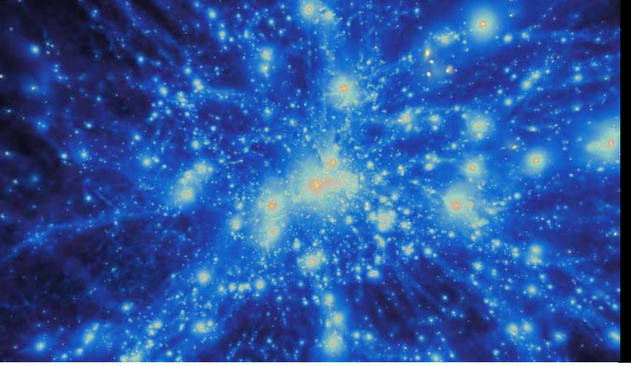
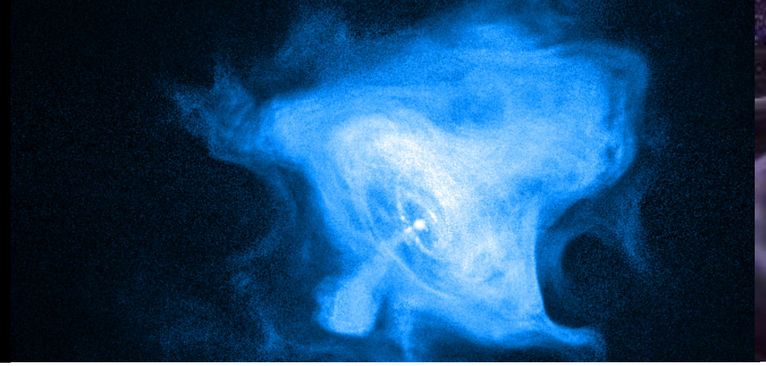





High-energy Neutrinos from Persistent and Transient Activities of Compact Objects

Ke Fang
NHFP Einstein Fellow, Stanford University

36th ICRC, Madison, WI
Jul 26, 2019

Production of High-energy Neutrinos

Photomeson/hadronuclear production $N + \gamma/p \to \pi^{\pm} + X$

Meson & muon decay $\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \to e^{\pm} + \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e)$

Neutron decay $n \to p + e^- + \bar{\nu}_e$

Step 1. Accelerate particles

Step 2. Make them interact

Step 3. Let pion, kaon, muon, neutron decay

To make PeV neutrinos

$$t_\pi^{\pm} \sim 1\,\mathrm{s}$$

$$t_\mu^{\pm} \sim 1\,\mathrm{min}$$

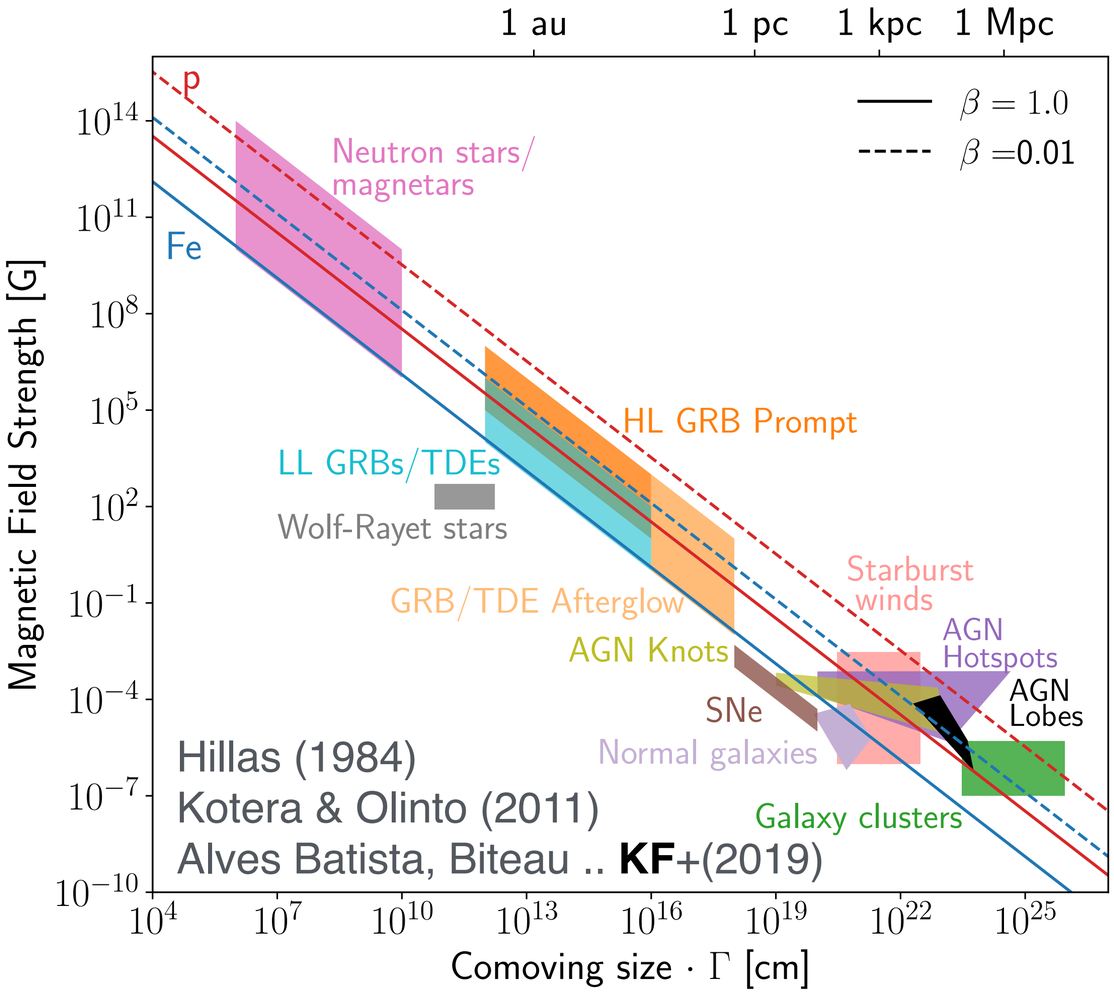
$$t_n \sim 60\,\mathrm{kyr}$$

1. Get the best steak
2. Season it well and cook
3. Rest to serve

The Accelerators

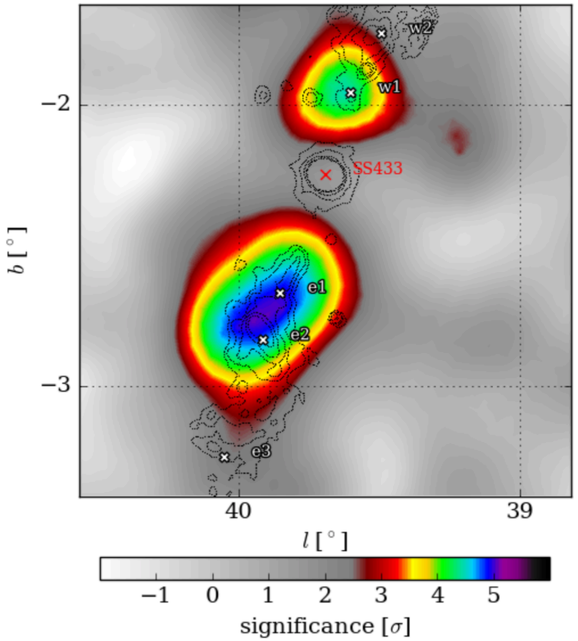
Nature's Accelerators - There are many of them!

Hillas plot:
Larmor radius <
Acceleration region

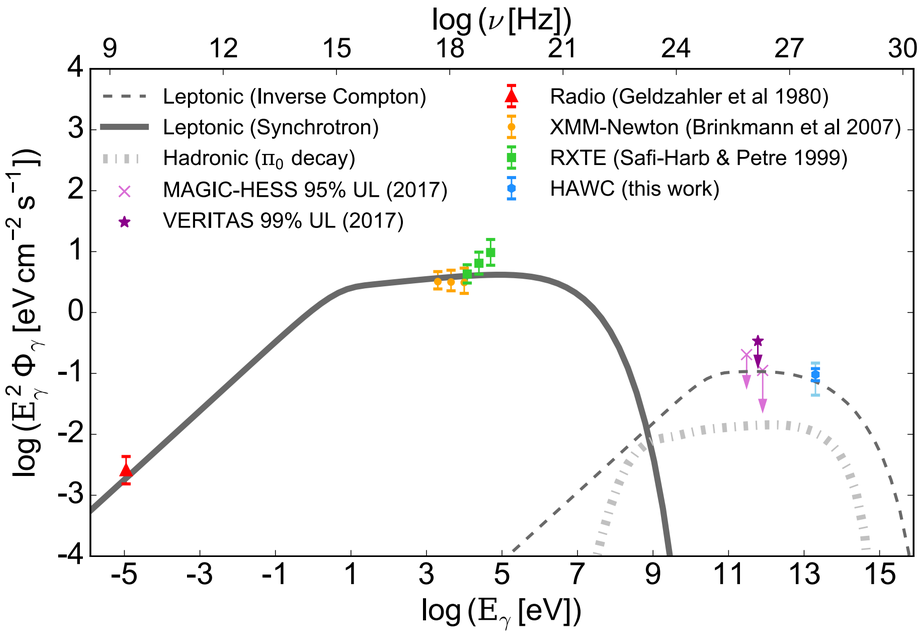


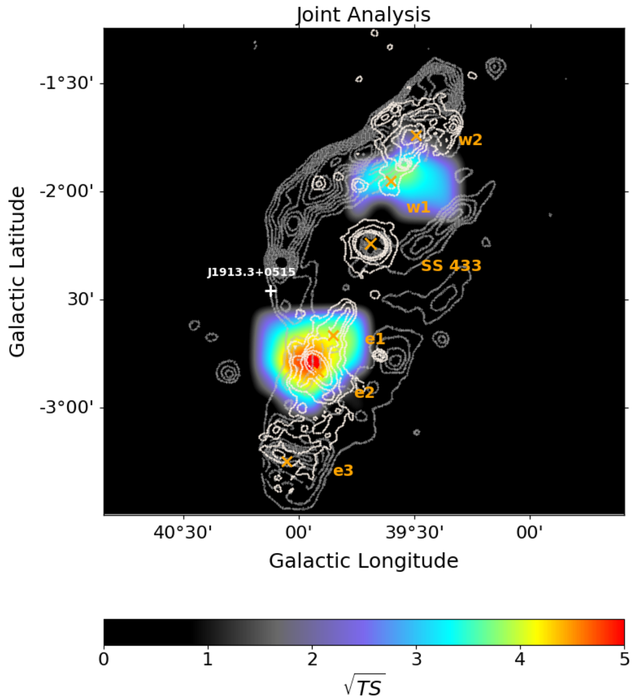
UHECR Energy density ~ $10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}} \sim 10^{51}\,\mathrm{erg} \times 0.1\%\,\mathrm{CCSNe\,rate}$

Known Highest Energy Accelerators - Jets



GeV-to-TeV gamma rays observed from the lobes of SS 433 show that **jets provide promising sites for particle acceleration**



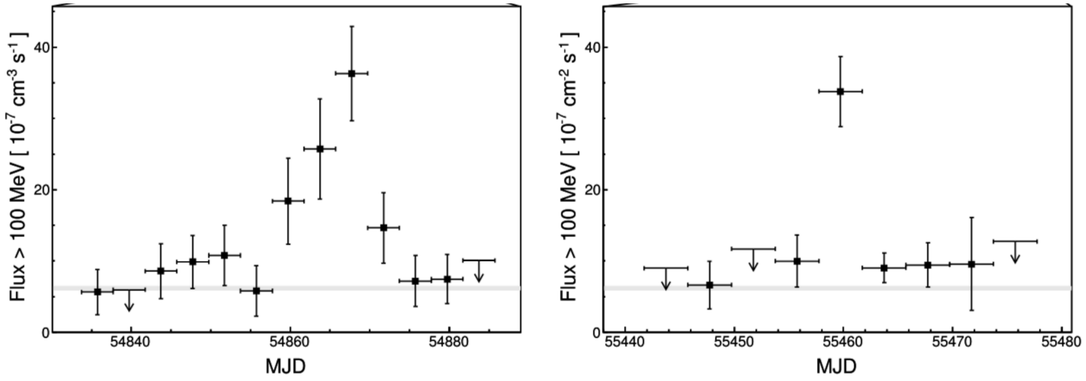


Talk by Rho/Zhou, GAI2f

HAWC Collaboration, *Nature* (2018)
Main authors: BenZvi, Brenda, **KF**, Rho, Zhang, Zhou

KF, Charles, Blandford, Li, *to be submitted*

Known Highest Energy Accelerators - Pulsars Wind Nebulae



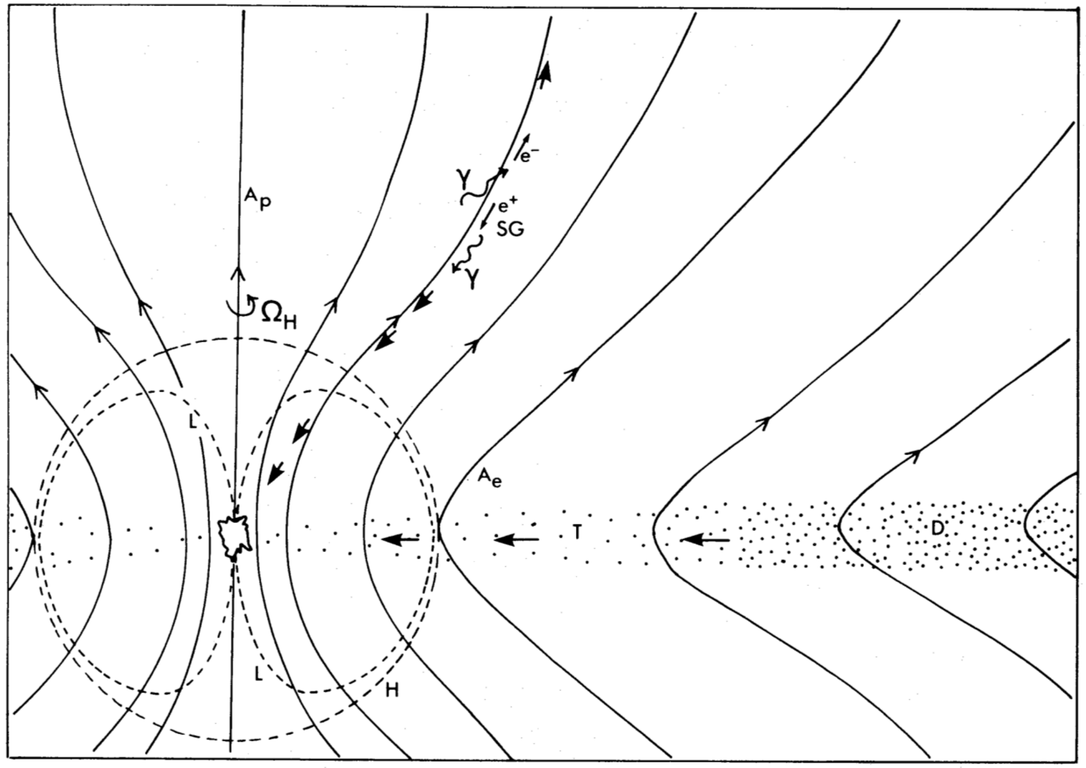
Day-week long GeV flares in the crab nebula -> PeV electrons

Fermi Collaboration, Science (2011)

Nature's Accelerators - How do they function?

Electromagnetic extraction of energy from spinning black holes

Blandford & Znajek (1977)

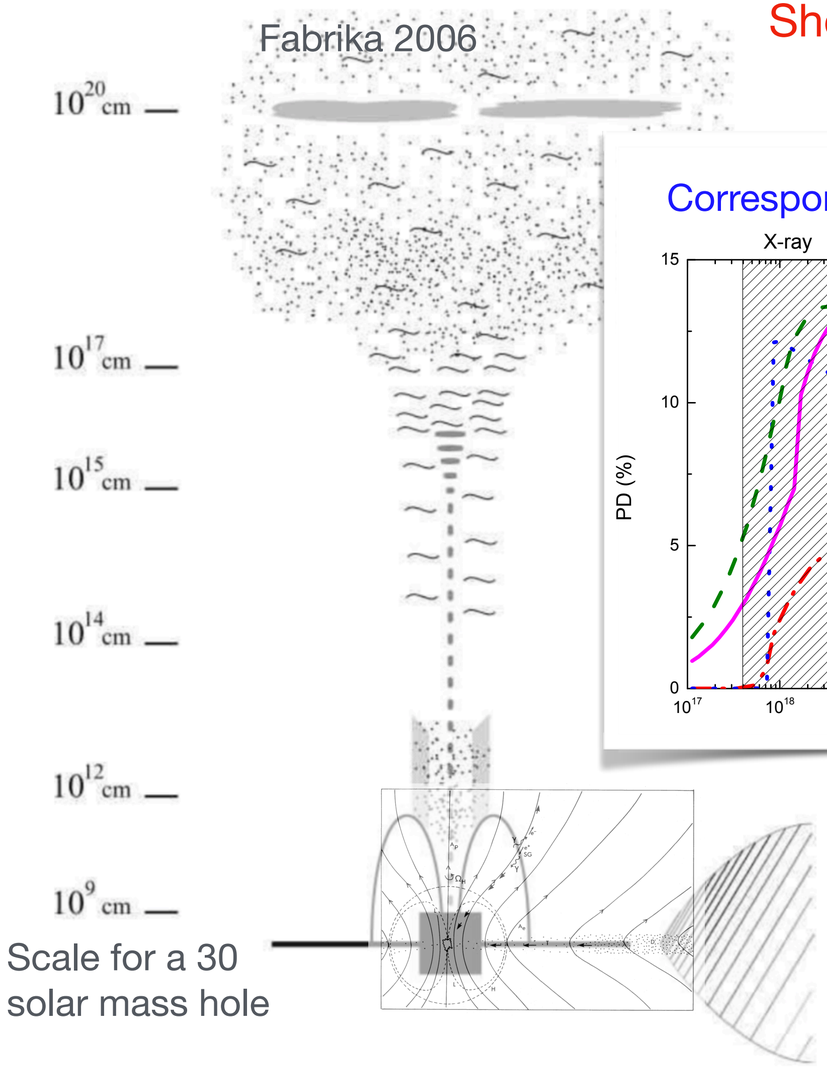


Voltage provided by hole

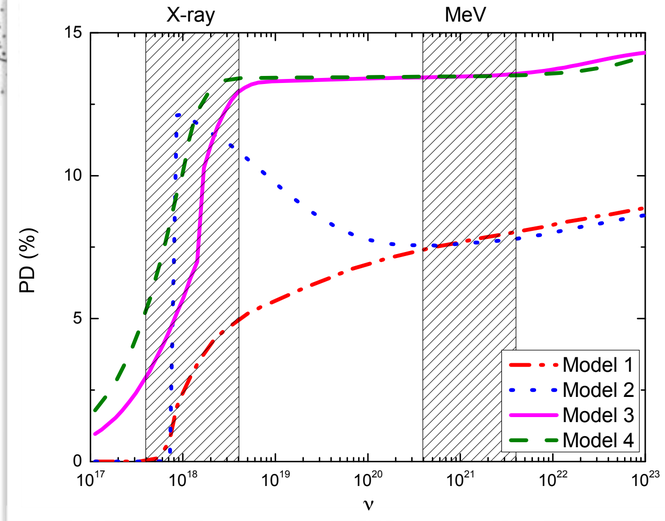
$$V \sim (50\, L_{\rm jet})^{1/2} \sim 10 \left(\frac{L_{\rm jet}}{10^{37}\,{\rm erg\,s^{-1}}} \right) {\rm PV}$$

Nature's Accelerators - How do they function?

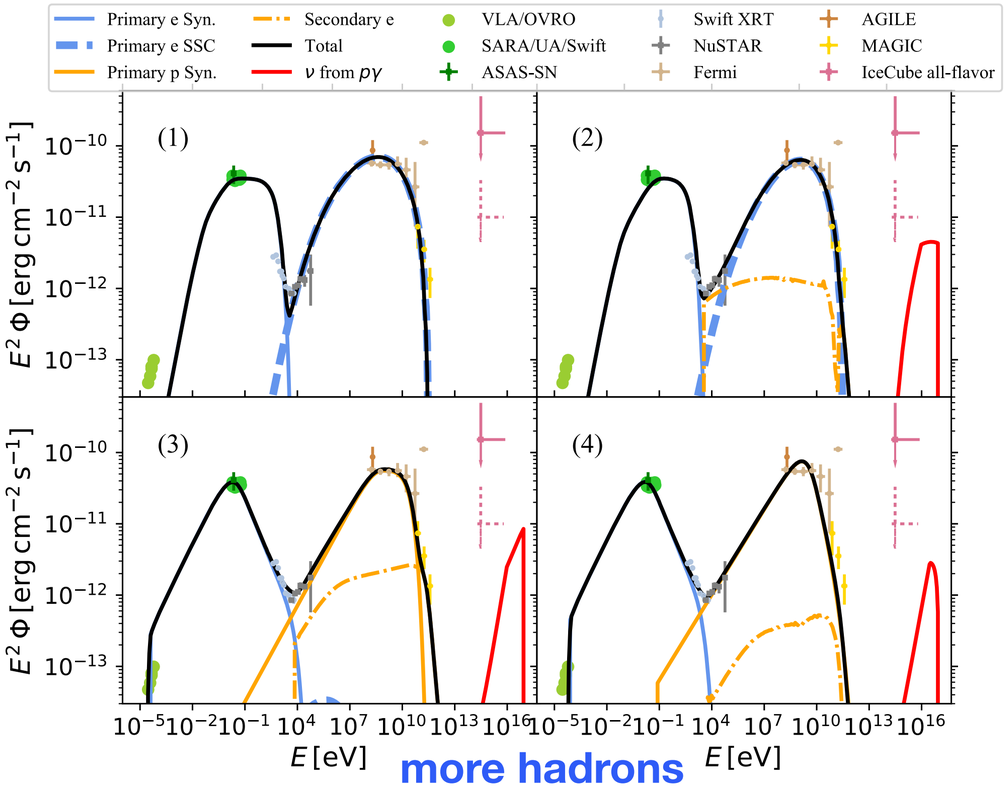
Shocks vs Magnetic fields? Pairs vs Hadrons? **Neutrinos + Polarization!**



Corresponding polarization levels



TXS 0506+056 SED



more hadrons

Zhang, **KF**, Li, Giannios, Bottcher, Buson ApJ (2019)

Poster by Zhang, 261

The Interaction

Neutrinos, Gamma-rays and Their Parents

Photomeson/hadronuclear production

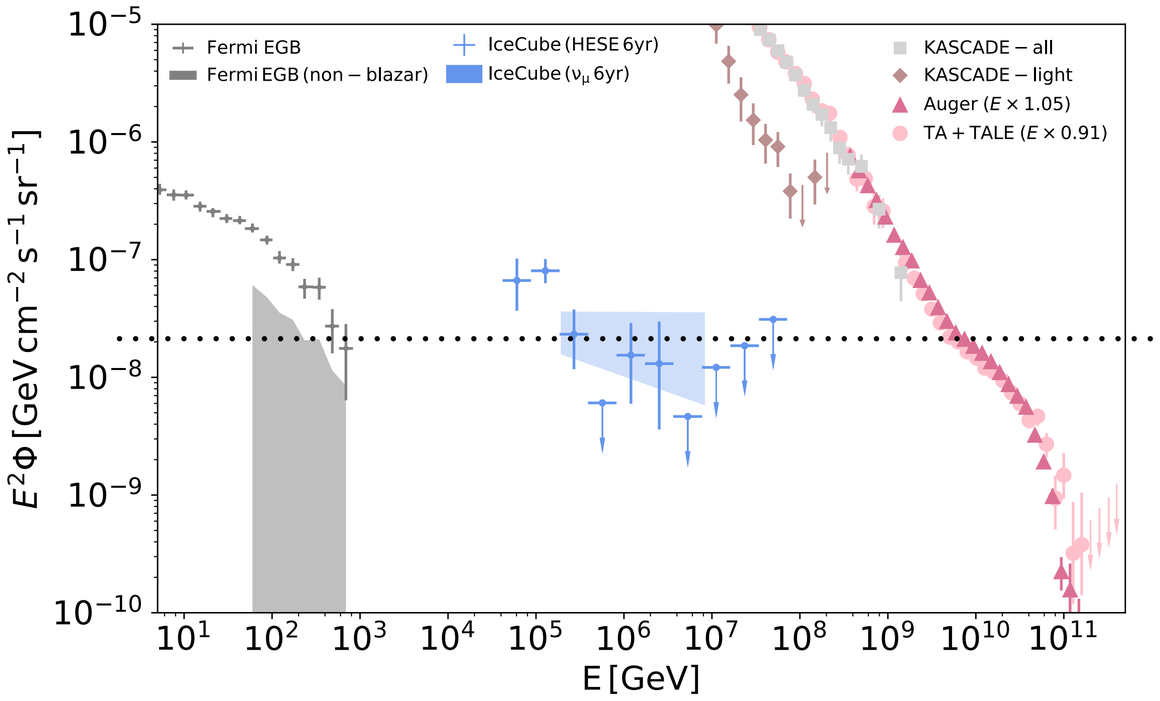
$$N + \gamma/p \to \pi^{\pm} + X$$

$$N + \gamma/p \to \pi^{0} + X$$

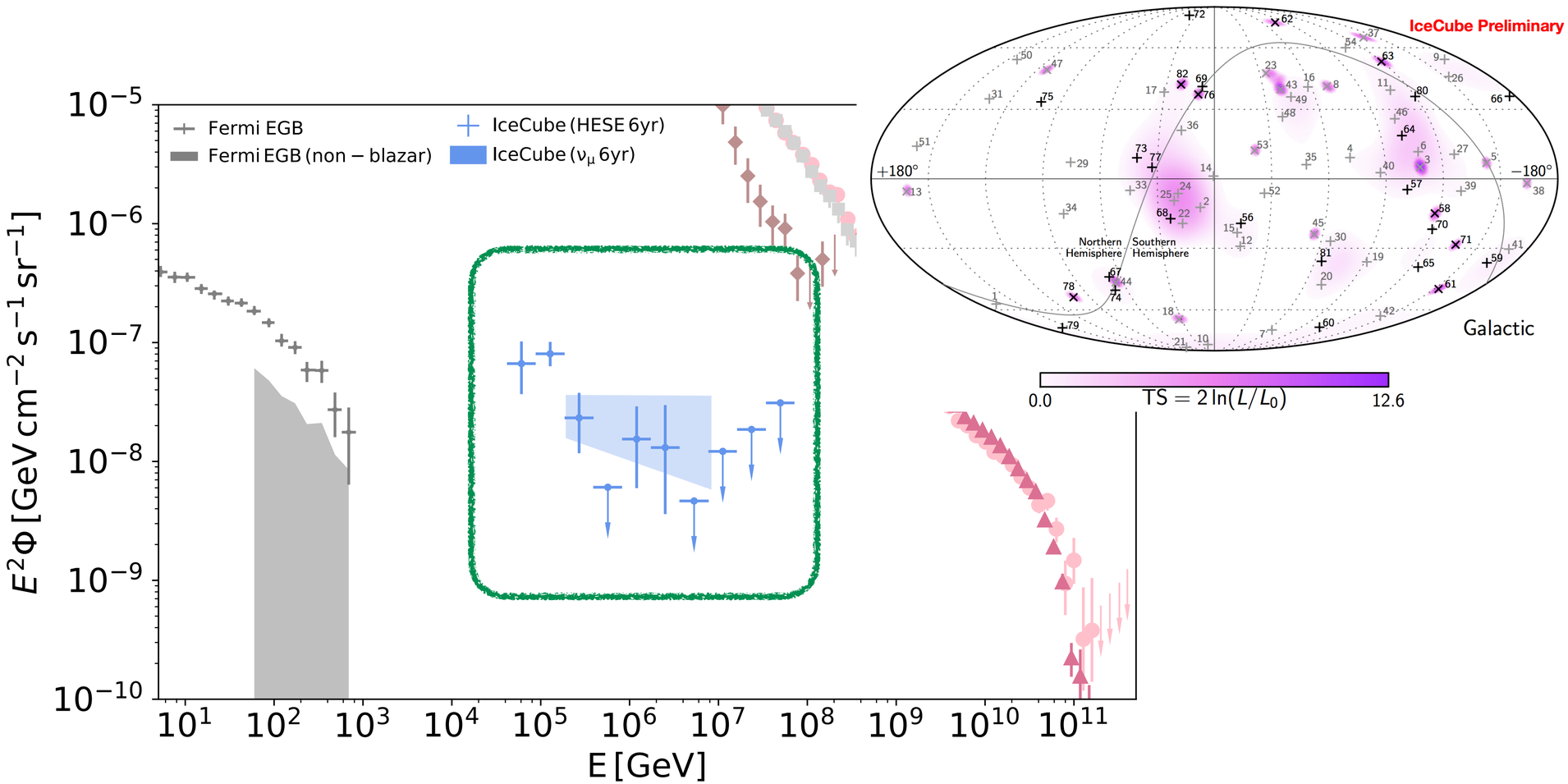
Meson & muon decay

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \to e^{\pm} + \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e})$$

$$\pi^{0} \to 2\gamma$$



Neutrinos, Gamma-rays and Their Parents



Talk by Halzen, RE1

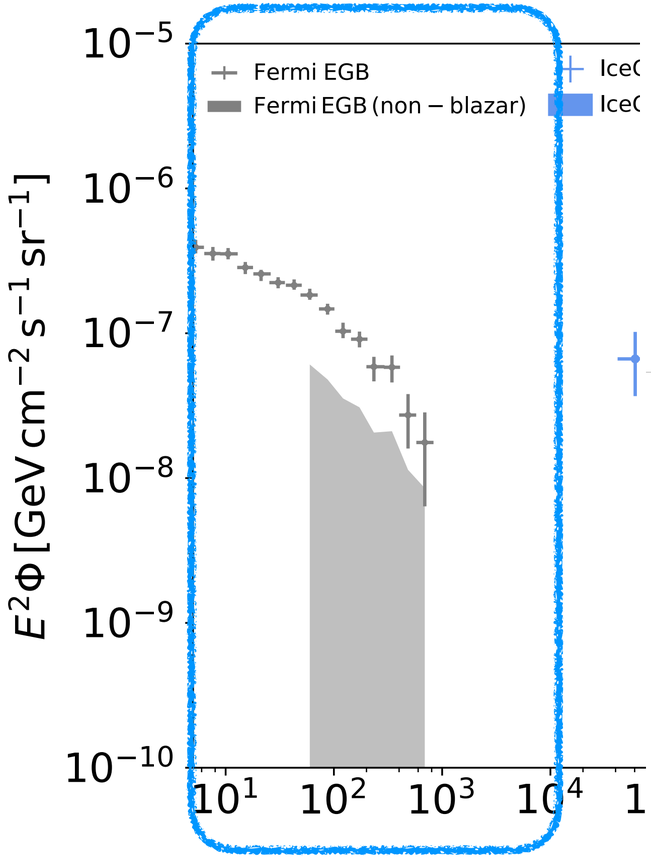
Sources of High-energy Neutrinos?

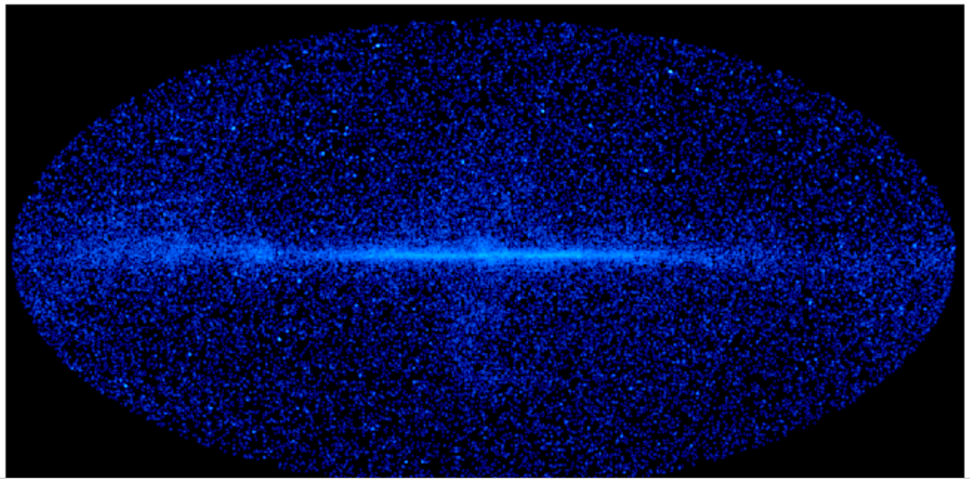
Papers on arXiv searched with keyword “IceCube neutrinos”, from Jul 17 to Jul 19 (**apologize for incompleteness**):

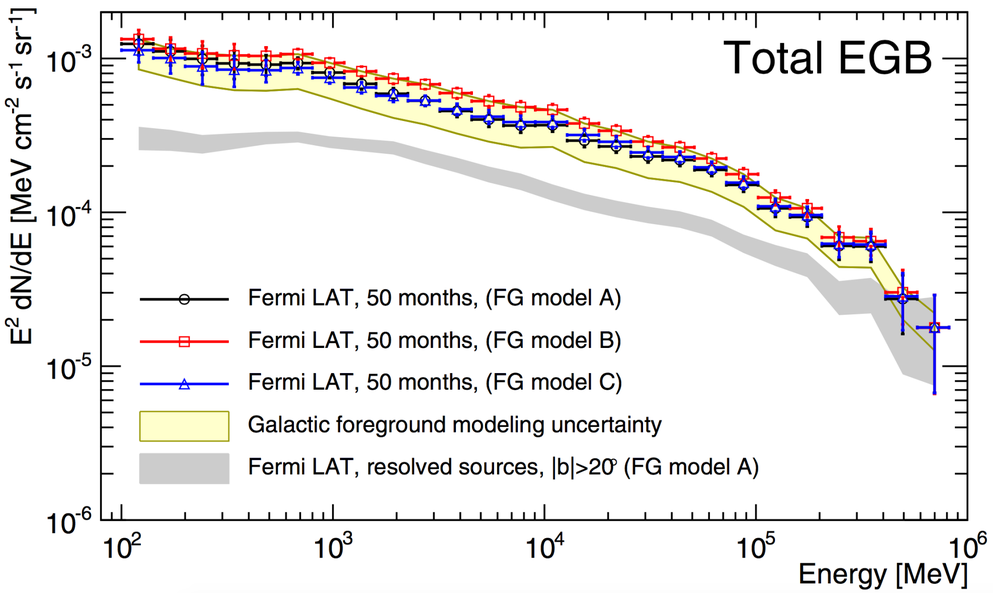
Blazars and flares: Oikonomou+19, Zhang, KF+19, Rodrigues+19, Reimer+19, Halzen+18, Cerruti+18, Wang+18, Sahakyan18, He+18, Belhaj & Ennadifi18, Righi+18, IceCube 18ab, Liao+18, Liu+18, Murase+18, Keivani+18, Cerruti+18, Ansoldi+18, Righi+18, Gao+18, Rodrigues17
AGN cores, AGN outflows, radio galaxies: Murase+19, Rodriguez-Ramirez+19, Hooper+18, Padovani+18, Richter & Spanier 18, Osmanov+18, Liu+17, Tavecchio+17, Lamastra+17, Blanco & Hooper17
GRBs, LLGRBs, Huang & Ma18,Wang+18, Zhang+17, Thomas+17, Xiao+17, Biehl+17
Choked jets: Guetta+19, Esmaili & Murase18, He+18, Denton & Tamborra18, 17
Starbursts: Lunardini+19, Palladino+18
TDEs Guepin,.. KF+17, Daniel+17
Galaxy clusters, mergers: KF & Murase 18, Yuan+17
Neutron Star Mergers: Kimura+18, ANTARES, IceCube, Auger 17, Kimura+17, KF & Metzger 17
FRB: IceCube 17
Minute-Scale transients, IceCube 18
Galaxy/Galactic: Blasi & Amato19, Marinelli+19, ANTARES & IceCube 18, Liu+18, Merten+18, ANTARES 17
Supernovae: Hansen+19, Choi+19, Heurtier+19, Alvey & Fairbairn 19, Li 18, Takiwaki & Kotake17, Bykov+17Senno+17, Petropoulou+17, Murase17
Individual sources: **NGC 1068** MAGIC Coll. 19, **SS 433** Reynoso & Carulli 19, **AT2018cow**: KF+19, **Fermi Bubbles**: Yang & Razzaque 18ab, Sherf+17, KF+17, **Cen A**: de Vries +17, **Cygnus-X** Guenduez17
Heavy Dark Matter/Beyond Standard model: Pandey+19, Hooper+19, Bhattacharya+19, Lambiase19, Murase & Shoemaker 19, Xu18, Aoki & Toma18, Denton & Tamborra 18, Kachelriess+18, Lambiase & Stabile 18, Bhadra & Banik18, Dhuria & Rentala17, Zhao, KF+17, Hiroshima+17

Neutrinos, Gamma-rays and Their Parents

Fermi Collaboration, PRL (2016)
Lisanti + ApJ (2016)

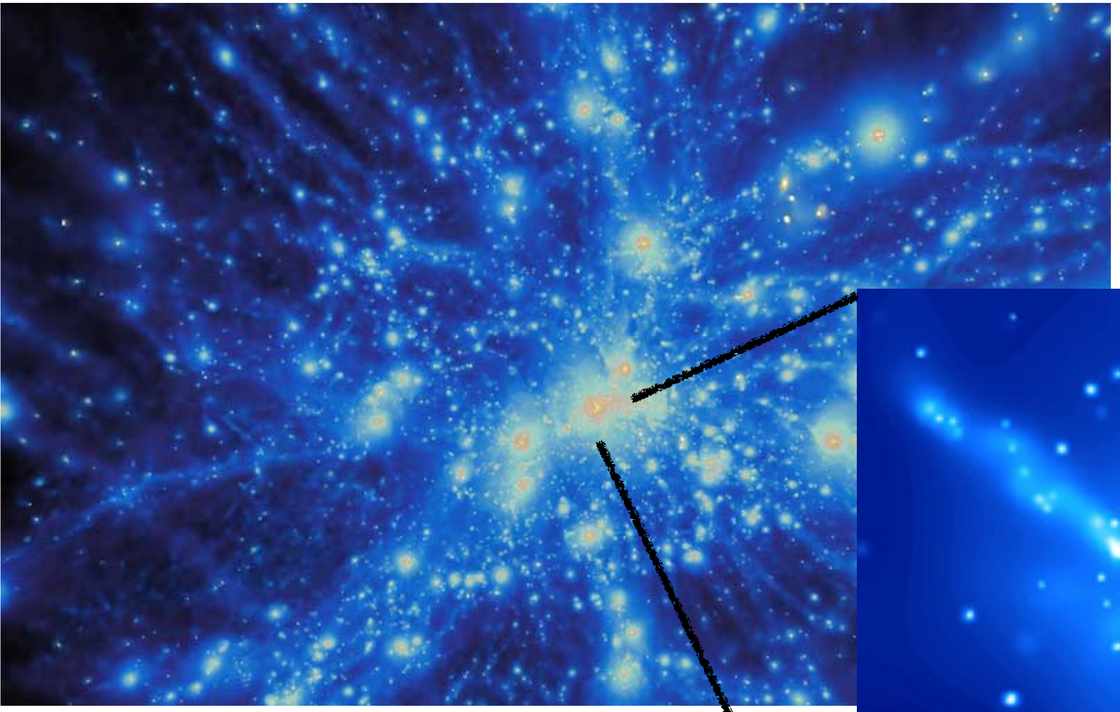


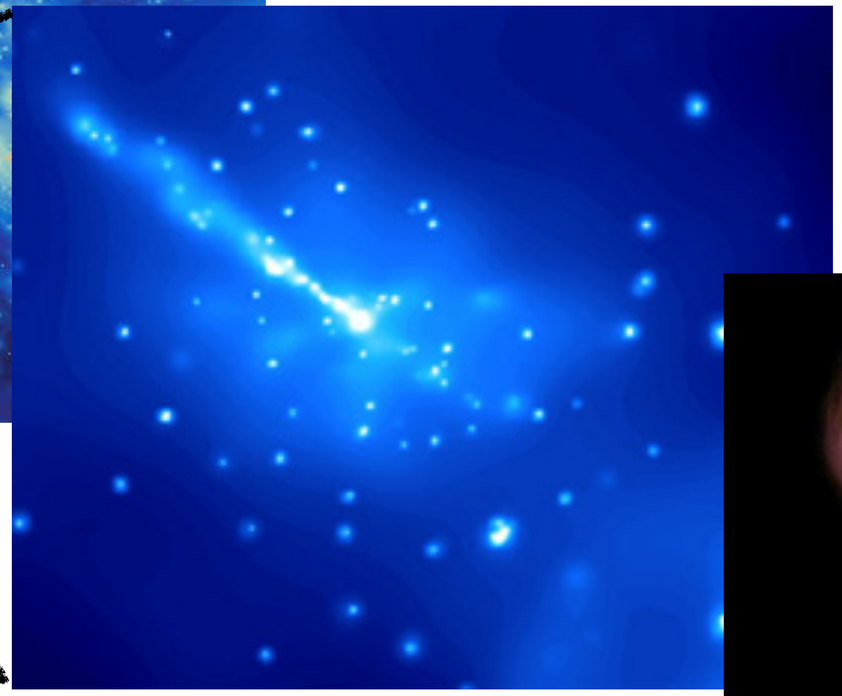


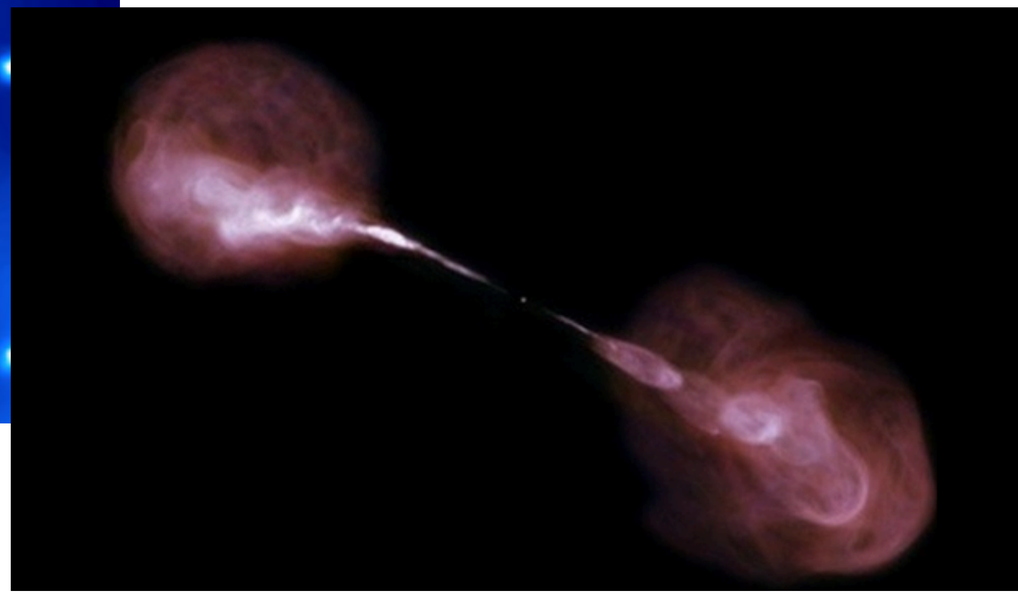


~14% of the Fermi extragalactic gamma-ray background is contributed by unknown sources.

Jets Inside Galaxy Clusters







Modeling the Intracluster Medium

ICM gas

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

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

[Cavaliere & Fusco-Femiano, A&A (1976)]

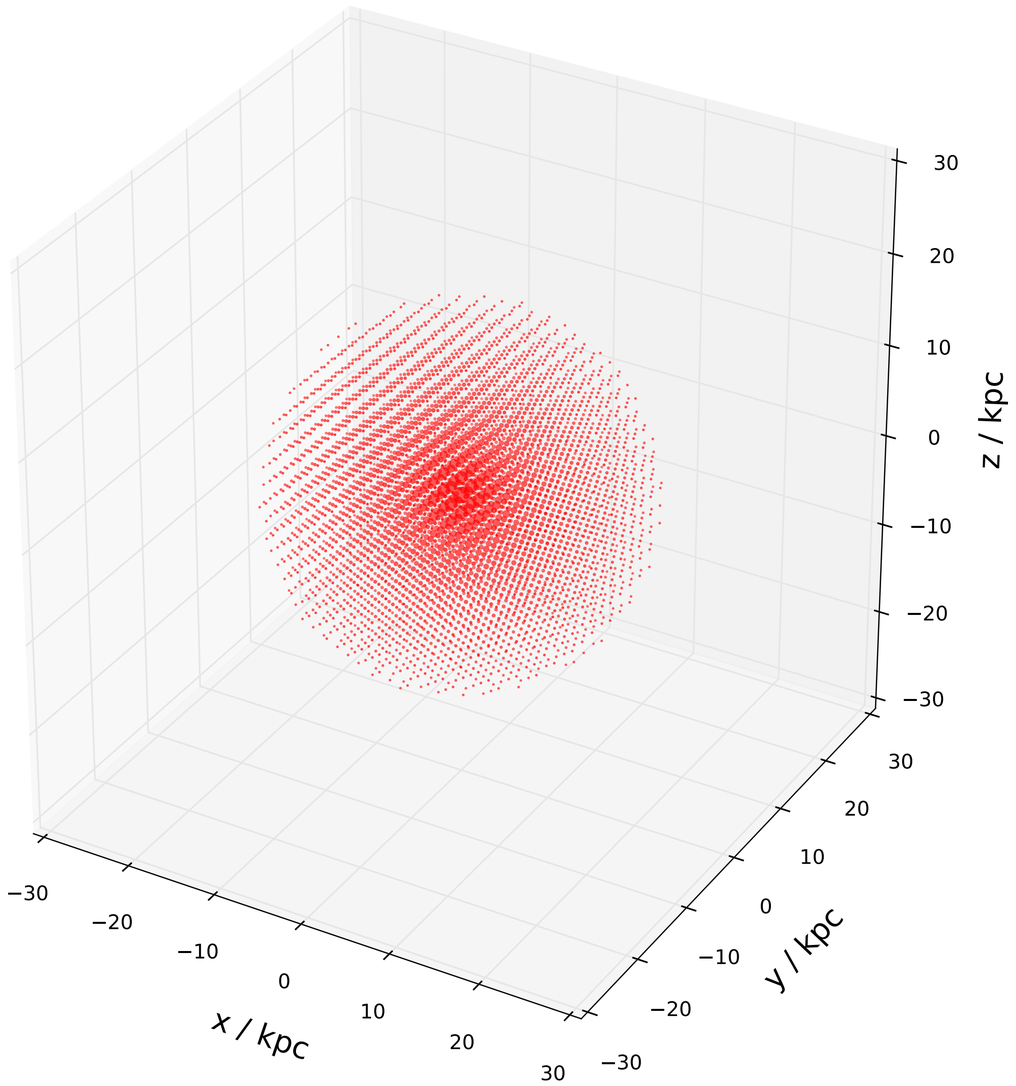
Infrared background from galaxies
[Takami & Murase ApJ 2012]

CMB, EBL

CRPropa3 + SOPHIA for turbulent field & $N\gamma$
[Alves Batista+ JCAP (2016)]

EPOS for Np
[KF, Kotera & Olinto ApJ (2012)]

Diffuse propagation
[Kotera & Lemoine PRD (2007), KF & Olinto ApJ (2016)]



Particle Trajectory in the Intracluster Medium - 10 EeV

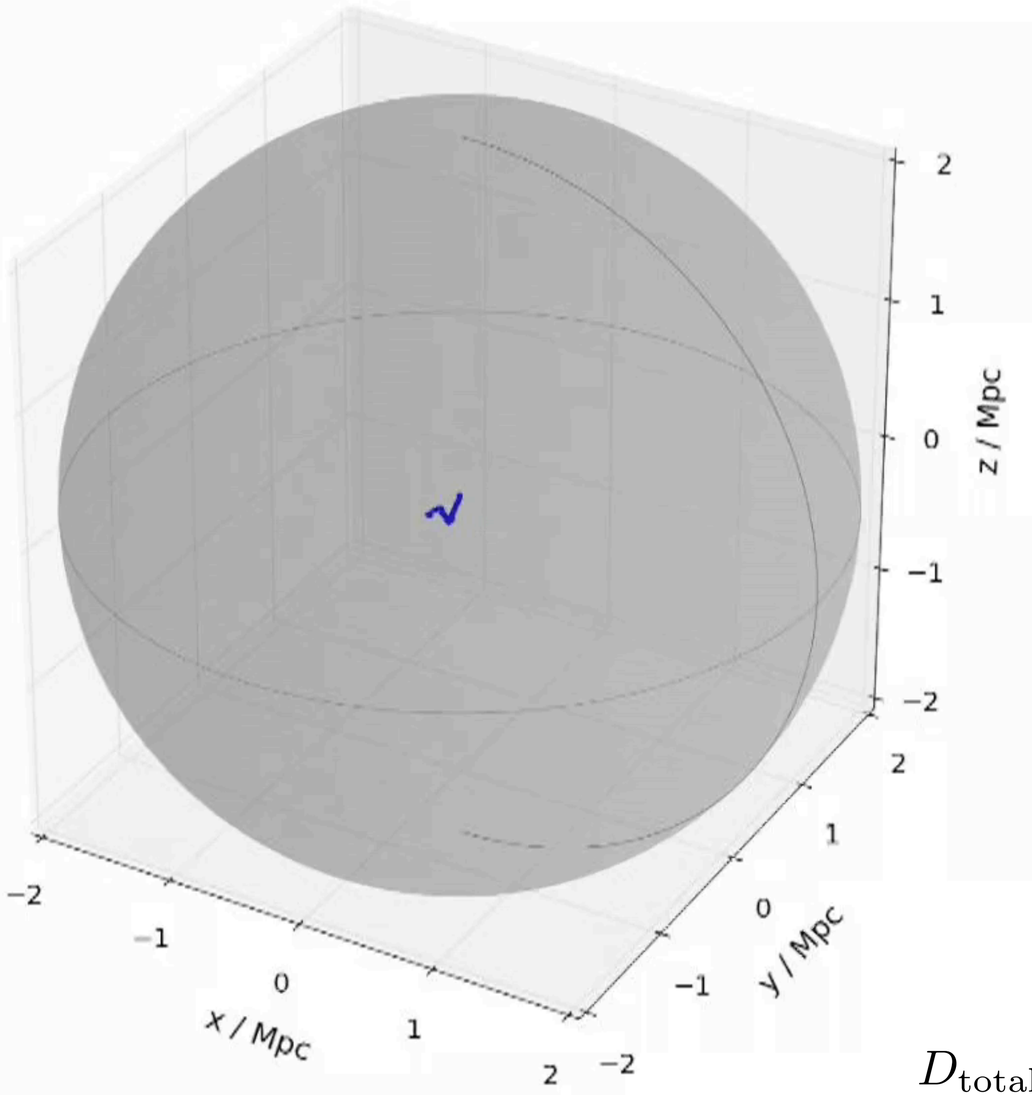
Particle Larmor Radius

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

Field Coherence Length

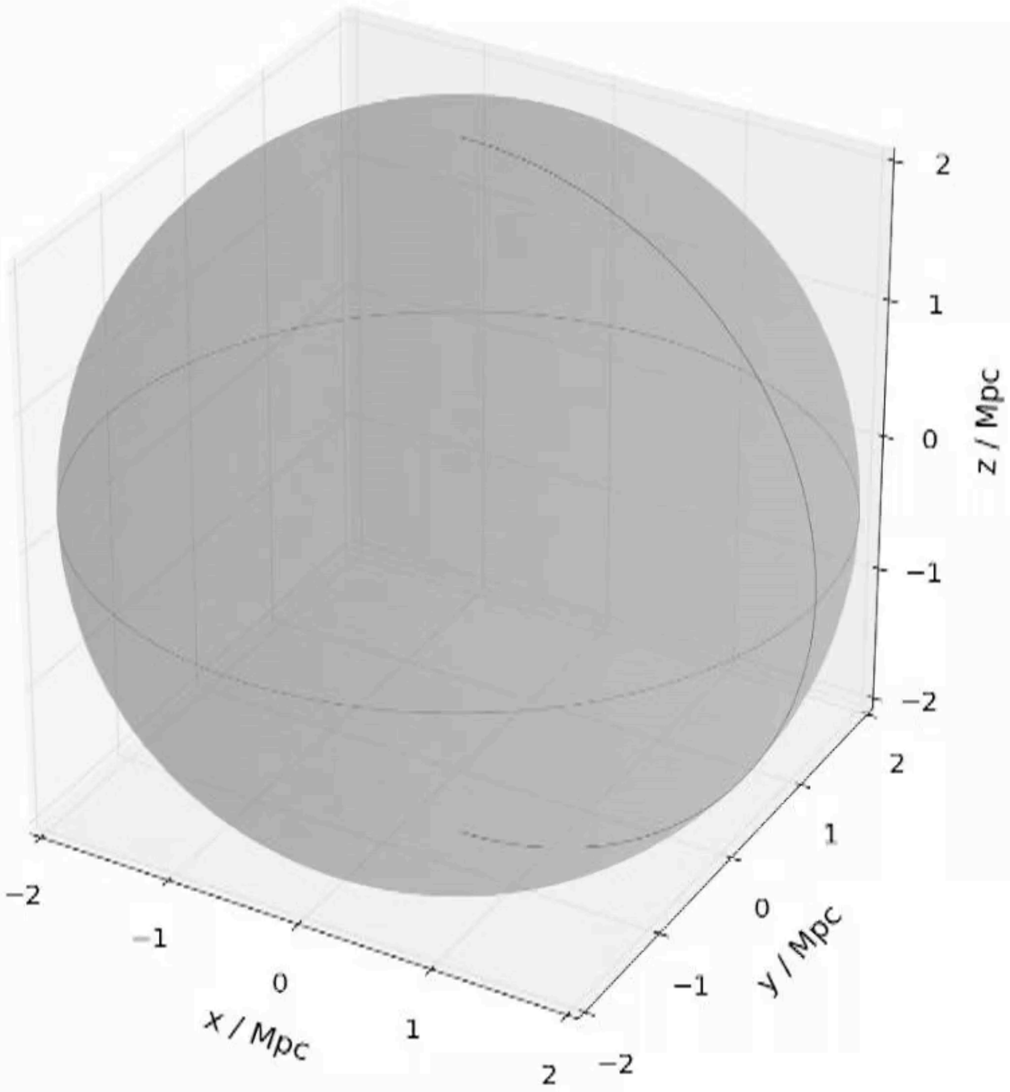
$$l_0 \sim 20\, \mathrm{kpc}$$

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



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

Particle Trajectory in the Intracluster Medium - 100 PeV



Particle Larmor Radius

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

Field Coherence Length

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

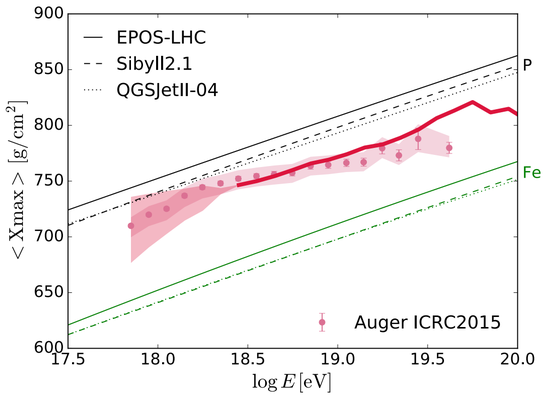
$$B_c = 10\, \mu G, M = 10^{15}\, M_\odot$$

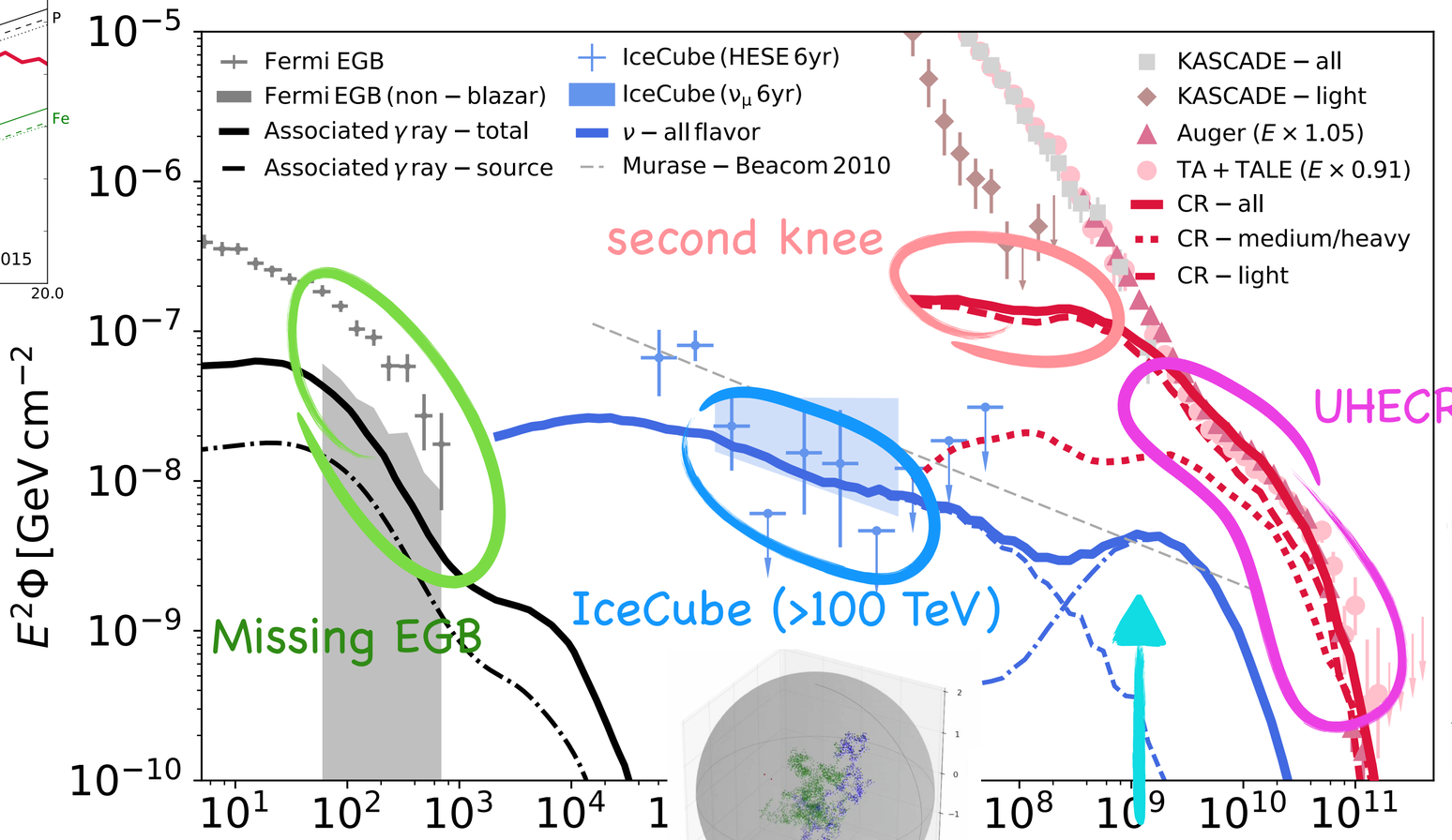
$$D_{\mathrm{total}} \sim t_{\mathrm{Hubble}}$$

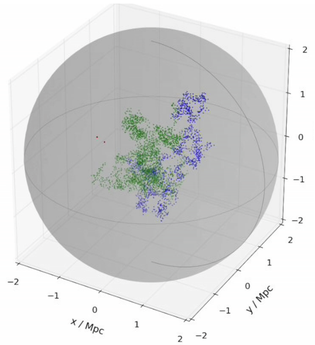
Cosmic Particles from Black Hole Jets in Galaxy Clusters

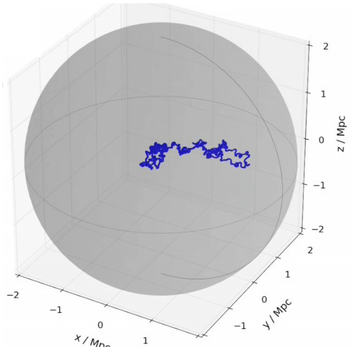
KF & Murase Nature Physics (2018)

Talk by Murase, NU2g







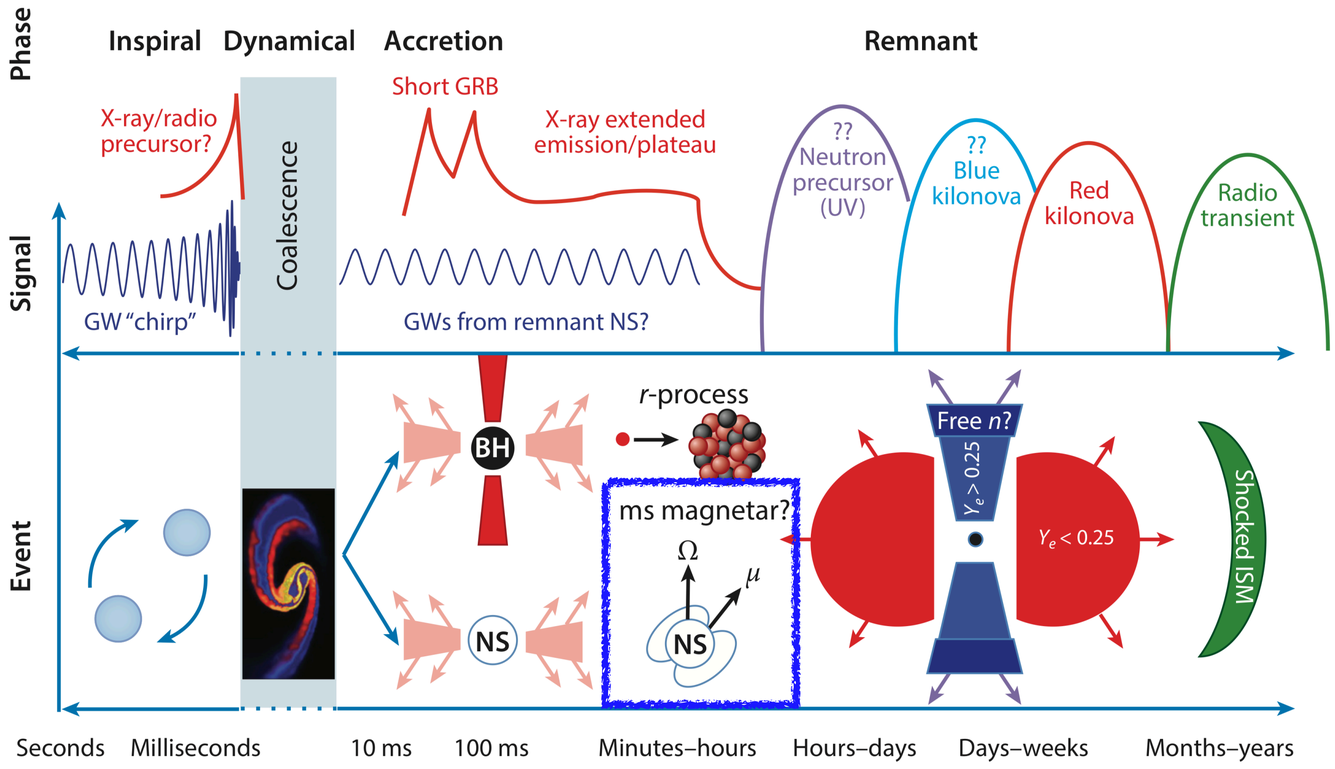


Injection Composition = Galactic CR abundance

IT'S ABOUT TIME

Timing and Resting

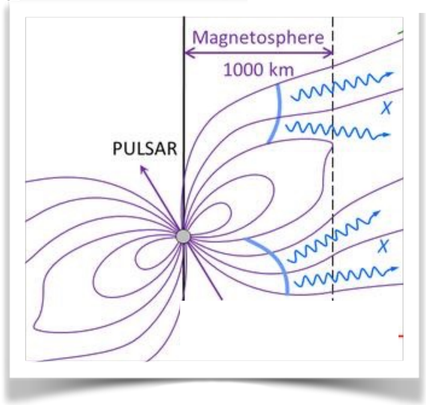
Long-term Emission from Merger Remnants of Binary Neutron Stars



Fernandez & Metzger (2015)

Talks by Bisaldi, H6; Bartos, RE6

Cosmic Ray Acceleration in Pulsar Magnetosphere



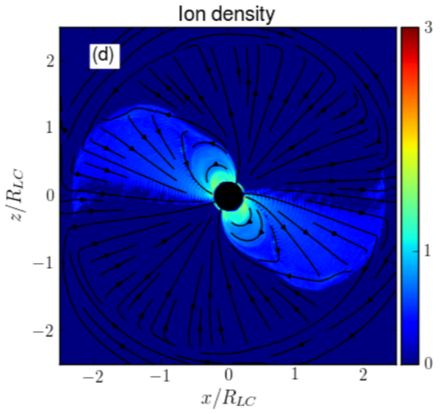
Wind efficiency

initial spin period

Magnetic Field

$$E_{\rm CR} = 10^{19}\, Z \left(\frac{\eta}{10\%}\right)\left(\frac{B}{10^{15}\,{\rm G}}\right)\left(\frac{P_i}{1\,{\rm ms}}\right)^{-2}\left(1+\frac{t}{t_{\rm sd}}\right)^{-1}\,{\rm eV}$$

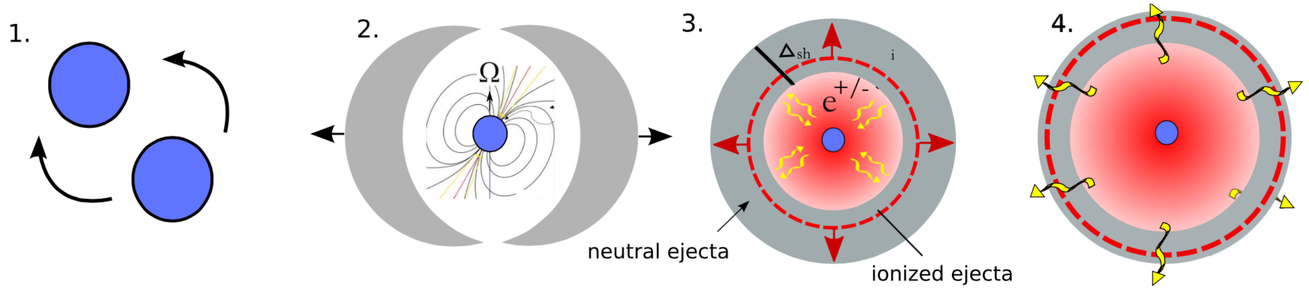
t ↑ E ↓



Philippov & Spitkovsky ApJ (2017)

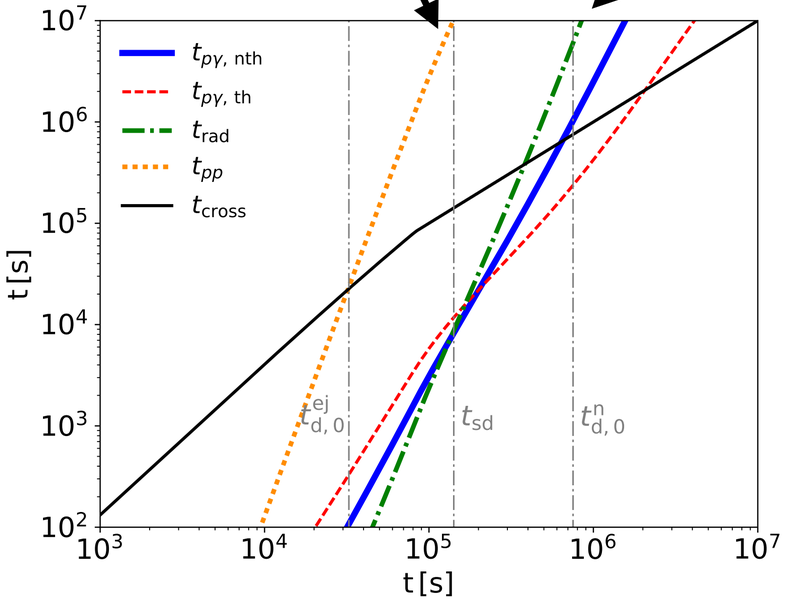
Venkatesan, Miller & Olinto *ApJ* (1997)
Blasi, Epstein & Olinto ApJ (2000)
Arons, ApJ (2003)
KF, Kotera & Olinto ApJ (2012) JCAP(2013)
…
Cerutti & Belodorodov SSRv (2017)

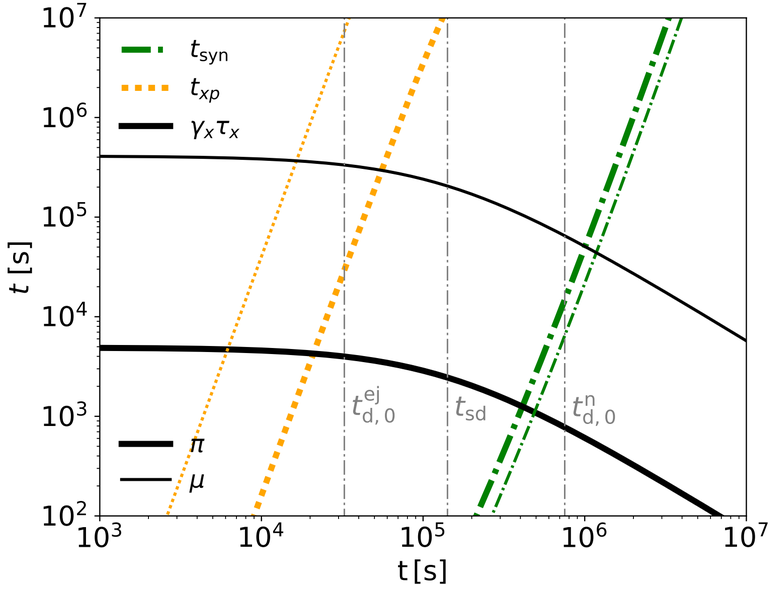
Timescales of Interaction



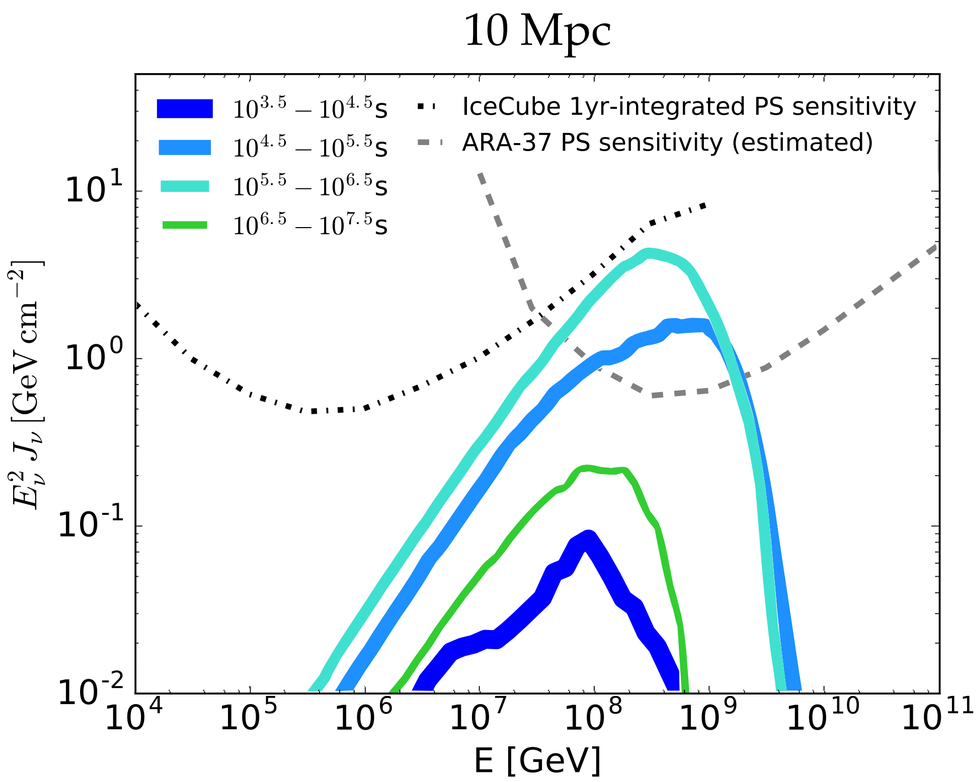
Magnetar spins down

Nebula becomes optically thin to thermal/non-thermal photons





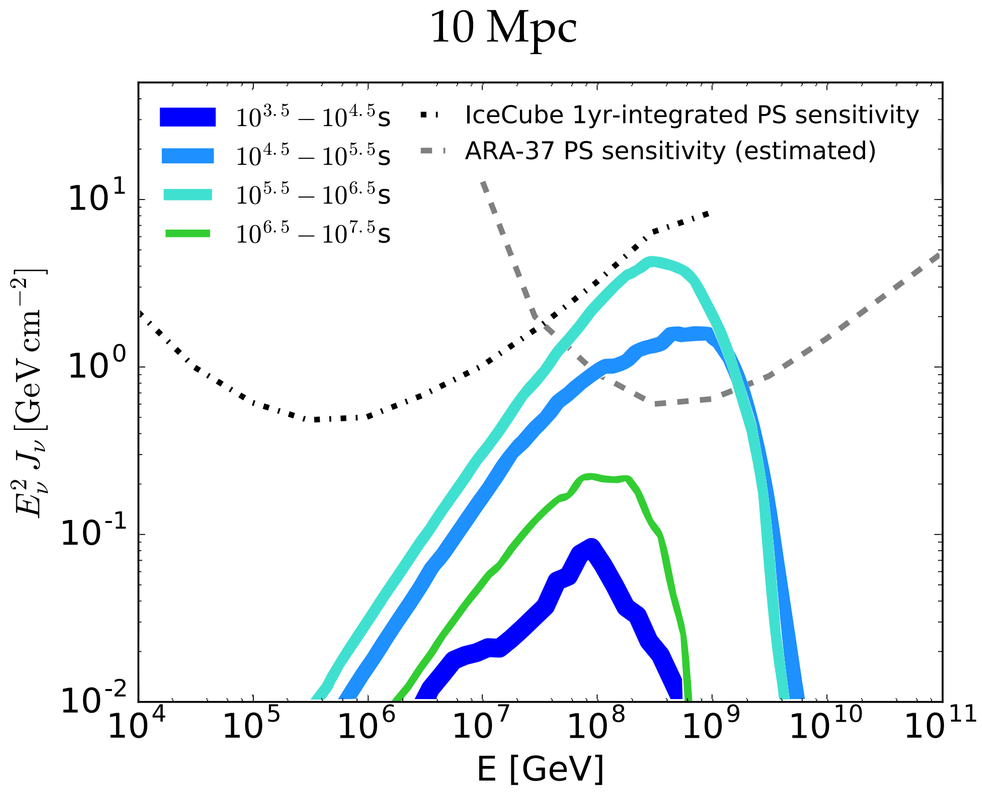
Light Curves of High-energy Neutrinos

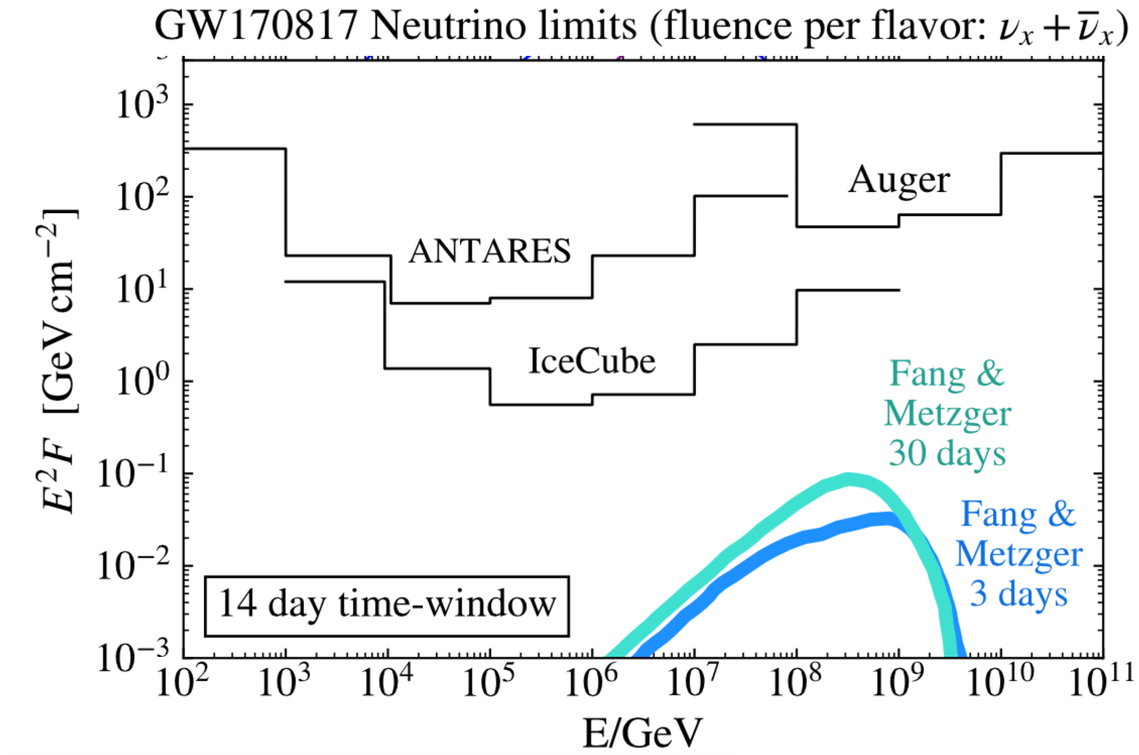


High-energy neutrinos may arrive in +10 days, providing clear evidence of the formation of a stable neutron star remnant.

KF & Metzger (2017)

Searches of High-energy Neutrinos from GW170817



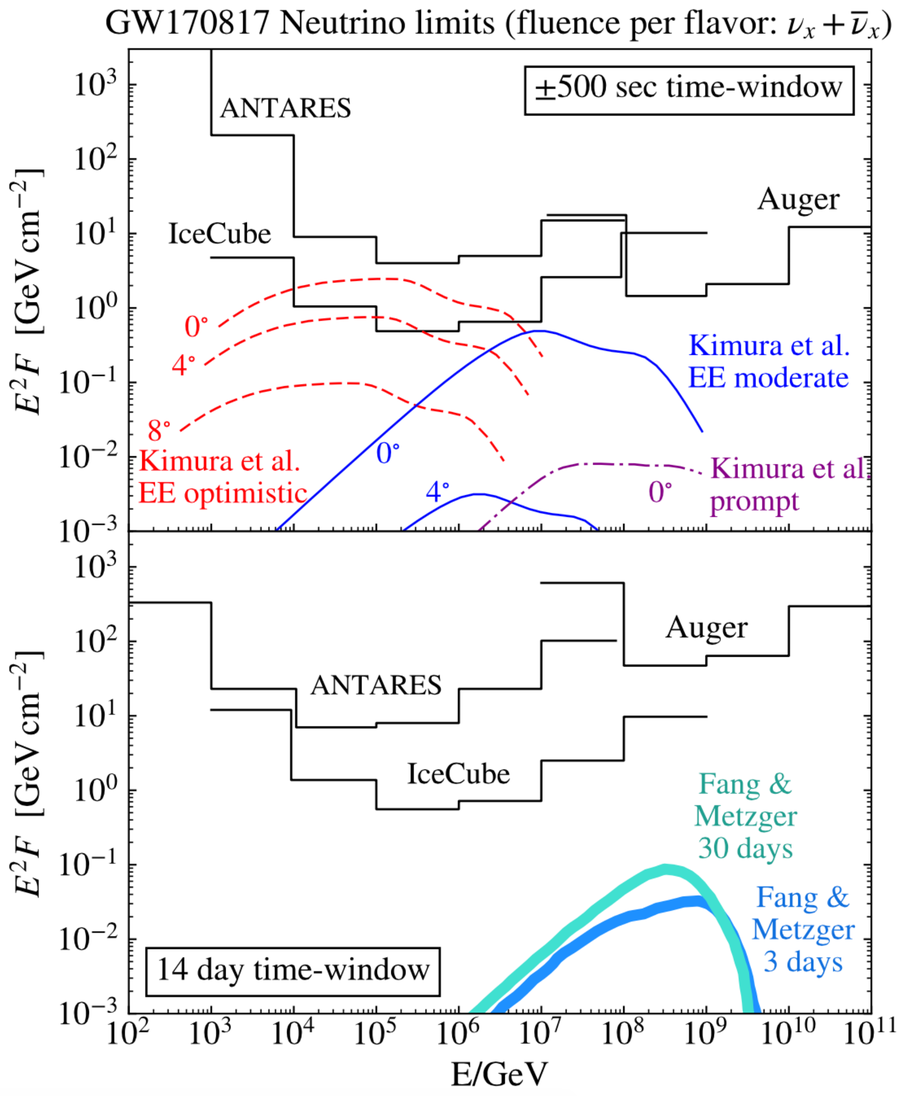


Joint Searches by IceCube, ANTARES and Auger for High-energy Neutrinos from GW170817 found **no excess over background**, consistent with prediction

KF & Metzger (2017)

ANTARES, IceCube, Auger Coll., ApJL (2017)

Searches of High-energy Neutrinos from GW170817



ANTARES, IceCube, Auger Coll., ApJL (2017)

Future detection would be possible with **closer events + better sensitivities** in both high-energy and ultrahigh energy

IceCube upgrade, Ishihara, NU7a
KM3NeT: Strandberg, NU7b
Baikal: Simkovic, NU7c; Dvornicky, NU4f
ARIANNA: Persichilli, NU7e; Lahmann, NU11h;
ARA: Oberla, NU7f; Connolly, NU3d
ANITA: Deaconu, NU3e
BEACON: Wissel, NU10e
GRAND: Decoene, CR1f; Martineau, NU10b
POEMMA: Olinto, CRI10h
TRINITY: Otte, NU10c
JEM-EUSO: Fenu, CRI1c, Bertaina, CRi1d; Bisconti, CRI3f

Summary

Compact objects offer **promising sites for particle acceleration**.

Particle propagation and interaction in cosmic environment is crucial to linking source physics and astroparticle observation.

High-energy Neutrinos are a **unique messenger to probe hadronic processes** in black hole jets and fast-spinning pulsars.