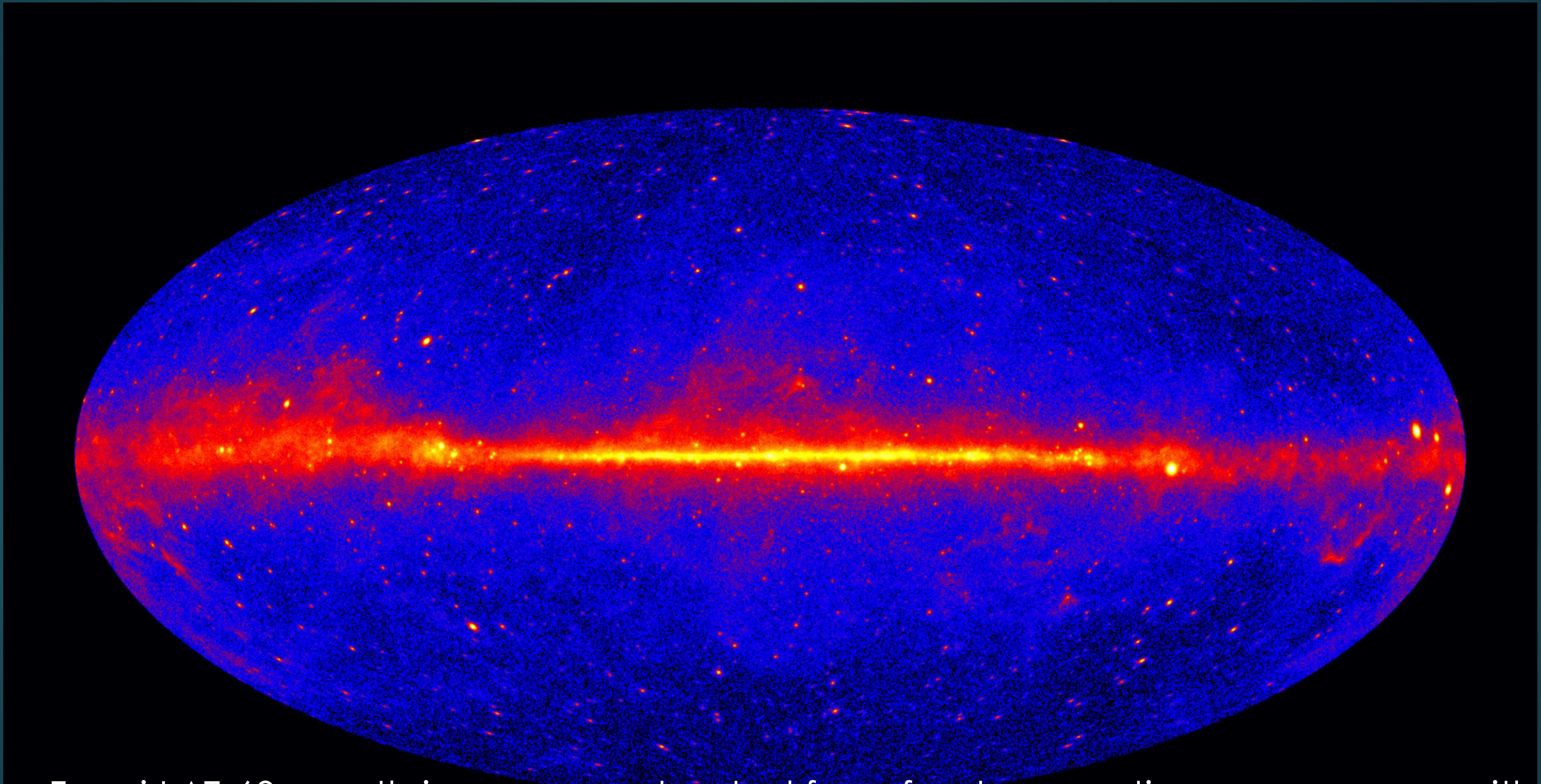
Extragalactic sources of gamma-rays, neutrinos and cosmic rays

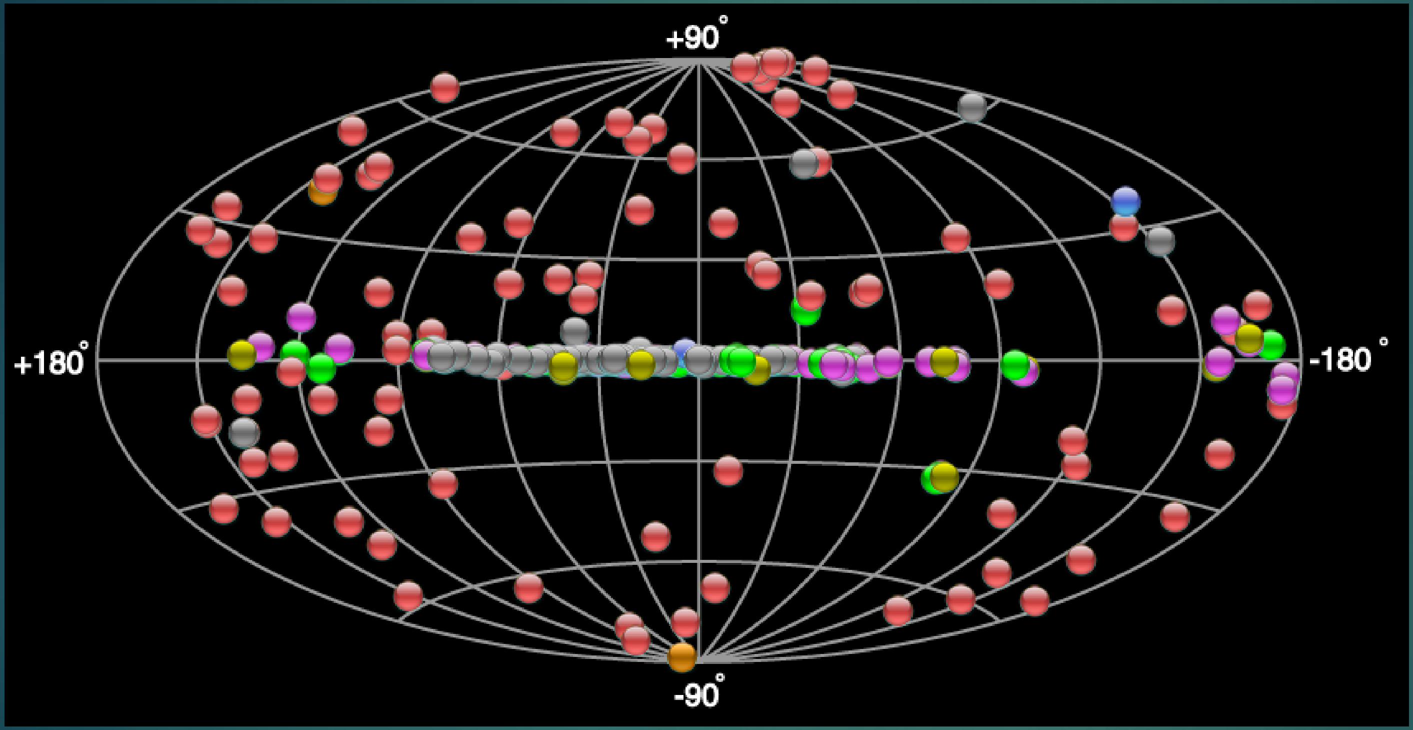
ELINA LINDFORS, UNIVERSITY OF TURKU, FINLAND

Gamma-ray sky seen by Fermi-LAT satellite (>1GeV)



The Fermi LAT 60-month image, constructed from front-converting gamma rays with energies greater than 1 GeV. Red dots=extragalactic, source count~thousands.

Very High Energy Gamma-Ray sky

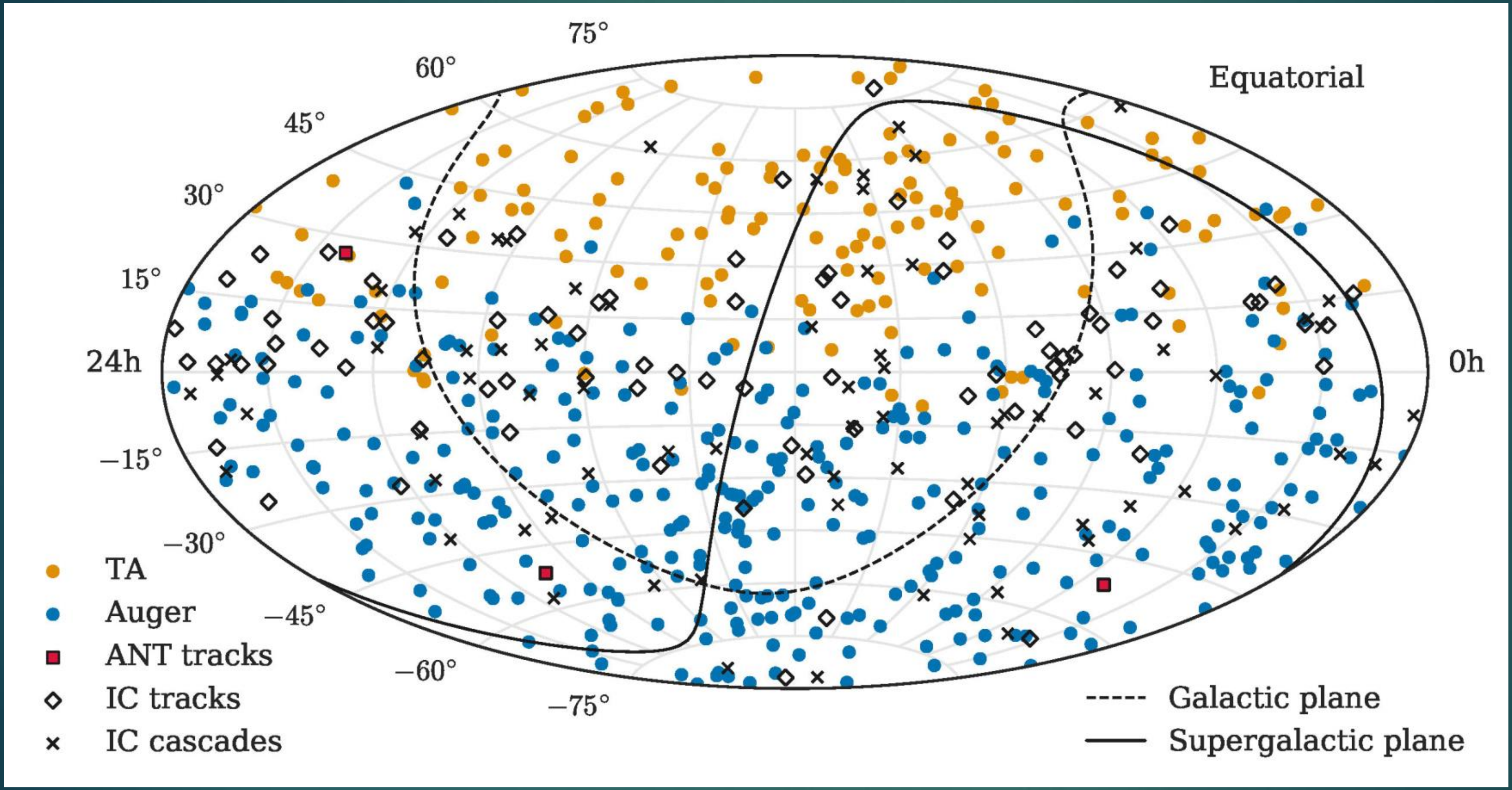


Red dots: extragalactic

Source count ~100

http://tevcat.uchicago.edu/

Skymap of Ultra High Energy Cosmic Rays and Neutrinos



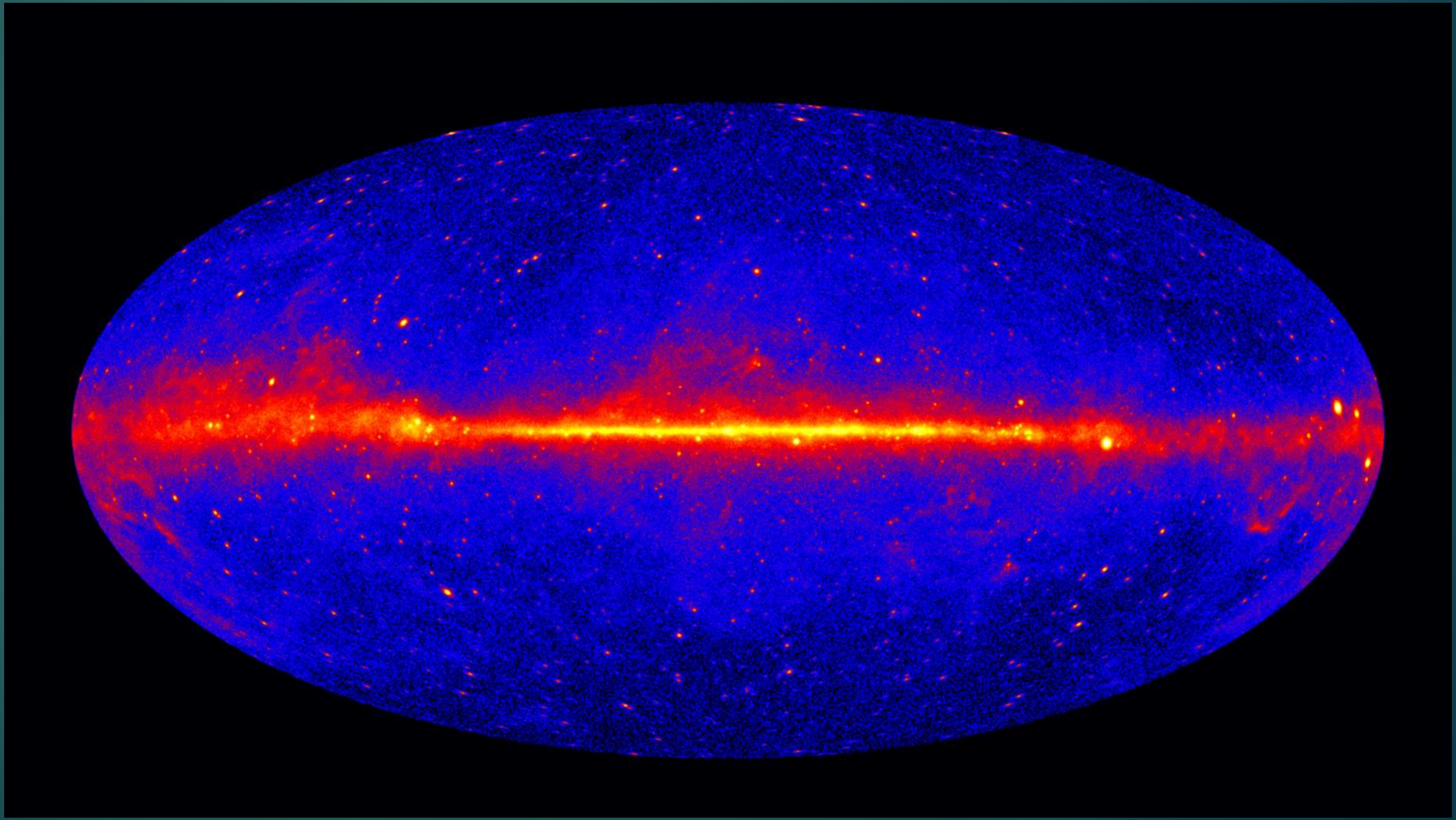
Sky map of the arrival directions of UHECR events from the Pierre Auger Observatory and the Telescope Array and high-energy neutrinos from IceCube and ANTARES. Credit: The ANTARES, IceCube, Pierre Auger and Telescope Array collaborations.

Gamma-rays, UHE neutrinos and UHECRs have extragalactic origin

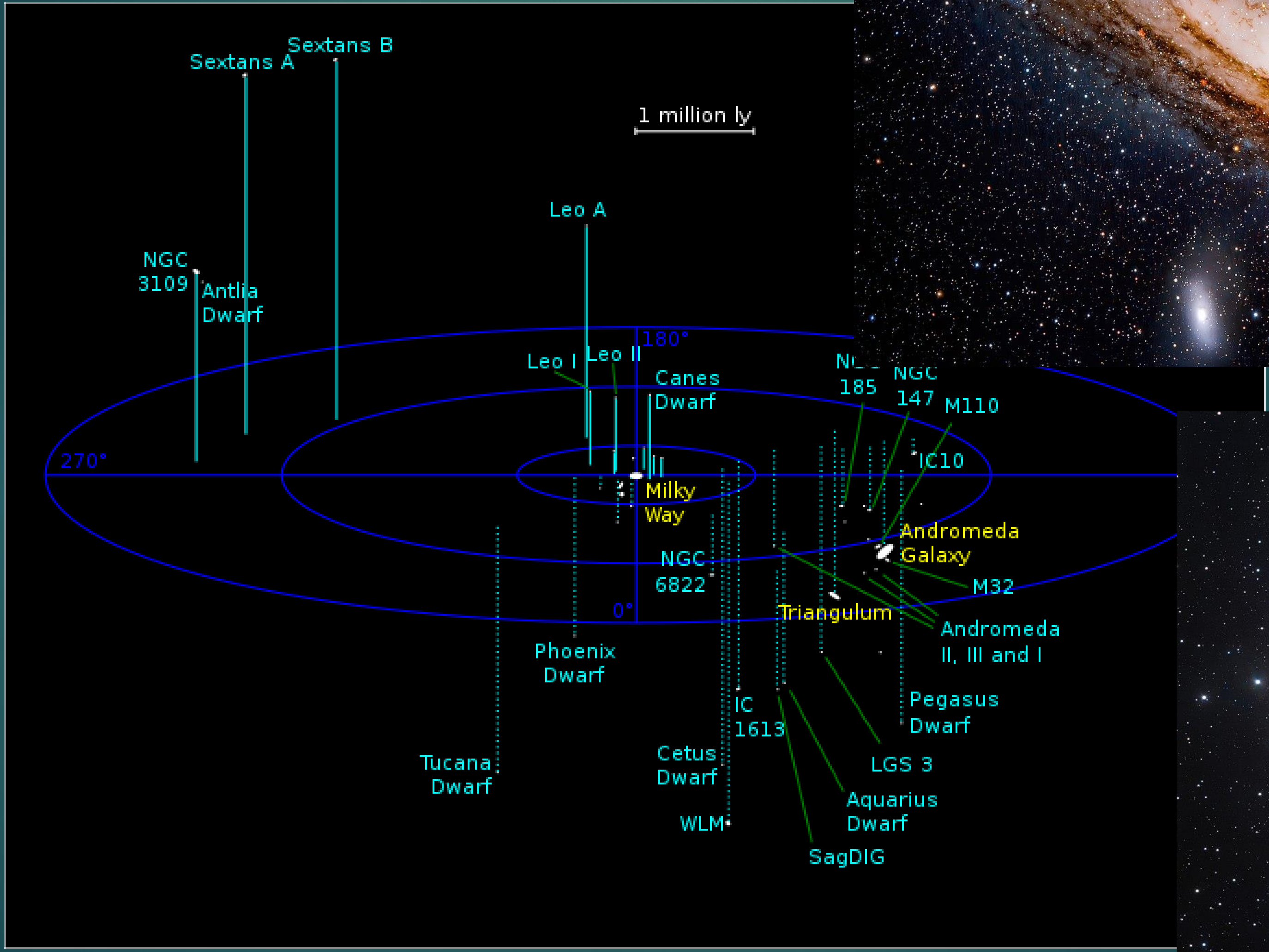
WHAT? HOW?

Normal galaxies

- Our galaxy is bright source of gamma-rays: cosmic rays interacting with molecular clouds. That is why we also see neutrinos.
- What about other galaxies?



Local group



Sextans B
Sextans A
1 million ly
Leo A
NGC 3109
Antlia Dwarf
180°
Leo I
Leo II
Canes Dwarf
270°
Milky Way
NGC 185
NGC 147
M110
IC10
Andromeda Galaxy
M32
NGC 6822
0°
Triangulum
Andromeda II, III and I
Phoenix Dwarf
Pegasus Dwarf
IC 1613
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG

Milky Way at distance of Andromeda

Astronomy 101: $F = \frac{L}{4\pi r^2}$

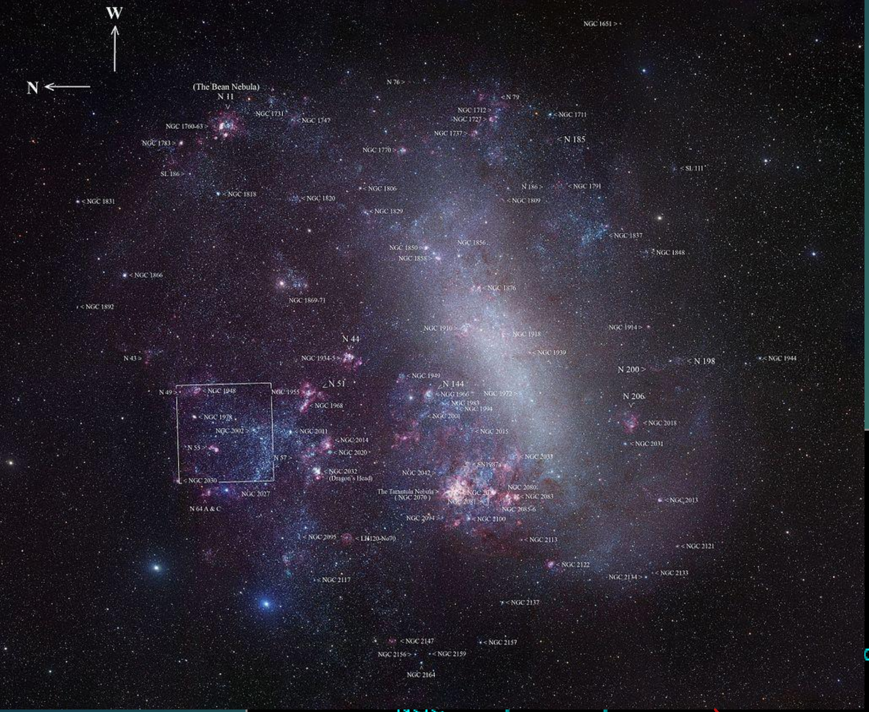
F(>100MeV)=1.17*10^{-5} photons/cm2/s/sr

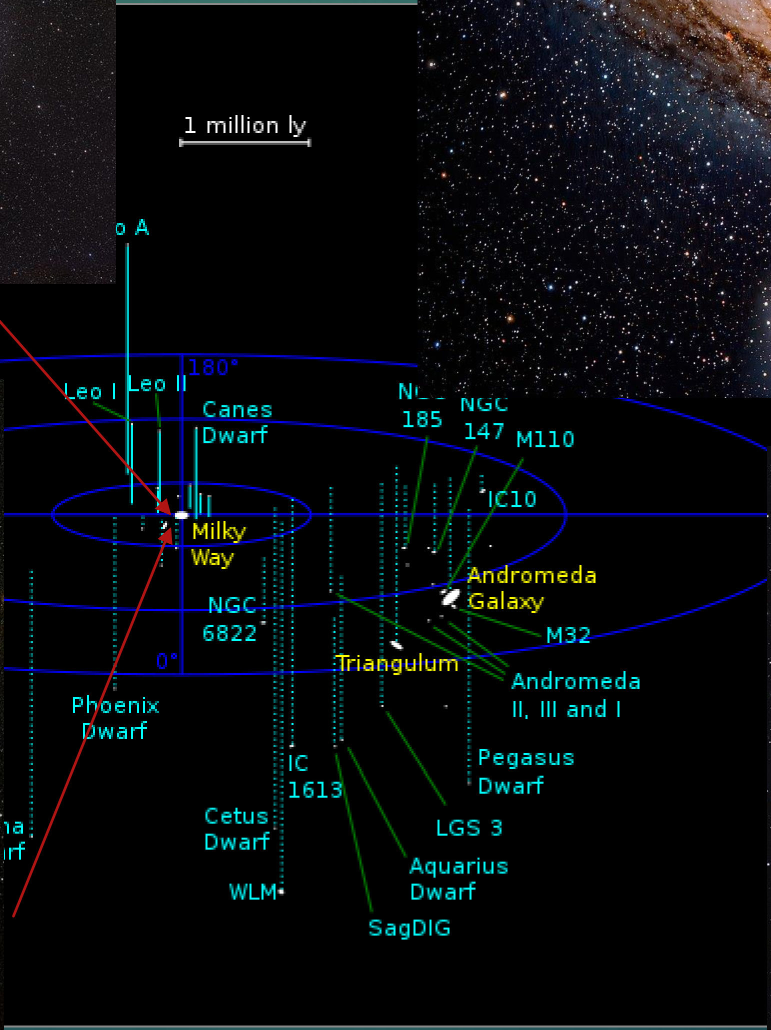
Radius of the Milky Way R=30kpc

L=1.17* 10^{-5} *8.57*10^{45} *4*pi

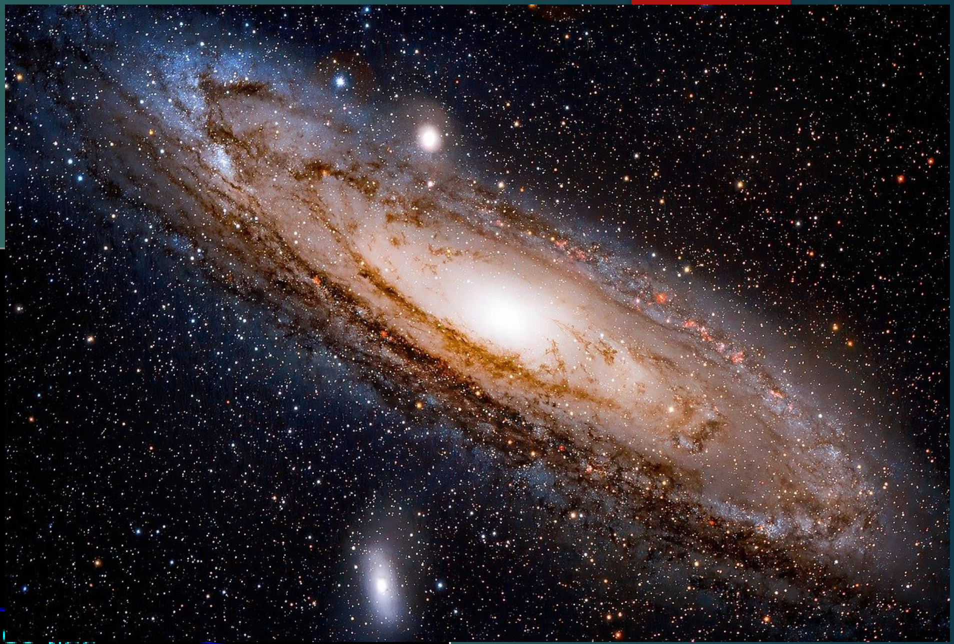
Distance to Andromeda r=570kpc

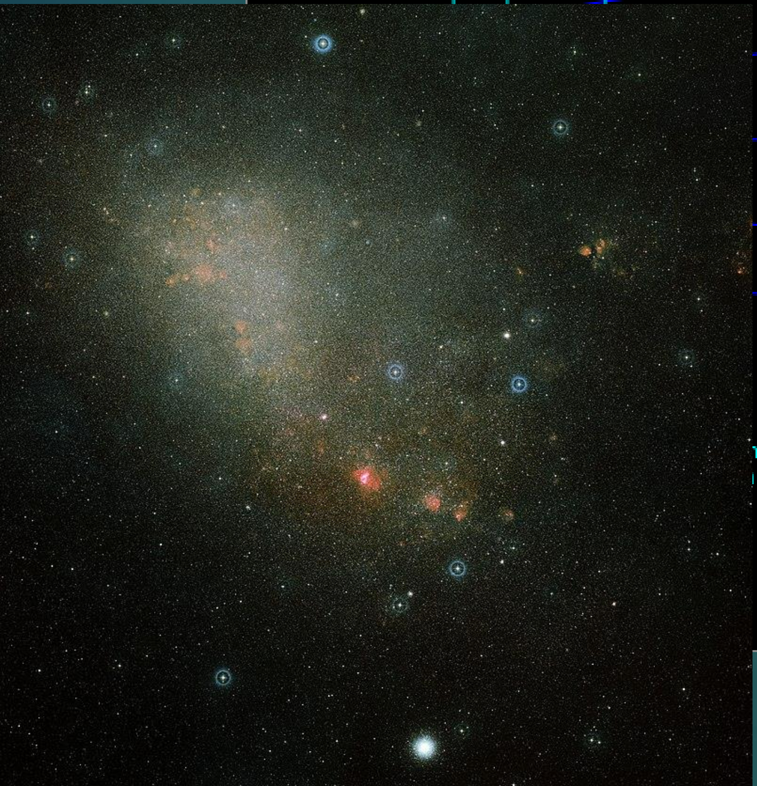
F=10^{41}/(3.1*10^{48})~0.3*10^{-7} photons/cm2/s





1 million ly
Antlia
Dwarf
3109
180°
0°
Leo I
Leo II
Canes
Dwarf
Milky
Way
NGC
185
NGC
147
M110
IC10
Andromeda
Galaxy
M32
NGC
6822
Triangulum
Andromeda
II, III and I
Phoenix
Dwarf
IC
1613
Pegasus
Dwarf
Cetus
Dwarf
LGS 3
Aquarius
Dwarf
WLM
SagDIG





Dwarf galaxies

- Dwarf galaxies are small and faint galaxies orbiting as satellites to more massive galaxies (like MW). MW has many and they are close!
- LMC (distance 52 kpc) is source of gamma-rays: Already EGRET saw diffuse emission (1.9+-1.4)*10^{-7} /cm2/s), Fermi-LAT *extended*, but 50% of the emission is coming from 30 Doradus, also detected at VHE by HESS telescopes. SMC also detected.
- The stars show large circular velocities and velocity dispersion that compared to their modest spatial extension indicates that the dynamics are dominated by dark matter
- Dwarf spheroidal galaxies are population of very faint galaxies with high mass to luminosity ratio => high density of dark matter
- The dwarf galaxies could produce gamma-rays via WIMP annihilation (not covered on this lecture)

Starburst galaxies

- In starburst galaxies: higher density of ISM, (high star formation rate=>) more SNR=> higher density of cosmic rays and cosmic ray accelerators

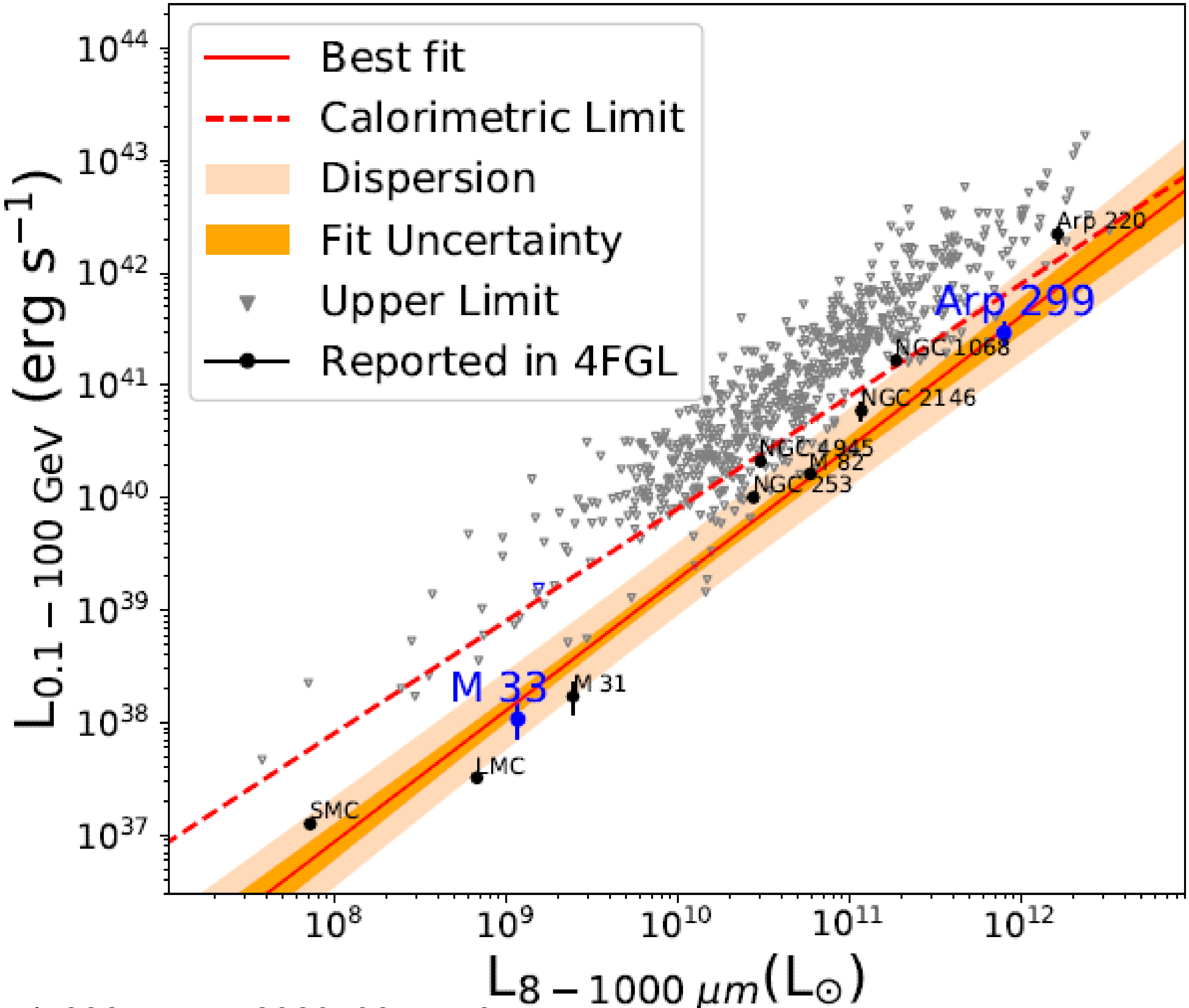
More is more:
Brighter gamma-ray sources
Can be detected from
creater distances!

Starburst galaxies - observations

- VHE gamma-rays have been observed from two starburst galaxies: M82 (d~5Mpc) by VERITAS and NGC 253 (d~5Mpc) by HESS
- Fermi-LAT sees in addition NGC4945, NGC2146, NGC1068, Arp 299

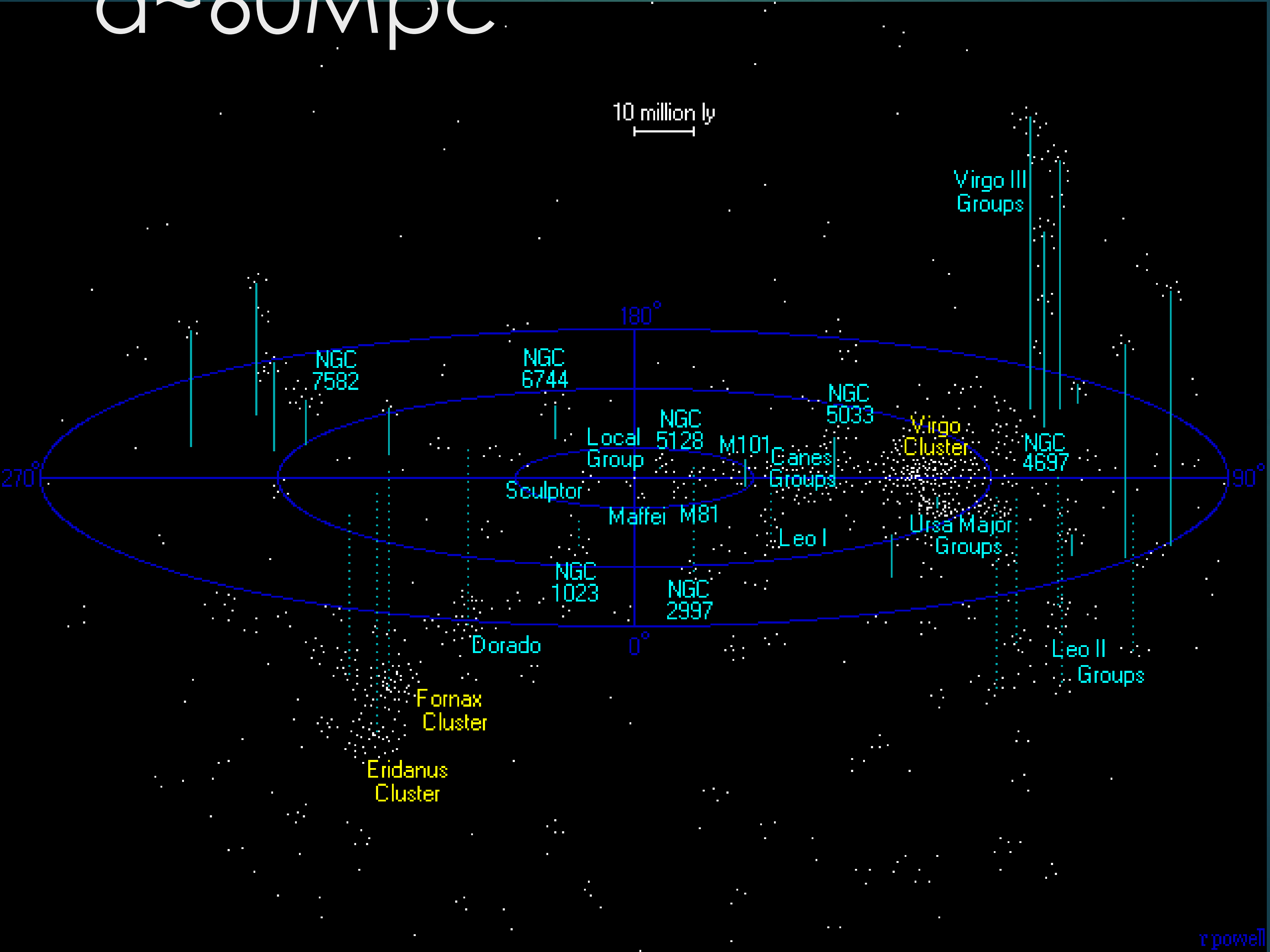
Ultraluminous infrared galaxies

- IR luminosity ~$10^{12}L_{sun}$
- Starbursting, nuclear activity, very dense environment
- Also very rare: the closest one (Arp220, d=72Mpc): no detection of VHE gamma-rays (yet).



Xi et al. 2021, ApJ, 2020, 901, 158

Virgo supercluster, d~60Mpc



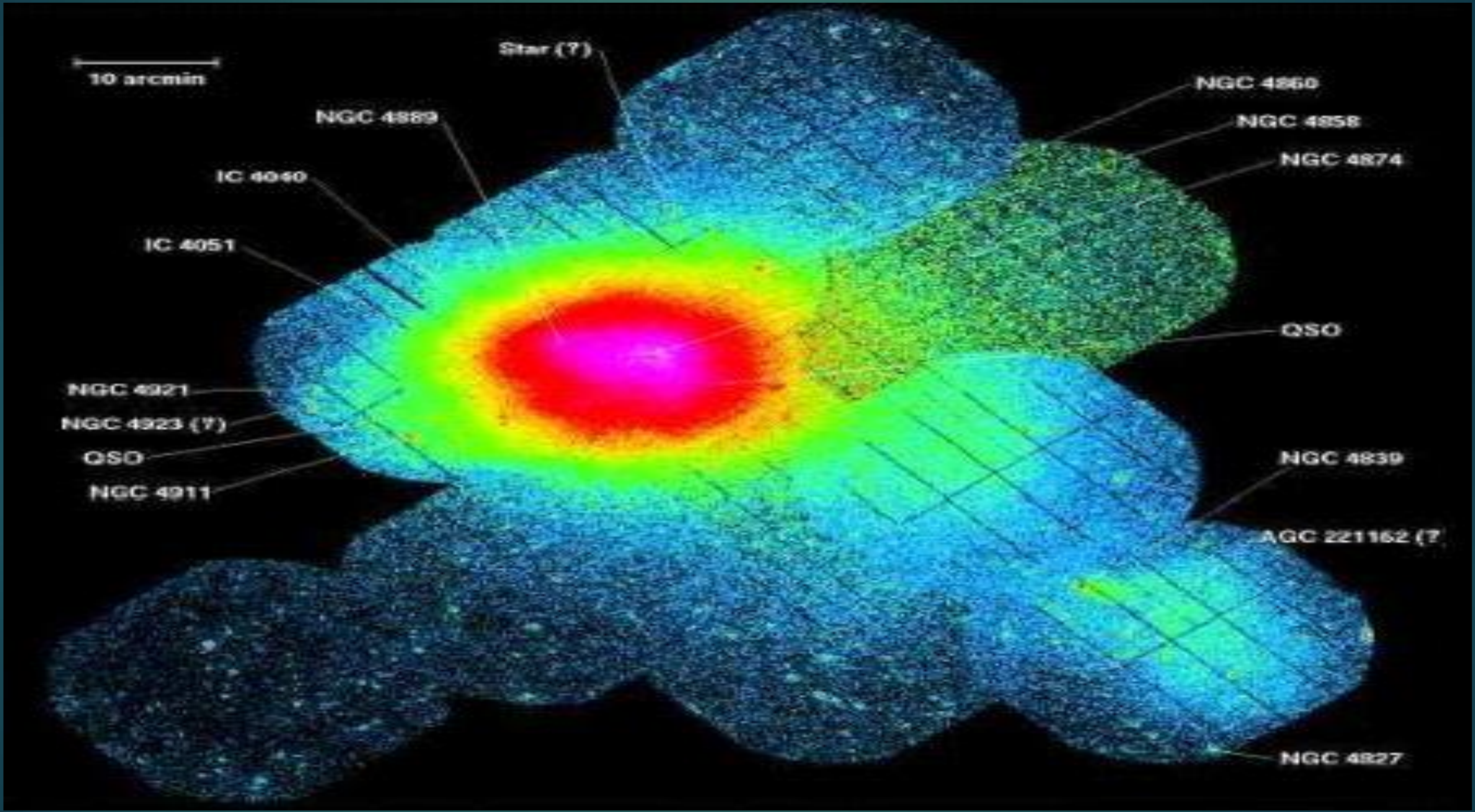
Galaxies of own supercluster ~handful of sources

WE NEED MORE, MAYBE THE CLUSTERS THEMSELVES?

Galaxy Clusters

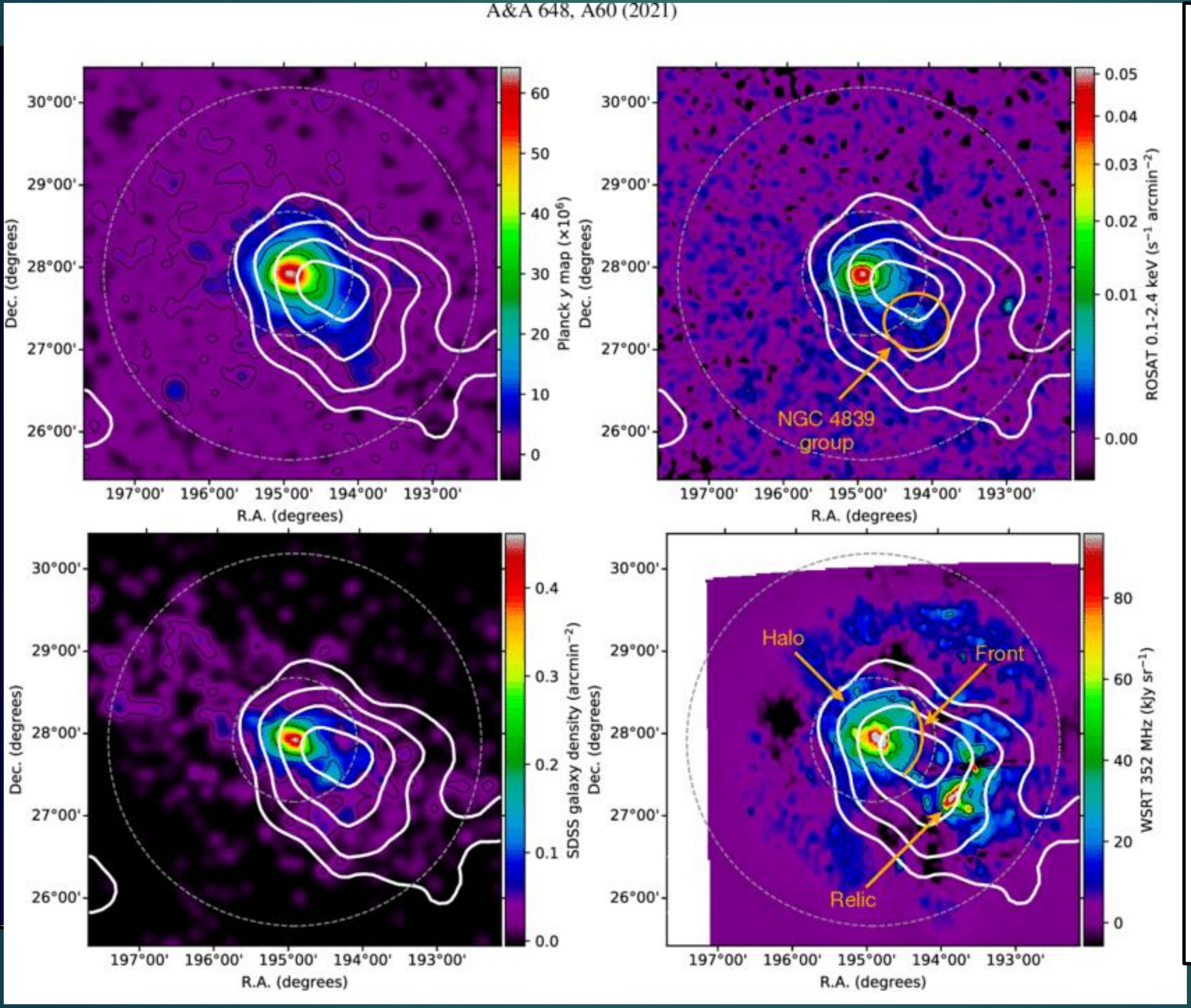
- Largest structures in the present universe in which gravitational force due to the matter overdensity overcomes the expansion of the universe
- Large collection of galaxies, gas and dark matter
- Rich clusters mass 10^{15} M_{sun}, mostly in form of dark matter, only 1% in galaxies, 5% in hot gas
- Non-thermal emission (radio, X-rays) = accelerated particles, i.e. relativistic electrons, magnetized ICM, magnetic field topologically complex

X-ray map of Coma Cluster



Hot gas + non-thermal emission

Clusters of Galaxies

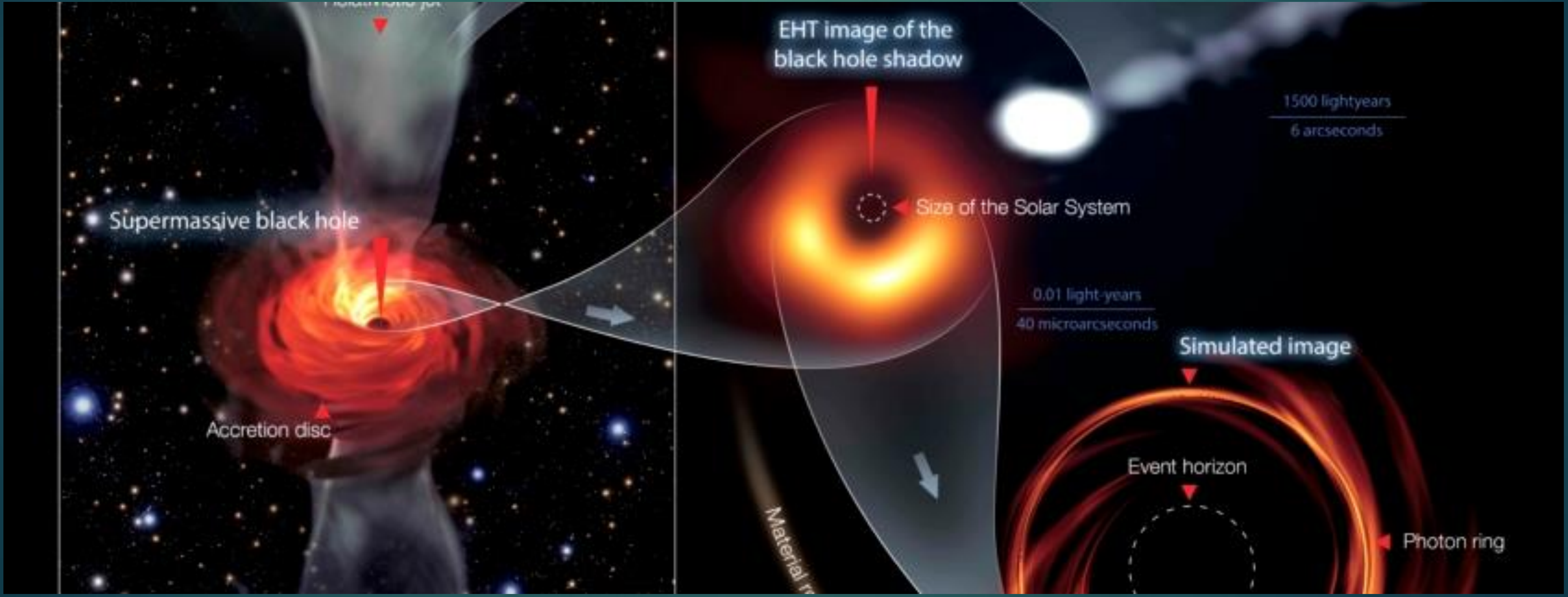


Multiwavelength morphological comparison of the Coma cluster signal to the Fermi-LAT TS map obtained in our baseline model. Top left: Planck tSZ. Top right: ROSAT X-ray. Bottom left: SDSS galaxy density. Bottom right: WSRT 352 MHz radio signal. The field of view of all images is 5 × 5 deg 2 . The white contours give the Fermi-LAT TS map (contours at 4, 9, 16, and 25) for the reference MINOT model (n CRp ∝ n 1/2 e). For all panels, the black contours correspond to the maximum of the image divided by 2 i , with i the index of the contours. The dashed gray circle provides the radius θ 500 and 3 × θ 500 . Several relevant features are also indicated in orange. For display purposes, the WSRT image has been apodized at large radii to reduce the larger noise fluctuations present on the edge of the field. As a complementary figure, Fig. 8 provides an optical image of the central region.
Ramzi et al. 2021, A&A

Clusters themselves: maybe few closeby…

…but clearly not the major population. What is the major population?

Centre of Virgo Cluster: M87, accreting supermassive black hole Active galactic nuclei

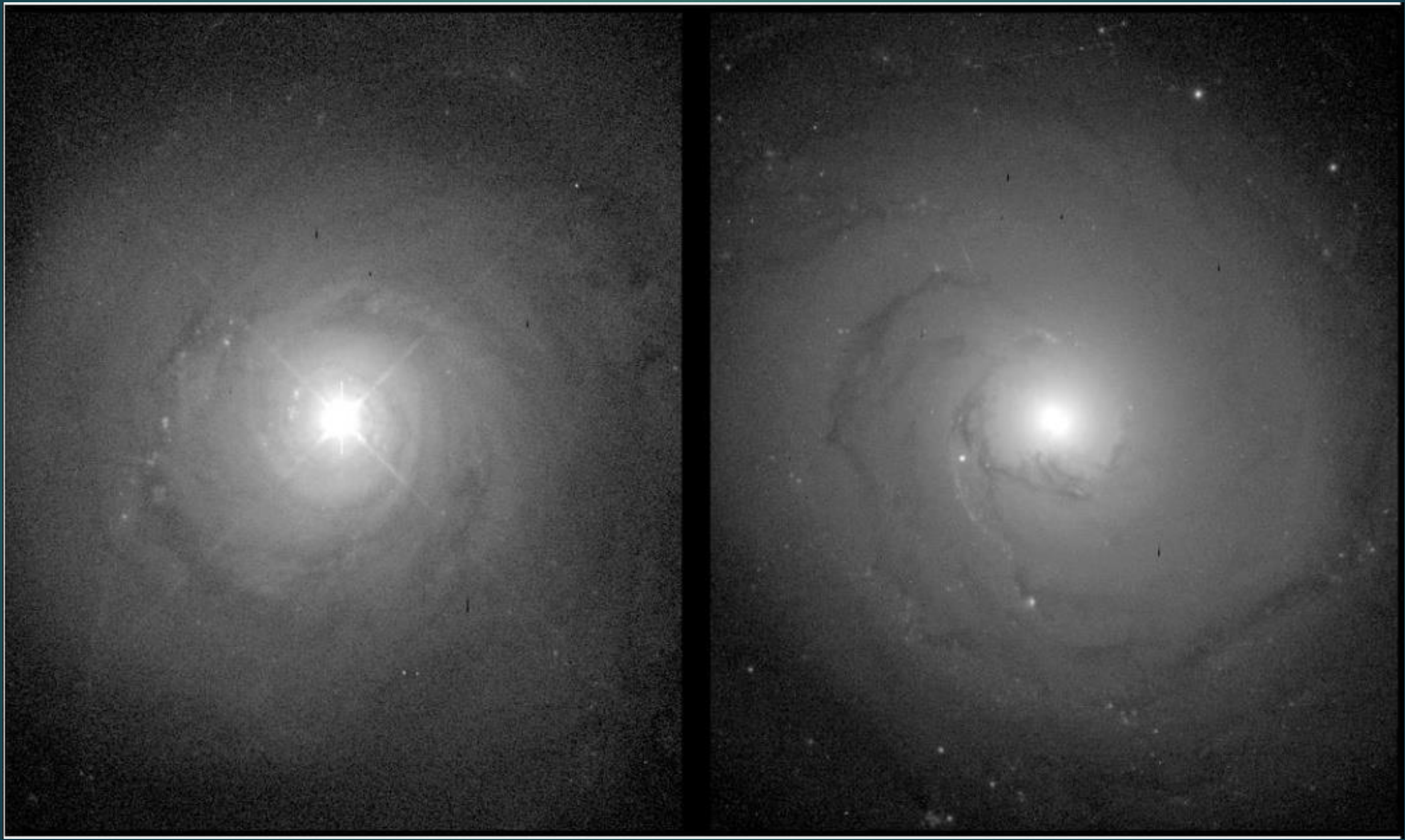


Active Galactic Nuclei

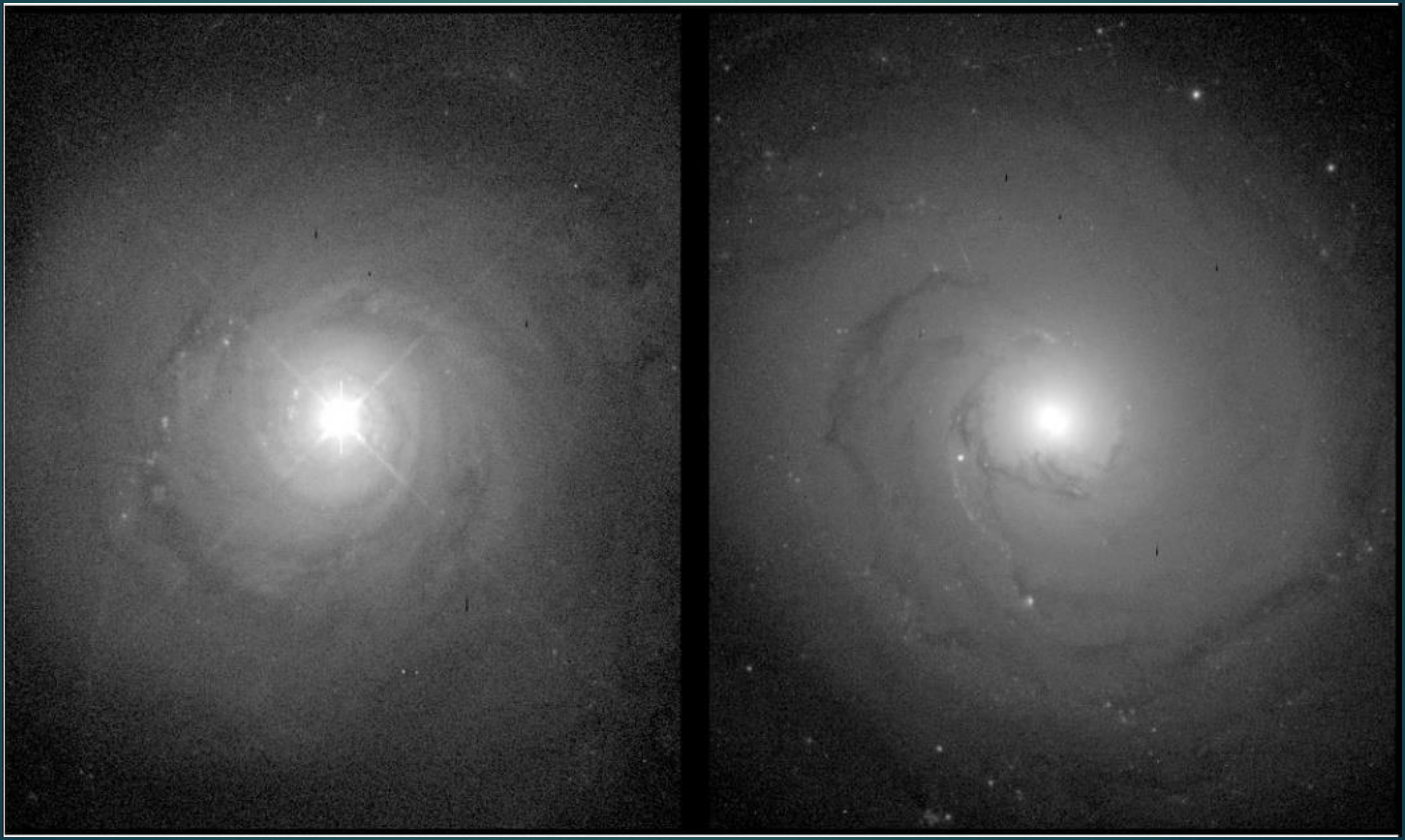
- Exceptionally bright compared to normal galaxies
- The luminosity originates from the very central region from matter accreting to supermassive black hole in the center of galaxies
- The luminosity of the nucleus outshines the thermal emission produced by the stars of the galaxy

Active Galactic Nucleus

Which one of these is AGN?

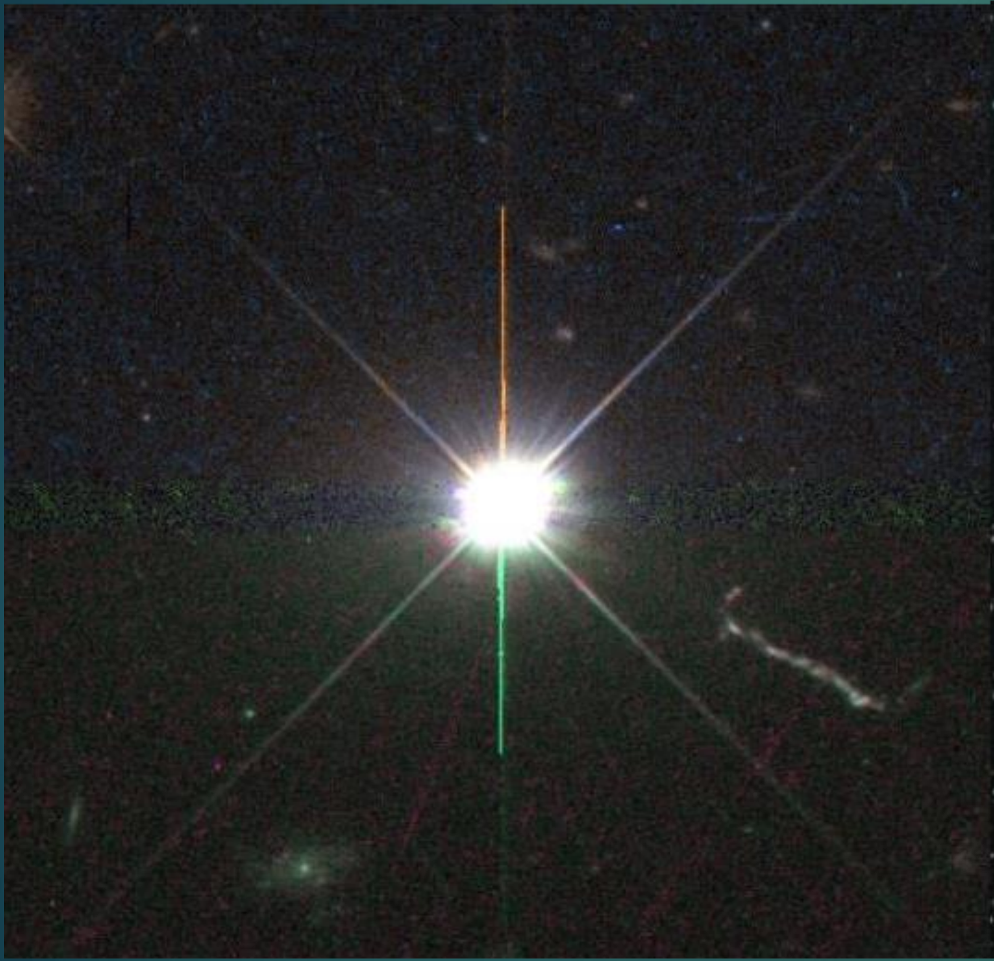


AGN?

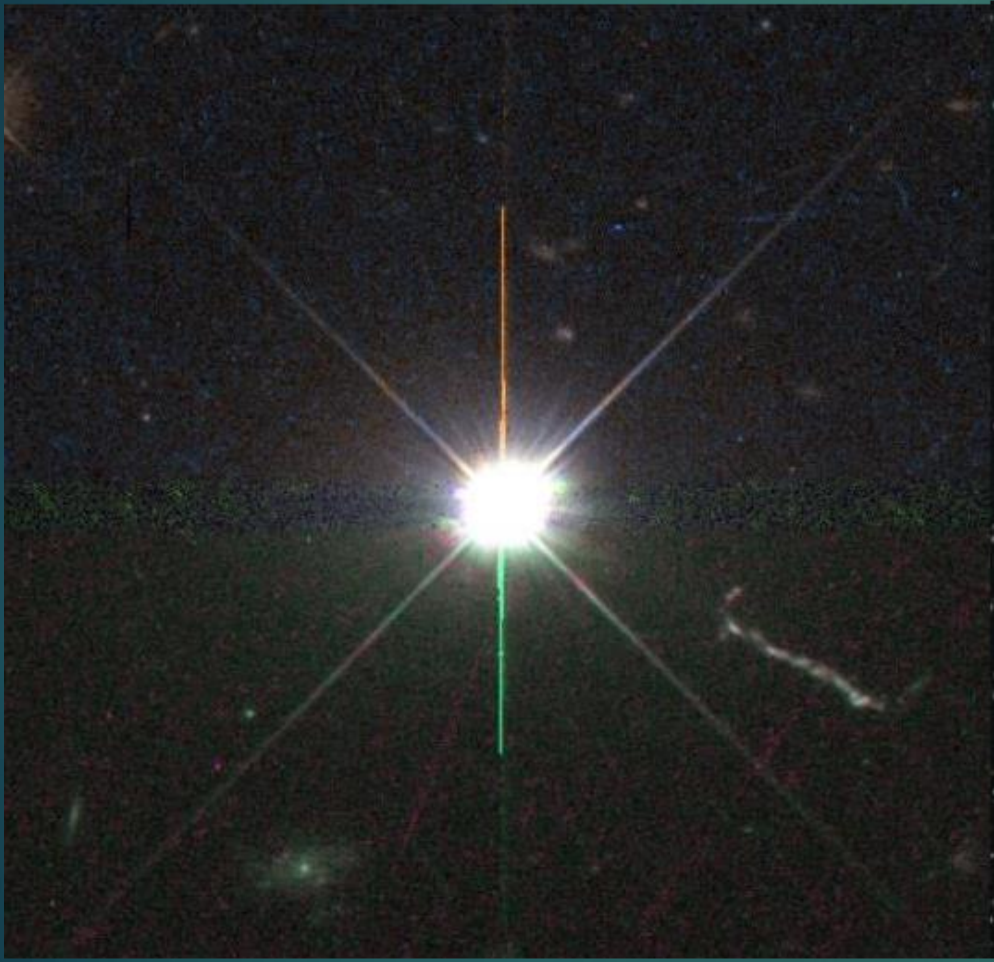


NGC5548 (Seyfert1) NGC3277 (Normal Spiral)

Next quiz



AGN?

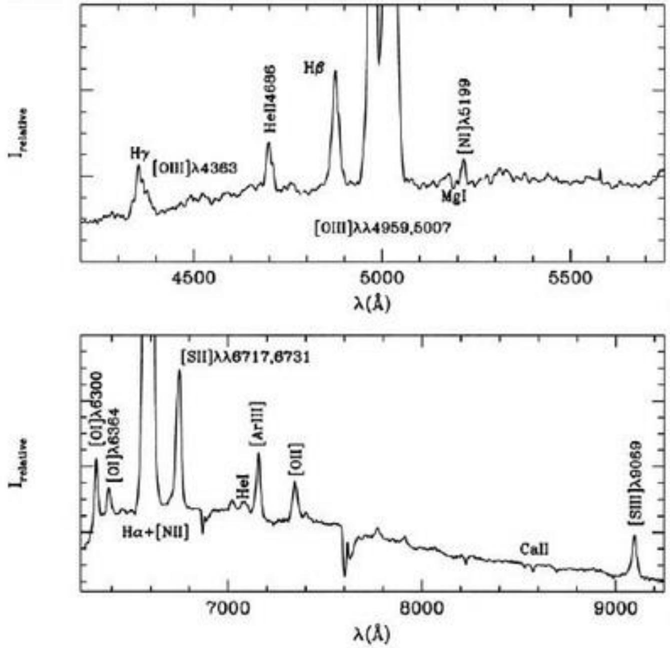


Quasar 3C273

”Obscured” AGN NGC 4945

First observations of AGNs

• Optical emission: **1908** – **Fath & Slipher** detect strong emission lines (from H, O, Ne) similar to planetary nebulae with high ionization levels and line-width of several hundred km/s in spiral nebulae, including NGC 1068.

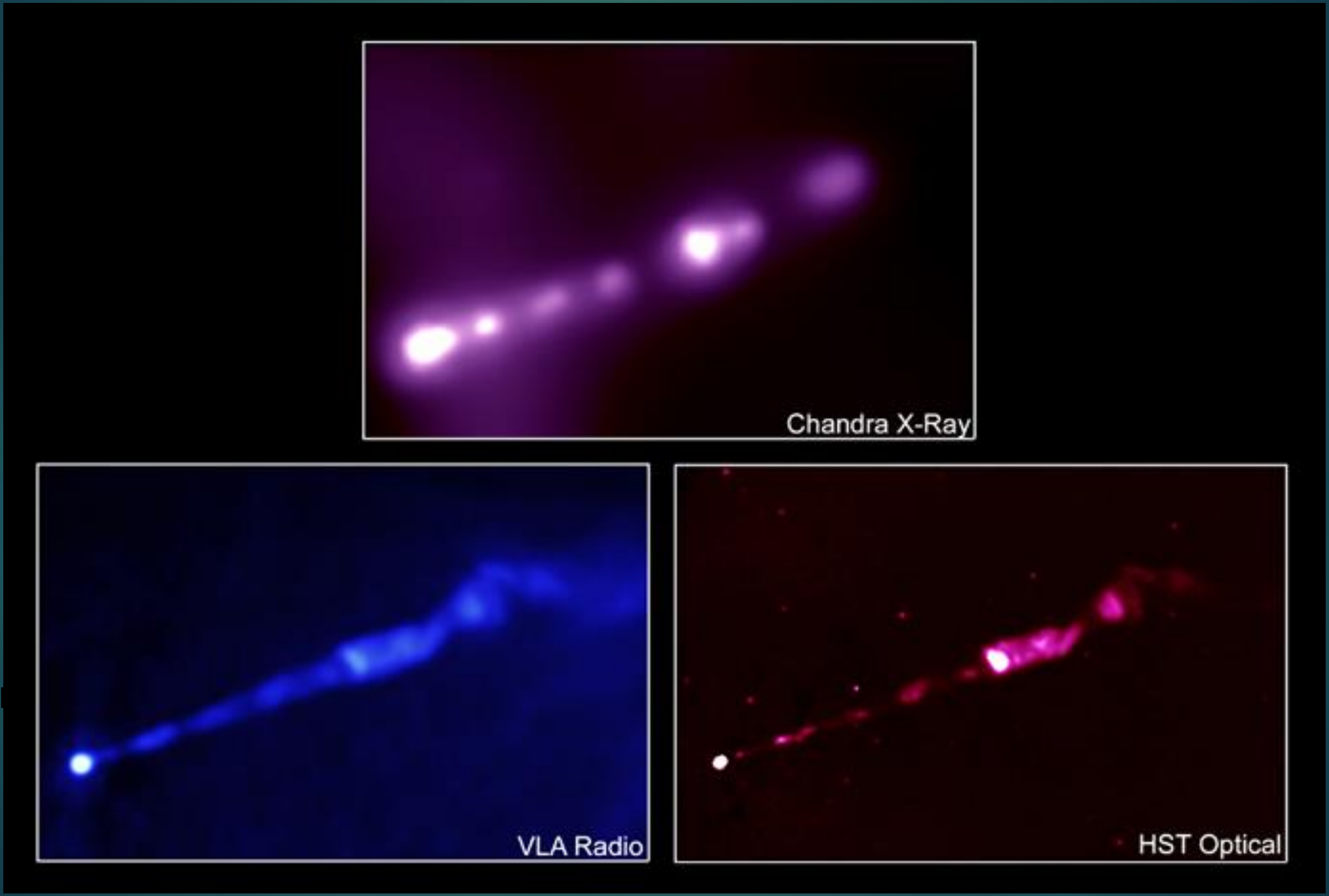


Optical spectrum of NGC1068
(Garcia-Lorenzo et al. 1999)

Credit: UCO/LickObservatory

H. D. Curtis noted a "curious straight ray" in M87 which was "apparently connected with the nucleus by a thin line of matter"

M87: Relativistic jets launched by supermassive black hole



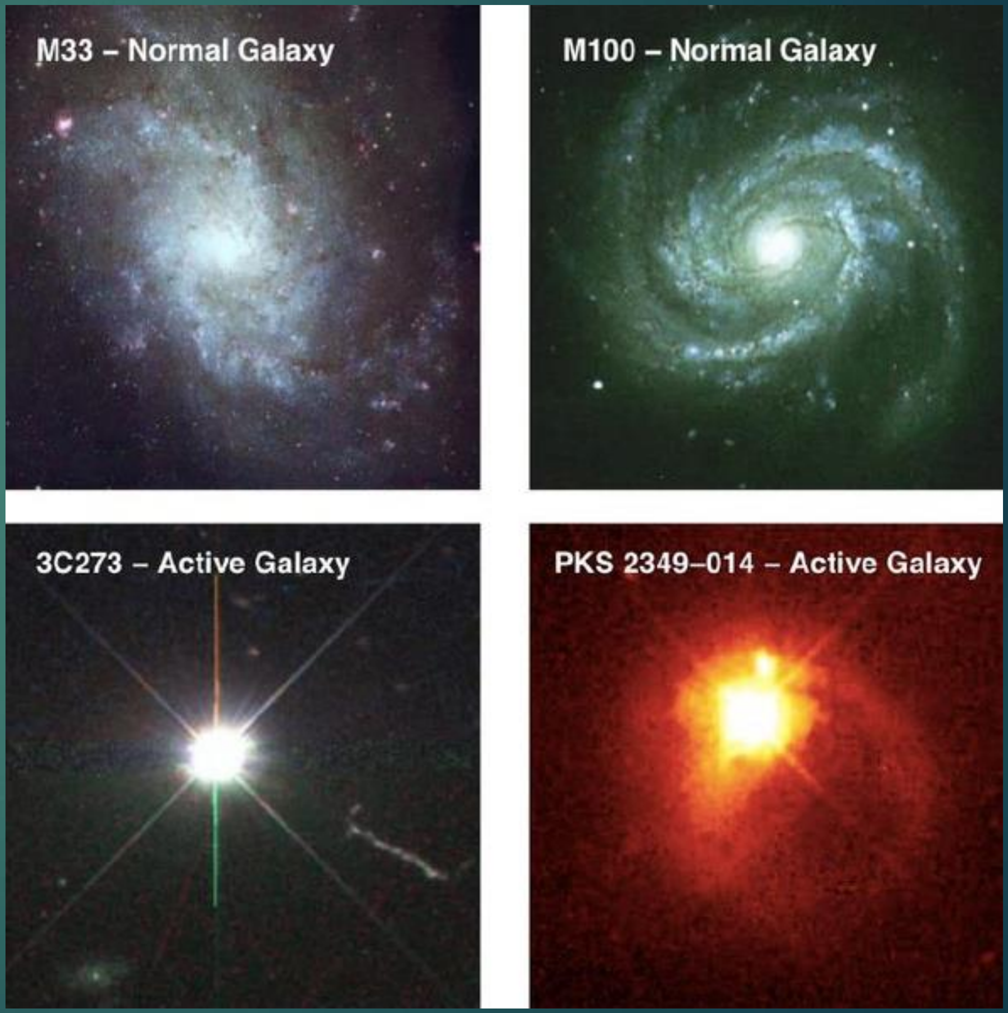
Cr

How common are AGN?

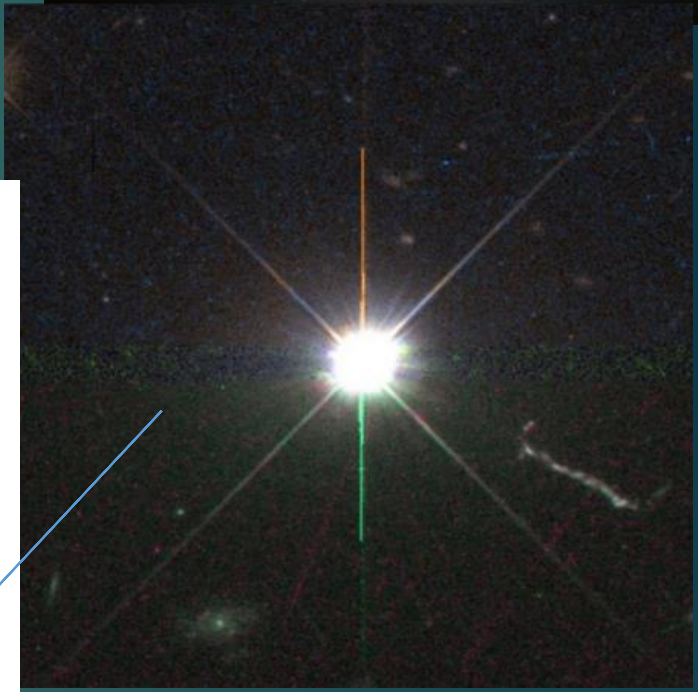
In local universe:
~ 10^{-6}
are bright quasars

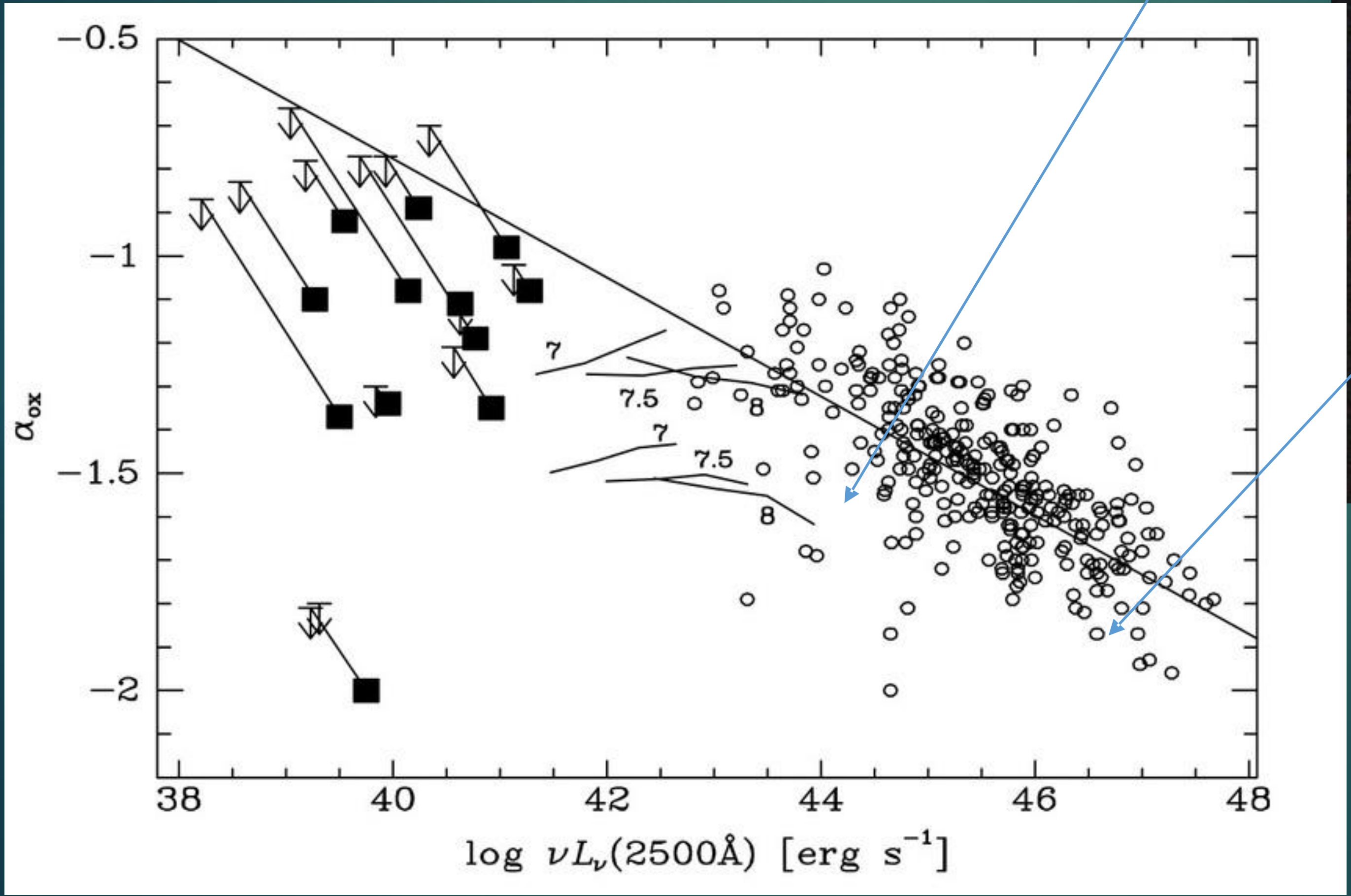
~ 5% are active (Seyfert galaxies)

~30% show "some mild activity"



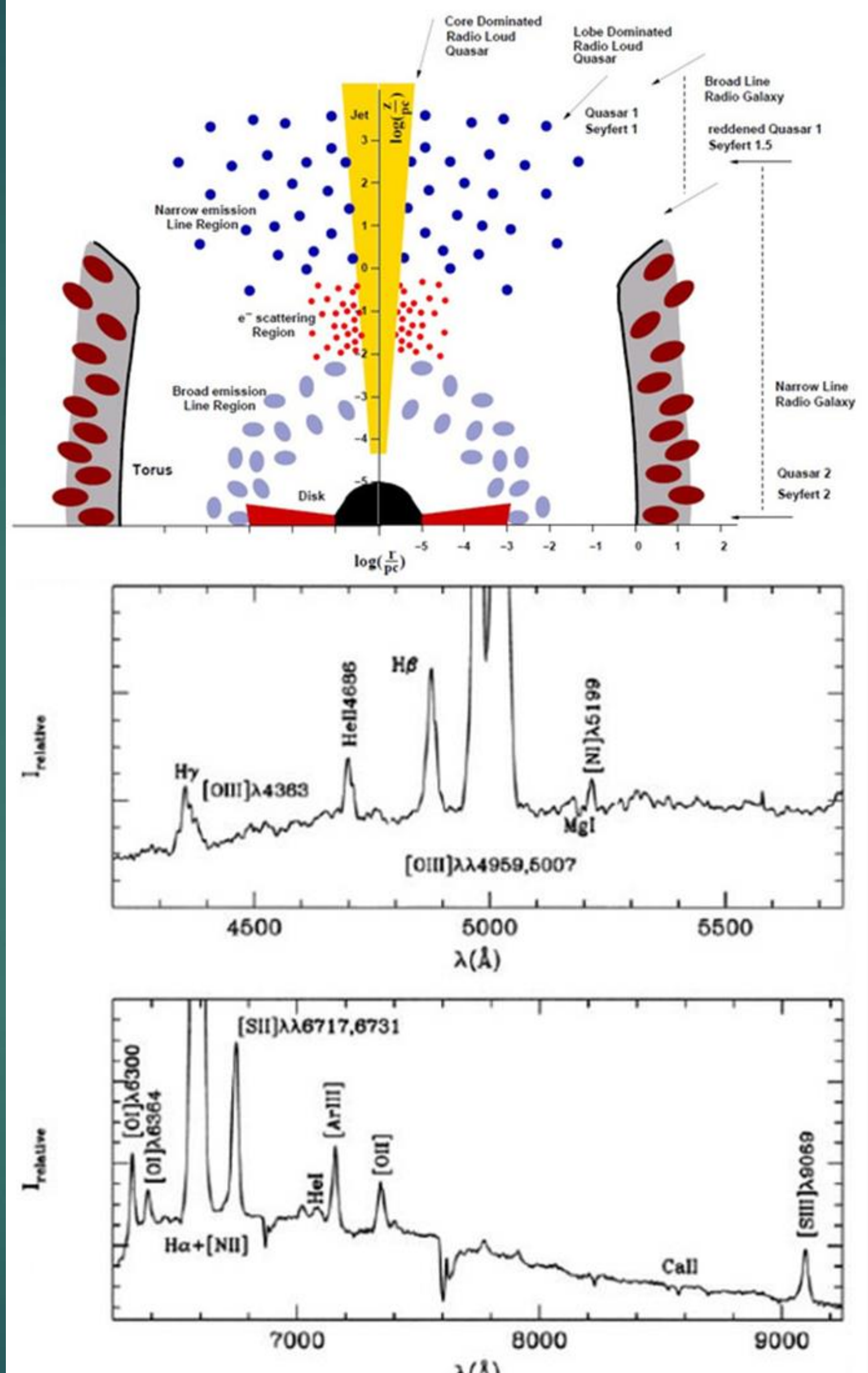
Different flavors of activity





Active Galactic Nuclei

- Central region: supermassive black hole, accretion disk, broad-line region clouds surrounded by toroidal dusty structure (dust torus)
- Note: only some ~10% supermassive black holes launch relativistic jets (10% of AGN radio loud, radio emission manifesting the existence of the jet)
- Relativistic jets: extreme particle accelerators: particle velocities close to that of speed of light



Optical spectrum of NGC1068 (Garcia-Lorenzo et al. 1999)

Active Galactic Nuclei

- Central region: supermassive black hole, accretion disk, broad-line region clouds surrounded by toroidal dusty structure (dust torus)
- Some ~10% supermassive black holes launch relativistic jets (10% of AGN radio loud, radio emission manifesting the existence of the jet)
- Relativistic jets with magnetic fields: extreme particle accelerators: particle velocities close to that of speed of light
- Blazars: Jets pointing very close to our line of sight: Doppler boosting

Doppler boosting

$$S_\nu = \delta^{3-\alpha} S'_\nu ,$$

- Magnifies the apparent flux
- Doppler factor

$$\delta = [\gamma(1 - \beta \cos\theta)]^{-1},$$

Spectral index

Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

γ = Lorentz factor

v = speed of moving observer

c = speed of light

Viewing angle (small <10 degrees)

v/c, usually very close to speed of light e.g. 0.998

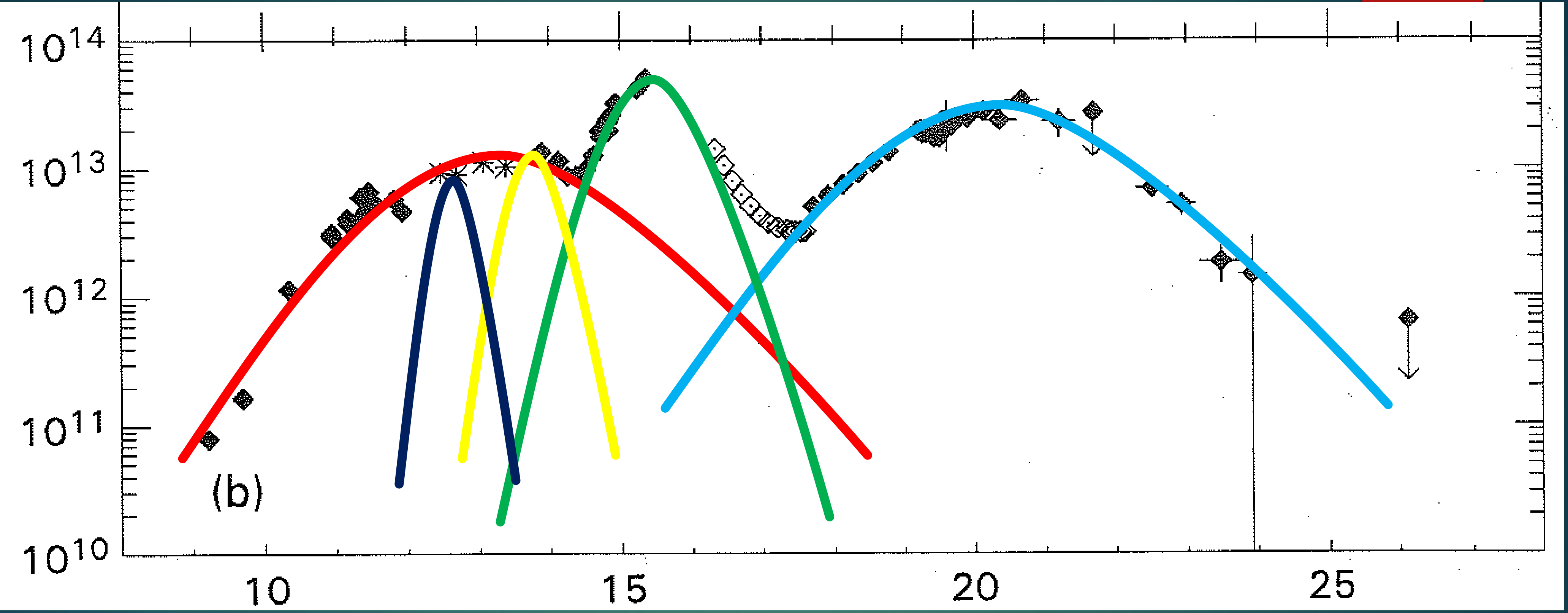
Doppler boosting

Also makes variability times shorter

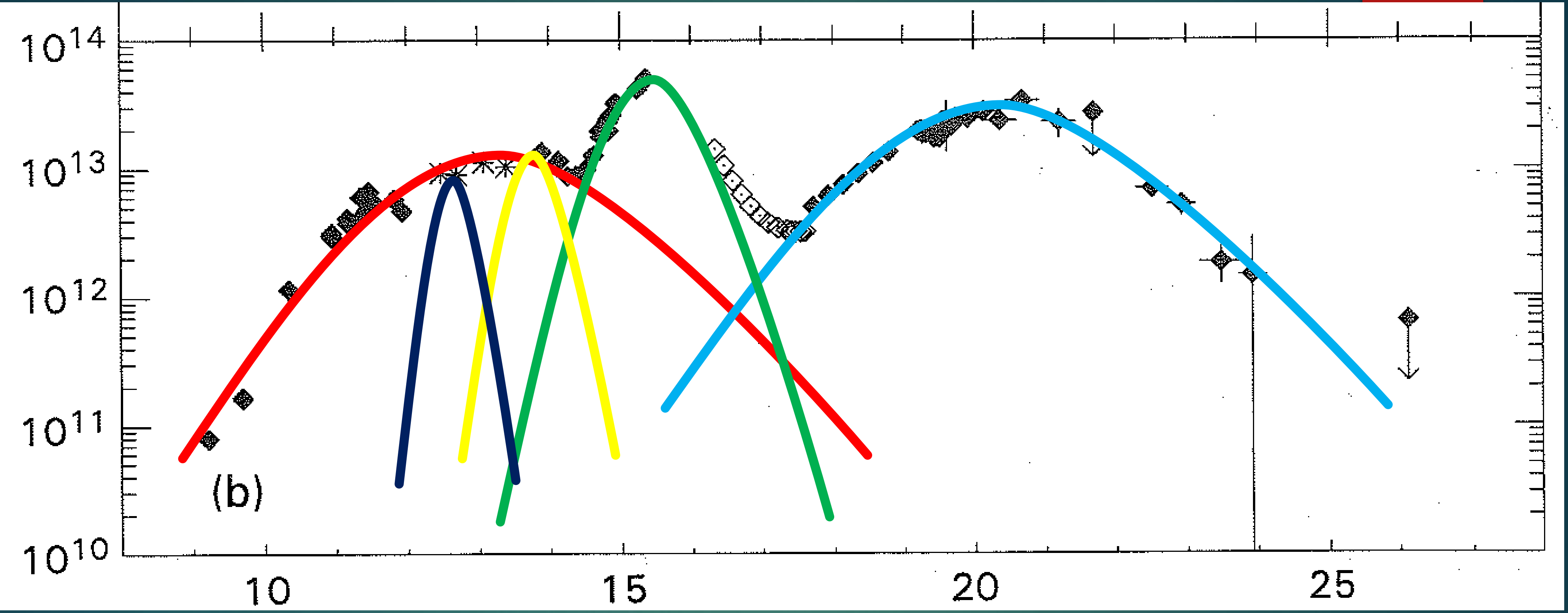
$$\Delta t_{\rm arr} = \delta^{-1} \Delta t'.$$

….Emission from the relativistic jets pointing close to our line of sight: very bright and very variable!

Radiative mechanisms in AGN in nutshell



Radiative mechanisms in AGN in nutshell



Synchrotron radiation from the relativistic jet

Inverse Compton? radiation from the relativistic jet

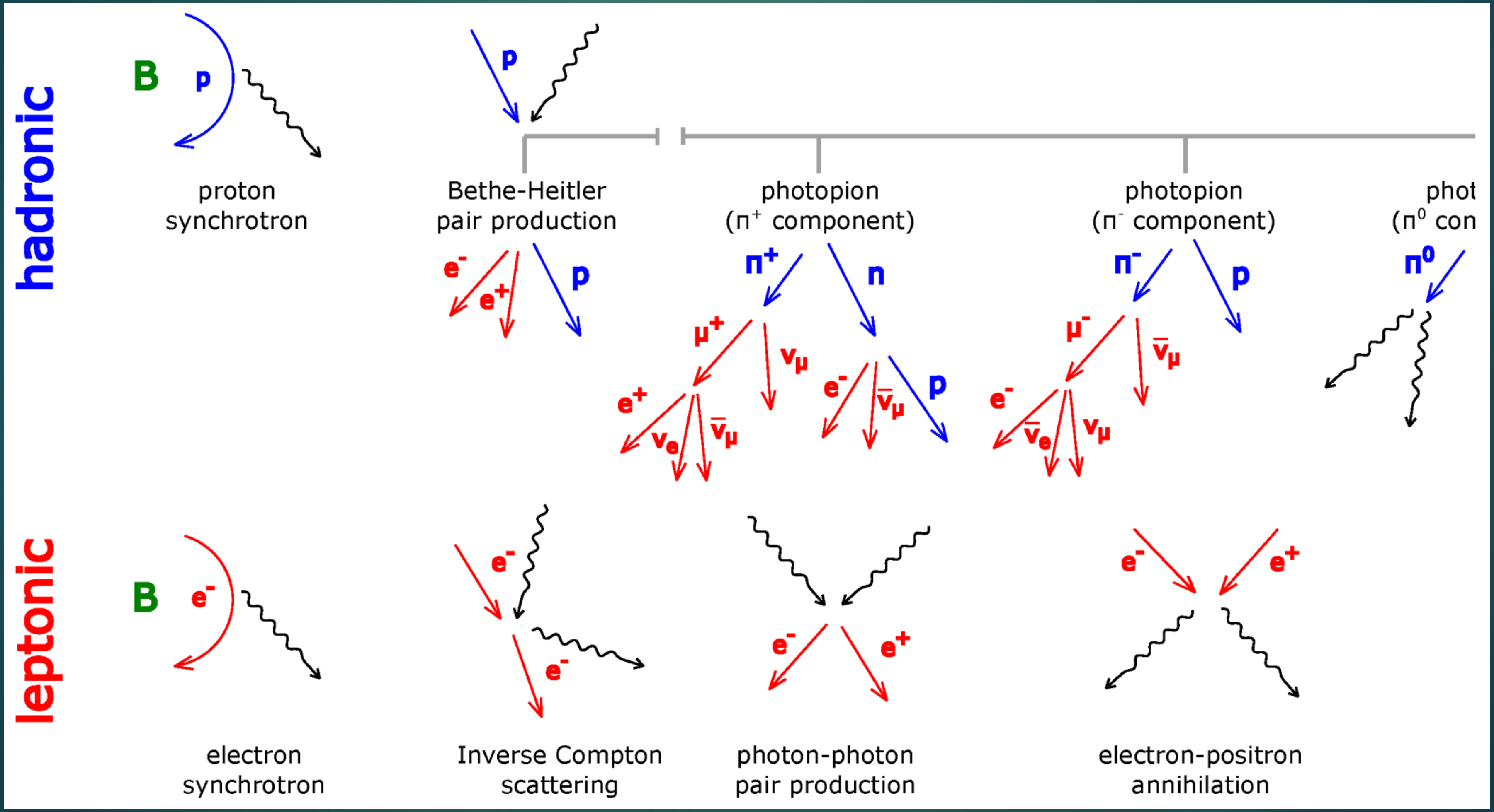
Blackbody (greybody) radiation from the accretion disk

Blackbody (greybody) radiation from the parent galaxy ($\Sigma 10^{11}$ stars)

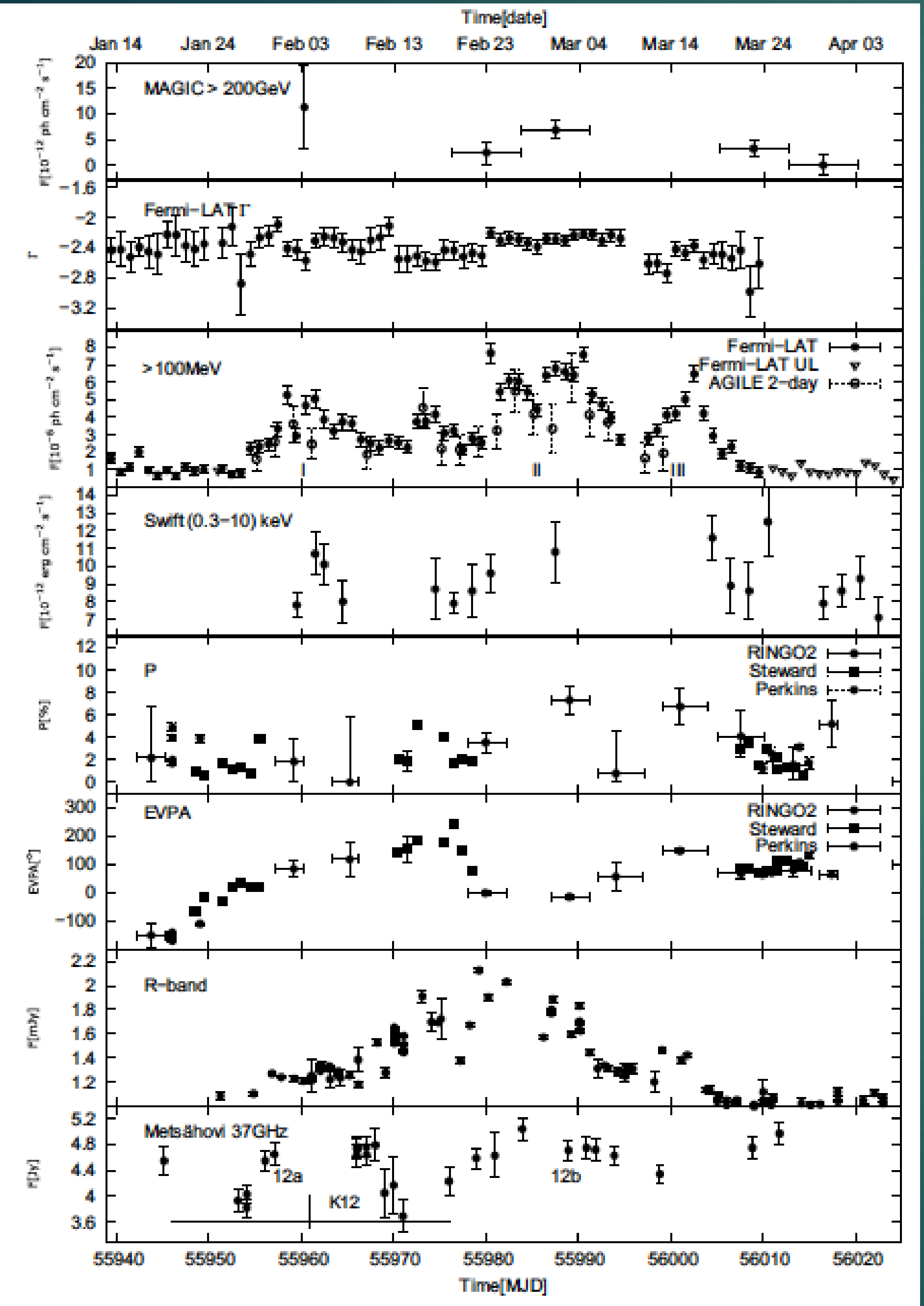
Blackbody (greybody) radiation from heated dust

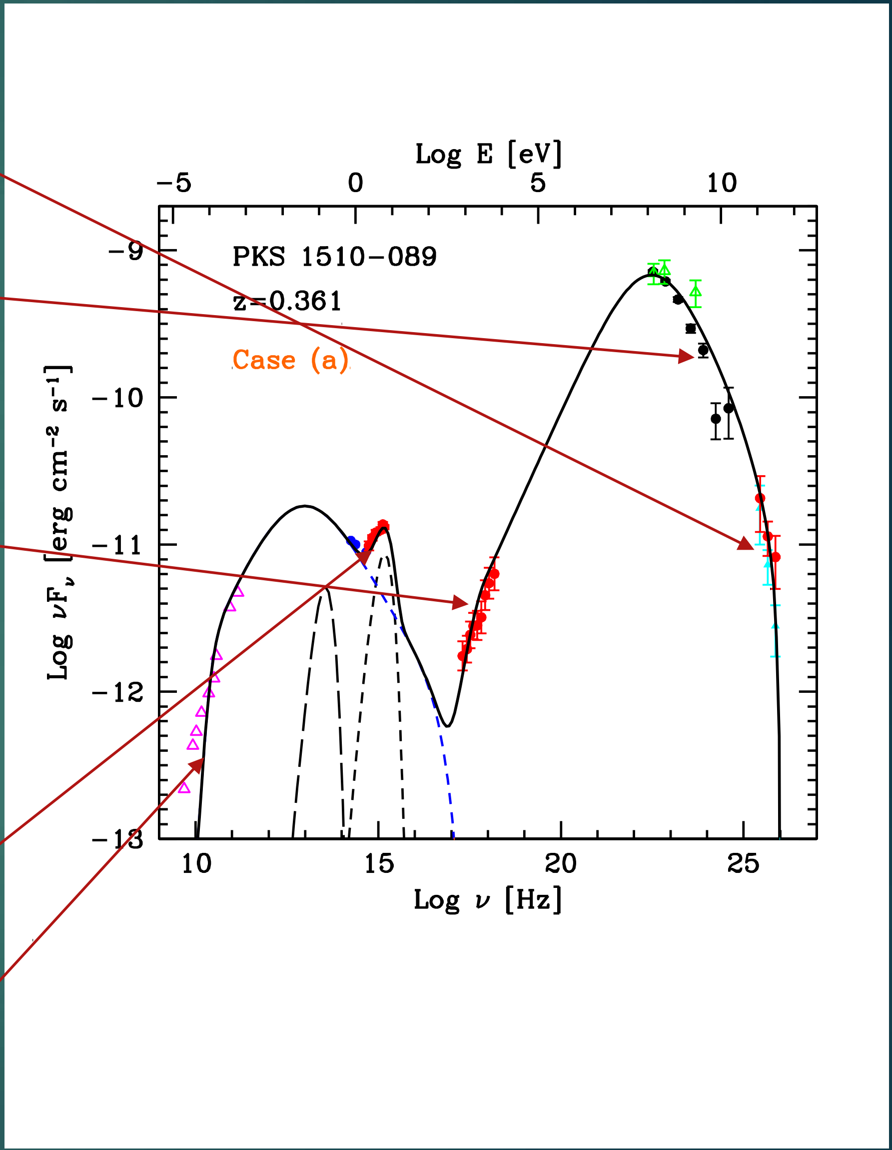
[**Line radiation (emission/absorption)** from gas]

Second SED peak; maybe also hadronic?



Variable emission





Gamma-rays

X-rays

Optical

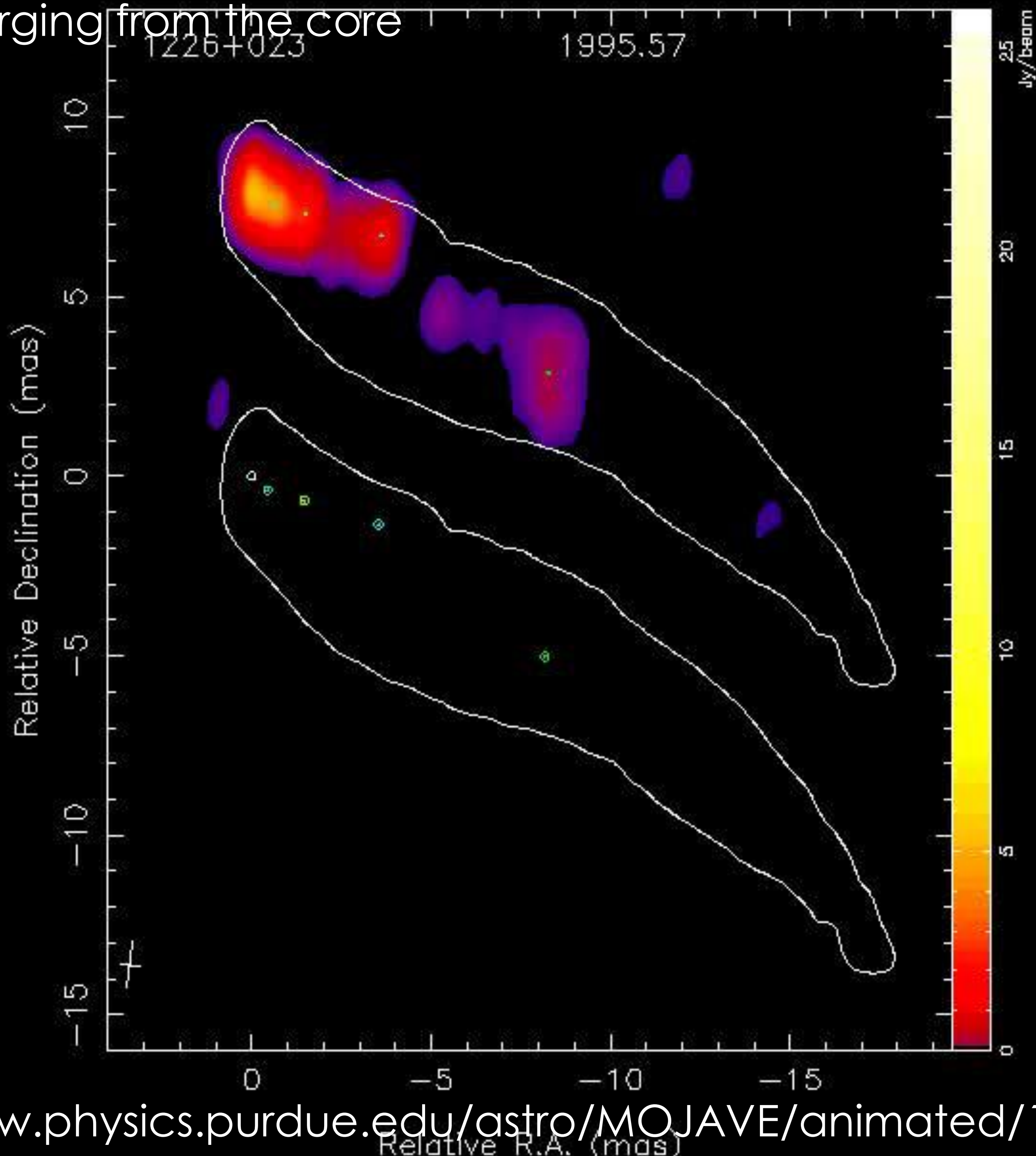
Radio

Plots from Aleksic et al. 2014

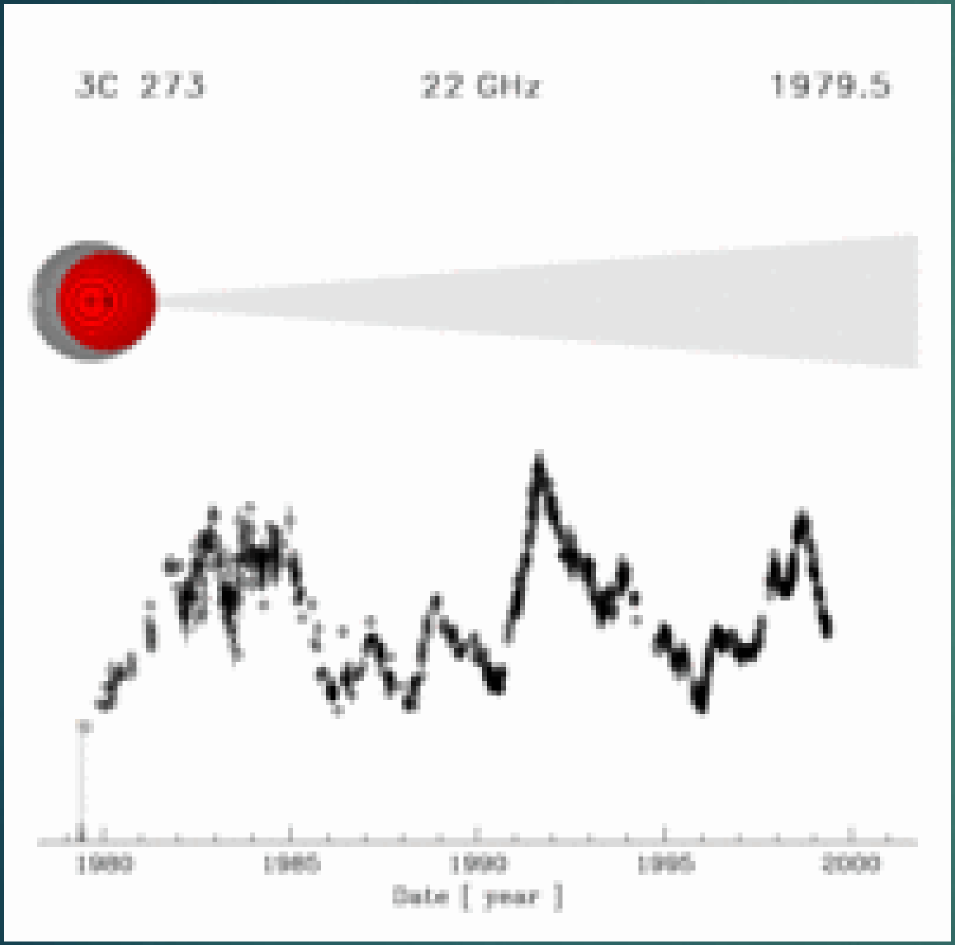
Origin of variability

OR THE BIT THAT WE THINK WE KNOW

Origin of variability in radio: Following the time evolution over several years allows one to see changes in the structure of the pc-scale jet and new "blobs" emerging from the core



http://www.physics.purdue.edu/astro/MOJAVE/animated/1226+023.i.mpg



Animation by Türler et al. 1999

It is possible to connect the blobs with variability seen on the light curves: Before a new blob emerges, the core is seen to brighten and then a blob is seen in traveling down the jet.

It is possible to connect the blobs with variability seen on the light curves: Before a new blob emerges, the core is seen to brighten and then a blob is seen in traveling down the jet.

The Astrophysical Journal, 846:98 (35pp), 2017 September 10 Jorstad et al.

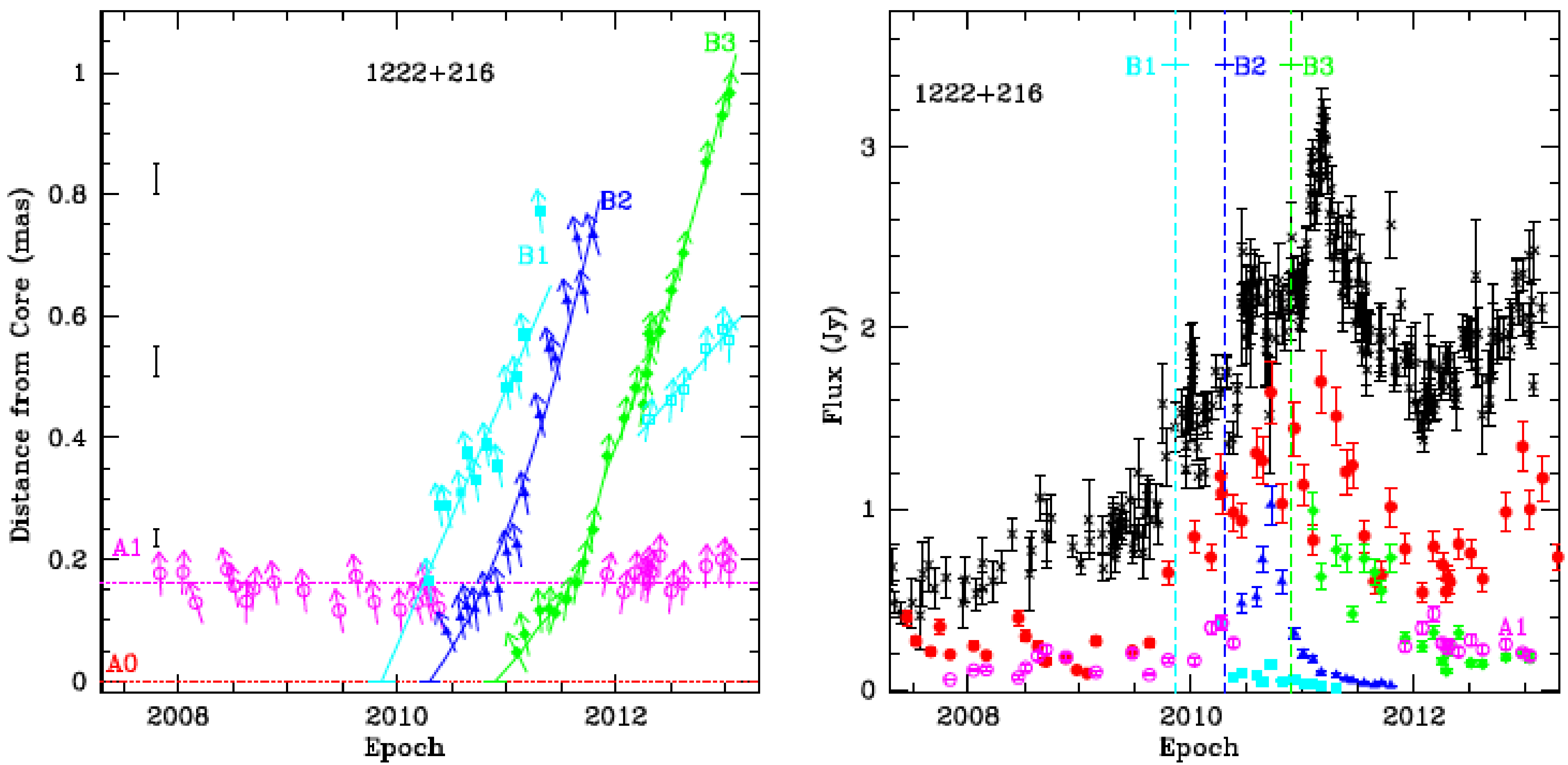
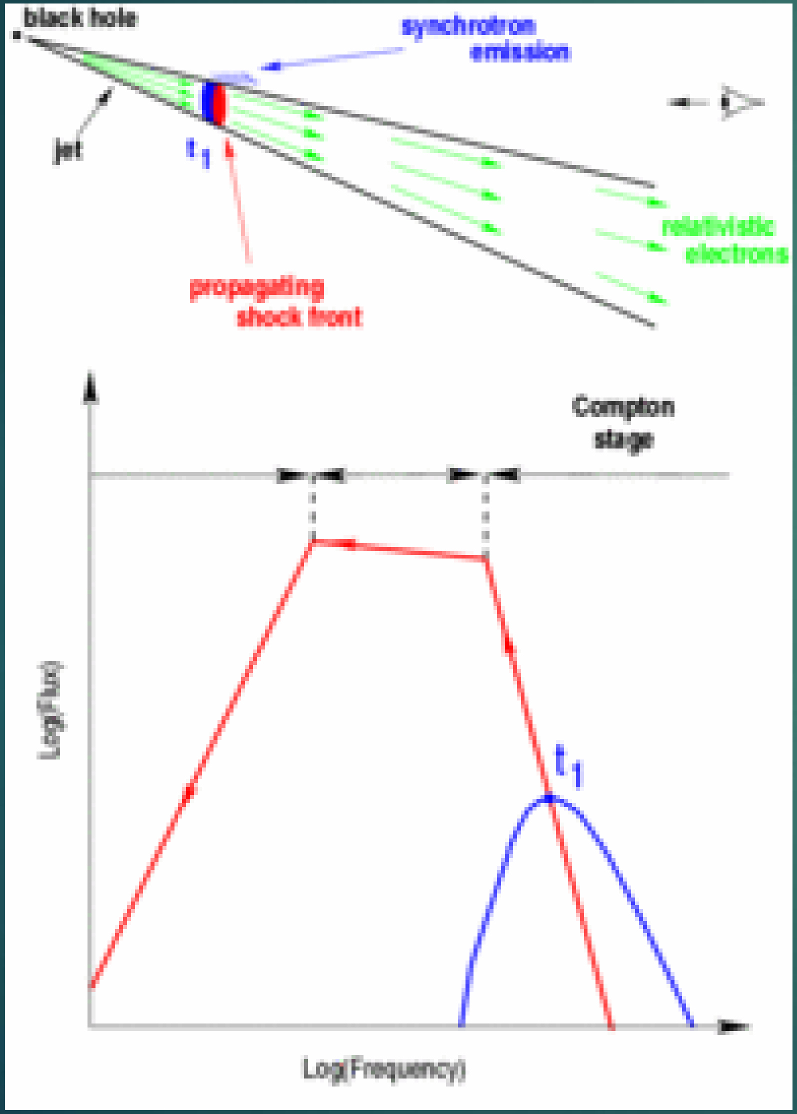


Figure 4. Separation of jet features from the core and their light curves. Left: separation vs. time of knots in the jet of the quasar 1222+216 from the VLBA-BU-BLAZAR sample. The vectors show the P.A. of each knot with respect to the core at the corresponding epoch. The solid lines or curves (depending on the parameter *l* in Table 5) represent polynomial fits to the motion, while the dotted red and magenta lines mark the position of the core, *A*0, and stationary feature, *A*1, respectively. The vertical black line segments show the approximate 1σ positional uncertainties based on $T_{b,obs}$. Right: the light curves of the core, *A*0 (filled circles, red), and jet components, and the light curve of the entire source at 37 GHz (black crosses); dashed lines indicate the epochs of ejection of the moving knots. Symbols and colors correspond to the same knot in the left and right plots. Plots for all sources in the sample are available in figure set.

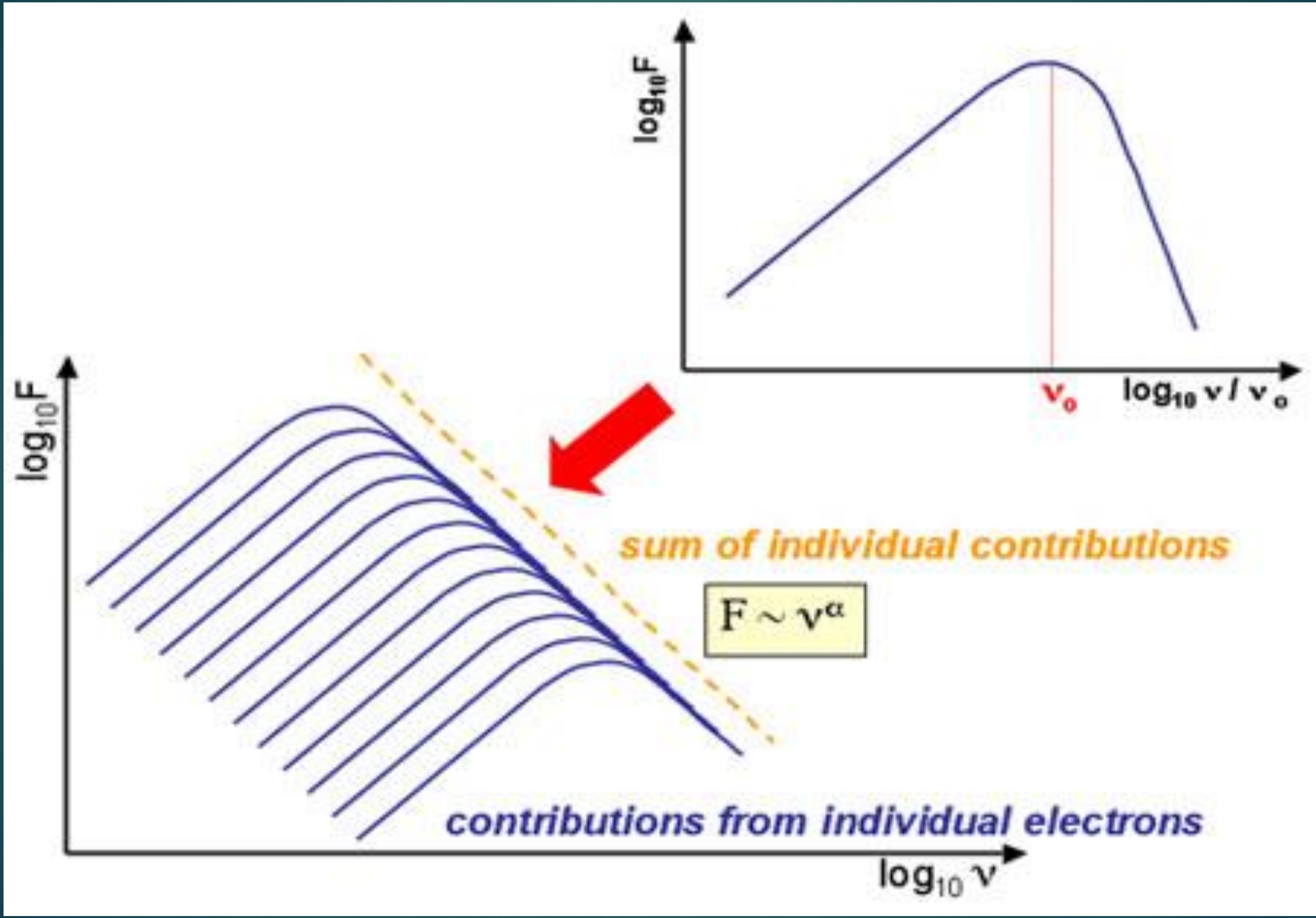
A physical explanation for this is shocks traveling down the jet. They cause the synchrotron spectrum of each individual blob to evolve in time.



Animation by Türler et al. 1999

- Before the shock model, the emission was modeled with pure adiabatic expansion – Van Der Laan model
  - Electrons simply lose energy due to expansion of the emission region
- Because the spectral shape was seen to evolve during flares, it became apparent that adiabatic expansion cannot be the cause of variability
- The first shock models were introduced in 1985 by Marscher & Gear and Hughes, Aller & Aller.
- Main difference to adiabatic model is the inclusion of inverse Compton and synchrotron radiation losses, and energy gain of the electrons in the shocks

Re-cap: What do we see in radio band? Final resulting power law spectrum is a sum of individual electron spectra



http://astronomy.swin.edu.au/cosmos/S/Synchrotron+Emission

Optically thin synchrotron spectrum between γ_1=10 and γ_2=10^4

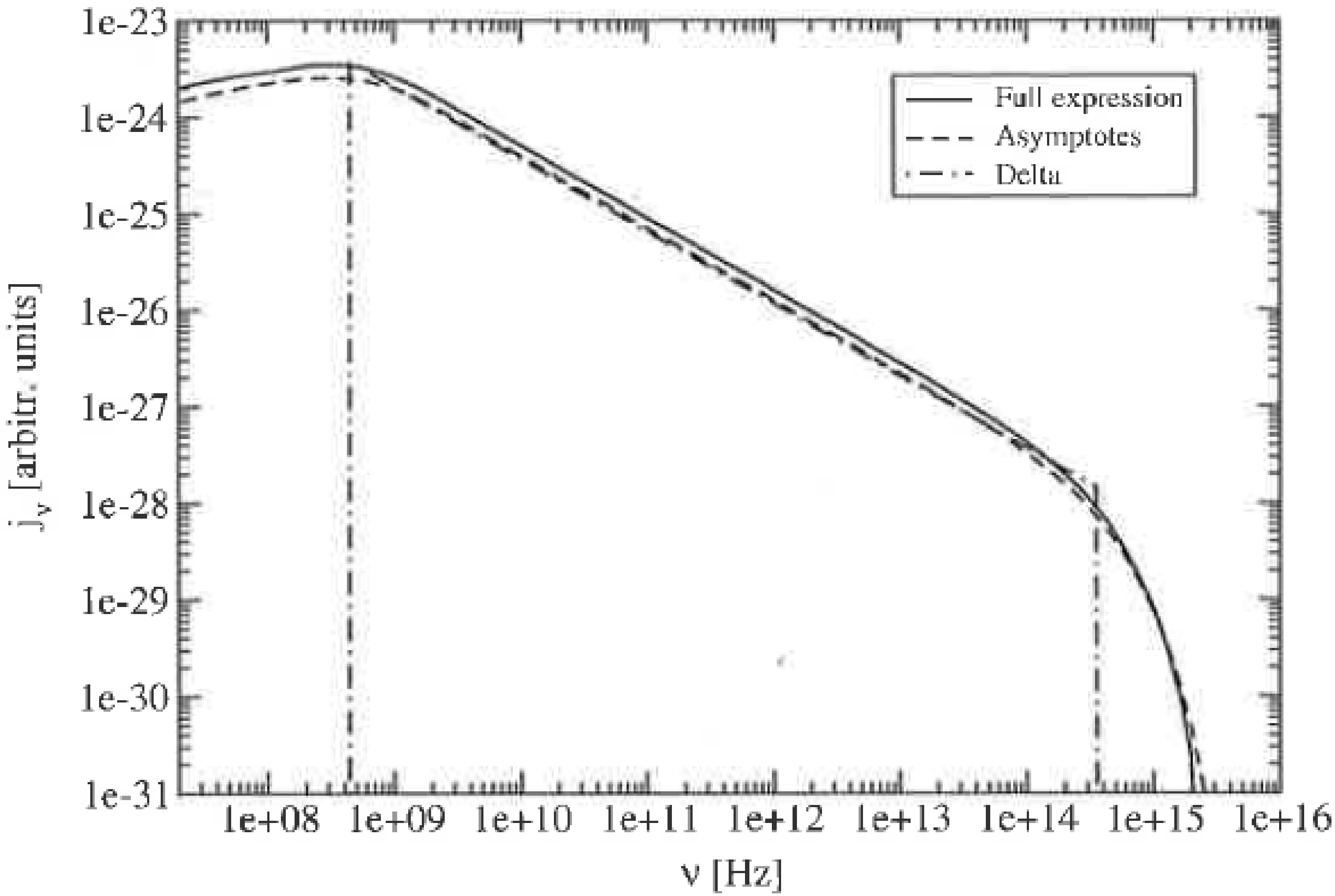


Figure 3.2 Optically thin synchrotron spectra from a power-law distribution of electrons with index $p = 2.5$ and cutoffs $\gamma_1 = 10$ and $\gamma_2 = 10^4$ for a magnetic field of $B = 1$ G. The figure compares the full expression (3.34), the $\nu^{1/3} e^{-\nu/\nu_c}$ approximation (3.38), and the δ function approximation (3.40).

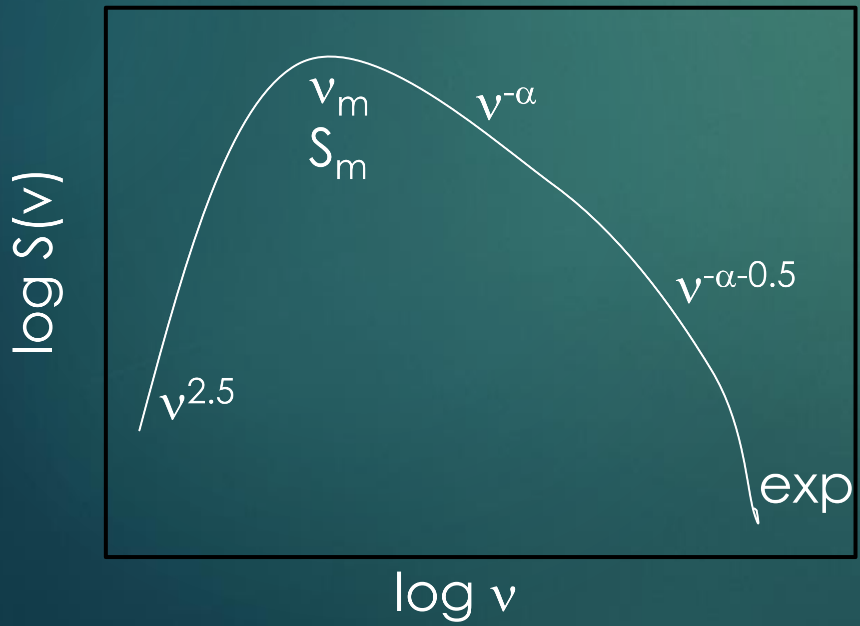
Böttcher: Relativistic Jets from AGN

Modifications

Low frequencies: *self-absorption* $\Rightarrow I(\nu) \propto \nu^{5/2}$. Also possible is a *low-energy cutoff* due to the lowest energy for accelerated electrons, E_{min}.

High frequencies: the acceleration process can only reach electron energies up to some E_{max} (Lorentz factor $\gamma_{max} = E_{max}/m_0c^2$) $\Rightarrow$ *exponential cut-off* at frequencies $\nu_h \geq 4B\,\gamma_{max}^2$

Energy losses: higher energy electrons lose energy faster $\Rightarrow$ *steepening* of the spectrum from α to $\alpha+0.5$. The steepening frequency moves to lower frequencies with time.



Maximum at $\nu_m \approx 8B^{1/5}\Theta^{-4/5}S_m^{2/5}$ [GHz, G, mas, Jy]

with Θ the angular diameter of the source in milliarcseconds. In principle B can be estimated from observations, in practice rather uncertain because of the large exponents.

What is the “core” seen in the VLBA images?

At centimeter wavelengths, it is typically assumed to be the point
where the jet becomes optically thin
for the synchrotron emission at that frequency.

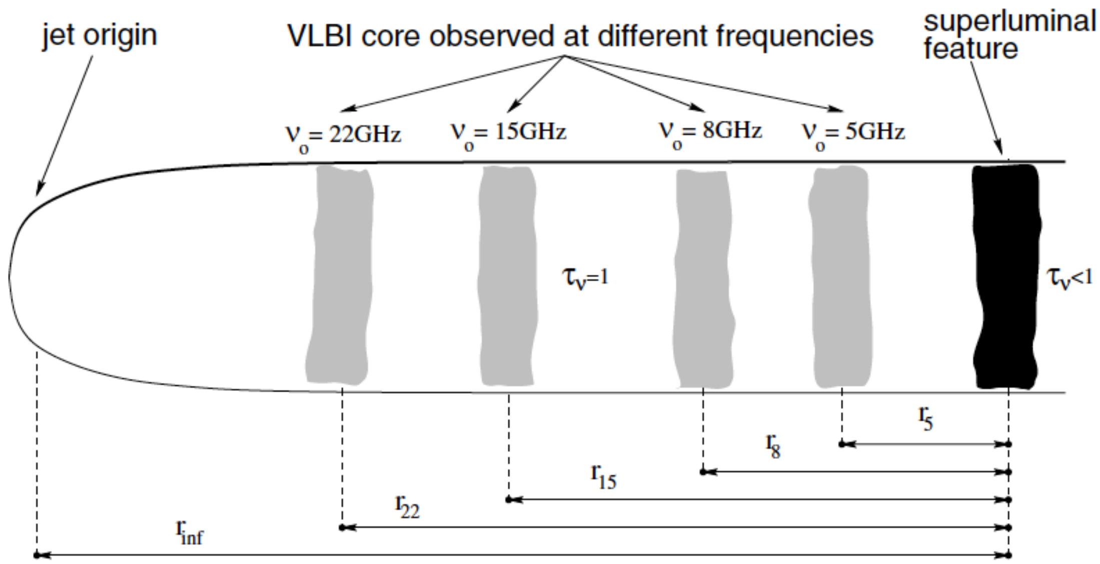


Fig. 1. A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

What is the “core” seen in the VLBA images?

At centimeter wavelengths, it is typically assumed to be the point where the jet becomes optically thin for the synchrotron emission at that frequency.

At millimeter wavelengths, where the jet is already optically thin, the core could be a recollimation shock

760 Y. Y. Kovalev et al.: Opacity in compact extragalactic radio sources

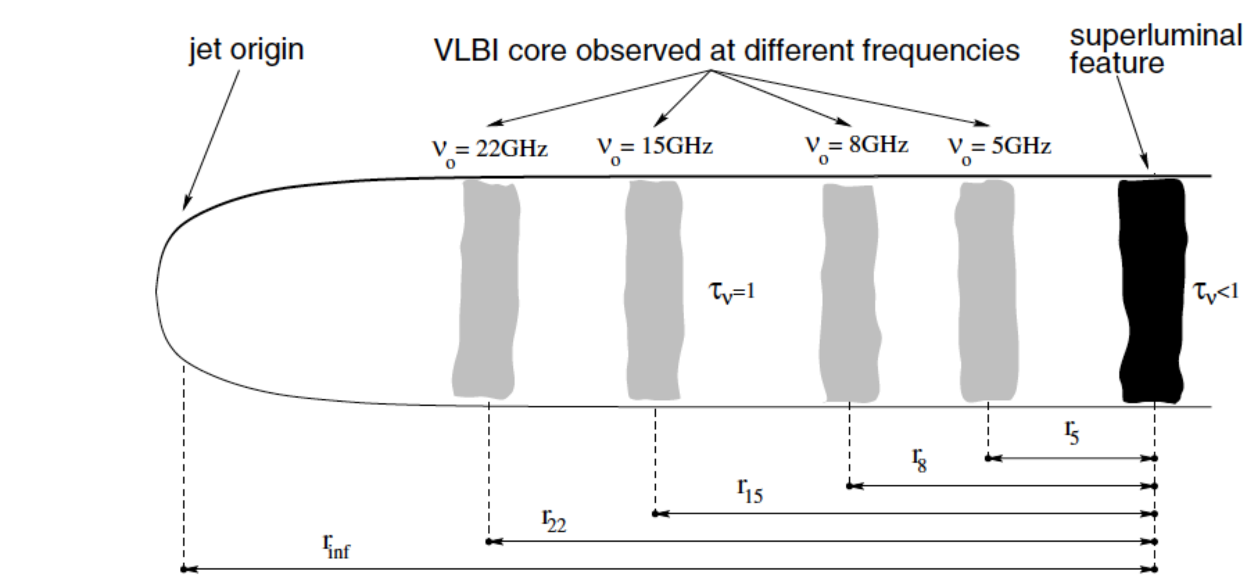
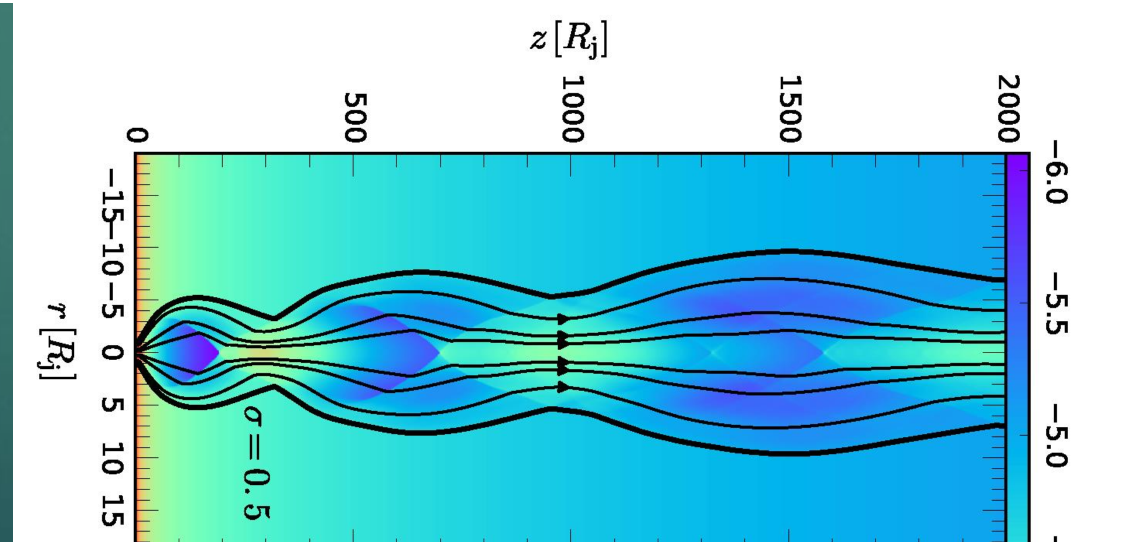
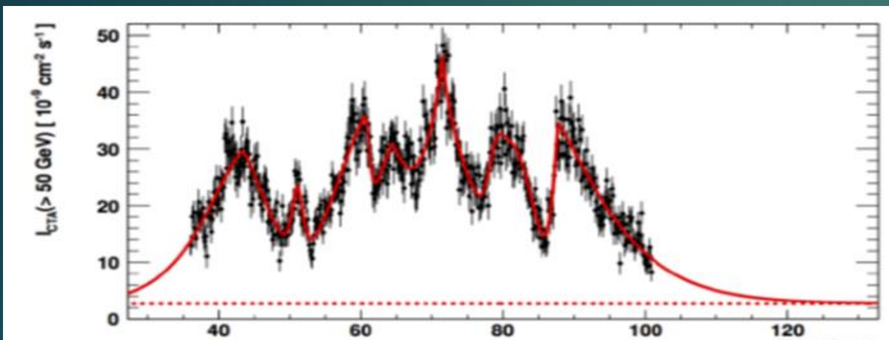


Fig. 1. A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

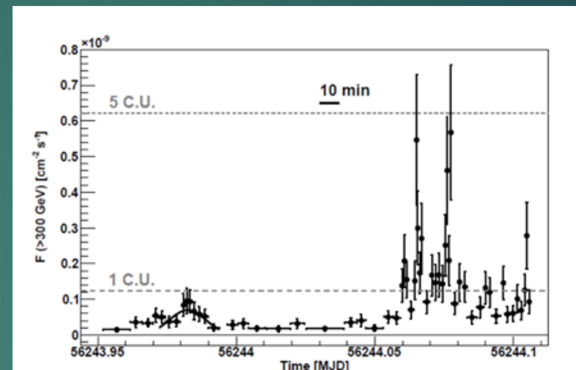


Fromm et al. 2017

What we see in radio bands is not all there is…



simulation J. Biteau
(H. Sol, AZ, C. Boisson et al. 2013)



Aleksić et al. 2014, *Science*

Variability in timescale of minutes at VHE gamma-rays cannot be explained with shock-in-jet model

Magnetic reconnection?

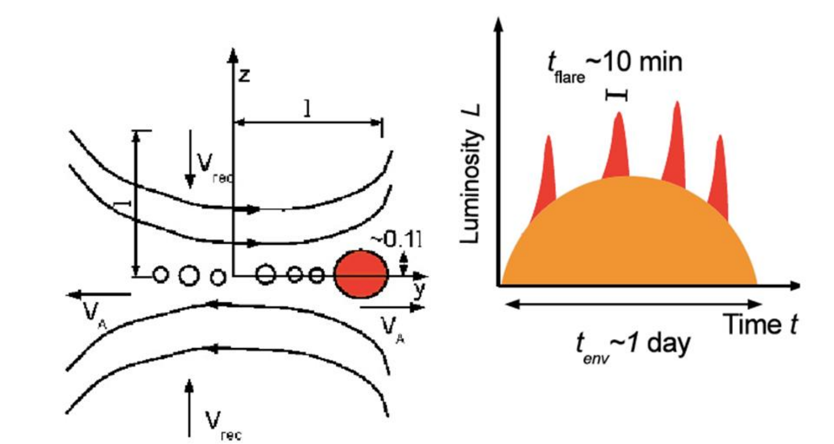


Fig. 14 *Left Panel*: Schematic representation of the geometry of reconnection process shown in a frame comoving with the jet. Magnetic field lines of opposite polarity annihilate at the $x - y$ plane with speed $v_{rec} = \beta_{in}c$. The reconnection layer fragments to a large number of plasmoids. Regularily, plasmoids undergo multiple mergers resulting in a "monster" plasmoid (shaded blob). *Right Panel*: Sketch of the emission from plasmoid-dominated reconnection. The reconnection proceeds on a global timescale $t_{rec} = l/\beta_{in}c$, powering $\sim$ 1day long flares (or envelope emission). Regularily, plasmoids grow to become "monster" plasmoids (shaded blob) giving rise to powerful, fast-evolving flares of duration $t_{flare} \sim$ 10 minutes. Several fast flares are expected from a single reconnection event.

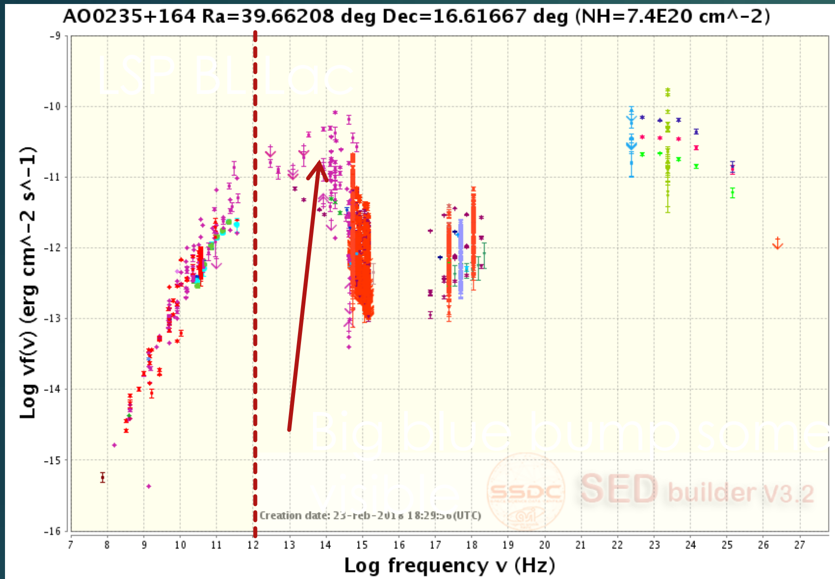
What we think we know about variability

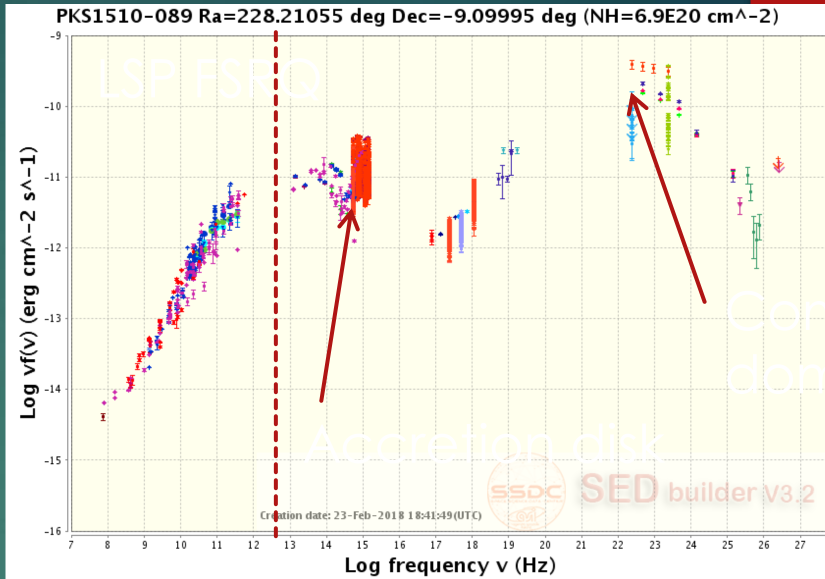
- It is there in all bands
- In radio band it probably has something to do with the emission features we see in the jet
- Emission features are likely to be shocks, but there are also standing shocks (recollimation shocks?), interacting shocks: *particle acceleration*
- Sometimes the variability in all bands have some similar patterns – common origin?
- The fastest variability in gamma-rays: extreme particle acceleration on very compact emission region (emission region much smaller than diameter of the jet)

DIFFERENT FLAVORS OF BLAZARS

What similarities / differences do you see in the SEDs below?

What similarities / differences do you see in the SEDs below?

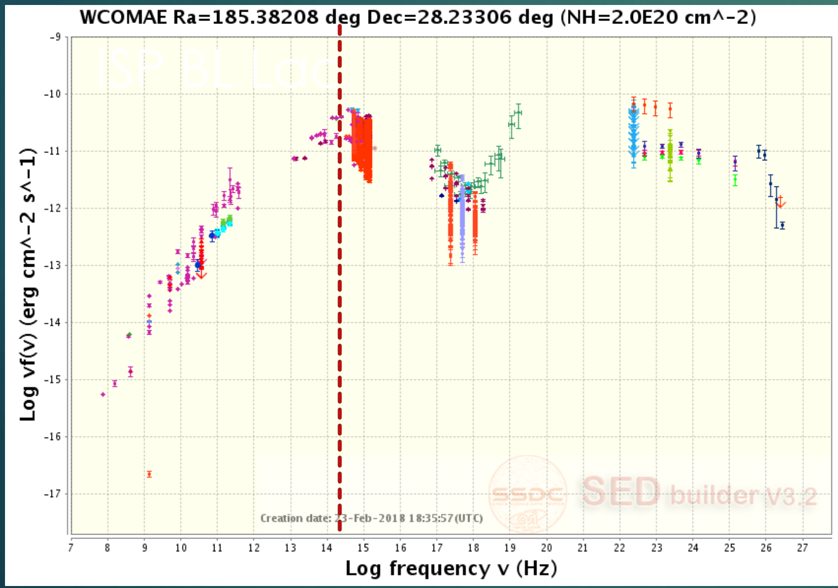




Big blue bump sometimes

Compton dominance

Peak frequency of the SED

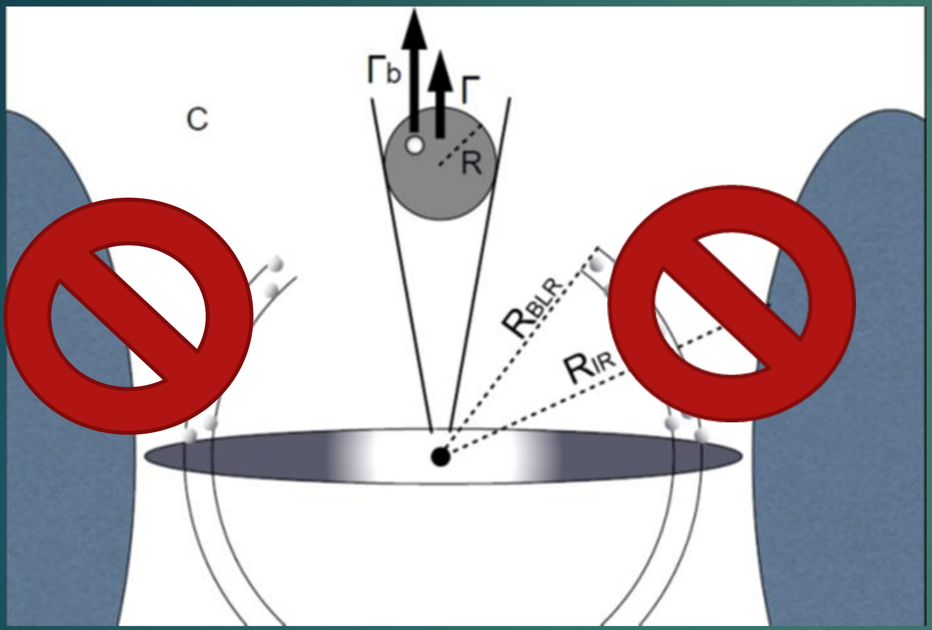


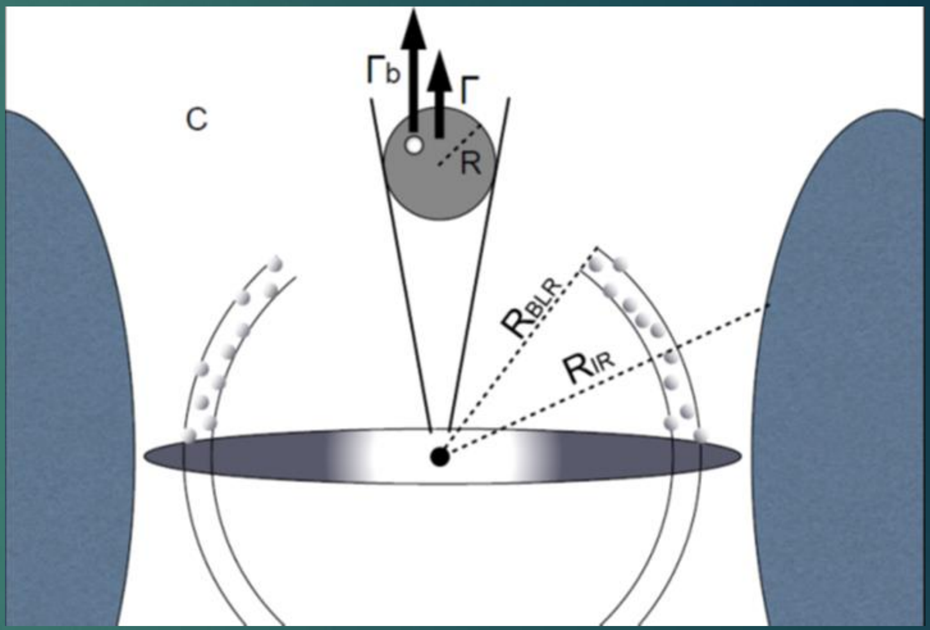
All have prominent gamma-ray emissio

LSP = Low synchrotron peaked, ISP = intermediate synchrotron peaked, HSP = h

$\nu_{peak} < 10^{14}$Hz $\quad 10^{14} < \nu_{peak} < 10^{15}$Hz $\quad \nu_{peak} >$

Why are they different

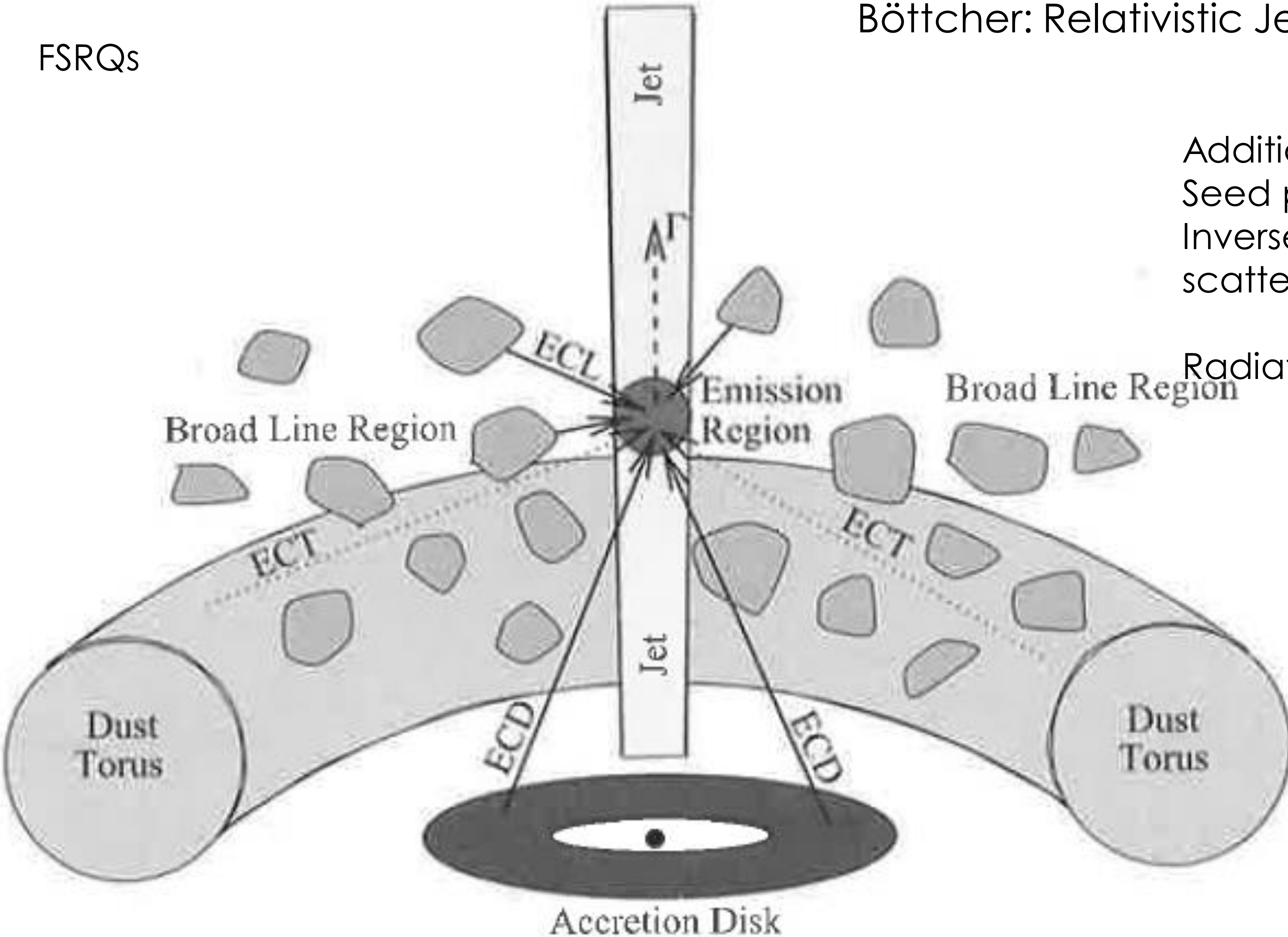




BL Lacs

FSRQs

FSRQs



Additional source of Seed photons for Inverse Compton scattering

Radiation=Cooling

Figure 8.4 Sketch of the central region of an active galaxy, illustrating the various external radiation fields that may be Compton scattered to form the high-energy emission observed from AGNs.

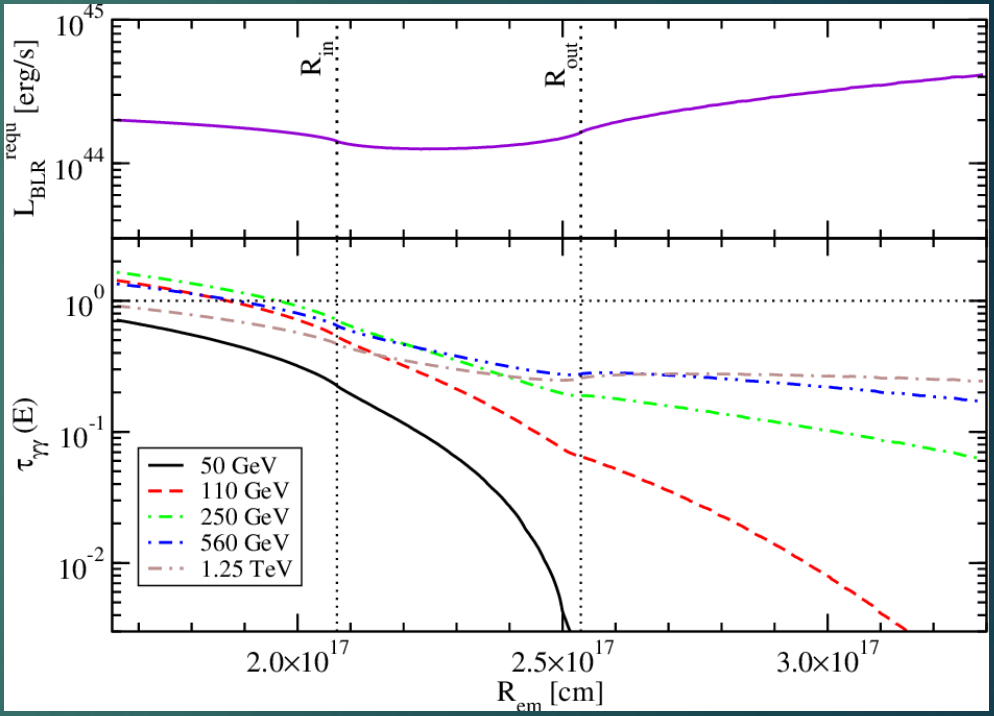
But it also absorbs

gamma+gamma ->
Electron+positron

The optical depth for the photon–photon absorption, $\tau(E)$, is calculated as (e.g. Liu & Bai 2006)

$$\tau(E) = \int_x^{R_{\rm BLR}} \int\int n(\nu, \Omega, l)\sigma_{\gamma\gamma}(E, \nu, \Omega)(1-\mu)\,{\rm d}\Omega\,{\rm d}\nu\,{\rm d}l, \quad (1)$$

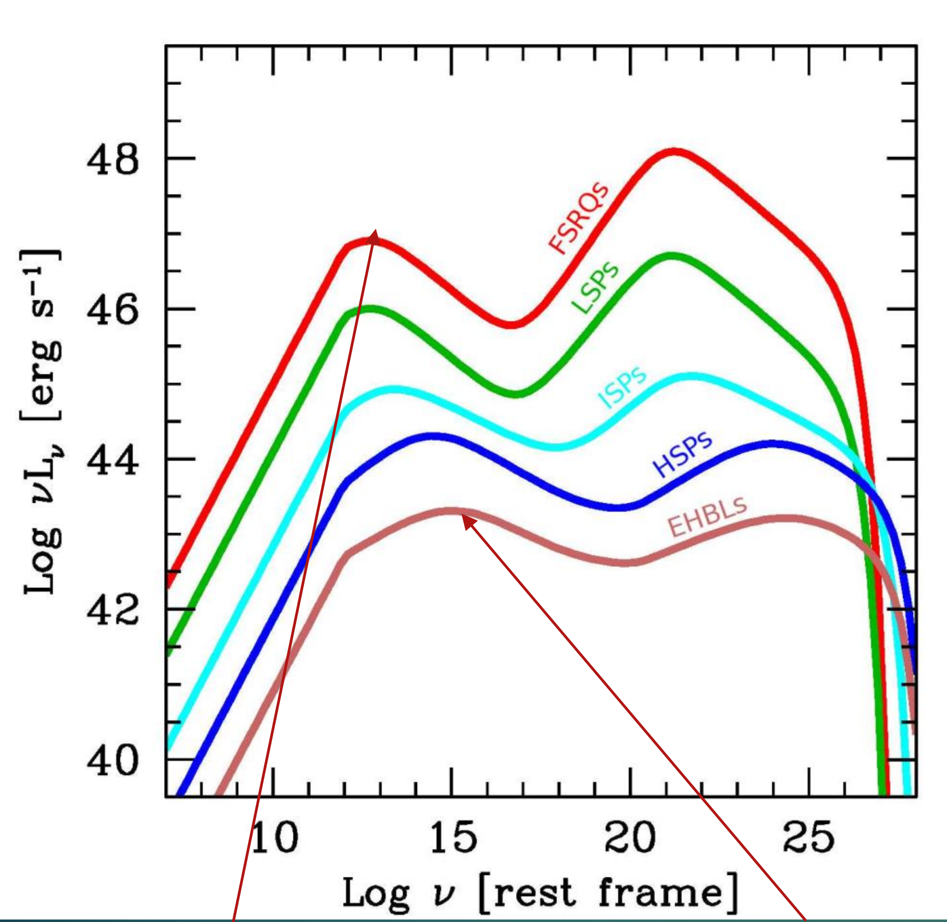
where E is the energy of the γ-rays, l is the distance of the photons from the black hole, $n(\nu, \Omega, l)$ is the number density of the radiation for solid angle at each location of the photon path, $\sigma_{\gamma\gamma}(E, \nu, \Omega)$ is the cross-section and $d\Omega = 2\pi d\mu$. Note that, given the characteristics of the cross-section, for a fixed geometry $\tau(E) \propto \nu n(\nu)$ with $\nu \propto 1/E$, i.e. the optical depth reflects the spectrum of the soft photon field (smeared by the cross-section).

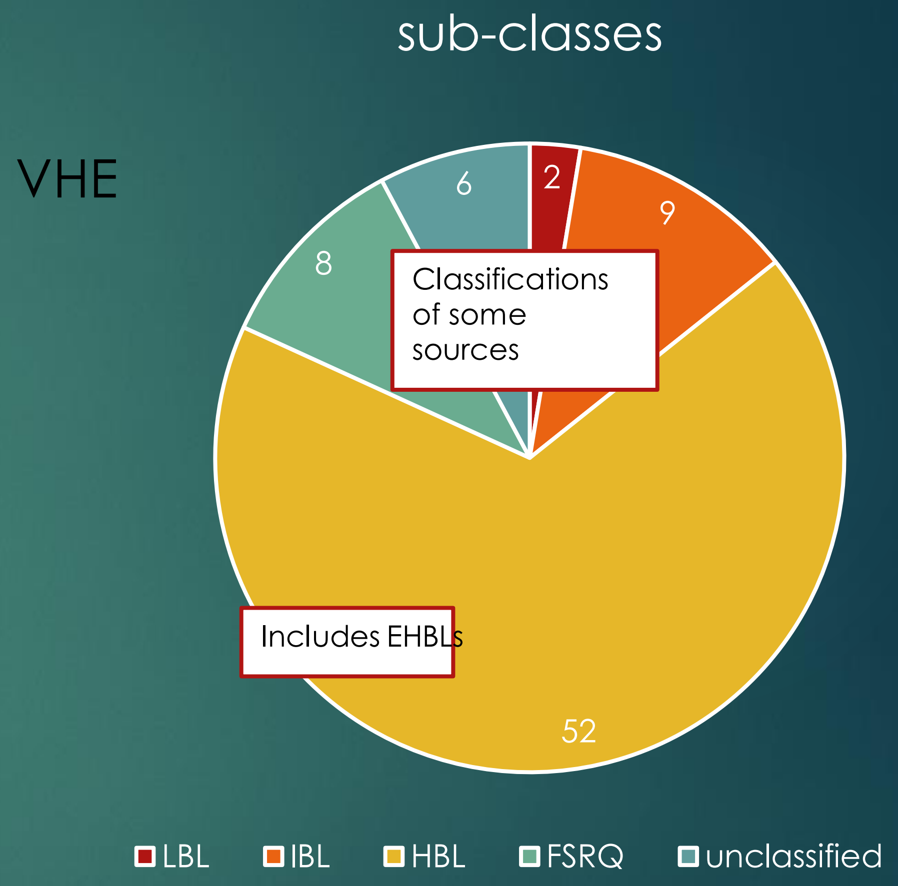


Which are more numerous sources of gamma-rays?

FSRQS OR BLLACS?

It depends…





FSRQs: most luminous

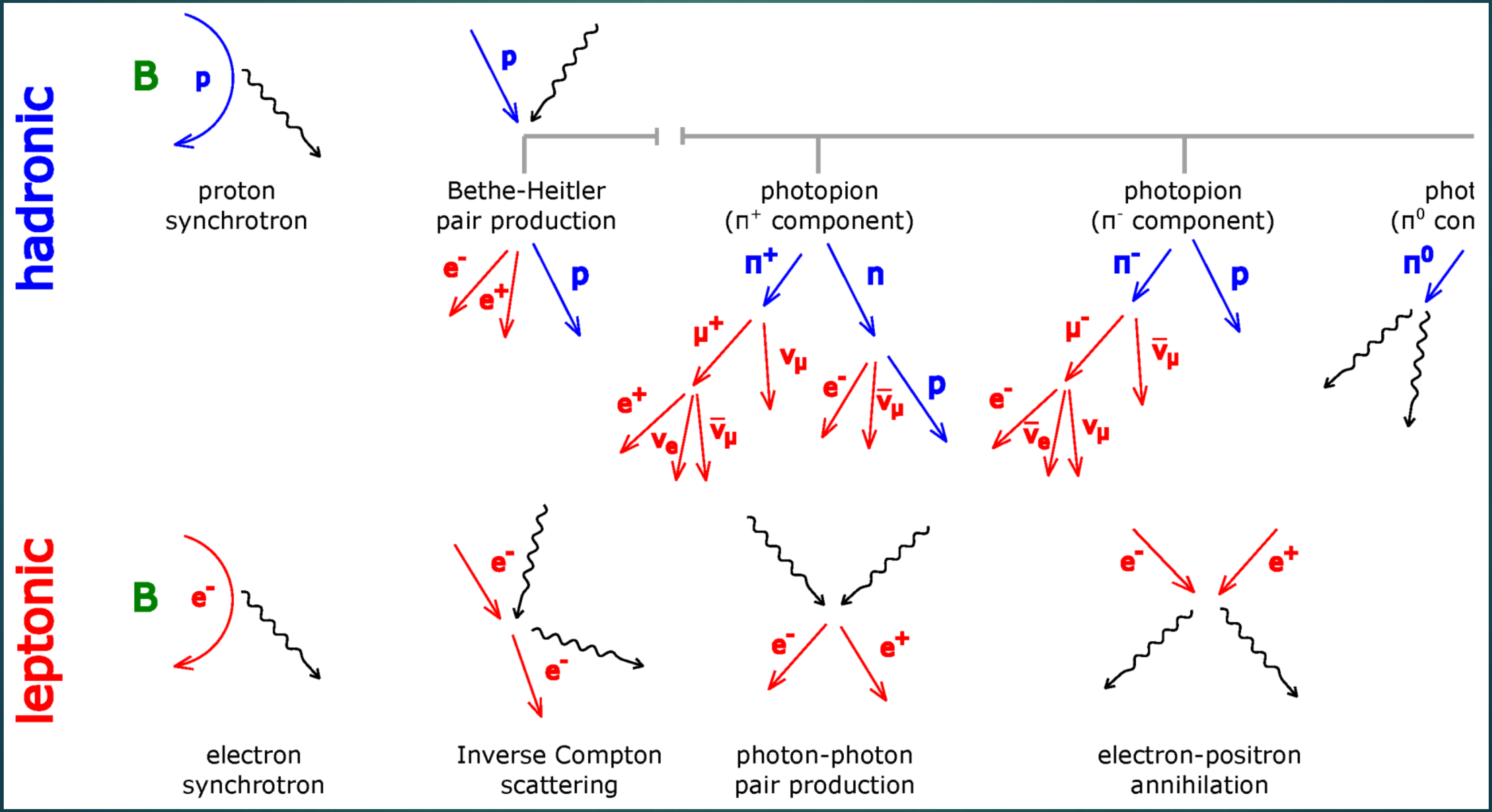
BL Lacs: higher synchrotron peak => higher IC peak

- HSPs most numerous objects
- Lower energies (Fermi) ~about equal

What about neutrinos? What are the best sources?

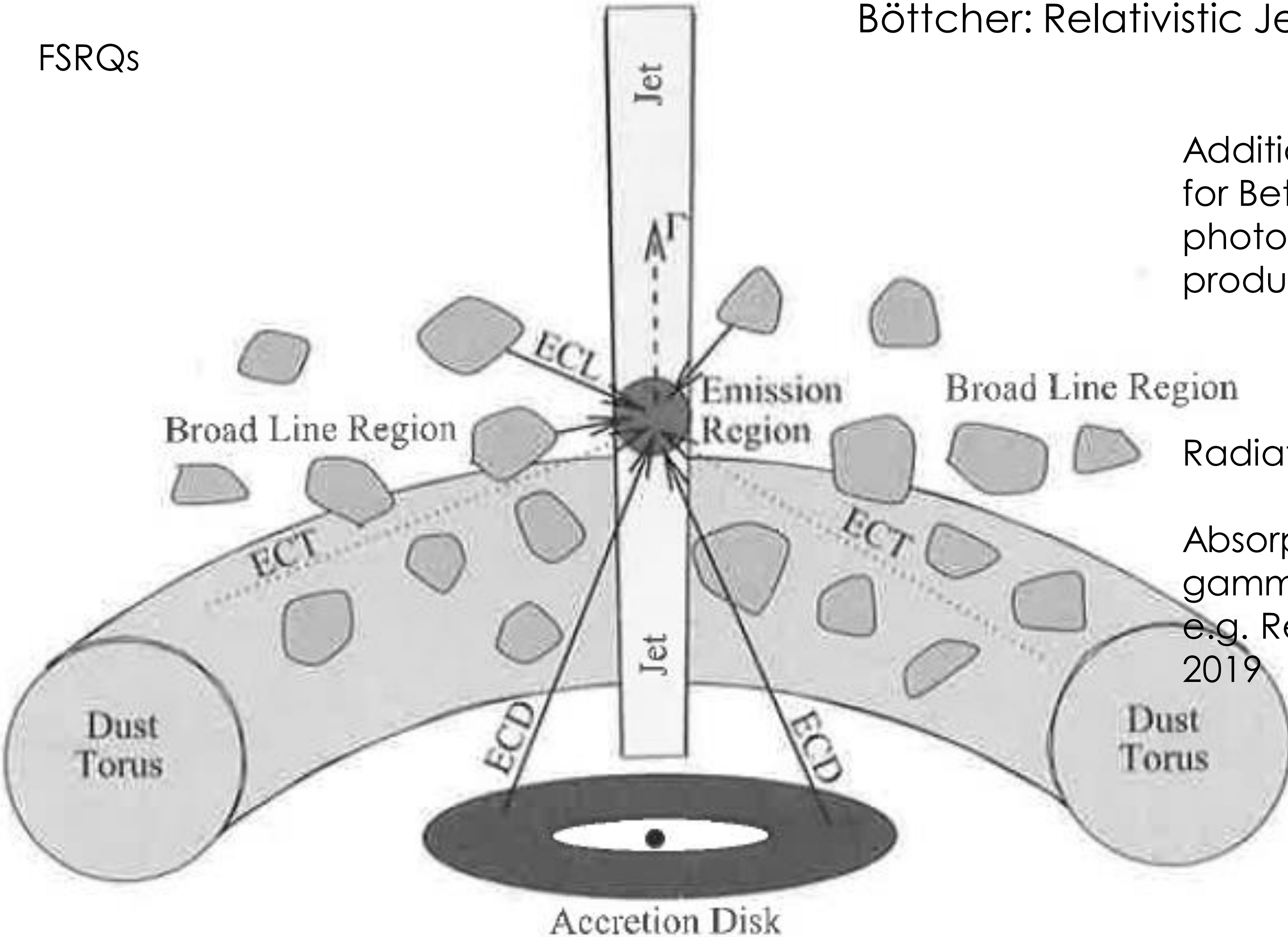
FSRQS OR BLLACS?

Reminder on what we need: protons and photons



Böttcher: Relativistic Jets from AGN

FSRQs



Additional photons for Bethe-Heitler or photopion production

Radiation=Cooling

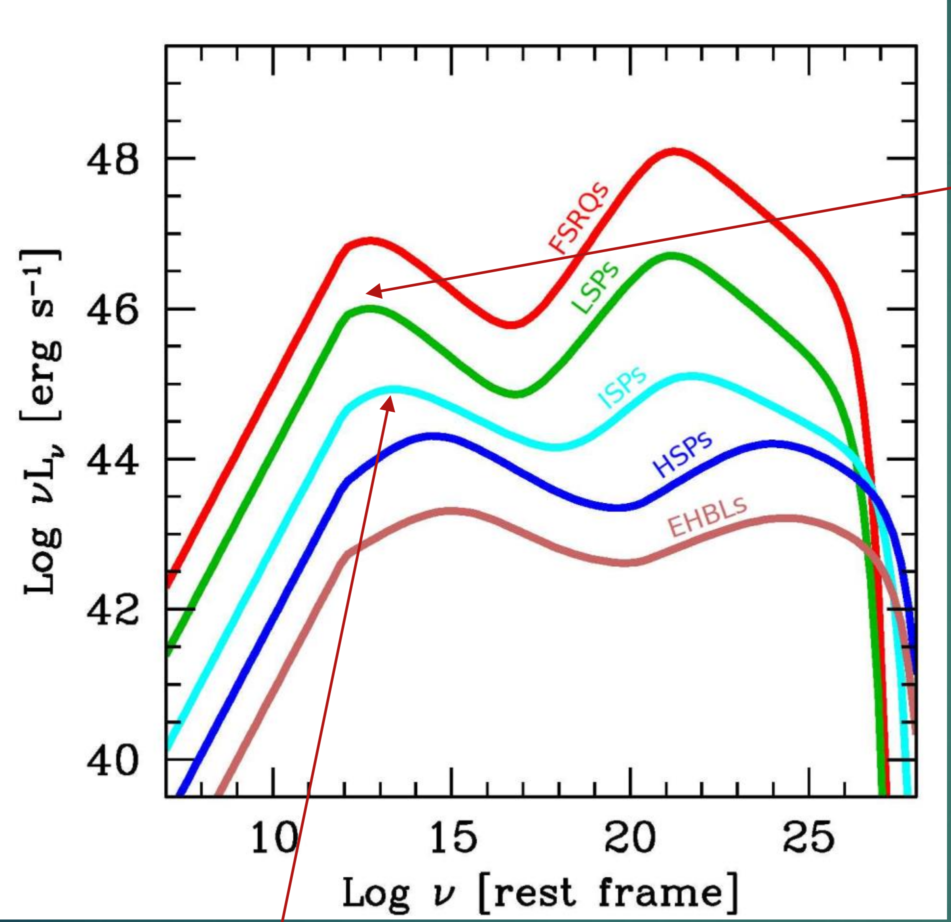
Absorption of gamma-rays (see e.g. Reimer et al. 2019

Figure 8.4 Sketch of the central region of an active galaxy, illustrating the various external radiation fields that may be Compton scattered to form the high-energy emission observed from AGNs.

What about neutrinos? What are the best sources?

FSRQS OR BLLACS?

Maybe just some weirdos?



There are also indications that radio brightness would have connection with neutrinos (Plavin et al. 2020) or that bright long-lasting radio flares would be connected to neutrinos (Plavin et al. 2020,2021, Hovatta et al. 2021, Kouch et al. 2024), FSRQs+LSPs favored?

TXS0506+056 is maybe ISP? But maybe with some hidden seed photon fields (called Masquering BL Lacs by Padovani)