Source Model Scenarios: AGNs and Starbursts

Ke Fang

UW-Madison

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1. Active Galactic Nuclei

2. Starburst galaxies

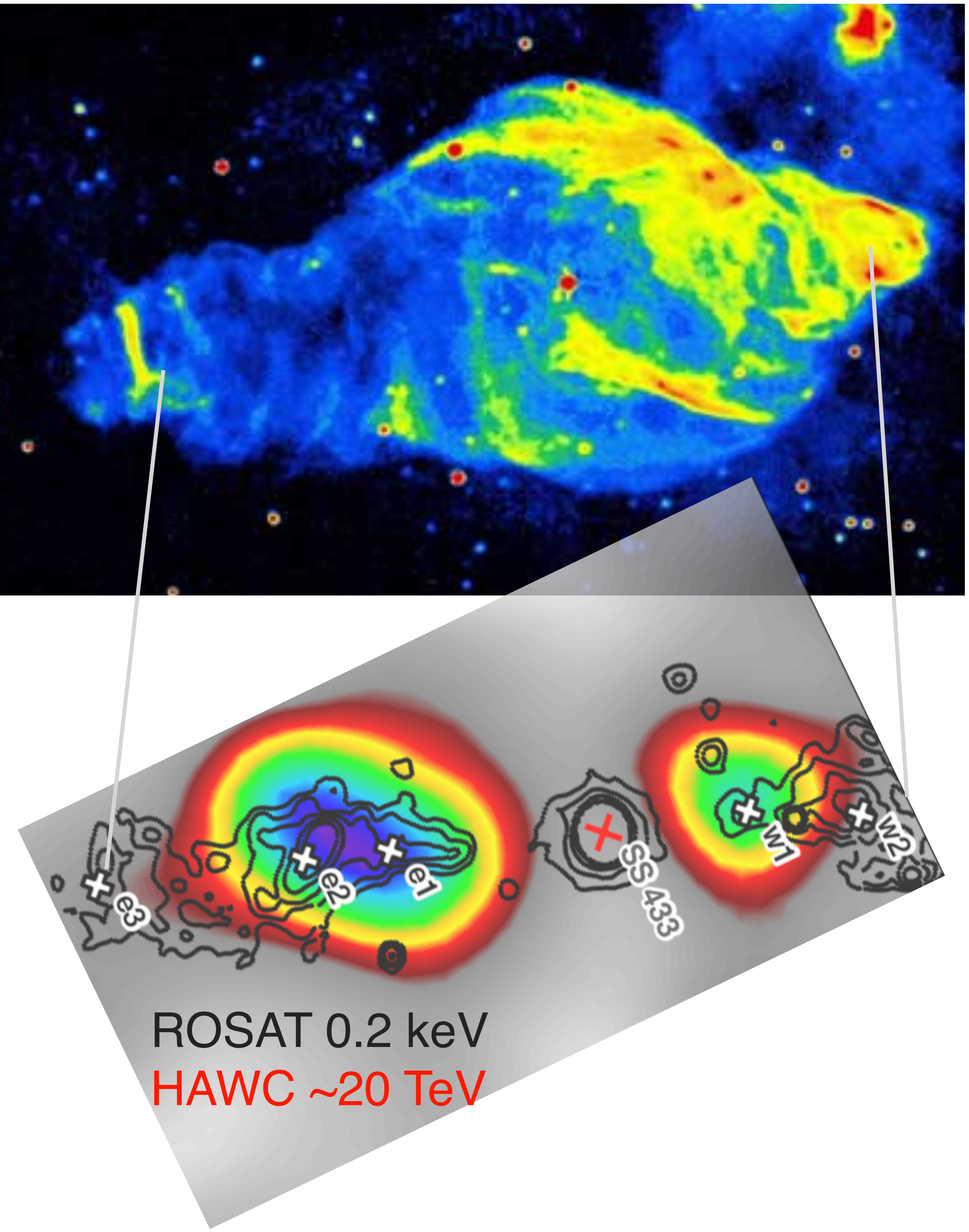
- A close look of their Galactic cousins
- Acceleration and survival of UHECRs

1. **Active Galactic Nuclei**

2. Starburst galaxies

- A close look of their Galactic cousin
- Acceleration and survival of UHECRs

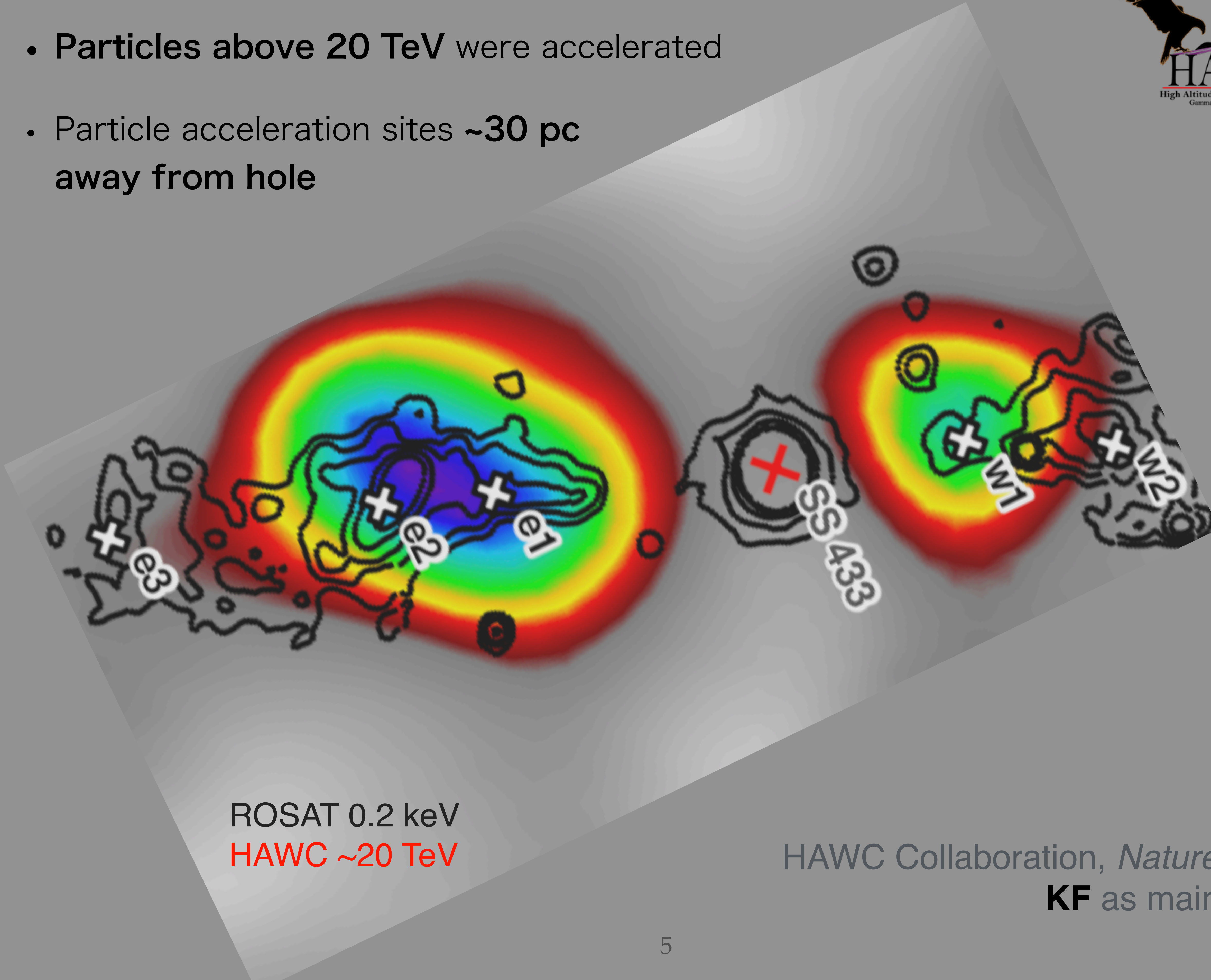
Mini AGN: **Microquasar SS 433**



- Extended X-ray jets with sub-relativistic speed
- **Point-like TeV gamma-rays in both lobes** detected by HAWC

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

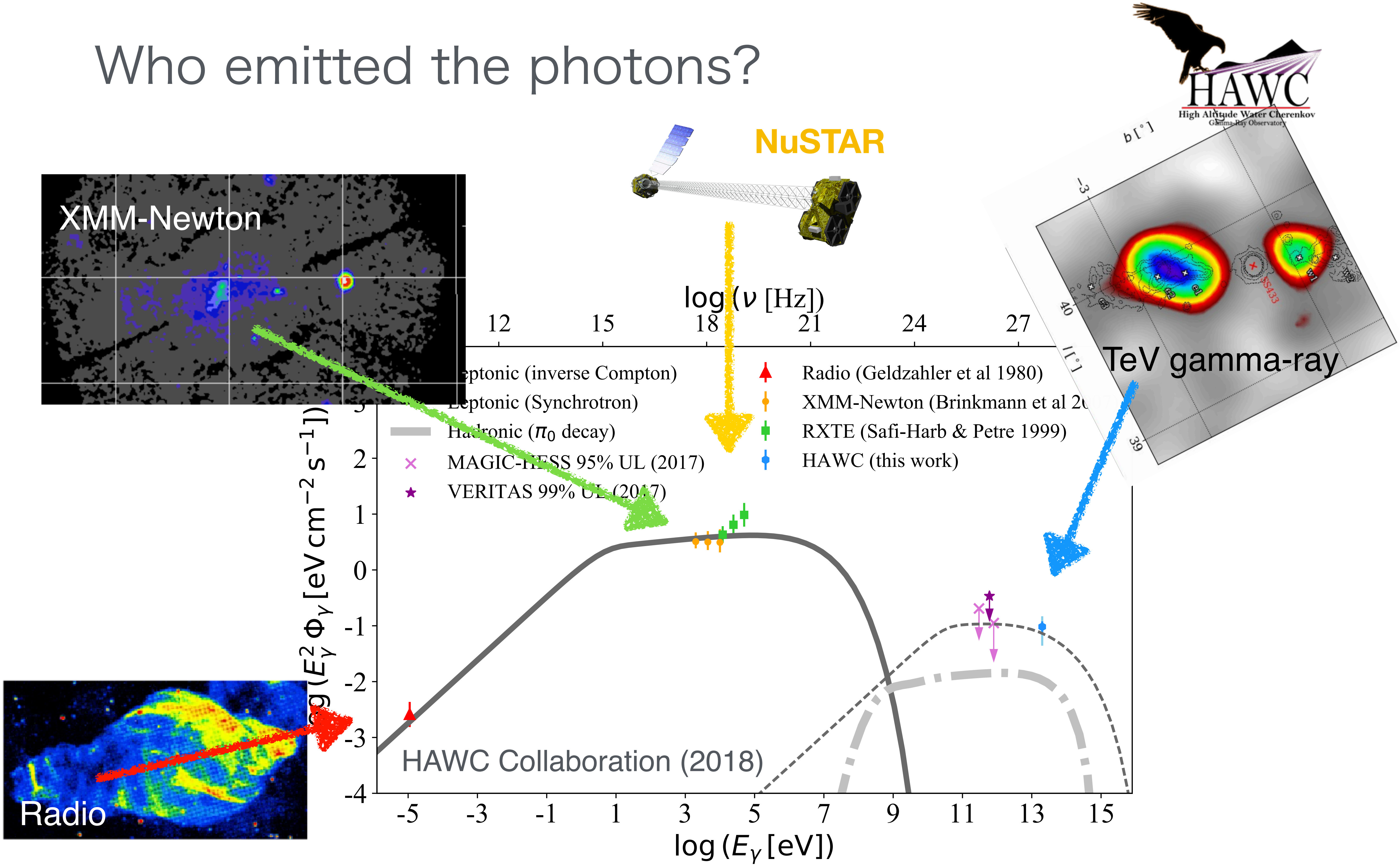
- **Particles above 20 TeV** were accelerated
- Particle acceleration sites **~30 pc away from hole**



ROSAT 0.2 keV
HAWC ~20 TeV

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

Who emitted the photons?

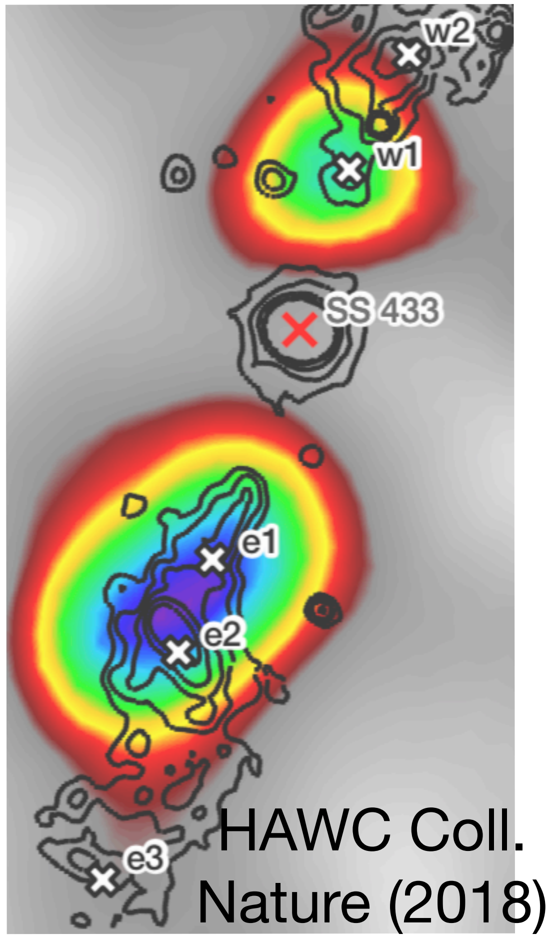


HAWC Collaboration, *Nature* (2018)
KF as a main author

KF, Charles, Blandford, ApJL (2020)

Scaling to Jets of Supermassive Black Holes

SS 433



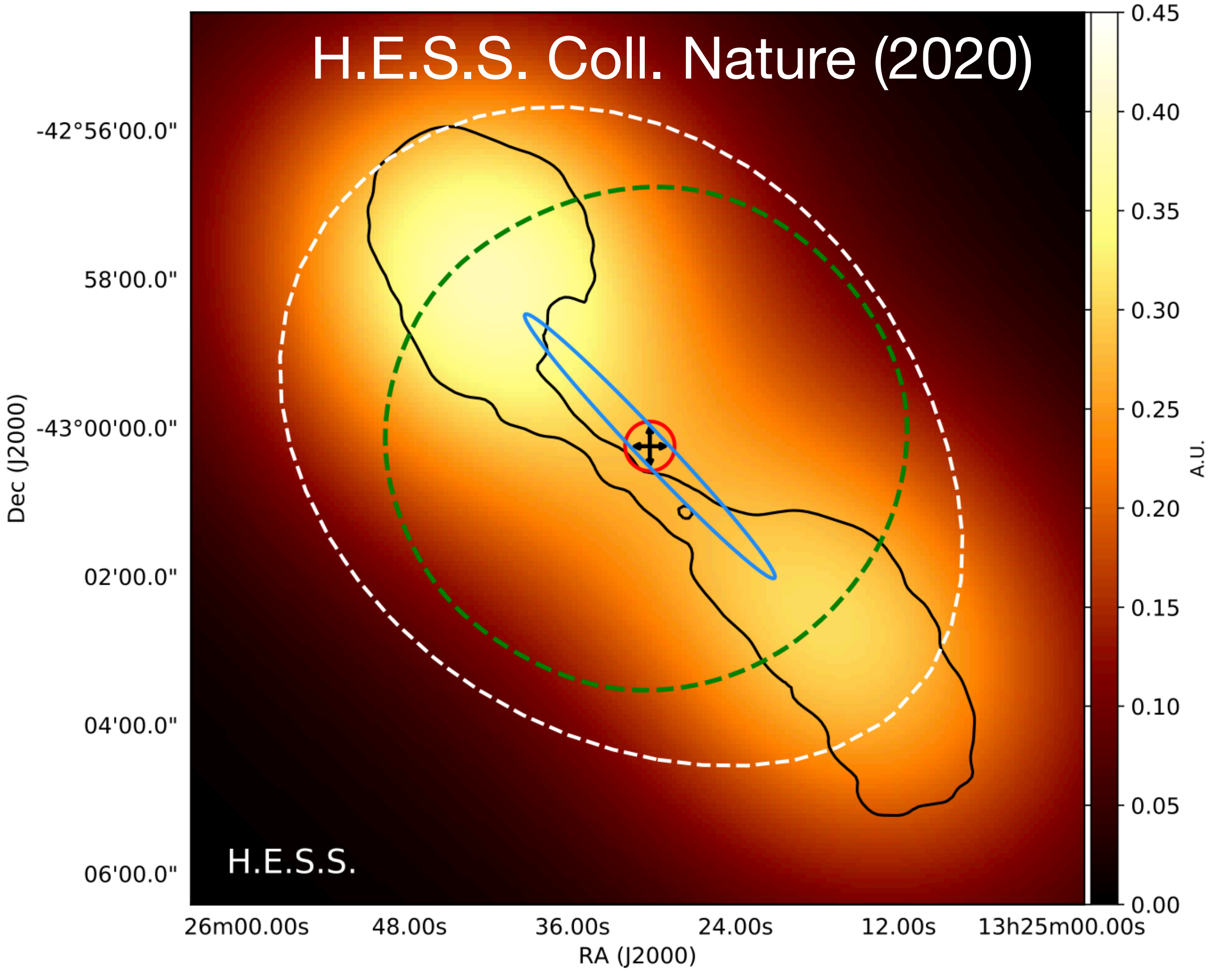
$$V_{\rm jet} = 0.25\,c$$

$$R_{\rm jet} \sim 30\,{\rm pc}$$

$$B \sim 16\,\mu G$$

$$E_{p,{\rm max}} \sim 10^{16}\,{\rm eV}$$

Cen A



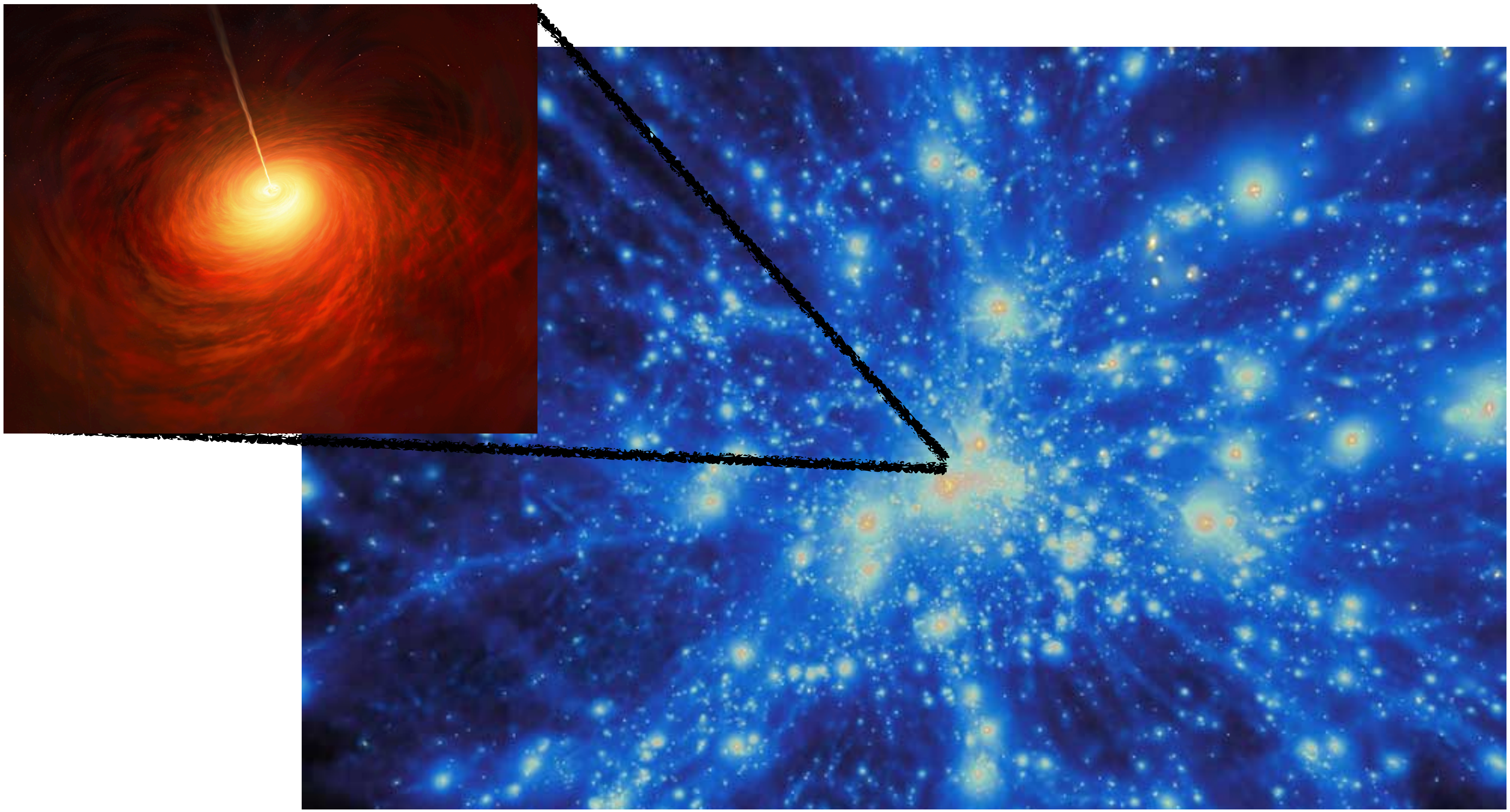
$$V_{\rm jet} = 0.5\,c$$

$$R_{\rm jet} \sim 0.5 - 4\,{\rm kpc}$$

$$B \sim 23\,\mu G$$

$$E_{p,{\rm max}} \sim 10^{18}\,{\rm eV}$$

Survival of UHECRs in Cosmic Environment



The Intracluster Medium Environment for Interactions

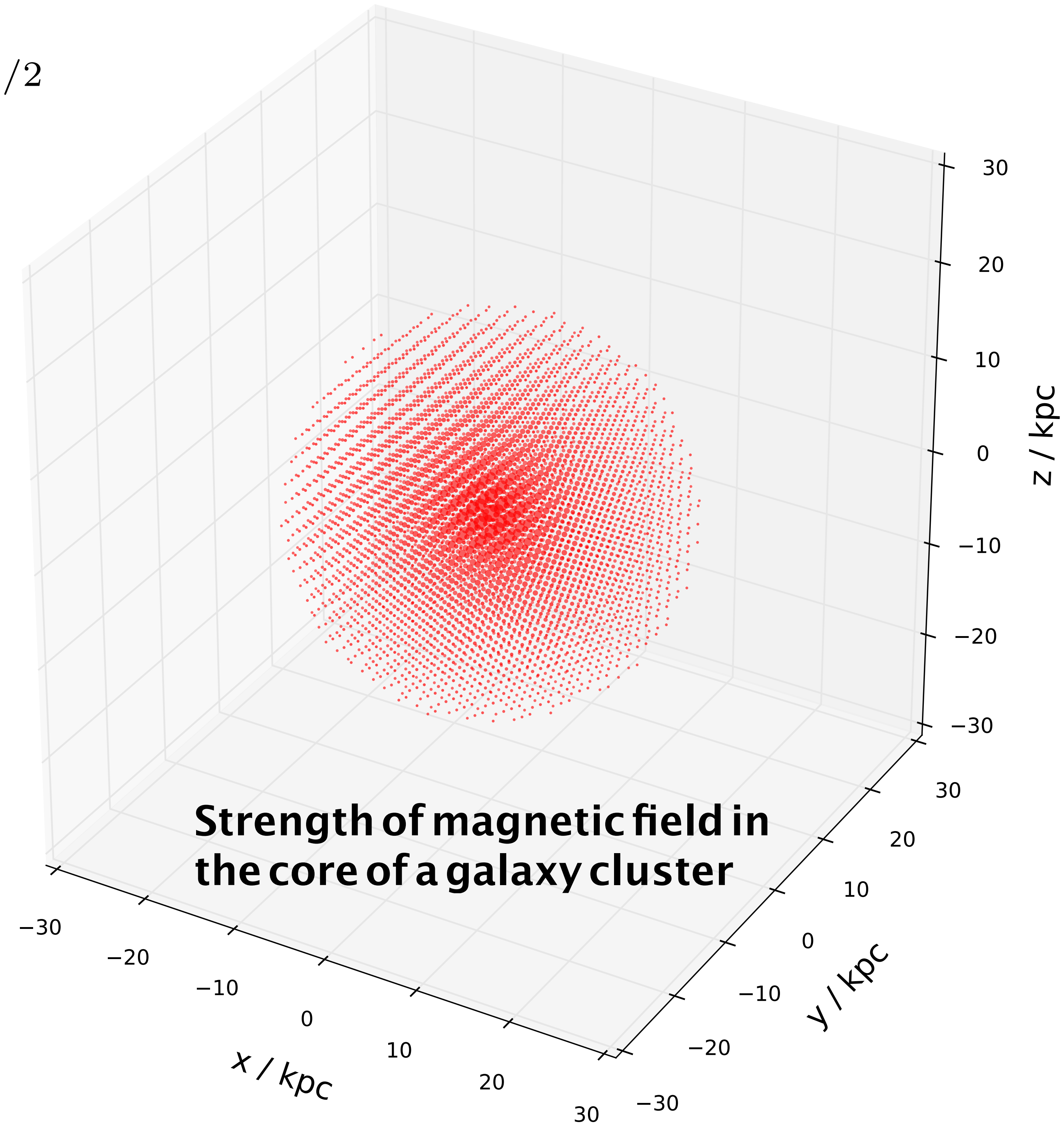
ICM gas

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

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

Magnetic field following Kolmogorov turbulence

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

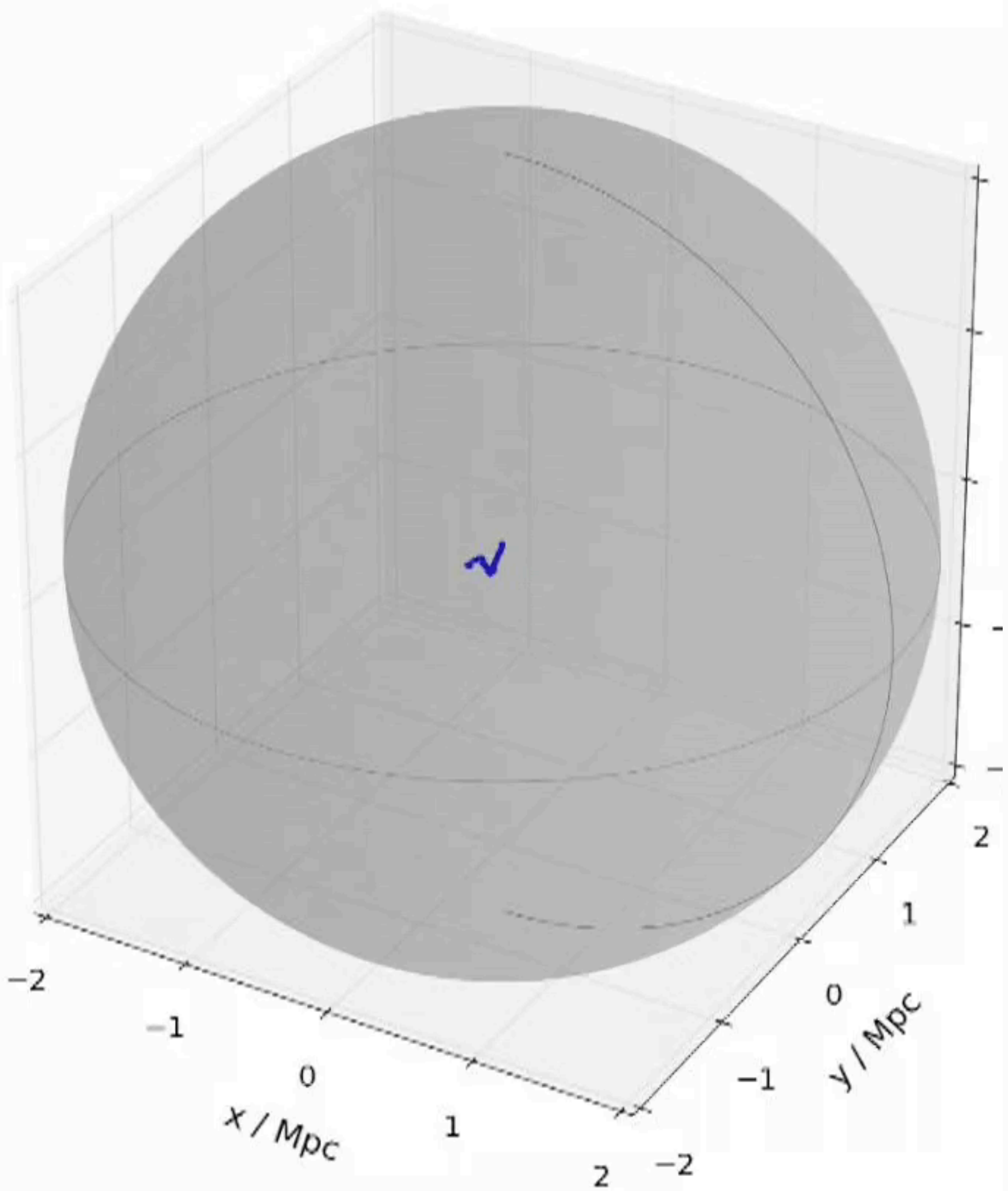


Strength of magnetic field in the core of a galaxy cluster

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

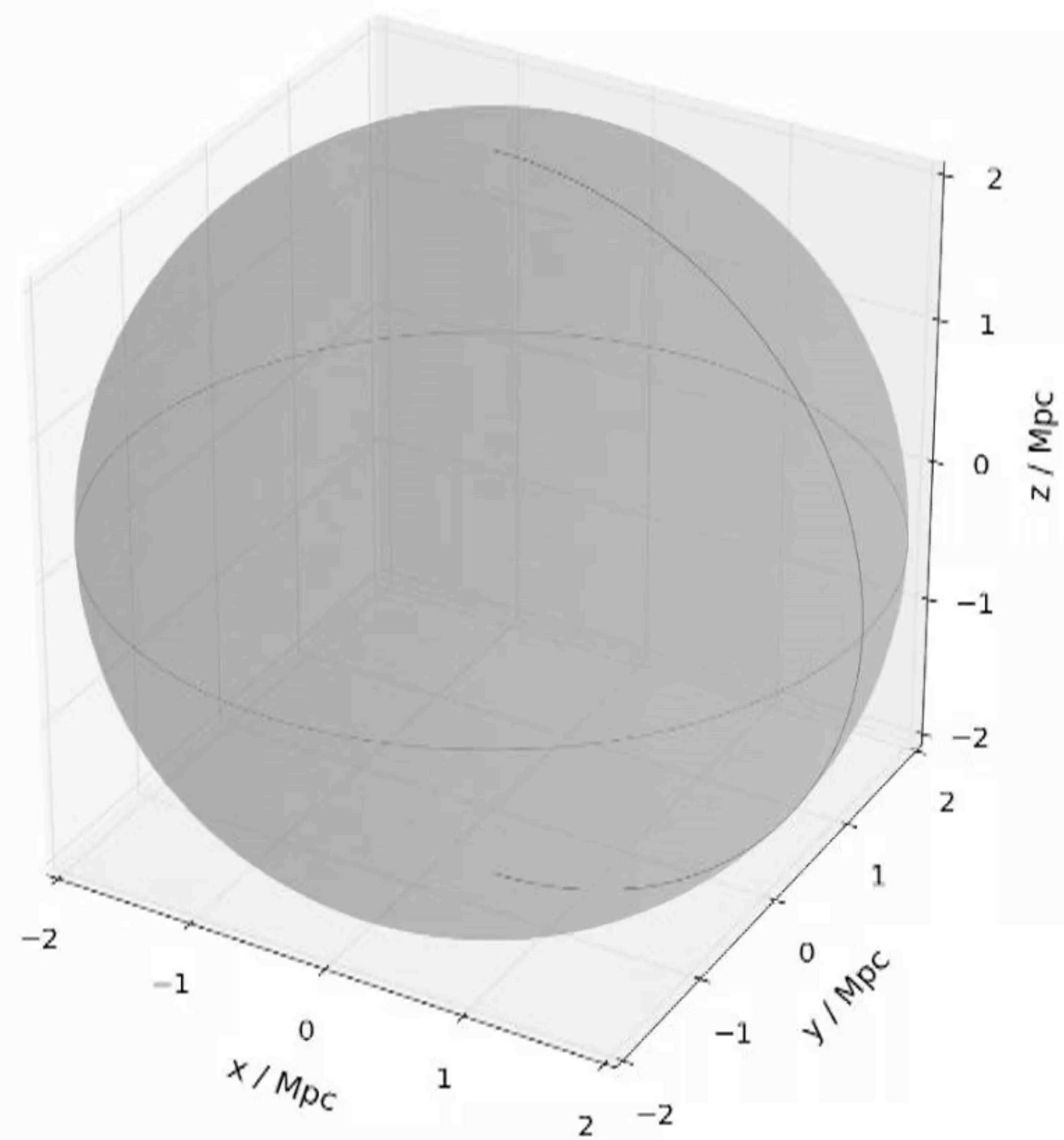
Particle Trajectory in the Intracluster Medium

10 EeV proton



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

0.1 EeV proton

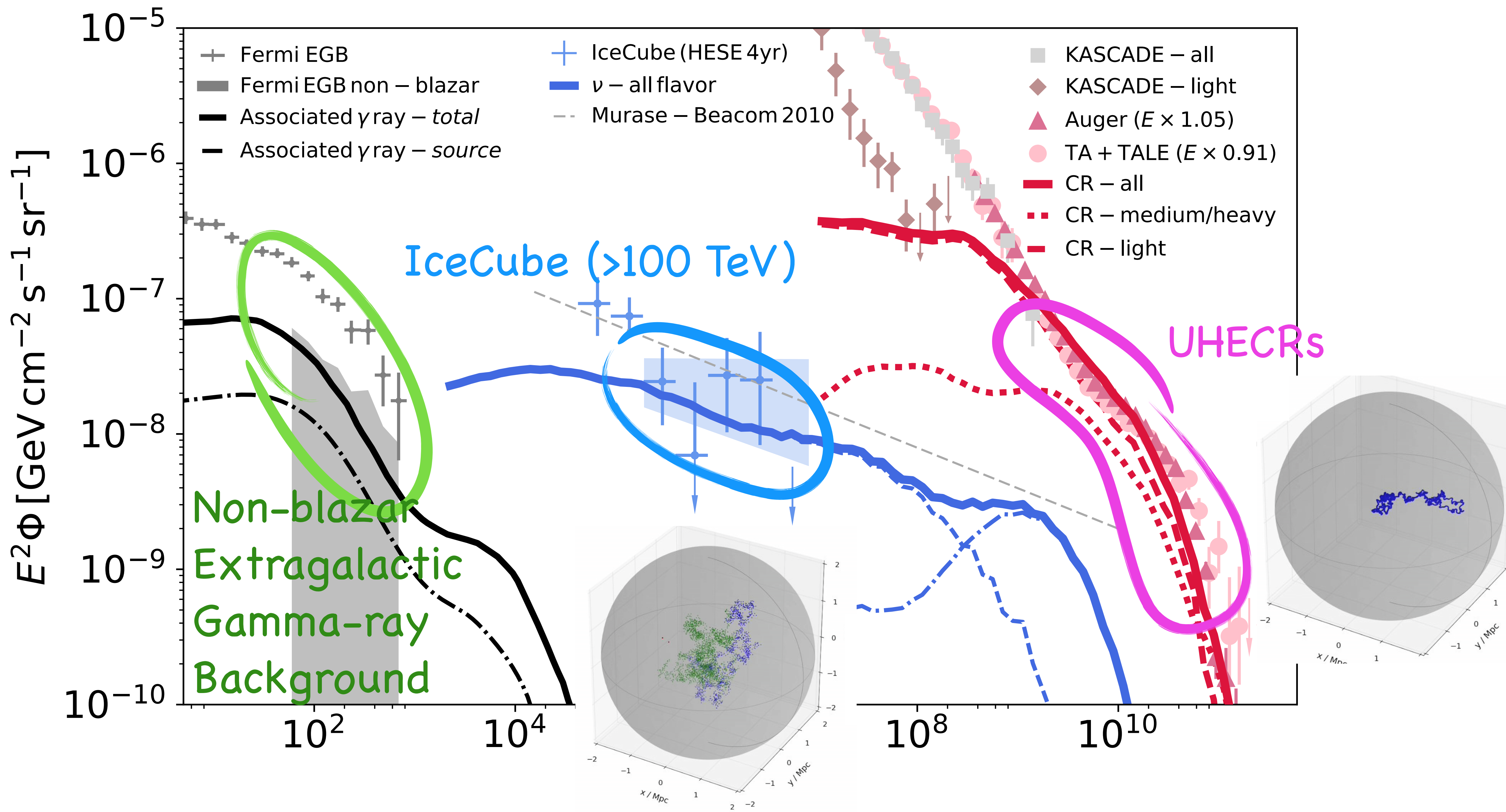


$$D_{\mathrm{total}} \sim t_{\mathrm{cluster}}$$

KF & Murase *Nature Physics* (2018)

Cosmic Particles from Black Hole Jets in Galaxy Clusters

KF & Murase *Nature Physics* (2018)

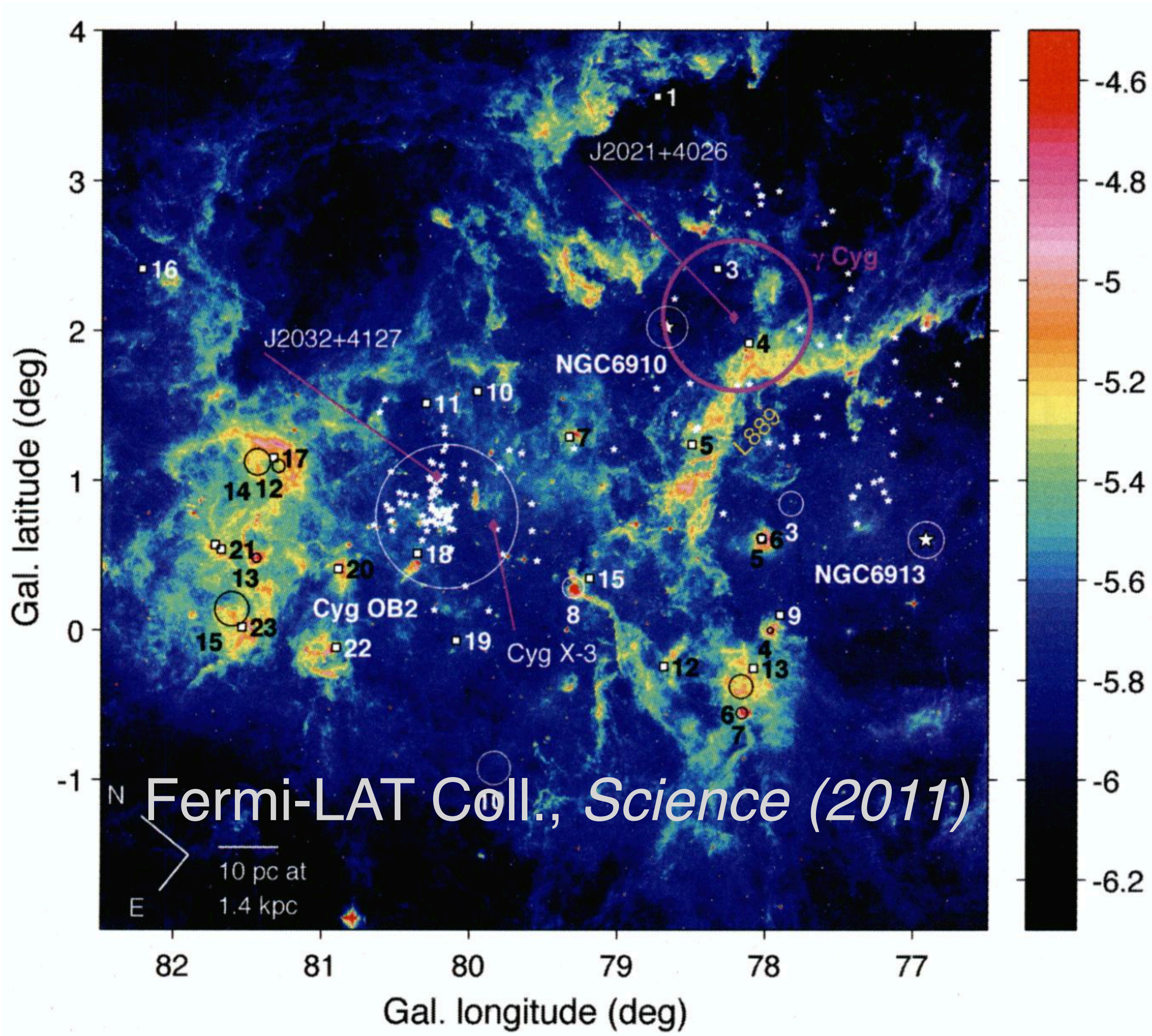


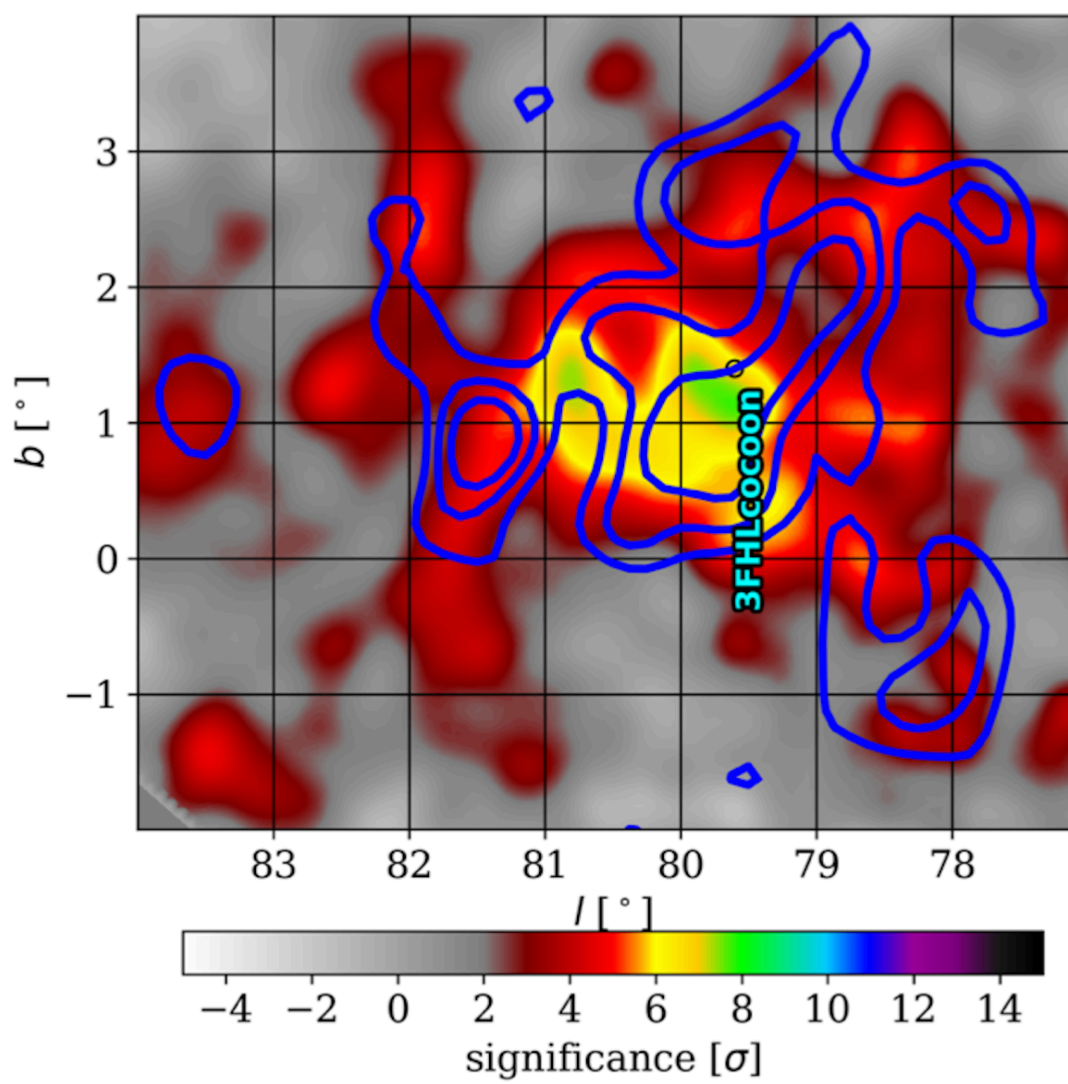
Injection Composition = Galactic CR abundance

1. Active Galactic Nuclei

2. **Starburst galaxies and superwinds**

Stellar winds: **Cygnus Cocoon**

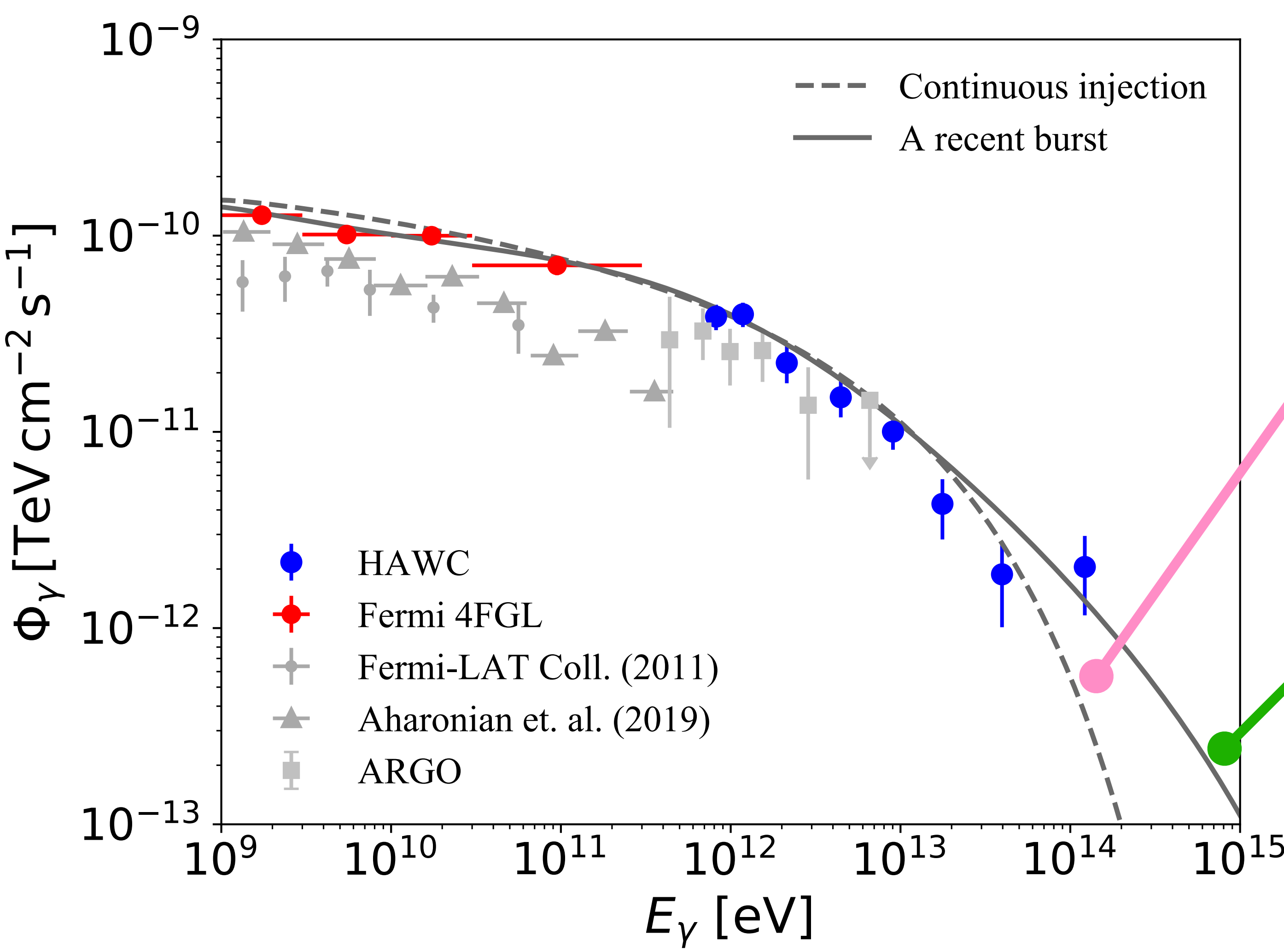




- GeV-to-TeV gamma-rays trace infrared emission
- 100 TeV gamma-rays observed, suggesting **PeV proton acceleration by stellar winds** (a.k.a. PeVatron)

HAWC Collaboration, *Nature Astronomy (2021)*
KF as correspondent author

Stellar winds: **Cygnus Cocoon**



HAWC Coll., *Nature Astro. (2021)*
KF as corr. author

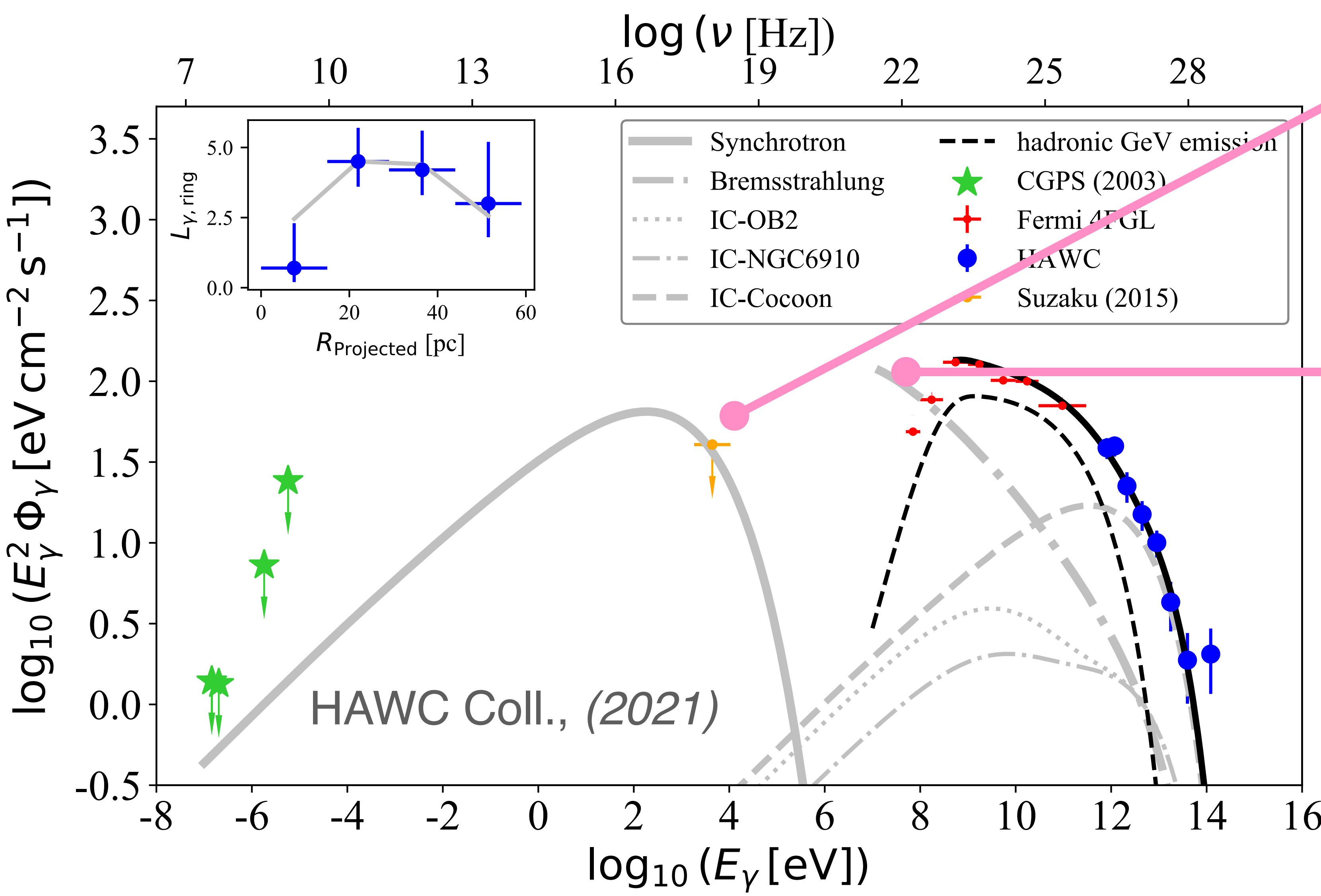
Continuous injection of protons with cutoff energy ~300 TeV

Recent burst of protons with cutoff energy > 1 PeV

Tibet Coll. PRL (2021) indicates >100 TeV emission

KF & Murase 2104.09491

Stellar winds: **Cygnus Cocoon**



Bremsstrahlung and Synchrotron radiation is constrained by multi-wavelength observations.

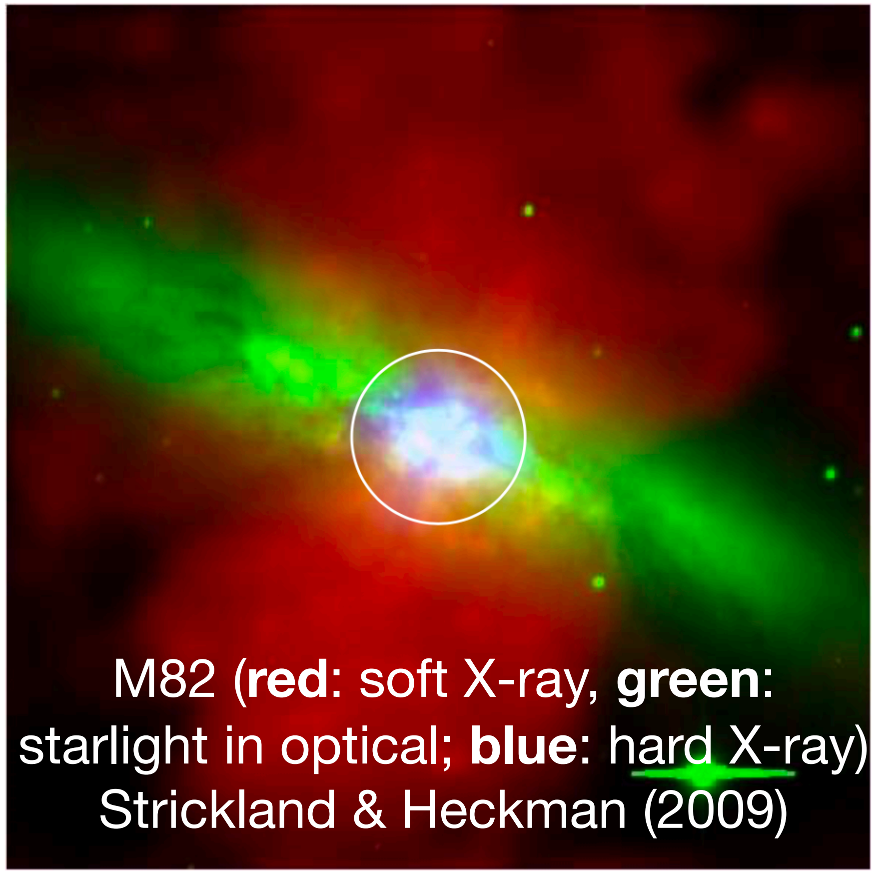
VHE observation of the Cygnus Cocoon suggests that **stellar winds are promising hadron accelerators.**

HAWC Coll., *Nature Astro. (2021)*
KF as corr. author

Scaling to **Superwinds in Starburst Galaxies**

- **Galactic-scale starburst-driven superwinds** are commonly observed in starburst galaxies with typical speed ~1500 km/s and size 1-10 kpc

- Stellar winds of OB2 stars in the Cygnus region reach 200-300 km/s. Size of Cygnus Cocoon ~ 60 parsec

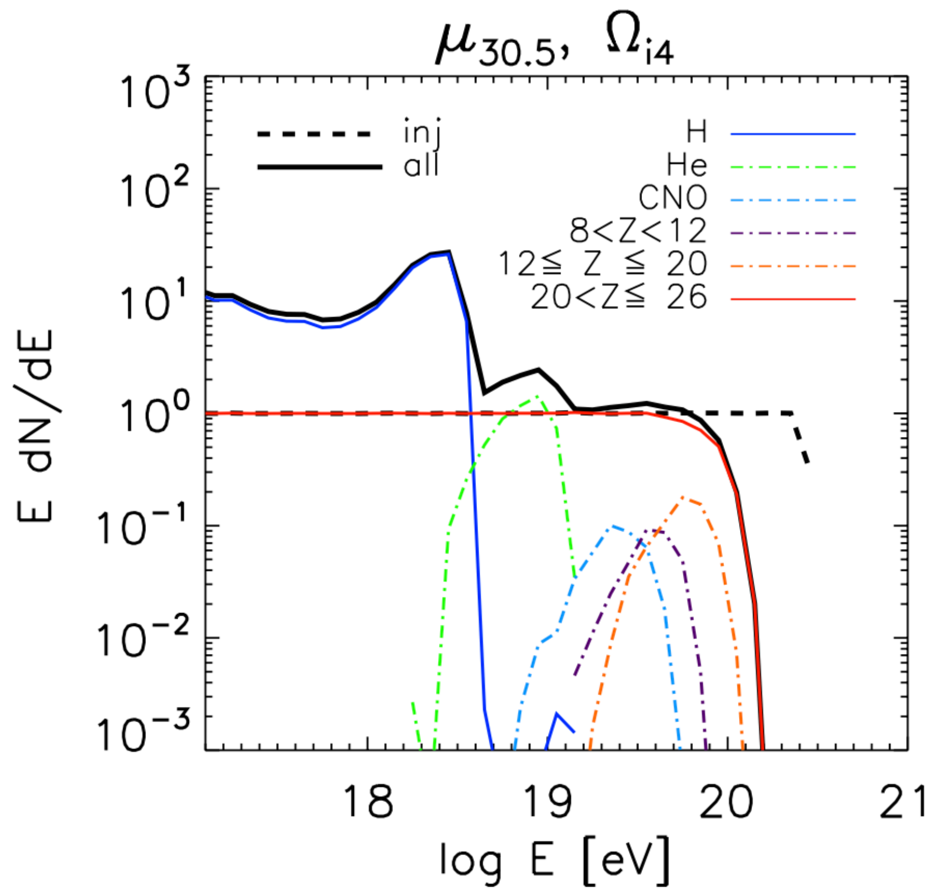


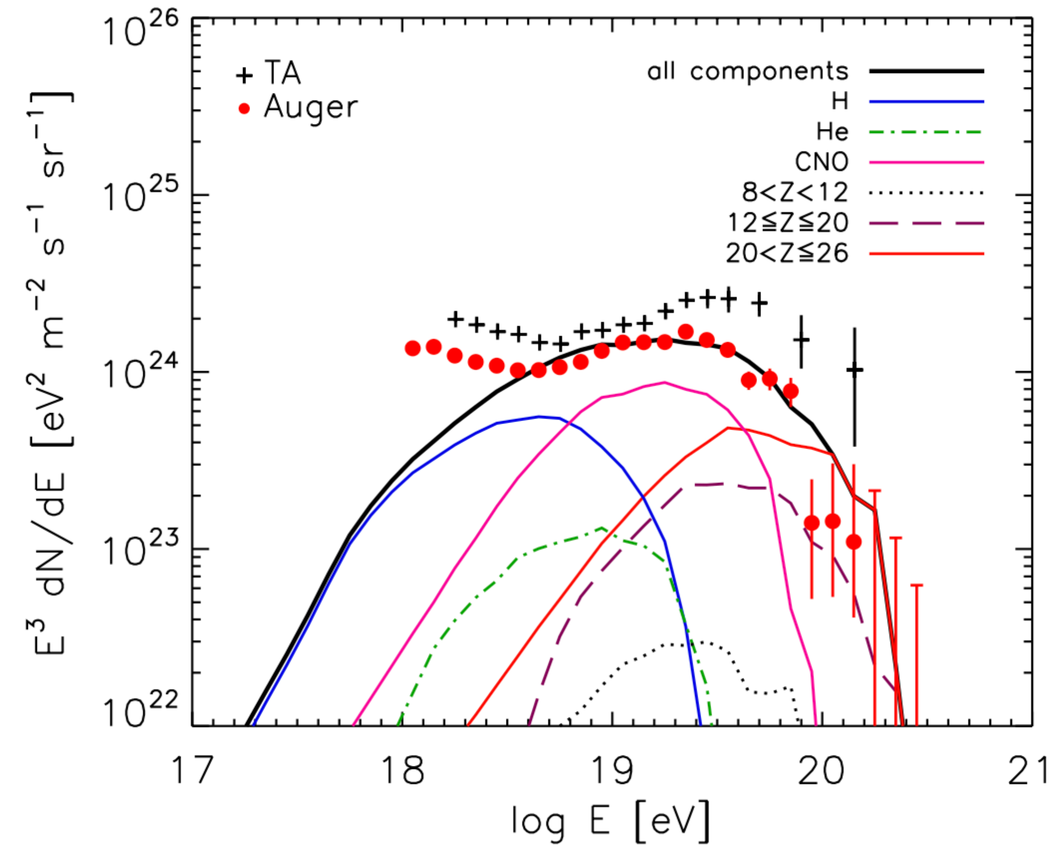
$$E_{\rm max}^{\rm starburst} \propto v_w \, R_w = (1 - 10\,{\rm EeV}) \left(\frac{E_{\rm max}^{\rm CygnusCocoon}}{10\,{\rm PeV}} \right)$$

Superwinds in starburst galaxies are promising UHECR accelerators

e.g. Anchordoqui (2018, 2019)

Sources hosted by **Starburst Galaxies**

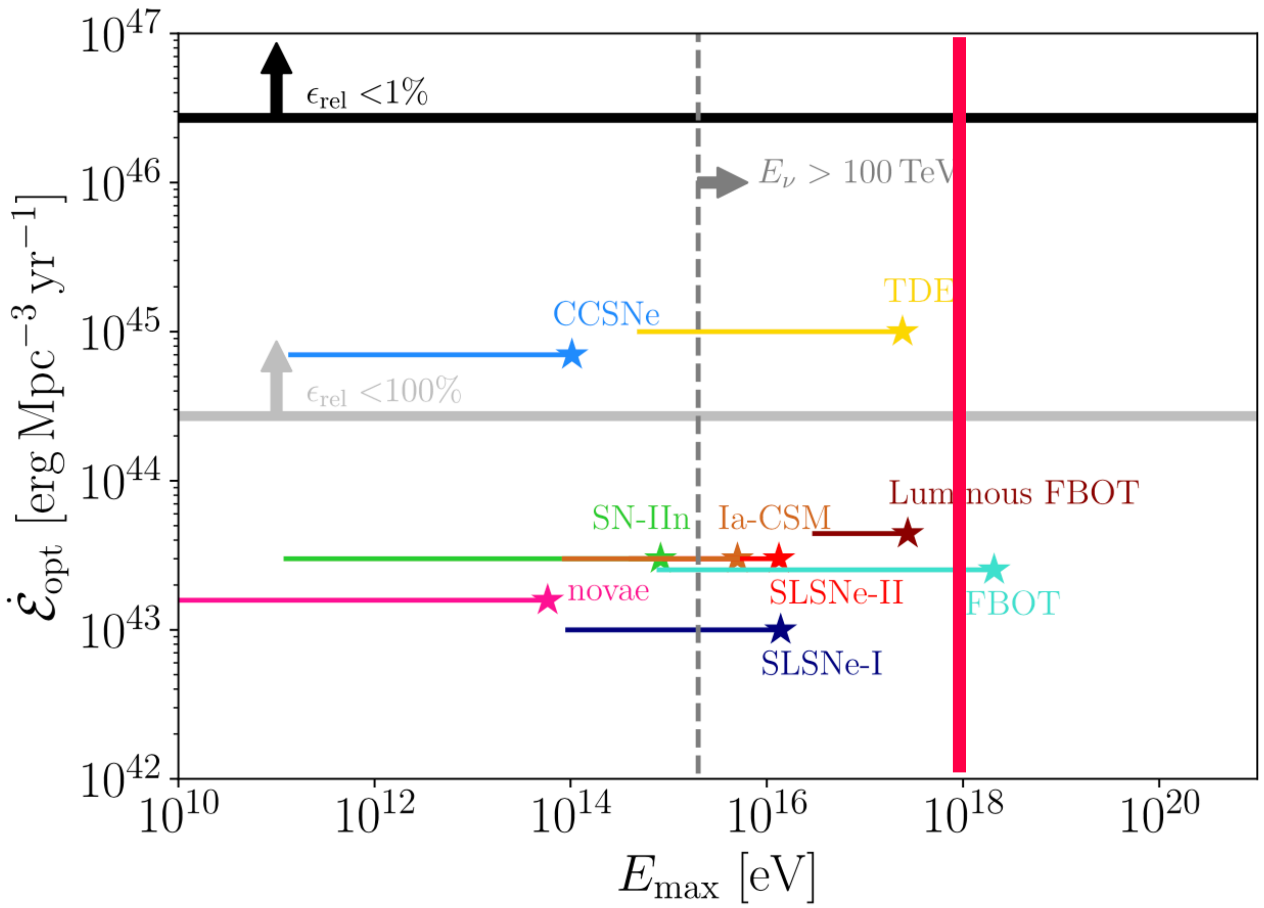




UHE protons and nuclei may be accelerated in energetic sources in starbursts, such as **newborn pulsars**

KF, Kotera, Olinto (2012, 2013)

Transients Powered by Non-relativistic Shocks



Emax < UHE

Observed Properties of Extragalactic Transient "Zoo"

Source	$\mathcal{R}_0$[b] (Gpc^{-3} yr^{-1})	$\log_{10} L_{\rm pk}$ (erg s^{-1})	$t_{\rm pk}$ (days)	$\bar{v}_{\rm ej}$ (10^3 km s^{-1})	$\log_{10} E_{\rm opt}$[c] (erg)	Z[d]	Shock Powered?
Novae	$(1-5)\times 10^8$	37–39	3	0.5–3	43.5–44.5	1	Y[e]
LRNe	$10^{5.5}$–$10^{6.4}$[f]	39-41	40–160	0.2–0.5	45–46	1	?[g]
SLSNe I	10–100[h]	43.3–44.5[i]	30–50	5–10	50–51	8	?
SLSNe II	70–300[j]	43.6–44.5	31–36	5–10	50–51	1	Y
SNe IIn[k]	3000[l]	42–43.7	20–50	5	49–50	1	Y
CCSNe	7×10^4[m]	41.9–42.9	7–20[n]	3	48–49	1,8	??
TDE	100–1000[o]	44–45[p]	40–200[q]	5–15	51–52	1	?
FBOT	~4800–8000[r]	~43	4–12[r]	6–30	48.5–49.5	?	?
Lum. FBOT	~700–1400[s]	~44	1-5[t]	6–30[u]	49.5–50.5	1	?
Type Ia-CSM	300–3000[v]	~43	20	10	49	6-8	Y

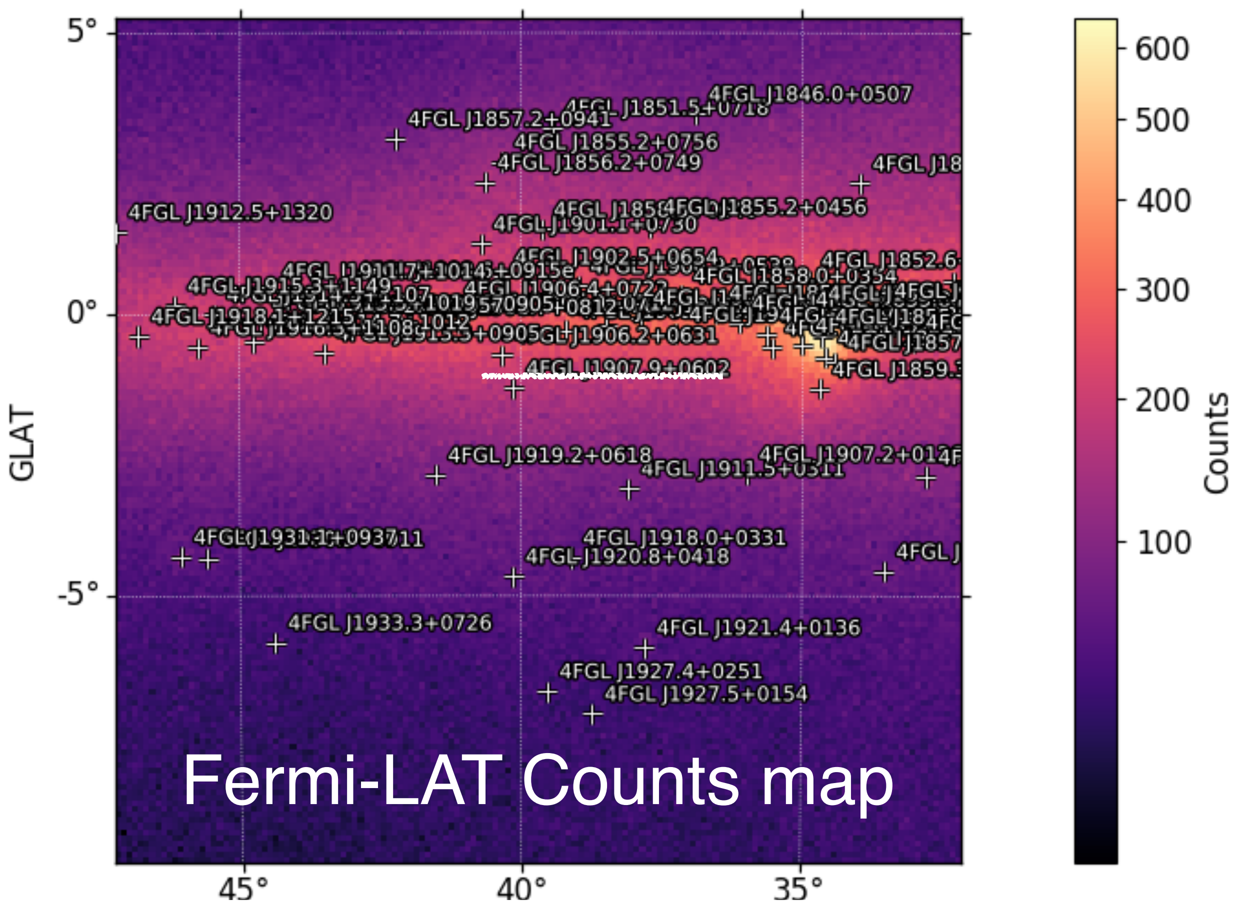
KF, Metzger, Vurm, Aydi, Chomiuk (2020)

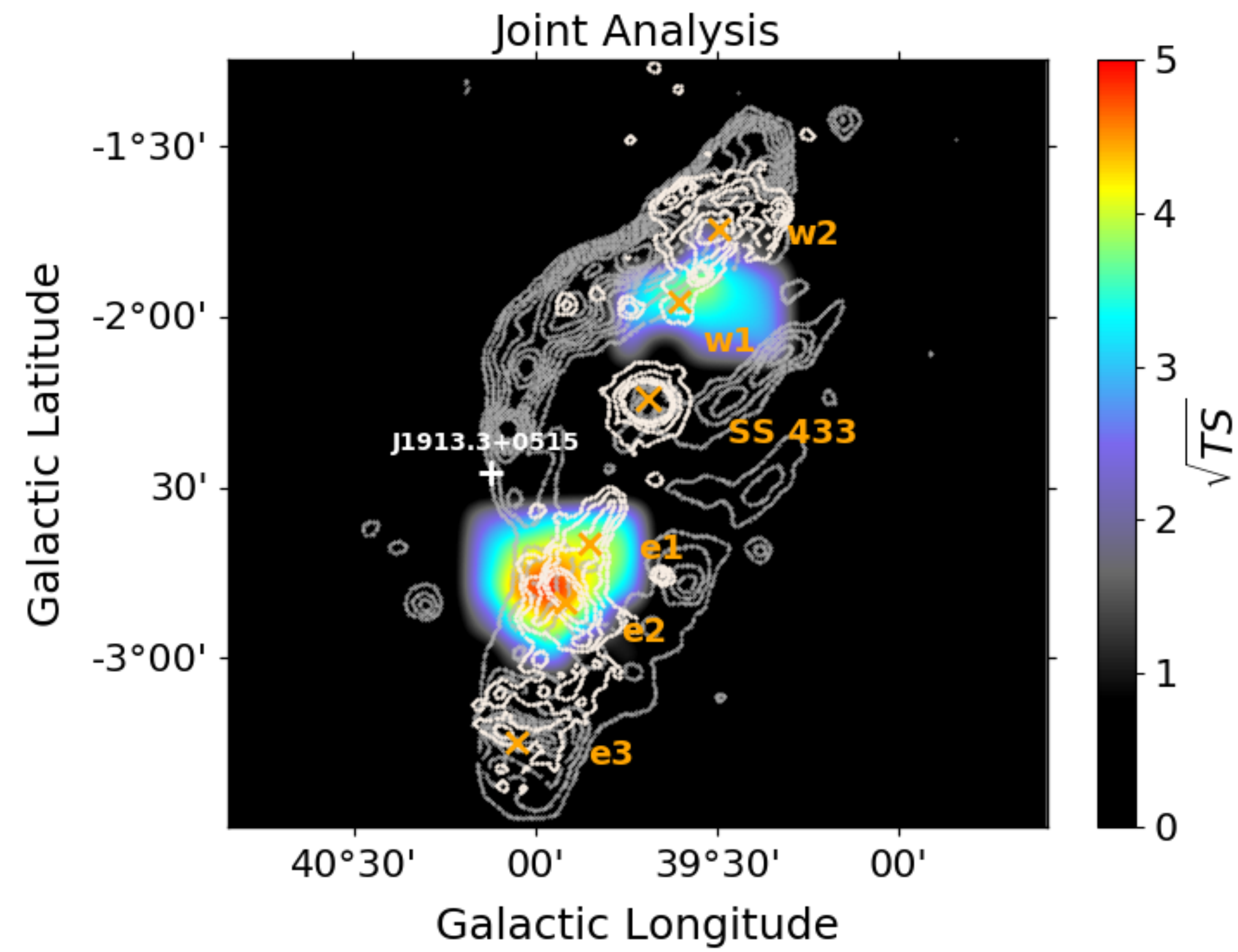
Conclusions

- Very-high-energy gamma-ray observations of microquasar and stellar winds **support UHECR acceleration** in their “scaled” analogies—**AGNs and starburst galaxies**

- **Transport of UHECRs in the cosmic environment** may produce secondary neutrinos and gamma rays

Joint Fermi-HAWC Analysis of SS 433





GeV-to-TeV Gamma-ray emission is detected in the lobes of the microquasar, consistent with emission of particles with energy above ~100 TeV.

KF, Charles, Blandford, ApJL (2020)