Georgia Tech Physics College of Sciences

# The Universe in Very-High-Energy Gamma Rays

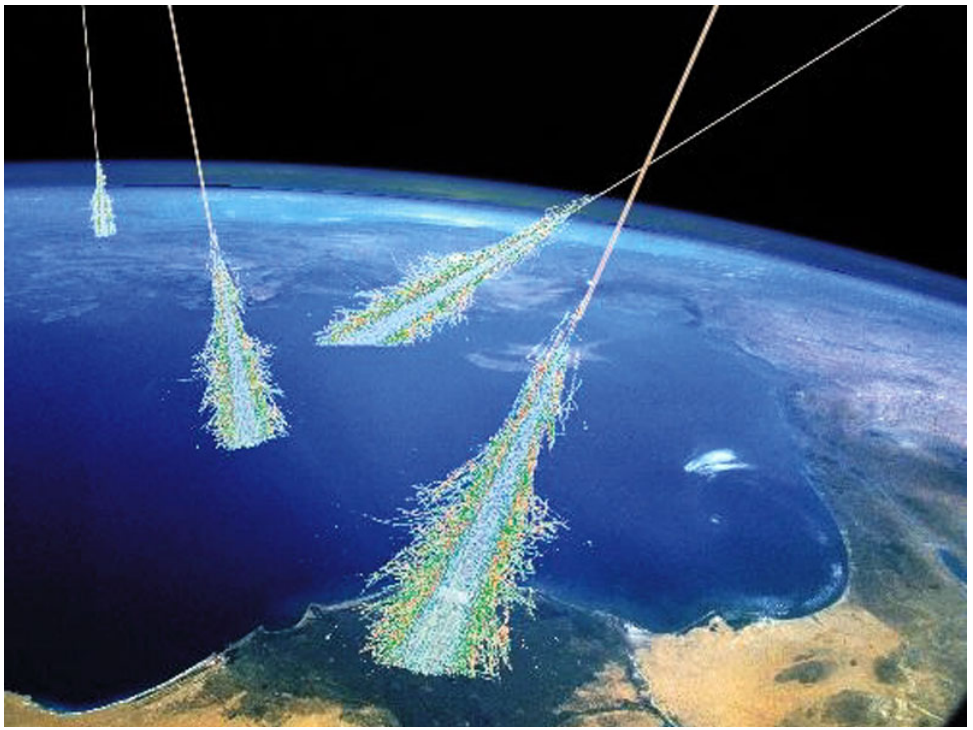
## From understanding cosmic particle accelerators to searches for new physics

Nepomuk Otte

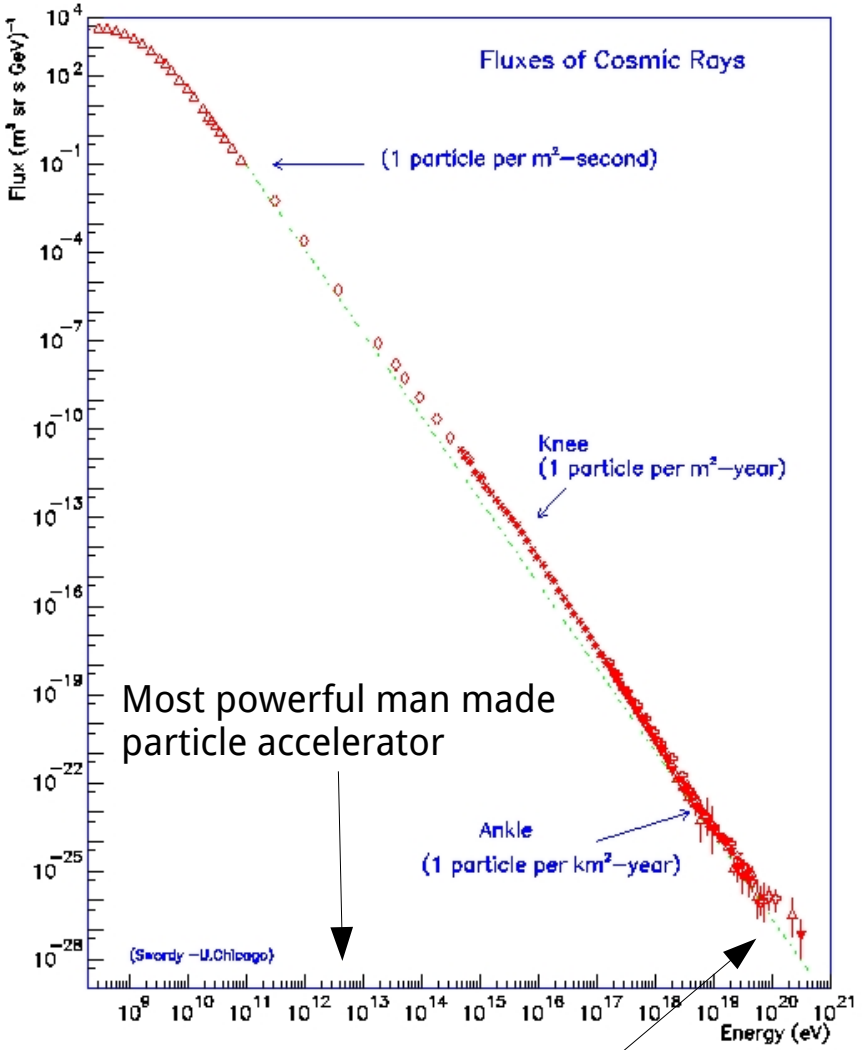
School of Physics &
Center for Relativistic Astrophysics
Georgia Institute of Technology

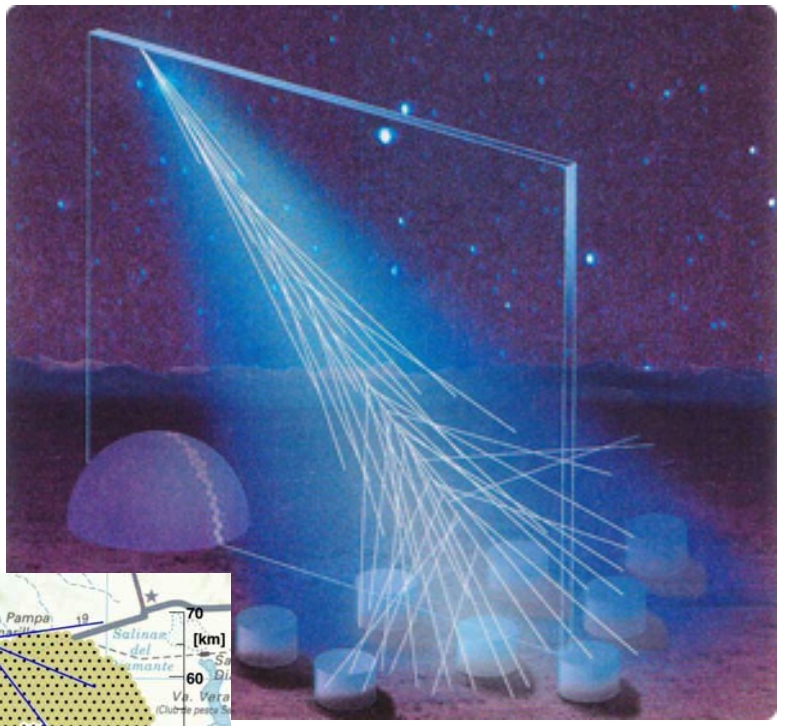
# Cosmic Rays

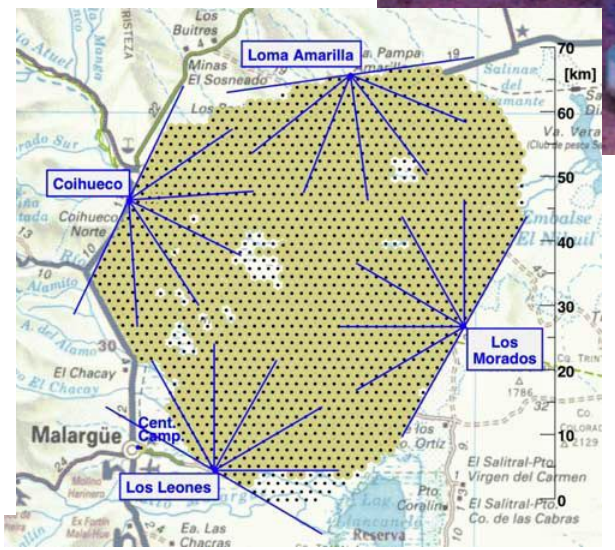
V. F. Hess (1912).
"Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten".
Physikalische Zeitschrift 13: 1084–1091



# The Cosmic Ray Spectrum



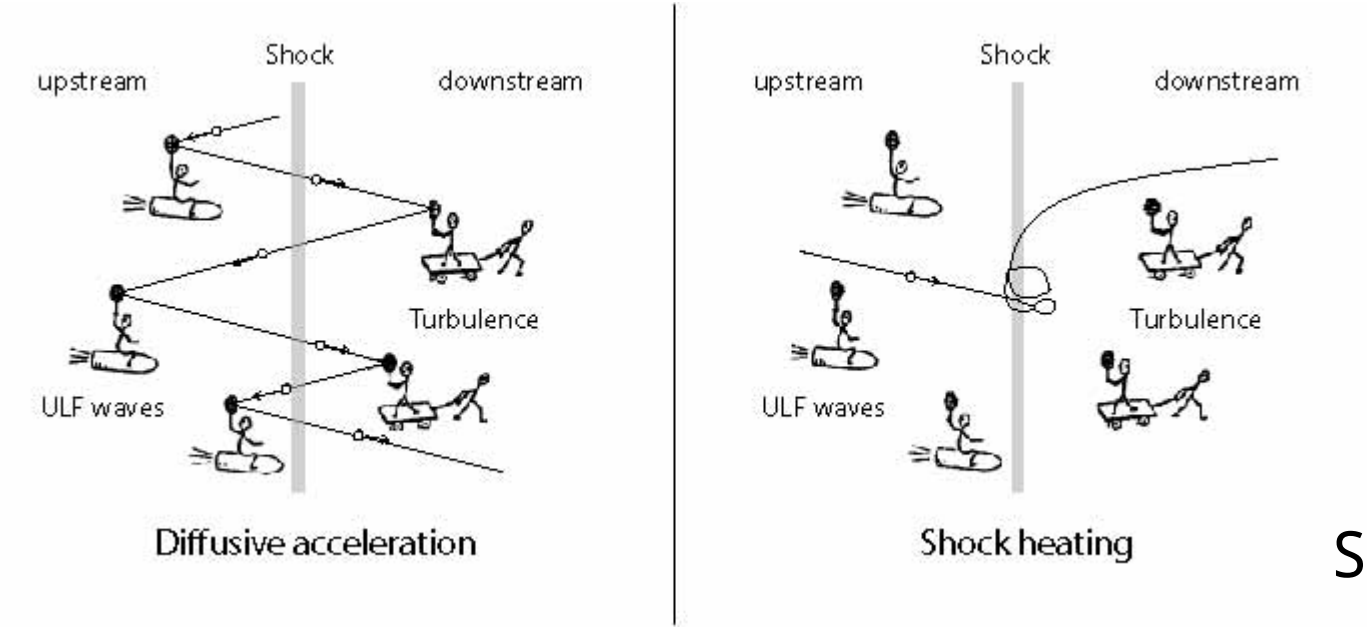



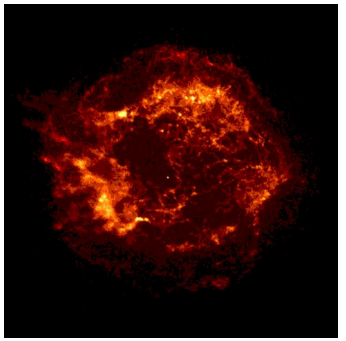



energy equivalent to
tennis ball going with 60 km/h = 35mph

**Where do cosmic rays come from?**

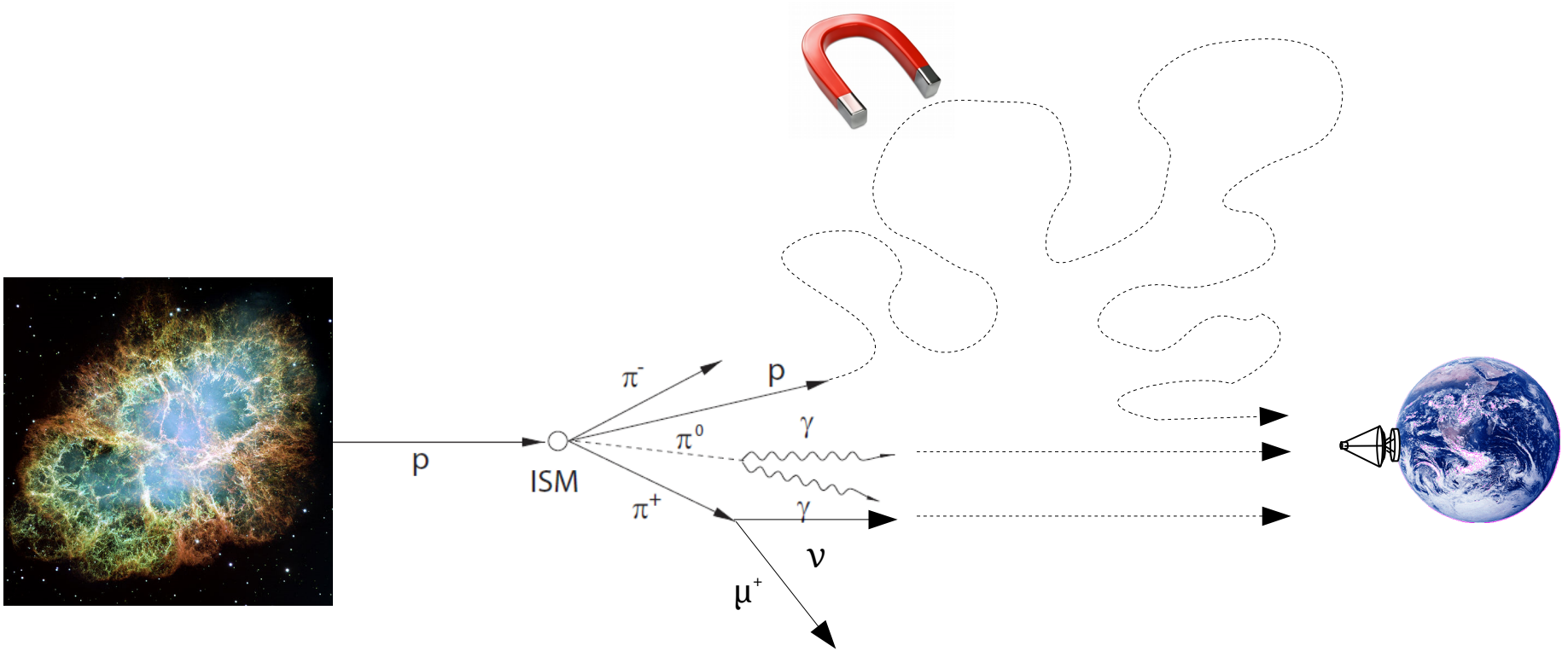
# Classical Shock Acceleration



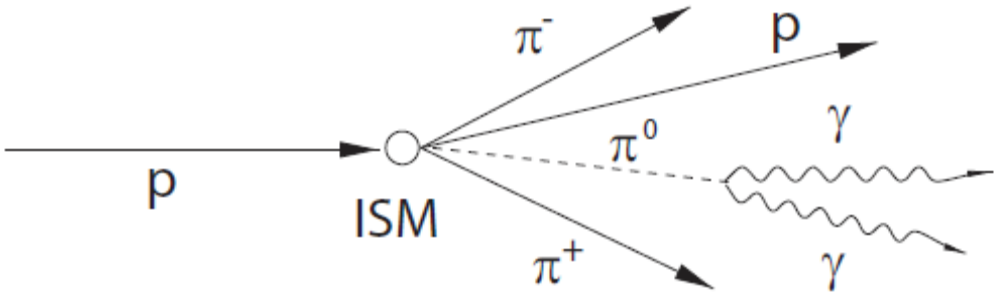
Supernova remnants

# Three Messengers

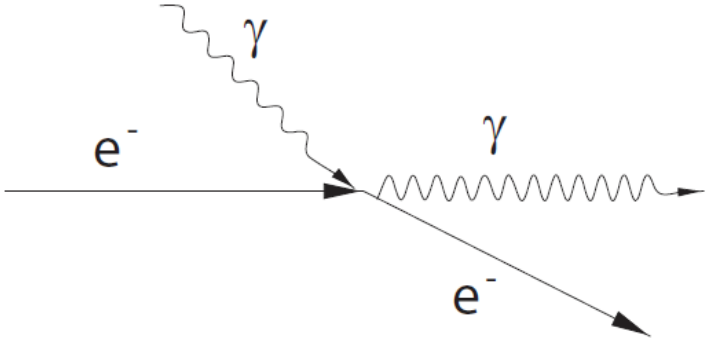



- Charged particles: $He^{++}$, $p^{+}$, $e^{+/-}$, ....
- Gamma-rays $\gamma$
- Neutrinos $\nu$

# VHE Gamma Ray Production




Collision of relativistic particles



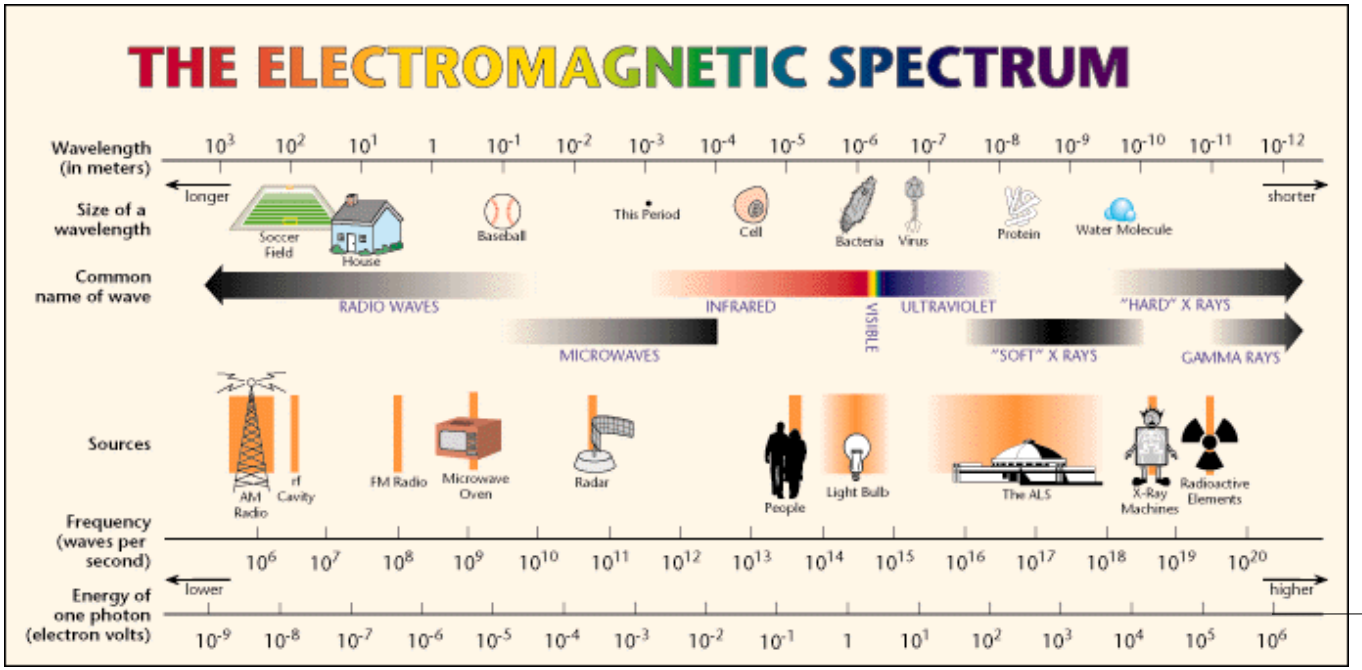

Collision of low energy photons with relativistic electrons

And maybe:

Decay or annihilation of dark matter particles

VHE gamma-rays probe cosmic particle accelerators

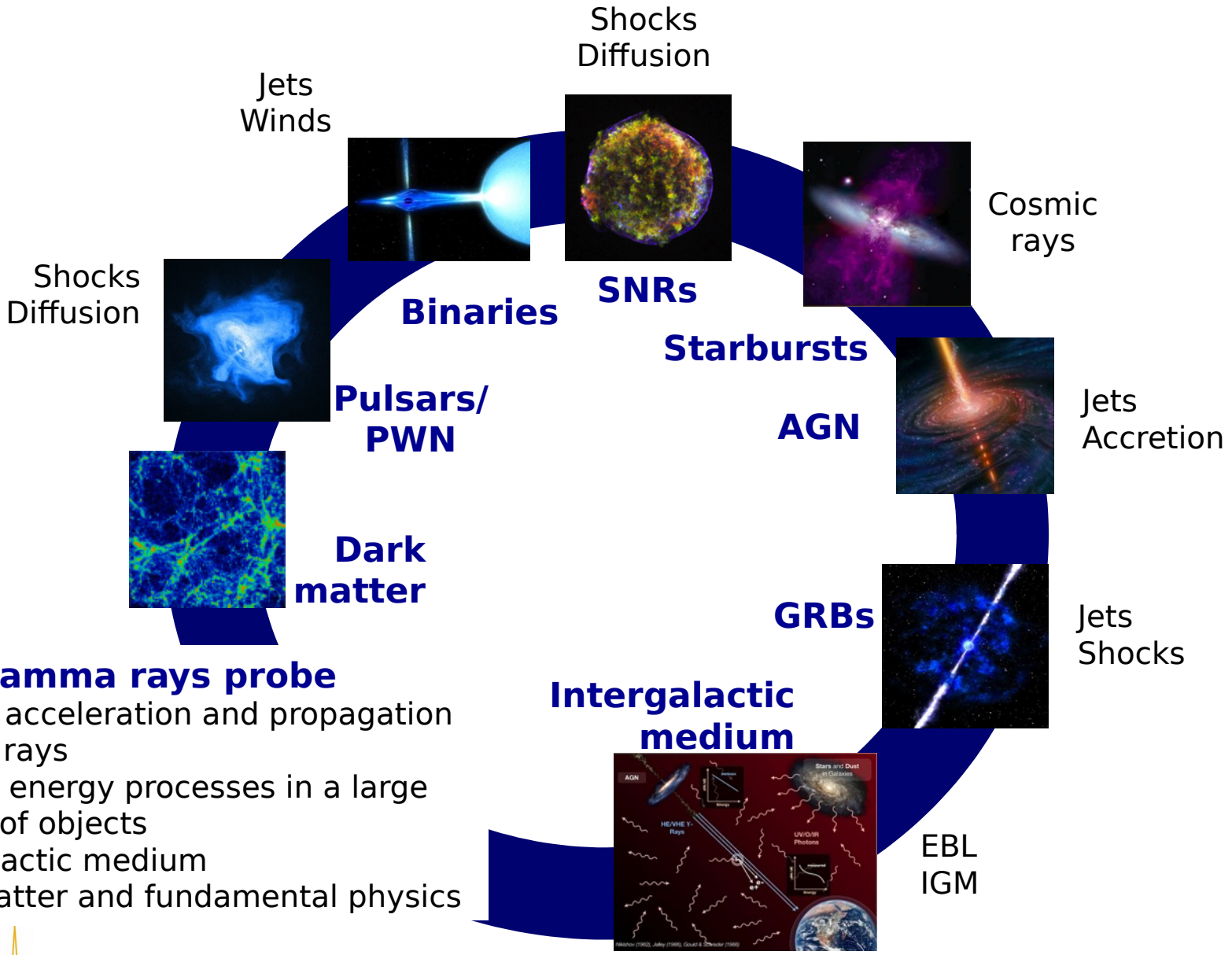
# Very High Energy Gamma-Rays




VHE gamma-rays are here

$10^{12}$ eV = 1 TeV

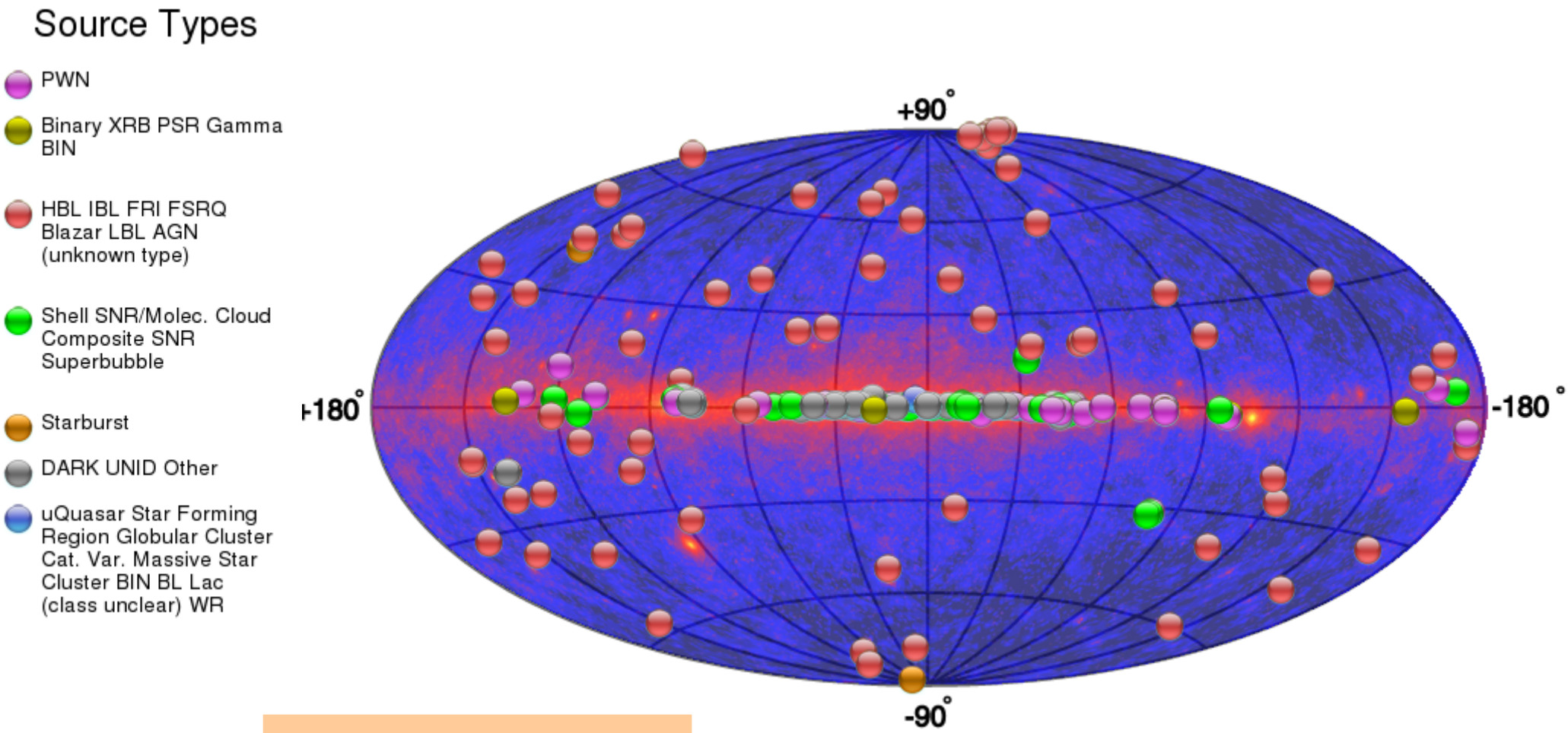
# Astronomy and more in the VHE Band




**VHE gamma rays probe**

Particle acceleration and propagation
Cosmic rays
Highest energy processes in a large variety of objects
Intergalactic medium
Dark matter and fundamental physics

# The VHE Sky is bright

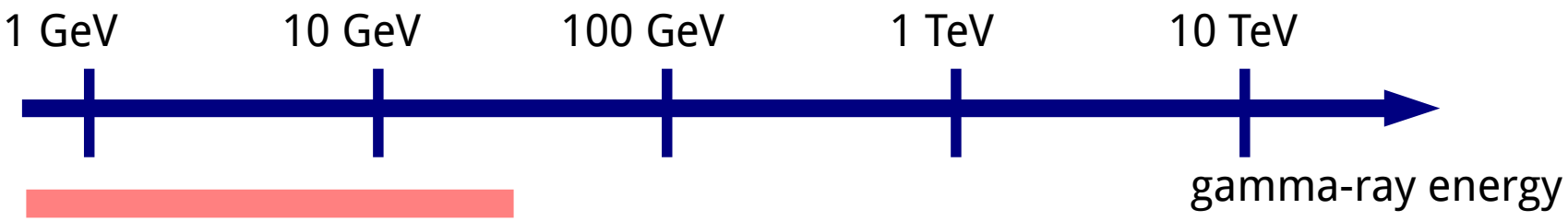



175 sources

Over the past 25 years

http://tevcat.uchicago.edu/

# Gamma-Ray Instruments




Satellites
Fermi-LAT

Cherenkov telescopes
VERITAS and CTA

Water Cherenkov detectors
HAWC

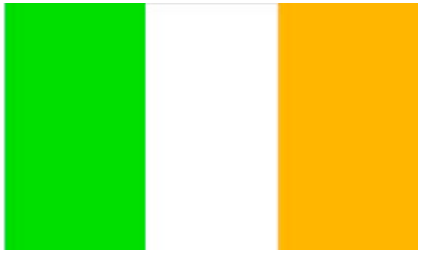
# VERITAS and other Cherenkov Telescopes

VERITAS (highest sensitivity)
Southern Arizona

MAGIC Canary Island La Palma

H.E.S.S. (best view of the Galactic center)
Namibia

# The VERITAS Collaboration



**~100 members, 20 institutions**

23 non-affiliated members

+35 associate members

Smithsonian Astrophysical Observatory

Adler Planetarium

Argonne National Lab

Barnard College / Columbia University

Bartol Research Institute / University of Delaware

Georgia Institute of Technology

Iowa State University

Purdue University

University of California, Los Angeles

University of California, Santa Cruz

University of Chicago

University of Iowa

University of Minnesota

University of Utah

Washington University in St. Louis

McGill University, Montreal

University College Dublin

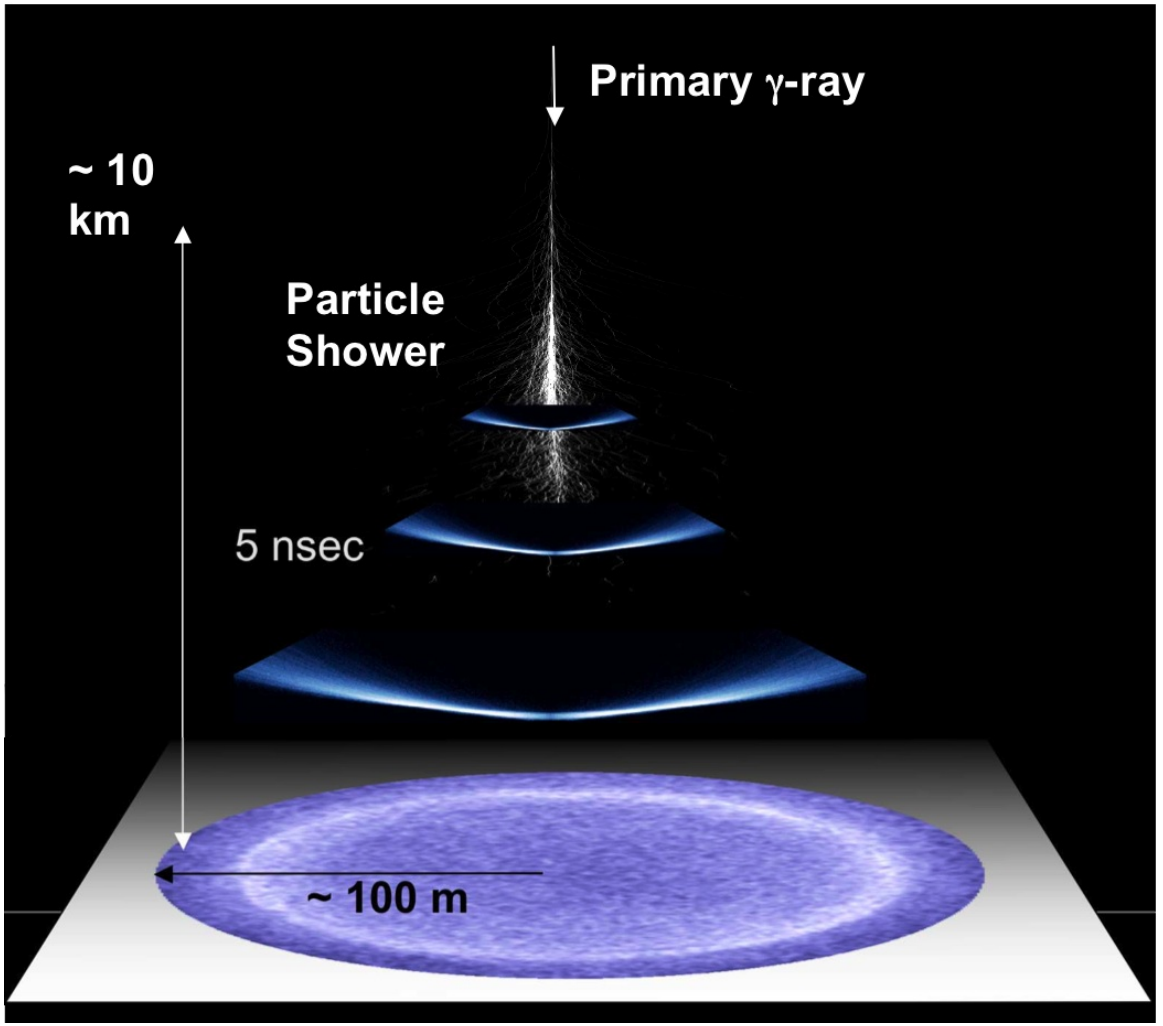
Cork Institute of Technology

Galway-Mayo Institute of Technology

National University of Ireland, Galway

**Acknowledgments: This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Science Foundation Ireland (SFI 10/RFP/AST2748). We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.**

# Imaging Atmospheric Cherenkov Technique




**Huge light pool of 100,000 m$^2$**

A very faint flash of blue light that last a couple of nanoseconds

150 Cherenkov photons / m$^2$ for 1 TeV gamma ray

VHE gamma rays come in small numbers:
Less than one gamma-ray per square meter per year

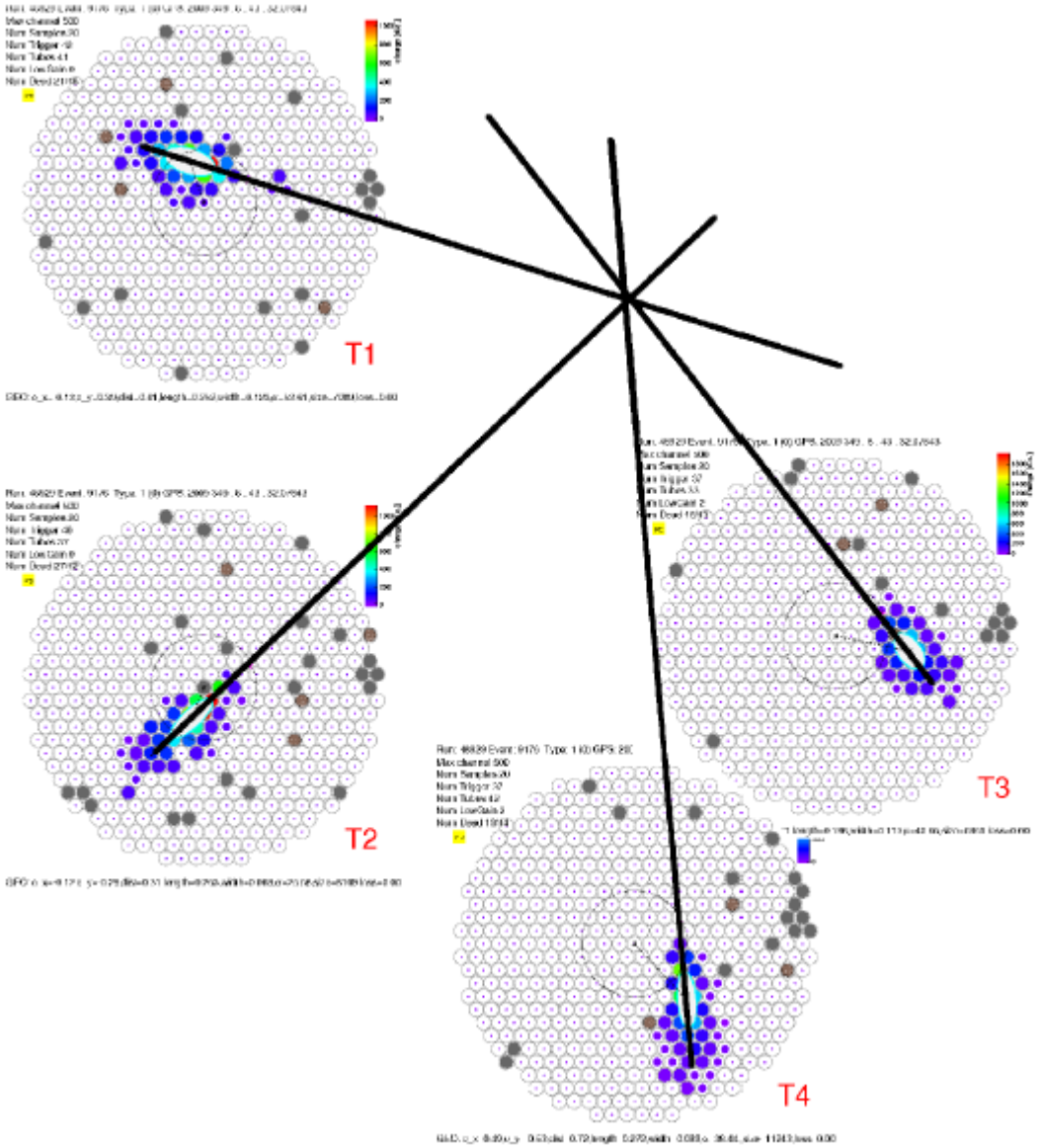
Georgia Tech

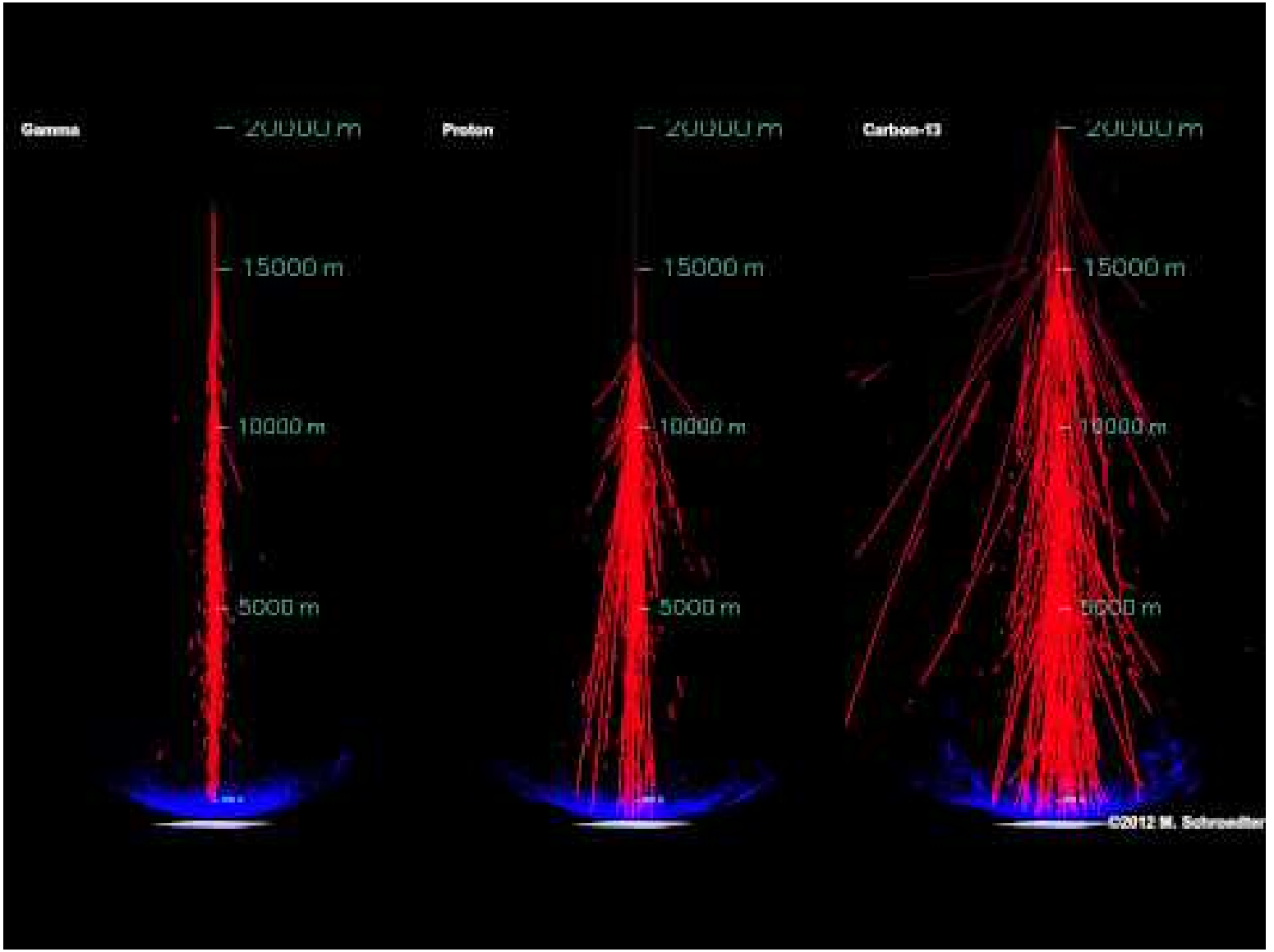
# The VERITAS Array

# Event Reconstruction

Stereo imaging of a shower
→ reconstruction of event origin

Intensity of light
→ energy of primary

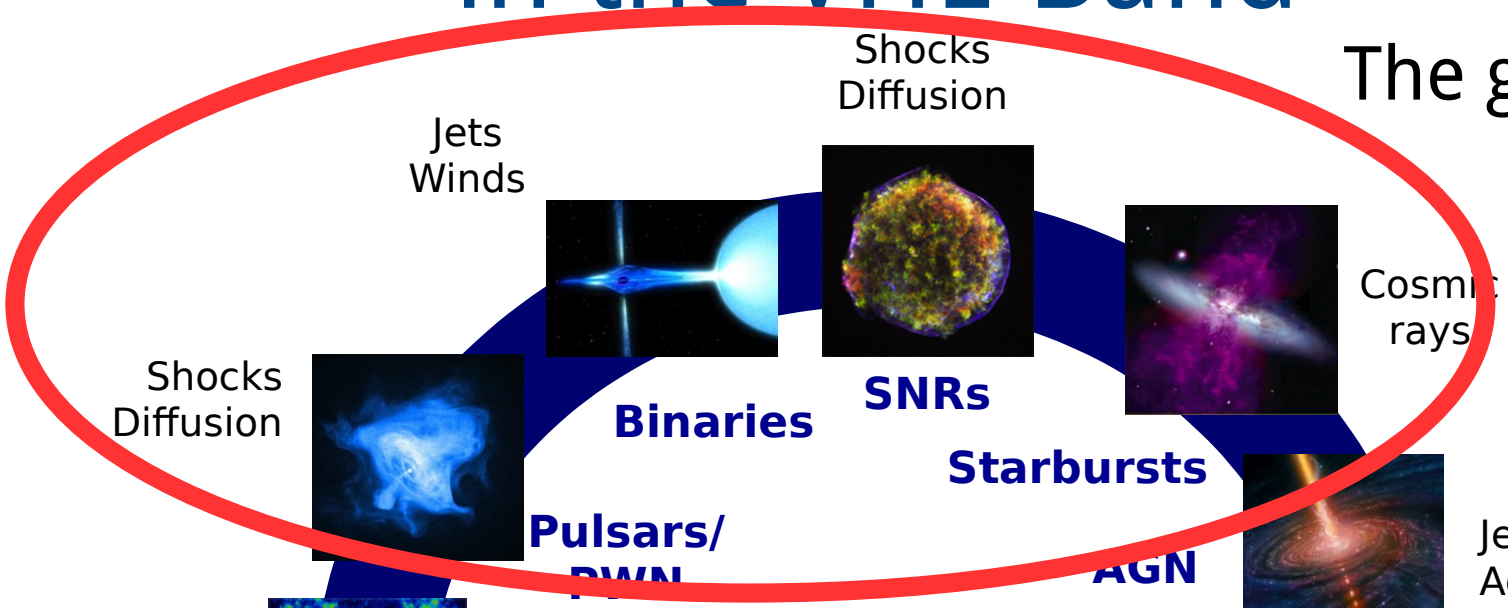





Images of air showers allow the identification of the primary particle

# Astronomy and more in the VHE Band

The galactic sky




**VHE gamma rays probe**

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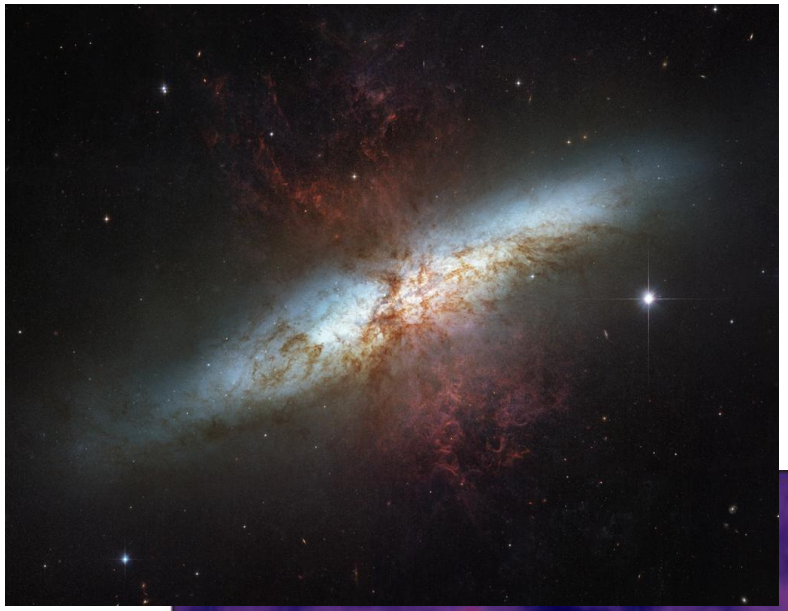
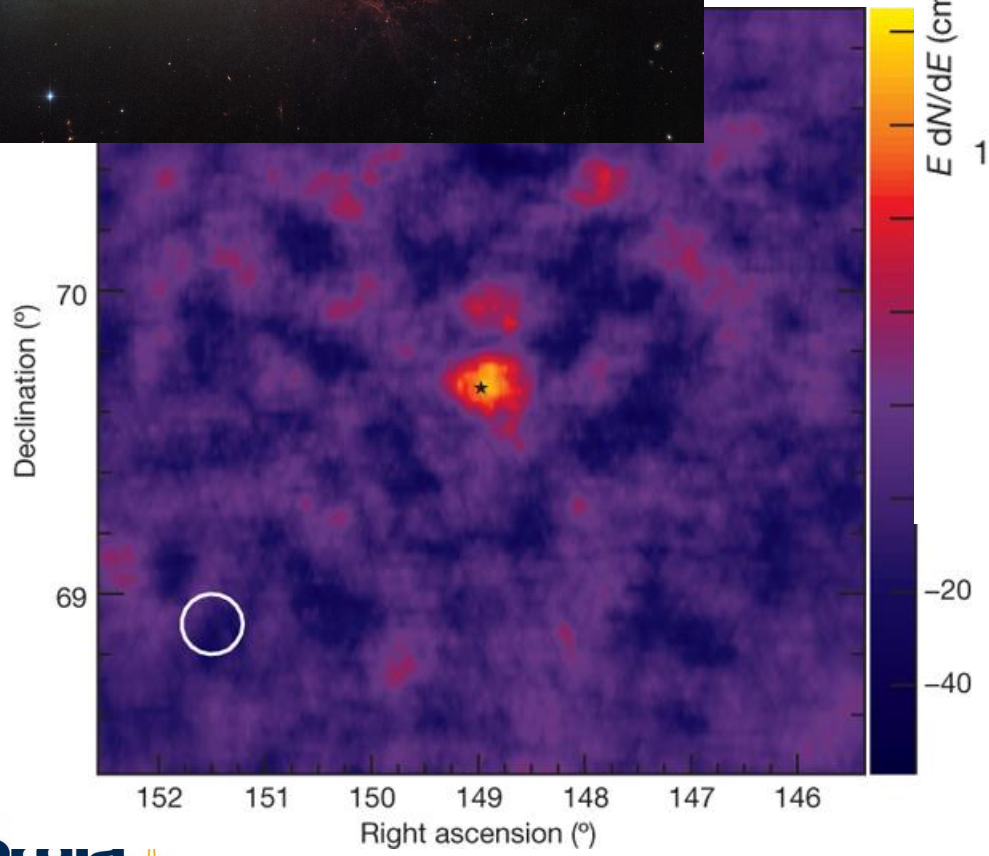
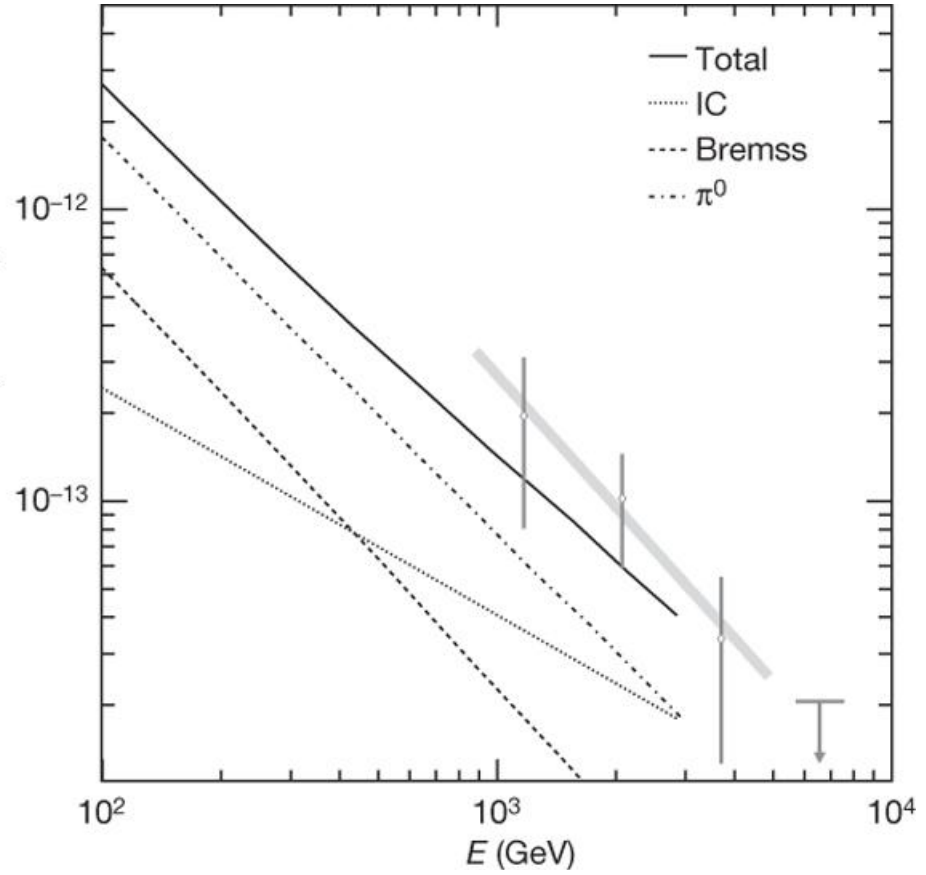
Highest energy processes in a large variety of objects
Intergalactic medium
Dark matter and fundamental physics

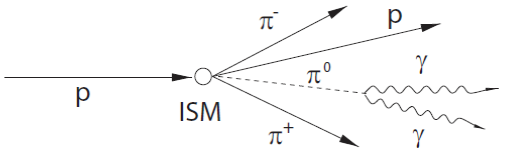
# Starburst Galaxy M82

VERITAS Nature: 462, p 770 (2009)





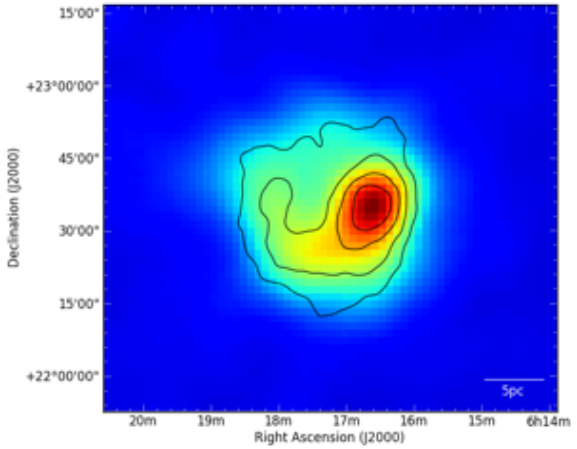



Dieter Willasch, Astro-Cabinet

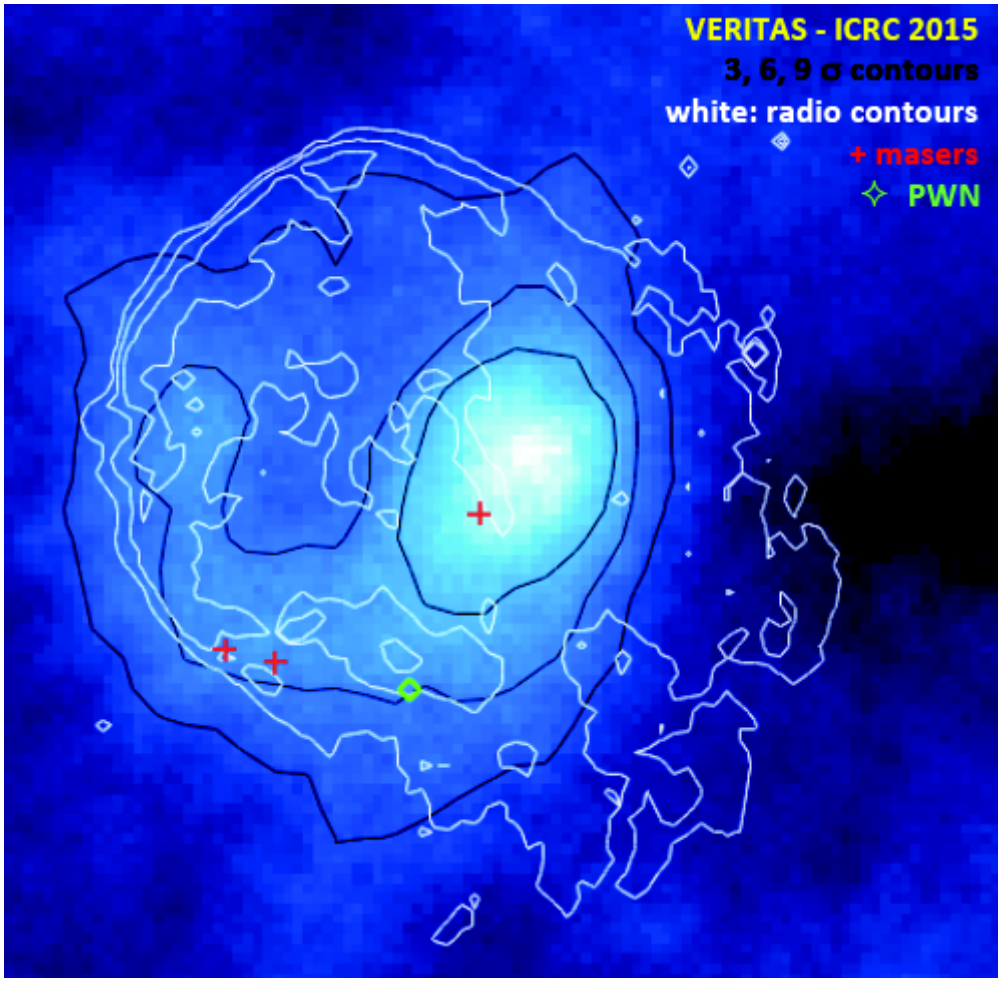
# IC 443

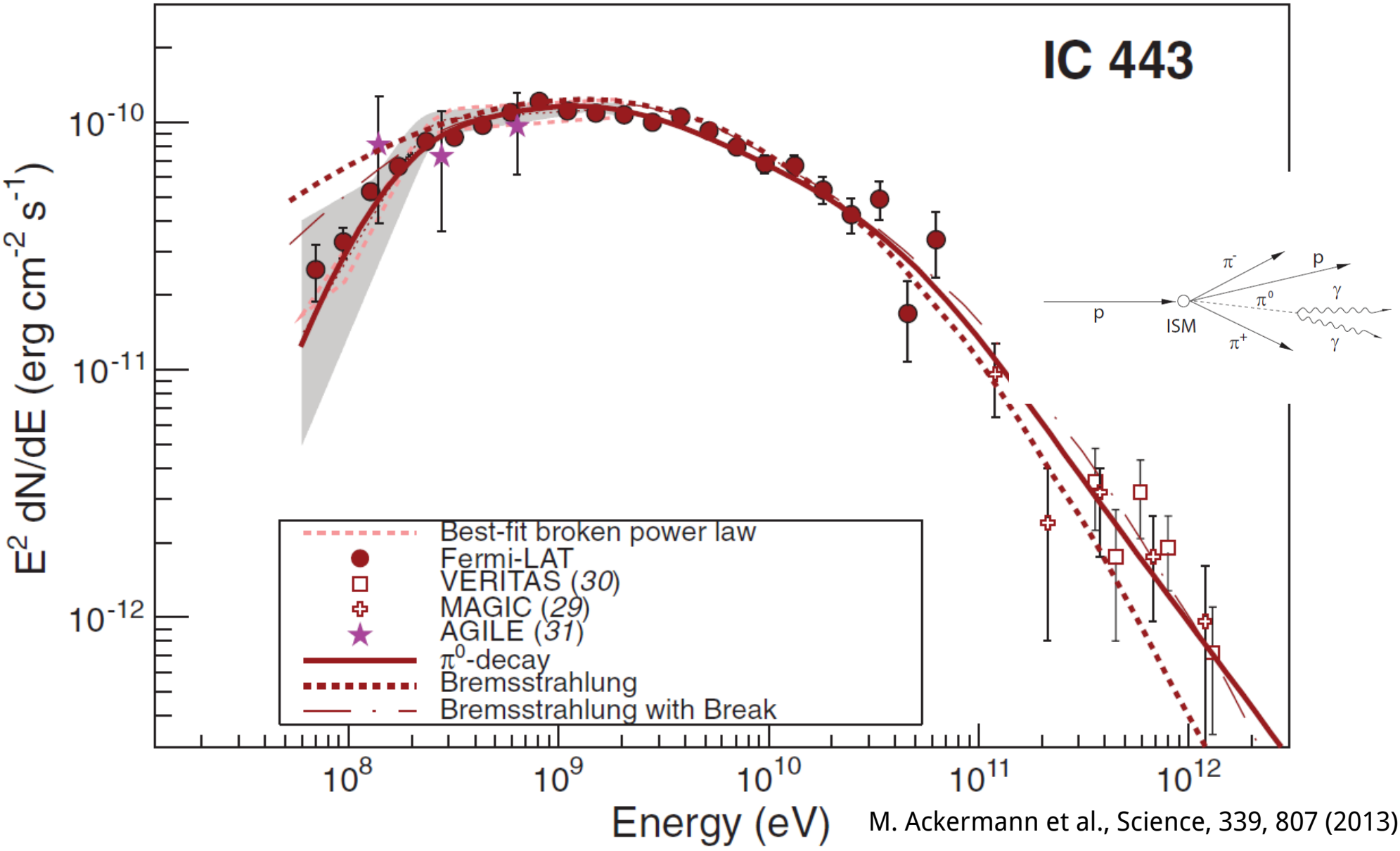
- GeV/TeV emission show remarkable spatial correlation
- Anti correlation with thermal X-rays
- VHE spectral indices do not vary across remnant

Single population of CR interacting with swept up / shocked gas?

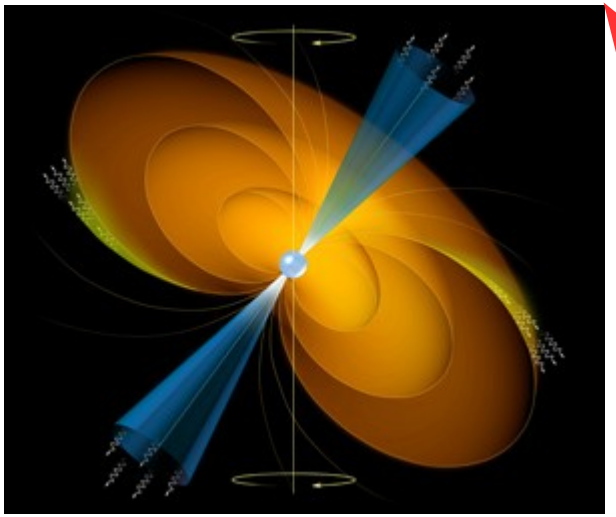


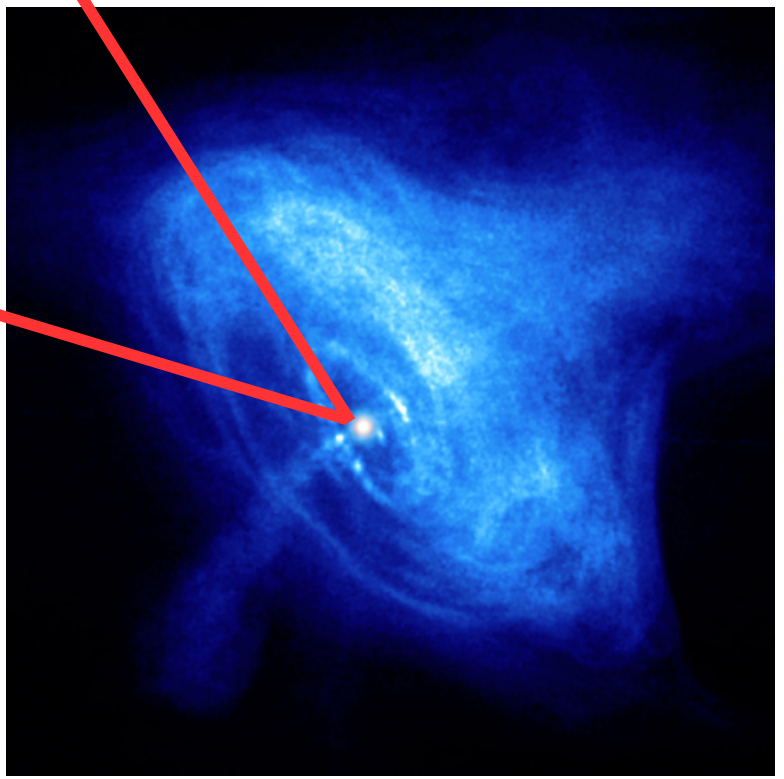

courtesy: J. Hewitt for Fermi-LAT Collaboration





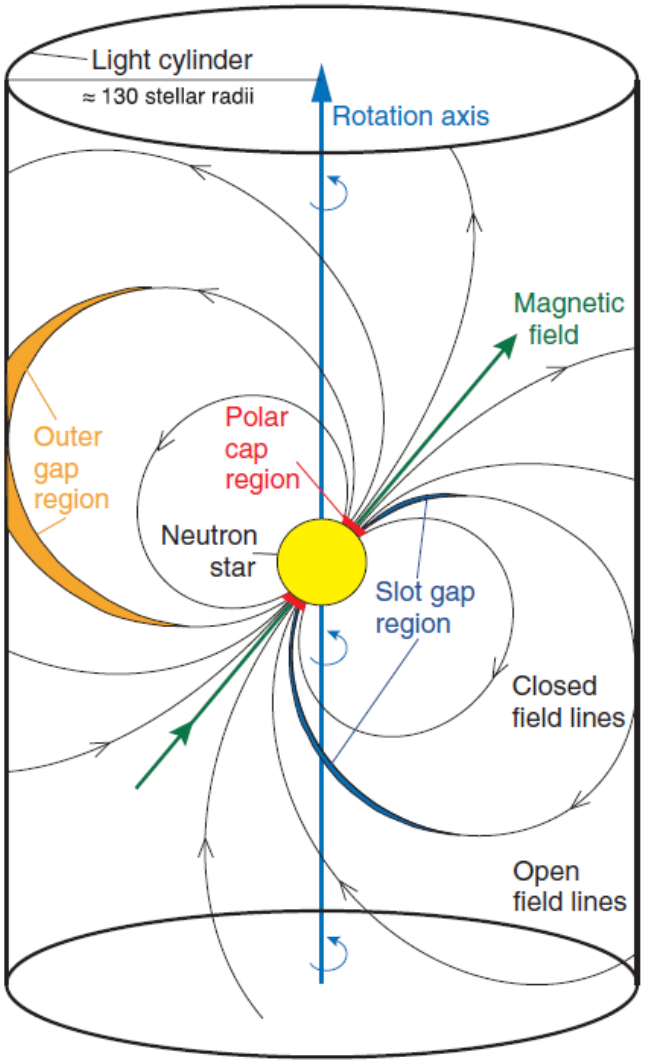

M. Ackermann et al., Science, 339, 807 (2013)





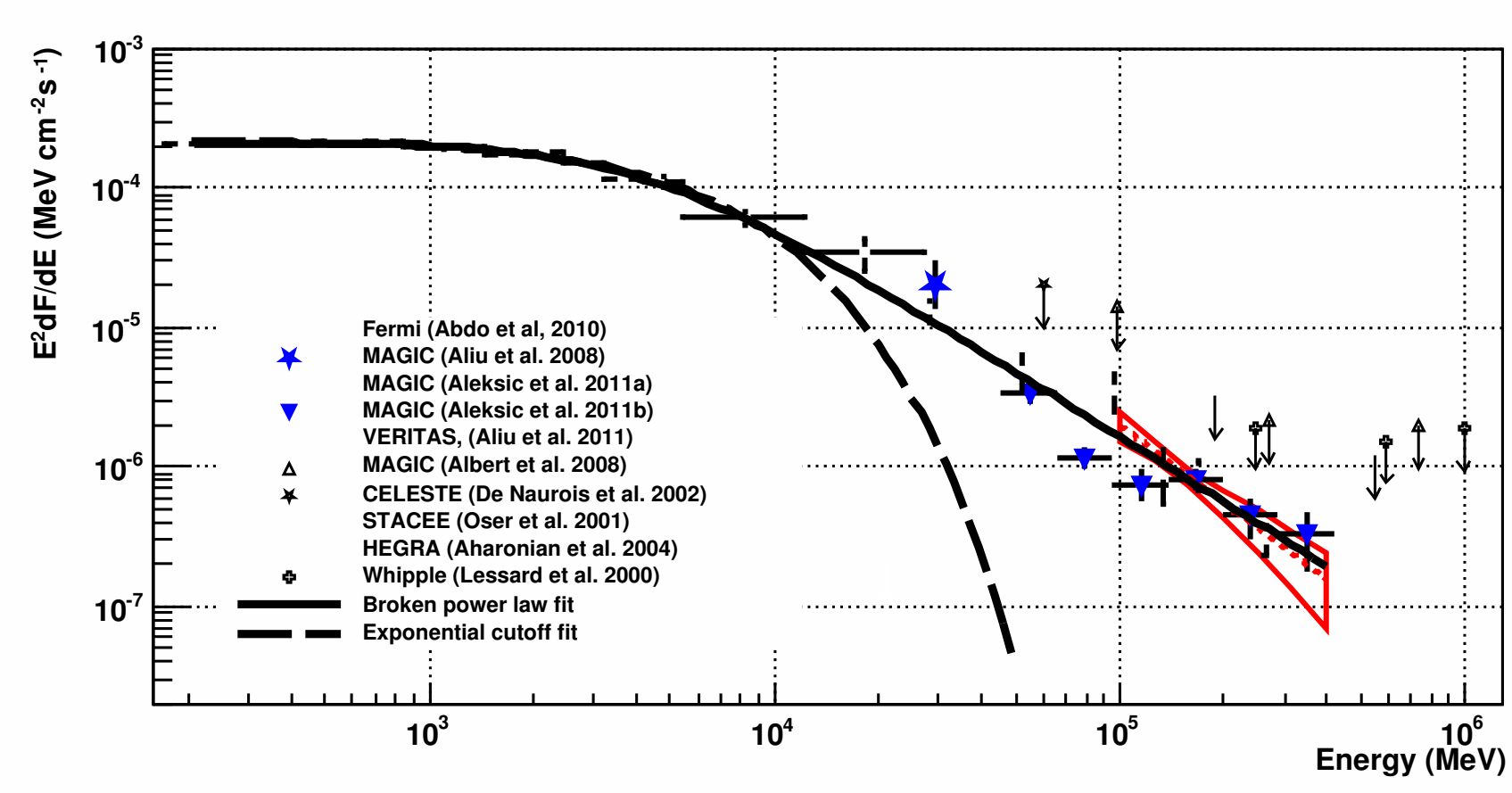
Pulsars
and
Pulsar Wind Nebulae

# Gamma-Ray Emission from the Pulsar Magnetosphere




- Stable vacuum gaps in the magnetosphere
- Potentials of ~$10^{12}$ eV
  → particle acceleration
- Curved particle trajectory
  → $\gamma$-ray emission
- Interaction with low energy photons
  → inverse Compton emission
- Gamma-rays are subject to absorption

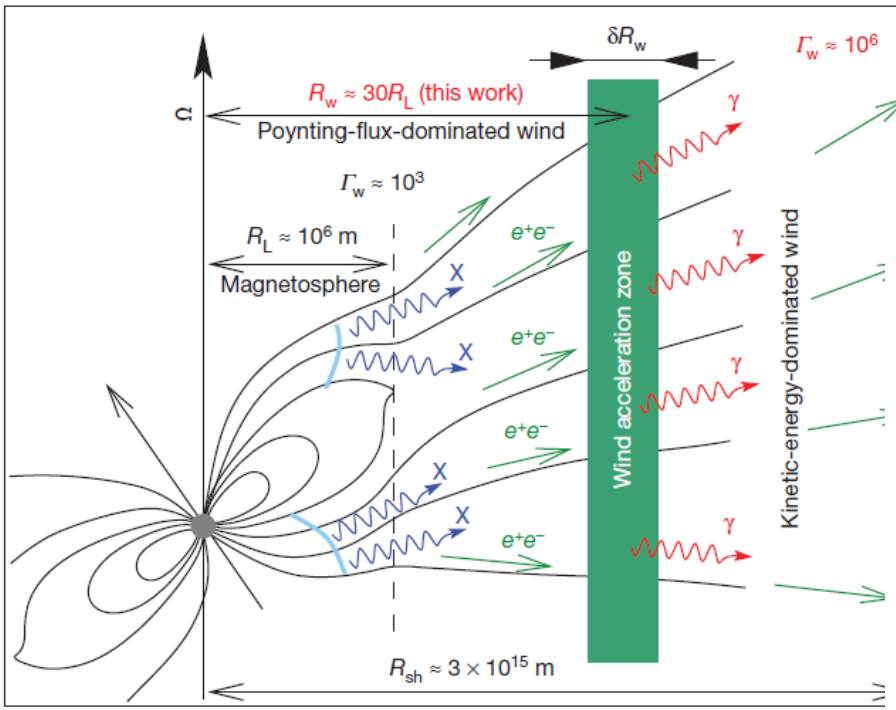
# Crab Pulsar: The GeV – TeV Connection

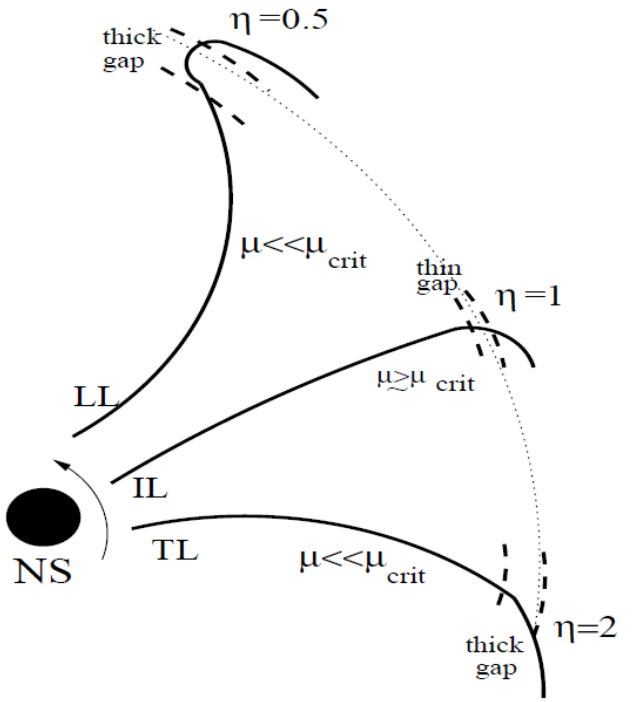


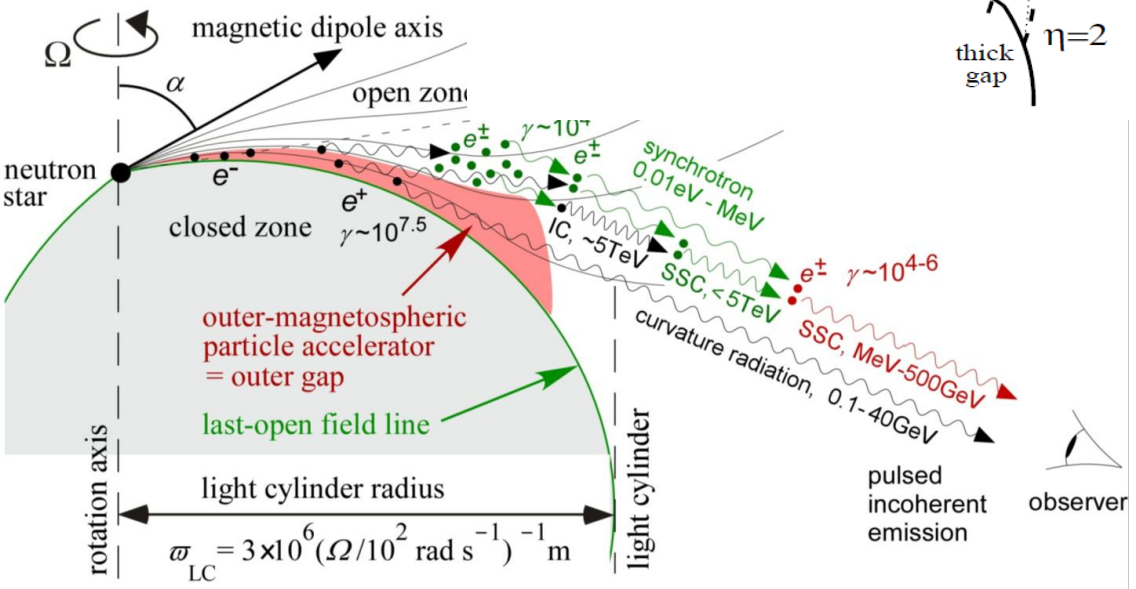

Good description with smooth broken power law
(does not exclude that two emission processes are at work)

# Possible Explanations

- Particle cascades in magnetosphere lead to significant inverse Compton scattering (Lyutikov (2012), Hirotani (2011), Du (2012))
- Topology of magnetic field allows for CR even >100 GeV (Bednarek 2012)
- Interaction of pulsed X-rays with $e^{+/-}$ in cold pulsar wind (Aharonian 2012)
- …



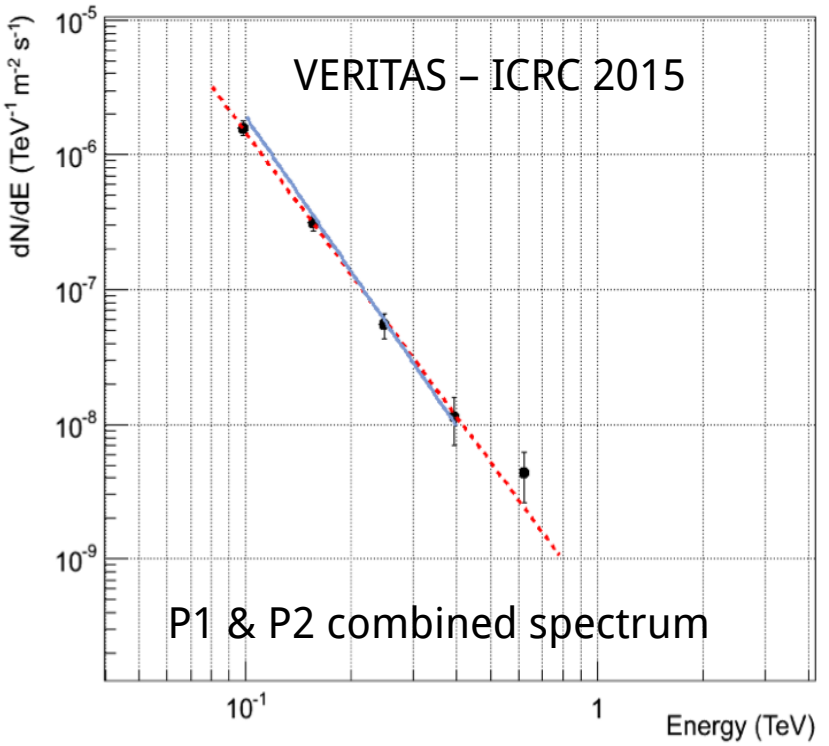



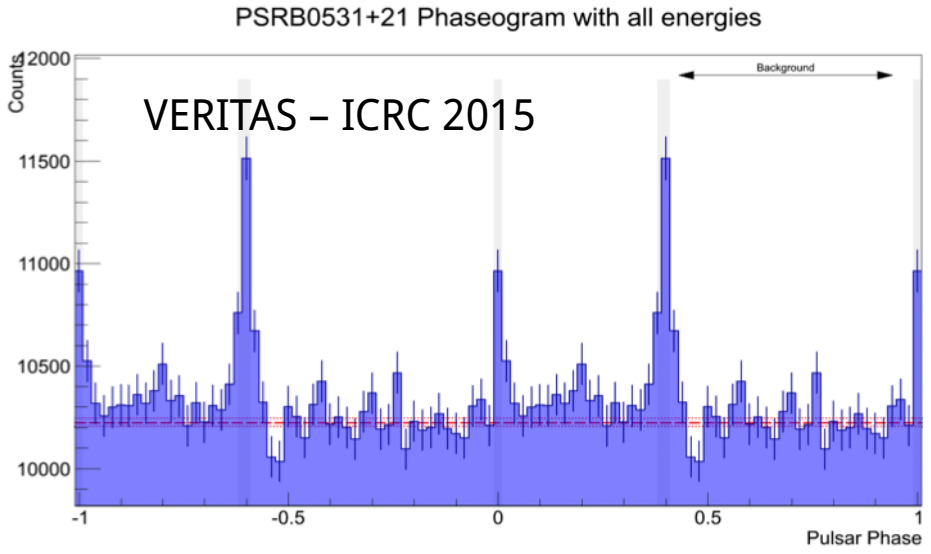



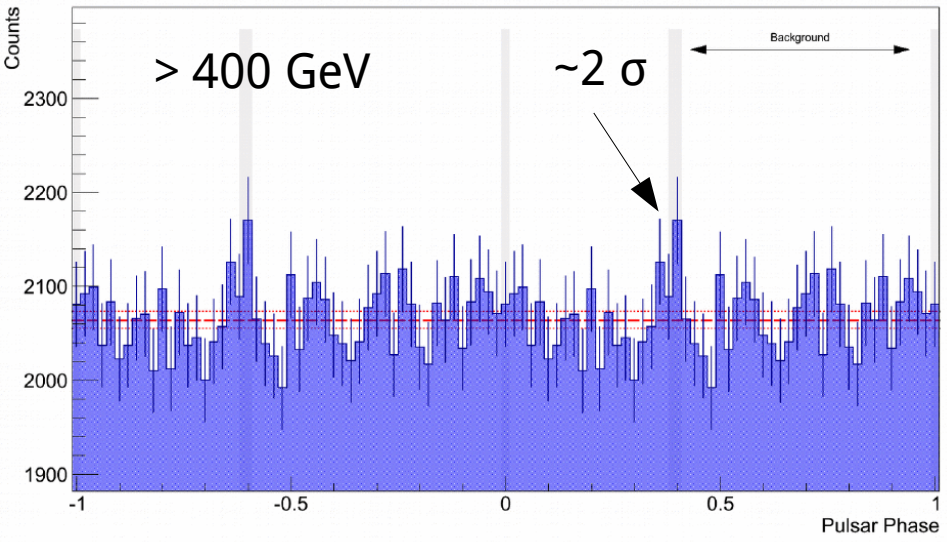
# Crab Pulsar

## What is the origin of pulsed VHE emission?

- Additional Crab pulsar observations extend VERITAS spectrum to 600 GeV.
- No signal above 600 GeV even after 200 hours of data.
- Analysis and data taking ongoing



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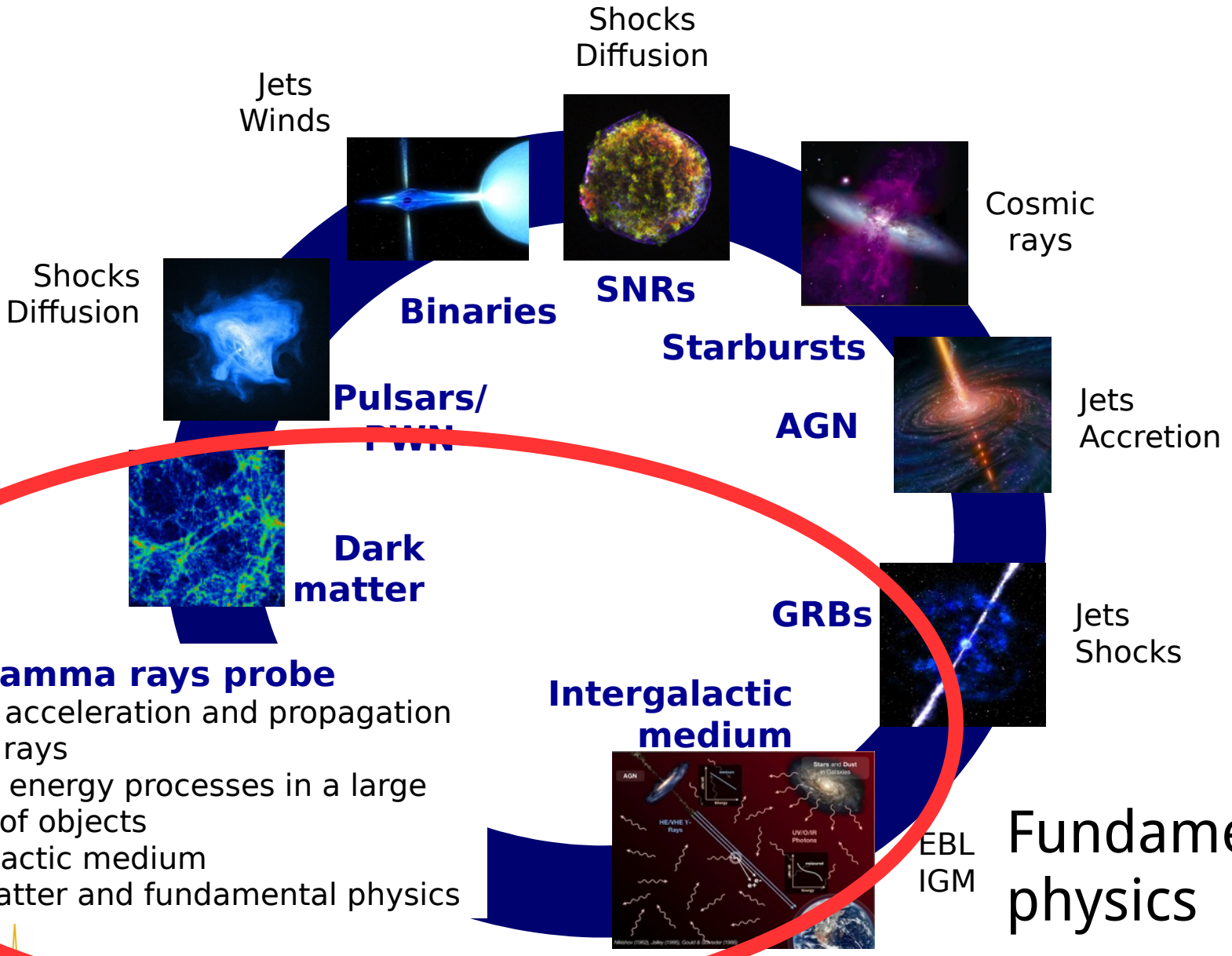


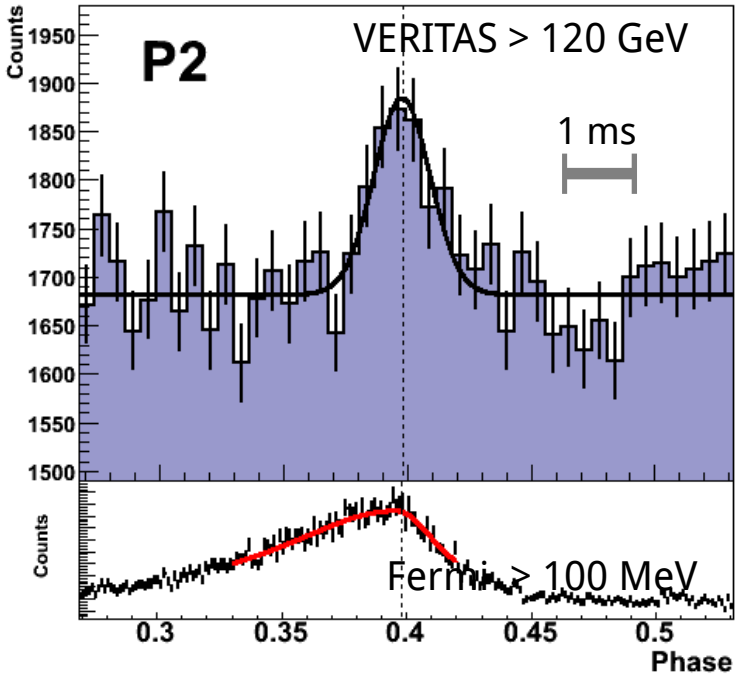

**VHE gamma rays probe**

Particle acceleration and propagation
Cosmic rays
Highest energy processes in a large variety of objects
Intergalactic medium
Dark matter and fundamental physics

Fundamental physics

Nepomuk Otte

# Pulsed Gamma Rays: Tools to Search for new Physics



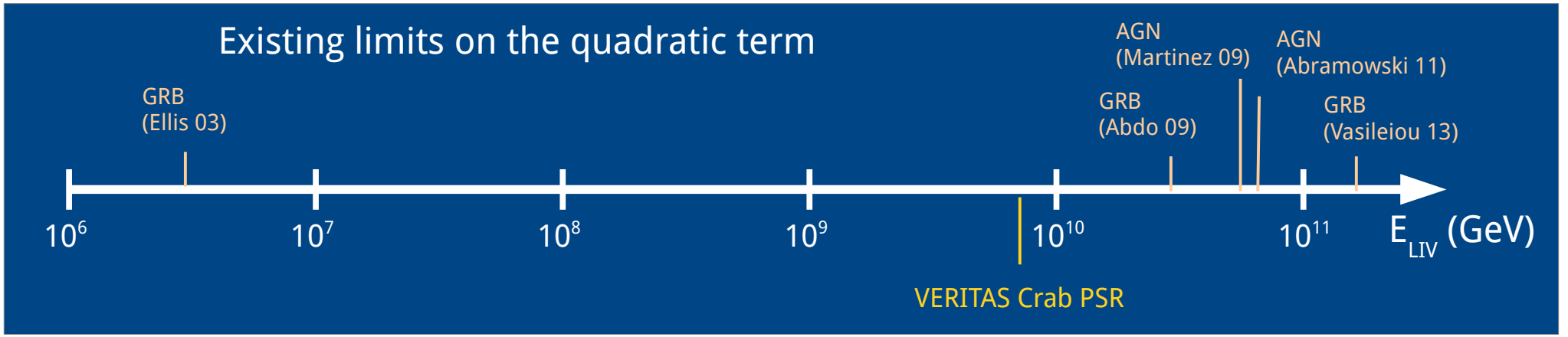

Pulsars are pulsed, broadband light sources with very high timing precision

Ideal conditions to search for energy dependent arrival time differences

$$c'(E) = c + \underbrace{a \cdot \frac{E}{E_{\mathrm{LIV}}}}_{} + \underbrace{b \cdot \left(\frac{E}{E_{\mathrm{LIV}}}\right)^2}_{}$$

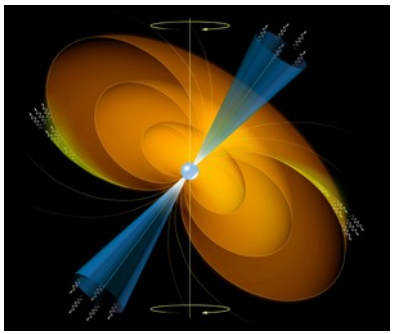
$$\Delta t_1 = \frac{d}{c} \cdot \frac{E_{\mathrm{h}} - E_{\mathrm{l}}}{E_{\mathrm{LIV}}} \qquad \Delta t_2 = \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{\mathrm{h}}^2 - E_{\mathrm{l}}^2}{E_{\mathrm{LIV}}^2}$$

Linear term Quadratic term



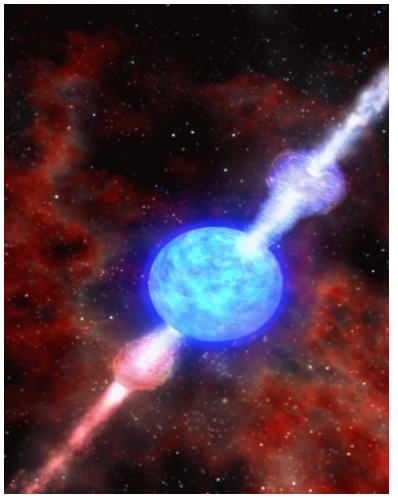
# Testing the Speed of Light in Gamma Rays

Pulsars



Flaring AGN


GRB



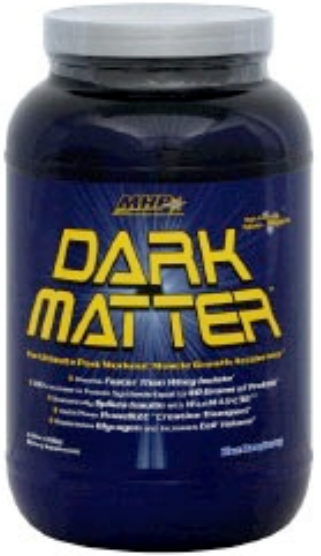
z=0 z=0.01 ... ~1 z > 1

Distance

**Advantages:**
- Photons with the highest possible energies
- Astronomical, cosmological distances

**Challenges:**
- Limited sample
- Not reproducible (AGN, GRB)
- Unknown source physics

Ultimate proof of LIV would be to show distance dependence of LIV


MHP
DARK
MATTER

# Indirect Dark Matter Searches

Search for particle DM annihilation or decay from 100 GeV to the multi-TeV scale

$$\frac{d\phi}{dE} = J(\psi) \cdot \frac{d\phi^{PP}}{dE}$$

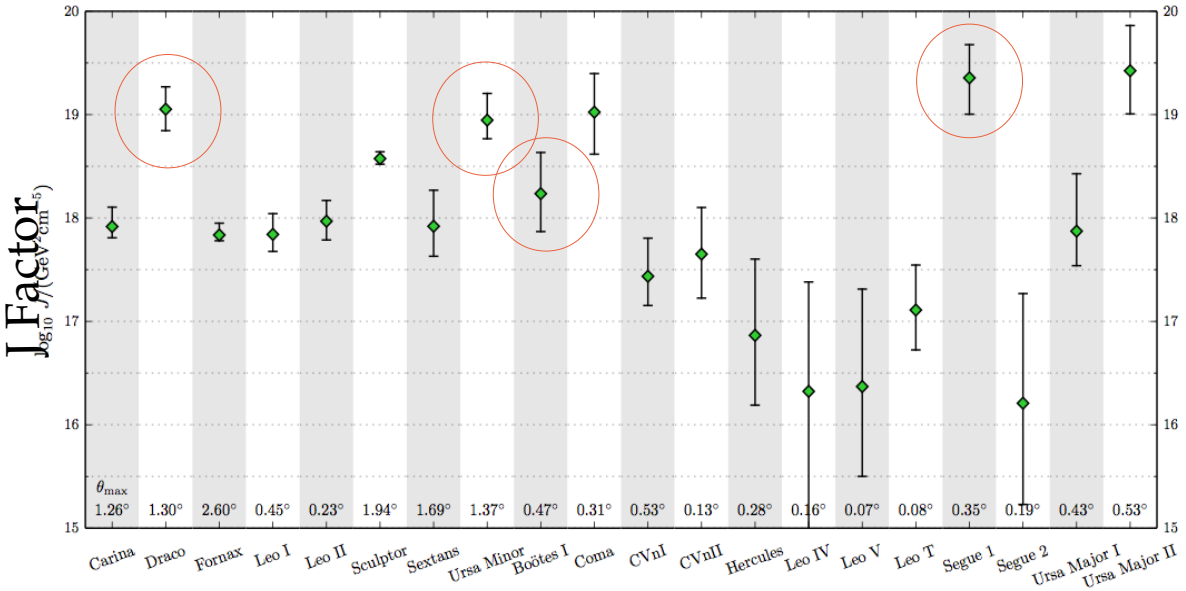
Particle physics model – WIMP, decay channels, etc

Astrophysical factor – DM density, morphology

- Search for signals in DM-dominated regions: ***Dwarf Spheroidal Galaxies (dSphs)***, the Galactic Center, Galaxy Clusters, and ***Fermi Unassociated Sources***

New result on observations of two sub-halo candidates identified from the 2FGL catalog

- Targets identified by lack of variability & MWL counterparts, detectability at VERITAS – 2FGL J0545.6+6018, 2FGL J1115.0-0701

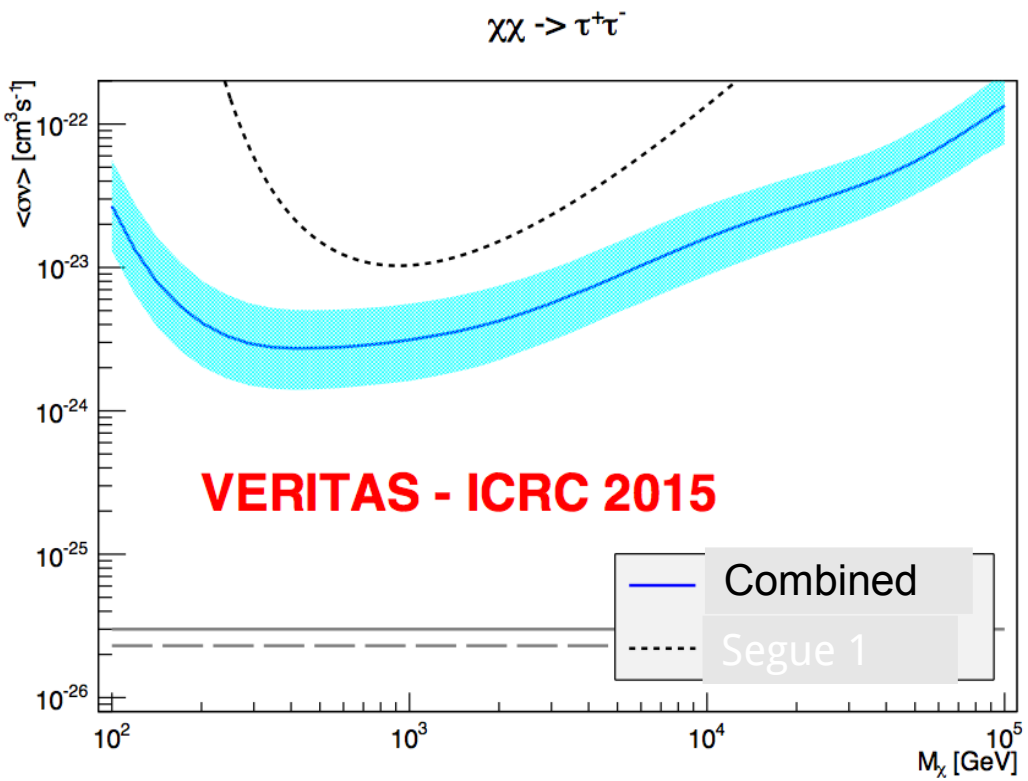



*from Geringer-Sameth, et al. PRD 91, 083535 (2015)*

150 hours annually
on ~all northern dSphs
and
deep exposures on several high J-factor objects

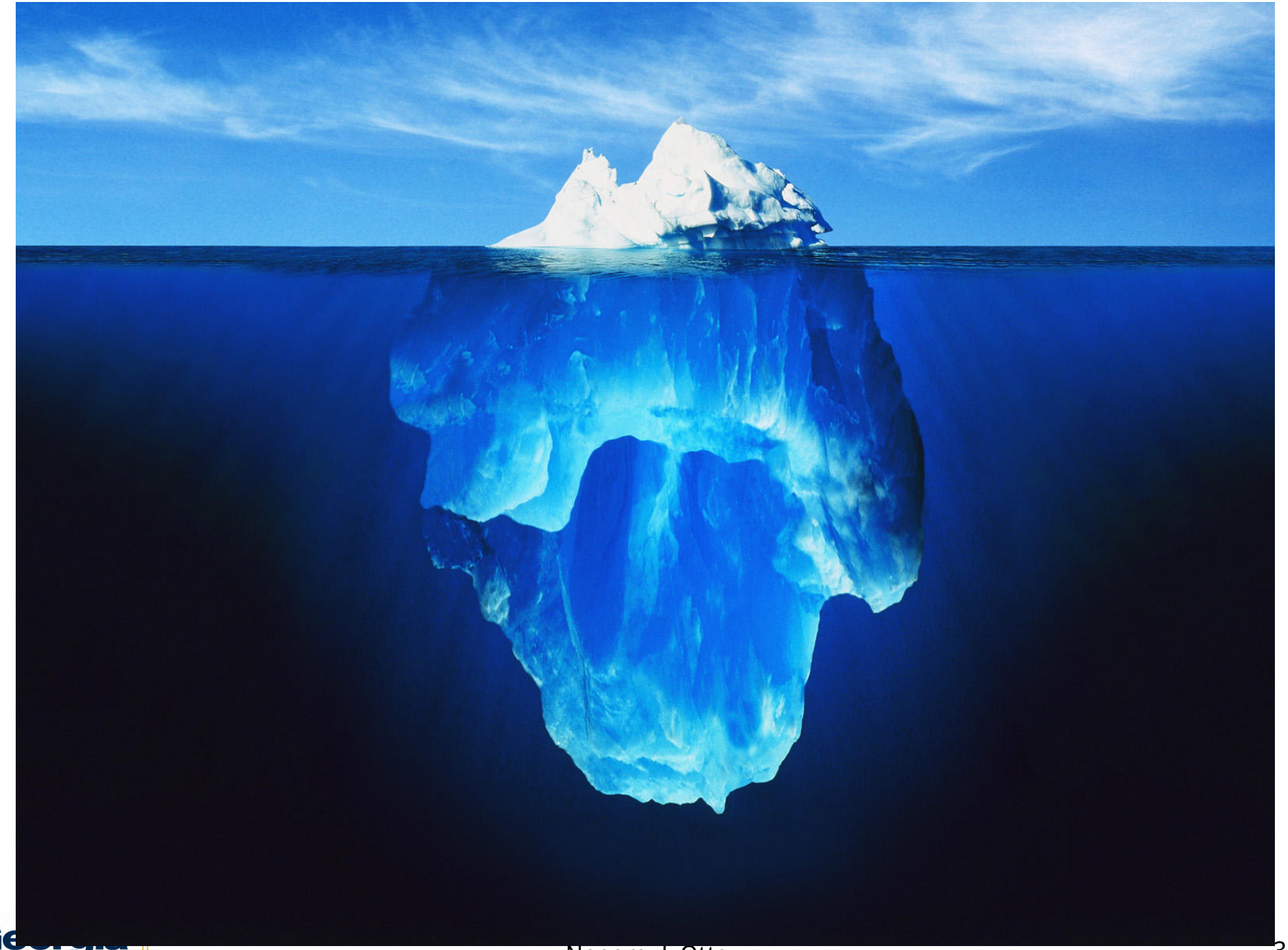
New combined result with data from 5 dSph galaxies

# VERITAS dSph Combined Dark Matter Limits



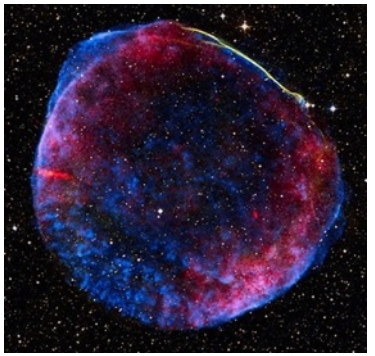

*Phys. Rev. D. 85, 062001 (2012)*
*(Erratum) Phys. Rev. D. 91, 129903 (2015)*

- Previous single-source results published by VERITAS, the most constraining from 48-hours on Segue 1
- Dark Matter Search/Limits using 216 hours of Dwarf Spheroidal data
- Methodology (Geringer-Sameth et al., 2015) utilizes individual event energy, dwarf field and direction information
- Limits presented as a band to represent systematic uncertainty in J-Factors



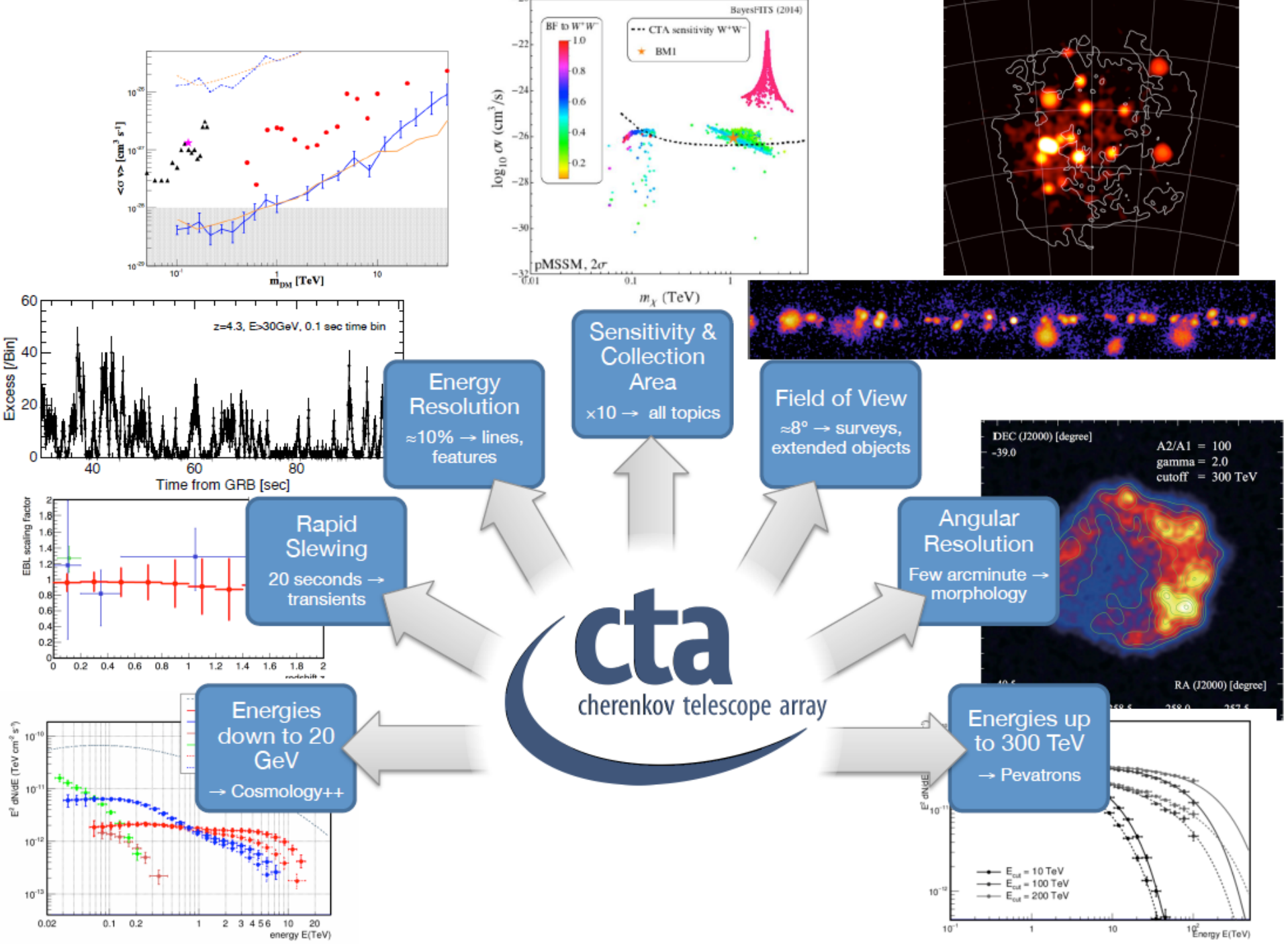
# CTA Key Science

**Cosmic Particle Acceleration**
How and where are particles accelerated?
How do they propagate?
What is their impact on the environment?

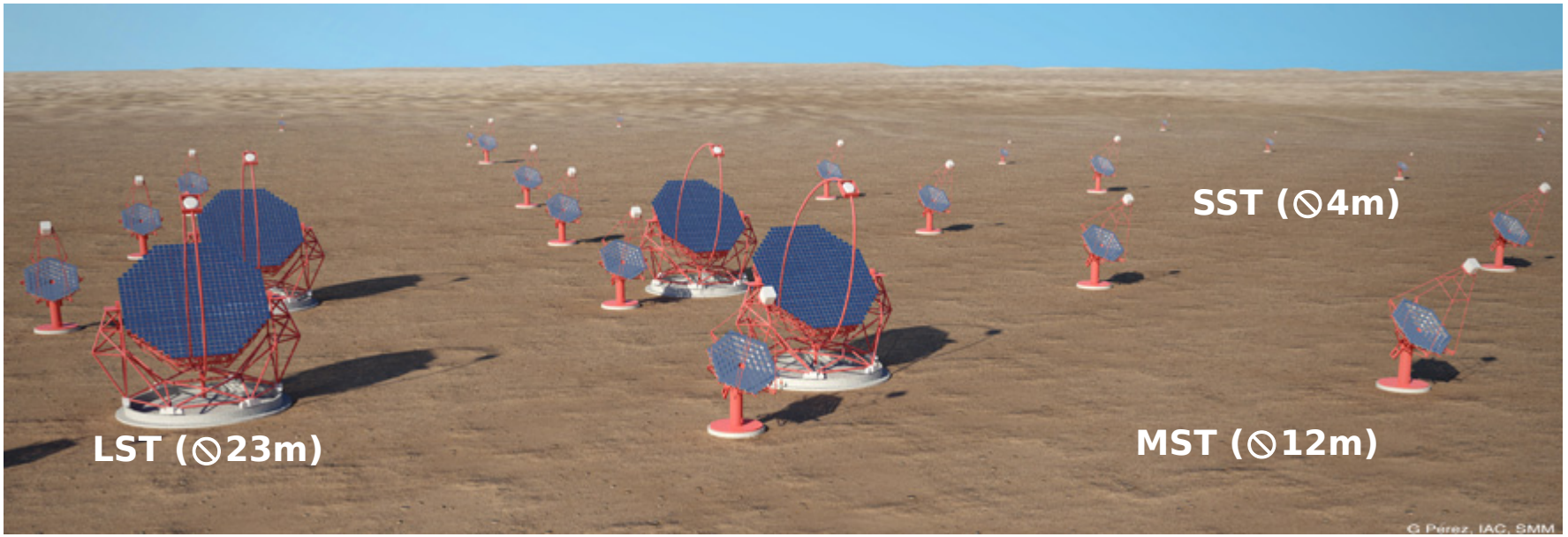


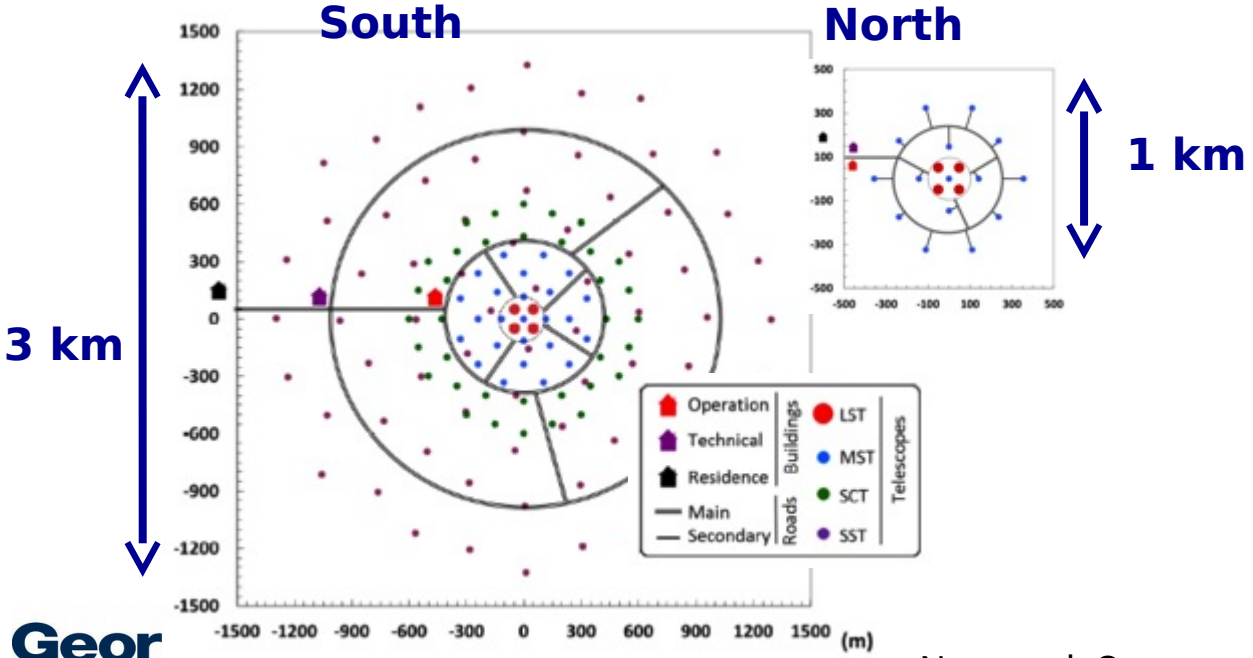
**Probing Extreme Environments**
Processes close to neutron stars and black holes?
Processes in relativistic jets, winds and explosions?
Exploring cosmic voids

**Physics frontiers – beyond the Standard Model**
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?

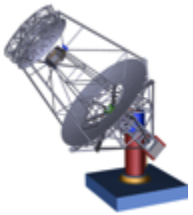

Energy Resolution
≈10% → lines, features
Sensitivity & Collection Area
×10 → all topics
Field of View
≈8° → surveys, extended objects
Rapid Slewing
20 seconds → transients
Angular Resolution
Few arcminute → morphology
Energies down to 20 GeV
→ Cosmology++
Energies up to 300 TeV
→ Pevatrons
cta
cherenkov telescope array
z=4.3, E>30GeV, 0.1 sec time bin
Excess [/Bin]
Time from GRB [sec]
EBL scaling factor
DEC (J2000) [degree]
RA (J2000) [degree]
A2/A1 = 100
gamma = 2.0
cutoff = 300 TeV
BayesFITS (2014)
CTA sensitivity W+W−
BM1
pMSSM, 2σ
energy E(TeV)
Energy E(TeV)

# The CTA Observatory



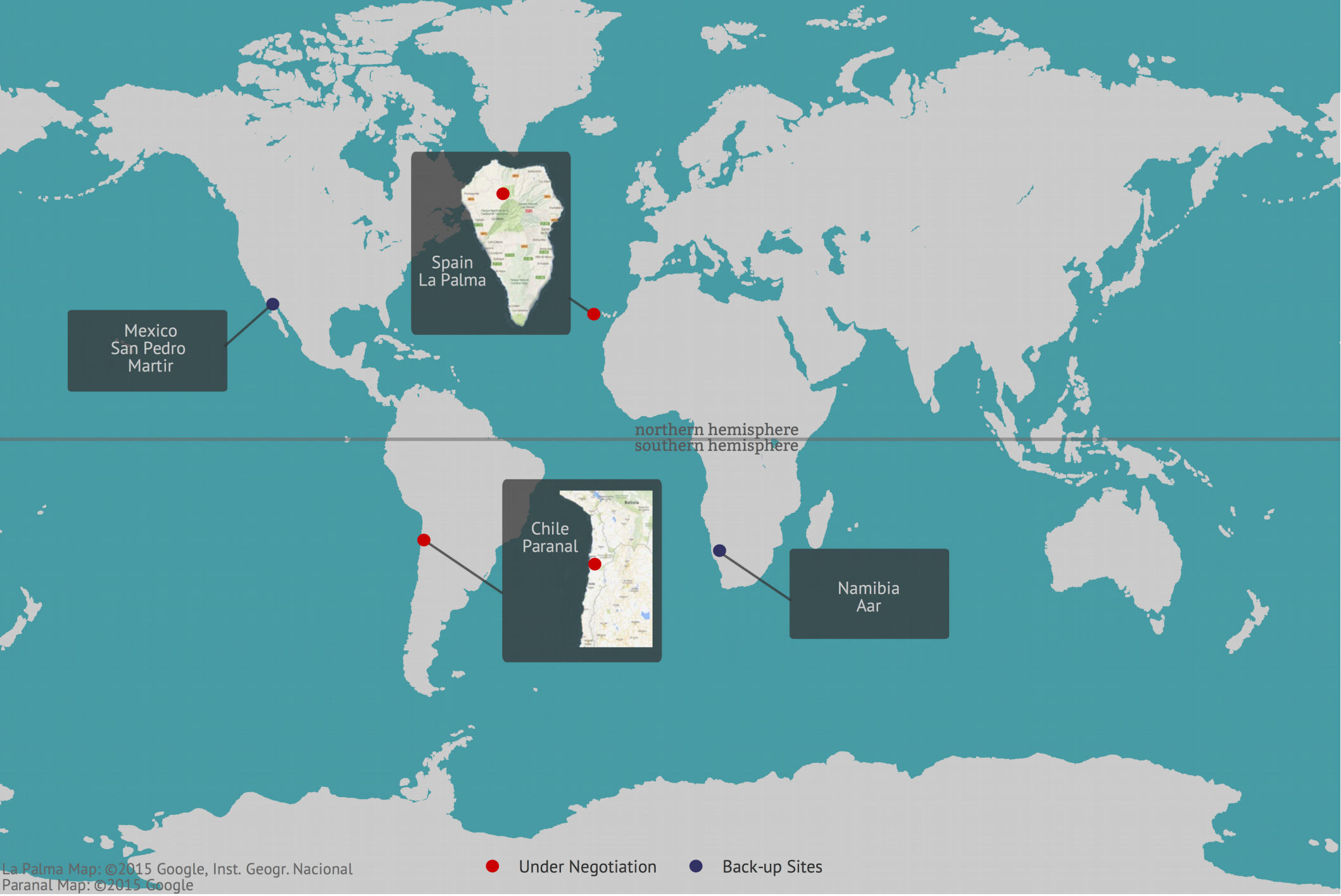




SCT (⦸10m)

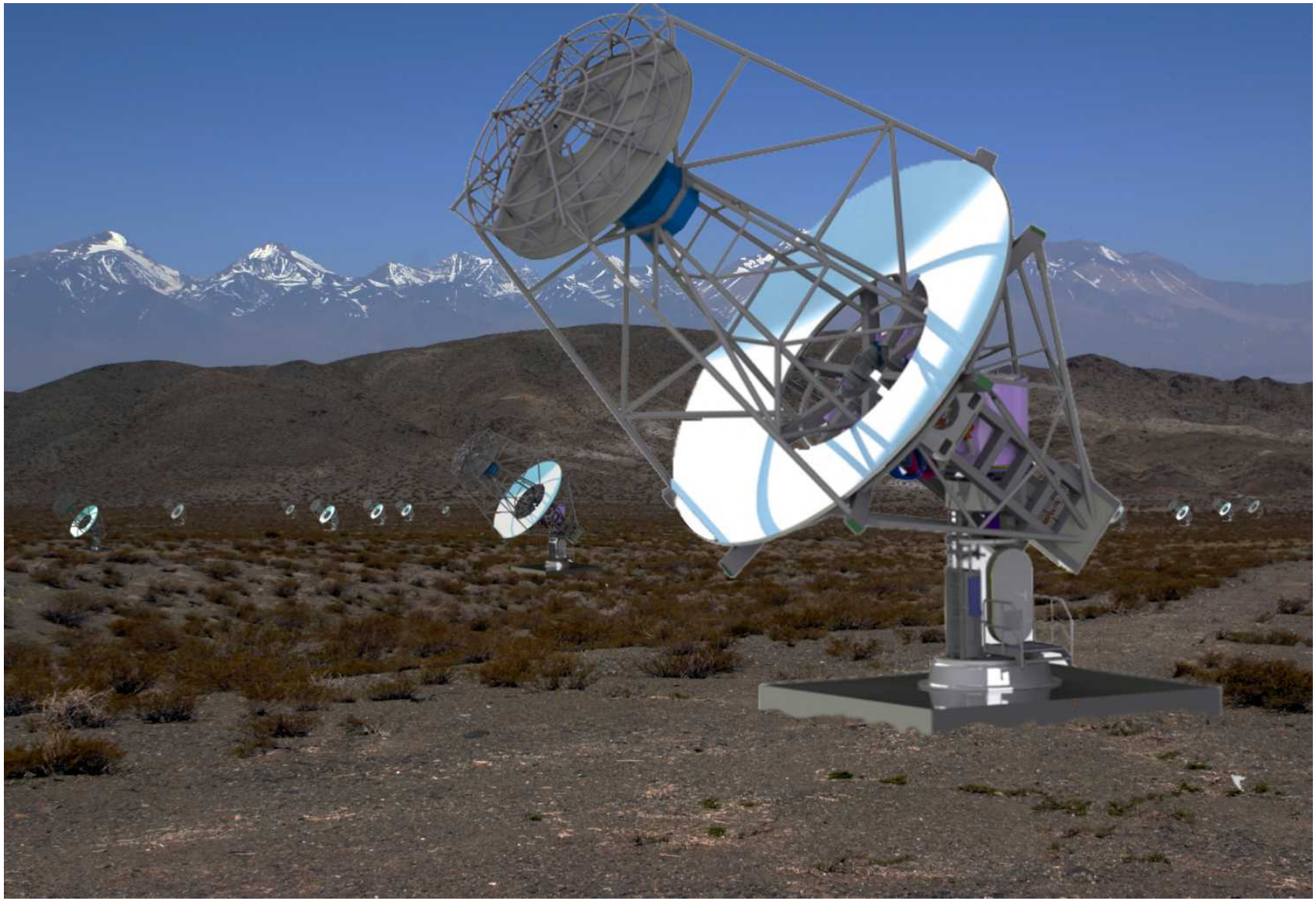


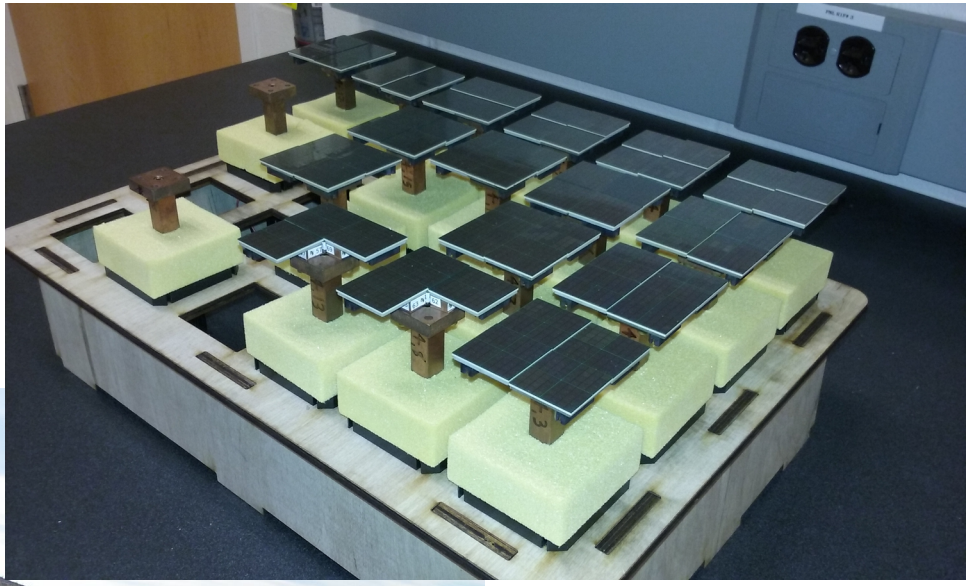
## Characteristics

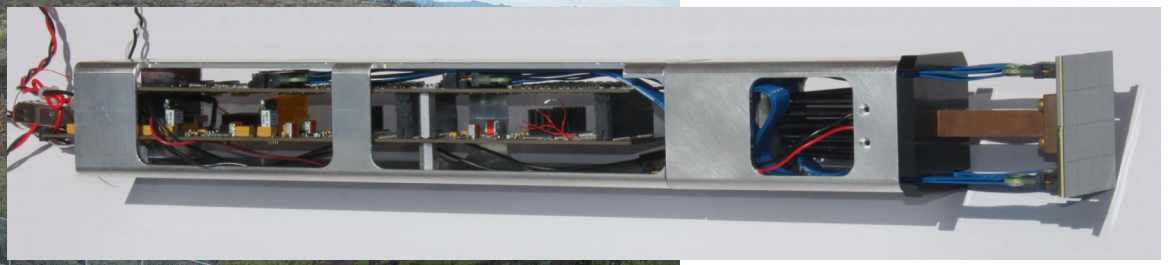
2 sites (north & south)
3 telescope size classes
About 120 telescopes in total
U.S. extension with about 05 SCT telescopes




La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google








Coming soon ....