TeV Astroparticle Physics: Recent Highlights from VERITAS

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Barnard College, Columbia University

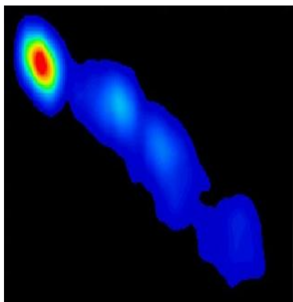
24 July 2018

Outline

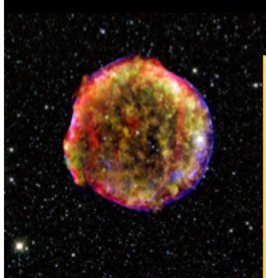
- Science topics
- Instrument
- Results
- Future plans

A Rich Variety of Science at E > 100 GeV

- Fundamental physics & cosmology
- Galactic particle acceleration
- Extragalactic particle acceleration

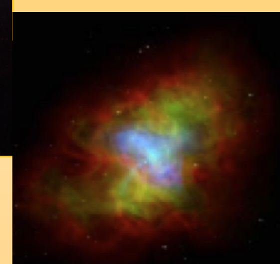



Starbursts, relativistic jets in active galaxies



Supernova remnants: shocks, Fermi acceleration, origin of CRs.

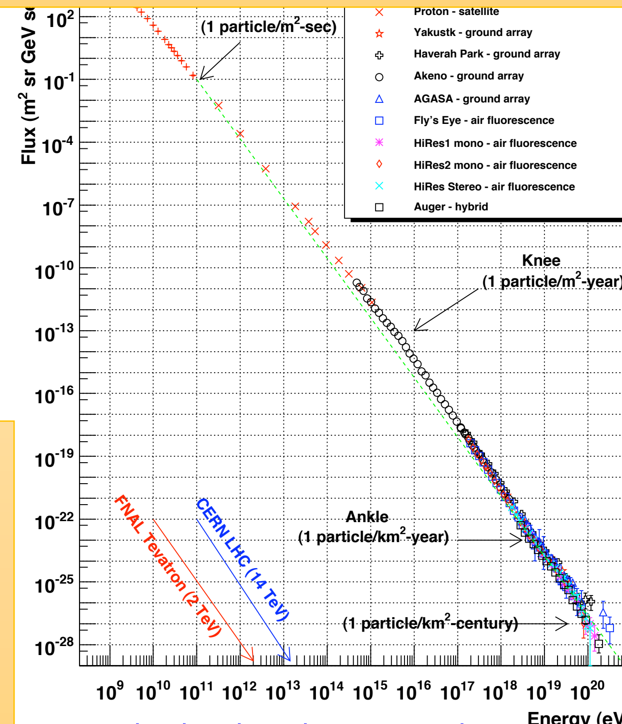
Binaries: jets (accretion-powered), colliding winds?



Pulsars, Pulsar wind nebulae

Star-forming regions

Origin of Cosmic Rays? Diffuse, all particle spectrum



Whanlon (based on S. Swordy)

Neutral messengers: γ, ν are required to directly observe cosmic accelerators.

Dark Matter, Astroparticle Physics, Cosmology

- Dark matter searches (Classical & ultra faint dwarf spheroidals; PRD 2017)
- Lorentz Invariance Violation (Energy dependent speed of light differences; targets – GRBs, pulse widths of γ-ray pulsars, AGN variability)
- Primordial Black Holes (could evaporate and produce bursts of VHE γs)
- Extragalactic Background Light ($\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^-$)
- Intergalactic Magnetic Fields (look for pair cascades/halos; ApJ 2017)
- Direct Cherenkov emission (produced by the primary particle, CR heavy nuclei)
- Electron-positron measurements (Galactic CR studies)
- Multi-Messenger Astrophysics
    - Gravitational Wave EM counterpart searches
    - IceCube neutrino follow ups (BL Lac object TXS 0506+056; ApJ Lett 2018)

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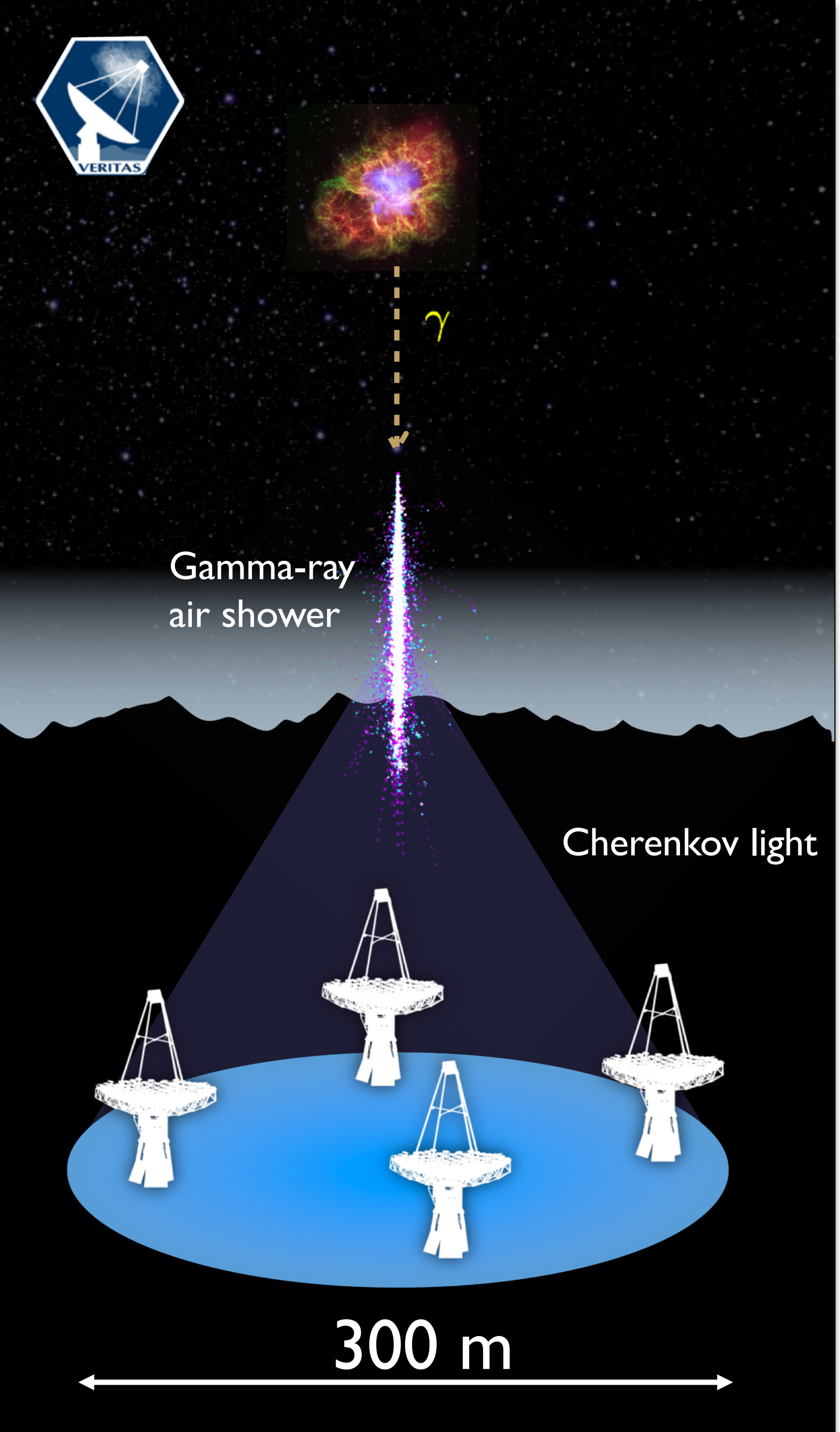
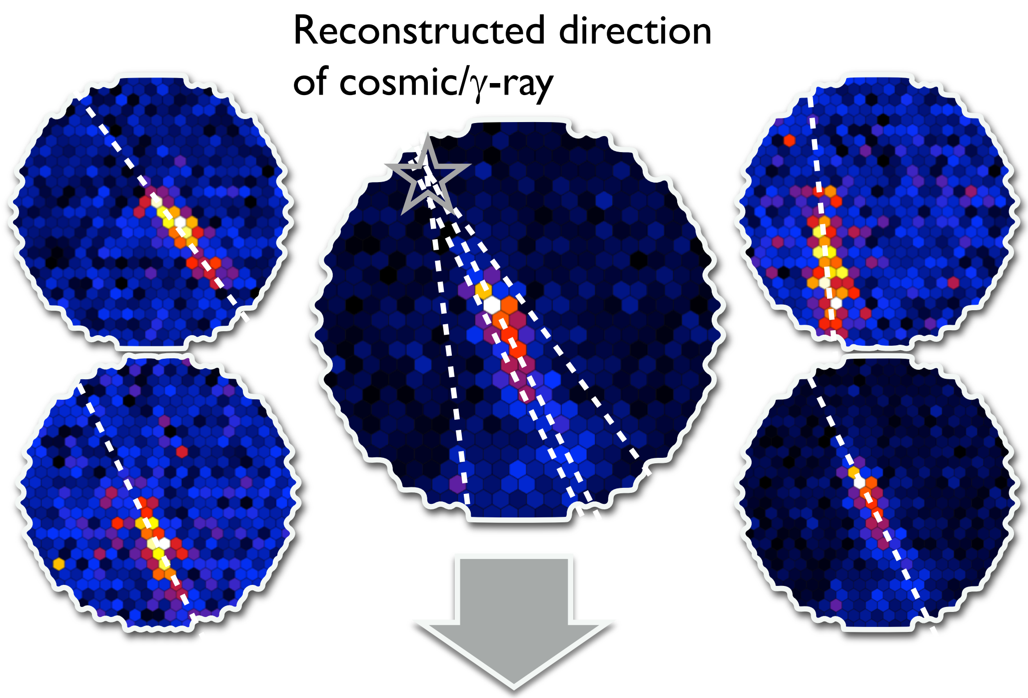
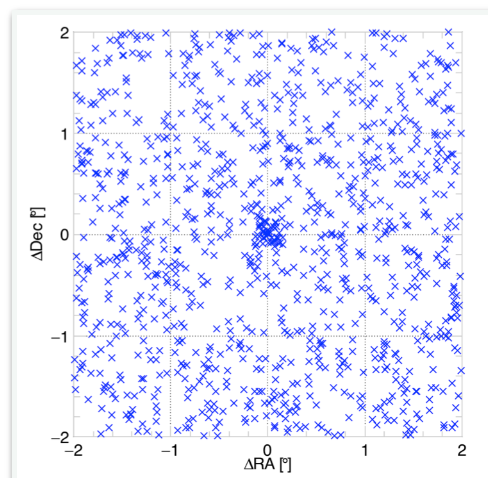
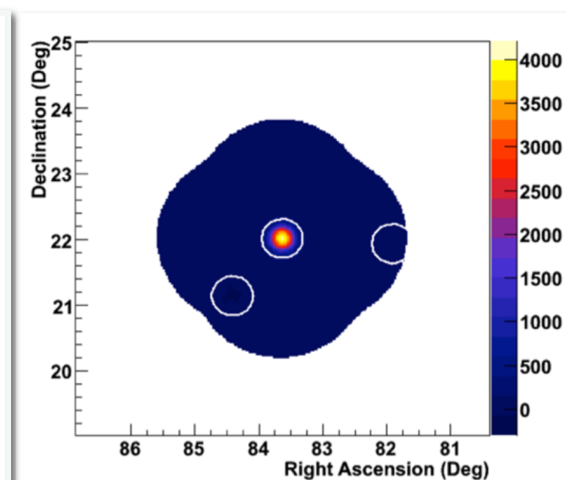
Imaging Air Cherenkov Technique



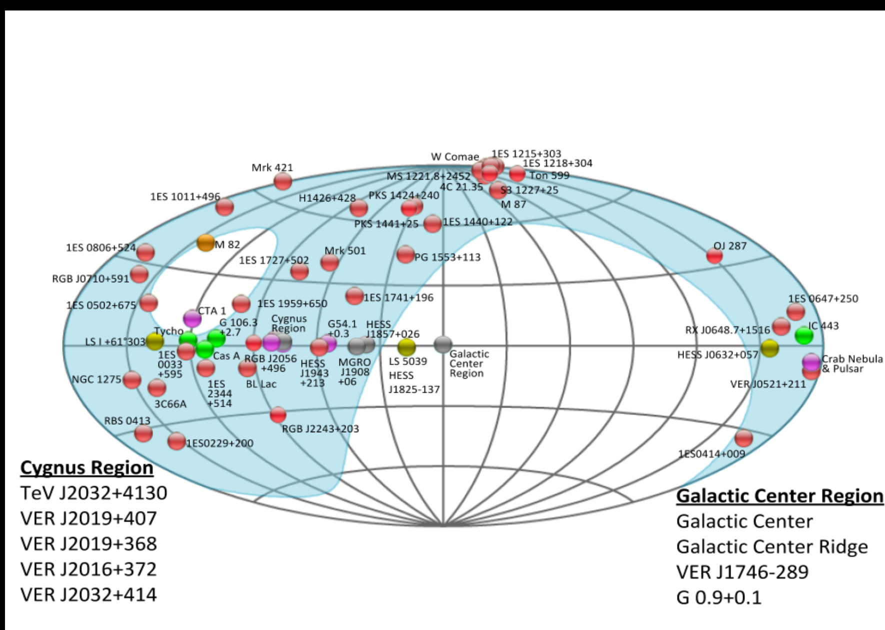


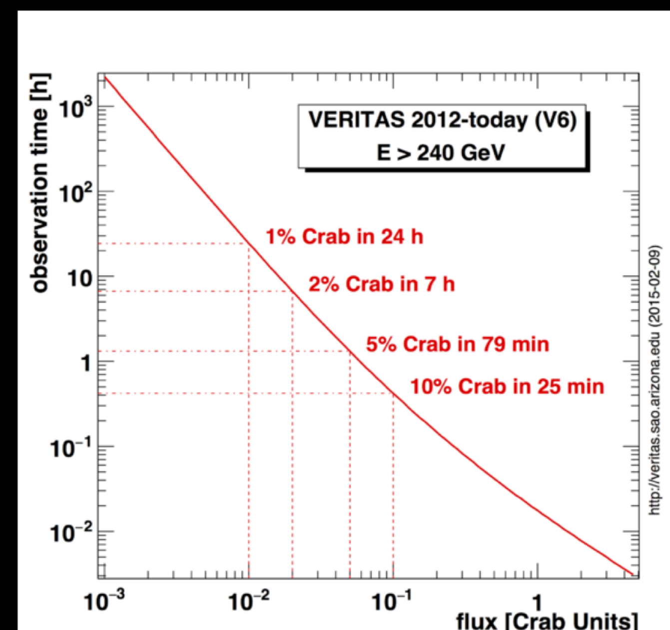




The VERITAS Instrument

- Sensitivity: 1% Crab in ~25 hr
- Energy range: 100 GeV to 30 TeV





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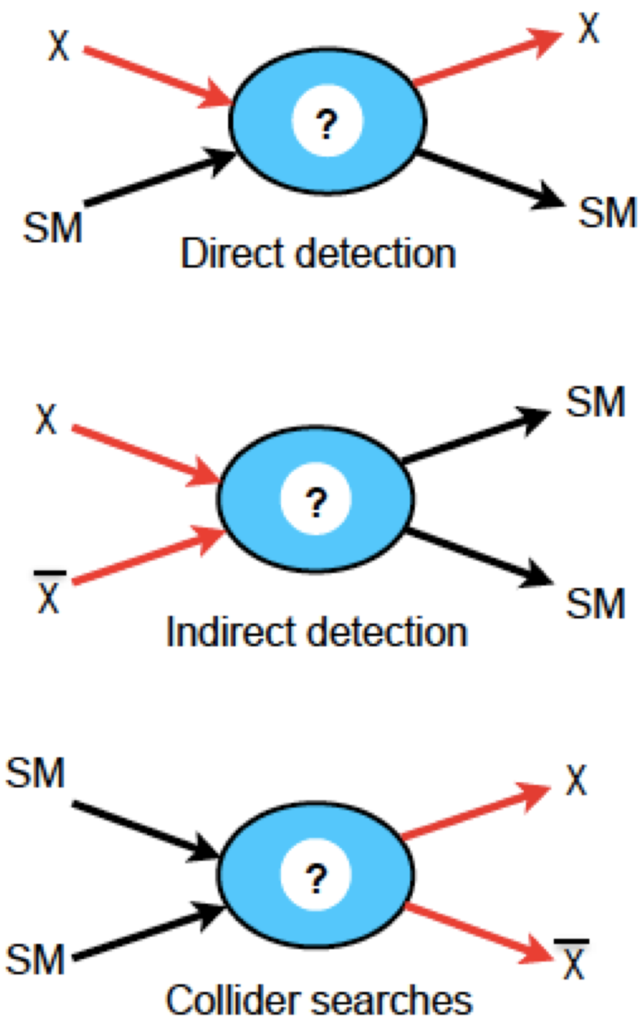
1. Indirect Dark Matter Searches with VHE γ rays

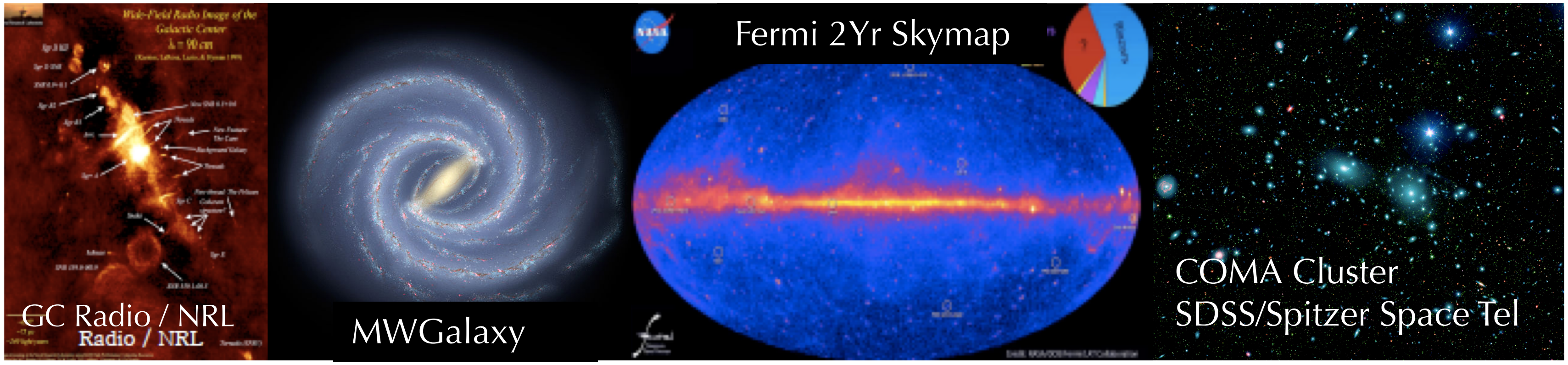


- Cold DM composes ~ 27% of the Universe.
- Well-motivated theoretically by extensions of the SM (SUSY, Kaluza-Klein) by weakly-interacting massive particles (WIMPs).
- WIMP annihilation production of gamma-rays
  - Gamma-ray line from direct annihilation
  - Gamma-ray continuum from hadronization
  - Enhanced near DM mass from internal bremmstraung.
  - Sensitivity for 10 GeV < m_χ < 100 TeV
- Complementary studies to indirect detection and collider experiments.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{<\sigma v>}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int\int \rho^2 ds d\Omega$$

> "J-factor" depends on dark matter distribution in object, distance to object, folded with instrument point spread function

VERITAS Dark Matter Targets



- Galactic Center: Nearby source, strong DM candidate, but need to measure large astrophysical γ ray background.

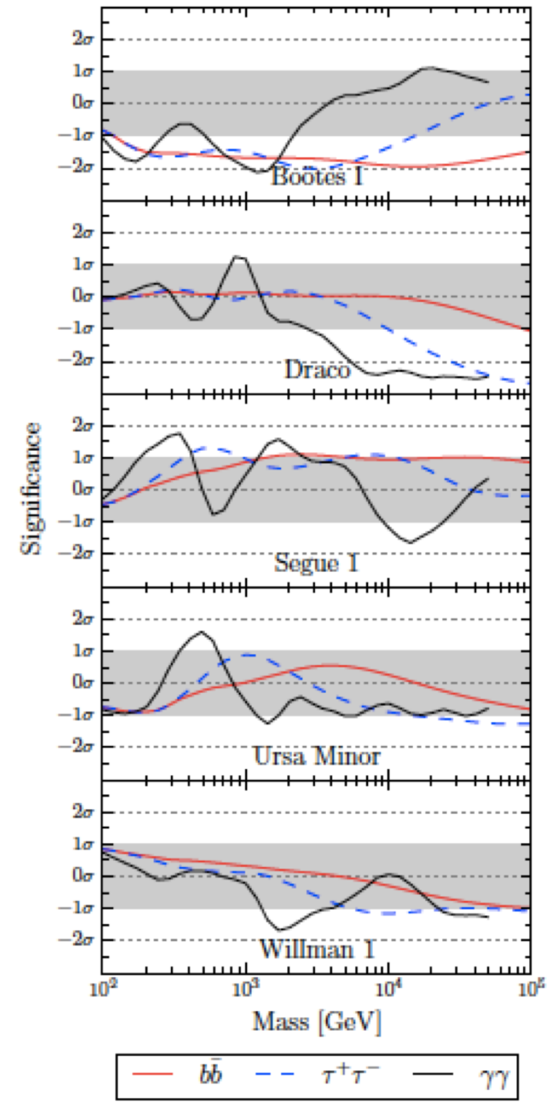
- Dwarf Galaxies: Attractive targets, large mass to light ration (O(10^3) times more DM/visible matter), no γ ray background, but DM distribution can be uncertain.

- Unidentified Fermi-LAT sources: Fermi-detected gamma-ray sources, Galactic ones are likely local, however nature and distance unknown.

- Galaxy Clusters: Largest DM concentration in the Universe, but distance is large, γ ray signal weak, sources are extended.

VERITAS: Search for annihilation in individual dwarfs

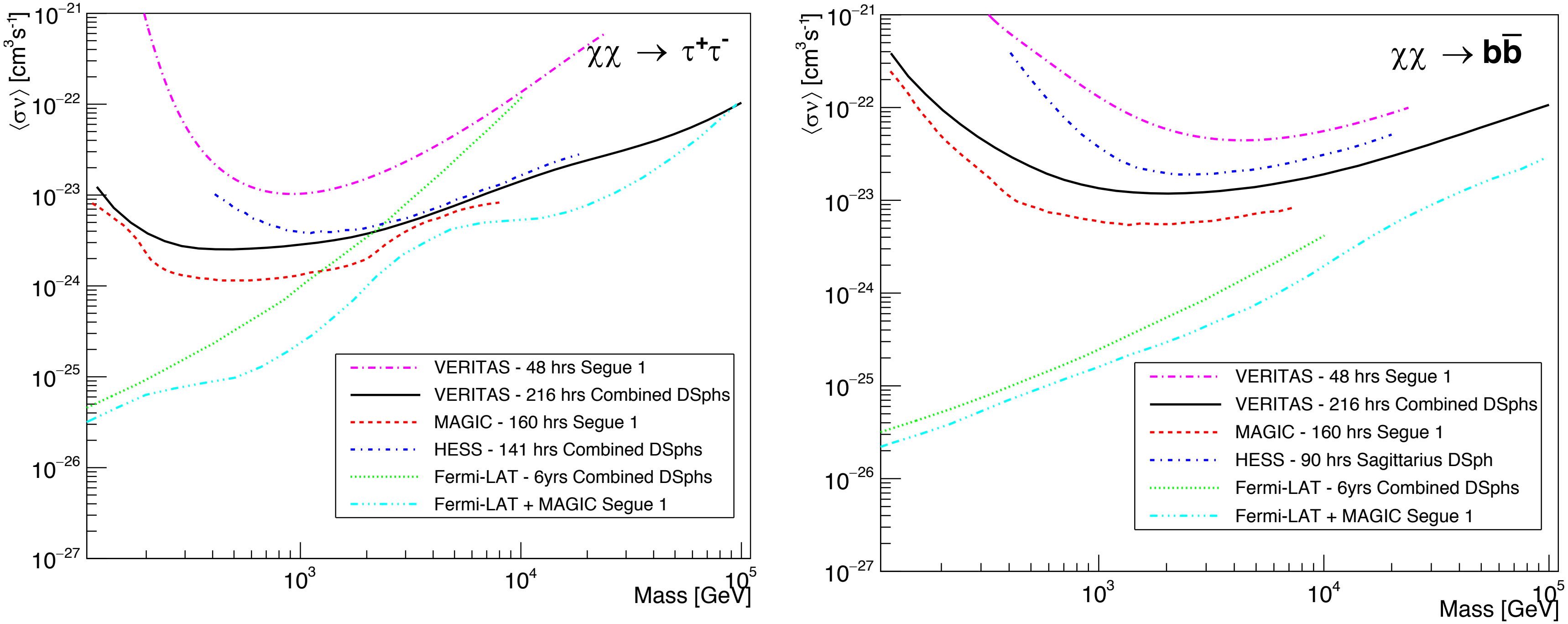
Dwarf	Zenith [deg]	Azimuth [deg]	Exposure [hours]	Energy Range [GeV]
Segue 1	15-35	100-260	92.0	80 - 50000
Draco	25-40	320-40	49.8	120 - 70000
Ursa Minor	35-45	340-30	60.4	160 - 93000
Boötes 1	15-30	120-249	14.0	100 - 41000
Willman 1	20-30	340-40	13.6	100 - 43000



2007 to 2013 Dwarf data:
VERITAS PhysRevD.95.082001

- 95% confidence interval on WIMP velocity-averaged cross section with assumption of 100% annihilation into specified channel.
- 216 hours combined with four different dwarf galaxies, "stacked" into a single limit.
- We find no evidence of gamma-ray emission from any individual dwarf nor in the joint analysis.

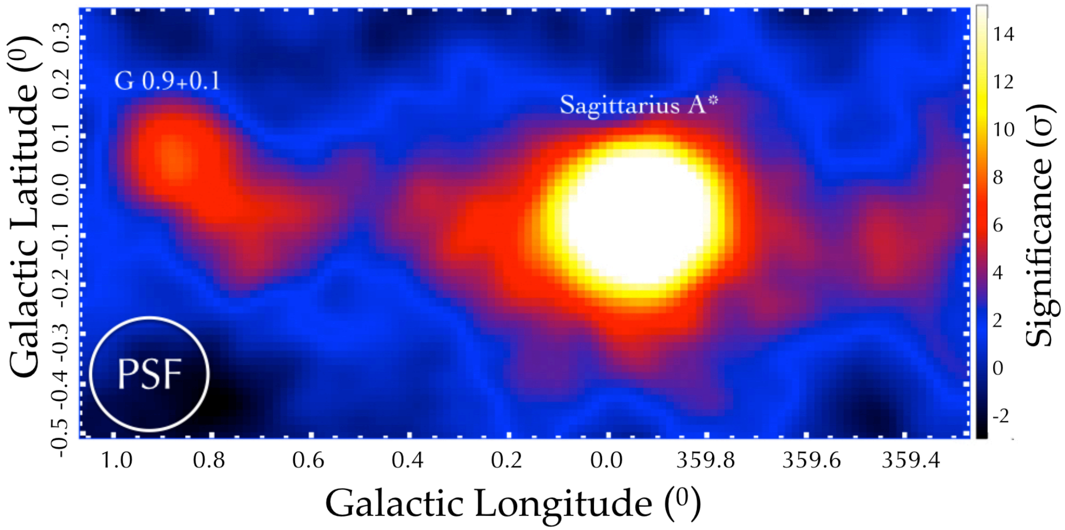
VERITAS: Dark Matter Limits



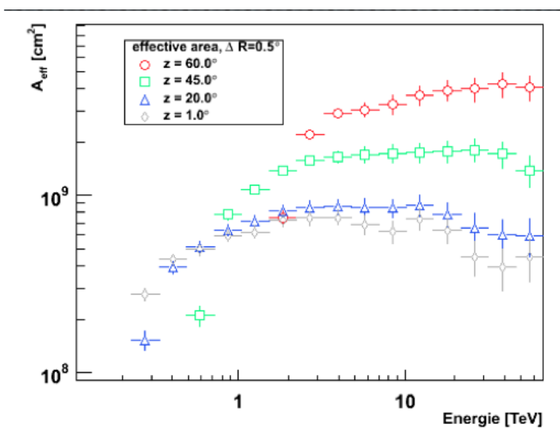
Archambault et al. PhysRevD.95.082001

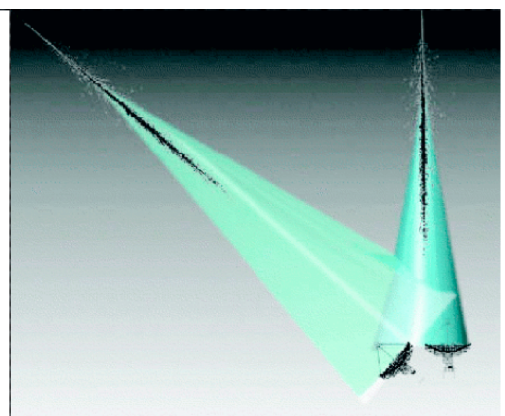
- Latest results: Combined analysis of several dSPhs.
- IACT results on Dwarfs agree with each other.
- Fermi-LAT competitive low-mass WIMPs – large duty cycle and low background.
- Benchmark cross section at ~ 3 x10^{-26} cm^{3}s^{-1} (thermal relic abundance).
- Expect improvements with larger datasets, broader survey, analysis improvements.

VERITAS: Galactic Center Observations



VERITAS ApJ (2016) arXiv:1602.08522v1





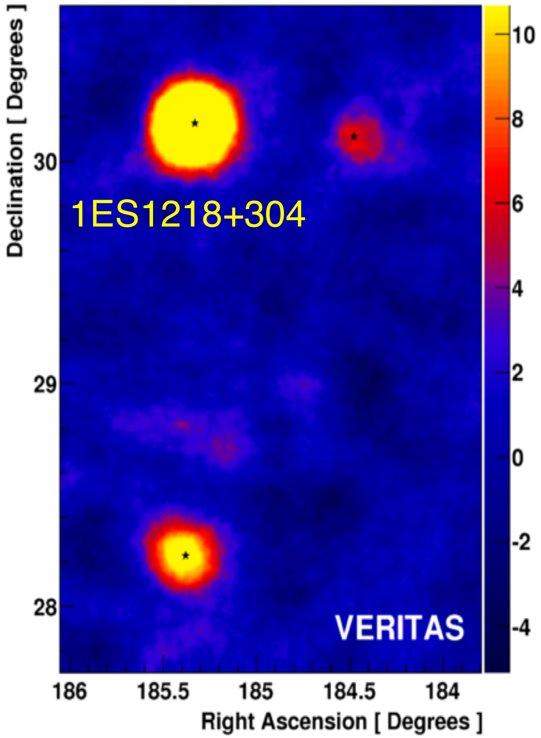
- DM halo around the center of our Galaxy.
- GC region is the closes DM target, ~ 8 kpc.
- J Factor better than dSPhs, however region is complicated because of astrophysical sources.
- Many bright sources along Galactic Plane.
- GC is at large zenith angles for VERITAS (> 50 deg).
- This raises energy threshold to ~ 1 TeV, but effective area is large at higher energies.
- Could be competitive for high mass WIMPs.

Future work: Combined Results from Dwarfs

See talk by Javier Rico (IFAE) "Dark matter searches with ground based Cherenkov gamma-ray telescopes" 23 July AstroParticle Session.

- The future: combining all IACTs:
  - Aim: Produce a global DM result combining all dSph observations by HESS, MAGIC and VERITAS.
  - Also exploring including Fermi-LAT and HAWC.
  - Future prospects with Cherenkov Telescope Array (CTA).
  - In the near future, the CTA will explore the region CTA will be sensitive WIMP masses above ~200GeV below the thermal relic cross-section for DM mass in the TeV range.

2. Extragalactic Science: Blazars as probes for cosmology

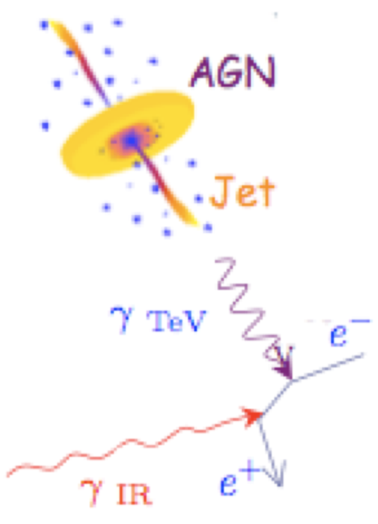


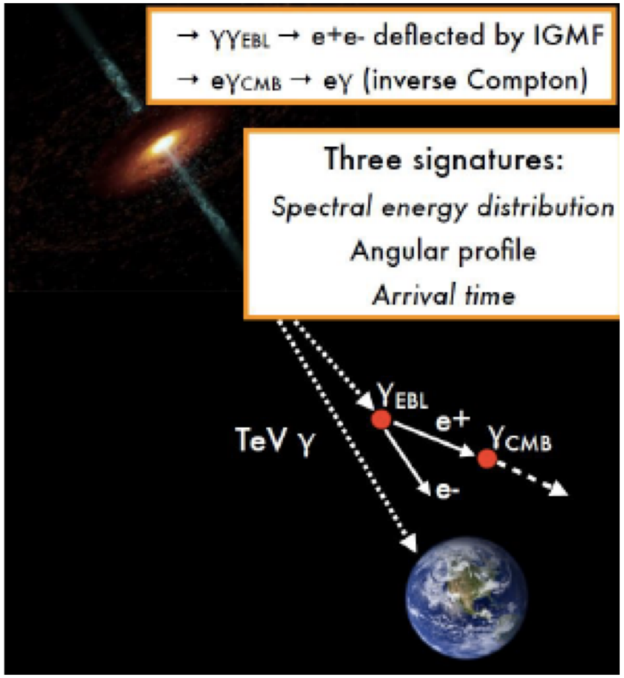
VERITAS ICRC 2011: arXiv 1110.0040v1

Blazars as probes for cosmology

- γ-ray opacity measurements, star formation history of the Universe ($\gamma_{TeV} + \gamma_{EBL}$ --> $e^+ + e^-$).

- IGMF: Were intergalactic magnetic fields seeded by primordial magnetic fields?

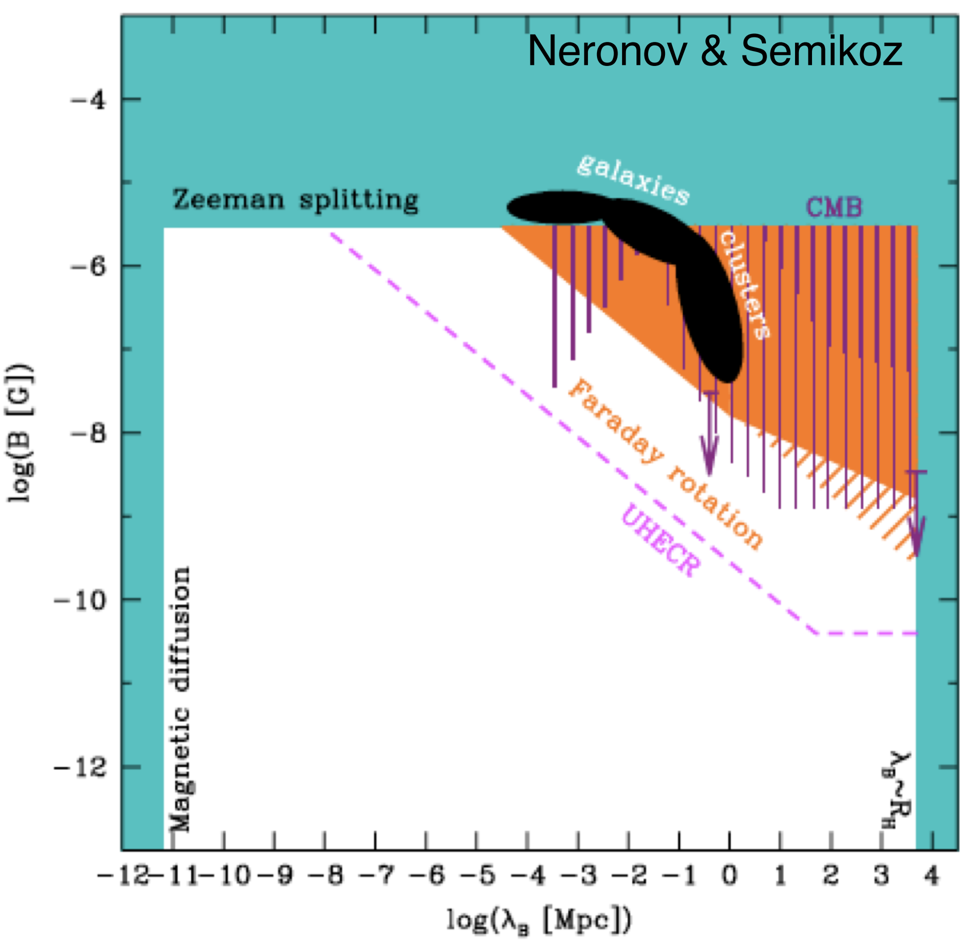




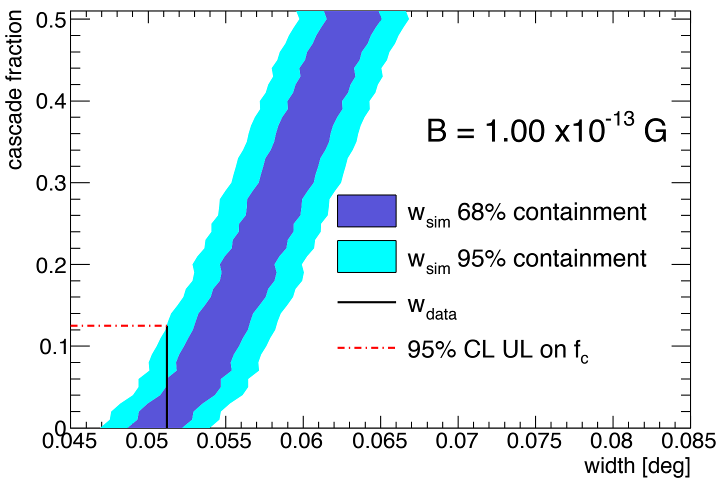
Intergalactic Magnetic Field

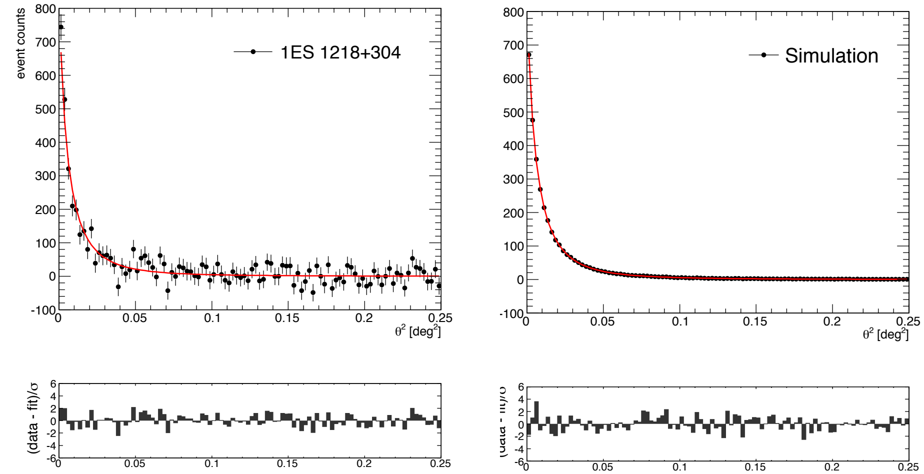
- How to produce strong B fields in galaxies/galaxy clusters?
  - Intergalactic magnetic field plausible seed field.
- Produced in early universe?
  - Inflation, phase transitions, recombination.
  - Probe earlier era than CMB?
- Produced astrophysically?
  - Magnetized plasma injected into interstellar medium.

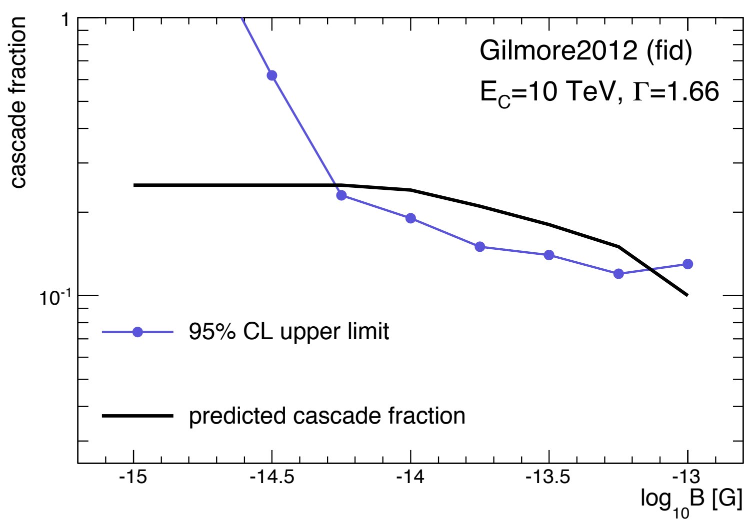
PHYSICAL REVIEW D 80, 123012 (2009)



VERITAS: IGMF Constraints from blazars



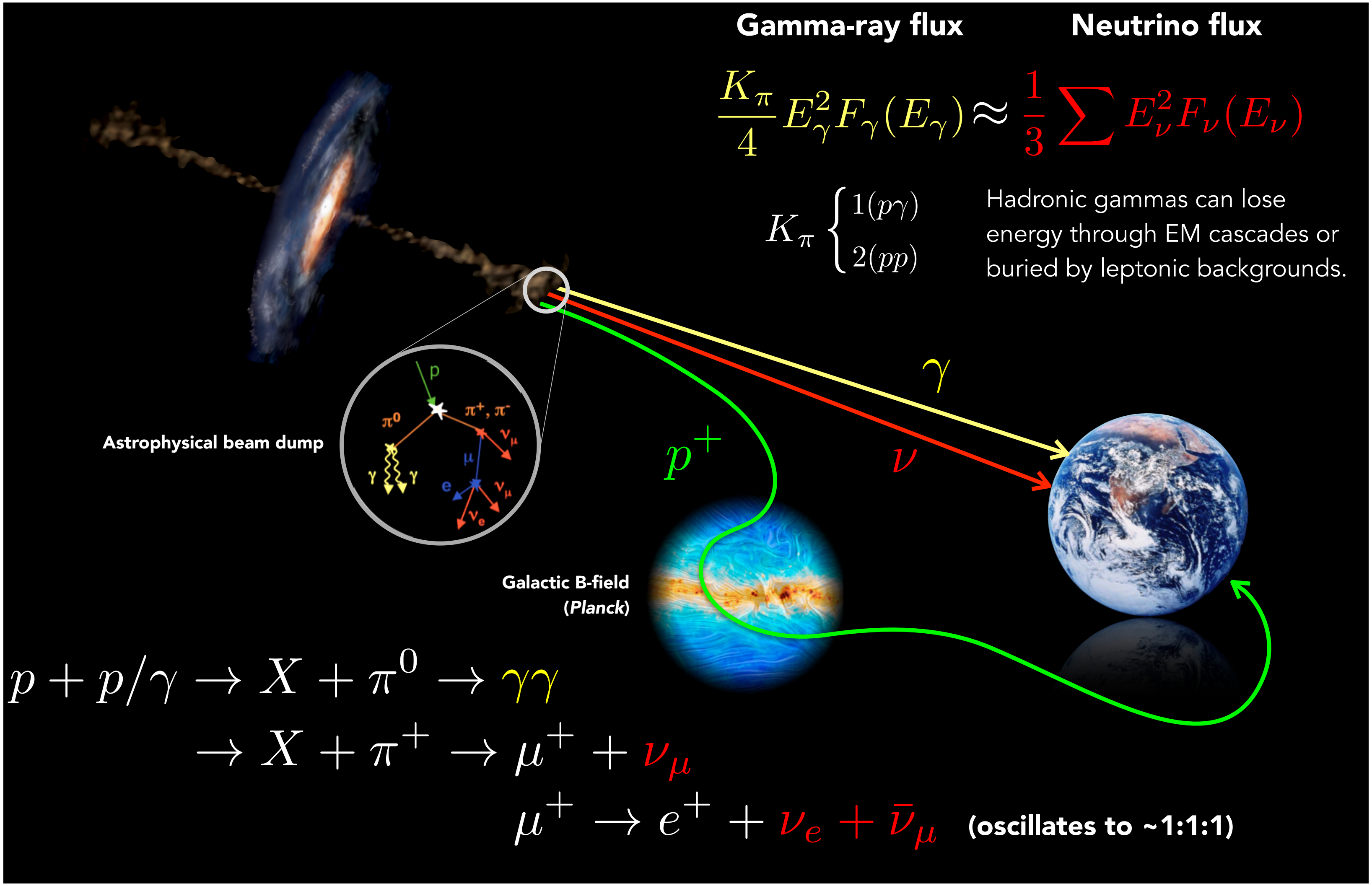




VERITAS ApJ 2017: arXiv:1701.00372

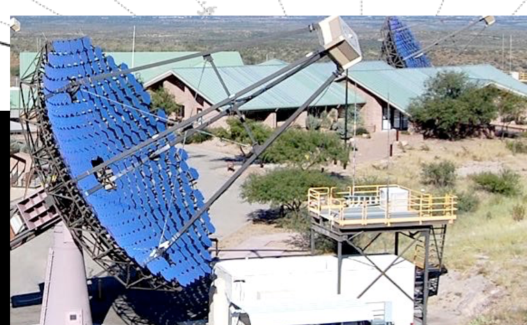
- Test for extended emission around blazars, none found.
- No deviation from simulated instrument PSF
- Exclude IGMF strengths around ~10^{-14} G at 95% confidence level.
- The dependence of the width of the simulated angular distribution on the cascade fraction fc for 1ES 1218+304 (Left Top).

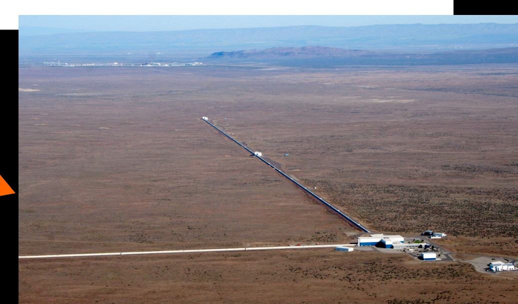
3. VERITAS Multi-Messenger Program



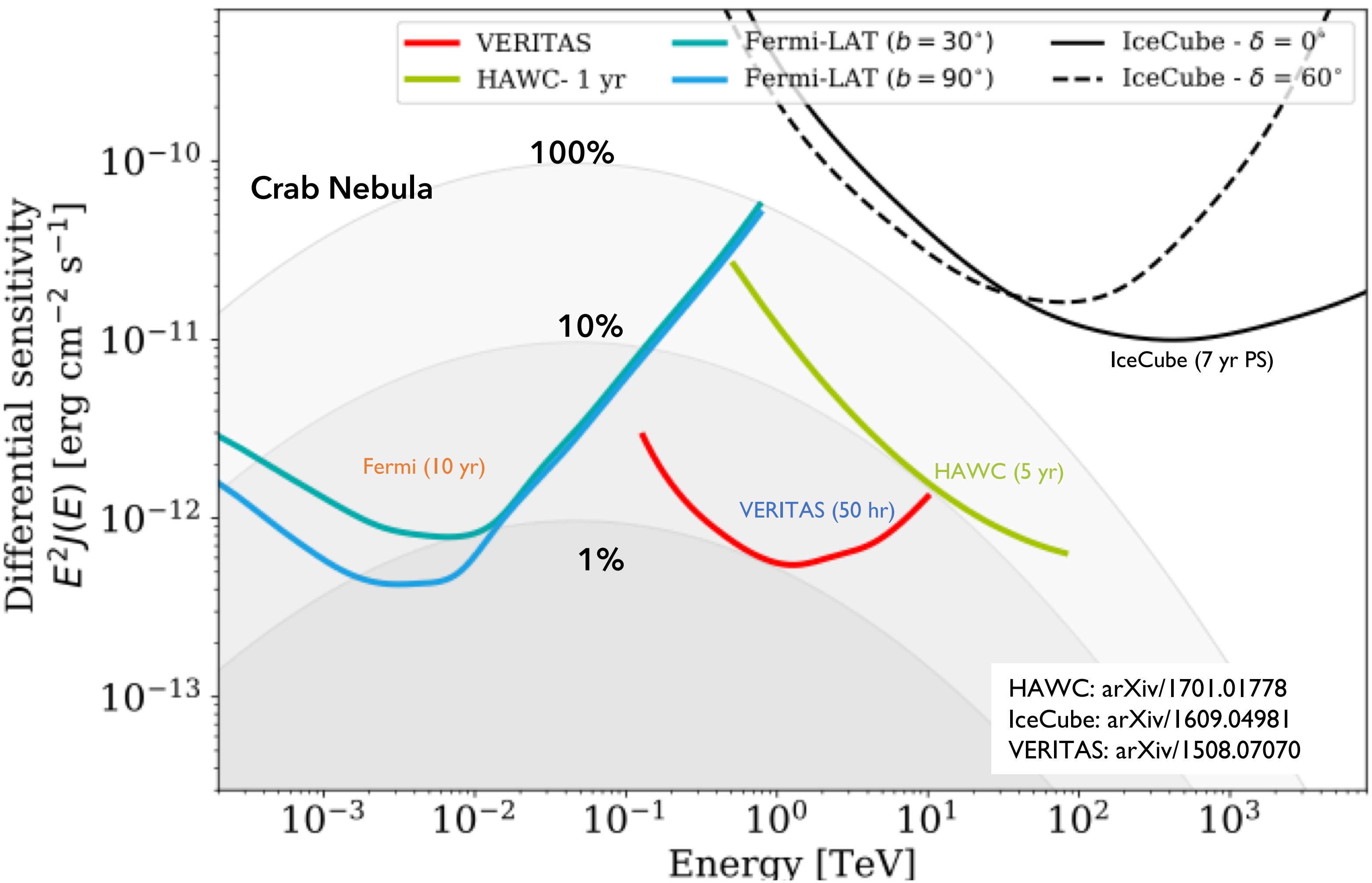
Instruments: Multi-Messenger Astronomy

From "Dawn of Multi Messenger Astronomy," Santander, 2016





Point-source sensitivities: γ and ν telescope

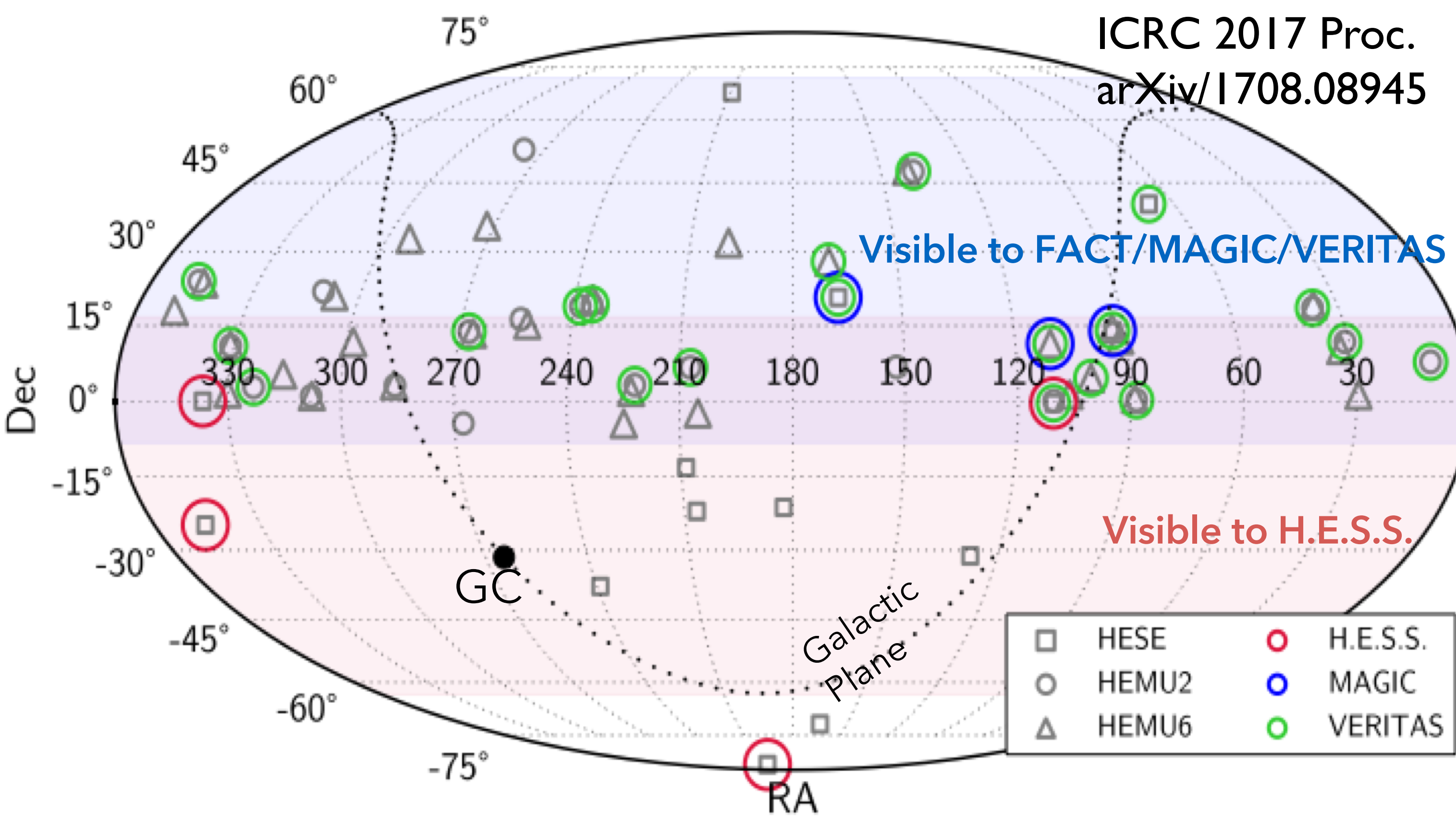


After "Dawn of Multi Messenger Astronomy," Santander, 2016

VERITAS follow-up programs for IceCube events

- (1) Archival searches:
  - Searches for VHE emission at "archival" muon neutrino positions that are likely astrophysical ($E_\nu \gtrsim 100$ TeV).
  - Correlation studies of neutrino and gamma-ray emission from VHE sources.
- (2) Day-week follow up latency:
  - Observation of neutrino "flares" from known VHE sources.
  - Observation of neutrino multiplets.
- (3) Instantaneous (seconds/minutes):
  - Observation of astrophysical neutrino candidate events.

Neutrino event selection for archival searches

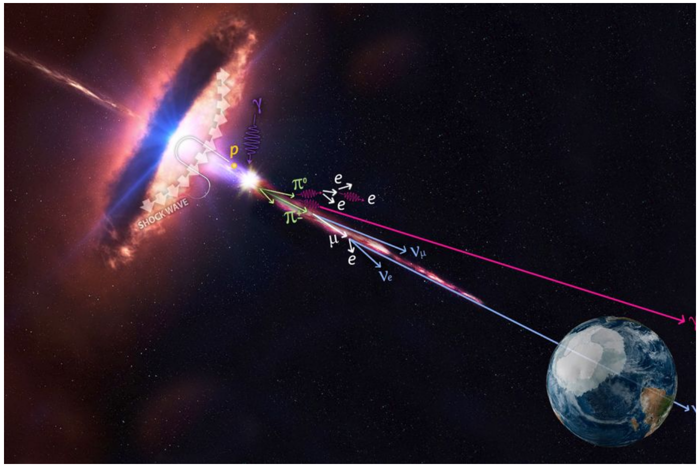


Requirements for VERITAS Observations

- **Good angular angular resolution:** Muon tracks have O(1°) resolution.
- **Observable from VERITAS:** Northern events or at low Southern declinations.
- **High astrophysical probability:** High-energy events have a low atmospheric prob.

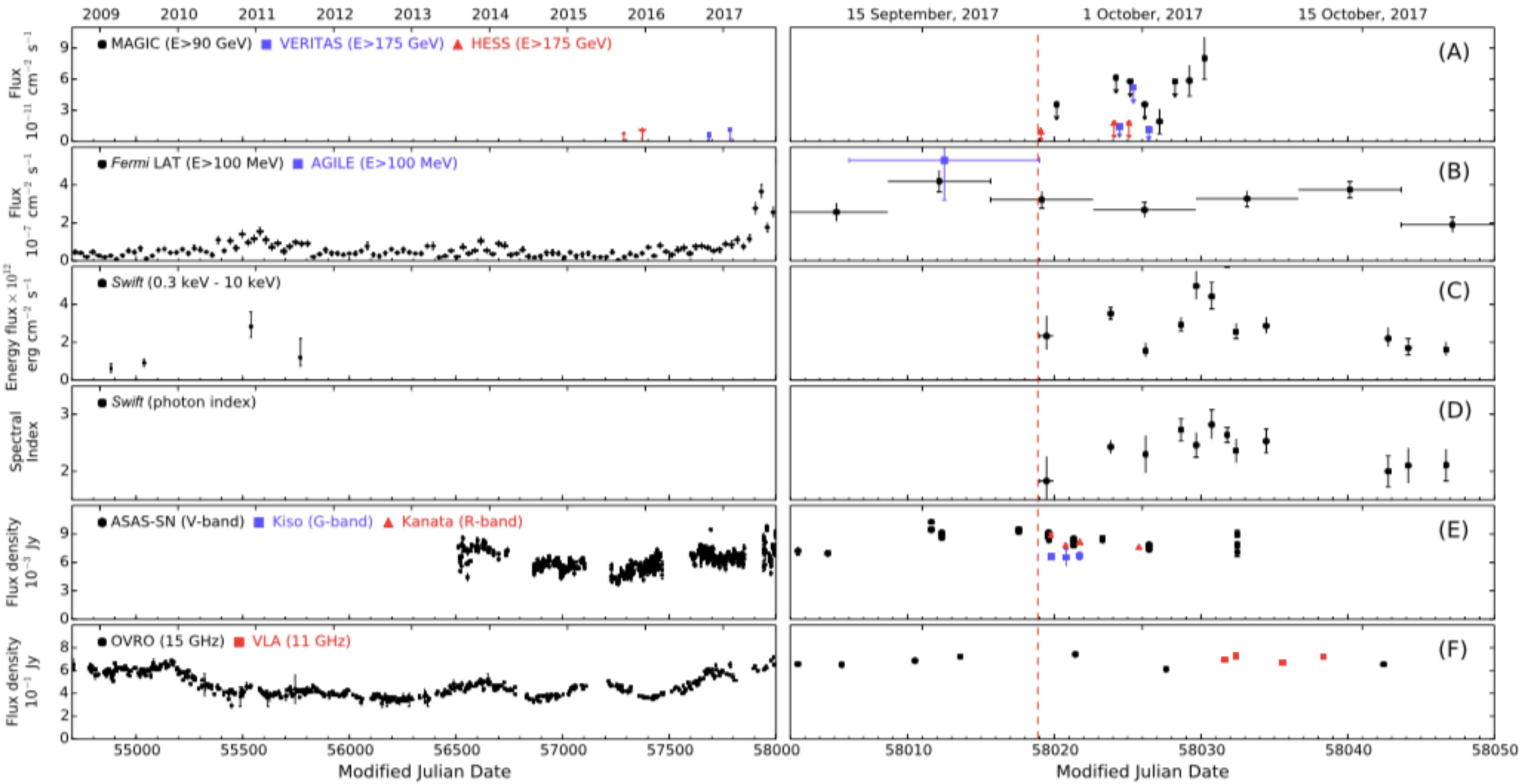
Prompt Multi-Messenger follow-up of IC170922A
First association of neutrino with γ-rays

- High-energy (>200 TeV) neutrino detected on Sep 22, 2017 (GCN #21916).
- Neutrino positionally-coincident (~ 0.1°) with the γ-ray blazar TXS 0506+056, observed by Fermi-LAT to be flaring during this period (ATel #10791).
- Follow-up observations across the EM spectrum. No VHE detection promptly after the alert.
- MAGIC detected blazar at >100 GeV in observations started 6 days after the neutrino (ATel #10817) and in long term observations (MNRAS 2018).
- VERITAS: No detection in observations 6.5 hours after the event (ATel #10833). TXS 0506+056 detected in 35 hours collected until February 2018 (ApJ Lett 2018).



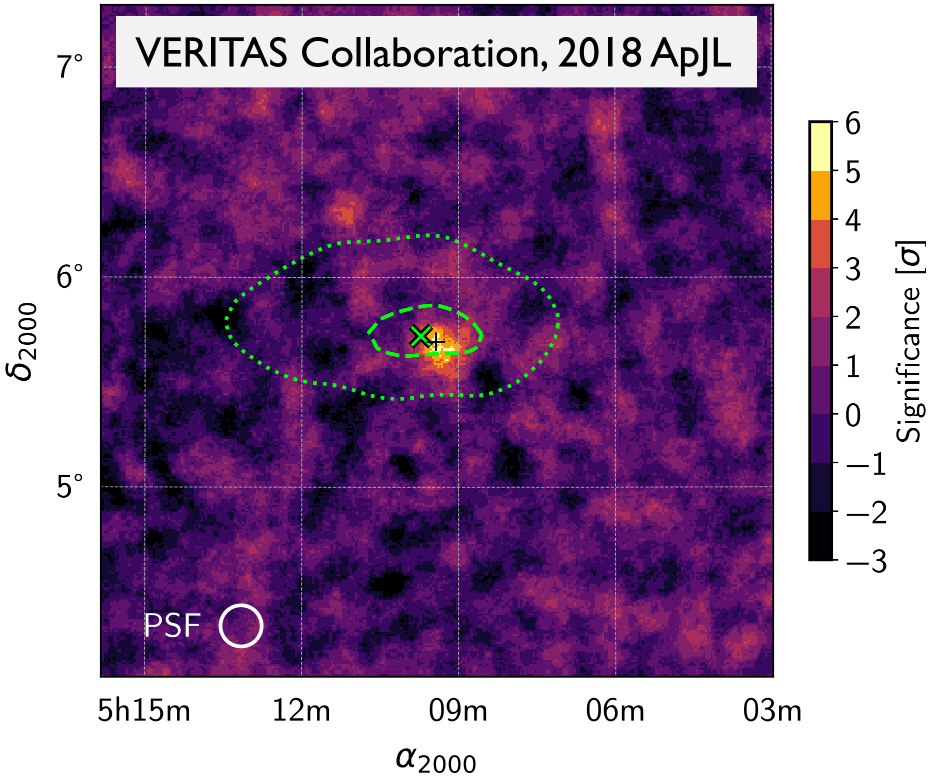
Credit: IceCube/NSF

IC170922A: First association of neutrino with γ-rays

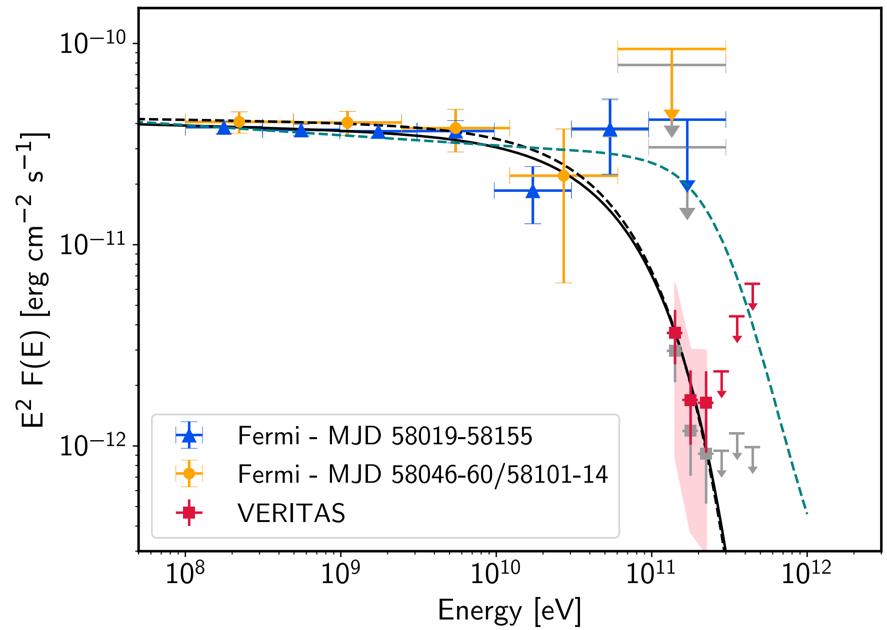


- Multi-messenger follow up by 17 observatories.
- Unprecedented time-dependent multi-wavelength observations of TXS 0506+056 before and after IceCube-170922A (Science 2018).

VERITAS: VHE γ-rays from the blazar TXS 0506+056



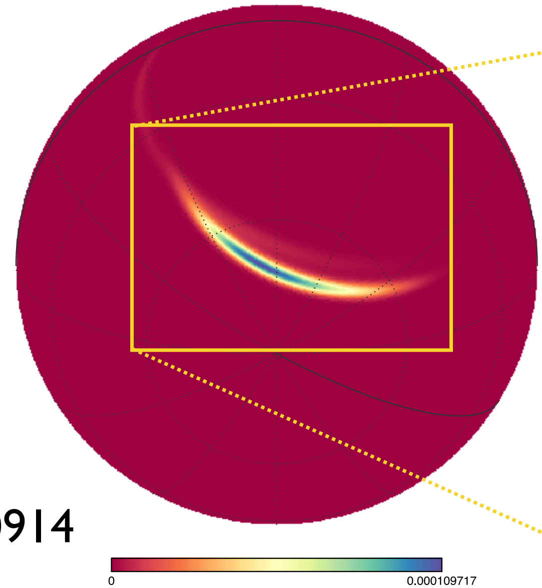
- VERITAS sky map for the region around TXS 0506+056.
- Data set: 35 hours, Sep 2017 to Feb 2018.



Gamma-ray SED of TXS 0506+056 from Fermi-LAT and VERITAS

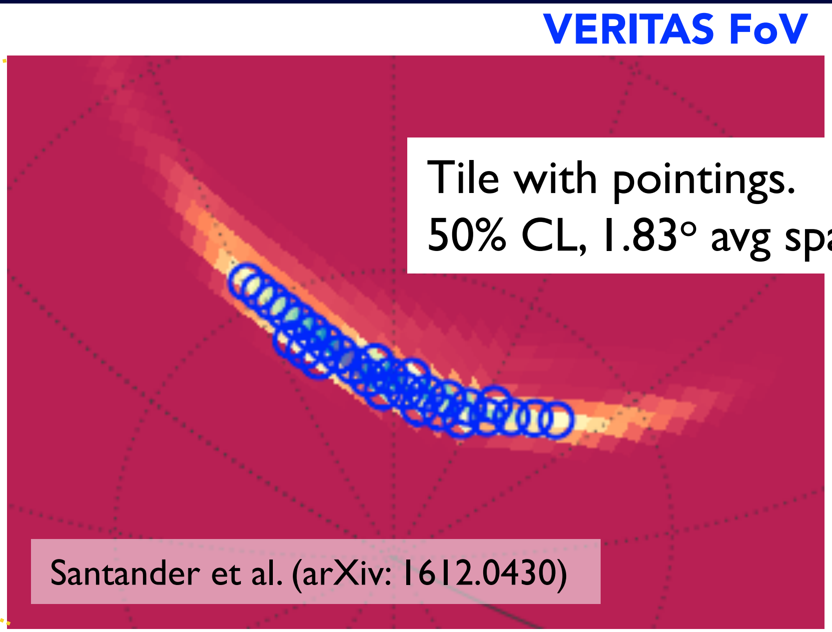
VERITAS Collaboration, 2018 ApJ Letters: arXiv:1807.04607

VERITAS: Gravitational Wave Follow-up Strategy



e.g. GW150914

Event localization probability map

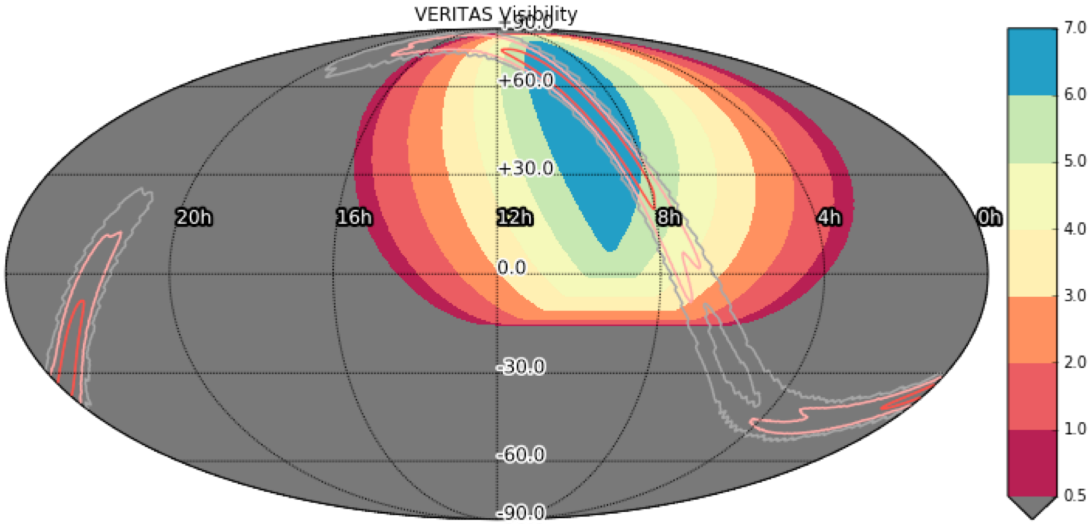


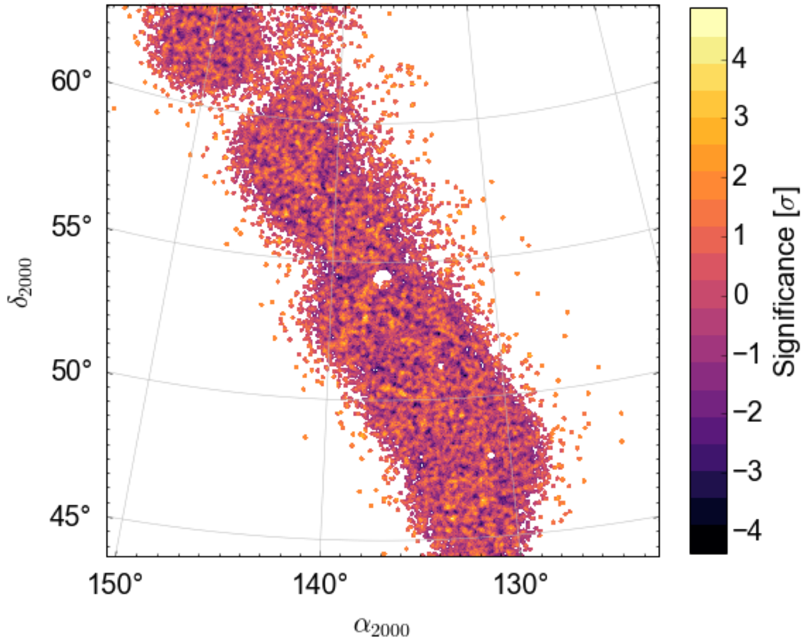
29 pointings to cover the 50% CI of GW150914

- The VERITAS FoV can cover O(10 deg^2) in a single pointing. Can cover the large GW uncertainty regions.
- Localization map for the GW alert is available a few minutes after detection, goes out to follow-up instruments after data quality checks are performed.
- Preparing for O3, the next LIGO run to start end of 2018/beginning of 2019.
- **GW170817: No VERITAS data due annual monsoon shutdown.**

First systematic IACT follow-up of a GW alert

- GW170104: 50-M_{sun} BBH merger at z = 0.2 detected by LIGO.
- No EM emission expected. Alert was 6.5 hours old when received. Good visibility of the core region of the event.

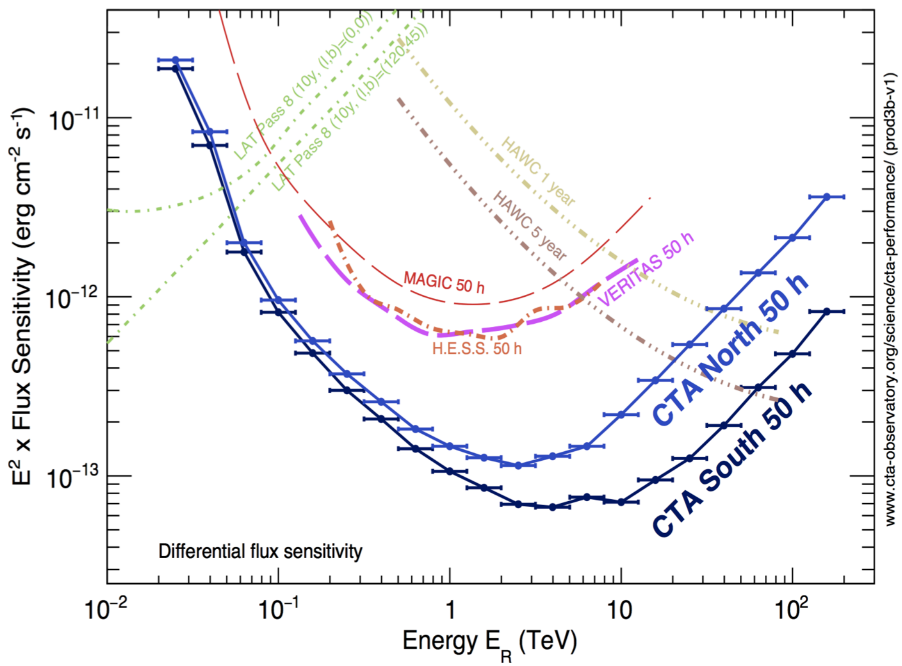




- The VERITAS FoV can cover O(10 deg^2) in a single pointing. Can cover the large GW uncertainty regions. Preliminary results circulated as GCN circular #21153
- Results affected by weather.

Conclusions and Outlook

- VERITAS has an active Astroparticle physics and offers significant complementarity.
- Astrophysical neutrinos: VERITAS can identify potential counterparts.
- Gravitational wave follow-ups: VERITAS is ready to carry out follow-up observations of GW events that are potentially EM.



- VERITAS can provide northern coverage with competitive sensitivity until the start of CTA operations and extending to its first phase.

The VERITAS Collaboration & Friends – 10 Year Celebration

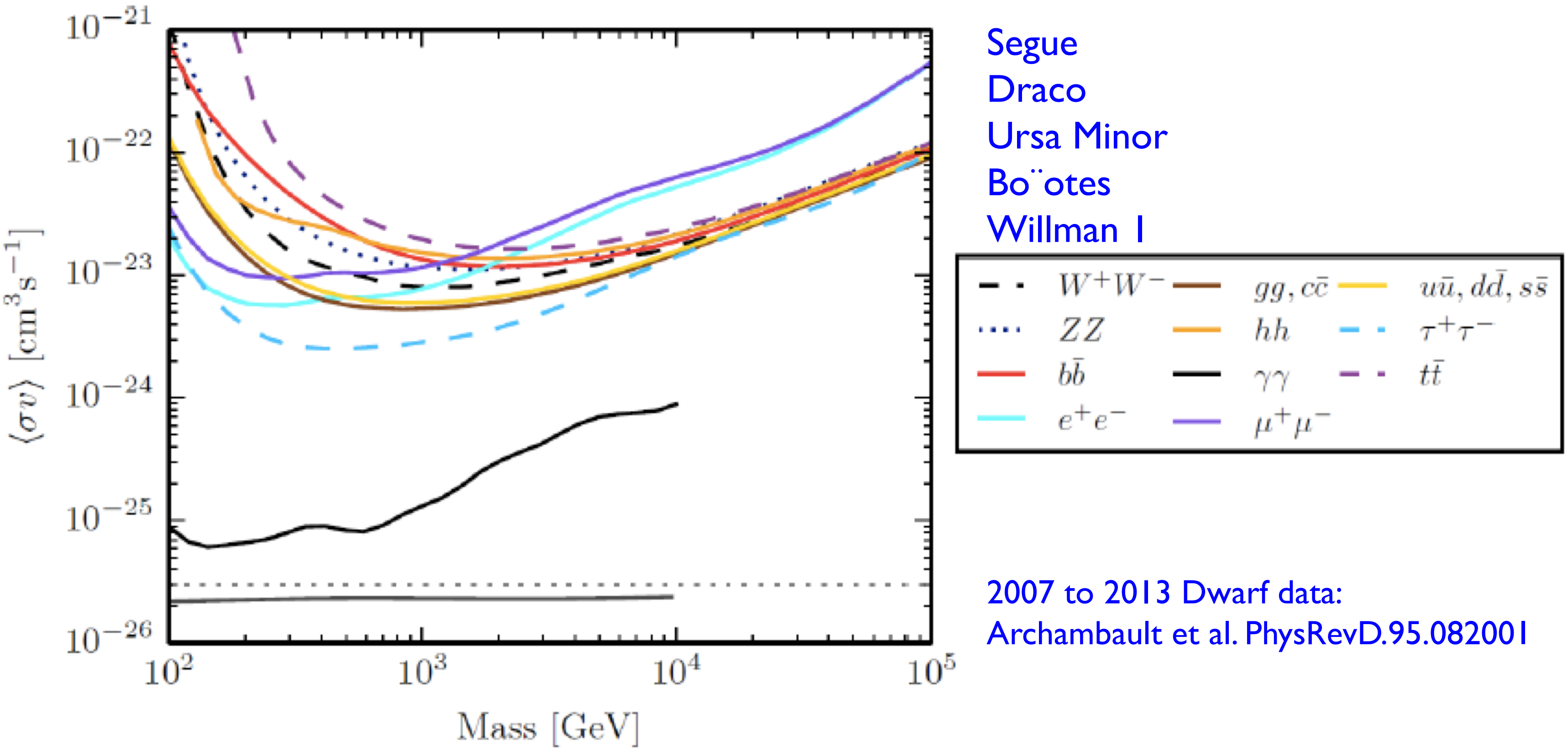
- Argonne, USA
- Barnard, USA
- Columbia, USA
- CIT, Ireland
- GeorgiaTech, USA
- Iowa State, USA
- McGill, Canada
- NUI, Ireland

- Purdue, USA
- Smithsonia, USA
- UCD, Ireland
- UCLA, USA
- UChicago, USA
- UDelaware, USA
- Uiowa, USA
- Uminnesota, USA

- UUtah, USA
- Washington U, USA
- PennState, USA
- Cal State EB, USA
- Cal Poly, USA
- DESY, Germany
- Potsdam, Germany
- UAlabama, USA

Extras

VERITAS: Combined Results from Dwarfs



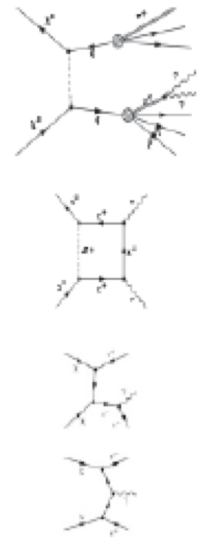
Segue
Draco
Ursa Minor
Boötes
Willman 1

2007 to 2013 Dwarf data:
Archambault et al. PhysRevD.95.082001

- 95% confidence interval on WIMP velocity-averaged cross section with assumption of 100% annihilation into specified channel.
- 216 hours combined with four different dwarf galaxies, "stacked" into a single limit.
- We find no evidence of gamma-ray emission from any individual dwarfs nor in the joint analysis.

Gamma Rays from Dark Matter

- Cold Dark Matter (DM) composes 27% of the universe
- Composition of DM still not understood
- Extension of SM that include weakly-interacting massive particles (WIMPs)
- Majorana particles that self-annihilate or decay to SM particles
- (Nearly) all roads lead to gamma rays!
- Complementary studies to Indirect detection and collider experiments



Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q}, gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l$, $W^{\pm} \to u\bar{d} \to \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l}, \nu\bar{\nu}, q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e$, $\tau \to \nu_\tau W^{\pm} \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$		γ	Loop suppressed
$\chi\chi \to Z^0\gamma$	Z^0 decay	γ	Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs!)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\phi < m_\chi$ to explain large electron signal and avoid overproduction of $\bar{p}, \gamma$

internal/final state bremms inverse Compton γ's

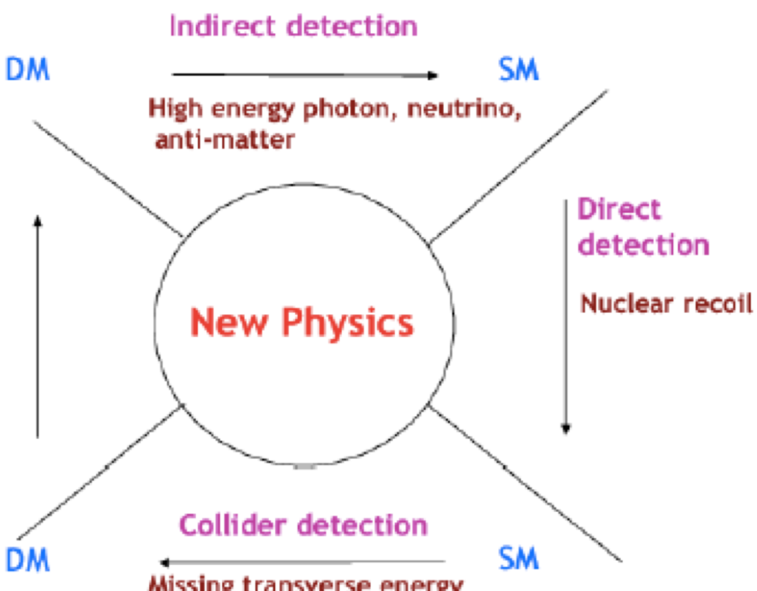


image from: Bi, Xiao-Jun et al. (2013)

- Gamma-ray flux from DM:

$$\frac{dF(E,\hat{\mathbf{n}})}{dE\,d\Omega} = \int d\ell\,\ell^2\,r(\ell\hat{\mathbf{n}})\frac{dN_\gamma(E)}{dE}\frac{1}{4\pi\ell^2}$$

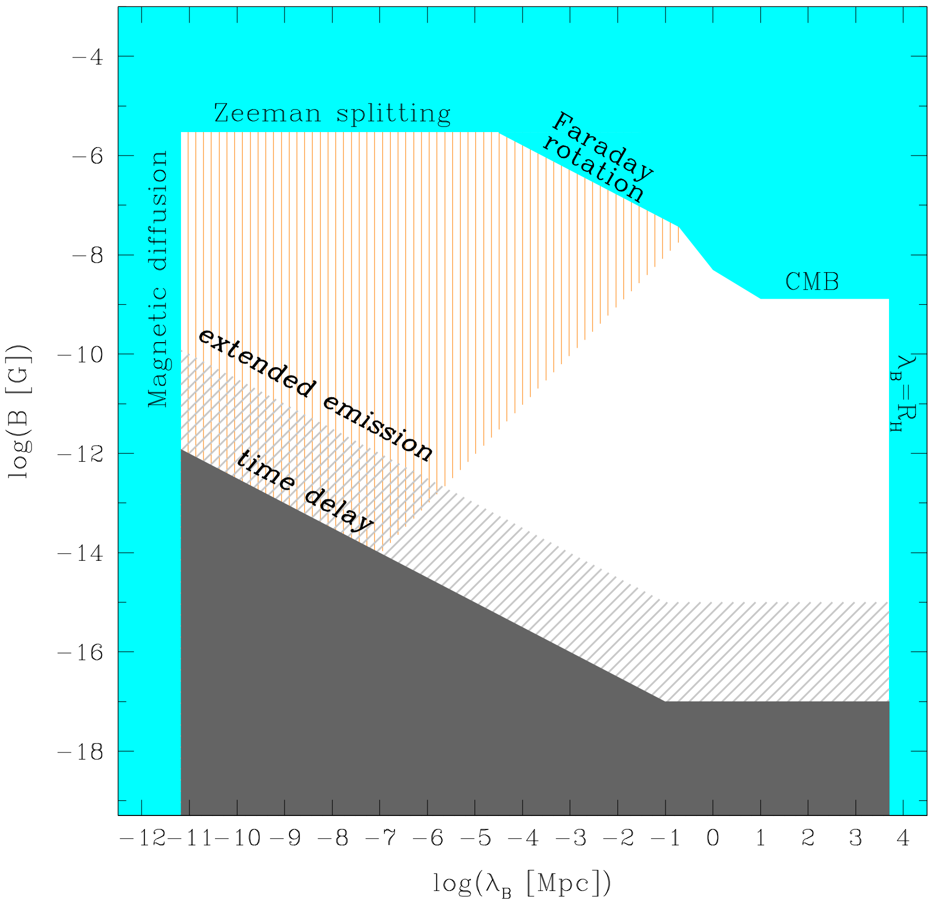
$$= \frac{\langle\sigma v\rangle}{8\pi M^2}\frac{dN_\gamma(E)}{dE}\int d\ell\,\rho^2(\ell\hat{\mathbf{n}})$$

Particle Physics

Astrophysics (J) Factor

Intergalactic Magnetic Field

- How to produce strong B fields in galaxies/galaxy clusters?
  - Intergalactic magnetic field plausible seed field.
- Produced in early universe?
  - Inflation, phase transitions, recombination.
  - Probe earlier era than CMB?
- Produced astrophysically?
  - Magnetized plasma injected into interstellar medium.



Taylor, Vovk, Neronov 2011, arXiv:1101.0932

The VERITAS Collaboration

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