

The Cherenkov Telescope Array : A TeV Gamma-Ray Observatory

Gavin Rowell Uni. Adelaide (for CTA)



CosPA Meeting Sydney Nov. 2016

The Cherenkov Telescope Array



- Next generation gamma-ray observatory
- Huge improvement in all aspects of performance

x10 better sensitivity, better FoV + angular resolution, wider energy coverage, collection area >few km², wider survey capabilities

- User facility / proposal-driven observatory

CTA Consortium time (Key Science Projects) to lead off

- An international project ~ €300M capital cost

Involves >90% of current TeV gamma-ray scientists
+ many others

- EU ESFRI ranked project

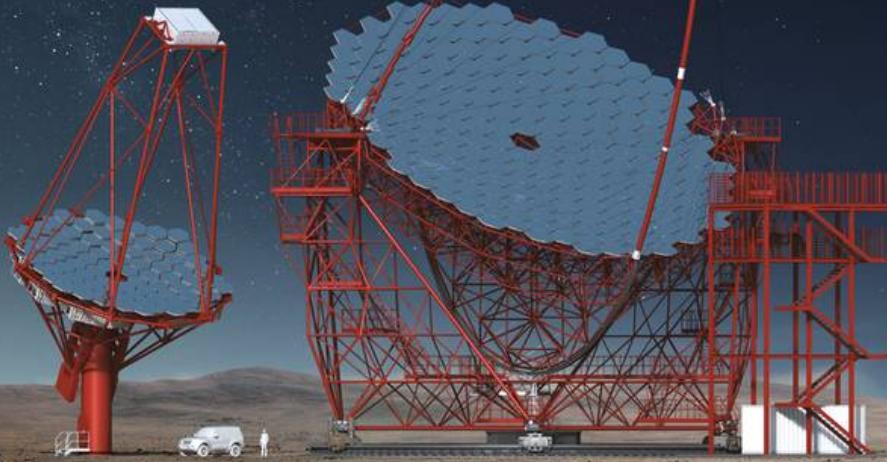




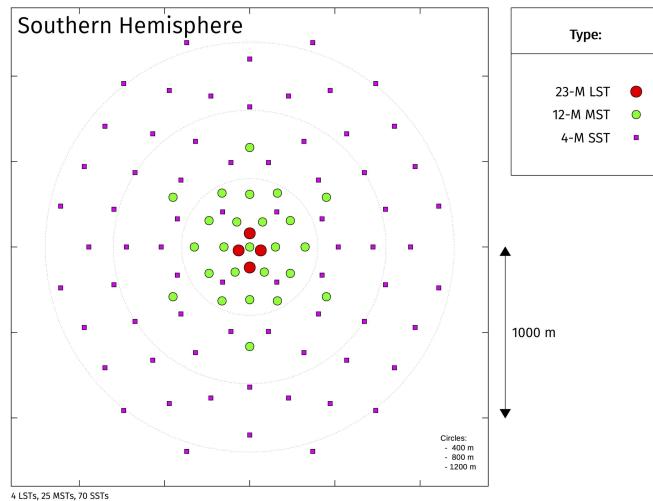
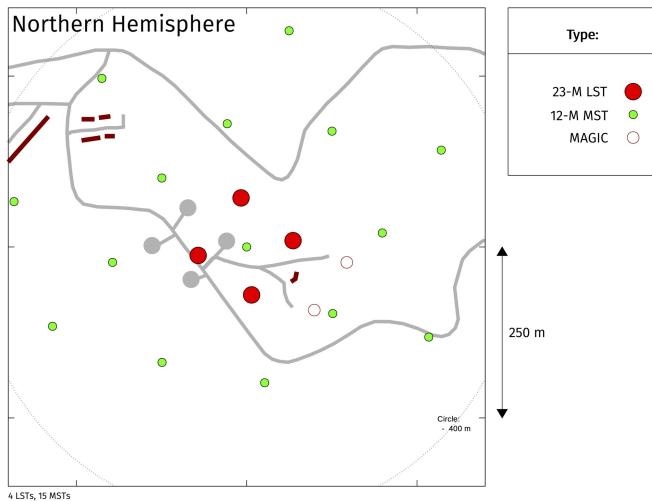
**Small Size
Telescope
SST (4m)**



**Medium Size
Telescope
MST (12m)**

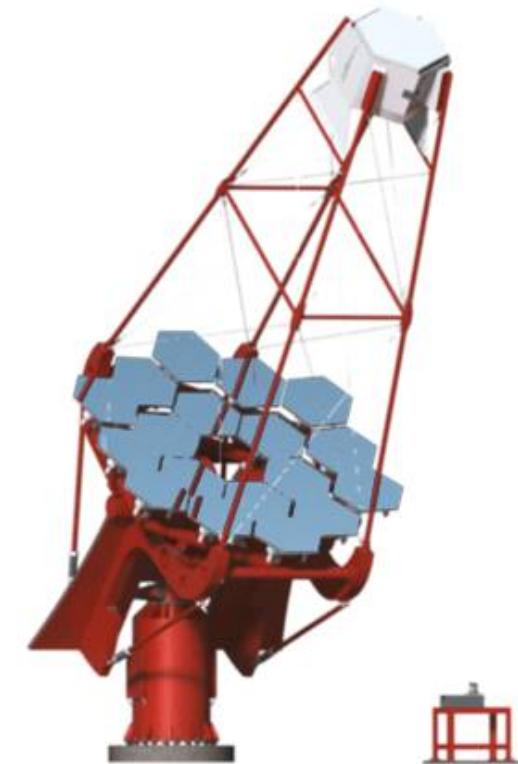


**Large Size
Telescope
LST (23m)**





Australia contributes funding
to the “GCT” SST





32 Countries
over 200 Institutes
over 1300 Members

CTA – Australia

U. Adelaide

G. Rowell, B. Dawson, R. Clay, P. Veitch, D. Ottaway, M. White, V. Stamatescu, L. Bowman, A. Malouf, N. Wild



UNSW

M. Burton, M. Ashley, C. Braiding, N. Maxted

WSU

M. Filipovic, N. Tothill



THE UNIVERSITY OF
NEW SOUTH WALES



ANU

G. Bicknell, R. Crocker, I. Seitenzahl

Monash

C. Balazs, D. Galloway

U. Syd

A. Green



WESTERN SYDNEY
UNIVERSITY



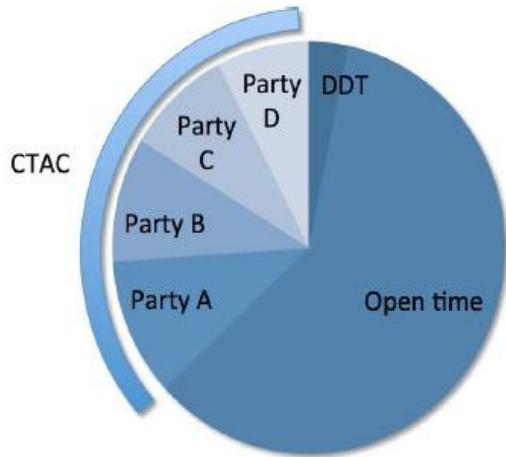
Funding

ARC LIEF 2015 + 2017-21
(hardware/commissioning/labour)

NCRIS/AAL (travel, meetings, CTAO membership)



CTA observing time

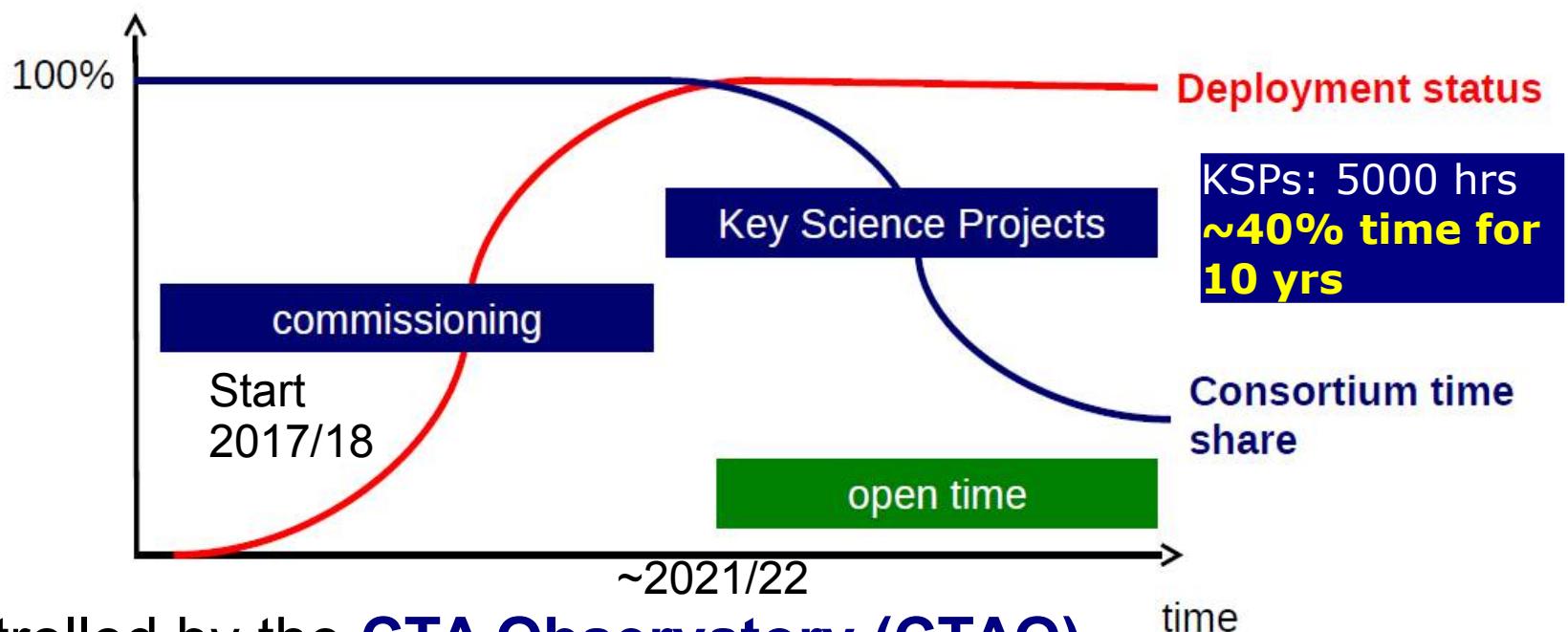


Current model

Contributing parties pool their time:

- Open time (accessible to scientists in contributing countries)
- CTA Consortium time (legacy Key Science Projects)
- Director's Discretionary Time

All data will become public to worldwide community after some proprietary period
(cf. C. Boisson)



Controlled by the **CTA Observatory (CTAO)**

Status (Nov. 2016) – Bologna meeting Oct

- Pre-production phase: towards 1st telescopes on site(s)
- Securing funding to prepare for full production phase:
'Implementation' funding threshold (62%) imminent
- Australia:
CTAC member
benefits → key science projects (40% time),
low level data, cutting-edge analysis
- CTAO member of CTAO Council
benefits → vote on governance/operating cost policies
- Governance policies maturing
(renewed MoUs, CTAO founding agreement underway)
- Strong and growing links with Australian astronomy
→ multi-messenger astronomy

GCT Prototype (Small Size Telescope) – Dec. 2015 Paris



Australia - LIEF 2015 + 2017-21 support for GCT hardware and commissioning.

Other prototypes.....

MST (Berlin)



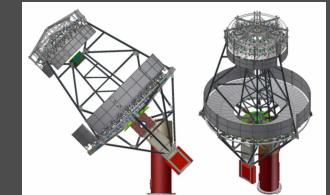
SST-2M ASTRI (Sicily)



SST-1M (Cracow)



SCT-MST (Arizona)



CTA sites selected 16 July 2015

Ground breaking Oct. 9, 2015



San Pedro
Mártir,
Mexico

La Palma, Canary
Islands, Spain

Northern
Hemisphere

Southern
Hemisphere

Paranal,
Chile

Aar, Namibia

- Chosen sites
- Backup sites

13 June 2016 - CTA HQ (Bologna)

- CTA Data Management Centre (DESY Berlin)

LST prototype status (La Palma)



cherenkov
telescope
array

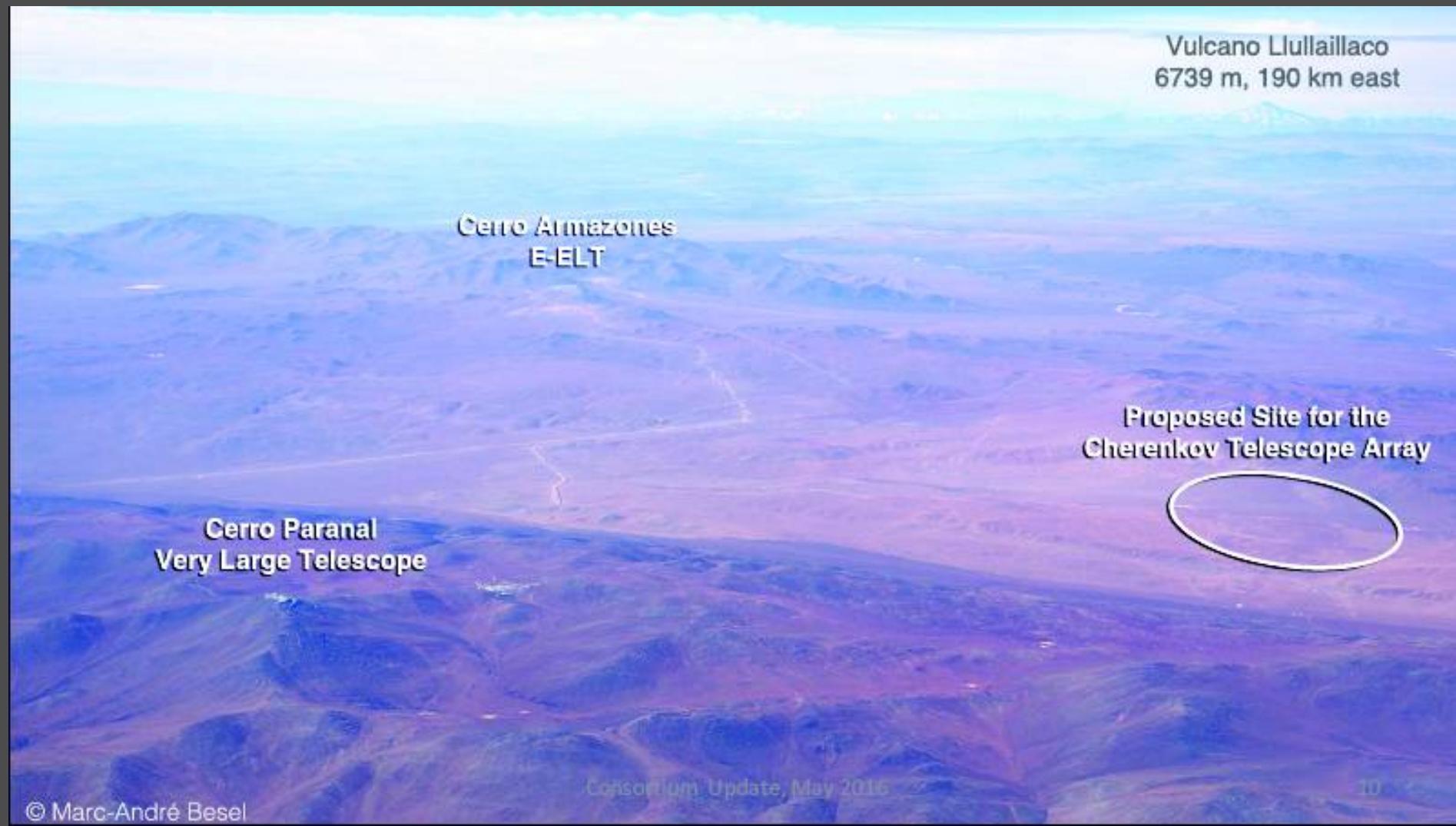
Oct 2016

D. Mazin



@Daniel Mazin

CTA South : Paranal, Chile



Negotiations with ESO ongoing: Infrastructure sharing/piggyback



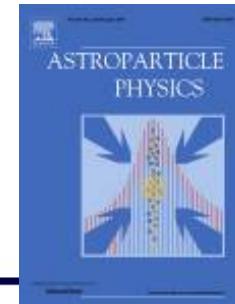
13 June 2016

CTA Headquarters
Bologna
**Part of new Bologna
University/INAF building**



**Data Management
Centre**
**DESY Zeuthen Campus
New building**

KEY SCIENCE PROJECTS



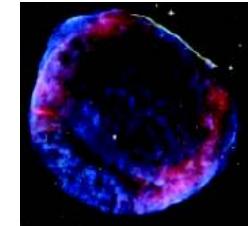
Special
Issue Vol
43, Pg 1-
356 (Mar
2013)



- Galactic Plane Survey
- Galactic Centre Survey
- Large Magellanic Cloud Survey
- Extragalactic Survey
- Transients
- Cosmic-Ray PeVatrons
- Star-Forming Systems
- Active Galactic Nuclei
- Clusters of Galaxies
- Dark Matter
- Non-Gamma-Ray Science
 - intensity interferometry
 - fast optical transients – milli-magnitude
 - occultations (Kuiper belt population..)

Three Themes

1. Cosmic Particle Acceleration



2. Probing Extreme Environments



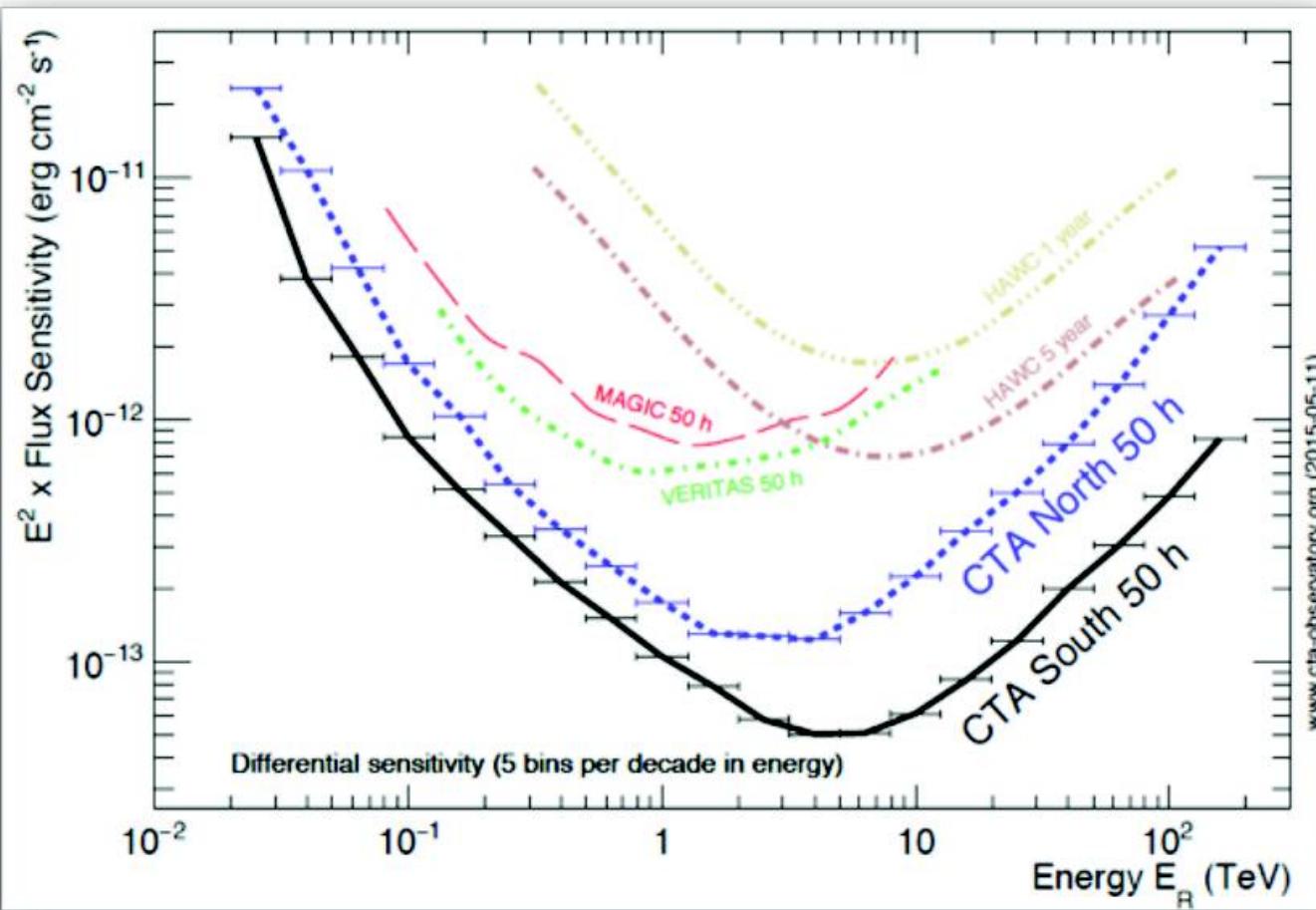
3. Physics Frontiers:
Beyond Standard Model



CTA Performance

Energy coverage ~20 GeV to >200 TeV

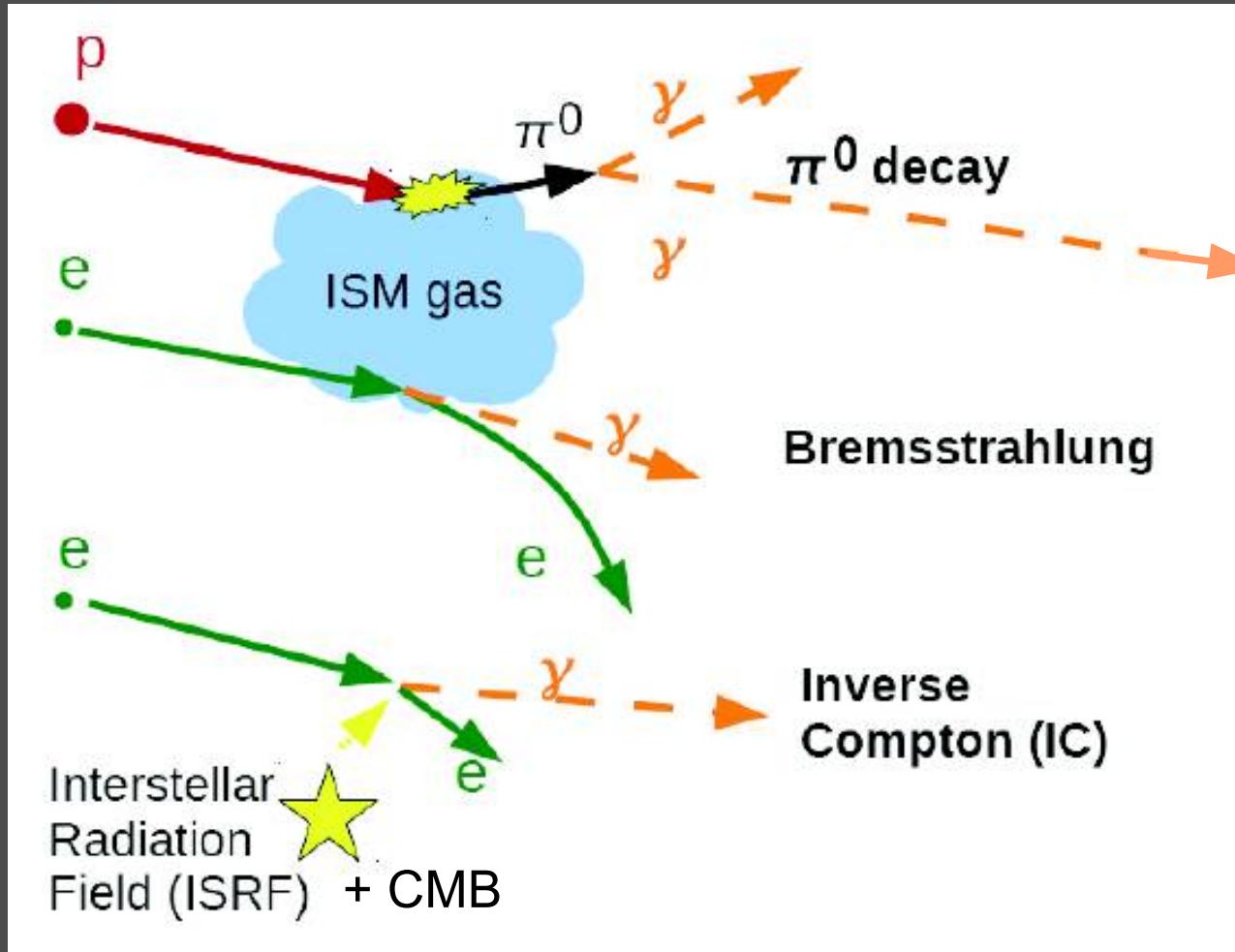
Differential Sensitivity



A factor of 5-10 improvement in sensitivity in the domain of about 100 GeV to some 10 TeV.

Extension of the accessible energy range from well below 100 GeV to above 100 TeV.

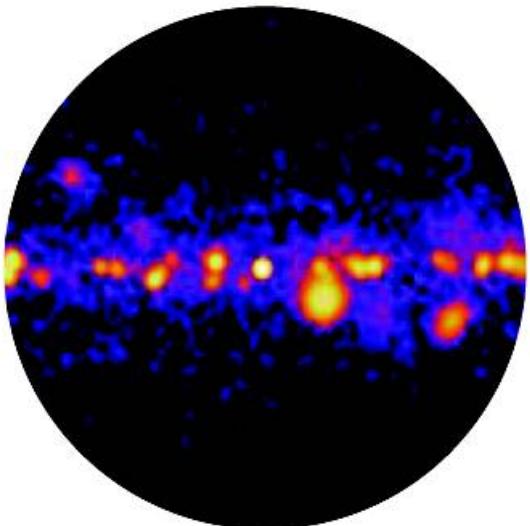
Gamma Rays from multi-TeV particles



Protons: Gamma-rays and gas targets are generally spatially correlated
(need to map atomic and molecular ISM → mm radio astronomy)

Electrons: Gamma-ray (IC) + non-thermal X-ray, radio emission (synchrotron)
highly coupled

The Galactic Plane Survey



Credits: The CTA Consortium

CTA will carry out a **survey of the full Galactic plane** using both the southern and northern CTA observatories.

The Survey will provide a **complete and systematic view of the Galaxy** to facilitate our understanding of Galactic source populations and diffuse emission, and a **comprehensive data-set and catalogue**.

The CTA GPS will be a factor of 5 – 20 more sensitive than surveys carried out by earlier or existing atmospheric Cherenkov telescopes.

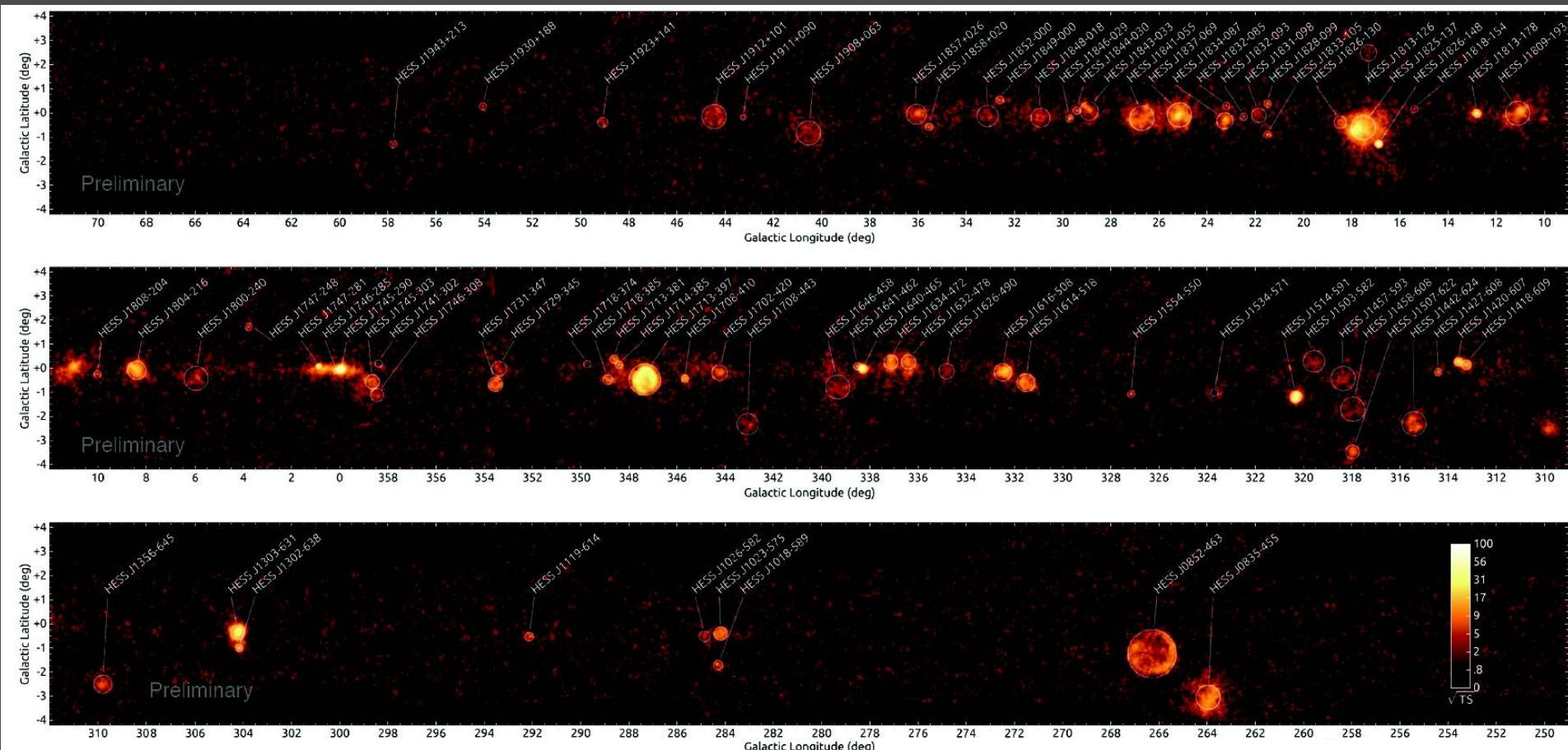
→ **300 to 500 new sources!**

In the Northern Hemisphere, the CTA will complement/extend observations made by HAWC. **CTA will go deeper by a factor of 5 – 10 compared to HAWC**, at much lower energy and with substantially better angular resolution.

HESS Galactic Plane Survey (HGPS) – Skymaps

Deil et al 2015

→ 77 sources (13 new sources)



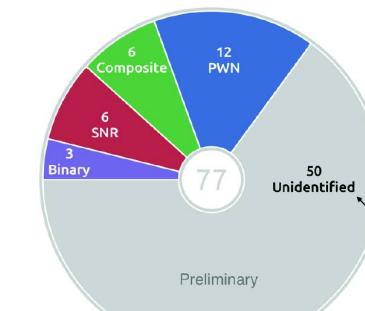
12 – pulsar wind nebulae

6 – SNRs

6 – composite SNRs

3 – binary (NS/BH + star)

50 – unidentified (confused associations) incl. GC region

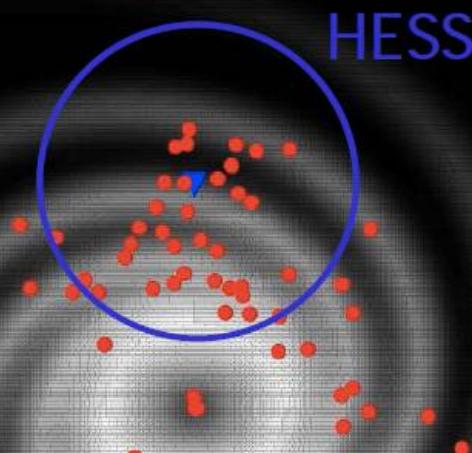


CTA Galactic Science



- e.g. Galactic objects
 - Newly born pulsars and the supernova remnants
 - have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects
 - CTA will see **whole** Galaxy
- Survey speed
 $\sim 300 \times$ HESS

Current Galactic VHE sources (with distance estimates)



CTA

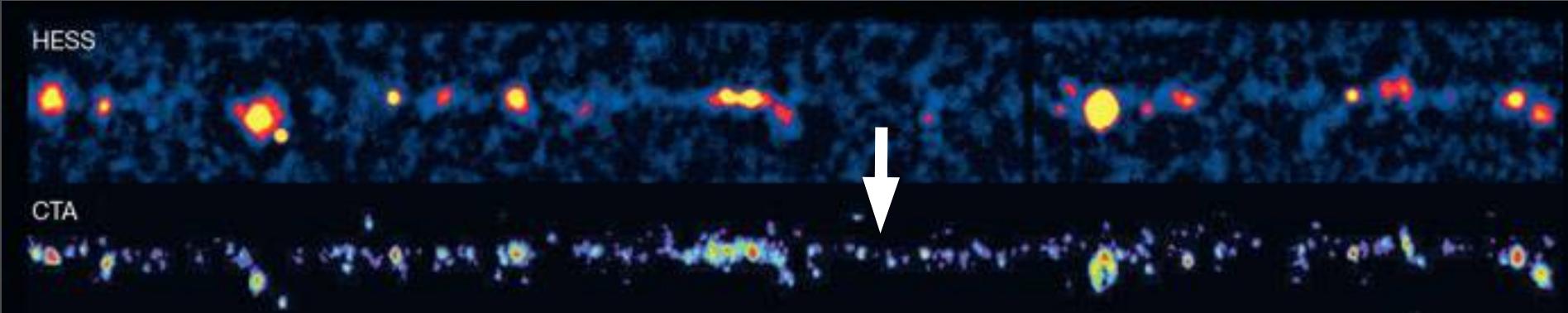
Free-escape
boundary

Forward Shock

ISM Clouds

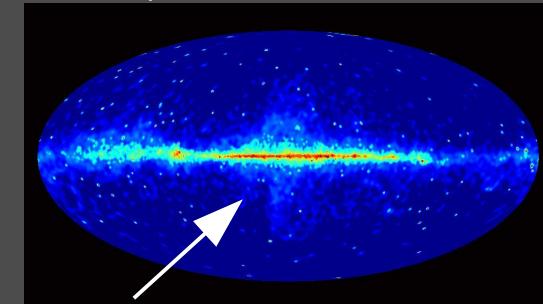
*Runaway
CRs*

CTA Galactic Plane TeV Surveys : Major Issue



Funk et al 2012

- CTA will provide Galactic Plane TeV Gamma-ray maps at ~arc-min scales
(sub-arc-min possible – with high quality cuts)
- >3 sources per deg^2 $|b|<0.2^\circ$ $|\ell|<30^\circ$ (Dubus et al 2013)
- Diffuse TeV components visible?
from CR 'sea' – maybe
local CR accelerator enhancements – yes

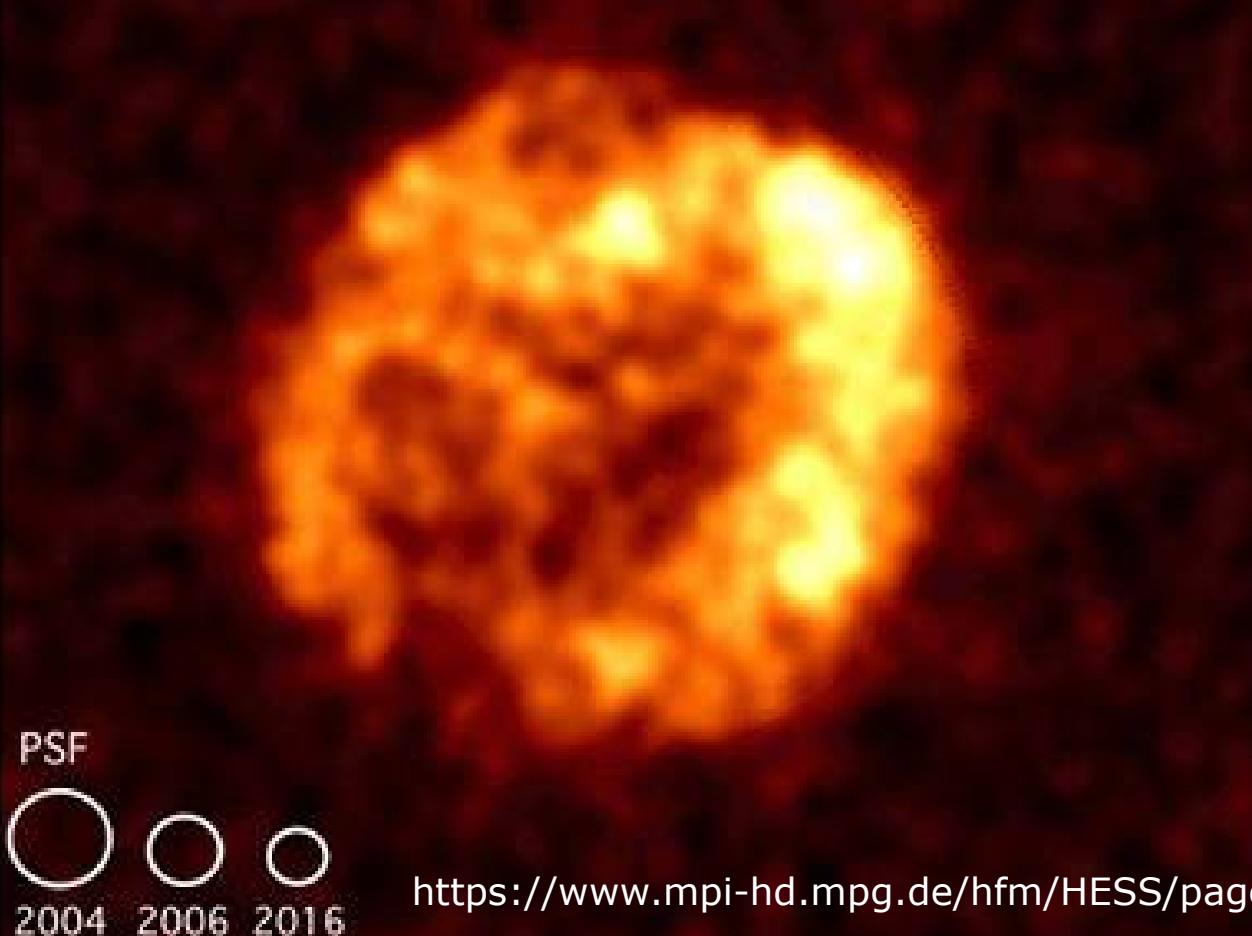


Confusion guaranteed (same as for Fermi-LAT at GeV energies!)

- *Mapping the ISM on arc-min scales over the plane will be essential*
Mopra (CO, CS), Nanten2 (CO), ASKAP (HI, OH), THz (CI, C+)

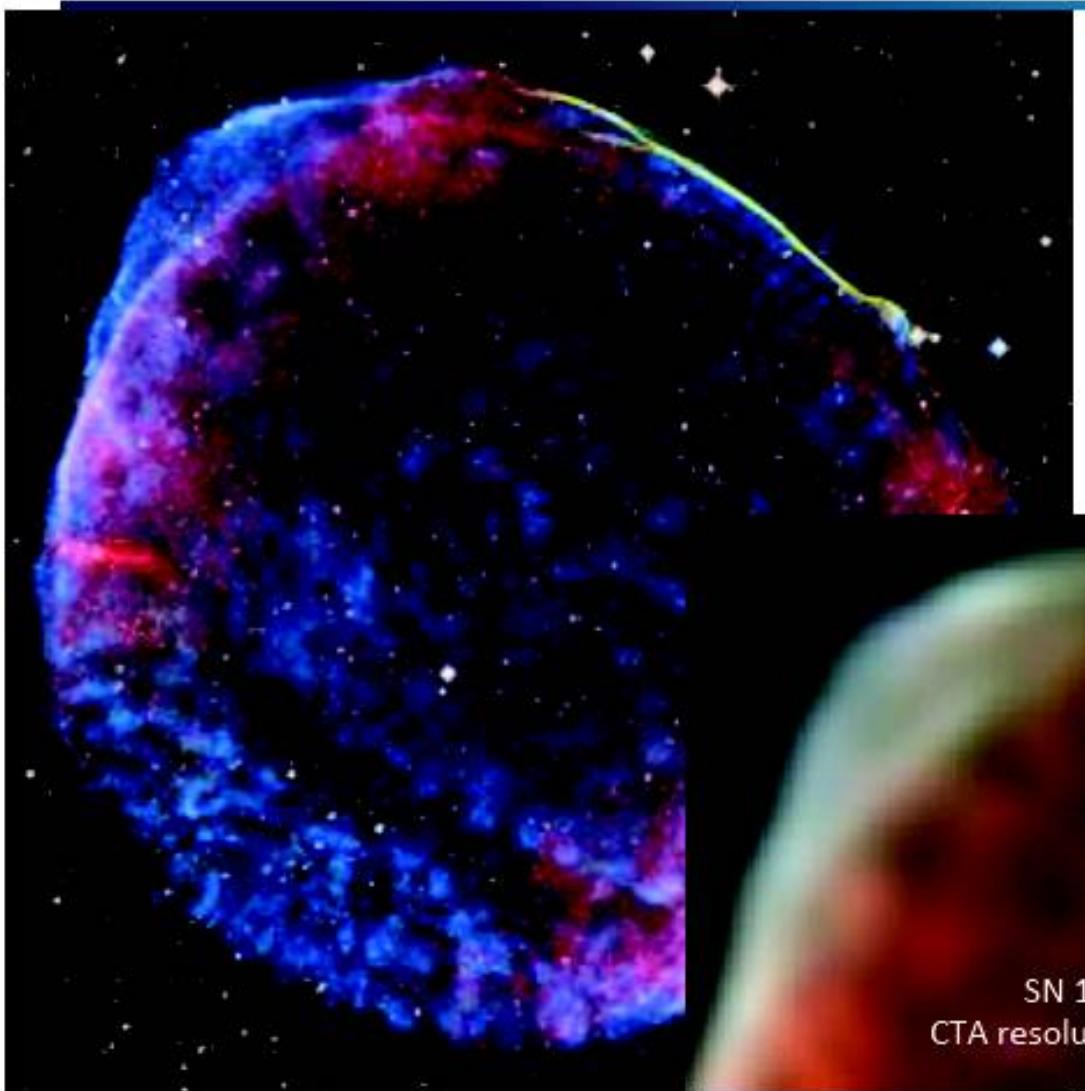
H.E.S.S. RX J1713.7-3946

**The sharpest gamma-ray image so far!
PSF (68%) ~ 2 arcmin (FWHM ~ 5 arcmin)**
HESS Collab. arXiv:1609.08671



Year	2016
Live-time	164h
Energy	> 0.25 TeV
PSF (R_{68})	2.9 arcmin
γ 's	31,000

Angular resolution



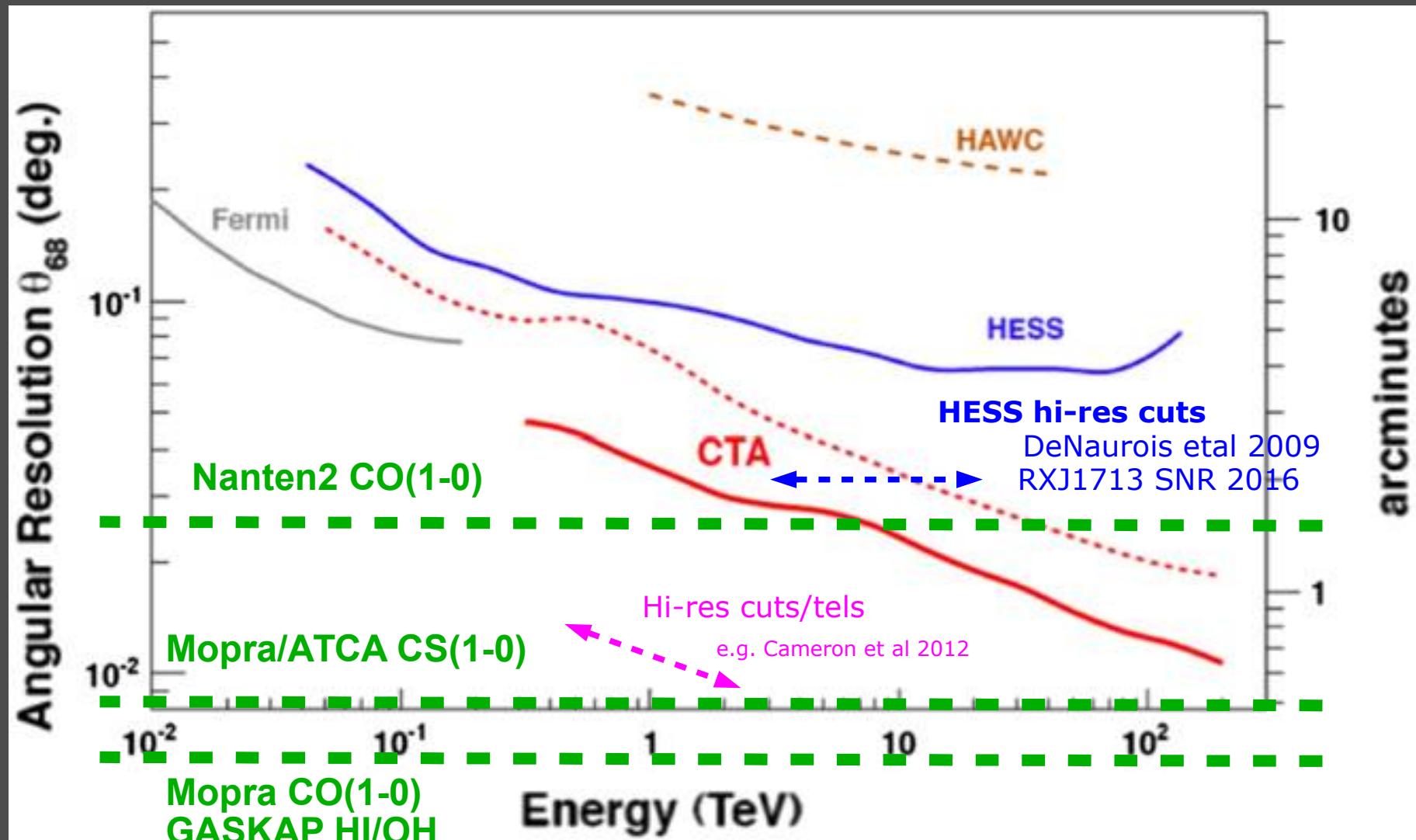
Towards 1 arc-min
(68% PSF) and better

→ Imaging of shocks!



Angular Resolution 68% PSF (HESS, CTA..)

Acharyara et al 2013



Beam Sizes 68% containment radius

Interstellar gas tracers & telescopes..

www.atnf.csiro.au/research/HI/sgps

HI (atomic H), OH, CS

Gas density

$\sim 10^1$ to 4 cm^{-3}

ATCA



Parkes



ASKAP-
GASKAP



CO

$\sim 10^3 \text{ cm}^{-3}$



HEAT – THz (Antarctica)
[CI] + [CII]

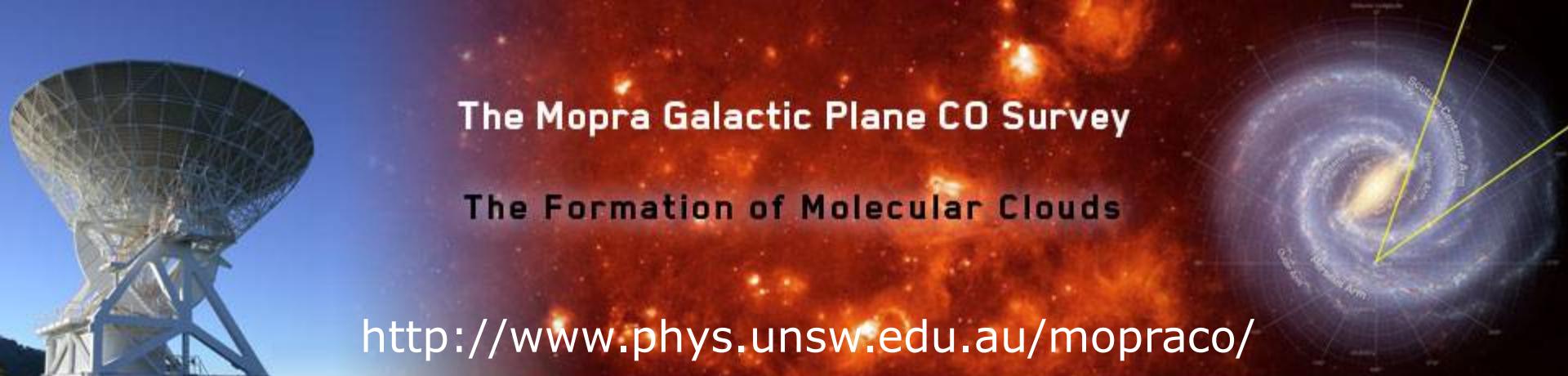


CO, NH₃, CS, SiO...

$> 10^3$ to 4 cm^{-3}

Mopra Telescope





The Mopra Galactic Plane CO Survey

The Formation of Molecular Clouds

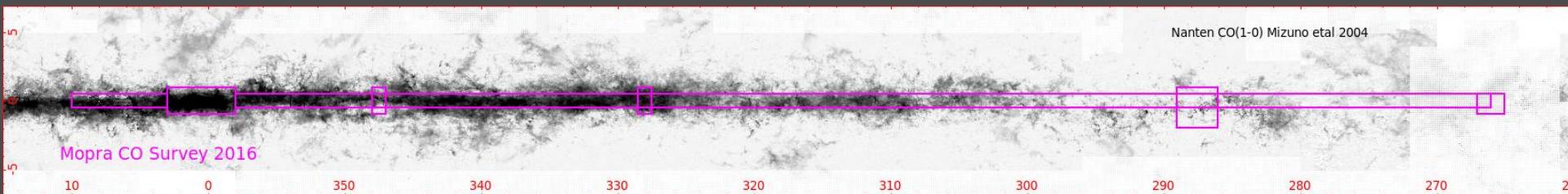
<http://www.phys.unsw.edu.au/moprac/>

35" beam @ ~0.1 km/s resolution (also 70" CO survey Barnes et al 2015)

CO(1-0), ^{13}CO (1-0), C ^{17}O (1-0), C ^{18}O (1-0)

$|l| = 265$ to 358 ; $b = \pm 0.5\text{deg}$ mostly complete

extension to $\pm 1.0\text{deg}$ $|l|=2$ to 10deg (compare to Dame et al 2000 ~8arcmin beam)



Data cubes publicly available once processed

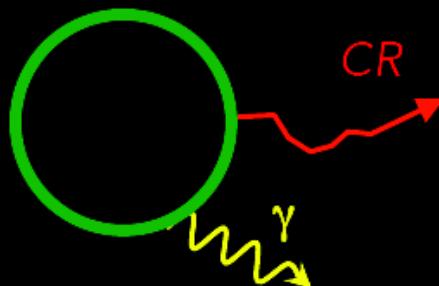
$|l| = 320$ – 330 deg available now

Complementary to Nanten2 CO (+ThruMMs) surveys over wider area
& Nobeyama CO survey (20" beam) in the north (Nishimura et al 2015)
& GASKAP HI/OH, VLA-THOR HI

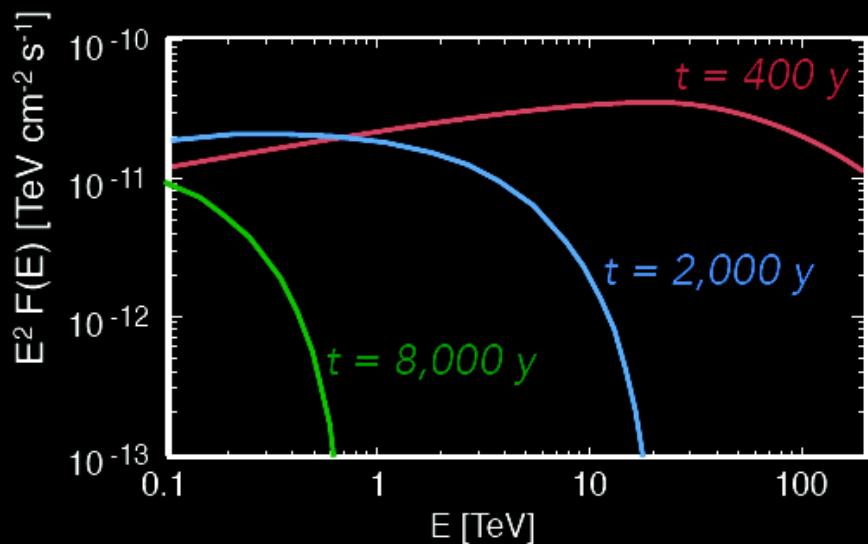
Gamma-ray spectra from local and escaped CRs

e.g. Aharonian & Atoyan 1996

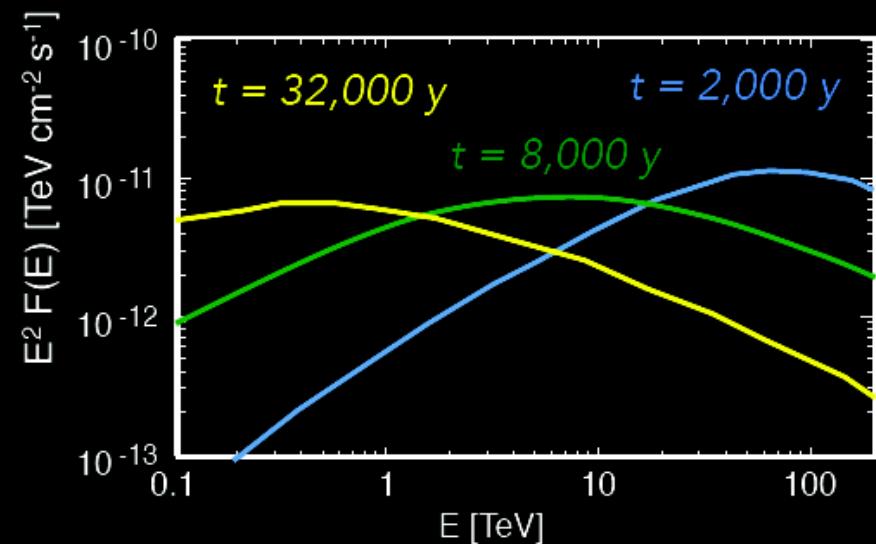
Source



Molecular Cloud
@100 pc

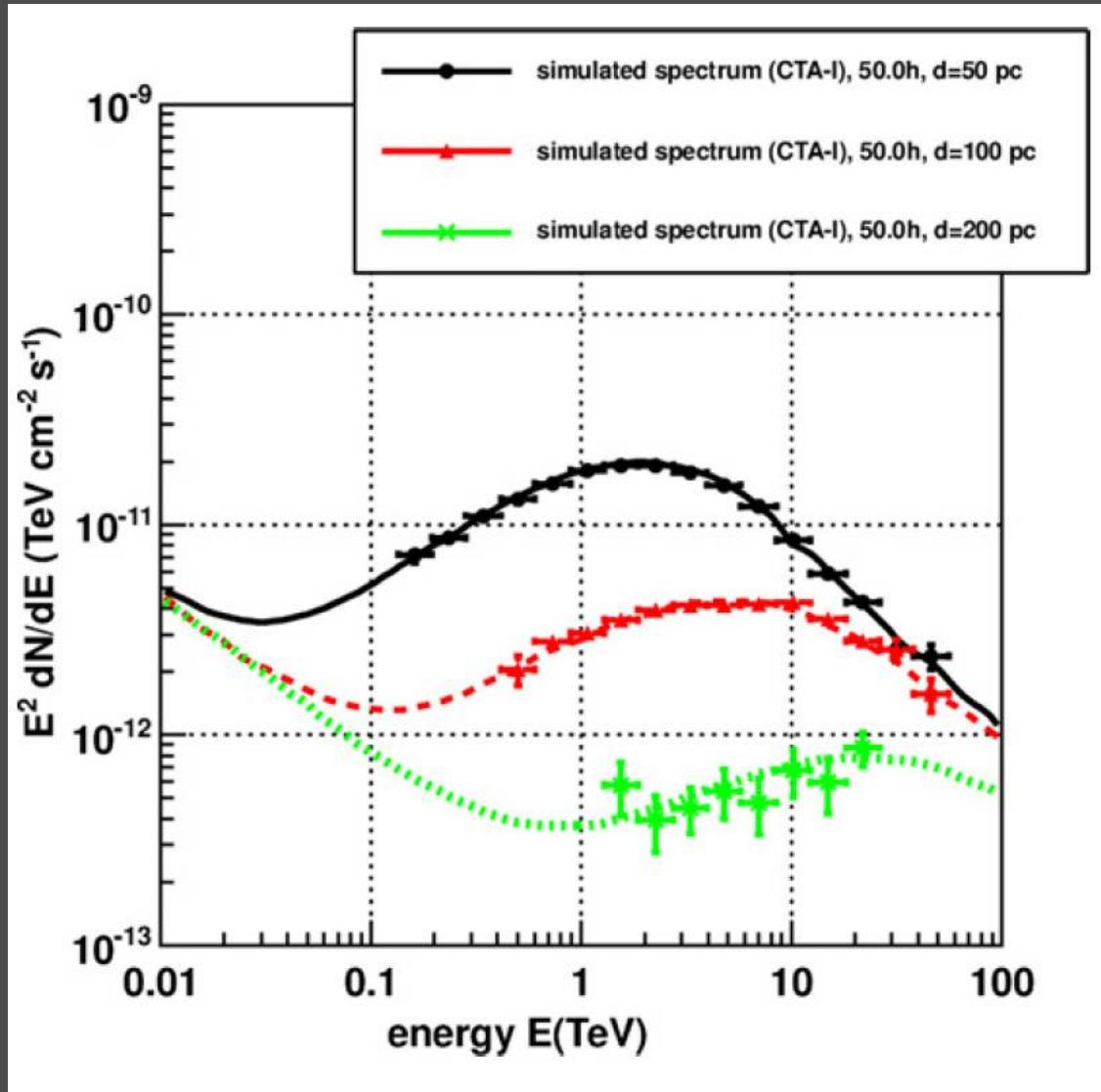


From Gabici & Aharonian (2007)



Slide from Richard White

CTA 50h Observation - CRs escaping accelerators Acero et al 2013



SNR age 2000 yr

Cloud mass $10^5 M_{\text{sun}}$

d = 1 kpc

$D = 10^{28} (E/10\text{GeV})^{0.5} \text{ cm}^2/\text{s}$

PeV CRs escape first and arrive at the cloud first!

Probe for CR PeVatrons

But confusion guaranteed in Gal. Plane!

Need wide ISM surveys
→ Mopra, Nanten2,
Nobeyma, ASKAP (S&N)

CR diffusion – not necessarily Isotropic!

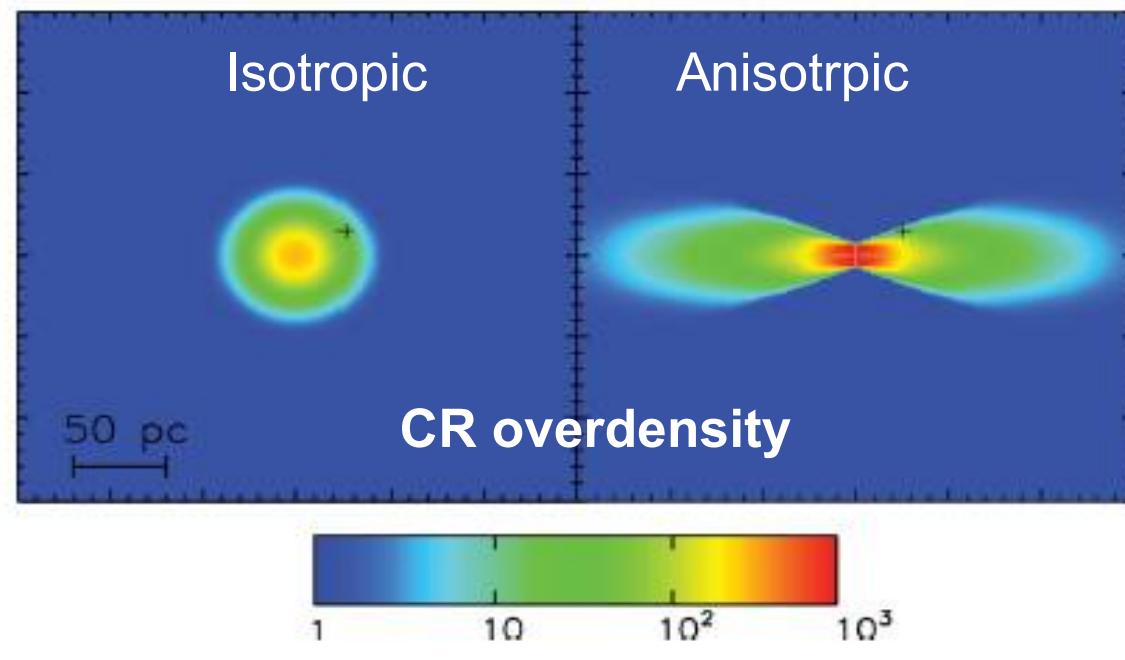
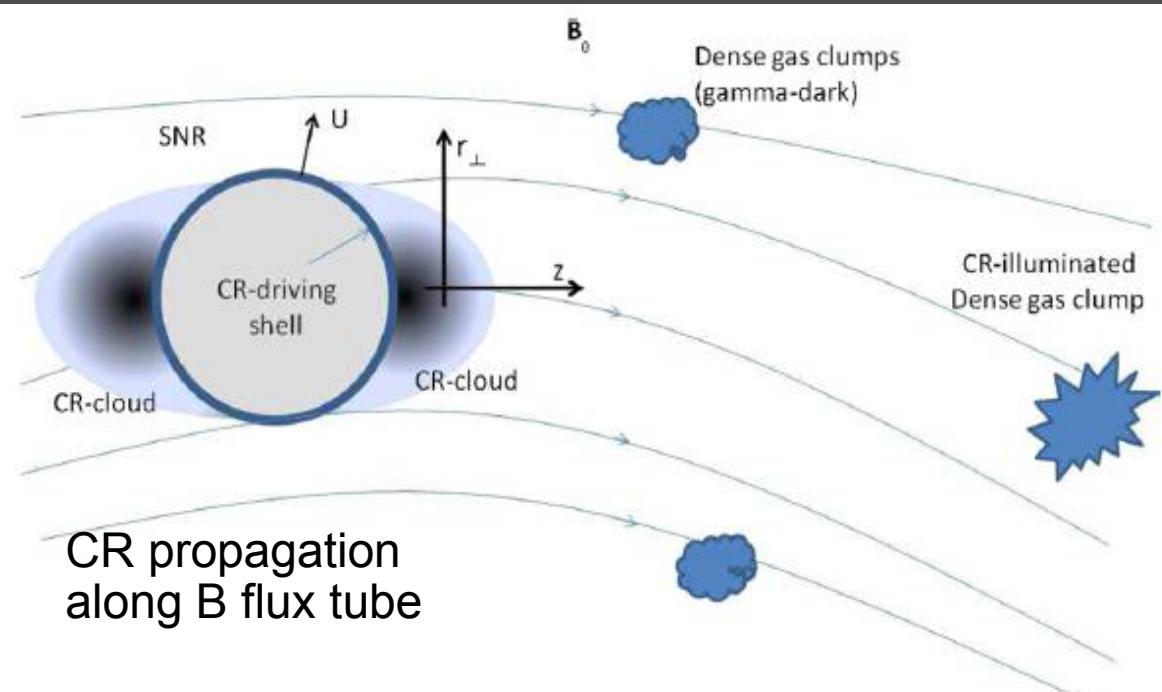
Malkov et al 2013
Nava & Gabici 2013

→ Nearby clouds will see different CR densities

→ Need detailed maps of ISM gas + B-field direction

B-field Faraday RM
Jansson & Fararr et al 2012

→ ASKAP POSSUM!



CR Diffusion *Into* Molecular Clouds

R = distance CR travels into molecular cloud core

e.g. Gabici et al 2007,
Inoue et al 2012

$$R \sim \sqrt{6 D(E_p, B) t}$$

10 TeV proton

1 TeV proton

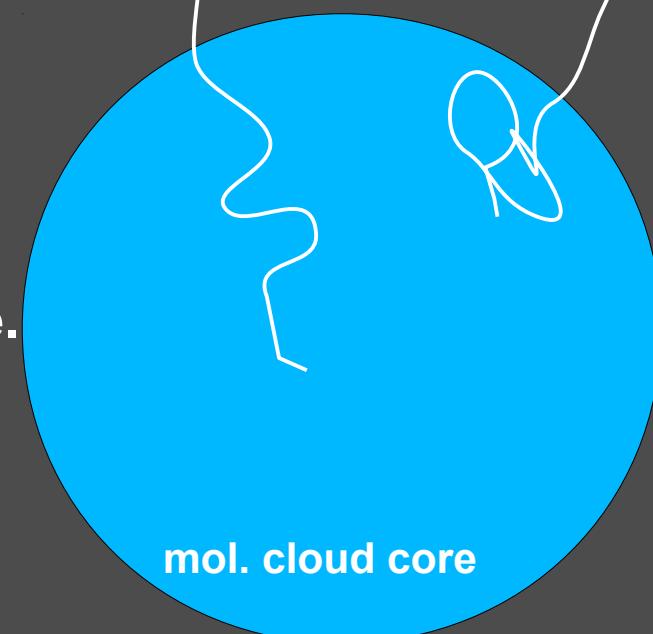
$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\text{GeV}}{B/3\mu\text{G}} \right)^{0.5} [\text{cm}^2 \text{s}^{-1}],$$

$$B \sim 10(n / 300\text{cm}^{-3})^{0.65} \mu\text{G}$$

Crutcher 2010

χ =diffusion suppression factor

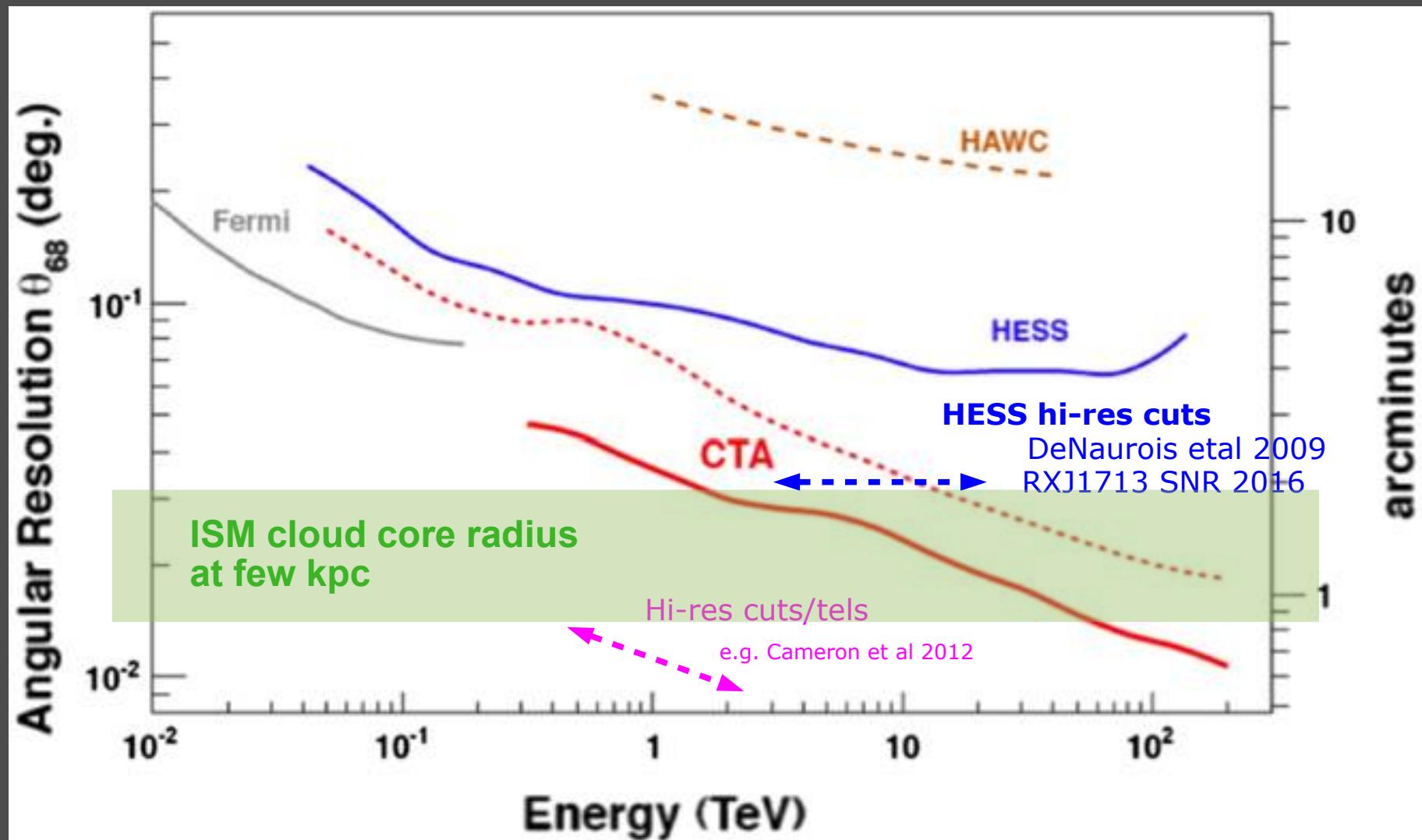
- Low energy CRs can't reach cloud core.
- Harder TeV spectra from cores.
- Depends on B-turbulence
(e.g. Morlino & Gabici 2015)
- ***Don't expect electrons to penetrate!!***
(due to sync. losses)



→ Need to map dense cloud cores ~1 arcmin or better

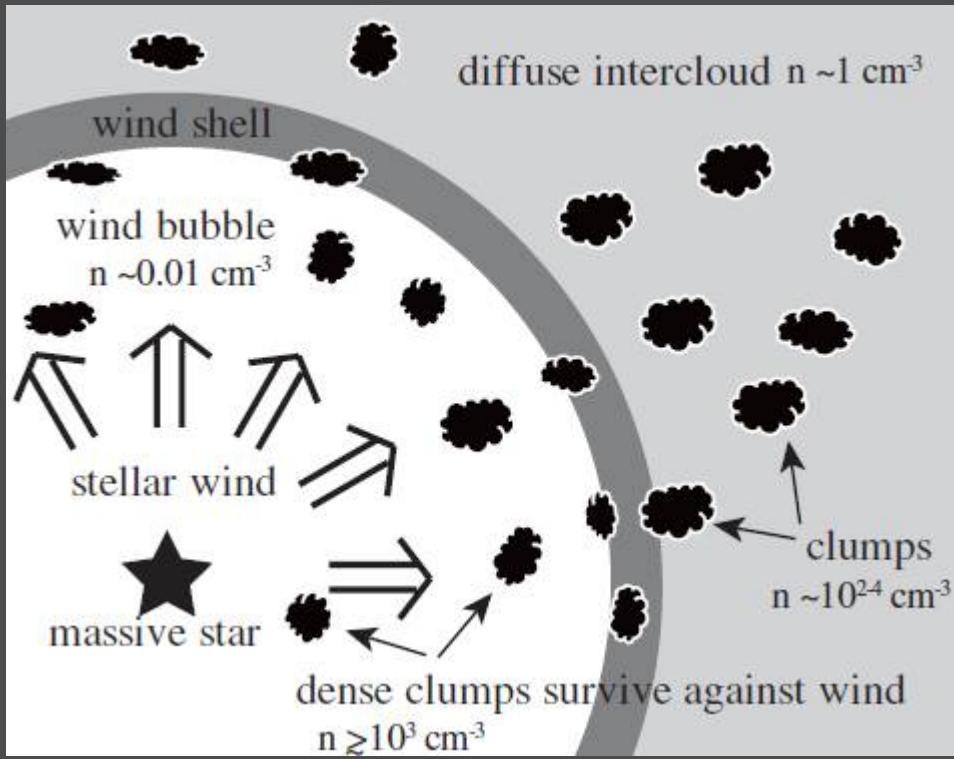
Angular Resolution 68% PSF (HESS, CTA..)

Acharyara et al 2013



Hadronic Gamma-Rays from Clumpy ISM SNR RXJ1713

Inoue et al. 2012



CR penetration depth

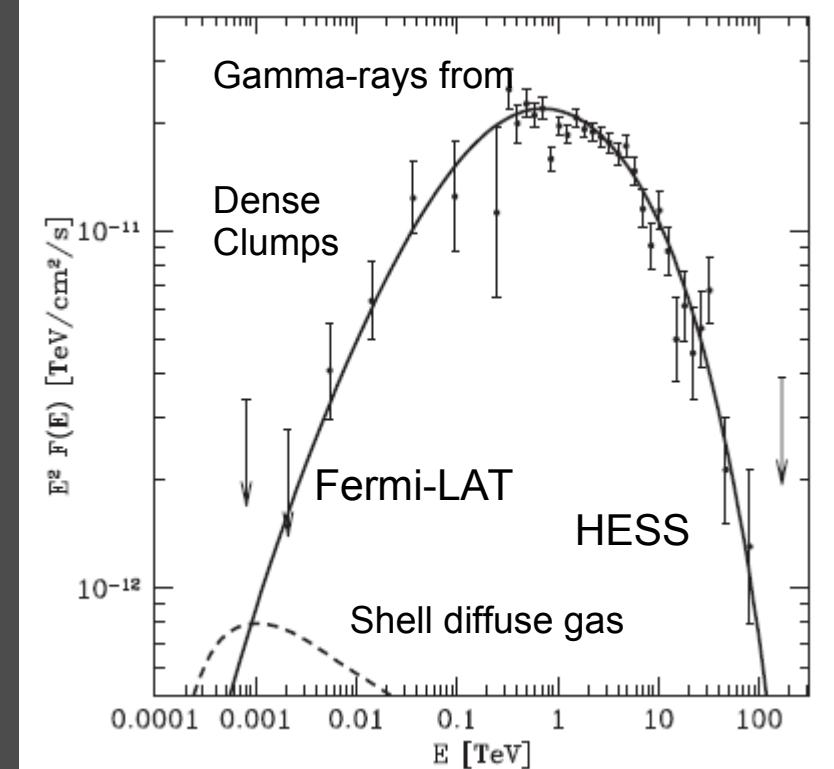
$$l_{pd} \simeq (\kappa_d t)^{1/2}$$

$$= 0.1 \eta^{1/2} \left(\frac{E}{10 \text{ TeV}} \right)^{1/2} \left(\frac{B}{100 \mu\text{G}} \right)^{-1/2} \left(\frac{t_{\text{age}}}{10^3 \text{ yr}} \right)^{1/2} \text{ pc}$$

$$\eta = B^2 / \delta B^2$$

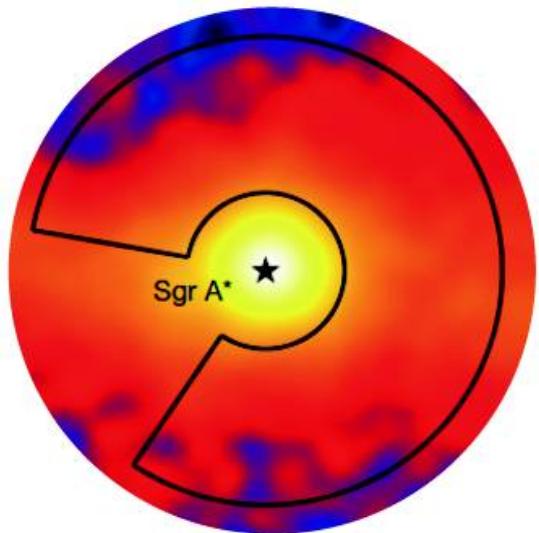
$$\kappa_d = 4 \eta l_g c / 3\pi \text{ (Skilling 1975)}$$

Gabici & Aharonian 2014



→ **Dense clouds/clumps could play critical role in hadronic component**

Cosmic-ray PeVatrons



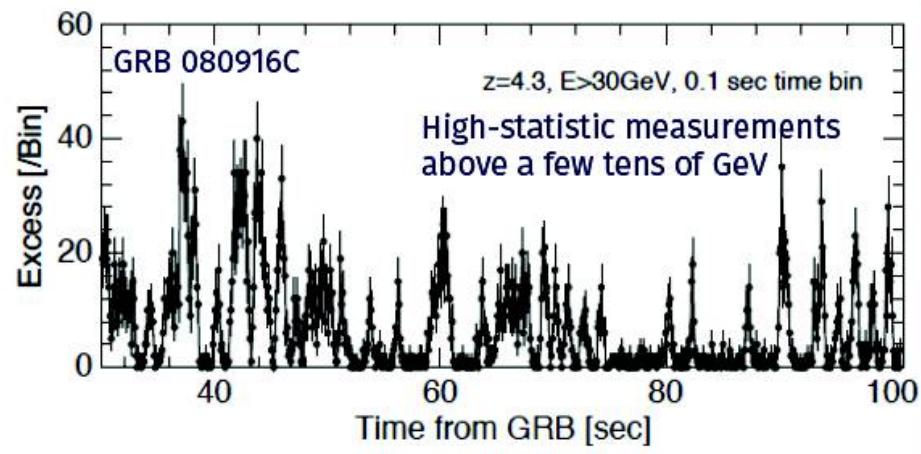
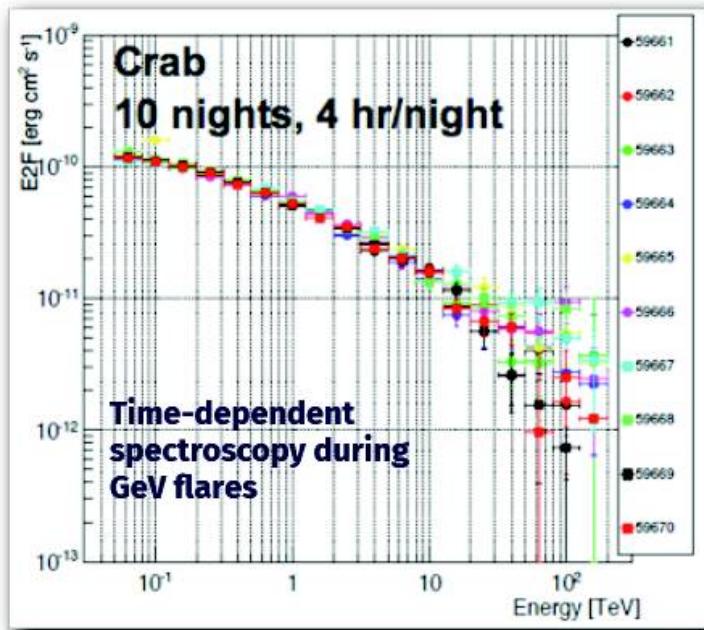
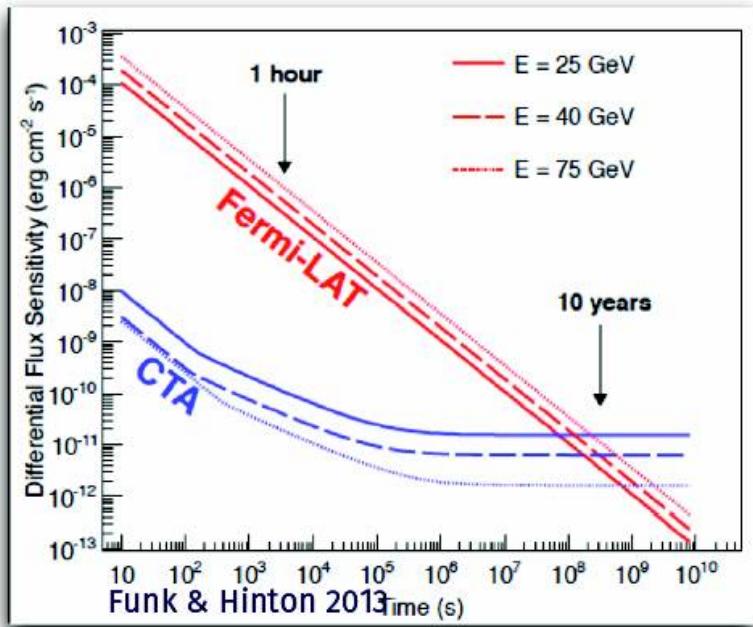
Credits: The H.E.S.S. Collaboration
PeVatron at Galactic Centre
→ continuous CR source

Cosmic rays are primarily **energetic nuclei**, which fill the Galaxy.

Supernova remnants might be able to satisfy the cosmic-ray energy requirement if they can somehow convert ~10% of the supernova kinetic energy into accelerated particles.

CTA will perform **deep observations of known sources with particularly hard spectra**. Moreover, it will search for **diffuse gamma-ray emission from the vicinity of prominent gamma-ray bright SNRs**. The interactions of such runaway PeV particles with the ambient gas produce gamma rays with a characteristic hard spectrum extending up to ~100 TeV.

Transients



Inverse-Compton component of the 2011 April Crab flare assuming $\Gamma=50$. The variable tail from 10 to 100 TeV is clearly detectable.

The assumed GRB template is the measured Fermi-LAT light curve above 0.1 GeV, extrapolating the intrinsic spectra to VHE with power-law indices as determined by Fermi-LAT. We expect to detect ~ 1 GRB yr⁻¹ site⁻¹.

Active Galactic Nuclei



Credits: ESA/NASA

Also TeV-Detected

- Radio galaxies
- Starburst gal.
- Grav. lensed flare

AGNs are known to emit **variable radiation** across the entire electromagnetic spectrum up to multi-TeV energies, with fluctuations **on time-scales** from **several years** down to **a few minutes**.

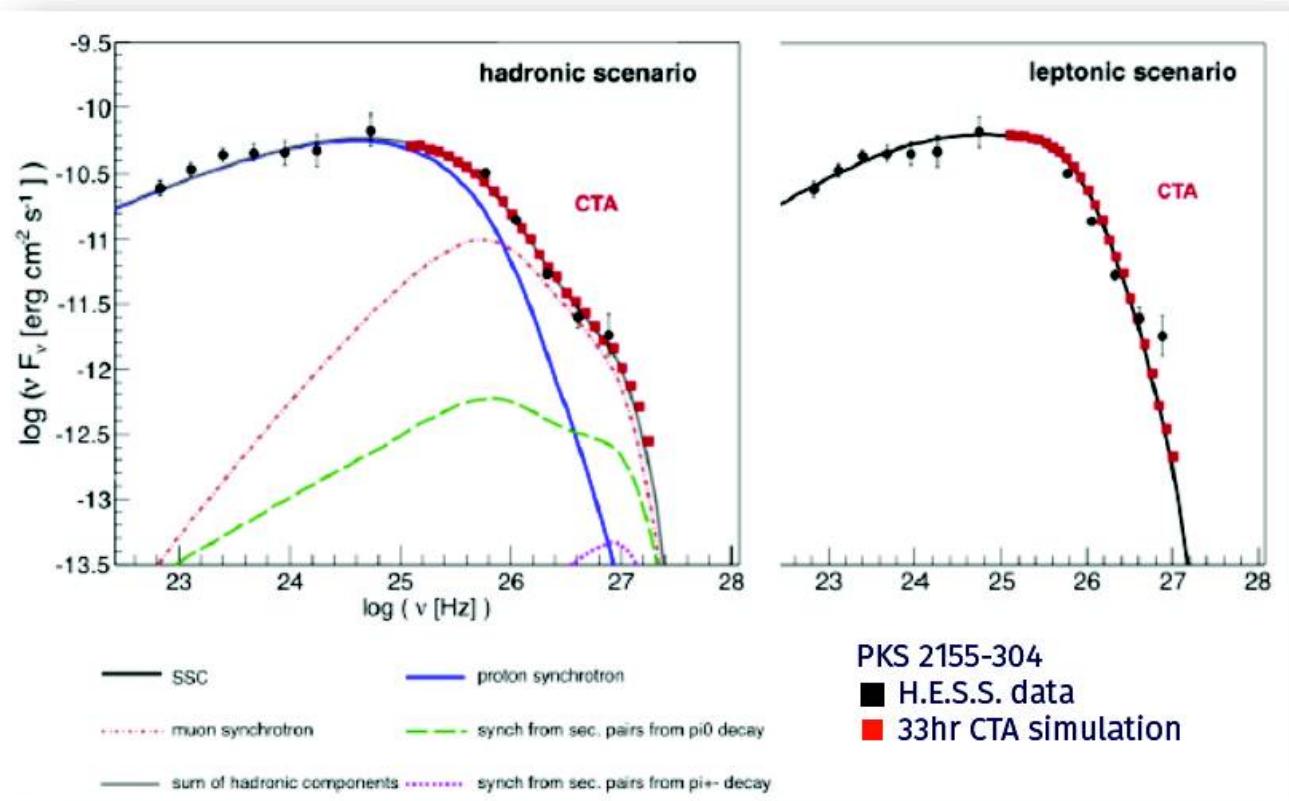
VHE observations of active galaxies harbouring super-massive black holes and ejecting relativistic outflows represent a unique tool to probe the **physics of extreme environments**, to obtain precise measurement of the **extragalactic background light** (EBL) and to constrain the strength of the **intergalactic magnetic field** (IGMF).

AGNs will be useful to investigate fundamental physics phenomena such as the **Lorentz invariance violation** and signatures of the existence of **axion-like particles**.

Active Galactic Nuclei



Testing emission scenarios



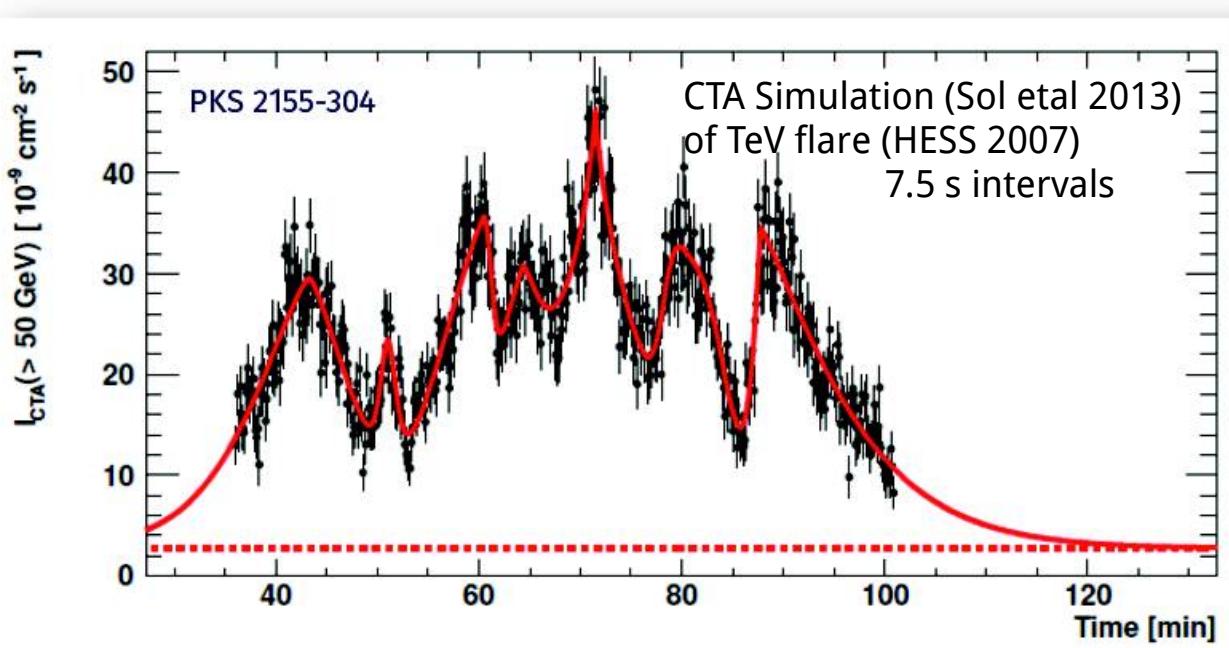
A set of high-quality spectra from different blazar types and different redshifts is needed to unambiguously distinguish intrinsic spectral features, such as shown here, from external absorption.

Zech et al 2013, Cerutti et al 2015,
CTA Science Case (2016 in prep)

Active Galactic Nuclei



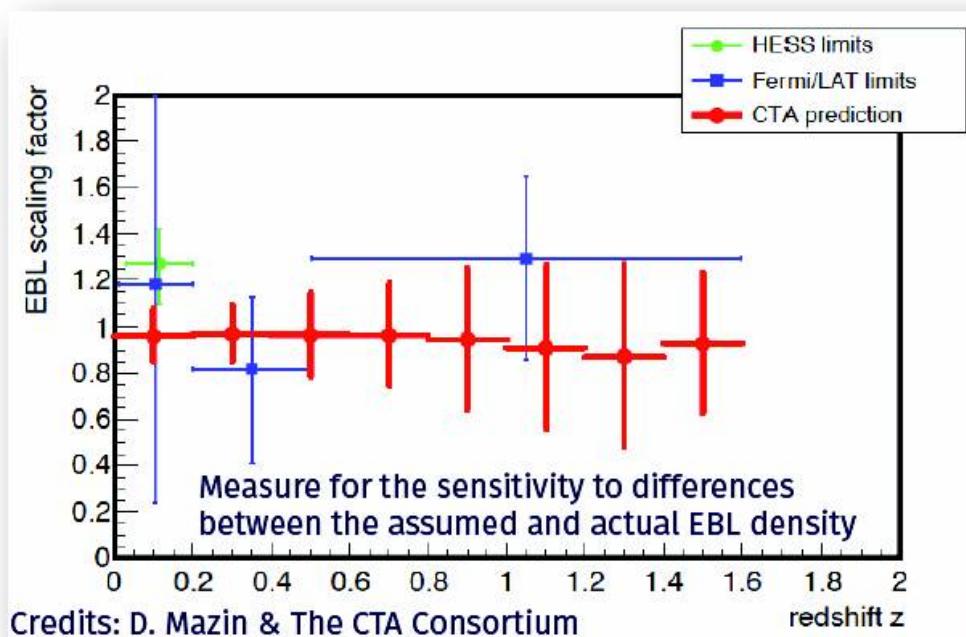
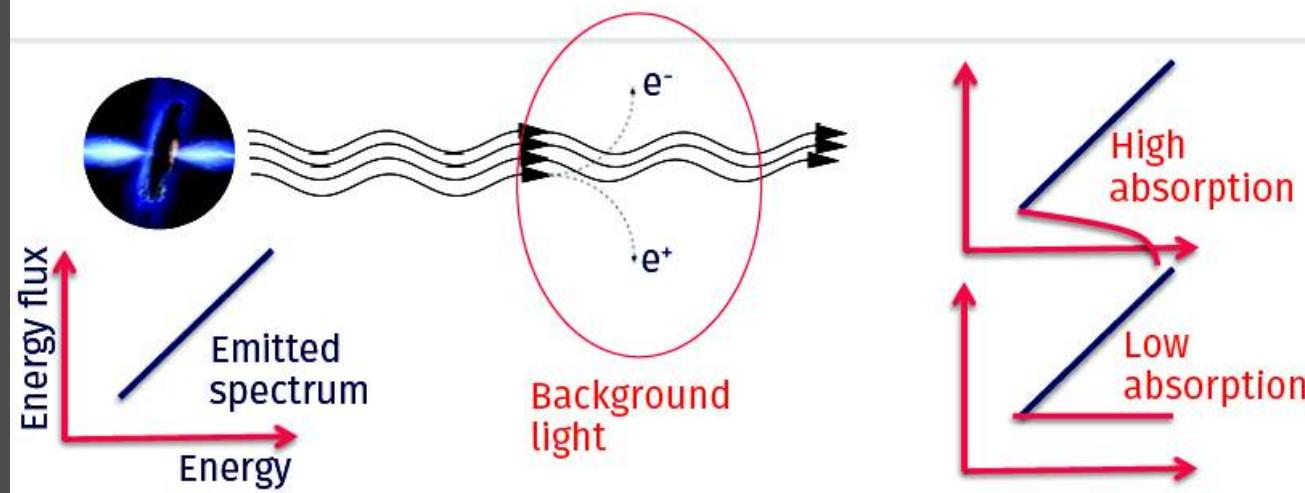
Testing variability in AGNs



Sampling blazar fluxes below the light-crossing time scale of the SMBH, $T_G \sim 3\text{hr} \times (M/10^9 M_\odot)$, is a key strategy to understand the flickering behaviour of blazars on short time scales.

Such measurements put strong constraints on the bulk Doppler factor, as well as on particle acceleration and cooling processes.

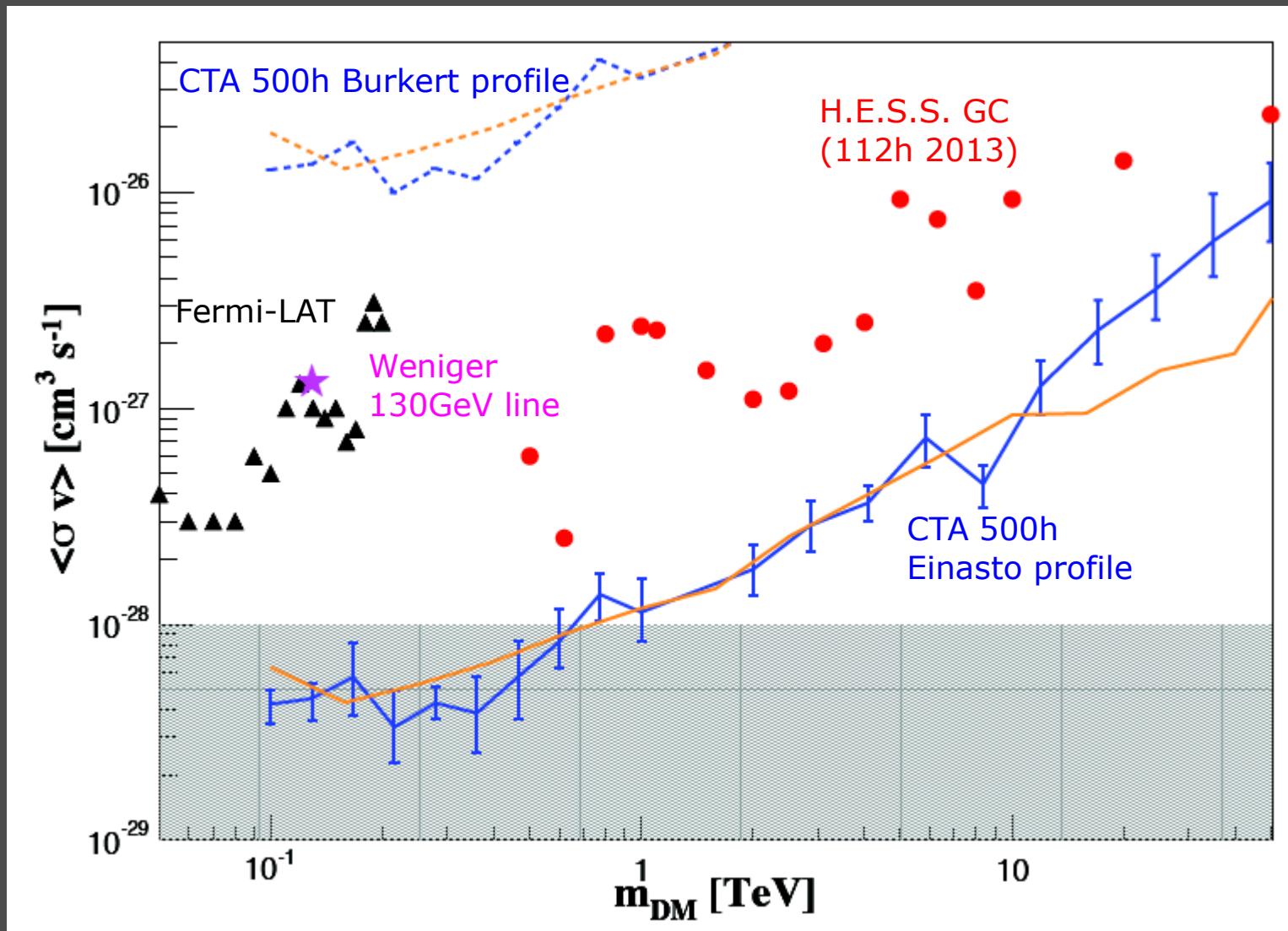
Active Galactic Nuclei



The AGN KSP will lead to the **first precision measurement of the EBL spectrum** at $z \sim 0$ and to a determination of its evolution up to $z \sim 1$.

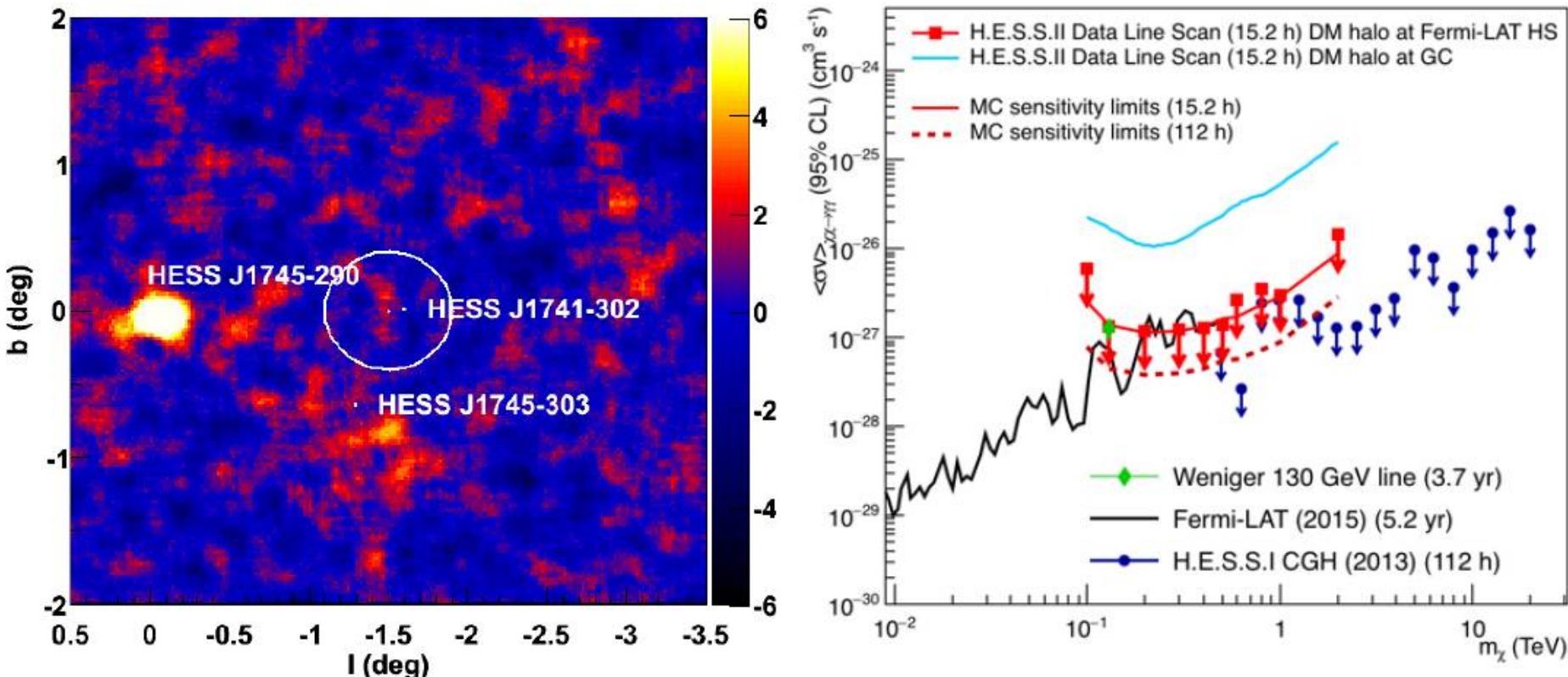
CTA will observe a large sample of blazars located at different redshifts. The detection of high-redshift sources, more likely during flares, would allow us to measure the evolution of the cosmic optical background.

CTA Dark Matter Gal.Centre ($r < 1^\circ$) 500hr $\chi\chi \rightarrow \gamma\gamma$



CTA Consortium - Science Case (in prep)

130 GeV Dark Matter Line at Fermi-LAT Hotspot? (Weniger 2012) Unfortunately No.



H.E.S.S. Collab Rhys Rev. Lett 2016

Australia's Roles in CTA:

CTA Hardware & Array Design

- Telescope hardware & commissioning (ARC LIEF funding)
- Atmospheric characterisation (LIDAR, cloud monitoring)
- Analysis techniques & effect of clouds on CTA performance

Multi-wavelength/messenger strengths

- ISM surveys/studies (Mopra, ATCA, ASKAP, SKA)
(sub)arcmin surveys vital for CTA's Galactic science
- Radio continuum: transients/steady (ATCA, MWA, UTMOST, ASKAP, SKA)
- X-ray astronomy (e-ROSITA, XMM-Newton, Chandra)

Theory Strengths

- Theoretical high energy astrophysics (e.g. Galactic Centre, jets/outflows)
- Astro-particle physics – Dark matter properties

Great potential to link with....

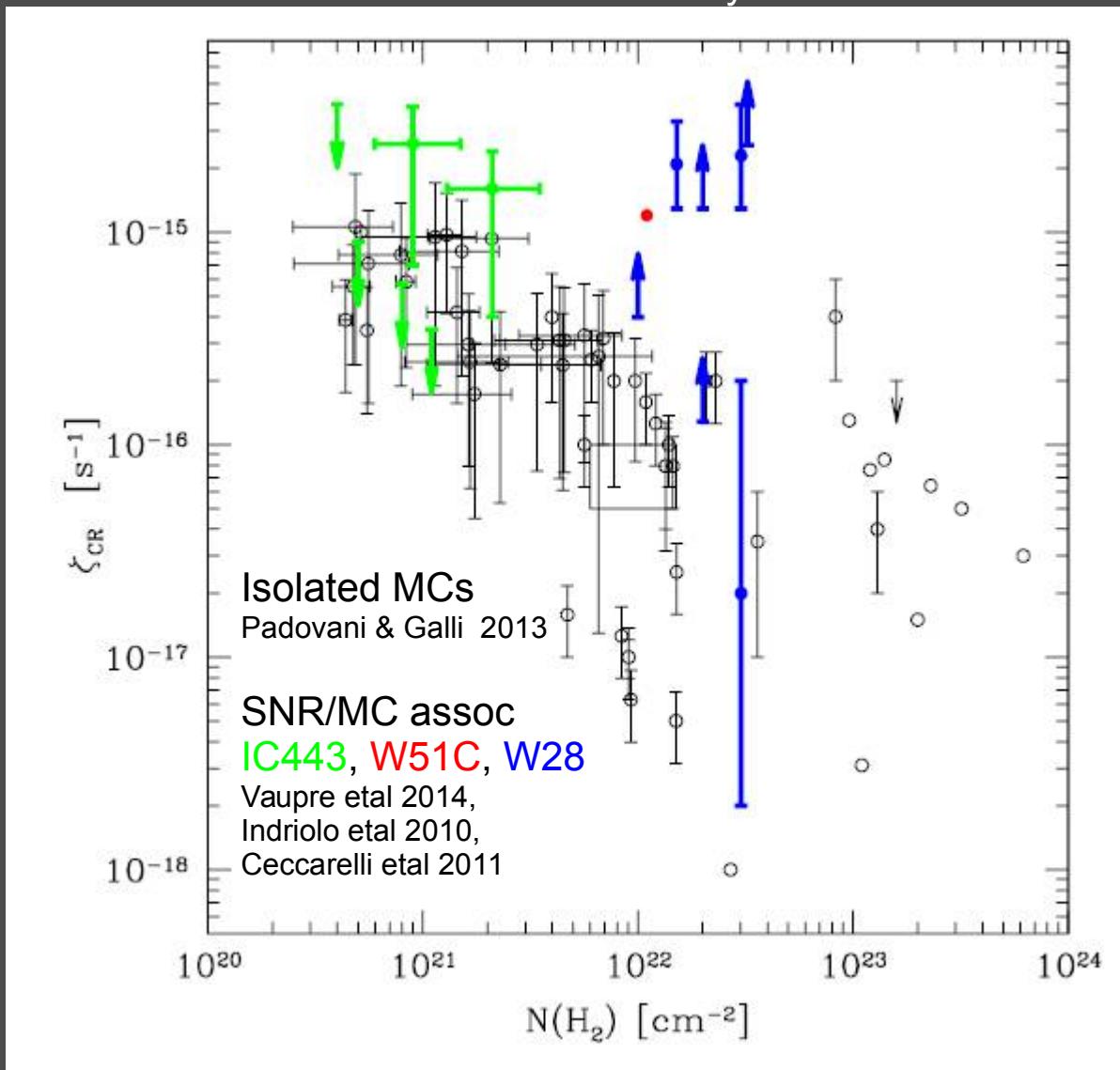
- Radio (ASKAP-EMU, -POSSUM, -VAST/CRAFT, MWA, UTMOST)
- Optical (e.g. GALAH, Skymapper), interferometry, transients
- Cosmic-rays (Pierre Auger Obs.)
- Grav. Waves (A/LIGO)
- Neutrinos (IceCube)
- HP Computing (Pawsey....) transients, MWL features,, local data centre

Thank you....



Sub-GeV CR penetration into MCs – ionisation rates

Review by Gabici & Montmerle 2015



- low E CRs less penetrating in denser clouds
- synergies with ionisation rate tracers: $\text{HCO}^+/\text{DCO}^+$; H_3^+ ; OH etc..

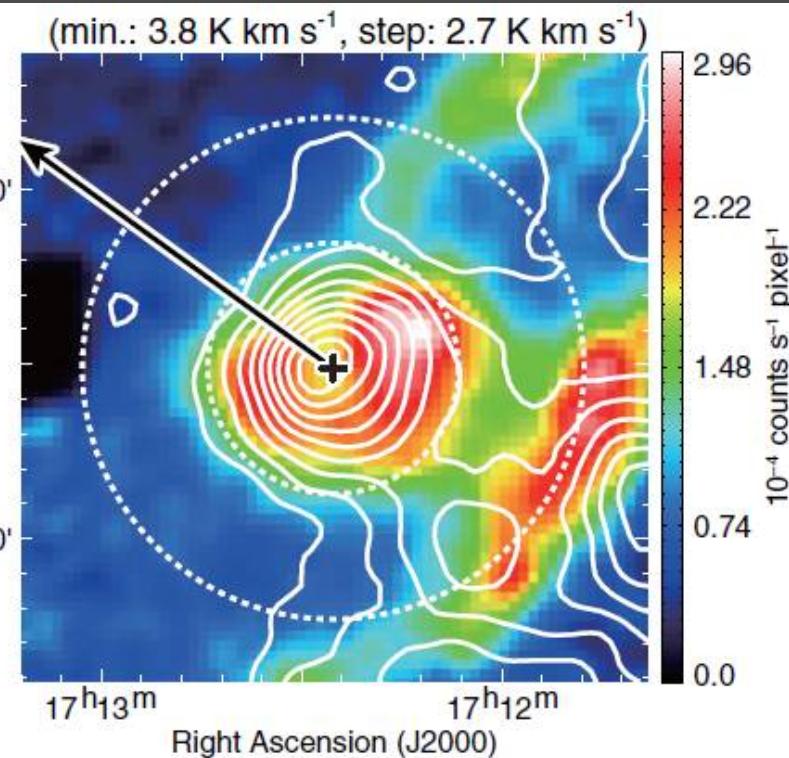
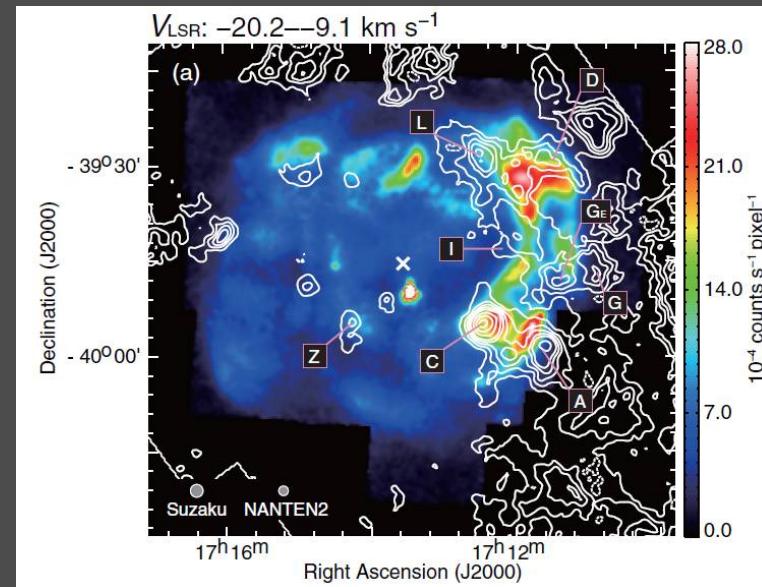
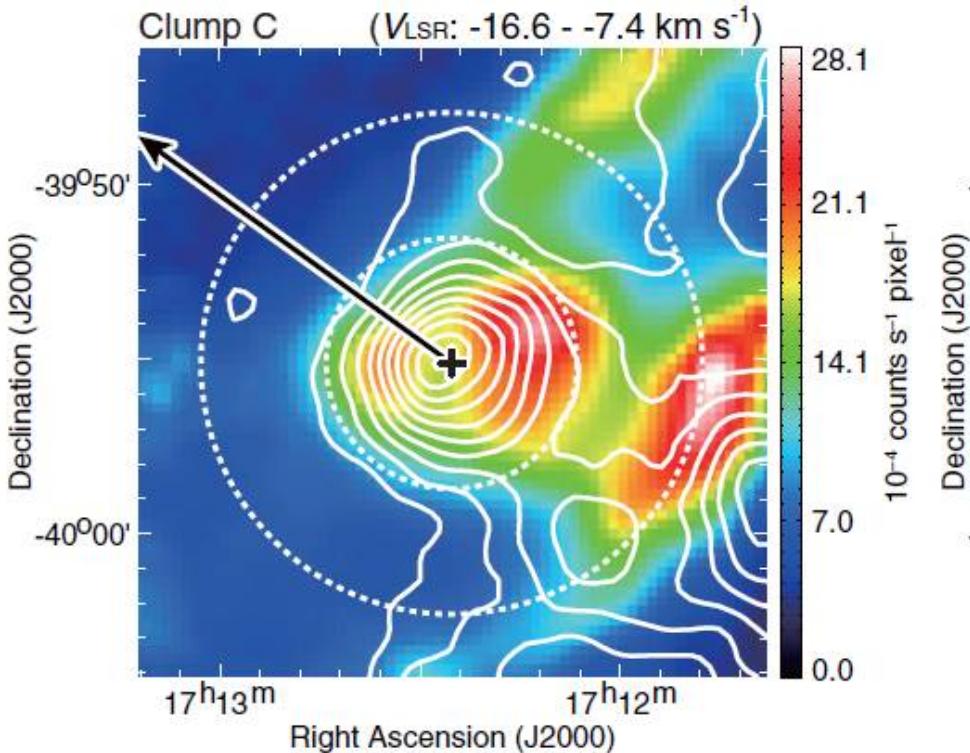
Dense Cores filter out external electrons! e.g. RXJ1713.7-3946:

Sano et al 2013

- CO(2-1) Nanten2 contours +X-ray images
- Synch cooling length < pc for 30 TeV electrons, 6 keV X-rays, $n=10^5/\text{cc}$, $B\sim 400\mu\text{G}$

See also Uchiyama et al 2007

Suzaku 1–5 keV (left) and 5–10 keV (right) images

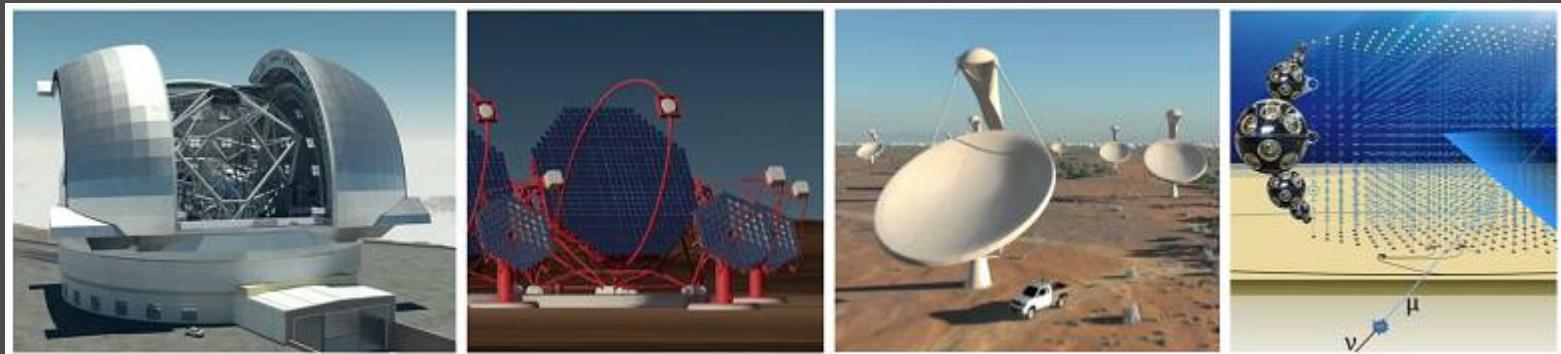




Astronomy ESFRI & Research Infrastructure Cluster



The Astronomy ESFRI and Research Infrastructure Cluster



15MEuro programme to tap synergies between:
E-ELT, CTA, SKA, KM3Net

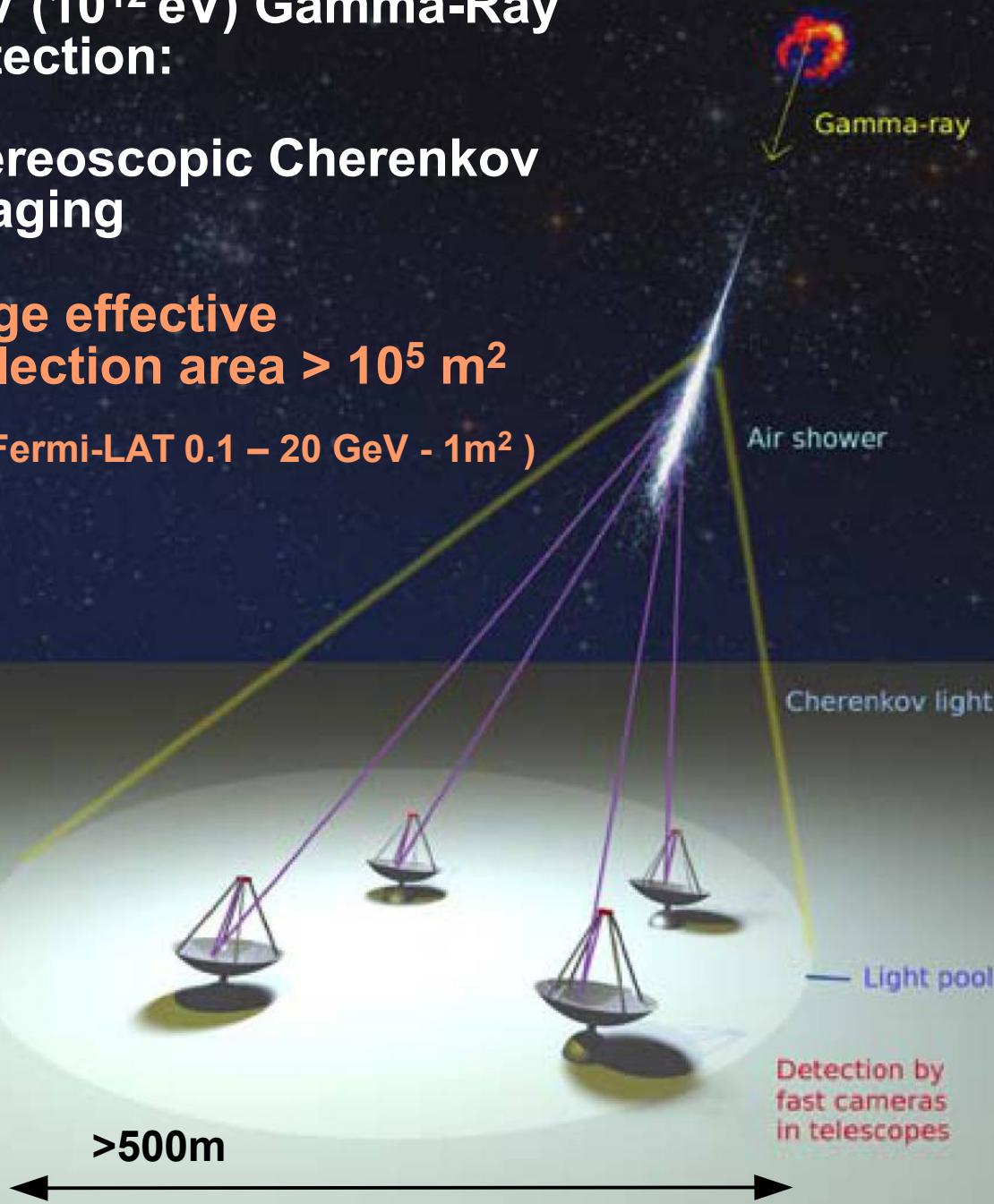
<https://www.asterics2020.eu>

TeV (10^{12} eV) Gamma-Ray detection:

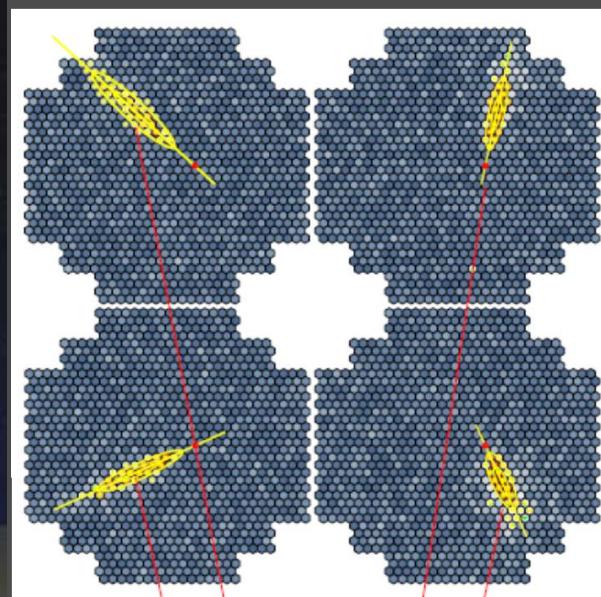
Stereoscopic Cherenkov Imaging

Huge effective collection area $> 10^5 \text{ m}^2$

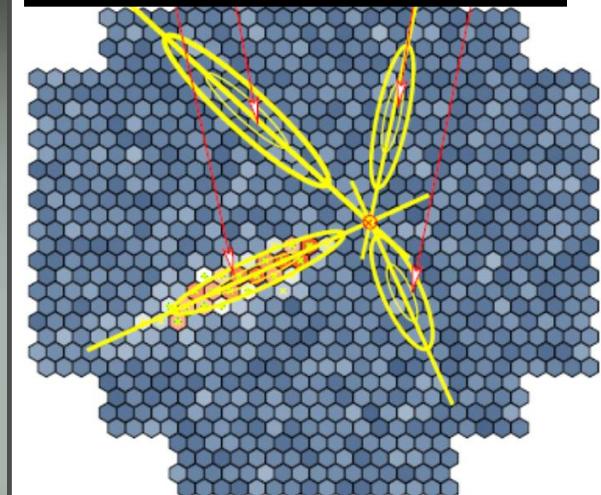
(cf. Fermi-LAT 0.1 – 20 GeV - 1m²)



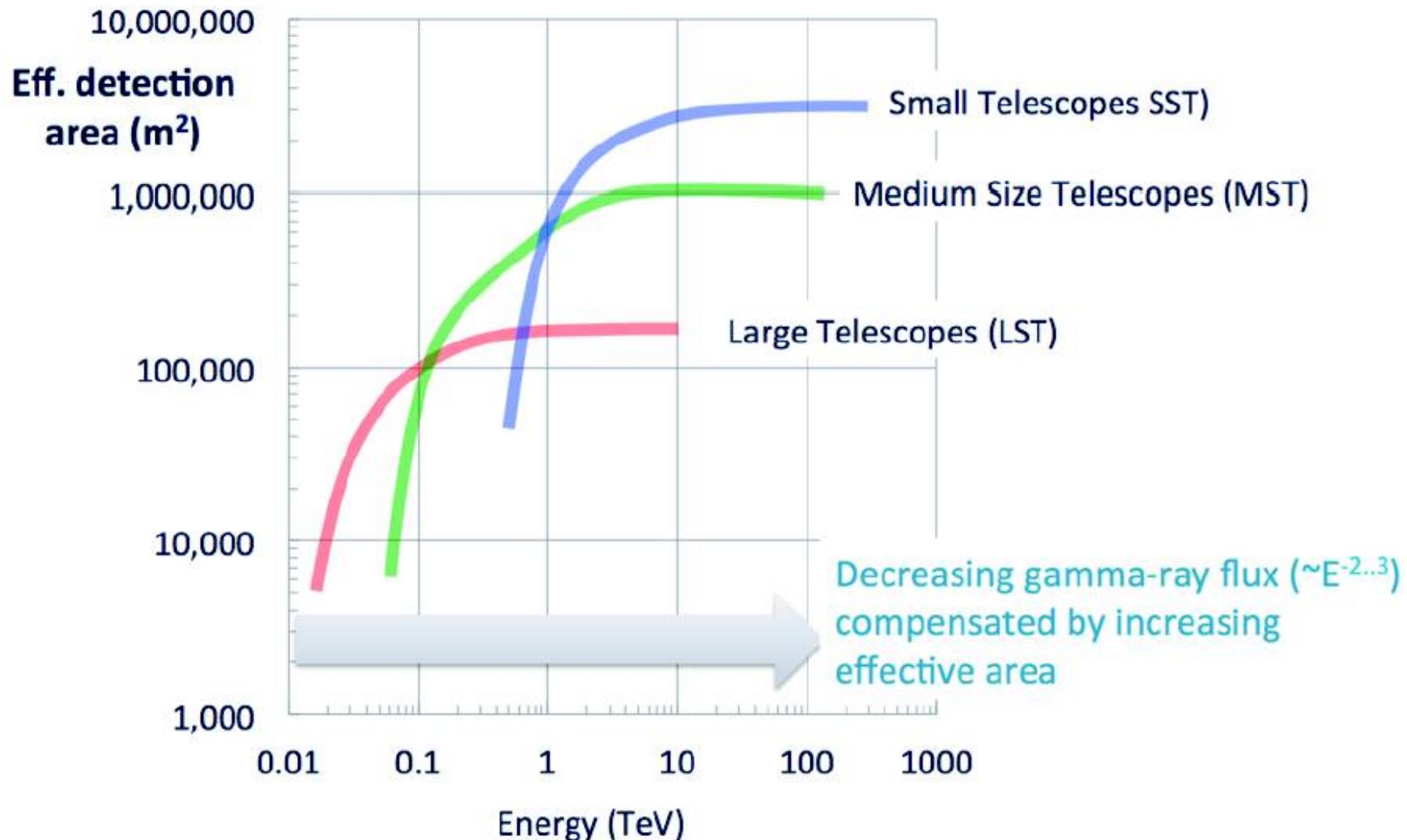
Cherenkov 'image' as viewed by each telescope



Combination:



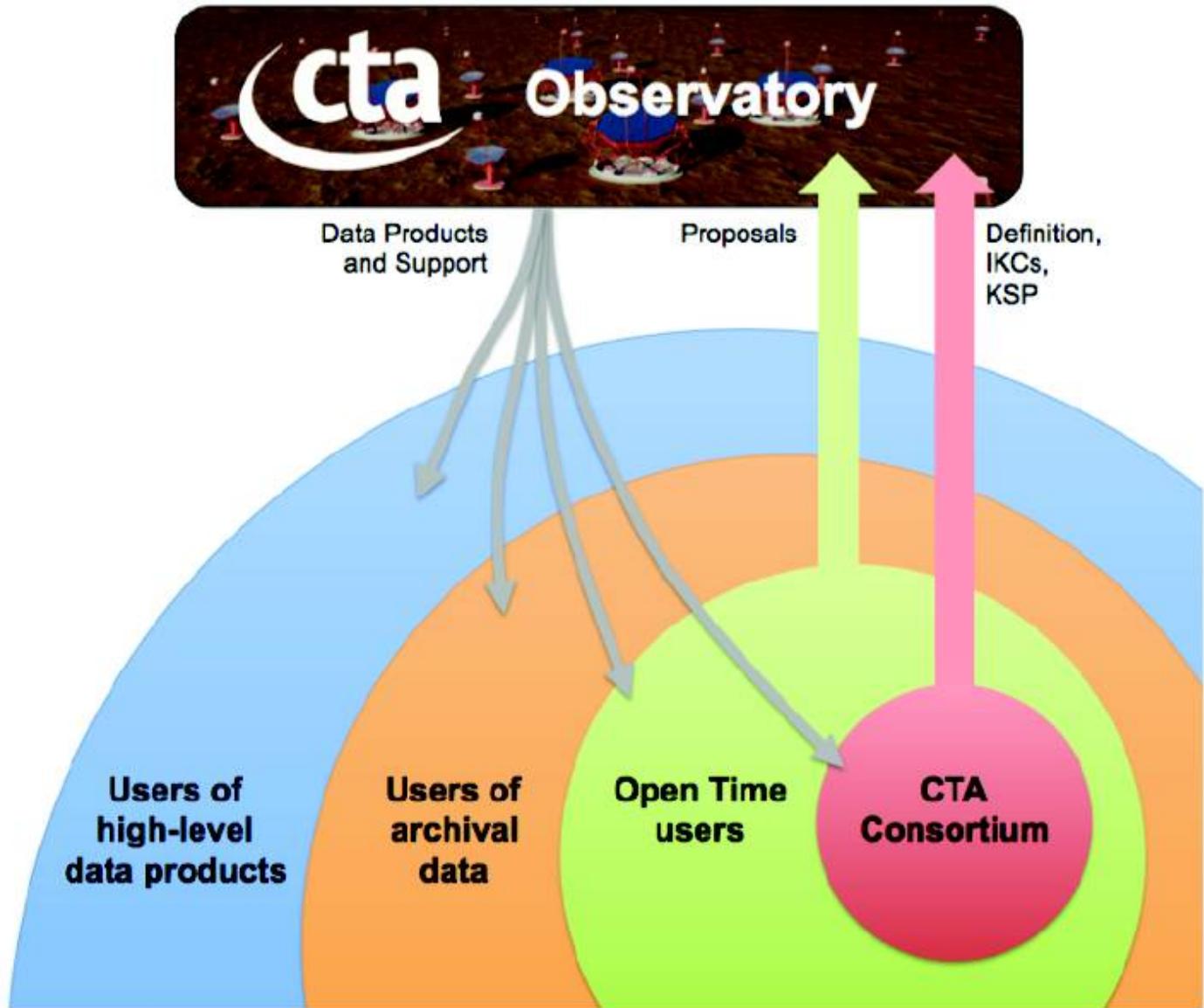
Cherenkov light pool



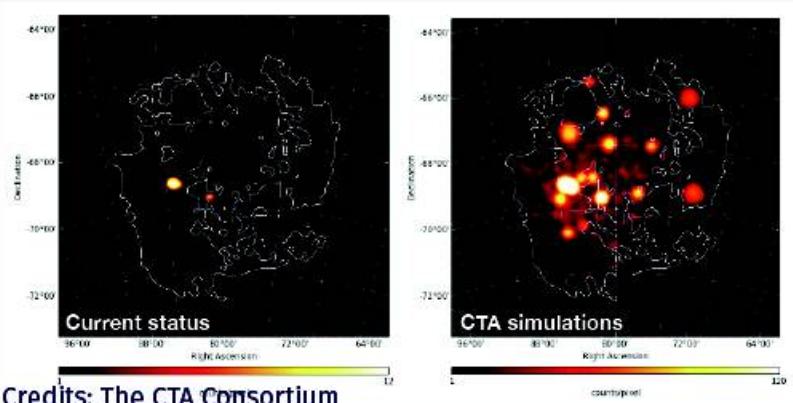
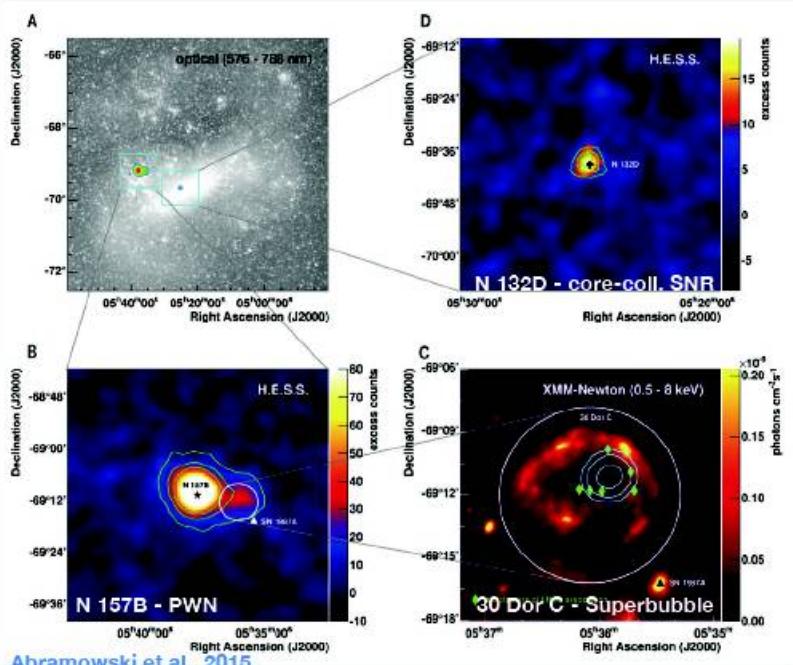
Organization: observatory



cherenkov
telescope
array



LMC Survey



Three luminous examples of cosmic-ray sources in an external galaxy.

HESS Collab. (2015)

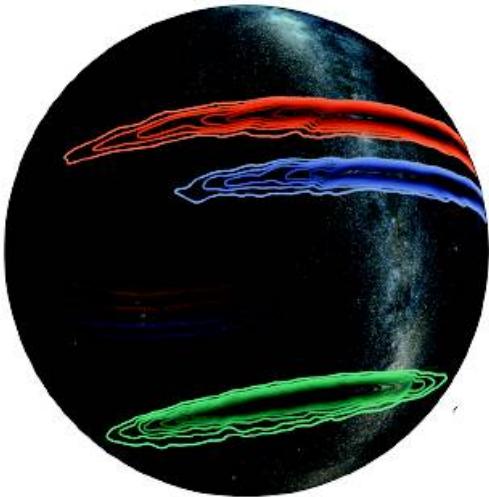
30 Dor C is the first super-bubble detected at VHE.

Super-bubbles may provide the right conditions for **particle acceleration up to very high energies**.

Simulation includes currently detected sources, plus ten point-like sources with $L_{(E > 1 \text{ TeV})} \sim 10^{34} \text{ erg s}^{-1}$, and a handful of regions enriched in cosmic rays.

Excellent prospects for CTA investigations of the LMC.

Transients



Credits: The LIGO Scientific Collaboration

Currently:

HESS follow-ups of Parkes SUPERB FRBs

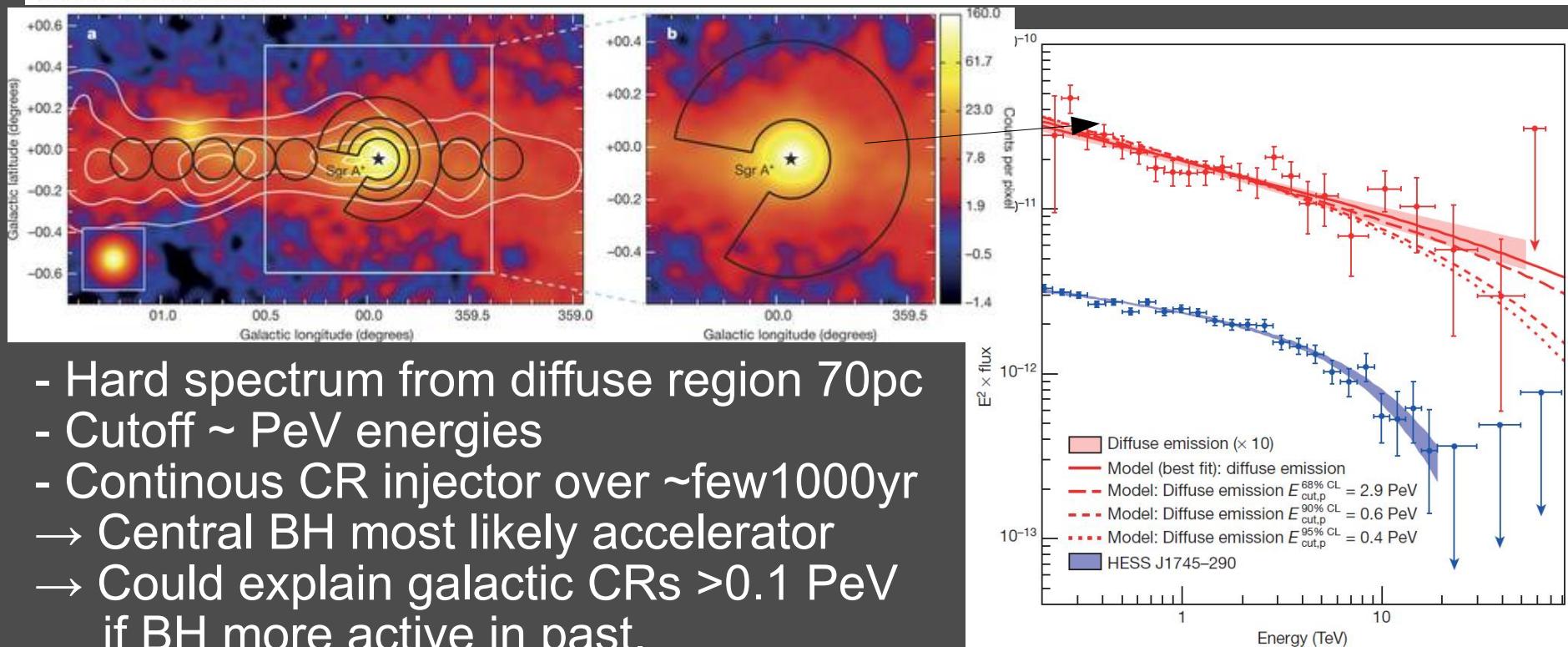
Transients are a diverse population of astrophysical objects. Some are known to be prominent **emitters of high-energy gamma-rays**, while others are sources of non-photonic, multi-messenger signals such as **cosmic rays, neutrinos and/or gravitational waves**.

Possible classes of targets

- Gamma-ray bursts
- Galactic transients
- High-energy neutrino transients
- Gravitational wave transients
- Radio, optical, and X-ray transients
- Serendipitous VHE transients

Acceleration of petaelectronvolt protons in the Galactic Centre

HESS Collaboration*



- Hard spectrum from diffuse region 70pc
- Cutoff \sim PeV energies
- Continuous CR injector over \sim few 1000yr
- Central BH most likely accelerator
- Could explain galactic CRs >0.1 PeV if BH more active in past.
(SNRs may still contribute some PeV CRs)

Figure 3 | VHE γ -ray spectra of the diffuse emission and HESS