Multi-Messenger Astronomy and the CTA Project

Jim Hinton
(Uni. Leicester)

North West Regional Meeting – Liverpool – Oct. 2013

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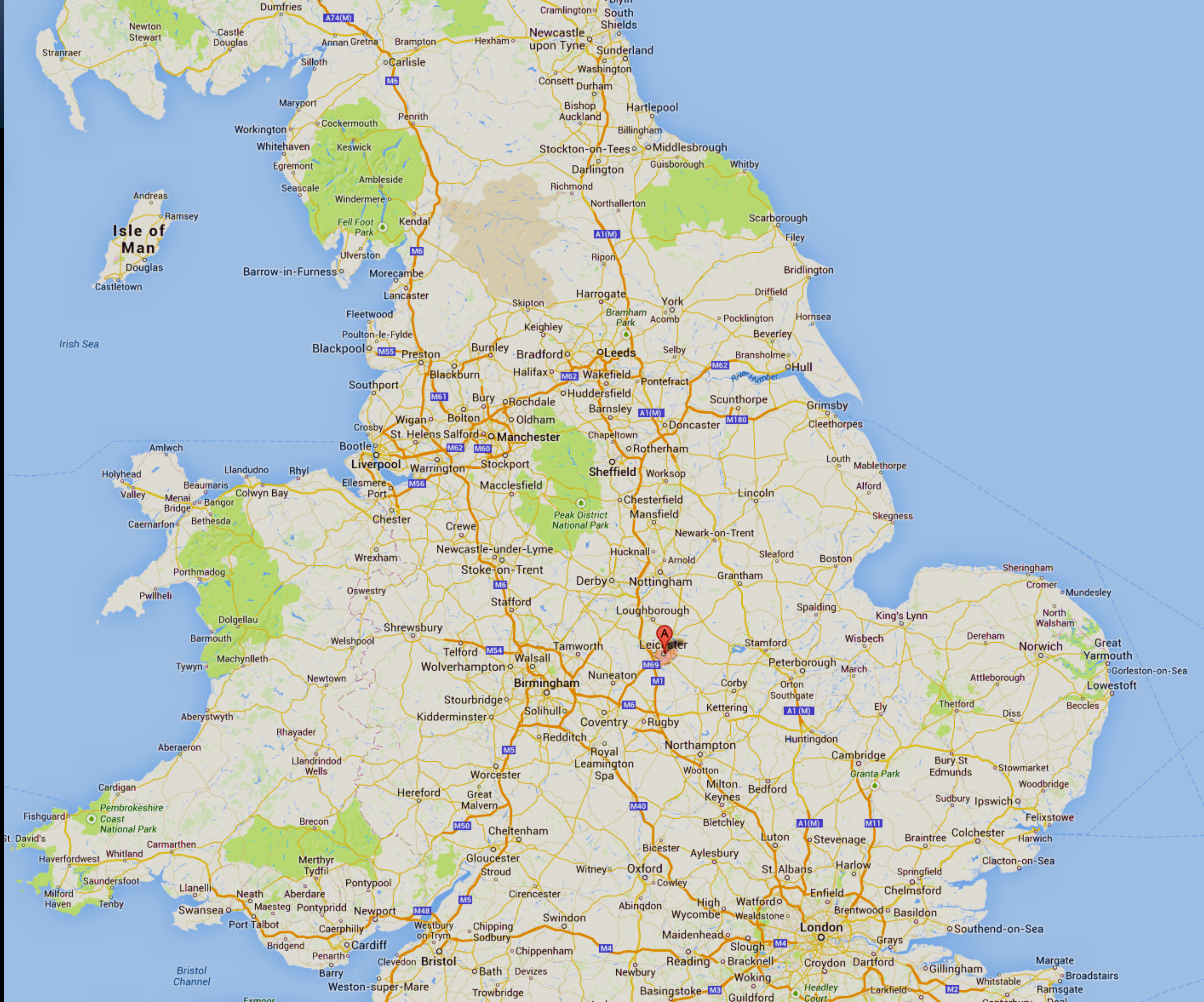

Dumfries
A74(M)
Cramlington
South Shields
Newton Stewart
Castle Douglas
Newcastle upon Tyne
Sunderland
Stranraer
Annan
Gretna
Brampton
Hexham
Washington
Silloth
Carlisle
Consett
Durham
M6
Maryport
Penrith
Bishop Auckland
Hartlepool
Workington
Cockermouth
Billingham
Whitehaven
Keswick
Stockton-on-Tees
Middlesbrough
Egremont
Guisborough
Whitby
Darlington
Ambleside
Seascale
Richmond
Windermere
Northallerton
Andreas
Scarborough
Ramsey
Fell Foot Park
Kendal
A1(M)
Filey
Isle of Man
M6
Ulverston
Ripon
Douglas
Bridlington
Castletown
Barrow-in-Furness
Morecambe
Harrogate
Driffield
Lancaster
York
Skipton
Bramham Park
Acomb
Pocklington
Hornsea
Fleetwood
Keighley
Beverley
Poulton-le-Fylde
Irish Sea
Blackpool
M55
Preston
Burnley
Bradford
Leeds
Selby
Bransholme
Hull
Halifax
M62
Wakefield
M62
Blackburn
Pontefract
River Humber
Southport
Huddersfield
Scunthorpe
Grimsby
M61
Bury
Rochdale
Barnsley
A1(M)
Wigan
Bolton
Oldham
M180
Cleethorpes
Crosby
Doncaster
St. Helens
Salford
Manchester
Chapeltown
Amlwch
Bootle
M62
M60
Rotherham
Liverpool
Warrington
Stockport
Louth
Mablethorpe
Holyhead
Llandudno
Rhyl
Sheffield
Worksop
Beaumaris
Ellesmere Port
M56
Macclesfield
Alford
Valley
Menai Bridge
Bangor
Colwyn Bay
Lincoln
Chesterfield
Bethesda
Chester
Peak District National Park
Mansfield
Skegness
Caernarfon
Crewe
Newark-on-Trent
Newcastle-under-Lyme
Hucknall
Sleaford
Boston
Wrexham
Arnold
Porthmadog
Stoke-on-Trent
Sheringham
Derby
Nottingham
Grantham
Cromer
Oswestry
M6
Mundesley
Pwllheli
Stafford
Spalding
Loughborough
North Walsham
King's Lynn
Dolgellau
Shrewsbury
Dereham
Barmouth
Welshpool
Leicester
Stamford
Wisbech
Great Yarmouth
Telford
M54
Tamworth
Norwich
Machynlleth
Walsall
Tywyn
Wolverhampton
M69
Peterborough
March
Gorleston-on-Sea
Nuneaton
Attleborough
Newtown
Birmingham
M1
Corby
Orton Southgate
Lowestoft
Stourbridge
Thetford
M6
Solihull
Kettering
Ely
Diss
Beccles
Kidderminster
A1(M)
Aberystwyth
Coventry
Rugby
Rhayader
Redditch
Huntingdon
Northampton
Aberaeron
Royal Leamington Spa
Cambridge
Llandrindod Wells
M5
Bury St Edmunds
Stowmarket
Wootton
Granta Park
Worcester
Cardigan
Milton Keynes
Bedford
Woodbridge
Hereford
Great Malvern
Pembrokeshire Coast National Park
Sudbury
Ipswich
M40
Fishguard
Brecon
M50
Bletchley
A1(M)
M11
Felixstowe
St. David's
Cheltenham
Braintree
Colchester
Luton
Stevenage
Harwich
Carmarthen
Gloucester
Bicester
Aylesbury
Haverfordwest
Whitland
Merthyr Tydfil
Stroud
Clacton-on-Sea
Harlow
St. Albans
Oxford
Witney
Springfield
Saundersfoot
Pontypool
Llanelli
Cowley
Milford Haven
Cirencester
Chelmsford
Enfield
Neath
Aberdare
Tenby
M5
Watford
Abingdon
High Wycombe
Swansea
Maesteg
Pontypridd
Newport
M48
Brentwood
Basildon
Wealdstone
Port Talbot
Caerphilly
Westbury on Trym
Chipping Sodbury
Swindon
London
Southend-on-Sea
Maidenhead
Bridgend
Cardiff
Slough
M4
M4
Grays
Penarth
Chippenham
Bristol
Reading
Bracknell
Croydon
Dartford
Margate
Clevedon
Barry
Bath
Devizes
Gillingham
Bristol Channel
Newbury
Woking
Broadstairs
Weston-super-Mare
Whitstable
Trowbridge
Basingstoke
M3
Headley Court
Larkfield
M2
Ramsgate
Guildford

3 Multi-messenger Astronomy?

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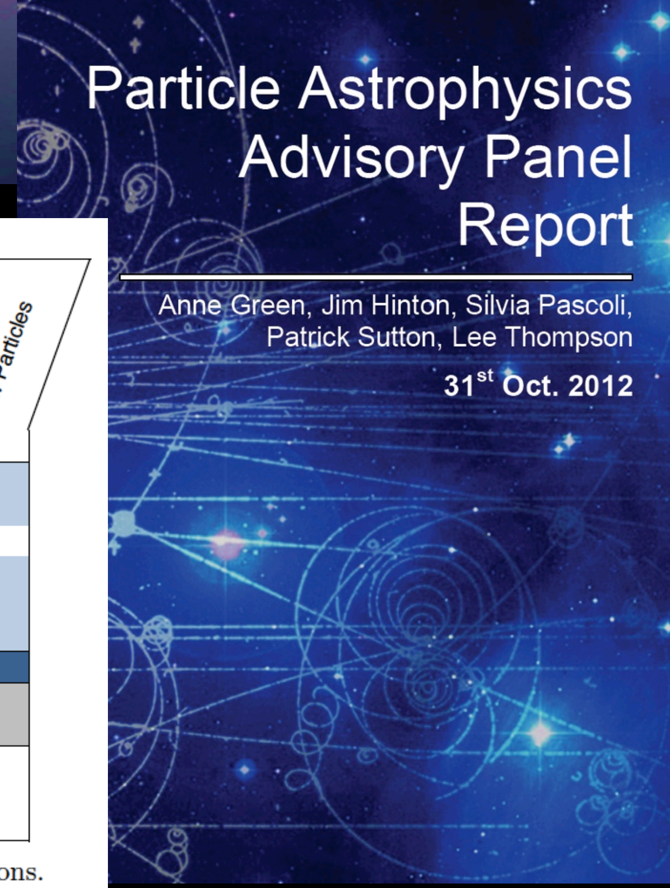
- "Traditional" astronomy (starting <1970s)
  - 10^{-7} – 10^{10} eV photons (radio – gamma-ray)
- Now - the new (photon) astronomy
  - VHE gamma-rays 10^{11}-10^{14} eV

  (+ neutrinos from SN 1987a and the sun)
- Soon (within ~10 years)
  - Charged particle astronomy (>10^{19} eV protons)
  - VHE-UHE neutrino astronomy
  - Gravitational wave astronomy

} Particle Astrophysics

4 UK Funding?



Type	Instrument	e.g.	Compact Objects 1a	SNR/GRB 1b	CR Origin 1c	CR Impact 1d	Dark Matter 2a	Dark Energy 2b	Relativity 2c	Neutrino Prop. 2d	New Particles 2e
PA	**GW Observatory**	*Adv. LIGO*	3	3				2	3		1
PA	**γ-ray Observatory**	*CTA*	1	2	3	3	2		2		1
PA	**VHE Neutrino**	*Km3Net*	1	2	2	1	2		1	2	
PA	**UHE Cosmic Ray**	*Auger*	1	1	3	1			1	2	1
PA	**UHE Neutrino**	*ARA*			2					2	1
PA	**Direct DM**	*DM-1T*					3				1
PA/PP	MT multi-purpose	*LAGUNA*	1	3			1		1	3	2
PP	Non-collider PP										
PP	Collider PP										
AP	Optical-IR Obs.										
AP	Radio Observatory										
AP	X-ray Observatory										

Figure 1: Correspondence between experimental/observational approach and our science questions. Core PA activities are shown in colour with a scale of 1-3 where 3: essential, 2: very important, 1: useful. Key non-PA approaches are also shown for comparison, in grayscale.

- Prog. Rev. outcome in December…

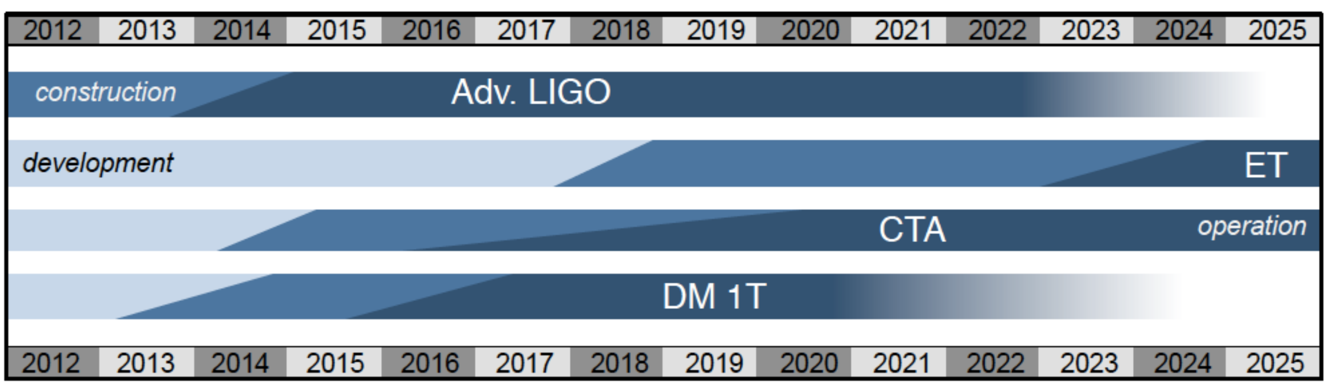
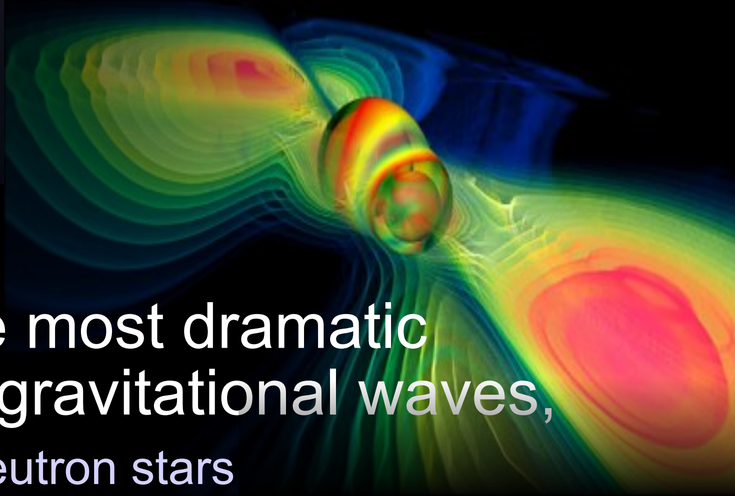


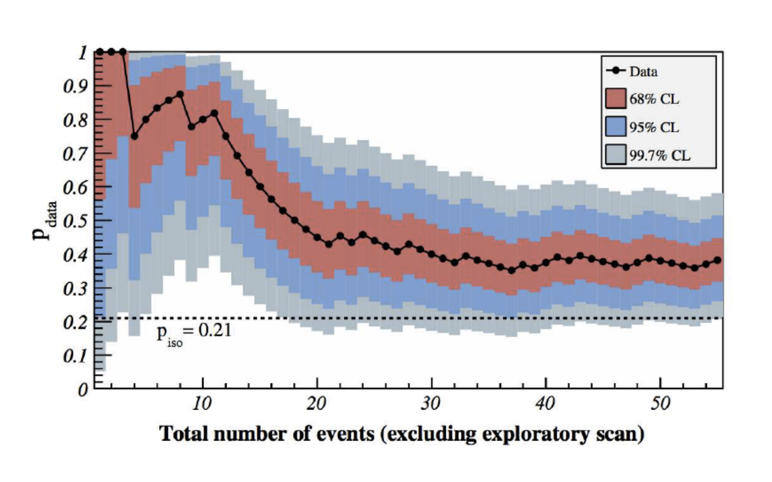
Figure 2: Proposed roadmap for UK PA, showing the transitions between different project phases.

5 Gravitational Waves



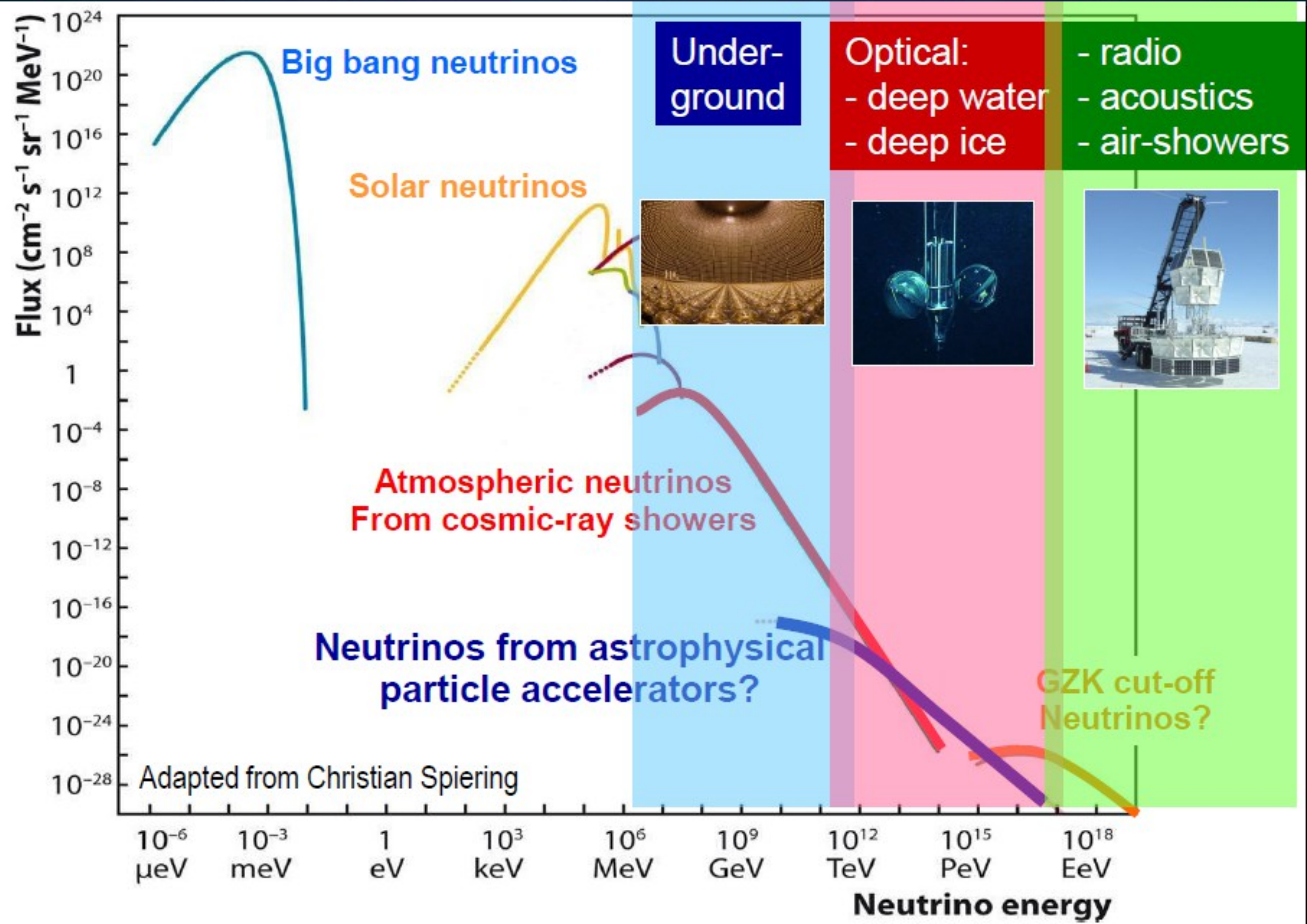
- Most of the energy from some of the most dramatic events in the universe is emitted as gravitational waves,
  - e.g. “Inspiraling”/merging black holes and neutron stars
- Allows precision tests of General Relativity as well as lots of key astrophysics – small technical problem:
  - Need to measure strain $\Delta l/l$ of 10^{-22} …
- Advanced LIGO will reach this by **2017**
  - Two sites in US, each with two 4 km arms + Adv. VIRGO in EU
  - Will see inspirals up to ~1 billion light years away
  - Very strong UK role
- Farther future
  - Einstein and LISA

6 UHE Cosmic Rays



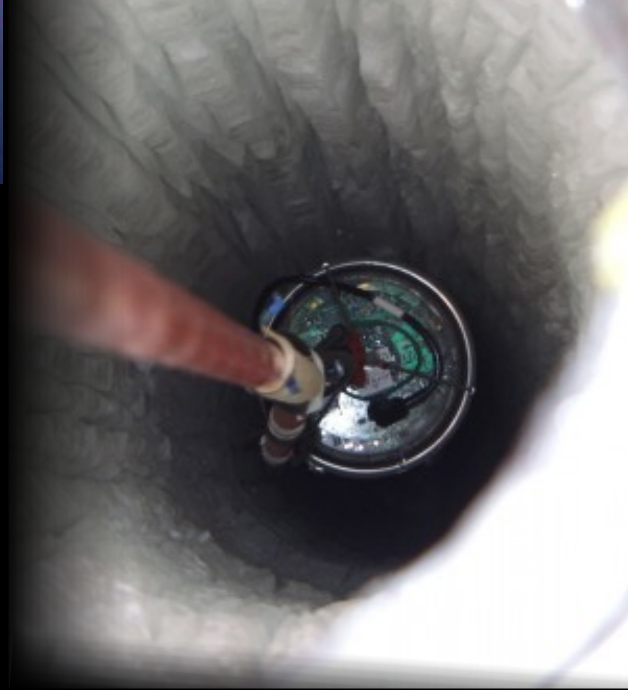
- Pierre Auger Observatory
  - Correlation with AGN on few degree scales (Science 2007), ***the dawn of proton astronomy?***
    - Weakened in the meantime
    - Much larger statistics needed
- JEM-EUSO
  - Launch date 2017
    - 5 year mission on ISS
  - Sensitive above 3×10^{19} eV
  - Collection area 65× Auger
    - 200,000 km^2

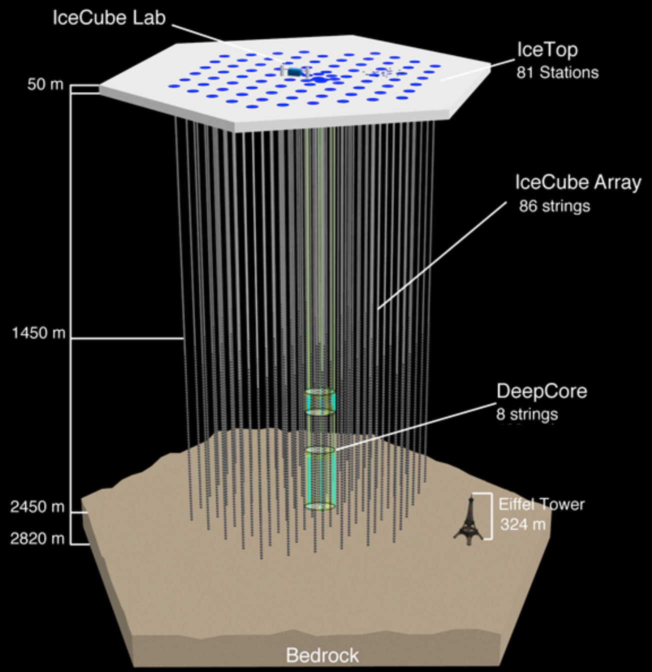
7 Neutrino Astronomy



8 Ice Cube

- Deep under ice polar detector
  - Neutrinos interact deep in the ice and produce charged leptons ➔ Cherenkov light (muon tracks, EM cascades, ….)
- IceCube completed 2011
  - 1 km^3 instrumented volume
  - Only atmospheric neutrinos detected until very recently
  - Now
    - 2 ~PeV events, unlikely to be atmospheric
    - 26 events 30-300 TeV cf estimated background of 10.6
- ***The dawn of TeV/PeV neutrino astronomy?***





9 Highest Energy Neutrinos

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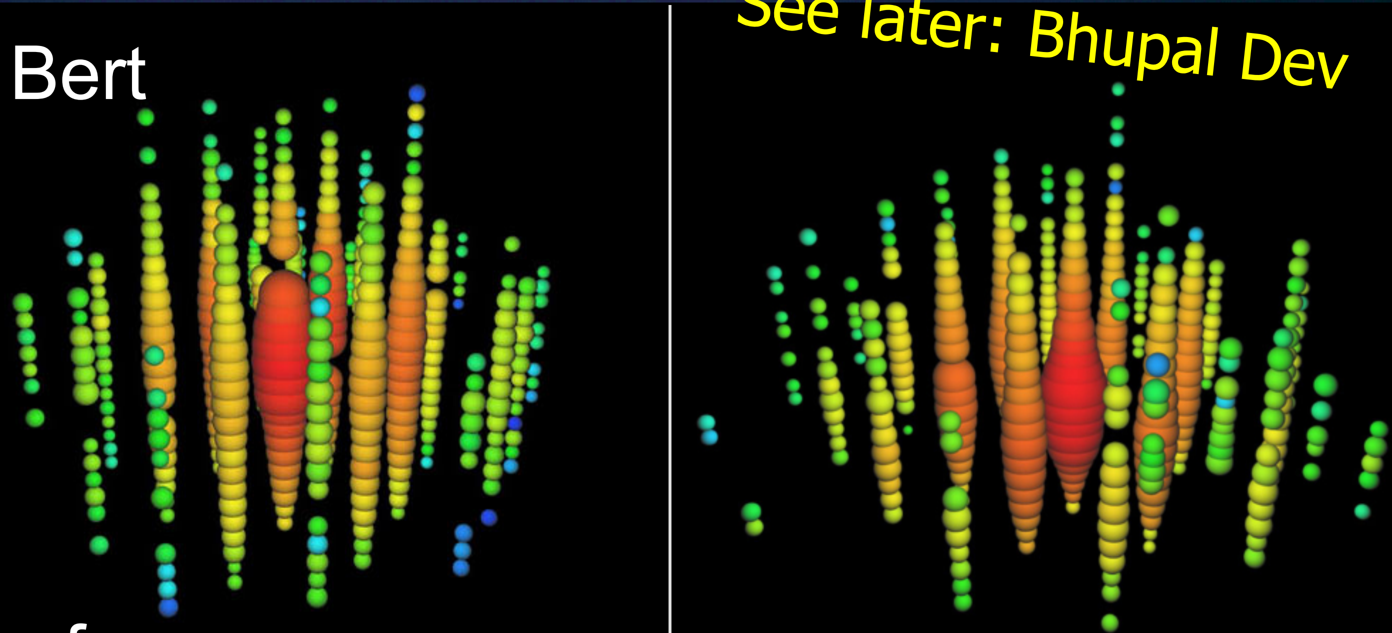
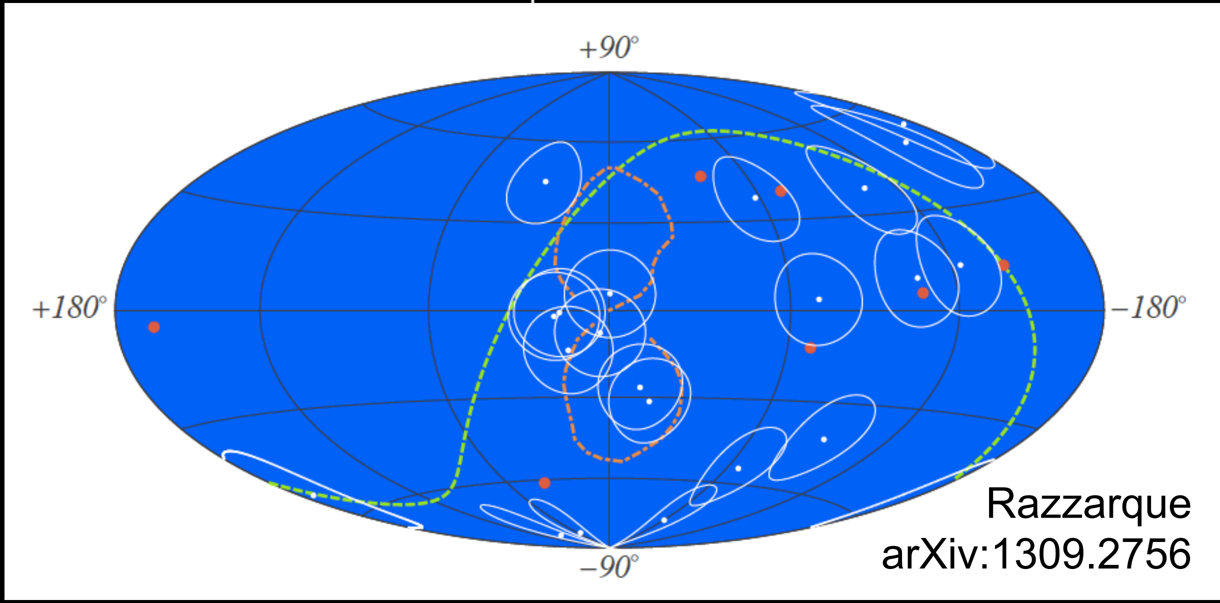
See later: Bhupal Dev

- Ernie and Bert



- Directions of the 26 events



10 Neutrinos versus Gammas

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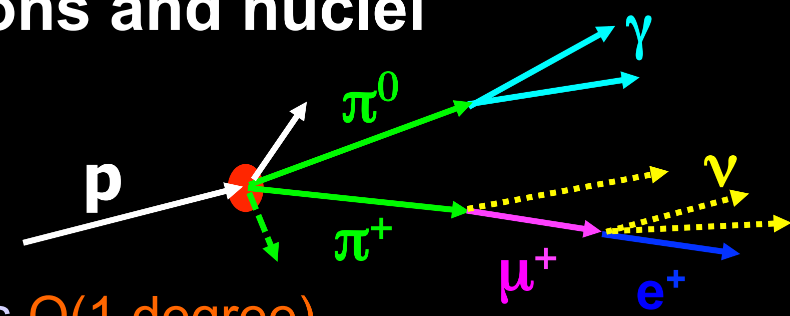
- **Both probe VHE and UHE protons and nuclei**
  - Pros and Cons:



- Resolution
  - TeV Gamma O(0.1 degree)
  - Nu Cascades O(10 degrees), Tracks O(1 degree)
- Statistics
  - Effective collection area of IceCube at 1 TeV ~1 m^2 (cf Fermi)
  - Typical ground-based gamma inst. at 1 TeV ~1 km^2
- Background
  - Atmospheric neutrino background is irreducible and significant below ~100 TeV
  - Background free operation possible above 10 TeV for gammas
- Ambiguity
  - IC gamma-ray emission from electrons
    - Need broad energy coverage and MWL to break degeneracy

Need Both

11 VHE Gamma Instruments

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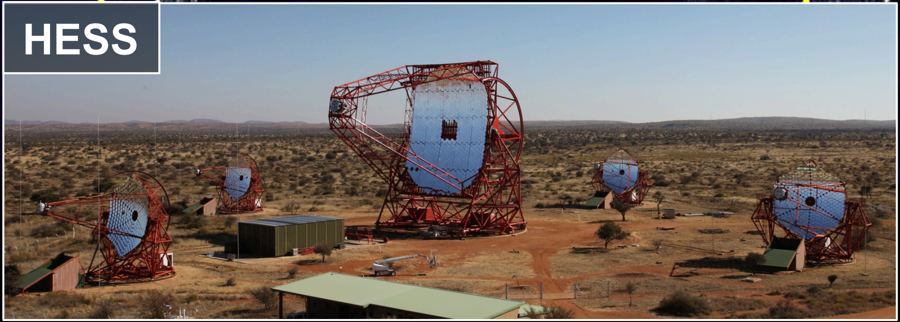
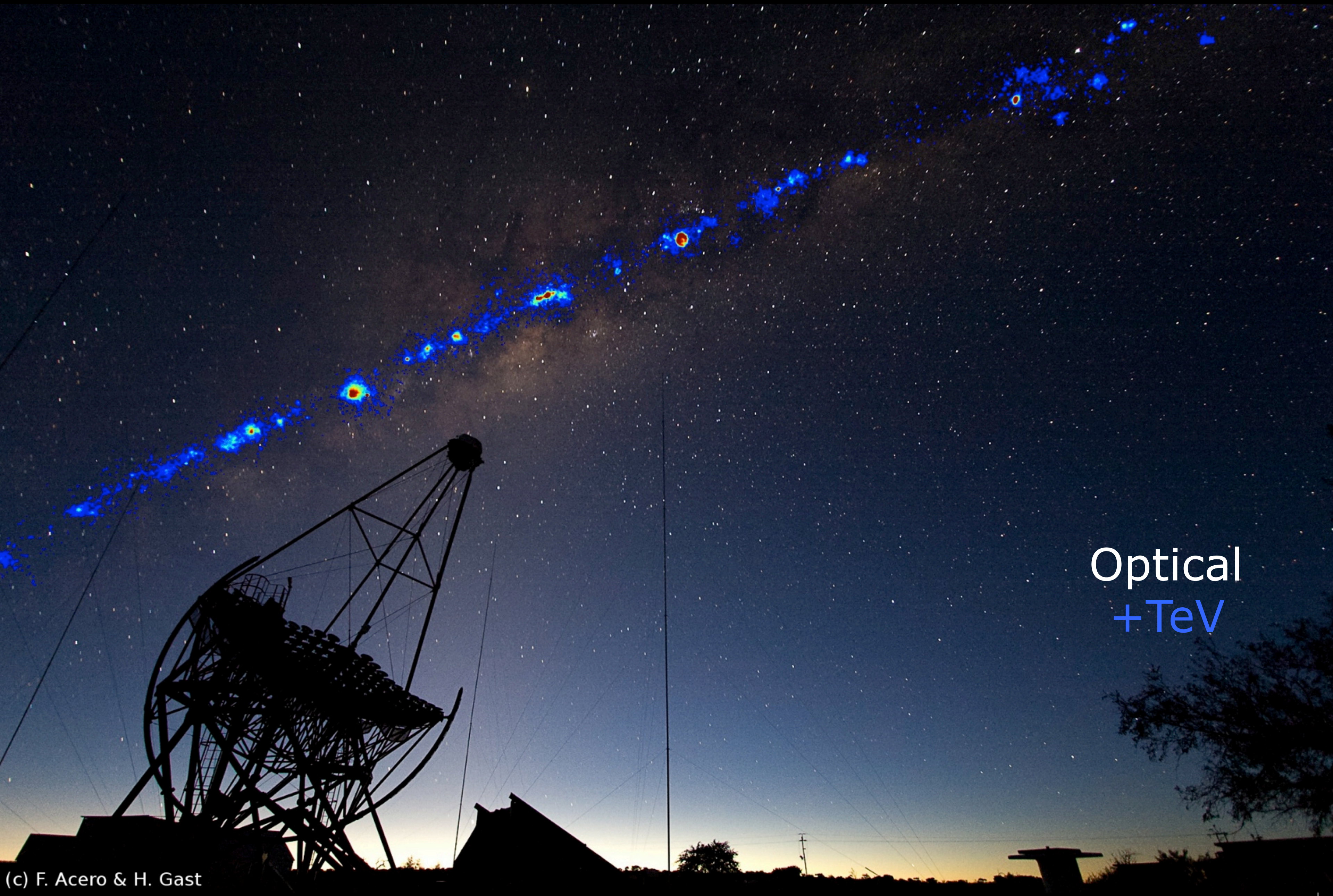
- 2 - 5 Telescopes
- 500-2000 pixel cameras*
- 3.5 - 5.0° FoV
- ~0.1° angular res.
- ~15% energy res.

+HAWC in Mexico under construction




Optical
© Fabio Acero



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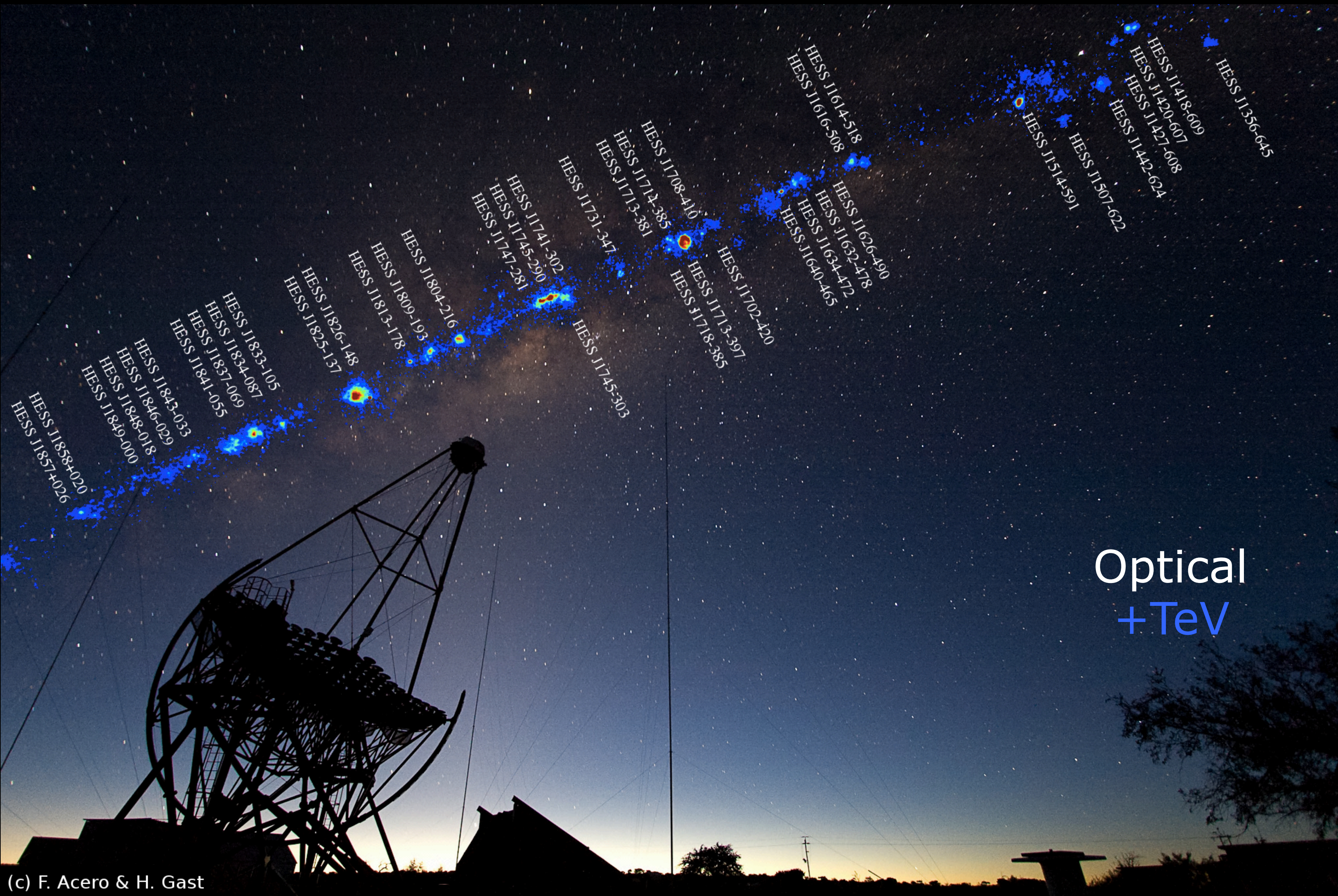

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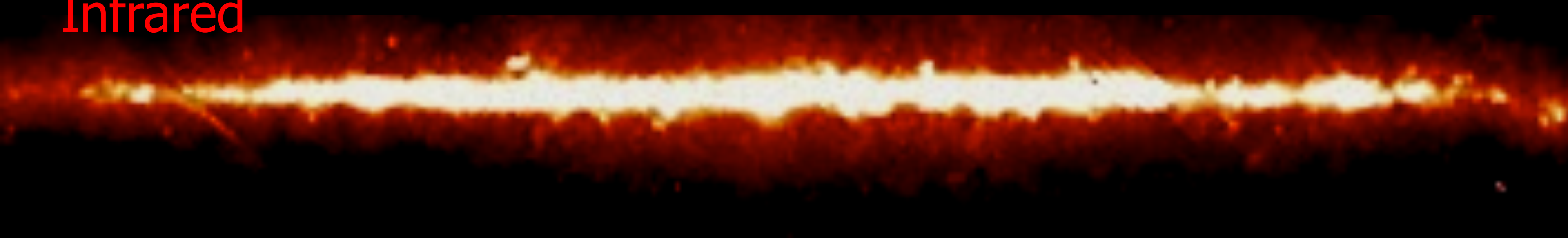
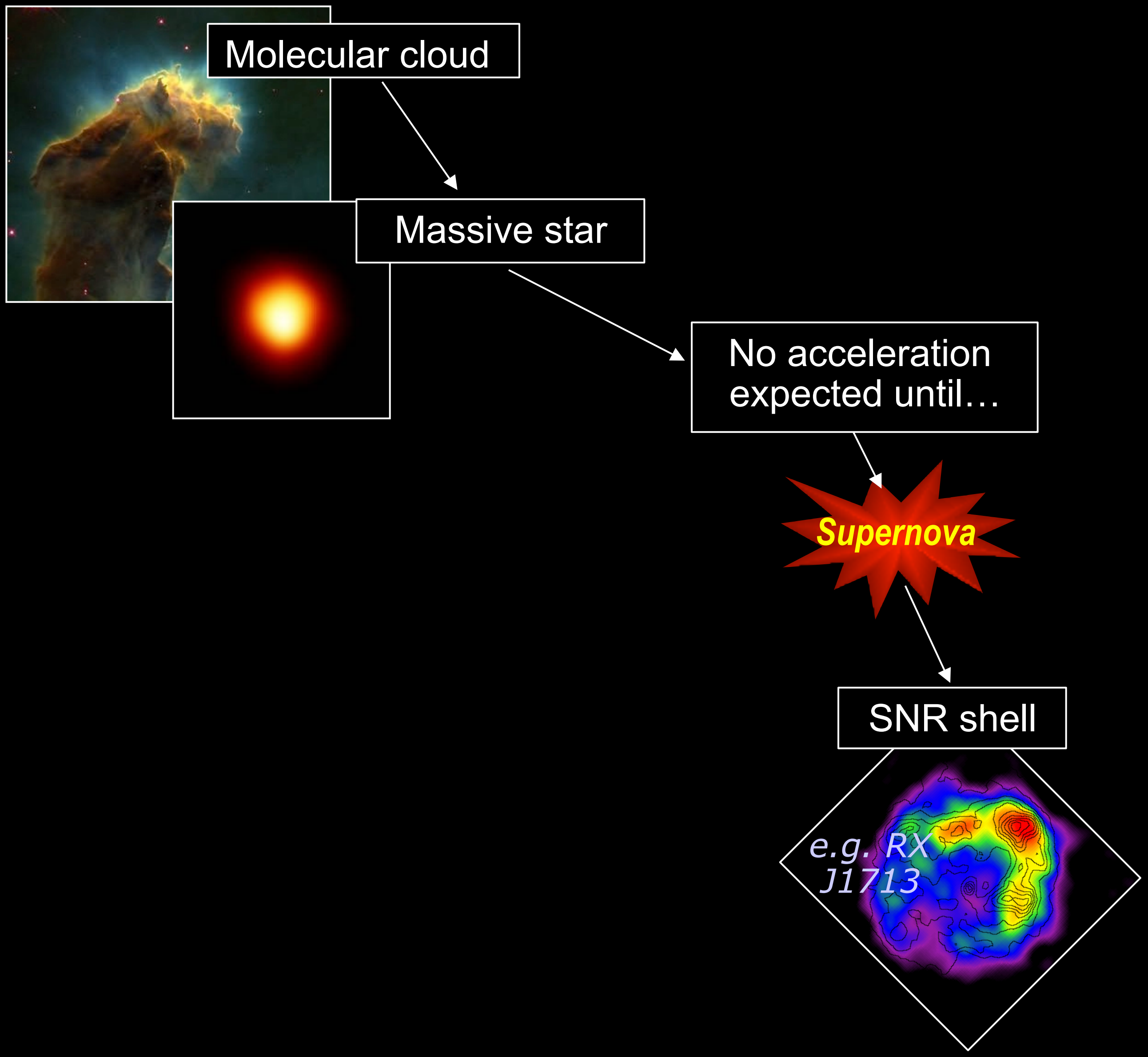
15 What are these Objects?

- Sites of particle acceleration
  - TeV emission requires >TeV particles (*cosmic rays*)
  - Associated with shocks?
  - Tightly clustered along the galactic plane:
  1) They are rather distant (several kpc) – no absorption
  2) They are associated with molecular gas / on-going massive star formation

VHE γ-ray

Infrared





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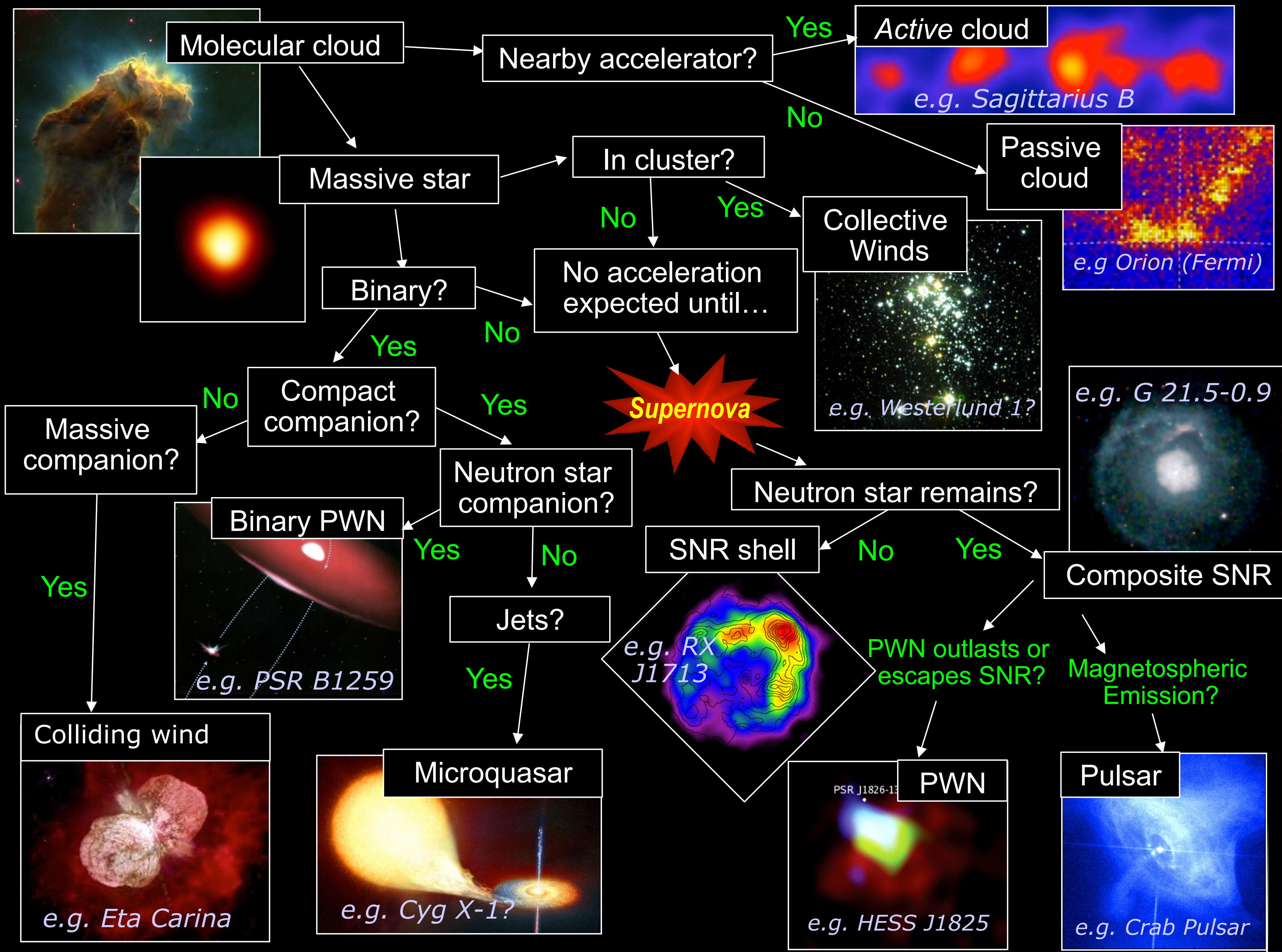
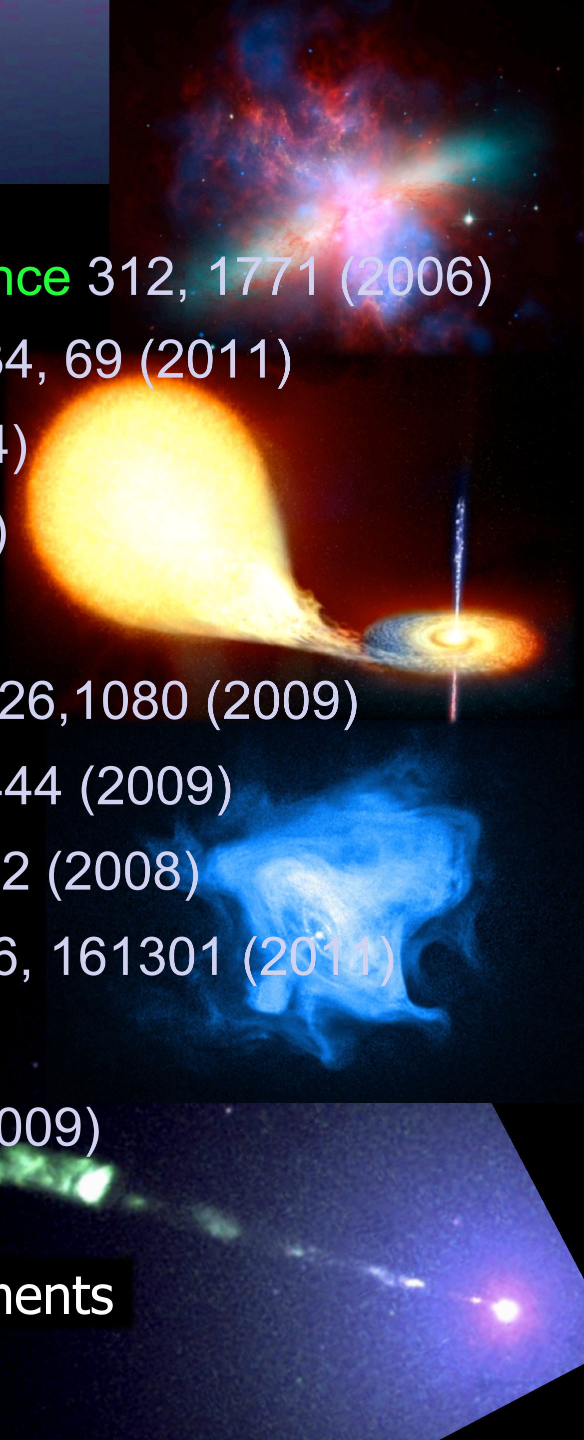

Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
e.g Orion (Fermi)
Massive star
In cluster?
No
Yes
Collective Winds
e.g. Westerlund 1?
Binary?
No acceleration expected until…
No
Yes
Supernova
Compact companion?
No
Yes
Massive companion?
Neutron star companion?
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?
Yes
e.g. RX J1713
PWN outlasts or escapes SNR?
Magnetospheric Emission?
Colliding wind
e.g. Eta Carina
Microquasar
e.g. Cyg X-1?
PWN
PSR J1826-13
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

18 TeV Highlights

- *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)

Results from ground-based gamma-ray instruments



19 TeV Highlights

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- *Pulsars:* Science 322, 1221 (2008), Science 334, 69 (2011)
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Results from ground-based gamma-ray instruments

How to do better?

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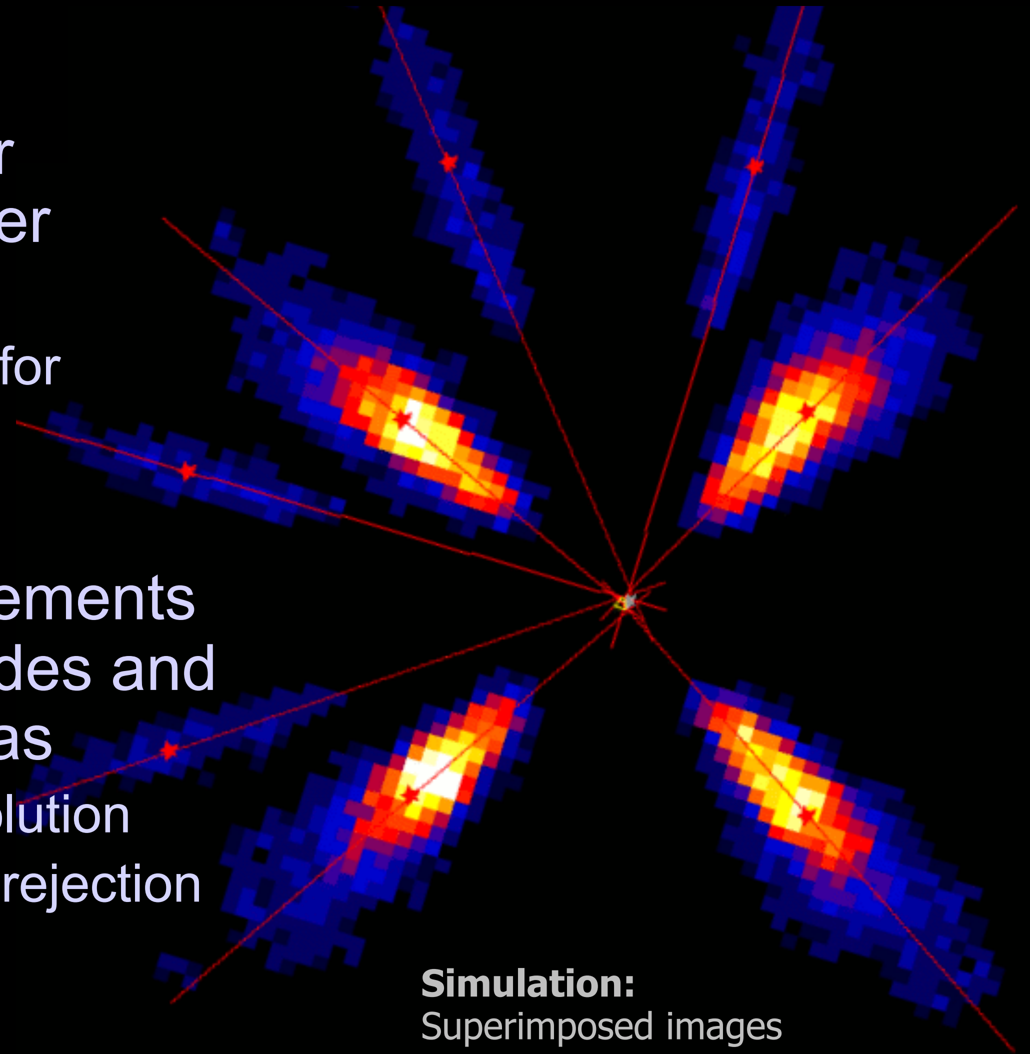
- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

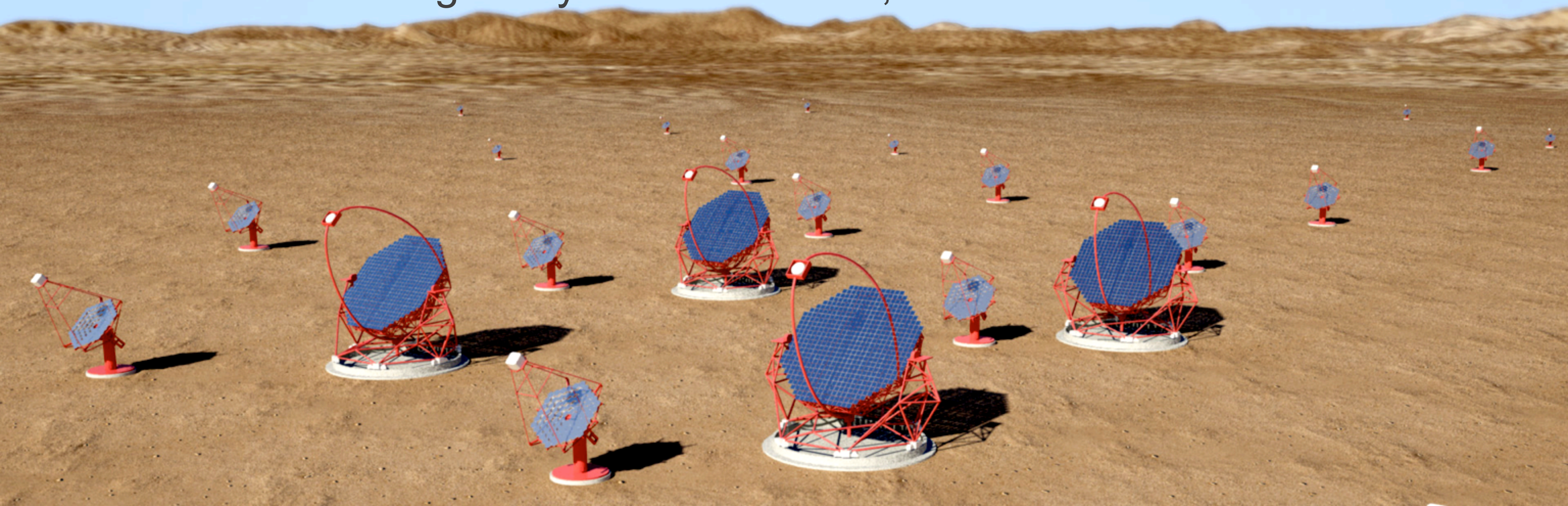
☛ More telescopes!

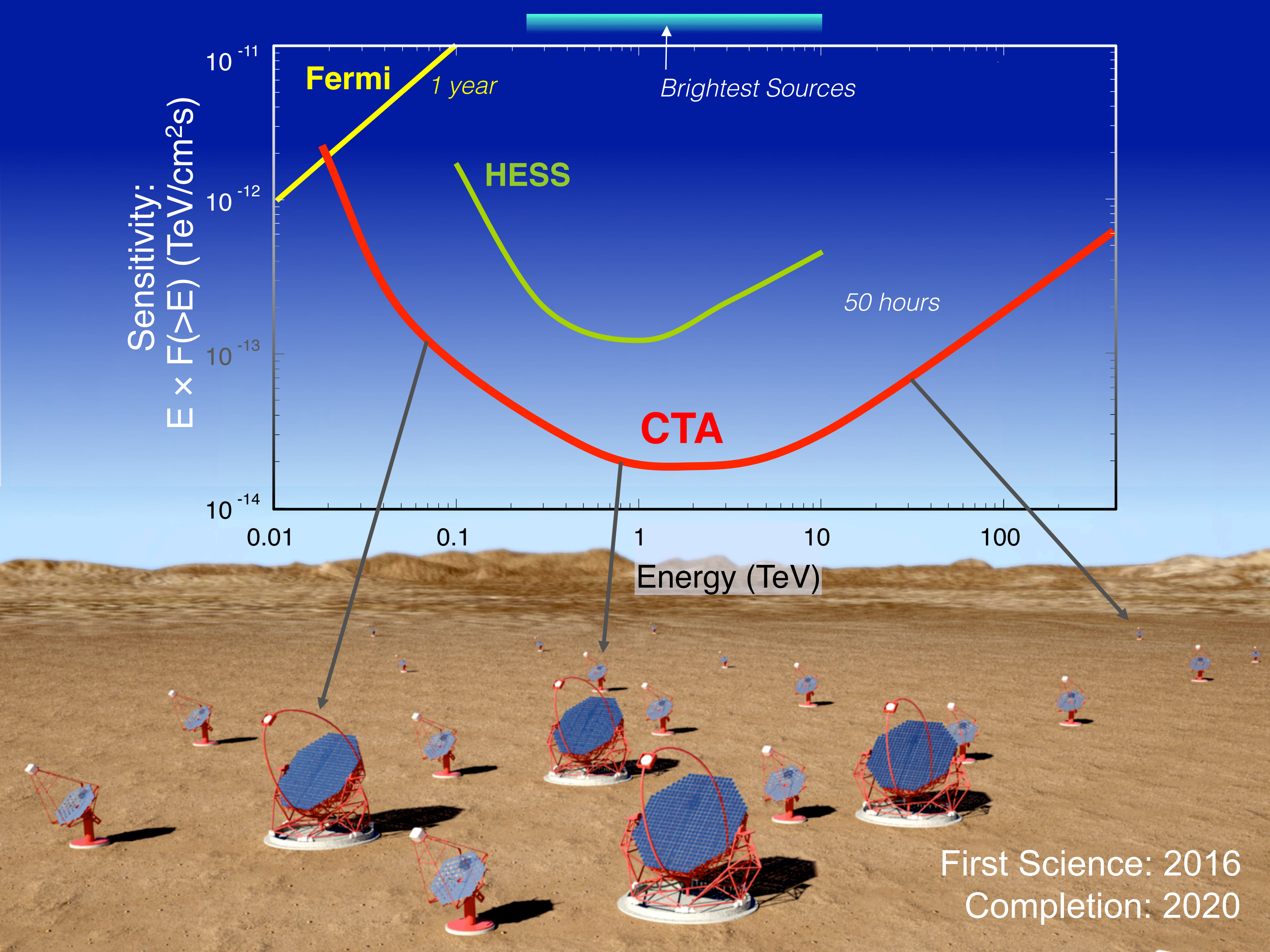


Simulation:
Superimposed images from 8 cameras

The Cherenkov Telescope Array

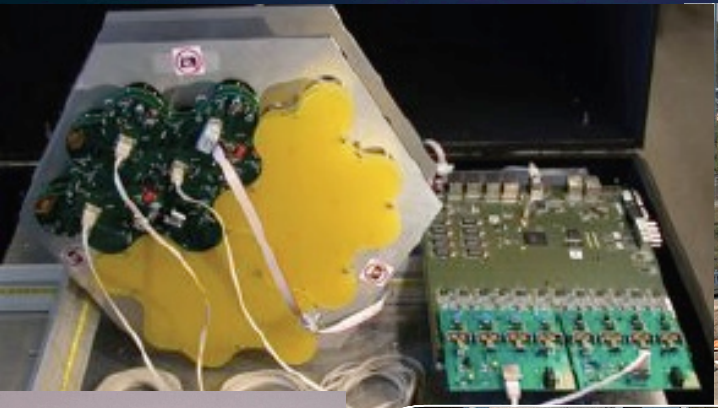
- A huge improvement in all aspects of performance
  - A factor ~10 in sensitivity, much wider energy coverage, much better resolution, field-of-view, full sky, …
- A user facility / proposal-driven observatory
  - With two sites with a total of >100 telescopes
- A 27 nation, >1000 person, ~€200M project
  - Including everyone from HESS, MAGIC and VERITAS

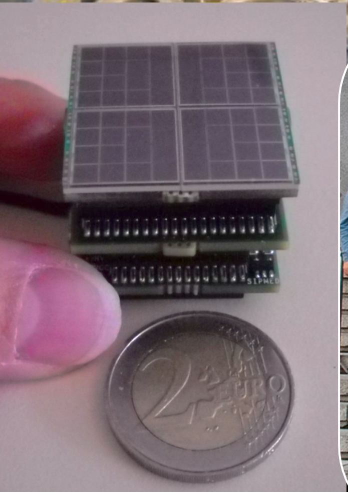


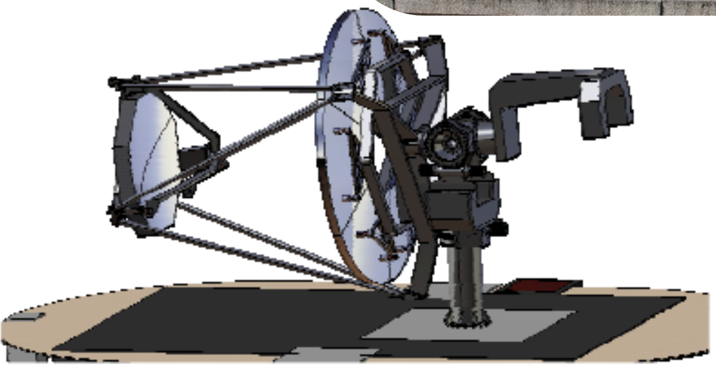


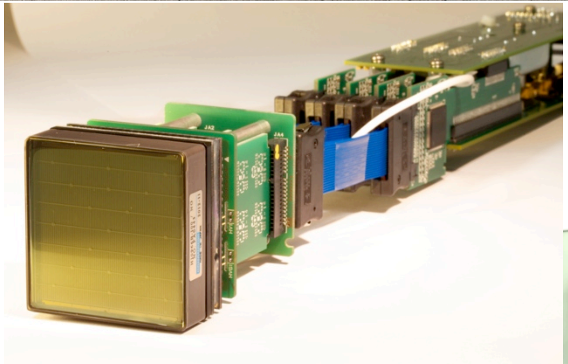
Brightest Sources
Fermi
1 year
HESS
CTA
50 hours
Sensitivity:
E × F(>E) (TeV/cm²s)
10 -11
10 -12
10 -13
10 -14
0.01
0.1
1
10
100
Energy (TeV)
First Science: 2016
Completion: 2020

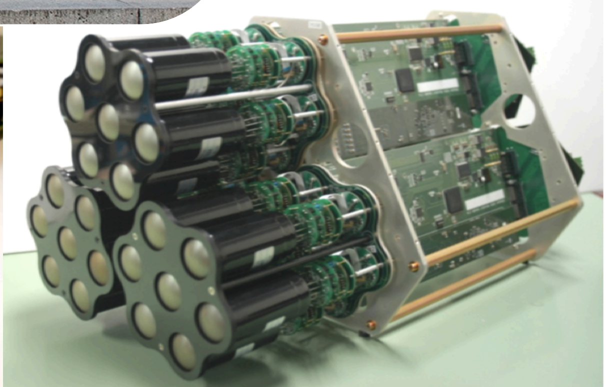
23 Huge technical effort



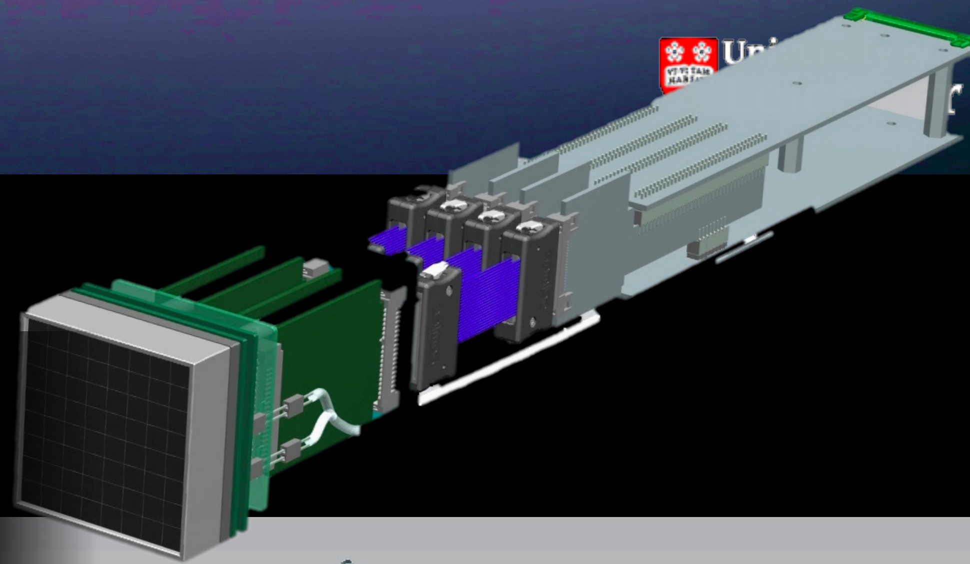




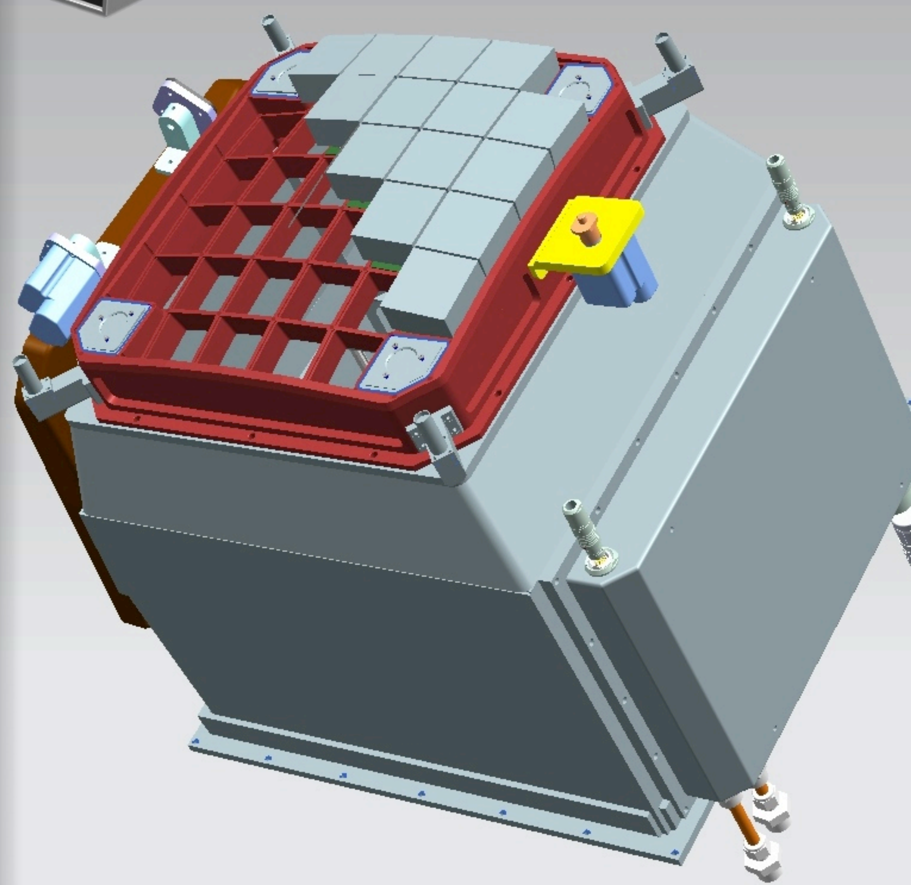


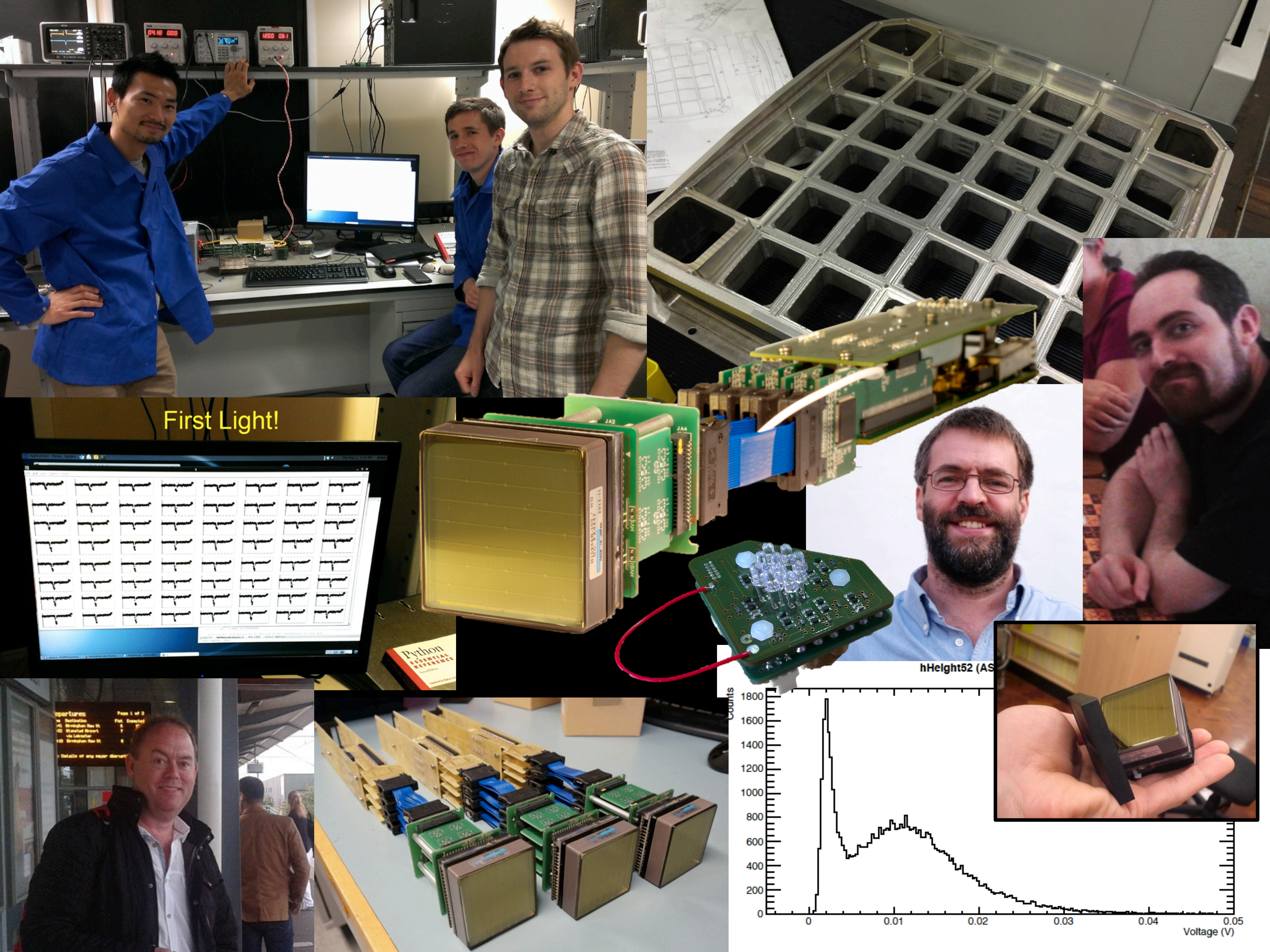


CHEC



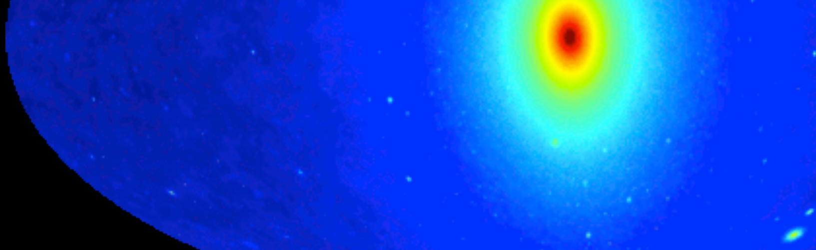
- **CHEC = Compact High Energy Camera**
  - Collaboration between UK, US, Netherlands and Japan
    - Primarily STFC funded - Leicester, Liverpool, Durham, + Oxford, LJMU, +++
    - Prototyping effort for the Small-sized telescope camera
  - Cheapest, lightest, widest FoV, advanced readout
    - TARGET ASIC: 1 ns samples in 16 μs buffer
- **1st CHEC ~May 2014**
  - Should be the first full camera prototype for CTA




First Light!
Python
ESSENTIAL REFERENCE
hHeight52 (AS
Counts
1800
1600
1400
1200
1000
800
600
400
200
0
0
0.01
0.02
0.03
0.04
0.05
Voltage (V)

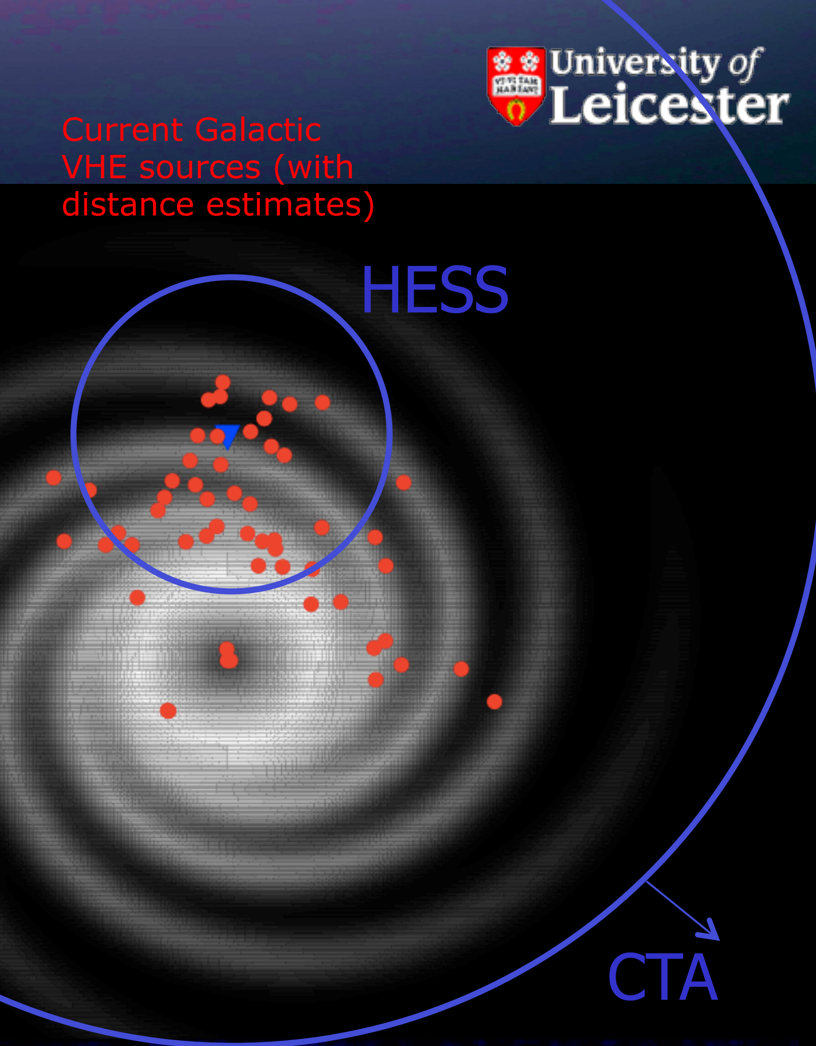
CTA Science

- **Cosmic Particle Acceleration, Propagation and Impact**
  - Mechanisms for particle acceleration, Galactic CR acceleration and Pevatrons, acceleration in jets and lobes of AGN, cosmic ray transport, …
  - What role do accelerated particles play in feedback on star formation and galaxy evolution?
- **Probing Extreme Environments**
  - Neutron stars and black holes, relativistic jets, winds and explosions, the contents of cosmic voids, …
- **Physics Frontiers**
  - 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?

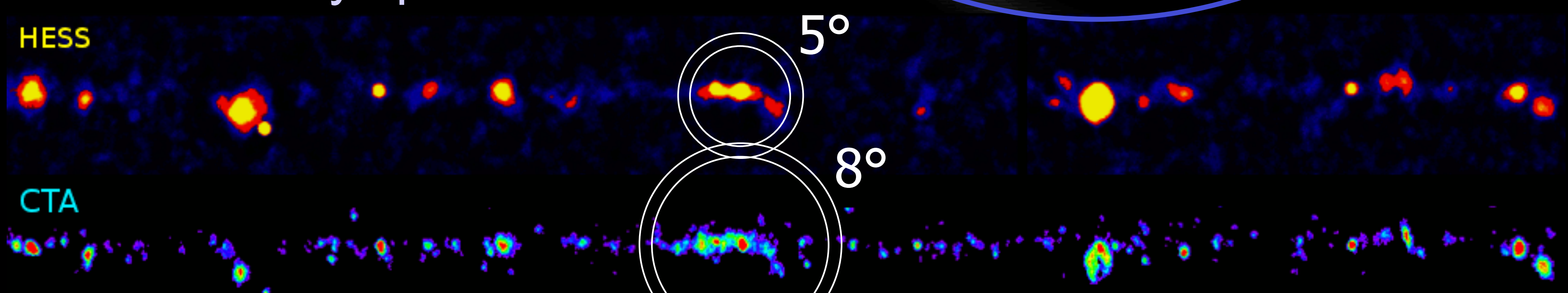


CTA Reach

- Galactic objects
  - Newly born pulsars and the supernova remnants
    - have typical brightness such that HESS etc can see only relatively local (<10,000 light years away) objects
  - CTA will see **whole** Galaxy

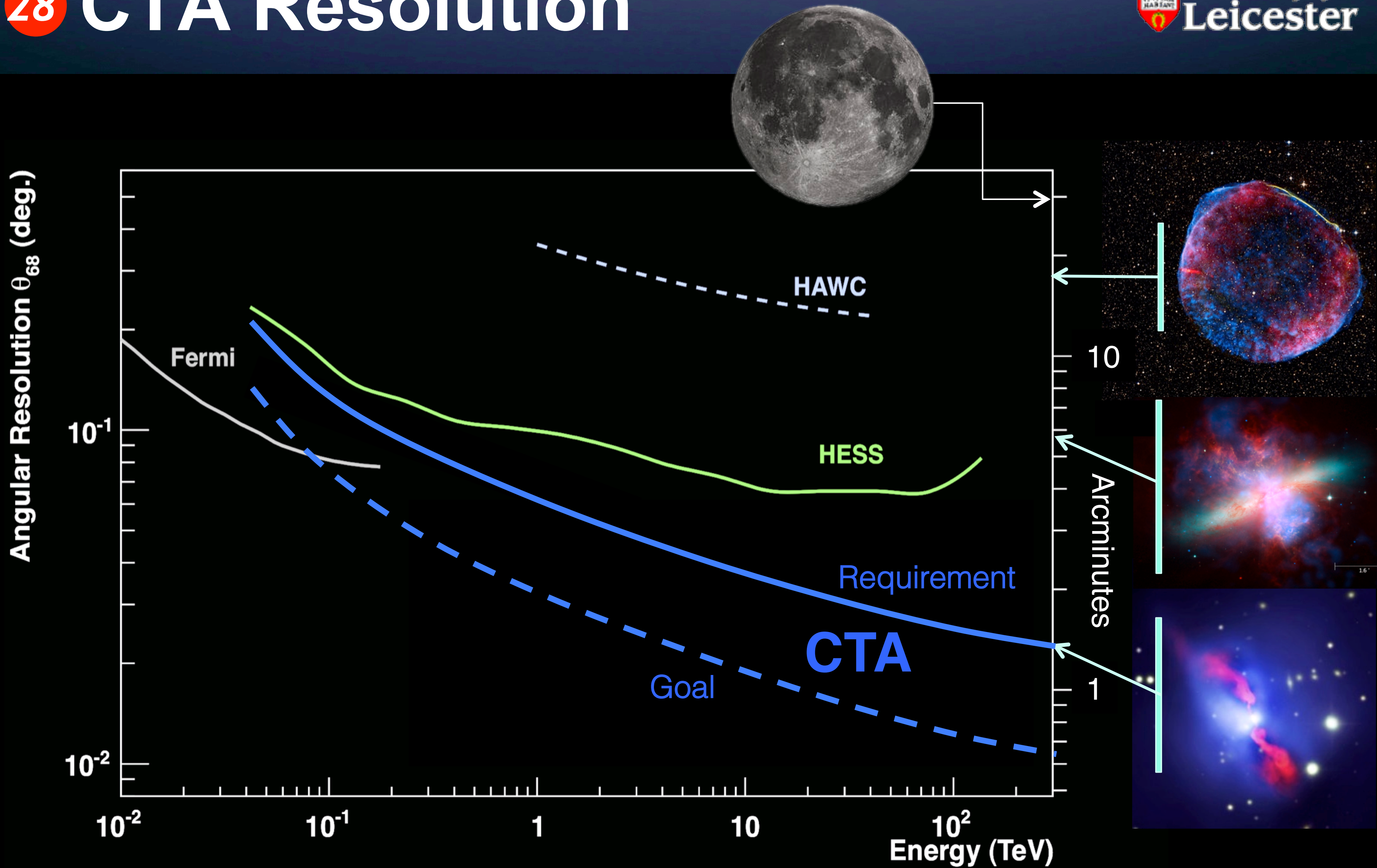


- Field of view + Sens.
  - Survey speed ~300×HESS



Galactic Plane Population Model: Funk+Hinton

28 CTA Resolution



29 The Biggest Bubbles

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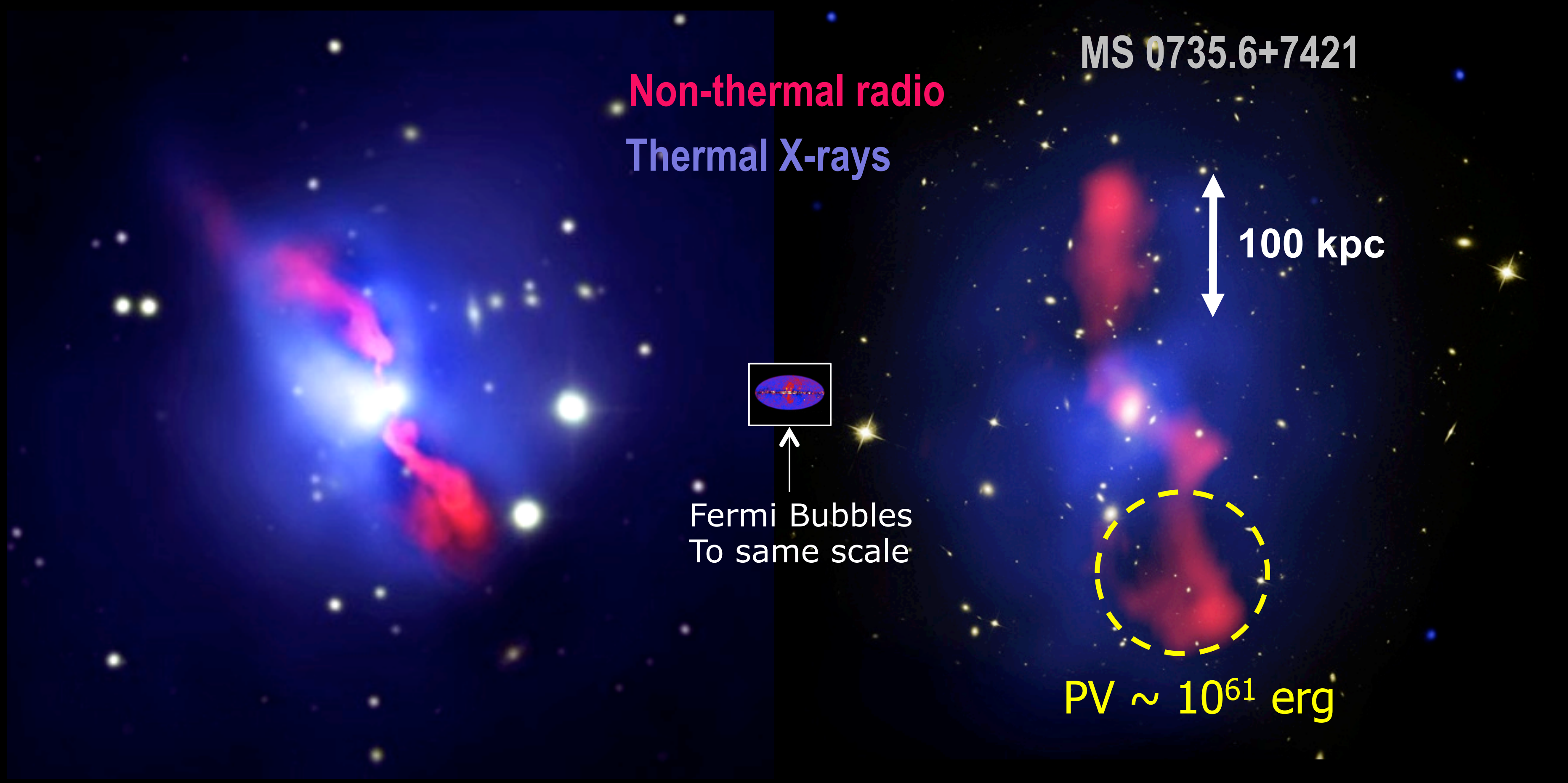
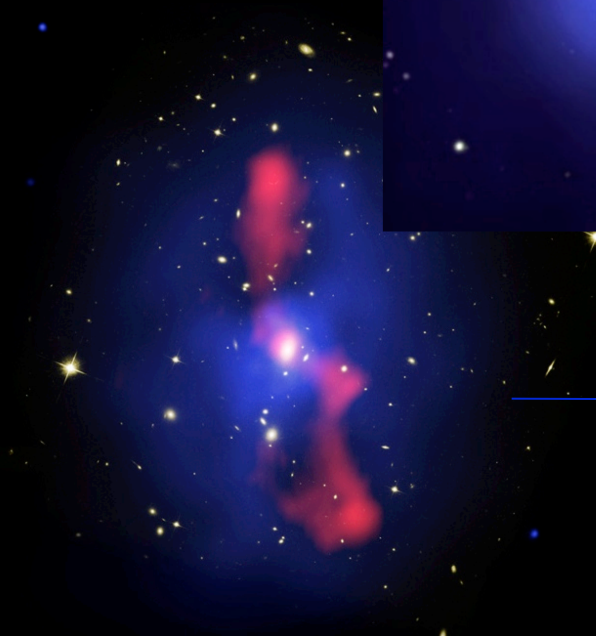


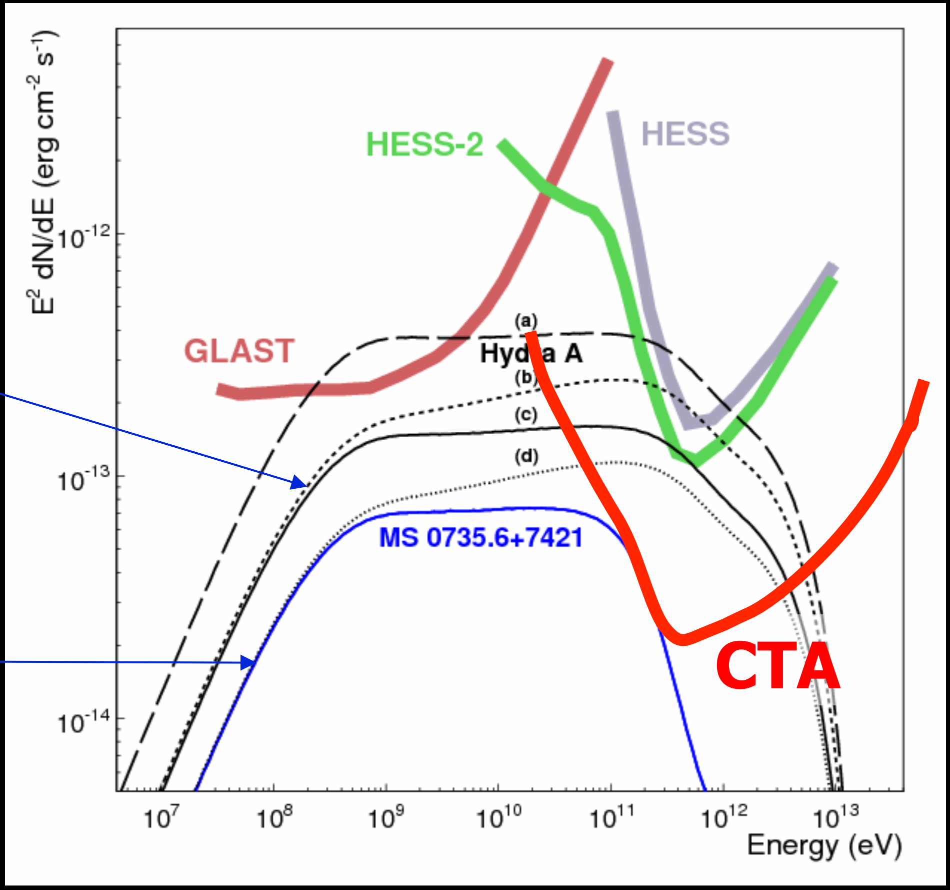
X-ray IC limits and lifetime arguments against just electrons+B-fields in bubbles

The Biggest Bubbles

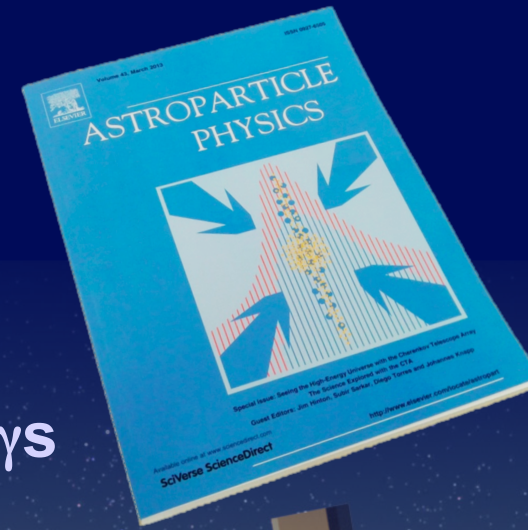
- If bubbles in Hydra A are supported by cosmic ray pressure – CTA will see them



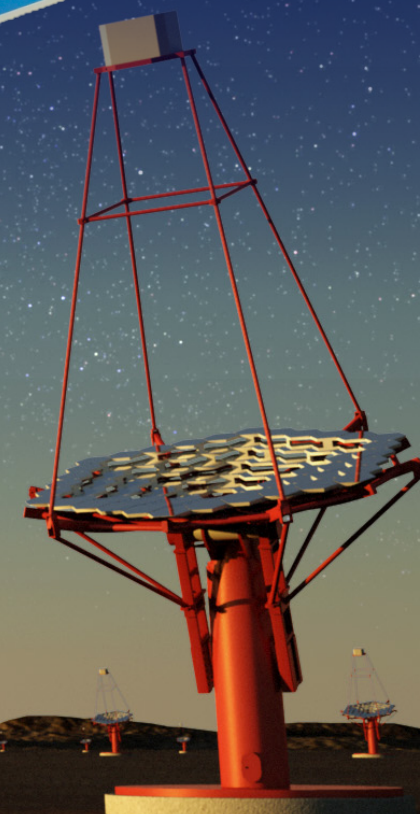
Hinton, Domainko & Pope MNRAS 2007

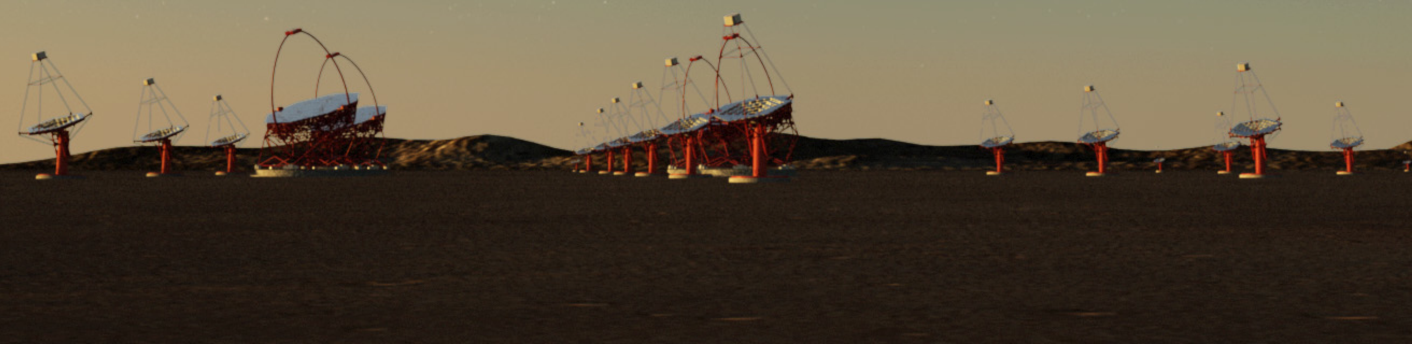


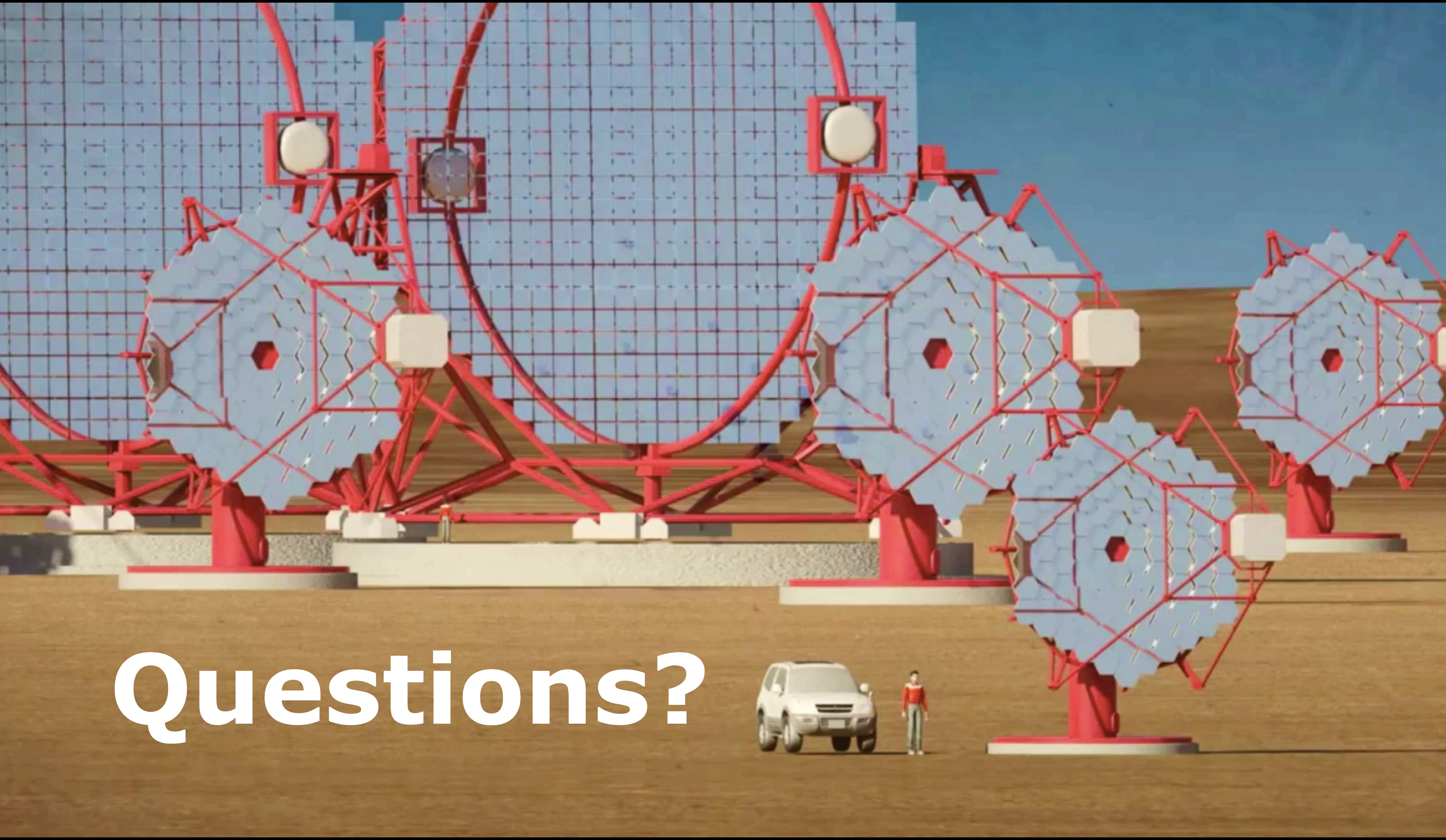
Conclusion



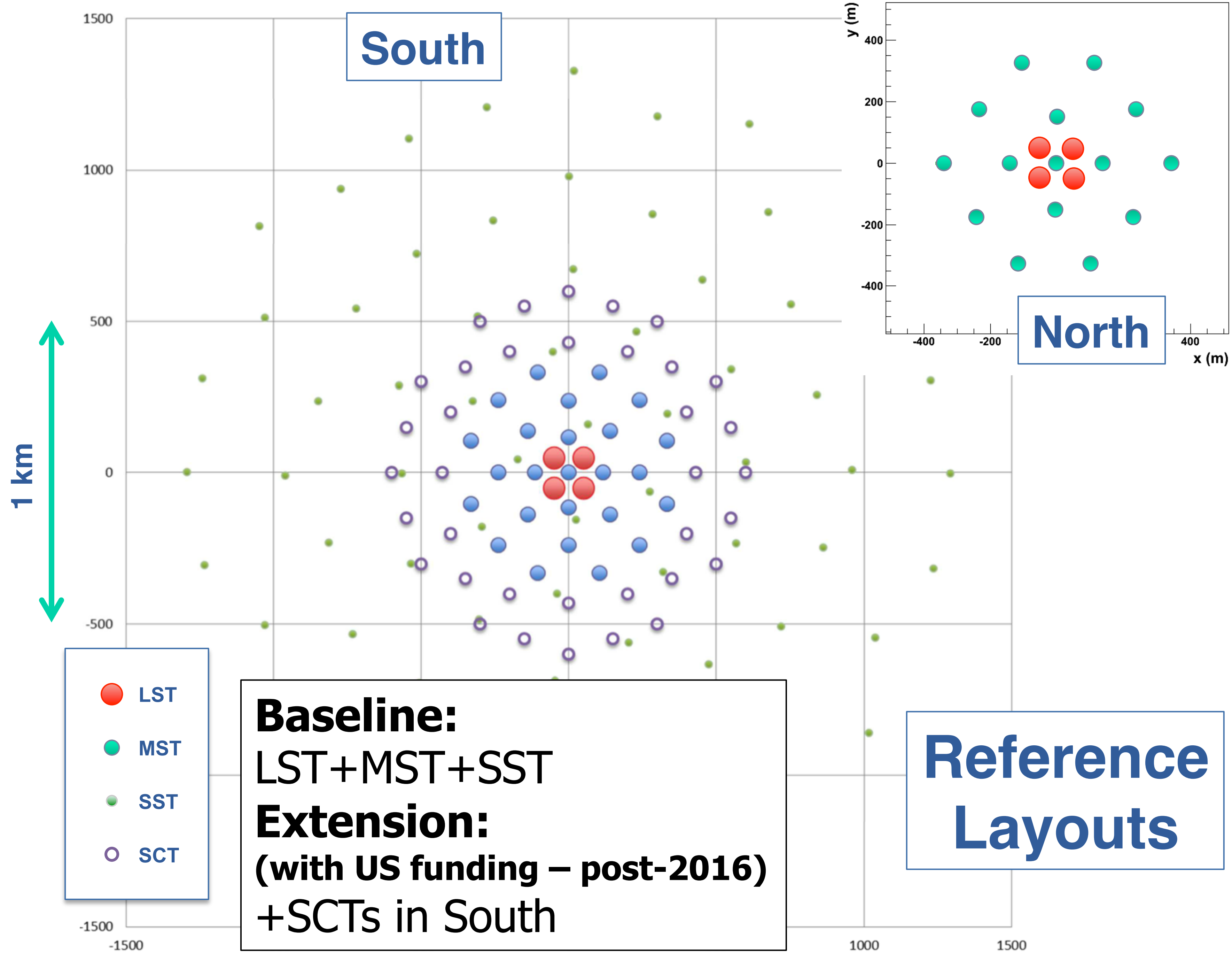
- Multi-messenger Astronomy is coming of age
  - **Neutrinos, GWs, UHECRs, VHE γs**
- **CTA is on track**
  - First science from 2016
  - User facility serving a large community by the end of the decade
  - Strong UK role
  - Enormous science potential
    - See special issue of Astropart. Phys





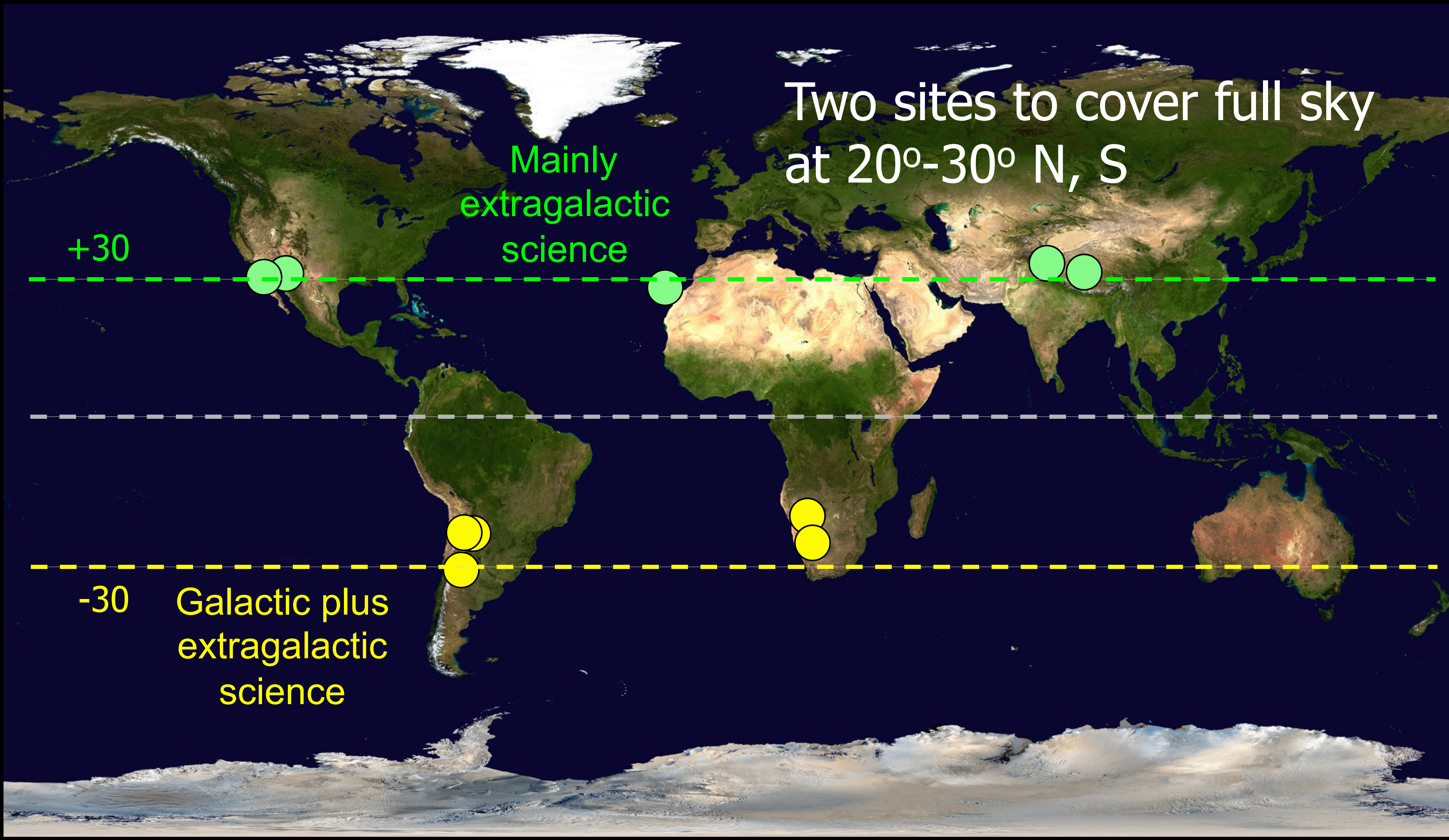

Questions?

Reference Layouts



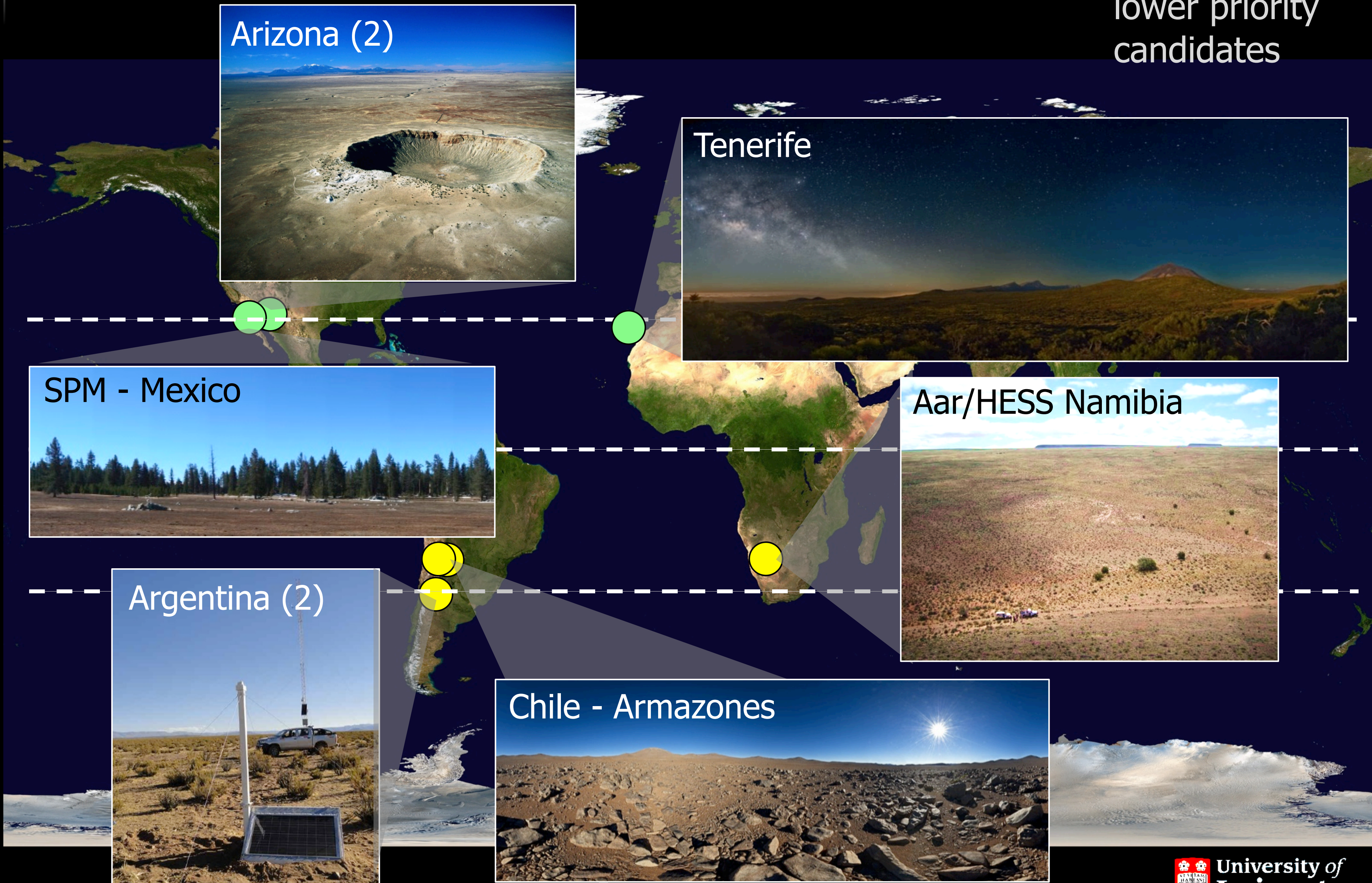
Baseline:
LST+MST+SST
Extension:
(with US funding – post-2016)
+SCTs in South

CTA Sites


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

Sites: Candidates

+additional lower priority candidates



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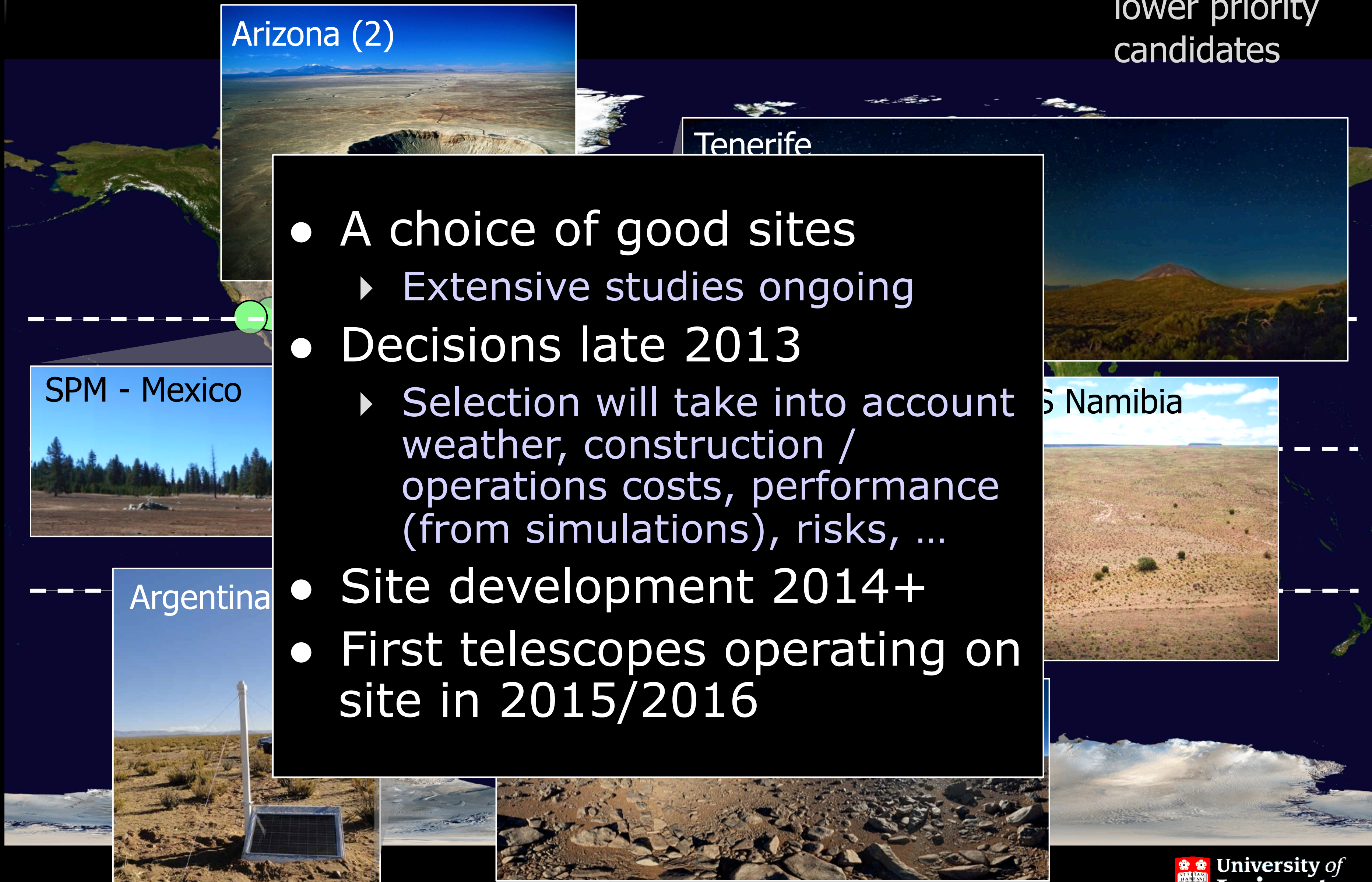
Sites: Candidates

+additional lower priority candidates



- A choice of good sites
  - Extensive studies ongoing
- Decisions late 2013
  - Selection will take into account weather, construction / operations costs, performance (from simulations), risks, …
- Site development 2014+
- First telescopes operating on site in 2015/2016

Milestones in 2013

- Publication of a **special issue** of the journal Astroparticle Physics dedicated to CTA
  - and detailed CTA science case studies
- Completion of first review by our Scientific and Technical advisory committee
  - Science Performance and Requirements
- Completion of **Preliminary Technical Design Report**
  - Submission to STAC Oct 19th
- Completion of **Site Evaluation Summary** document
  - Comprehensive comparison of candidate sites, basis for site selection

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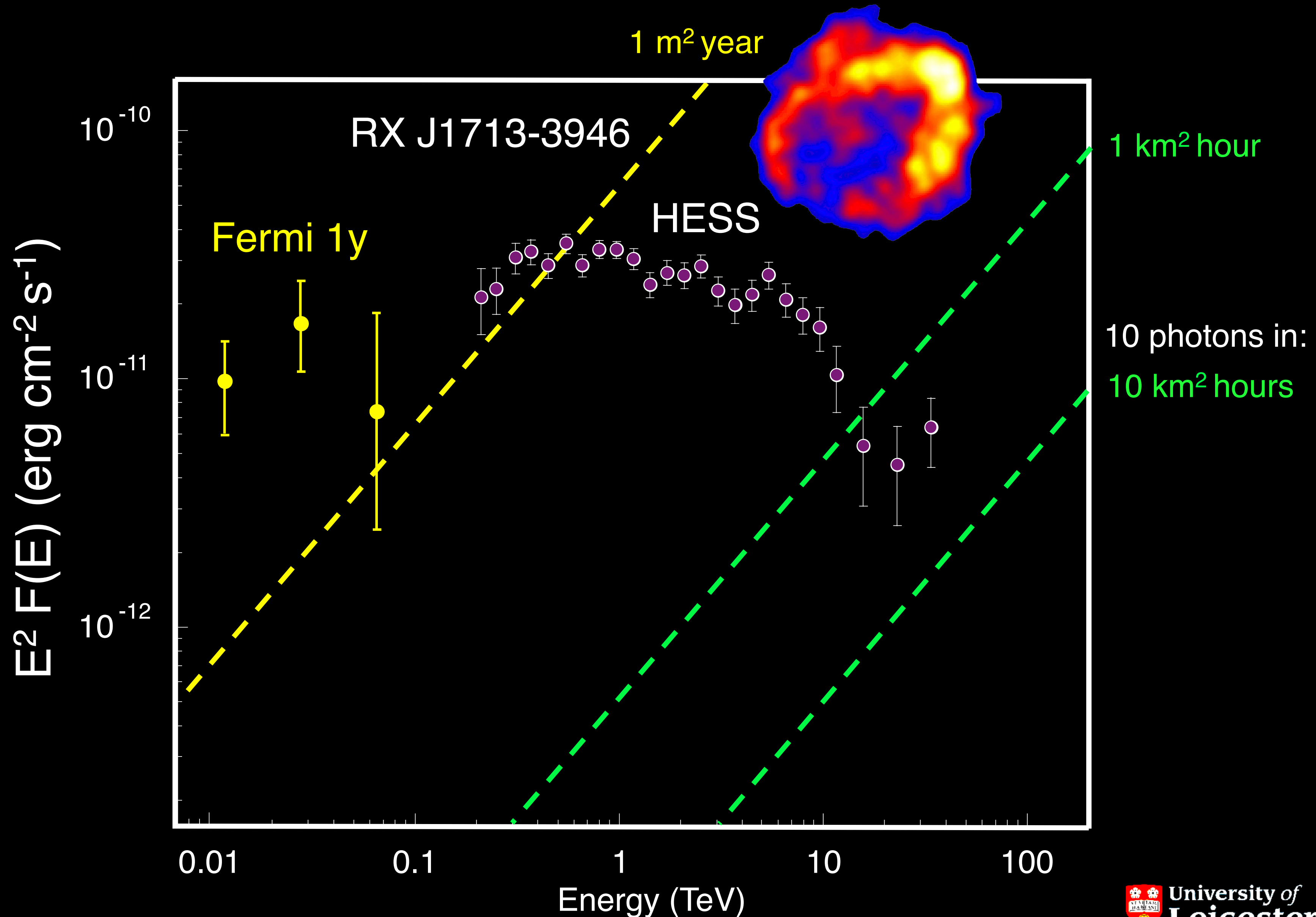
CTA Area



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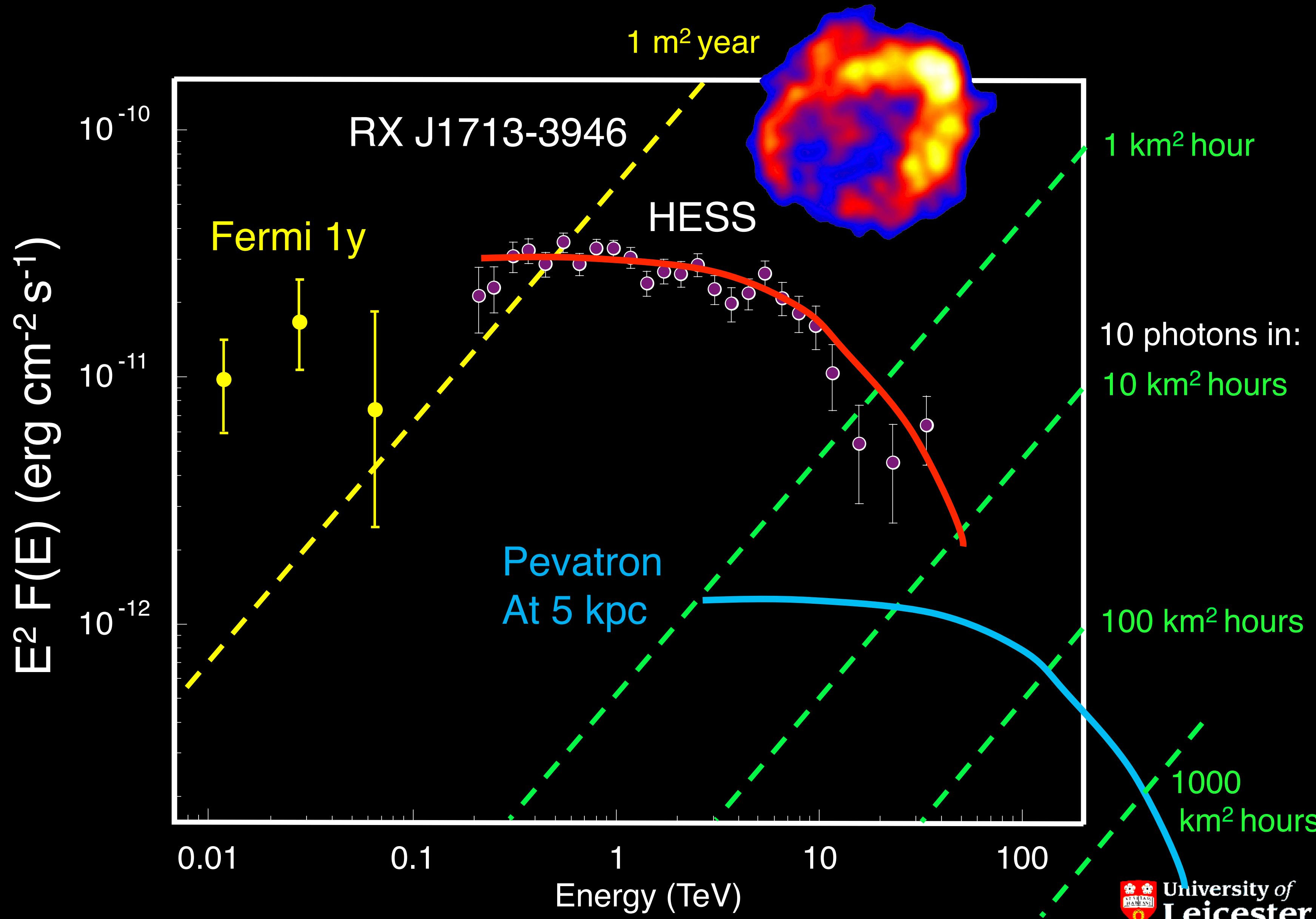
CTA Area



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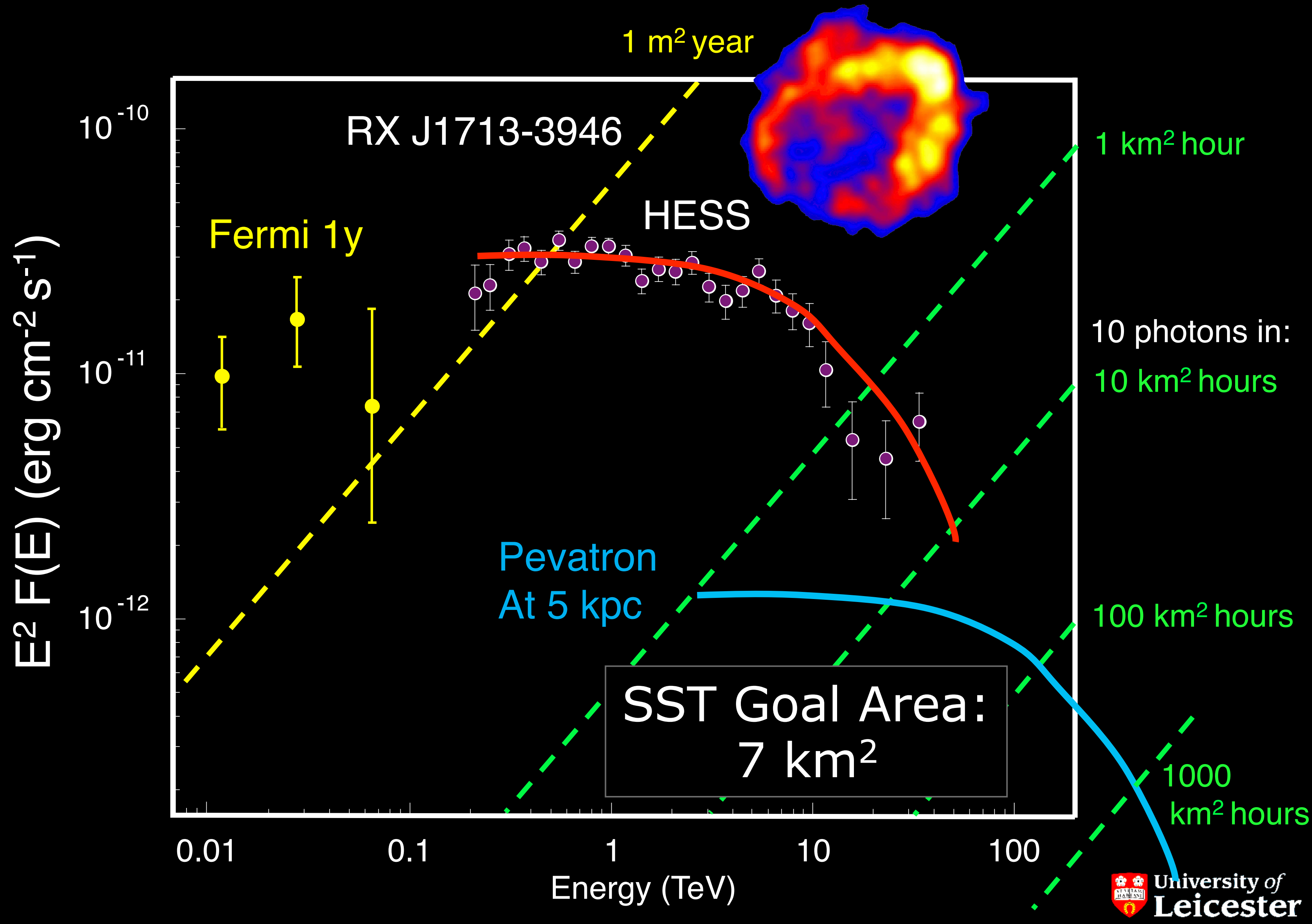
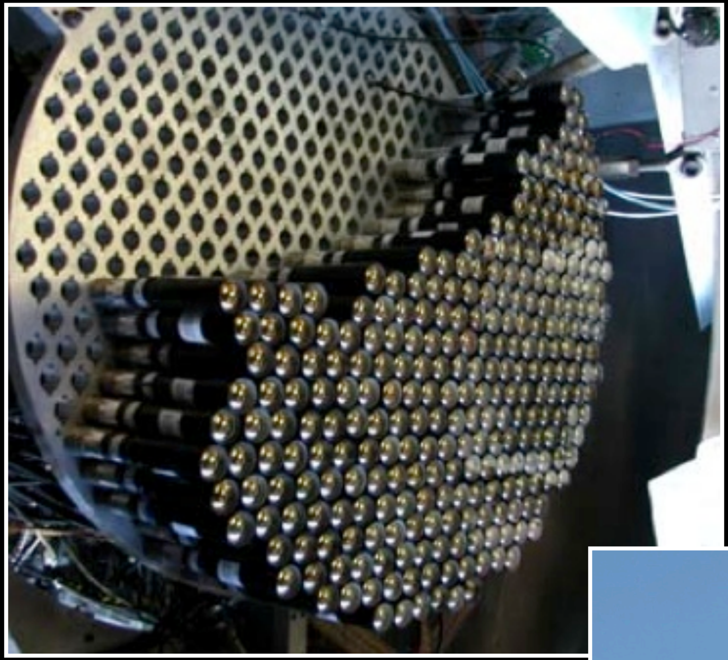
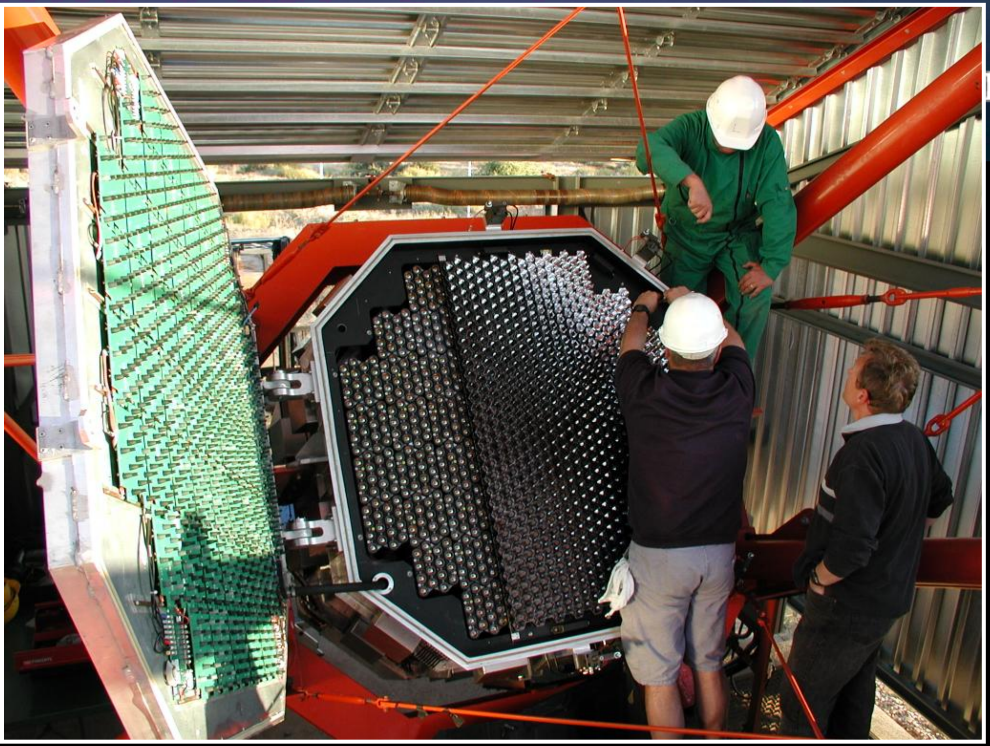
CTA Area



SST Goal Area:
7 km^2

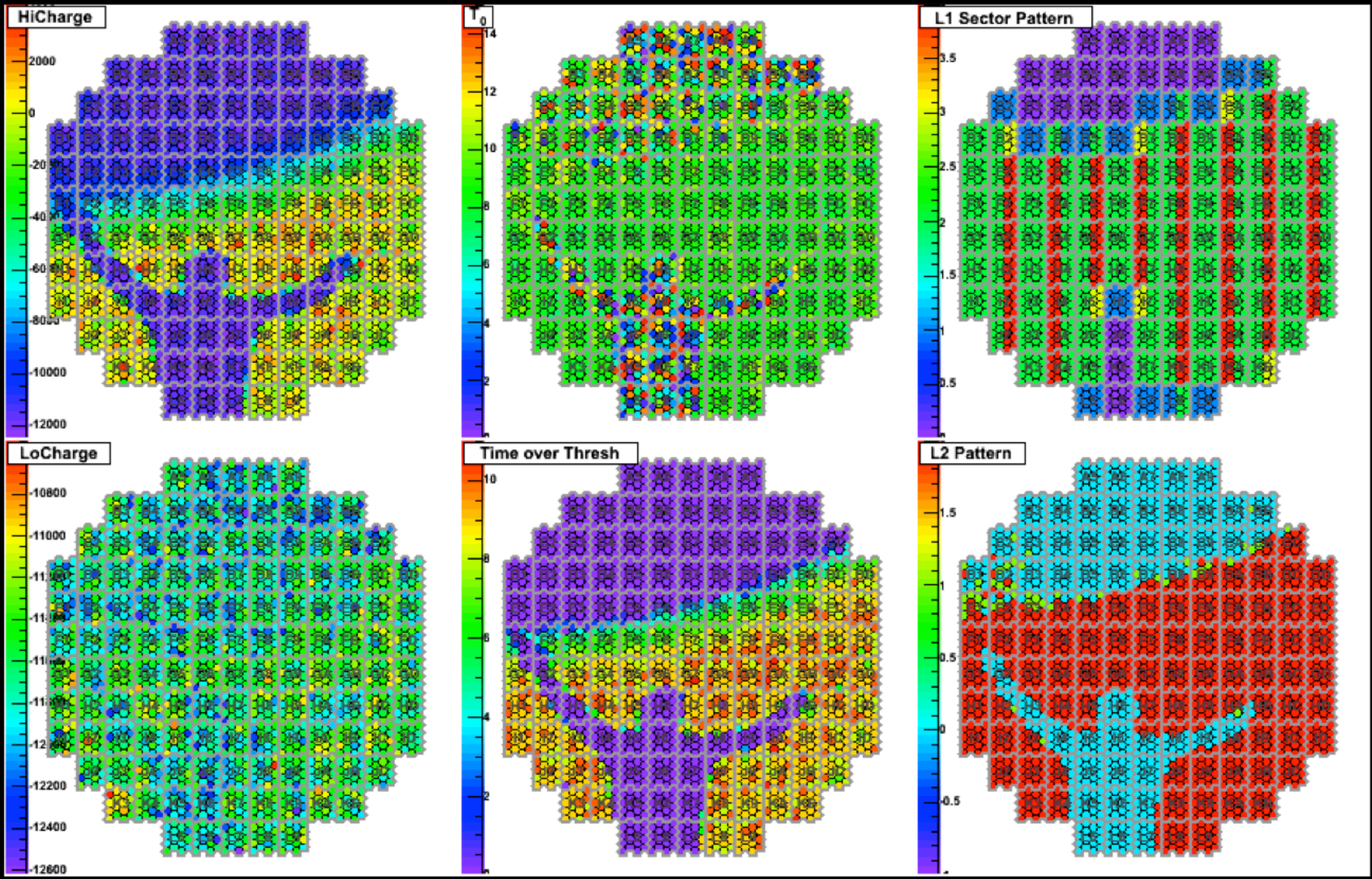
41 Cameras





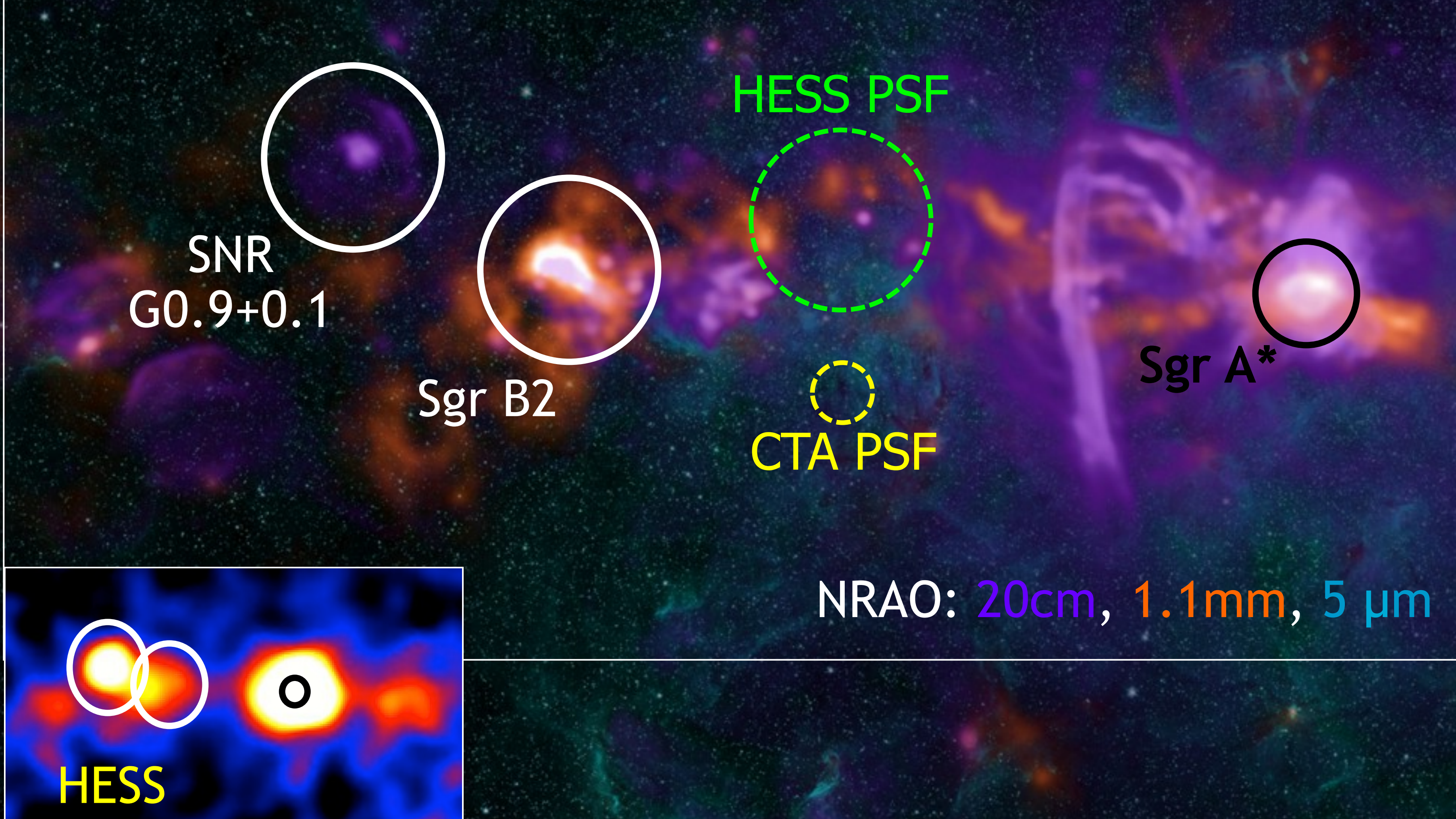

HESS-2

NB: They are BIG

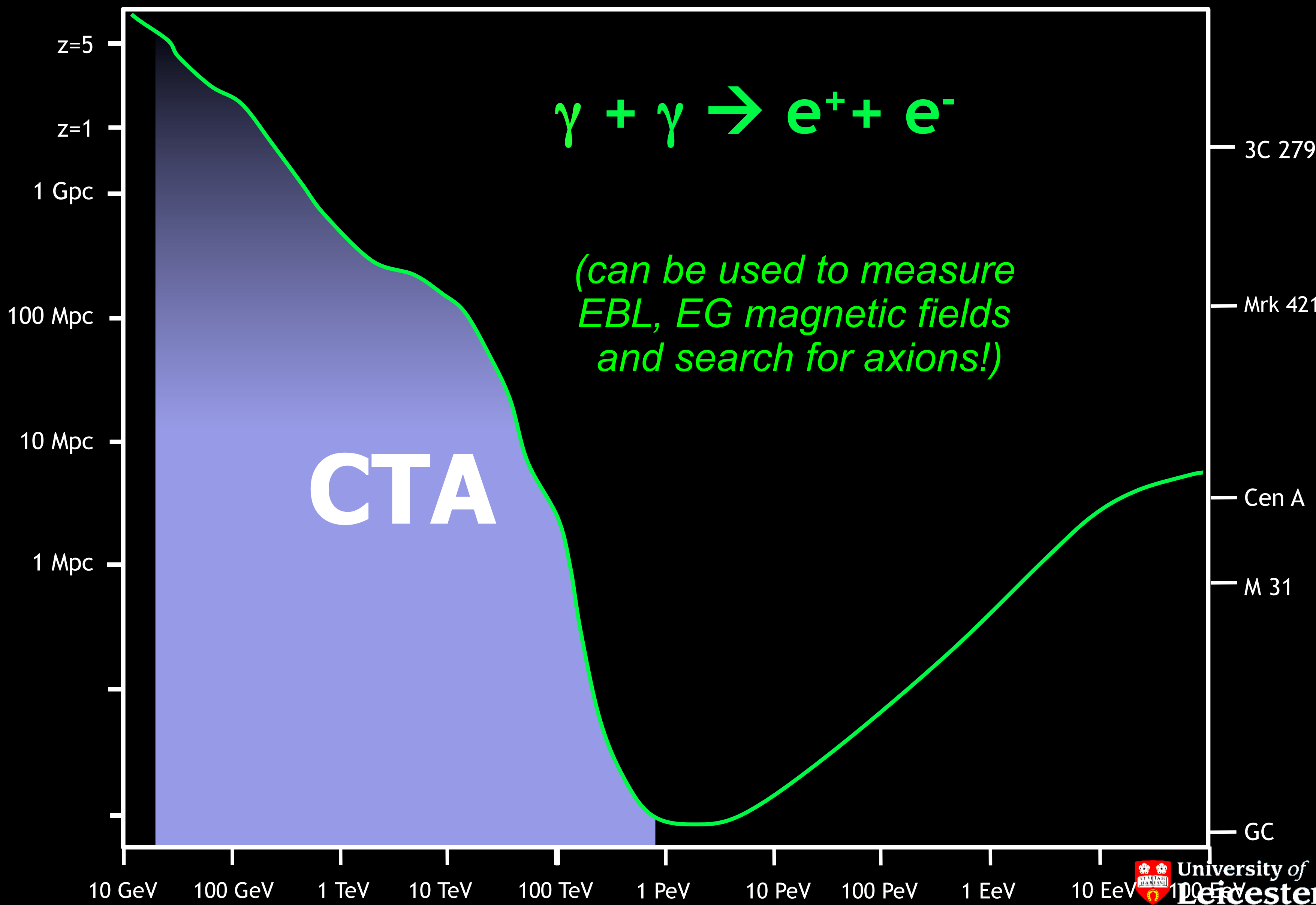


e.g. The Galactic Centre

- CTA resolution+sensitivity can disentangle emission



CTA Reach: The γ Horizon



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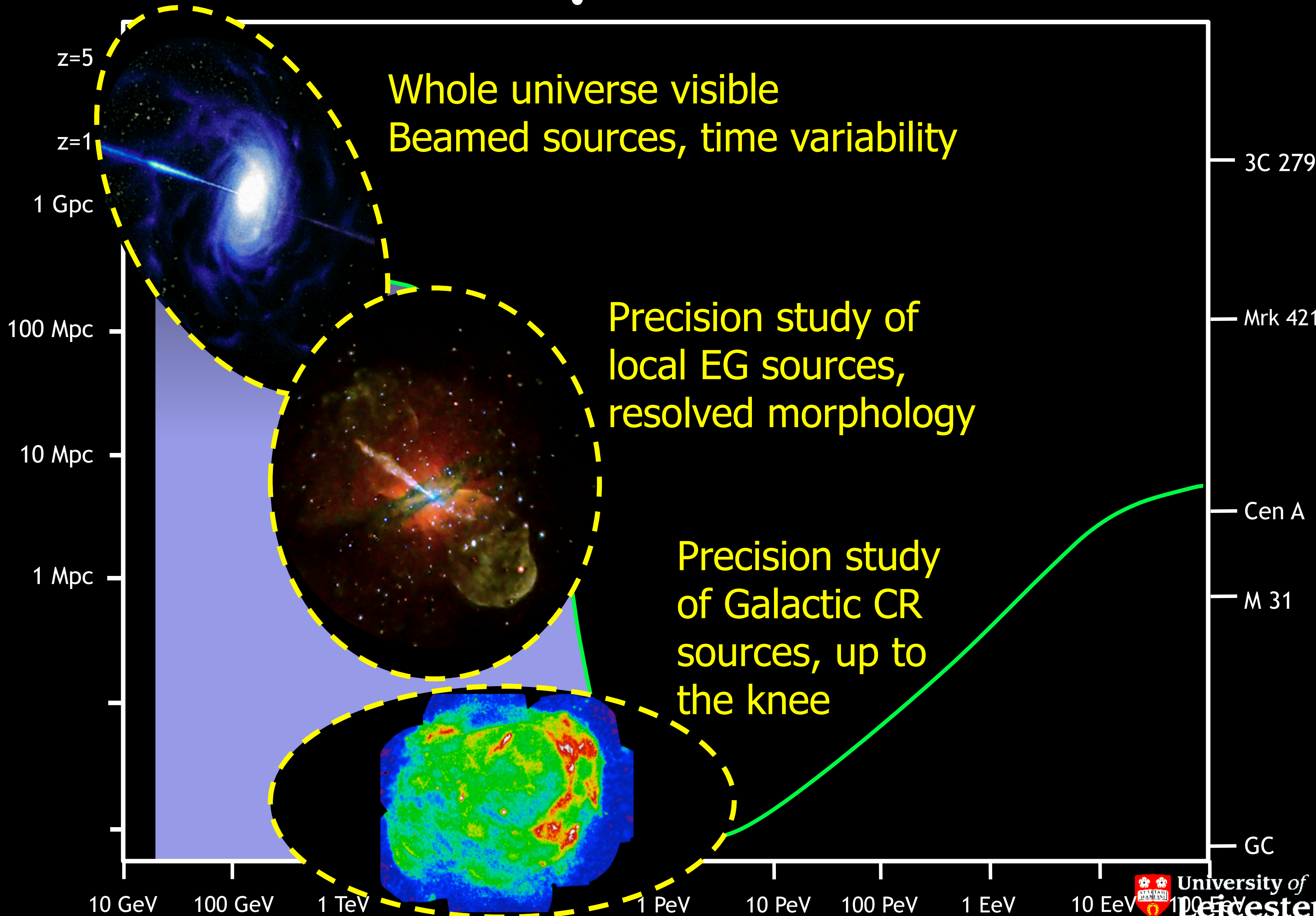
CTA Reach: The γ Horizon



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cta
cherenkov telescope array

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 Jan. 2014
  - Critical Design Review 2014
- Construction Phase
  - Site development and first telescopes on site 2015
  - First science 2016
  - Completion ~2020

Why Ground-based?

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- To do astronomy at the highest (photon) energies with high statistics
  - Typical flux $\sim 10^{-12}$ erg cm^{-2} s^{-1} :
    - ~1 photon/day/m^2 @1 GeV
    - ~0.2 photons **per year per m^2** @ **1 TeV**
    - (or ~20 per **hour per km^2**)
- In addition
  - Best **precision** above X-ray possible from the ground (e.g. ~1’ resolution in future)

Near future

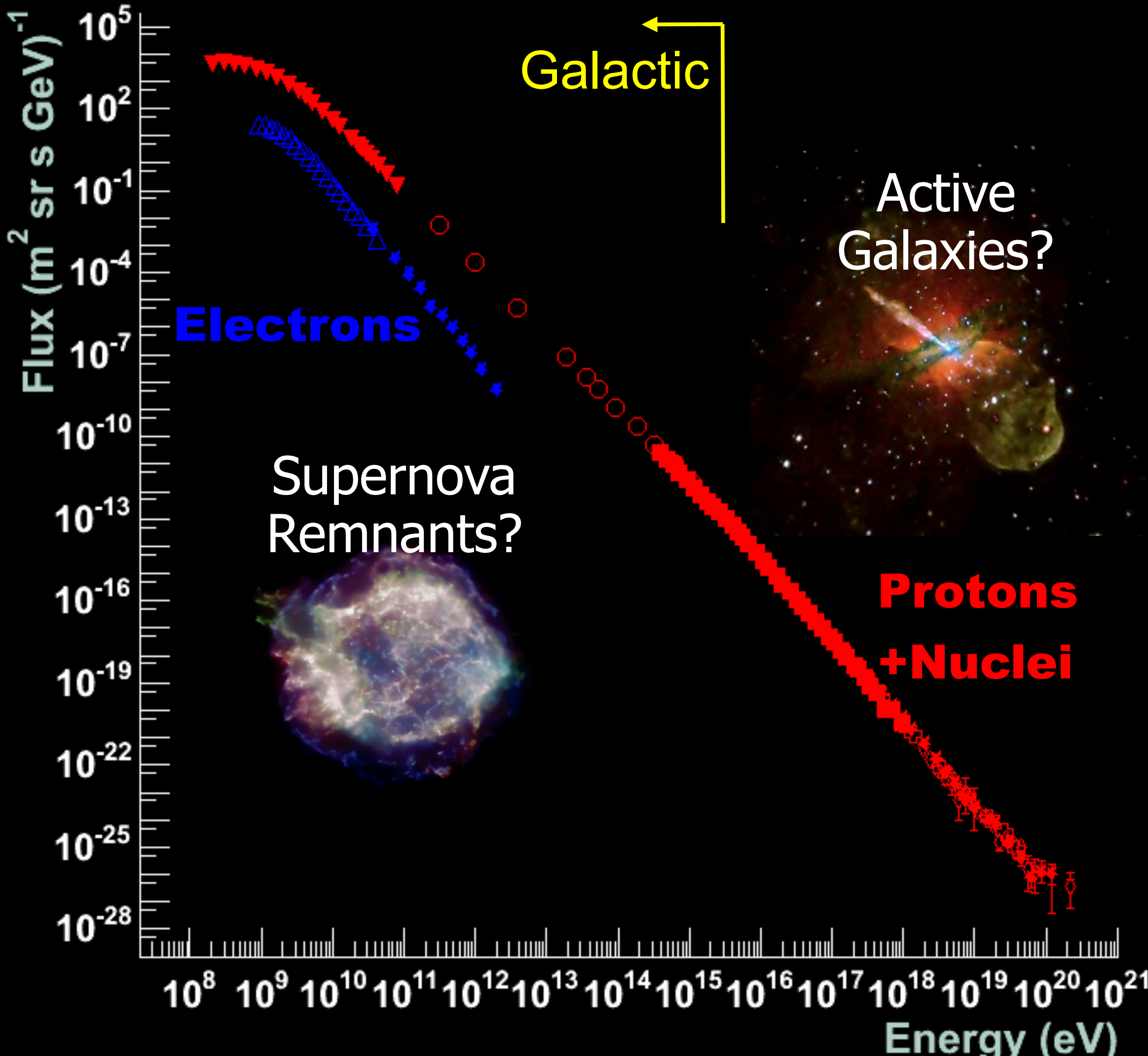
- EC framework programme 7 supported "Preparatory Phase" ends mid-2014
- An interim legal entity will be set up to support central project administration and site negotiations and development
- Transition to final entity "The CTA Observatory" in 2015-2016
- **Critical design review** late next year
- **Approval of construction funding** by agencies (hopefully!) in 2015

The CTA Project is seeking a

Senior Project Manager/ Technical Director

with outstanding management abilities, for overall management of the prepro-
duction phase and ideally later of the implementation of the CTA telescope array,
providing a solid basis for the final approval of the project by the funding agen-
cies, and ensuring that the instrument can be realized within a realistic schedule
and cost, meeting the required high standards for reliability and performance.

The Cosmic Rays



- Our galaxy is filled with ultra-relativistic particles
  - Energy density ~1 eV/cm^3 comparable to starlight, magnetic fields, turbulent motions of IS gas, CMBR...
  - 99% protons+nuclei
  - Galactic origin at least up to ~10^{15} eV – *sources?*

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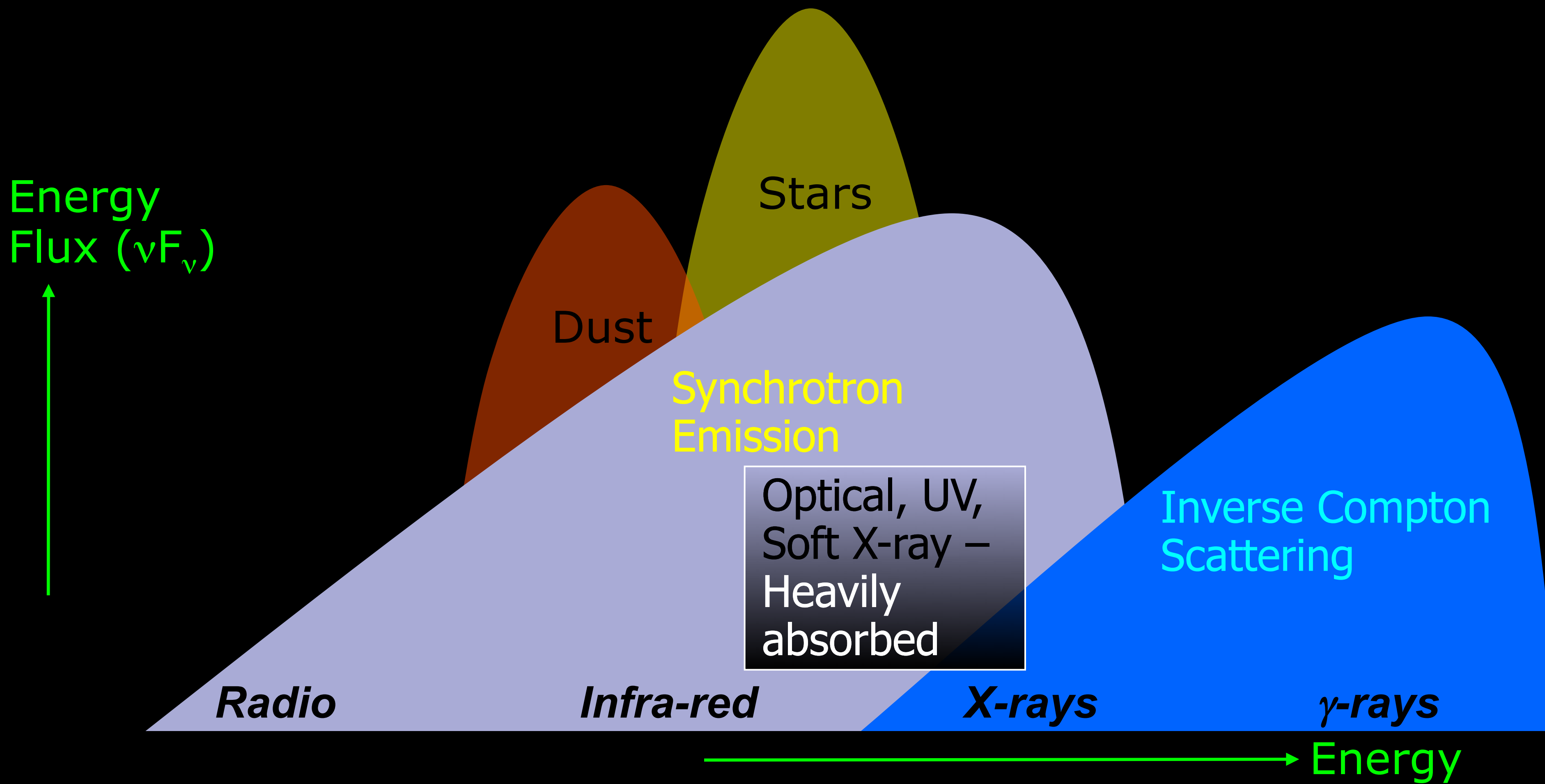
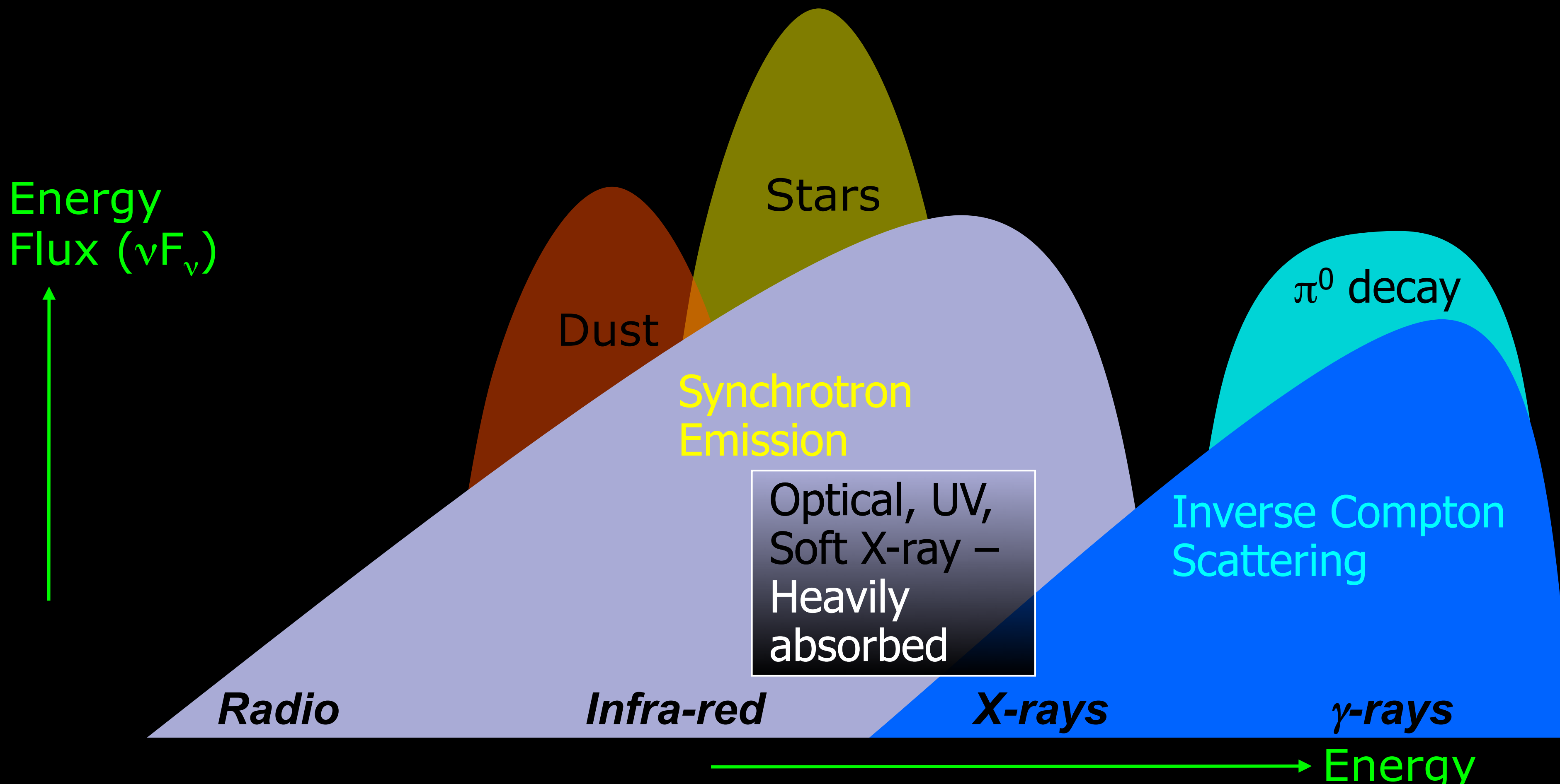
The Non-thermal Windows

- **Tracers for ultrarelativistic electrons**



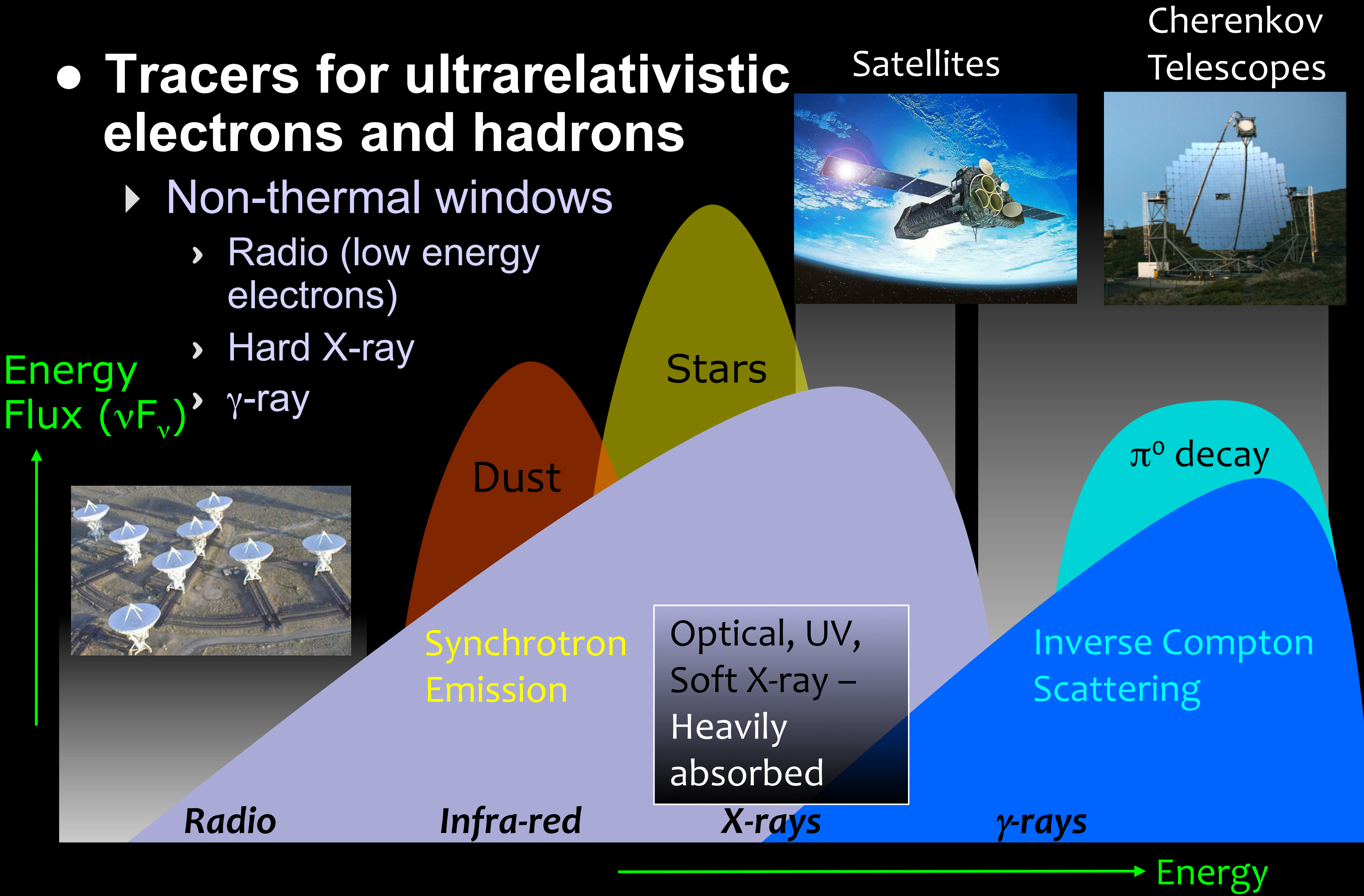
The Non-thermal Windows

- **Tracers for ultrarelativistic electrons and hadrons**



The Non-thermal Windows

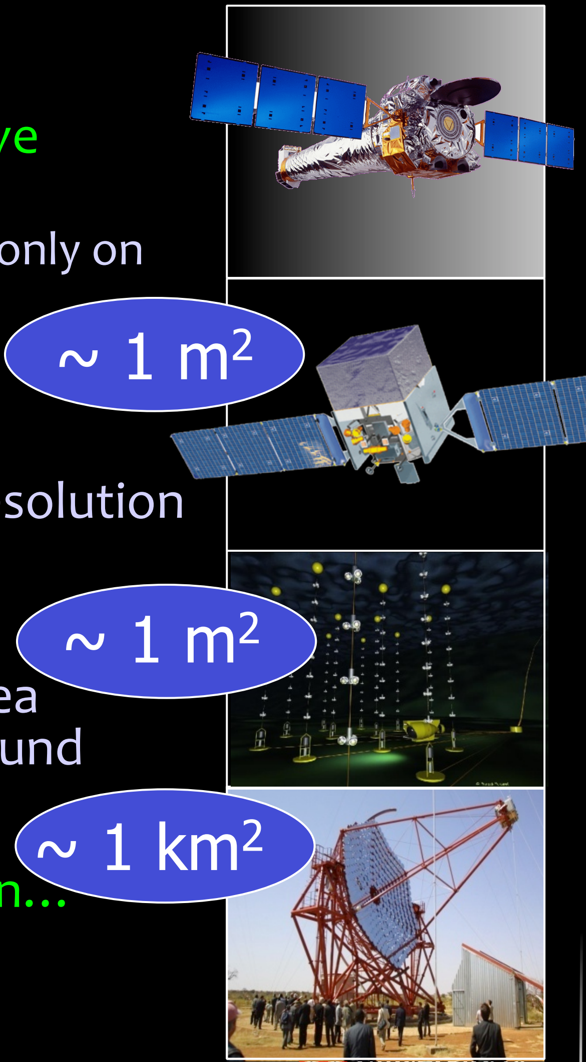
- **Tracers for ultrarelativistic electrons and hadrons**
  - Non-thermal windows
    - Radio (low energy electrons)
    - Hard X-ray
    - γ-ray



Comparison of Tracers

- X-rays
  - Soft X-rays still dominated by thermal emission
  - 2-10 keV band excellent resolution, very sensitive instruments
    - – but – Synchrotron emission gives information only on energetic electrons ($\times B^2$), usually small FoV
  - Hard X-ray detectors not yet as sensitive
- MeV-GeV γ-rays?
  - Hard to launch large detectors, poor angular resolution (< a few GeV), full sky coverage
- TeV Neutrinos?
  - Unambiguous, but small effective collection area (neutrino cross-section!), atmospheric background

TeV γ-rays?
  - Large detection areas, better angular resolution…



Combination of **<u>all</u>** is extremely powerful

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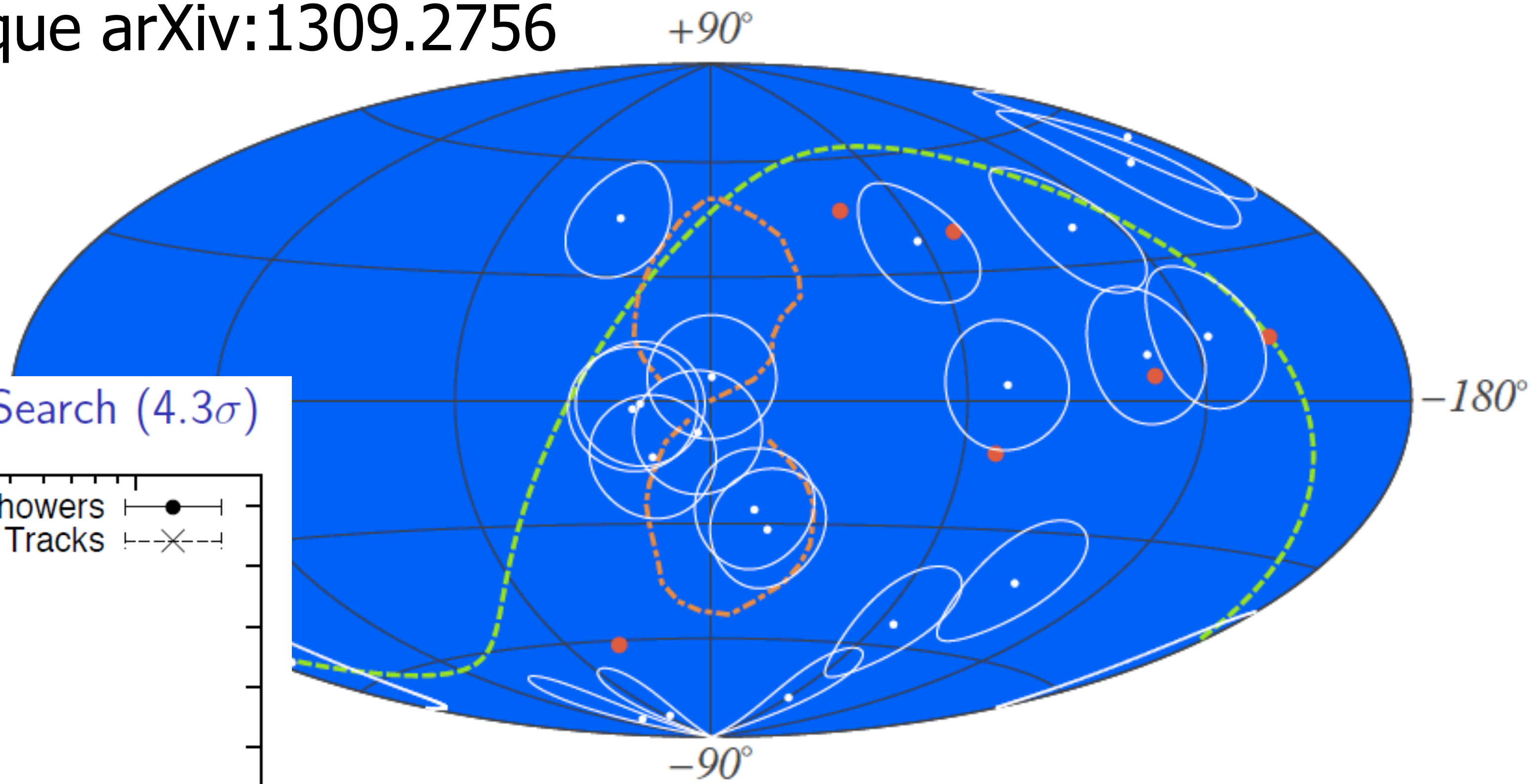
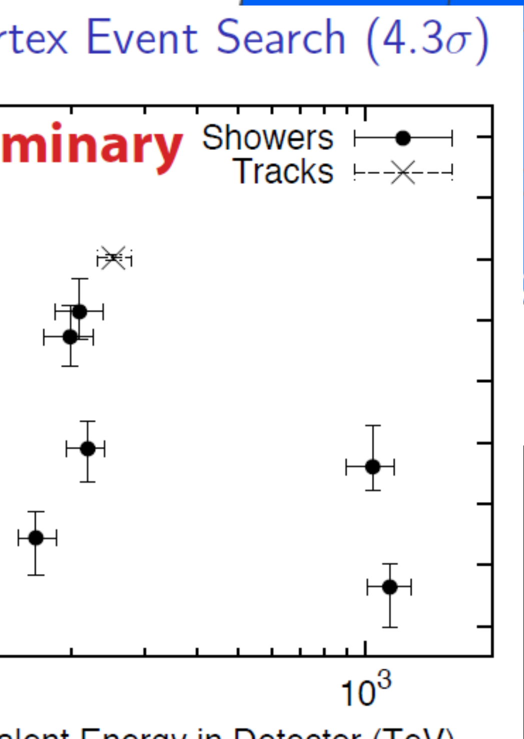
Razzarque arXiv:1309.2756





26 events 30-300 TeV (BG of 10.6)

Contents

- A big field – not much time
- Things that I am excited about:
  - PeV neutrinos!
    - The latest from IceCube
  - Gravitational waves!
    - Towards aLIGO
  - Cosmic antimatter!
    - AMS and Pamela
  - Dark Matter!
    - Direct measurements close in
  - Documentation!
    - And my personal role in the CTA project

UK Funding?

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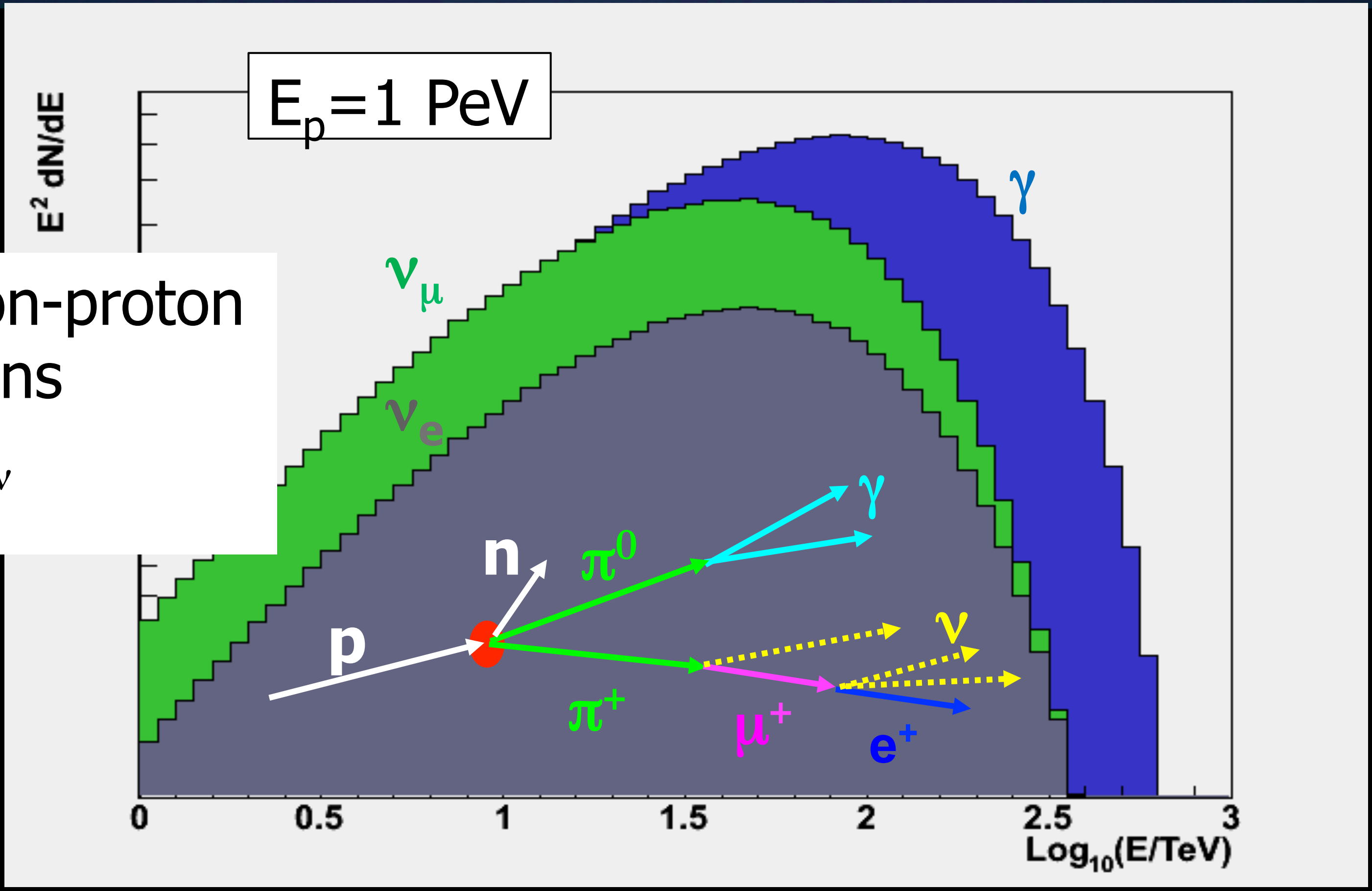
- Only for gravitational waves in previous programmatic review
- In the meantime – some R+D squeezed in:
  - Gamma-ray astronomy – CTA camera prototyping
  - Direct dark matter detection – several R&D projects
- PAAP input to this programmatic review:
  - Please support some diversity in particle astrophysics in the UK: strong community, strong track record, exciting science, lots of potential for technology development/ industrial involvement/KE
    - We will see what happens
  - Highest priorities: aLIGO, DM-1T, CTA

59 Interactions in Sources



e.g. proton-proton Interactions

$E_p : E_\gamma : E_\nu$

20 : 2 : 1

- Gamma+neutrino to identify parent particles
  - Removes ambiguity with IC scattering
  - Challenge – expect very few neutrino events/km^3.year

60 Focal Plane

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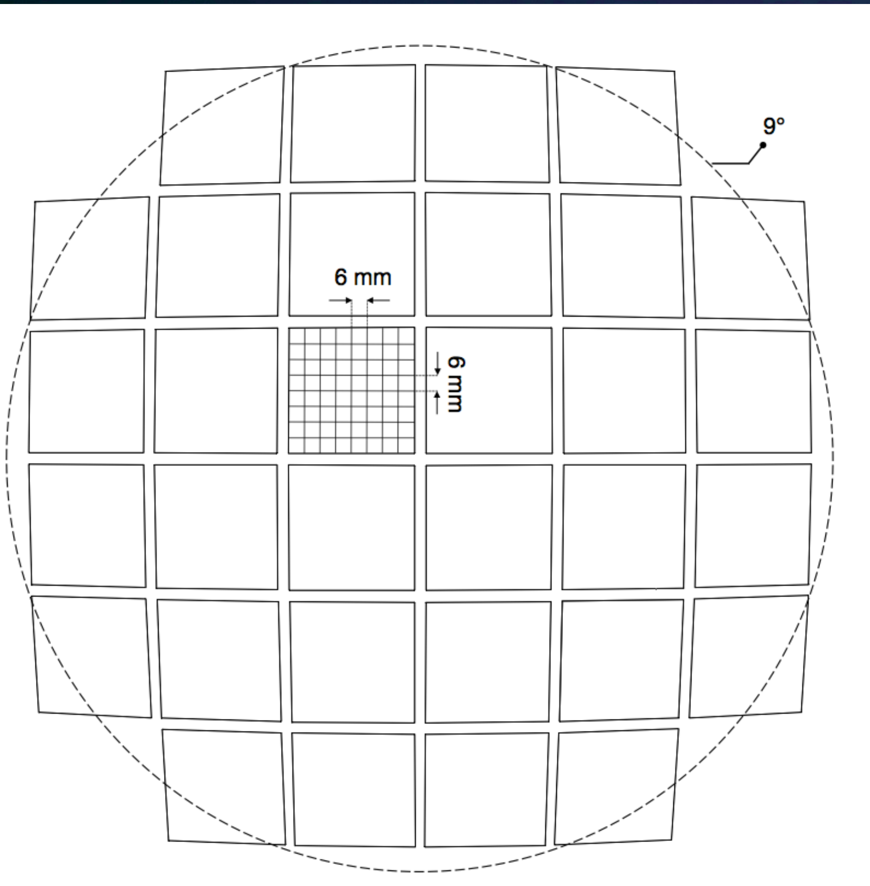

- 2048 pixels
- 0.17°
- 9° FoV (with ASTRI optics)
- 32 x 64 pixel modules

CHEC-M MAPMs

- Hamamatsu H10966
- 32 devices now in house