lecture 8. multi-messenger astrophysics

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Advanced Astroparticle Physics

NPAC M2

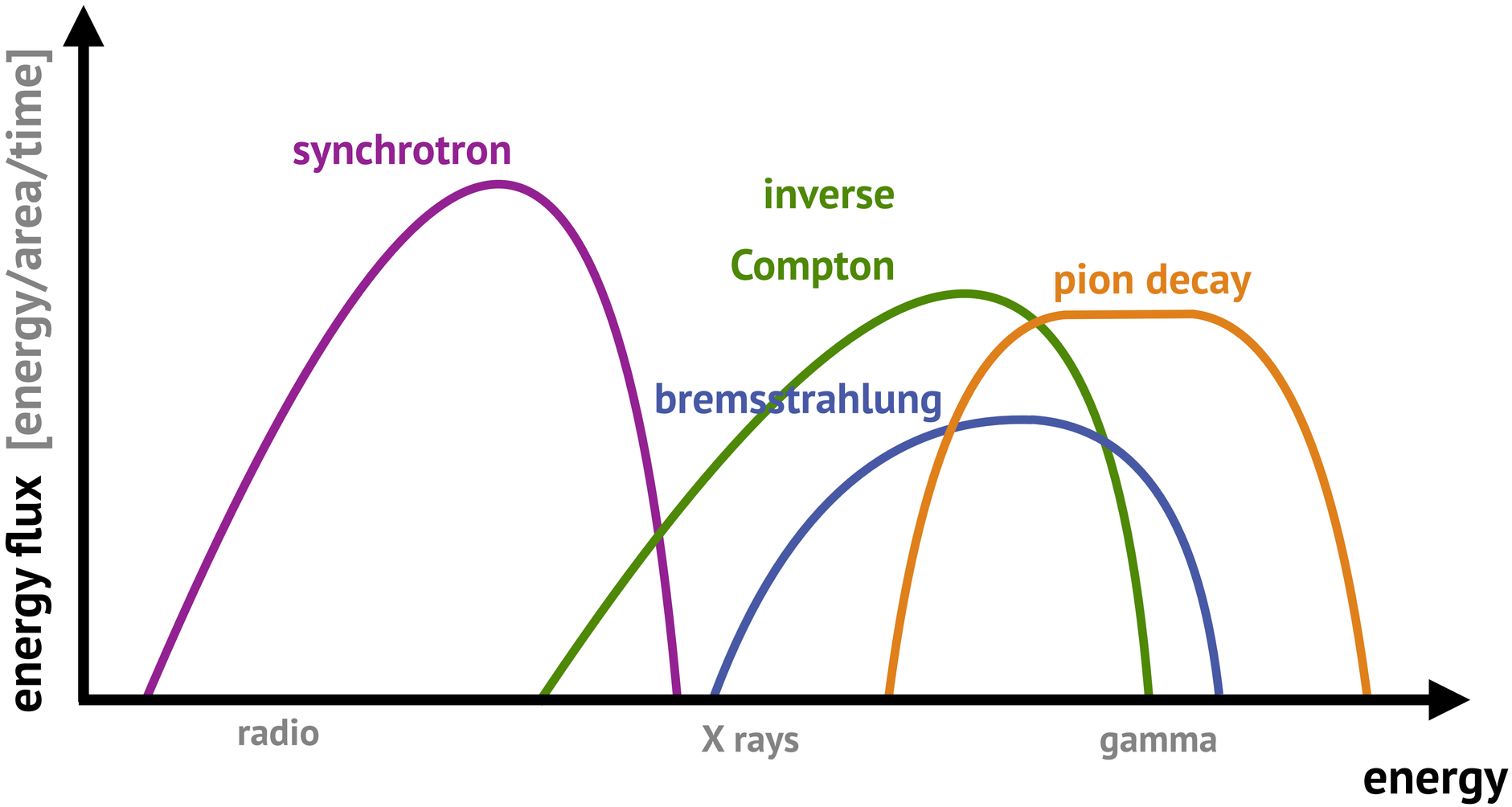
2024-2025

in today's class...

- **interaction processes**
  - leptonic
  - hadronic
  - lepto-hadronic
- **multi-messenger observations**
  - milestones
  - networks
- **astroparticles as probes of BSM**

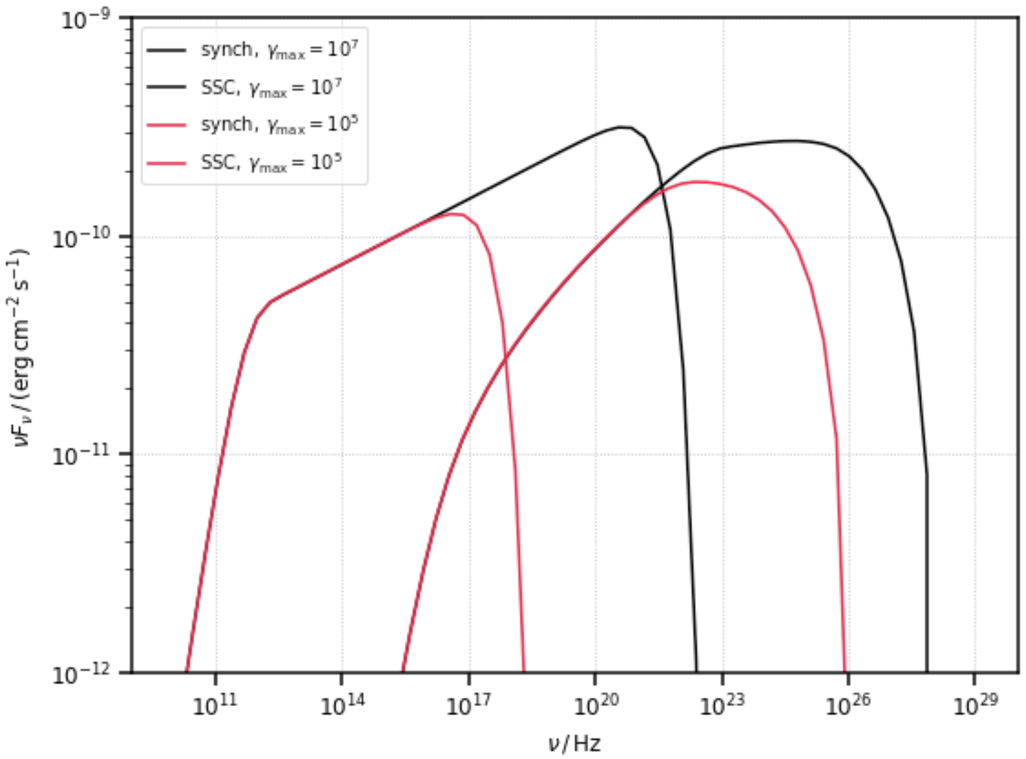
particle interactions in astrophysical objects

non-thermal spectral energy distribution

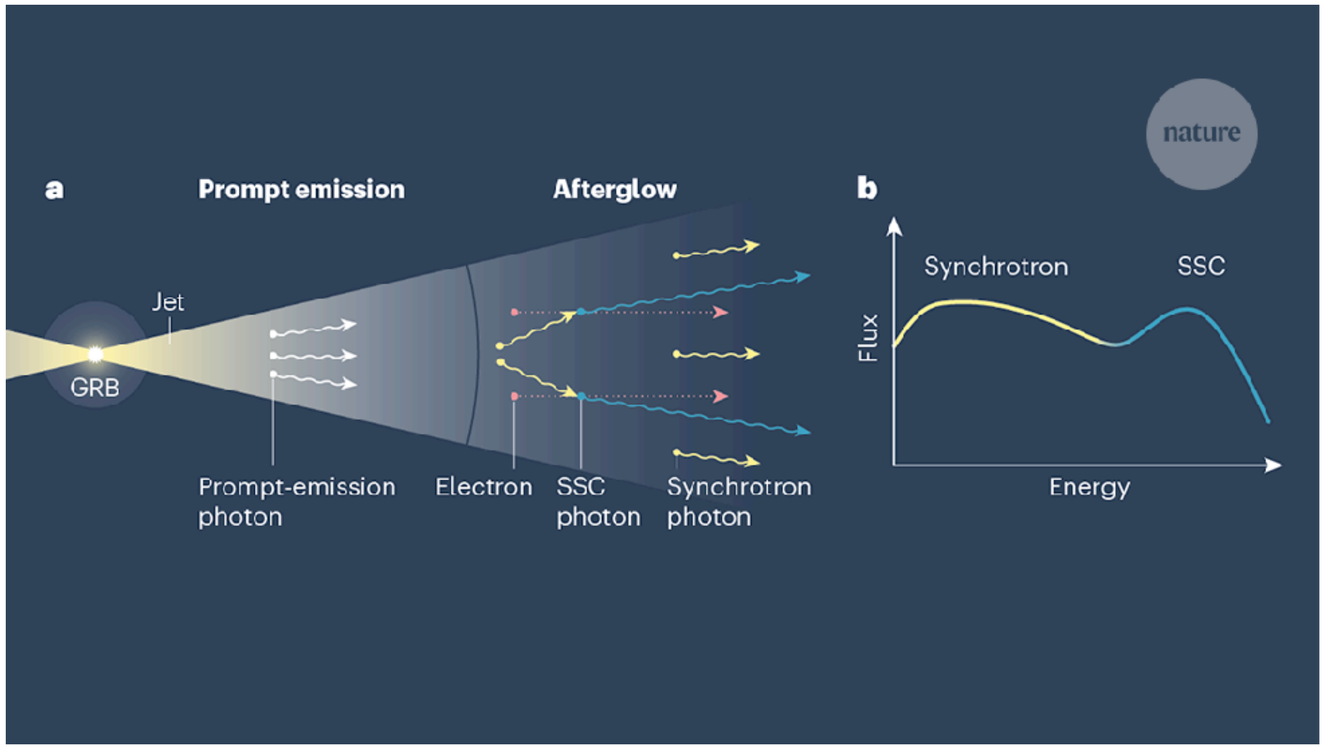


synchrotron self Compton (SSC)

- electrons emit synchrotron radiation
- synchrotron photons become targets for Compton scattering



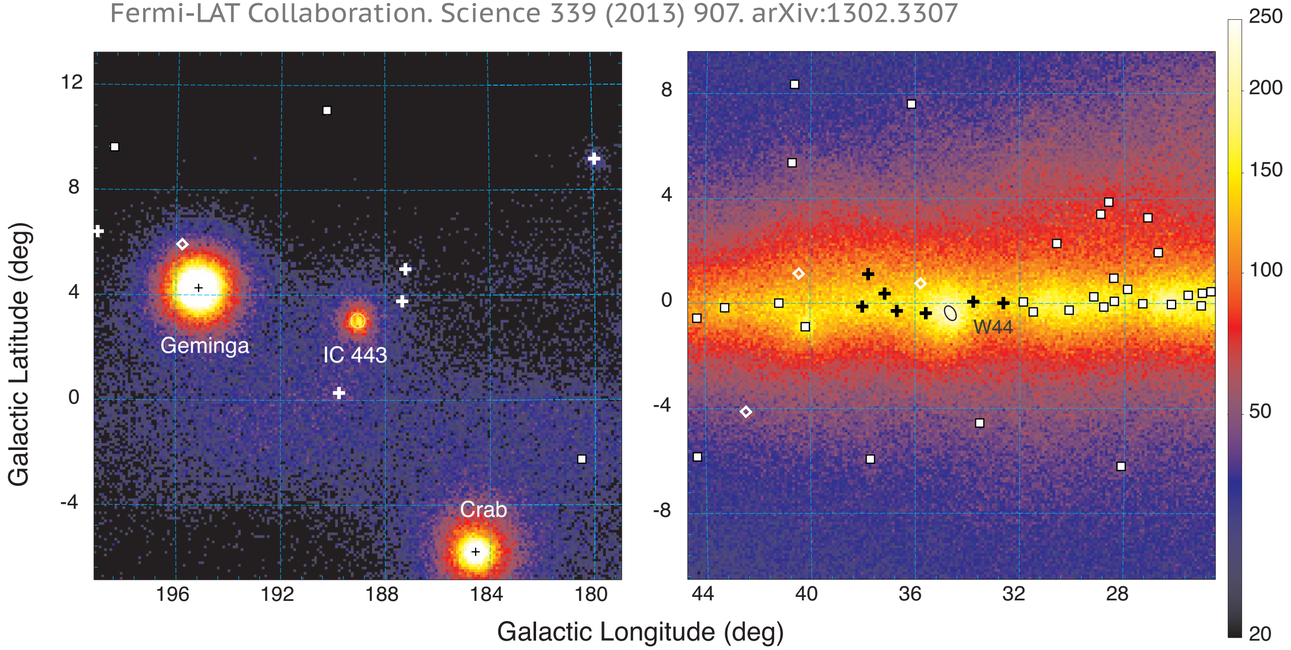
Simulated with agnpy: https://agnpy.readthedocs.io/en/latest/tutorials/synchrotron_self_compton.html

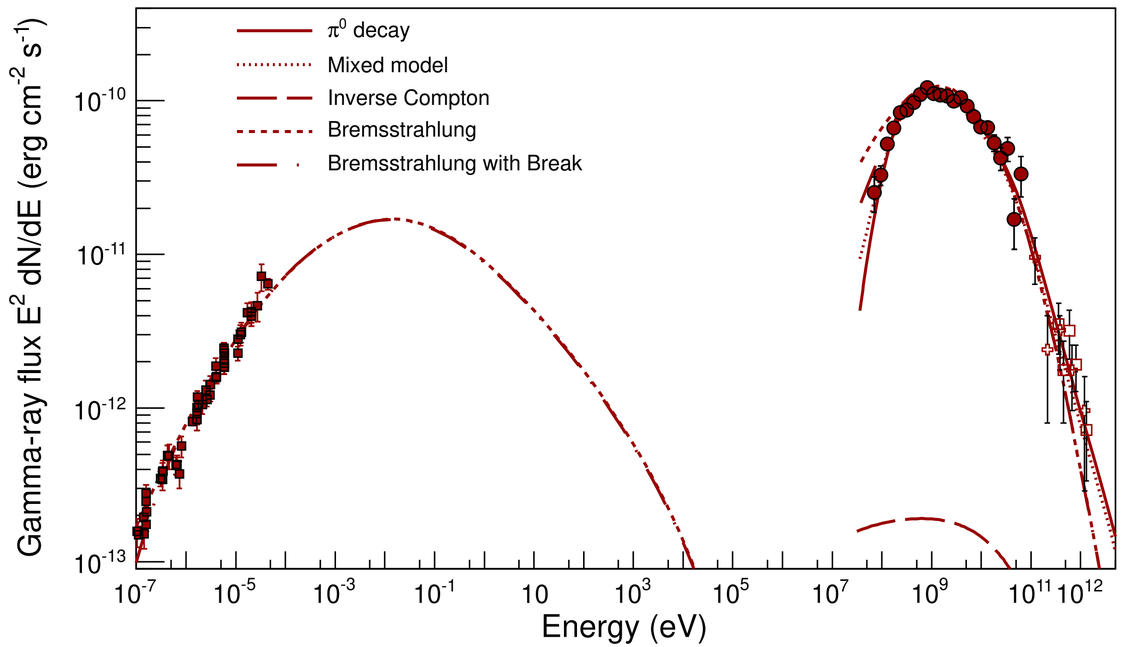


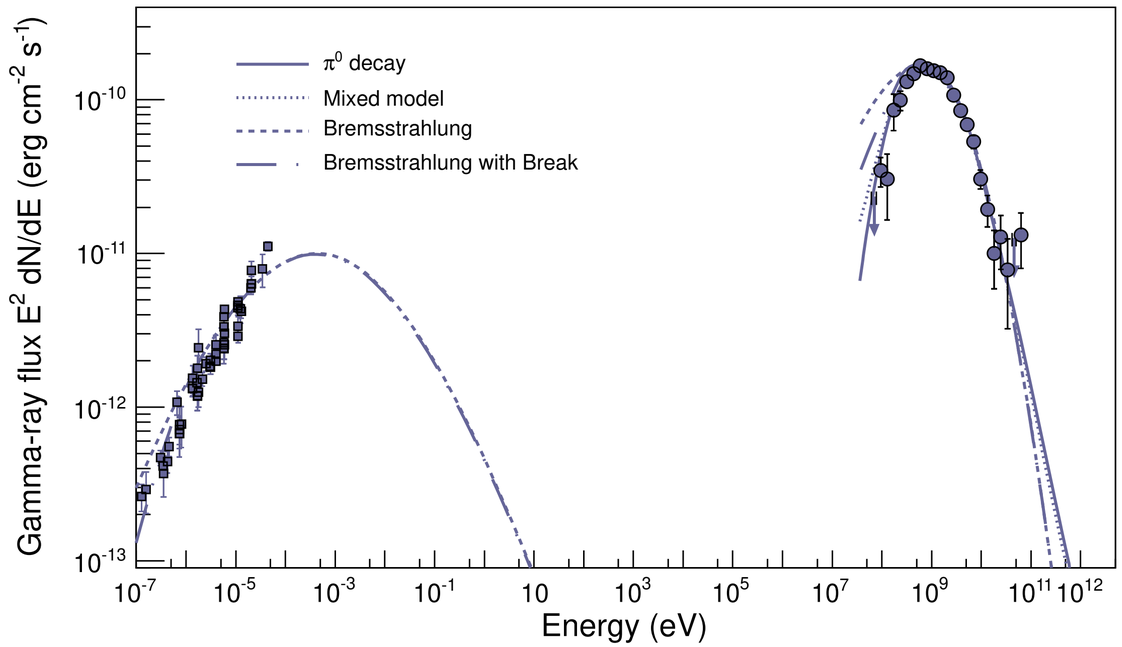
Zhang. Nature 575 (2019) 448.

the pion bump

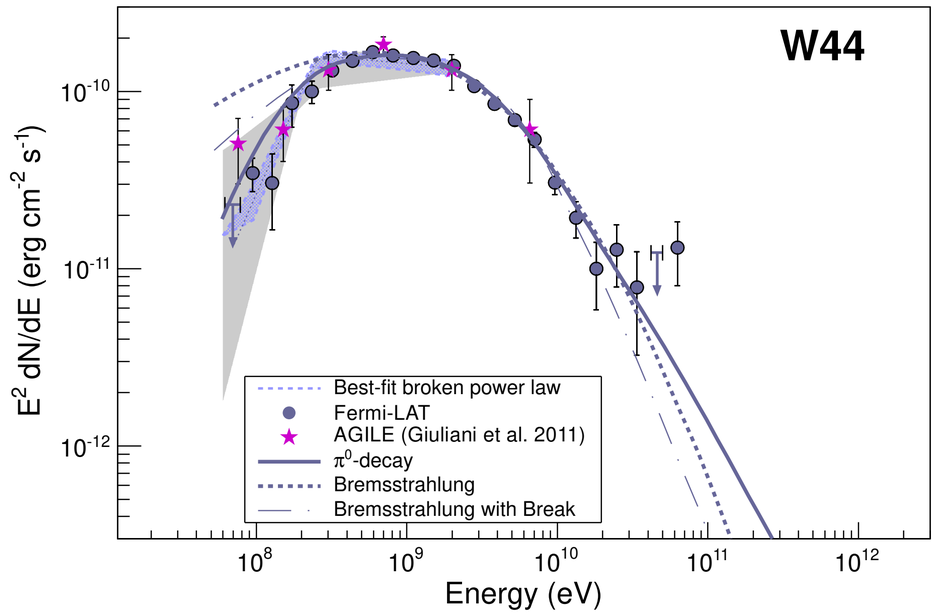
Fermi-LAT Collaboration. Science 339 (2013) 907. arXiv:1302.3307

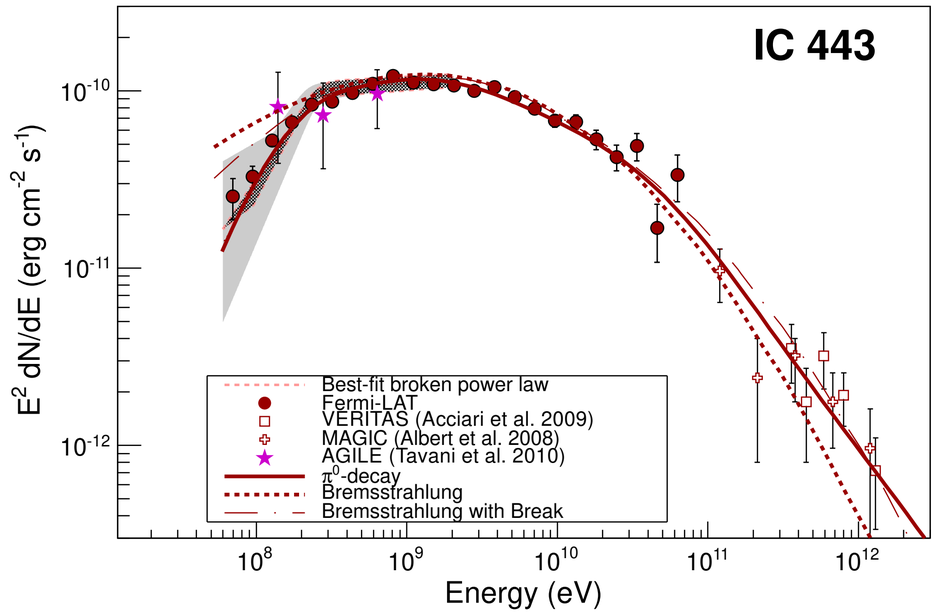






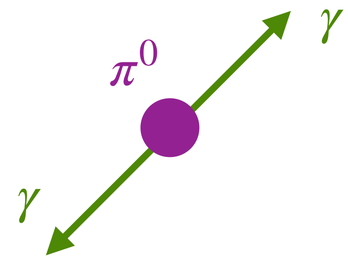
the pion bump





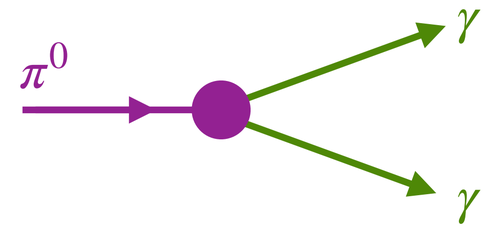
Fermi-LAT Collaboration. Science 339 (2013) 907. arXiv:1302.3307

CoM frame



$$E^\star = \frac{1}{2} m_{\pi^0} c^2$$

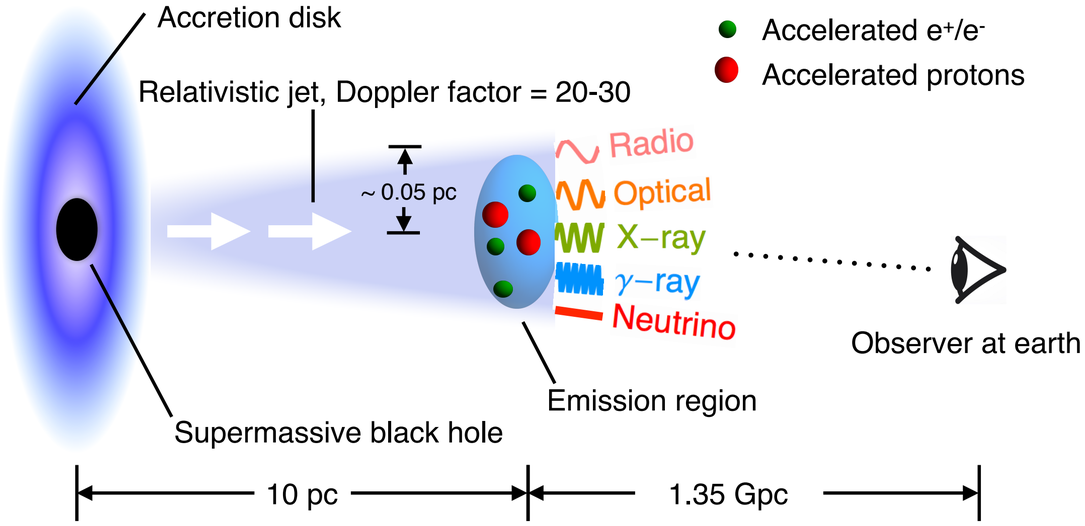
lab frame



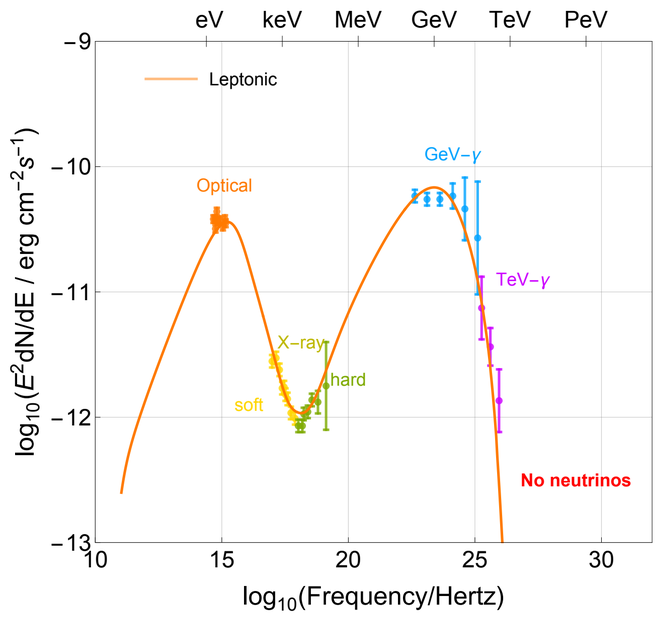
$$\frac{m_{\pi^0}c^2}{2}\sqrt{\frac{1-\beta}{1+\beta}} \leq E \leq \frac{m_{\pi^0}c^2}{2}\sqrt{\frac{1+\beta}{1-\beta}}$$

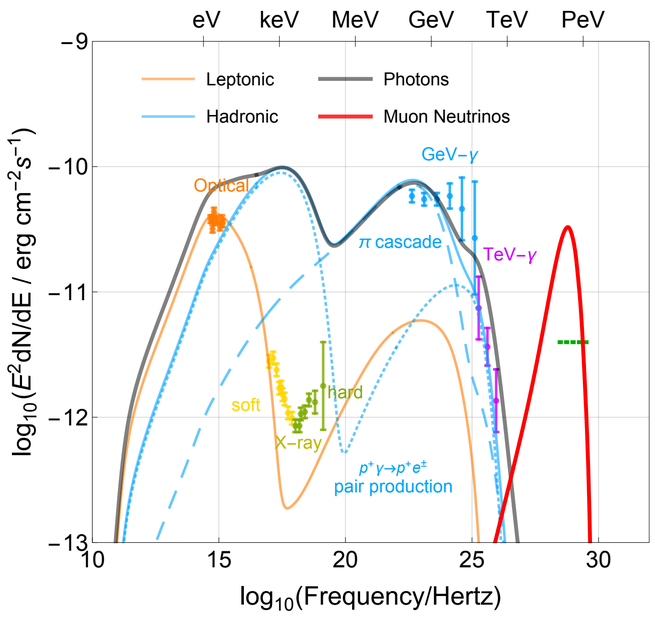
- cross section only mildly dependent on energy
  - pions and gammas have roughly the same spectrum
- characteristic spectral feature observed in several sources

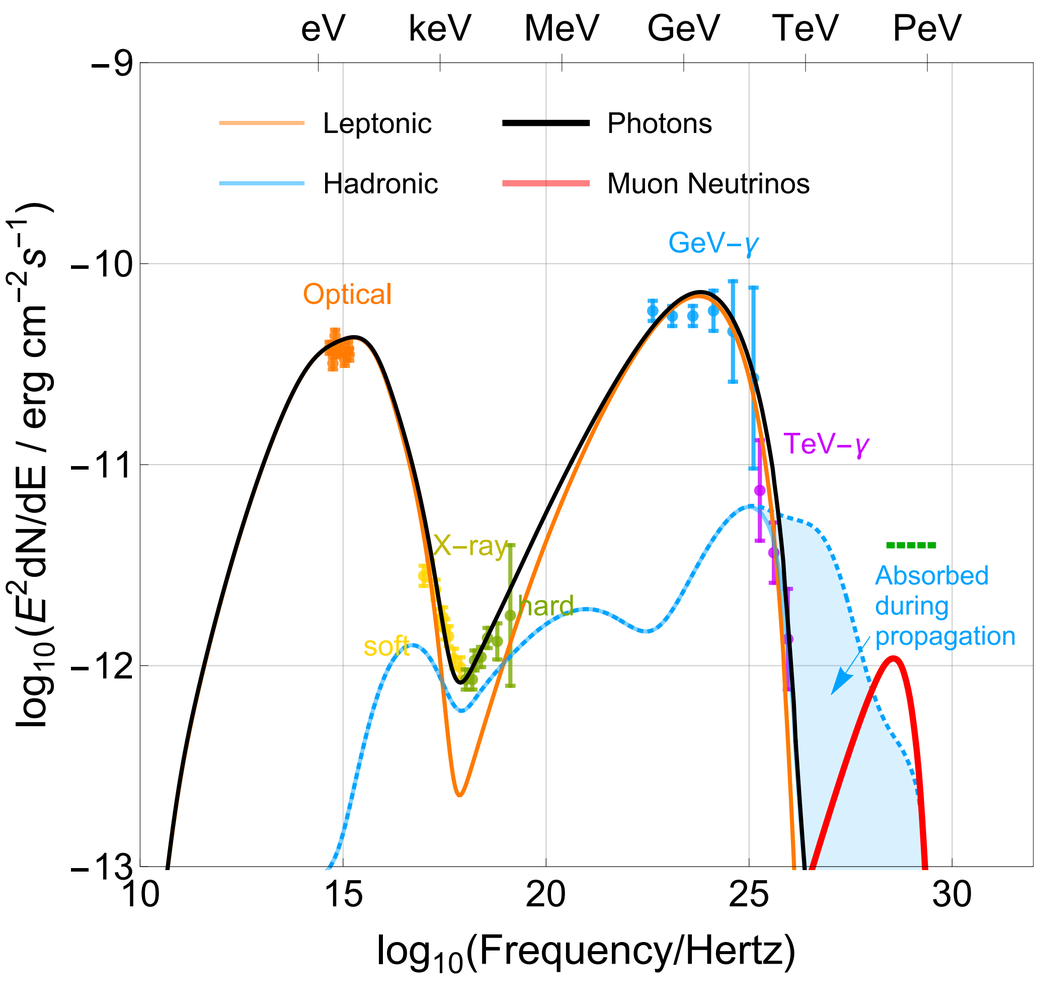
leptonic vs. hadronic processes



- **blazar** TXS 0506+056
- correlated neutrino observation







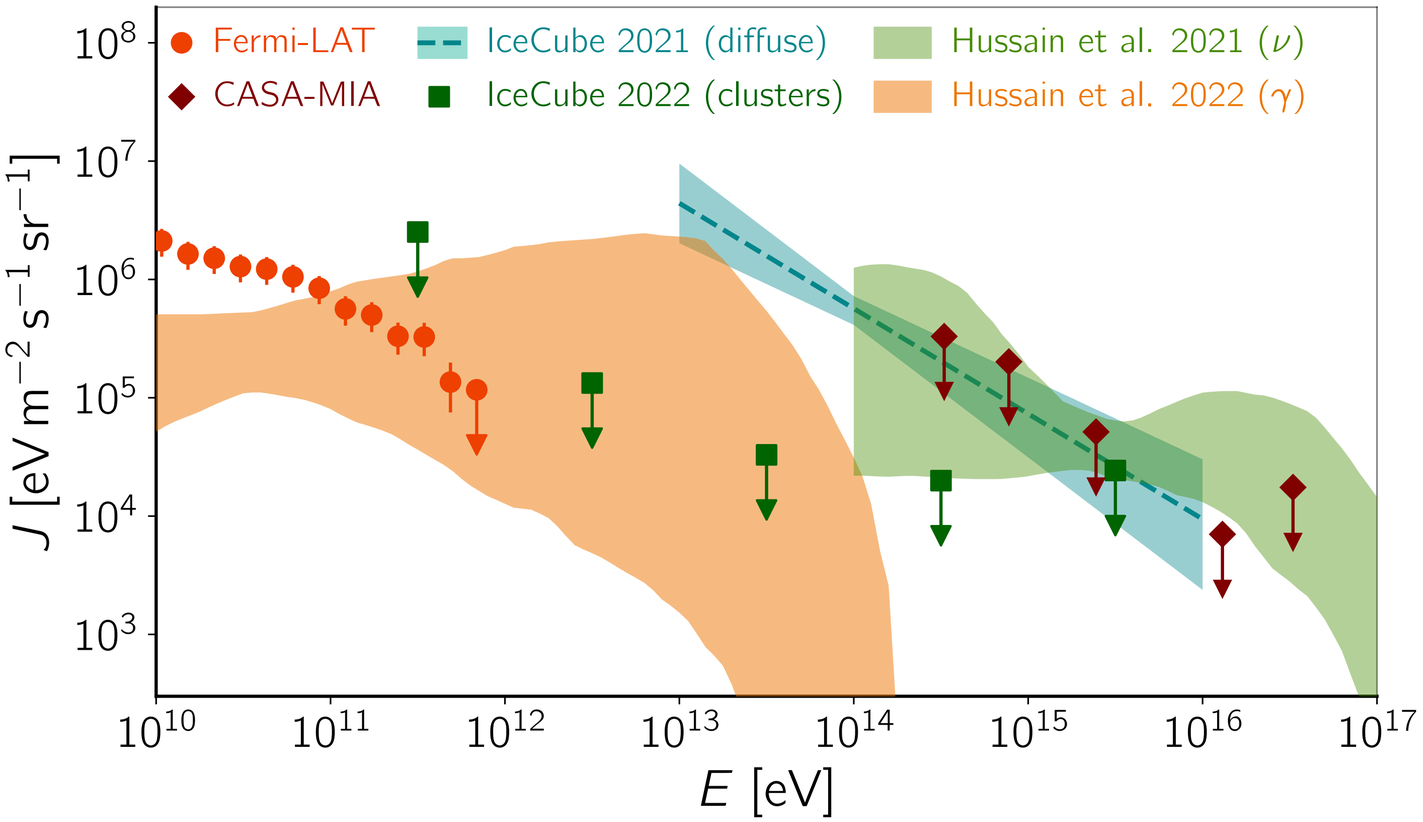
Gao et al. Nature Astron. 3 (2019) 88. arXiv:1807.04275

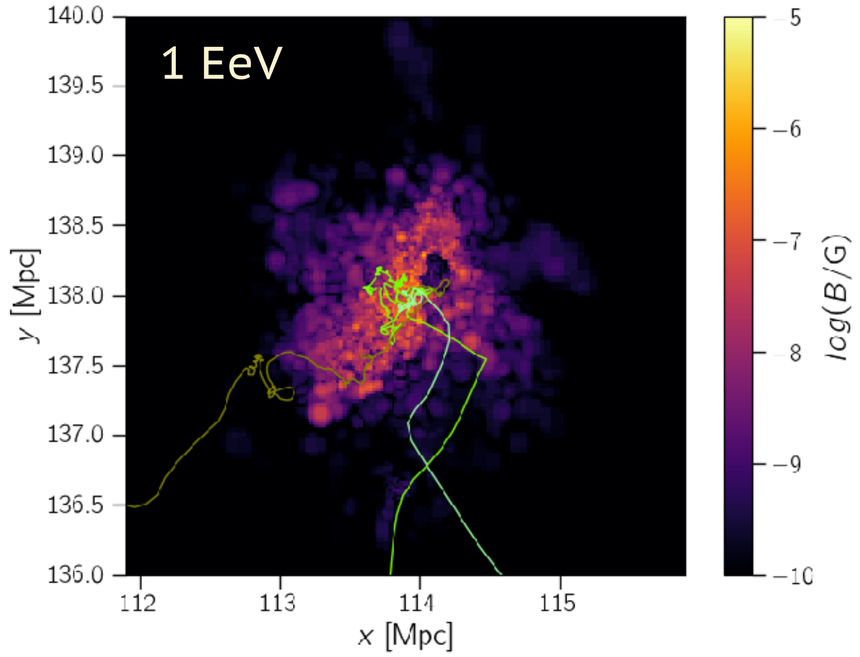
multimessenger emission from galaxy clusters

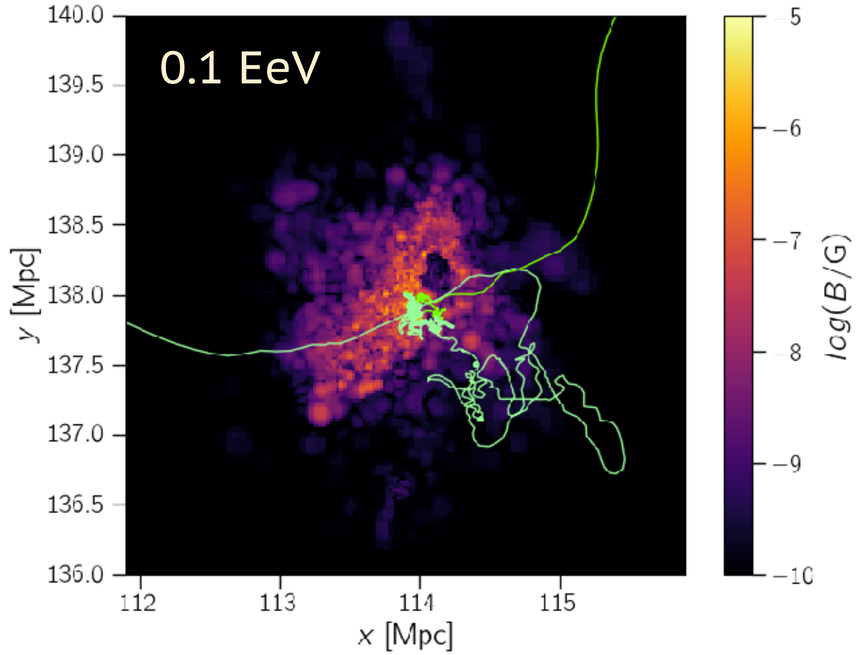
Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. Nature Comms 14 (2023) 2486. arXiv:2203.01260

- high-energy neutrinos are produced via hadronic processes
- cosmic rays are affected by magnetic fields
- rate of CR interactions increases if magnetic fields are strong



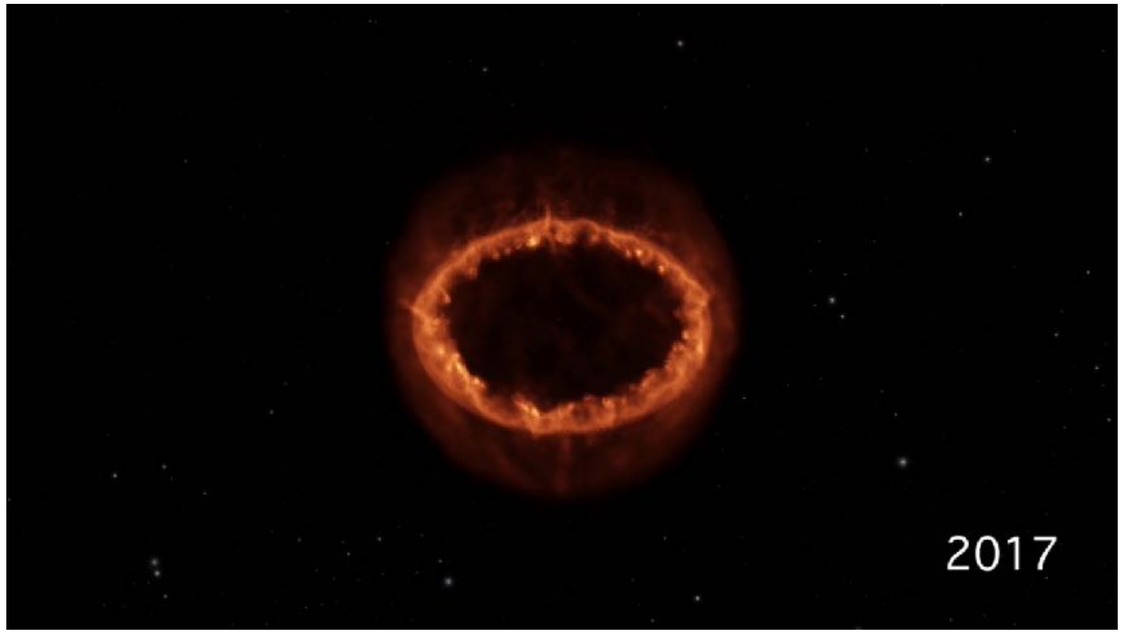


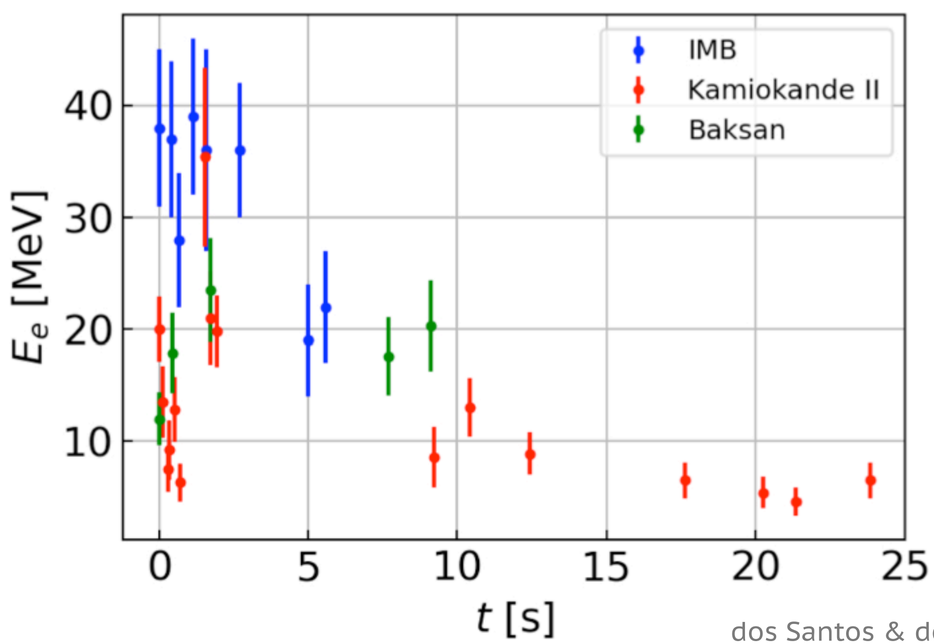


multi-messenger paradigm

a few milestones. SN1987A

event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗



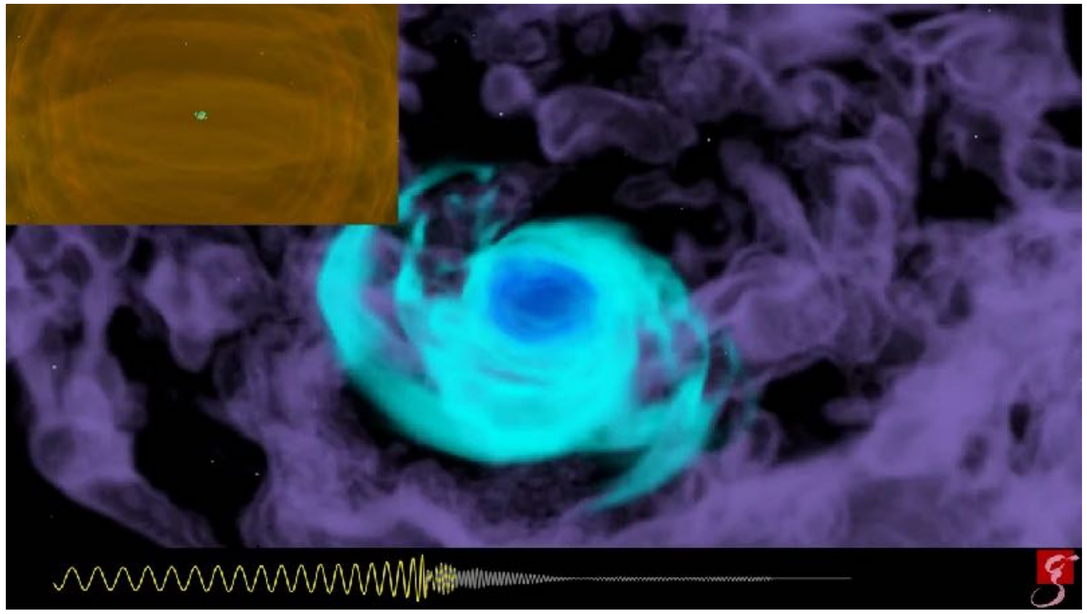


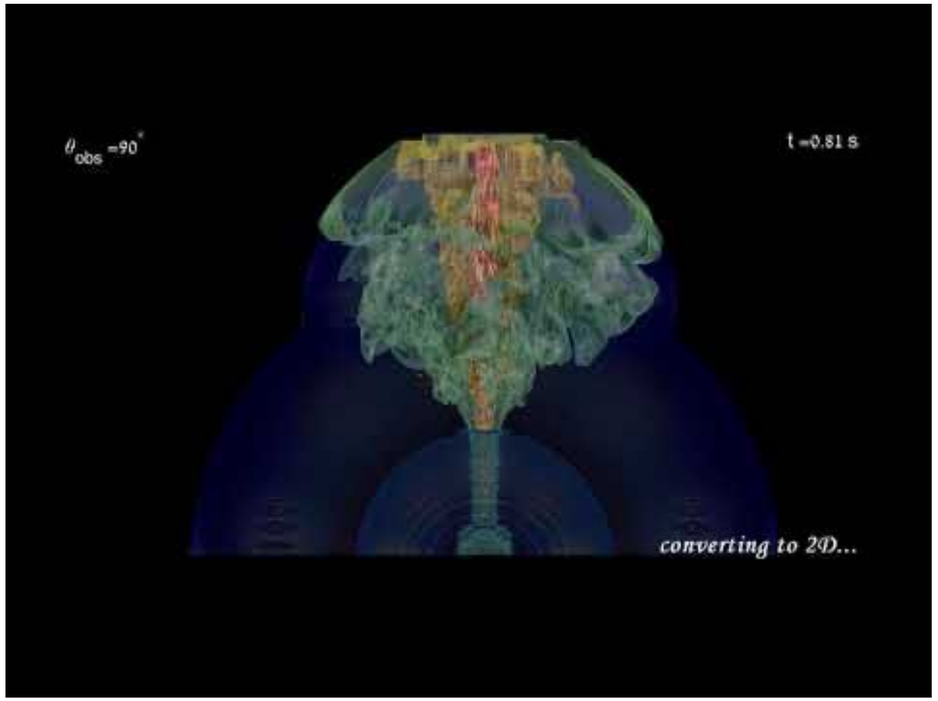
dos Santos & de Holanda. EPJ C 82 (2022) 145. arXiv:2108.06448

a few milestones. GW170817

event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗

https://youtube.com/watch?v=V6cm-0bwJ98



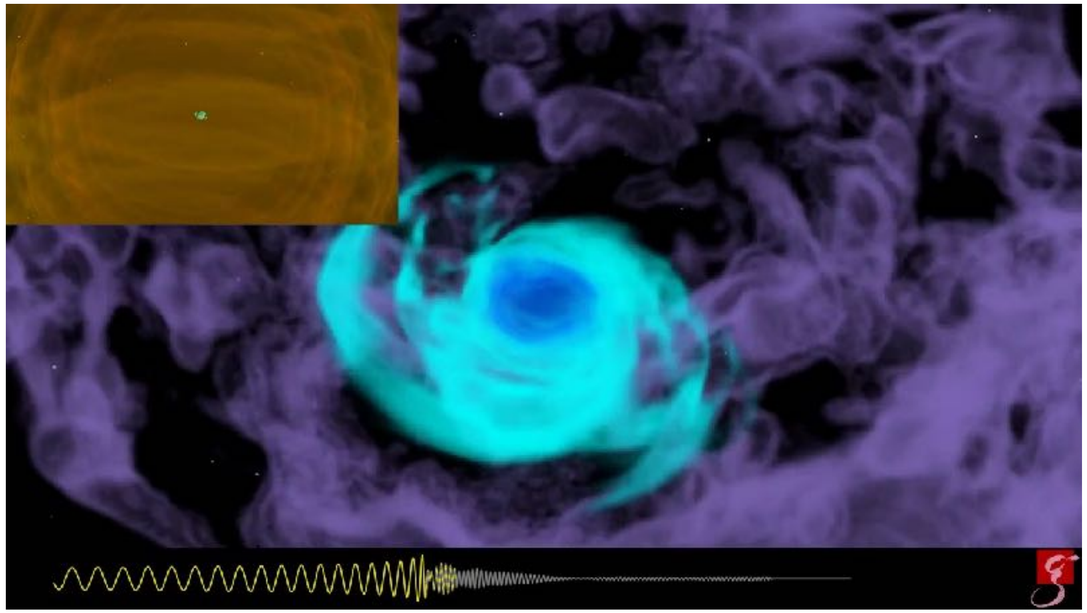


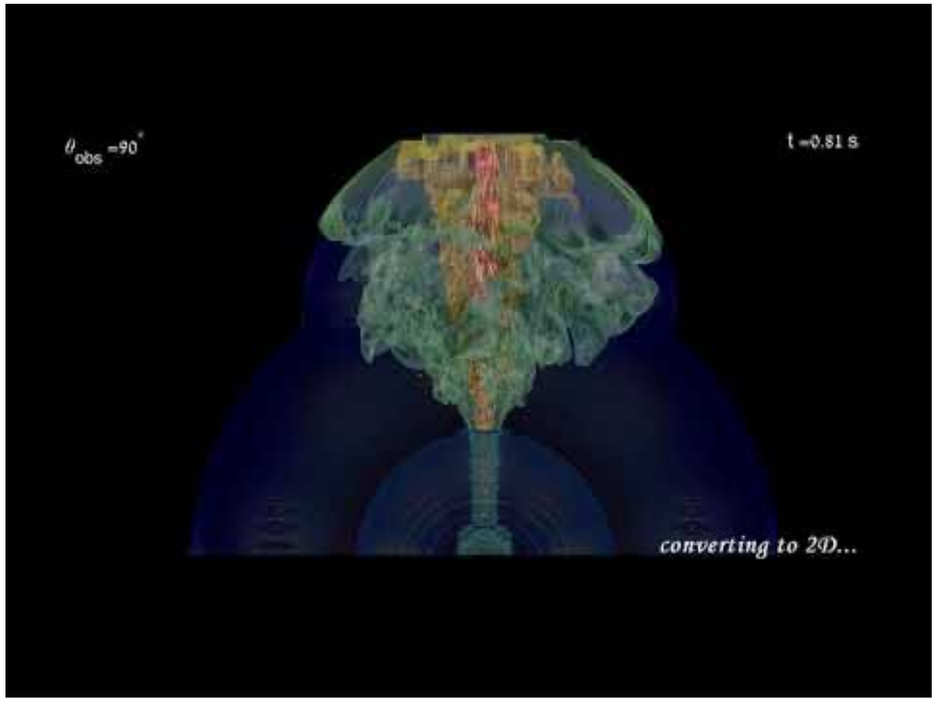
https://www.youtube.com/watch?v=WoxmlY4Odlg

a few milestones. GW170817

event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗

https://youtube.com/watch?v=V6cm-0bwJ98

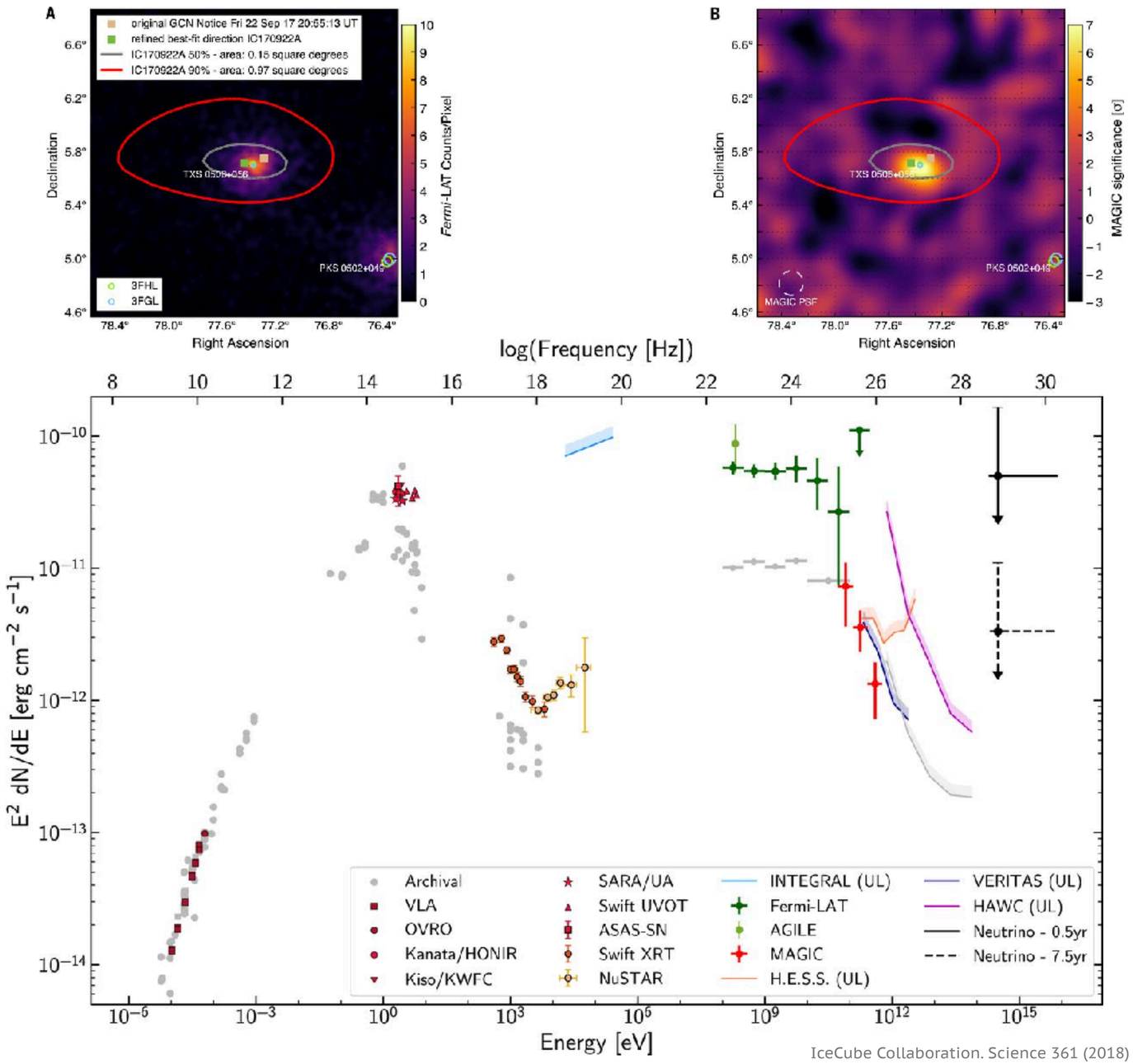




https://www.youtube.com/watch?v=WoxmlY4Odlg

a few milestones. TXS 0506+056

event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗

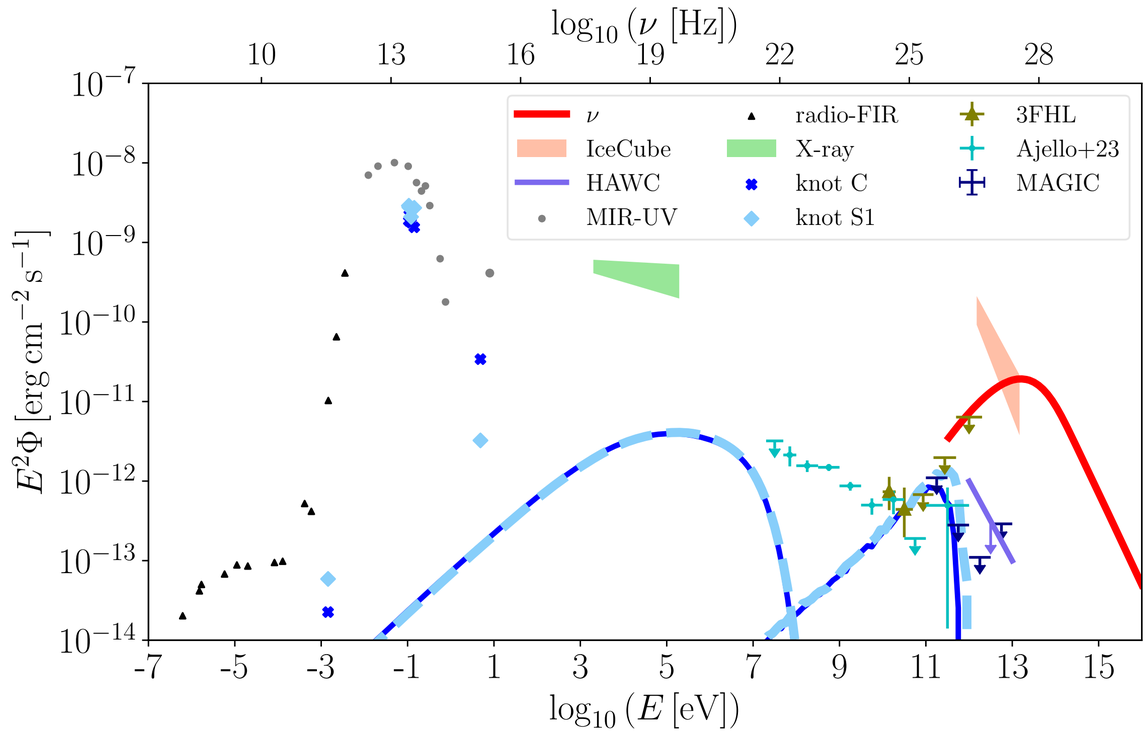


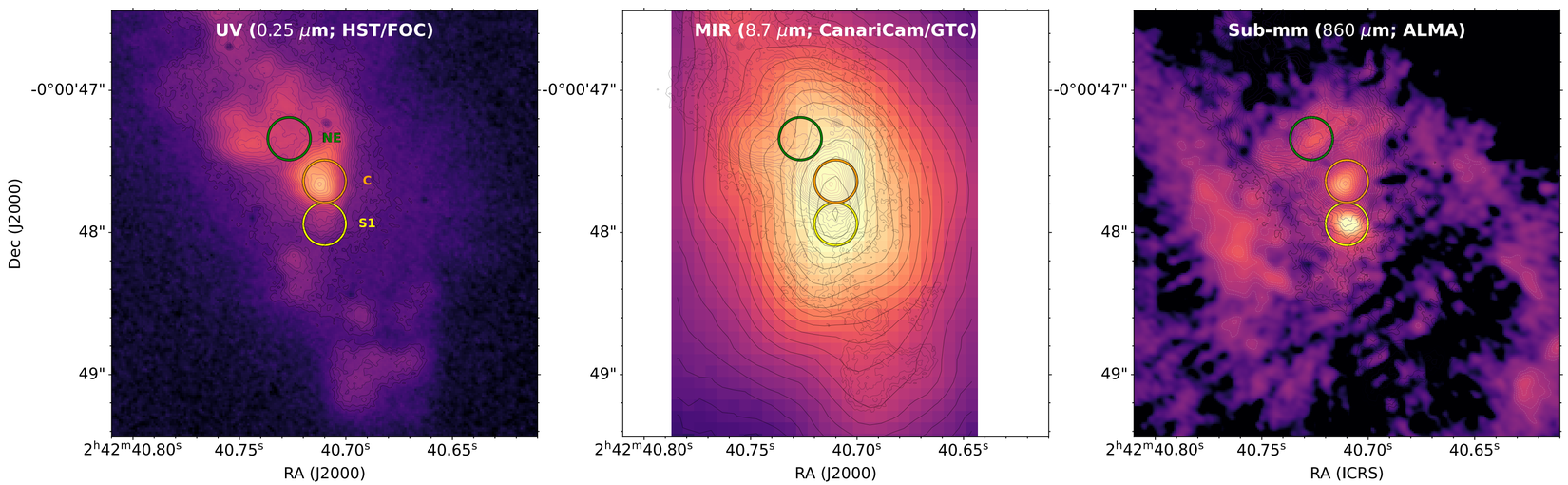
IceCube Collaboration. Science 361 (2018) 147. arXiv:1807.08794

IceCube Collaboration. Science 361 (2018) eaat1378. arXiv:arXiv:1807.08816

a few milestones. NGC1068

event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗

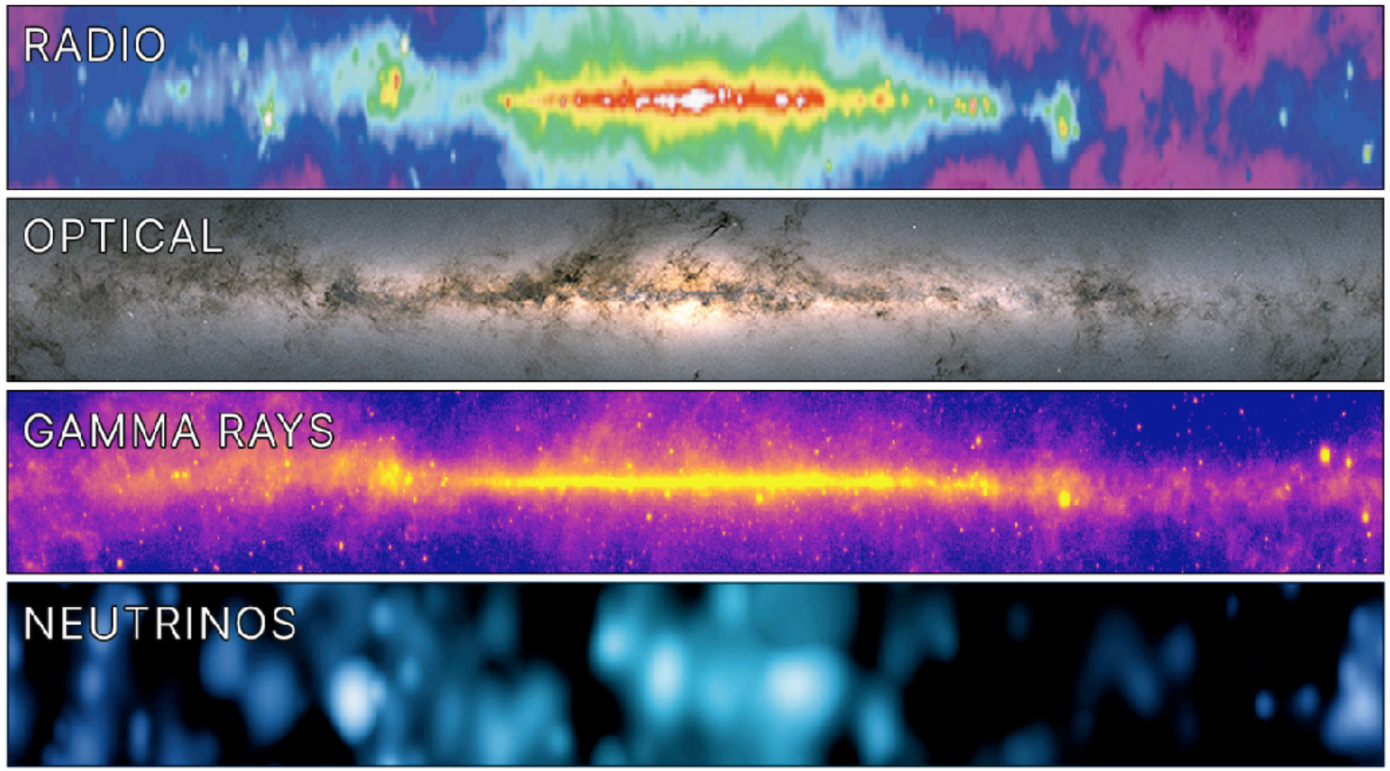


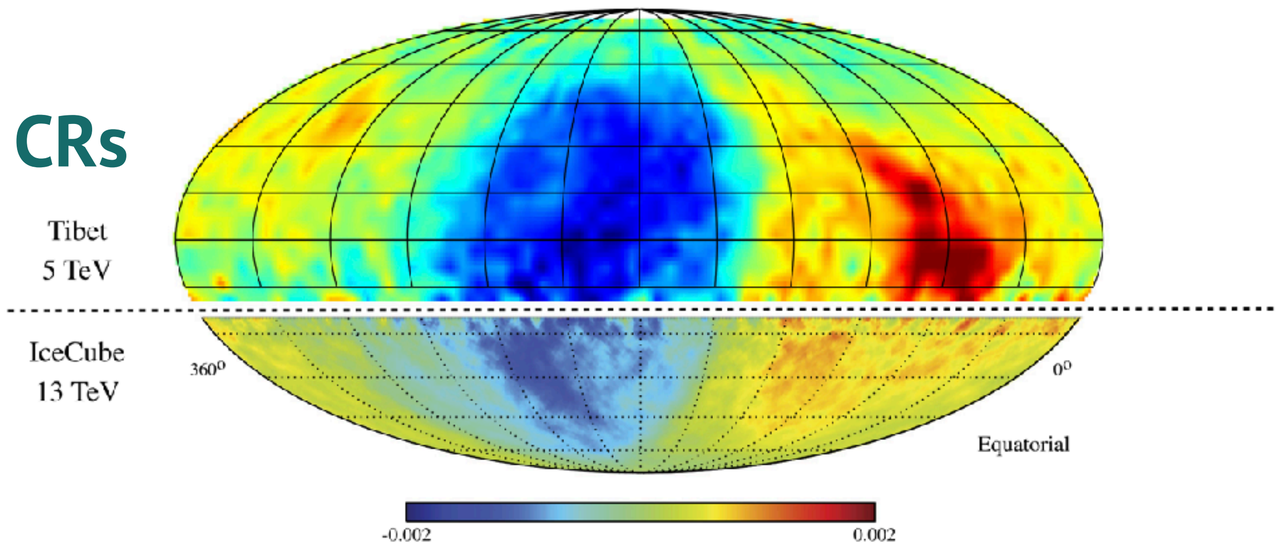


Fang et al. Astrophys. J. 956 (2023) 9. arXiv:2307.07121

a few milestones. Galactic plane

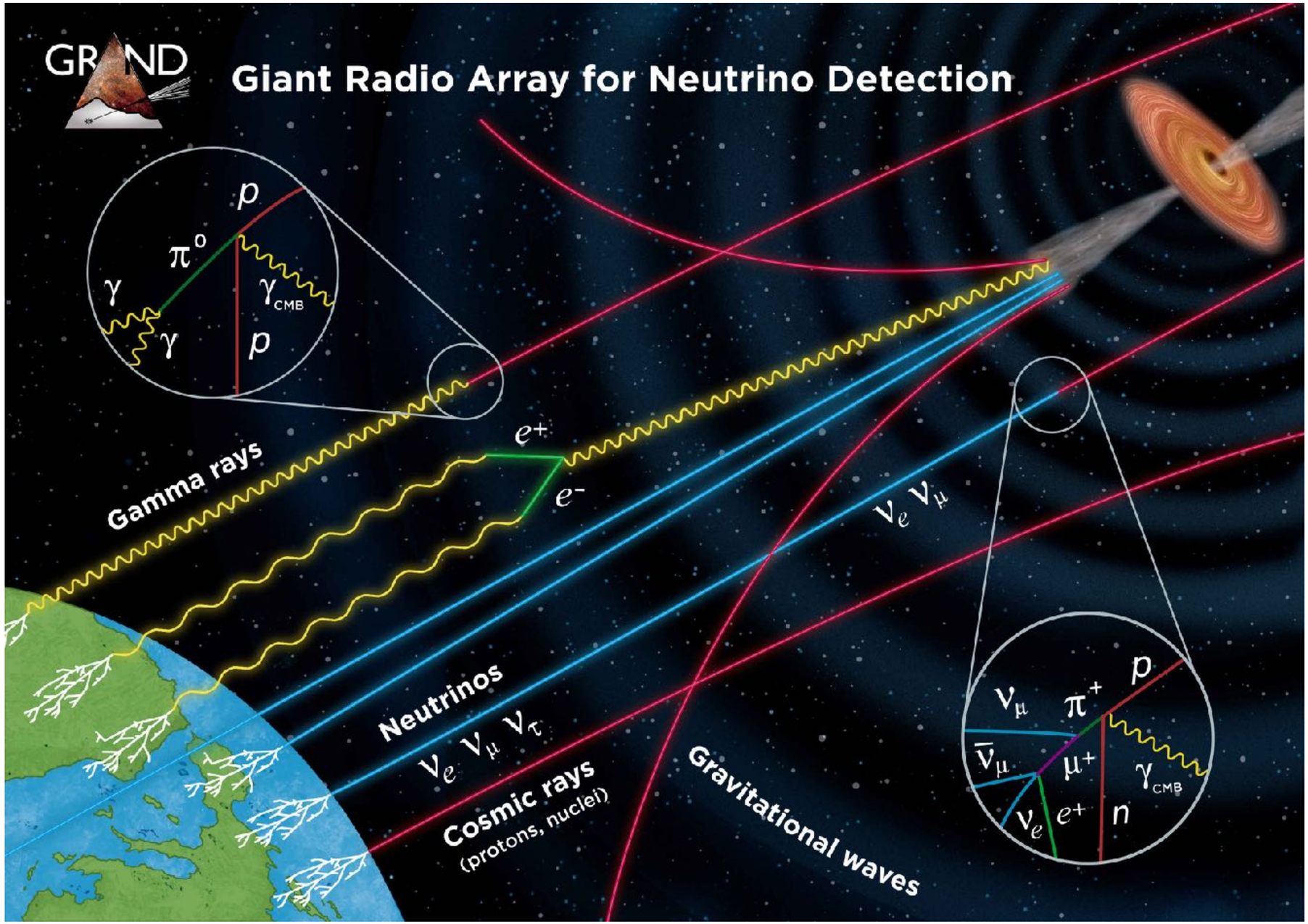
event	EM	CR	ν	GW
SN 1987A	✔	✗	✔	✗
GW170817	✔	✗	✗	✔
TXS 0506+056	✔	✗	✔	✗
NGC 1068	✔	✗	✔	✗
Galactic plane	✔	✔	✔	✗



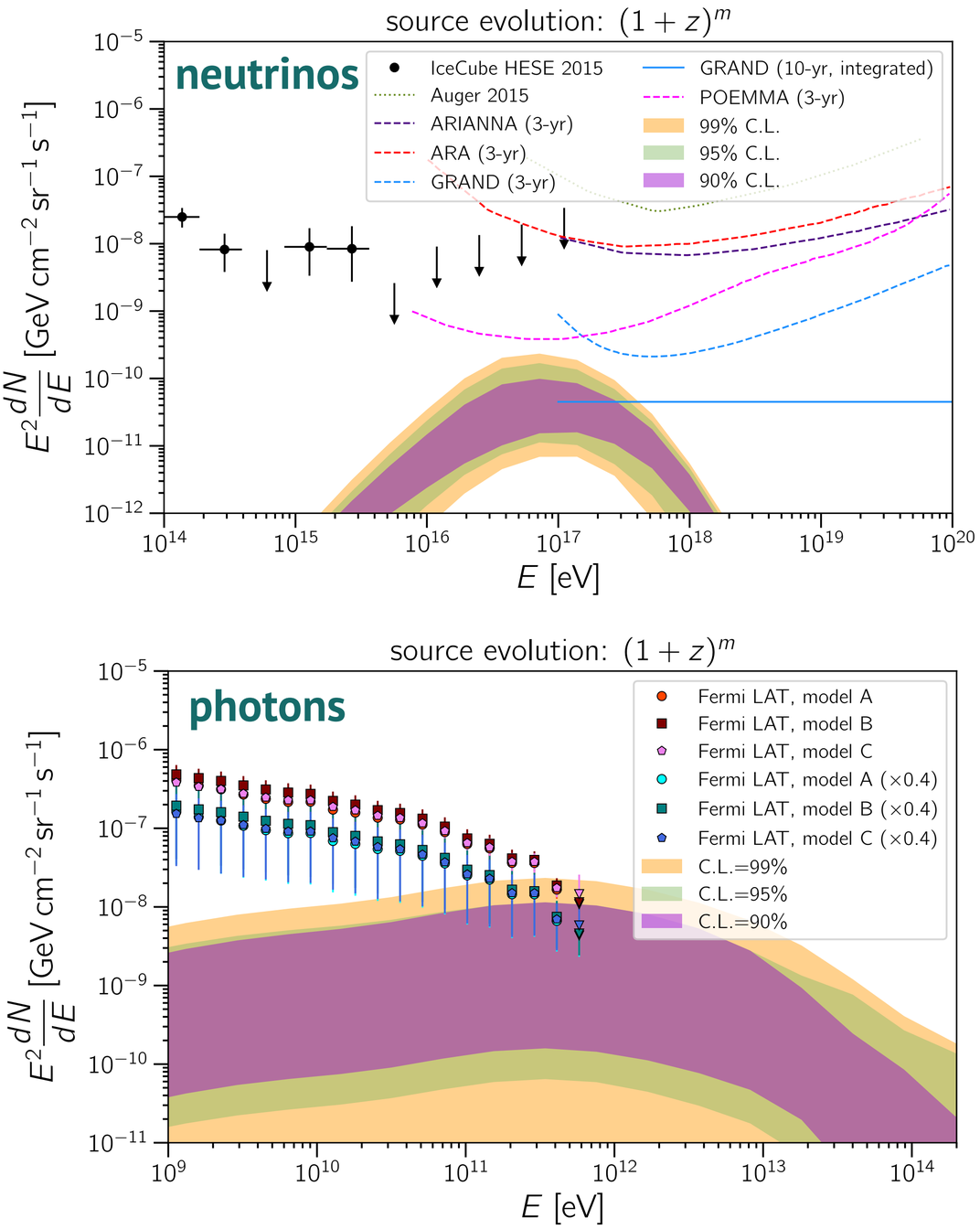


Ahlers & Mertsch. Prog. Part. Nucl. Phys. 94 (2017) 184. arXiv:1612.01873

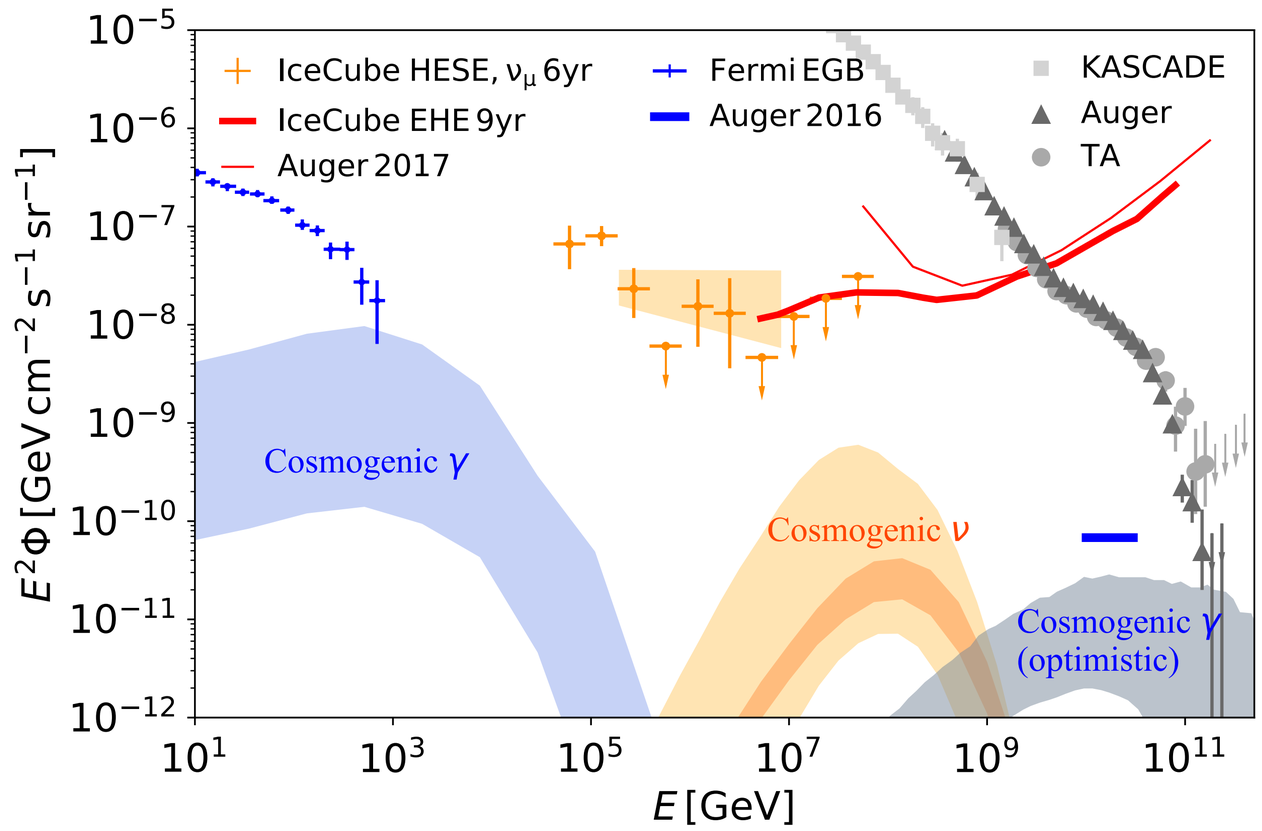
cosmogenic particles



cosmogenic particles



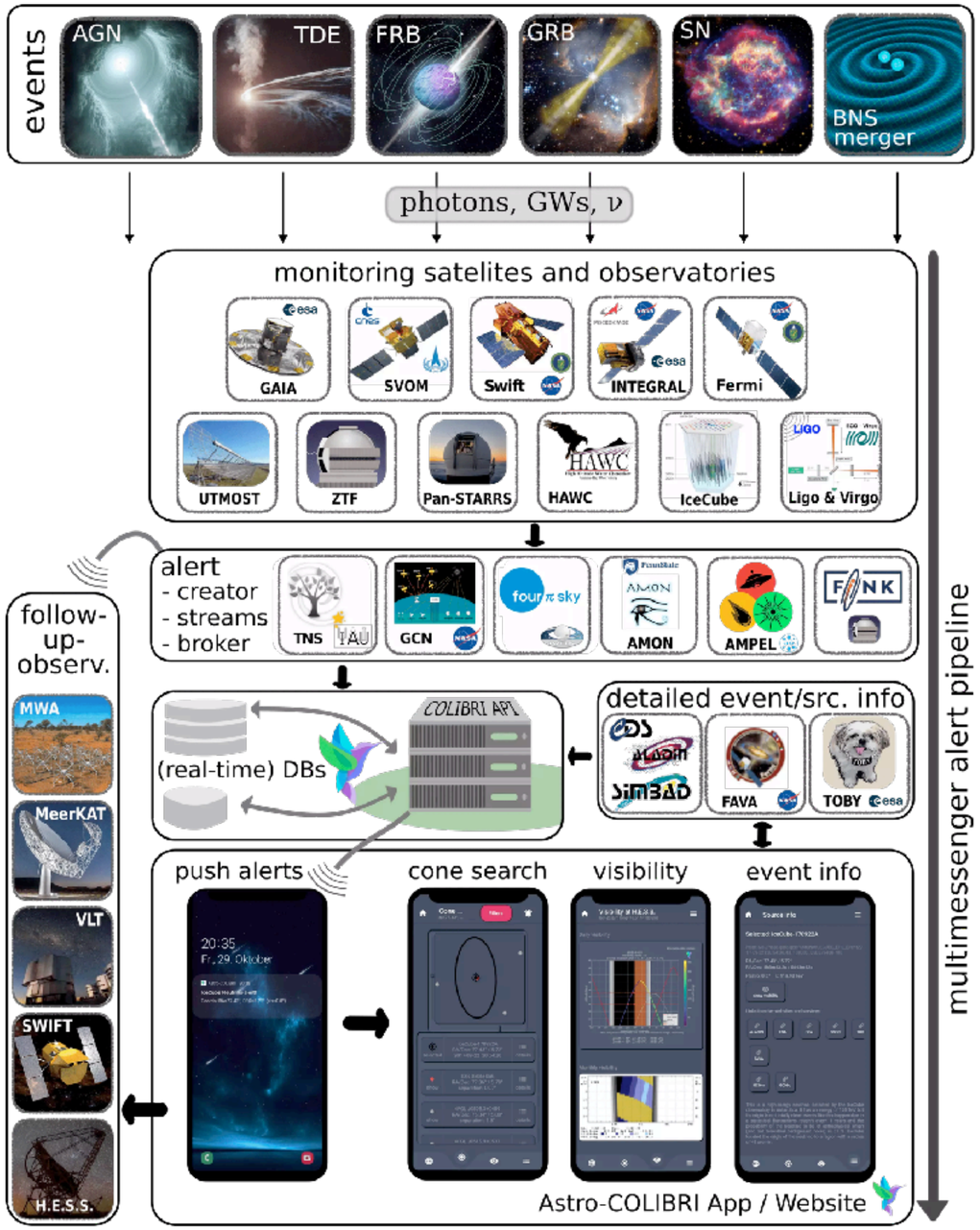
- no cosmogenic neutrinos have been confirmed yet
- only one neutrino with E>100 PeV
- no confirmed detection of cosmogenic photons



Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

multi-messenger networks and alert systems



Astro-COLIBRI