Multi-messenger Astrophysics: Probing Compact Objects with Cosmic Particles

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Virtual Seminar SFB1258
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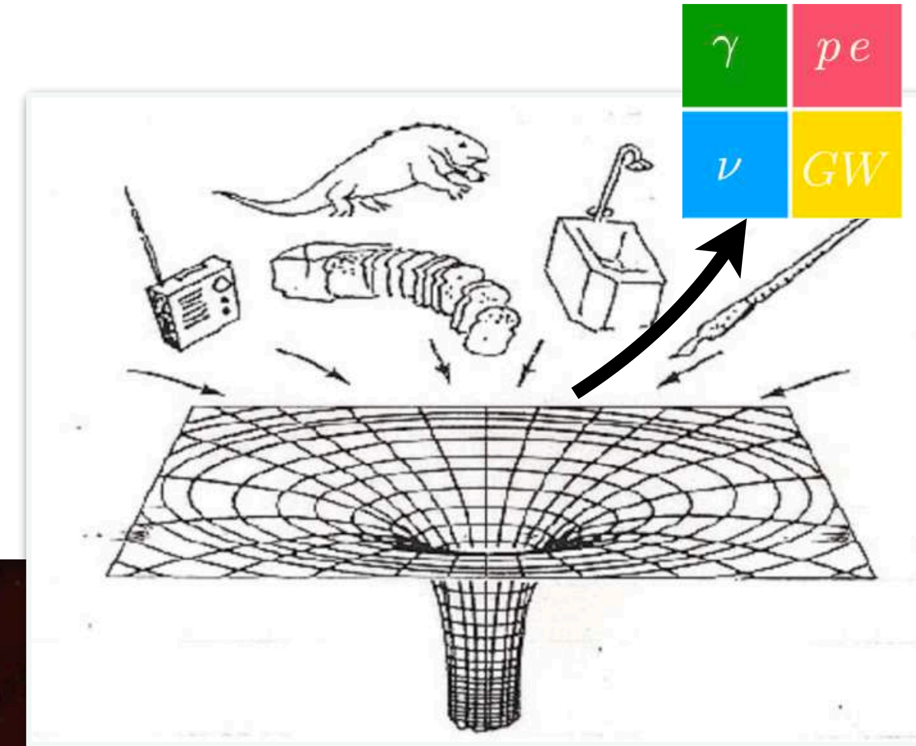
Compact Objects



Why are compact objects interesting?

- The brightest objects in the Universe
- Extremely strong gravity
- Many unknowns including how they are formed, how they interact with their environment, how they radiate

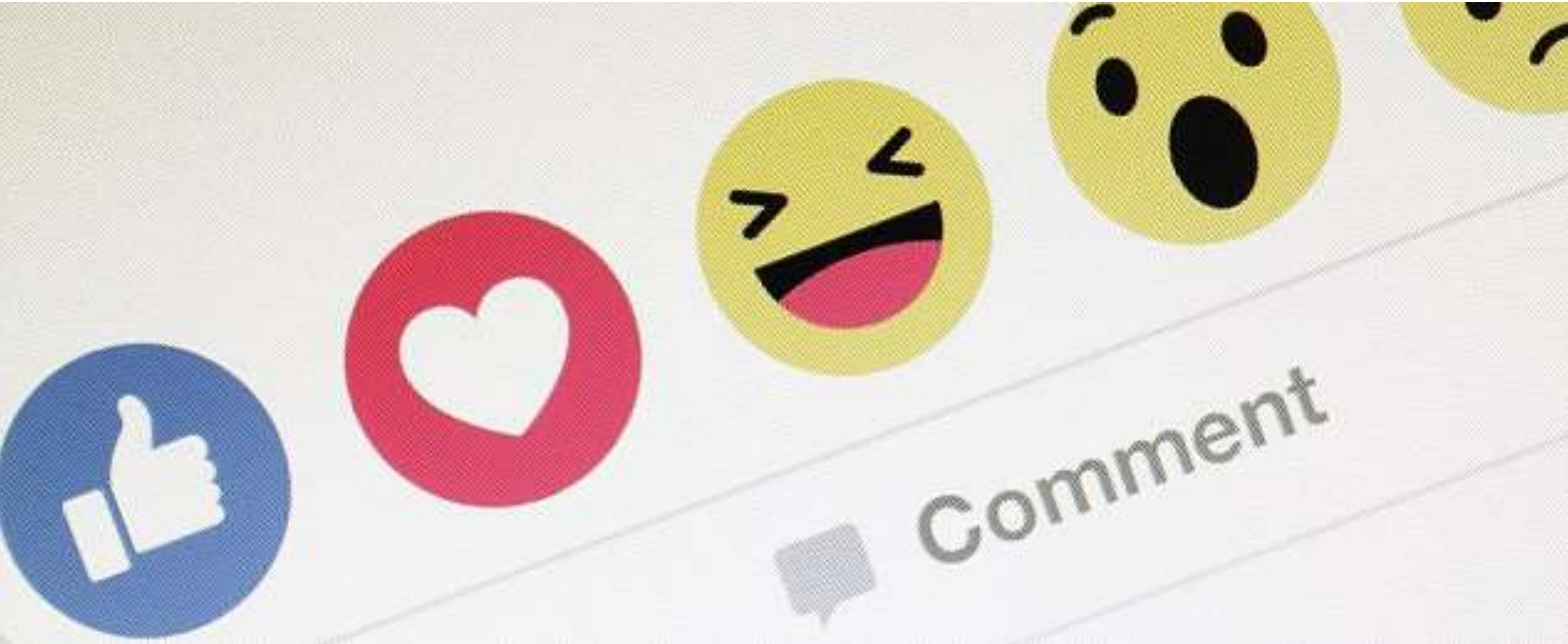
Multi-messengers provide a new way to study compact objects

M87 Black hole Simulation (credit: ESO)

Multi-messengers: **what** are they?

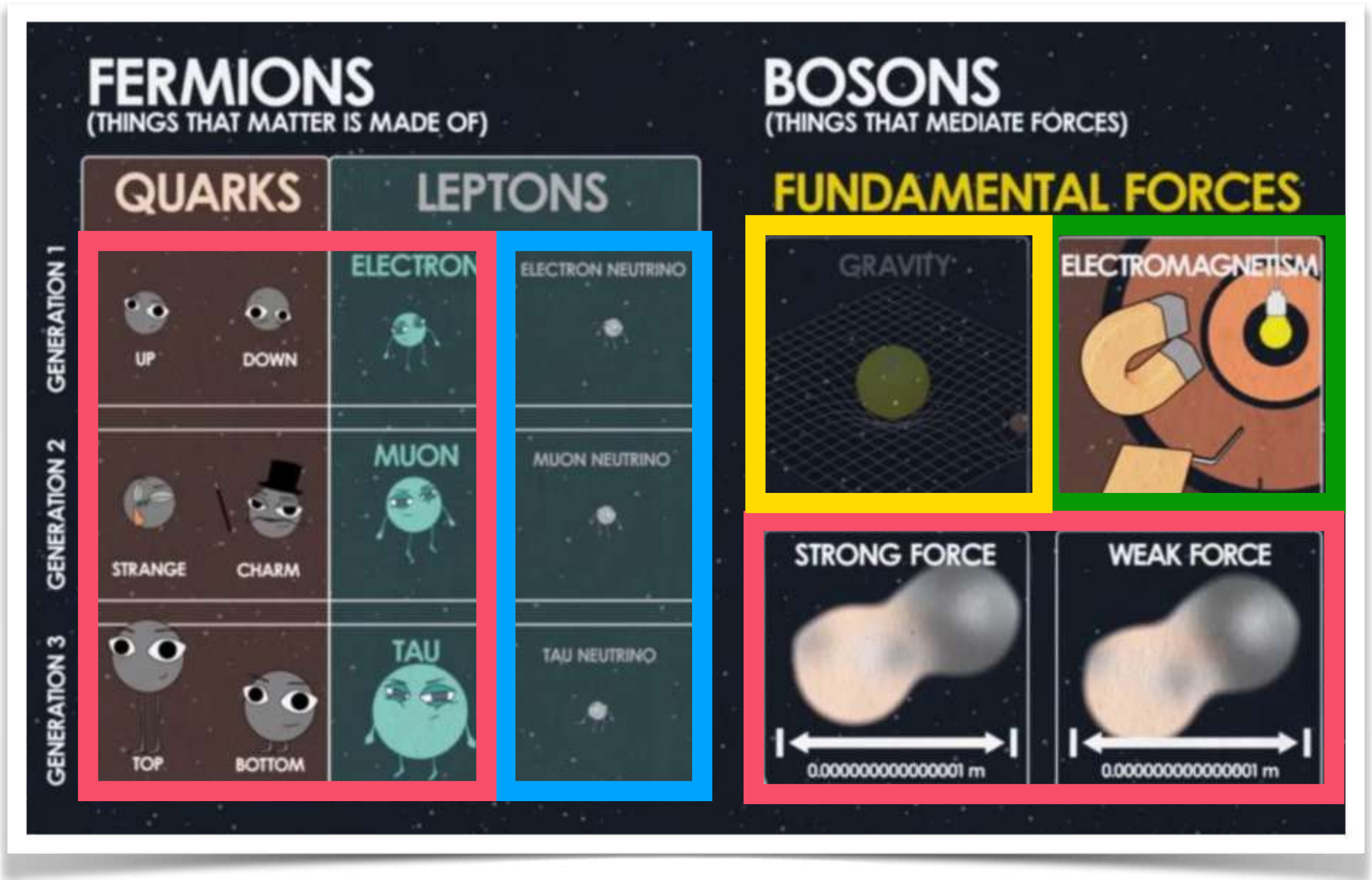
How do we use them?

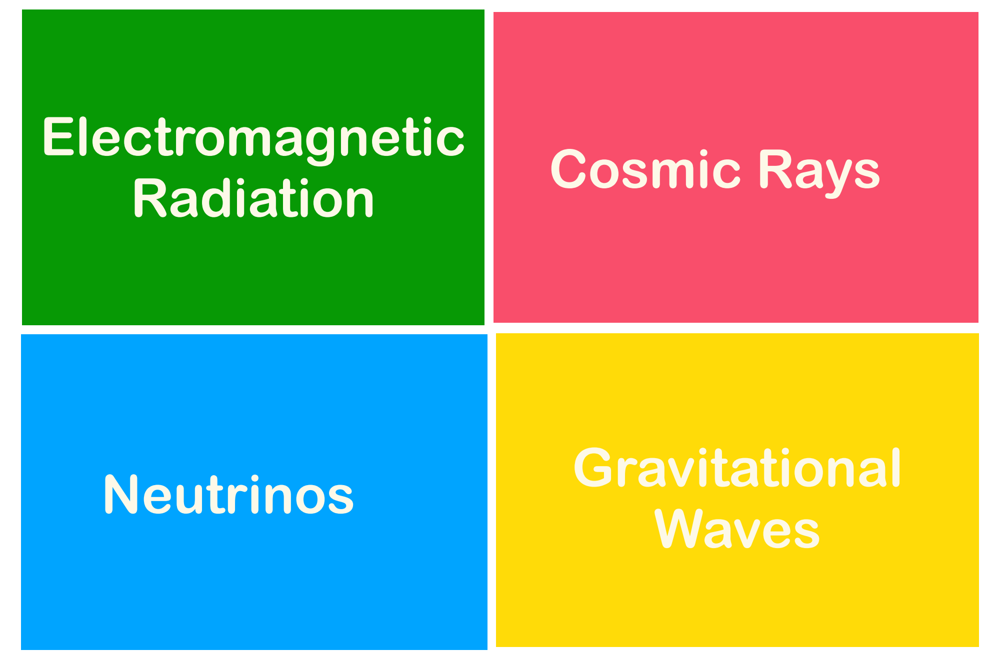
Multi-messengers: what are they?



Multi-messengers:

Different types of particles and waves sent by our Universe

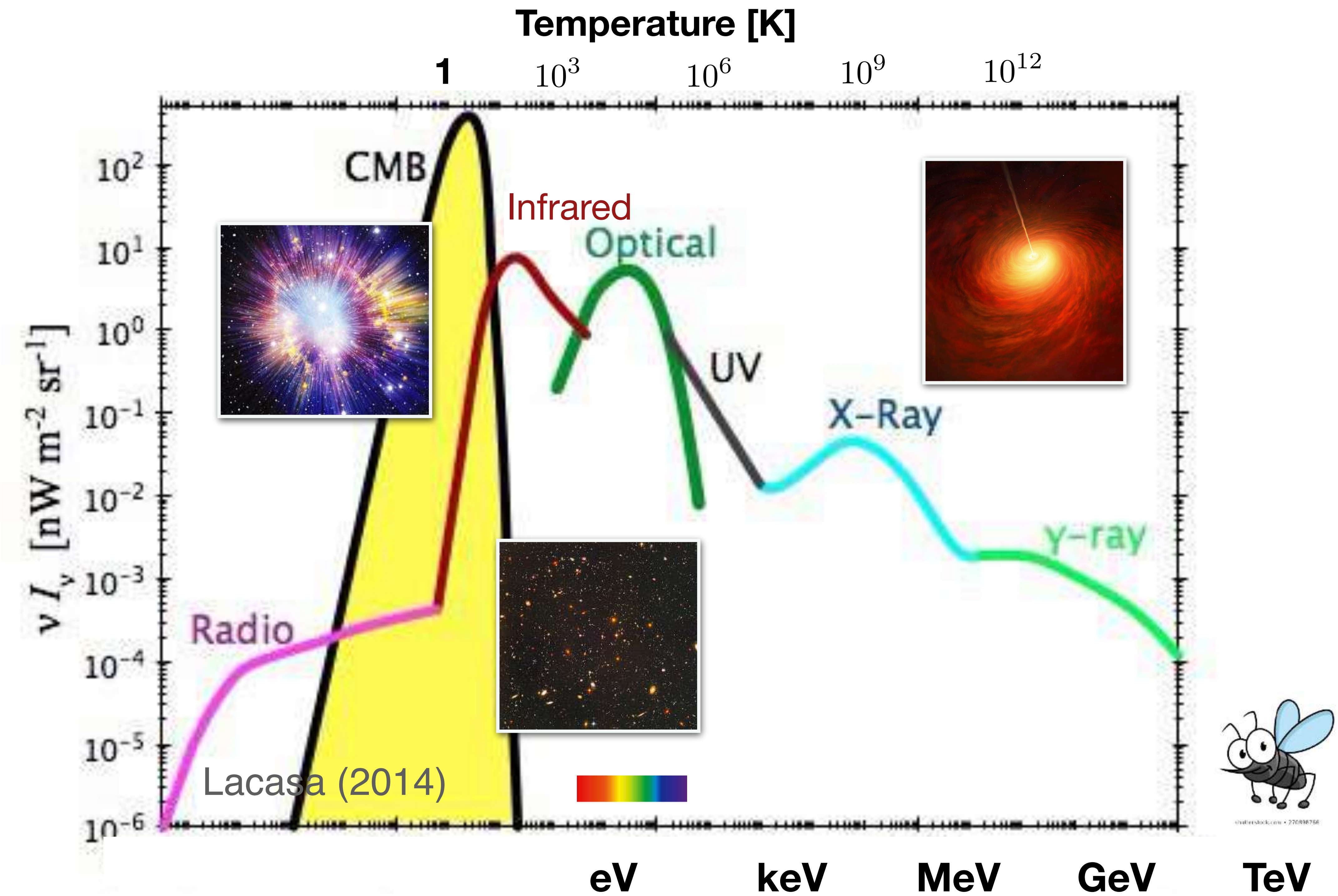




Cosmic particles:

High-energy photons, cosmic rays, and neutrinos produced by extreme activities of the Universe.

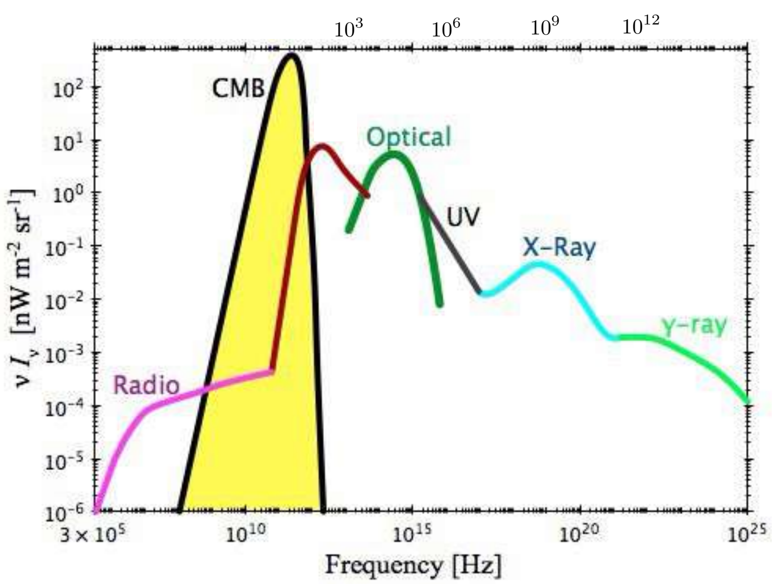
Cosmic Electromagnetic Radiation Background

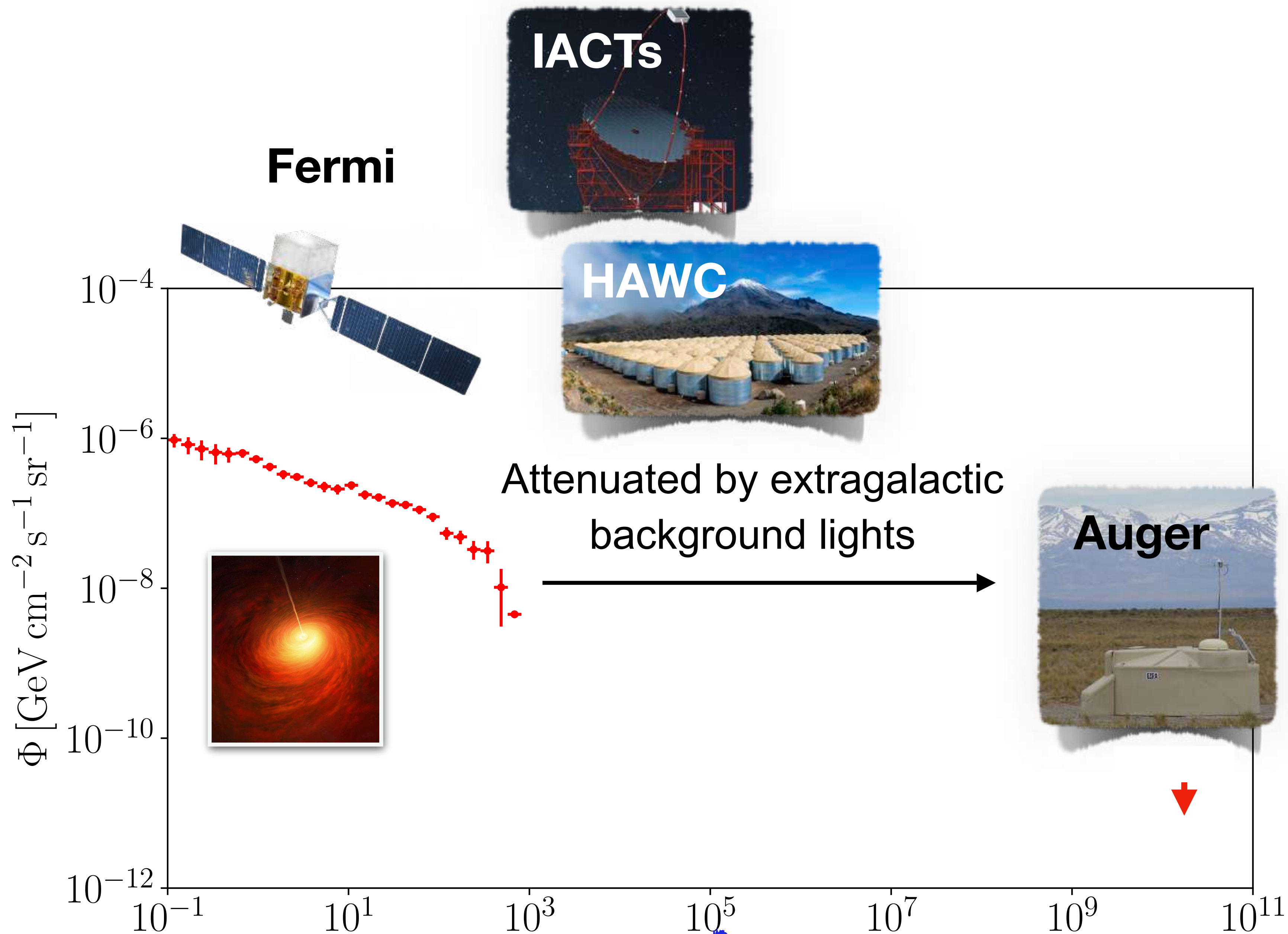


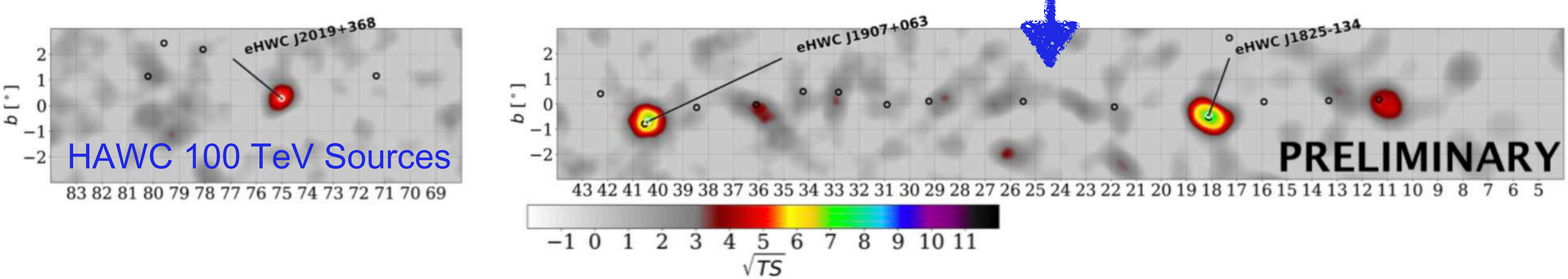
Big bang Galaxies & stars

Active Galactic Nuclei, starburst galaxies

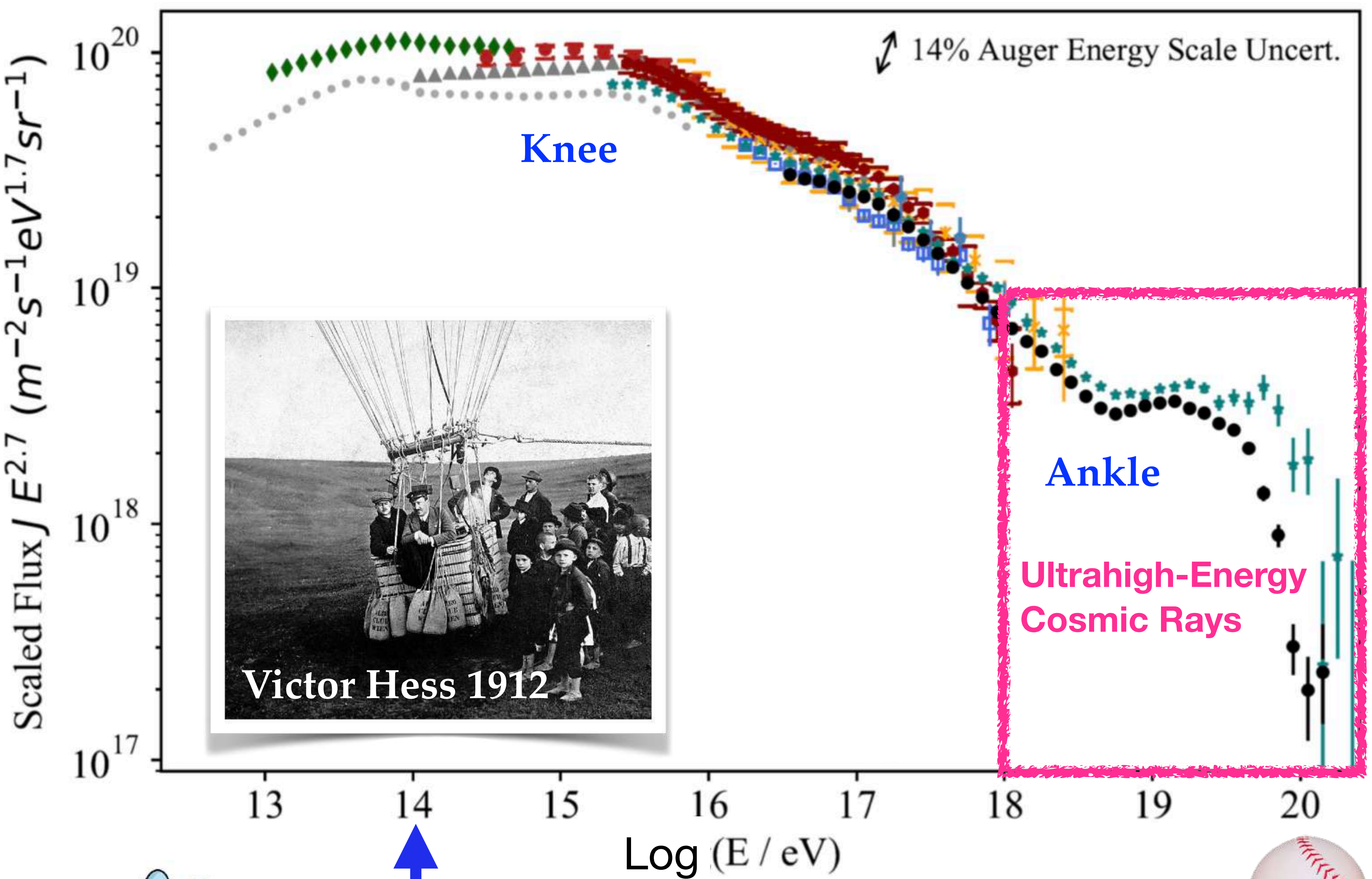
Cosmic Electromagnetic Radiation Background







Cosmic Rays

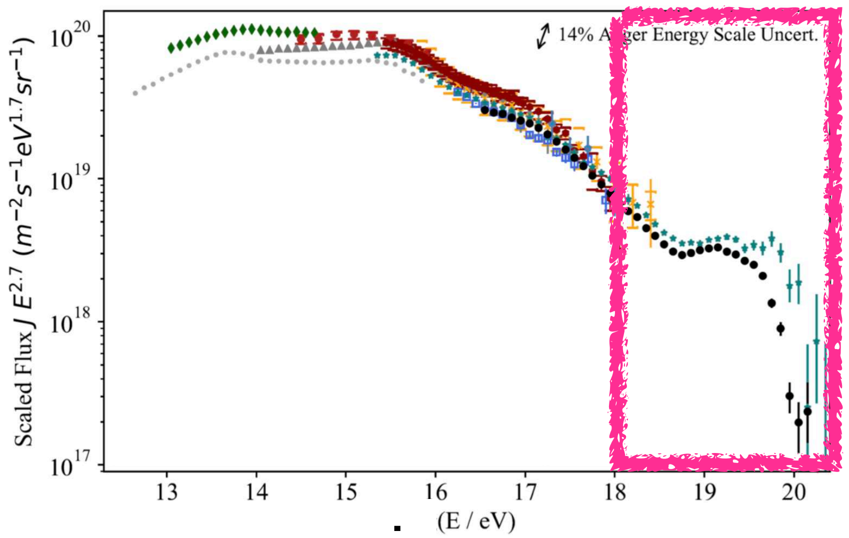


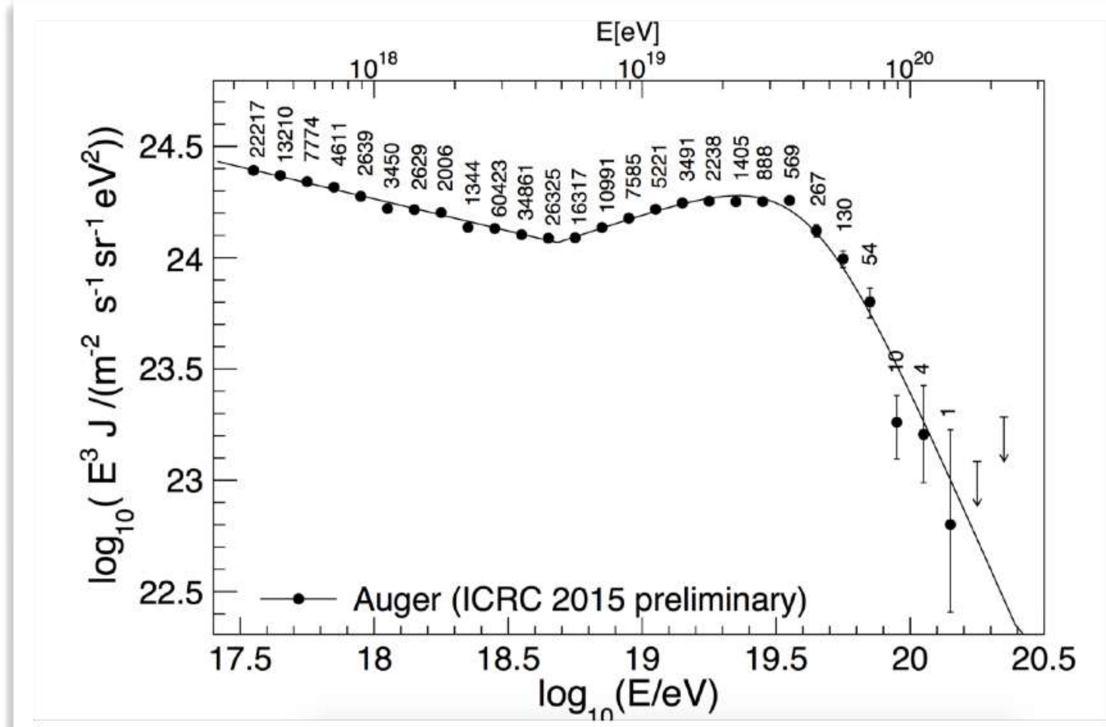
Man-made accelerators

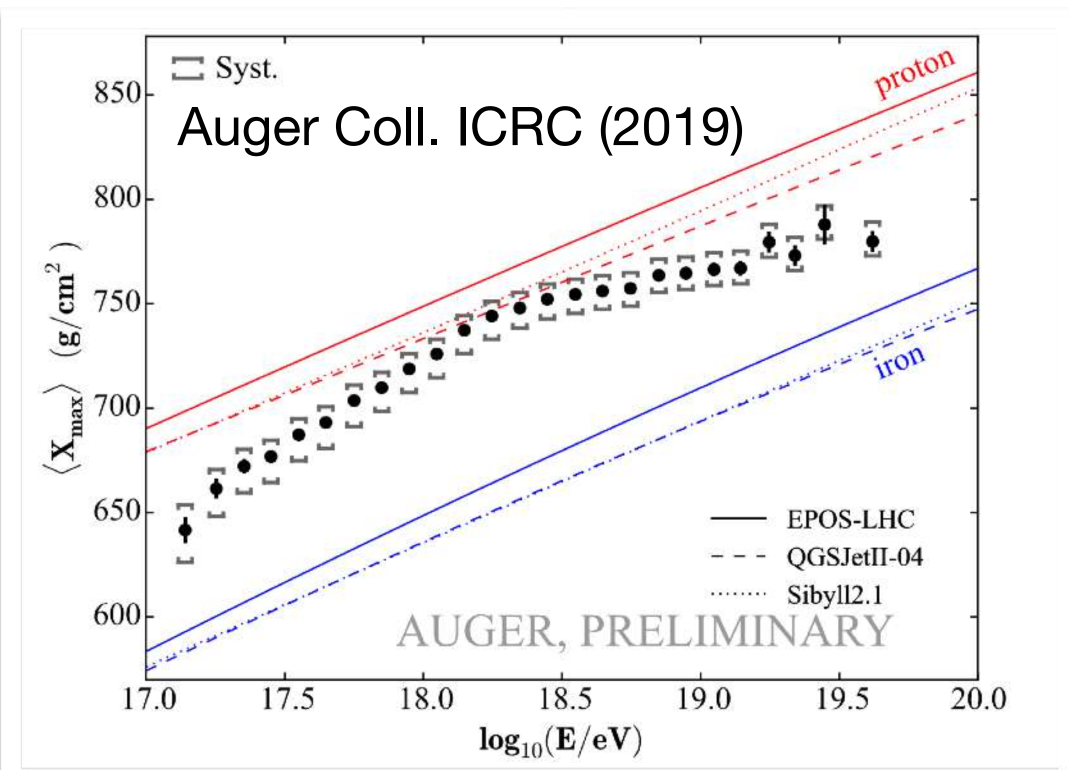
Cosmic Rays

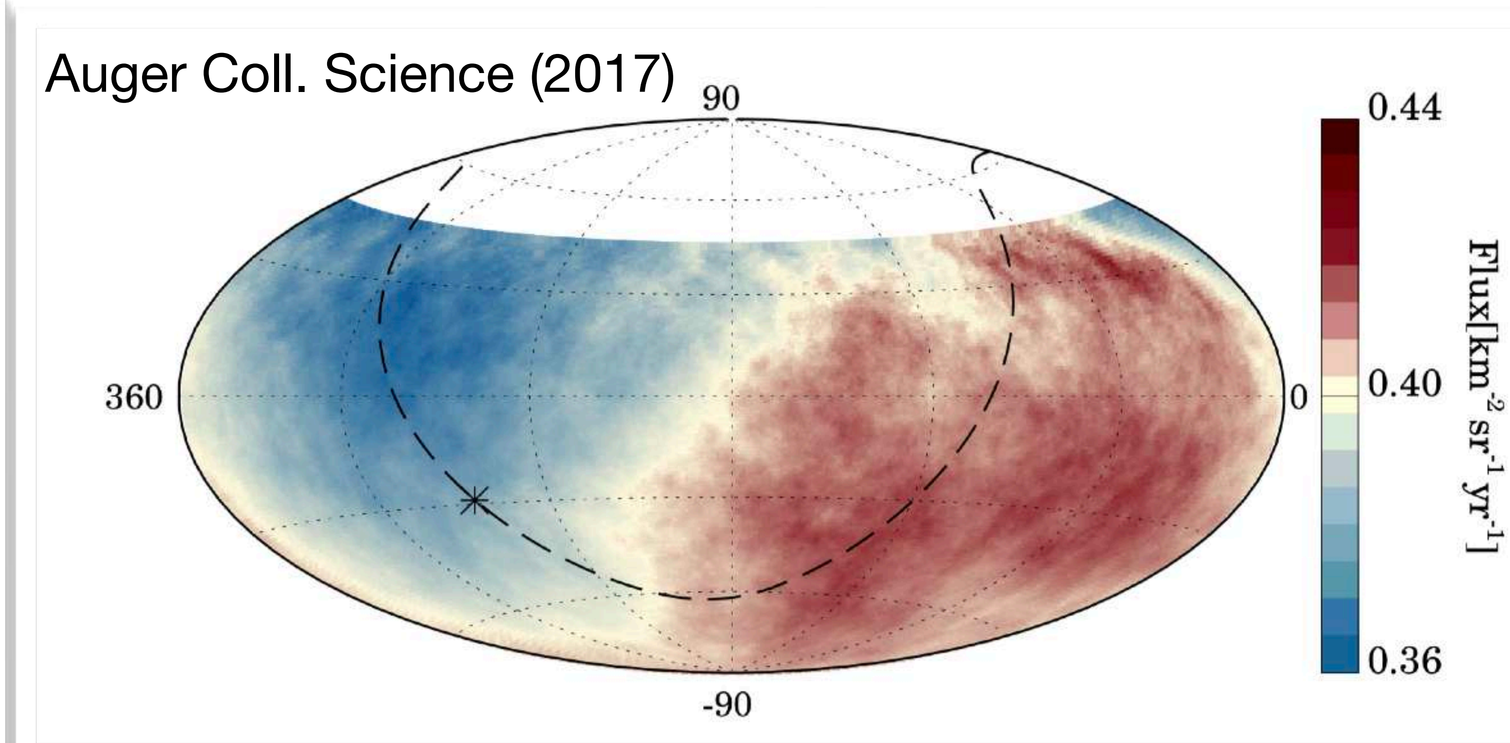
Sources Unknown!

Compact objects provide promising sites for extreme-energy particle acceleration.



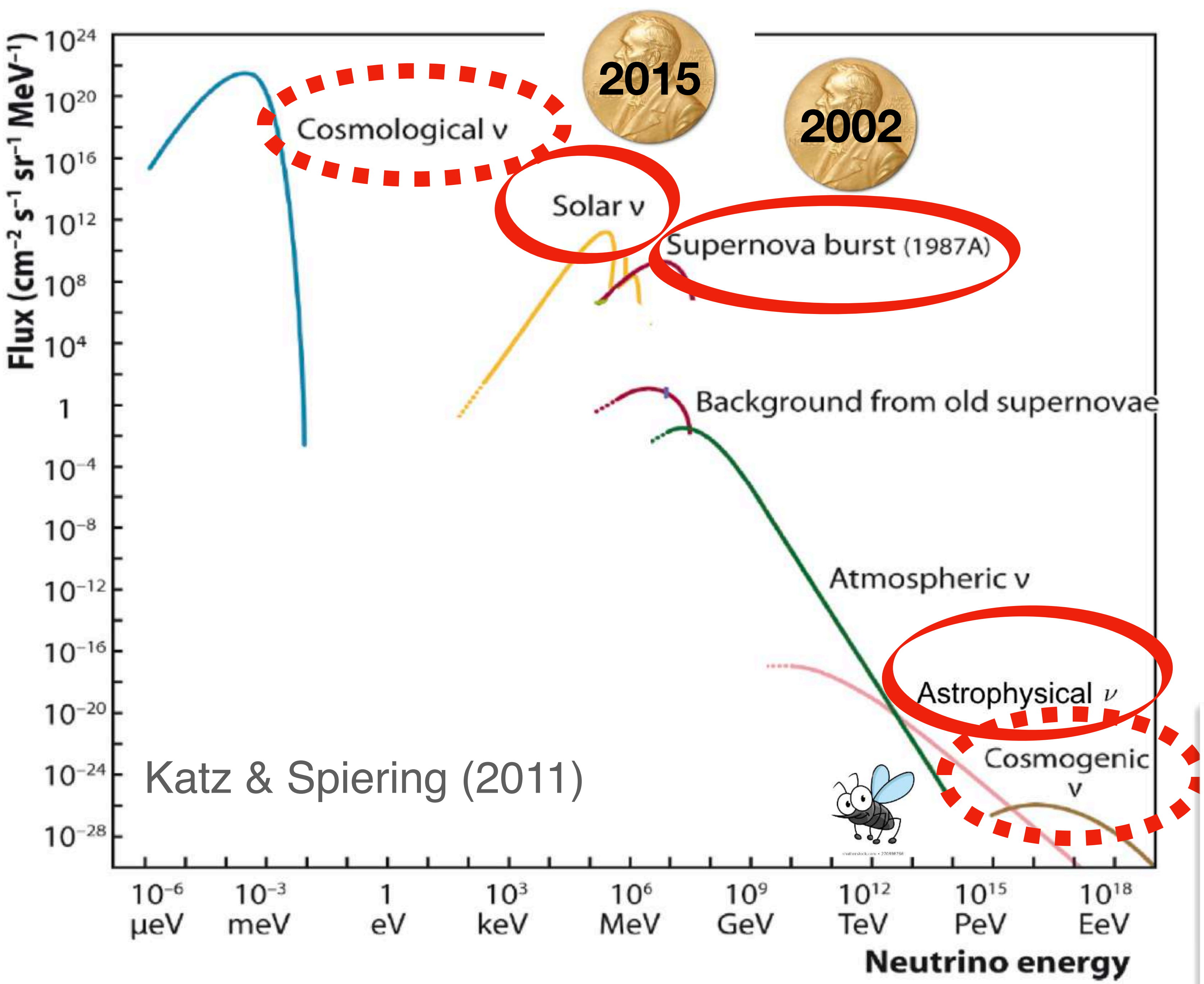


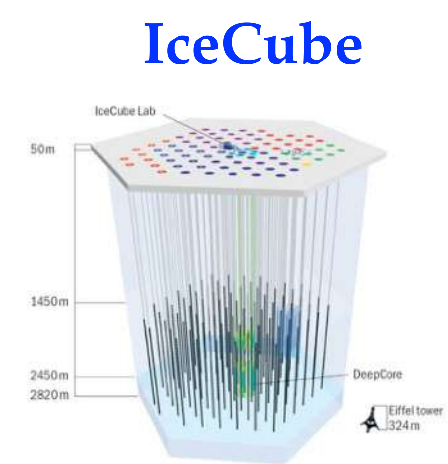


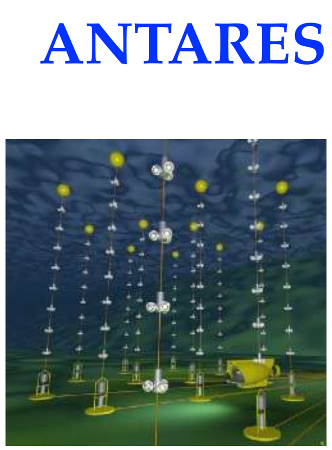


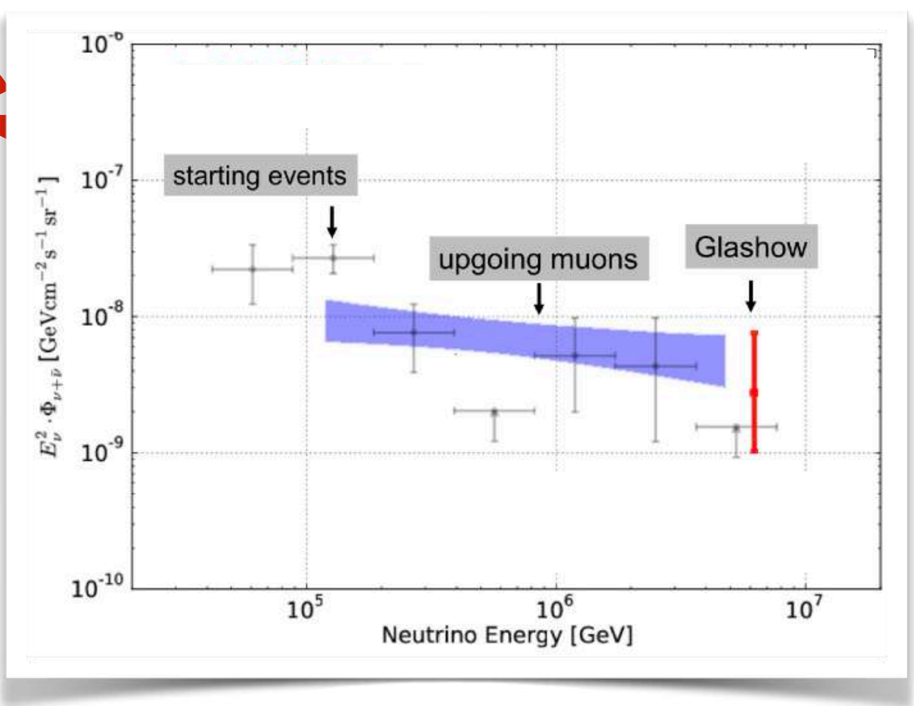
Cosmic Neutrino Background

IceCube Coll., ICRC (2019)
IceCube Coll., Science (2013, 2018a,b)





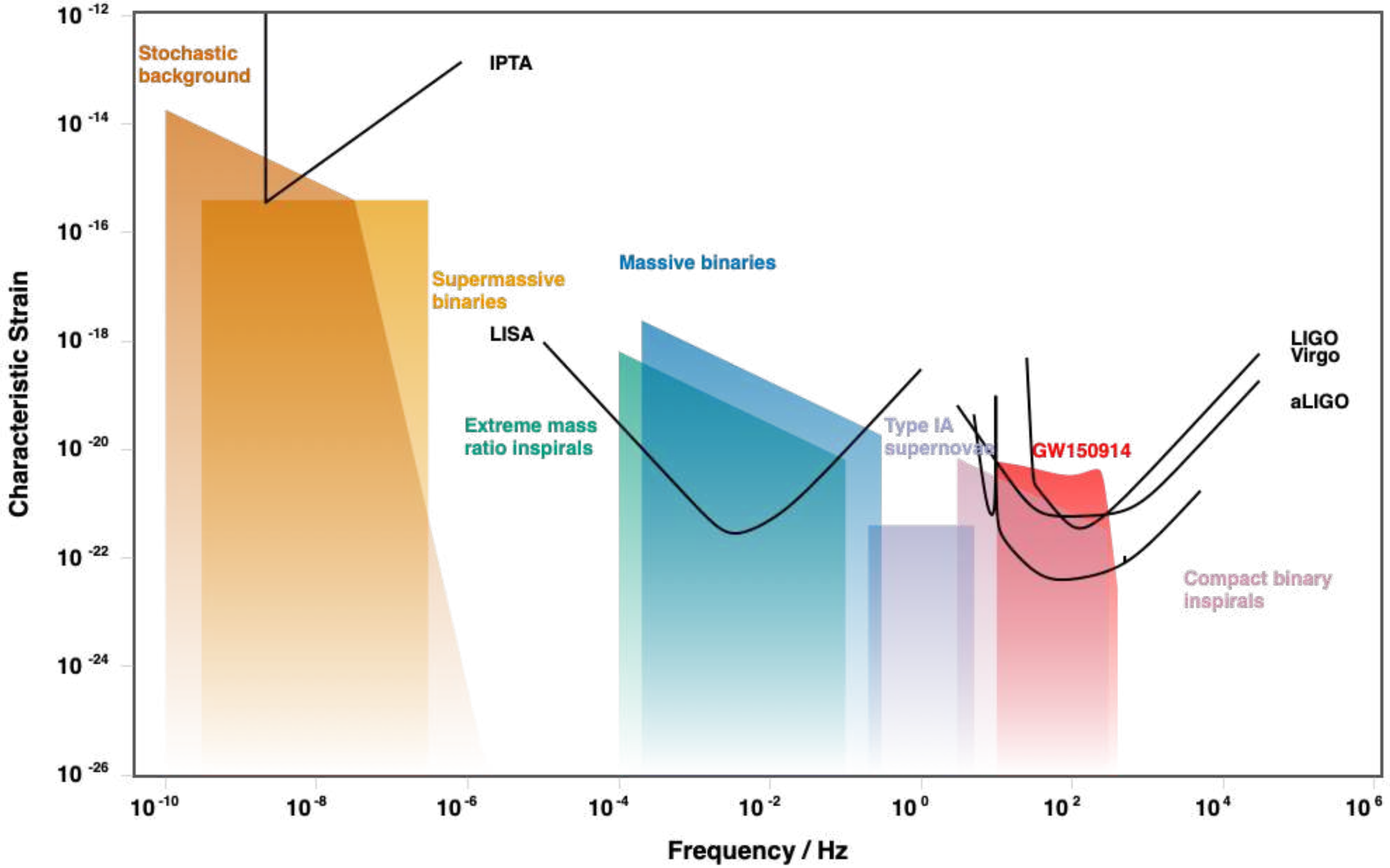




- 3 sigma source identified: TXS 0506+056
- The origin of the bulk of astrophysical neutrinos is unknown

Gravitational Waves

From compact objects



Moustakas (2017)
http://gwplotter.com

Multi-messengers: what are they?

Different types of particles and waves.

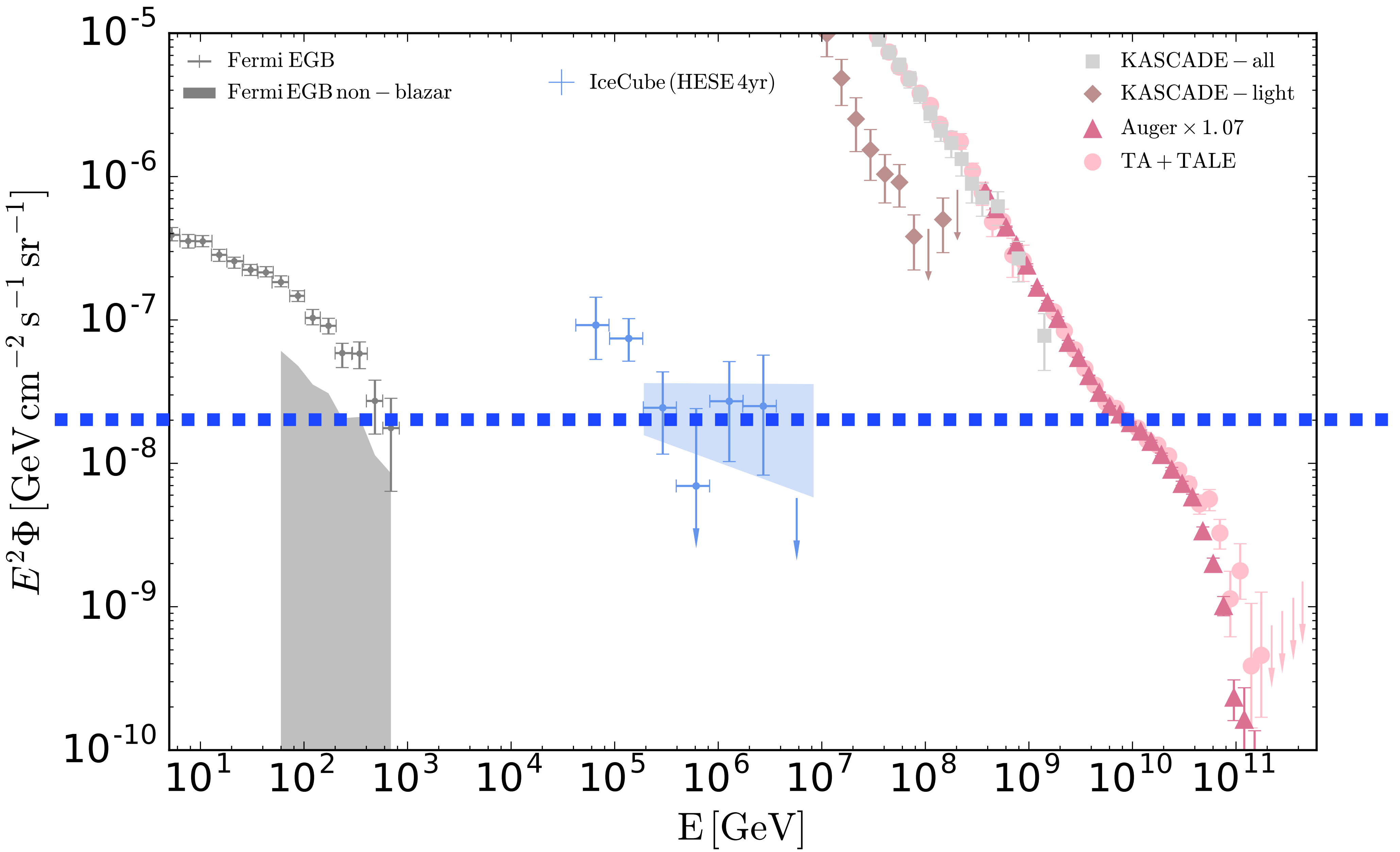
How do we use them?

How do we use them?

1. Numerical Study of Source Physics
2. Joint Data Analysis

1. Numerical Study of Source Physics

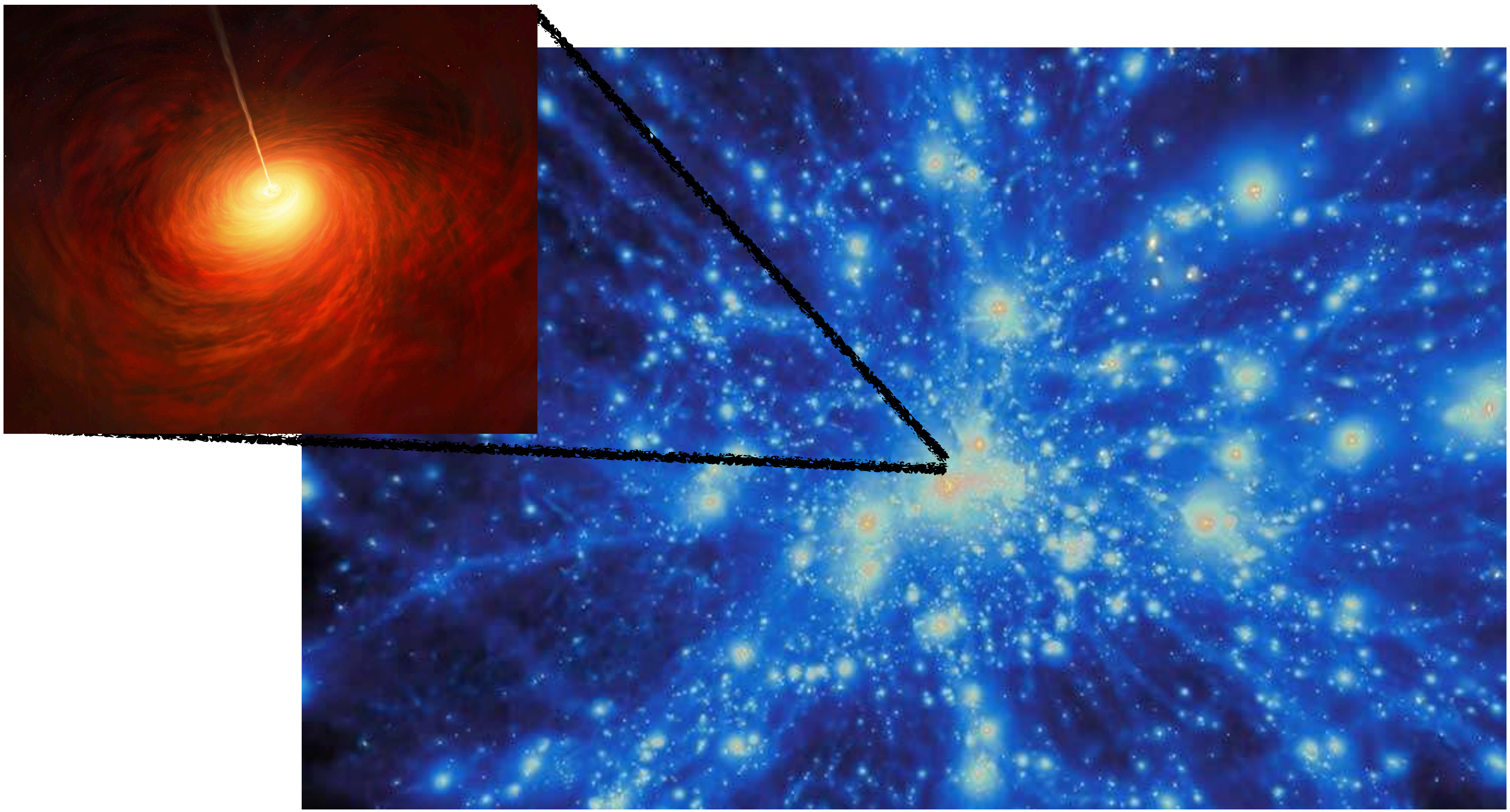
When putting Gamma-rays, Neutrinos, Cosmic rays together..



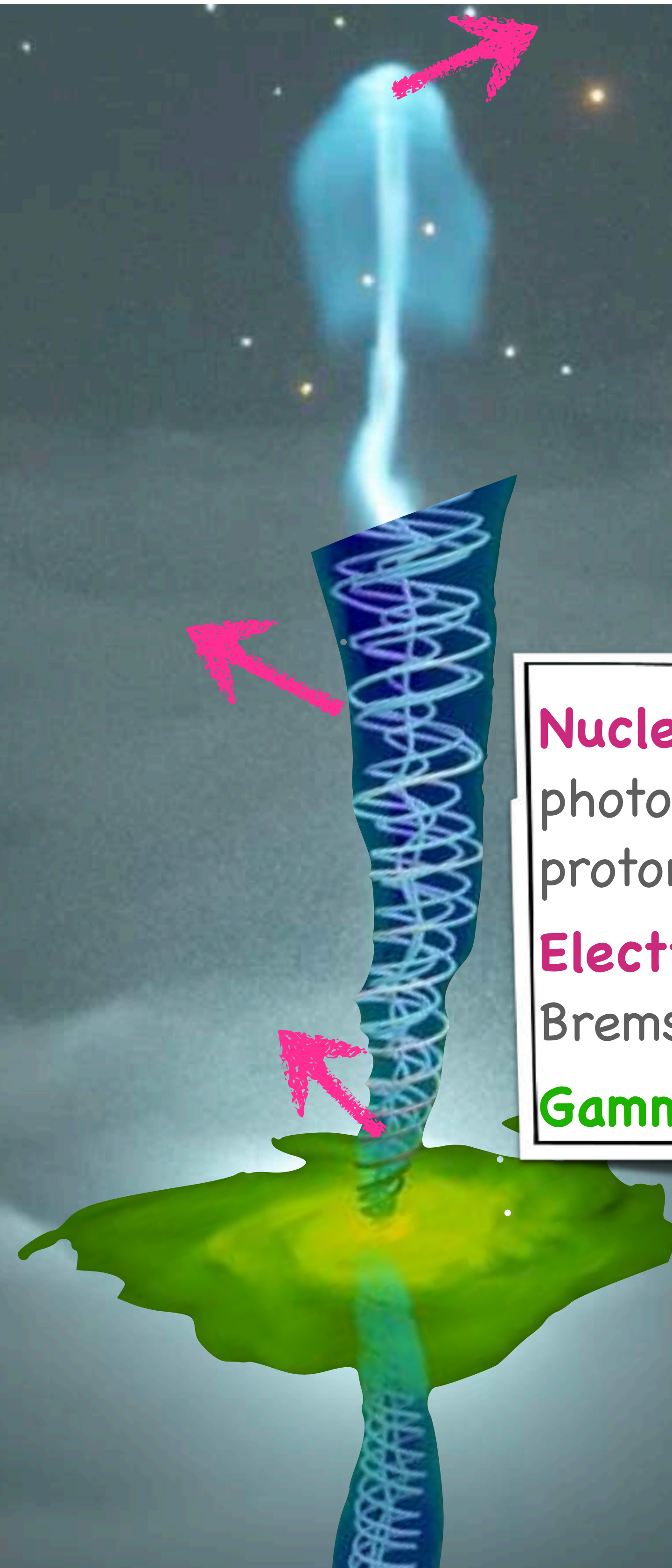
Despite ten orders of magnitudes difference in energy, UHECRs, IceCube neutrinos, Fermi non-blazar EGB share similar energy injection rate.

Murase, Ahlers & Lacki, PRD (2013)
Waxman 1312.0558
Giacinti et al (2015)
Murase & Waxman PRD (2016)
Wang & Loeb PRD (2017) …

Multi-messengers Produced by Supermassive Black Hole Jets



Particle Acceleration and Interaction in Black Hole Jets



Nuclei: nuclei-photon (Photo-disintegration, photopion, photo-fragmentation), nuclei-proton

Electrons: Synchrotron, Inverse-Compton, Bremsstrahlung

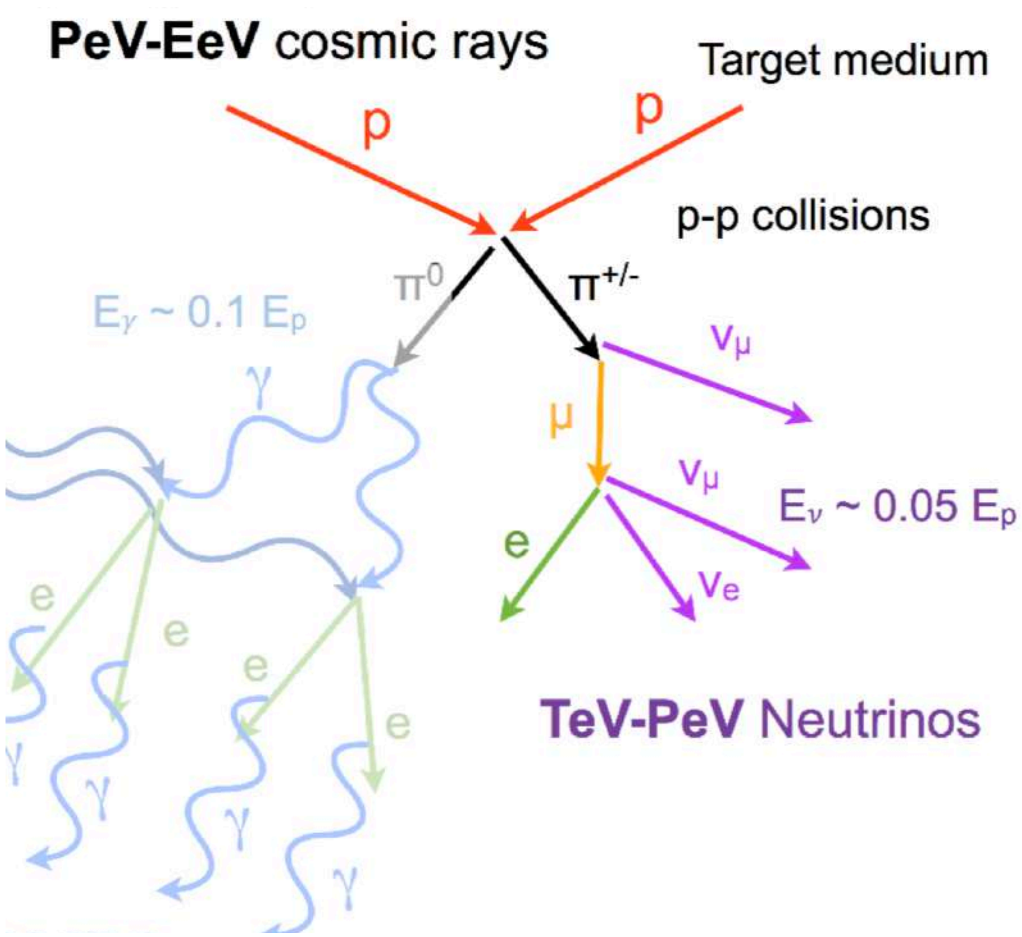
Gamma-rays: Pair, Bethe-Heitler, Compton

Electromagnetic extraction of energy from spinning holes: Blandford & Znajek 1977

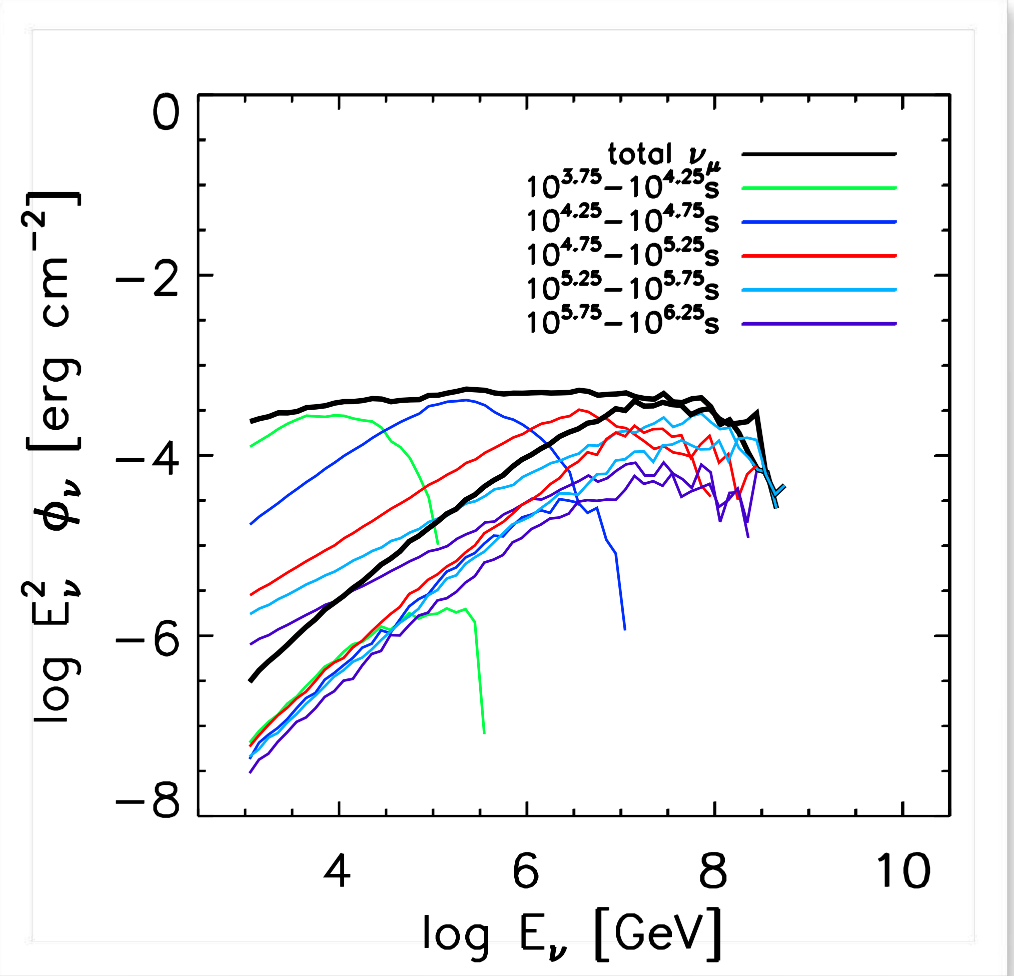
Background image: DESY
Cartoon: shanegarison.org

What happens at each interaction

KF, Kotera, Olinto (2012, 2013)
KF (2015)
KF, Metzger, Murase, Bartos, Kotera (2018)



Neutrinos from hadronuclear interaction in supernova ejecta



Test-particle Monte Carlo

- Transport in magnetic field
- Particle interaction
- Tracking of secondary particles

Our numerical approach is crucial to linking models with observation

The Intracluster Medium Environment for Interactions

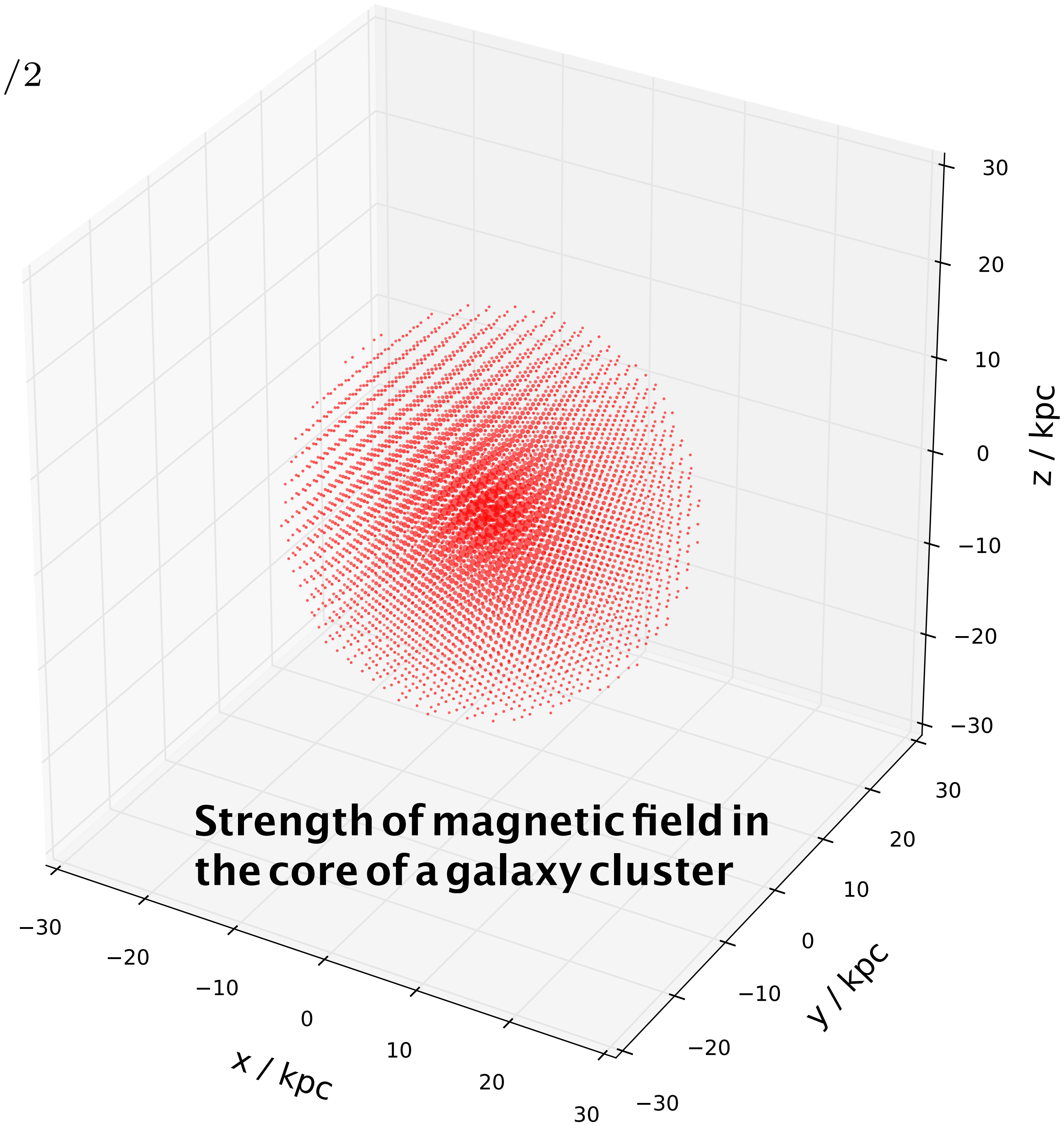
ICM gas

$$n_{\mathrm{ICM}}(r) = n_{\mathrm{ICM},0}\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

Radiation backgrounds: Infrared background from galaxies, CMB, Extragalactic background lights

Magnetic field following Kolmogorov turbulence

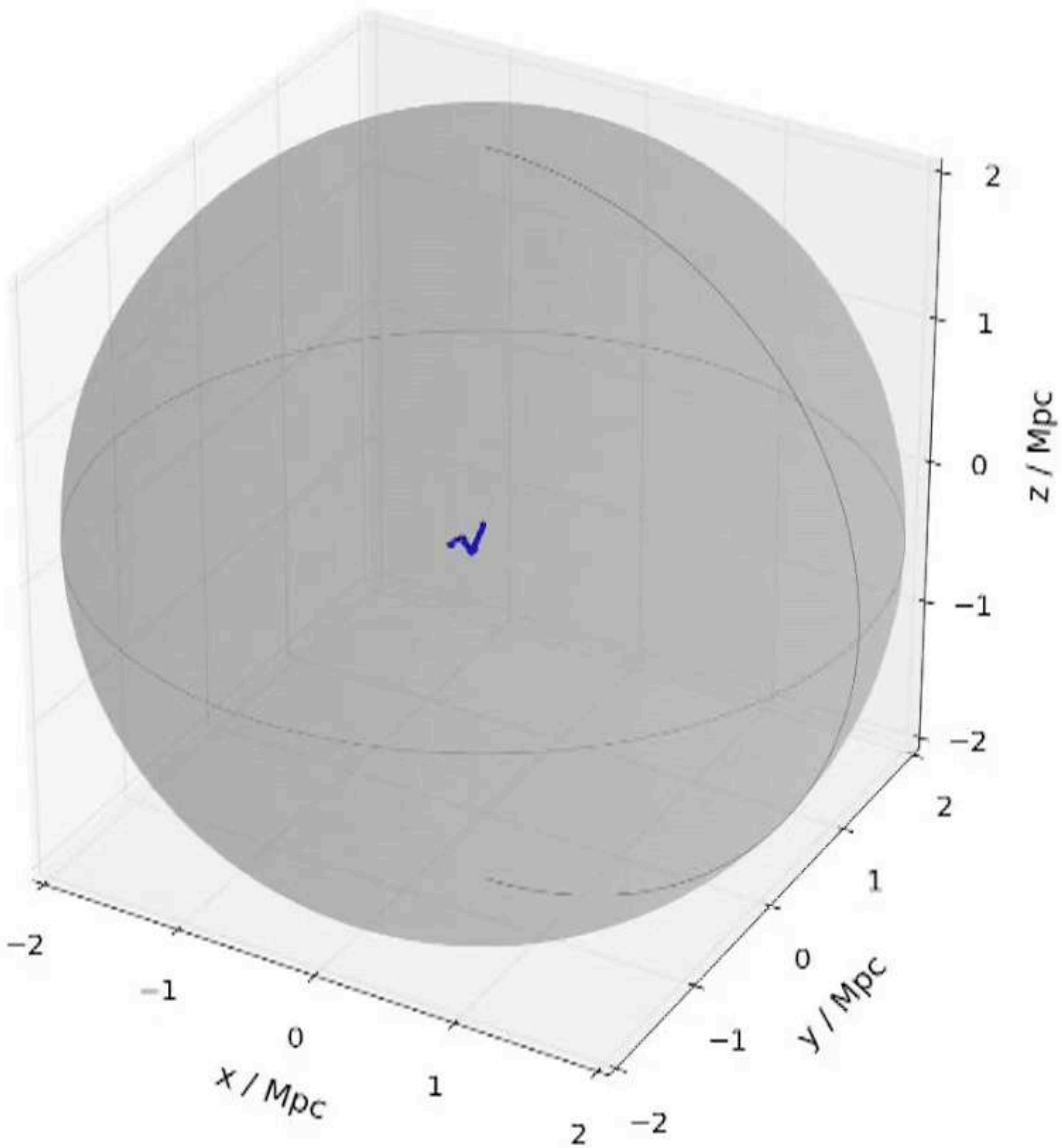
$$B(M, r) \propto n(M, r)^{2/3}$$



Strength of magnetic field in the core of a galaxy cluster

KF & Olinto (2017)
KF & Murase *Nature Physics* (2018)

Particle Trajectory in the Intracluster Medium - 10 EeV



Particle Larmor Radius

$$r_L = 10\,E_{19}\,B_{-6}^{-1}\,Z^{-1}\,\mathrm{kpc}$$

Field Correlation Length

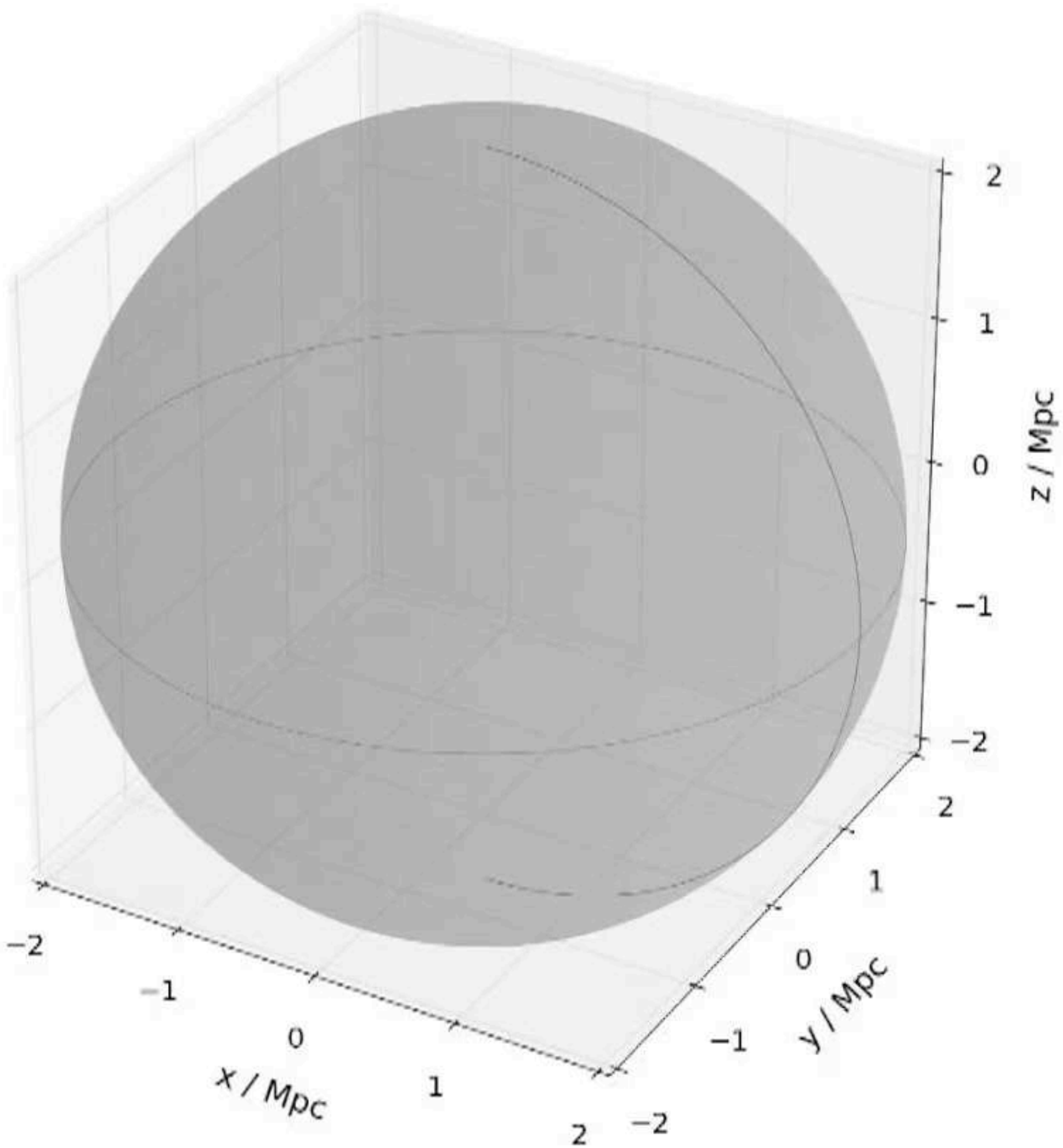
$$l_0 \sim 20\,\mathrm{kpc}$$

$$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$$

$$D_{\mathrm{total}} = 46\,\mathrm{Mpc}$$

KF & Murase *Nature Physics* (2018)

Particle Trajectory in the Intracluster Medium - 0.1 EeV



Particle Larmor Radius

$$r_L = 0.1\, E_{17}\, B_{-6}^{-1}\, Z^{-1}\,\mathrm{kpc}$$

Field Correlation Length

$$l_0 \sim 20\,\mathrm{kpc}$$

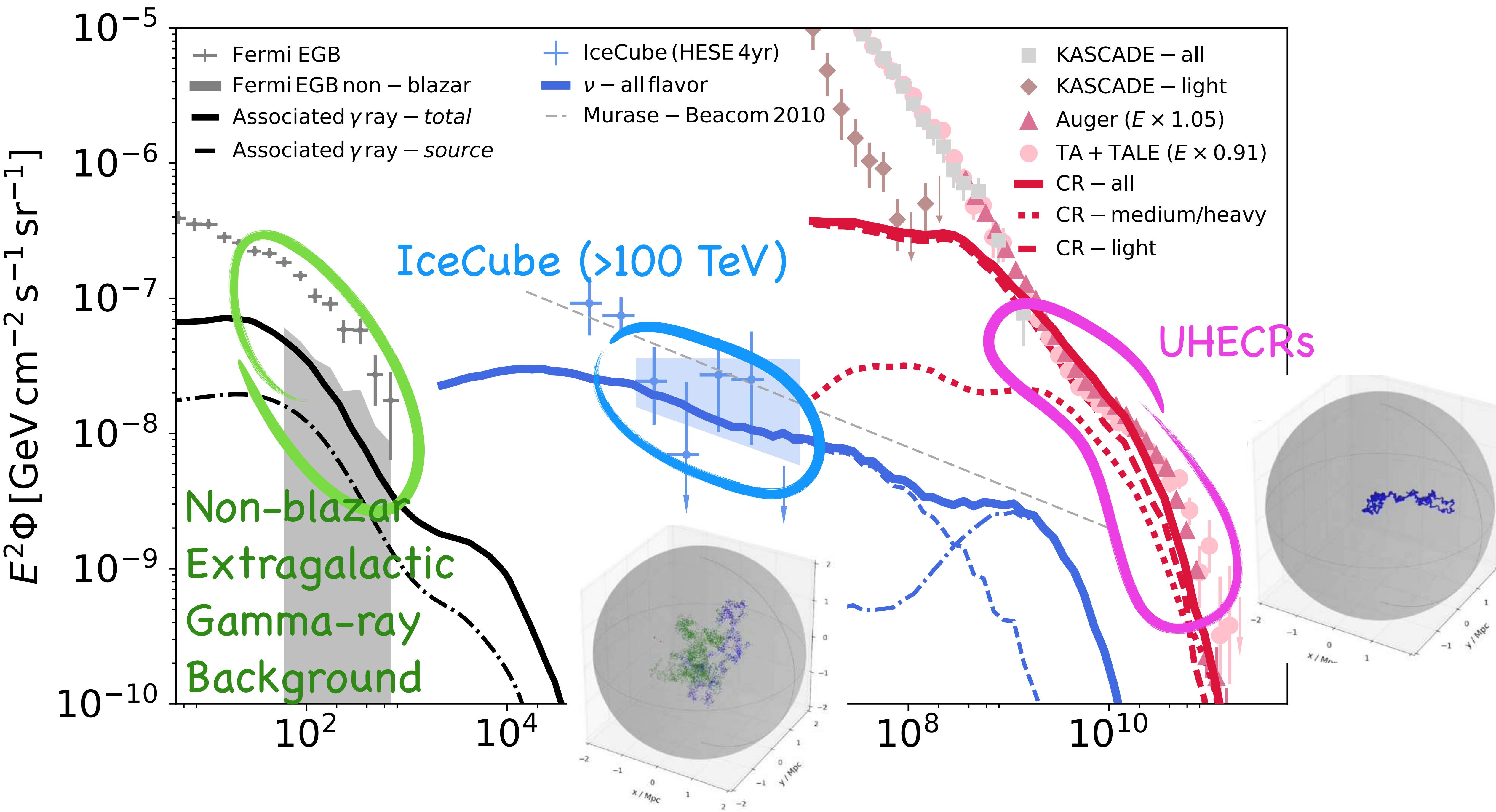
$$B_c = 10\,\mu G, M = 10^{15}\, M_\odot$$

$$D_{\rm total} \sim t_{\rm cluster}$$

KF & Murase *Nature Physics* (2018)

Cosmic Particles from Black Hole Jets in Galaxy Clusters

KF & Murase *Nature Physics* (2018)



Injection Composition = Galactic CR abundance

2. Joint Data Analysis

Challenges:
Limited event rate
Poor angular resolution

Opportunities:
Observatories with wide-field & wide-energy coverage, fast-responses
Natural connections between messengers

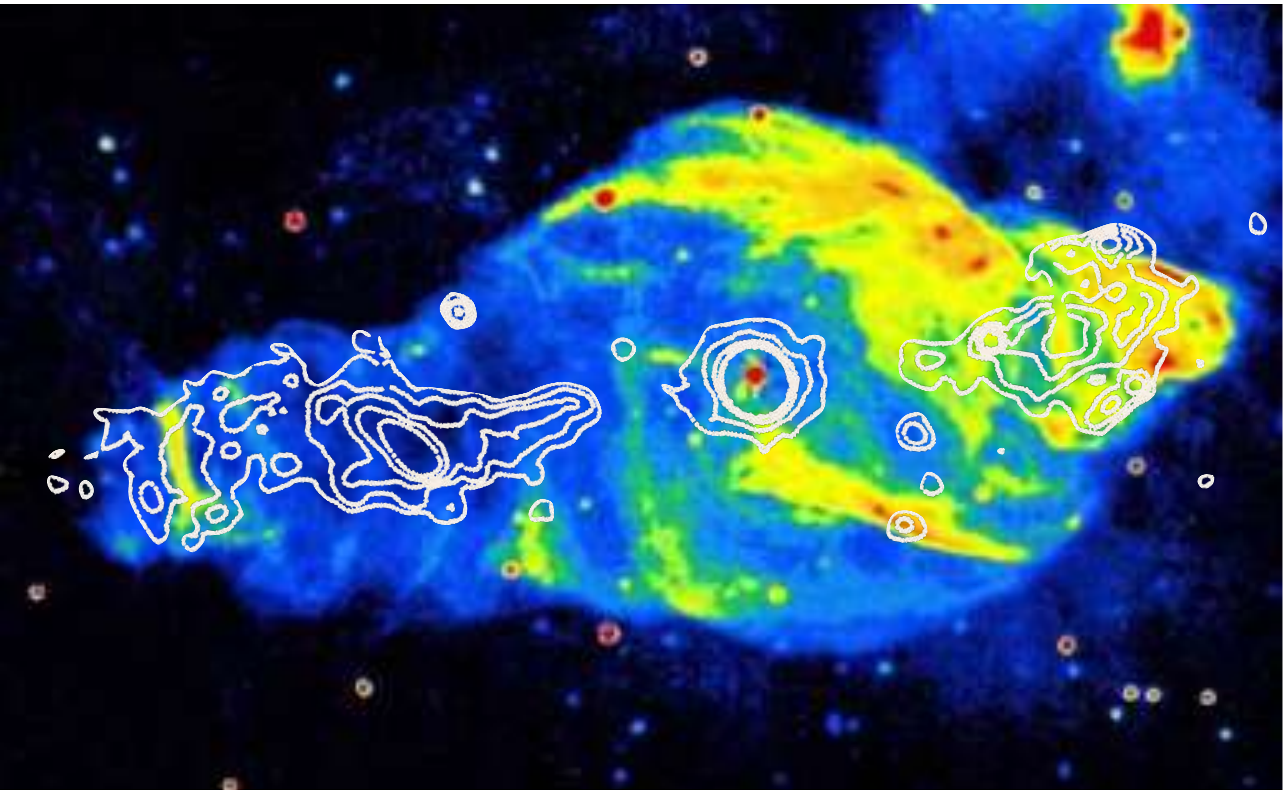
Needed:
Efficient source search algorithms
Joint analysis of multi-wavelengths/messengers

- 24185 LIGO/Virgo S190425z: Fermi GBM Observations
- 24184 LIGO/Virgo S190425z: Swift/BAT Counterpart Search
- 24183 LIGO/Virgo S190425z: SQUEAN Observation
- 24182 LIGO/Virgo S190425z: MMT Follow-Up Observations
- 24181 LIGO/Virgo S190425z: INTEGRAL IBIS prompt observation
- 24180 LIGO-Virgo S190425z: AGILE MCAL observation
- 24179 LIGO/Virgo S190425z: Lick/KAIT Follow-Up Observations
- 24178 LIGO/Virgo S190425z: further analysis of INTEGRAL data
- 24177 LIGO/Virgo S190425z: MAXI/GSC Observations
- 24176 LIGO/VIRGO S190425z: IceCube Neutrino Search
- 24175 LIGO/Virgo S190425z: Hobby-Eberly Telescope VIRUS observations of target galaxies.
- 24174 LIGO/Virgo S190421ar: Fermi-LAT search for a high-energy gamma-ray counterpart
- 24173 LIGO/Virgo S190425z: HAWC follow-up
- 24172 LIGO/Virgo S190425z: SAGUARO follow-up observations
- 24171 LIGO/Virgo S190425z: Potential host galaxies from the GLADE catalog
- 24170 LIGO/Virgo S190425z: INTEGRAL SPI-ACS prompt observation
- 24169 LIGO/Virgo S190425z: INTEGRAL prompt observation
- 24168 LIGO/Virgo S190425z: Identification of a GW compact binary merger candidate

Blind search using event pairs:
KF & Miller 2016
Cross-correlation of neutrino events and galaxies: **KF** et al 2020

2. Joint Data Analysis

The Microquasar SS 433



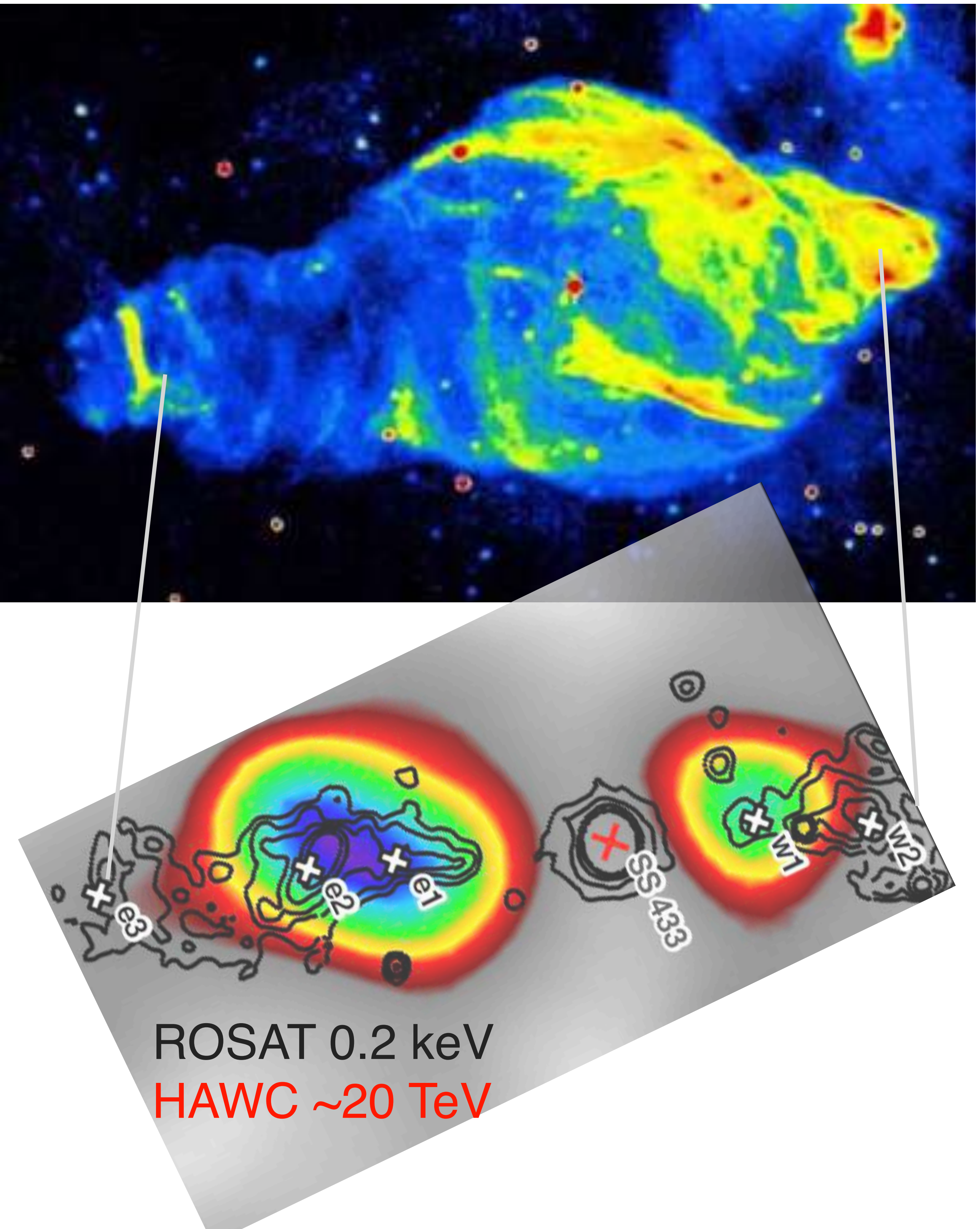
- "Mini active galactic nucleus"
- Extended X-ray jets piercing supernova remnant detected in 1990s

How is the emission produced?

Where do particles get accelerated in black hole jets?

2. Joint Data Analysis

The Microquasar SS 433



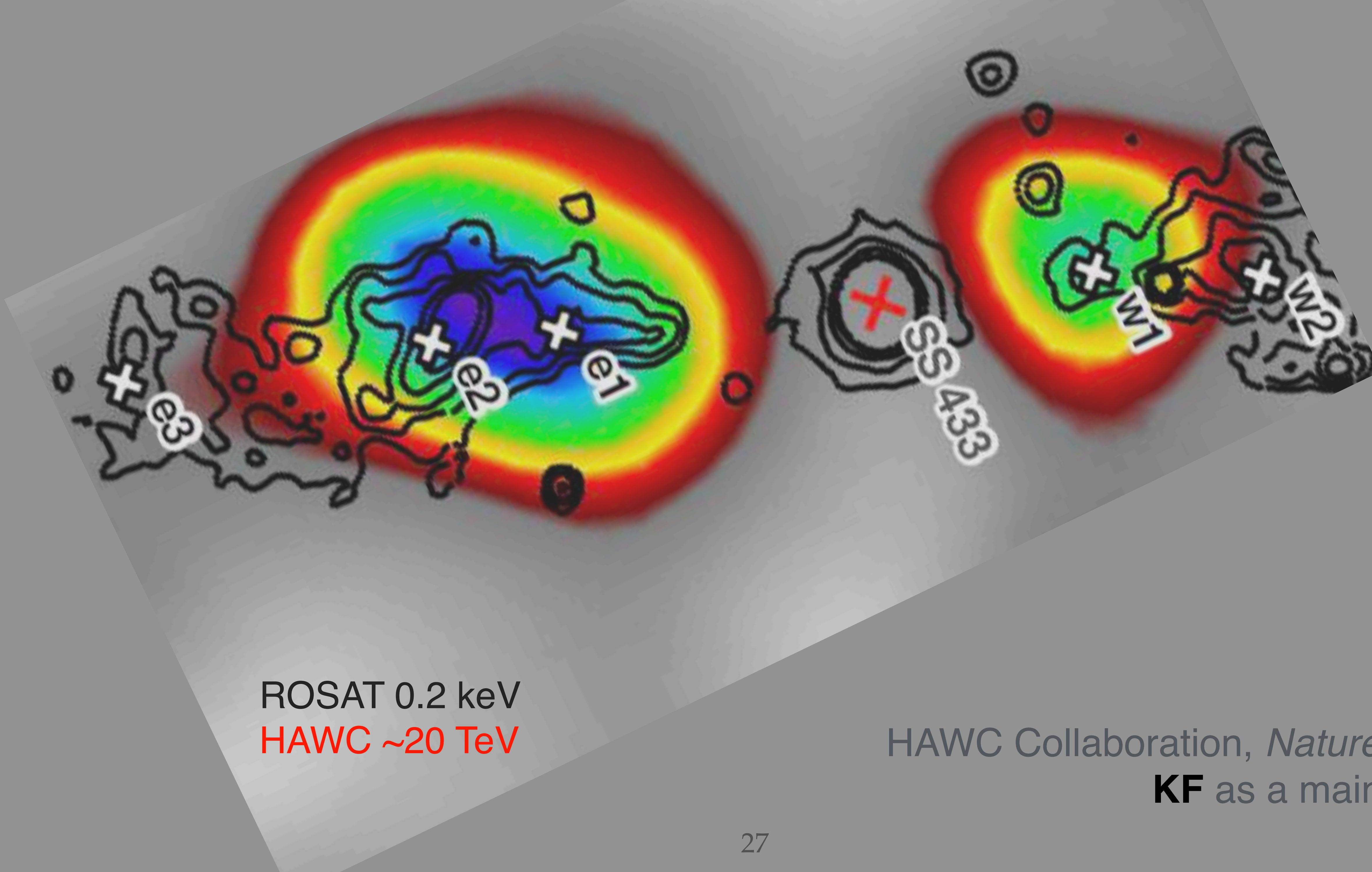
- **Point-like TeV gamma-rays in both lobes** detected by HAWC

- Particle acceleration happen at **intermediate distances** from the hole

HAWC Collaboration, *Nature* (2018)
KF as a main author

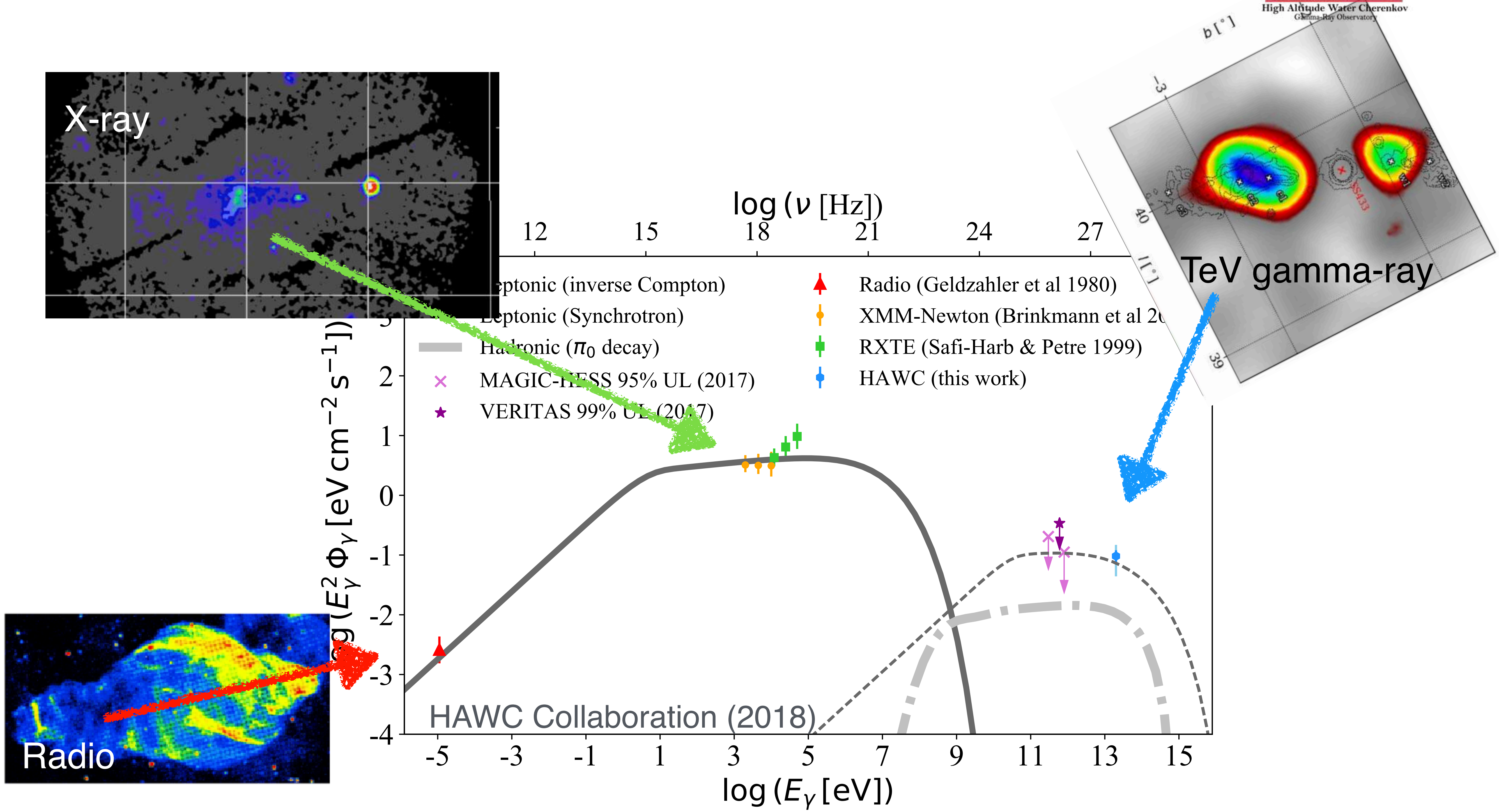
- **Electrons above 20 TeV** were accelerated

- Particle acceleration sites **~30 pc away from hole**



HAWC Collaboration, *Nature* (2018)
KF as a main author

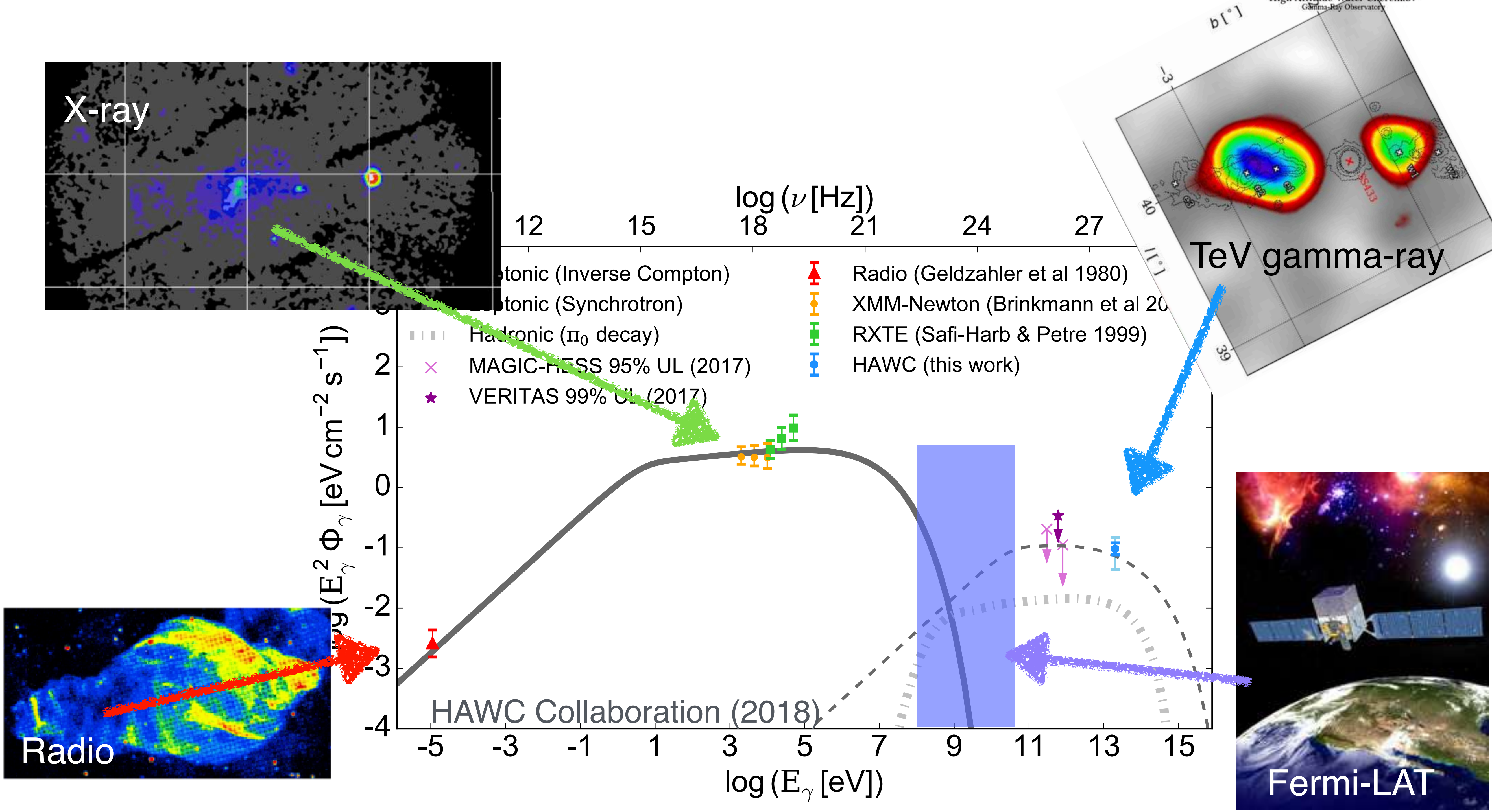
Who emitted the photons?



HAWC Collaboration, *Nature* (2018)

KF as a main author

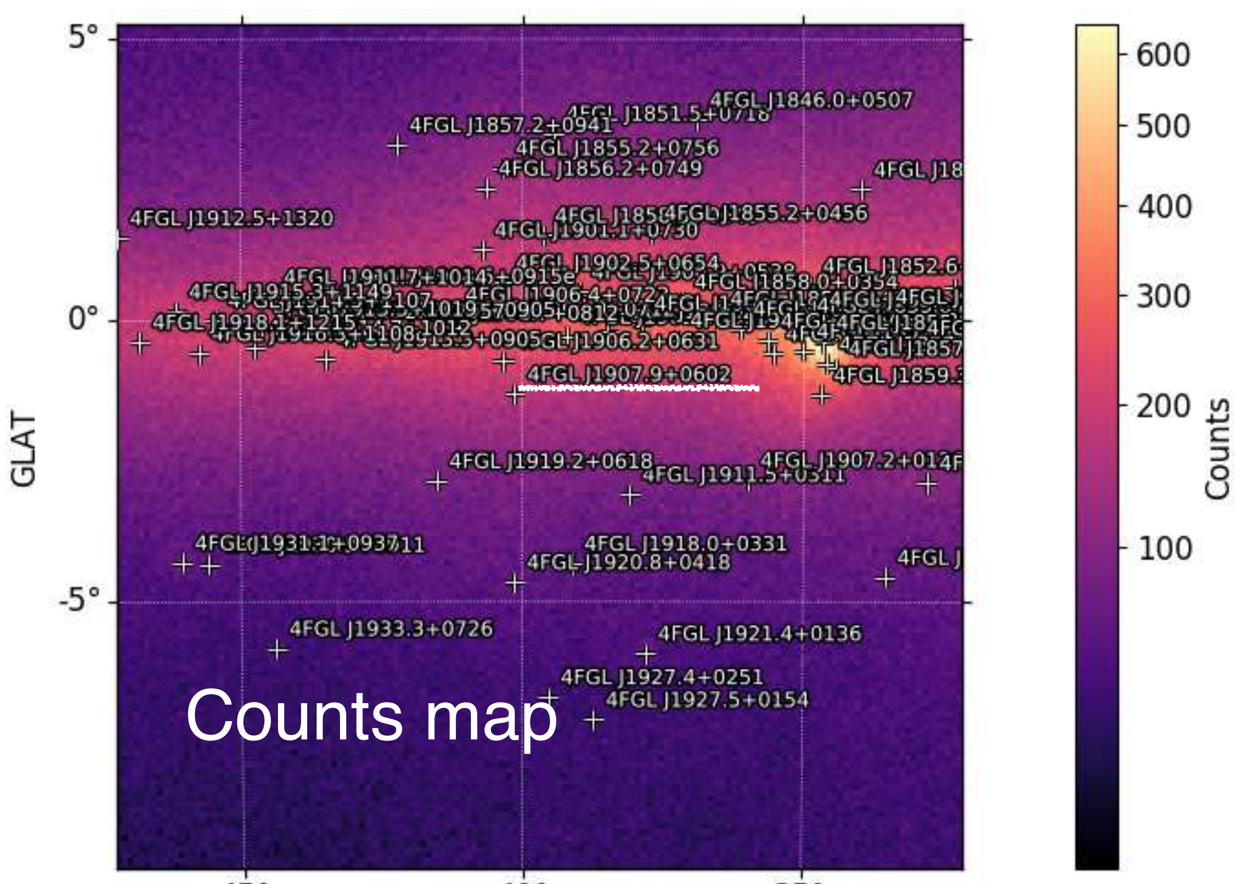
A Missing Piece in the Broadband Spectrum

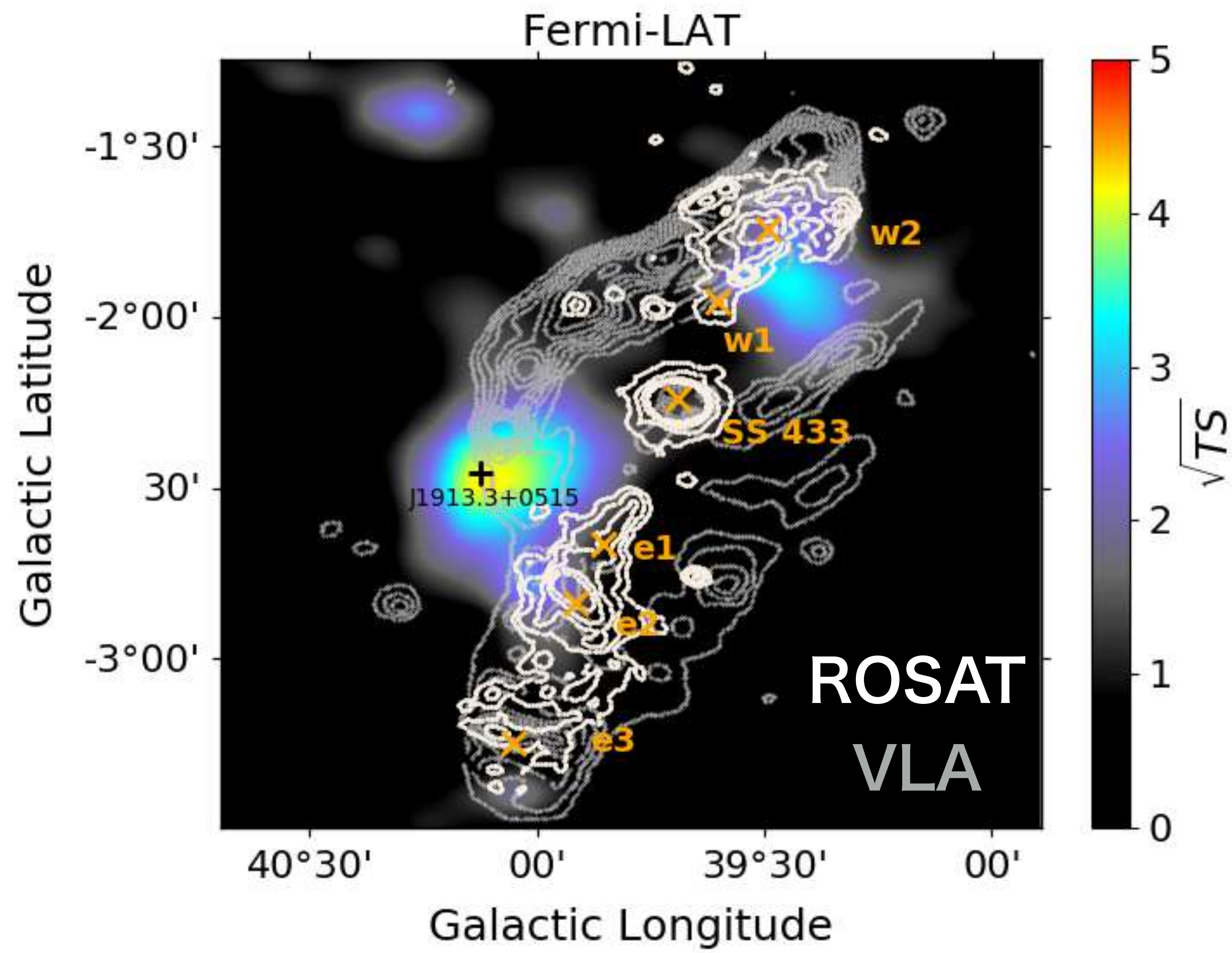


What do the lobes look like **between 100 MeV and 100 GeV?**

Fermi-only Analysis of SS 433

Gamma-ray Space Telescope

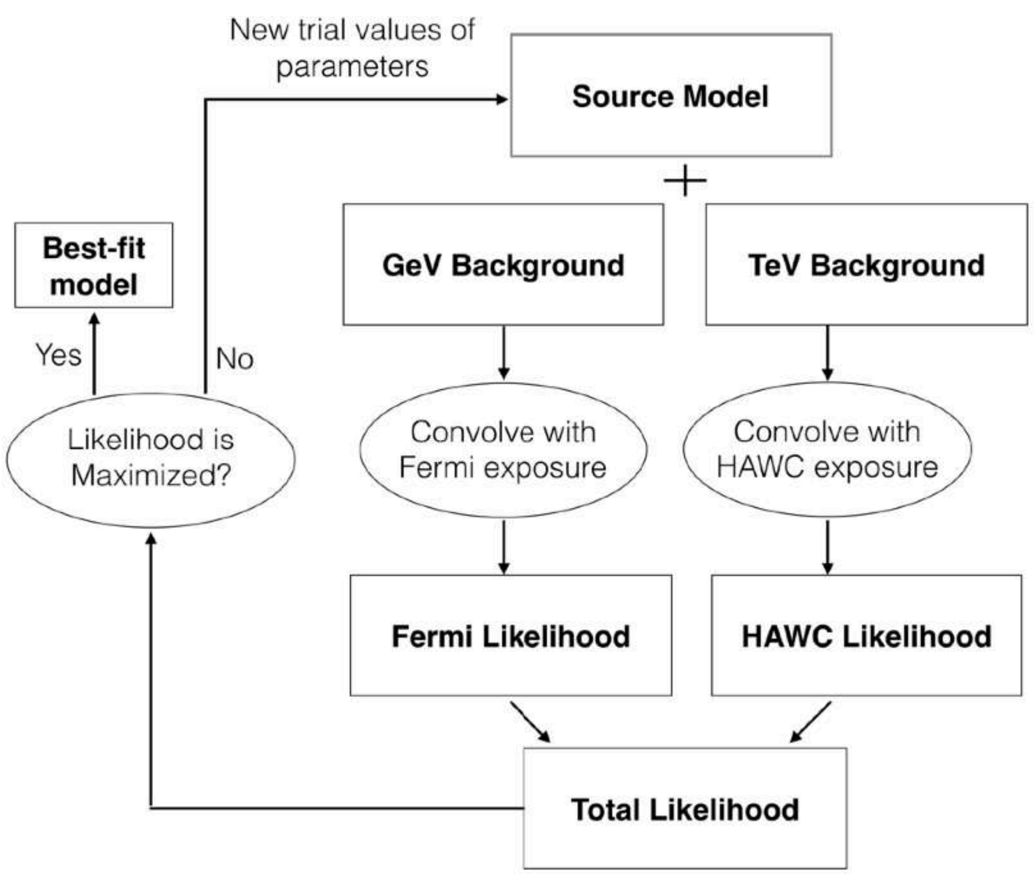


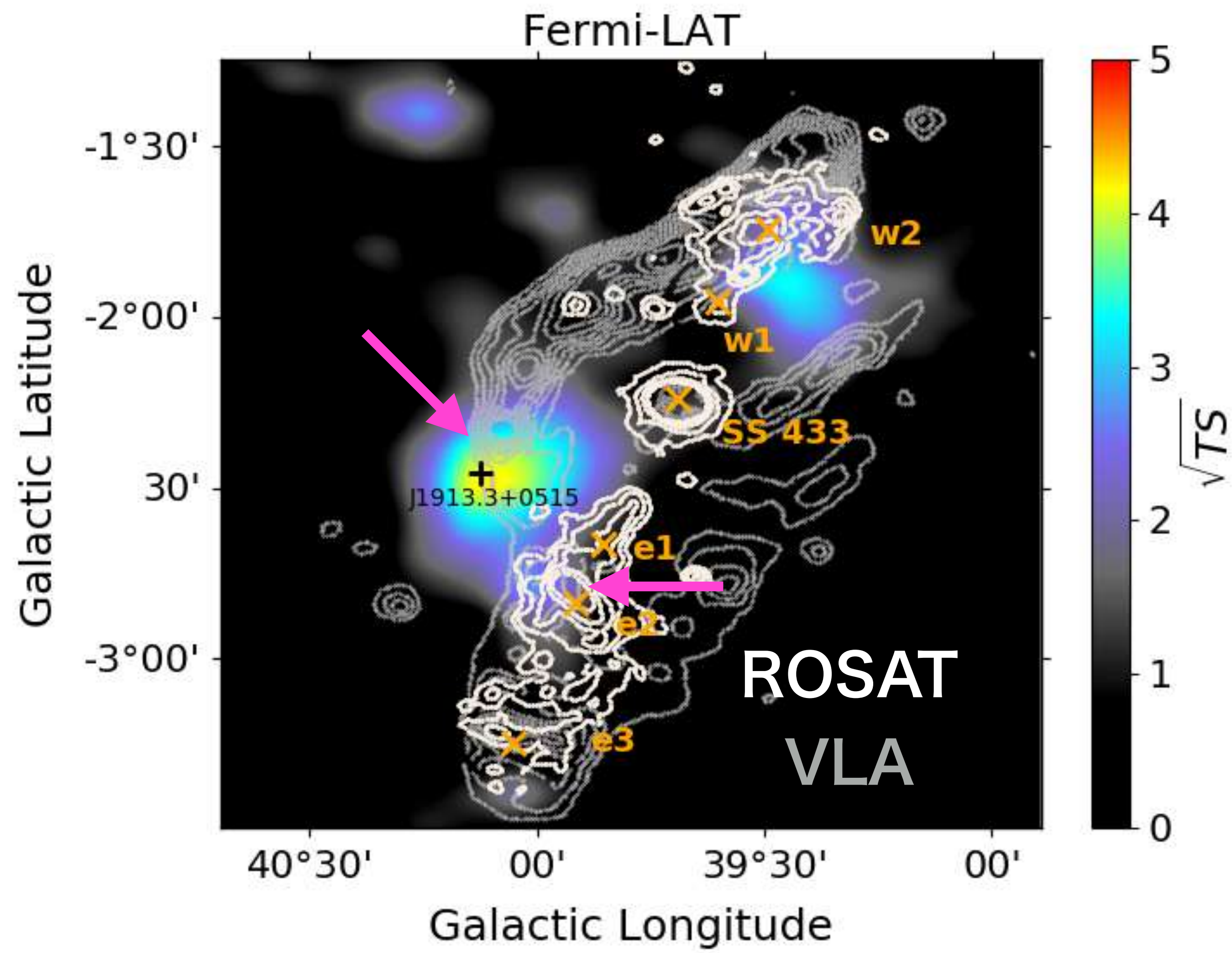


Hint of emission in the eastern lobe is found in11-year Fermi-LAT data but suffers from **confusion with nearby sources.**

KF, Charles, Blandford, ApJL (2020)

Joint Analysis Disentangles Source from Background

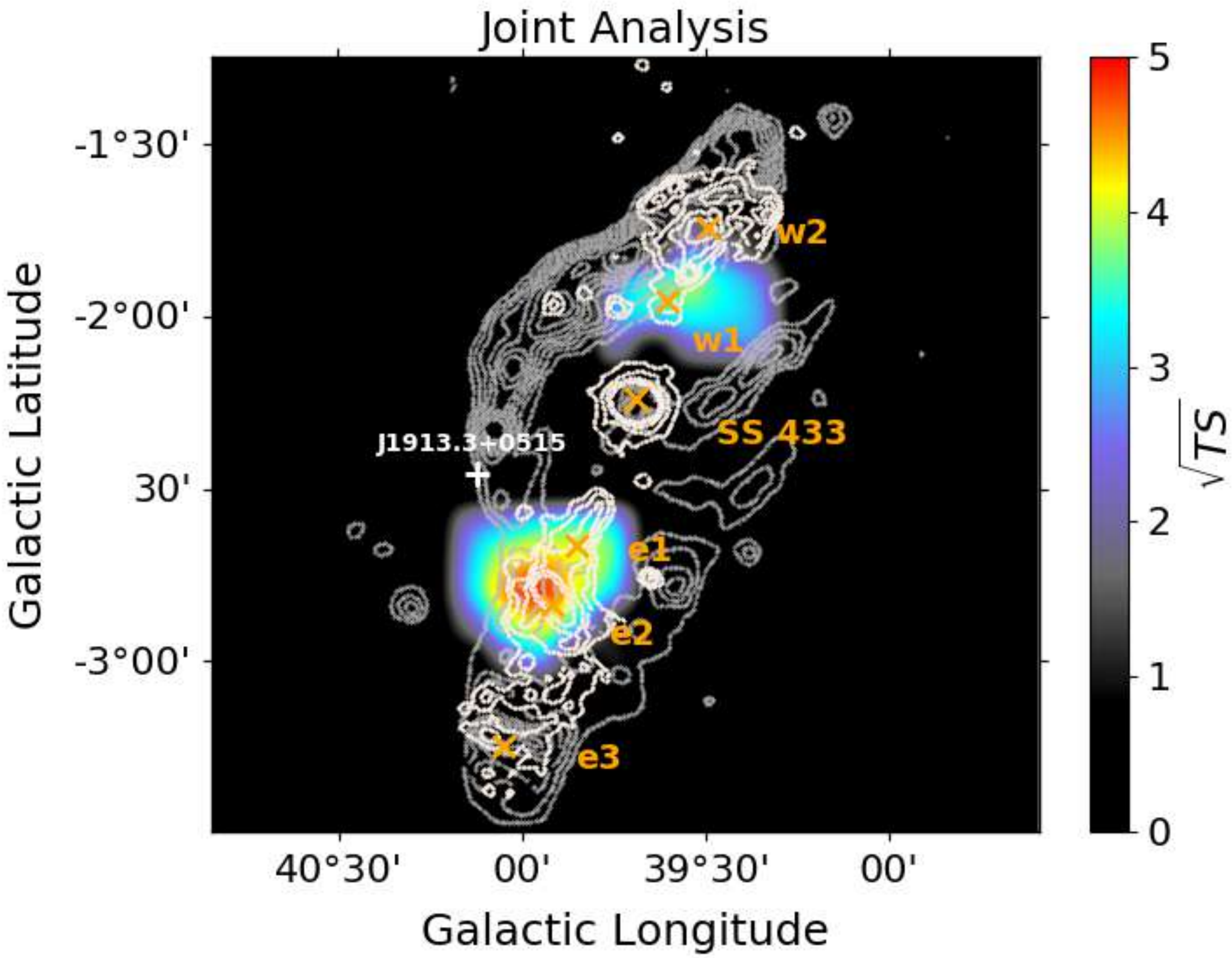




Statistical significance of region-of-interest w. two separate sources is higher (by 4.5 sigma) than w. one common source, suggesting that **J1913 is not a TeV emission site**

KF, Charles, Blandford, ApJL (2020)

Joint Analysis of Fermi-LAT and HAWC Data



GeV-to-TeV Gamma-ray emission can be explained by inverse Compton emission relativistic electrons that cool efficiently.

Joint analysis framework can be extended to include other wavelengths and messengers.

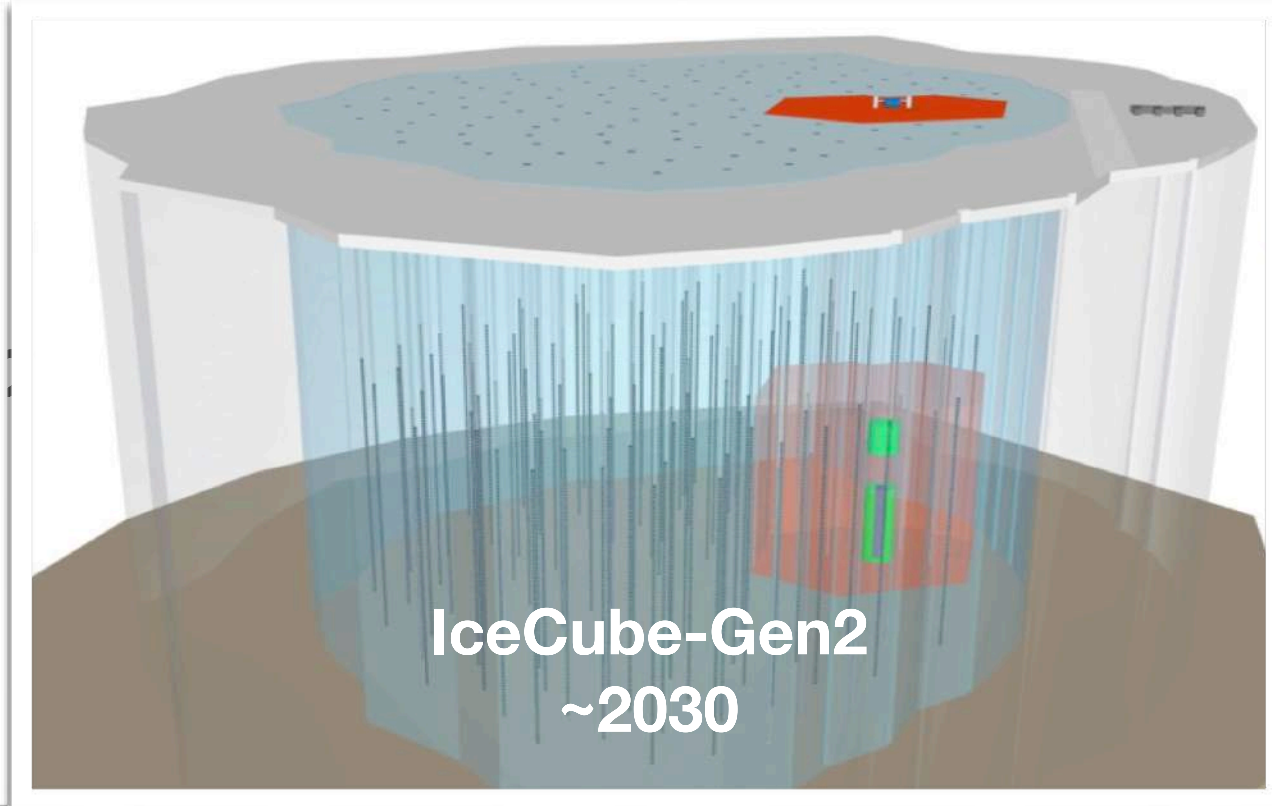
KF, Charles, Blandford, ApJL (2020)

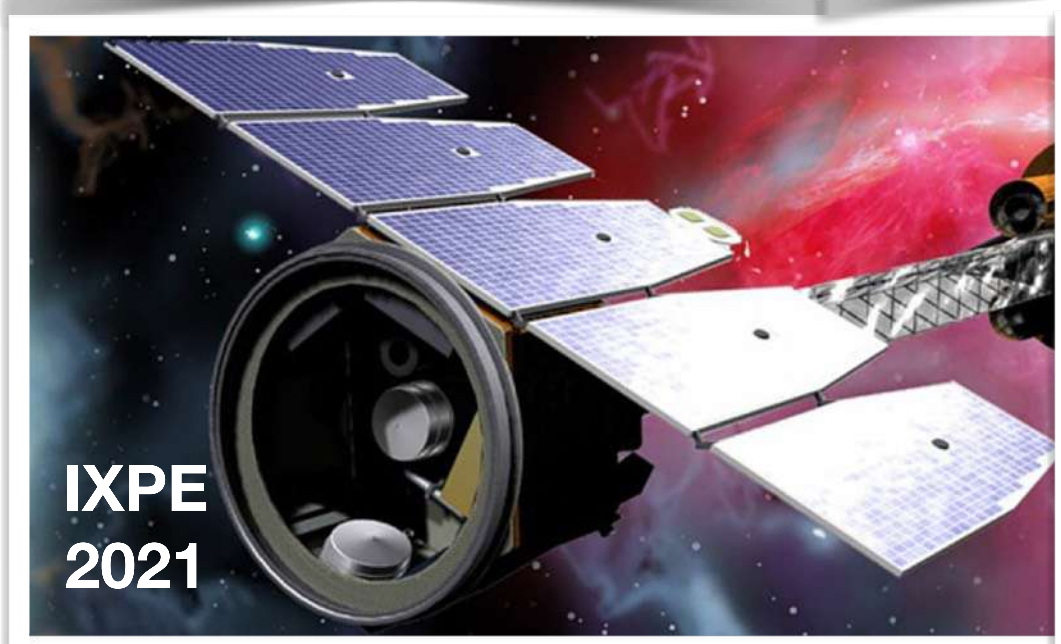
Multi-messengers: **what** are they?

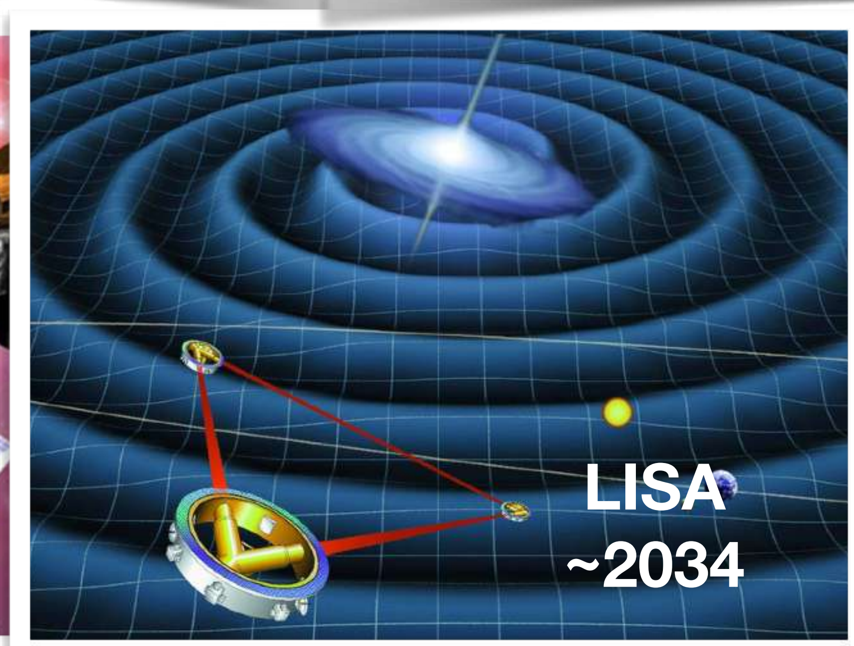
Different types of particles and waves.

How do we use them?

By coordinated modeling and observation.





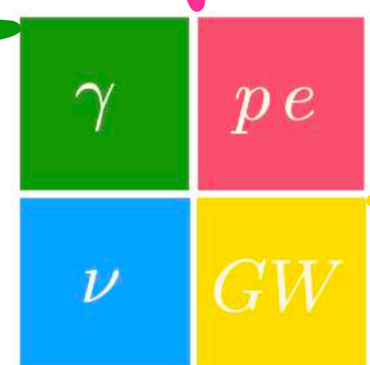


The Future of Multi-messenger Astrophysics

An Incomplete List of Future Missions and Concepts

Radio: SKA
IR: JWST, WFIRST
Optical: LSST
UV: LUVOIR
X-ray: IXPE, LYNX, Athena
MeV: AMEGO
GeV: HERD
TeV: CTA
10 TeV: SWGO

>EeV: TAx4, AugerPrime, POEMMA, GRAND, EUSO
PeV-EeV: GRAND3k
TeV-PeV: HERD



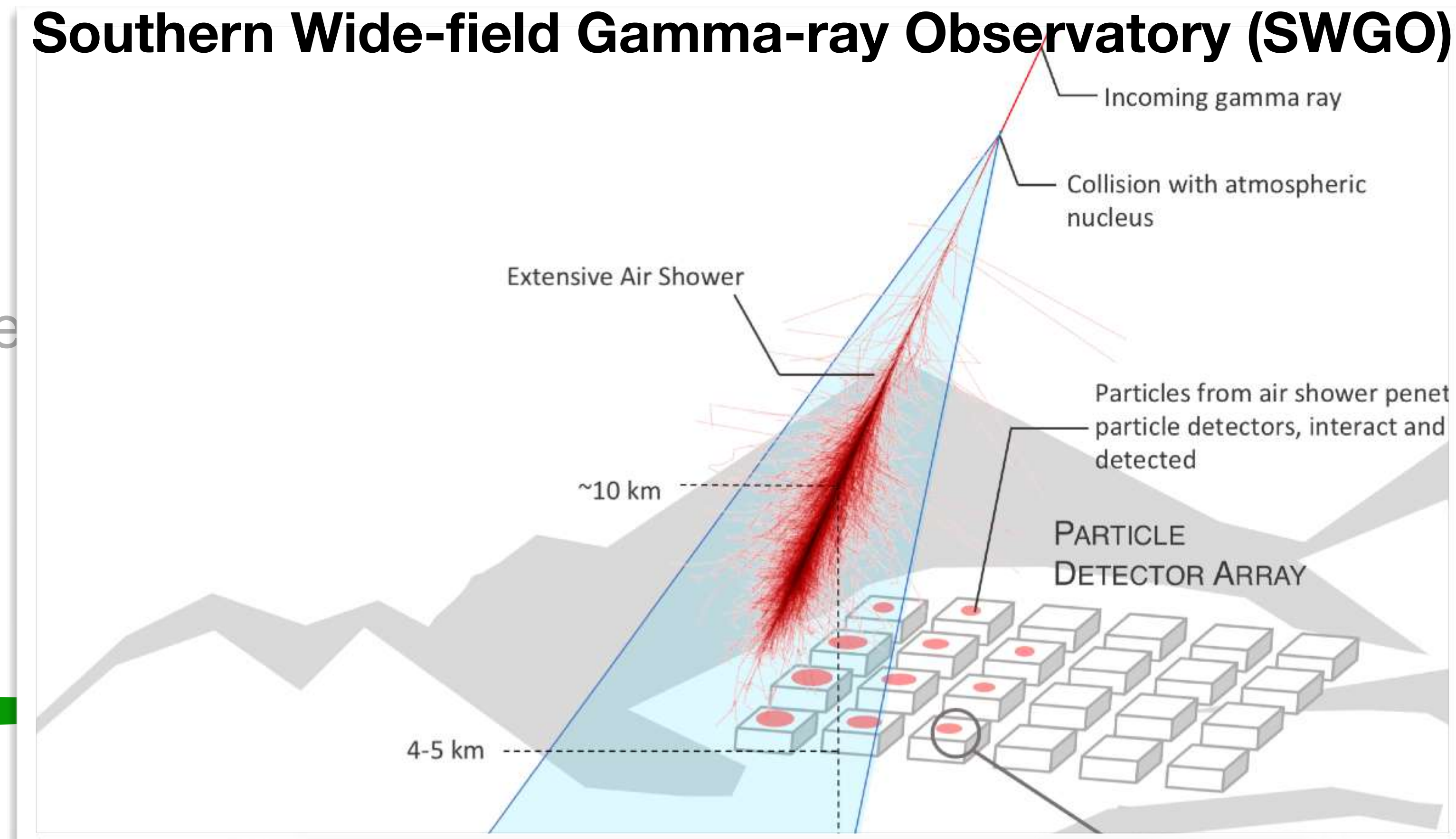
>EeV: ARA, ARIANNA, POEMMA, GRAND
TeV-PeV: IceCube-Gen2, KM3Net
MeV-GeV: DUNE, Hyper-Kamiokande, JUNO

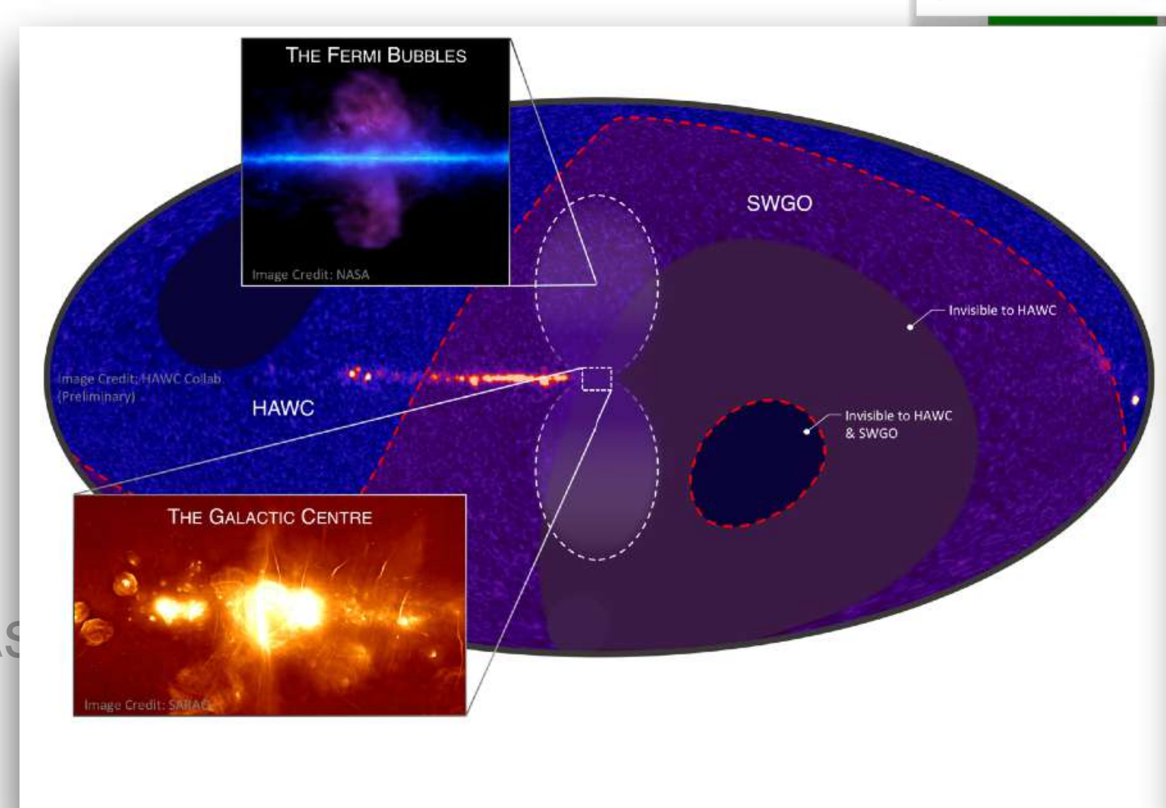
Ground-based: Einstein Telescope, Cosmic Explorer
Space-based: LISA
Pulsar Timing Arrays

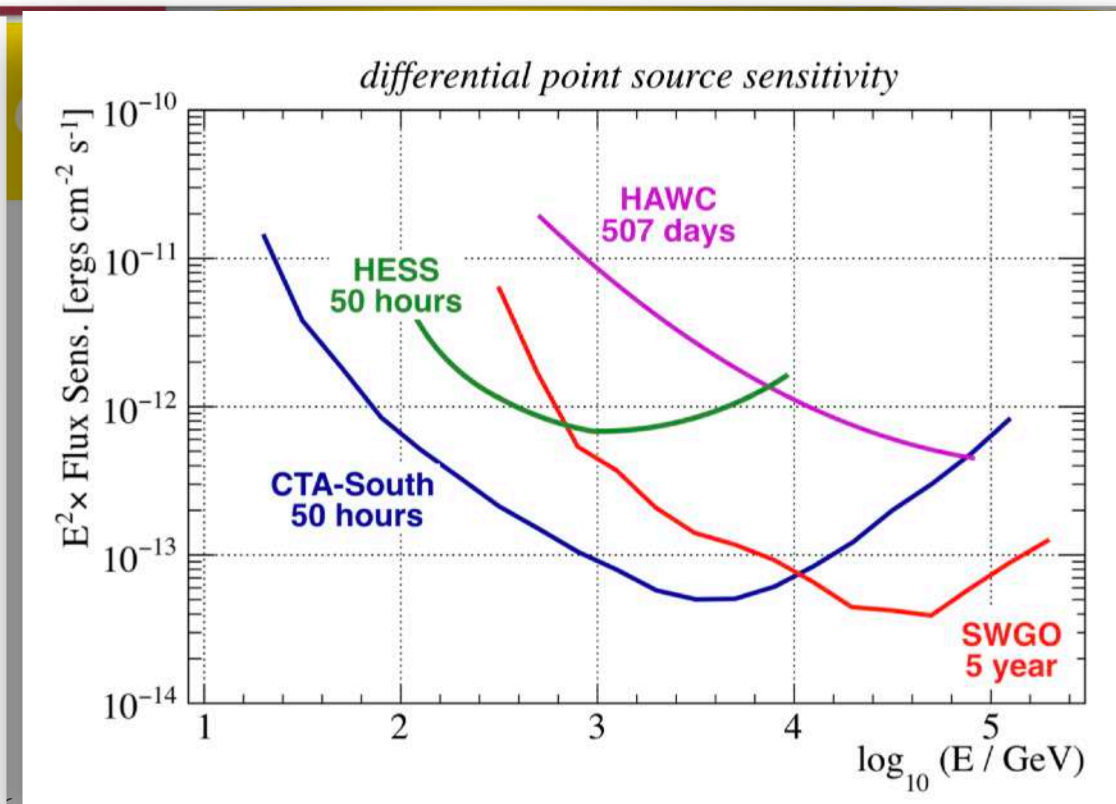
Astro2020 white paper, Buson, **KF**+ 1903.04447

An Incomplete List of Future Missions and Concepts

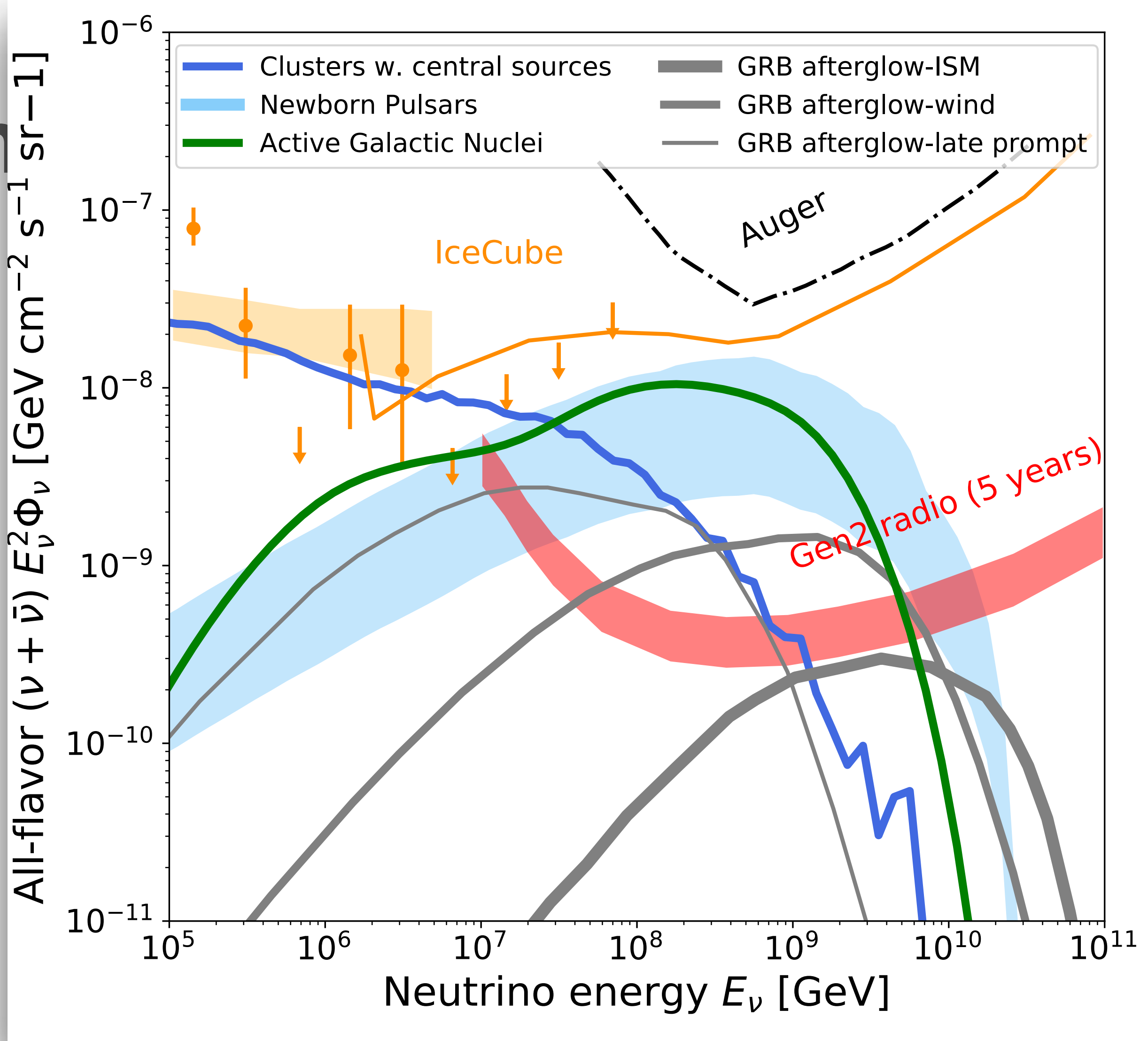
- Radio: SKA
- IR: JWST, WFIRST
- Optical: LSST
- UV: LUVOIR
- X-ray: IXPE, LYNX, Athe
- MeV: AMEGO
- GeV: HERD
- TeV: CTA
- 10 TeV: SWGO



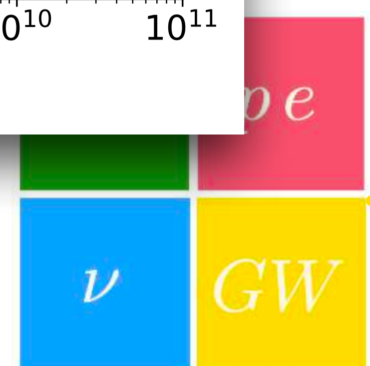




An… Missions and Concepts



>EeV: TAx4, AugerPrime, POEMMA, GRAND, EUSO
PeV-EeV: GRAND3k
TeV-PeV: HERD



>EeV: ARA, ARIANNA, POEMMA, GRAND
TeV-PeV: IceCube-Gen2, KM3Net
MeV-GeV: DUNE, Hyper-Kamiokande, JUNO

Ground-based: Einstein Telescope, Cosmic Explorer
Space-based: LISA
Pulsar Timing Arrays

Astro2020 white paper, Buson, **KF**+ 1903.04447

Vast Discovery Space

(Nearly) Solved questions	Unsolved questions	Unexpected questions
Existence of TeV-PeV neutrinos	Neutrino sources	TeV halos around pulsars
Spectrum, composition, arrival directions of Cosmic rays	Mechanism of cosmic accelerators	Wide-angle emission & violation of maximum synchrotron frequency in GRB jets
Gravitational waves from compact binaries, kilonova	Nature of merger remnants	Particle physics at extreme energy (e.g. Muon excess)
…	Nature of dark matter	Positron excess
	…	…

Conclusions

- The key to developing Multi-messenger Astrophysics is to **understand the connection between messengers.**

- **Numerical study of high-energy particle interaction and propagation** is crucial to linking source physics and observation

- **Efficient algorithms and analysis frameworks** are needed to fully exploit the data and to enable collaboration across wavelengths and messengers.