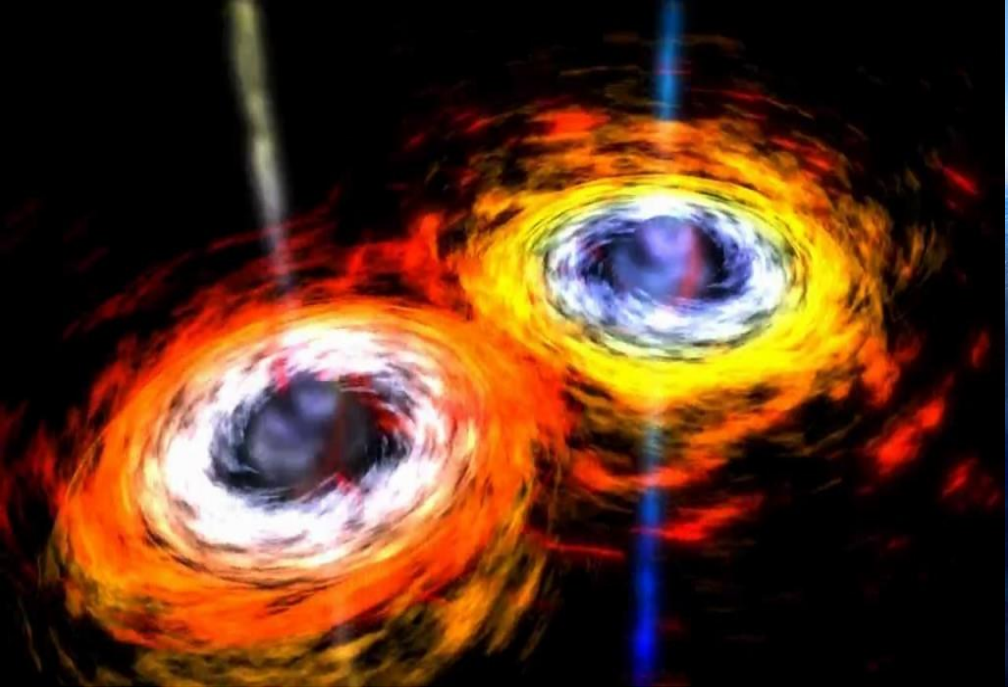
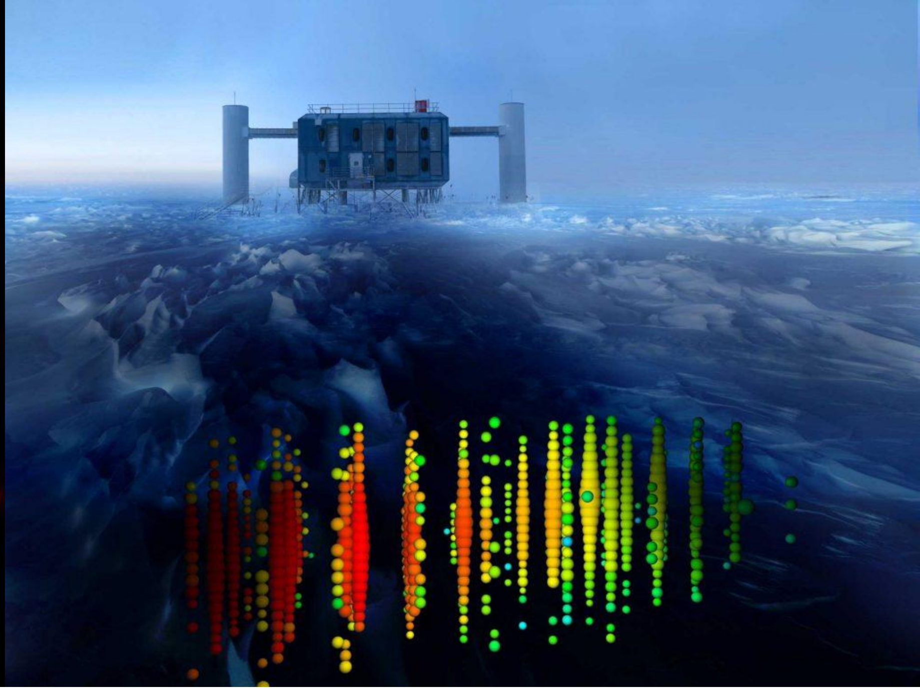

JET CHARACTERISTICS OF GRAVITATIONAL WAVE SOURCES

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UNIVERSITY OF SZEGED
DEPARTMENT OF EXPERIMENTAL PHYSICS

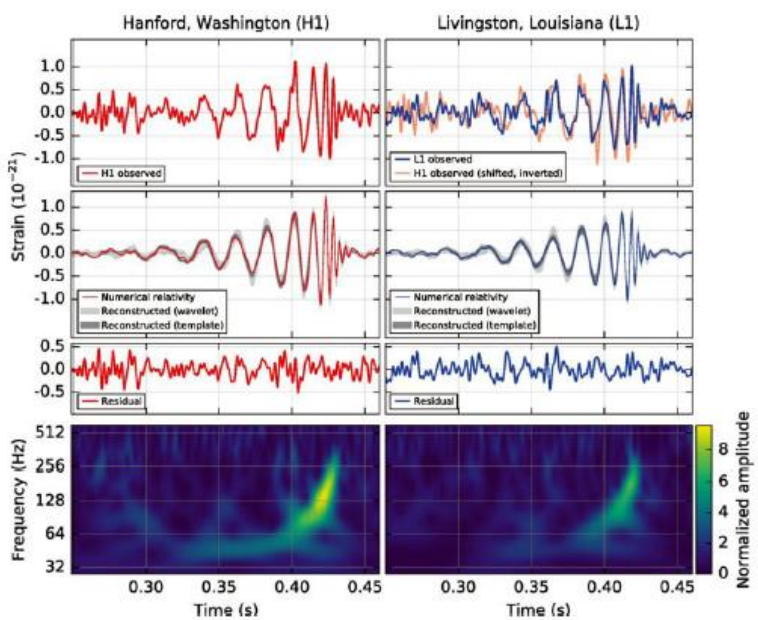
BGL 17: 10th Bolyai-Gauss-Lobachevsky Conference
22.08.2017, Gyöngyös

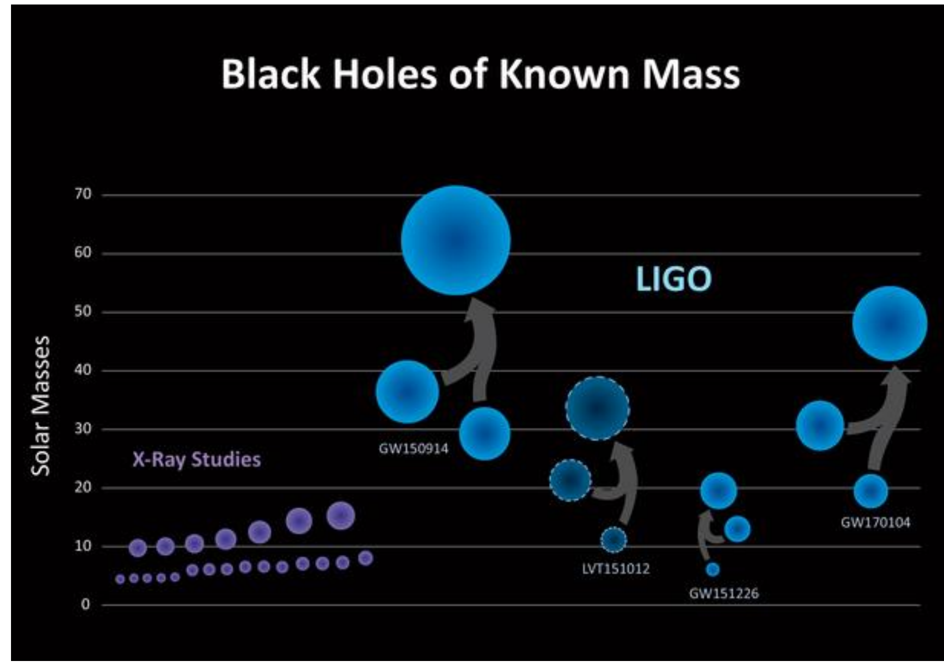
The talk will cover

- Introduction
- Active galactic nuclei and their jets
- Observation of possible sources of low-frequency gravitational waves
- Detection of neutrinos by the IceCube Neutrino Observatory
- Reorienting jets, as sources of high-energy neutrinos, with a case-study

3rd window to the Universe – gravitational wave emission

First gravitational wave observation in September 14, 2015



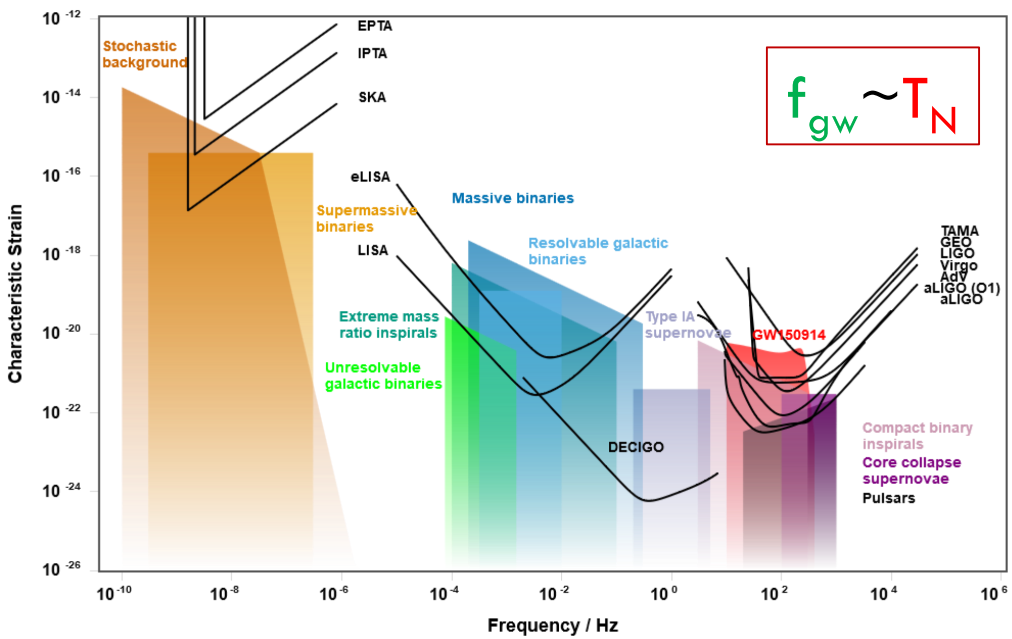


https://www.ligo.caltech.edu/gallery

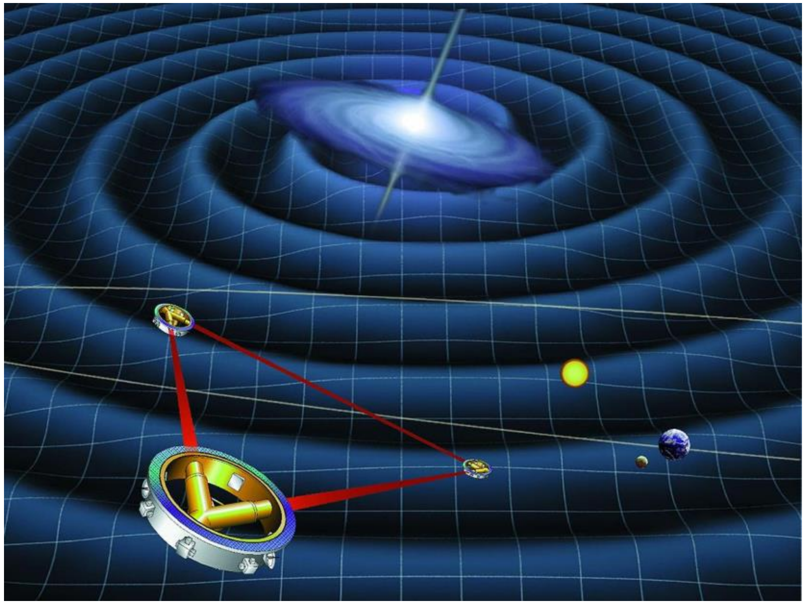
A brand-new window to the Universe

Coalescence of astrophysical black holes

Gravitational wave (GW) detectors and sources



http://rhcole.com/apps/GWplotter/



Laser Interferometer Space Antenna

http://lisa.jpl.nasa.gov/gallery/lisa-waves.html

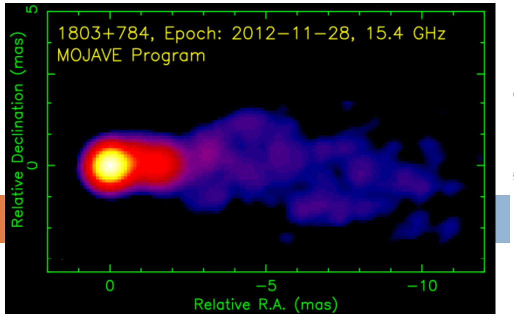
The stellar mass binary BHs are already discovered

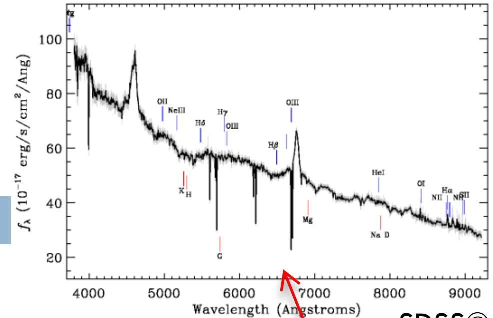
Next challenge is the detection of low-frequency GWs, emitted by more massive black hole binaries

EM counterparts of GW emission

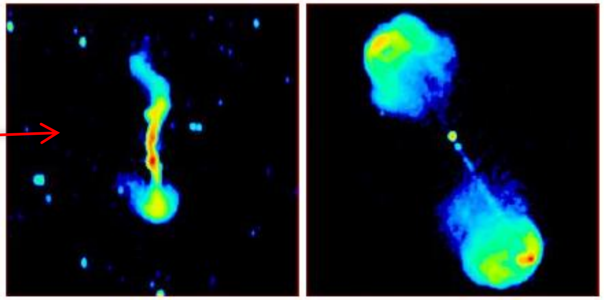
- The observations will enable testing general relativity in the strong, nonlinear regime
- Bode et al. (ApJ, 715,2,2010) found that variable electromagnetic (EM) signatures correlated with GWs can arise in merging systems as a consequence of shocks and accretion combined with the effect of relativistic beaming.
- In the case of the most massive binaries observable by the LISA, calculated luminosities imply that they may be identified by EM searches to $z \sim 1$, while lower mass systems and binaries immersed in low density ambient gas can only be detected in the local universe.

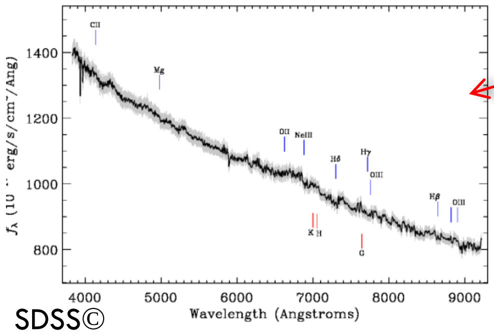
Active galactic nuclei
(AGN)



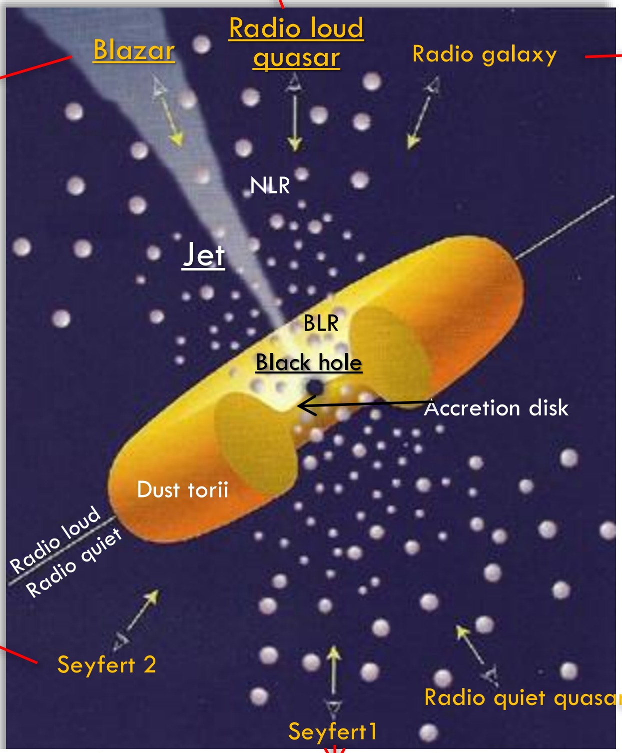


SDSS©


http://www.jodrellbank.manchester.ac.uk/atlas/object/

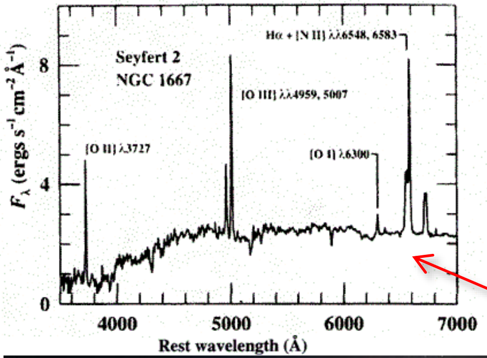


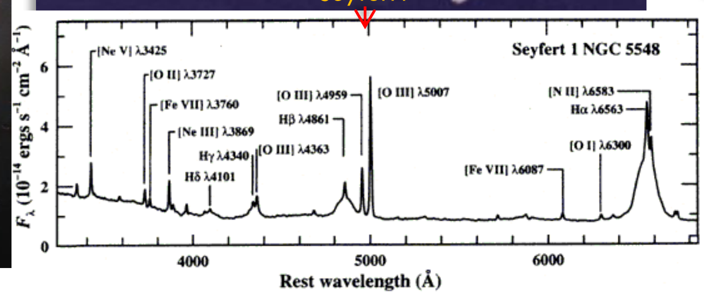
SDSS©

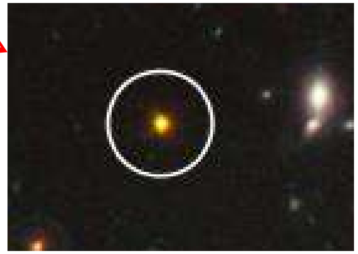


They host supermassive black holes (10^6-10^{11} M_{Sun})

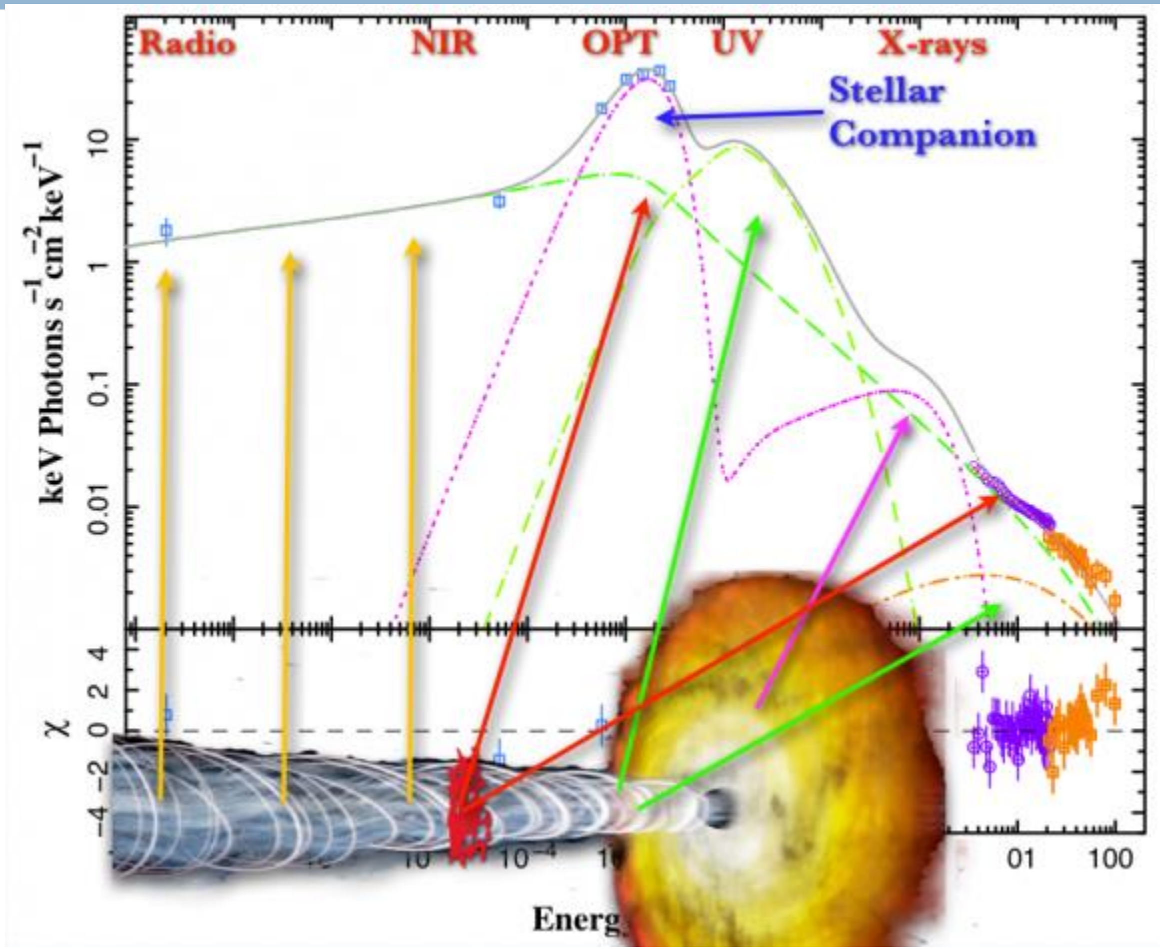
Unification theory of the radio loud AGN: the observed type of the AGN depends in the inclination angle of their jets





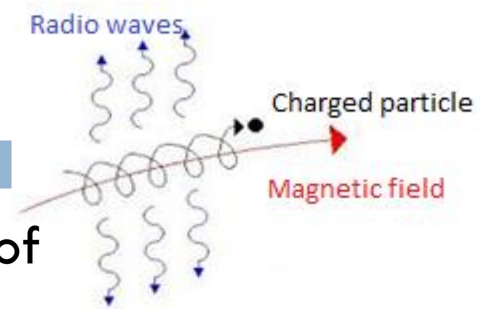


Continuum spectrum of AGN

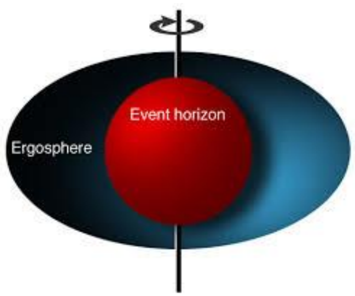


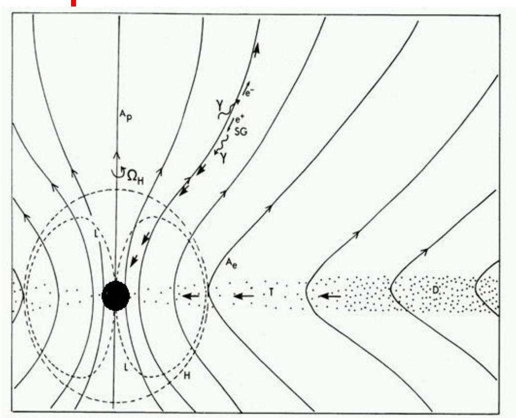
Schematic overview of a broadband jet model and the various components contributing to the spectral energy distribution (Migliari et al. 2007).

Relativistic jets



Blandford–Znajek-effect



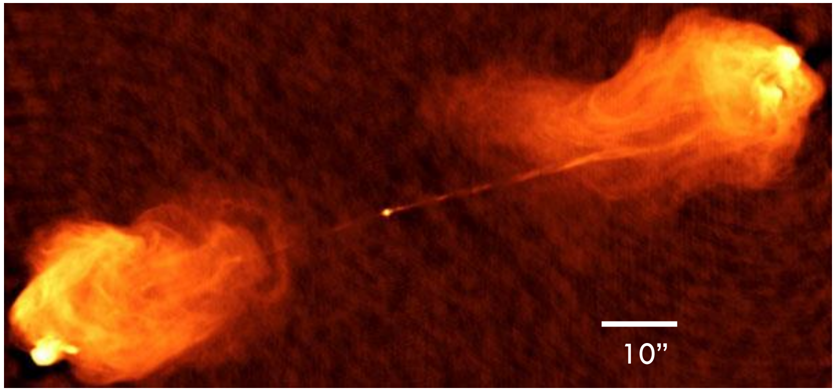


Critical frecquency of synchrotron radiation:

$$\upsilon_{c,e^-} = \frac{3}{4\pi}\frac{eB\chi}{m_{0,e^-}c}\gamma^2 = 16{,}1 \times \left(\frac{B\chi}{\mu G}\right)\left(\frac{E}{GeV}\right)^2 \text{MHz}$$

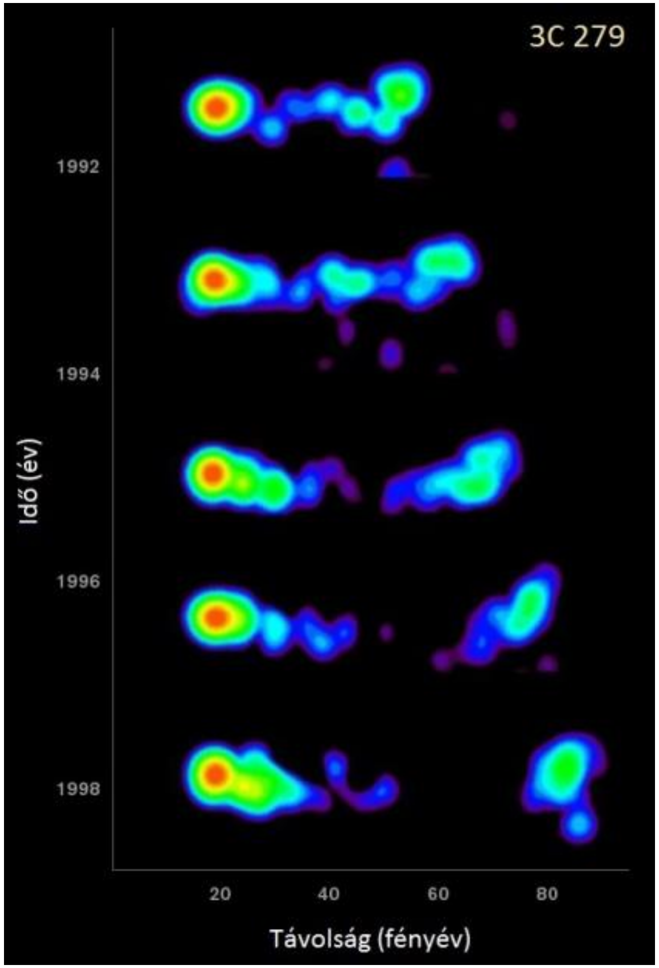
$B_\chi = 0{,}1\,\mu G$, $E = 10\,GeV$ → $\upsilon_{c,e^-} \approx 160$ MHz

The collimated jets are observed as radio loud AGN



The Cygnus–A AGN at 5GHz (VLA)
The source-distance is 760 mega-lightyear (z=0,056, scale 1,096kpc/”)
National Radio Astronomy Observatory (NRAO)

Apparent superluminal motion

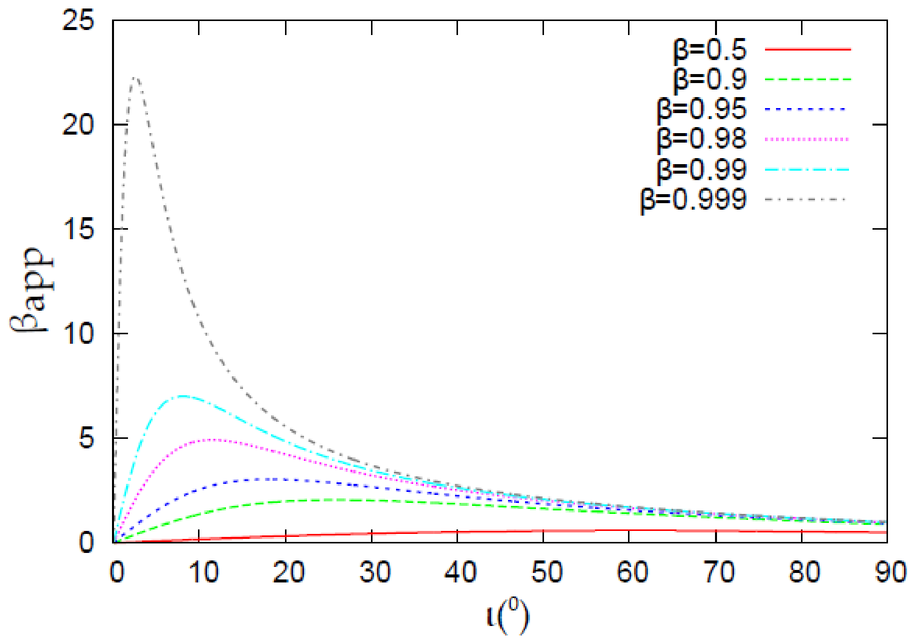


Jet moving with apparent superluminal speed.
Source : NRAO

Due to projection effects in relativistic jets

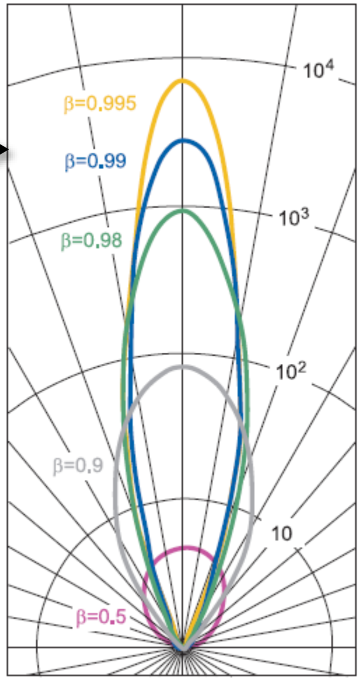
$$\beta_{app} = \frac{\beta \sin \iota}{1 - \beta \cos \iota}$$

β_{app}: apparent speed (in unit of c)
β: jet speed (in unit of c)
ι: „inclination” angle



Relativistic beaming

- The synchrotron radiation is beamed within a cone having half-opening angle ~$1/\gamma$ ($\gamma=1/(1-\beta^2)^{1/2}$ Lorentz factor)



The apparent luminosity $L=L_0\delta^n$ as function of the jetspeed and line-of-sight angle.
/Kellerman et al., 2007/

- $F_{obs}(\upsilon)$ apparent spectral flux density:

$$F_{obs}(\upsilon)= F(\upsilon)\delta^{\,n-\alpha}$$

(Jansky, 1 Jy=10^{-26} W/m²/Hz)

$\delta=1/[\gamma(1-\beta\cos\iota)]$ Doppler factor,
α: spectral index,
n: jetgeometric factor

- Intrinsic flux density: $F(\upsilon)\sim \upsilon^{+\alpha}$
- Depending on the α spectral index, the continuum spectrum can be
  - inverted: $\alpha>0$ (optically thick)
  - flat: $-0,5<\alpha<0$ (optically thick)
  - steep: $\alpha<-0,5$ (optically thin)
- The ratio of the Doppler beaming and debeaming

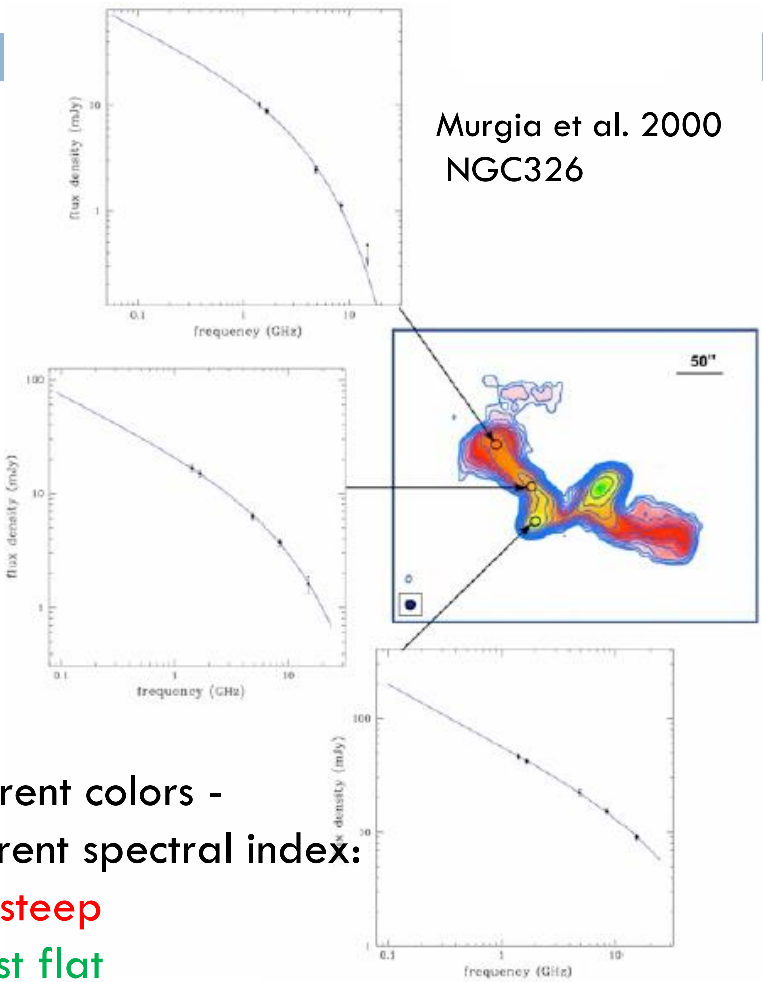
$$R=\left(\frac{1+\beta\cos\iota}{1-\beta\cos\iota}\right)^{(n+\alpha)}$$

E.g..: $\beta=0,992$, $\iota=7^0$, $n=2$, $\alpha=-0,05$ → $R=13000$

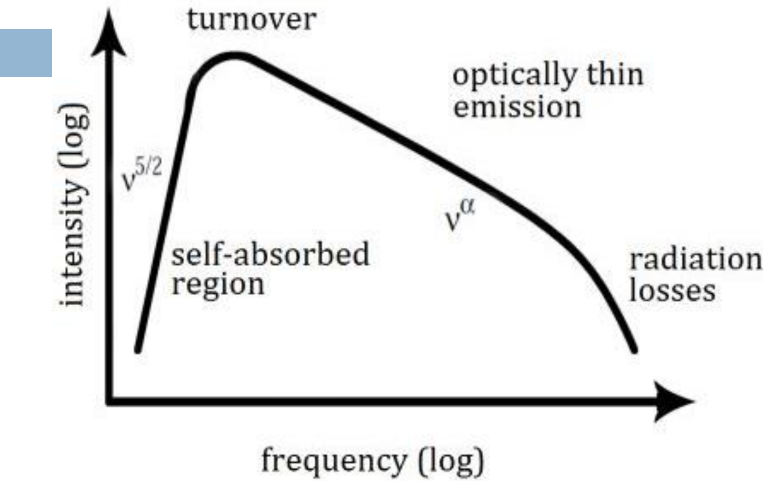
- Only the approaching jet is seen if the jet is relativistic, and has small inclination

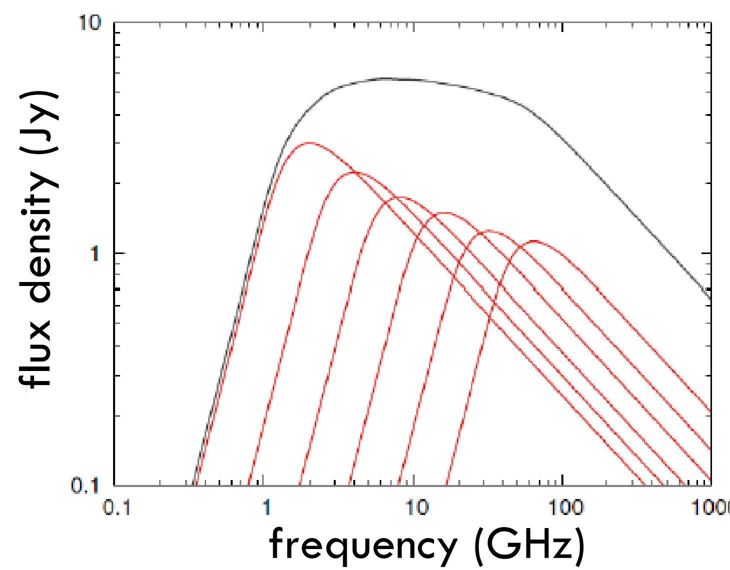
Continuum radio spectrum of AGN

Murgia et al. 2000
NGC326



Different colors - different spectral index:
very steep
almost flat





Flat spectrum is due to **energetic electrons**, with **high Lorentz factors**

Gravitational radiation dominated phase of the merger, from observational point of view

- Sub-parsec separated binary systems with years/**months/days** orbital period, leading to decades of gravitational lifetime
- Possible candidates of gravitational waves to detect by the future LISA
- It is not possible to spatially resolve these systems, even with the astronomical techniques giving the finest angular resolutions
- Indirect methods:
  - X-shaped galaxies,
  - double AGN,
  - periodic jet structures,
  - periodical optical light curves,
  - double peaked emission lines,
  - accretion disks with central cavities,
  - **ripples in FeKα X-ray lines**
  - **high-energy neutrino emission**

binary BHs are usually in the inspiral far from the final merger

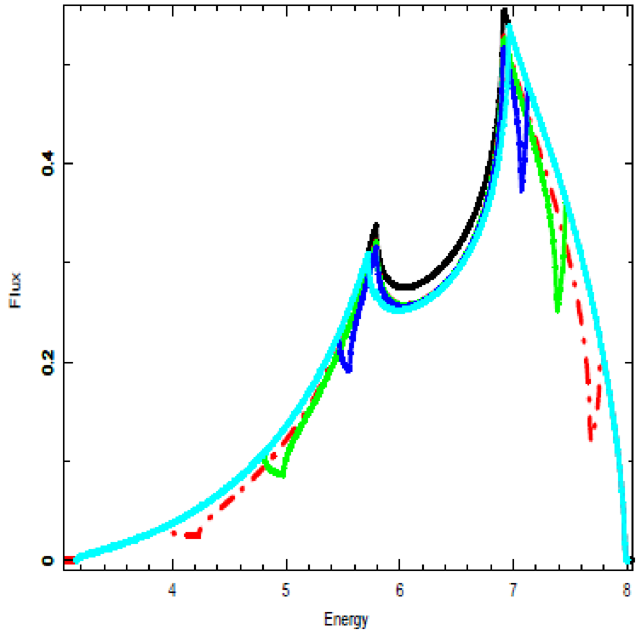
Total mass, m^a ($M_\odot$)	8.13×10^8
Orbital period, T (yr)	4.78 ± 0.14
Binary separation, r (pc)	0.0128 ± 0.0003
PN parameter, ε	≈ 0.003
Mass ratio, ν	$[0.21 : 1/3]$
Spin–orbit precession period, T_{SO} (yr)	4852 ± 646
Gravitational lifetime, T_{merger} (yr)	$(1.44 \pm 0.19) \times 10^6$

Total mass, m^* ($M_\odot$)	$\approx 4 \times 10^8$
Orbital period, T^* (yr)	4.0 ± 0.2
Binary separation, r^* (pc)	≈ 0.01
Post-Newtonian parameter, ε	≈ 0.002
Mass ratio, ν	$\nu > 0.08$
Spin–orbit precession period, T_{SO} (yr)	$<14\,100$
Gravitational lifetime, T_{GR} (yr)	$<7.2 \times 10^6$

Kun et al., 2014, 2015

Ripples in FeKα X-ray lines

- The inner edge of the accretion disk is hot enough to ionize this emission line(E=6.4 keV, λ=0.19nm)
- The orbital motion of the secondary BH opens a gap in the disk, and it affects the line profile

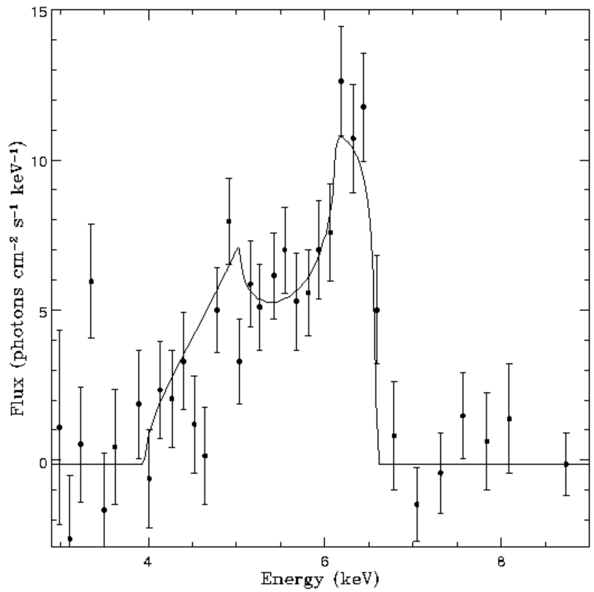


unperturbed FeKα line
$r=90\pm9\ R_S$
$r=50\pm5\ R_S$
$r=20\pm2\ R_S$
$r=10\pm1\ R_S$

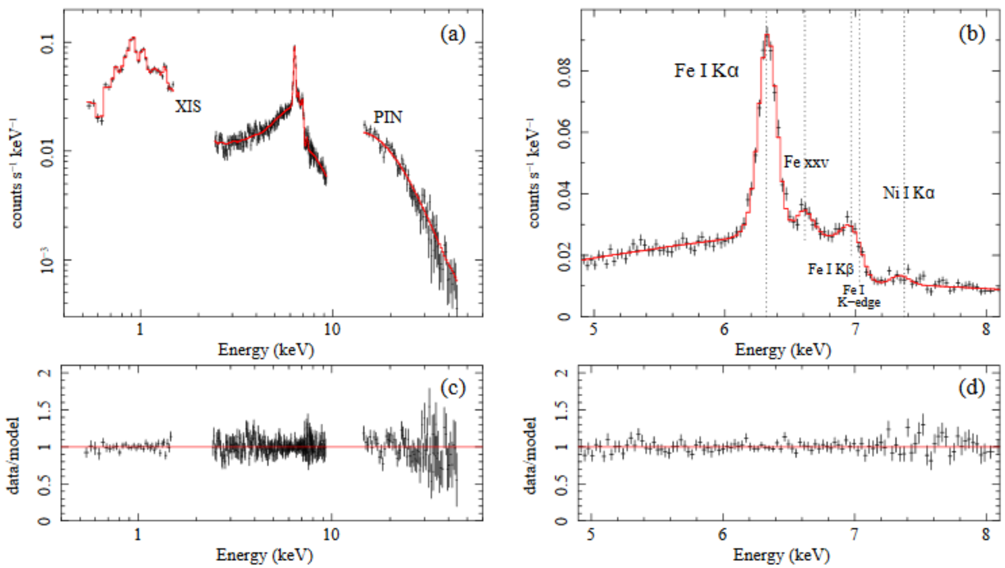
McKernan, B. *et al.* MNRAS, 432, 1468, 2013

Possible sources of strong GW burst within decades

The X-Ray observations are far more difficult in technique, than e.g. optical observations
The S/N of the present X-Ray spectra does not allow to fit such rippled FeKα models



ASCA: A model fit (Bromley et al. 1996) to the Fe K-alpha line profile of MCG-6-30-15 [Tanaka et al., Nature 375, 659, 1996]



Fit of the Suzaku data of Markarian 3 [Yaqoob et al. MNRAS, 454, 973, 2015]

Reorienting jets

Before the merger

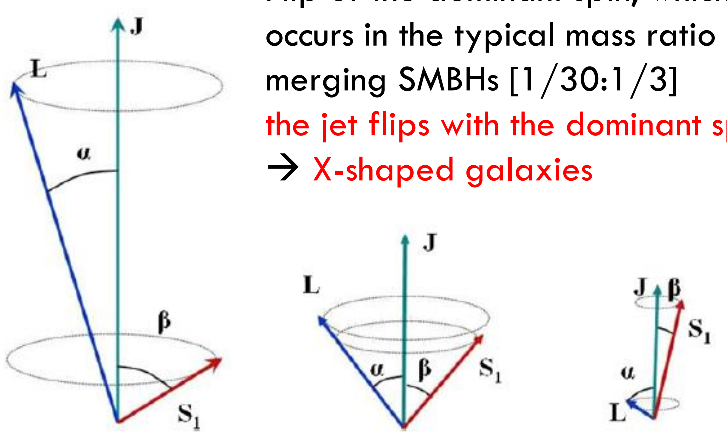
Precession of the dominant spin

If the spin is misaligned to the orbital angular momentum:

$$\dot{S_1} = \Omega_1 \times S_1$$

The spin-direction points the jet direction
→ the jet is precessing with the spin

„spin-flip"
Flip of the dominant spin, which typically occurs in the typical mass ratio of merging SMBHs [1/30:1/3]
the jet flips with the dominant spin
→ X-shaped galaxies

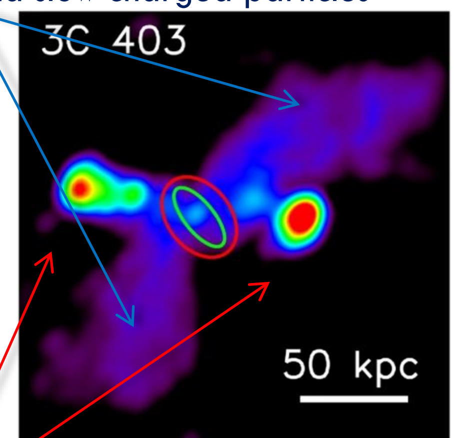


Gergely and Biermann, 2009

X-shaped galaxies

The remnant of the old jet can be seen with the freshly made jet, forming an X-shape

Old jet-pair:
- steep spectra
- old and slow charged particles



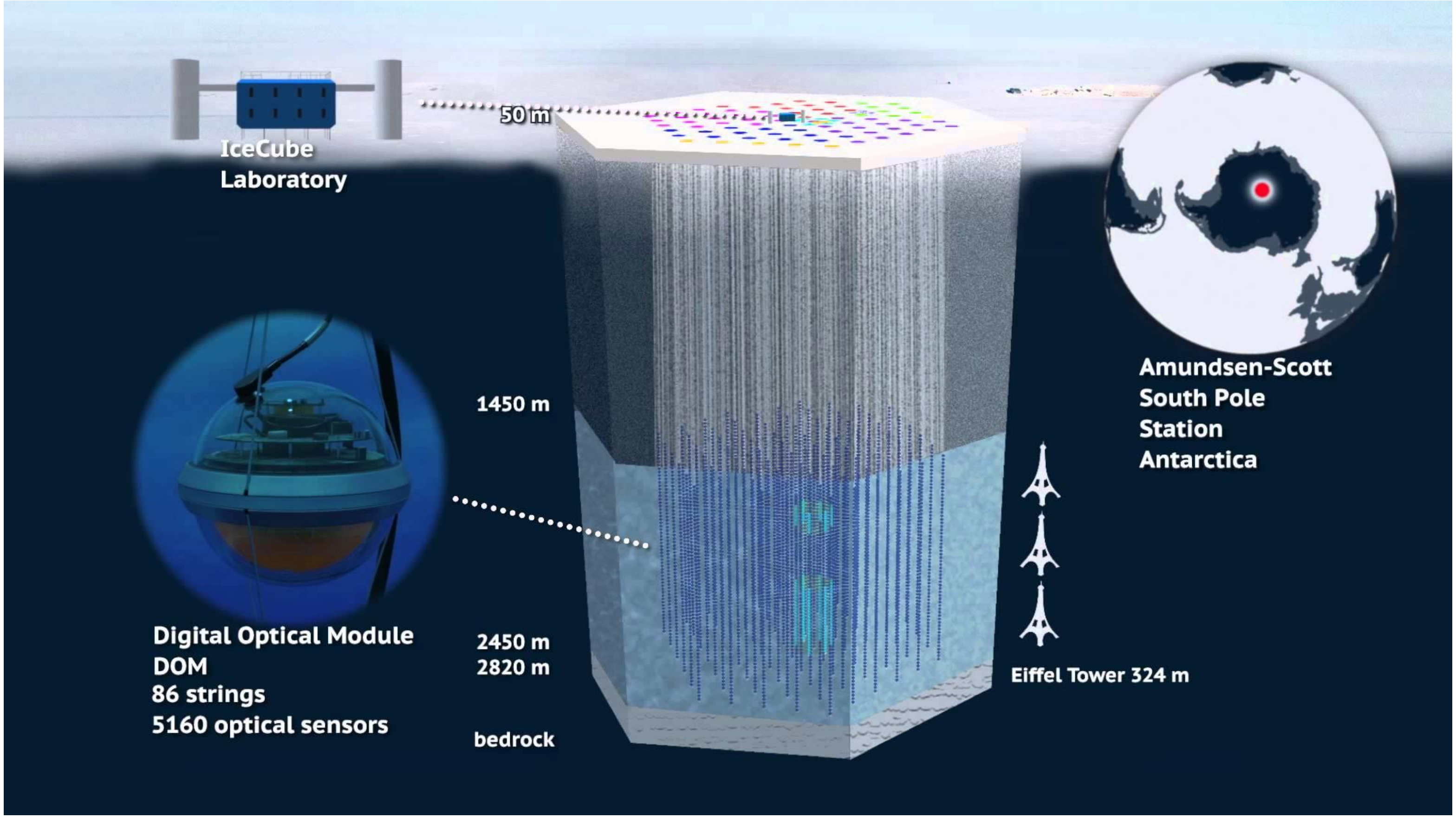
Hodges-Kluck and Reynolds, 2011

New jet-pair:
- bright and flat spectrum
- young and fast charged particles

They may hide SMBH binaries that would collide within decades

IceCube and high-energy neutrinos

- IceCube: detection of 55 high-energy neutrino of cosmic origin
  (IceCube collaboration, *Phys. Rev. Lett.*, 113, 101101, 2014; IceCube collaboration, arXiv: 1510.05223; Schoenen Raedel, AT, 7856, 2015)
- Their actual origin is not clear, most probably it is the AGN



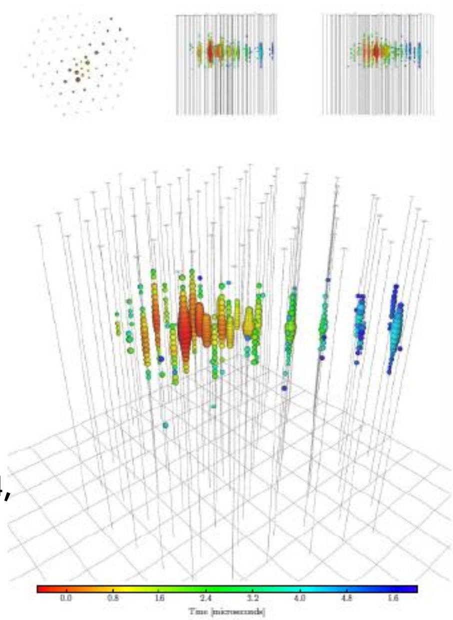
https://icecube.wisc.edu/

„Track” and „shower”-type neutrino events

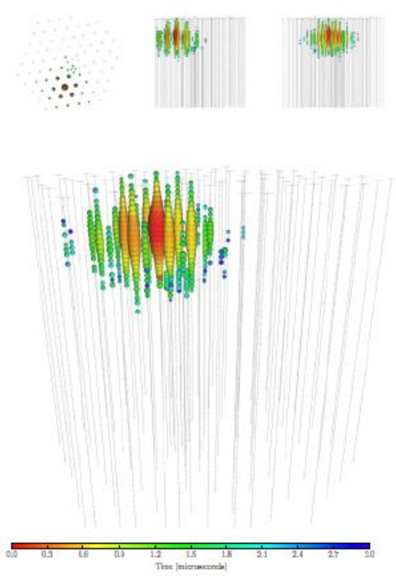
- The electron neutrinos create electrons, the muon neutrinos create muons
- The electron neutrinos generates „shower”-type neutrino events
- The muon neutrinos generates „track”-type neutrino events

directional uncertainty
~1,2°

Blazar PKS 0723–008
Kun et al., MNRAS Lett. 466, 34, 2017



Track-type (e.g. ID5)

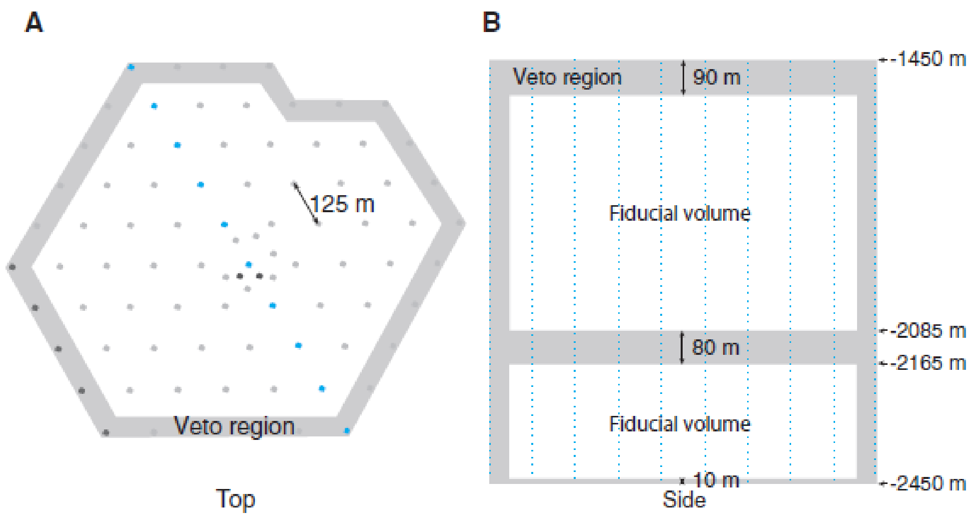


Shower-type (e.g. ID35)

directional uncertainty
~16°

Blasar PKS B1424-418
Kadler et al.,
Nature, 12, 807, 2016

Selection of cosmic neutrinos



[IceCube Collaboration, *Science* 342, 1242856, 2013]

Background events (99.9% of the events):

Events producing first light in the veto region (shaded area) were discarded as entering tracks (usually from cosmic ray muons entering the detector).

The deposited energy is also a veto, only the high-energy (TeV, PeV) neutrinos are considered to be extragalactic.

Where can be the neutrinos created in AGN?

- Energetic proton-proton collisions lead to pion creation

$E_{0,\mu+}$=105,66 MeV
E_{LEC}=55,91 MeV

$$p^+p^+ \rightarrow p^+ + n^0 + \pi^+$$
$$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\upsilon}_\mu + \upsilon_e$$

$E_{p+,min} \approx 290$ MeV
$v_{p+,min} \approx 0{,}65c$

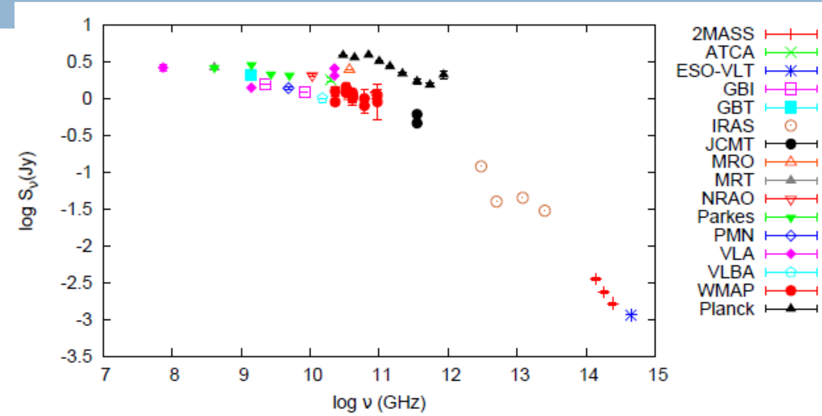
- The plunge of a newly formed jet into the environment of the BBH
  - The Lorentz factor of the freshly made jet is high
  - Enhanced radiation in all EM frequencies
    - The spectrum of the AGN is flat up to THz frequencies
    - Its radio flux density is increasing as the electrons are speeding, leading to enhanced synchrotron radiation
  - Neutrino emission

    Their sources might be the energetic proton-proton collisions ($E \geq E_{p+,min}$)
- New jet tunnel forms after the coalescence of the BBH

Case study: the blazar PKS 0723–008

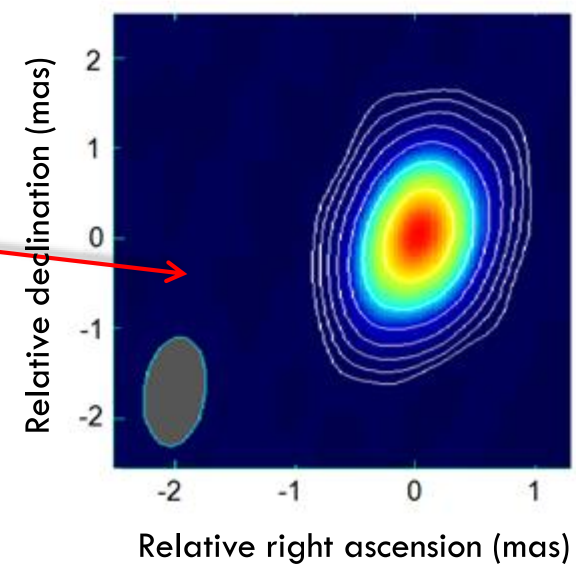
E. Kun, P. L. Biermann, L. Á. Gergely, *MNRAS Letters*, **466**, 34, (2017)

- Cross-correlation of AGN positions in radio catalogues with the arrival direction of the 15, track-type high-energy neutrino detected by the IceCube (mispointing ~1,2°)
- The blazar PKS 0723–008 is the candidate-source to neutrino event ID5
- Its spectrum is flat upt to 857 GHz
- MOJAVE data (15 years)
  - mapping with point sources
  - modeling with Gauss components
  - no visible component motion

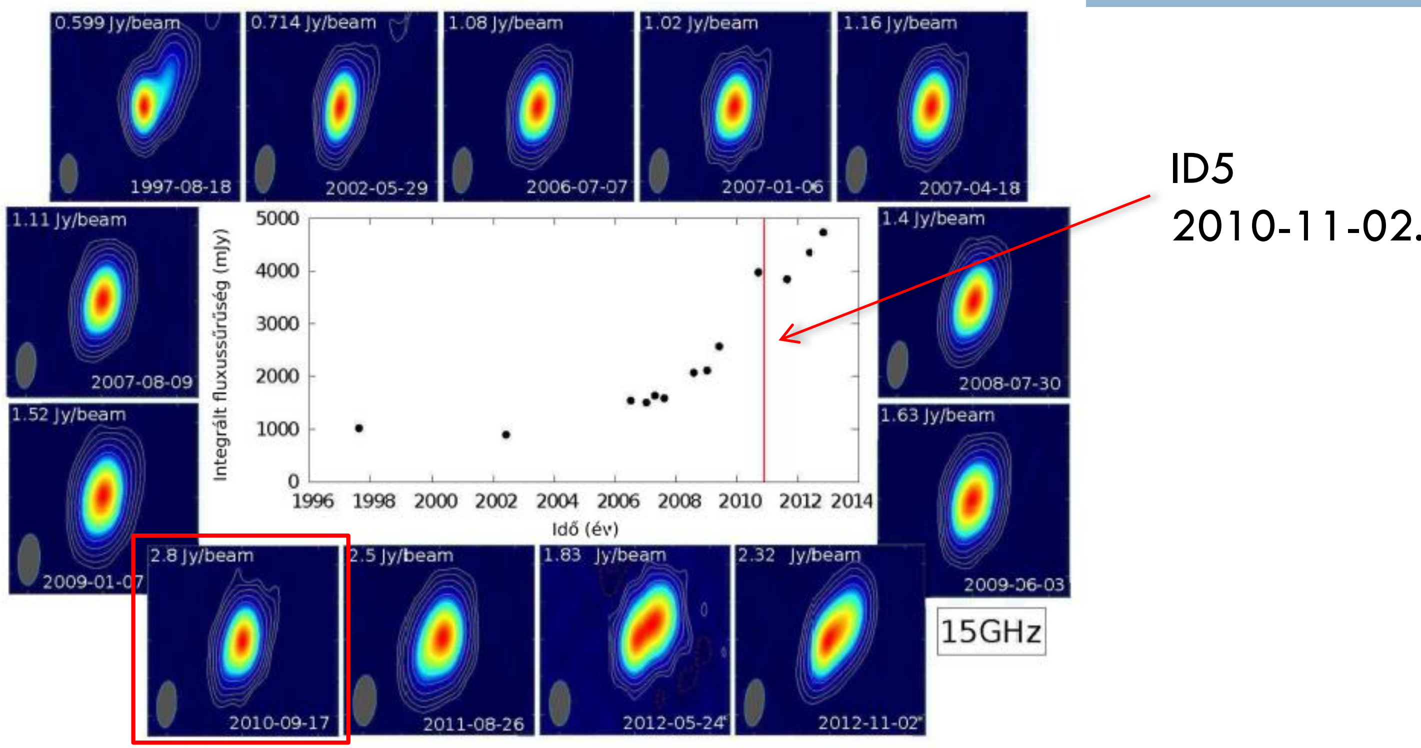


Spectrum of PKS 0723–008 (NASA/IPAC Extragalactic Database)

PCCS2: $\alpha_{30GHz,857GHz}$ = -0,18± 0,04, $\alpha_{70GHz,545GHz}$ = -0,45±0,03



Surface brightness distribution of the blazar PKS0723-008 at the 15 GHz observing frequency



BBH merger→freshly made jet→increasing radio flux density, hardened spectrum, neutrino emission.

A possible way to confirm the sources of low-frequency gravitational wave bursts is the detection of high-energy neutrinos accompanied by enhanced radio flux density, and flat radio spectrum.

Thank you for the attention!