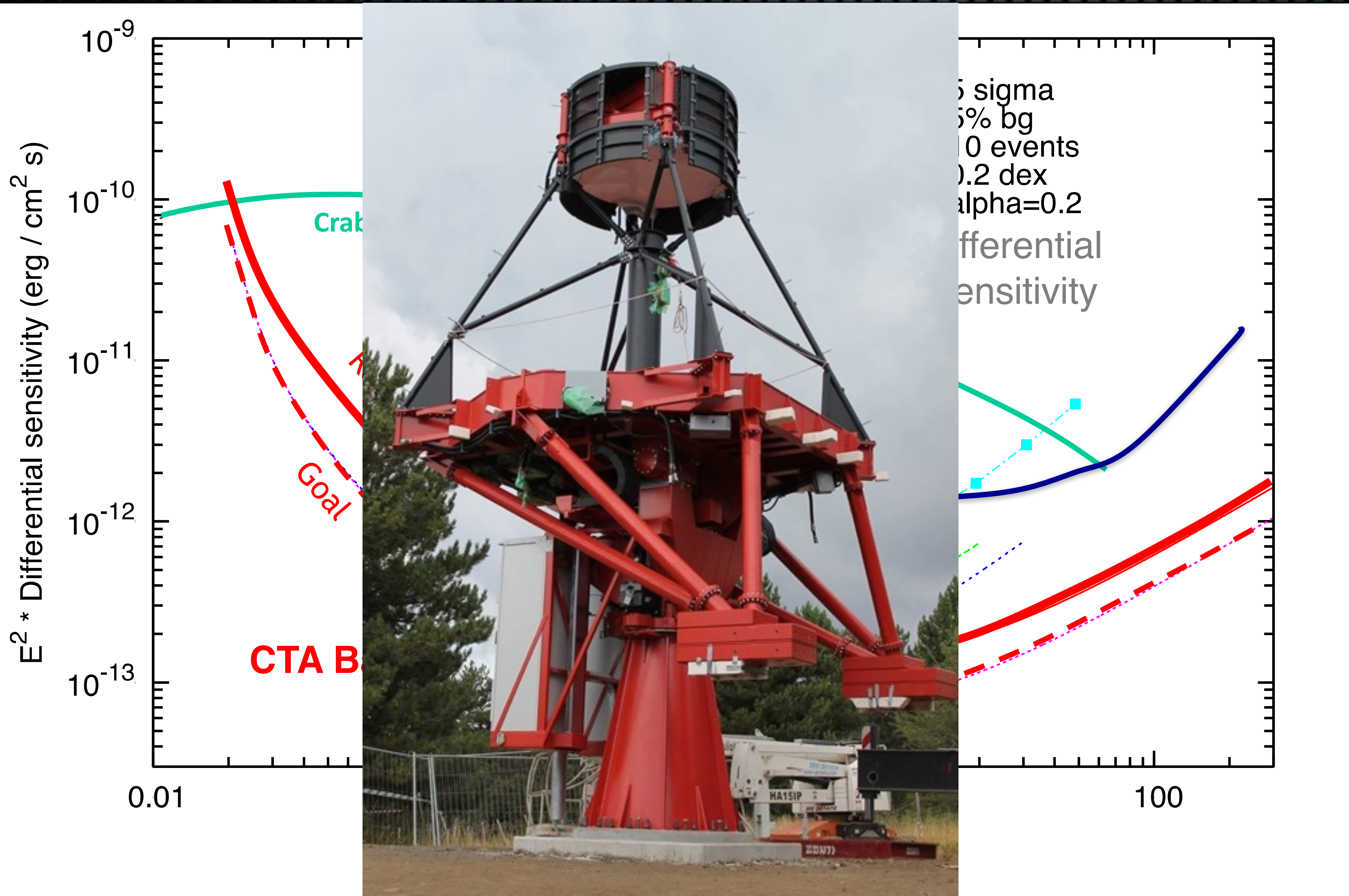
- CTA resolution+sensitivity can disentangle diffuse emission from point sources, localize shocks within SNR…



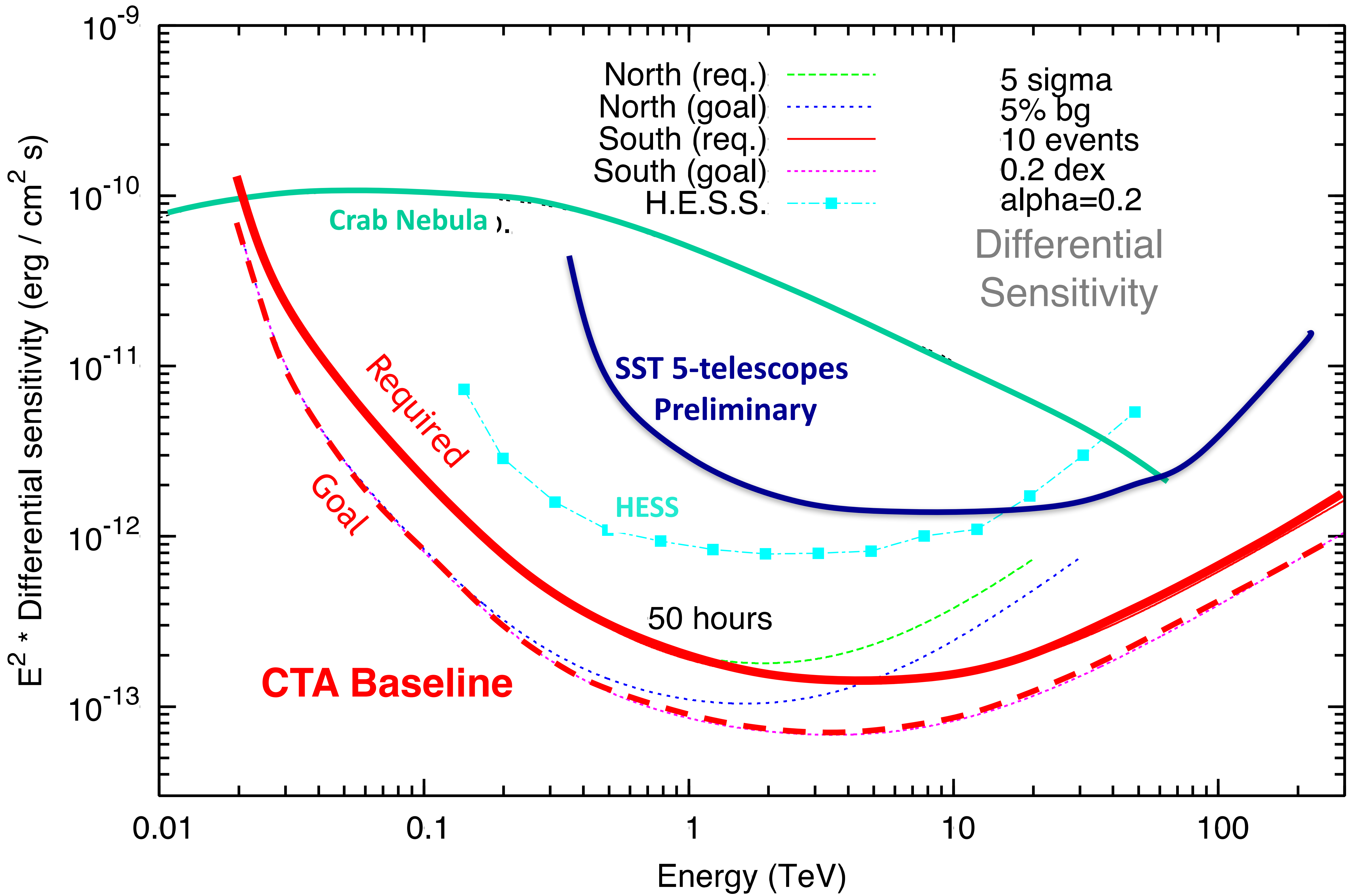
Transients with CTA



CTA Prototyping: Seed Array/ASTRI



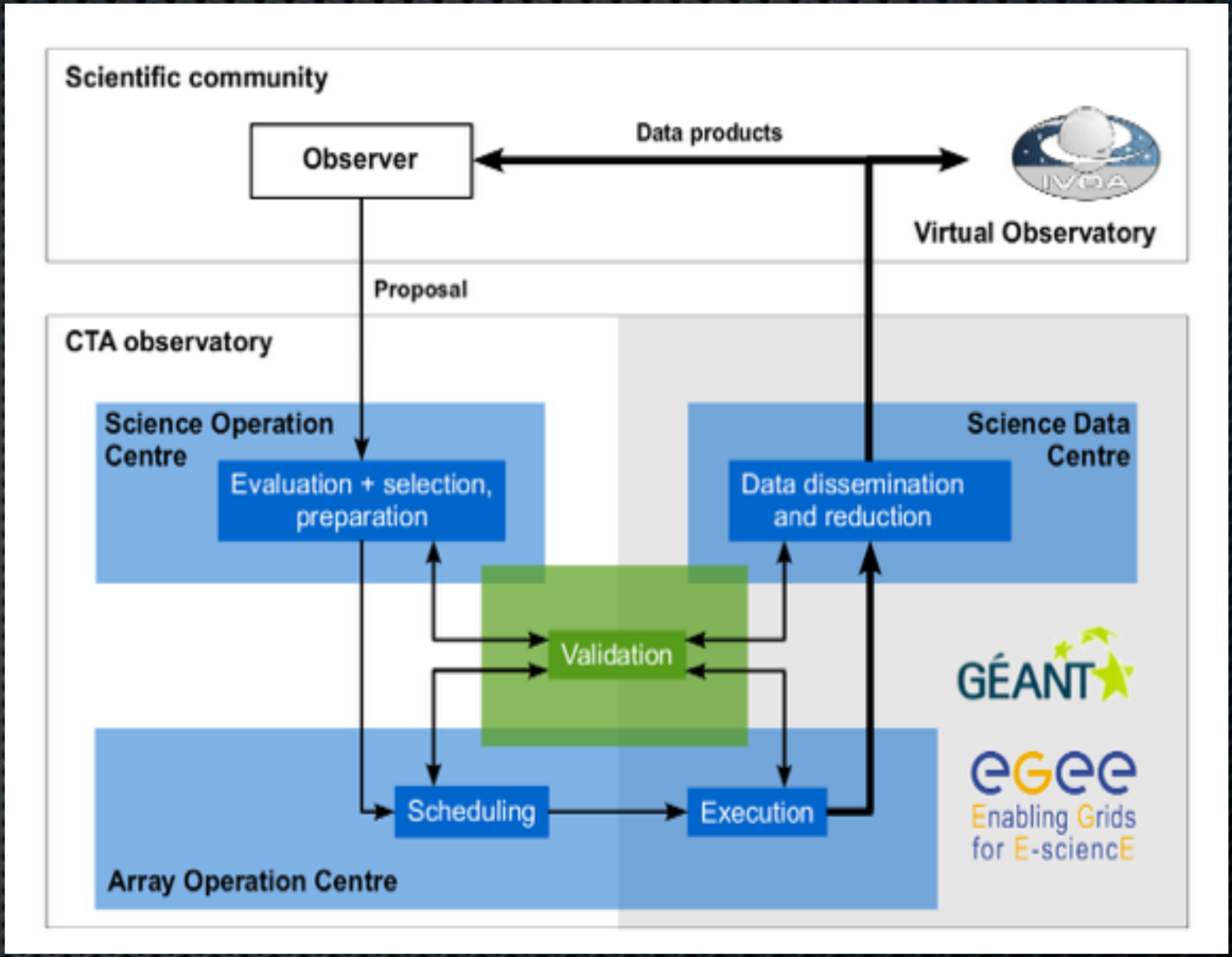
CTA Prototyping: Seed Array/ASTRI



CTA as an astronomical observatory!

- **CTA will operate like other major astronomical facilities**
  - Calls for proposals, proprietary period, data archive, high level data products in FITS, user support, …
- **Early science**
  - Science verification phase followed by Key Science Projects + open* time (small at first but growing during construction)
  - Consortium guaranteed time 30-50% over 10 years

    **probably limited to scientists from contributing countries*



- **CTA "Science User Group"**
  - Consider joining – NOT limited to consortium members
  - What do you would you want as a potential CTA proposer/user?

Things to think about for synergy/cooperation

- **The Observatory TDR is being drafted right now, with overview of plans for transients in first ~5 yrs of operation**
  - **CTA will be able to trigger quite quickly w/external triggers: i.e., LST can trigger in ~ subminute + ~30s to determine if there's a source, MST/SST slew after**
  - **At moment strategy based on X-ray/MeV/GeV triggers, with event rates far lower than what transient factories (radio/optical) will offer**

Table 1: Summary of GRB follow-up strategy and observi
and South sites.

Strategy	Expected event rate (yr^{-1})
Prompt follow-up of accessible alerts	$\sim$12
Extended follow-up for detections	0.5-1.5
Late-time follow-up of LAT GRBs not accessible promptly	$\sim$1

Table 2: Summary table of Galactic transients proposed within the Transient KSP durin
(High Energy), SXT (Soft X-ray Transient), LMXB (Low Mass X-ray Binary), HXTs (Ha
Binary), VHE (Very High Energy), inverse Compton (IC). Site codes are N (North), S (So

Rank	Source or type	Known @ VHE	Physics goal	Trigger	Rate (yr^{-1})	U
1	Magnetar giant flares	No	Highest E	GRB-like	0.1	1
2	Crab Nebula flares	Not the flares	Test IC comp.	HE	1	1
3	Cygnus X-3	No, but HE	Highest E	HE/X-ray	0.5	1
4	Cygnus X-1	Maybe HE/VHE	Highest E	HE/X-ray	0.2	1
5	HE transients	Probably not	Detection/nature	HE	1	1
6	SXTs (LMXBs)	No	Highest E	X-ray/radio	1	1
7	X-ray novae	No, but HE	Hadronic nature	HE/opt.	1	1
8	Transitional pulsars	No, but HE(?)	HE cuttoff	Radio/opt.	0.5	1
9	HXTs (HMXBs)	No	Highest E	X-ray	1	1

Things to think about for synergy/cooperation

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  - CTA will be able to trigger quite quickly w/external triggers: i.e., LST can trigger in ~ subminute + ~30s to determine if there's a source, MST/SST slew after
  - At moment strategy based on X-ray/MeV/GeV triggers, with event rates far lower than what transient factories (radio/optical) will offer
  - CTA will also have realtime analysis and potentially find its own transients to trigger radio/optical/Xray
- What is best for LOFAR TKP? MoU/agreement? Gives access to early science. But then what is our current "trading transient" policy? And/or we apply for GO time (later) for our favourite transients?

Things to think about for synergy/cooperation

Table 3: Summary table of maximum observation times for the Transients KSP of CTA.

Transient type	Observation times ($h\ yr^{-1}\ site^{-1}$) Early phase (2 years)	Years 1–2	Years 3–10	Years 1–10
GRBs	50	50	50	50
neutrinos & GWs	20	10	10	10
Galactic	150	0	0	0
Serendipitous VHE in FoV	100	50	50	50
Total per site ($h\ yr^{-1}\ site^{-1}$)	320	110	110	110
Total both sites ($h\ yr^{-1}$)	640	220	220	220
Total in different CTA phases (h)	1280	440	1760	2200

optical) will offer

- CTA will also have realtime analysis and potentially find its own transients to trigger radio/optical/Xray

- What is best for LOFAR TKP? MoU/agreement? Gives access to early science. But then what is our current "trading transient" policy? And/or we apply for GO time (later) for our favourite transients?

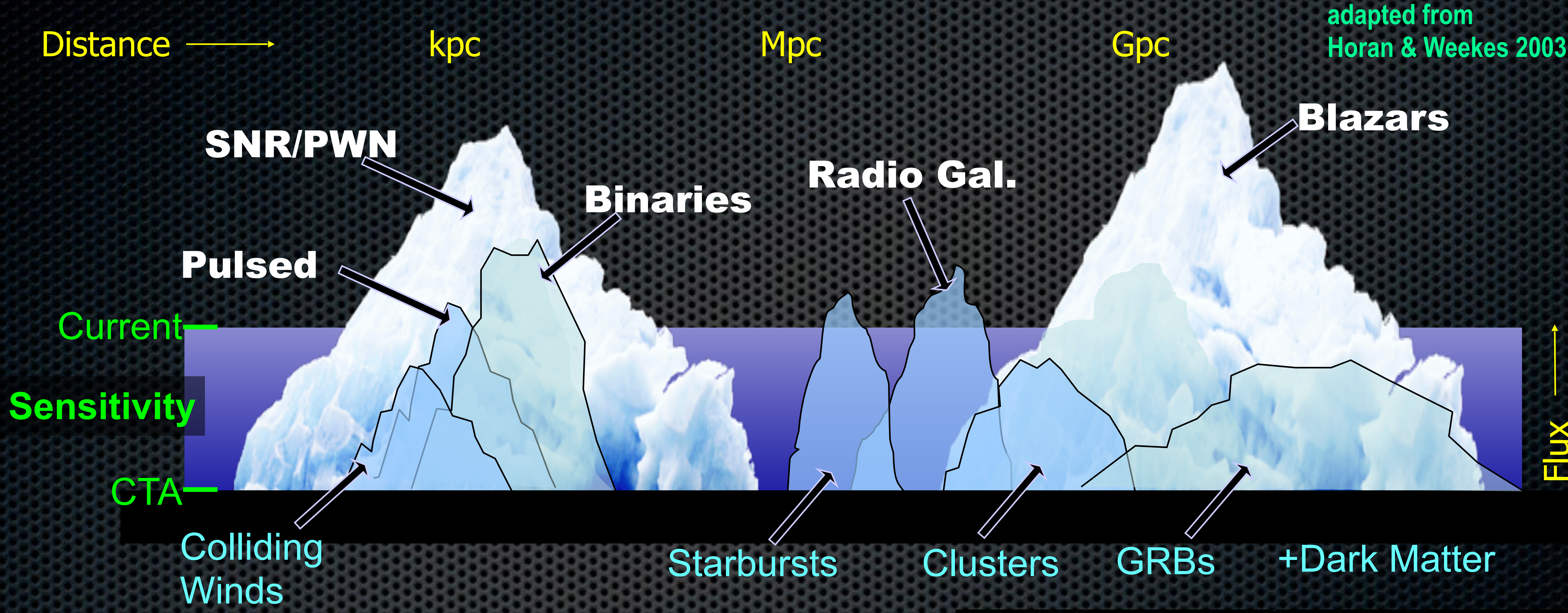
Summary & Outlook

- VHE (~TeV) γ-ray astronomy is the highest energy EM window on the universe: Exciting new era of development for IACT astronomy
- CTA is the international VHE γ-ray facility on the horizon with first science expected 2016/2017: Improved sensitivity, resolution and pointing will allow ToOs and maybe even RTA ➠ transient discovery. Can also localise regions of particle acceleration/interaction w/in extended sources
- CTA represents new transition from experiment to observatory: Opens door to a wider range of projects, community access, user end support
- LOFAR TKP: Agreements may be advantageous for early access to science commissioning data, and “mini-array" prototype, but GO program coming
- Interested? Read all about CTA in the special issue of Astroparticle Physics:

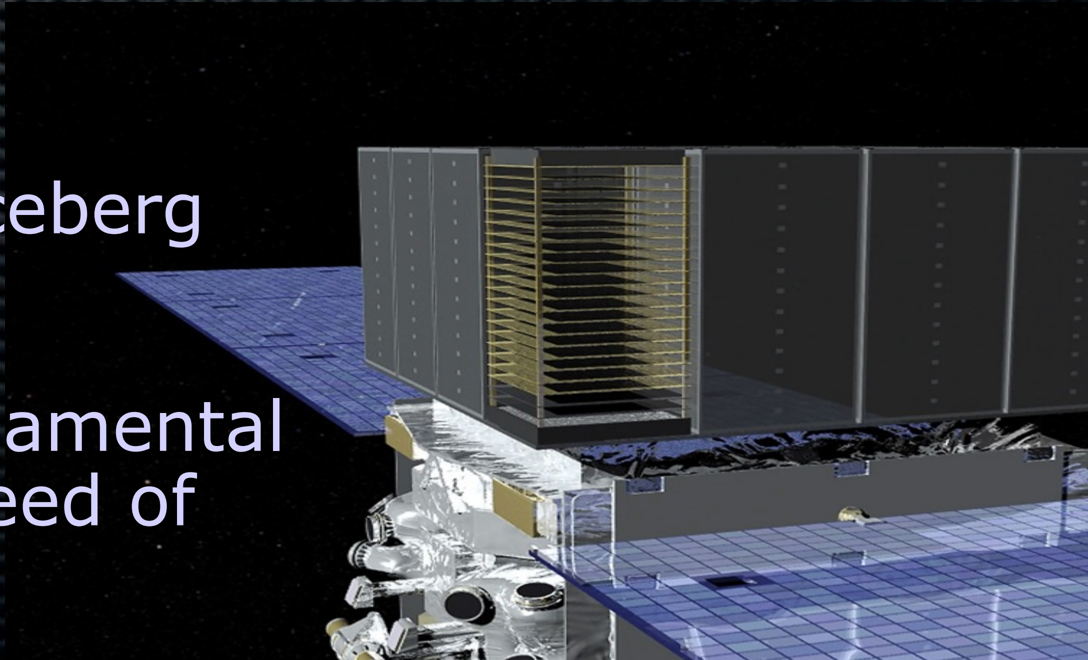
(c) F. Acero & H. Gast

EXTRA SLIDES

CTA Science Targets



- Guaranteed astrophysics
  - Current detections are the tip of the iceberg
- Major discovery potential
  - Probing extreme environments + fundamental physics: DM, axions, constancy of speed of light

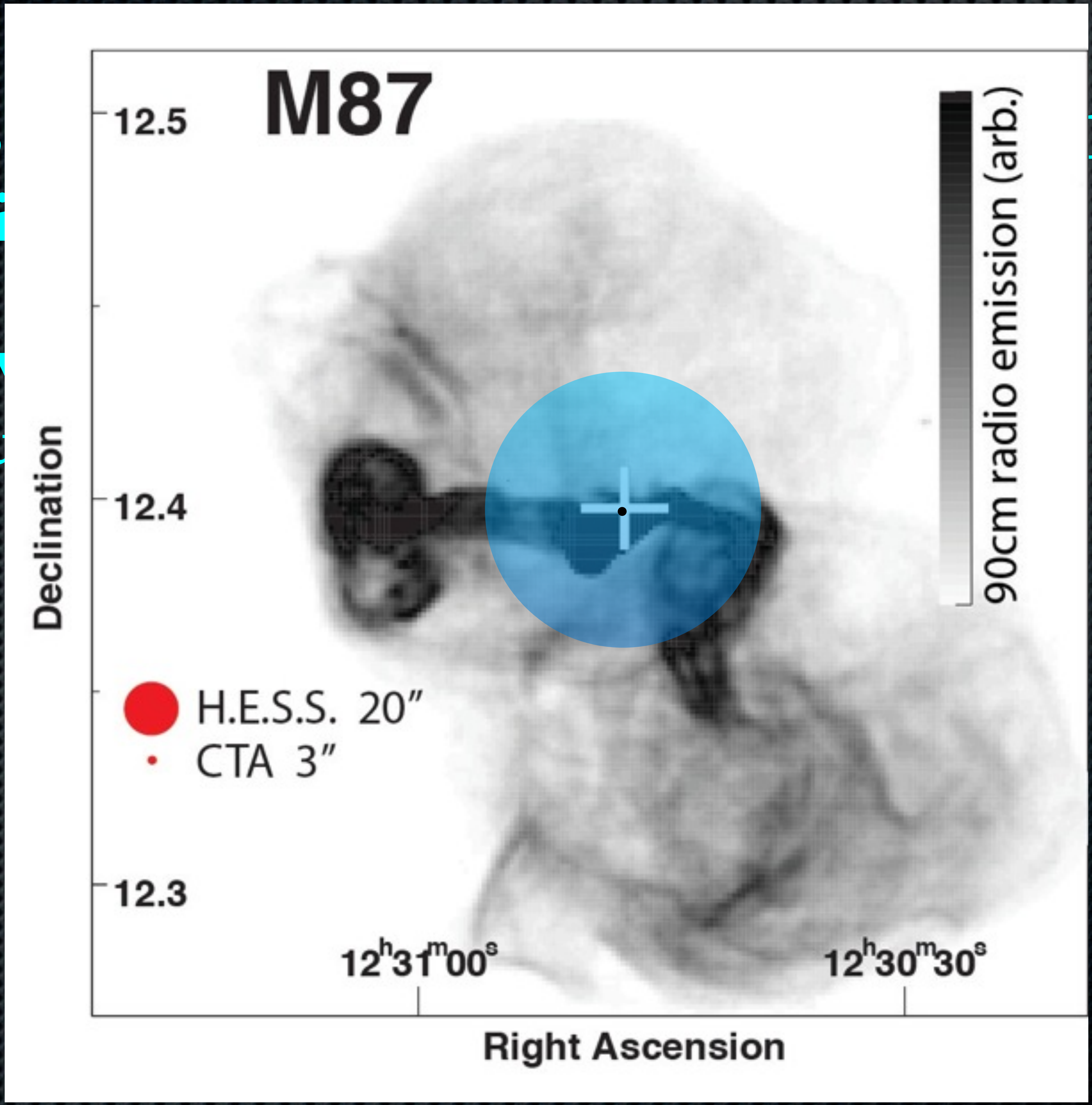


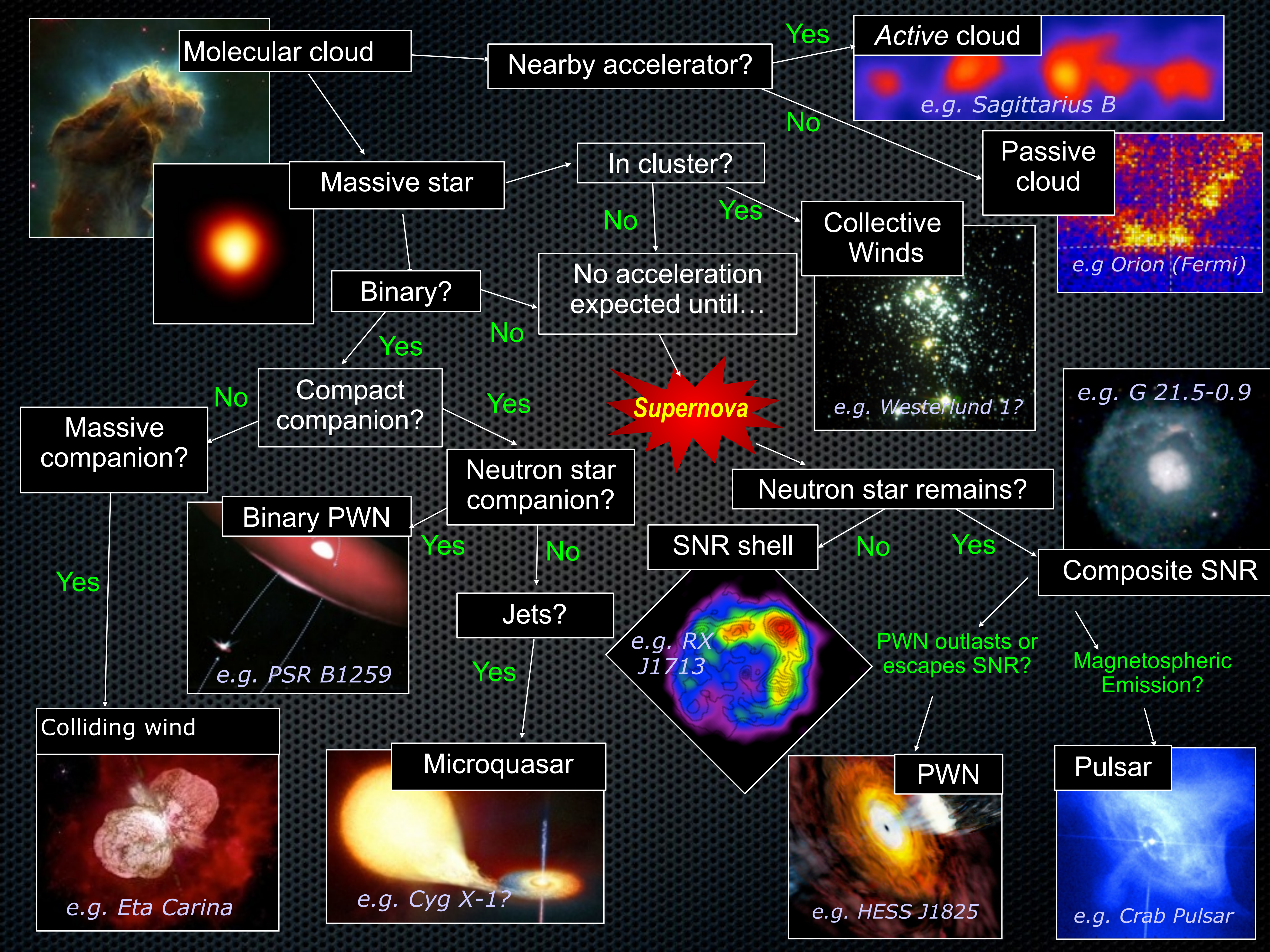
CTA Pointing Accuracy (Astrometry)

- HESS on a good day (with effort) has ~10” pointing accuracy, usually around 20”
- That would be 30% uncertainty for the 1’ angular resolution of CTA
- Goal: improve pointing reconstruction to ~3”

CTA Pointing Accuracy (Astrometry)

- HESS … 10”
  pointi…
- That … 1’ angular
  resolu…
- Goal: … to ~3”




Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
e.g Orion (Fermi)
Massive star
In cluster?
No
Yes
Collective Winds
e.g. Westerlund 1?
Binary?
No
No acceleration expected until…
Yes
Compact companion?
No
Yes
Supernova
Massive companion?
Neutron star companion?
Neutron star remains?
e.g. G 21.5-0.9
Binary PWN
e.g. PSR B1259
Yes
No
SNR shell
No
Yes
Composite SNR
Yes
Jets?
e.g. RX J1713
PWN outlasts or escapes SNR?
Magnetospheric Emission?
Yes
Colliding wind
e.g. Eta Carina
Microquasar
e.g. Cyg X-1?
PWN
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

The Era of Big Surveys

SDSS: 4.3 MB/sec, ~40 TB total

LSST: 160 MB/sec, ~13 TB/night, 30 PB over 5 years

LOFAR: ~100 TB/night, 6-10 PB/yr archived data

MWA: 16 GB/sec, 6 PB/yr archived data

ASKAP: spectral line data 80 PB/yr, Cont./HI sky

1-4 PB/yr

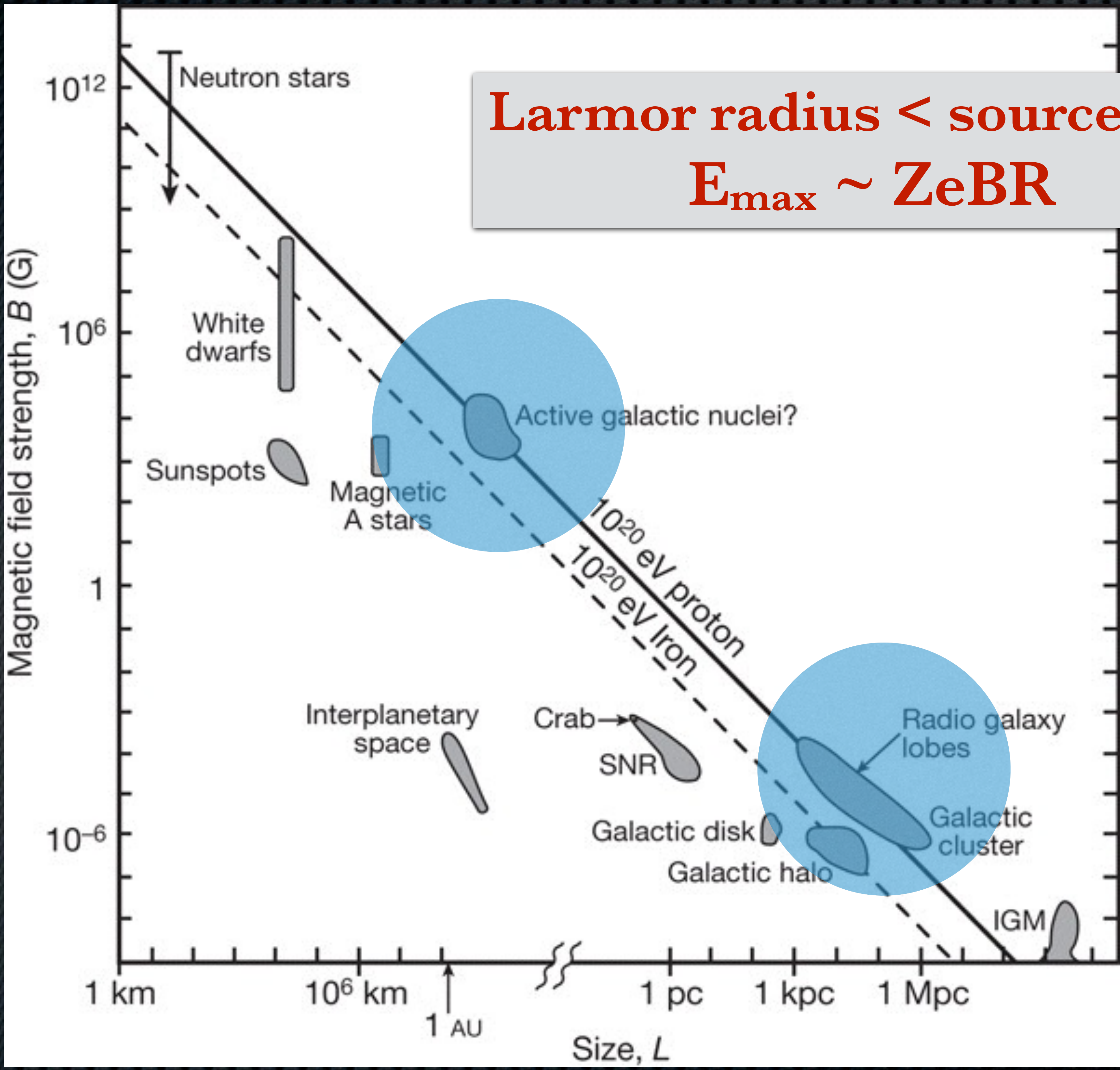
CTA: 3-10 PB/yr archived data, raw data 10x higher

SKA: 0.1-3 EB/yr archived science-ready data

Modern sky surveys obtain ~ 10^{12} – 10^{18} bytes of images
Catalogs ~ 10^{8} – 10^{9} objects (stars, galaxies, etc.)
and measure ~ 10^{2} – 10^{4} numbers per object

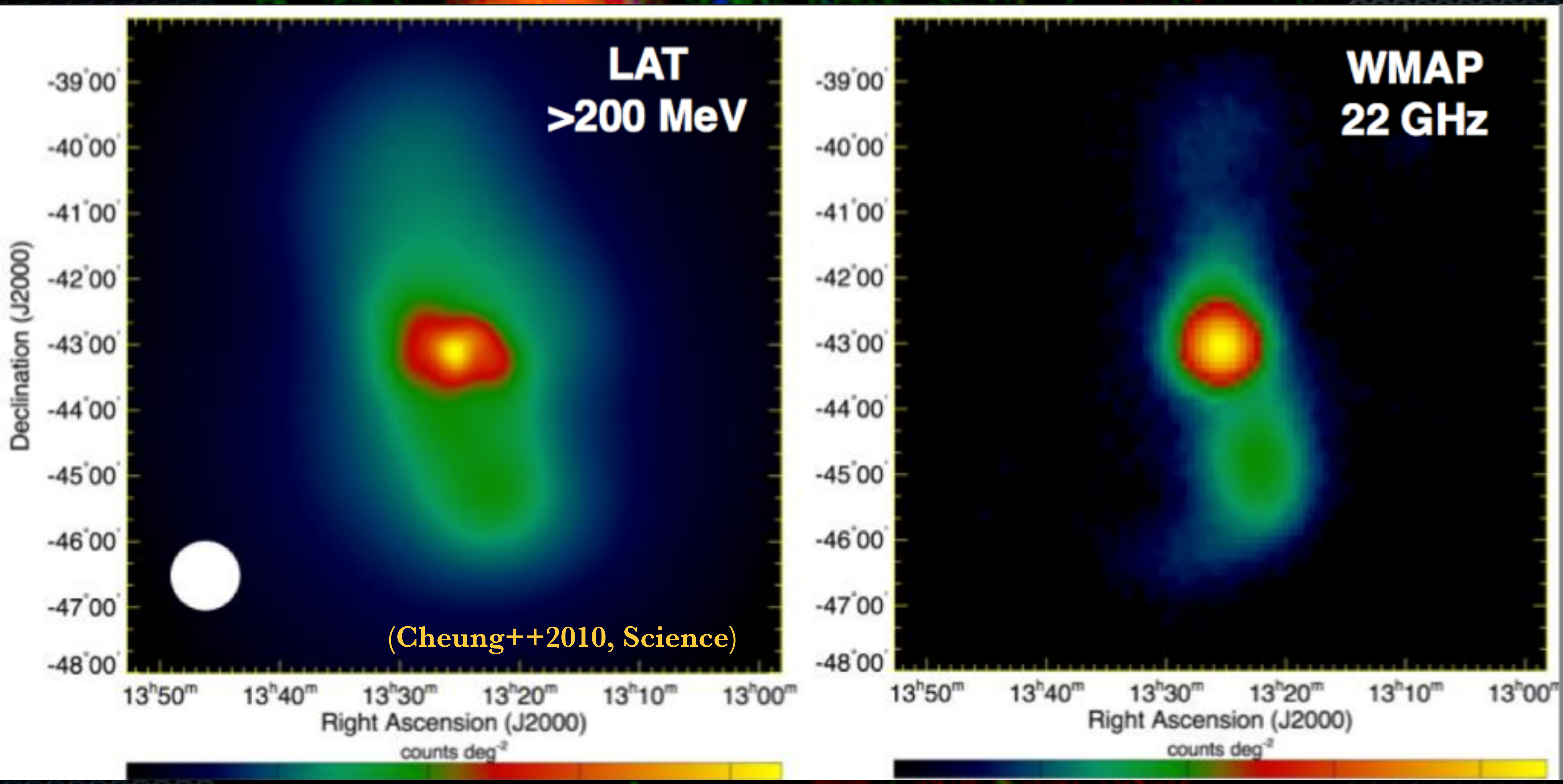
Hillas Diagram: estimates of CR accelerator sites

Larmor radius < source size:
$E_{max} \sim ZeBR$



Surprise: FRI's/Blazars are the GeV/TeV γ-ray sources!

Cen A



(Cheung++2010, Science)