Active Galactic Nuclei: a brief introduction

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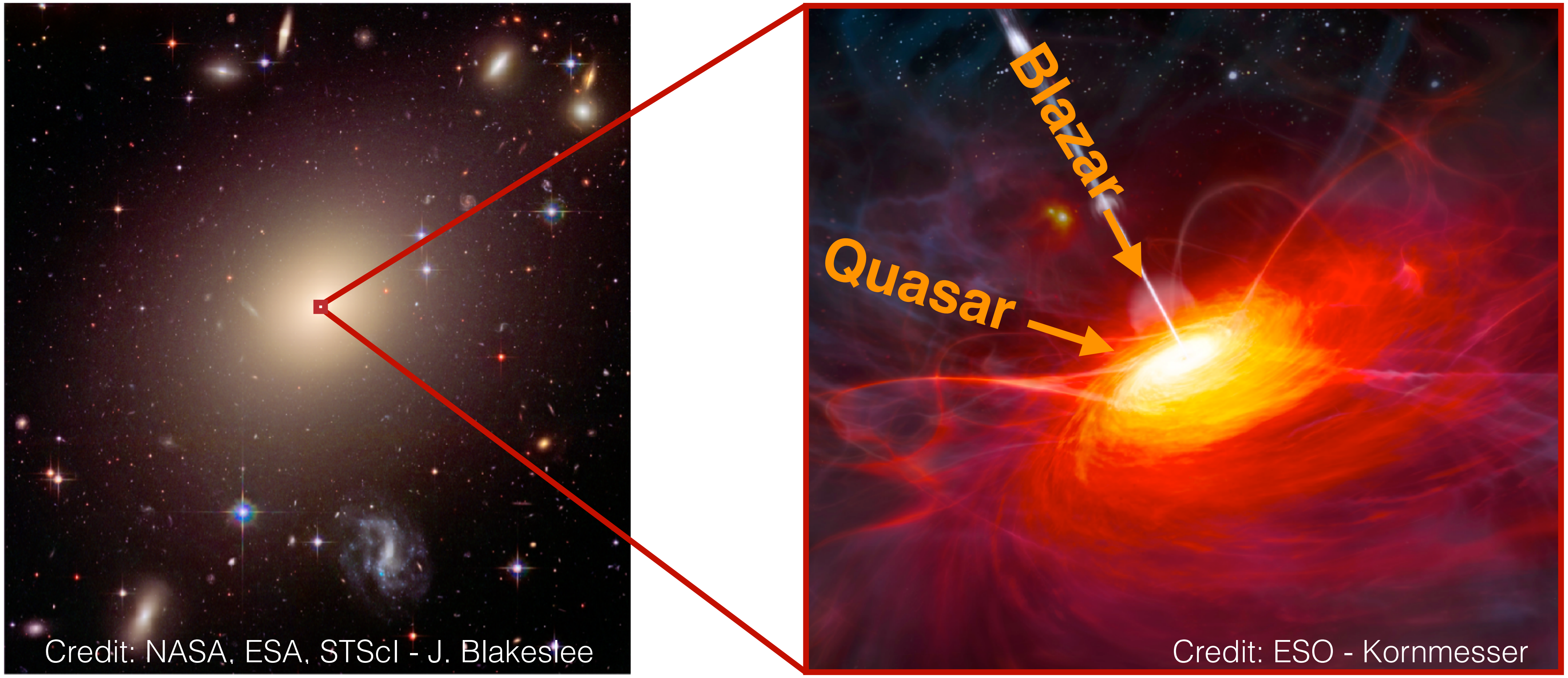
- Ask me about
  - AGN, blazars, and relativistic jets
  - Ground-based gamma-ray observatories (VERITAS, CTA)
  - X-ray and gamma-ray polarization
  - Light curves and time series

- Don't ask me about
  - VAR in soccer

Supermassive black holes



- 10^5 - 10^9 $M_\odot$ black holes located at the center of galaxies.
- When supermassive black holes are actively growing they become quasars (or blazars), the brightest objects in the Universe.
- The growth of the central supermassive black holes drives the evolution of the entire galaxy.
- Relativistic jets powered by accretion onto supermassive black holes are among the most powerful particle accelerators in the Universe.

The power source of AGN

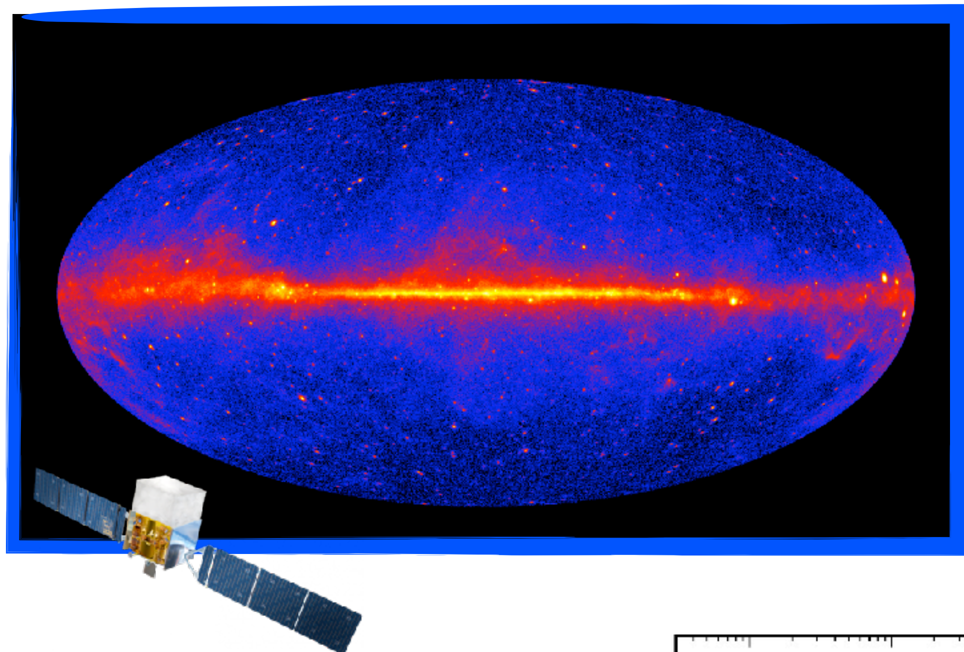
- The luminosity (L) of quasars, i.e. how much power they put out, can be as high as 10^{12} L_{sun} ~ 10^{40} W~ 10^{48} erg/s.
  - Nuclear fusion:

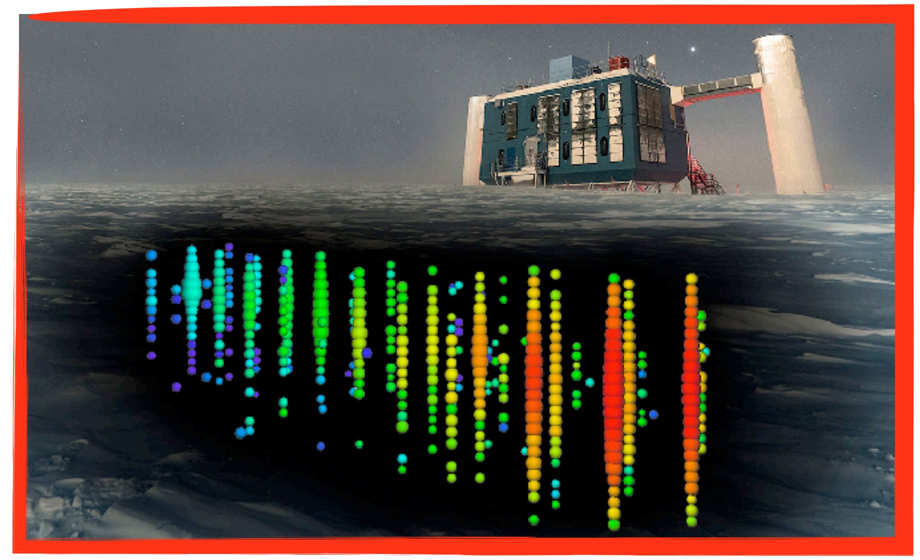
$$E_{\text{nuc}} = 0.007mc^2 \approx 6 \times 10^{18}\,\text{erg g}^{-1}$$

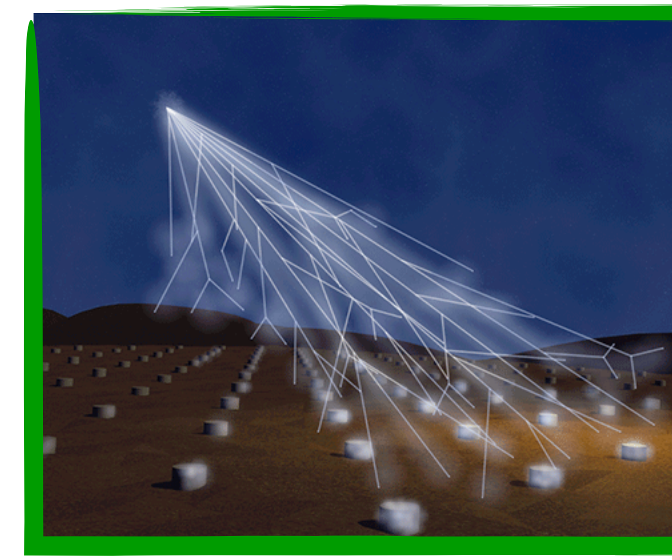
  - Accretion power:

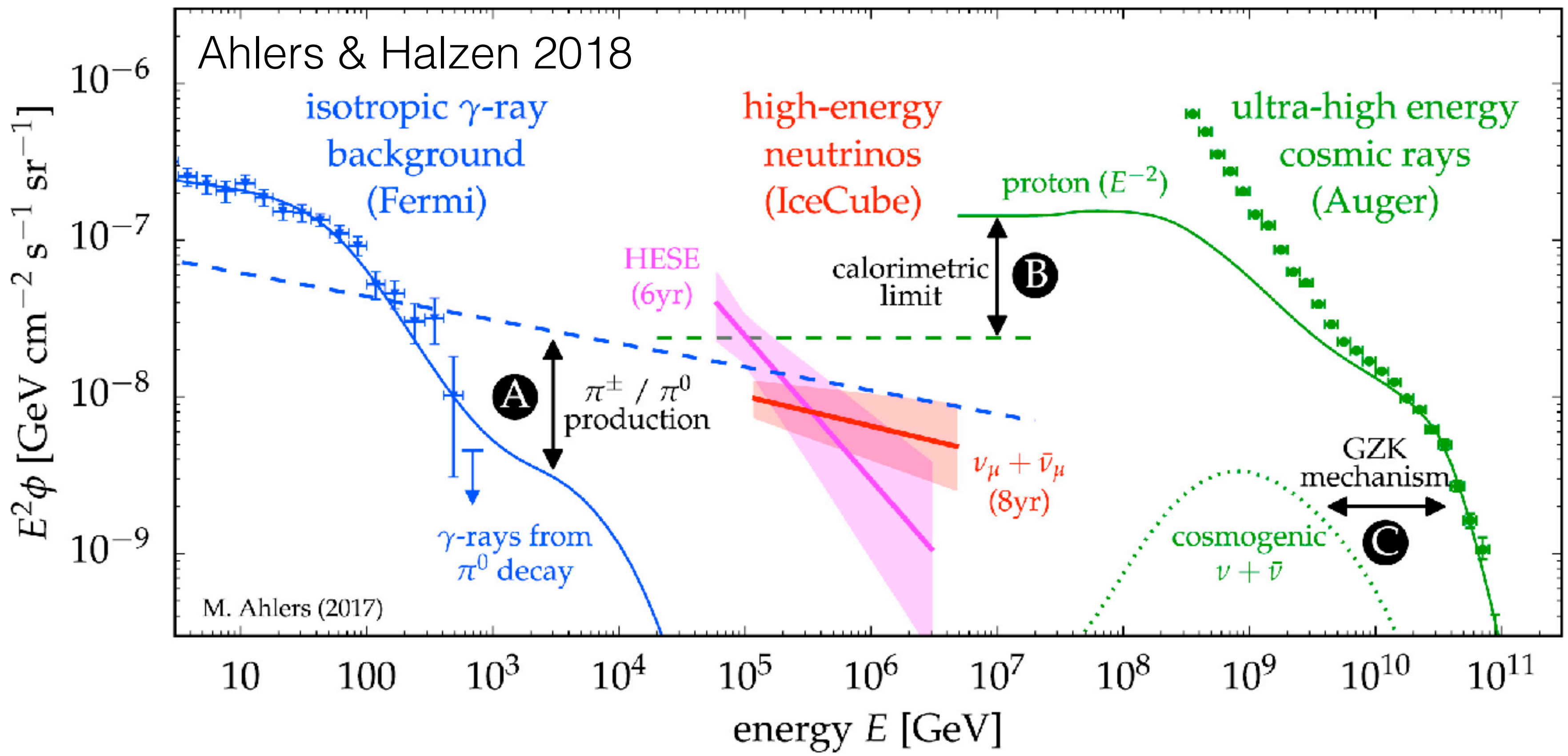
$$E_{\text{acc}} = \frac{GMm}{R} \approx 10^{20}\,\text{erg g}^{-1}$$

Accretion, i.e matter falling onto a black hole, is the only energy source that is powerful enough to fuel the very bright luminosity of quasars.

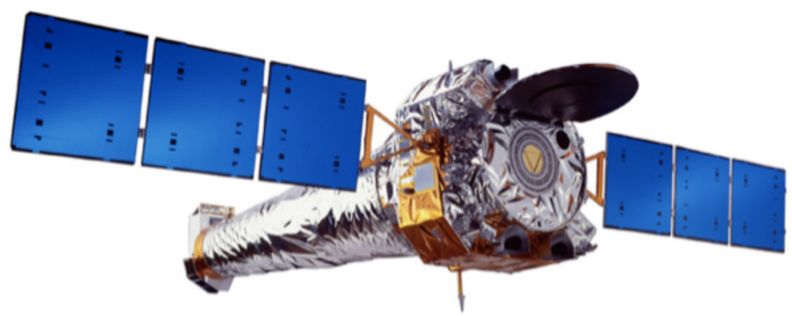


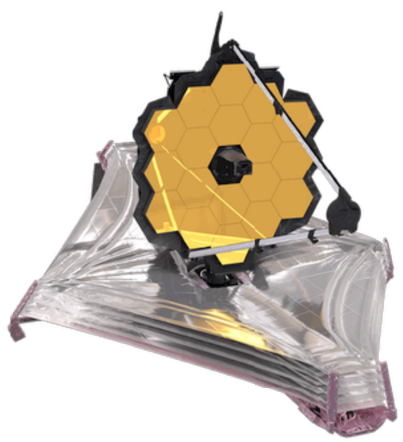


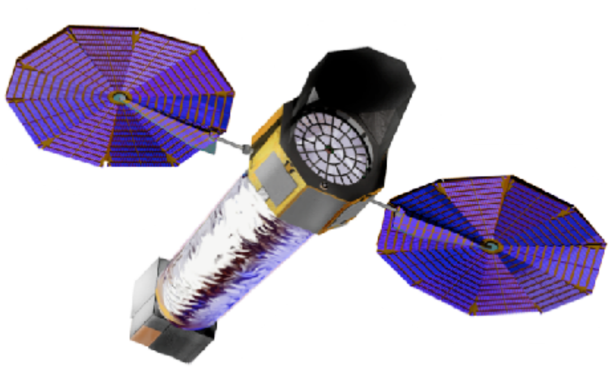


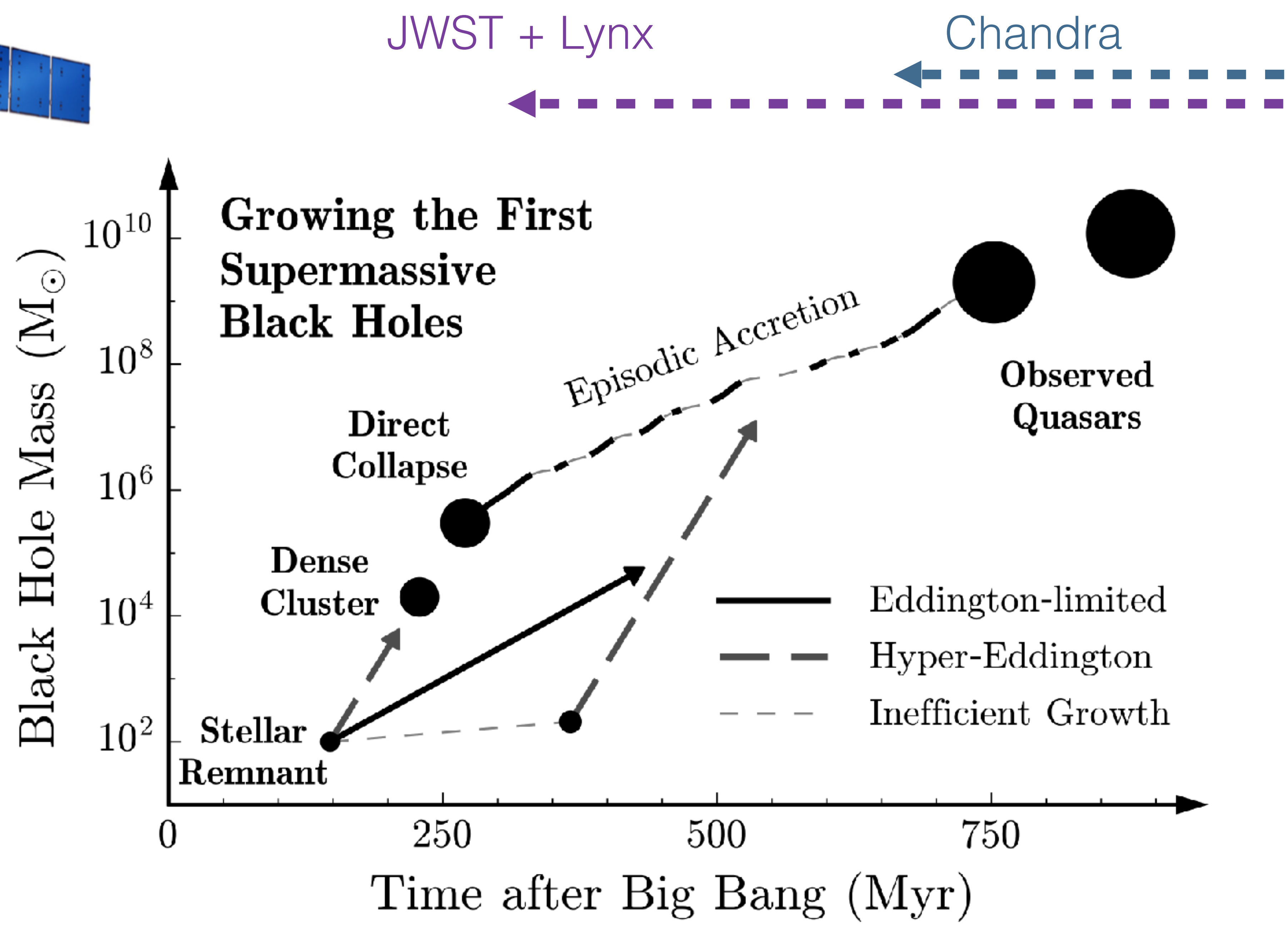


Active galactic nuclei are a potential source of cosmic rays and neutrinos.









Smith, Bromm & Loeb 2007

Supermassive black holes are important drivers of galaxy evolution. But we don't yet fully understand how they first appeared in the early Universe.

Eddington limit: maximum rate of mass accretion onto a compact object assuming accretion is spherical.

When matter falls onto a compact object the gas heats up and becomes very bright. That light moving away from the compact object carries pressure that pushes the incoming gas away, limiting the accretion rate.

Evolution of supermassive black holes

Spiral

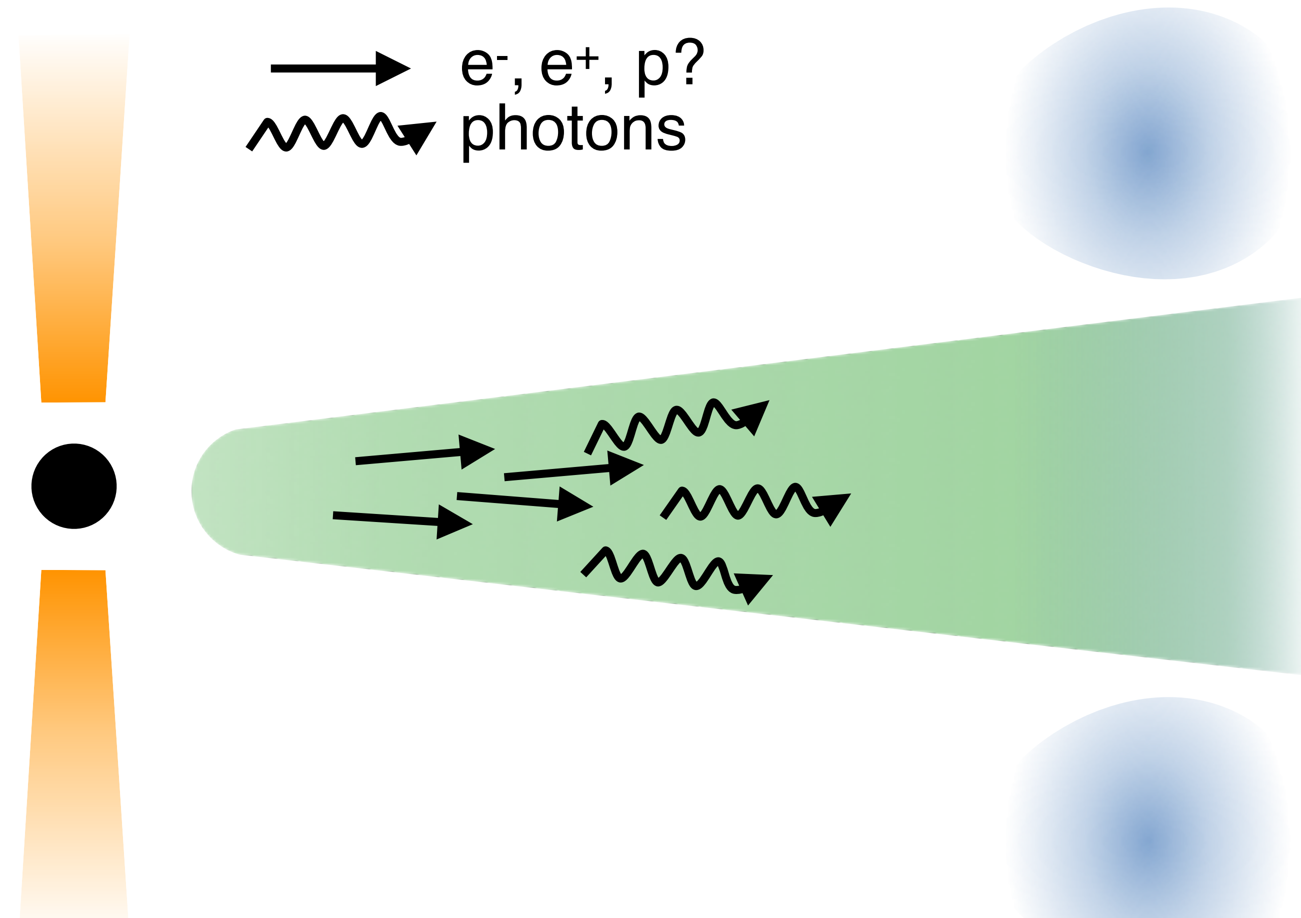
Galaxy **merger**

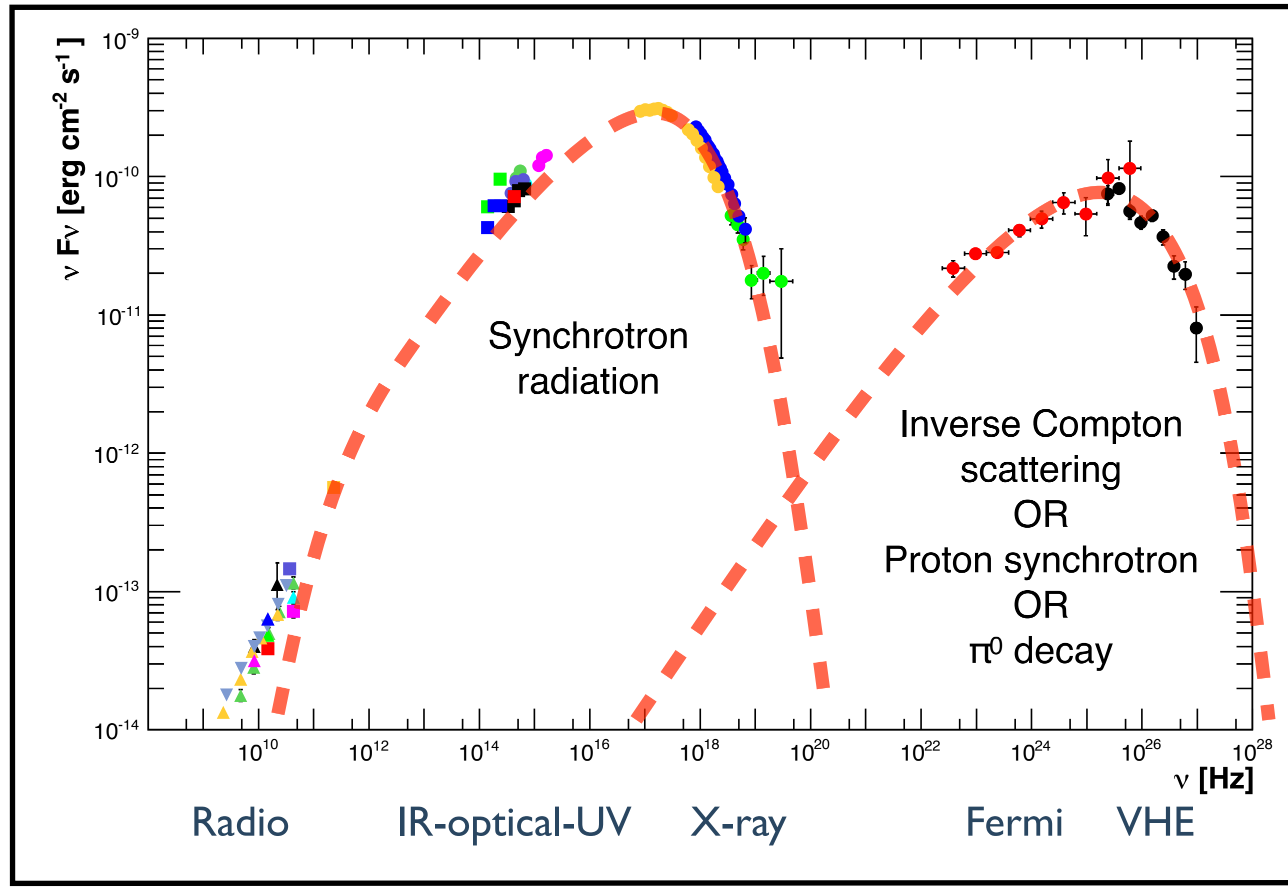
Elliptical

Accretion ($\dot{m}$) ramps up, starting a very luminous, **quasar phase** with very powerful jets

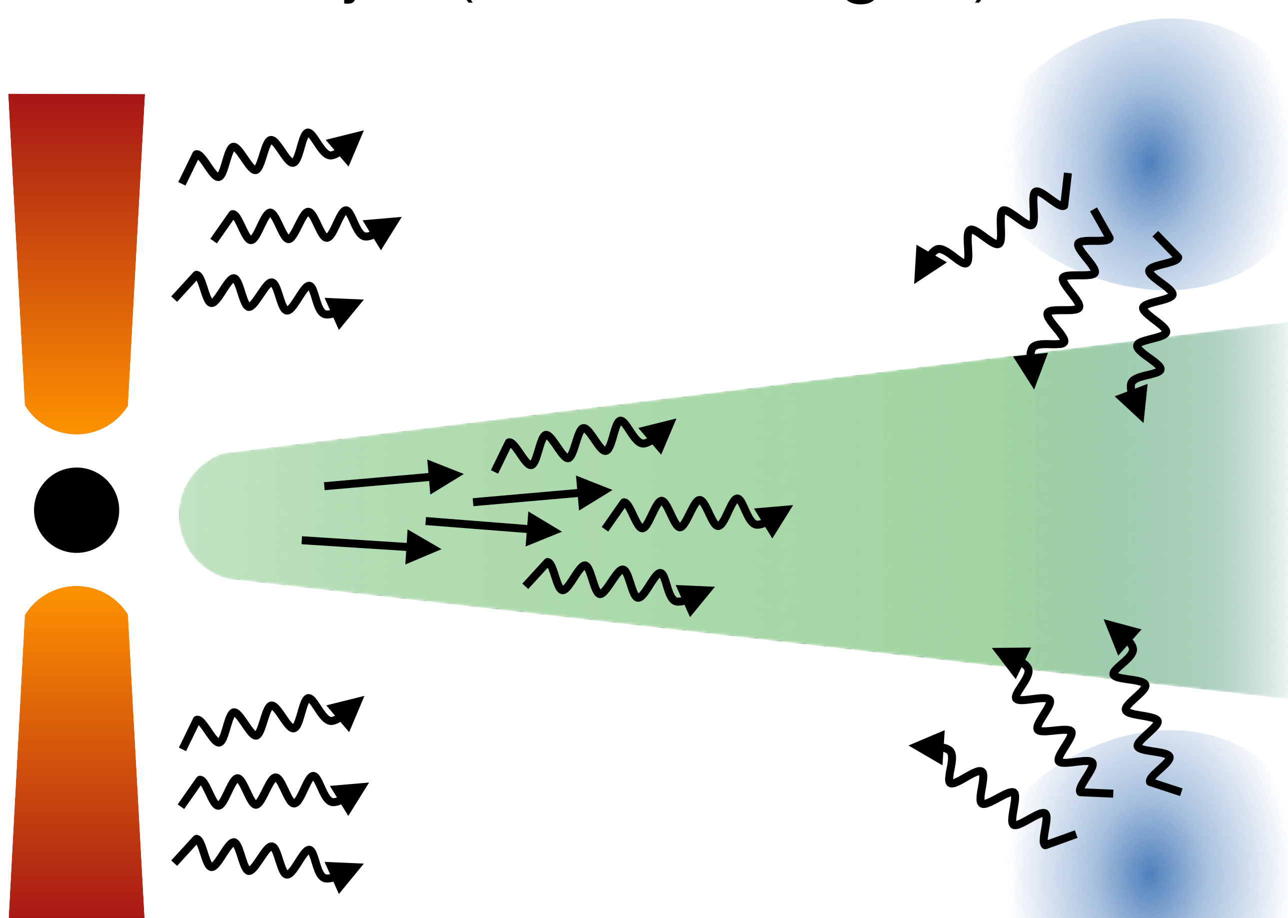
Reduced gas supply, reduced radiative cooling. Jet gets weaker but particle acceleration reaches TeV energies.

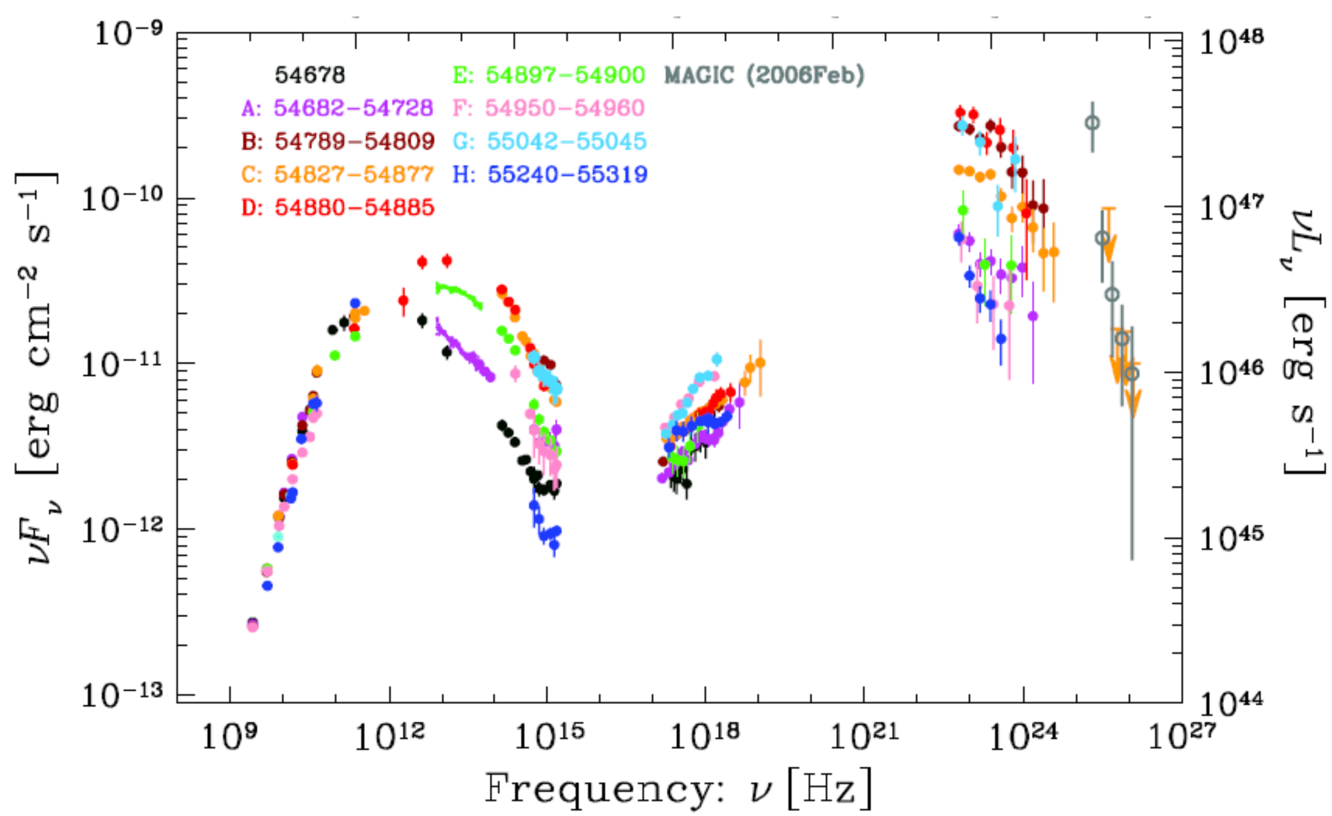
$\dot{m}$ starts to decrease, decreasing luminosity, optically-thick disk. **BL Lac phase**.



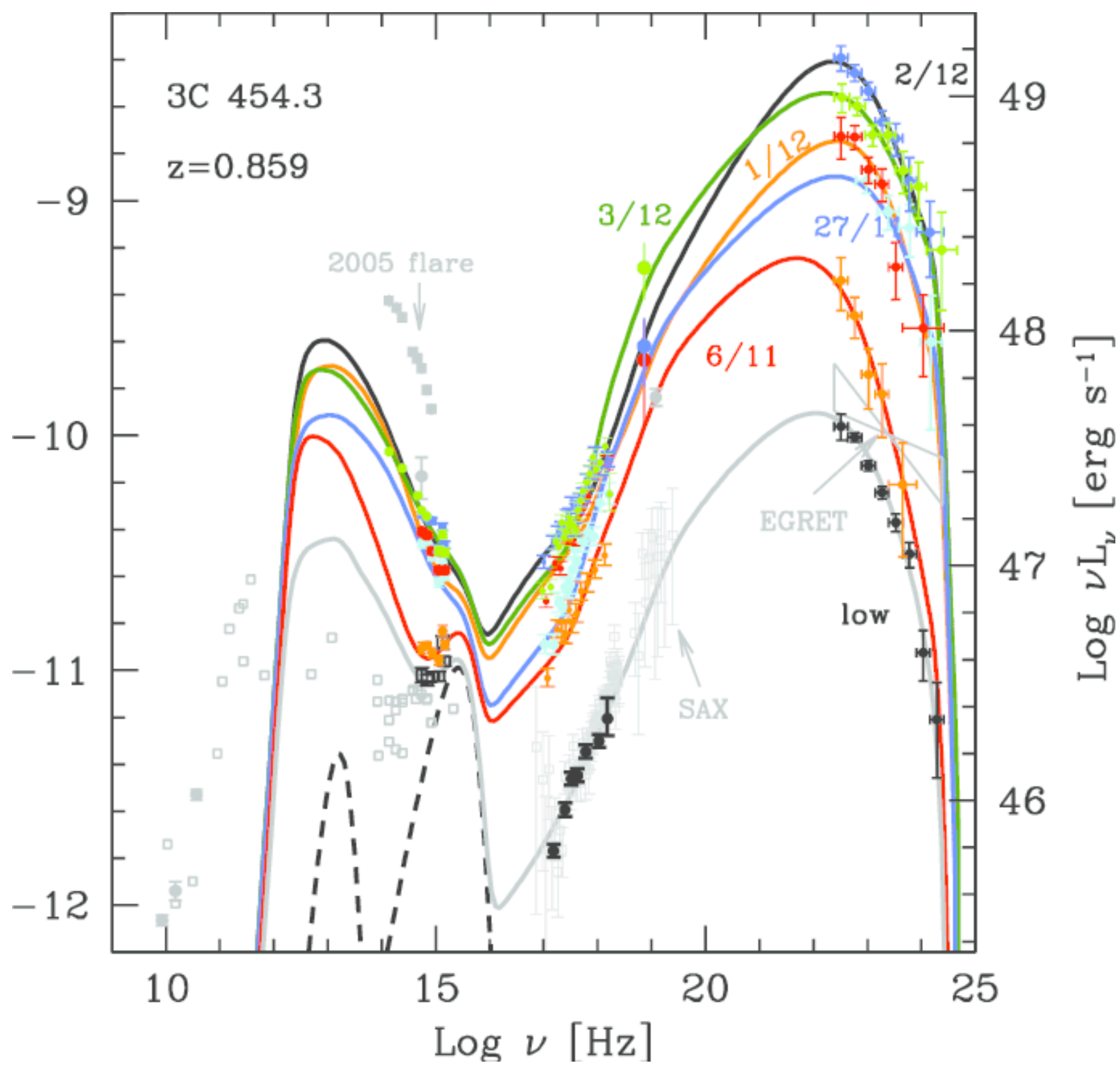


Weak, old jet (ran out of gas)





Strong, young jet (gas is available)

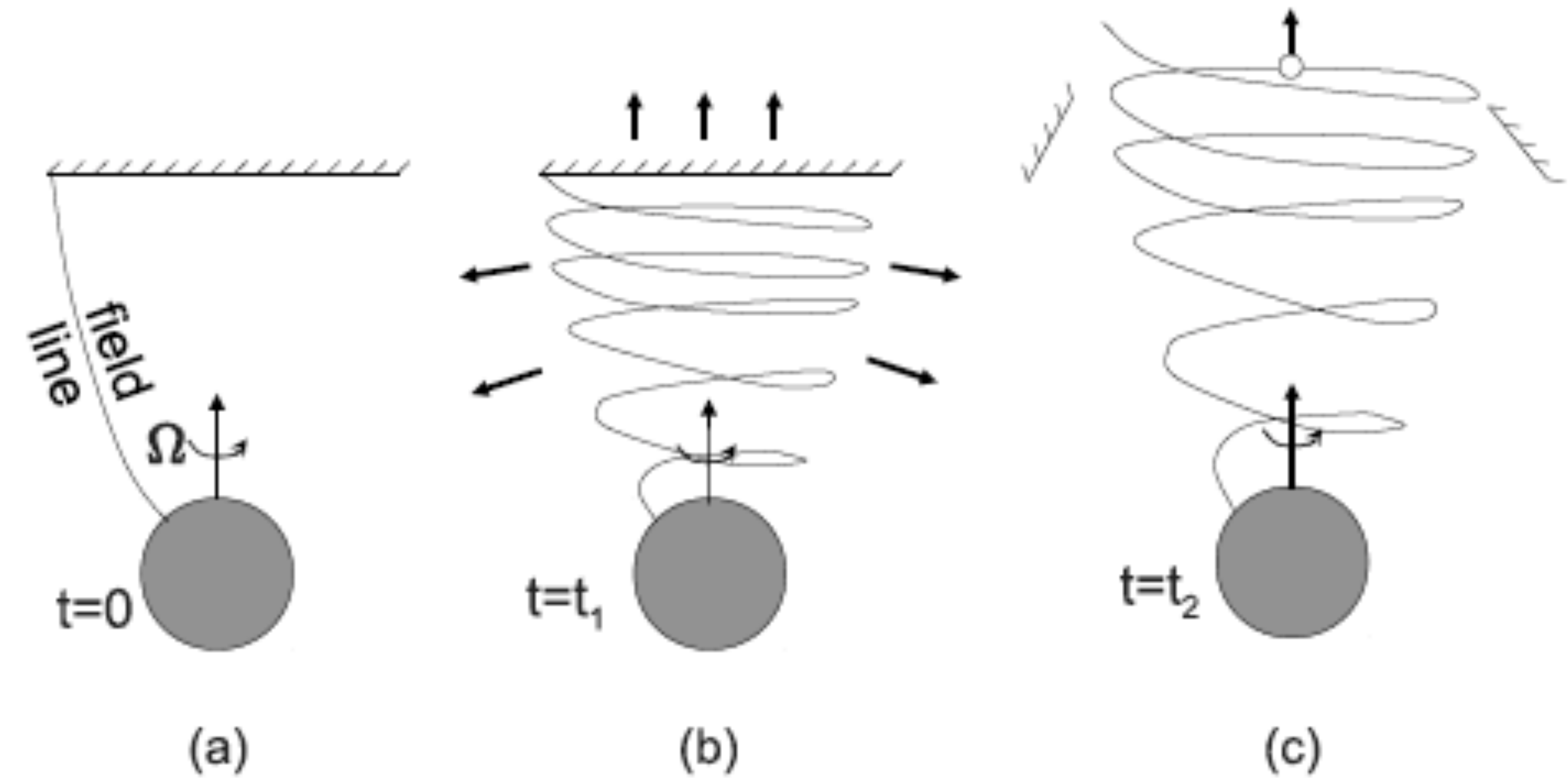


SSDC SED visualization tool

U Geneva SED simulation tool

Spectral energy distribution (SED): Figure that shows how much power a source is emitting as a function of energy (or frequency).

The Blandford-Znajek mechanism



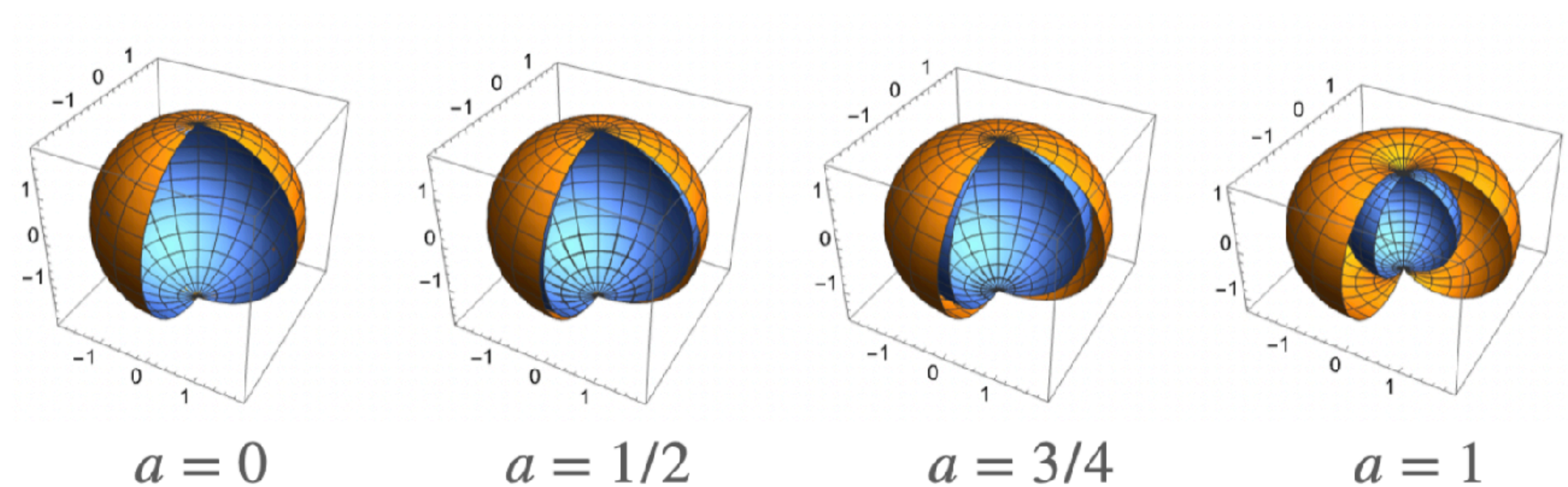
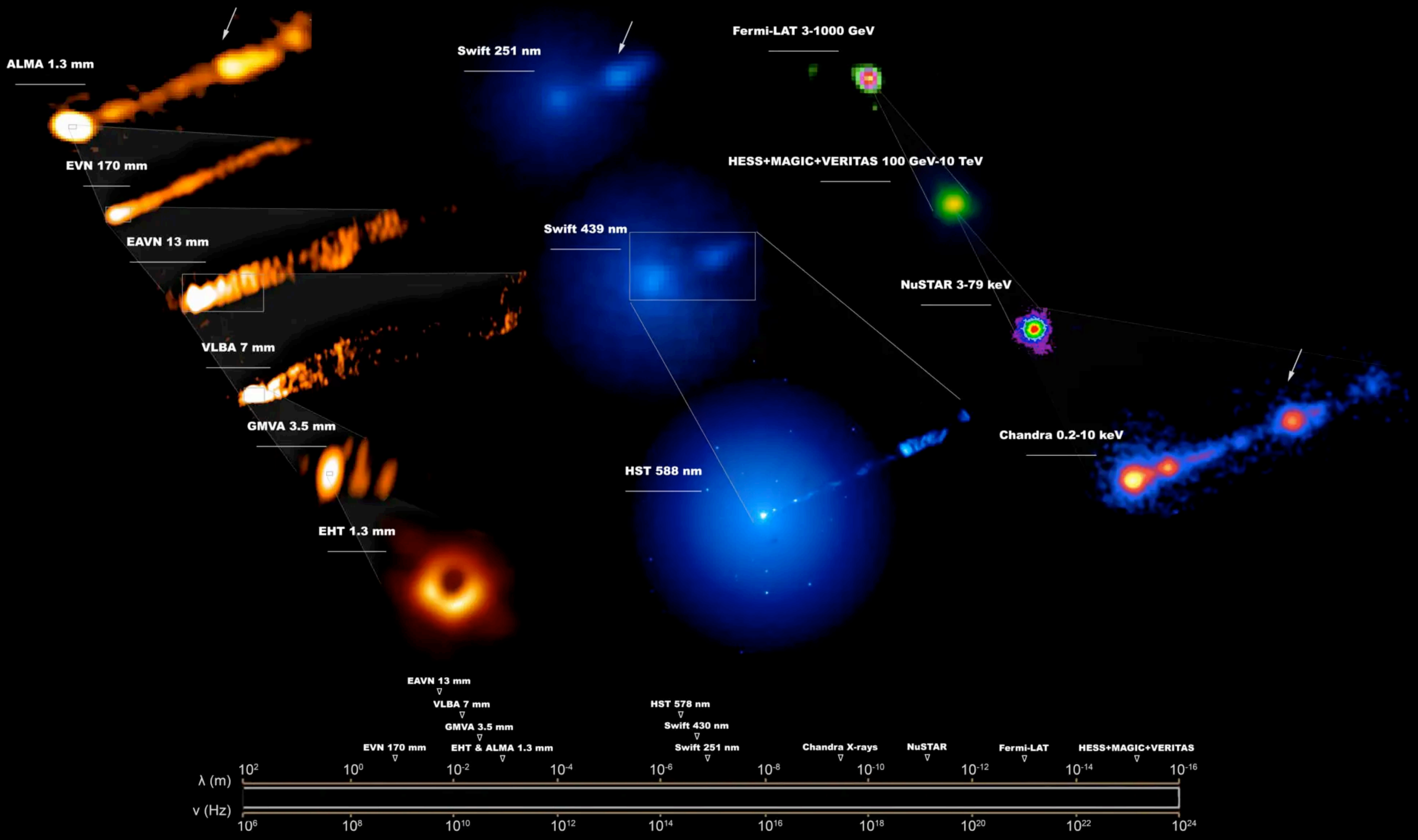
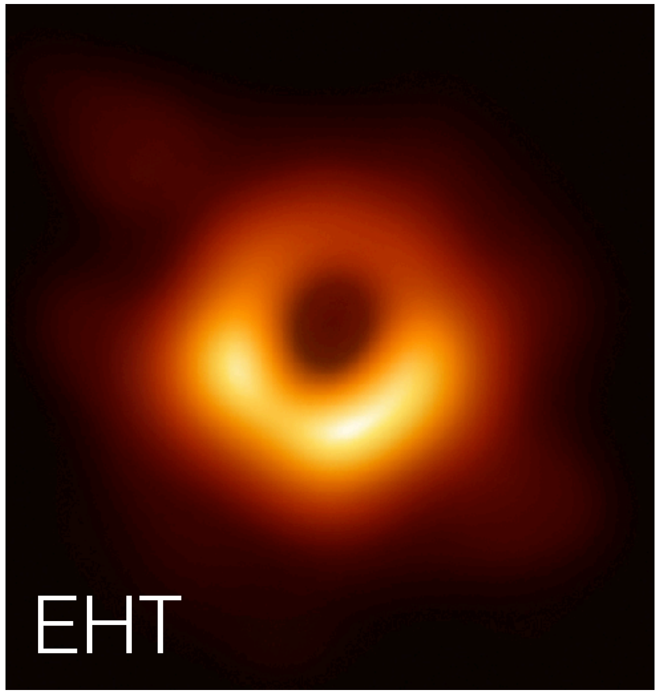


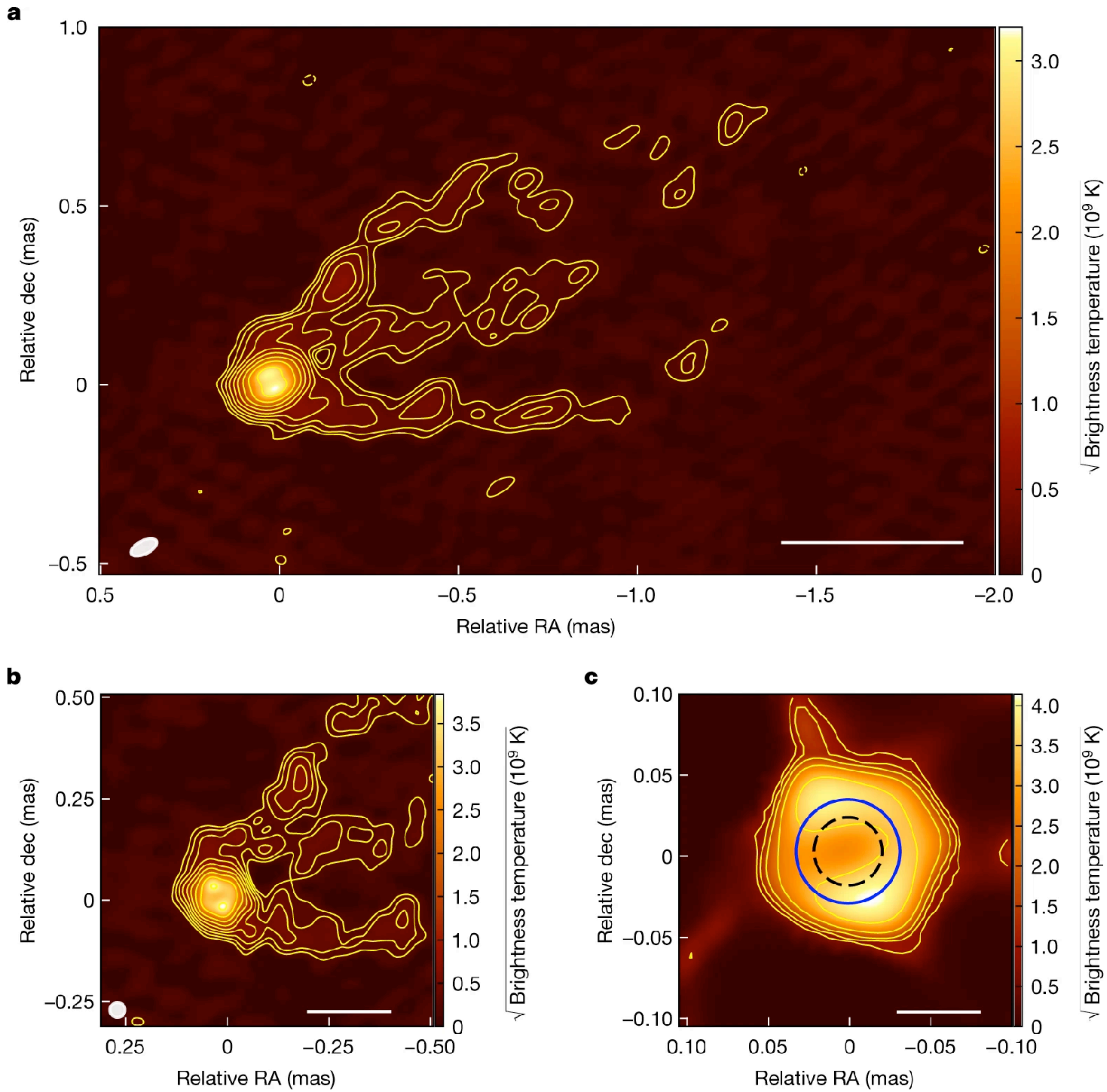
Figure 3. The event horizon (blue) and ergosphere (orange) for different values of a with $G = c = M = 1$



ALMA 1.3 mm
EVN 170 mm
EAVN 13 mm
VLBA 7 mm
GMVA 3.5 mm
EHT 1.3 mm
Swift 251 nm
Swift 439 nm
HST 588 nm
Fermi-LAT 3-1000 GeV
HESS+MAGIC+VERITAS 100 GeV-10 TeV
NuSTAR 3-79 keV
Chandra 0.2-10 keV
EAVN 13 mm
VLBA 7 mm
GMVA 3.5 mm
EVN 170 mm
EHT & ALMA 1.3 mm
HST 578 nm
Swift 430 nm
Swift 251 nm
Chandra X-rays
NuSTAR
Fermi-LAT
HESS+MAGIC+VERITAS
λ (m)
ν (Hz)



Photosphere → General relativity

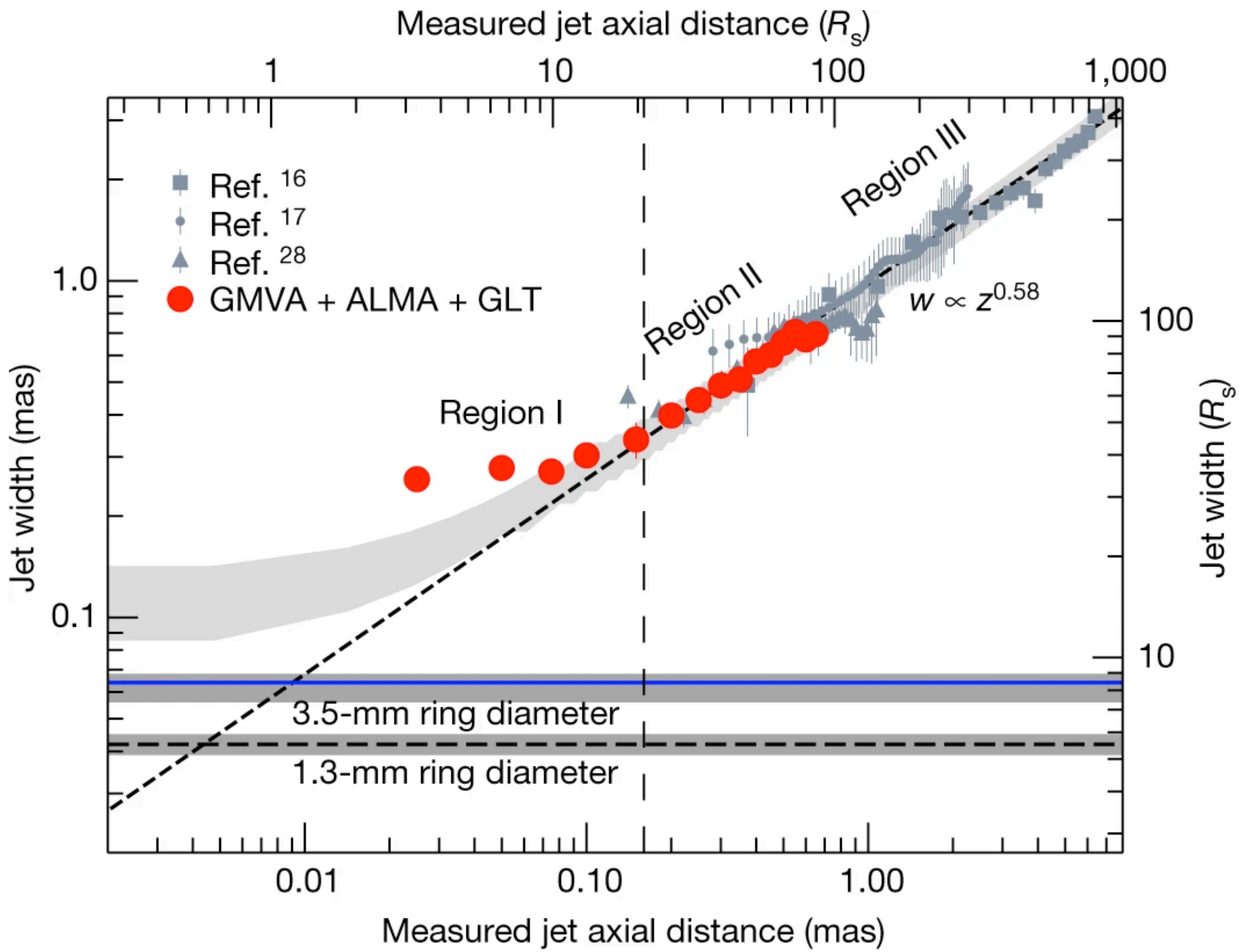


<u>A ring-like accretion structure in M87 connecting its black hole and jet</u>, Lu et al. Nature, 2023

Ergosphere → Accretion flow + jet formation

Optically thin: transparent. The medium lets radiation go trough.

Optically thick: opaque. The medium does not let radiation go through.



A ring-like accretion structure in M87 connecting its black hole and jet, Lu et al. Nature, 2023

Blazar populations

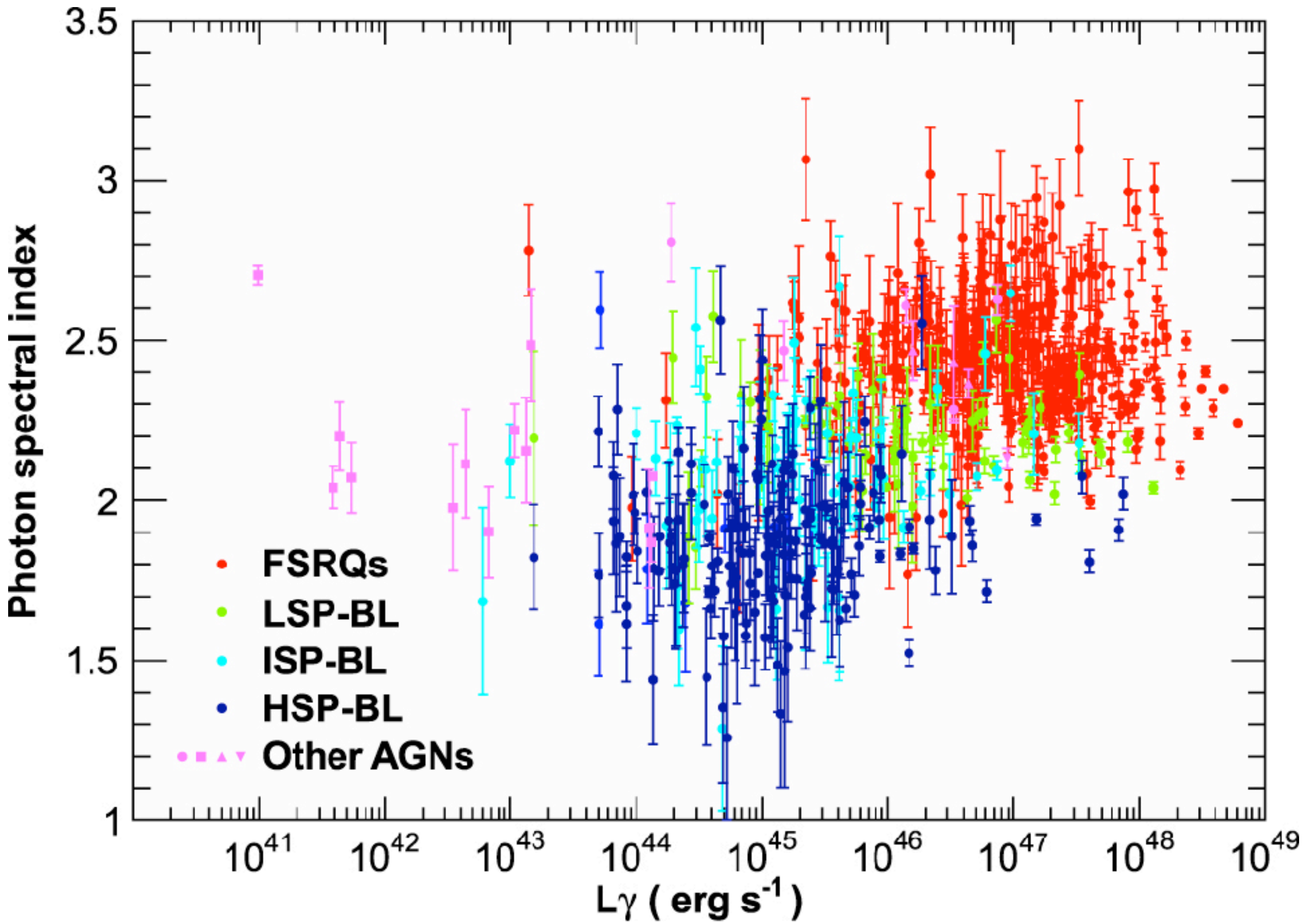


Figure 14: Photon index vs. gamma-ray luminosity. Red: FSRQs; green: LSP-BL Lacs; light blue: ISP-BL Lacs; dark blue: HSP-BL Lacs; magenta: other AGNs (circles: NLSy1s; squares: radio galaxies; up triangles: SSRQs; down triangles: AGNs of other types).

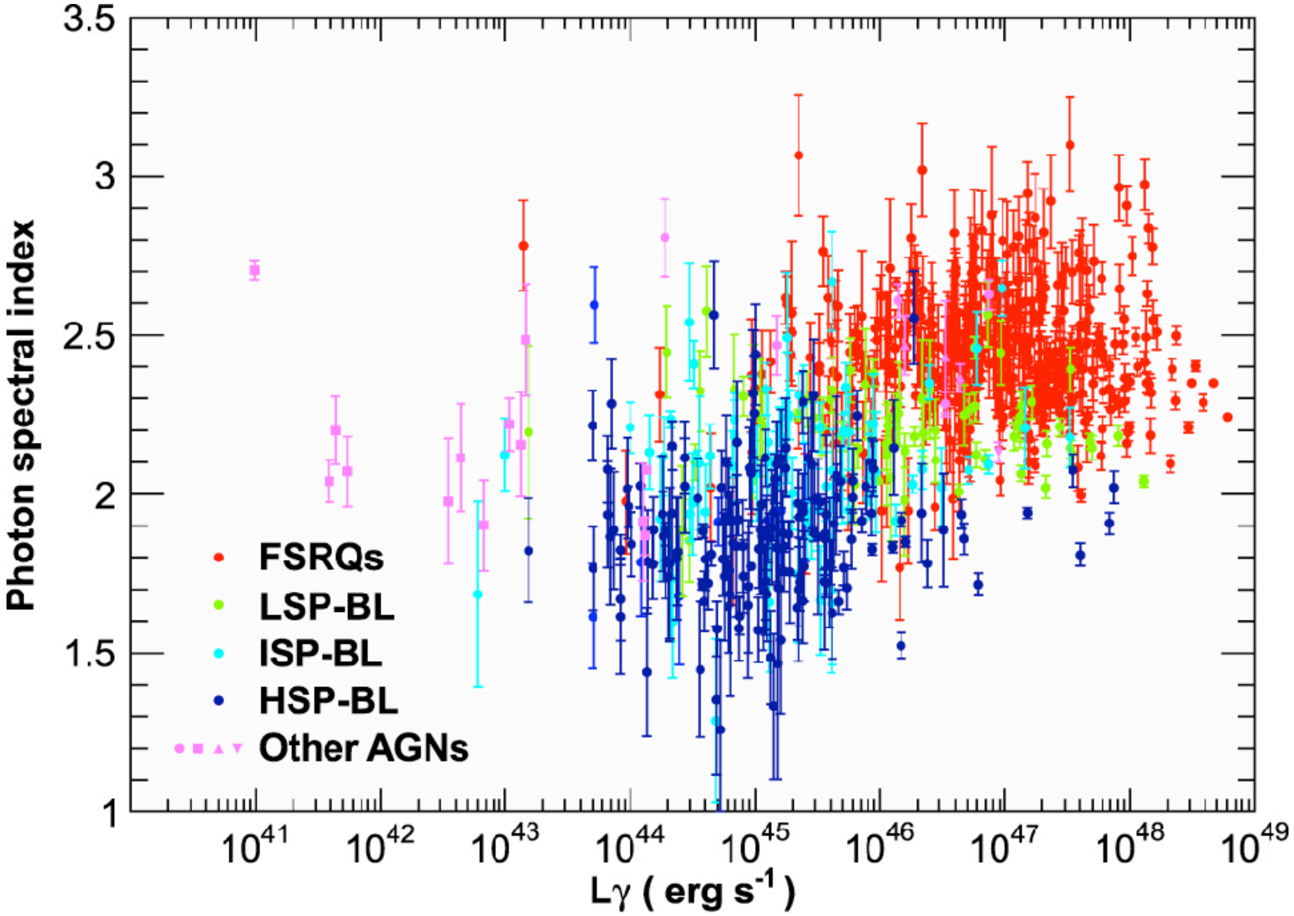
Photon spectral index (Γ), where Γ<2.0 means increasing energy flux with energy.

Luminosity ($L\gamma$):

$$L_\gamma = 4\pi d^2 F_\gamma$$

The Third Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope; Ackermann et al. 2015, ApJ, 810, 14

Question #1



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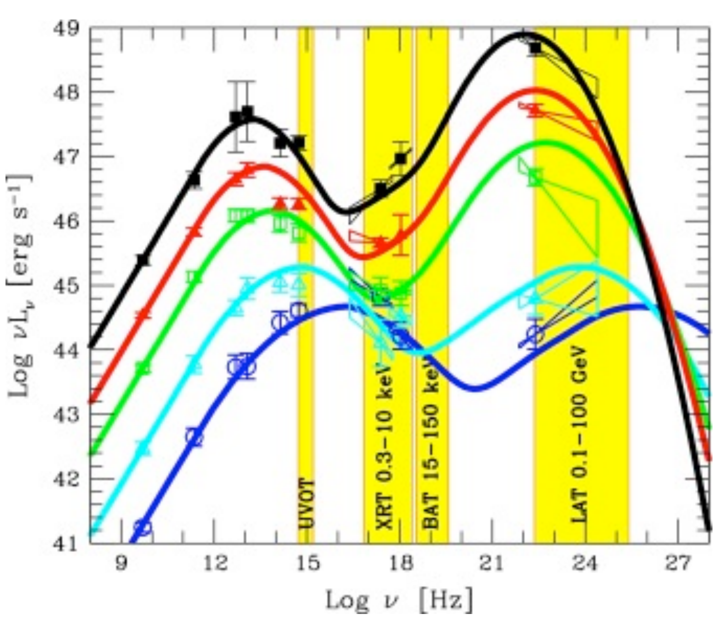
- If one looks at all the blazars detected by LAT, why would their spectral index be correlated with gamma-ray luminosity?
- Hint:



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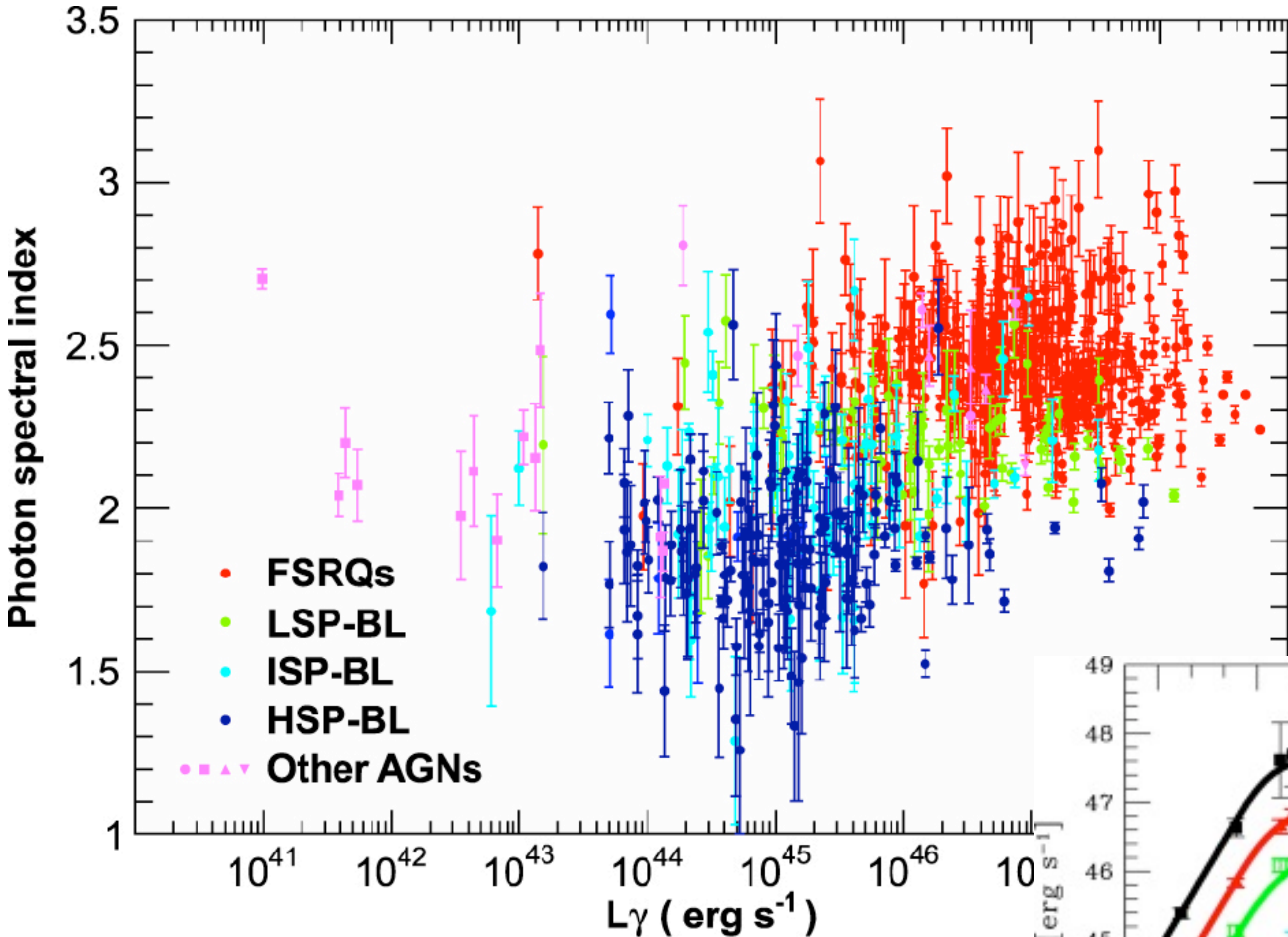
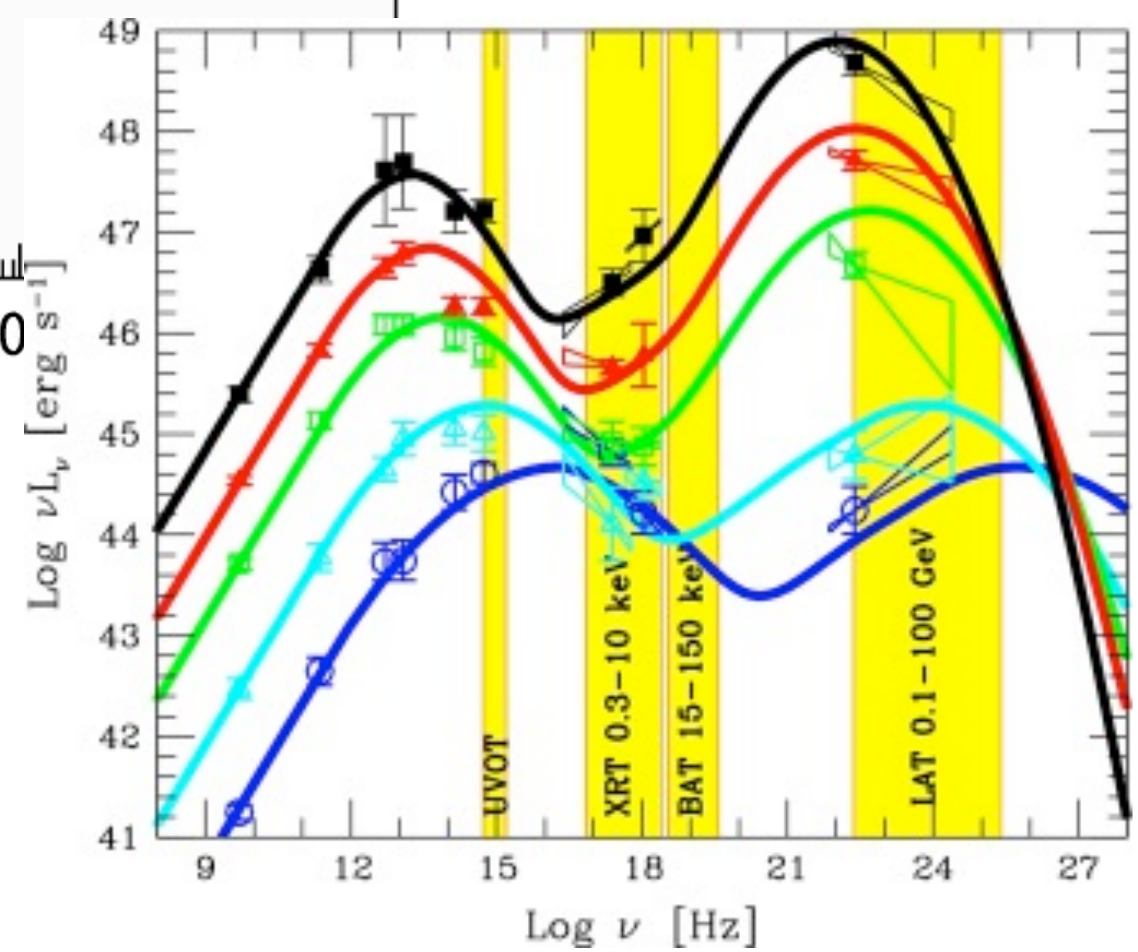
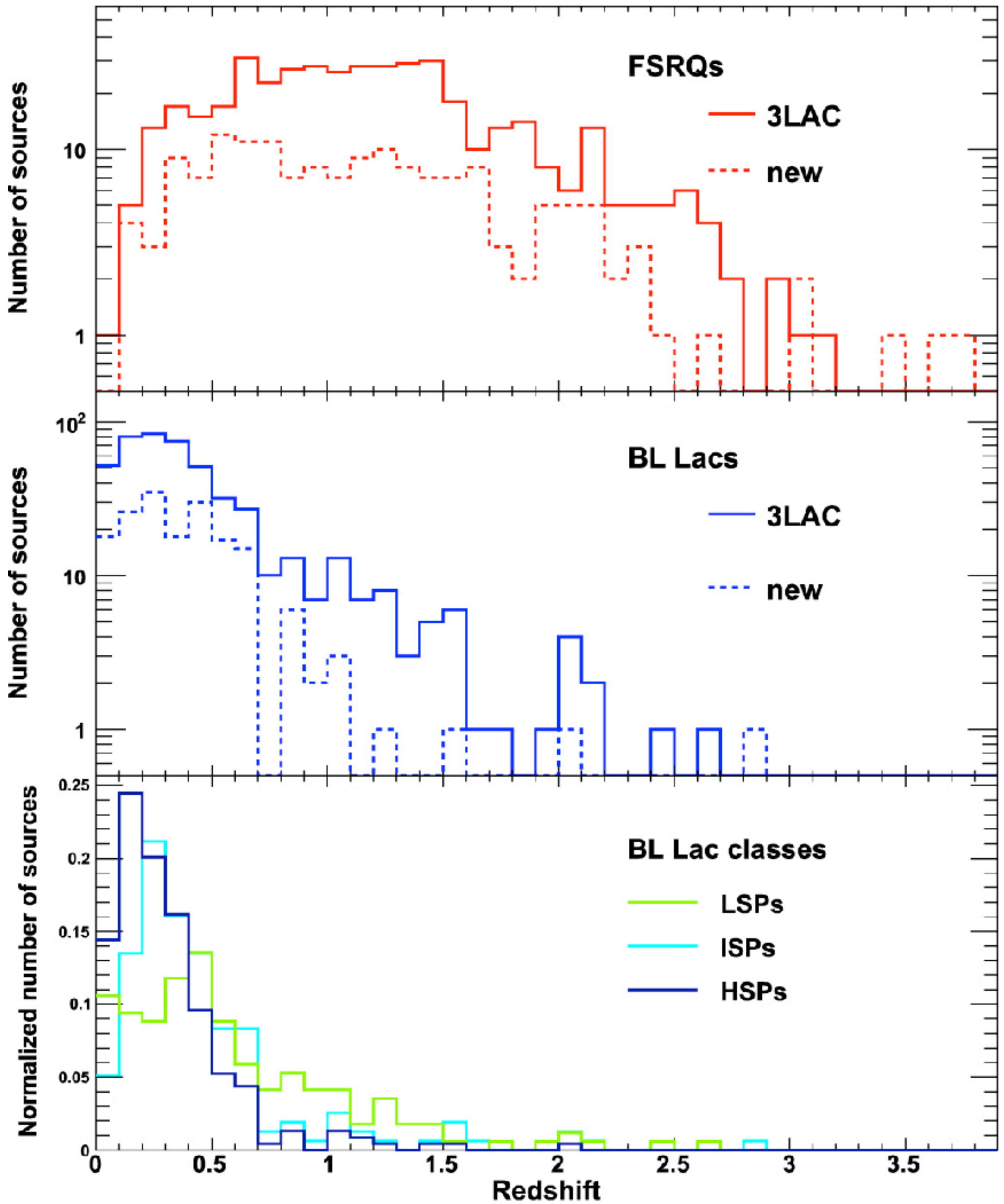




Blazar sequence: powerful AGN ionize nuclear gas, leading to higher Compton cooling rate and relativistic particles with smaller maximum energies.

Question #2



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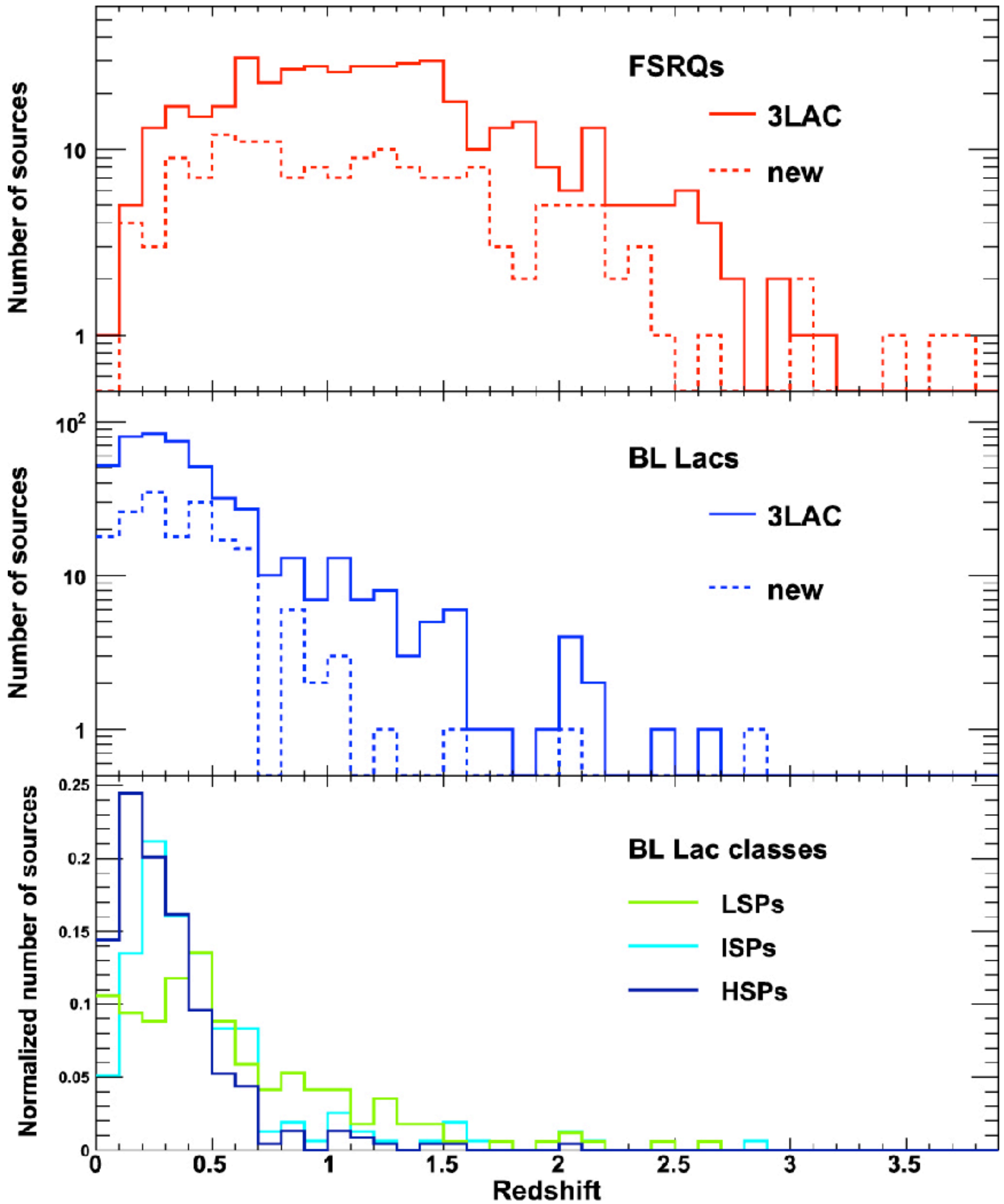
Quasars are typically found at higher redshifts than BL Lacs. How do we explain that?

Question #2



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Quasars are typically found at higher redshifts than BL Lacs. How do we explain that?

Quasars are the first evolutionary stage of AGN. When gas runs out, they turn into a BL Lac stage.

Summary

- There is a lot we don't yet know about how supermassive black holes grow, and how they shape star formation in their host galaxies.
- Radiation from accreting supermassive black holes (AGN) is the best tracer we have of black hole evolution.
- Basic models exist that explain the radiation we observe from relativistic jets.
- Most models break down when observational data becomes more abundant and more detailed.

Future: what am I excited about?

- New surveys: First eROSITA survey will find more hard X-ray blazars.
- Better time-domain data: Longer LAT light curves in gamma, TESS, Rubin in optical.
- X-ray (IXPE) and gamma-ray (COSI) polarization.
- Super-massive black hole binaries.
- Link between supermassive black hole growth and galaxy evolution (feedback mechanisms).

References

- Complete up-to-date review of relativistic jets in AGN: Blandford, Maier, Redhead 2019, ARAA, 57, 467
- Flux variability in gamma rays: Begelman, Fabian & Rees 2008, MNRAS, 384, 19
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- Properties of AGN at all wavelengths: Active Galactic Nuclei, Robson 1996, Wiley
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Email me if you have further questions:
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