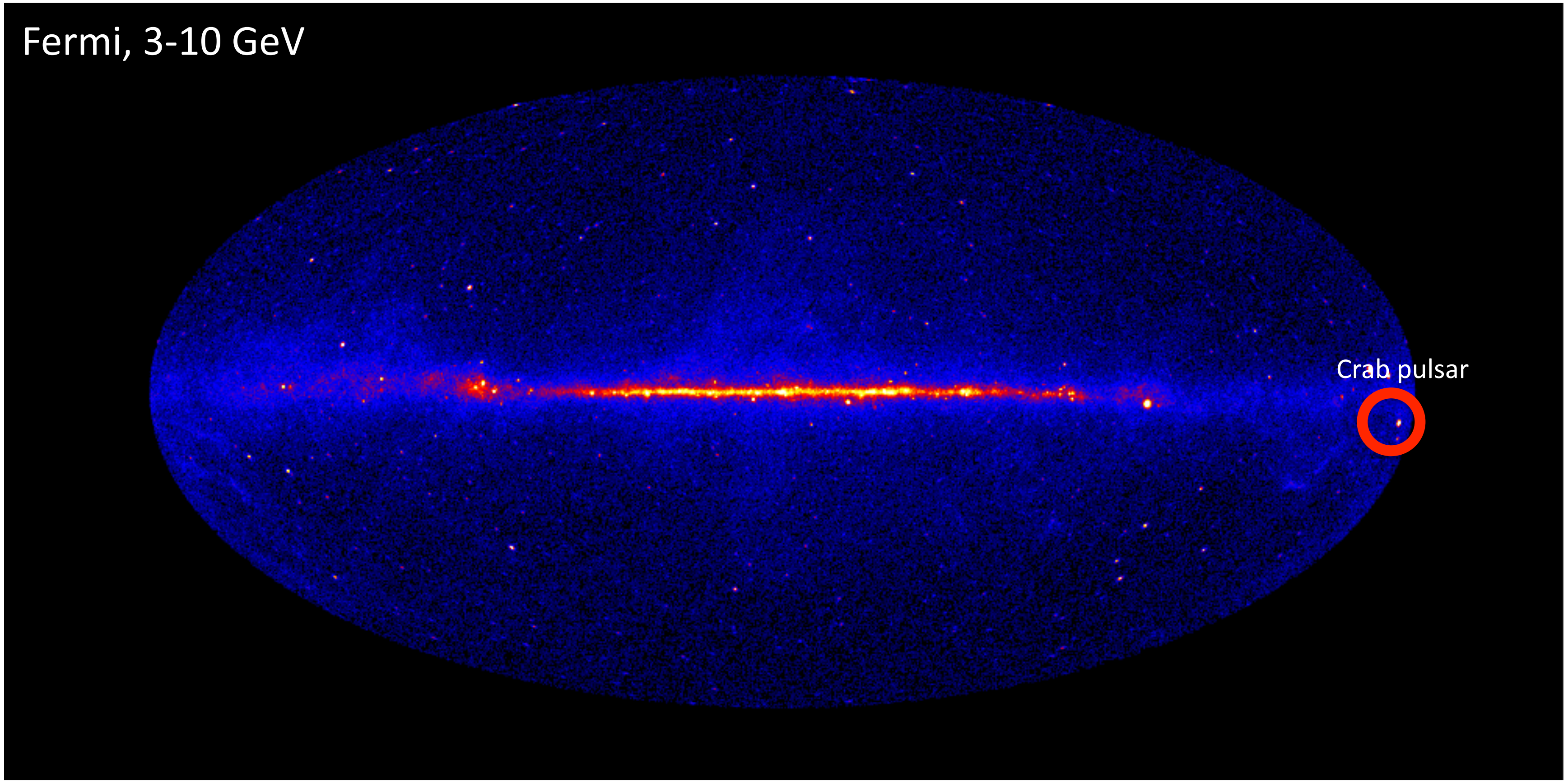
Lecture 3

Particle acceleration and interactions in active galactic nuclei

Andrii Neronov

ISDC Data Center for Astrophysics

Reminder of the previous lecture



Tools of Multi-wavelength and Multi-messenger astronomy to study astronomical sources working as particle accelerators.

Crab pulsar example.

Plan of lecture 3

Extragalactic sources of high-energy gamma-rays.

Example of Cen A: the closest-to-us AGN.

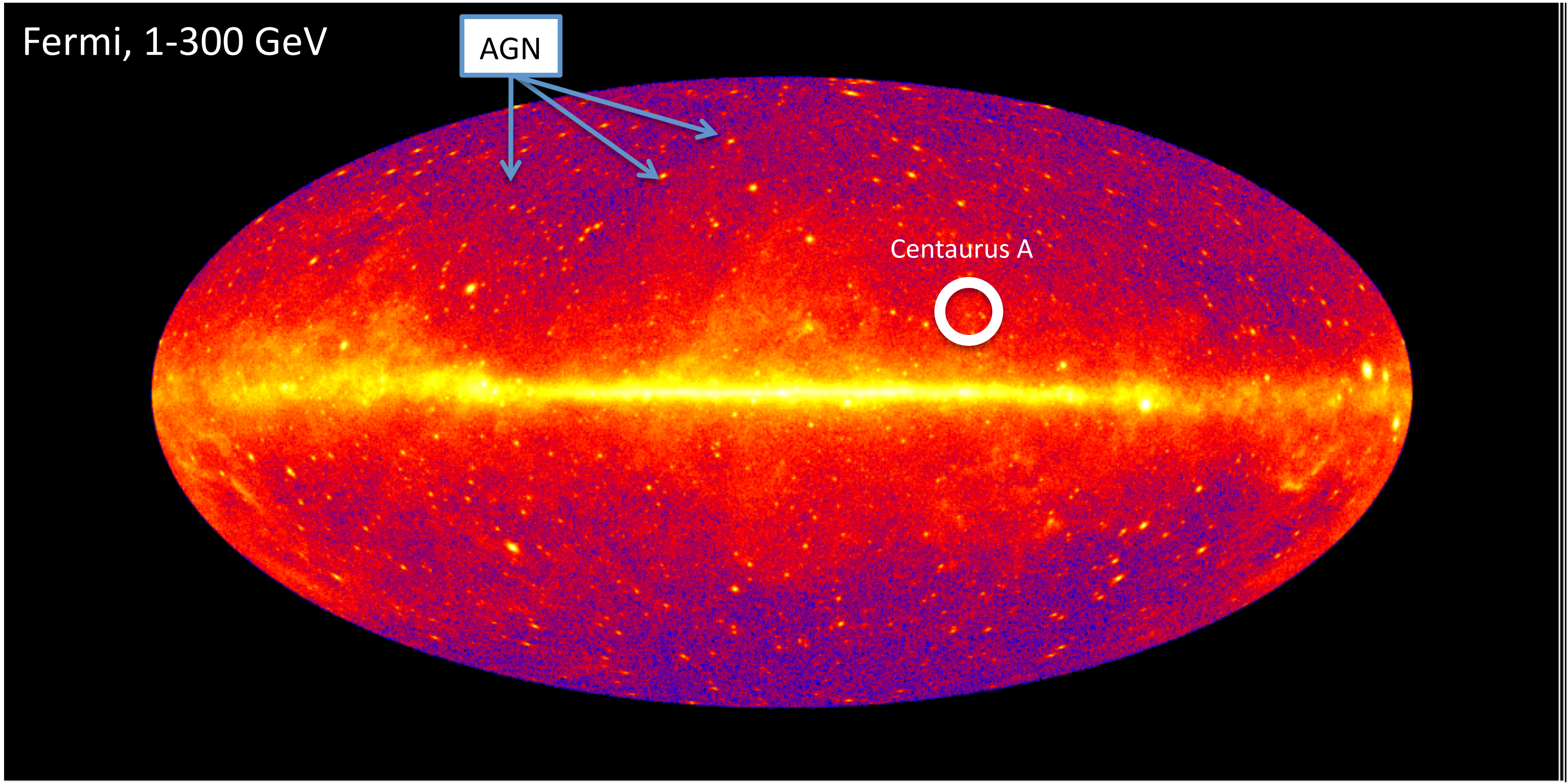
AGN classification.

Supermassive black holes and accretion flows onto them.

AGN jets.

Paricle acceleration in the jets, cores and lobes of radio galaxies.

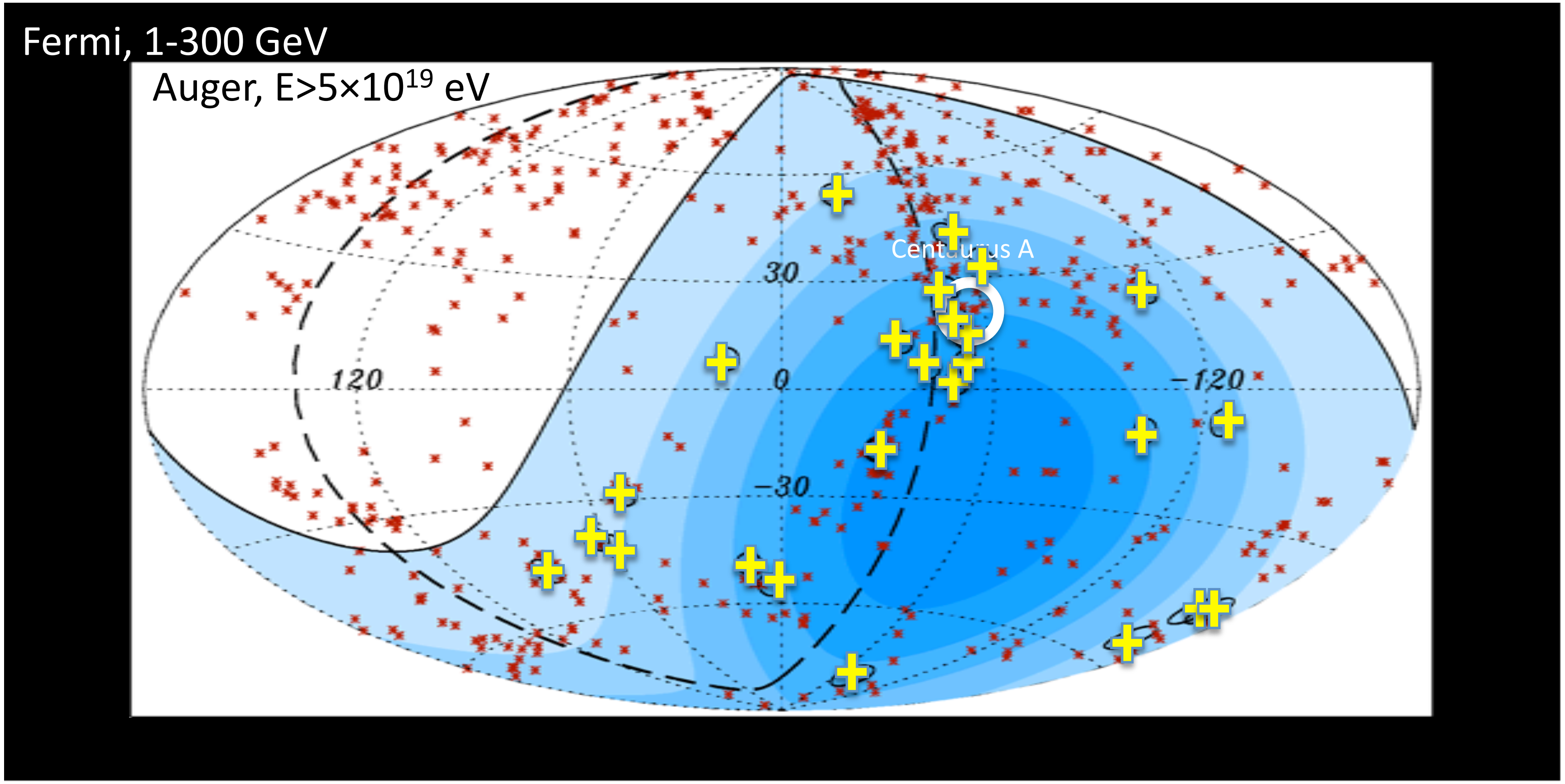
Extragalactic gamma-ray sources



All known extragalactic High-Energy (HE) and Very-High-Energy (VHE) γ-ray sources are active Galactic Nuclei (AGN).

AGN work as particle accelerators. How?

AGN as UHECR sources

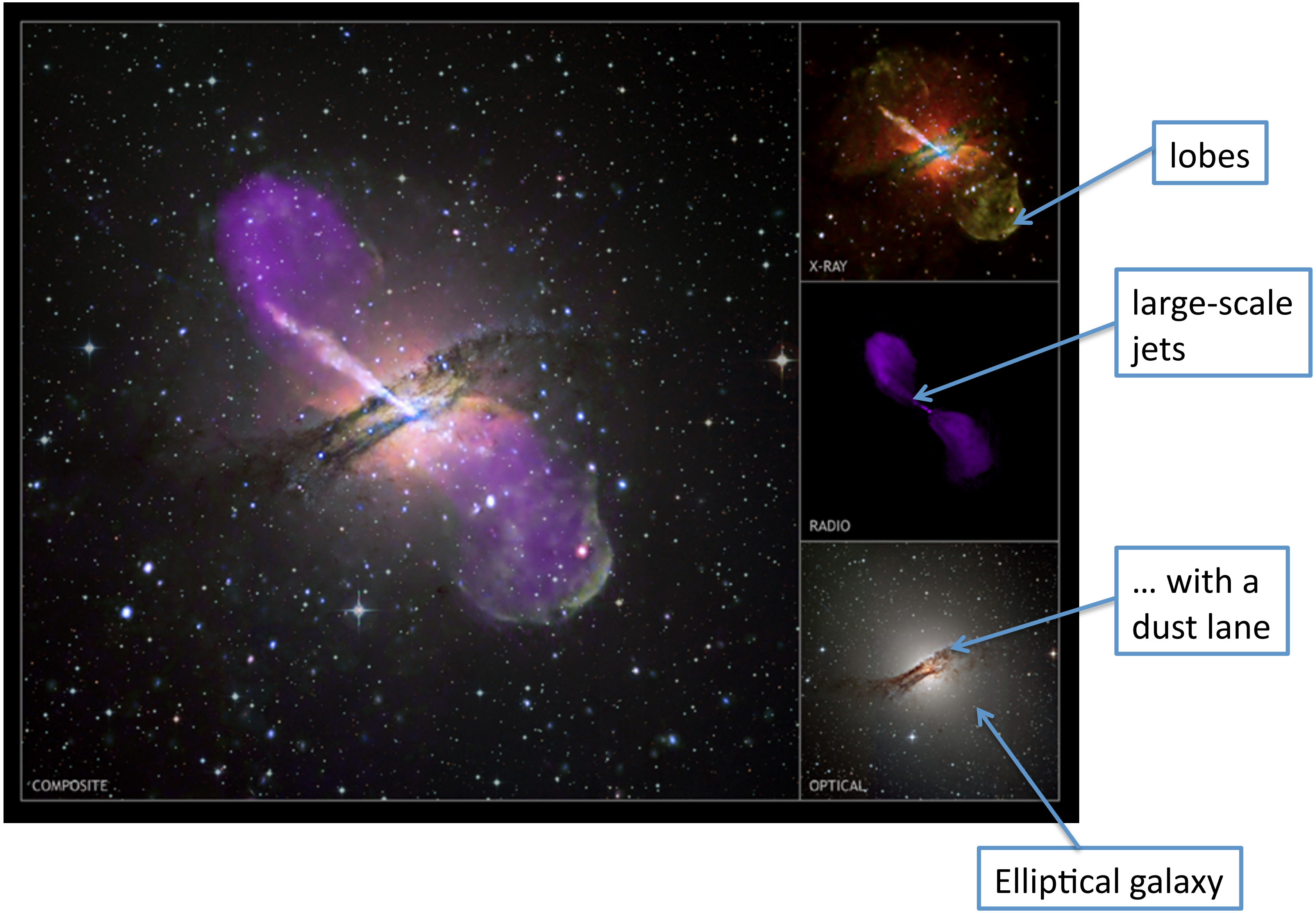


Nearby AGN could be sources of observed Ultra-High-Energy Cosmic Rays (UHECR).

Cen A is the closest-to-us AGN.

Excess of UHECR events in the direction of Cen A was reported by Pierre Auger Observatory.

Centaurus A



X-RAY
RADIO
OPTICAL
COMPOSITE
lobes
large-scale jets
... with a dust lane
Elliptical galaxy

Centaurus A in GeV gamma-rays

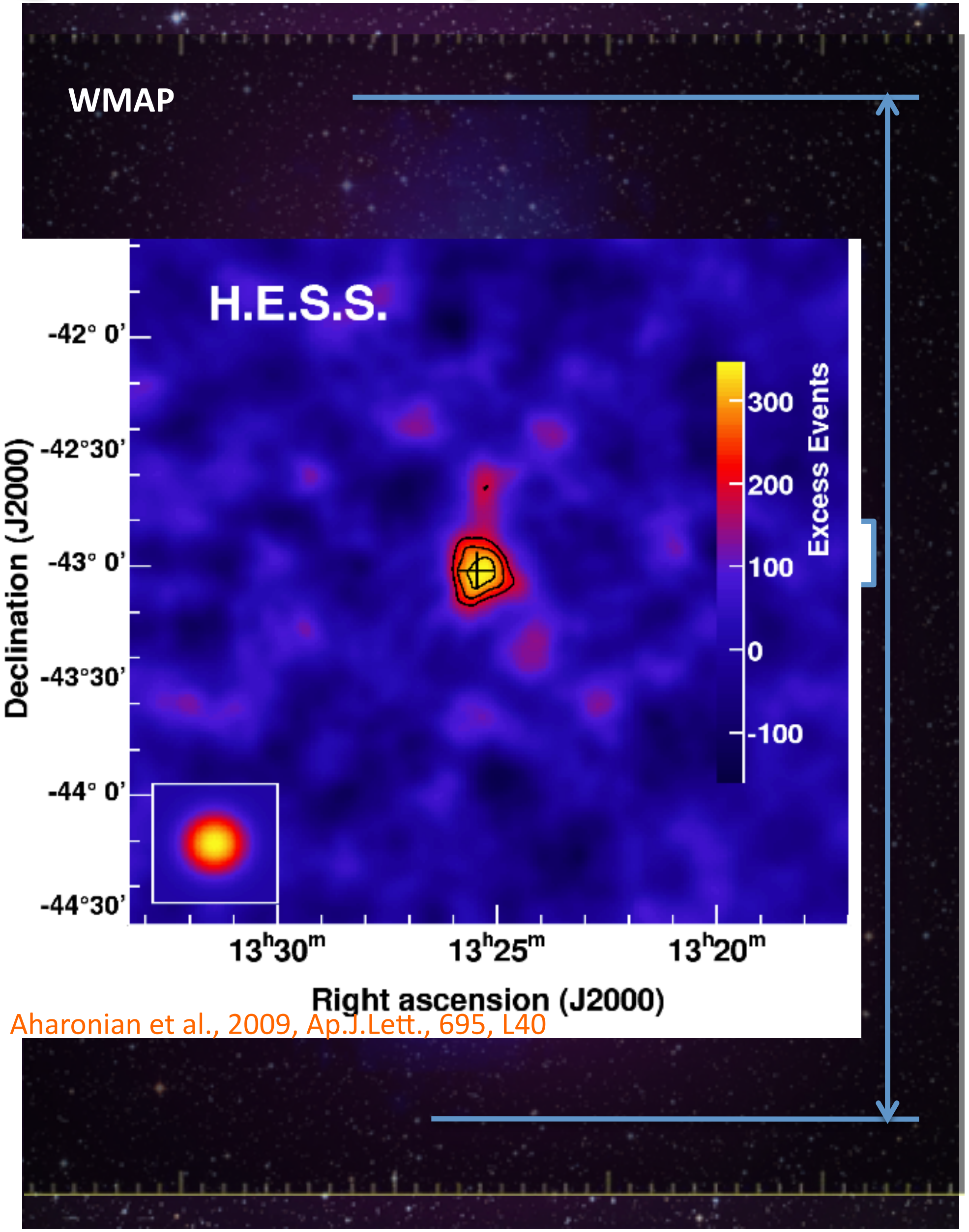
γ-ray emission from Cen A is spatially resolved in the GeV band.

Distance $D \approx 3.5$ Mpc (1 Mpc=3×10^{24} cm). Angular size $\Theta\sim10^{o}$. Linear size R=D$\Theta\sim$1 Mpc.

This is much larger than the size of the elliptical galaxy Cen A.

Extended γ-ray emission is accompanied by extended radio emission on the same distance scale.

Core of Cen A galaxy hosts a bright unresolved source of gamma-rays with energies up to 30 TeV.



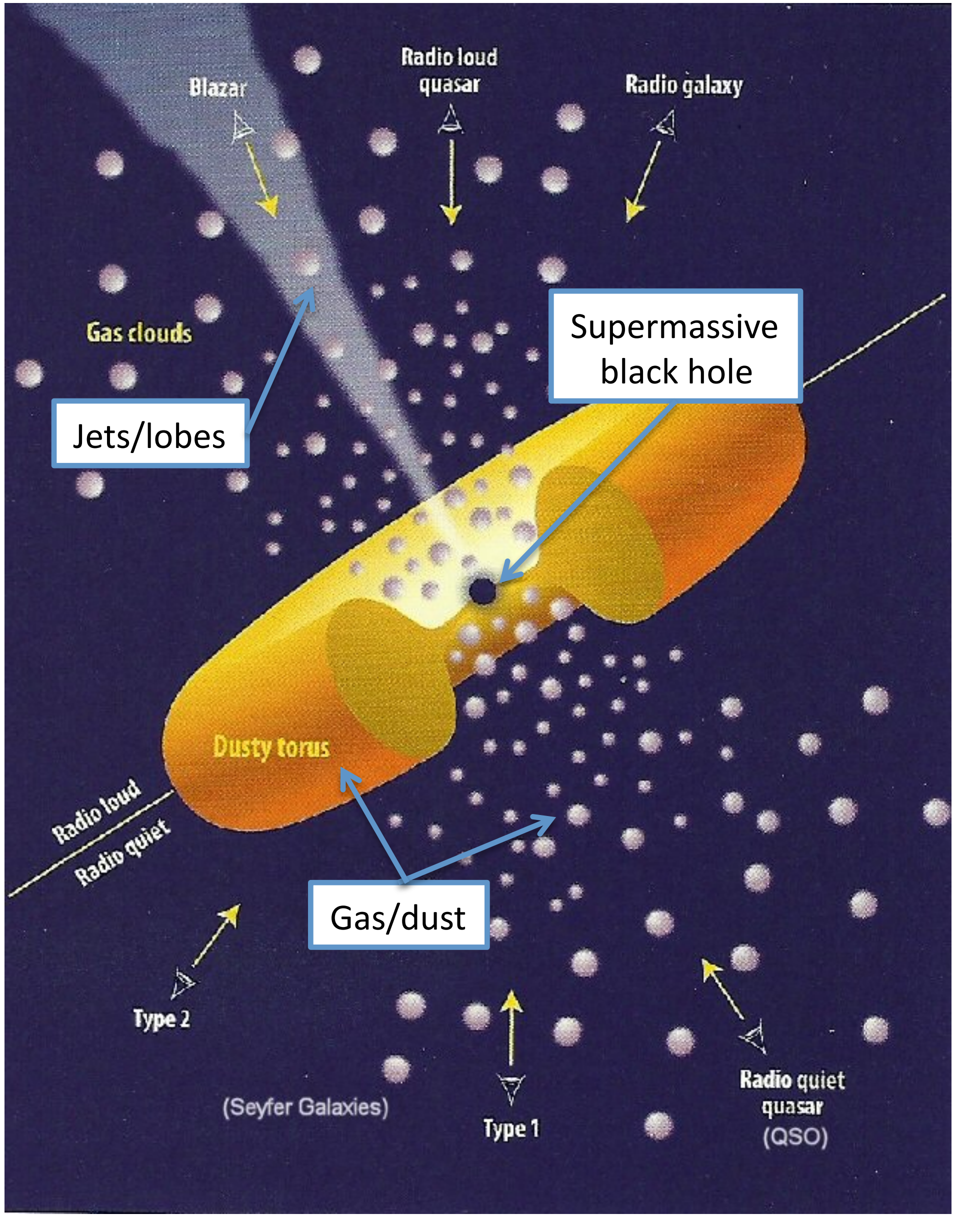
Aharonian et al., 2009, Ap.J.Lett., 695, L40

AGN classification

All AGN are povered by a compact central source, believed to be a black hole of the mass $M_{BH} \sim 10^6 – 10^{10} M_{Sun}$.

Radio-loud AGN generate jets extending from the smallest (~ 10 $R_{schwarzschild}$) to the largest (0.1-1Mpc) scales. Jets end in a large scale (~ 1 Mpc) radio lobes.

Radio-quiet AGN (Seyfert galaxies) mostly have only bright "core" powered by accretion onto the supermassive black hole. Emission from the core can occasionally be re-processed (reflected, absorbed, re-emitted) in a somewhat extended (pc-scale) region filled with dense gas clouds and/or obscured by the dust.



Problems of AGN physics

Is the "central engine" of AGN really a black hole?

What is the mechanism of black hole activity?

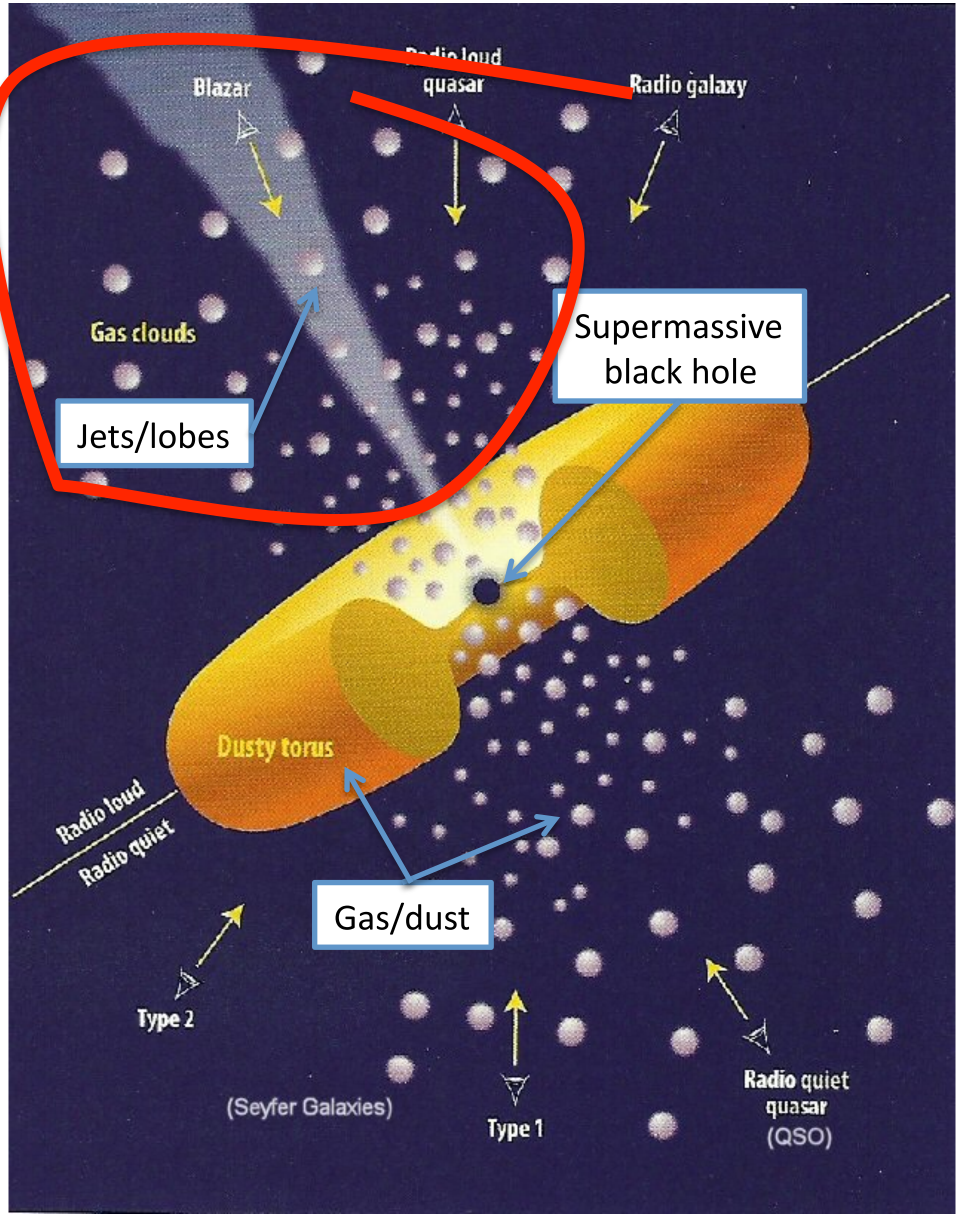
Why some of the active black holes produce jets while others do not?

What is the mechanism of jet ejection and collimation?

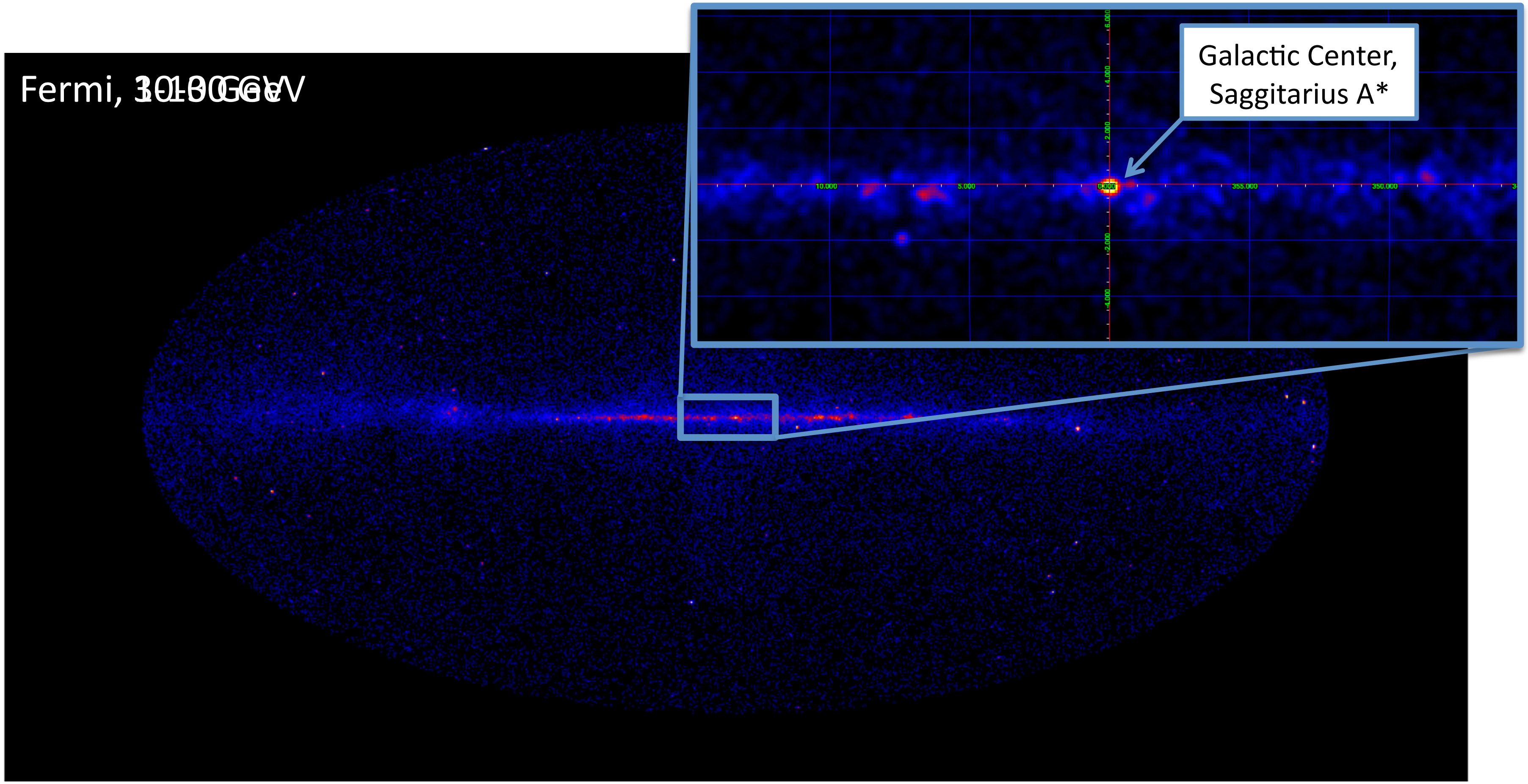
What is ejected into the jet (protons/ nuclei + electrons or electrons + positrons)?

What are the mechanisms of radio-to-gamma-ray emission from the jets?

What is the mechanism of particle acceleration (electrons or protons?). Where is the acceleration site?



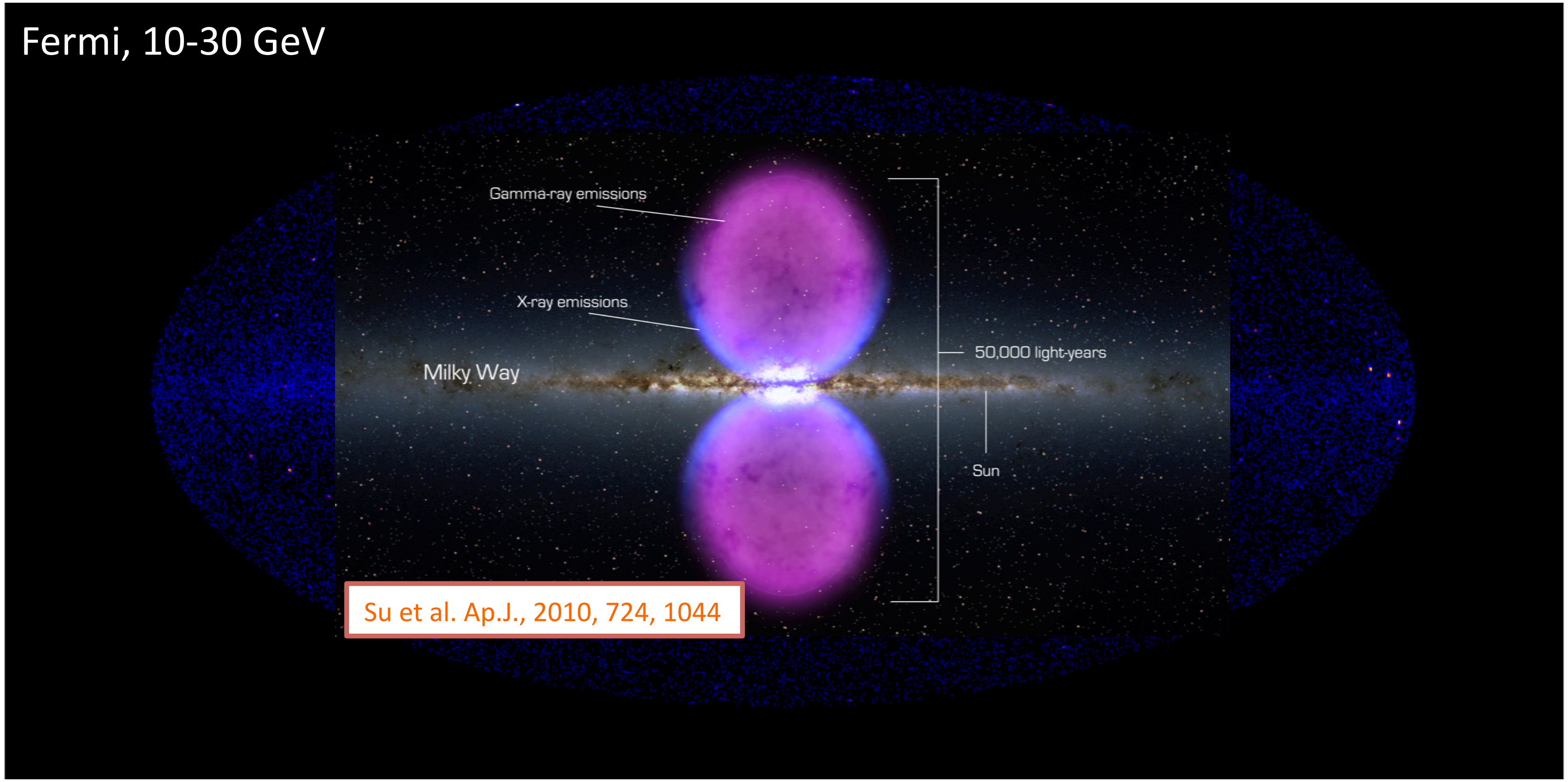
Galactic Center black hole



Center of the Milky Way galaxy is a "low-luminosity" AGN, $L_{\mathrm{Sgr\ A*}} \sim 10^{36}$ erg/s (compare with a luminosity of a massive star, $L_{*} \sim 10^{38}$ erg/s).

Center of the Milky Way galaxy hosts a "compact central object" of the mass $M_{BH} \approx 4 \times 10^{6} M_{Sun}$.

Galactic Center black hole



Large-scale γ-ray "bubbles" revealed by Fermi might be remnants of past activity of the Galactic Center black hole

Evidence for a black hole in the Galactic Centre

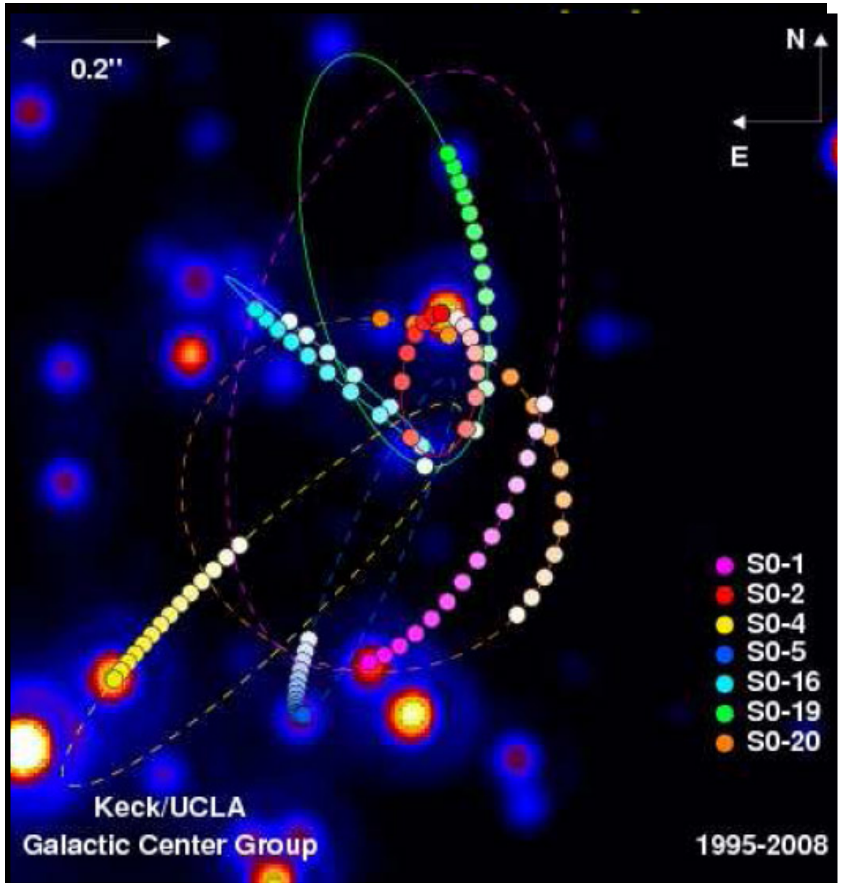
For the Galactic Centre black hole a constraint on the mass and compactness of the object could be derived from the stellar dynamics (observed in the infrared).

Periastron (point of closest approach of the elliptical orbit) of a star "S2" is $<10^{16}$ cm from the compact object.

Estimated mass of the compact object is $4\times10^6 M_{Sun}$. Schwarzschild radius

$$R_{\rm Schw} = 2G_N M \approx 10^{12}\left[\frac{M}{4\times10^6 M_{\rm Sun}}\right]\,\text{cm}$$

i.e. size of the object is no more than $\sim10^4 R_{Schw}$.



An alternative to a black hole would be a dense star cluster. However, life-time of a star cluster is estimated as $t_{\rm Cluster} \approx 10^6 \left[N_*/10^7\right]^2 \left[v/v_p\right]^{-3}$ yr, where N_* is number of stars, v is the velocity dispersion and v_p is the Keplerian velocity on the surface of stars.

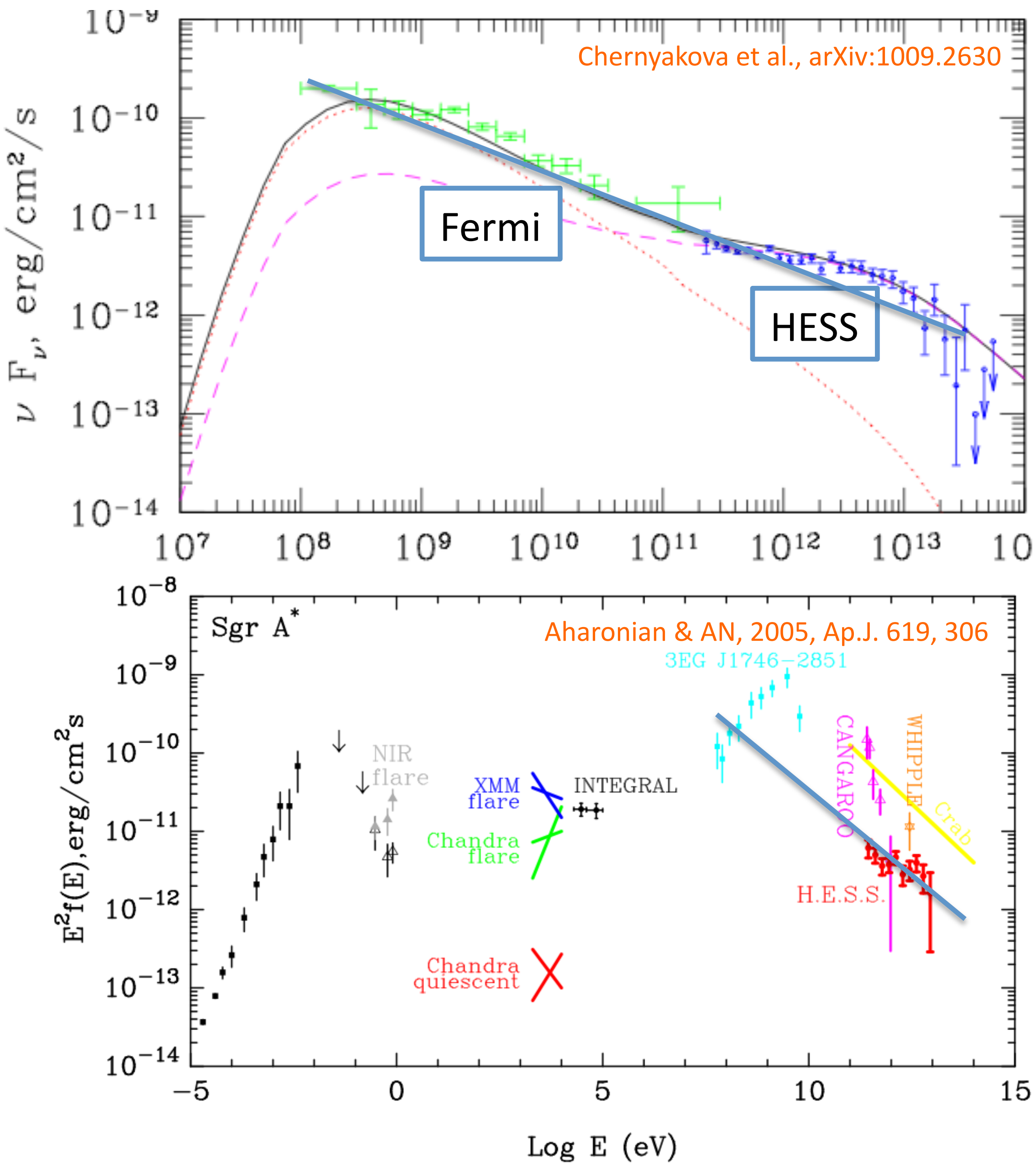
Dynamical evolution of the cluster leads to gravitational collapse. The "least exotic" outcome of the gravitational collapse of a star cluster would be a black hole.

Particle acceleration in the Galactic Centre

Gamma-ray spectrum of the Galactic Centre extends up to ~30 TeV. Gamma-ray signal is not variable on months time scale.

Gamma-ray emission in the 100 MeV band dominates the energy output of the source across the electromagnetic spectrum.

Infrared and X-ray emission from Sgr A* is variable by a factor $>10^2$ on very short time scales, ~10 min.



Galactic Centre flaring activity

Variability time scale of infrared and X-ray emission is comparable to the characteristic time scales associated to a black hole of the mass $M_{BH} \approx 4\times10^{6} M_{Sun}$

$$t_{lc} = \frac{2R_{\rm Schw}}{c} \approx 10^{2}\,{\rm s}$$

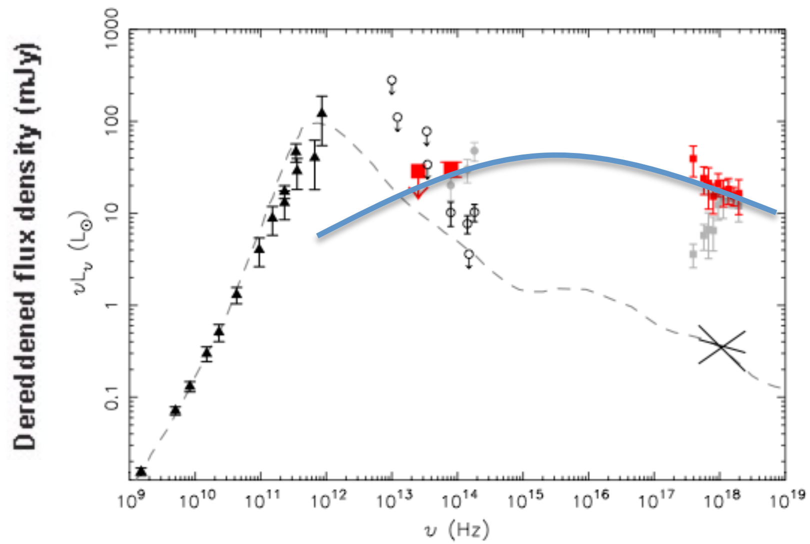
$$t_{rot} = \frac{12\sqrt{6}\pi R_{\rm Schw}}{c} \approx 2\times10^{3}\,{\rm s}$$

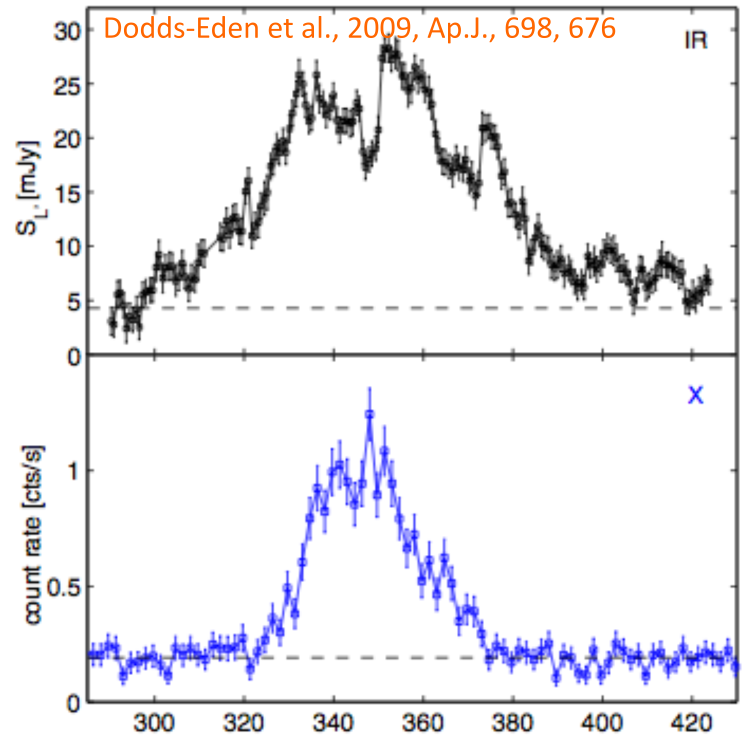
This implies that this emission comes from the direct vicinity of the black hole.

X-ray emission is, most probably, synchrotron emission from high-energy (GeV) electrons

Particle acceleration takes place in the direct vicinity of black hole horizon

There is no commonly accepted model of particle acceleration close to the Galactic Center black hole





Radiatively inefficient accretion

Radio emission from the Galactic Center is thought to be produced by accretion flow.

A black hole placed in a medium accretes matter from a volume of the size R_{acc}

$$\frac{mc_s^2}{2} \sim \frac{G_N M_{BH} m}{R_{acc}}$$

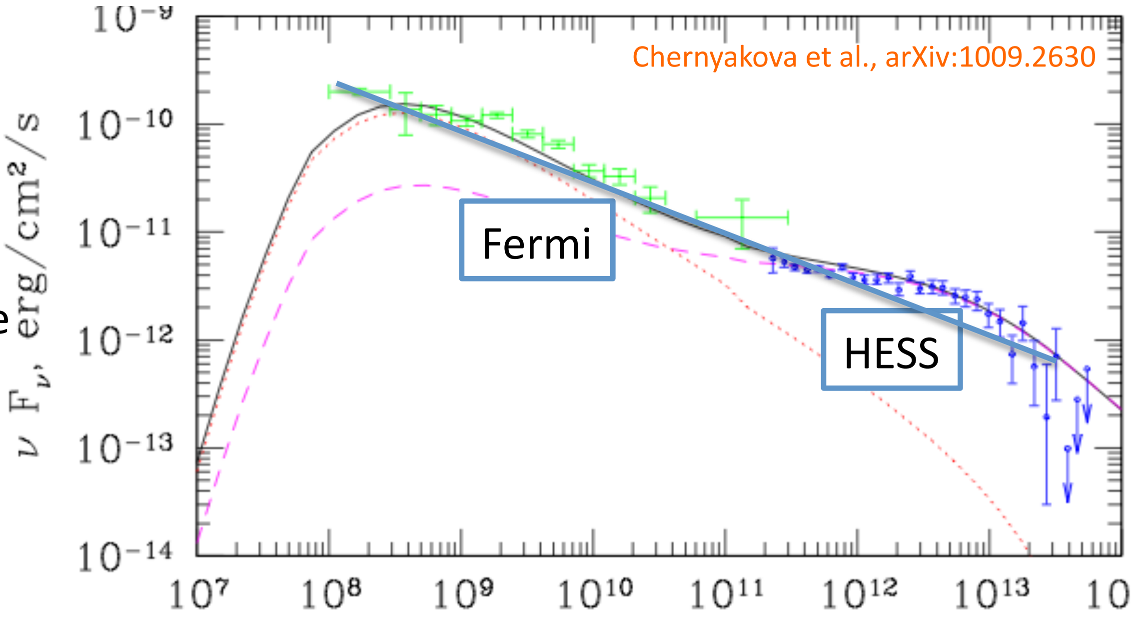
$$R_{acc} \sim \frac{G_N M_{BH}}{c_s^2} \sim 10^{18}\left[\frac{c_s}{200\ \mathrm{km/s}}\right]^{-2} \mathrm{cm}$$

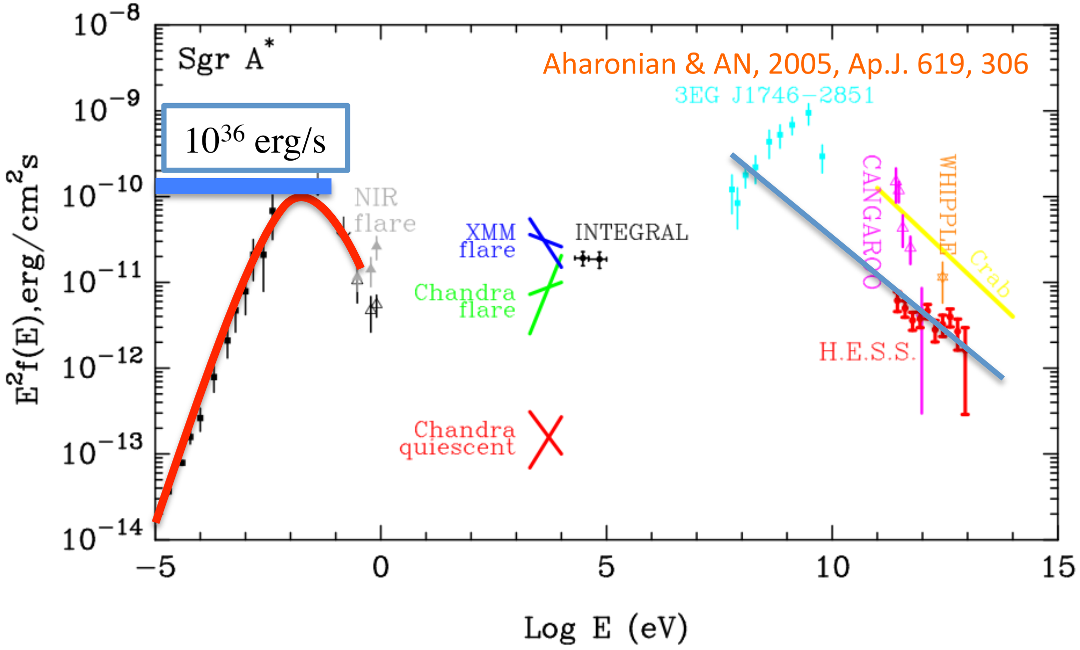
Accretion rate onto Galactic Center is

$$P_{acc} \sim \frac{\rho_{ISM} R_{acc}^3}{R_{acc}/c_s} \sim 10^{-5} M_{Sun}\left[\frac{n_{ISM}}{10^2\mathrm{cm}^{-3}}\right]\mathrm{yr}^{-1}$$

Liberated gravitational energy of each particle reaching "last stable circular orbit" near black hole is $\eta \sim 0.1\text{-}0.4mc^2$. Expected luminosity of the accretion flow

$$L_{acc} \sim \eta P_{acc} \sim 10^{42}\left[\frac{n_{ISM}}{10^2\mathrm{cm}^{-3}}\right] \mathrm{erg/s}^{-1}$$





Radiatively inefficient accretion

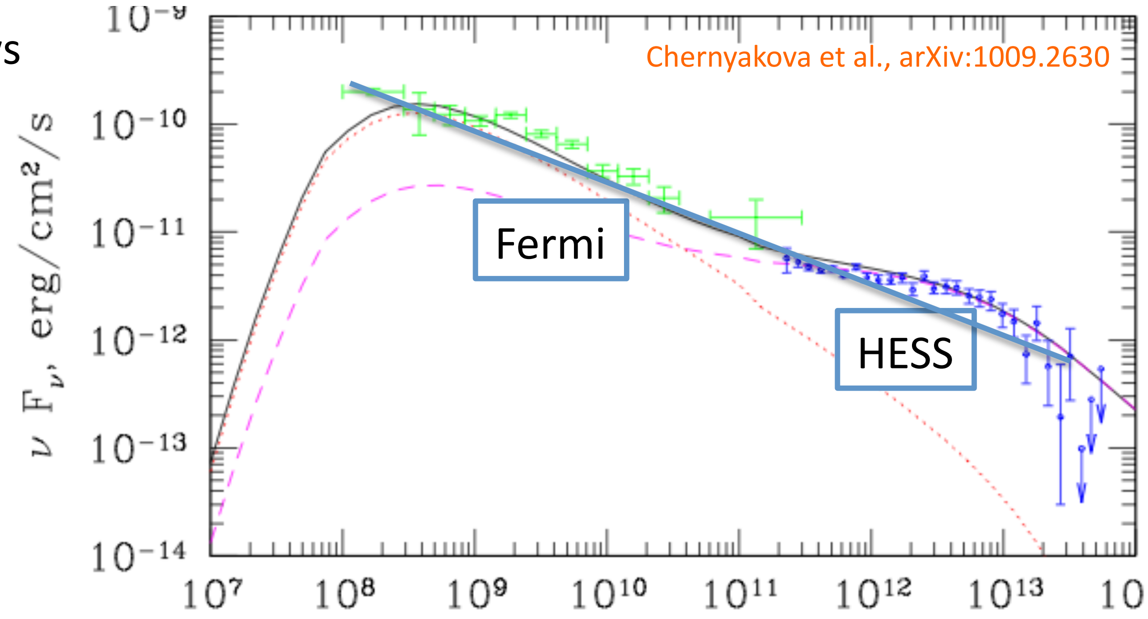
Radiatively inefficient accretion flows are typically found in all AGN accreting at a rate much below the "Eddington limit" rate P_{Edd}

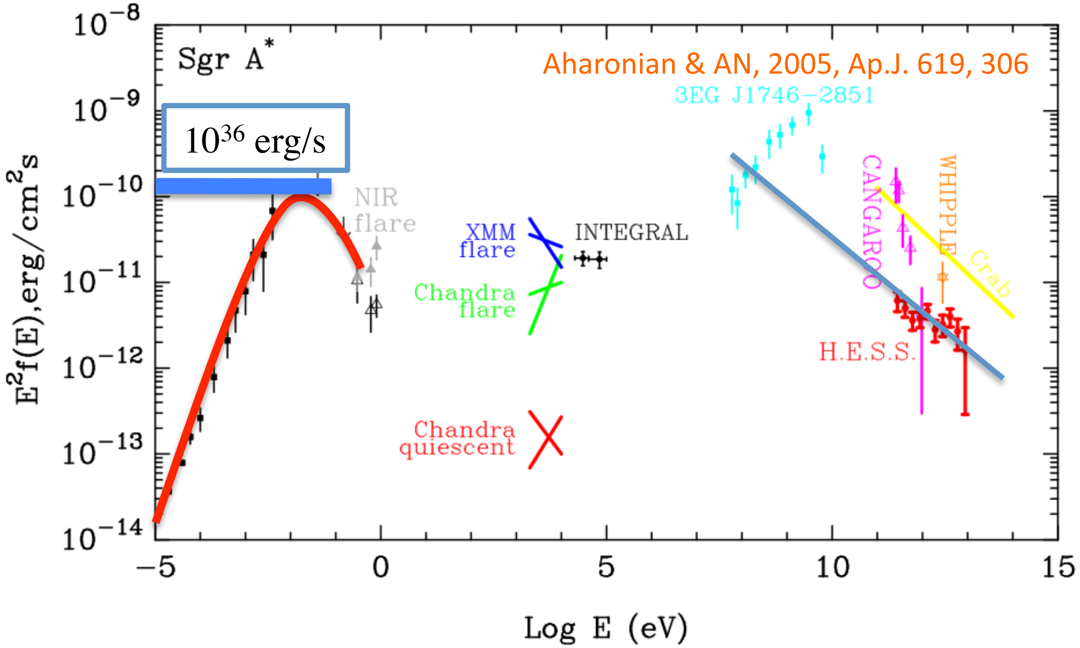
$$\frac{G_N M_{BH} m}{R^2} \sim \frac{\sigma_T L_{Edd}}{4\pi R^2}$$

$$P_{Edd} = \frac{L_{Edd}}{\eta} \sim 0.2 M_{Sun} \left[\frac{M_{BH}}{10^7 M_{Sun}}\right] \text{yr}$$

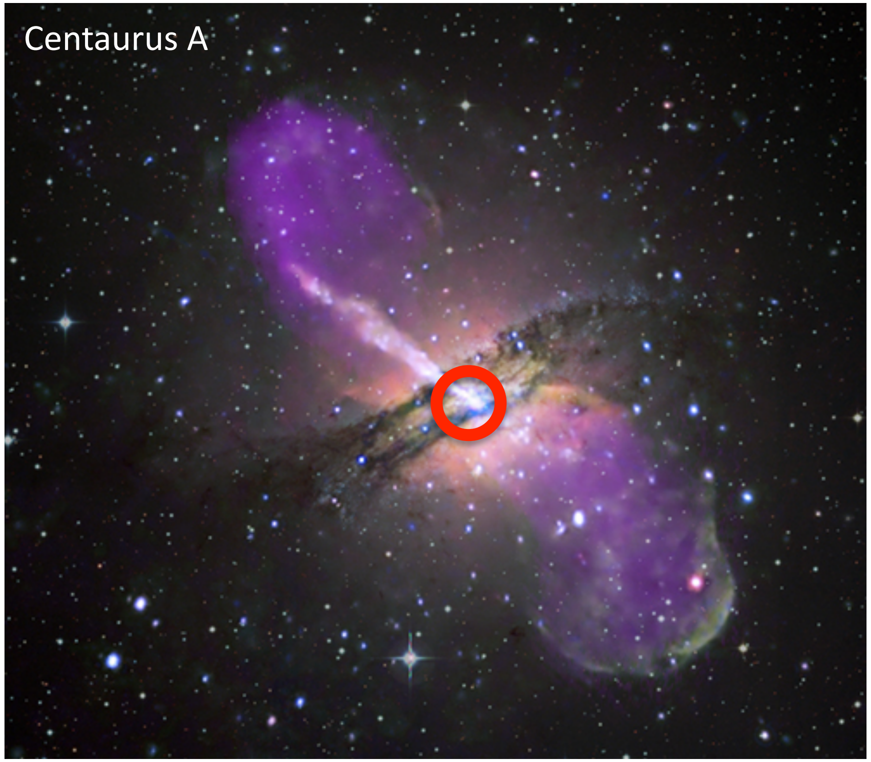
$$L_{Edd} \sim 10^{45} \left[\frac{M_{BH}}{10^7 M_{Sun}}\right] \text{erg/s}$$

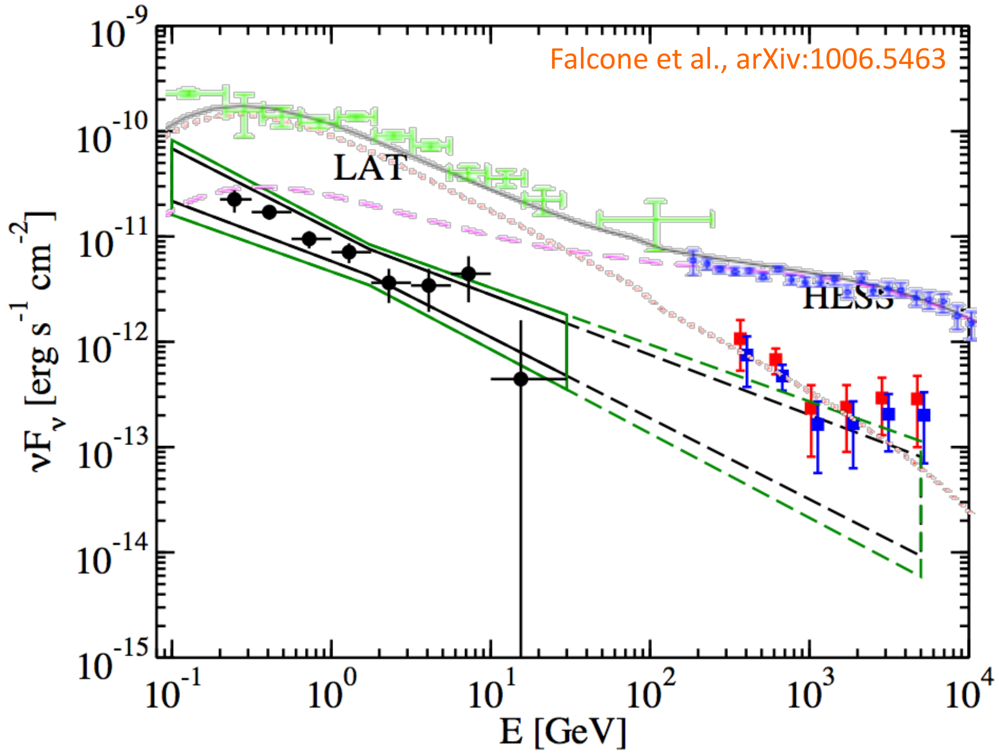
Models of RIAF assume that the gravitational energy is used mostly to heat accreting matter, rather than onto radiation.





Centaurus A

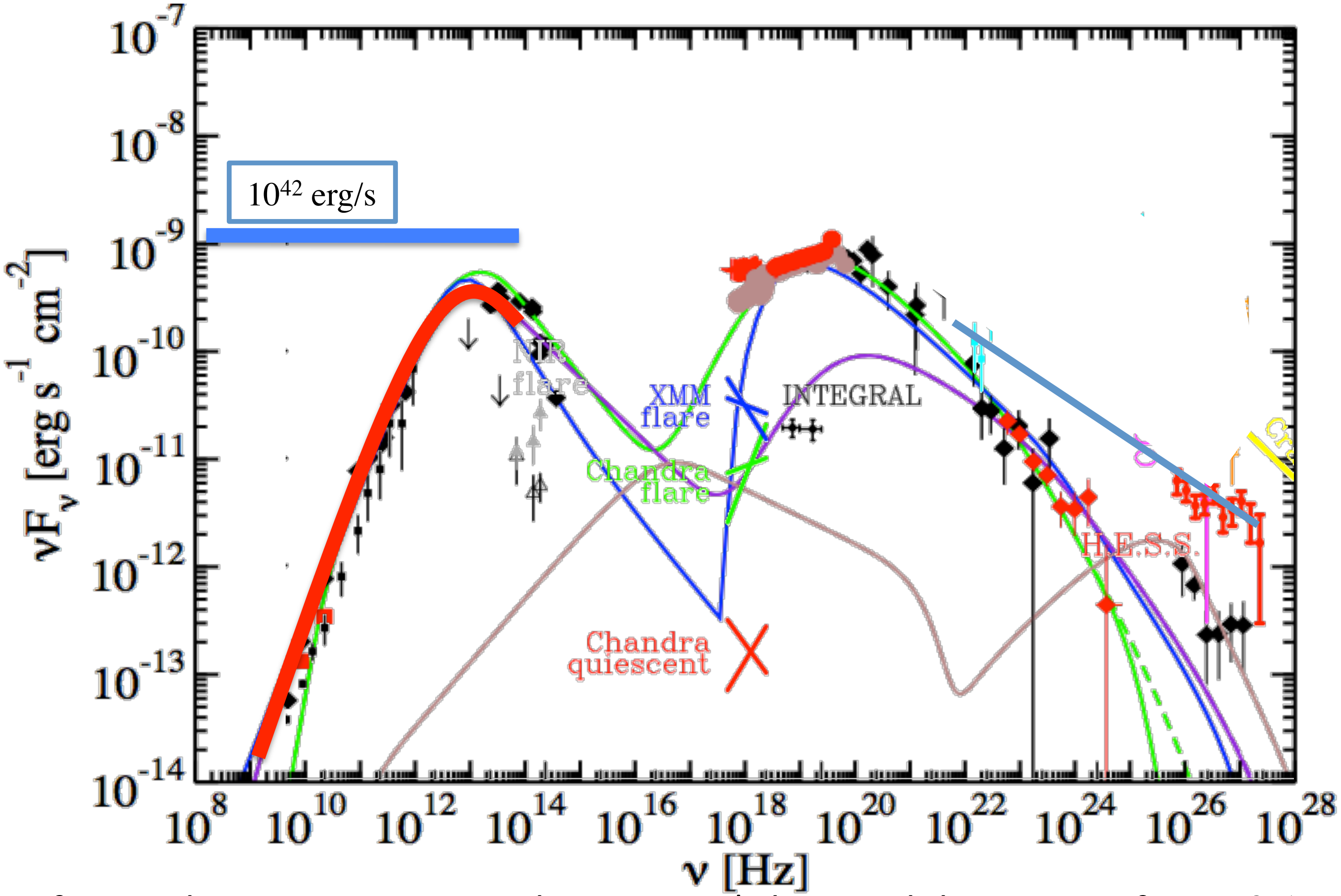




Gamma-ray spectrum of Cen A extends into the TeV band, similarly to the Galactic Center spectrum.

Cen A flux is lower by a factor ~ 10. Its luminosity is larger by a factor $0.1\times(D_{CenA}/D_{GC})^2 \sim 10^4$ than that of the Galactic Center.

Radiatively inefficient accretion in Cen A



Radio spectrum of Cen A has a spectrum similar to Sgr A*, but with luminosity factor $0.1\times (D_{CenA}/D_{GC})^2 \sim 10^5$ times larger. Estimated black hole mass in Cen A is $\sim$10 times larger than the mass of the Galactic Center black hole.

$$L_{acc} \sim \eta P_{acc} \sim 10^{44}\left[\frac{n_{ISM}}{10^2 \mathrm{cm}^{-3}}\right] \mathrm{erg/s}^{-1}$$

Problem of the origin of AGN jets

General properties of accretion flows onto the black holes in Cen A and in the Galactic Centre are similar (RIAF).

Broad band spectral energy distributions of the two sources are similar.

Why does the black hole in Cen A produce a large scale jet, while the Galactic Centre black hole does not?

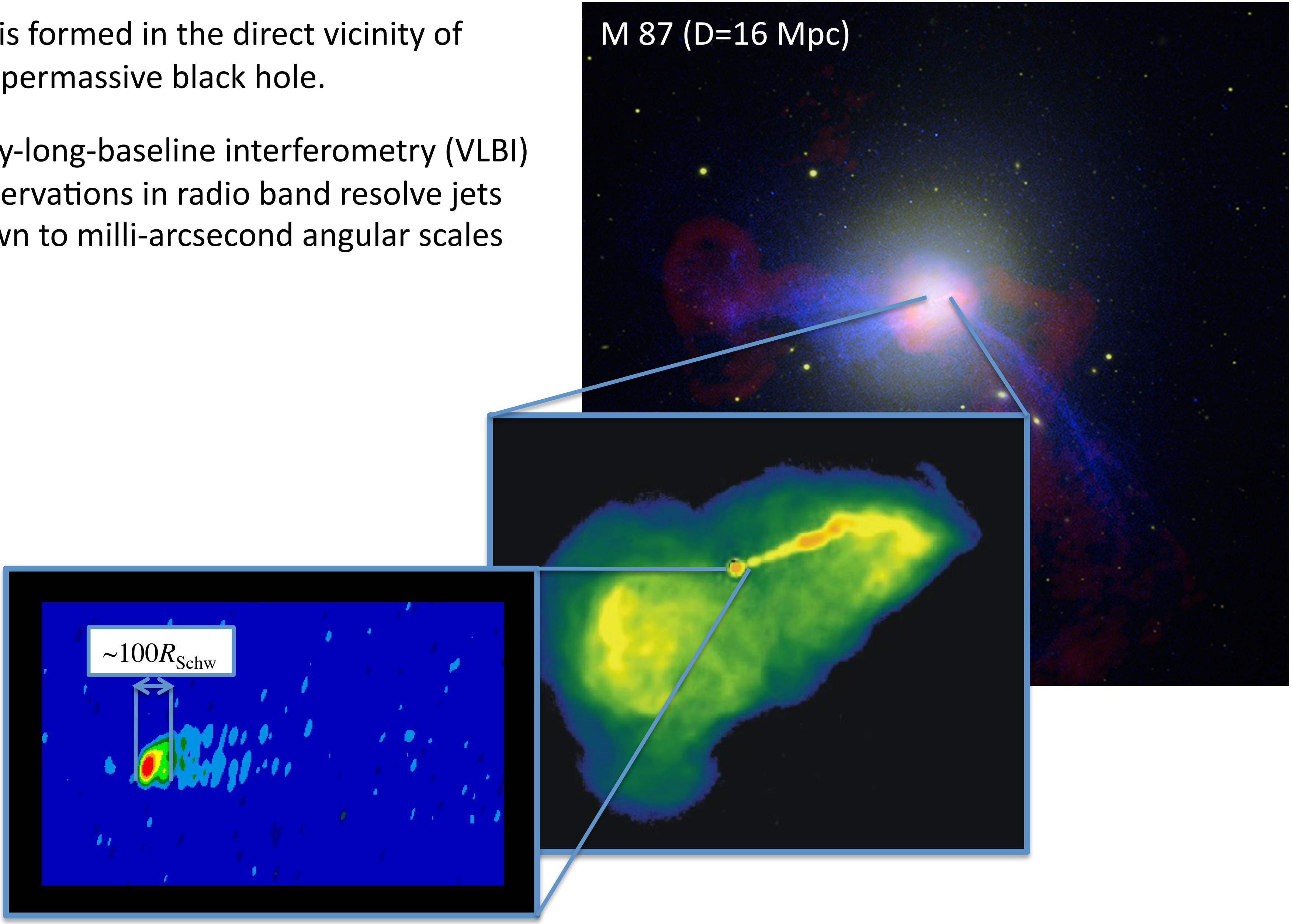
What is the mechanism of jet formation?

What is the source of jet power?

AGN jets phenomenology

Jet is formed in the direct vicinity of suppermassive black hole.

Very-long-baseline interferometry (VLBI) observations in radio band resolve jets down to milli-arcsecond angular scales



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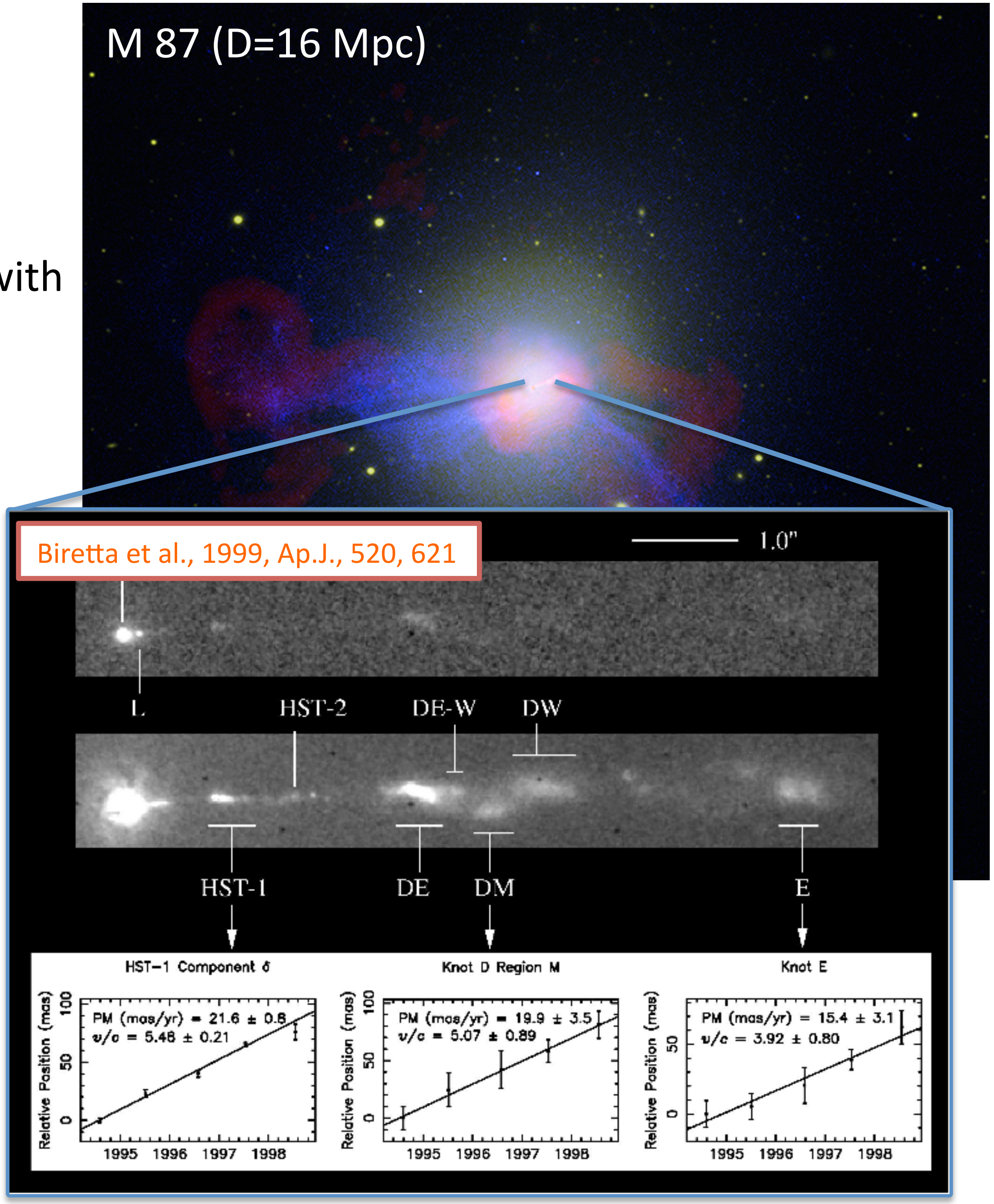
Typical jet outflows consist of series of "knots" escaping from the "central engine" (the supermassive black hole) with relativistic speed.



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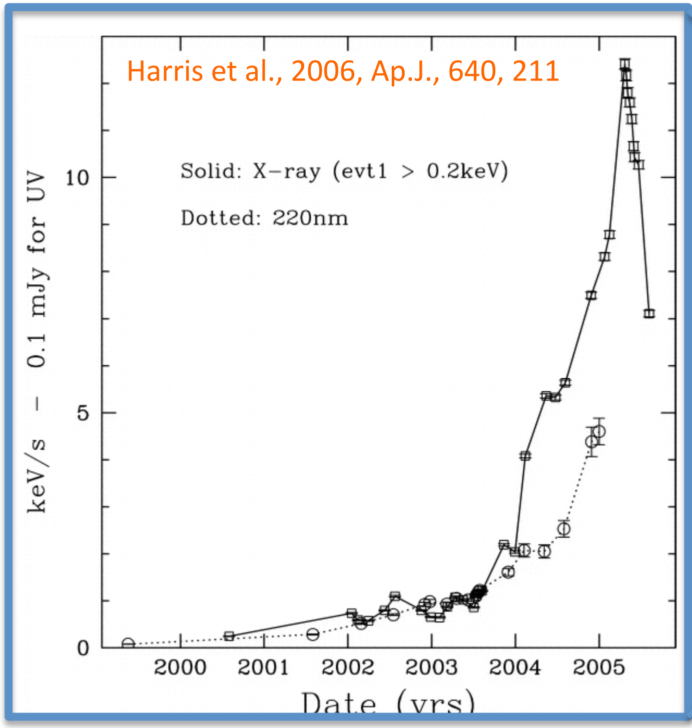
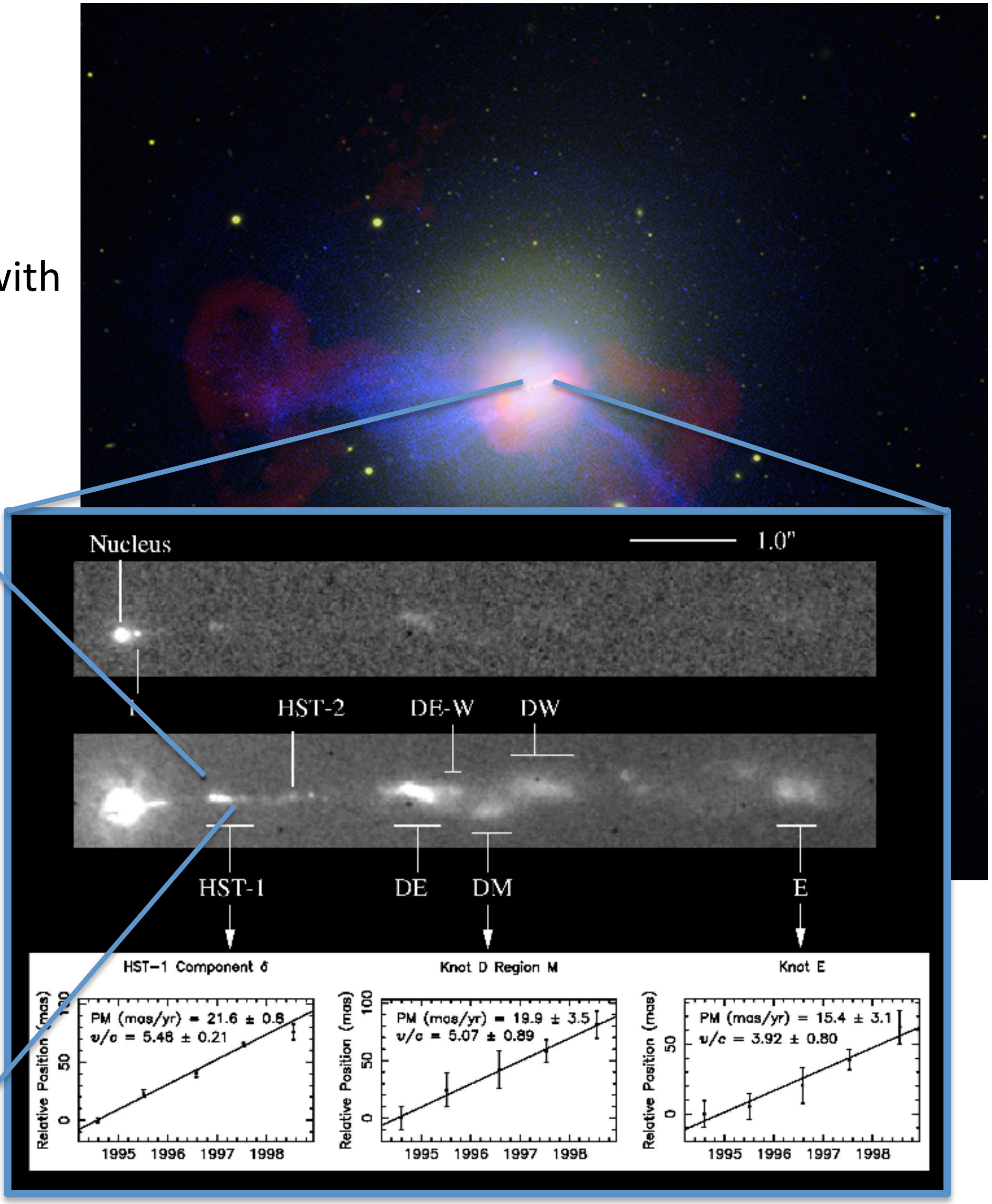
Jet outflows contain electrons (and/or positrons) with energies up to 100 TeV.





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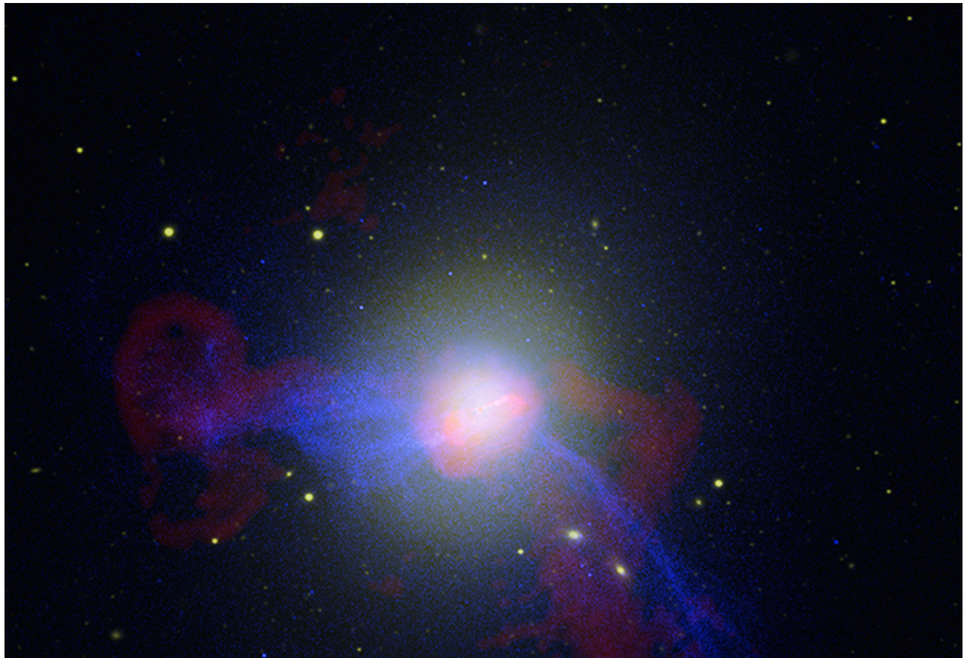
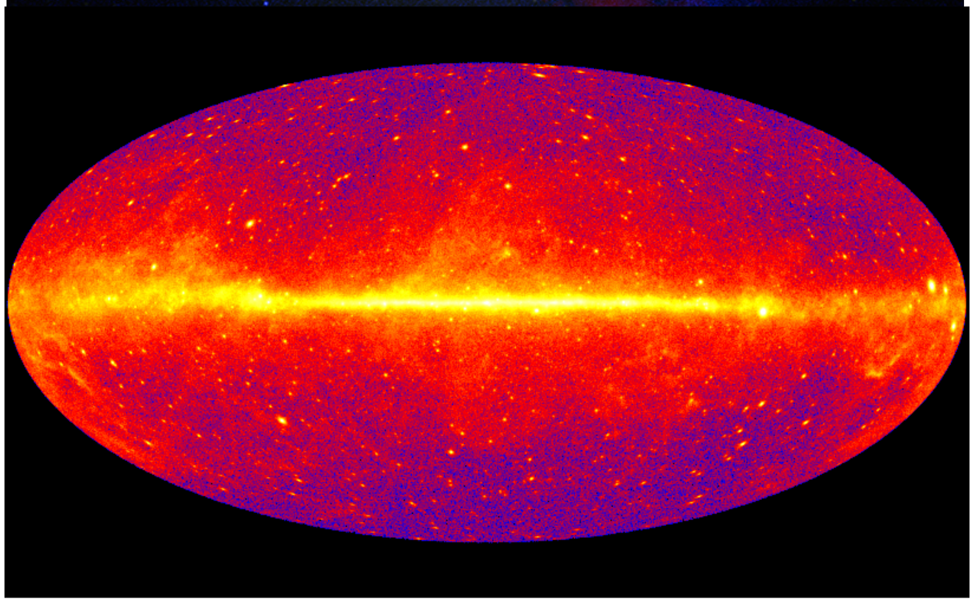


Most of the known extagalactic gamma-ray sources are blazars, radio galaxies with jets aligned with the line of sight. Blazar emission is Doppler boosted

$$\delta = \Gamma^{-1}(1-\beta\cos\theta_{los})^{-1} \sim \Gamma \sim 10, \quad \theta_{\rm los} \sim \Gamma^{-1}$$

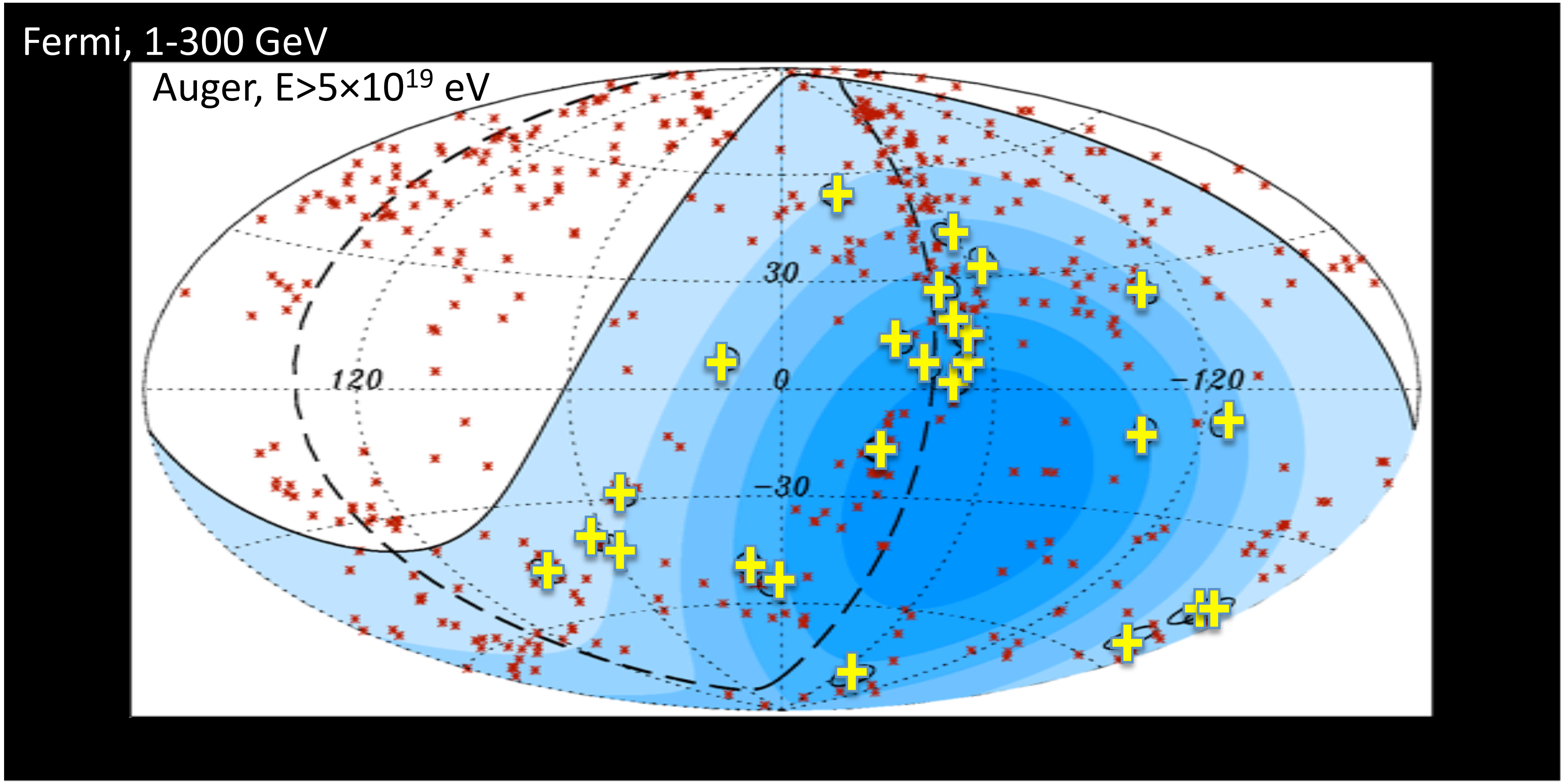
$$L_{app} = L\delta^4 \sim 10^4 L\left[\frac{\Gamma}{10}\right]^4$$



Power emitted in the jet could be comparable to the power of emission from the AGN core.

Mechanism of jet ejection is not known.

AGN as sources of UHECR?



AGN as sources of UHECR?

Possible cosmic ray acceleration sites:

a) AGN core

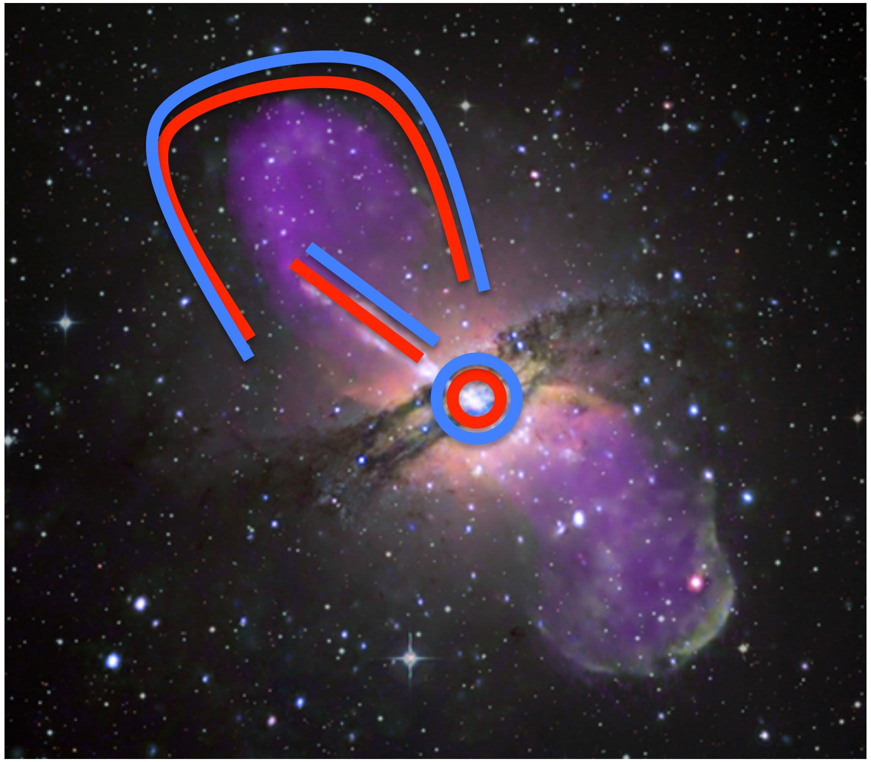
b) AGN jet

c) extended radio lobes

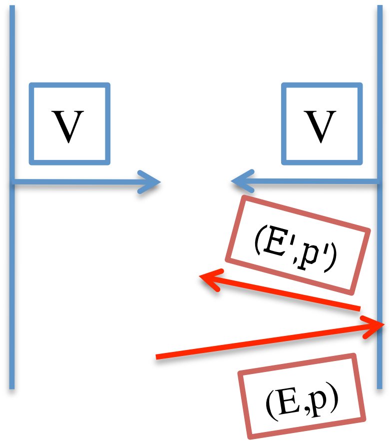
Possible cosmic ray acceleration mechanisms:

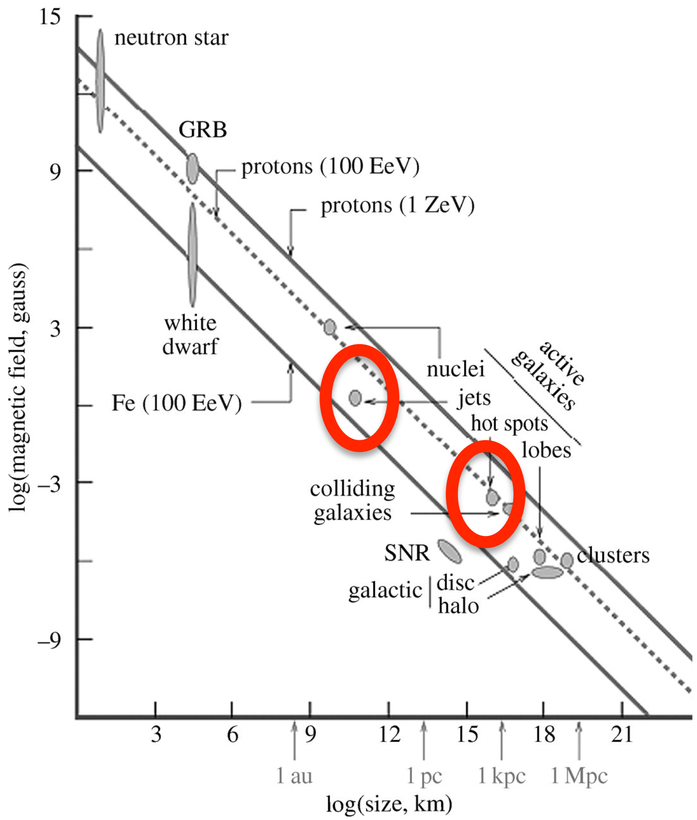
a) diffusive shock acceleration

b) acceleration by large scale electric fields



Shock acceleration mechanism





Energy gain for a particle reflected from a moving shock wave (Lorentz transformation)

$$E' = \Gamma^2\left((1+V^2)E + 2Vp\right) \sim (1+V)E, \quad V << 1$$

$$\Delta E \sim VE = \beta E$$

Energy gain rate $\dfrac{dE}{dt} = \dfrac{\beta E}{T}$ where T is time interval between subsequent reflections.

Particles are deflected by magnetic field, so that $T \sim R_L / c \sim \dfrac{E}{eBc}$

$$\frac{dE}{dt} = \beta eB, \quad \beta < 1$$

Maximal energies of particles are limited (a) by lifetime of the shock, (b) size of the shock, (c) energy losses

$$R_L < R, \quad E_{\max} < eBR \sim 10^{20}\left[\frac{B}{10^{-6}\ \mathrm{G}}\right]\left[\frac{R}{100\ \mathrm{kpc}}\right]\ \mathrm{eV}$$

Acceleration by large scale electric fields

Accretion flows generate magnetic fields

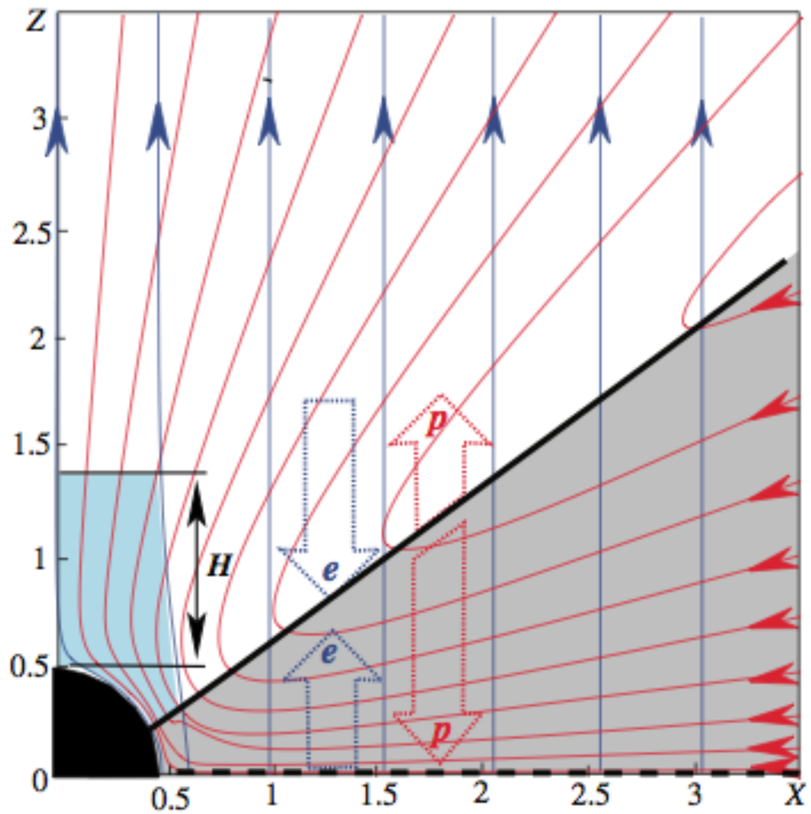
Rotating black hole drags of magnetic field into co-rotation.

Rotating magnetic field generates electric field with the strength

$$\left|\vec{E}\right| \sim \frac{a}{M}\left|\vec{B}\right|, \;\; a = \frac{J}{M} \leq M$$

Electric field lines are alighned with magnetic field lines in the "polar caps" (close to the North and South magnetic poles).

Polar caps work as linear particle accelerators.



AN et al. arxiv:0712.1737

$$\frac{dE}{dt} \sim e\frac{a}{M}B; \quad E_{\max} = \frac{dE}{dt}\frac{R_{Schw}}{c} \approx \frac{a}{M}eBR_{Schw} \approx 10^{20}\left[\frac{B}{10^4 \text{ G}}\right]\left[\frac{M_{BH}}{10^8 M_{Sun}}\right]\text{eV}$$

Blazars

Particle acceleration near black hole and/or in the innermost part of the jet is inevitably accompanied by electromagnetic emission.

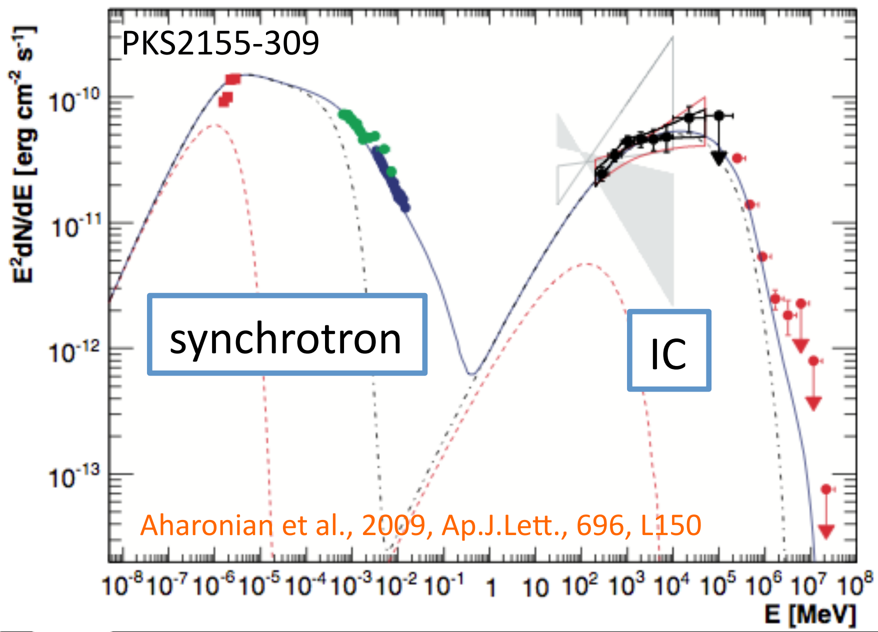
For electrons, main energy loss channels are synchrotron and inverse Compton emission.

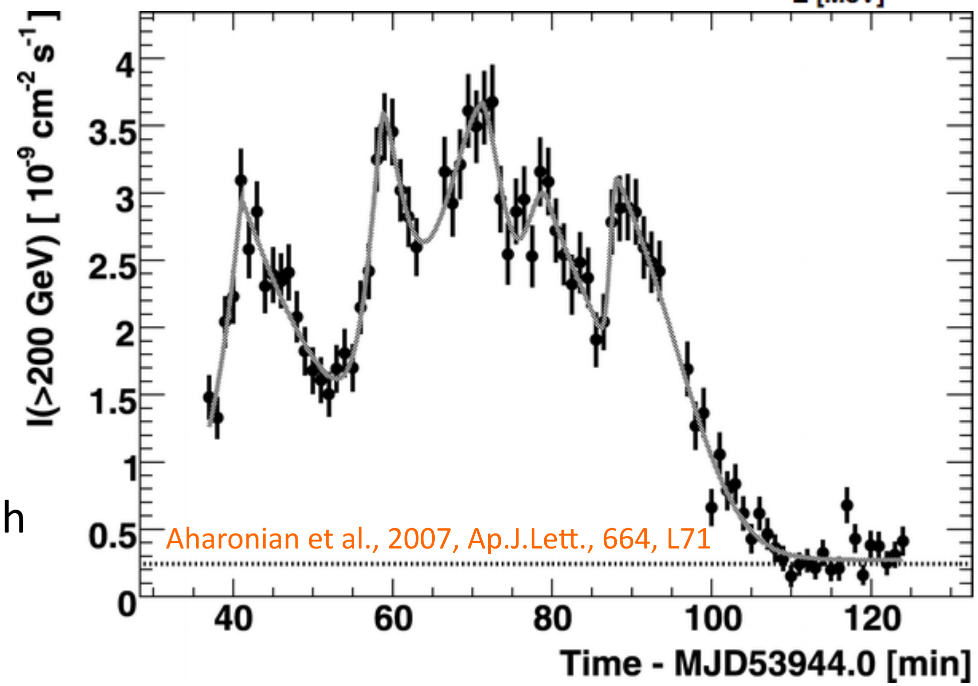
Electromagnetic emission is expected to be variable on the time scale comparable to the light-crossing time of the black hole.

$$t_{BH} \sim \frac{R_{Schw}}{c} \sim 10^2 \left[\frac{M_{BH}}{10^7 M_{Sun}}\right] \mathrm{s}$$

Fast-variable gamma-ray outbursts are commonly observed in blazars (radio galaxies with jets aligned with the line of sight.

Monitoring of blazars in the GeV band with Fermi available since 2008 enables systematic study of blazar flares.





Summary

AGN as candidate UHECR sources.

High-energy gamma-ray emission from AGN (blazars and radio galaxies).

Supermassive black holes and origin of AGN activity.

Phenomenology and origin of AGN jets.

Mechanisms of particle acceleration in AGN.