IceCube in Multi-Messenger Astronomy

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IceCube Bootcamp
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Multi-Messengers: what are they?

Why multi-?

What can be learnt from MMA w. Neutrinos?

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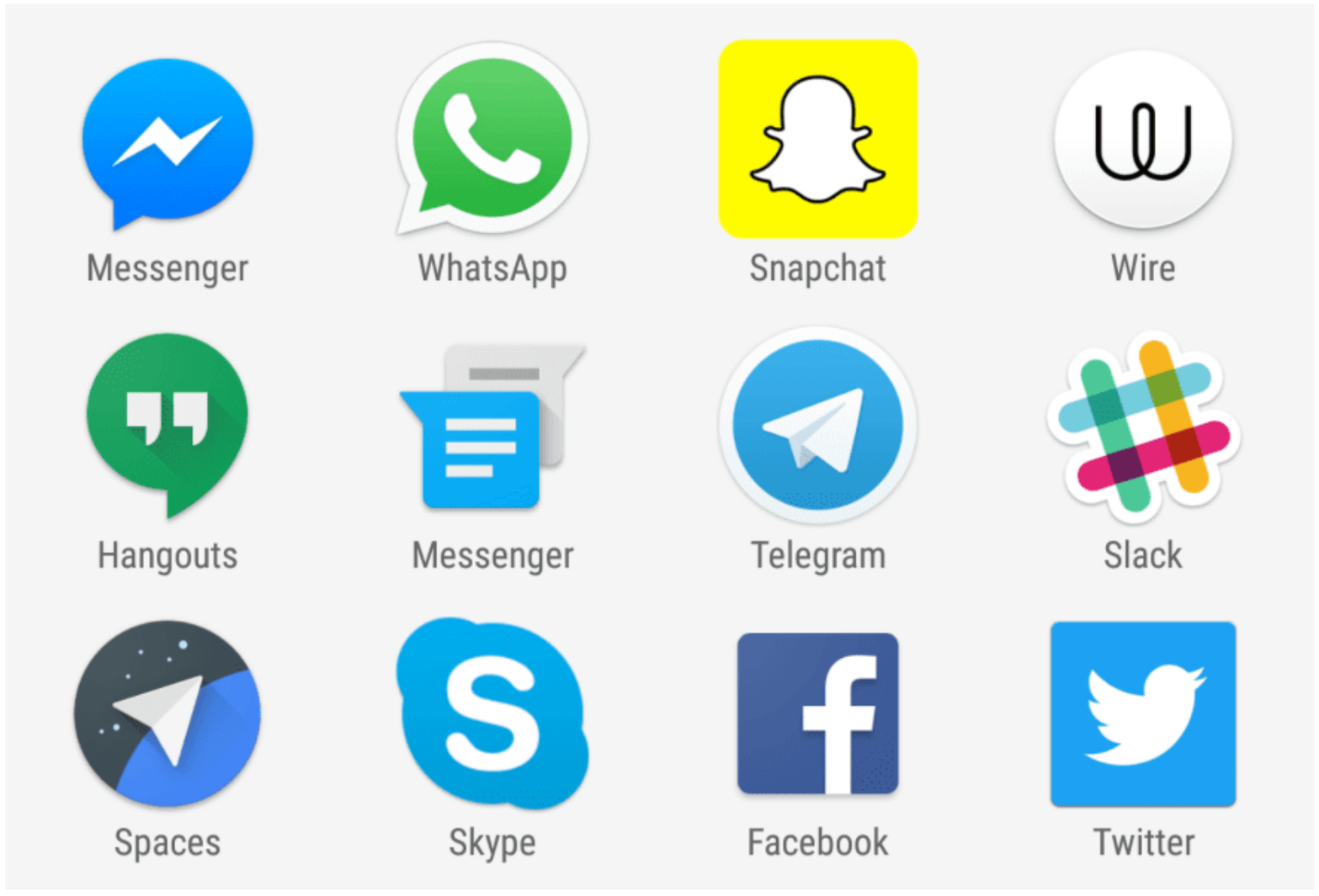
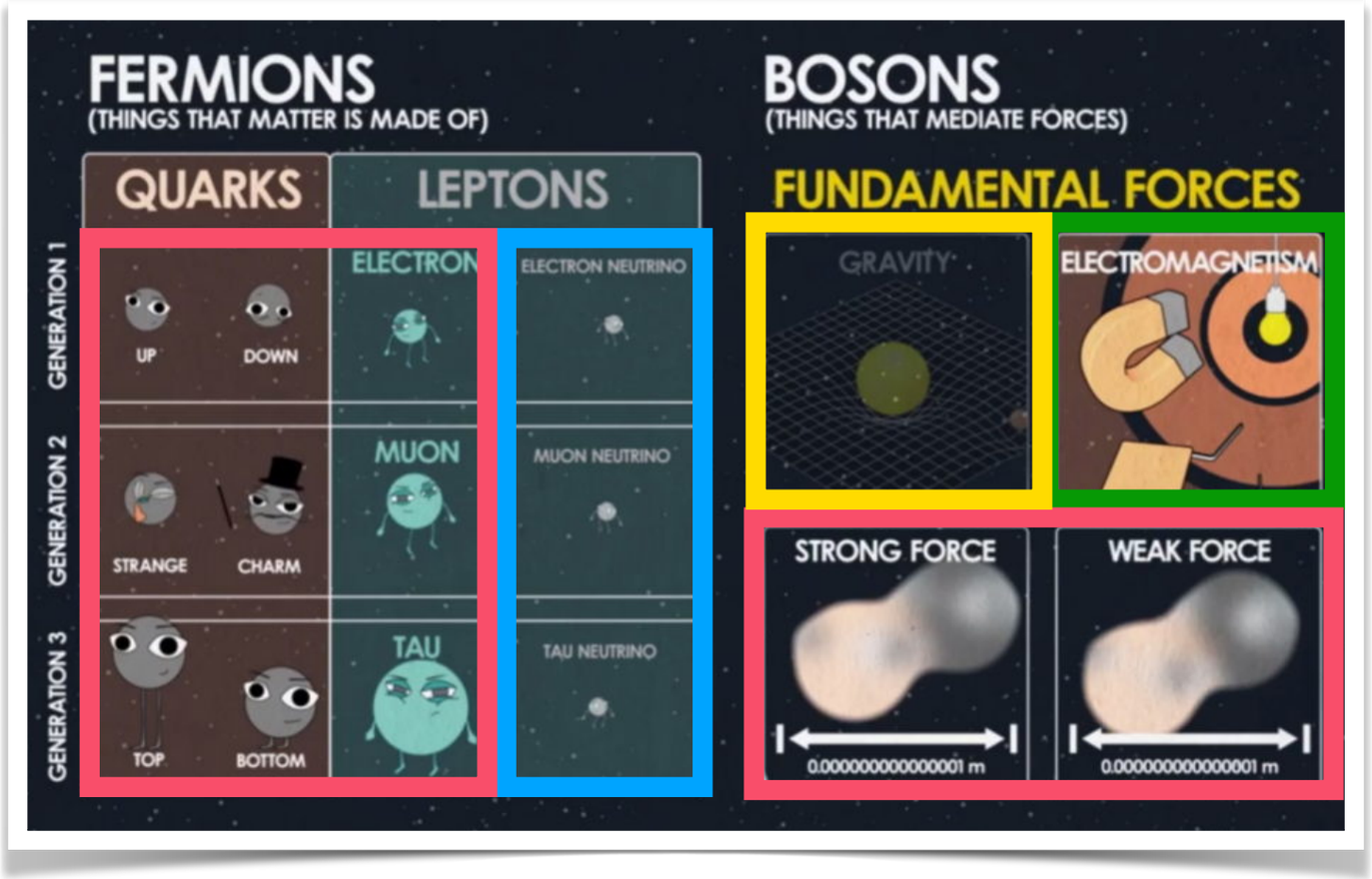
How do you message someone?

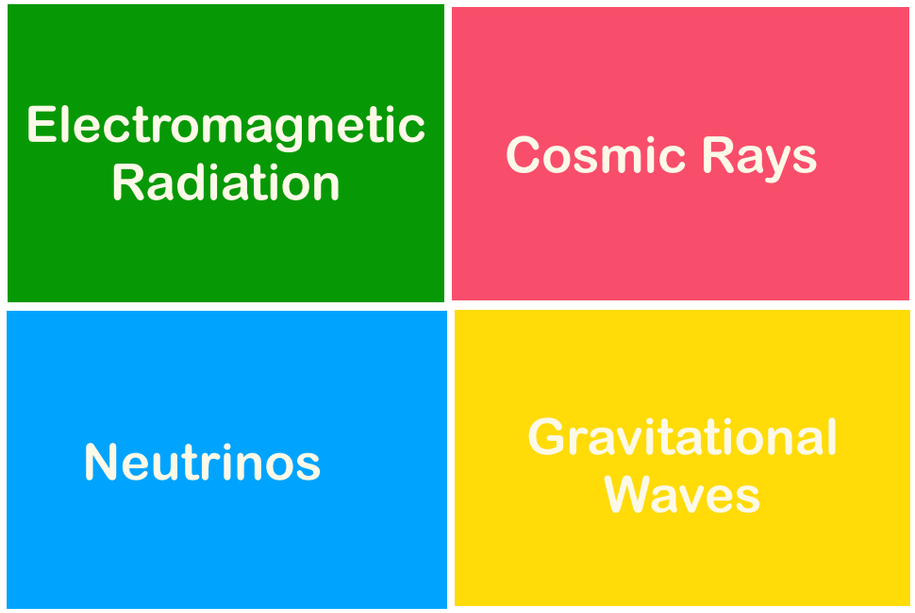


You have multiple ways. So does Nature

Multi-messengers:

Different types of particles and waves sent by our Universe

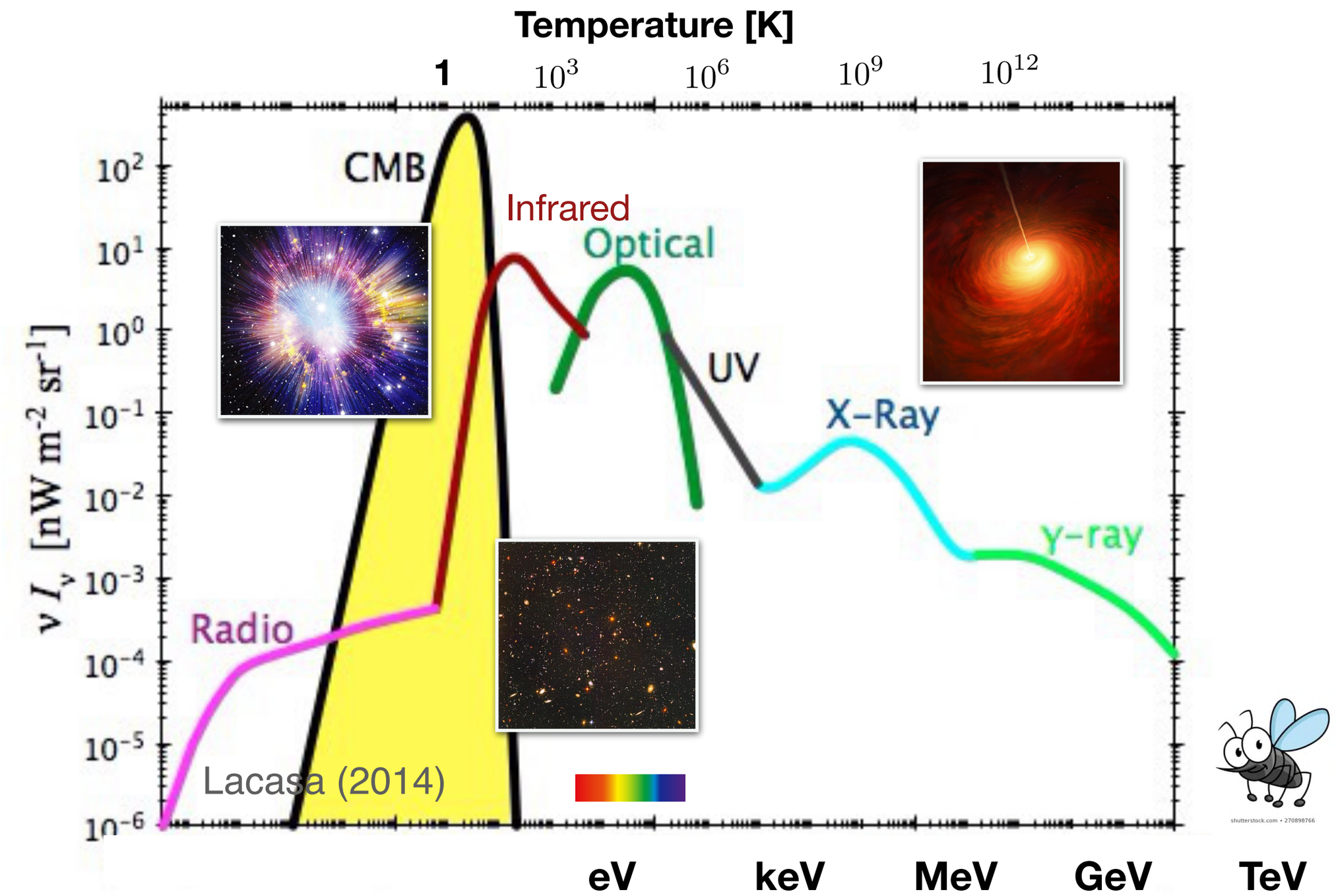




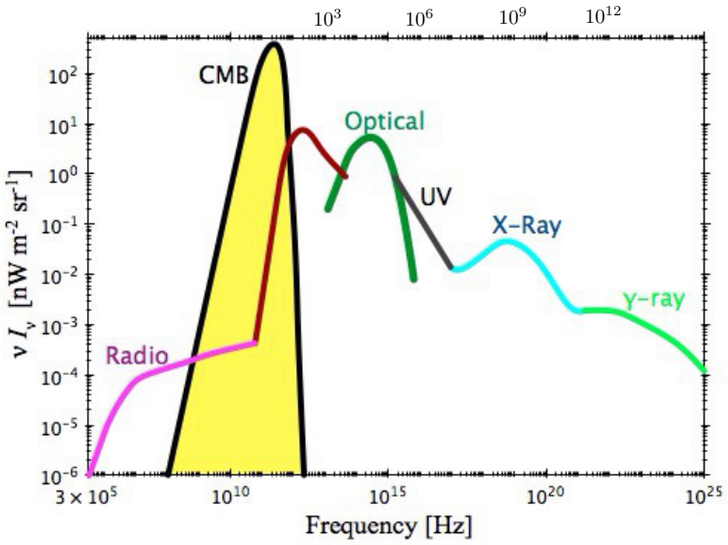
Cosmic particles / Astroparticles:

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

Cosmic Electromagnetic Radiation Background



The Universe in Light



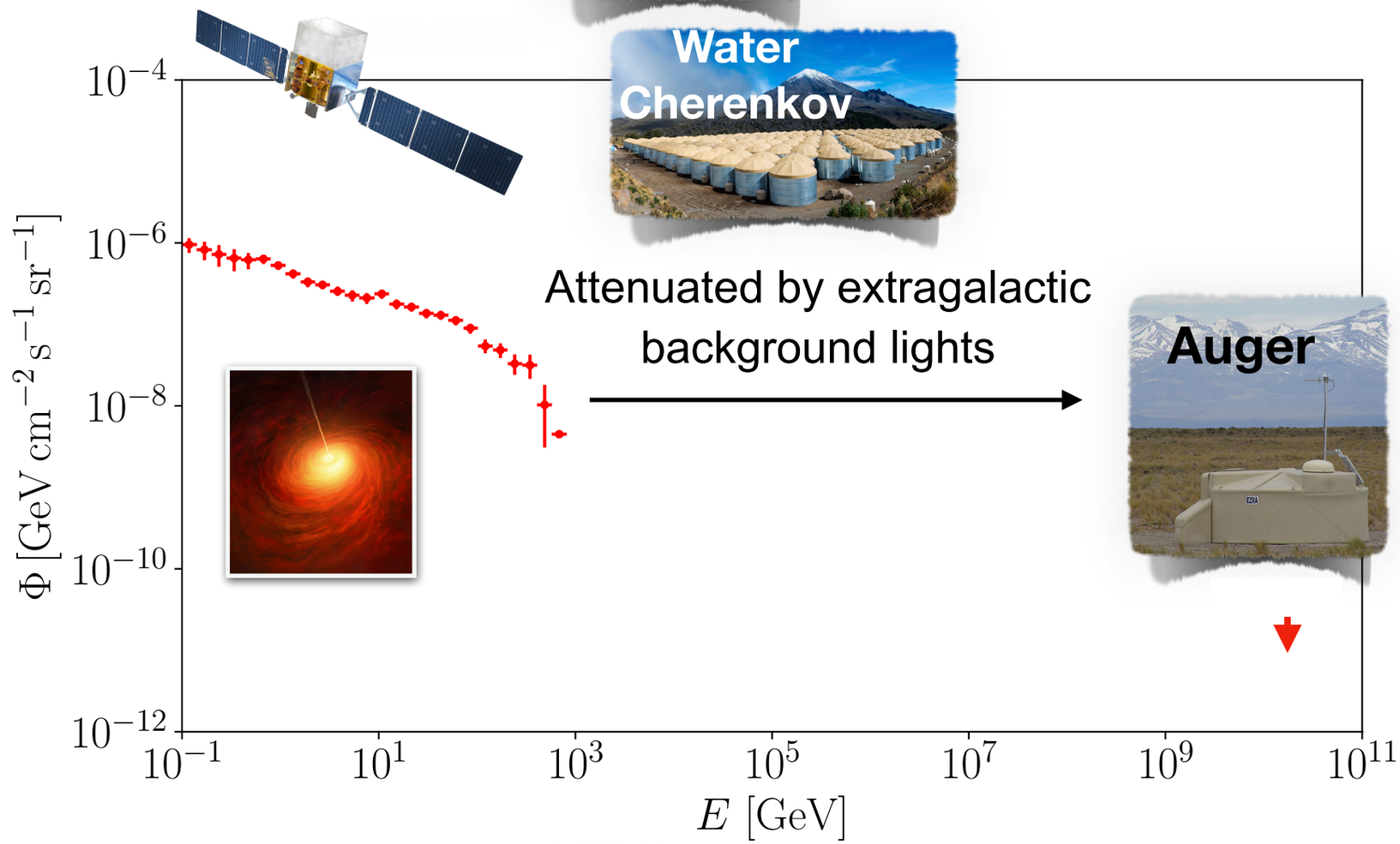
Fermi

IACTs
MAGIC
HESS
VERITAS

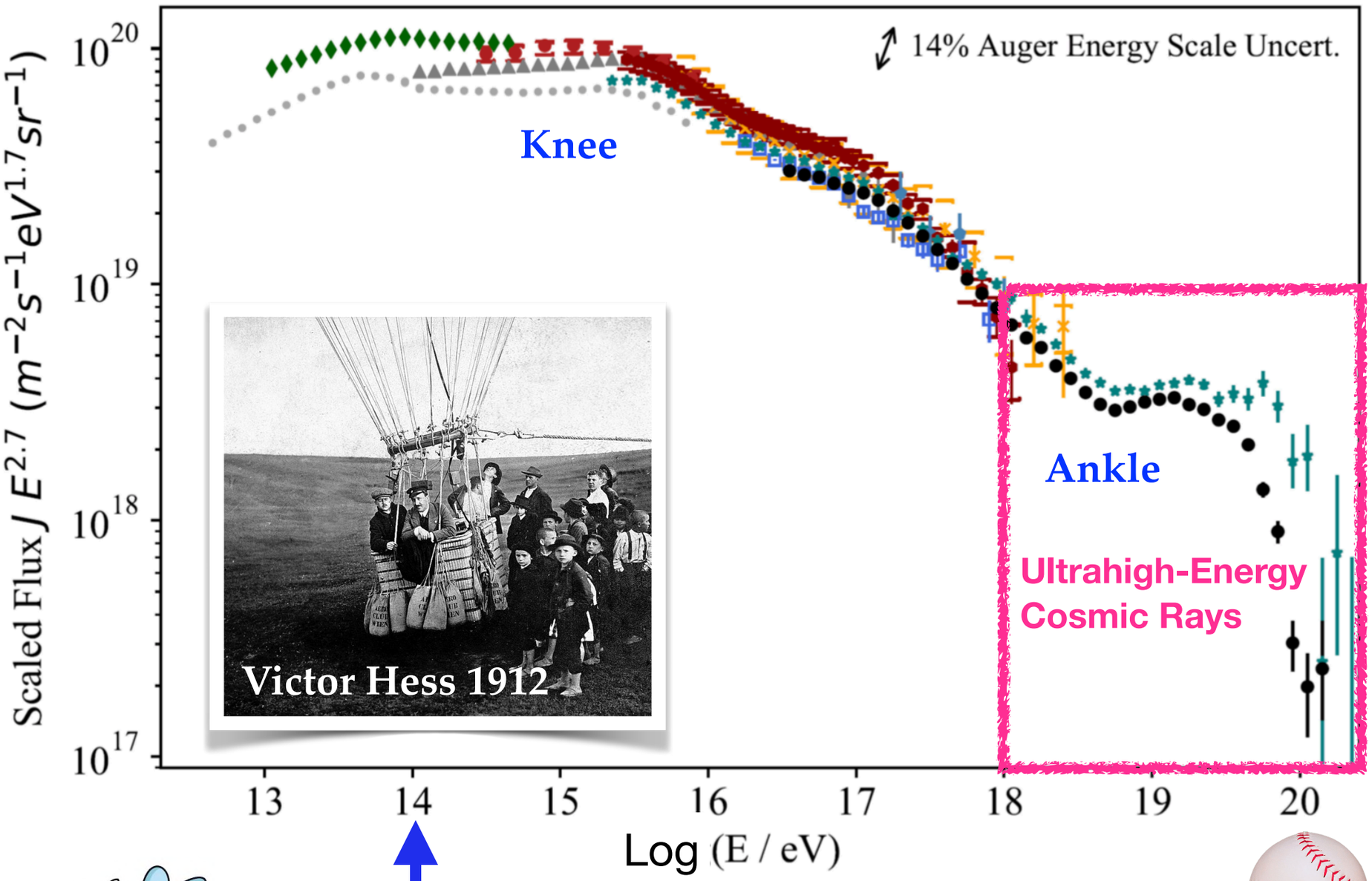
Water Cherenkov

Attenuated by extragalactic background lights

Auger



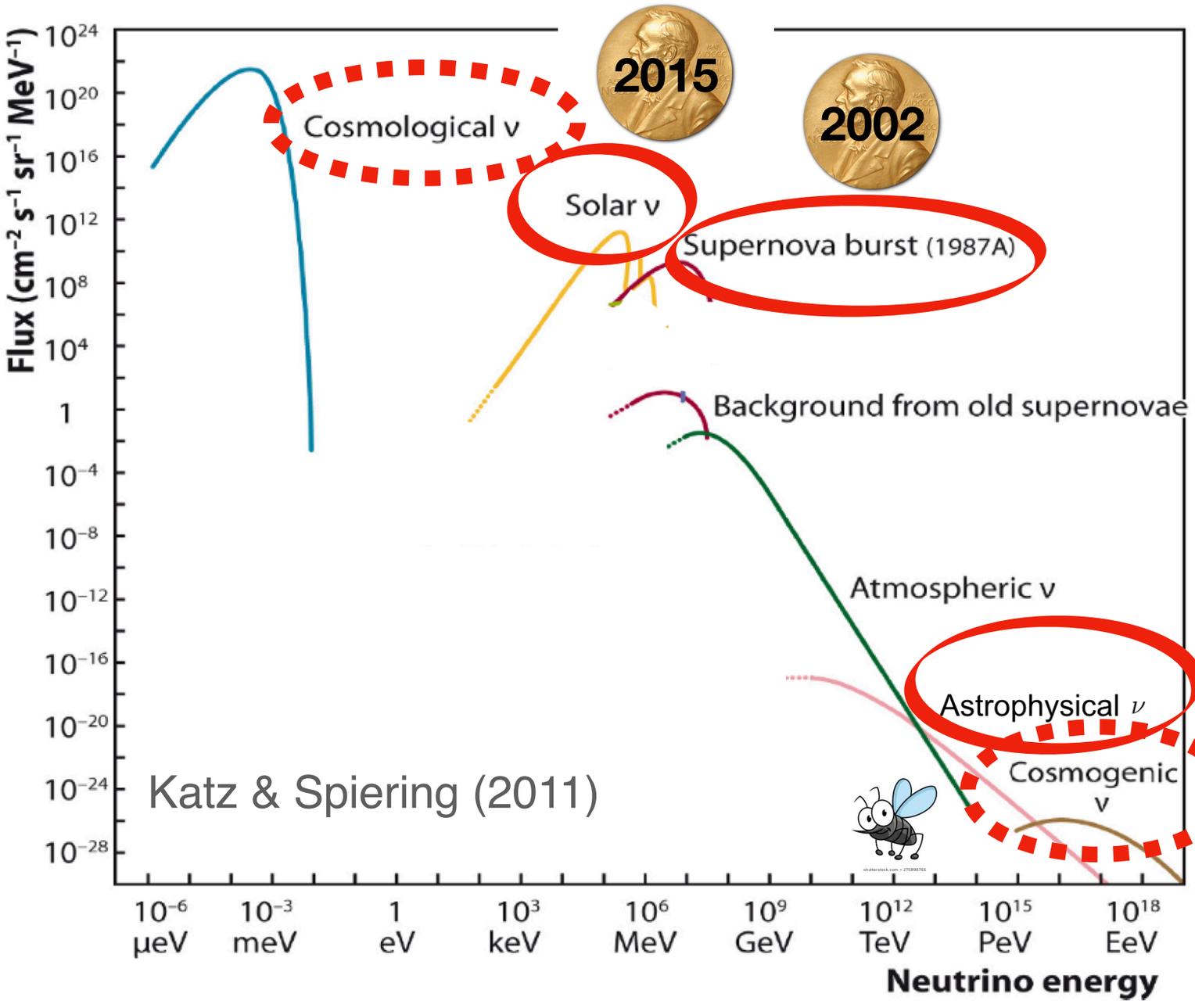
Cosmic Rays



Man-made accelerators

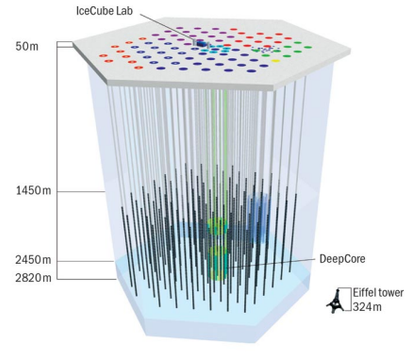
Cosmic Neutrino Background

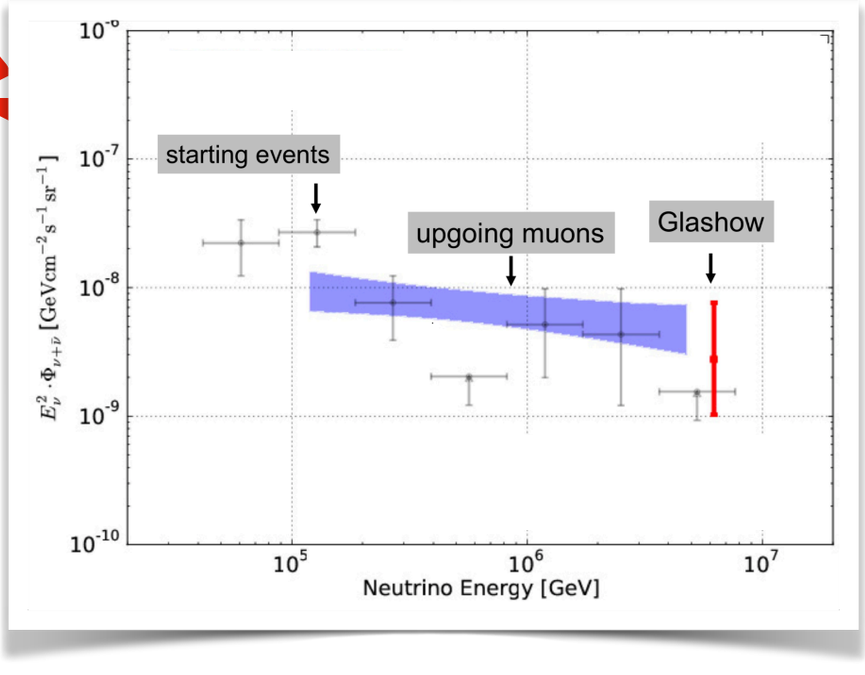
IceCube Coll., ICRC (2019)
IceCube Coll., Science (2013, 2018a,b)



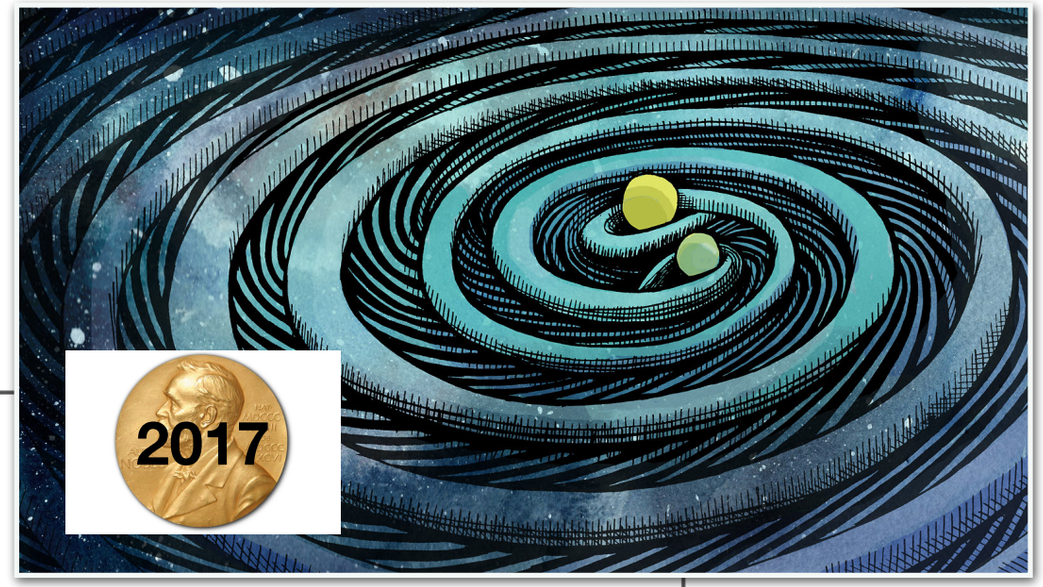
- First sources identified: TXS 0506+056, NGC 1068
- The origin of the bulk of astrophysical neutrinos is unknown

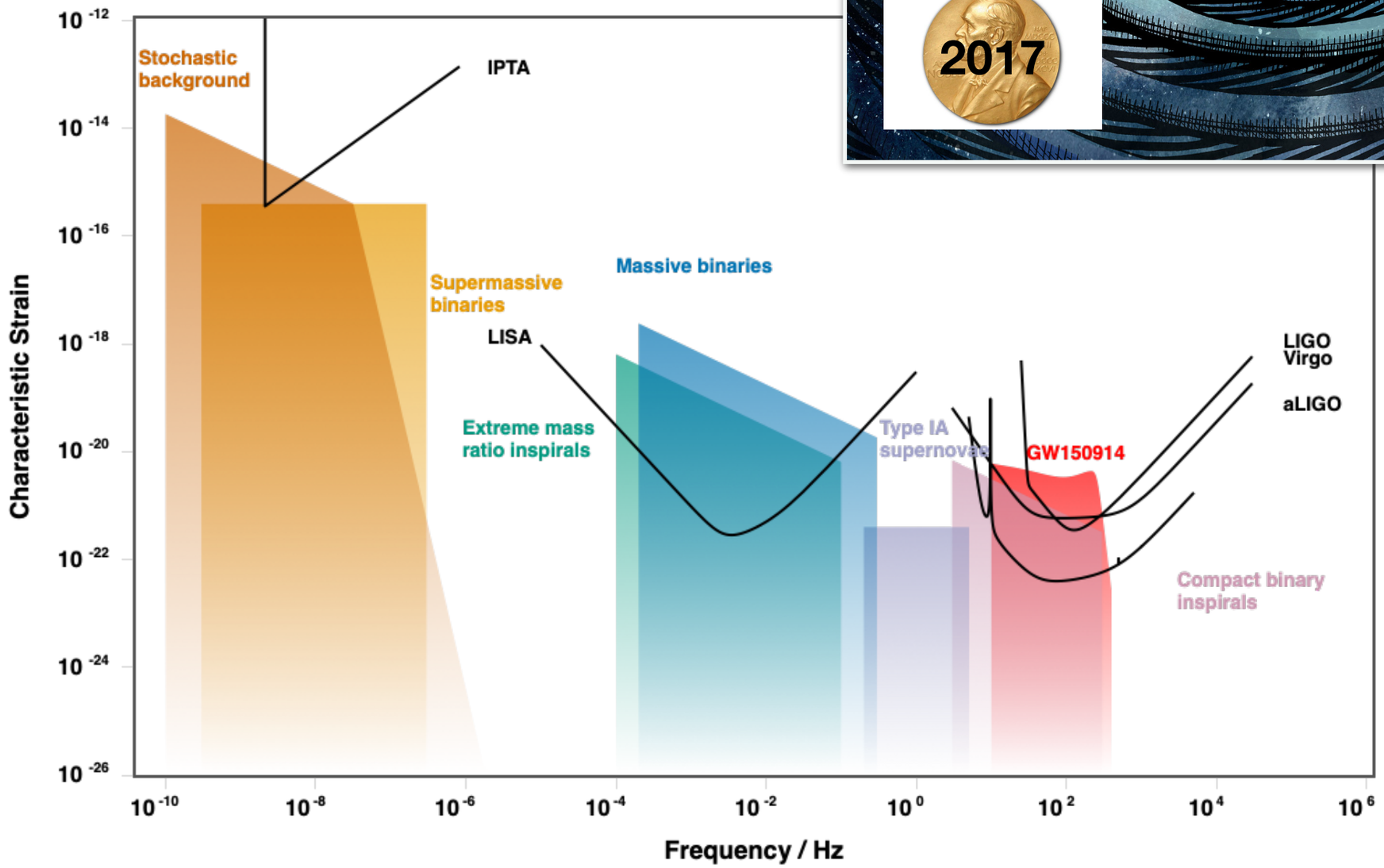
IceCube





Gravitational Waves





Moustakas (2017)
http://gwplotter.com

Multi-Messengers: what are they?

Different types of particles and waves

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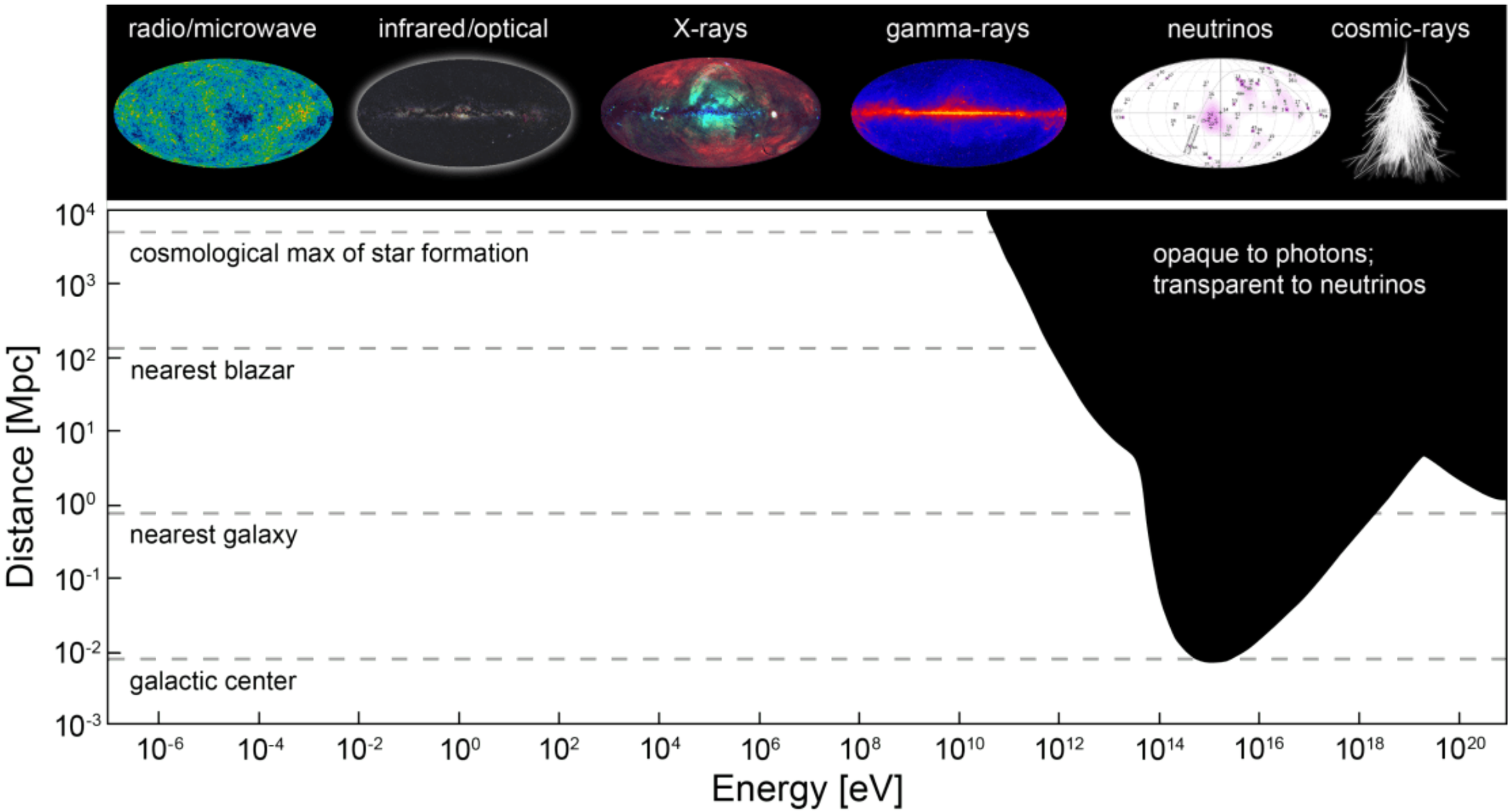
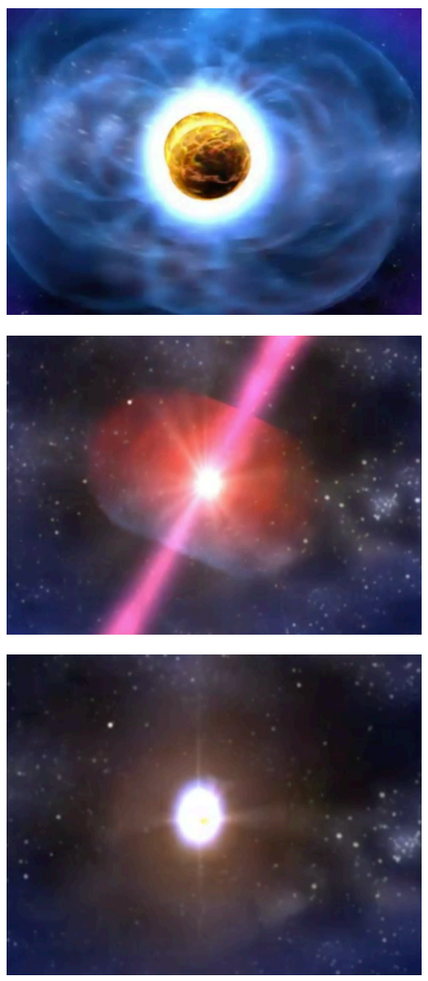
Why multi-? Because **more than one are needed**



Why multi-? Because **they show different aspects of the Universe**

GW170817



0 s

GW

GW: masses of the binary

+2 s

$e\,p \rightarrow \gamma$

Gamma-ray: short gamma-ray burst

+days

γ

Optical, Infrared: nucleosynthesis

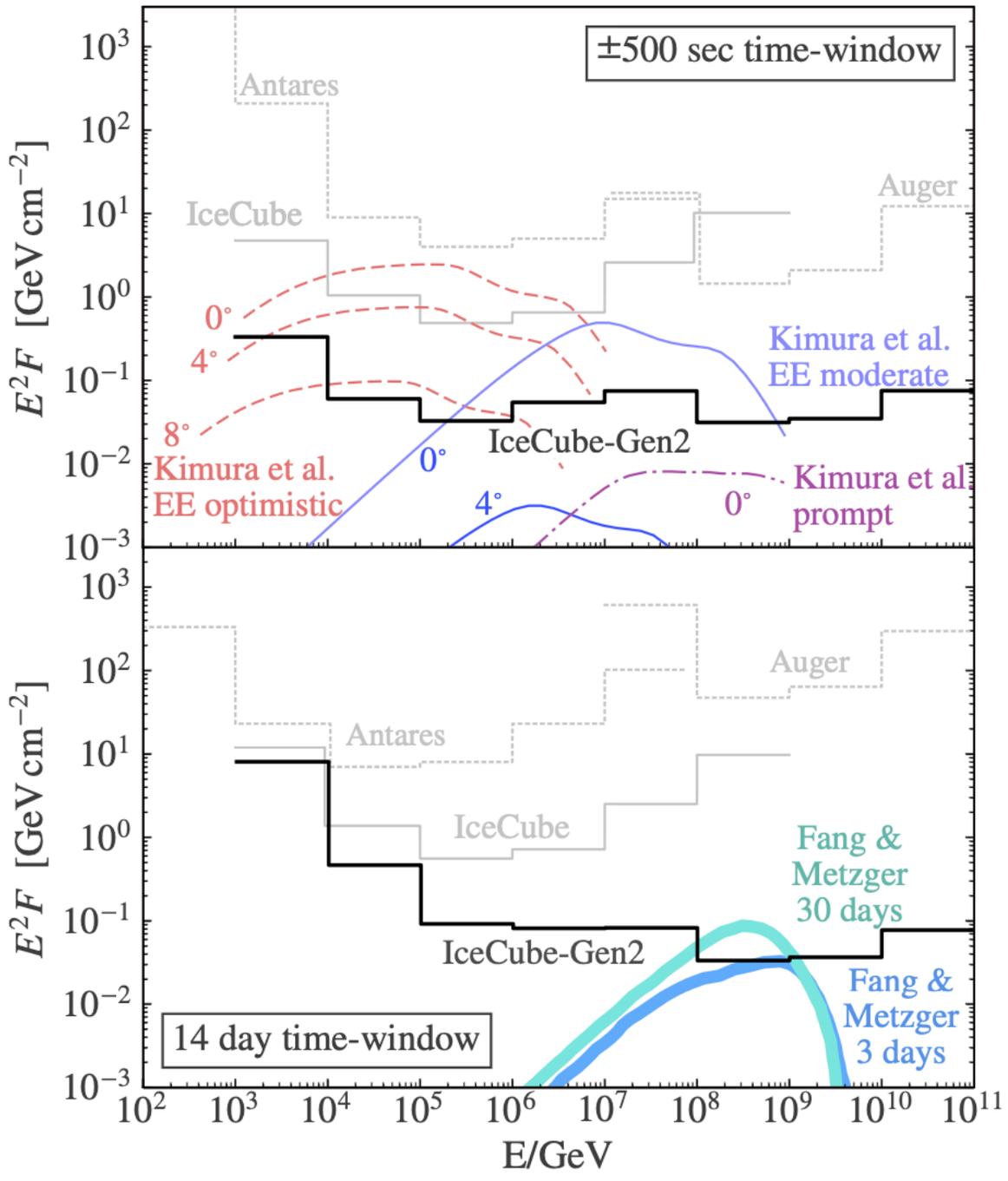
+week -year

$e\,p \rightarrow \gamma$

X-ray, radio: afterglow emission

Nature of merger remnants: black hole or neutron star?

A GW170817-like neutron star merger with IceCube-Gen2



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Connections between Cosmic Rays, Gamma Rays, and Neutrinos

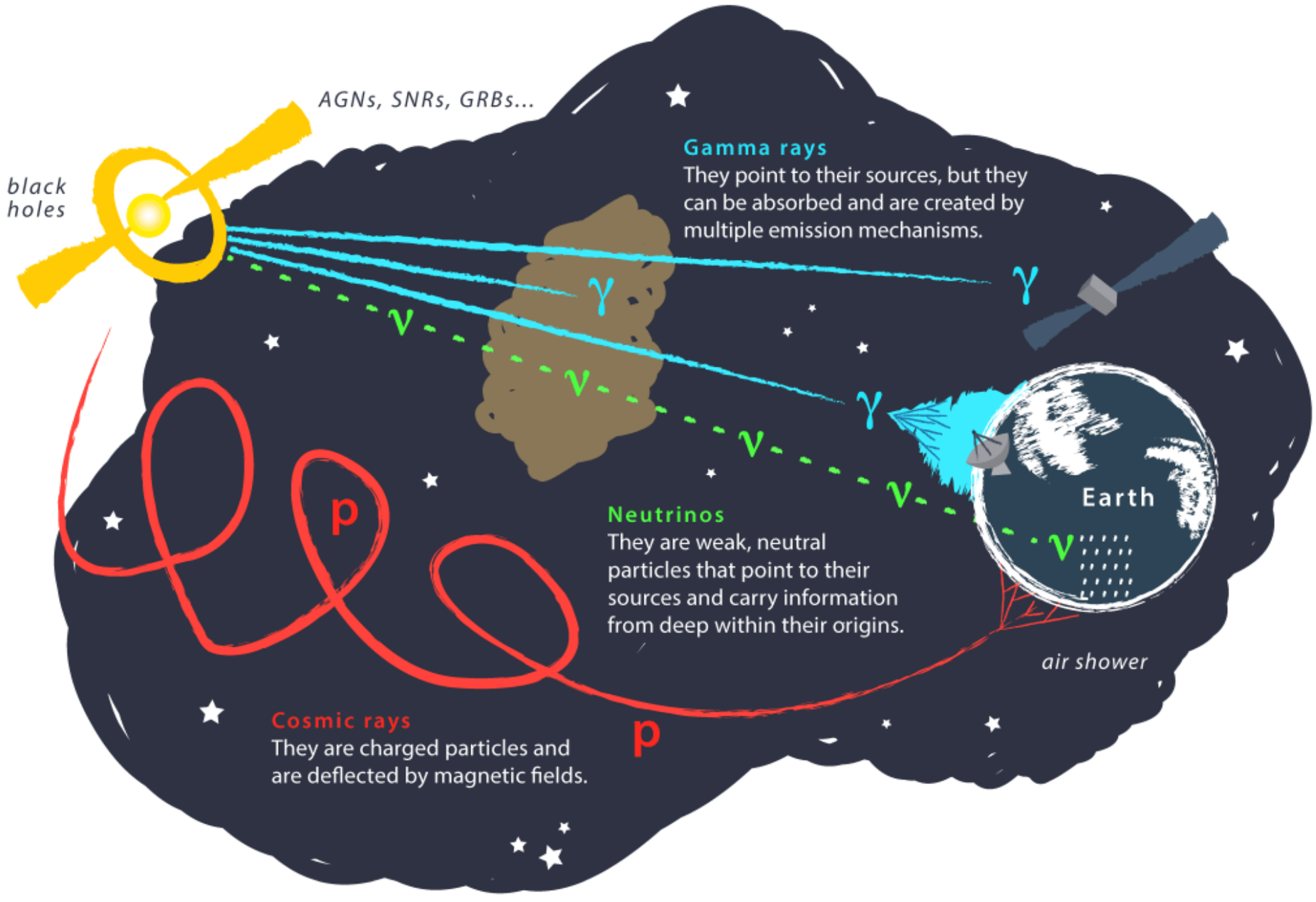
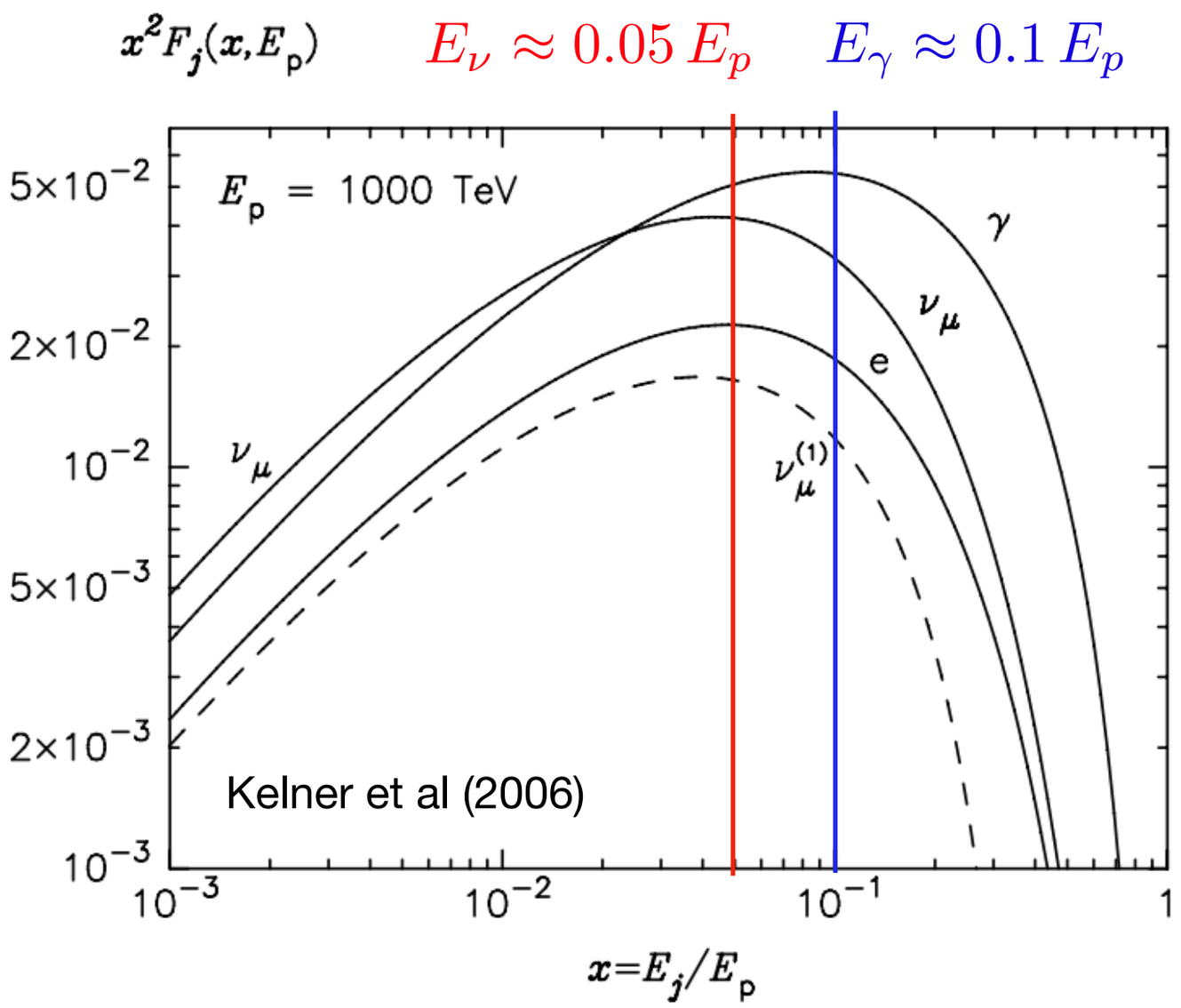


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

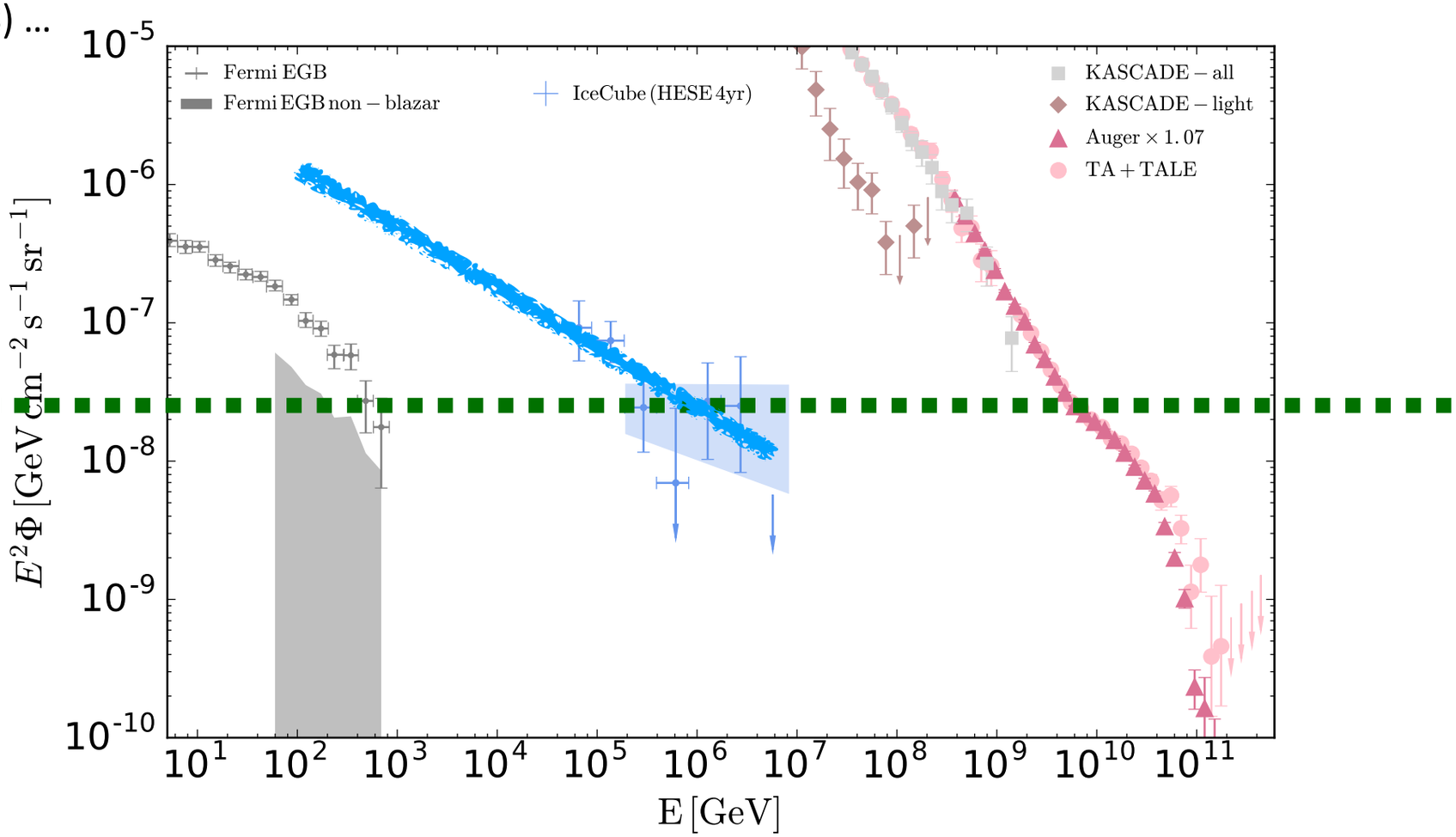
Connections between Cosmic Rays, Gamma Rays, and Neutrinos

$$\begin{array}{ll} pp & \\ p\gamma & \rightarrow \end{array} \quad \begin{array}{l} \pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu + \nu_\mu \\ \pi^0 \rightarrow 2\gamma \end{array}$$



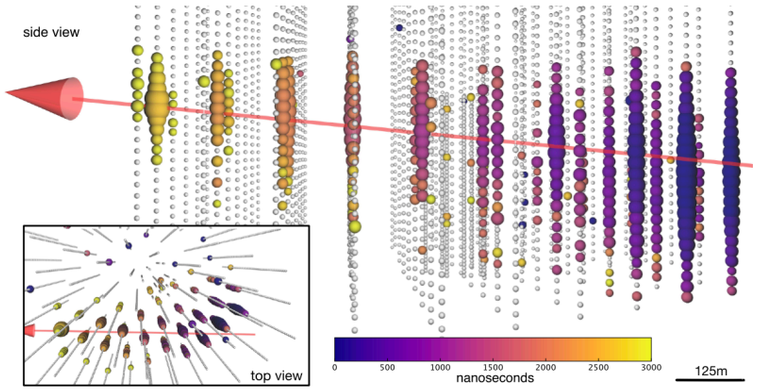
Connections between Cosmic Rays, Gamma Rays, and Neutrinos

Murase, Ahlers & Lacki (2013)
Giacinti et al (2015)
Murase & Waxman (2016)
Fang & Murase (2018) …

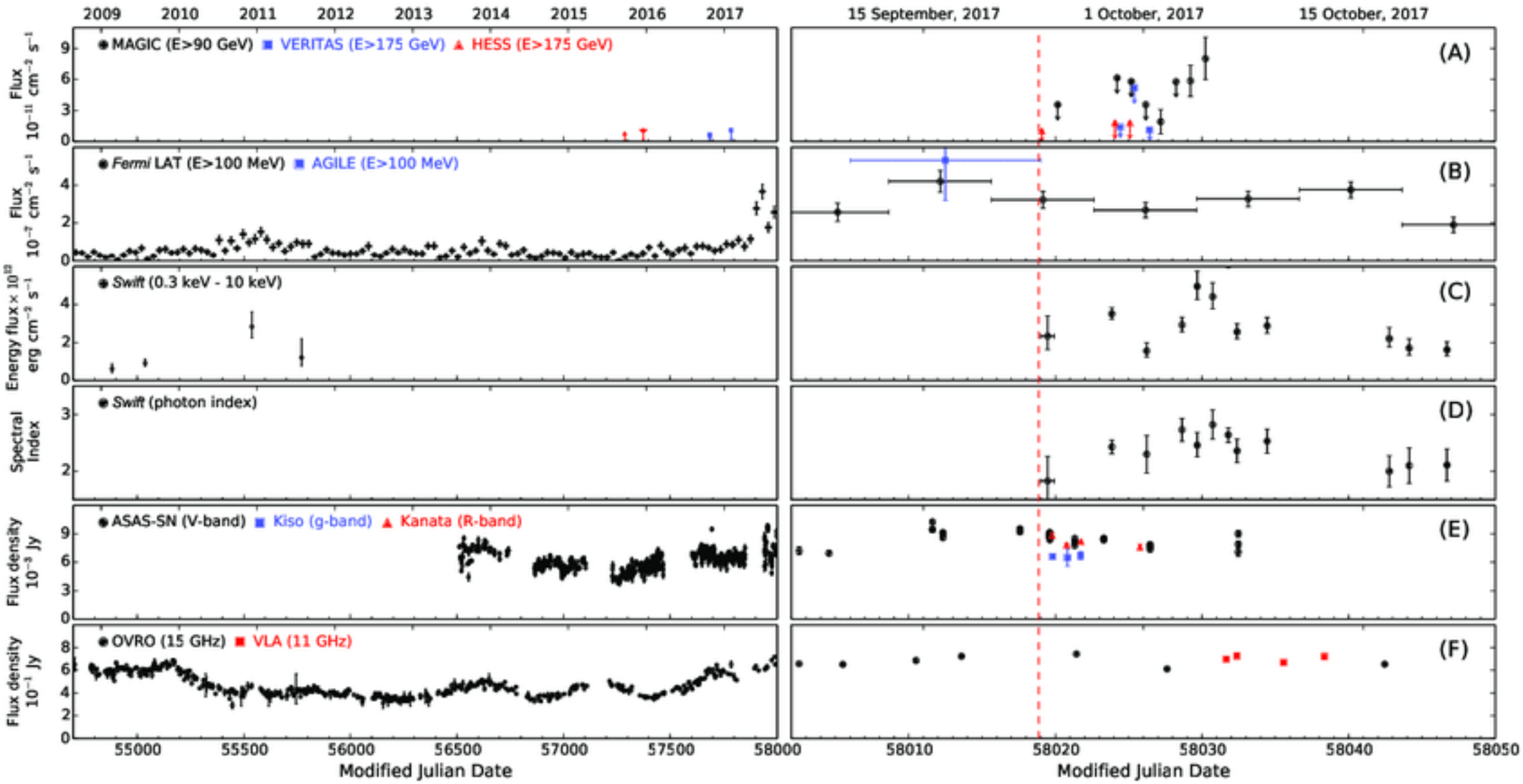


- Despite ten orders of magnitudes difference in energy, UHECRs, IceCube neutrinos, Fermi non-blazar **EGB share similar energy injection rate**
- The sources of the diffuse neutrinos either **do not produce many gamma rays** (have a hard spectrum) **or are gamma-ray dark**

MM Observations and Transient Event Follow-ups

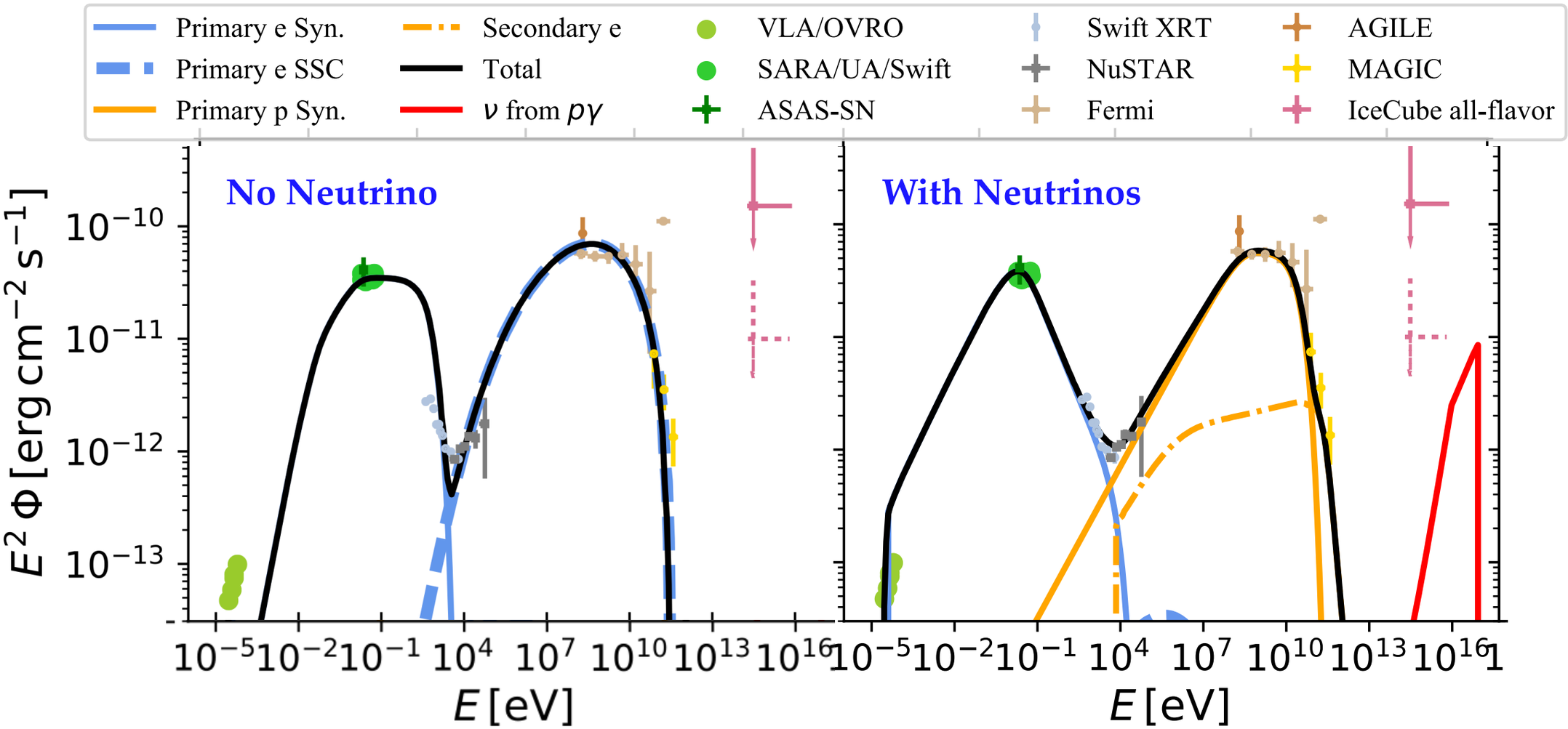


TXS 0506+056



IceCube Collaboration, Science (2018) a, b

Lessons from TXS 0506+056



A significant fraction of the jet energy may be carried by hadrons.
Same conclusion applies to NGC 1068.

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High-energy neutrinos open up a new window on Nature's hadronic accelerators

Take-home Messages

- Multi-messengers are different types of particles and waves
- Together they provide a complete view of the Universe
- High-energy neutrinos open up a new window on Nature's hadronic accelerators

Questions?