Recent Highlights from VERITAS.

Astronomy, Astrophysics, and Cosmology with γ-rays.

Henrike Fleischhack
VERITAS Collaboration
28th Rencontres de Blois
01.06.2016

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

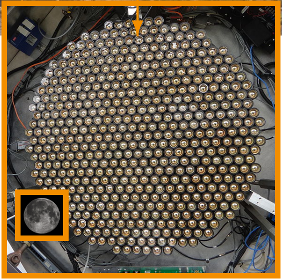
VERITAS

HUMBOLDT-UNIVERSITÄT ZU BERLIN

DESY

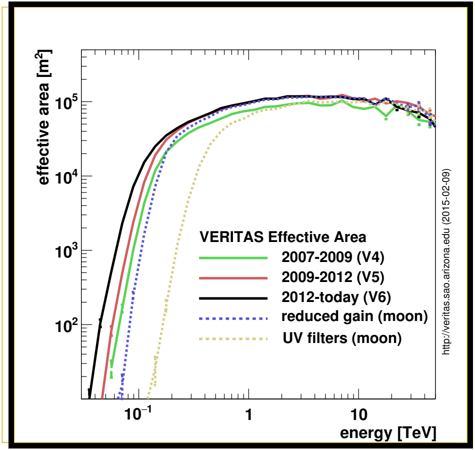
VERITAS

- Very Energetic Radiation Imaging Telescope Array System [Holder et al., 2008]
- Sensitive to γ-rays from $\sim$ 85 GeV to $>$ 30 TeV.
- Field of view 3.5°.
- Upgrades since 2007:
  - 2009: Array layout optimized.
  - 2011: Trigger upgrade.
  - 2012: PMT upgrade; moonlight observations.

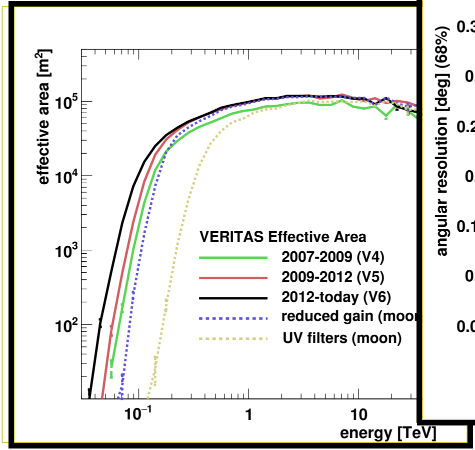


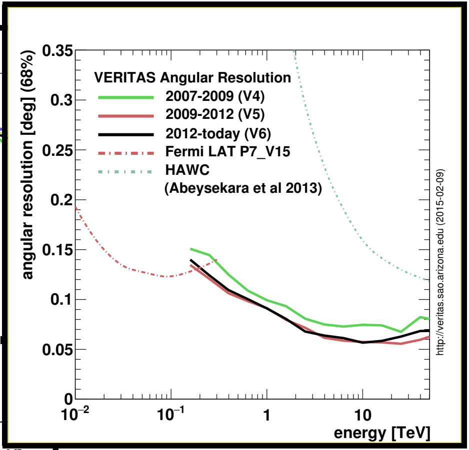
VERITAS camera without lightcones.
Image credit: VERITAS; Gregory H. Revera

The Instrument

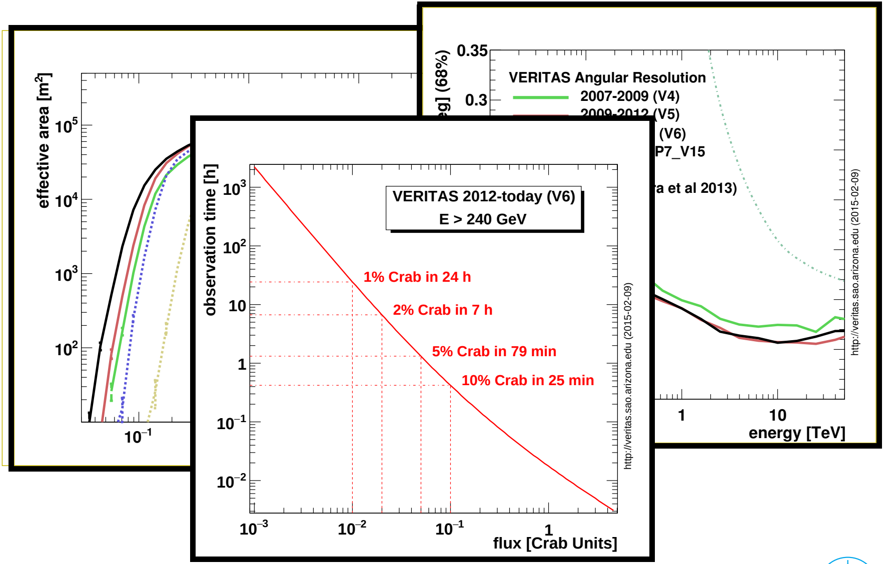


The Instrument

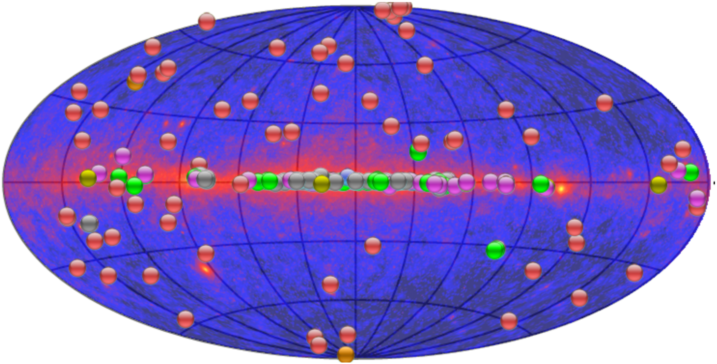


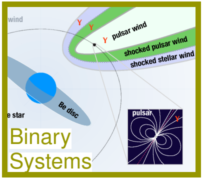


The Instrument



The γ-ray Sky





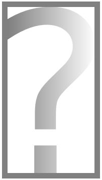
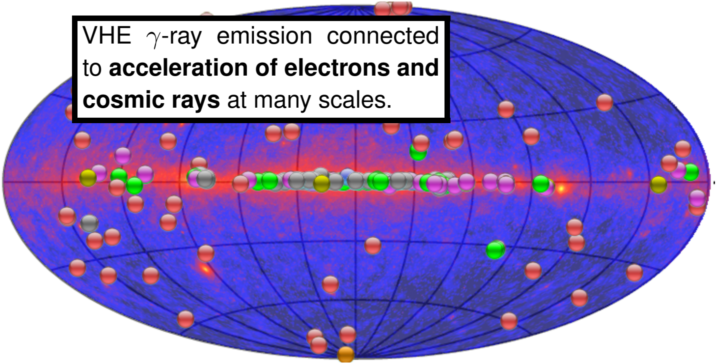
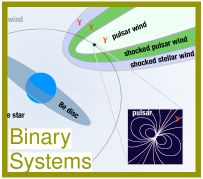


Image credit: NASA, ESA, J. Hester and A. Loll (ASU), Dubus [2013], Aurore Simonnet, `http://tevcat.uchicago.edu`

The γ-ray Sky

VHE γ-ray emission connected to **acceleration of electrons and cosmic rays** at many scales.





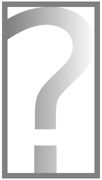
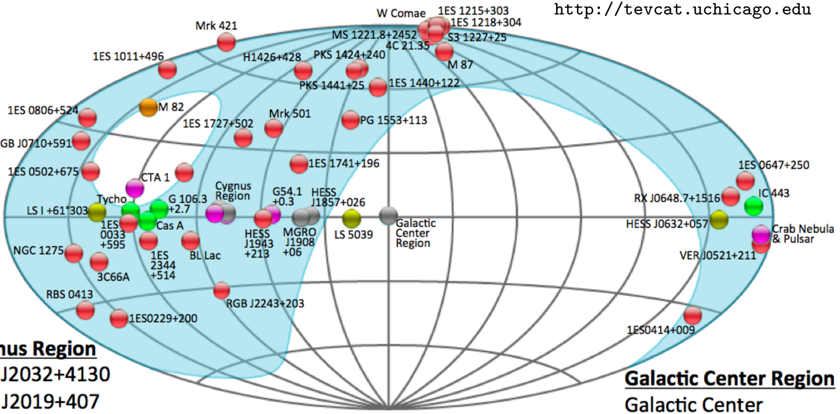


Image credit: NASA, ESA, J. Hester and A. Loll (ASU), Dubus [2013], Aurore Simonnet, `http://tevcat.uchicago.edu`

... as seen by VERITAS

Image credit: J. Holder;
http://tevcat.uchicago.edu



Cygnus Region
TeV J2032+4130
VER J2019+407
VER J2019+368
VER J2016+372

Galactic Center Region
Galactic Center
Galactic Center Ridge
G 0.9+0.1

54 sources: **34** Active Galactic Nuclei, **1** Starburst Galaxy, **3** binary systems, **4** Supernova Remnants, **4** Pulsar Wind Nebulae, **8** other/unidentified.

We Are Not Alone

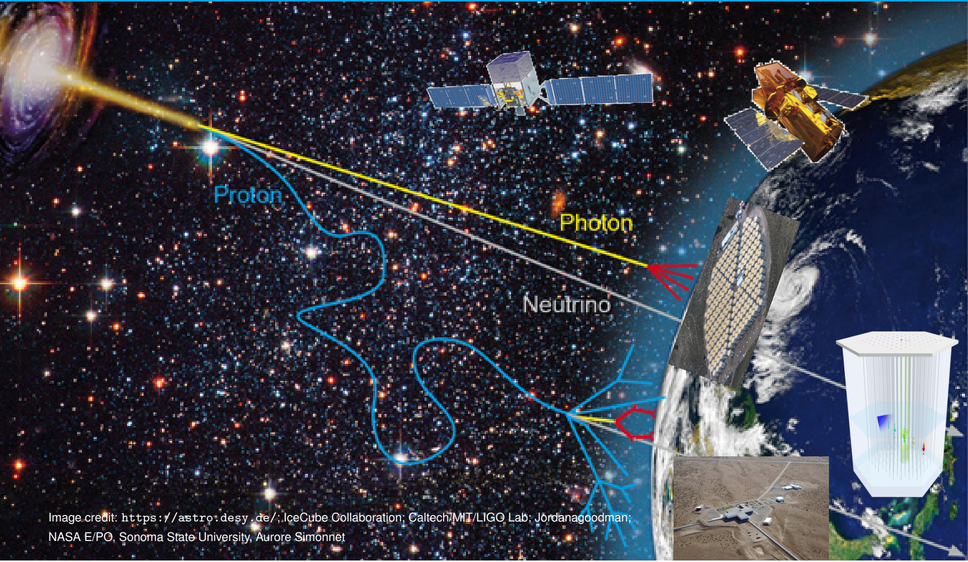


Image credit: https://astro.desy.de/; IceCube Collaboration; Caltech/MIT/LIGO Lab; Jordanagoodman; NASA E/PO, Sonoma State University, Aurore Simonnet

We Are Not Alone

- Multi-wavelength, multi-messenger astronomy.
- Cooperation with many other observatories:
  - Coordinated campaigns.
  - Alerts about transient events.
  - Follow-up observations.

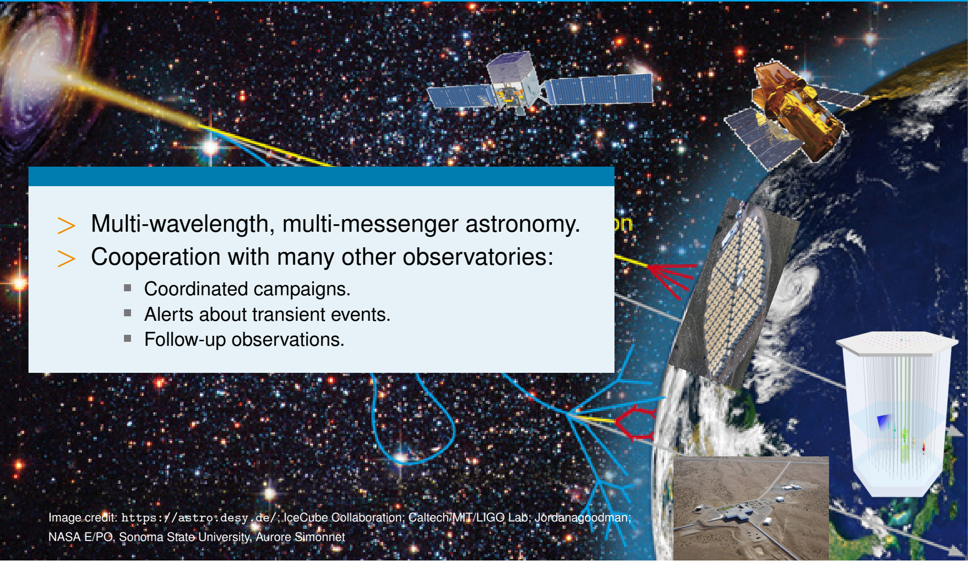
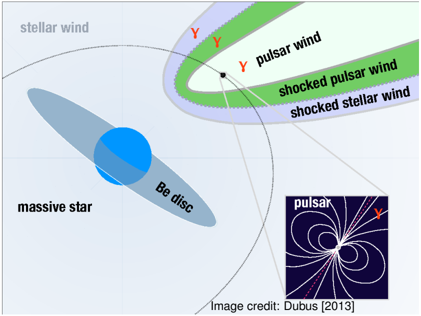
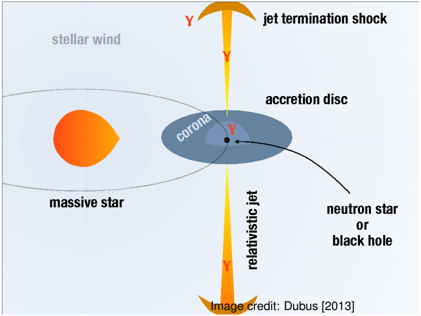


Image credit: `https://astro.desy.de/`; IceCube Collaboration; Caltech/MIT/LIGO Lab; Jordanagoodman; NASA E/PO, Sonoma State University, Aurore Simonnet

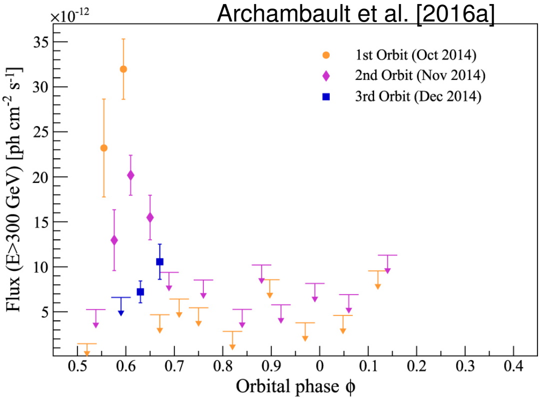
Gamma-ray Binaries





- Only 5 binary systems are known emitters of VHE γ-rays.
- Massive star + compact object (black hole or neutron star).
- Orbital periods of days to months; orbital modulation of γ-ray emission.
- Different models to explain the γ ray emission.

LS I 61+303



- Be star + compact object.
- Orbital period of 26.5 days.
- Generally detected in VHE in phases 0.5-0.9.

LS I 61+303 in 2014:

- Two bright flares
- sub day-scale variability.
- γ-ray emission up to 10 TeV.

Fast variability and presence of 10-TeV-particles challenging for current models.

Active Galactic Nuclei

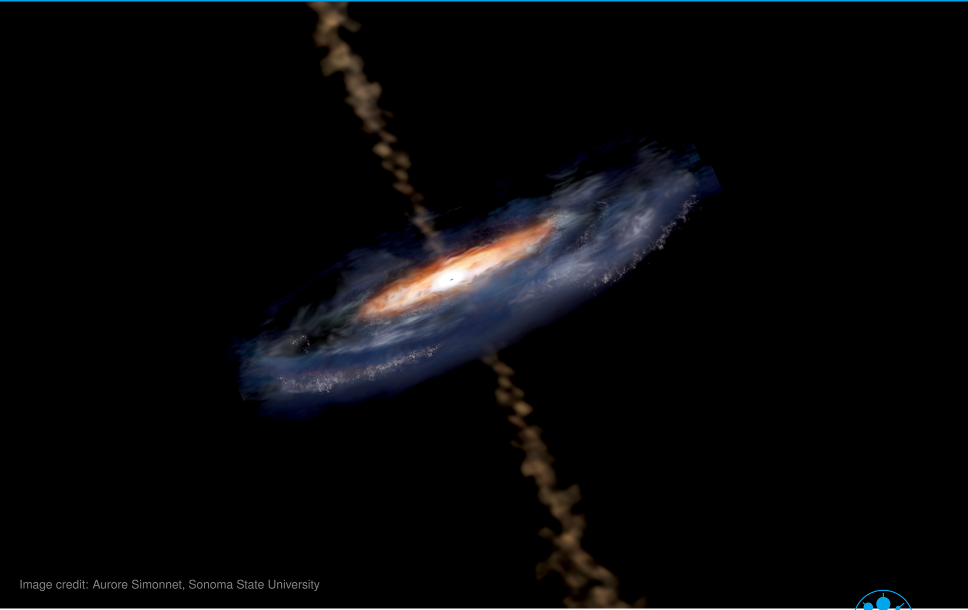


Image credit: Aurore Simonnet, Sonoma State University

Active Galactic Nuclei

Blazar physics:

- Interaction of black holes with their environments, jet formation.
- Sources of ultra-high energy cosmic rays?

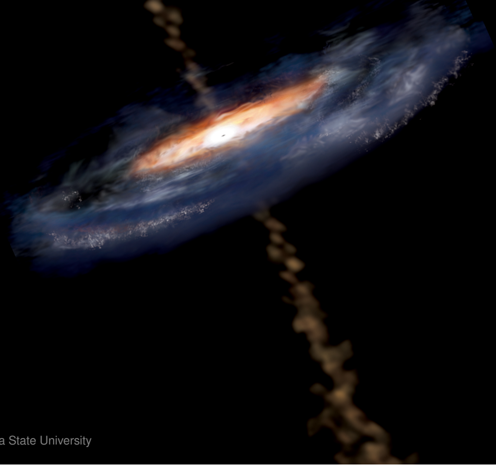


Image credit: Aurore Simonnet, Sonoma State University

Active Galactic Nuclei

Blazar physics:

- Interaction of black holes with their environments, jet formation.
- Sources of ultra-high energy cosmic rays?

Blazars as tools:

- Cosmology (extra-galactic background light, inter-galactic magnetic field, . . .).
- New physics (searches for axions, LIV, . . .).

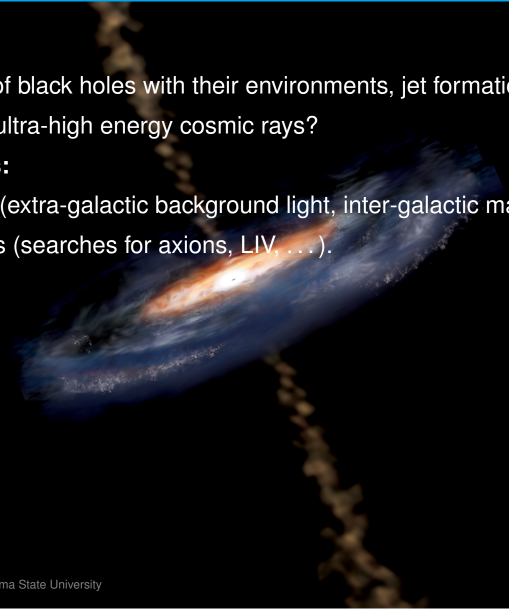


Image credit: Aurore Simonnet, Sonoma State University

Active Galactic Nuclei

Blazar physics:

- Interaction of black holes with their environments, jet formation.
- Sources of ultra-high energy cosmic rays?

Blazars as tools:

- Cosmology (extra-galactic background light, inter-galactic magnetic field, . . .).
- New physics (searches for axions, LIV, . . .).

Observing Strategies:

- Variability on timescales from minutes too hours.
- About 50% of observing time spent on blazars.
  - Discovery program.
  - Regular snapshots.
  - Target-of-Opportunity observations.
  - Deep exposures.
- MWL coverage when possible.

Image credit: Aurore Simonnet, Sonoma State University

Active Galactic Nuclei

Blazar physics:

- Interaction of black holes with their environments, jet formation.
- Sources of ultra-high energy cosmic rays?

Blazars as tools:

- Cosmology (extra-galactic background light, inter-galactic magnetic field, . . .).
- New physics (searches for axions, LIV, . . .).

Observing Strategies:

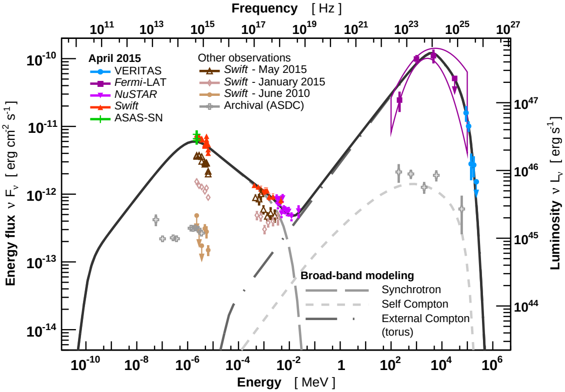
- Variability on timescales from minutes too hours.
- About 50% of observing time spent on blazars.
  - Discovery program.
  - Regular snapshots.
  - Target-of-Opportunity observations.
  - Deep exposures.
- MWL coverage when possible.

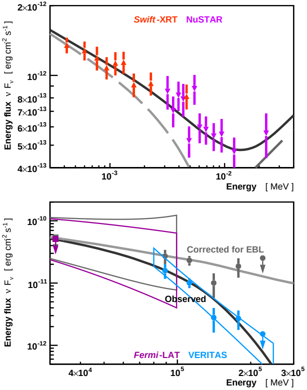
Upper limits from 113 non-detected blazars [Archambault et al., 2016b].

Image credit: Aurore Simonnet, Sonoma State University

PKS 1441+25, a blazar at $z = 0.939$

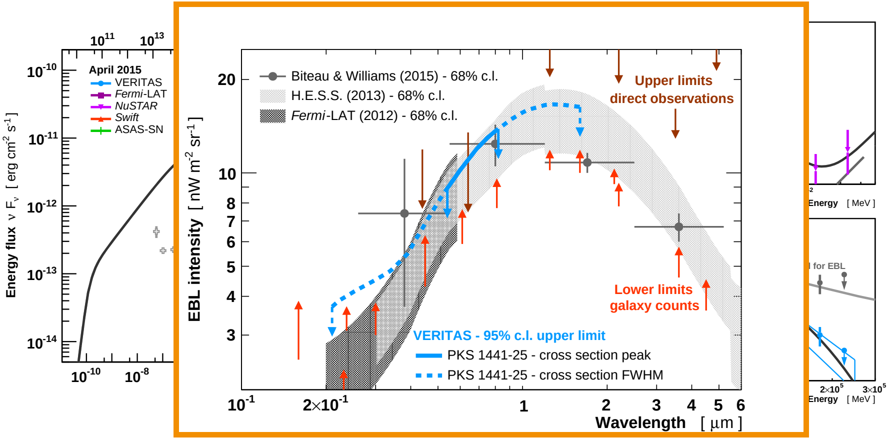
- Multi-wavelength flare in April 2015, VHE detection by MAGIC [Ahnen et al., 2015] and VERITAS [Abeysekara et al., 2015].
- Single emission region, located $10^4 - 10^5$ Schwarzschild radii from black hole.





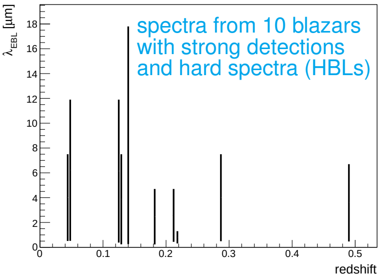
PKS 1441+25, a blazar at $z = 0.939$

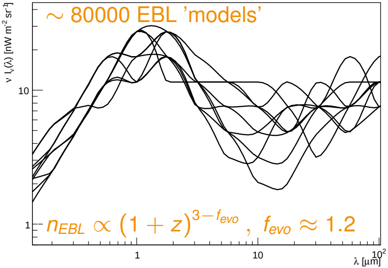
- Multi-wavelength flare in April 2015, VHE detection by MAGIC [Ahnen et al., 2015] and VERITAS [Abeysekara et al., 2015].
- Single emission region, located $10^4 - 10^5$ Schwarzschild radii from black hole.



Extra-galactic Background Light

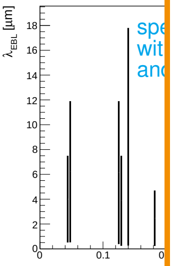
- Light emitted by stars, galaxies, dust since beginning of the universe.
- Attenuation of VHE (E>100 GeV) gamma-rays: $\gamma_{VHE}\gamma_{EBL} \rightarrow e^+e^-$
- $\left(\frac{dN}{dE}\right)_{obs} = \left(\frac{dN}{dE}\right)_{int} \cdot \exp\left(-\tau_{\gamma\gamma}(E,z)\right)$
- intrinsic spectrum from Fermi-LAT data.

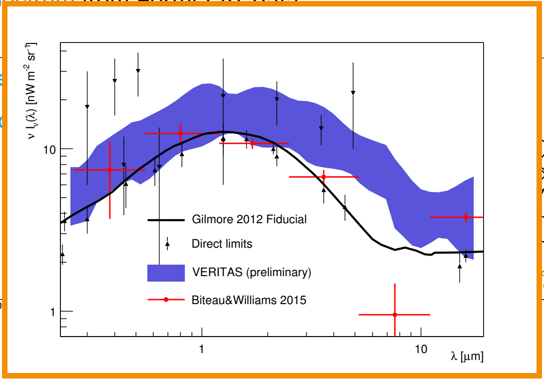


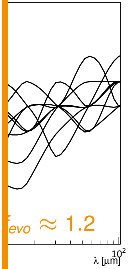


Extra-galactic Background Light

- Light emitted by stars, galaxies, dust since beginning of the universe.
- Attenuation of VHE (E>100 GeV) gamma-rays: $\gamma_{VHE}\gamma_{EBL} \rightarrow e^{+}e^{-}$
- $\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{obs} = \left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{int} \cdot \exp\left(-\tau_{\gamma\gamma}(E,z)\right)$
- intrinsic spectrum from Fermi LAT data



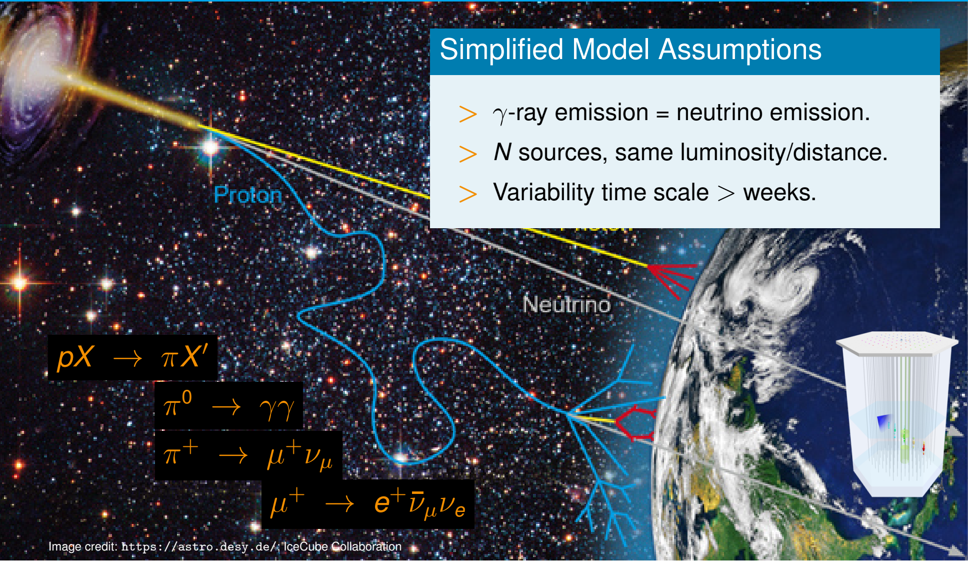




Sources of Astrophysical Neutrinos

Simplified Model Assumptions

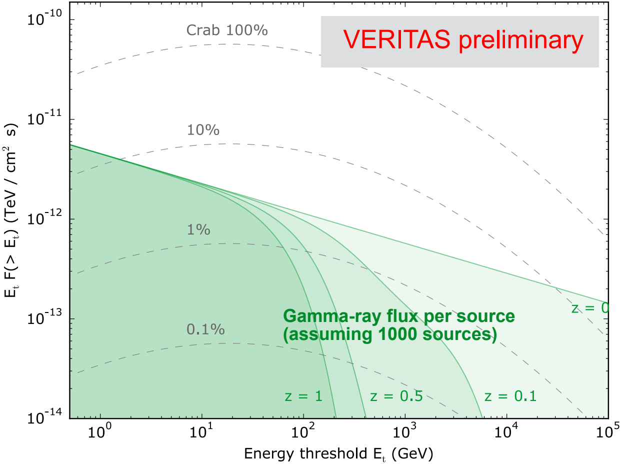
- γ-ray emission = neutrino emission.
- N sources, same luminosity/distance.
- Variability time scale $>$ weeks.



$$pX \rightarrow \pi X'$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^+ \rightarrow \mu^+\nu_\mu$$
$$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$$

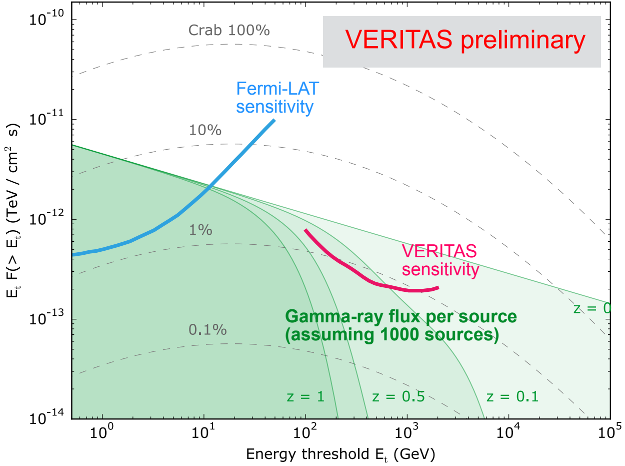
Image credit: `https://astro.desy.de/`; IceCube Collaboration

Sources of Astrophysical Neutrinos



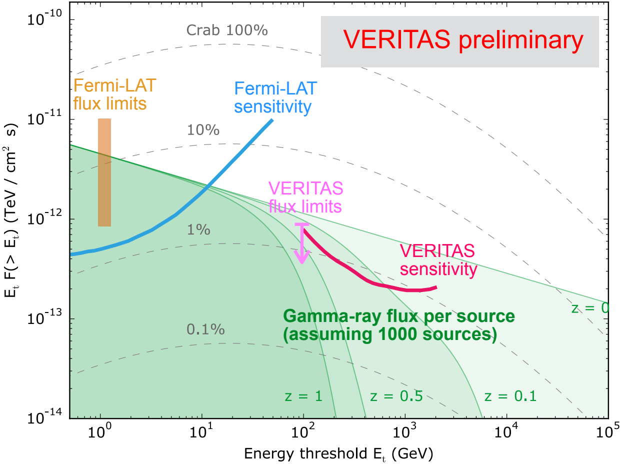
Sources of Astrophysical Neutrinos

> Search for γ-ray excess near 18 IceCube neutrino positions.



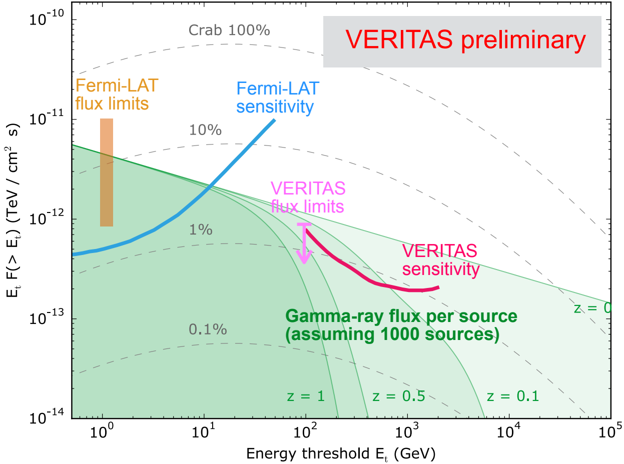
Sources of Astrophysical Neutrinos

> Search for γ-ray excess near 18 IceCube neutrino positions.
> No excess found, upper limits $1\% - 10\%$ of the flux of the Crab Nebula.



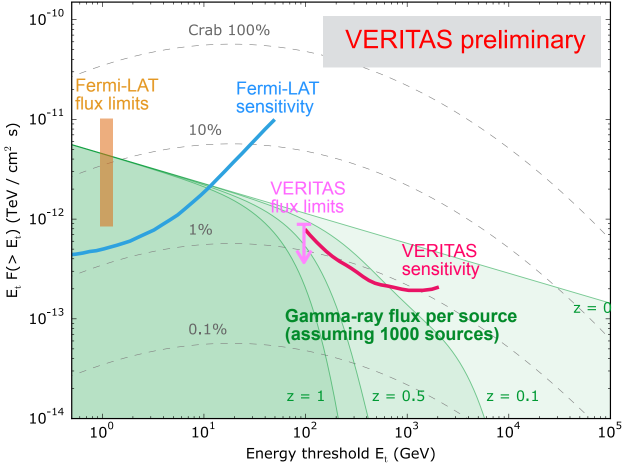
Sources of Astrophysical Neutrinos

- Search for γ-ray excess near 18 IceCube neutrino positions.
- No excess found, upper limits $1\% - 10\%$ of the flux of the Crab Nebula.
- VERITAS results starting to constrain N=1000 scenario.



Sources of Astrophysical Neutrinos

- Search for γ-ray excess near 18 IceCube neutrino positions.
- No excess found, upper limits $1\% - 10\%$ of the flux of the Crab Nebula.
- VERITAS results starting to constrain N=1000 scenario.
- New: Real-time alerts from IceCube (not included here).



Conclusions...

- VERITAS running stable, improved through upgrades.
- Fruitful collaboration with other instruments.
- Rich datasets, deep observations.
- More to come soon:
  - Cosmic ray physics
  - Cosmology: EBL, IGMF
  - Dark matter
  - . . .

Image credit: M. Santander

... and Outlook

http://cta-psct.physics.ucla.edu/

Thank you for the attention!

Backup.

Bibliography I

Abeysekara, A. U. et al. (2015). Gamma-Rays from the Quasar PKS 1441+25: Story of an Escape. *The Astrophysical Journal Letters*, 815(2):L22.

Ahnen, M. L. et al. (2015). Very-high-energy gamma-rays from the Universe's middle age: detection of the z=0.940 blazar PKS 1441+25 with MAGIC. *Astrophys. J.*, 815(2):L23.

Archambault, S. et al. (2016a). Exceptionally Bright TeV Flares from the Binary LS I +61 303. *The Astrophysical Journal Letters*, 817(1):L7.

Archambault, S. et al. (2016b). Upper Limits from Five Years of Blazar Observations with the VERITAS Cherenkov Telescopes. *The Astronomical Journal*, 151(6):142.

Dubus, G. (2013). Gamma-ray binaries and related systems. *Astron. Astrophys. Rev.*, 21:64.

Holder, J. et al. (2008). Status of the VERITAS Observatory. In *American Institute of Physics Conference Series*, volume 1085, pages 657–660.