MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

IDPASC

11th IDPASC School, Olomouc 2022
High Energy Gamma-rays

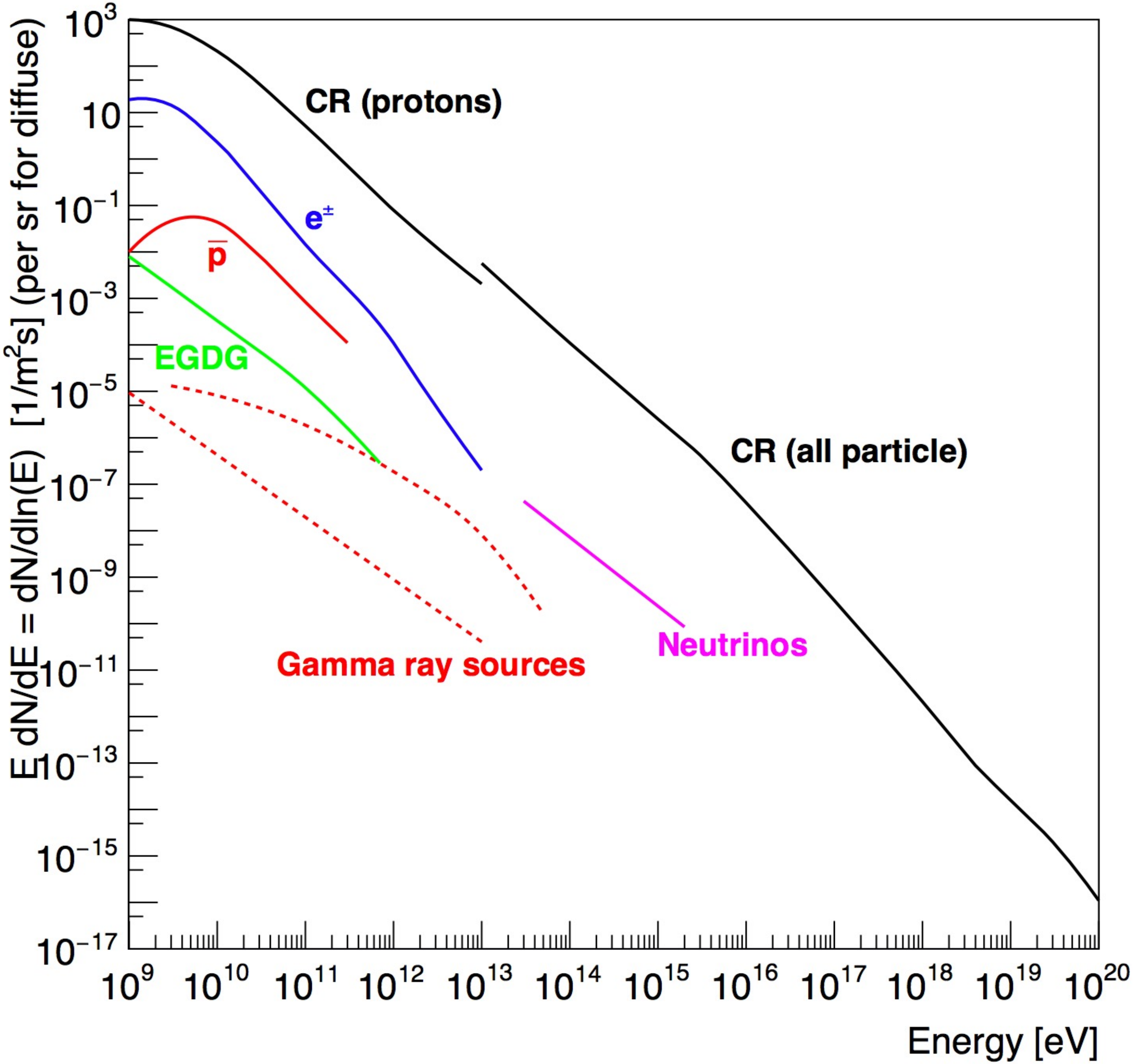
Jim Hinton – MPIK, Heidelberg

A totally biased overview

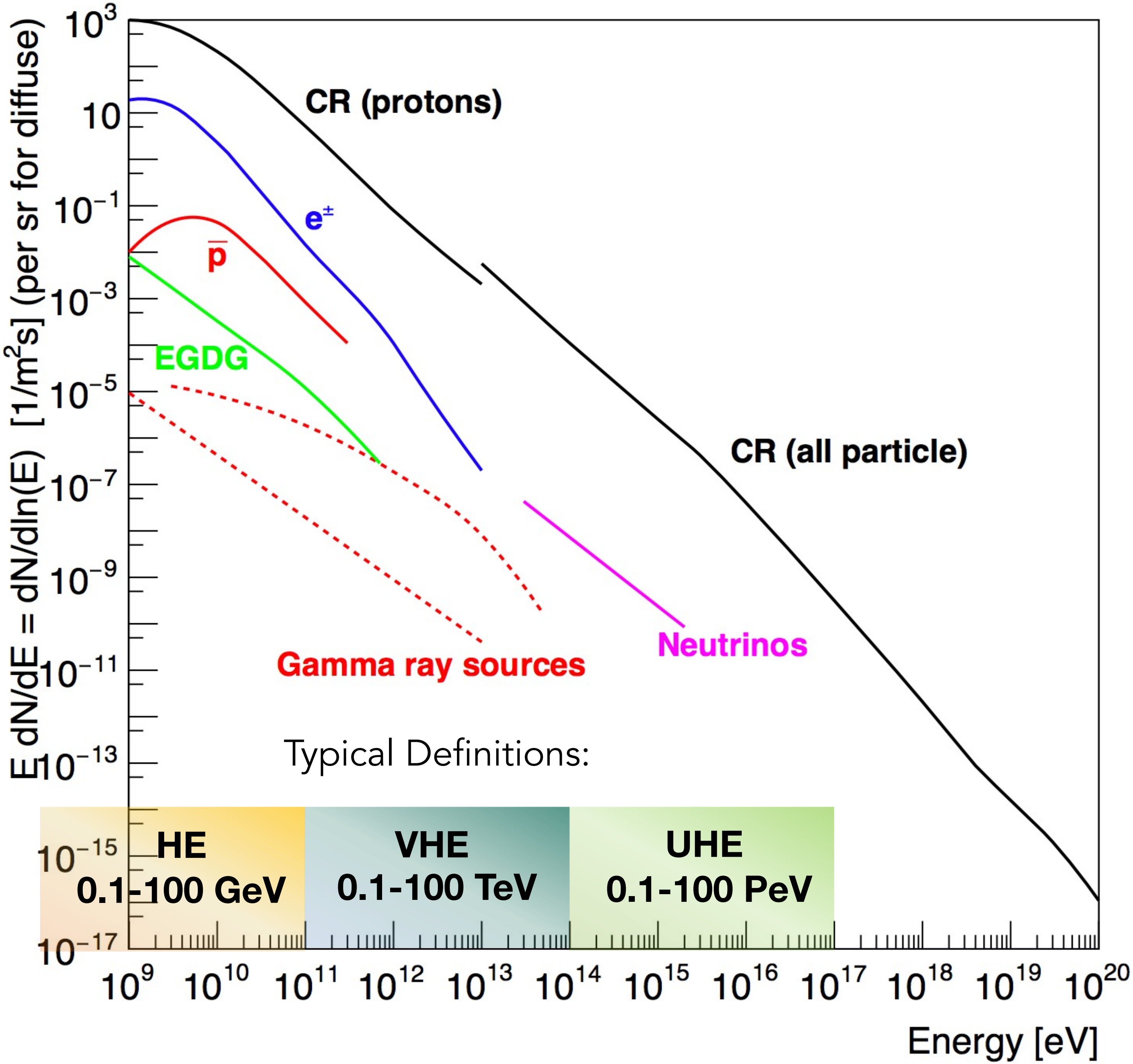
Context / This Talk

- Non-thermal astrophysics
  - Somehow arrange for a very small fraction of particles to take on a large fraction of the available energy → acceleration
  - Propagation and radiation of accelerated particles
  - Their influence on the evolution of their host systems
- Multi-messenger astronomy
  - Combining information from neutrino astronomy, gravitational waves, direct cosmic ray measurements with electromagnetic tracers: including/especially: gammas
- Search for beyond standard model physics
  - Nature of Dark Matter, Quantum Gravity effects, +++

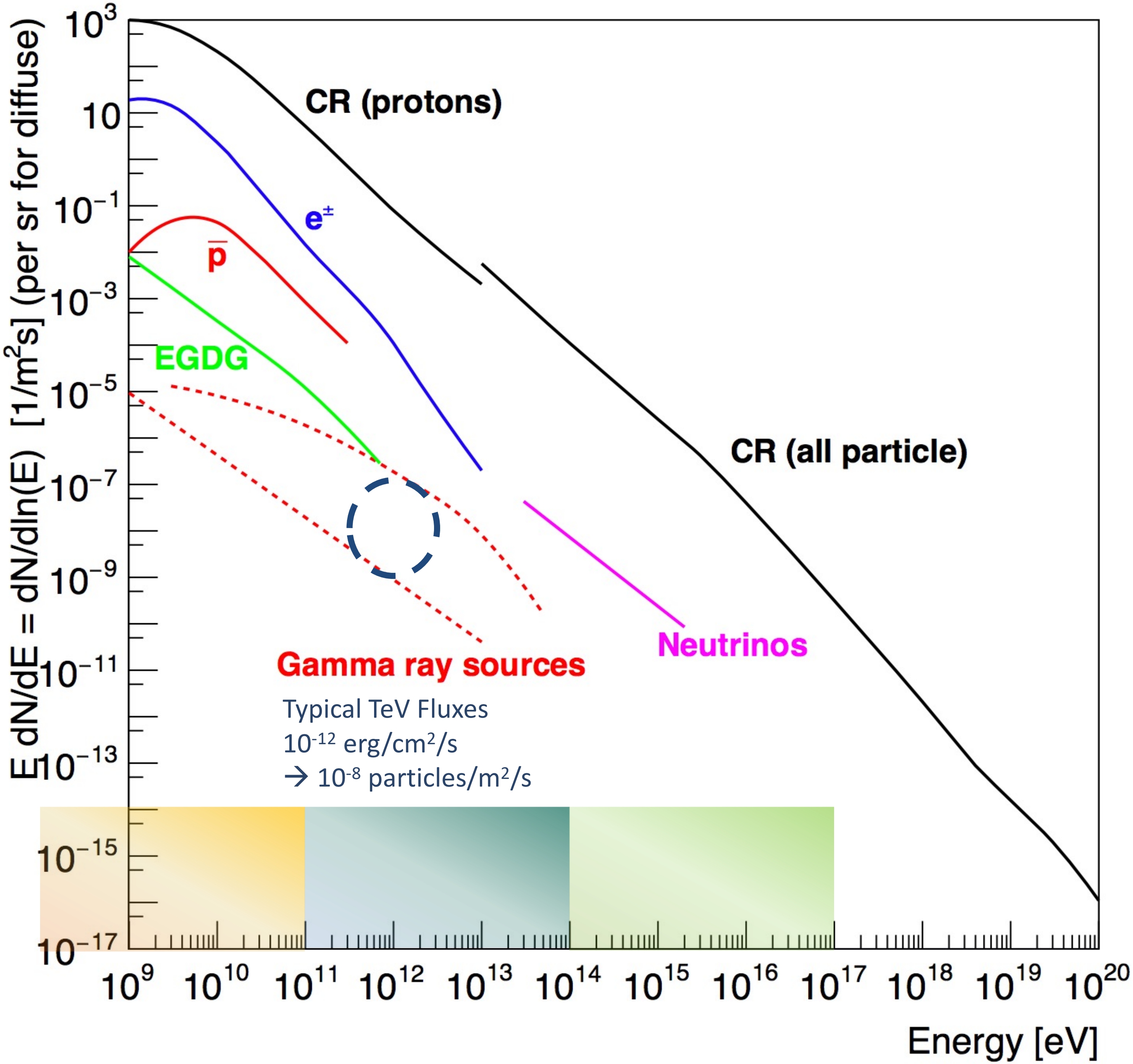
This Talk:
1. Gamma-ray astronomy from the ground, approaches and instruments
2. Gamma-ray production and absorption
3. The VHE-UHE sky – **Galactic** and Extragalactic sources
4. Future Instrumentation



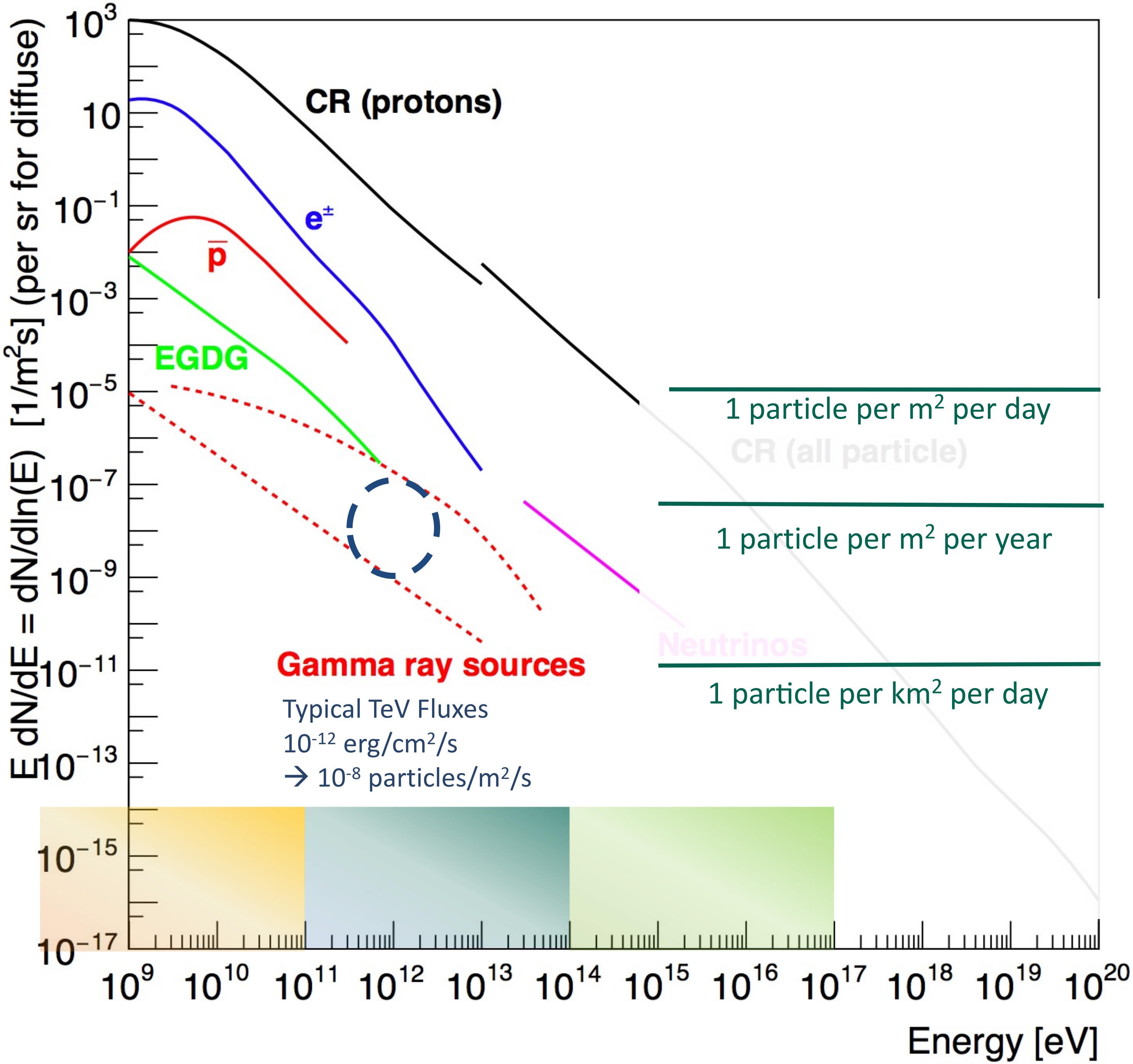
CR (protons)
e±
p̄
EGDG
CR (all particle)
Neutrinos
Gamma ray sources
E dN/dE = dN/dln(E) [1/m²s] (per sr for diffuse)
Energy [eV]



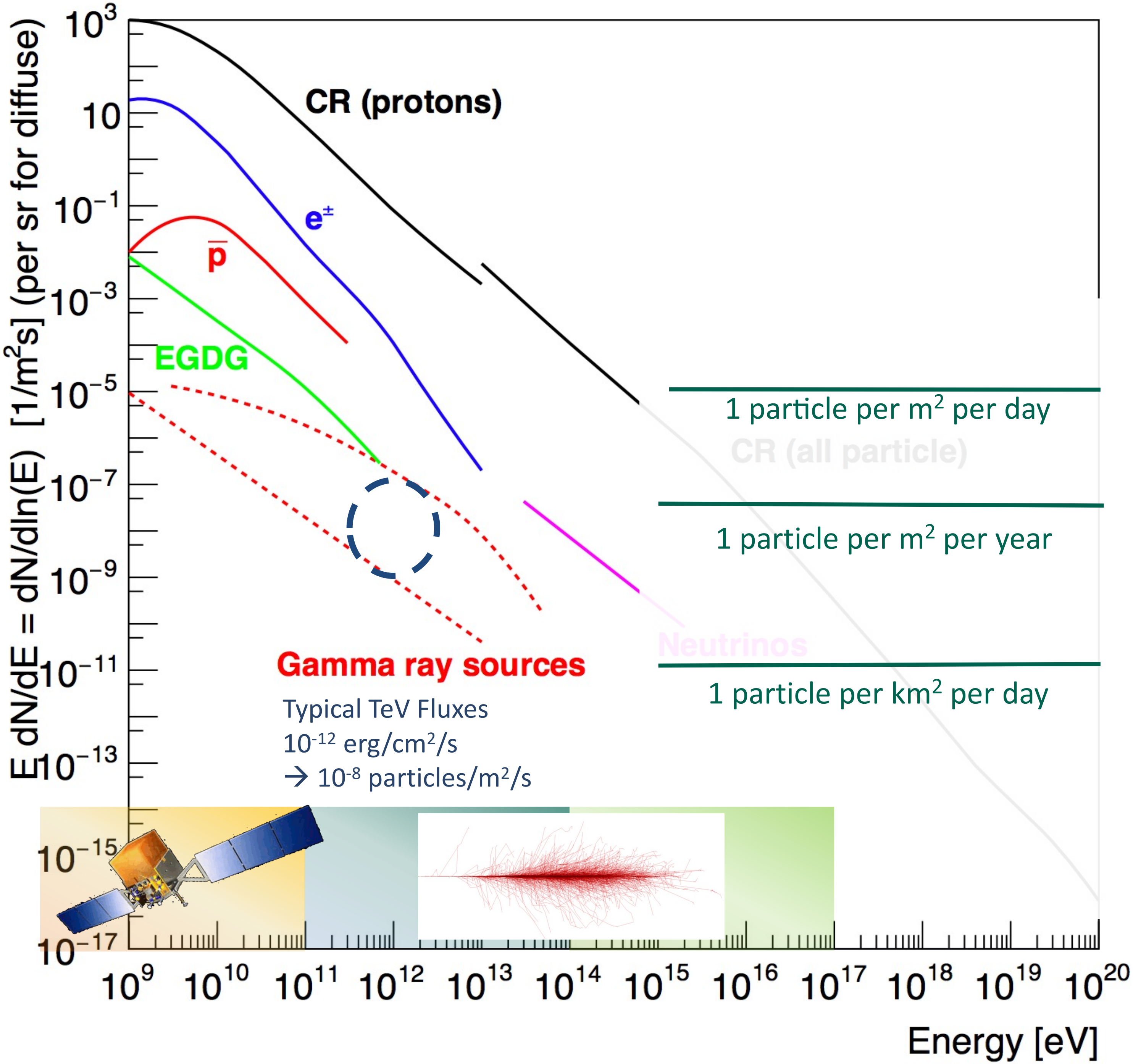
CR (protons)
e±
p̄
EGDG
CR (all particle)
Neutrinos
Gamma ray sources
Typical Definitions:
HE
0.1-100 GeV
VHE
0.1-100 TeV
UHE
0.1-100 PeV
E dN/dE = dN/dln(E) [1/m²s] (per sr for diffuse)
Energy [eV]



CR (protons)
e±
p̄
EGDG
CR (all particle)
Neutrinos
Gamma ray sources
Typical TeV Fluxes
10^{-12} erg/cm^2/s
→ 10^{-8} particles/m^2/s
E dN/dE = dN/dln(E) [1/m^{2}s] (per sr for diffuse)
Energy [eV]



E dN/dE = dN/dln(E) [1/m²s] (per sr for diffuse)
10³
10
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
10⁻⁹
10⁻¹¹
10⁻¹³
10⁻¹⁵
10⁻¹⁷
CR (protons)
e±
p̄
EGDG
Gamma ray sources
Typical TeV Fluxes
10⁻¹² erg/cm²/s
→ 10⁻⁸ particles/m²/s
1 particle per m² per day
CR (all particle)
1 particle per m² per year
Neutrinos
1 particle per km² per day
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy [eV]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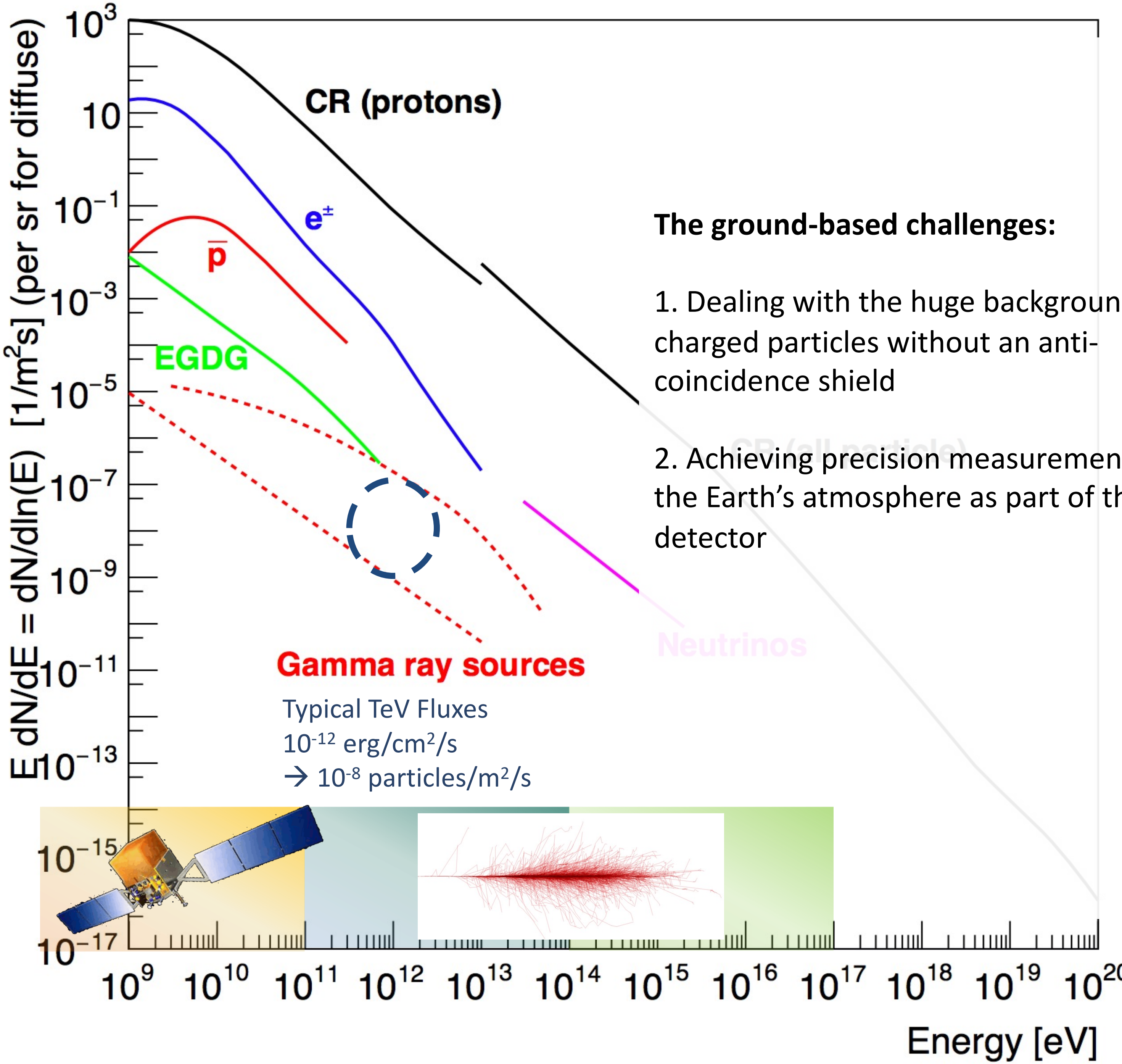


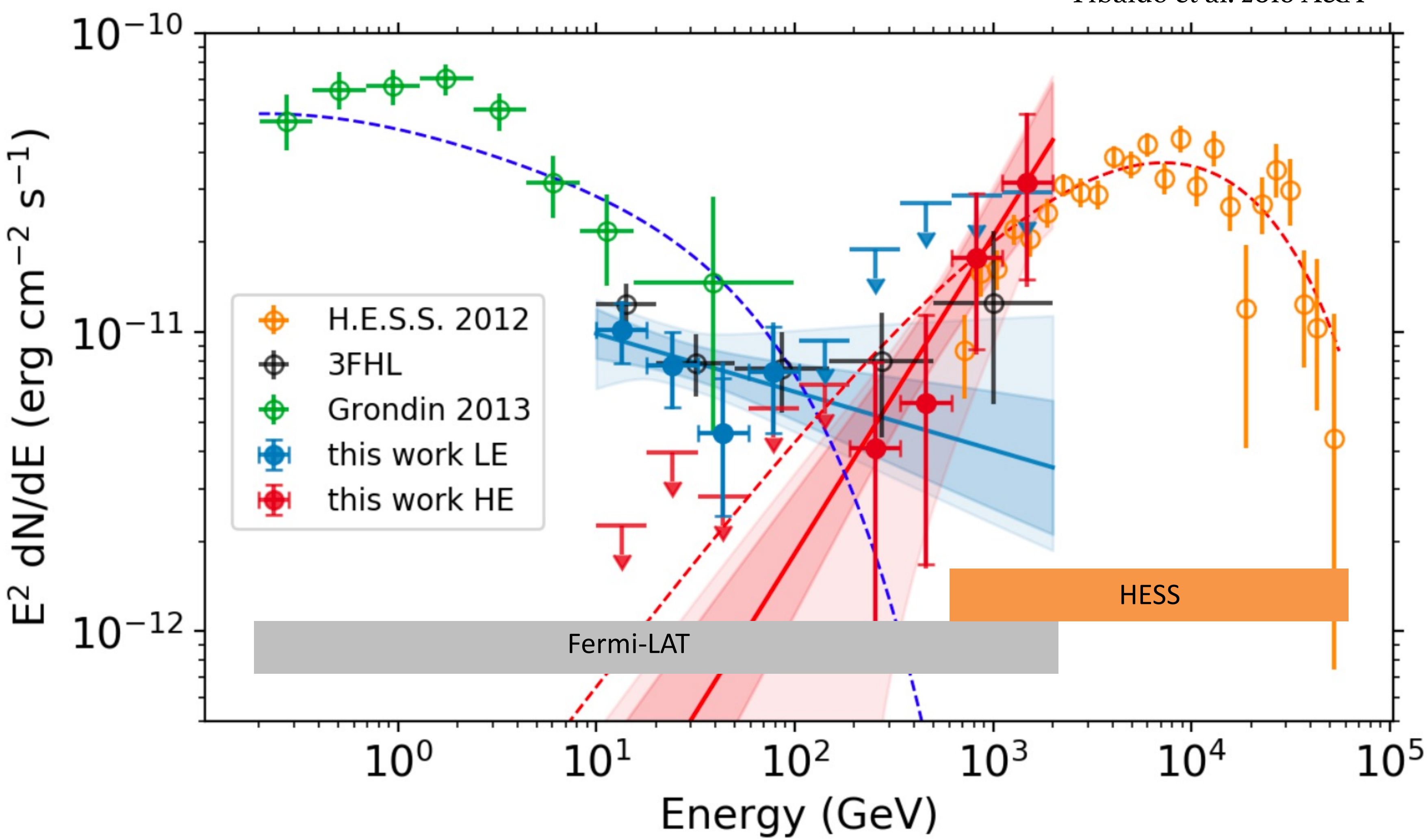
The ground-based challenges:

1. Dealing with the huge background of charged particles without an anti-coincidence shield

2. Achieving precision measurements with the Earth's atmosphere as part of the detector

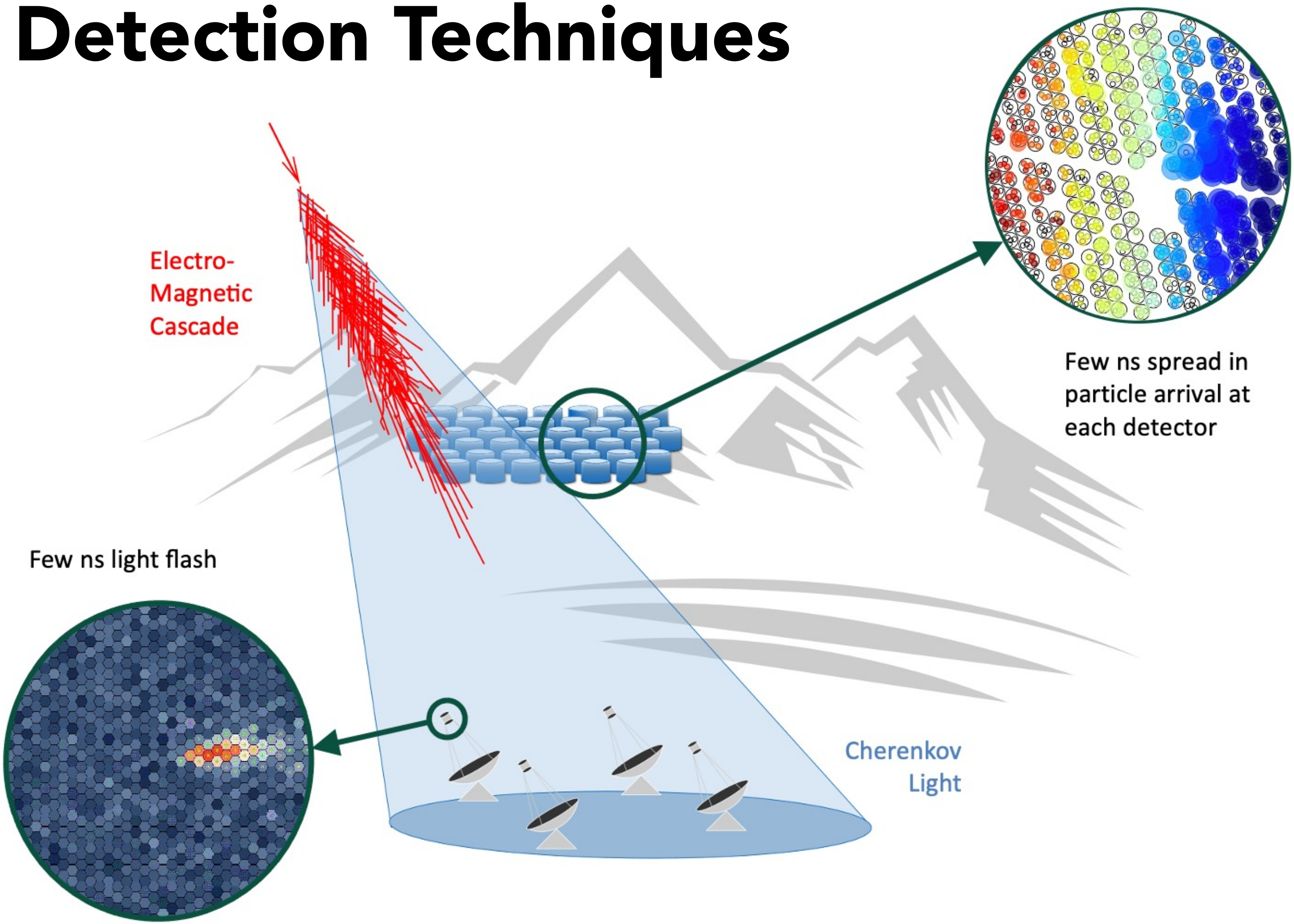
But it works…

Tibaldo et al. 2018 A&A

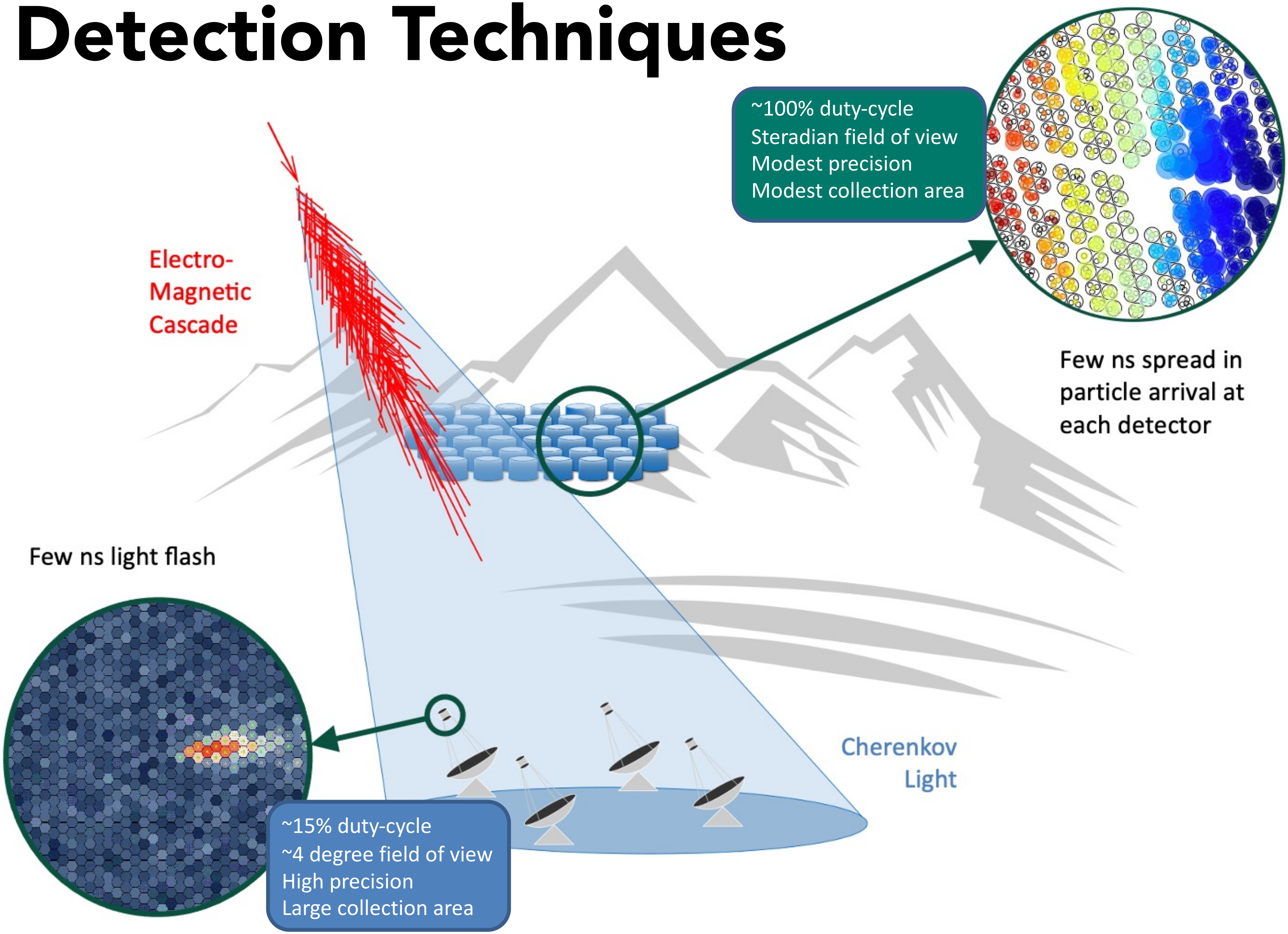


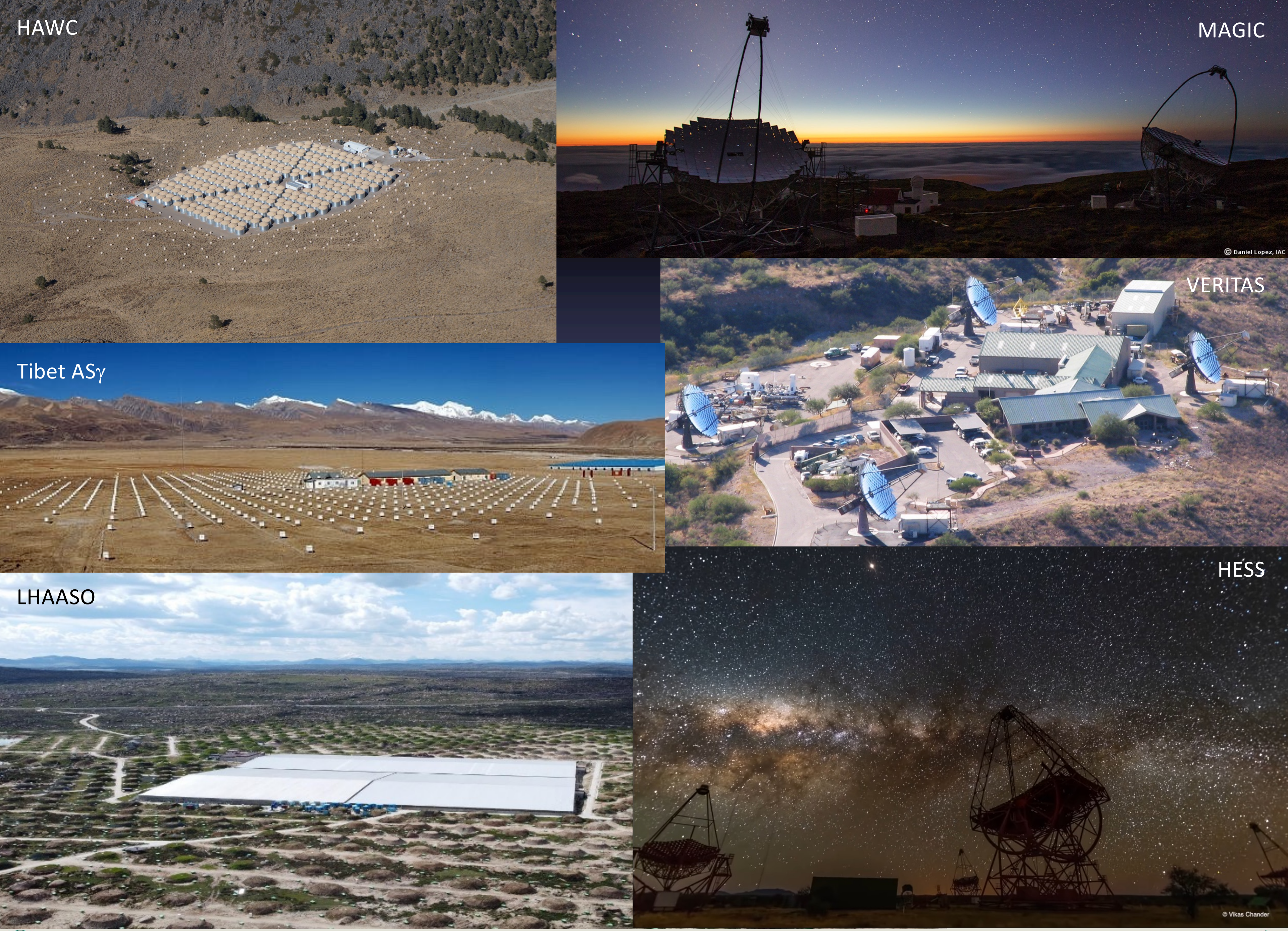
Example: The Vela Pulsar Wind Nebula

Detection Techniques

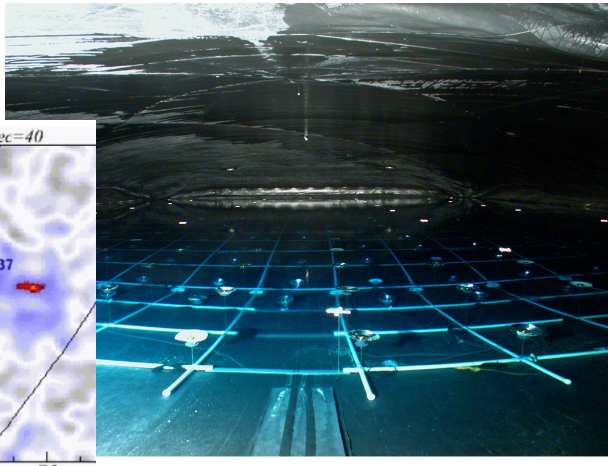


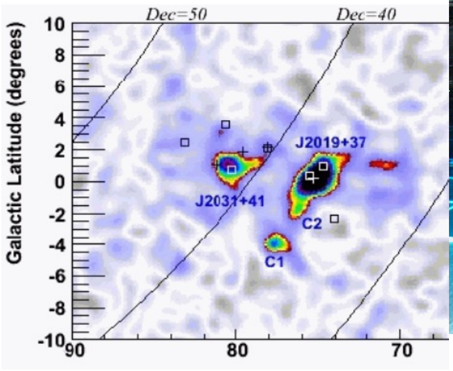
Detection Techniques



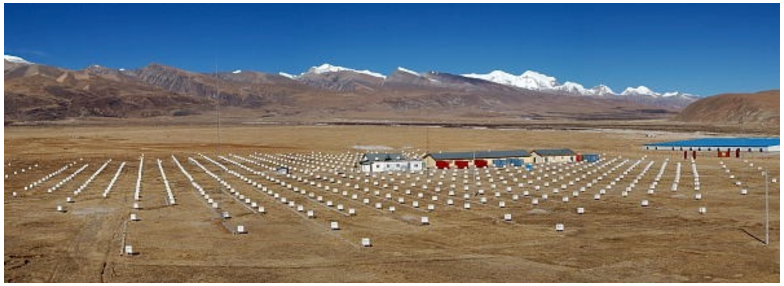

HAWC
MAGIC
© Daniel Lopez, IAC
VERITAS
Tibet ASγ
LHAASO
HESS
© Vikas Chander

Ground-particle Detectors





- 2.5 km ⊙ MILAGRO – 2001-2008
- 4.1 km ⊙ HAWC – 2015 -
- 4.3 km ⊙ Tibet AS γ +ARGO – 1990s -
- 4.4 km ⊙ LHAASO – 2021 -
- 4.4-5.0 km ⊙ SWGO – 202X -



Drivers of performance:

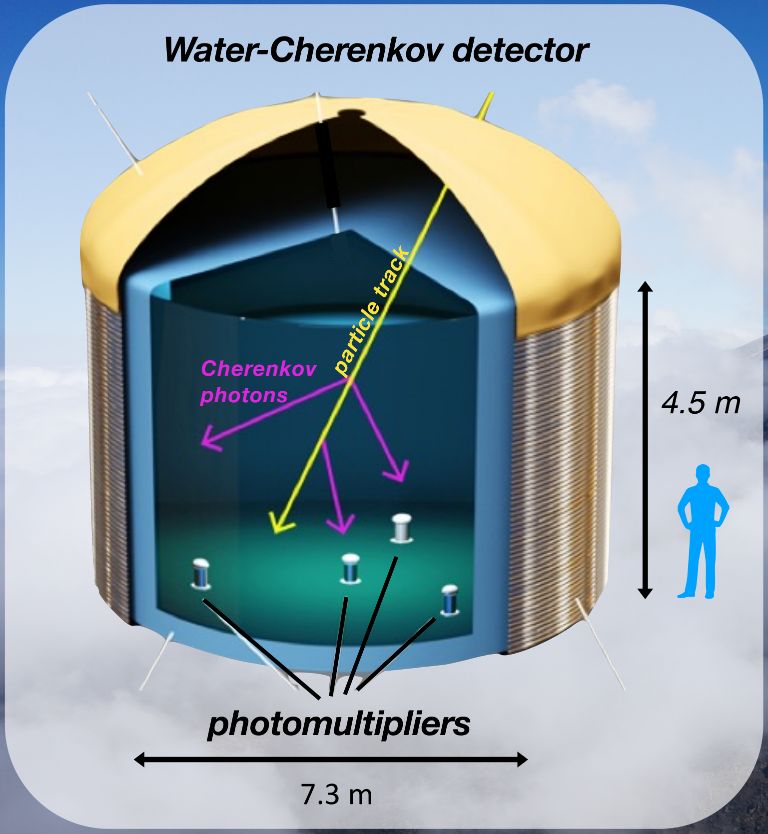
size, fill factor and altitude (move detector up to shower max)

Increase altitude: MILAGRO → HAWC → SWGO

Increase also fill-factor and size: Tibet → LHAASO & SWGO

+ muon detection

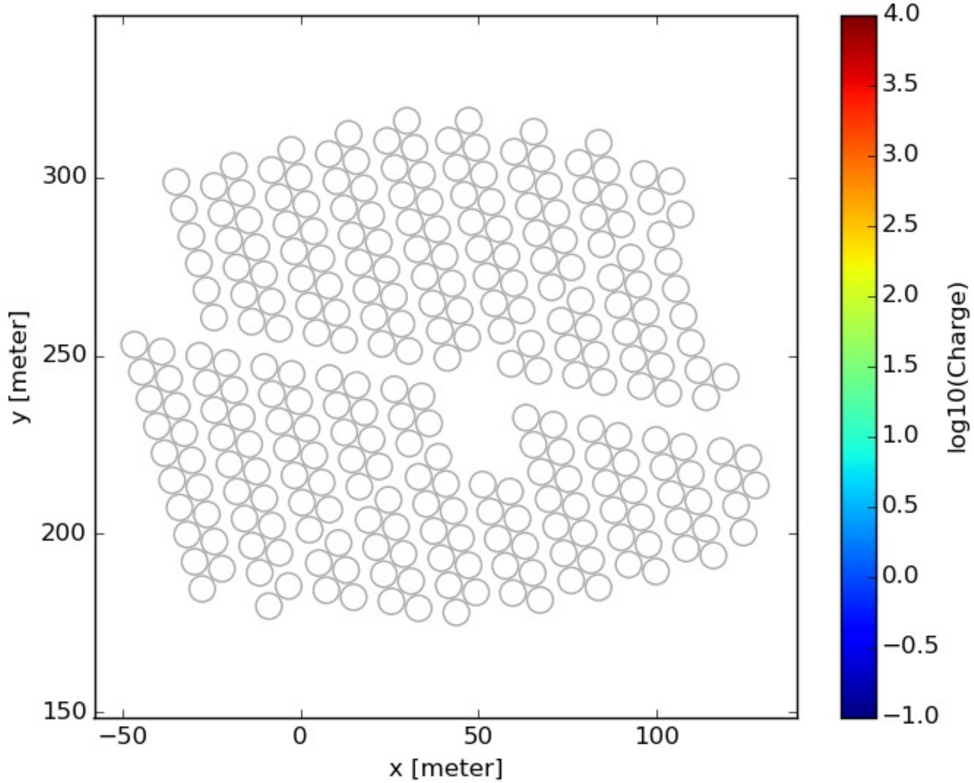
e.g. HAWC



- 300 Water Cherenkov Particle detectors
- 1200 Photo-Multiplier-Tubes
- Completed March 2015
- ~95% uptime
- Area 22000m^2

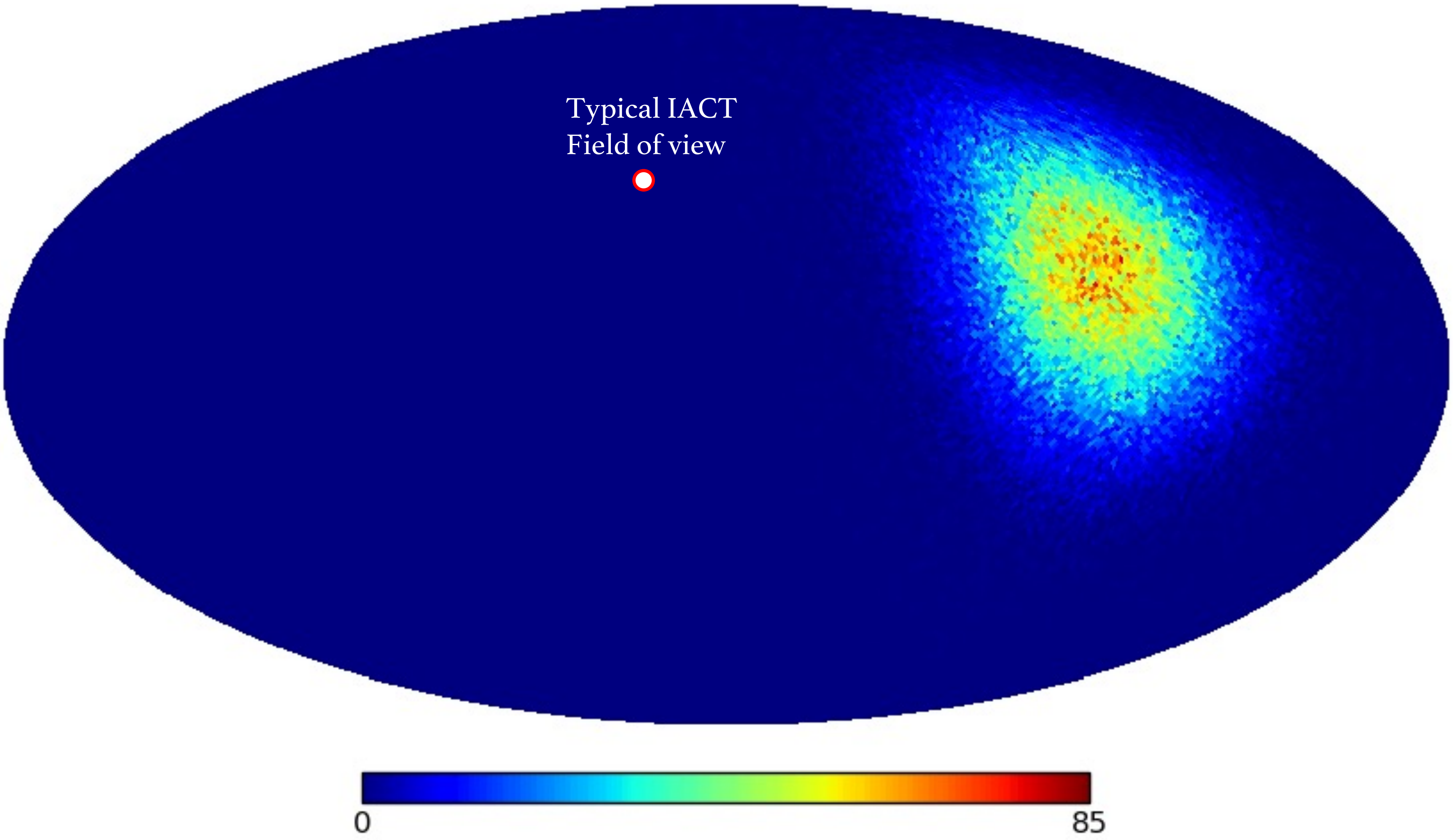
+outrigger upgrade 2018

Events



- Direction from arrival times
  - time resolution ~ns over 100 m lever-arm → angular resolution ~(1 ns * c / 100 m) rad ~ 0.2°
- Energy?
  - More tricky – can measure ground-level size but big fluctuations doing to X_{max} differences / shower development
- Hadron Rejection?
  - Later

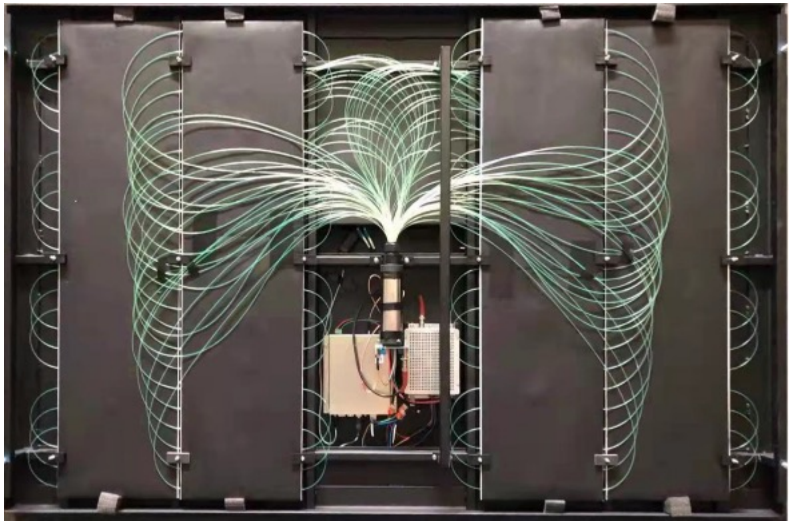
e.g. HAWC

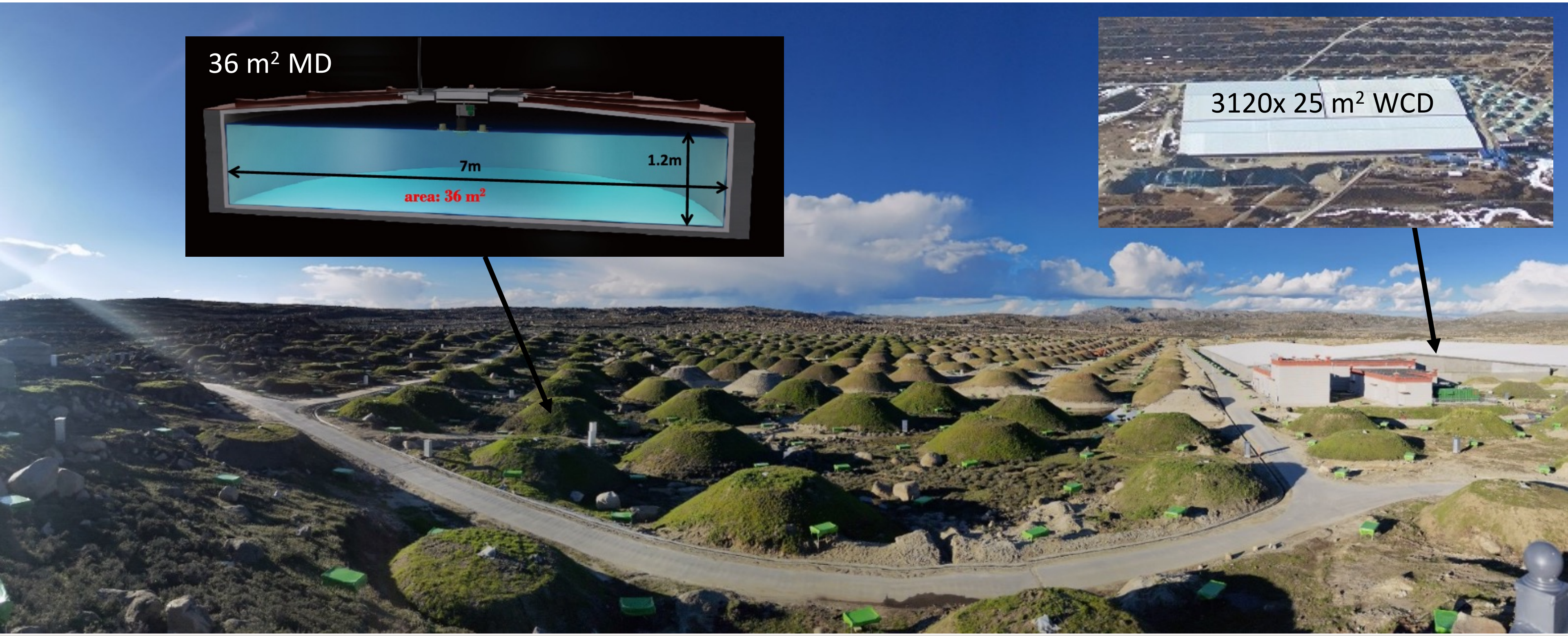


LHAASO

- Completed 2021
  - KM2A
    - ED scintillators, MD buried muon dets

1 m² ED
Green Boxes
Below





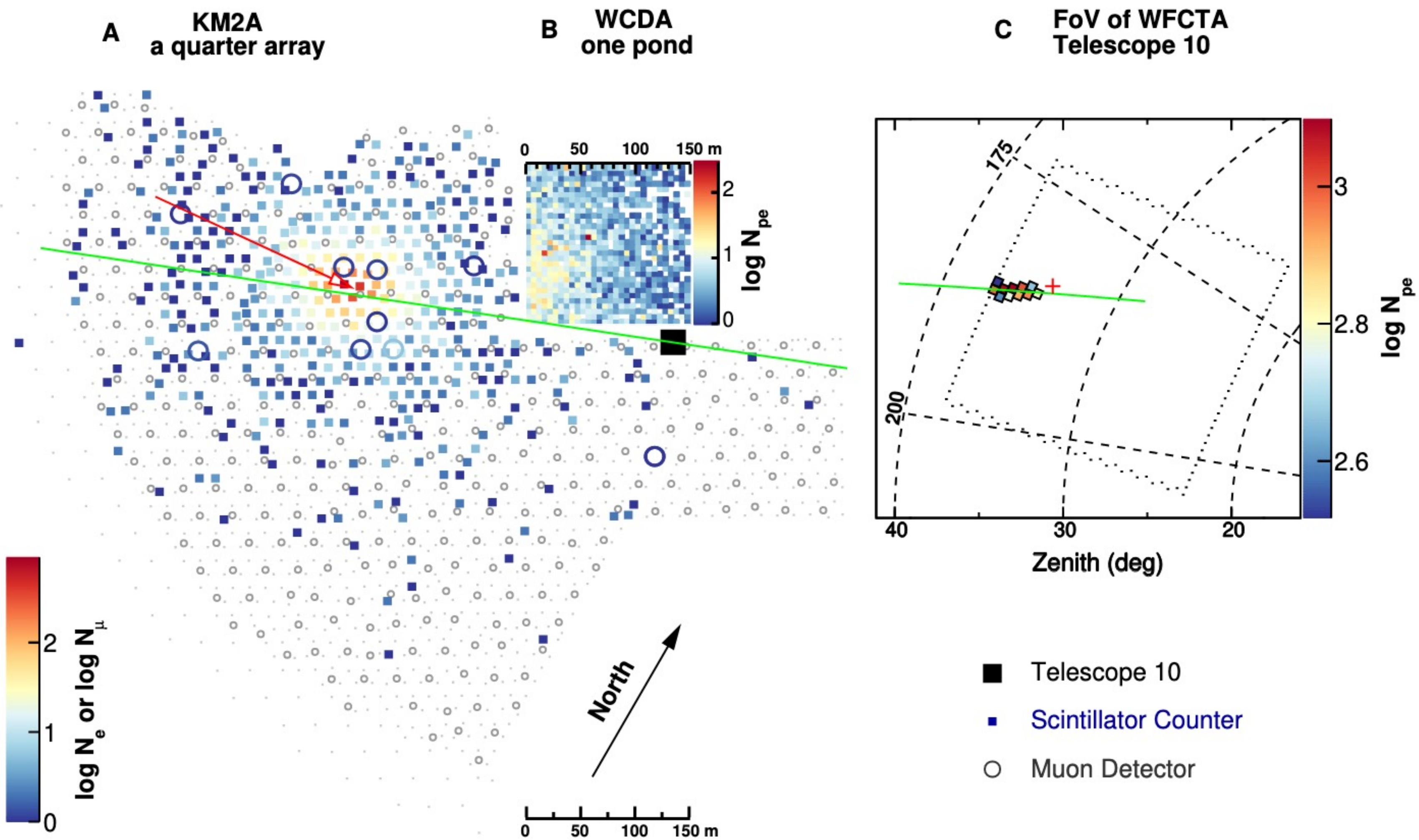
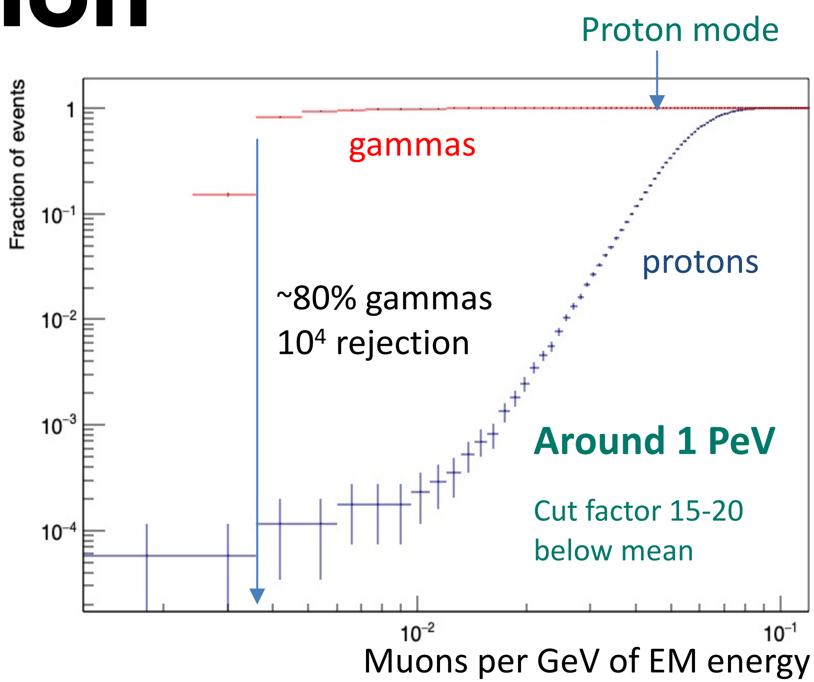


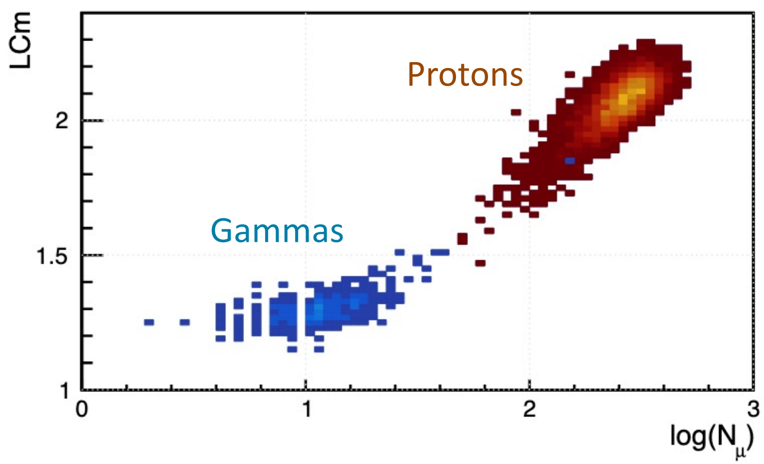
Figure 1: **The 0.88 PeV γ-ray event from the Crab recorded by the LHAASO detectors.** In panel A, squares indicate the scintillator counters of KM2A, colored according to the logarithm of number of detected particles N_e (color bar). The open circles indicate the 11 Muon Detectors of KM2A triggered by the shower. The position of the core is indicated by the red arrow, which is orientated in the arrival direction of the primary photon. The panel

Background Rejection

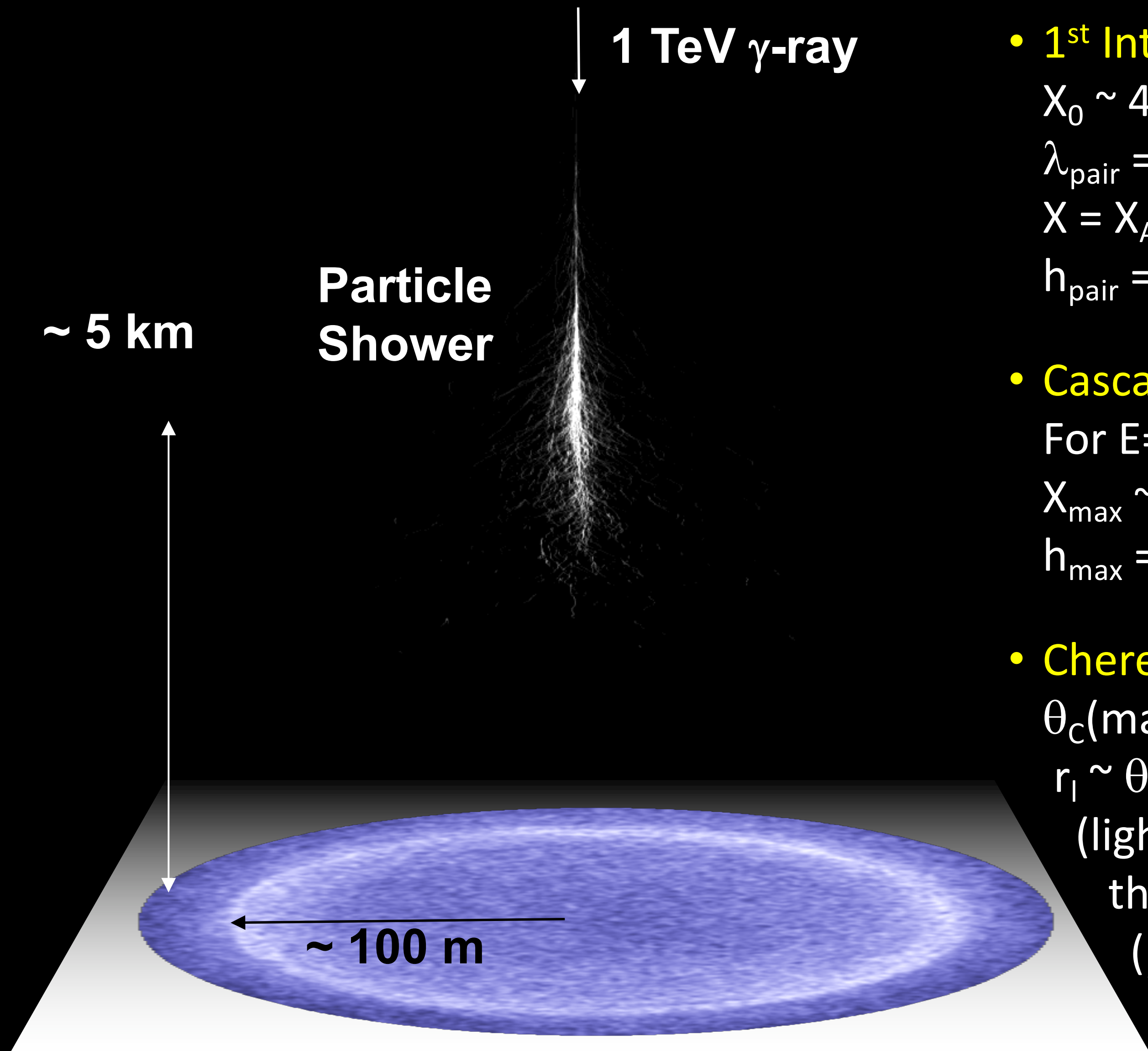
- Muons
  - Pion production in hadronic showers – lots of muons. Rare muon pair production in gamma showers
  - Most shower muons > 1 GeV, reach buried LHAASO MDs, electromag. component absorbed
- LDF, sub-structure, azimuthal asymmetry
  - Sub-showers in hadronic showers produce additional fluctuations, closely correlated with muon number – tail of very gamma-like protons



Conceição et al arXiv 2204.1233



Cherenkov Light

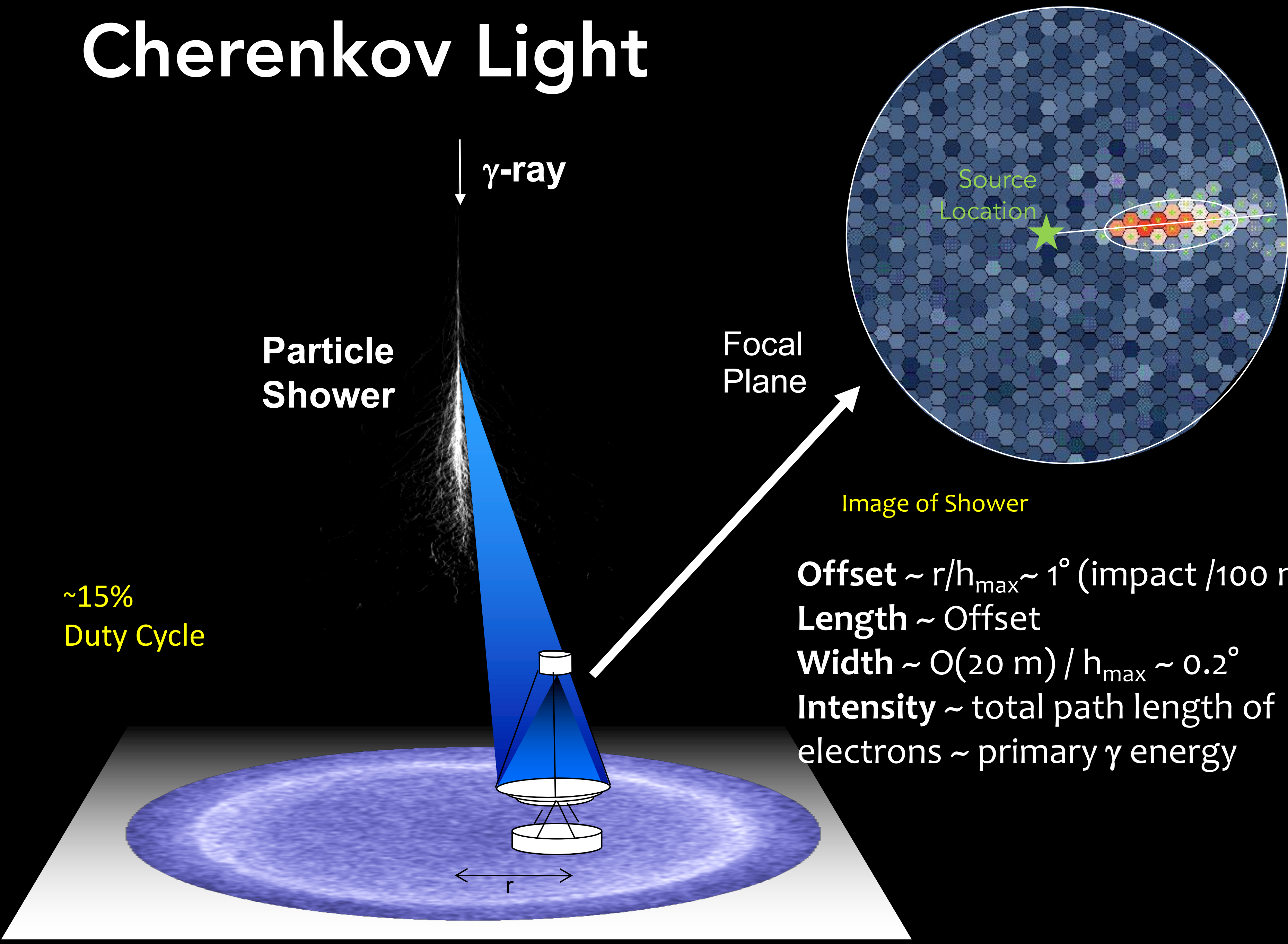


- 1st Interaction:
  $X_0 \sim 40\ g/cm^2$
  $\lambda_{pair} = 9/7\ X_0 \sim 50\ g/cm^2$
  $X = X_A\ e^{-h/h0}$ and $X_A \sim 10^3\ g/cm^2$
  $h_{pair} = h_0 \ln(X_A/\lambda_{pair})$ ☛ 20 km

- Cascade:
  For E=1 TeV ($E_C \sim 80$ MeV)
  $X_{max} \sim X_0 \ln (E/E_C) / \ln 2$
  $h_{max} = h_0 \ln(X_A/X_{max})$ ☛ 5 km

- Cherenkov light:
  $\theta_C(max) = acos\ (1/n) \sim 1.4º$
  $r_l \sim \theta_C(max)\ h_{max}$ ☛ 100 m
  (light pool radius)
  threshold ~20 MeV
  ($\beta > 1/n$ e^+/e^- sea level)

Cherenkov Light



Offset ~ r/h_{max}~ 1° (impact /100 m)
Length ~ Offset
Width ~ O(20 m) / h_{max} ~ 0.2°
Intensity ~ total path length of electrons ~ primary γ energy

IACTs

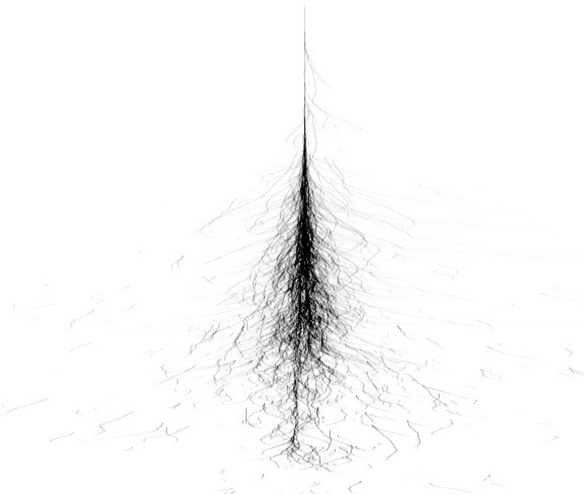
- Whipple, HEGRA, CAT, ++
  - Single telescope → array
  - Finer pixilation
- HESS, MAGIC, VERITAS
  - Arrays of large telescopes, since 2004
- → CTA

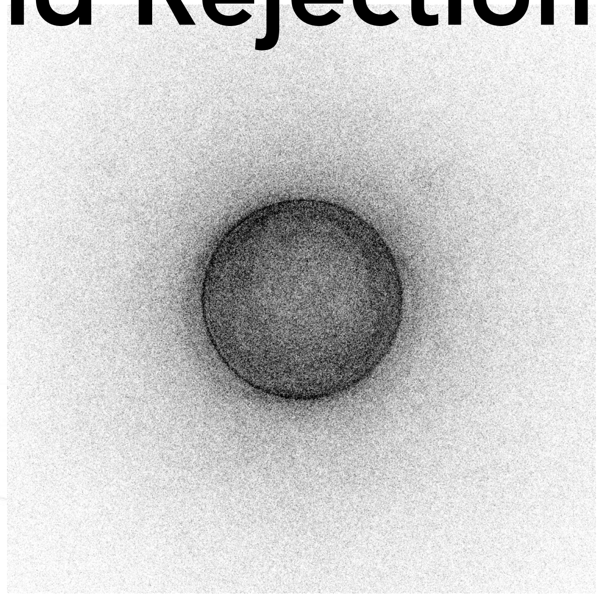
Collection area of single tel ~10^5 m^2
~10% duty cycle, pointed → typ. 50 hours of obs.
Exposure O(10^{14} cm^2 s)

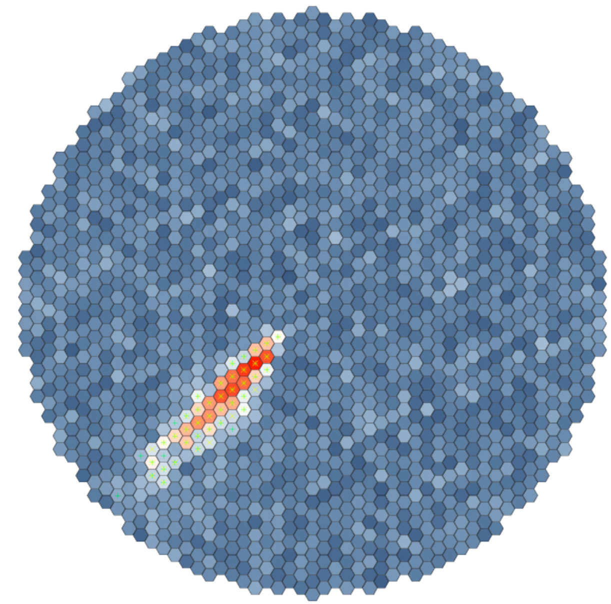
→ For 10 events > 100 TeV →**10^{-11} erg cm^2 s**
→ **No known source this bright**
Current ACT spectra to ~80 TeV

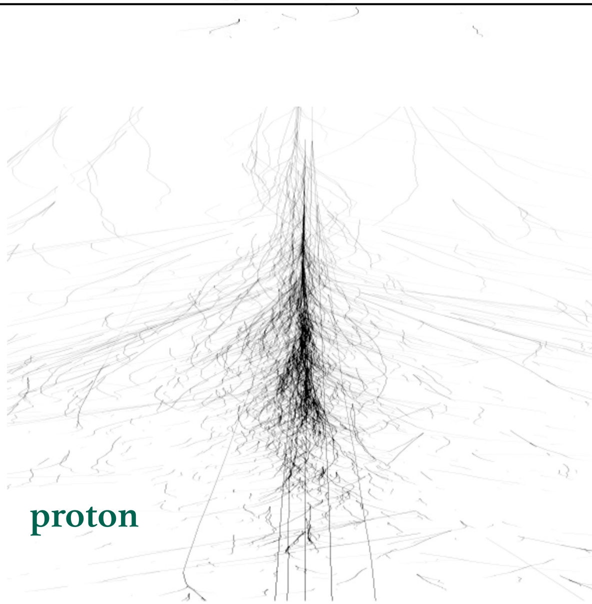
Background Rejection

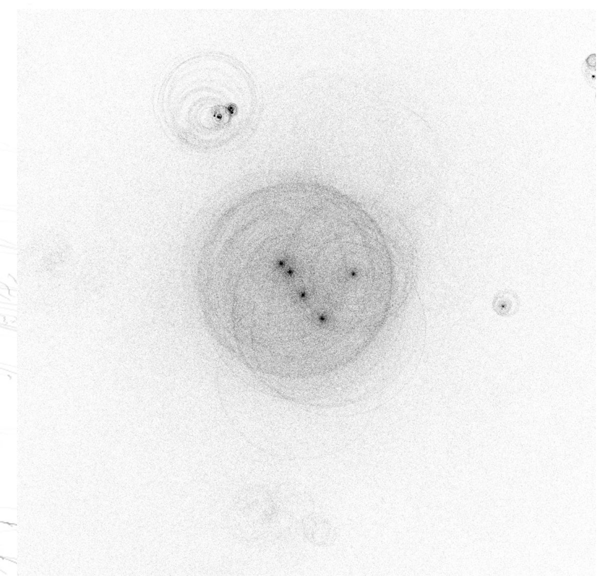
gamma

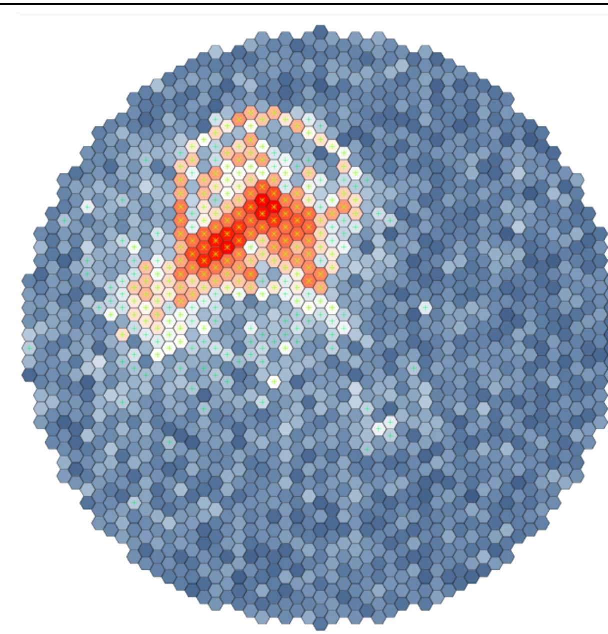












proton

But what are we looking for?

- Gamma-rays produced in interactions of **accelerated** electrons, protons and nuclei
  - Interactions close to acceleration sites or in the general interstellar medium

- Gamma-rays produced in hypothetical beyond standard model processes
  - E.g. Dark Matter annihilation, DM decay, axion conversion
  - SPOILER ALERT: no significant evidence for beyond SM physics from gammas yet → but reaching critical sensitivity for a **thermal relic**

Radiation: Electrons

$$E_{s,\mathrm{eV}} = 0.087 E_{e,\mathrm{TeV}}^2 B_{\mu\mathrm{G}}.$$

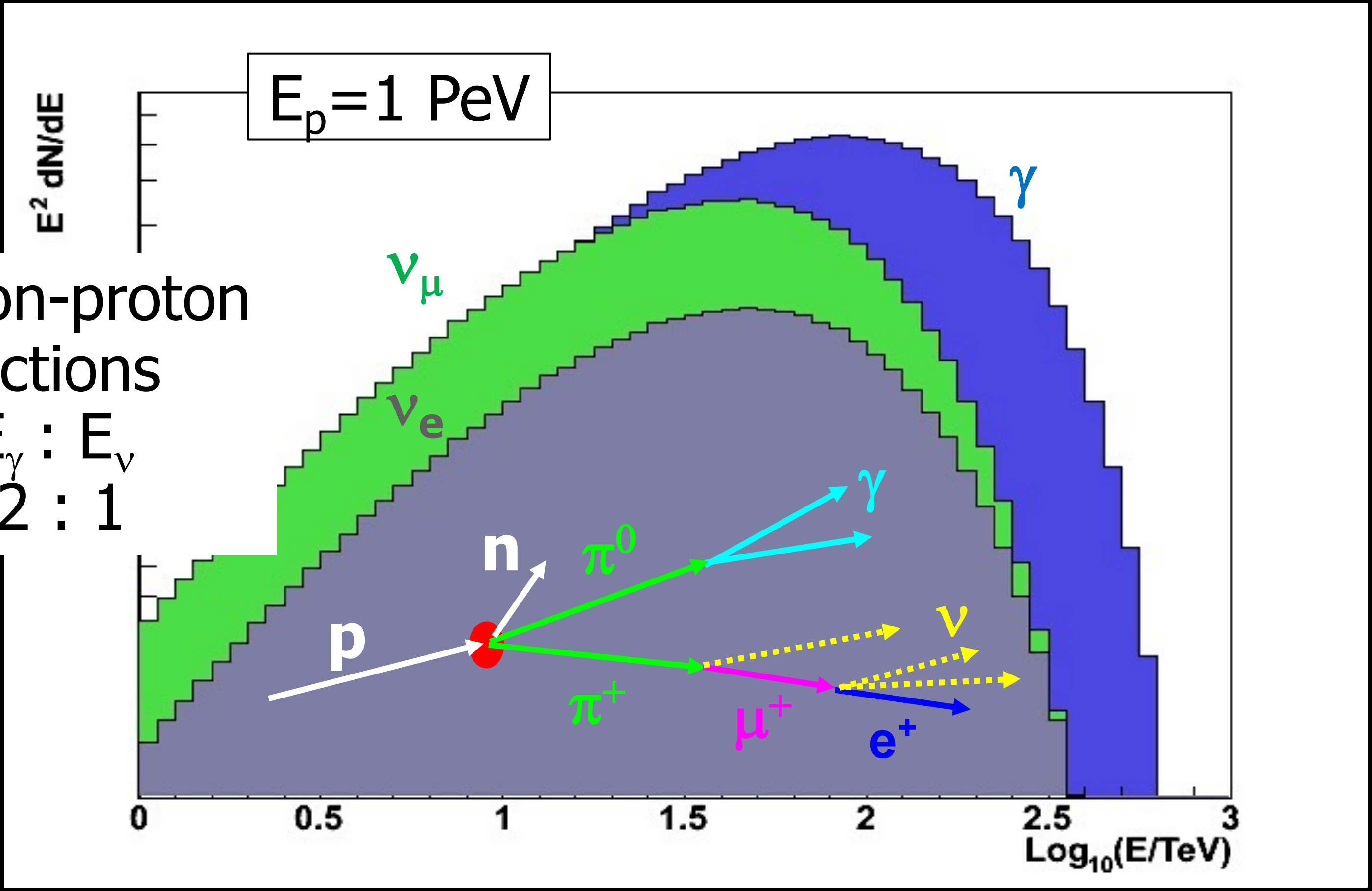
- Synchrotron emission
  - Flux is proportional to energy density of magnetic field ($\propto B^2$)
  - Energy of synchrotron photons is proportional to B and goes with E^2 (until a "crisis" at ultra-high energies "Klein-Nishina regime")
  - $dE/dt \propto E^2$ – high energy particles radiate much more efficiently, "cooling time" $\equiv E/(dE/dt)$ is $\propto 1/E$

$$E_{\gamma,\mathrm{TeV}} \approx 33 E_{e,\mathrm{TeV}}^2 k T_{\mathrm{eV}},$$

- Inverse Compton scattering
  - Flux is proportional to energy density of radiation field
  - Energy of IC photons is proportional to target photon energy and goes with E^2 (until a "crisis" when $4E_eE_T/m_e^2c^4 \sim 1$, then $E\gamma \propto E$ – Klein-Nishina regime)
  - $dE/dt \propto E^2$ – "cooling time" $\equiv E/(dE/dt)$ is $\propto 1/E$
- Bremsstrahlung
  - Important when density is high (i.e. >200 cm^{-3}), $E/dE/dt$ = const

(cf 1 TeV IC emission on CMB)

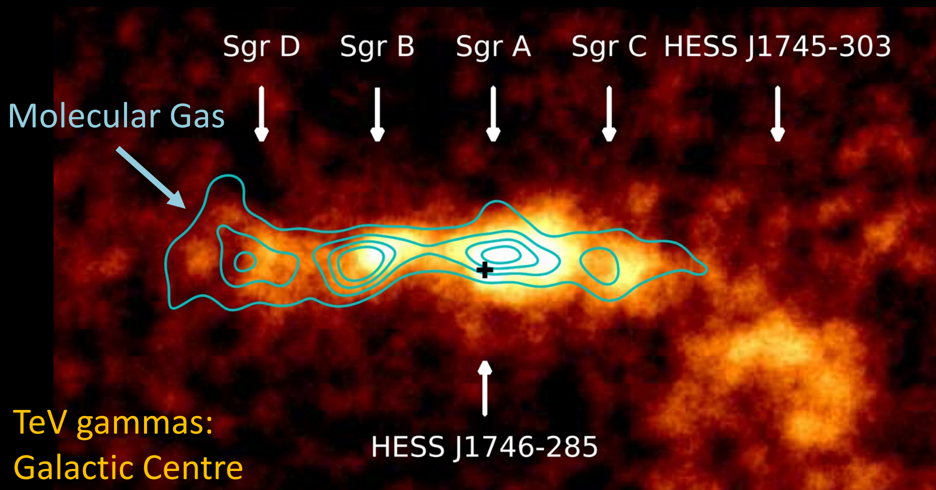
Radiation: Protons & Nuclei



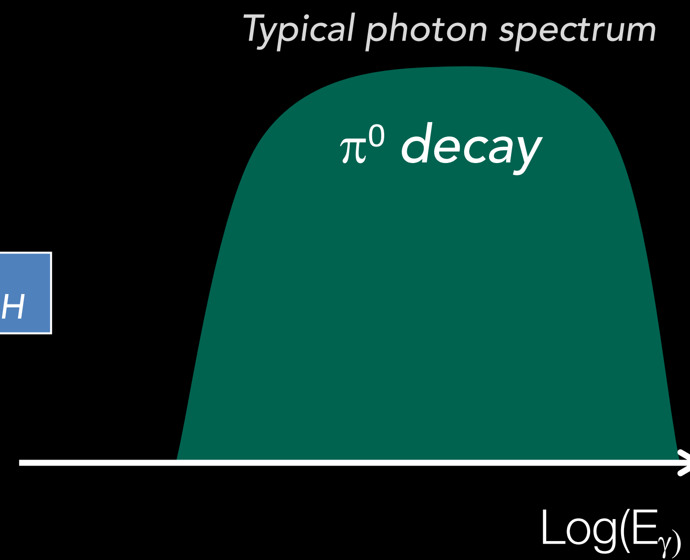
e.g. proton-proton
Interactions
$E_p : E_\gamma : E_\nu$
20 : 2 : 1

- Most important – pion production in nuclear or photo-nuclear reactions
  - p-p (above), p-gamma (in particular excitation of the Delta++ resonance)

Radiation: Protons & Nuclei

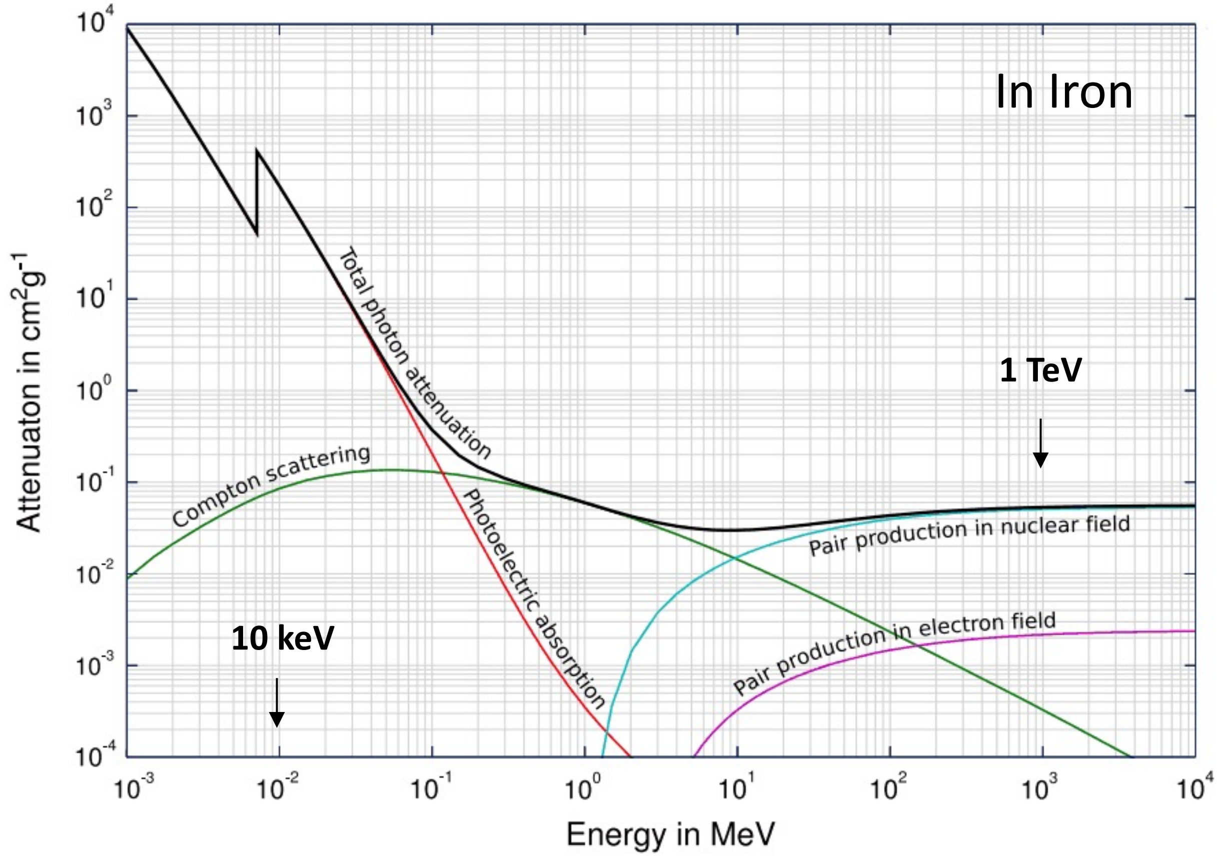


$F_\gamma \sim n_H$



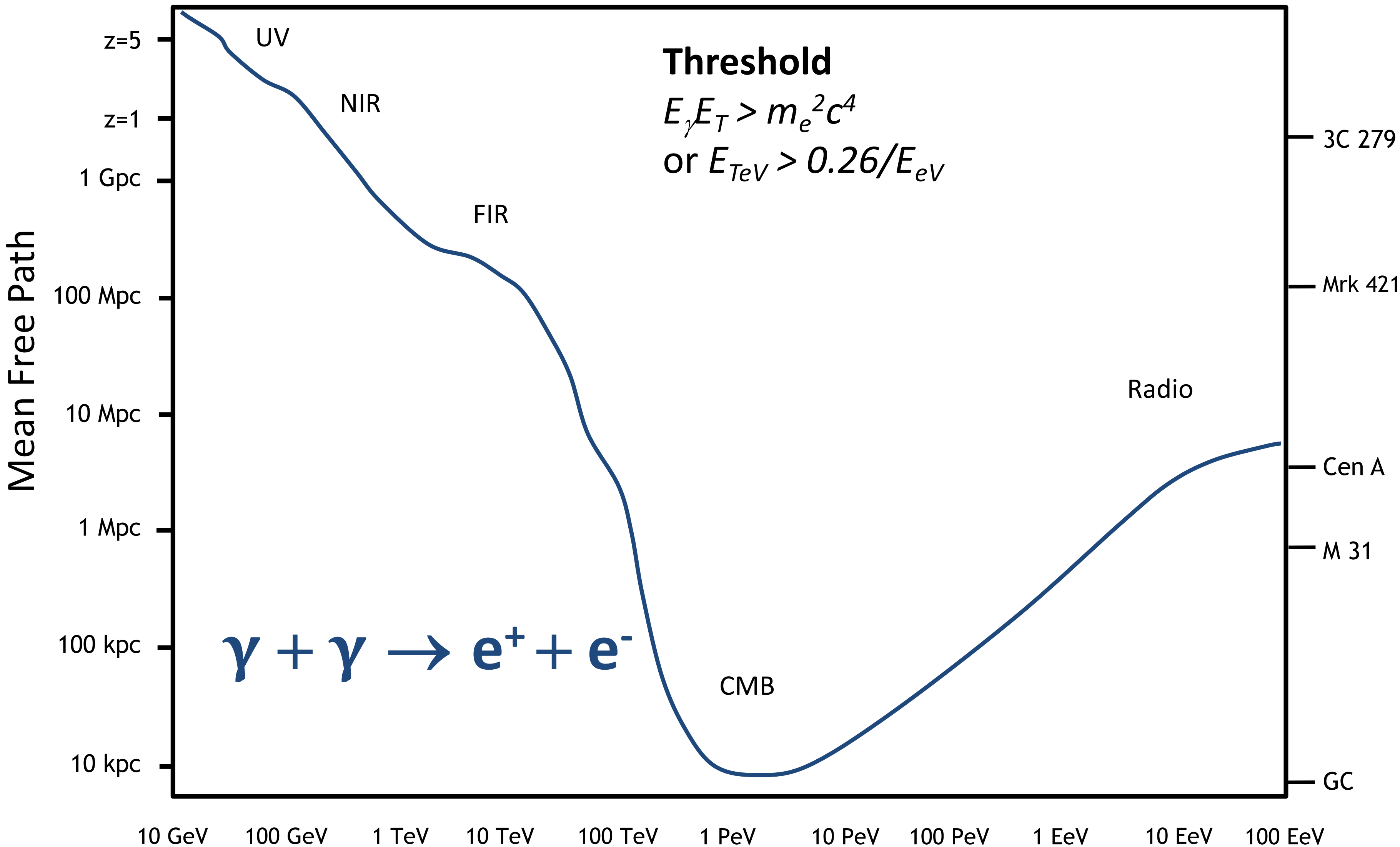
- Dominant proton losses by interactions with (background) protons and nuclei
  - flux proportional to target density as well as cosmic ray density
- Synchrotron emission of protons suppressed by factor $(m_e/m_p)^4$ for equal energy protons and electrons

Propagation: in Matter



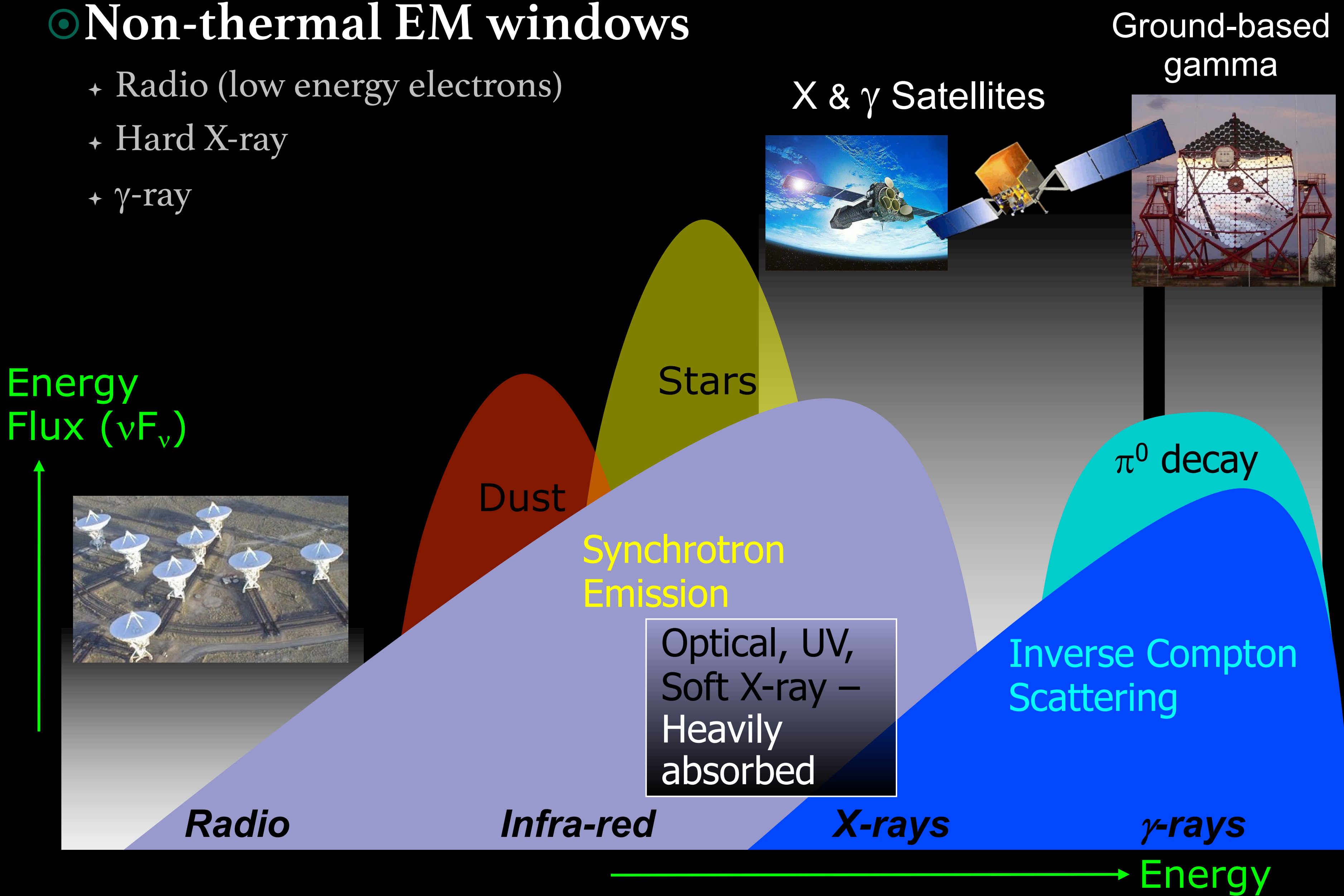
- Pair production mean free path → 9/7 X_0 → 100 g/cm² (in hydrogen)
  - Typical interstellar medium density 1 H atom/cm³ → 100 g/cm² is ~20 Mpc

Propagation: γ-γ interactions

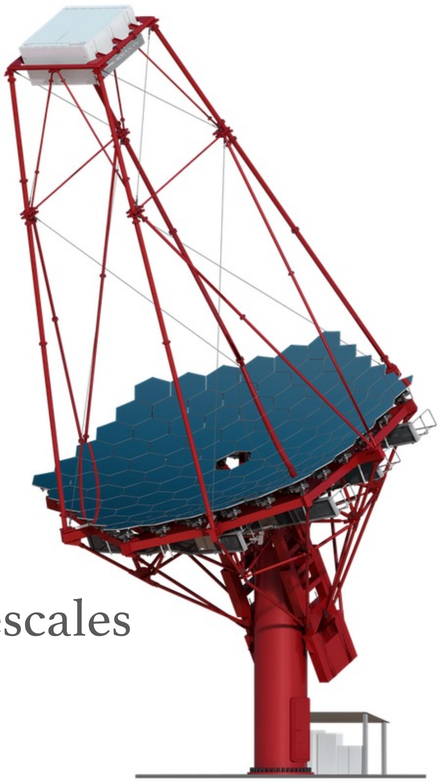


Non-thermal EM windows

- Radio (low energy electrons)
- Hard X-ray
- γ-ray

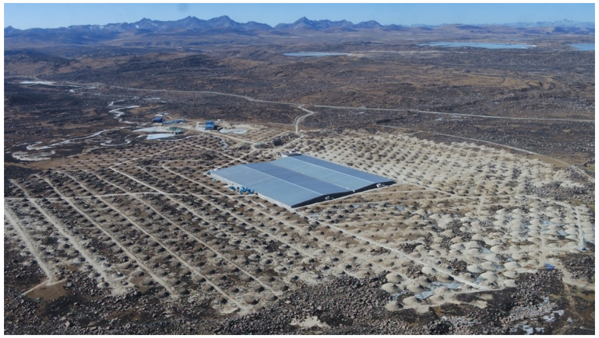


Ground-based γ-rays as a tracer



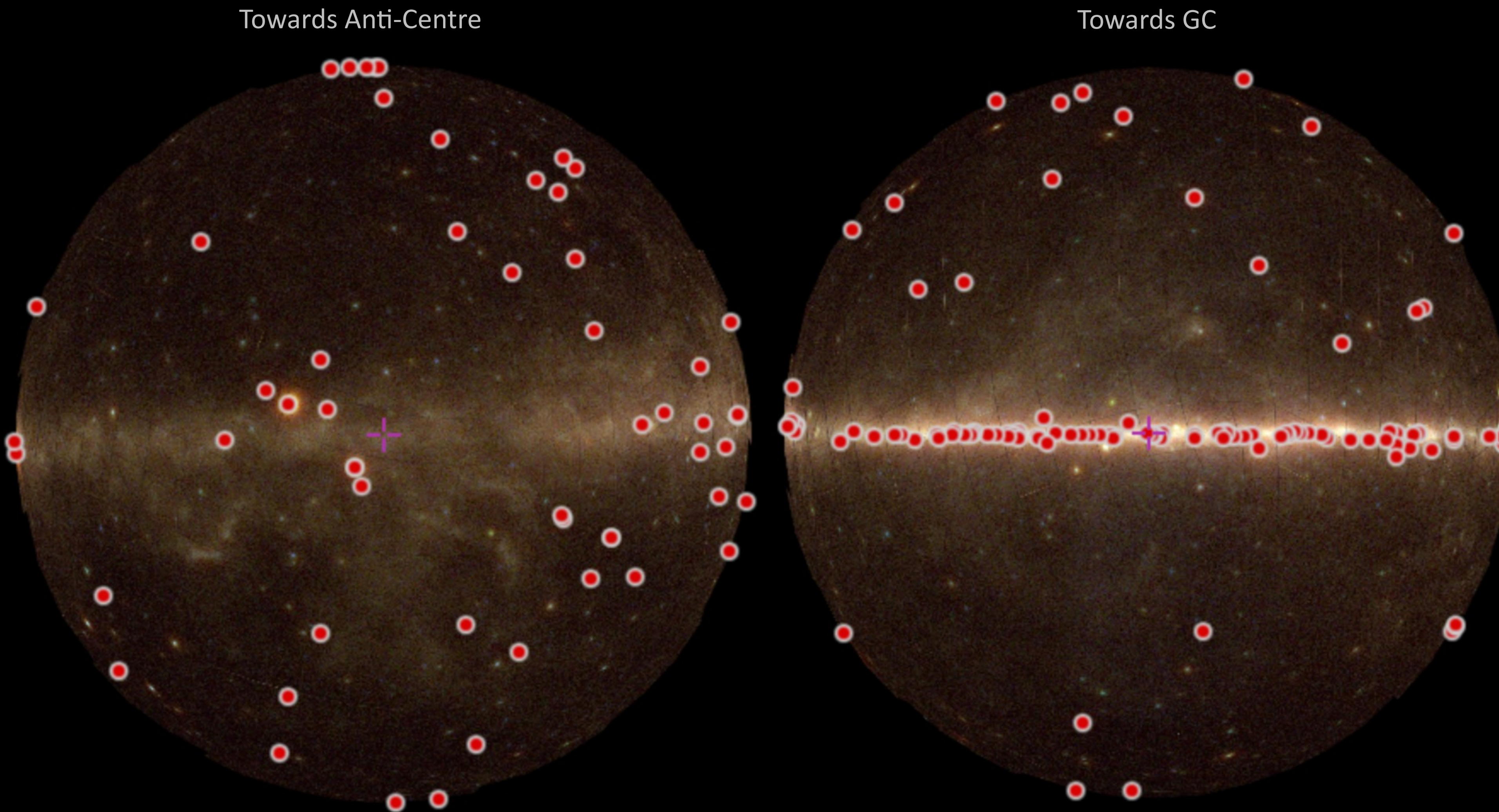
- The VHE-UHE band
  - ~10 GeV - 1 PeV accessible from the ground right now
- cf GeV gammas
  - Large collection areas, high statistics even on short timescales
  - Higher resolution possible
  - Higher energies → the knee, the UHECRs, +++
- cf Neutrinos
  - Cross-section! Much higher statistics
  - (but sometimes ambiguity IC/p-p, absorption)
- cf radio-X-ray sync
  - proton-proton, unknown magnetic fields, ...

Collection area 10^5 – 10^6 m^2 versus 1-100 m^2



The VHE-UHE Sky

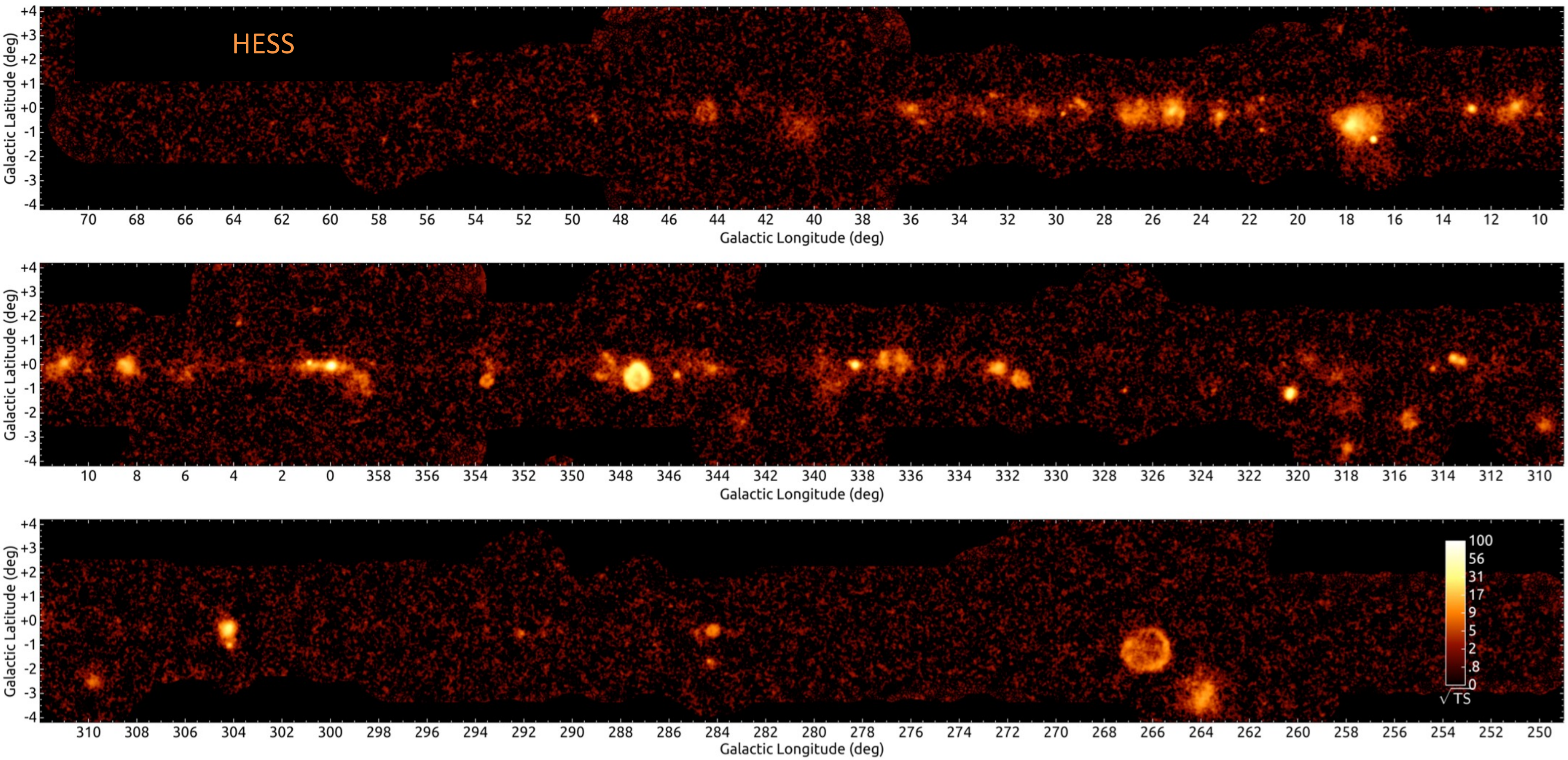
251 sources in Aug 2022



Background: Fermi-LAT

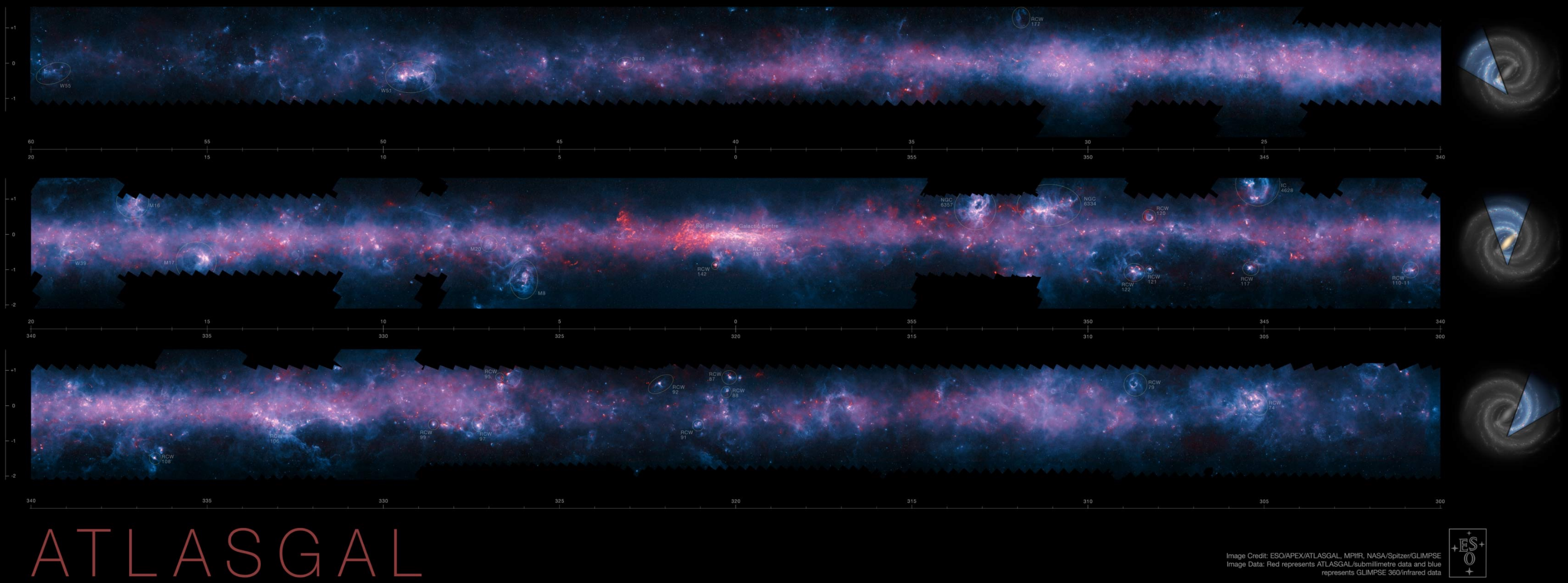
HESS Galactic Plane Survey

2700 h data 2004-2013

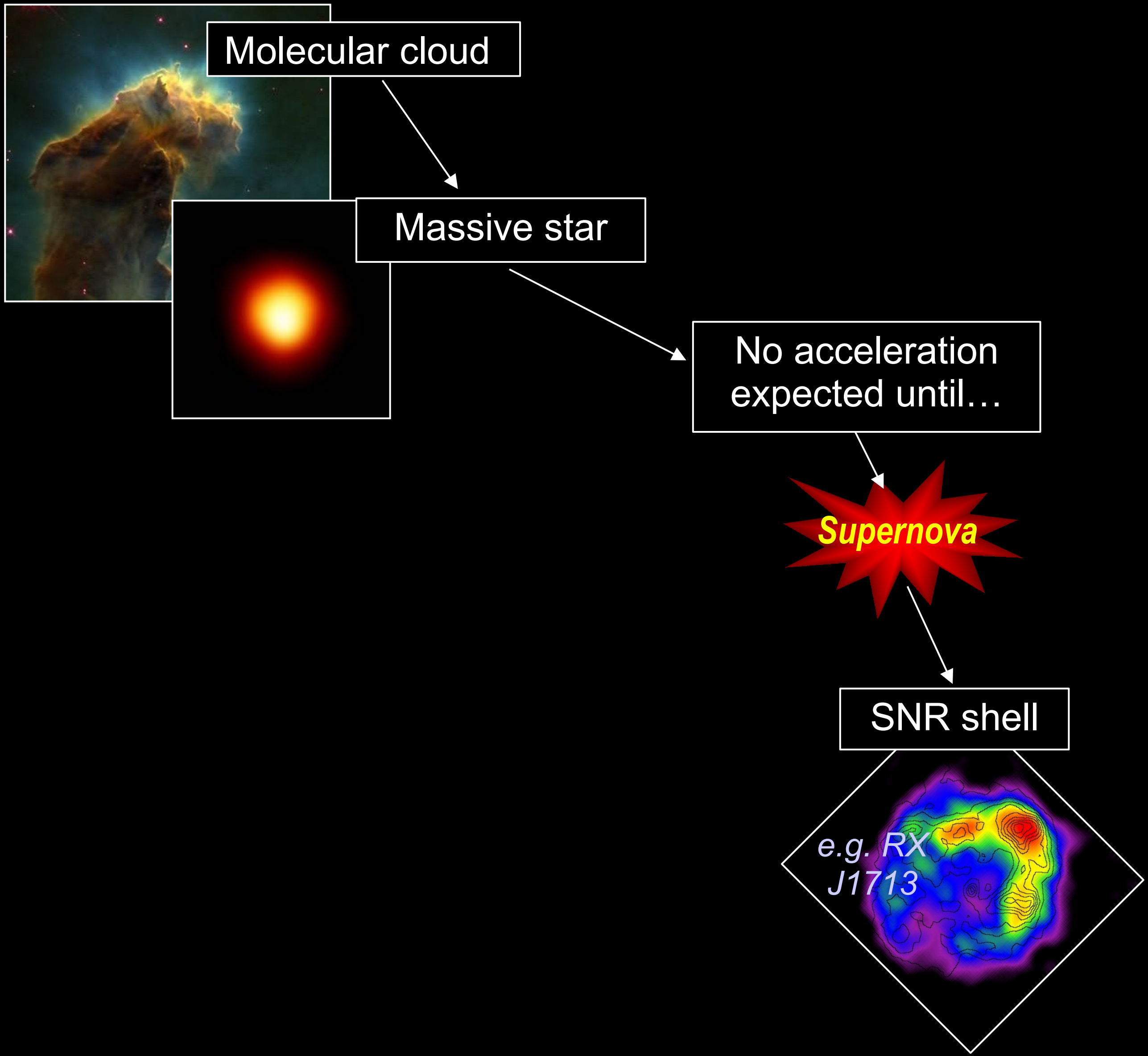


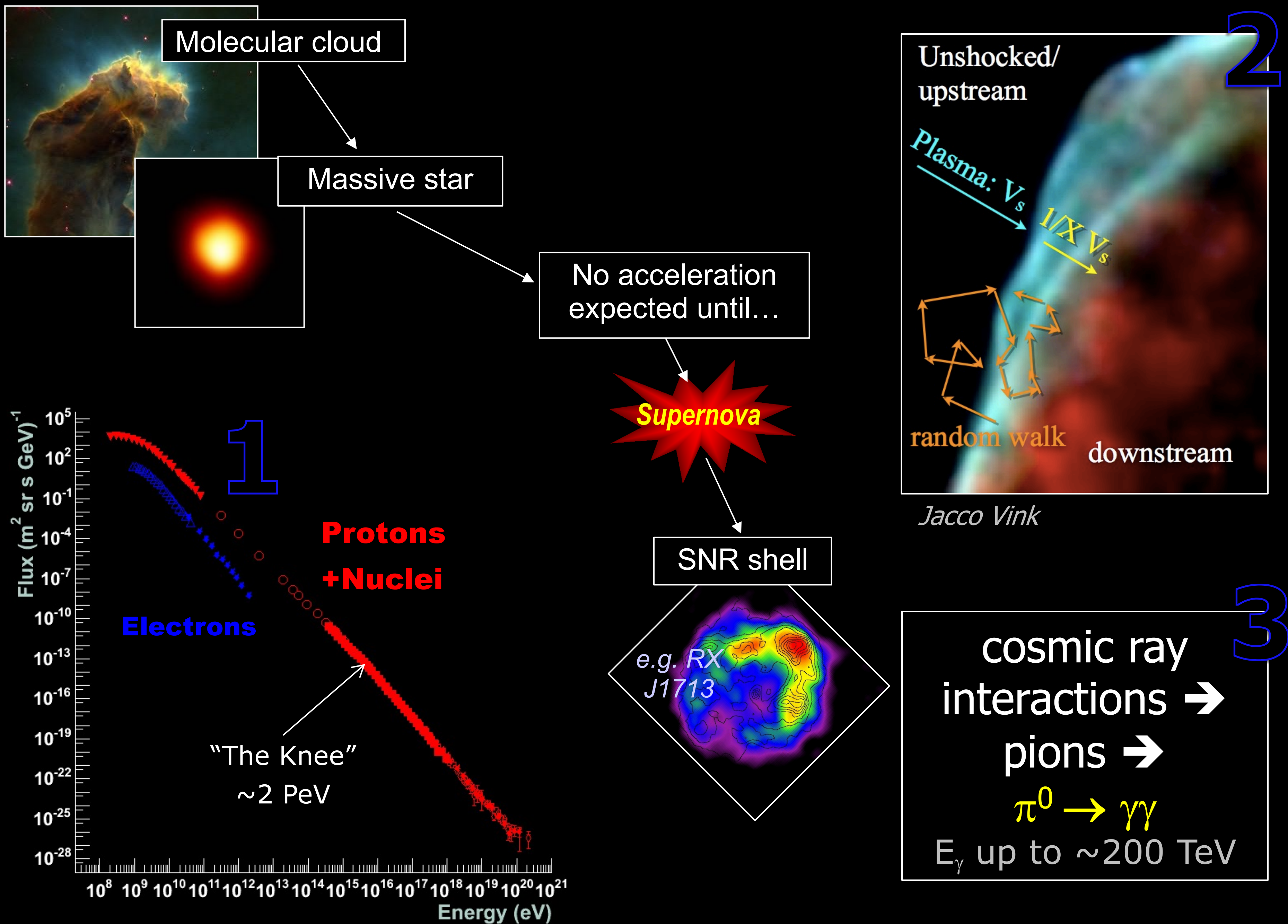
H.E.S.S. phase-I observations of the plane of the Milky Way (A&A Special Issue April 2018)

Molecular Disc

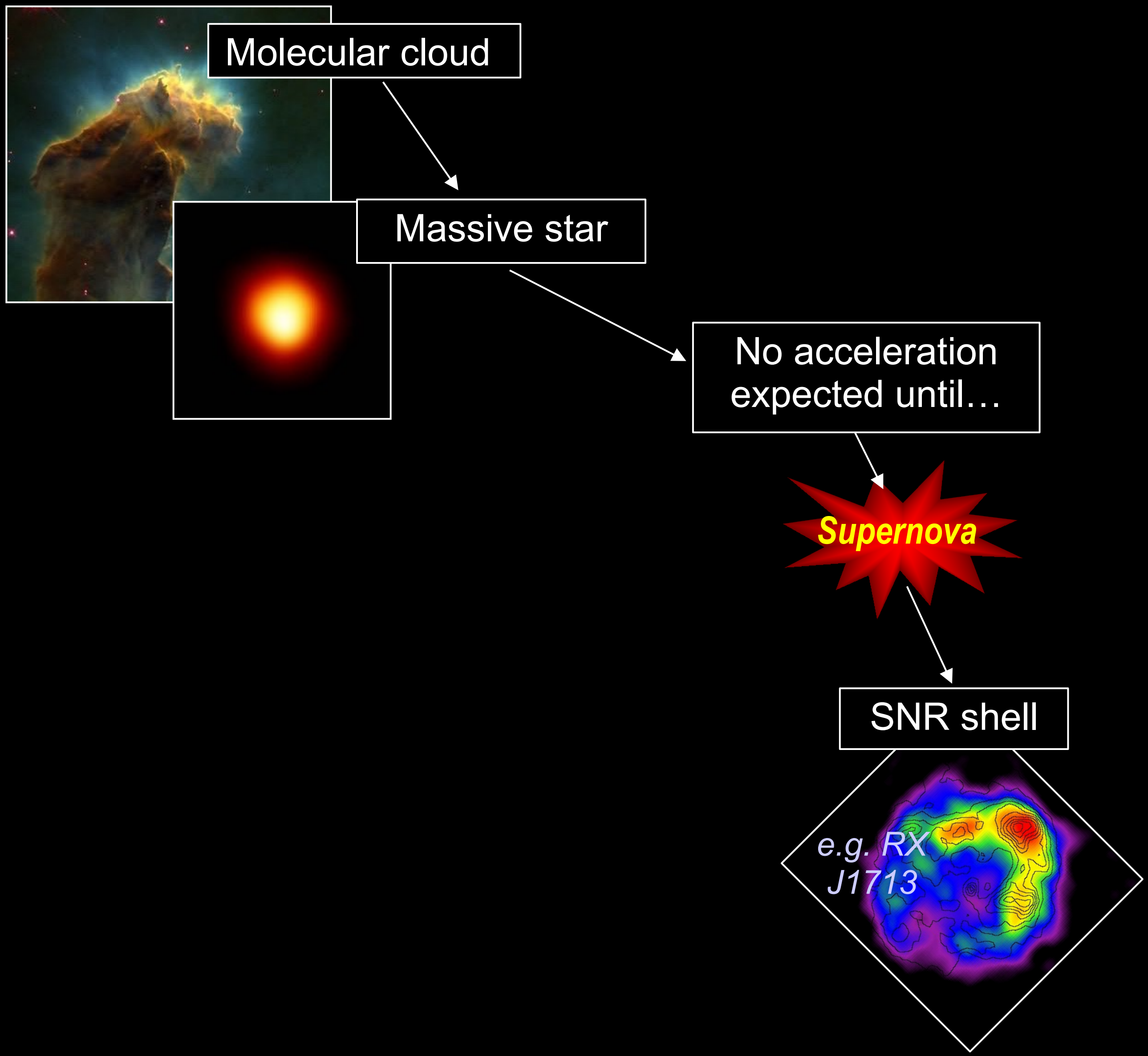


- mm emission from molecules - 50 pc scale height


Molecular cloud
Massive star
No acceleration expected until…
Supernova
SNR shell
e.g. RX J1713



Molecular cloud
Massive star
No acceleration expected until…
Supernova
SNR shell
e.g. RX J1713
1
Flux (m2 sr s GeV)-1
Energy (eV)
Protons +Nuclei
Electrons
"The Knee" ~2 PeV
2
Unshocked/ upstream
Plasma: Vs
1/X Vs
random walk
downstream
Jacco Vink
3
cosmic ray interactions →
pions →
π0 → γγ
Eγ up to ~200 TeV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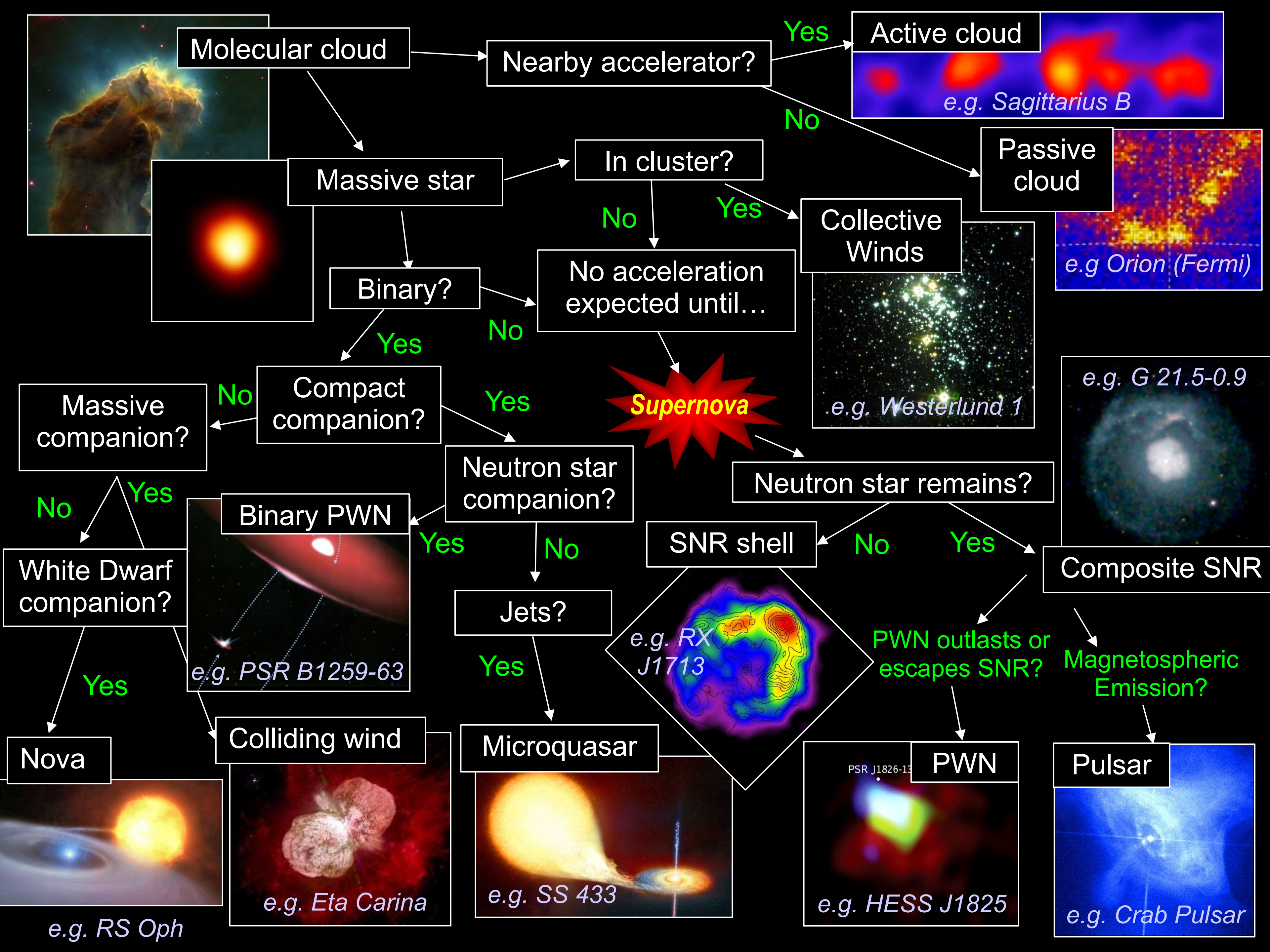
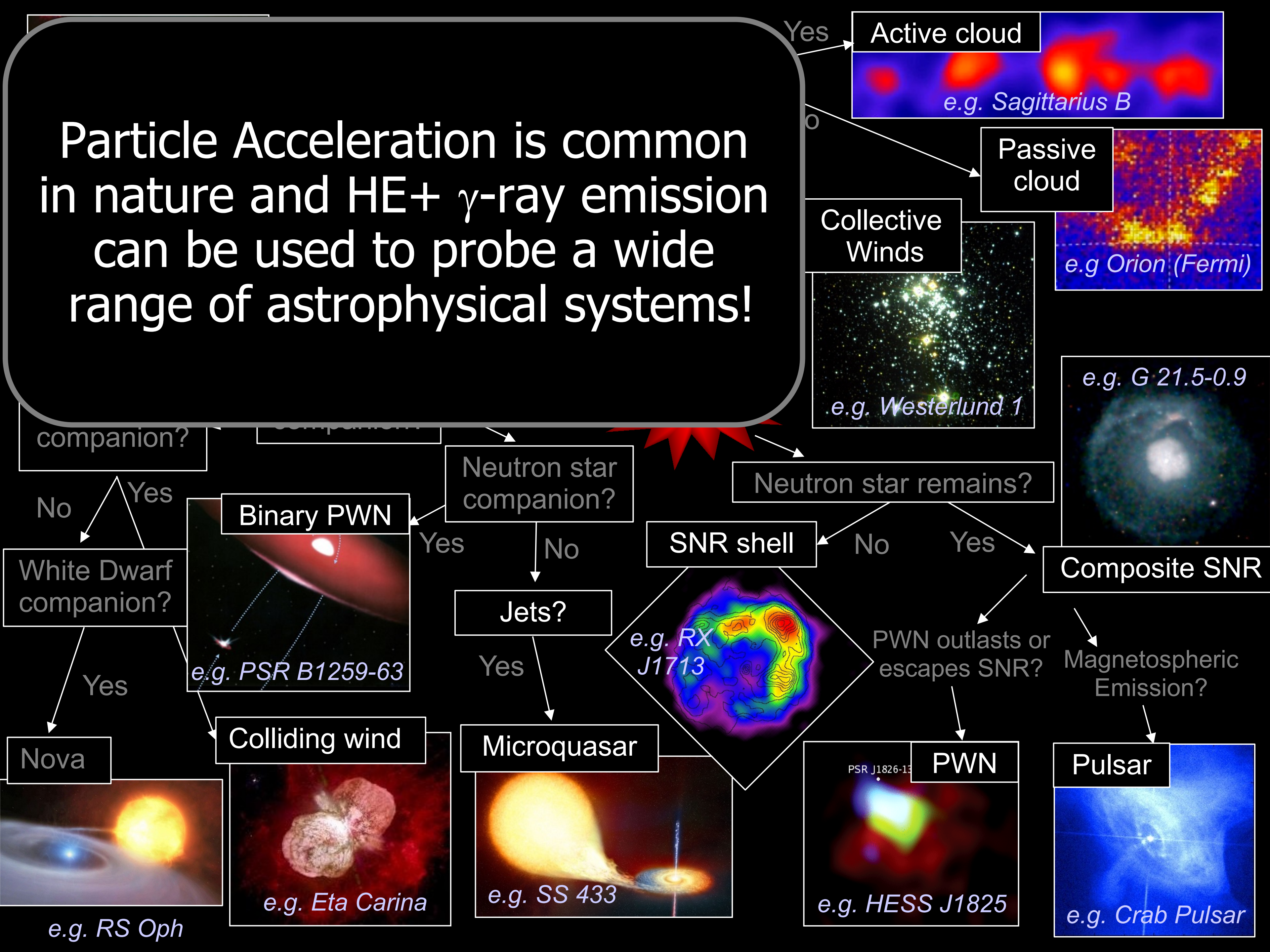
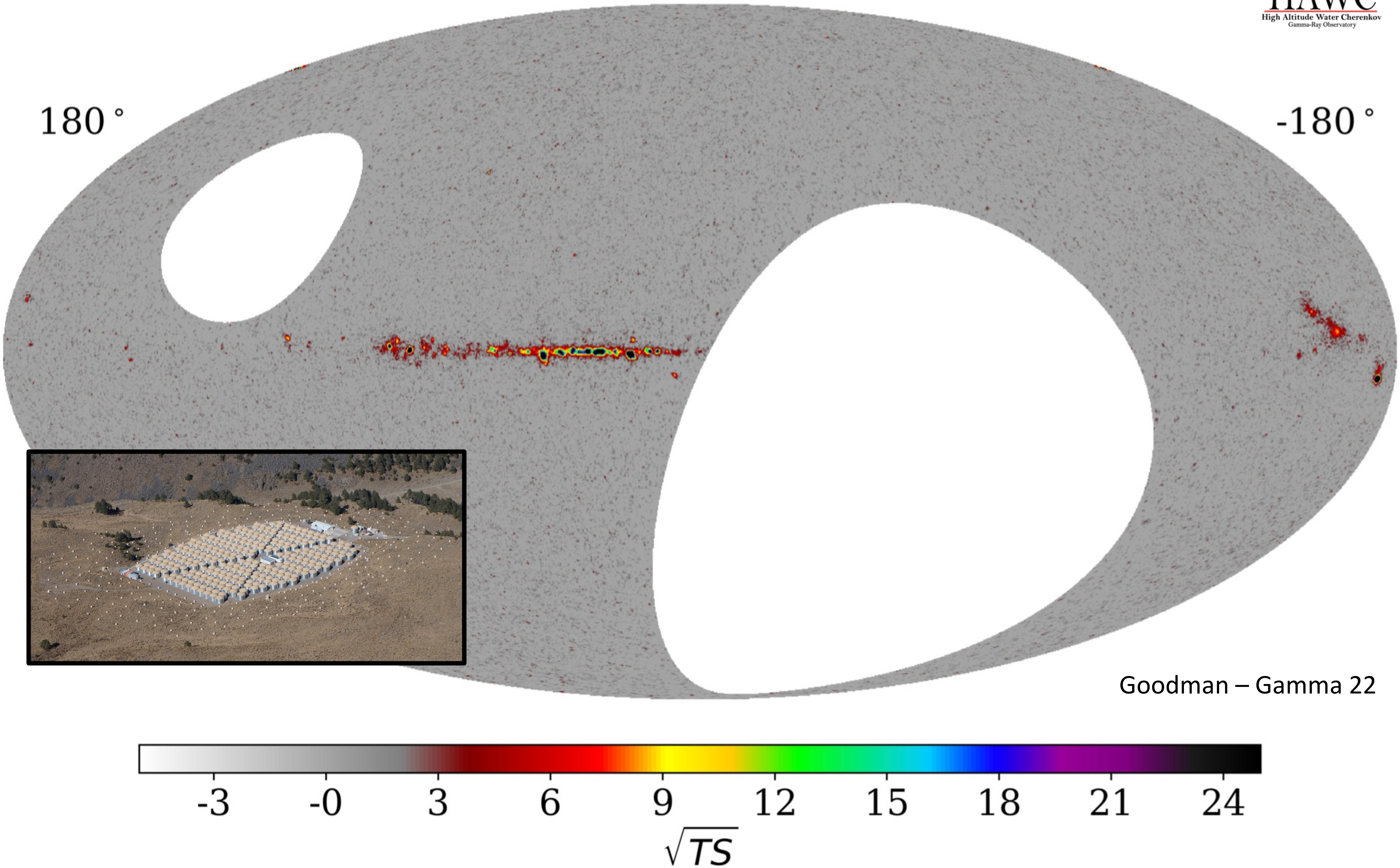


Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
e.g Orion (Fermi)
Massive star
In cluster?
Yes
Collective Winds
e.g. Westerlund 1
No
No acceleration expected until…
Binary?
No
Yes
Supernova
Compact companion?
No
Massive companion?
Yes
Neutron star companion?
Neutron star remains?
e.g. G 21.5-0.9
No
Yes
White Dwarf companion?
Binary PWN
e.g. PSR B1259-63
Yes
No
Jets?
SNR shell
e.g. RX J1713
No
Yes
Composite SNR
PWN outlasts or escapes SNR?
Magnetospheric Emission?
Yes
Yes
Nova
e.g. RS Oph
Colliding wind
e.g. Eta Carina
Microquasar
e.g. SS 433
PWN
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

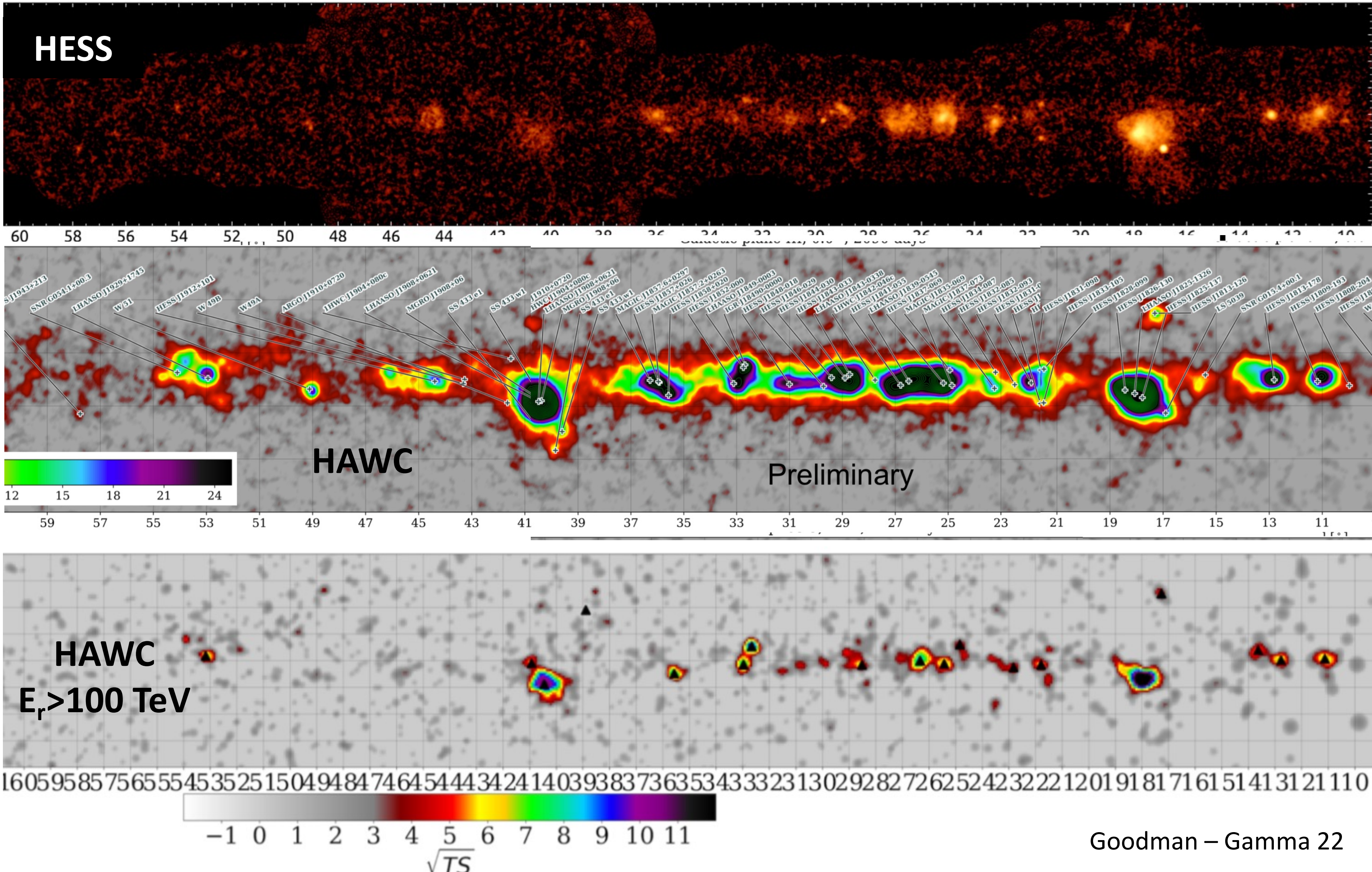


Particle Acceleration is common in nature and HE+ γ-ray emission can be used to probe a wide range of astrophysical systems!
Yes
Active cloud
e.g. Sagittarius B
Passive cloud
e.g Orion (Fermi)
Collective Winds
e.g. Westerlund 1
e.g. G 21.5-0.9
companion?
No
Yes
White Dwarf companion?
Binary PWN
e.g. PSR B1259-63
Neutron star companion?
Yes
No
Jets?
Yes
Neutron star remains?
SNR shell
No
Yes
Composite SNR
e.g. RX J1713
PWN outlasts or escapes SNR?
Magnetospheric Emission?
Yes
Nova
e.g. RS Oph
Colliding wind
e.g. Eta Carina
Microquasar
e.g. SS 433
PWN
PSR J1826-13
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

HAWC 2090-Day TeV Sky Survey Pass 5



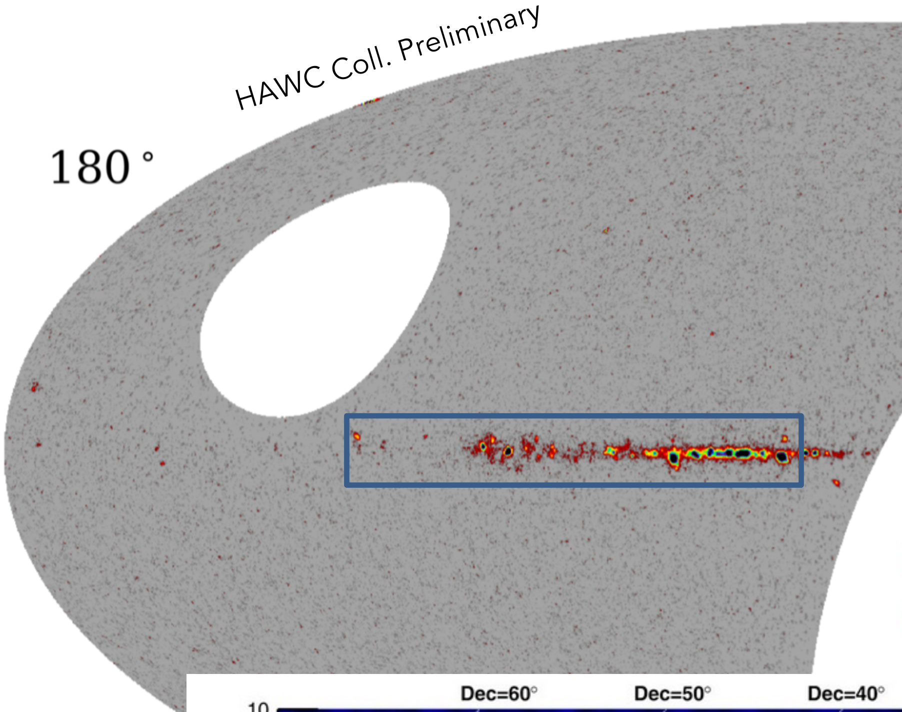
Goodman – Gamma 22

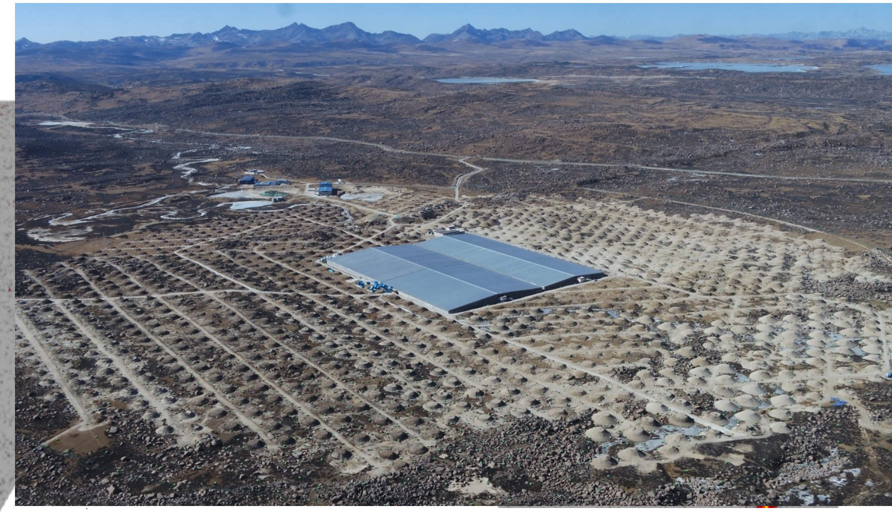


Goodman – Gamma 22

2090 days – Pass 5

LHAASO

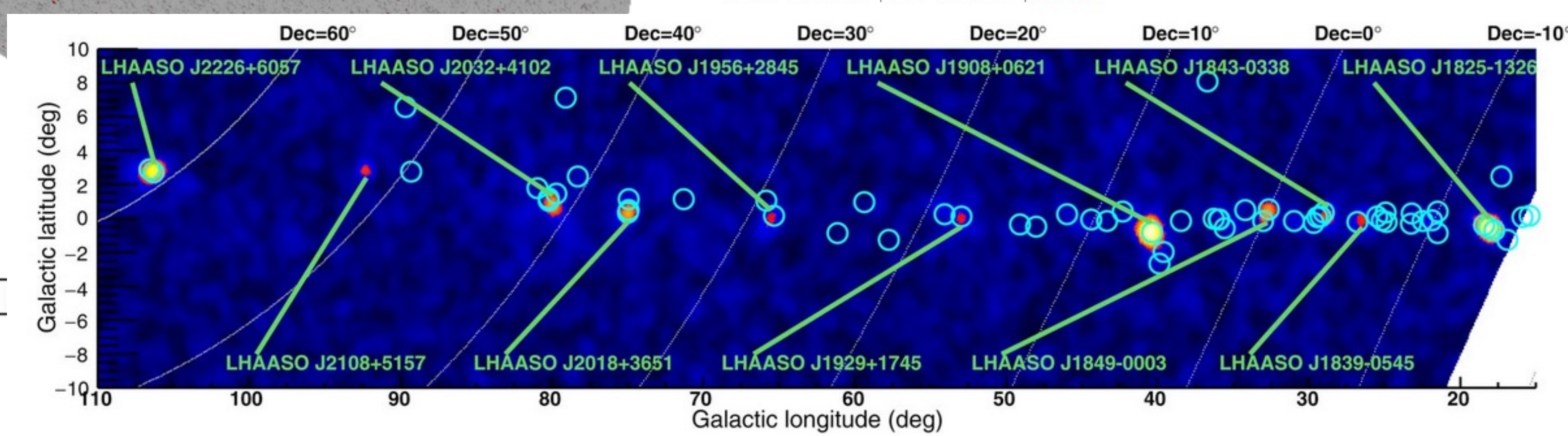




Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

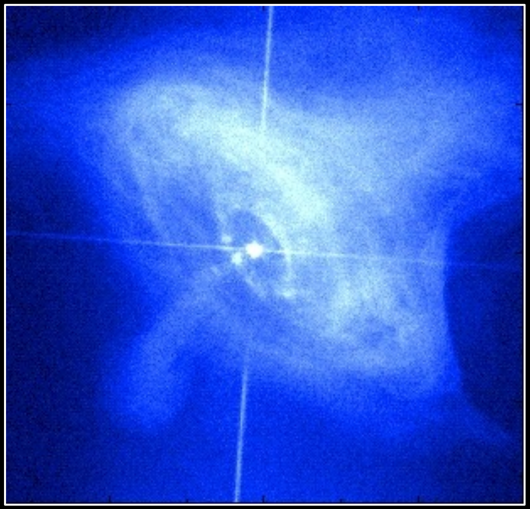
Zhen Cao, F. A. Aharonian, […]X. Zuo

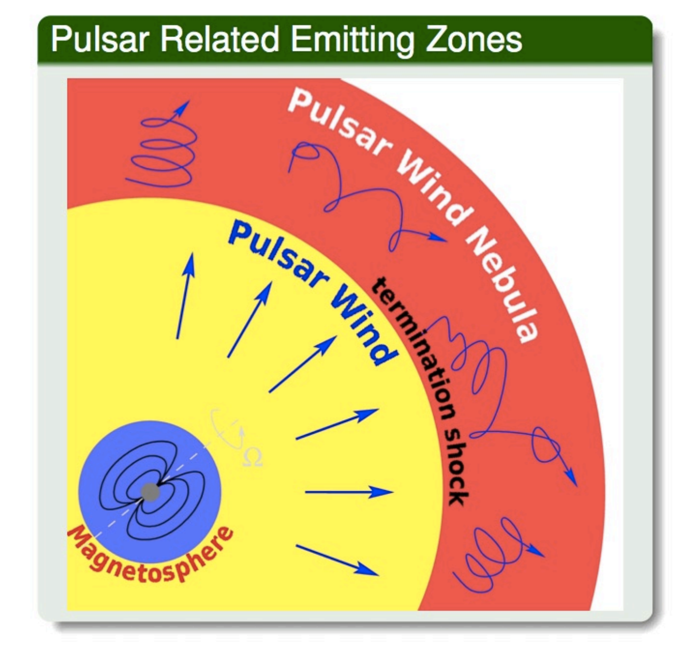
Nature **594**, 33–36 (2021) | Cite this article

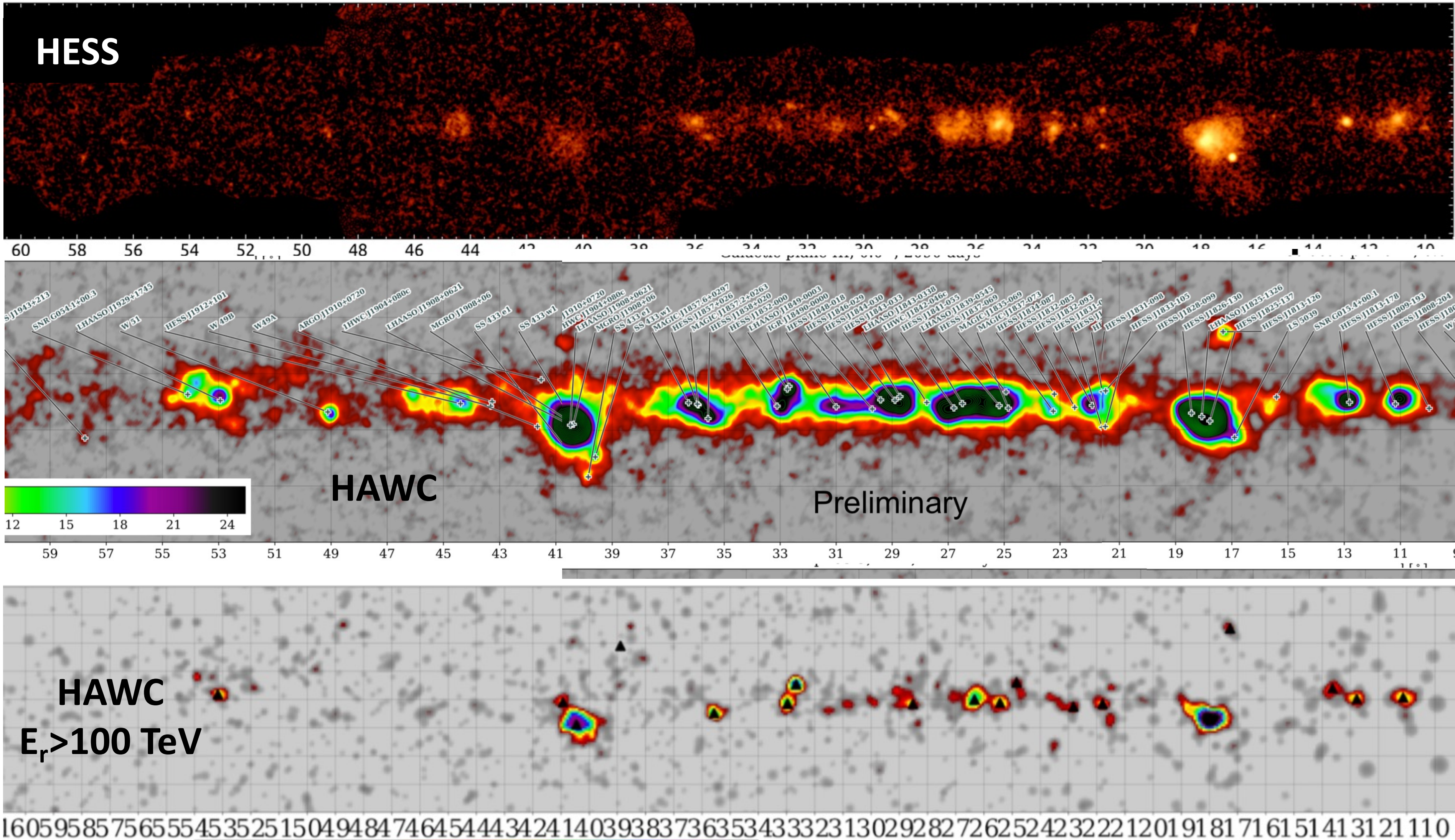


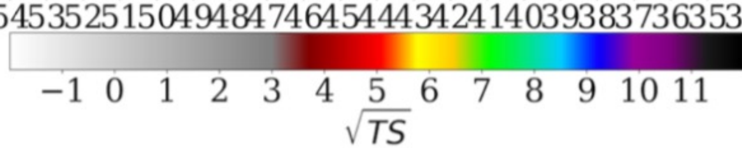
Pulsar Wind Nebulae

- Spinning magnetised object
  - Spin axis not aligned with magnetic axis
    - Pulsed emission from magnetosphere
  - Beyond the 'light cylinder' – relativistic outflow
    - Poynting flux → e^+e^- pairs
    - Somehow – e.g. arXiv:astro-ph/0303194
  - Termination shock due to pressure confinement
    - Particle acceleration at this shock
  - Turbulent zone beyond the shock



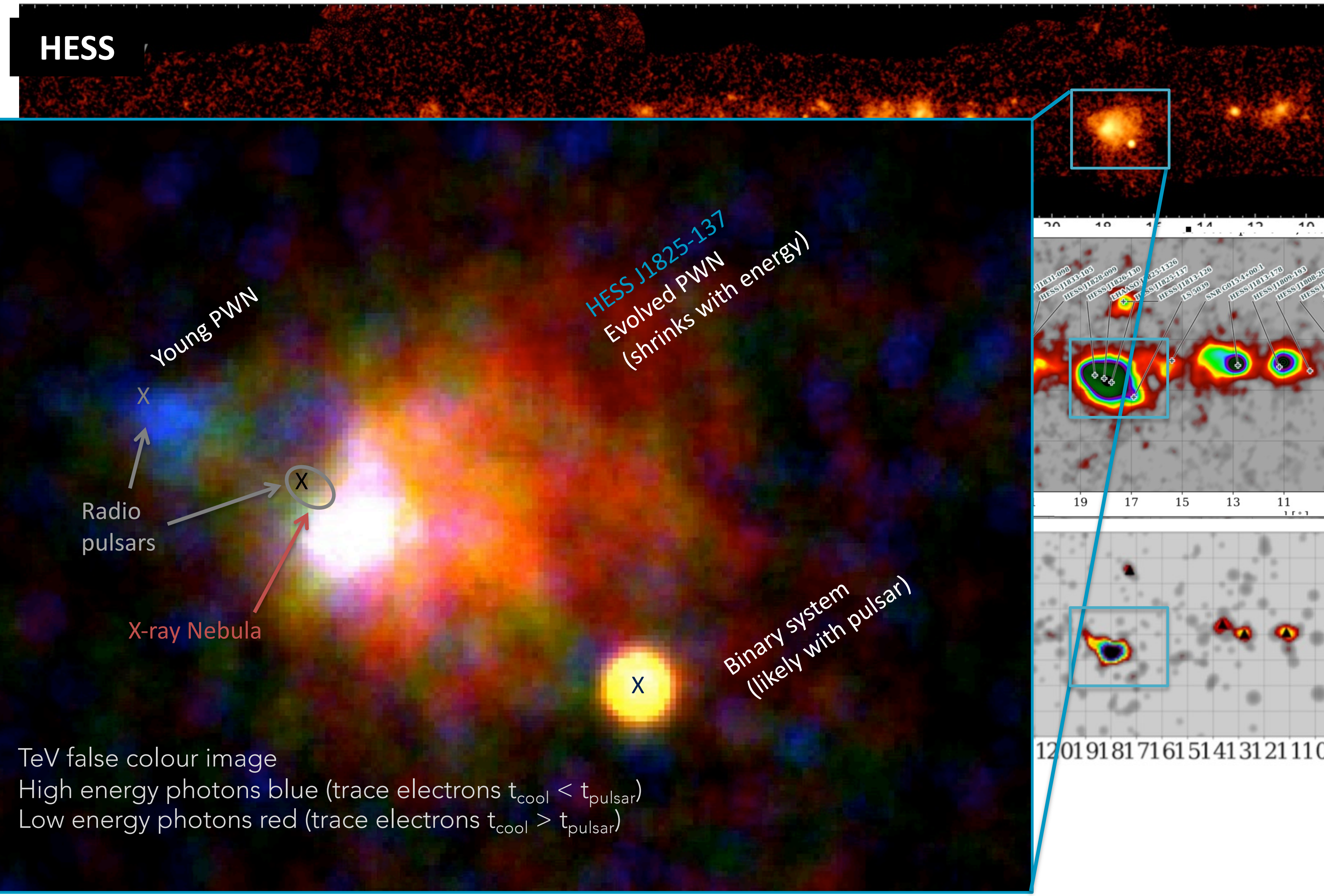


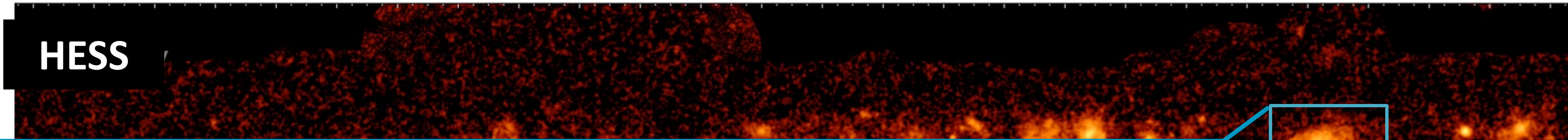


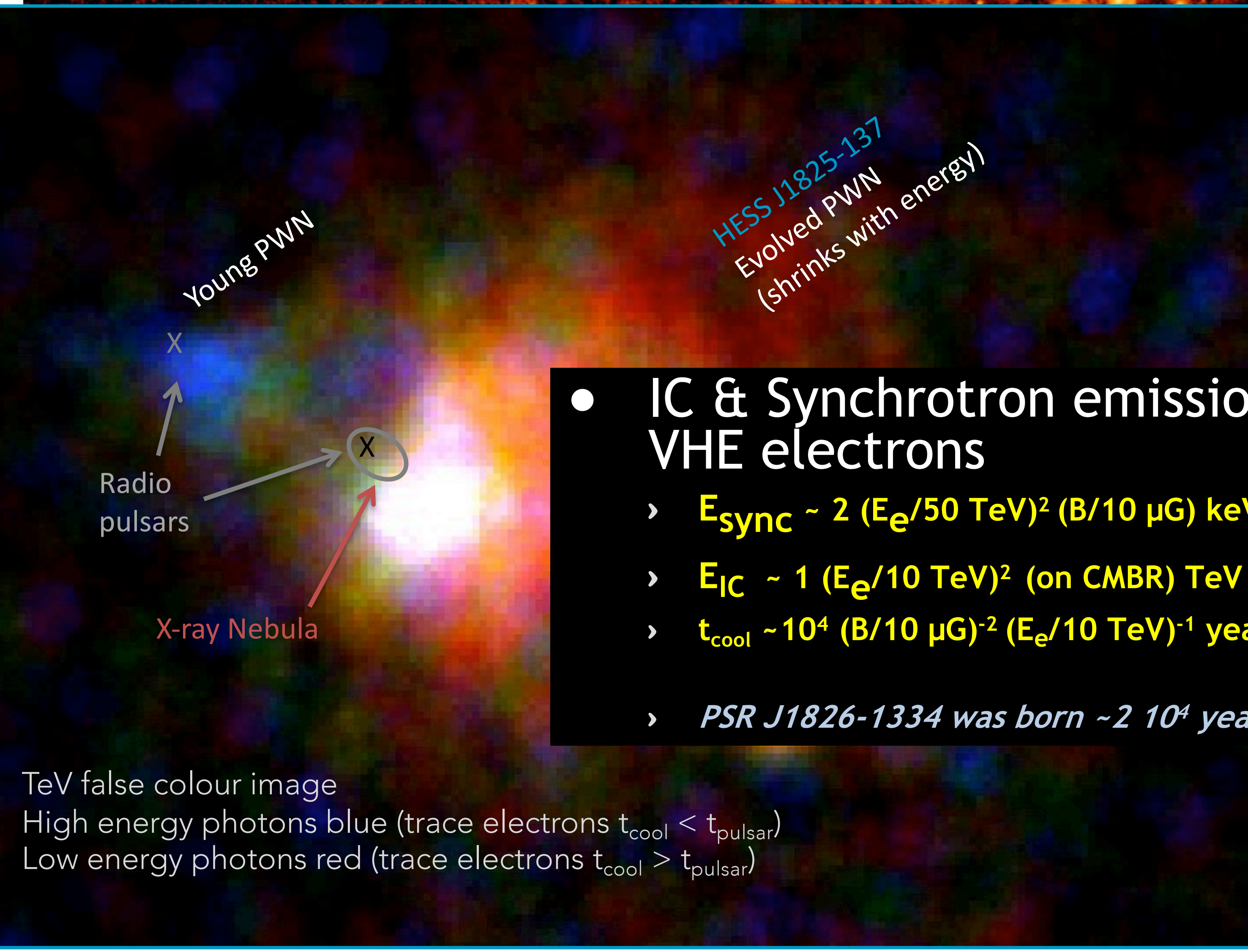


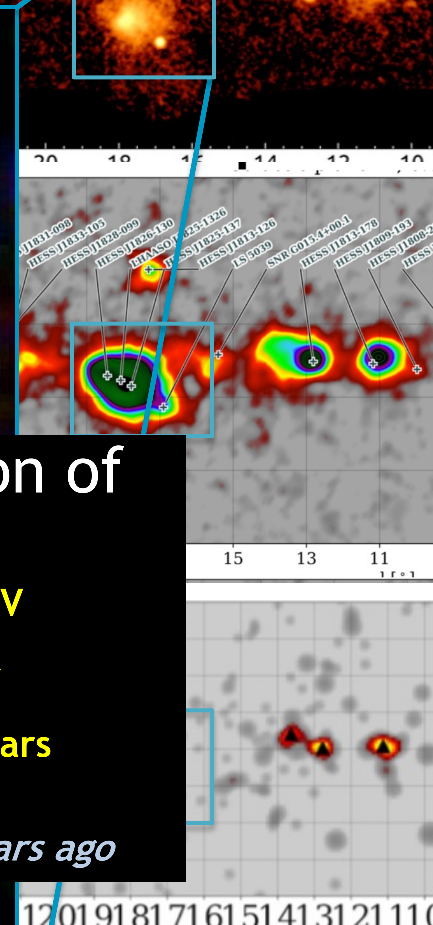
Goodman – Gamma 22

2090 days – Pass 5


HESS
Young PWN
HESS J1825-137
Evolved PWN
(shrinks with energy)
Radio
pulsars
X-ray Nebula
Binary system
(likely with pulsar)
TeV false colour image
High energy photons blue (trace electrons $t_{cool} < t_{pulsar}$)
Low energy photons red (trace electrons $t_{cool} > t_{pulsar}$)



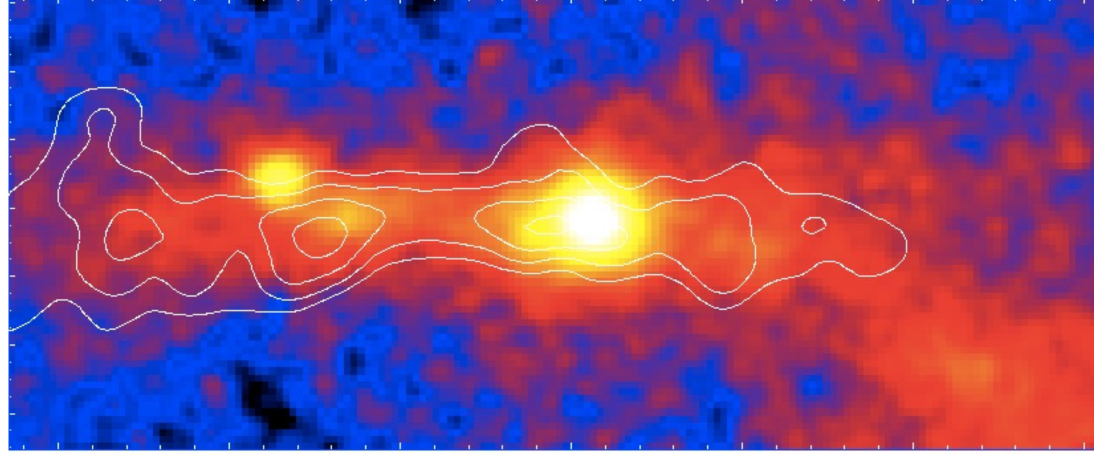




- IC & Synchrotron emission of VHE electrons
  - E_{sync} ~ 2 $(E_e/50\ \mathrm{TeV})^2$ $(B/10\ \mu G)$ keV
  - E_{IC} ~ 1 $(E_e/10\ \mathrm{TeV})^2$ (on CMBR) TeV
  - t_{cool} ~10^4 $(B/10\ \mu G)^{-2}$ $(E_e/10\ \mathrm{TeV})^{-1}$ years
  - *PSR J1826-1334 was born ~2 10^4 years ago*

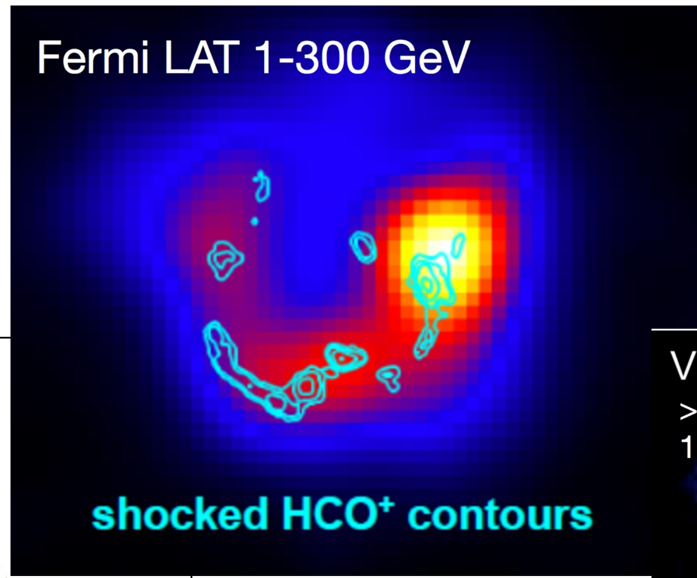
TeV false colour image
High energy photons blue (trace electrons $t_{cool} < t_{pulsar}$)
Low energy photons red (trace electrons $t_{cool} > t_{pulsar}$)

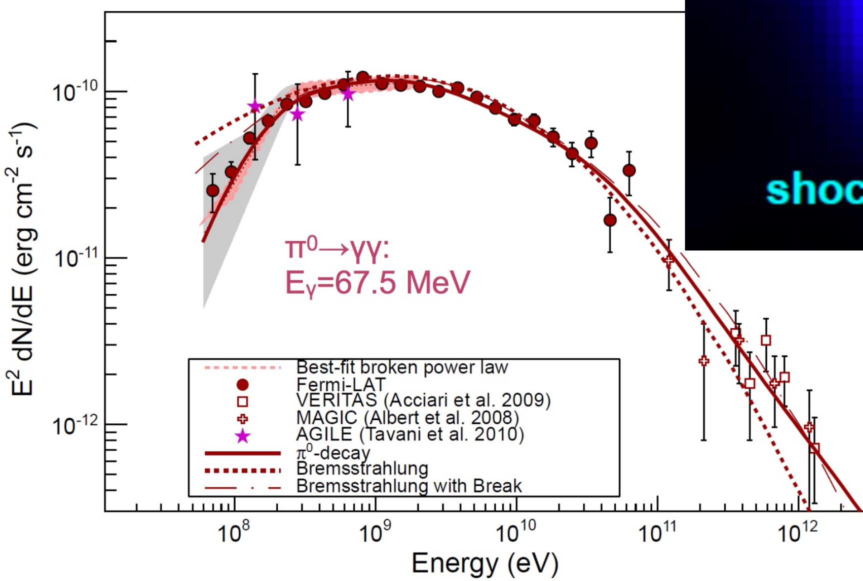
Protons? (and nuclei)



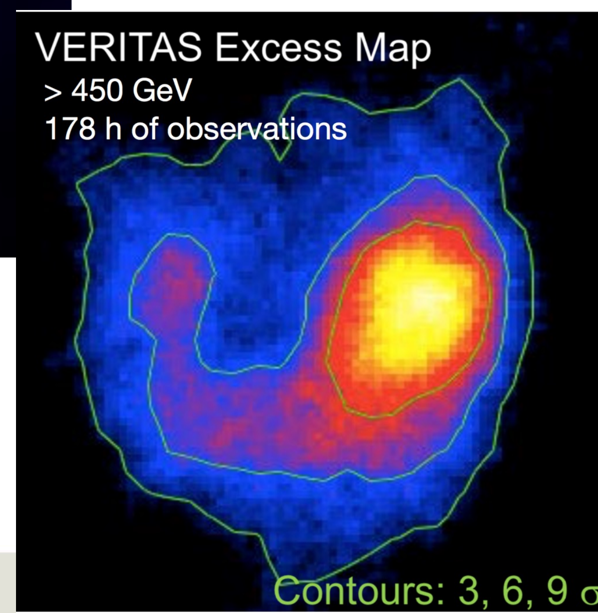
CMZ
HESS with CS
contours

- Central Molecular Zone
  - Correlation with molecular gas in inner 100 pc
  - Spectrum implies protons beyond ~500 TeV
- Interacting SNRs
  - But no evidence for protons>100 TeV



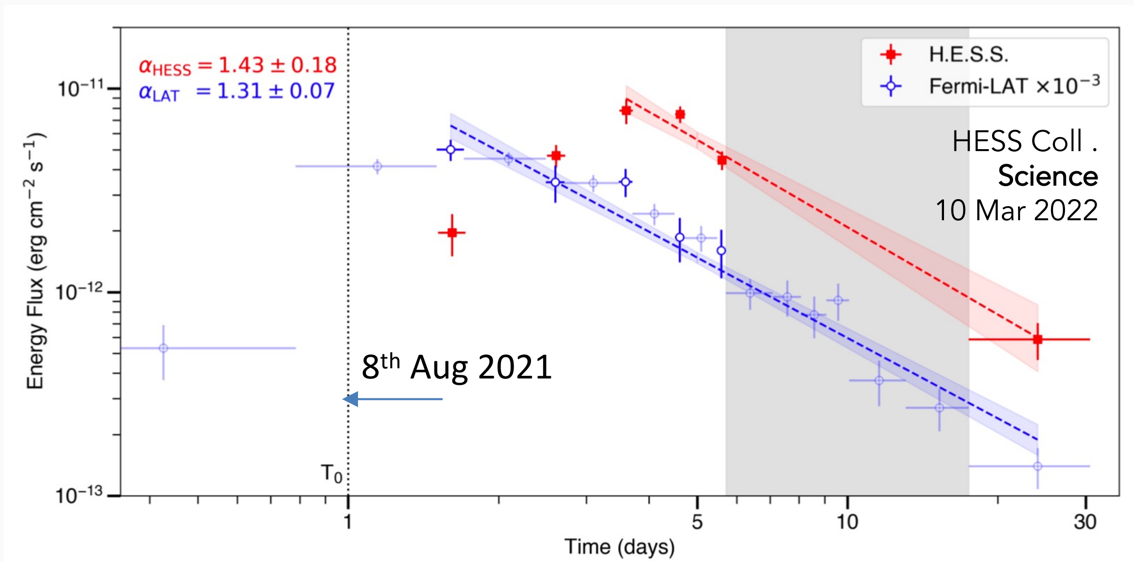


e.g. IC443



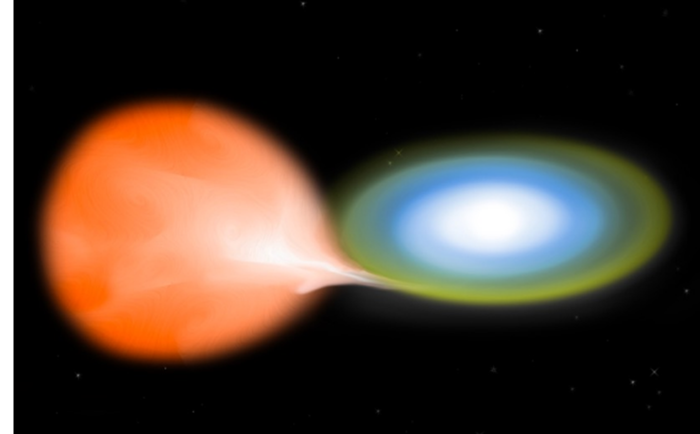
Nova RS Oph

- White dwarf accretes from companion
  - Occasional thermo-nuclear explosion
  - Acceleration of particles in blast wave



Confinement limit (Bell et al. 2013)

$$E_{\max} = 1.5|Z| \left(\frac{\xi_{\rm esc}}{0.01}\right) \left(\frac{\dot{M}/v_{\rm wind}}{10^{11}\ {\rm kg\ m^{-1}}}\right)^{1/2} \left(\frac{u_{\rm sh}}{5000\ {\rm km\ s^{-1}}}\right)^{2}\ {\rm TeV}$$



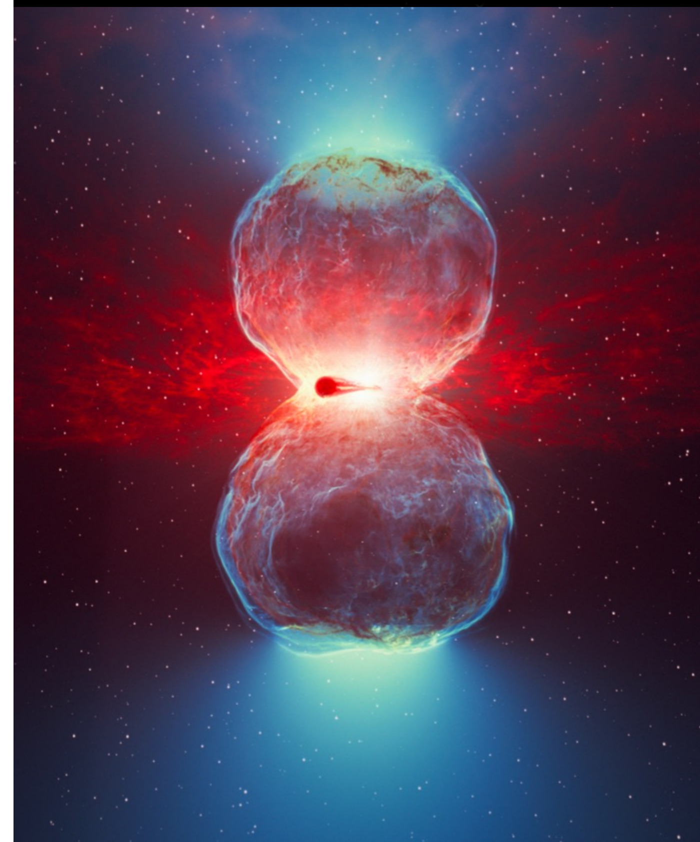
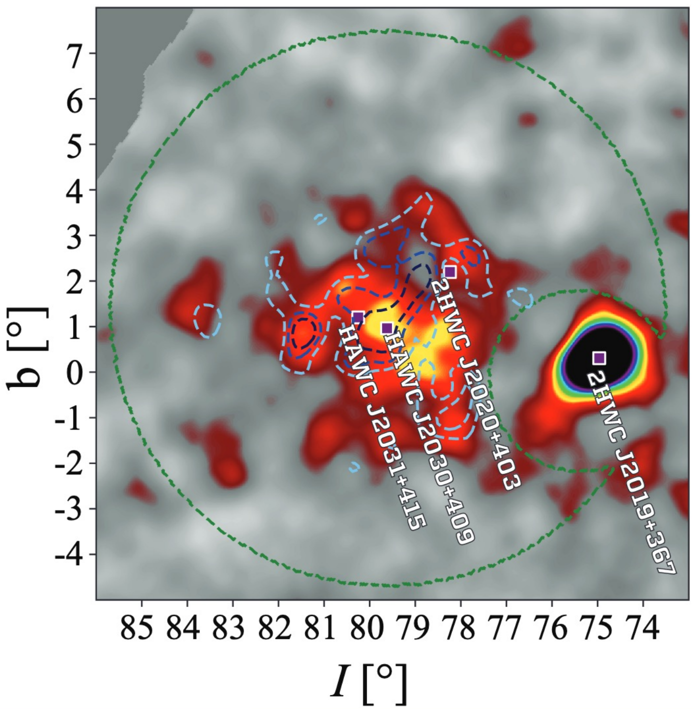


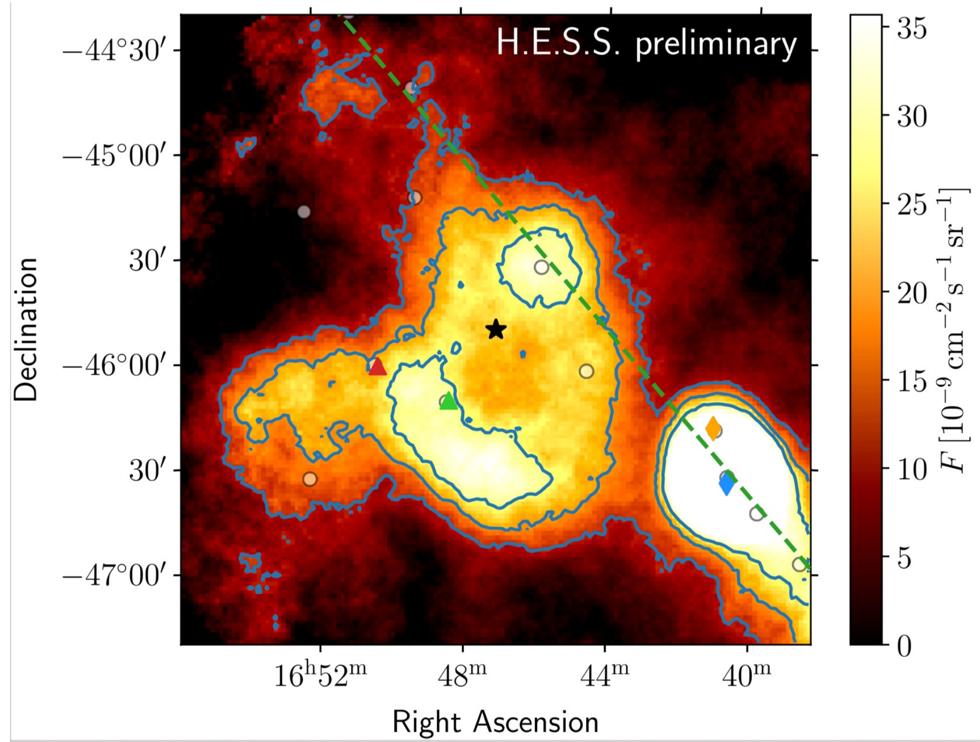
Image Credit: DESY/H.E.S.S., Science Communication Lab

Massive Stellar Clusters

HESS: Westerlund I

HAWC: Cygnus Cocoon





nature astronomy

ARTICL

https://doi.org/10.1038/s41550-019-0

Massive stars as major factories of Galactic cosmic rays

Felix Aharonian[1,2,3,7], Ruizhi Yang[2,7]* and Emma de Oña Wilhelmi[4,5,6,7]

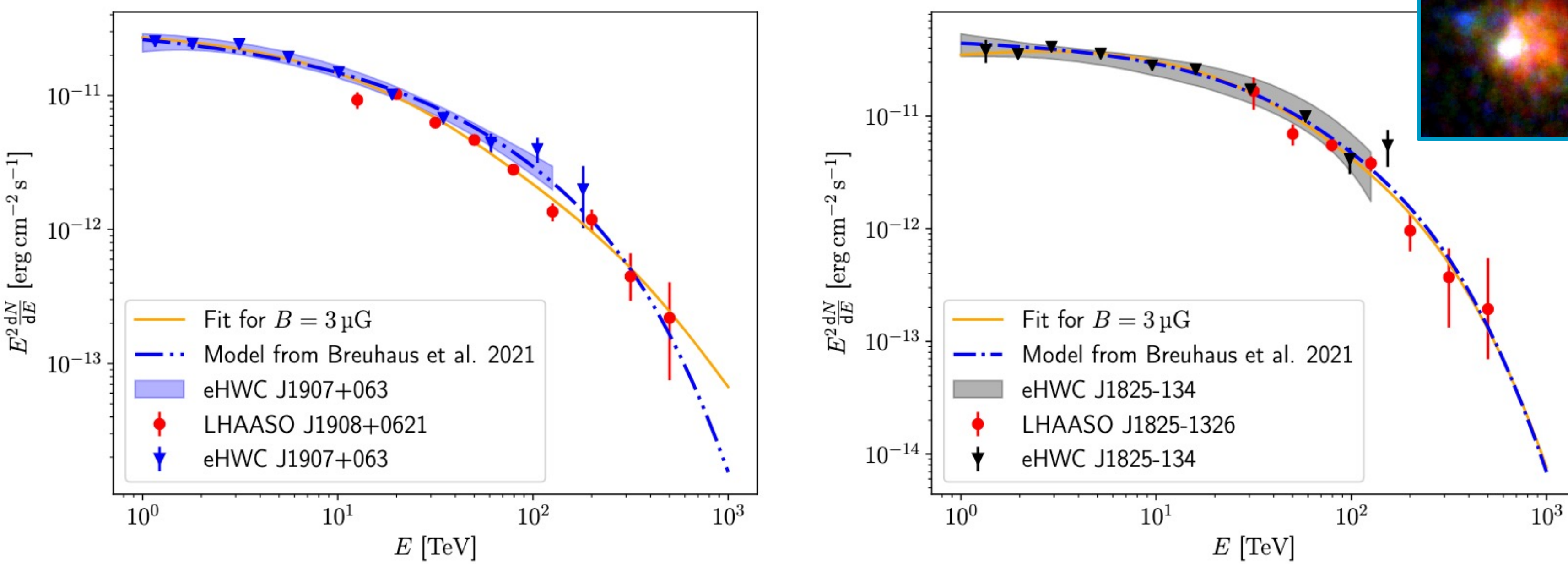
Table 1 | Physical parameters of three extended γ-ray structures and their related stellar clusters

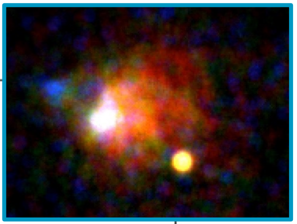
Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[39]	3–6	2–7	4–6
Kinetic luminosity, L_{kin}, of cluster (erg s^{-1})	2×10^{38} (ref. 17)	1×10^{39} (ref. 40)	1×10^{39} (ref. 41)
Distance (kpc)	1.4	8.5	4
ω_0 (>10 TeV) (eV cm^{-3})	0.05	0.07	1.2

The LHAASO UHE Sources?

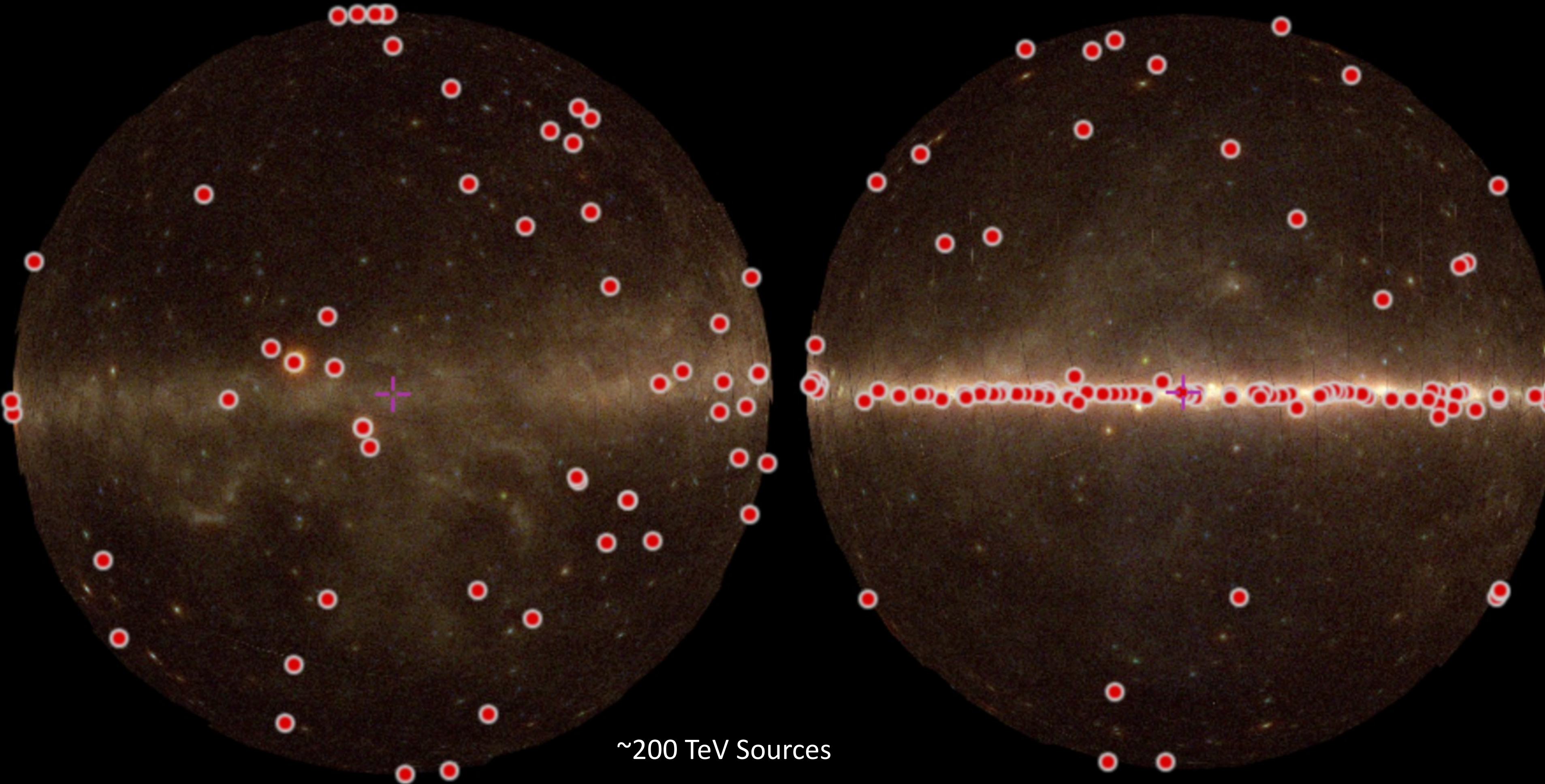
- Some (or all) could be evidence of PeV proton acceleration
- But still possible that this is IC emission from e^+/e^- in PWN
  - As long as magnetic fields are low in emitting region – or radiation fields a bit stronger than average (IC dominated cooling)

Breuhaus et al.: Leptonic modeling of LHAASO detected UHE γ-ray sources





TeV Sources

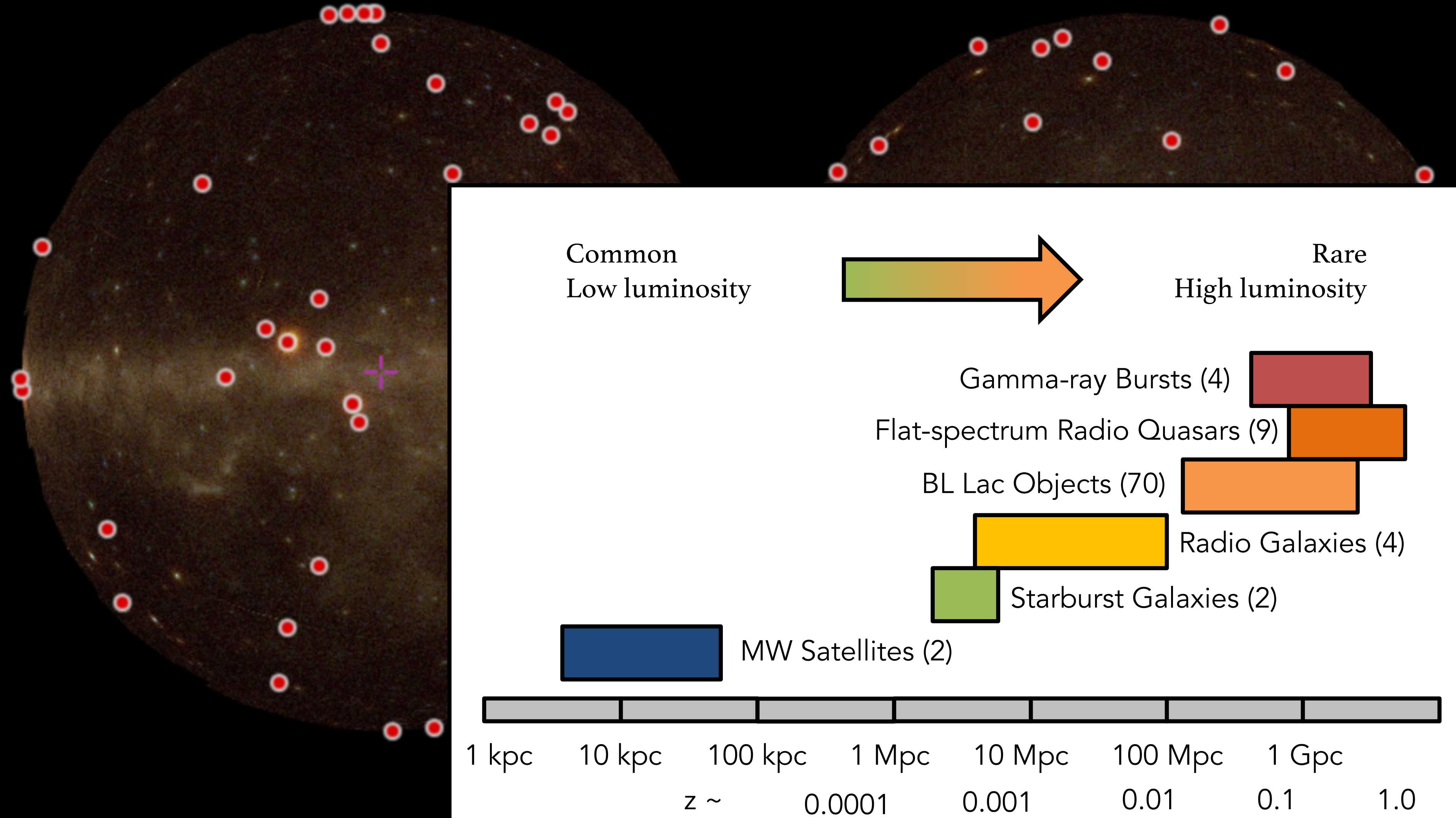


~200 TeV Sources

Background: Fermi-LAT

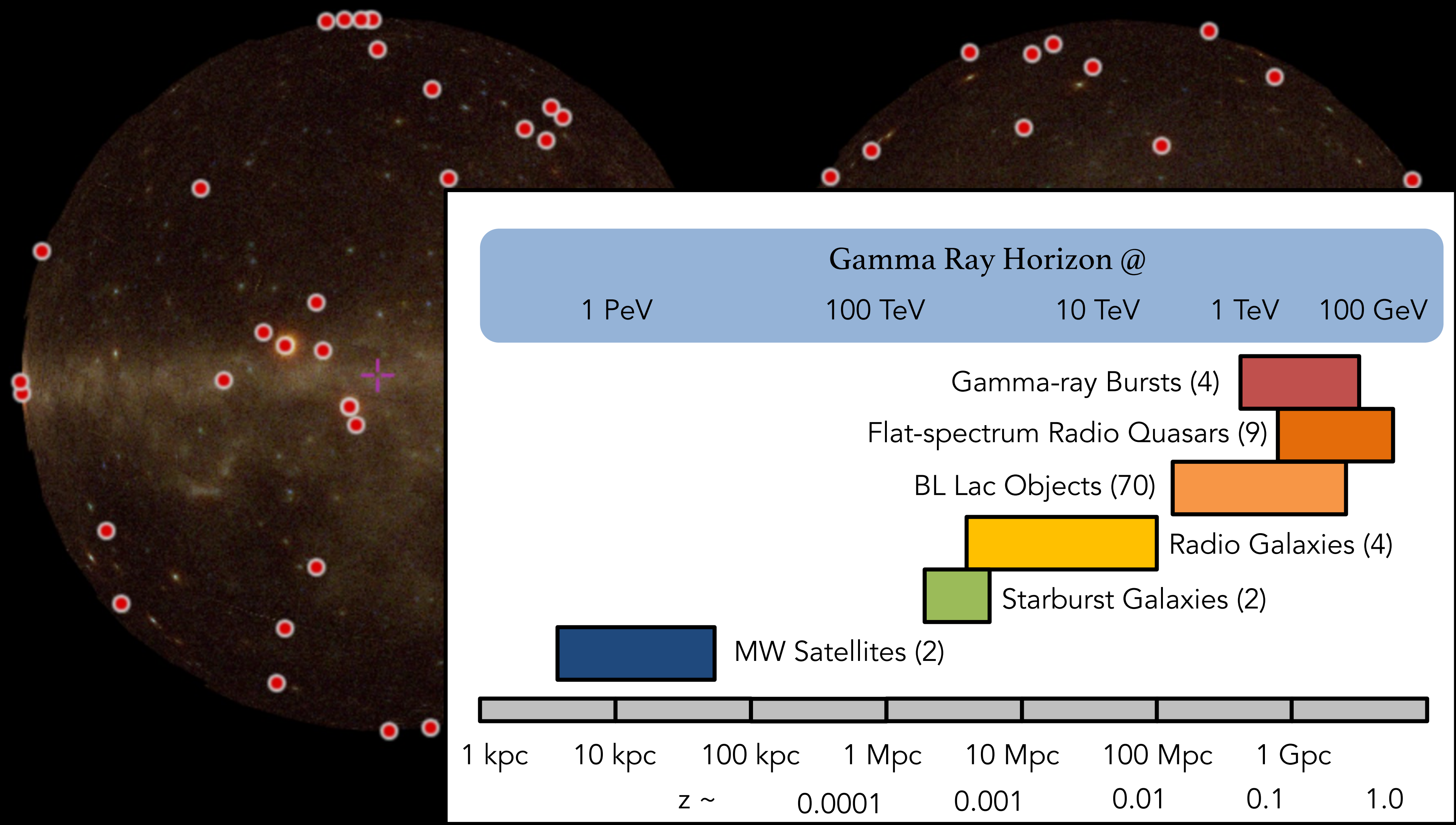
Extragalactic TeV Sources

Numbers and classifications from TeVCat

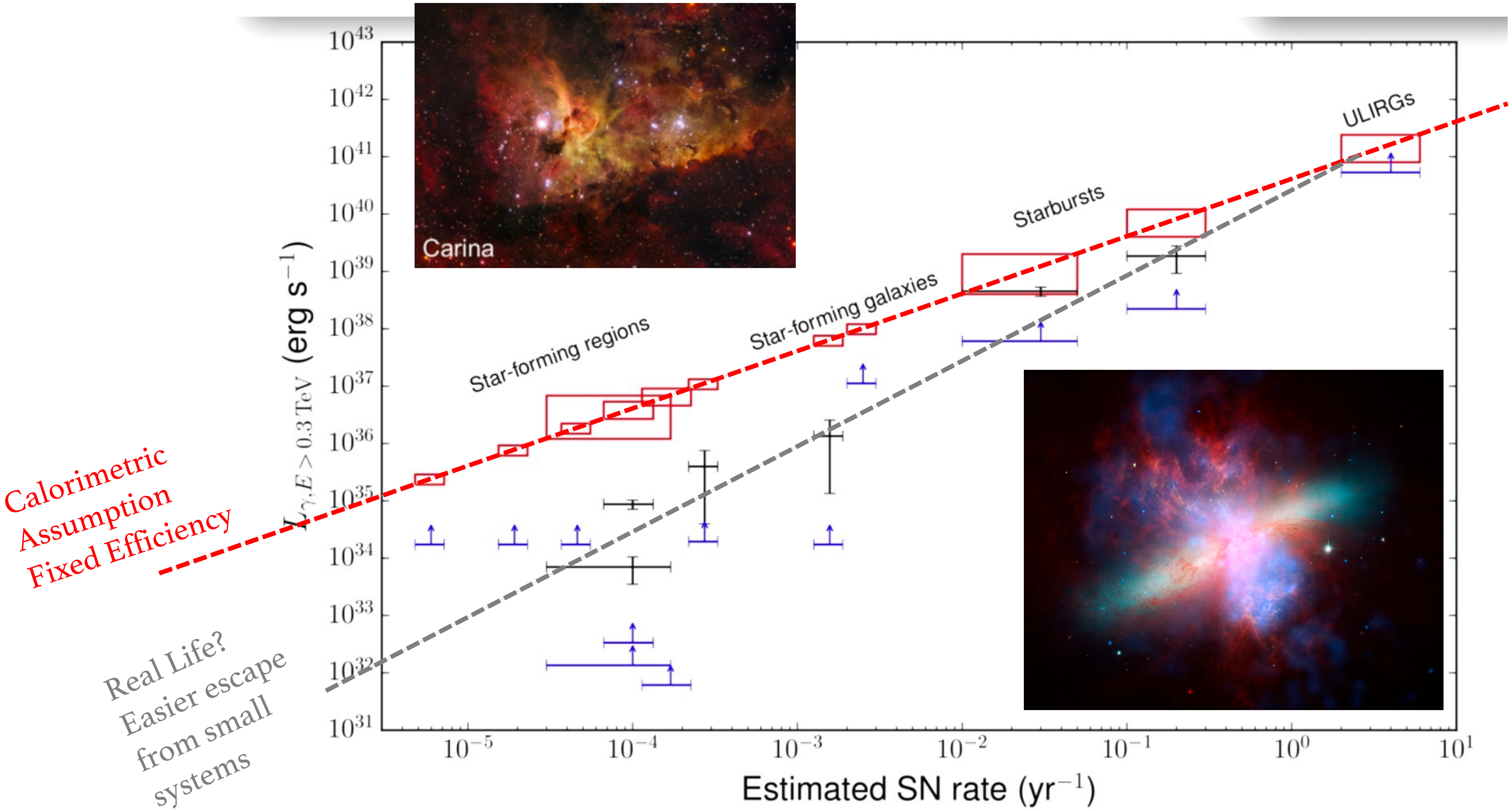


Extragalactic TeV Sources

Numbers and classifications from TeVCat

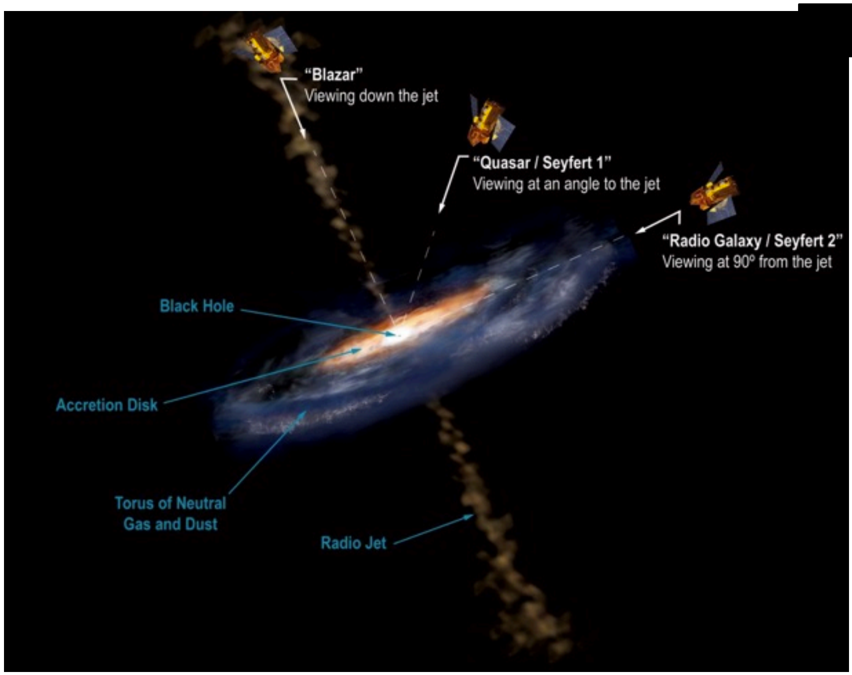


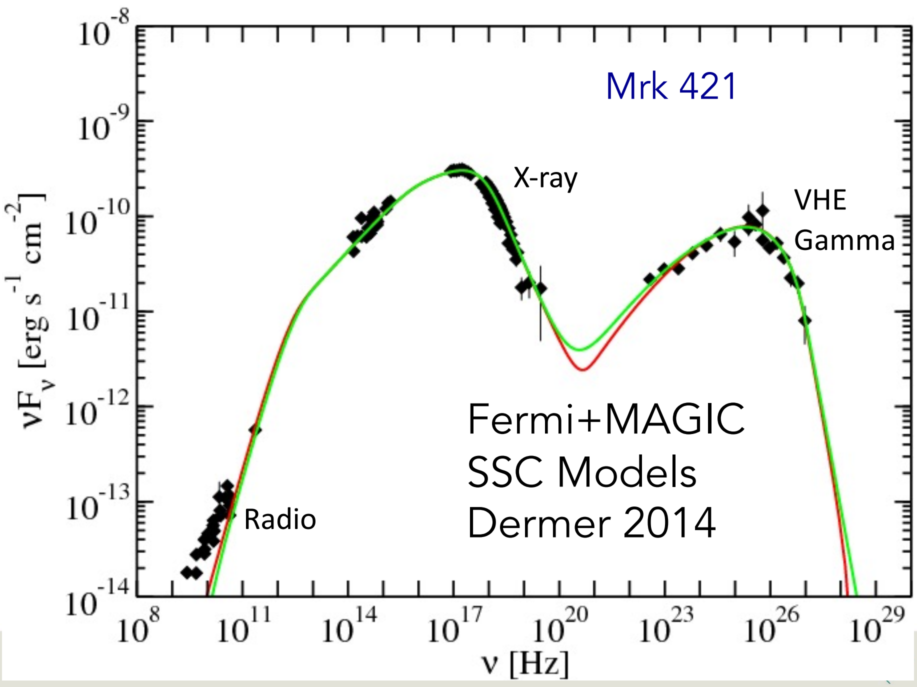
Star-forming Systems



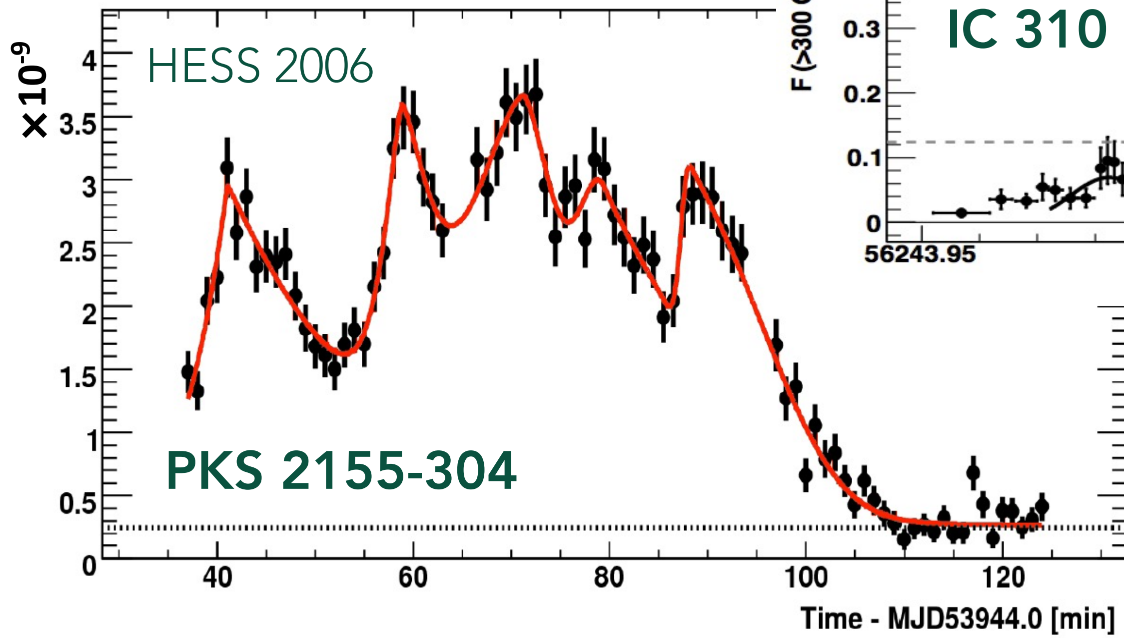
Active Galaxies

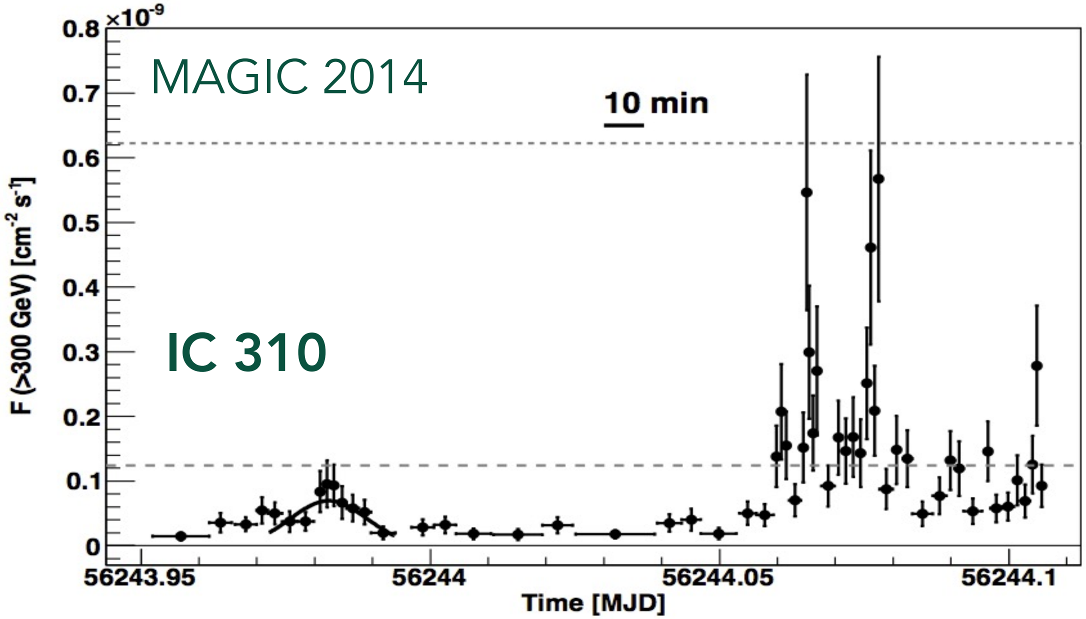
- Emission (might be) expected from
  - Core – v. close to central engine
  - Jets – from pc to 100 kpc scales
  - Lobes (as seen in radio – mm)
  - On-galaxy cluster scales – mixing/interaction of accelerated protons
- So far
  - In all but **one case** VHE emission consistent with point-like emission consistent with SMBH location
  - i.e. from inner jet or close to SMBH
  - Jet resolved in Cen A (ask!)
- Usual interpretation: Inverse Compton emission
  - With target photon field of synchrotron emission of same electrons or radiation fields associated with AGN or host galaxy





TeV Blazar Variability



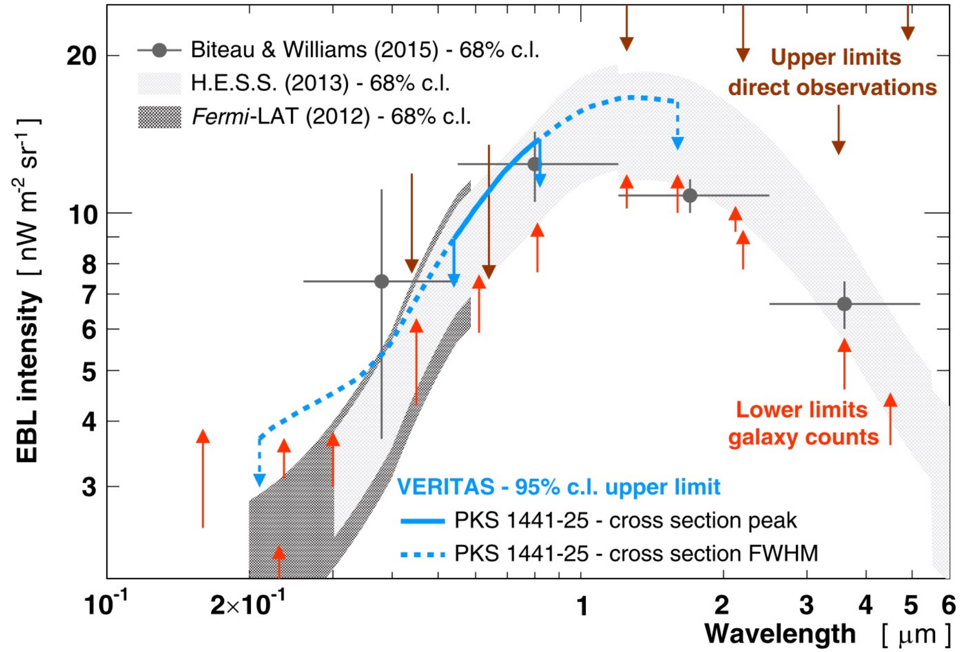


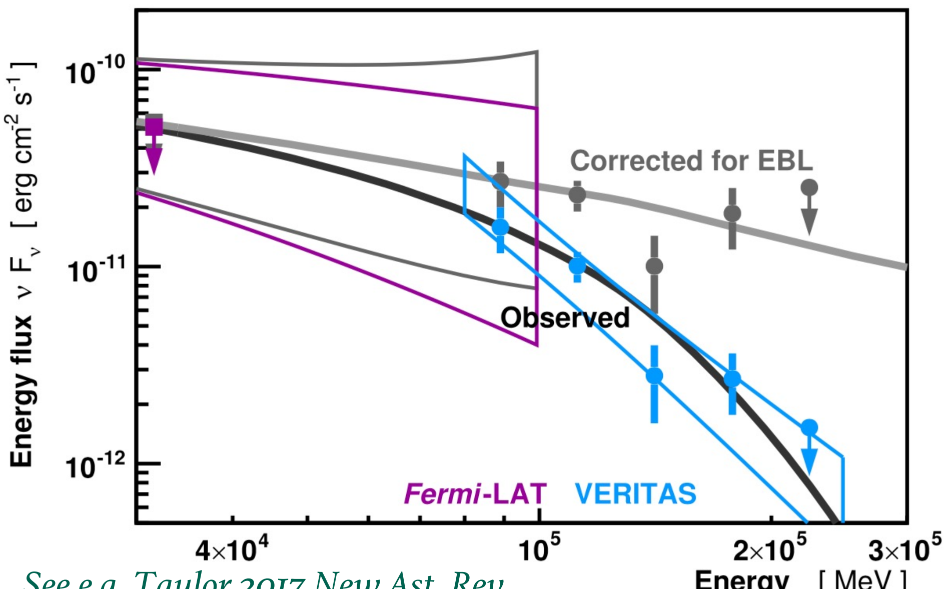
- IC 310 has long radio jet
  - Viewing angle > ~15 degrees

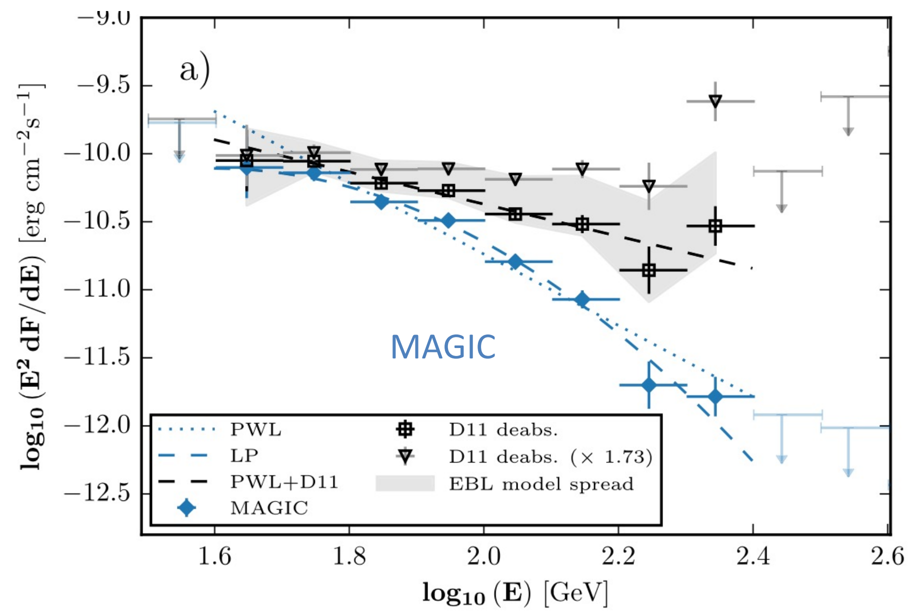
- Variability timescales down to ~1% R_S c – with huge luminosity
  - Causality requires R < $ct_{var}\,\delta$, emission region is tiny and there is bulk relativistic motion with high lorentz factor

Distant Blazars

- e.g PKS 1441+25
  - Flat Spectrum Radio Quasar
  - z=0.94
- Increasingly constrained and consistent picture of the EBL
  - Gamma horizon is more distant than thought a decade ago





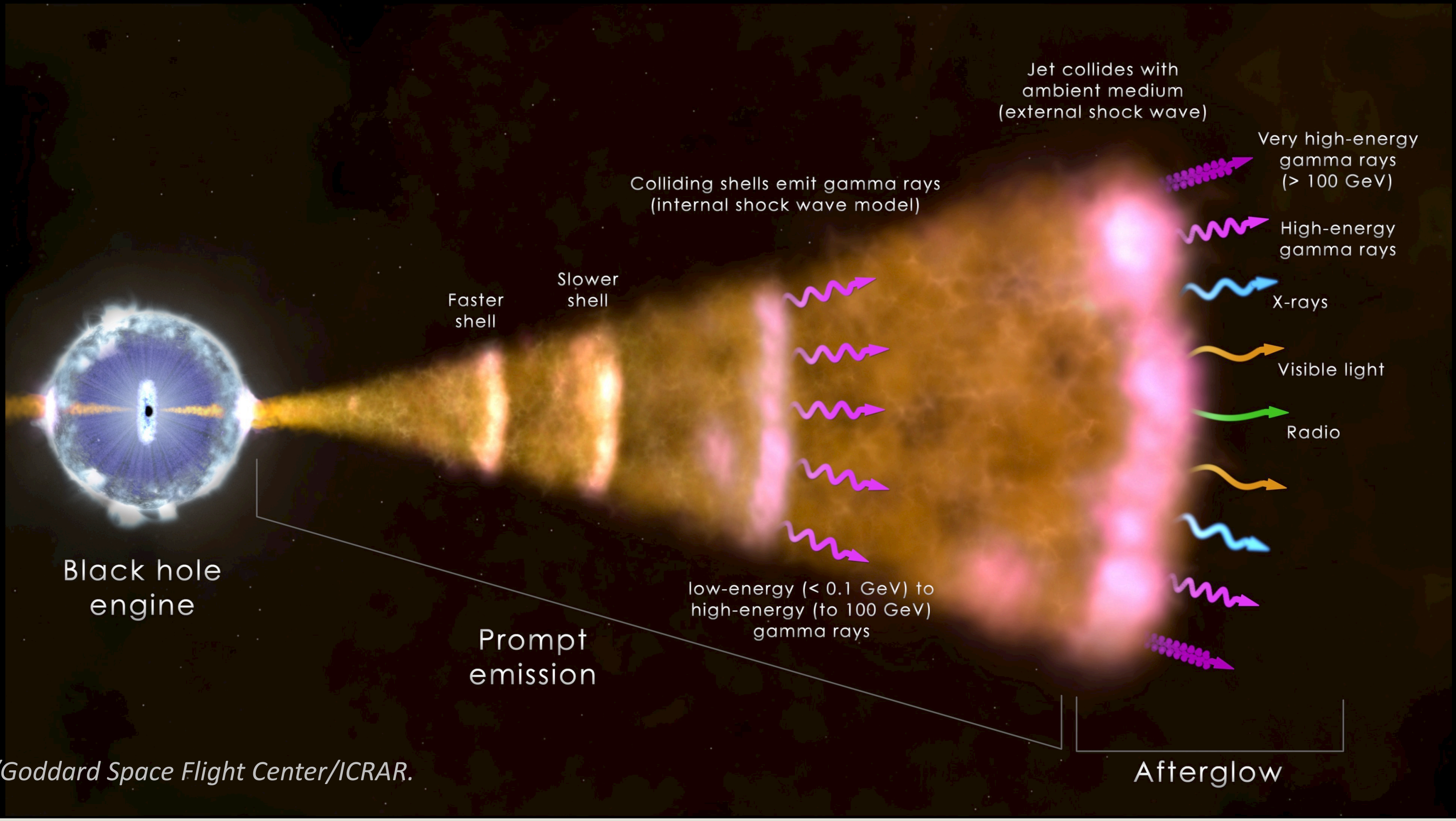


See e.g. Taylor 2017 New Ast. Rev.

Fig. 1. The spectral energy distribution of PKS 1441+25, taken from (The VERITAS collaboration, 2015) and (The MAGIC collaboration, 2015).

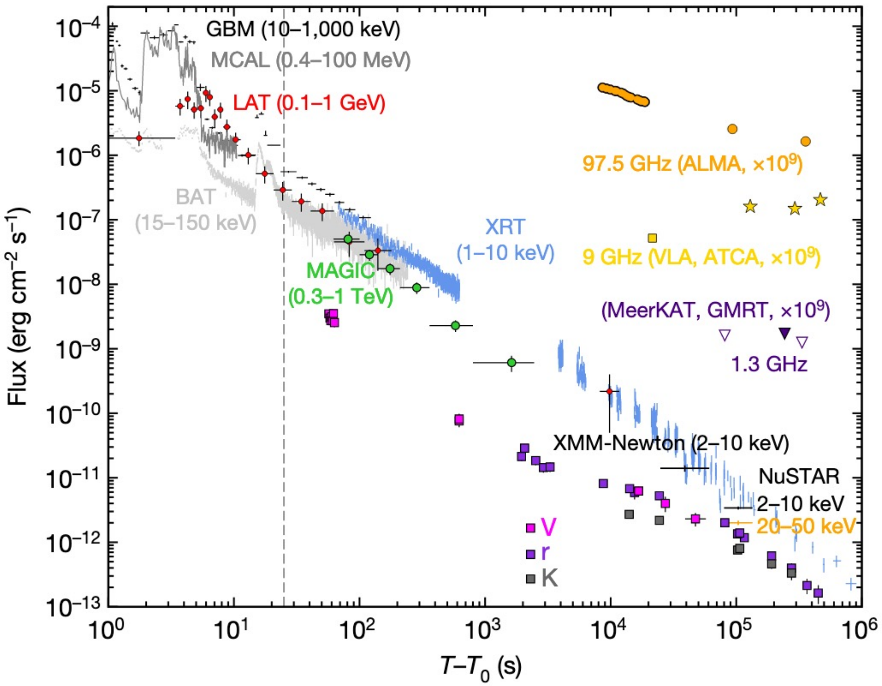
Gamma-ray Bursts

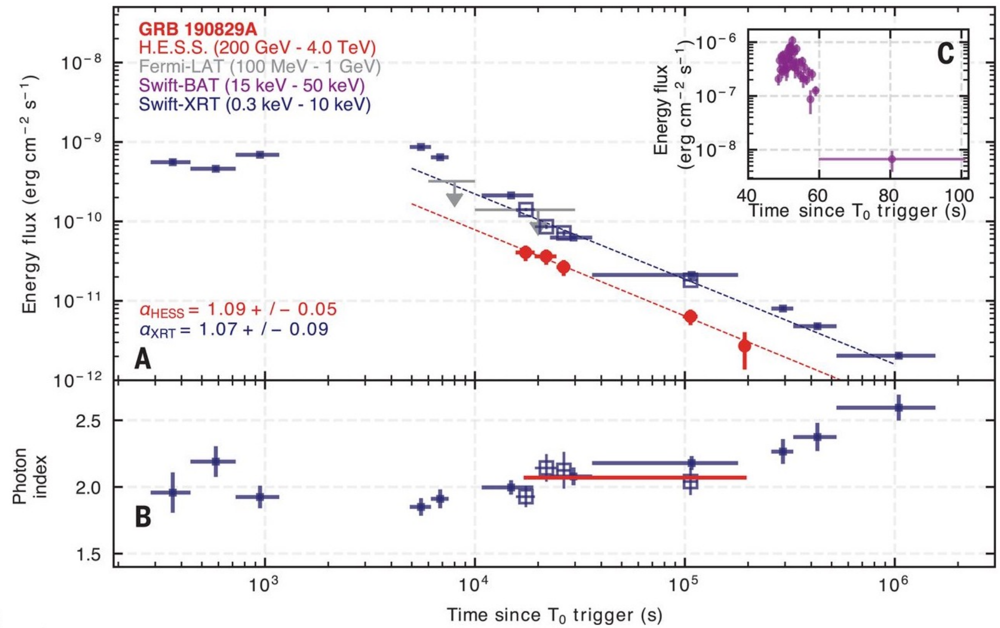
- Four GRBs detected 2018-2020 with IACTs – after a long wait!
  - Two HESS, two MAGIC (plus two more a bit marginal statistically)



NASA/Goddard Space Flight Center/ICRAR.

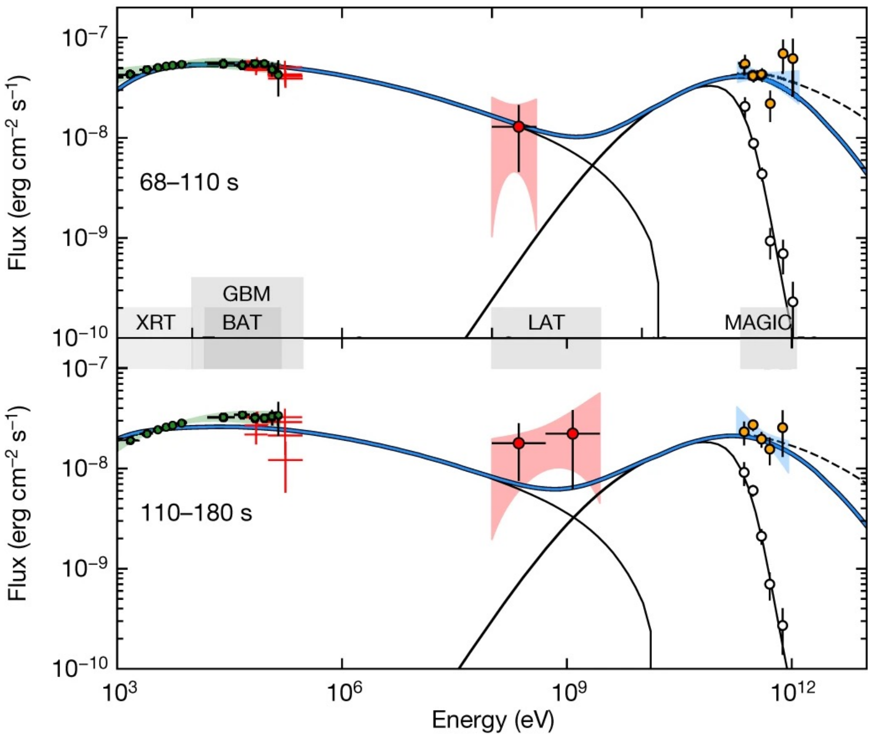
Gamma-ray Bursts

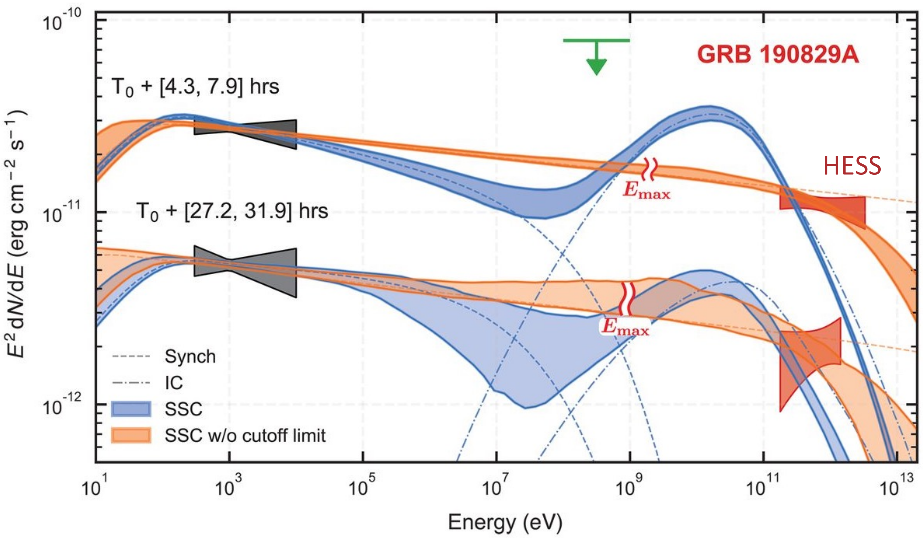




- Emission to very high energies and late times!
  - **From 1 minute post burst to 3 days later**
  - **Afterglow emission** – associated to external shock?
- Only long GRBs so far
  - Core-collapse SN rather than compact binary mergers
  - BUT surely only a matter of time – afterglow properties v. similar short/long GRBs

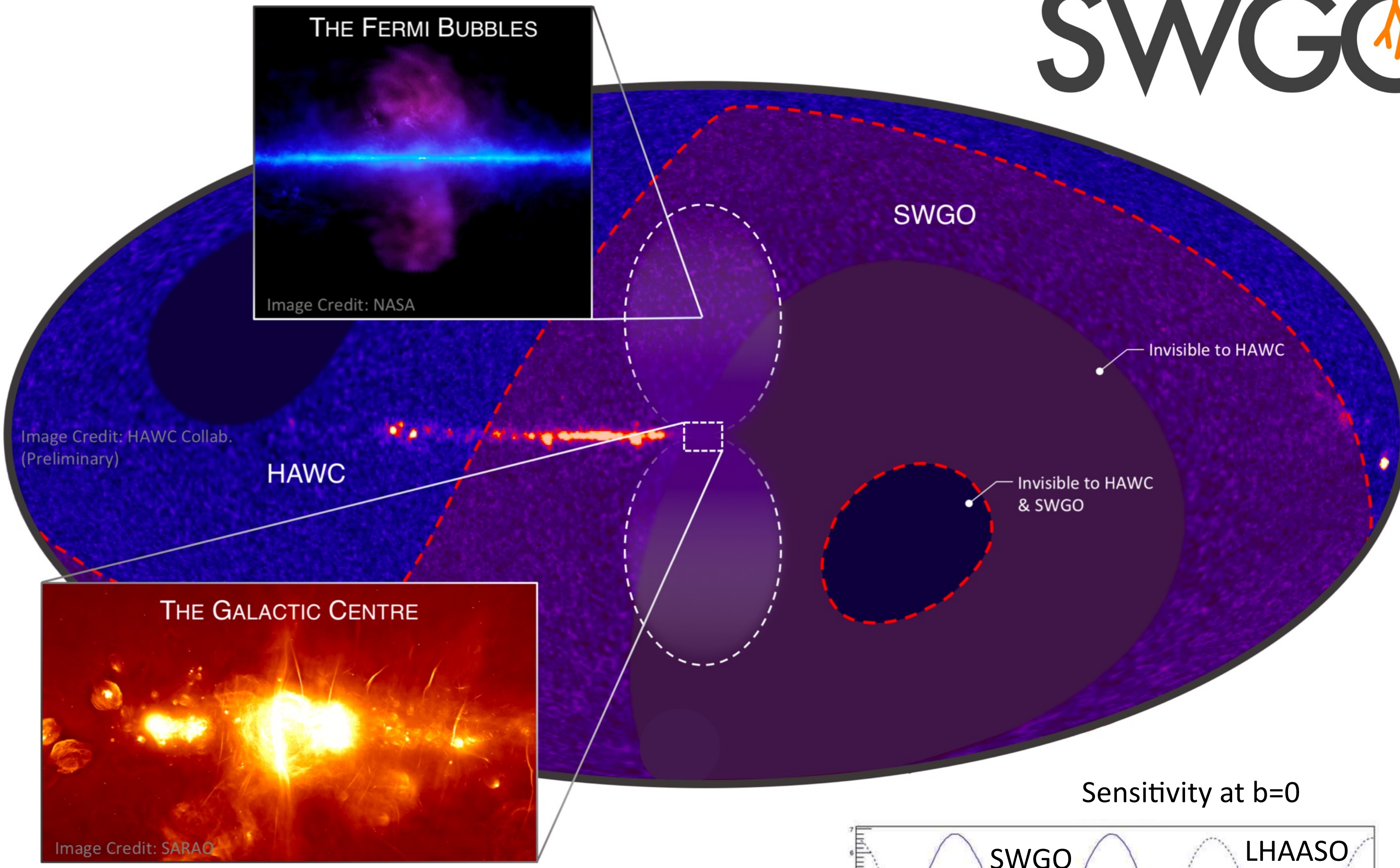
The GRB Spectral Mystery



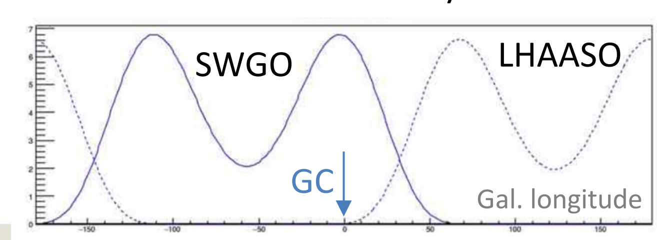


- Flux level, time-dep. and spectrum similar in X-ray & gamma-ray
  - One single component? Synchrotron emission to TeV energies??
  - Or inverse (Synch Self-) Compton emission kicking in at ~same level
- If TeV synchrotron – need extreme particle acc. + at least two-zones

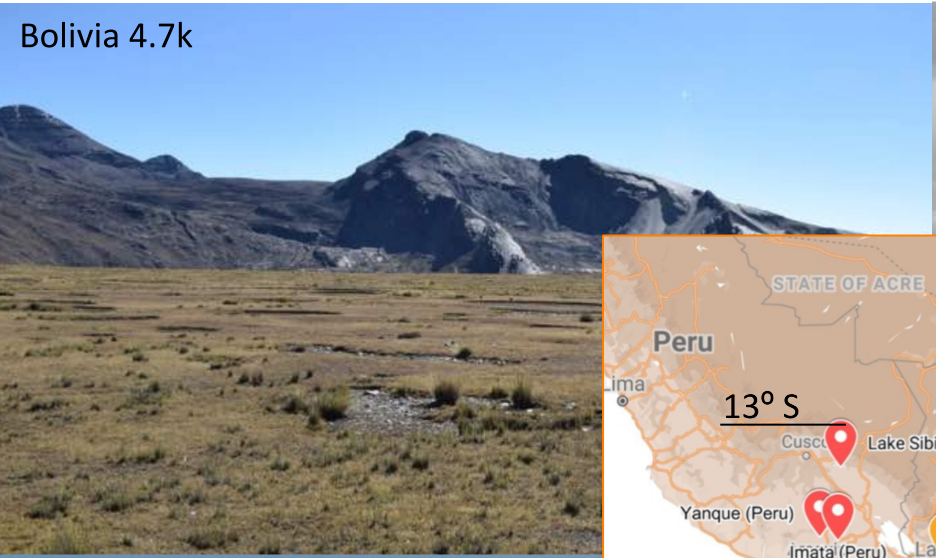
The Future?

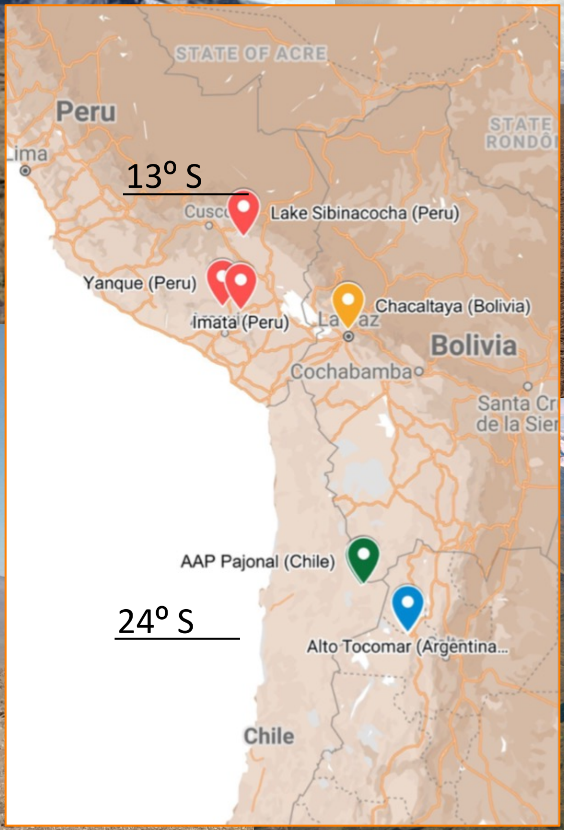


Sensitivity at b=0

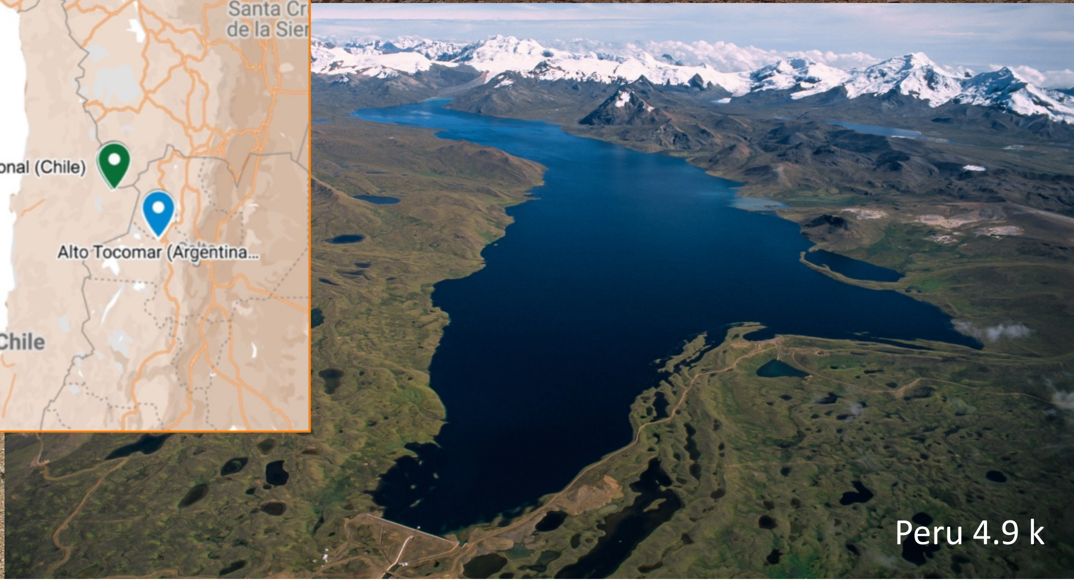


1 TeV – 1PeV gamma-sky
To compare with neutrinos!

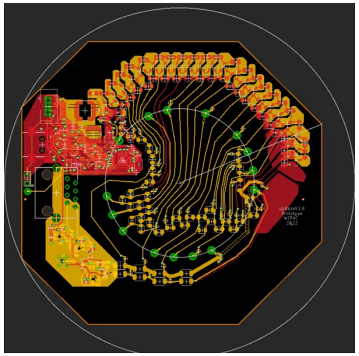




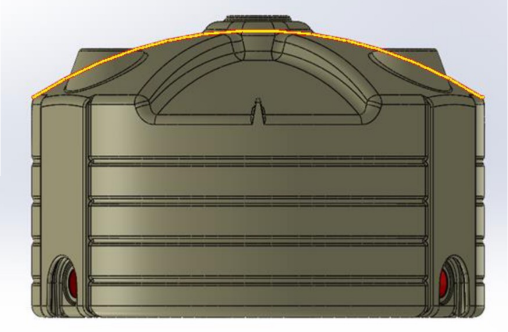
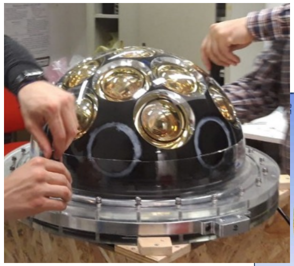
Site shortlisting: September 2022
Site team visits: October 2022
Preferred Site identified: Autumn 2023
On-site prototyping activities: from 2022




Bolivia 4.7k
Chile 4.8 k
Ask Dušan !
STATE OF ACRE
Peru
STATE RONDÔ
13° S
Cusco
Lake Sibinacocha (Peru)
Yanque (Peru)
Imata (Peru)
La Paz
Chacaltaya (Bolivia)
Bolivia
Cochabamba
Santa Cr de la Sier
AAP Pajonal (Chile)
24° S
Alto Tocomar (Argentina...
Chile
Site shortlisting: September 2022
Site team visits: October 2022
Preferred Site identified: Autumn 2023
On-site prototyping activities: from 2022
Argentina 4.8 k
Peru 4.9 k

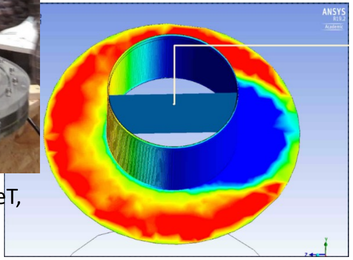


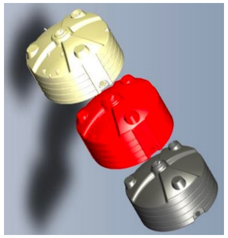

- **WCD Unit**
  - **Lake**
    - Natural Lake
    - Artificial Lake/Pond
  - **Tank**
    - Steel Tank
    - Rotomolded Plastic

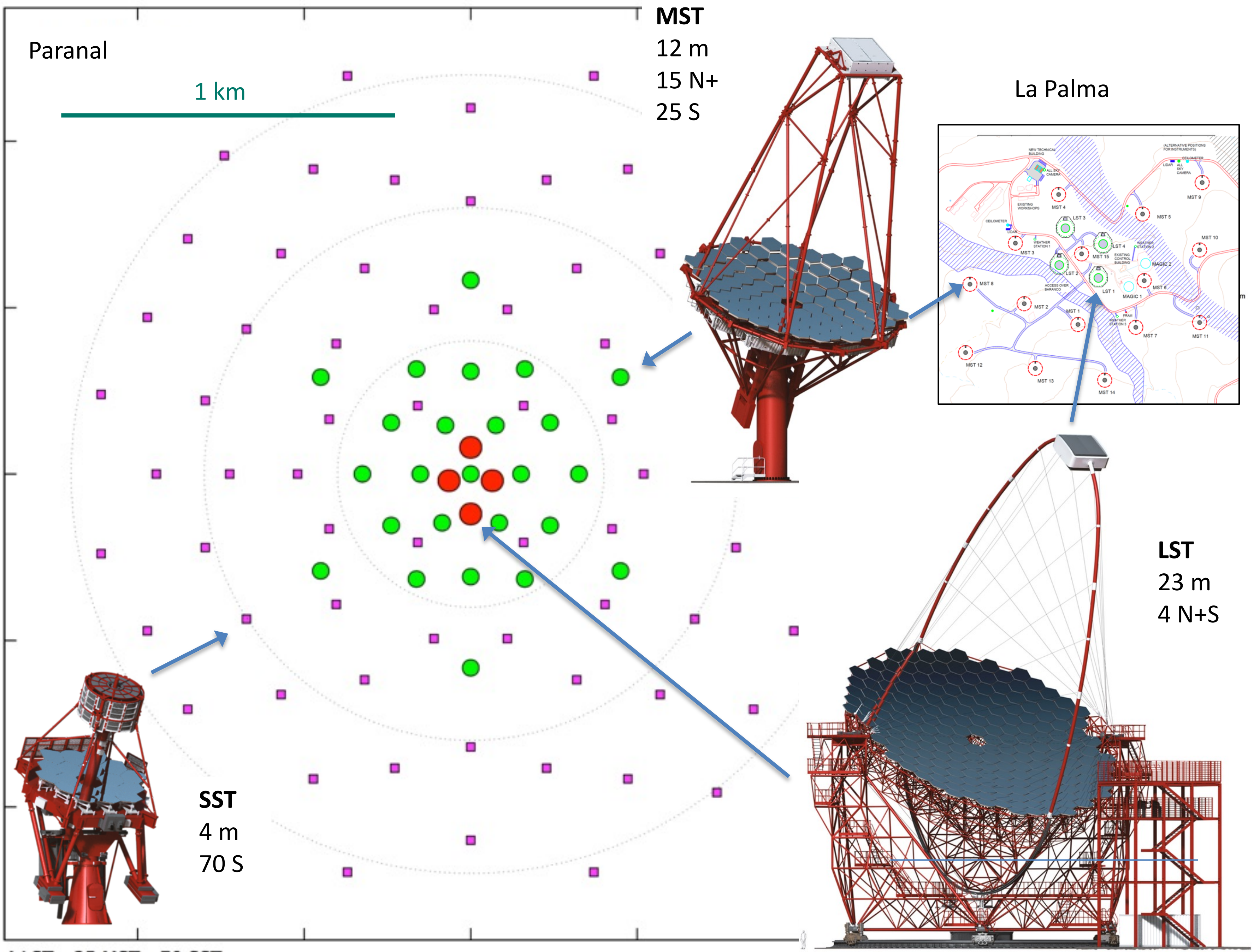




*cooperation with KM3NeT,

MoU in prep.



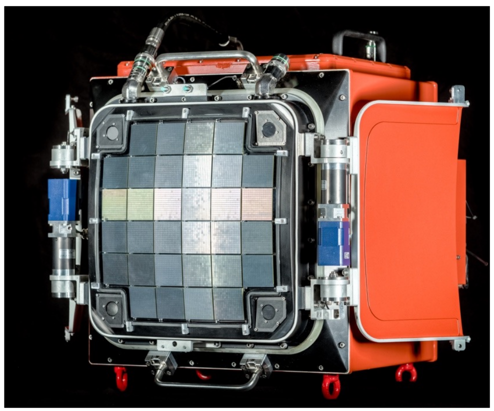





4 LSTs, 25 MSTs, 70 SSTs

SST

- 4m dual reflector
  - Design based on ASTRI and CHEC prototypes



Prototype Sicily

MST

- 12 m single reflector
  - Northern MSTs: NectarCam, Southern MSTs: FlashCam
- Trial run in HESS
  - 12 m tels – Nectar ASICs
  - 28 m tel – FlashCam prototype
- Pathfinders soon

Prototype Berlin

LST

- 23 m single reflector
  - Advanced planning for the north, recent break through: funding for 2 tells in south
  - Single tel. running in La Palma since 2018

First telescope CTA North

SST (42)

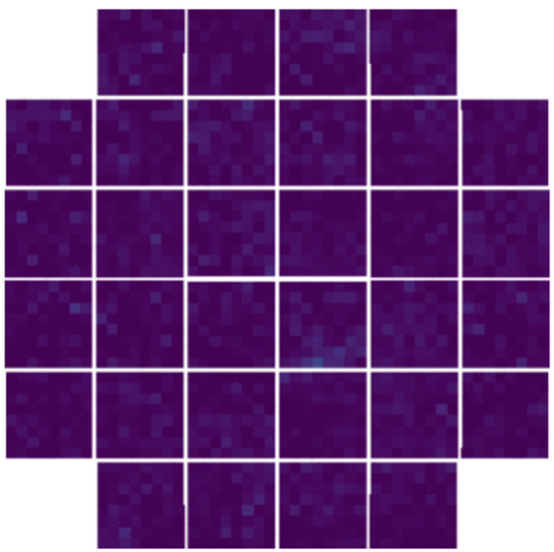
- 4m dual reflector
  - Design based on ASTRI and CHEC prototypes

MST (9+14)

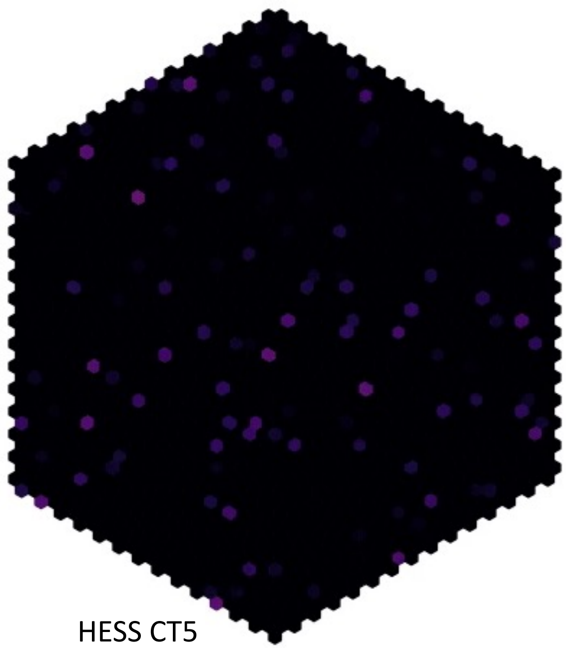
- 12 m single reflector
  - Northern MSTs: NectarCam, Southern MSTs: FlashCam
- Trial run in HESS
  - 12 m tels – Nectar ASICs
  - 28 m tel – FlashCam prototype

LST (2+4)

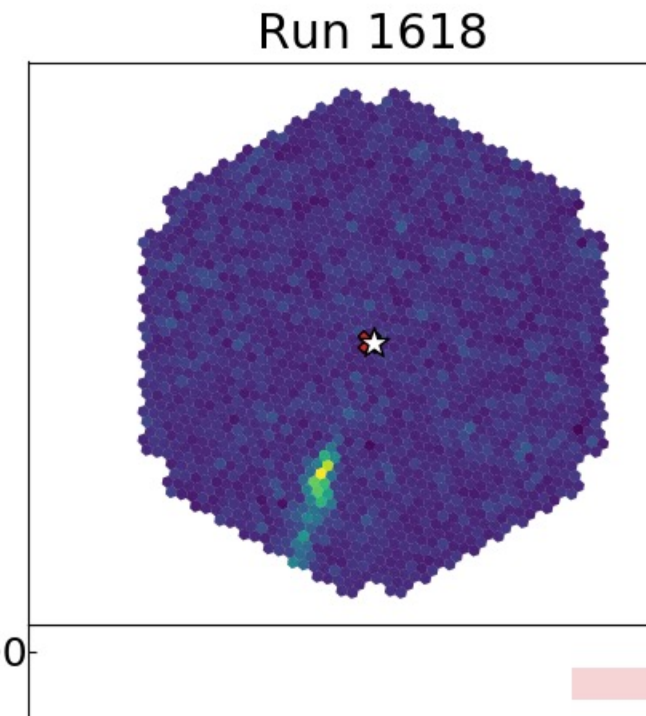
- 23 m single reflector
  - Advanced planning for the north, recent break through: funding for 2 tells in south
  - Single tel. running in La Palma since 2018



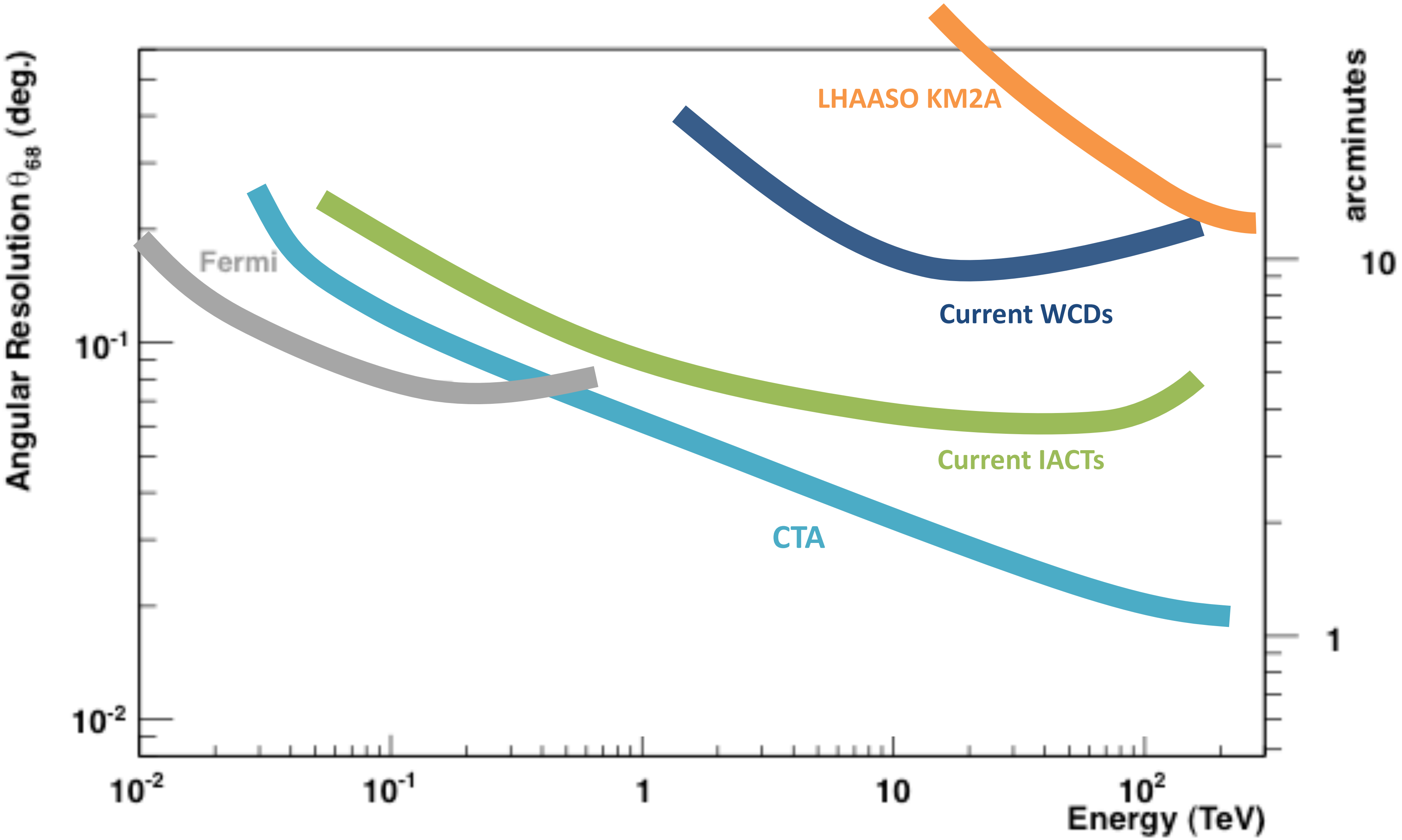
Prototype Sicily



HESS CT5

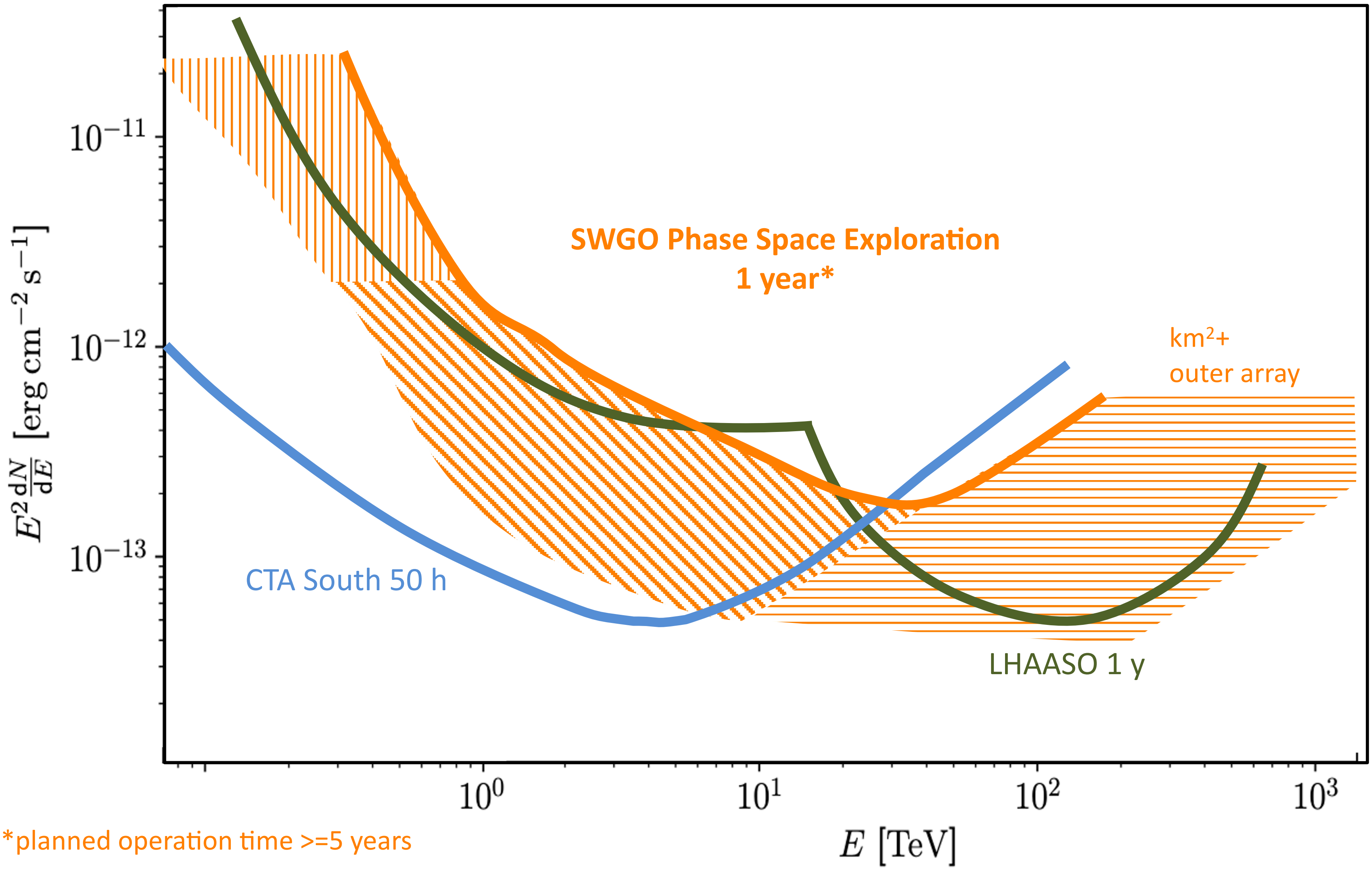


Angular Resolution

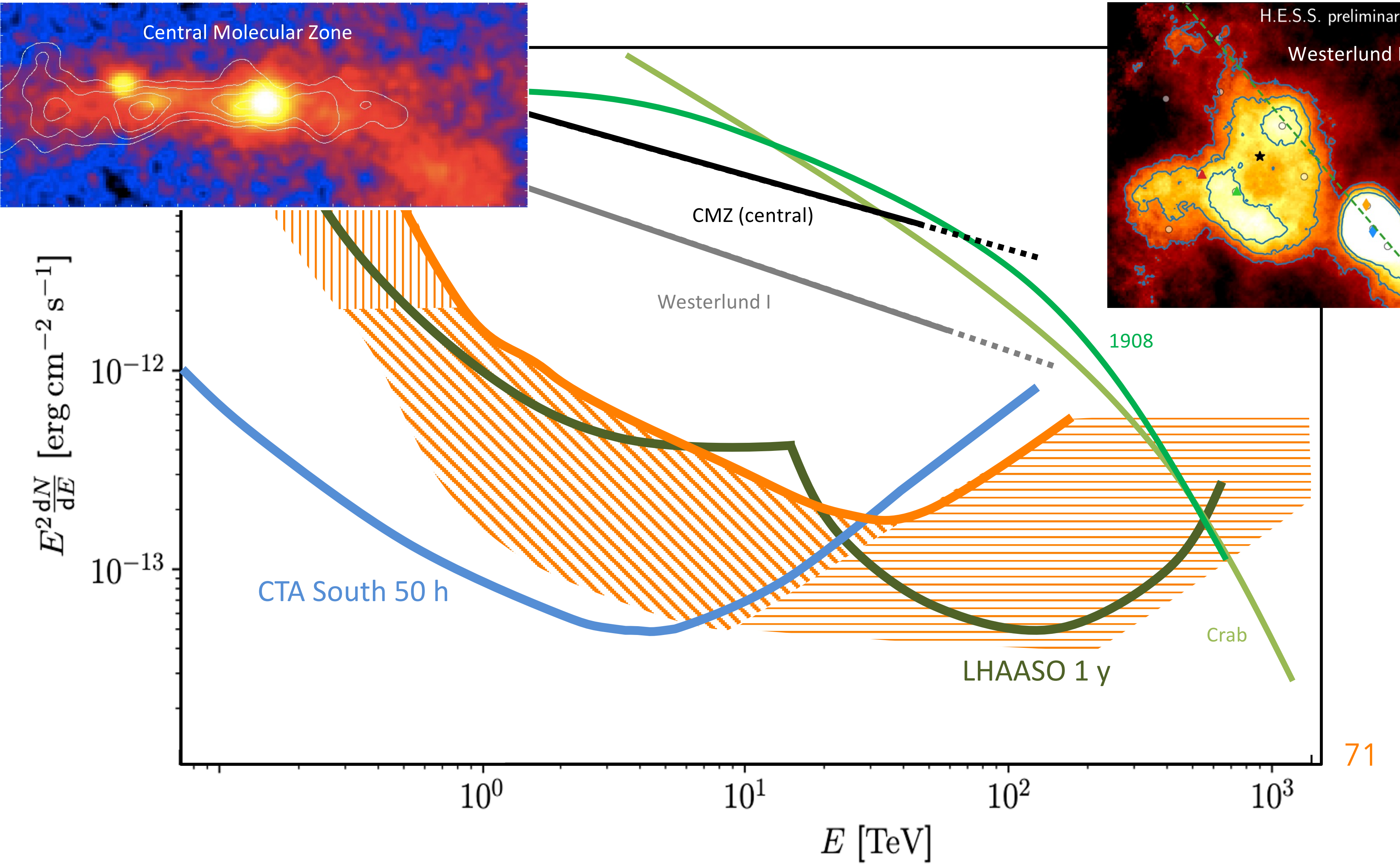


Sensitivity

Point-like source differential sensitivity, 5 bins per decade, 5 sigma each



*planned operation time >=5 years


Central Molecular Zone
H.E.S.S. preliminary
Westerlund I
CMZ (central)
Westerlund I
1908
Crab
CTA South 50 h
LHAASO 1 y
10^{-12}
10^{-13}
$E^2 \frac{dN}{dE}$ [erg cm^{-2} s^{-1}]
10^0
10^1
10^2
10^3
E [TeV]

Summary

- The VHE/UHE gamma-ray sky is rich and complex
  - Particle acceleration is common in nature and very-high to ultra-high energy gammas are an effective probe
- Supernova remnants accelerate particles up to ~100 TeV
  - Protons are accelerated as well as electrons
  - But no evidence yet that the can reach 'the knee'
- Proton acceleration to ~PeV in the Galactic Centre
  - and perhaps in association with massive stellar clusters and/or PWN
- Very efficient acceleration in pulsar winds
  - Right at the limit of theoretical possibility - but may be purely e+/e- acc.
- Active galaxies
  - Electrons accelerated in compact regions of the jet (very fast variability) – protons? No compelling evidence yet from gammas – see neutrinos
- GRBs! – early days but mysteries already

Questions?