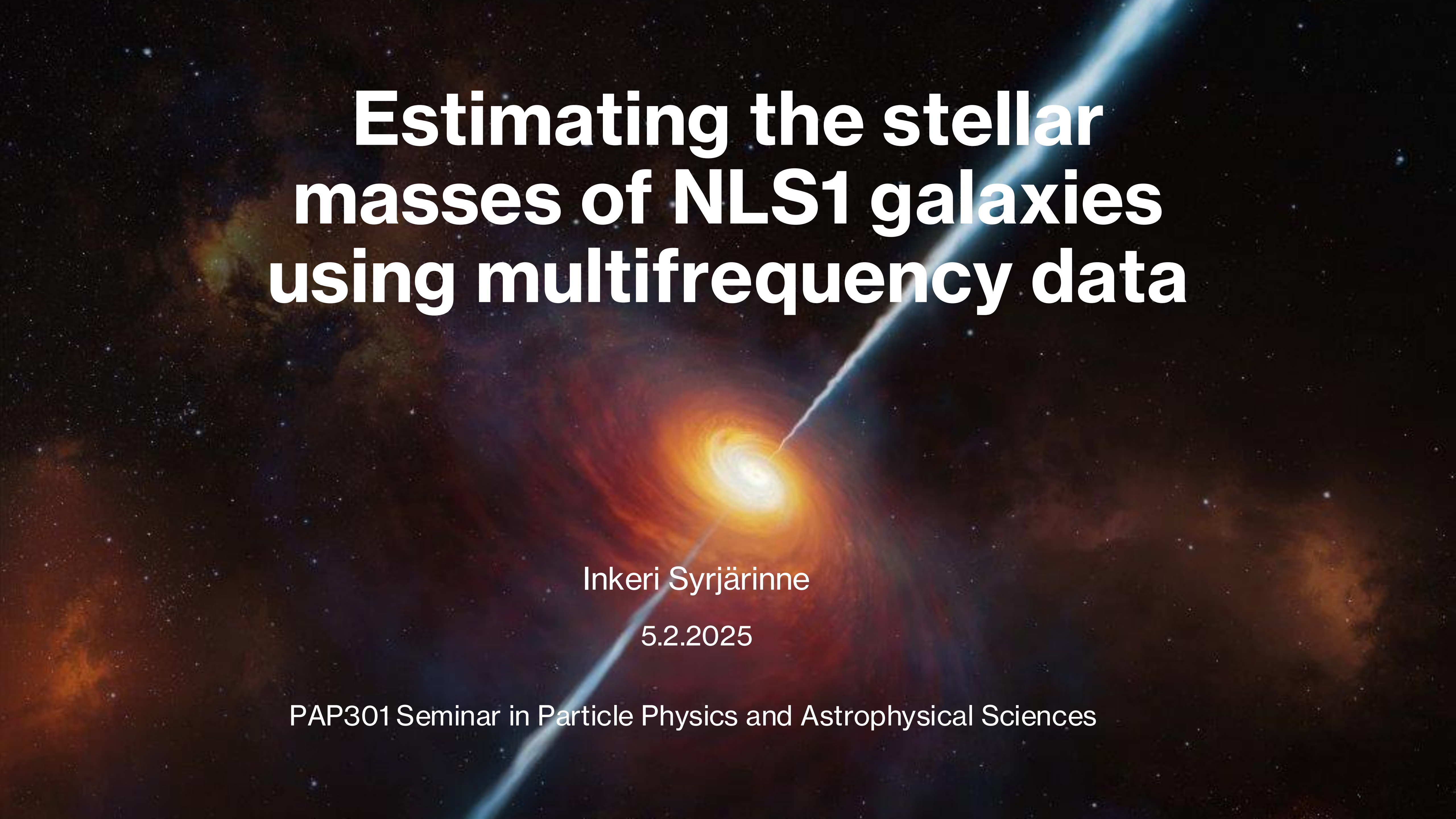

Estimating the stellar masses of NLS1 galaxies using multifrequency data

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PAP301 Seminar in Particle Physics and Astrophysical Sciences

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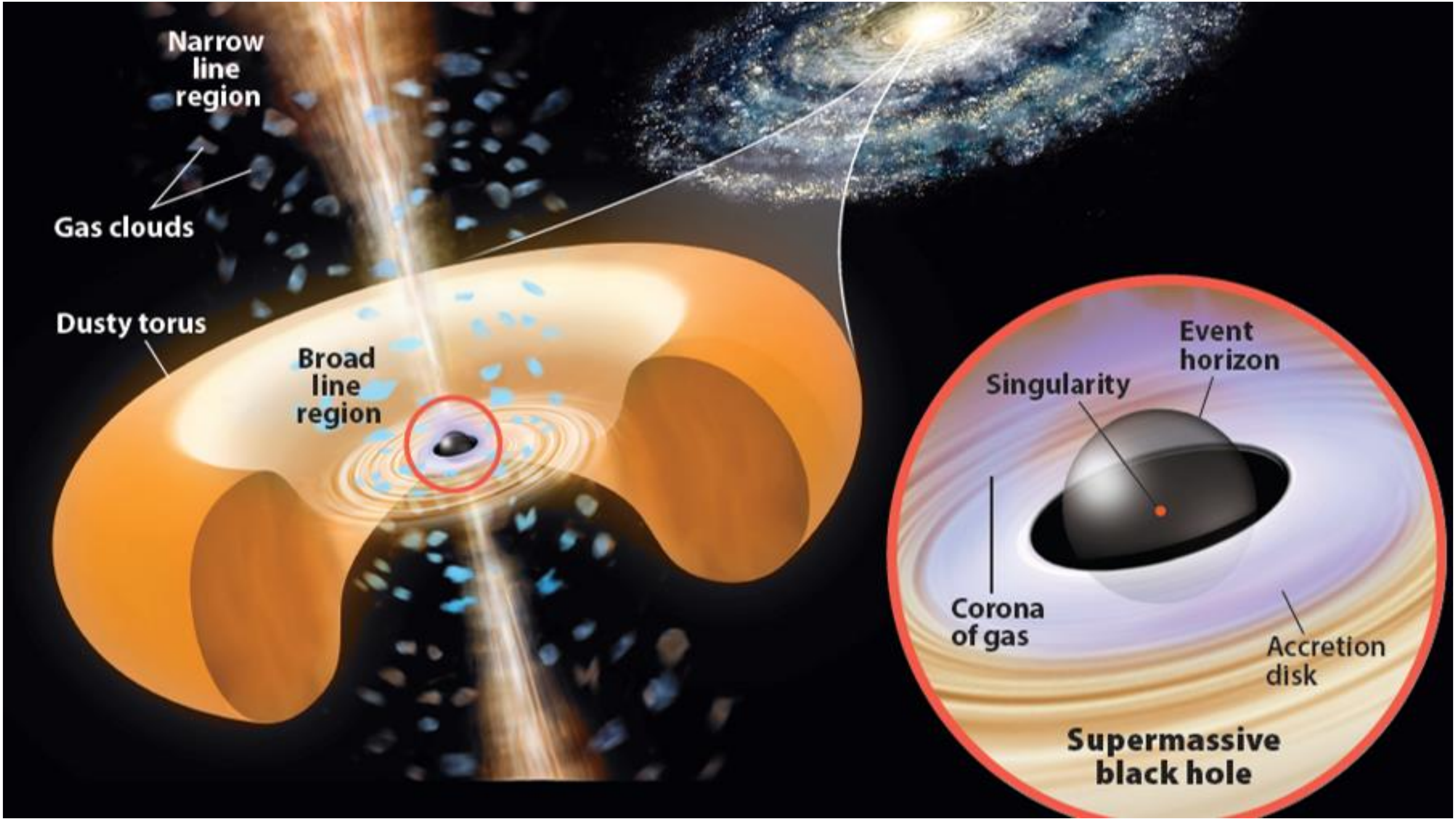
Active galactic nuclei (AGN)

- Galaxies with active supermassive black holes (SMBHs)
- Typical characteristics:
  - Very high luminosities
  - Broad emission lines
  - Variability
  - Jets
- Categorisation: blazars, quasars, radio galaxies and Seyfert galaxies

Structure of the AGN

1. **Supermassive black hole**
2. **Accretion disk**
   - Matter orbiting the black hole
3. **Broad-line region (BLR)**
   - Right outside the accretion disk
   - Matter very hot and fast -> broad emission lines due to Doppler broadening
4. **Dusty torus**
   - A donut-shaped dust cloud that absorbs most of BLR emission
5. **Narrow-line region (NLR)**
   - Outside the torus, matter colder and less dense -> narrow emission lines


Narrow line region
Gas clouds
Dusty torus
Broad line region
Event horizon
Singularity
Corona of gas
Accretion disk
Supermassive black hole

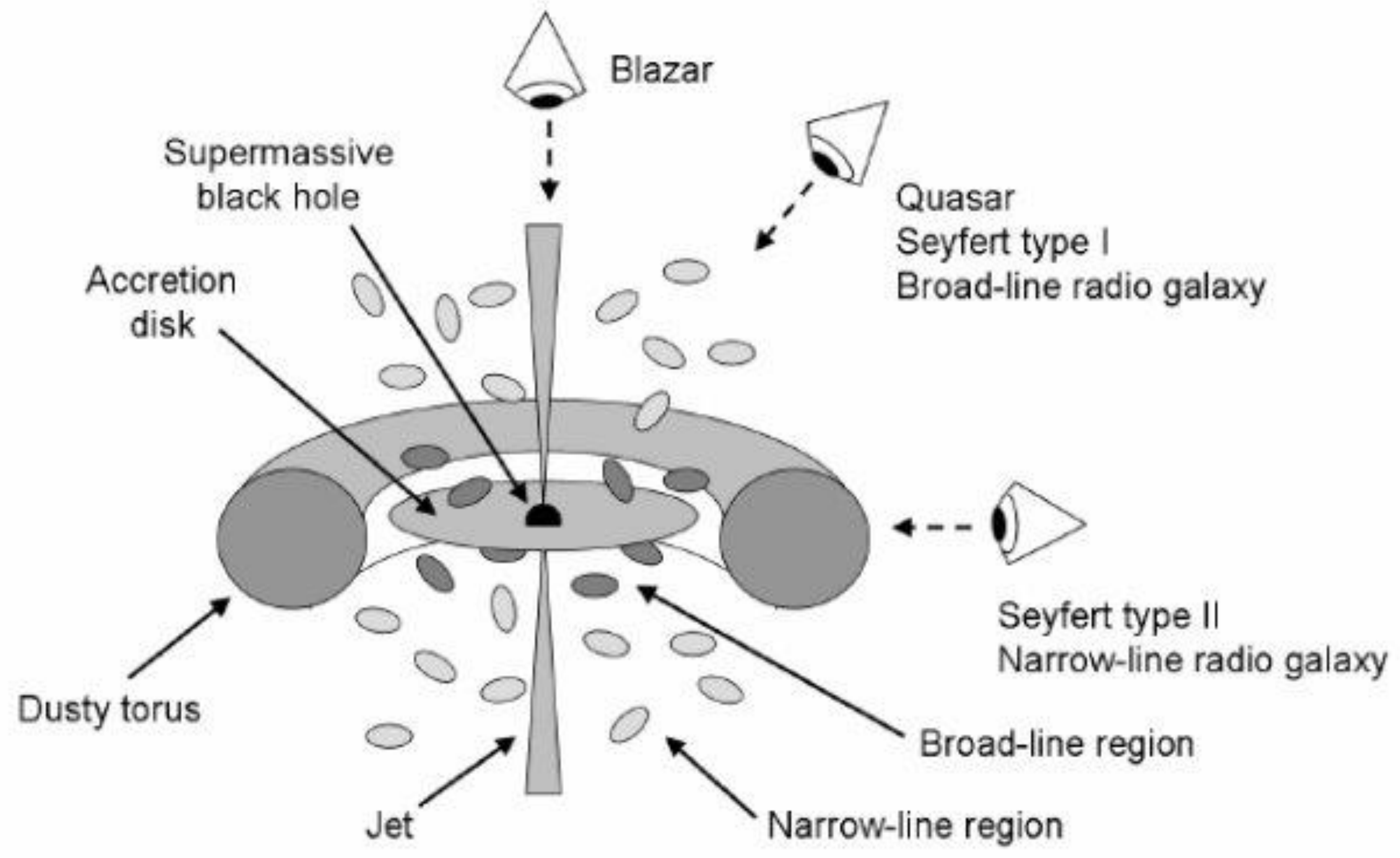
Categorisation

- **Blazars**
  - Seen from small angles
  - Usually massive ellipticals

- **Quasars**
  - Seen from slightly larger angles
  - Usually massive ellipticals

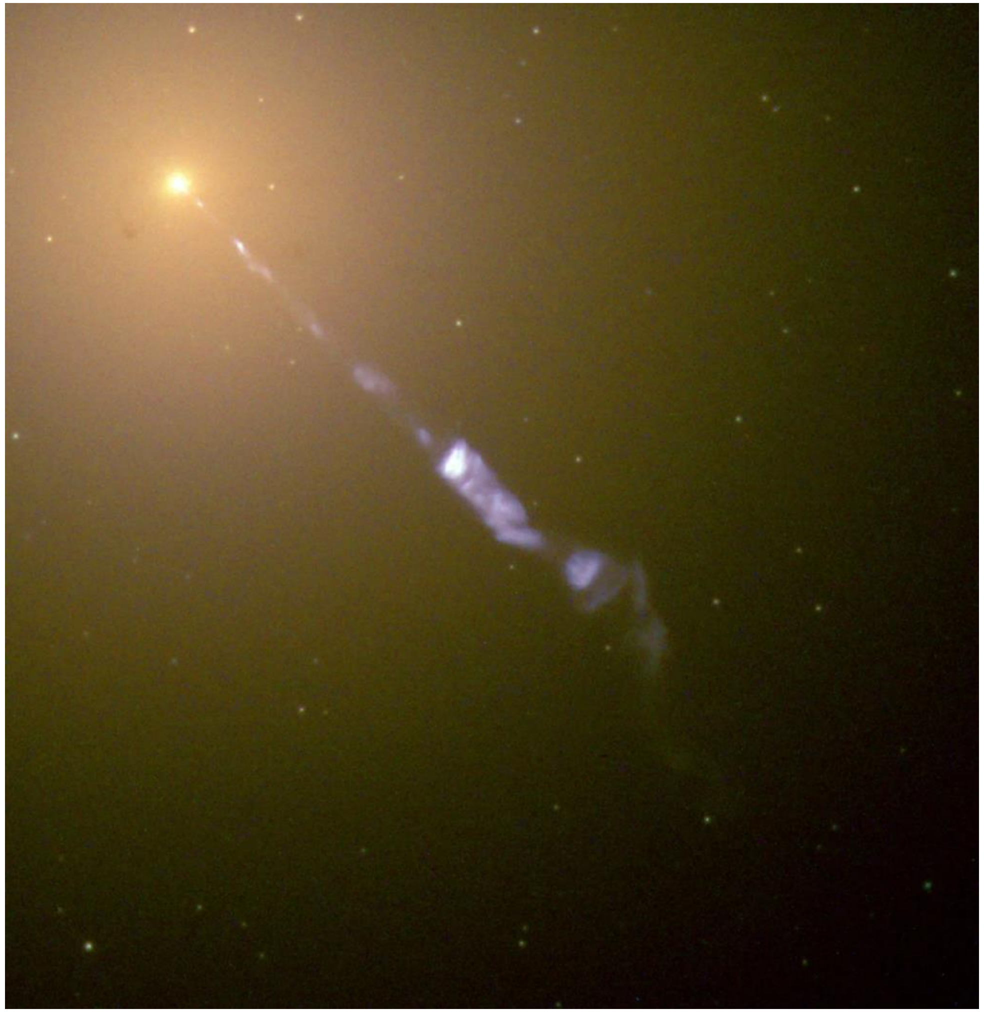
- **Radio galaxies**
  - Seen from large angles (usually)

- **Seyfert galaxies**
  - Type 1: seen from small angles
  - Type 2: seen from large angles
  - Spiral galaxies



Jets in AGN

- A result of interaction between the magnetic field and matter in the accretion disk
  - Not completely understood but magnetic reconnection plays a role
- An AGN can have one or two jets, sizes vary from parsecs to megaparsecs
- Some jets are relativistic (move close to the speed of light)
- The old jet paradigm: only massive elliptical AGN can have relativistic jets
  - This has been proven wrong

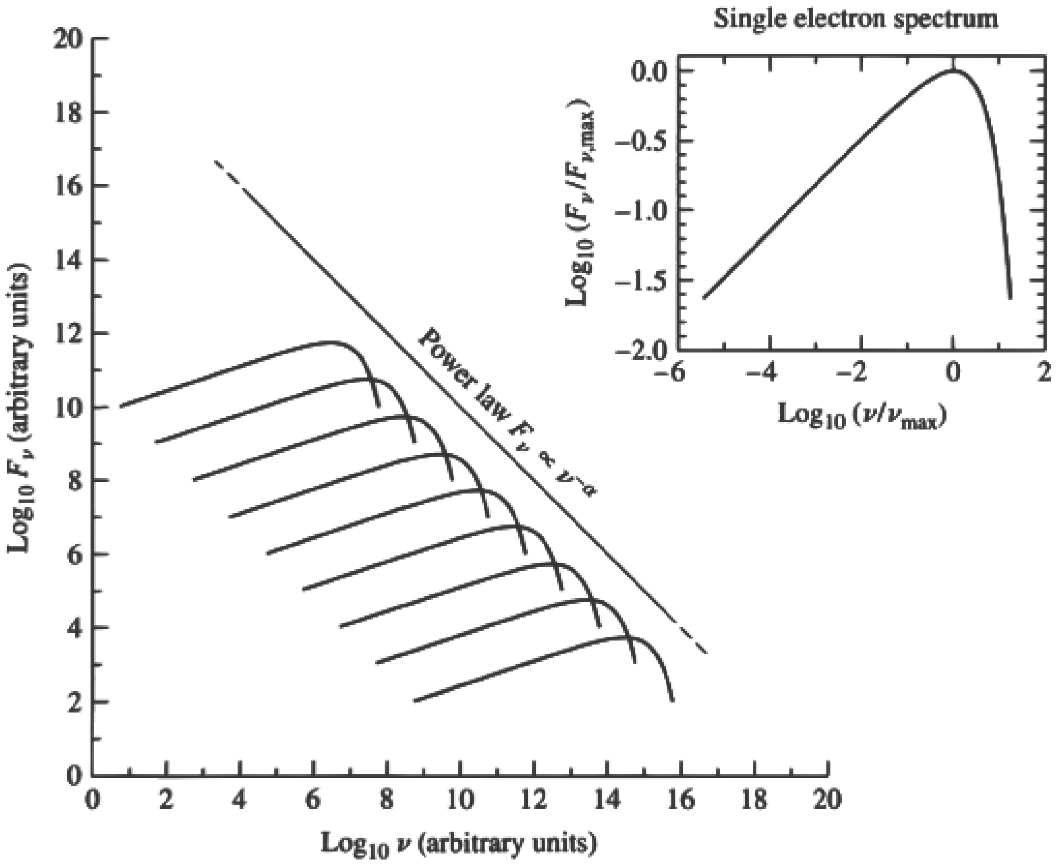


Jet in M87 (NASA, ESA and the Hubble Heritage Team)

Detecting jets: two emission mechanisms

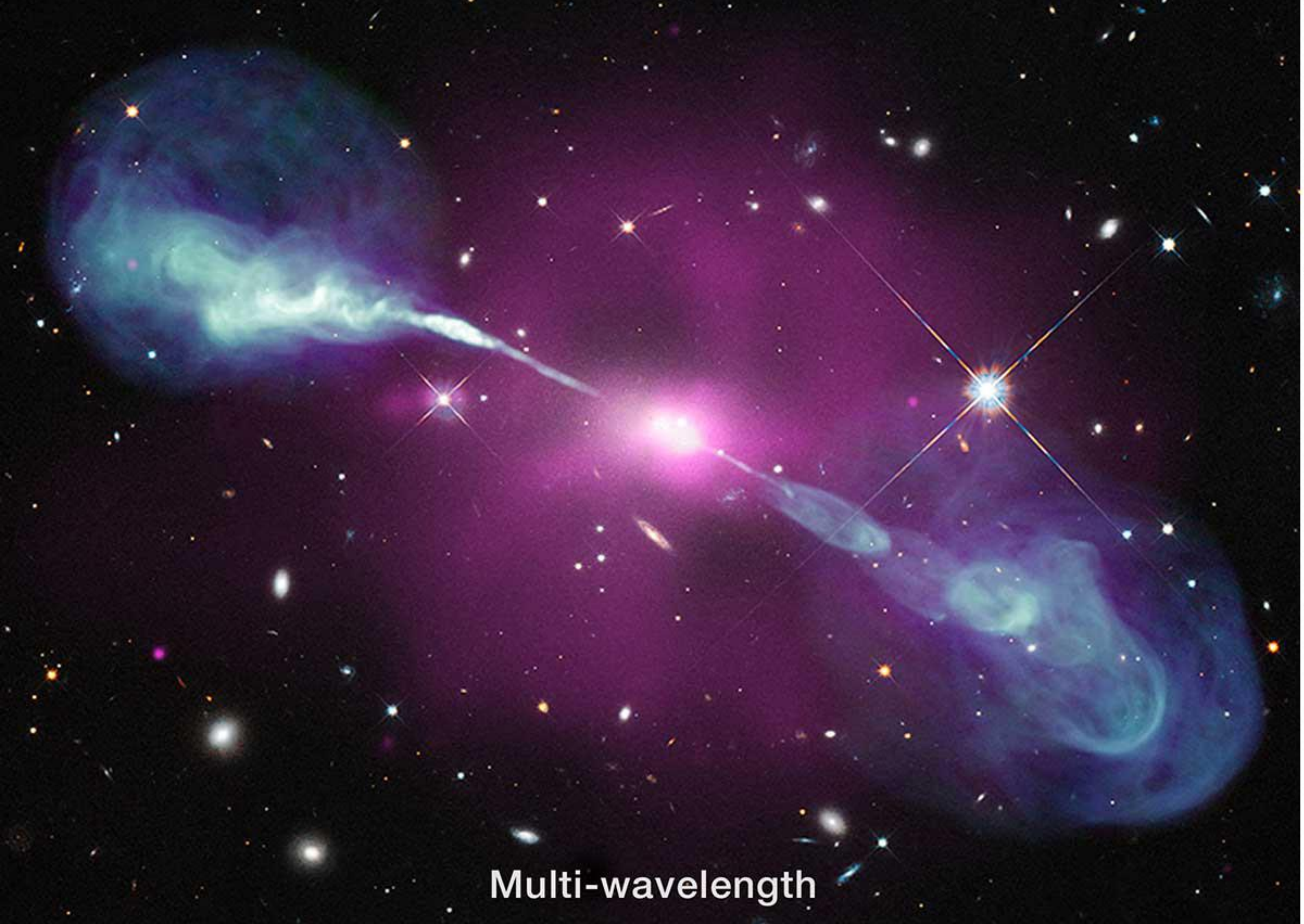
- **Synchrotron radiation**
  - Charged particles in the magnetic field of a relativistic jet
  - Produces non-thermal radio emission and the very recognisable synchrotron spectrum

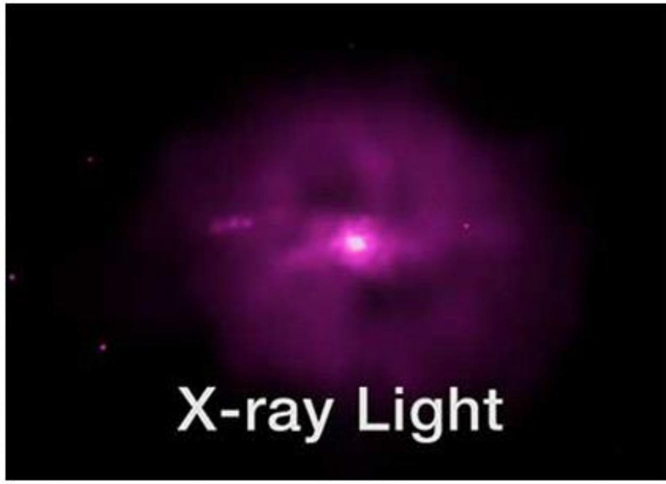
- **Inverse Compton process**
  - Relativistic electrons collide with photons, increasing the photons' energy
  - Photons move up to gamma-ray frequencies
  - Only happens in very powerful jets

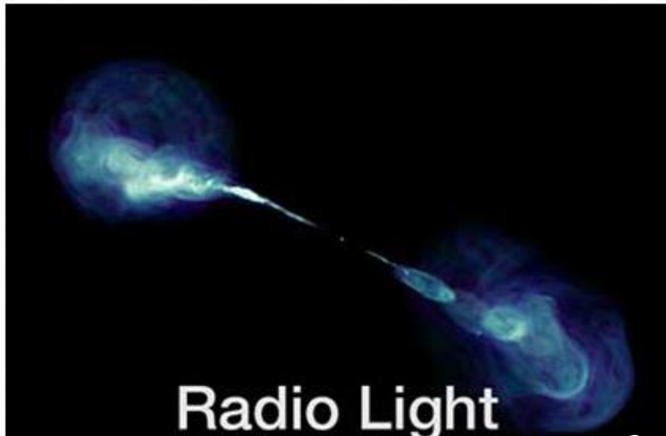


The synchrotron spectrum (Carroll and Ostlie 2017)

X-ray: NASA/CXC/SAO; visual: NASA/STScI; radio: NSF/NRAO/VLA.



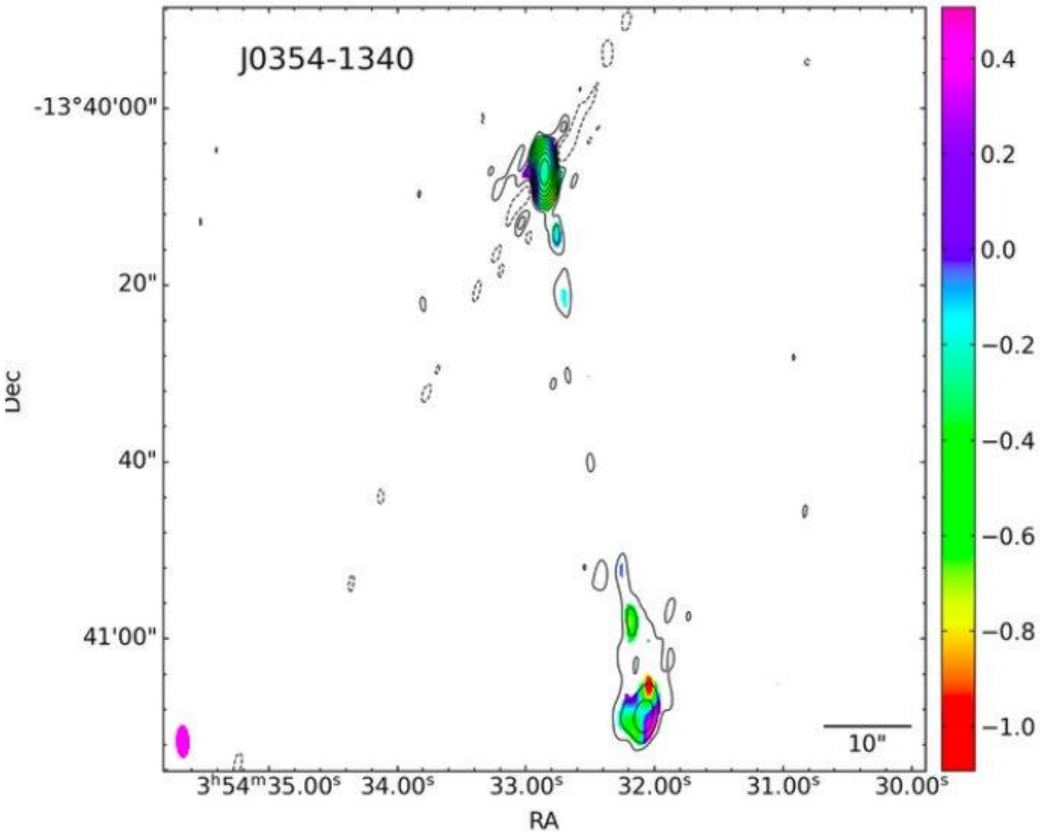




Narrow-line Seyfert 1 galaxies (NLS1s)

- Type 1 Seyfert galaxies but their broad line region emission lines are narrow
- SMBH mass only around 10^6-10^7 M_sun
- Disk-like host galaxies
- Most probably young, unevolved AGN
- Against all expectations gamma-ray emission has been observed in some NLS1s
  - This means they can host relativistic jets!
  - Jet paradigm debunked

NLS1 properties



J0354-1340 (Vietri et al. 2022)

- Only 15 % have been observed to emit at radio frequencies
  - Jets are even more rare
- However, no major physical differences between jetted and non-jetted NLS1s
- Also very high variability (time scales only a few days) which makes studying them harder
  - An on-going NLS1 detection campaign has been operating at the Metsähovi Radio Observatory for more than 15 years
- We want to understand what leads to the formation of a powerful jet

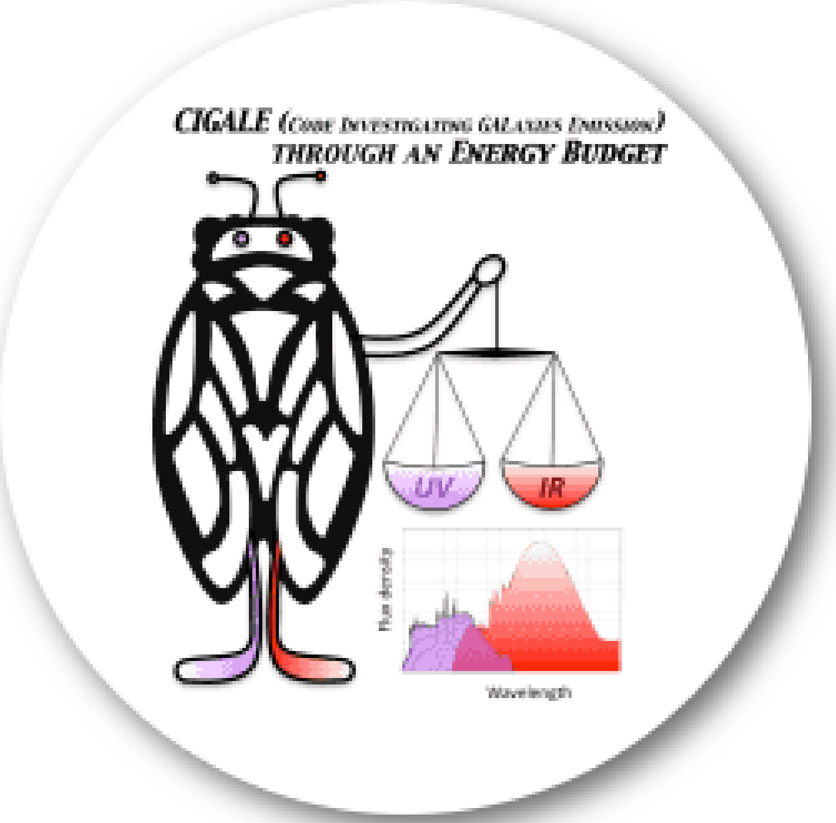
Stellar masses of NLS1s

- Stellar mass is the total mass of stars within a galaxy
- Only a few stellar mass estimates of NLS1s exist so far
- Knowing the stellar masses help with understanding the properties of the host galaxies of NLS1s
- Maybe there are differences between non-jetted and jetted NLS1s? Or differences between radio detected vs non-radio detected sources?

- One way to estimate the stellar mass is by using the spectral energy distribution (SED) of a galaxy

CIGALE

- A python Code Investigating GAlaxy Emission (Noll et al. 2009, Boquien et al. 2019)
- Calculates SEDs of galaxies based on galaxy emission models
- Produces modelled SEDs and compares them with observed SEDs through Bayesian statistical analysis
- Also estimates physical quantities, such as stellar mass



Data collection

- Initial sample of 4000 NLS1s
- This was filtered only to galaxies with far-infrared observations
  - -> 175 galaxies left
- Far-infrared region arises from star formation processes
  - Optical and UV radiation absorbed by dust clouds and re-emitted in far-infrared
- After this, I collected multifrequency observations for the remaining sources

Observational data

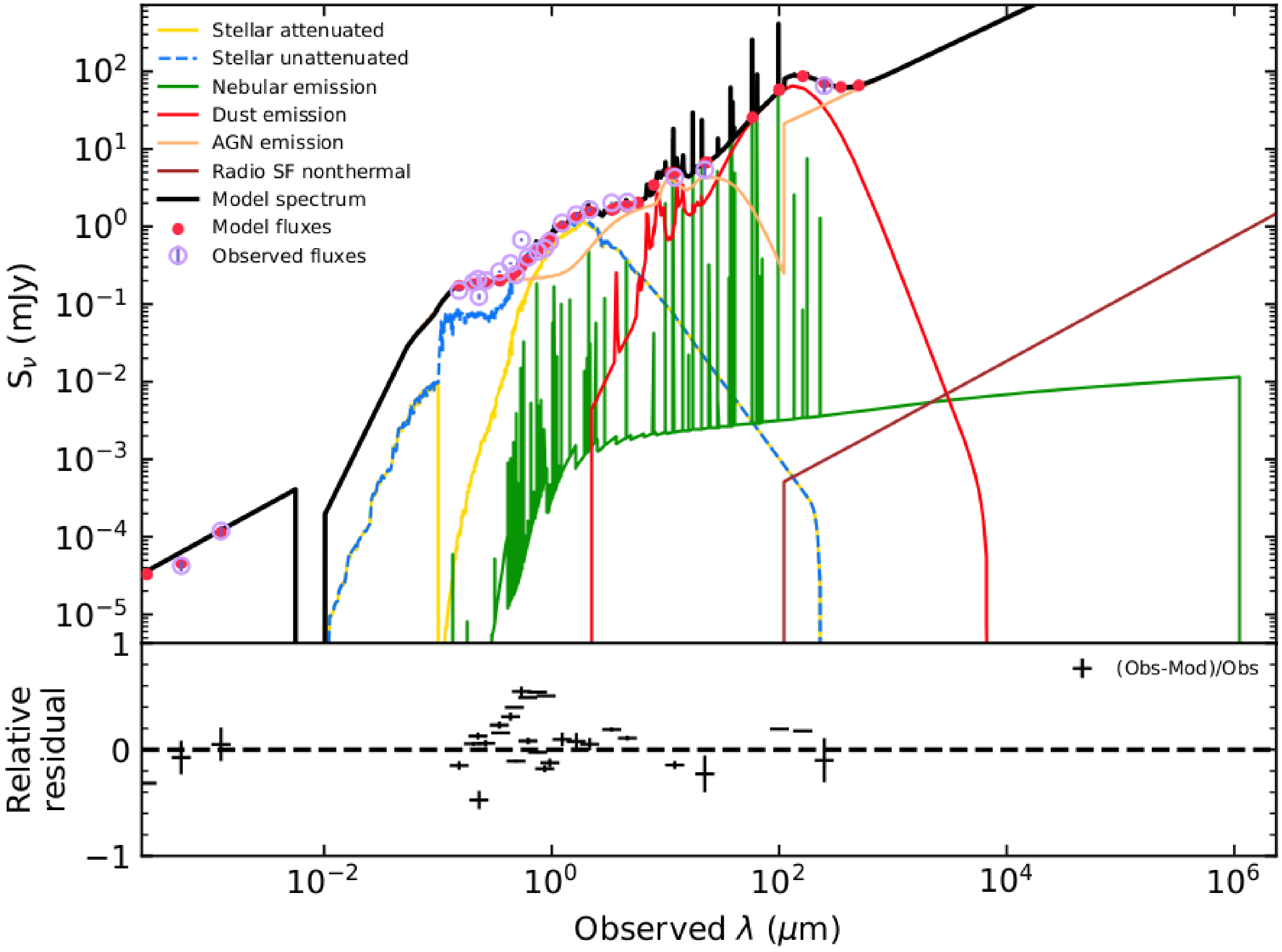
Instrument/survey	Wavelength region	Amount of observations
Herschel	Far-IR	137
IRAS	Far-IR	32
2MASS	Near-IR	117
WISE	Near-IR, mid-IR	169
Spitzer IRAC	Near-IR, mid-IR	35
SDSS	Optical	170
PanSTARRS	Optical	169
Swift UVOT	UV, optical	11
VLASS	Radio	36
LOFAR	Radio	63
Swift-XRT	X-Ray	11

Fitting process

- CIGALE produces best-fit models that are created based on parameters and modules chosen by the user
- Because some sources use different modules, I had to divide my sources into 3 groups:
    1. Sources with no radio and x-ray data
    2. Sources with also radio data
    3. Sources with radio- and x-ray data
- These groups were run separately
- Although this was done for practical reasons, comparing the results for different groups proved to be interesting

Module	Parameter	Values	Description
sfhdelayed	Age main	200,500,700,1000,2000,3000,4000,5000 Myr	Stellar Age
	τ_{main}	1500,2000,4000,5000,7000,10000,12000 Myr	E-folding time of the main stellar population
	Age burst	20,100 Myr	Age of the late burst
	τ_{burst}	20,50,100 Myr	E-folding time of the late burst
	f_{burst}	0.0,0.01,0.015,0.02,0.05	Mass fraction of the late burst
bc03	IMF	1 (Chabrier)	Initial mass function
	Z	0.02	Metallicity
nebular	log U	-2.0	Ionisation parameter
dustatt_modified_ starburst	E(B-V) lines	0.05,0.3,0.5,1.1	Colour excess of the nebular lines
	δ	-0.6,-0.2,0.0	Power law slope
dale2014	α	0.5,1.5,3.0	Alpha slope
	fracAGN	0.0	AGN fraction
skirtor2016	i	30,70	Inclination
	fracAGN	0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,0.99	AGN fraction
	E(B-V)	0.0,0.2,0.4	Exctinction in polar direction
radio	qir_sf	2.4,2.6	Value of the FIR/radio correlation coefficient for SF
	R_AGN	0,10,100,(1000)	Radio-loudness
x-ray	alpha_ox	-1.9, -1.7, -1.5, -1.3, -1.2, -1.1	

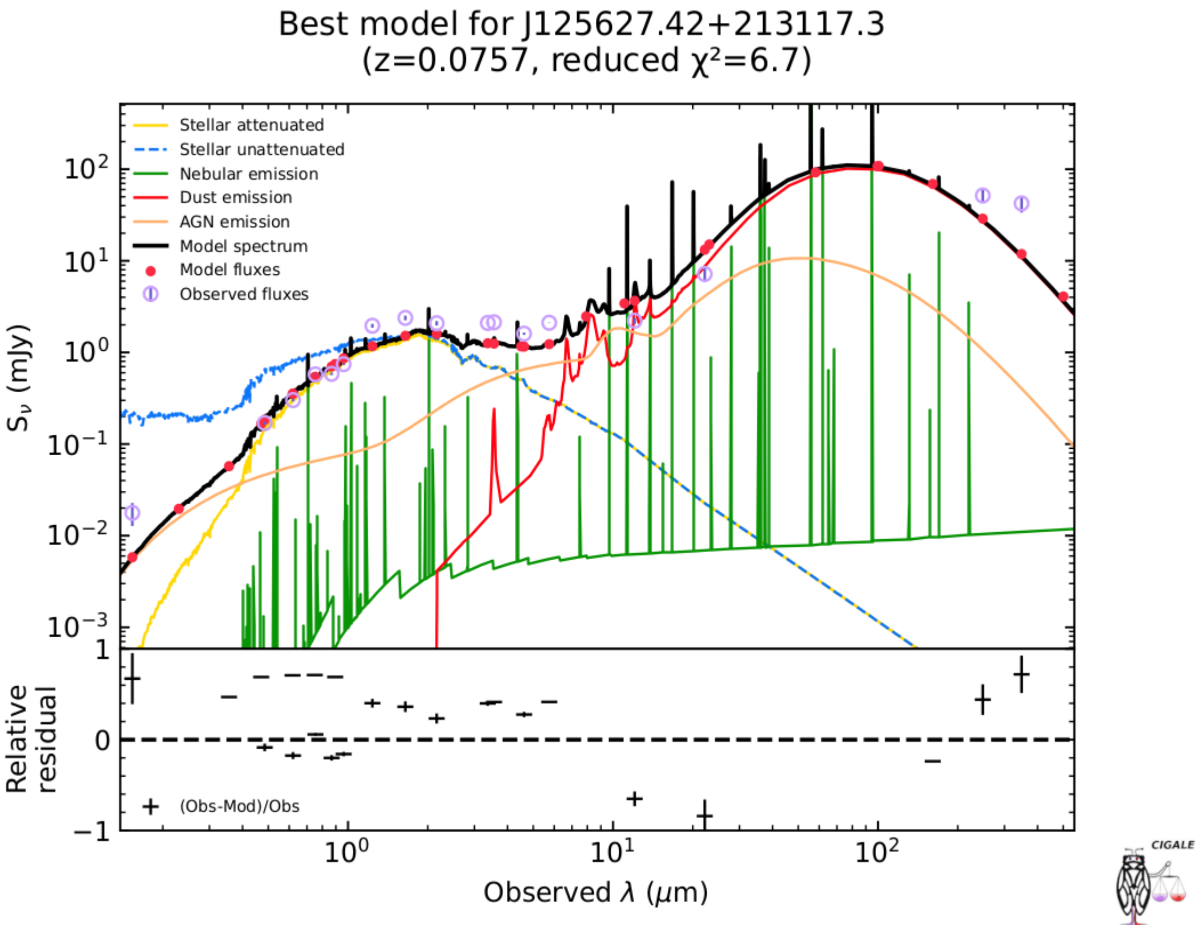
Best model for J123113.12+120307.2
(z=0.116, reduced χ^2=2.3)

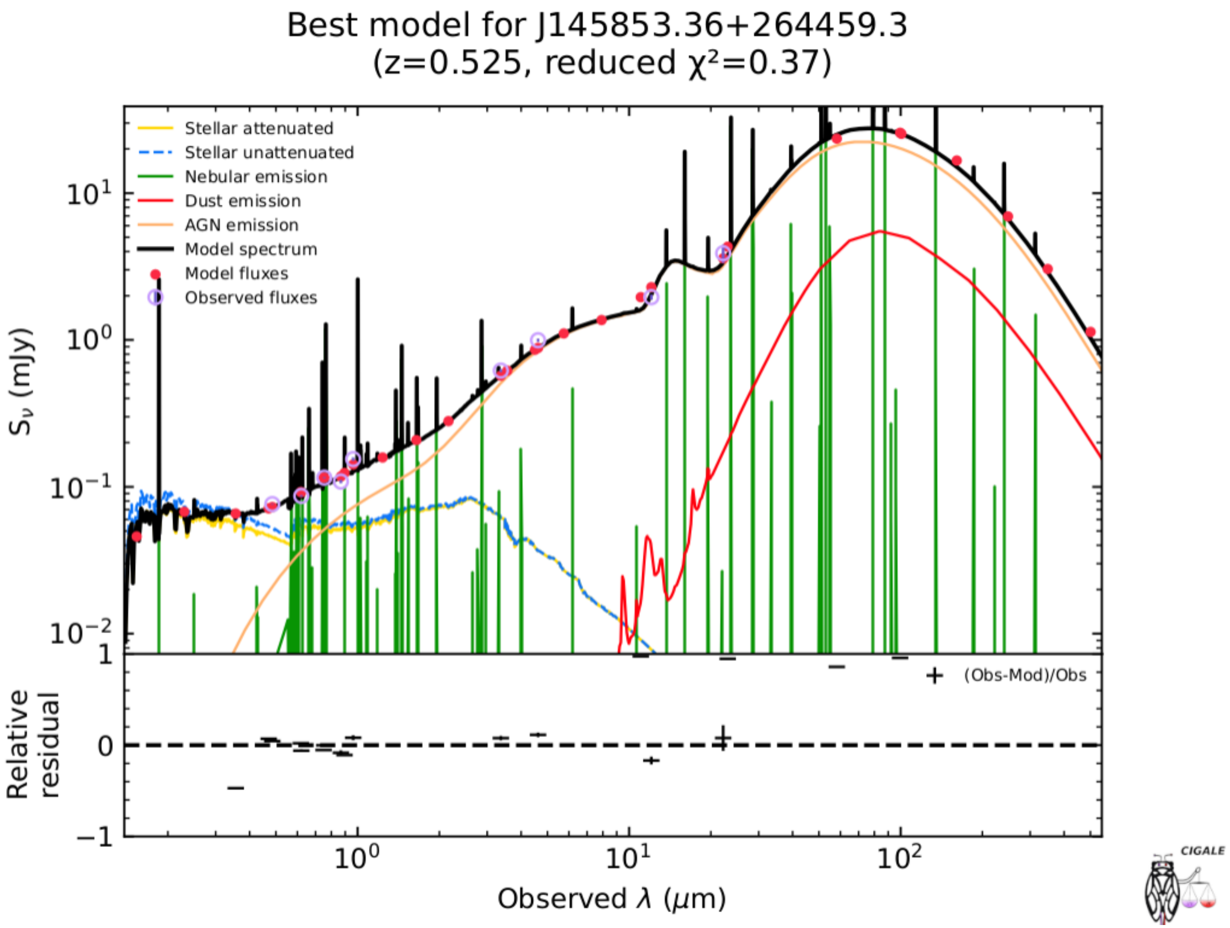


Removing bad fits

- The goodness of the fit is evaluated by the reduced chi-squared statistic that is computed for the best-fit model
- After the first few runs, I removed sources with too high (X^2 > twice the median) or too low (X^2 < 0.5) chi-squared values
    - Too high X^2 means that the data doesn't fit the model well
    - A very low X^2 means that the fit is "too good" - most likely due to very few observations. This makes the result unreliable.
- After removing sources with bad fits, I was left with 138 galaxies

Too high and too low chi-squared values





Results

- Average stellar mass of all 138 sources: 3.0×10^{10} M_sun
  - This is consistent with typical spiral galaxy stellar masses
- For the individual groups:
  - Group 1 (no radio or x-ray): 2.66×10^{10} M_sun
  - Group 2 (radio): 3.84×10^{10} M_sun
  - Group 3 (radio and x-ray): 2.50×10^{10} M_sun
- No major differences but it seems that Group 2 has slightly larger stellar masses

Uncertainties

- I could have used more parameter options but the computing time would've been too long
  - Even a supercomputer was not able to complete the run without the memory running out
- I used the same parameters and modules for all sources but naturally the results would be better if the parameters were tailored for each individual source
- However:
  1. The time this would take is unrealistic
  2. The results couldn't be compared with each other

Conclusions

- Narrow-line Seyfert 1 galaxies are young and small AGN that surprisingly seem to be able to host relativistic jets
- These sources are extremely interesting because studying them can help us understand jet formation better
- Estimating the stellar masses is a step towards understanding the host galaxies of NLS1s
- The stellar mass was estimated for 138 sources. Unfortunately, my conclusions are still not fully ready
- In the future, it would be interesting to compute the stellar masses individually for each source to get a more reliable value