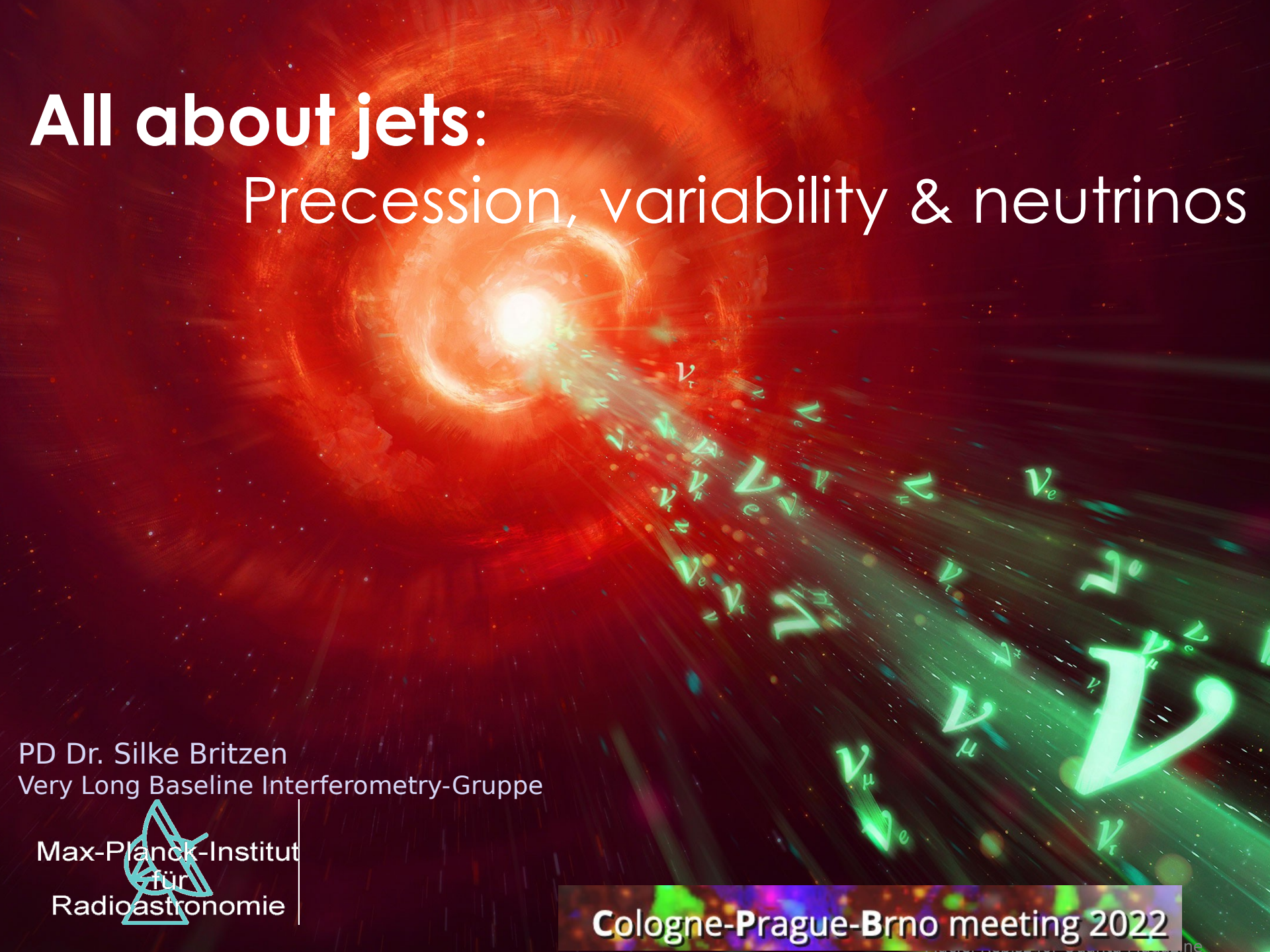
All about jets:
Precession, variability & neutrinos

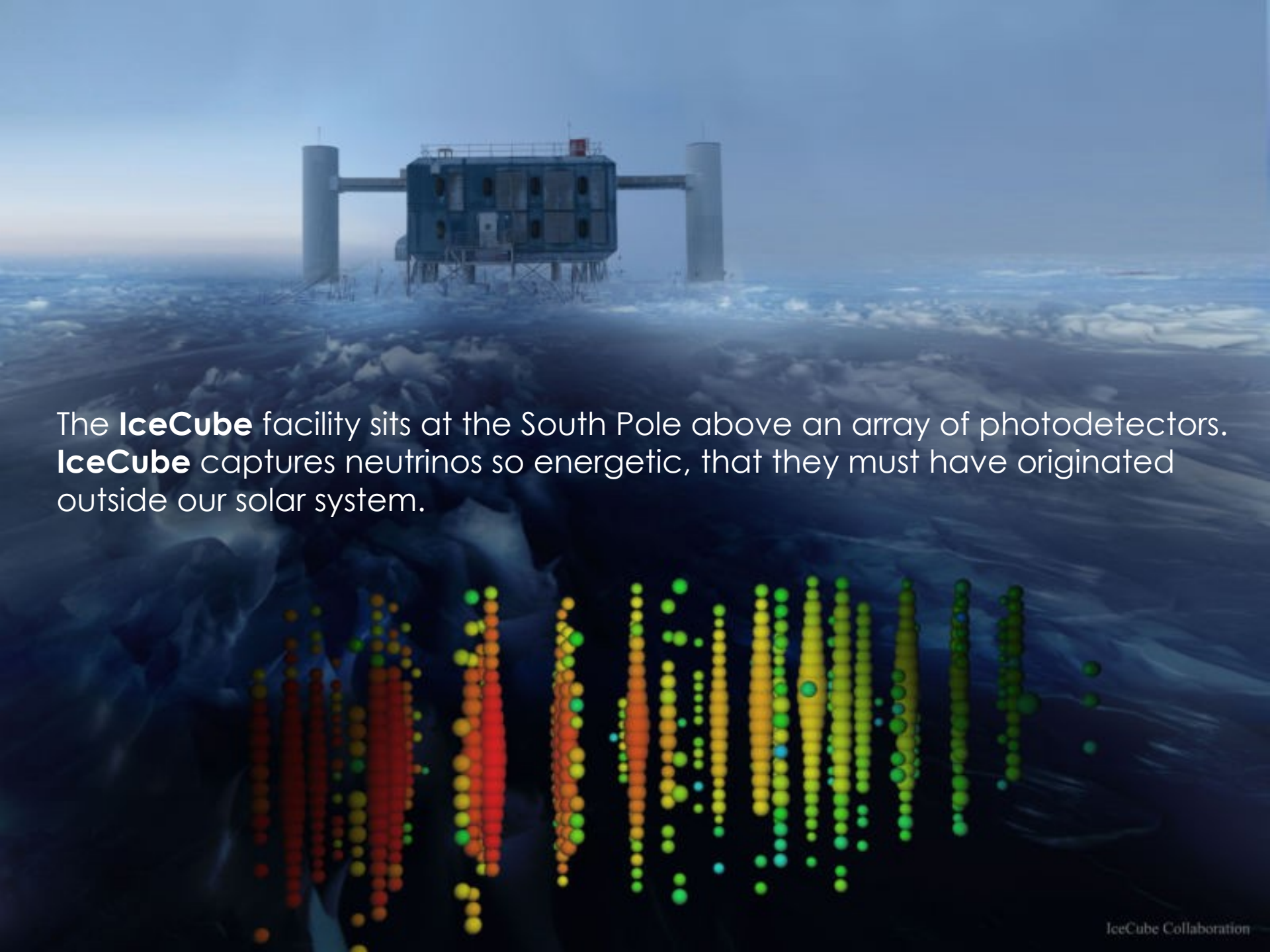


PD Dr. Silke Britzen
Very Long Baseline Interferometry-Gruppe

Max-Planck-Institut
für
Radioastronomie

Cologne-Prague-Brno meeting 2022


Ernst Mach Honorary Medal –
Congratulations Andreas !



The **IceCube** facility sits at the South Pole above an array of photodetectors. **IceCube** captures neutrinos so energetic, that they must have originated outside our solar system.

Neutrinos and gamma rays, a partnership to explore the extreme universe

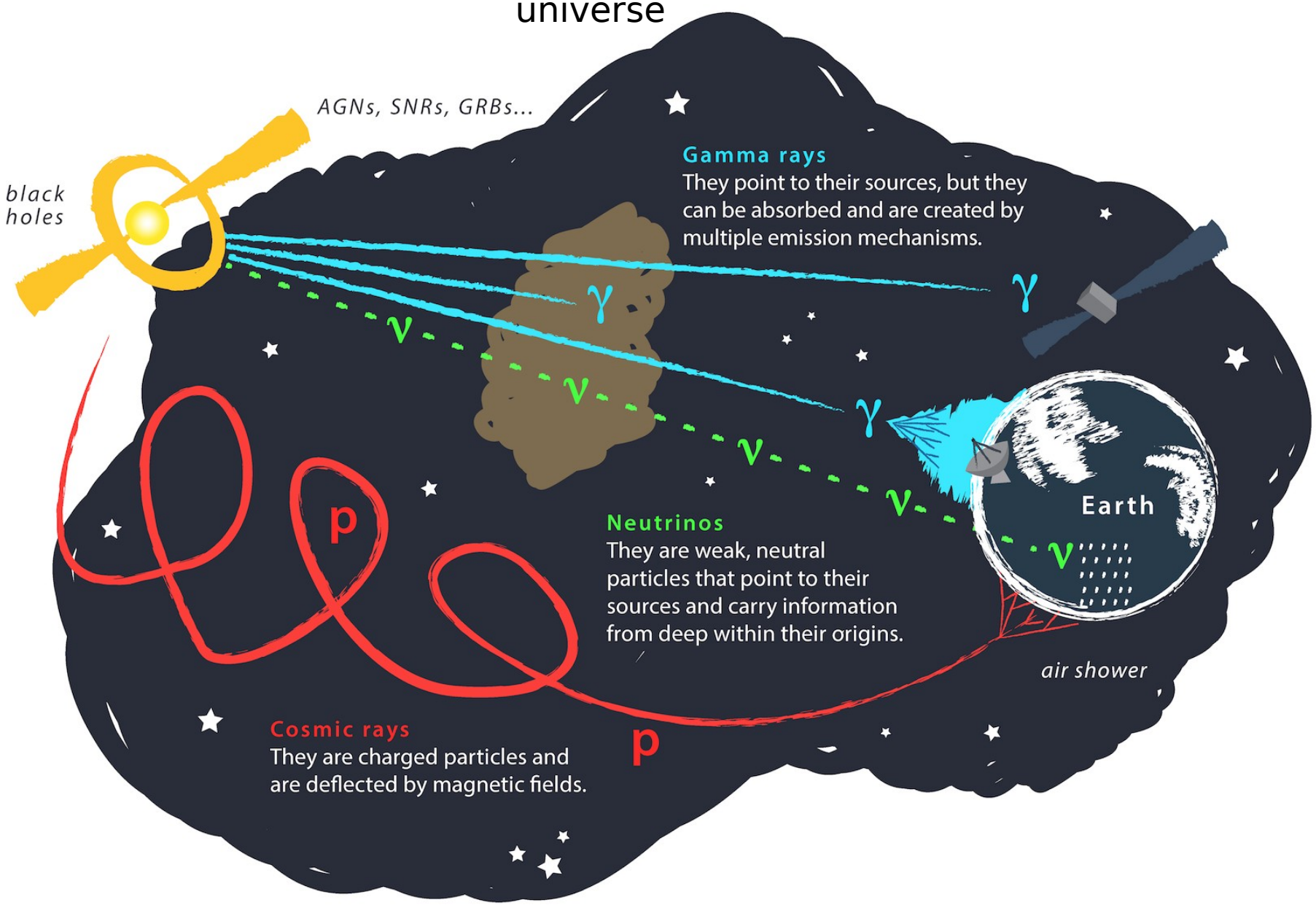
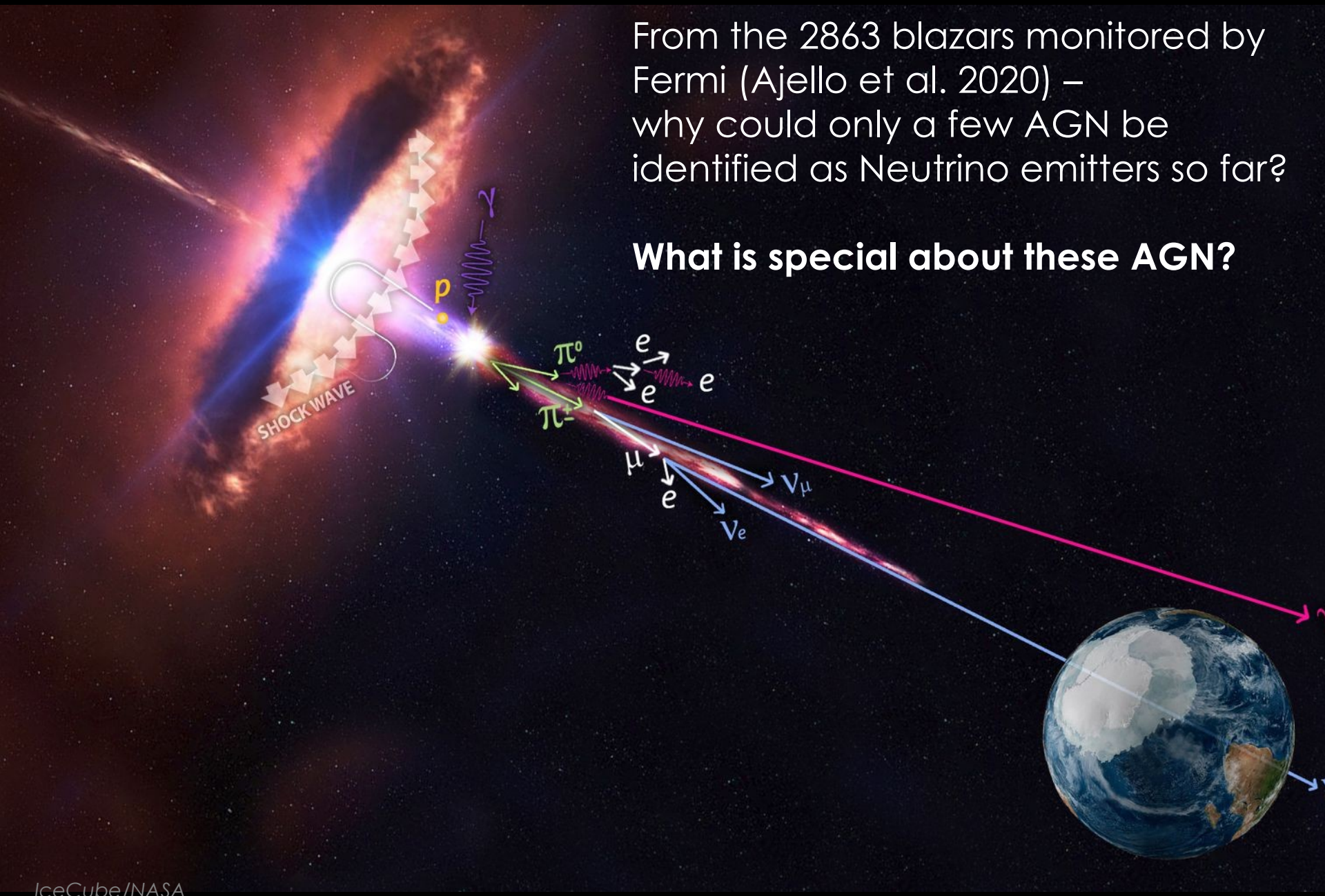


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

https://icecube.wisc.edu/news/view/455

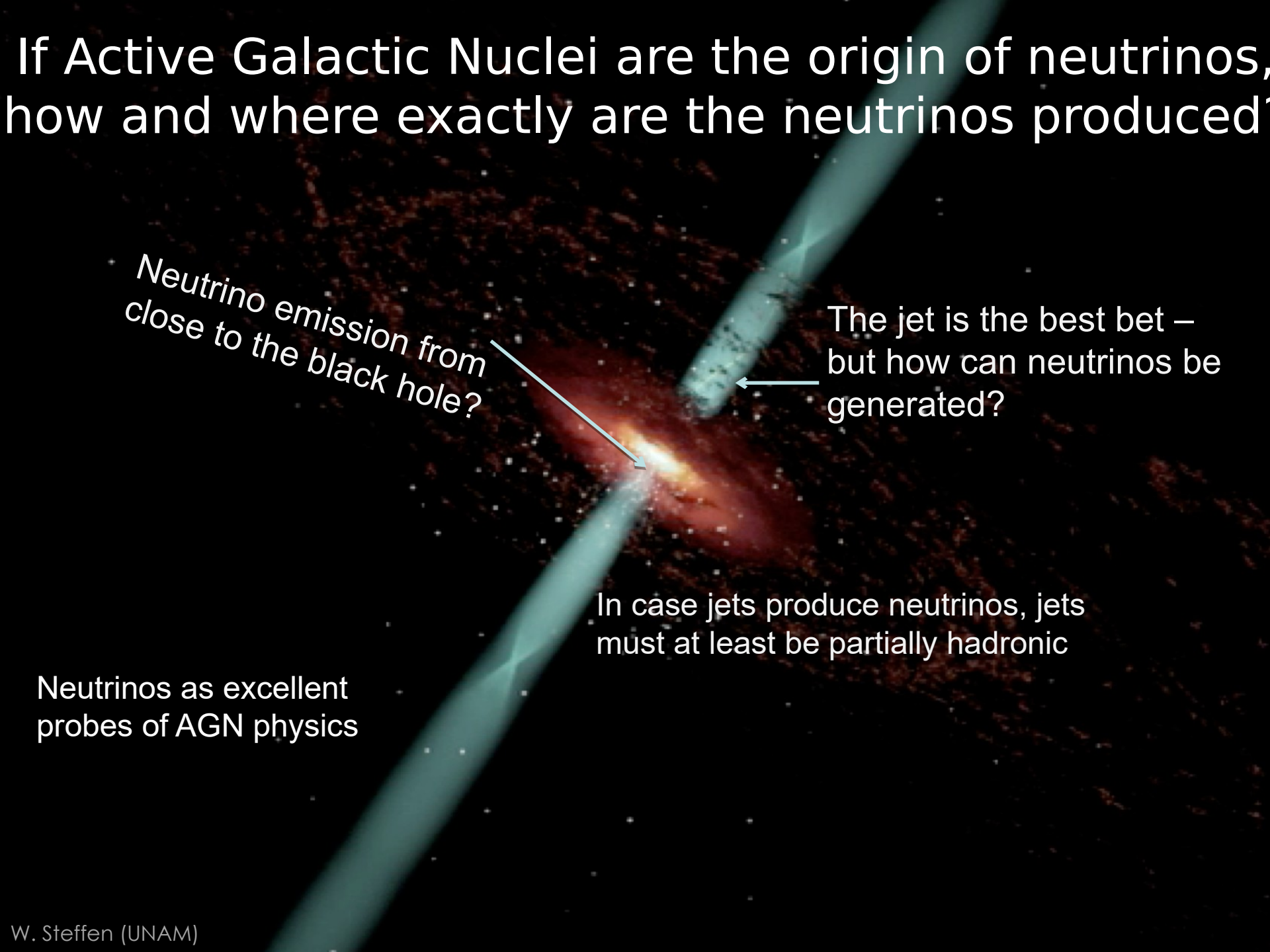
From the 2863 blazars monitored by Fermi (Ajello et al. 2020) –
why could only a few AGN be identified as Neutrino emitters so far?

What is special about these AGN?



IceCube/NASA

If Active Galactic Nuclei are the origin of neutrinos, how and where exactly are the neutrinos produced?



TXS 0506+056

TXS 0506+056

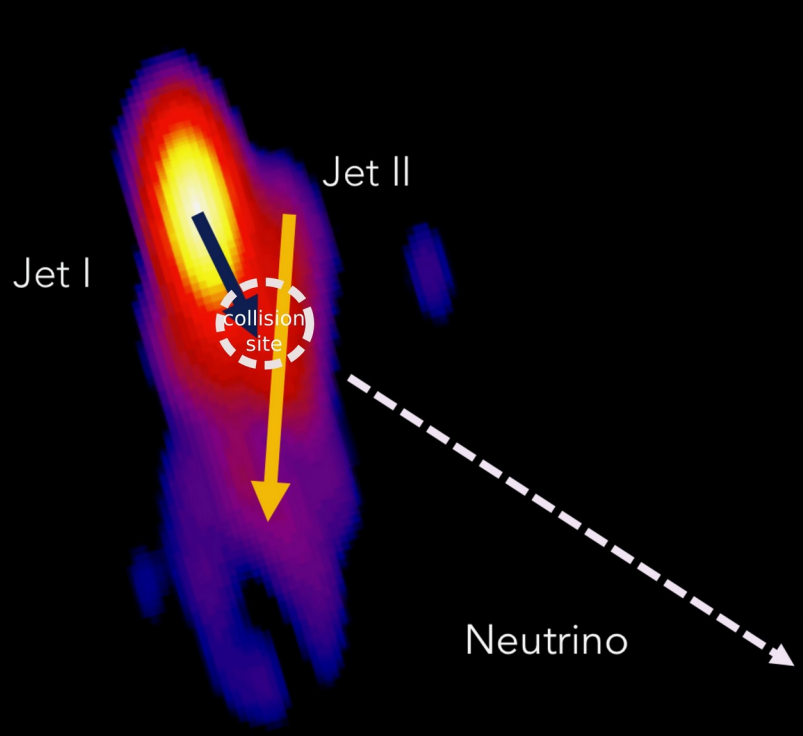
$z = 0.3365 \pm 0.0010$ (Paiano et al. 2018)
Type of AGN: BL Lac Object
enhanced neutrino activity in 2014–15 and
an extremely high-energy (EHE) neutrino
IceCube−170922

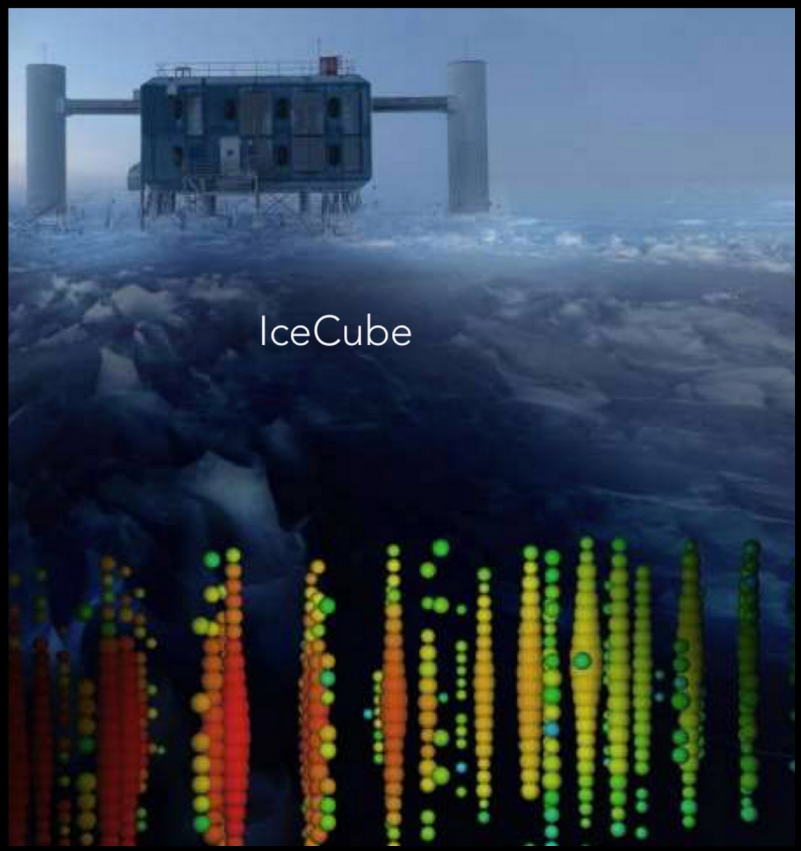
IceCube Collab. (2018), Ansoldi et al. (2018), Kun et al. (2019),
Halzen et al. (2919), Rodrigues et al. (2019),
Reimer et al. (2019), Ros et al. (2020),
Petropoulou et al. (2020), Li et al. (2020),
Sahu et al. (2020), Sumida et al. (2022), etc.

NASA/Fermi and Aurore Simonnet, Sonoma State University

Cosmic Collider:

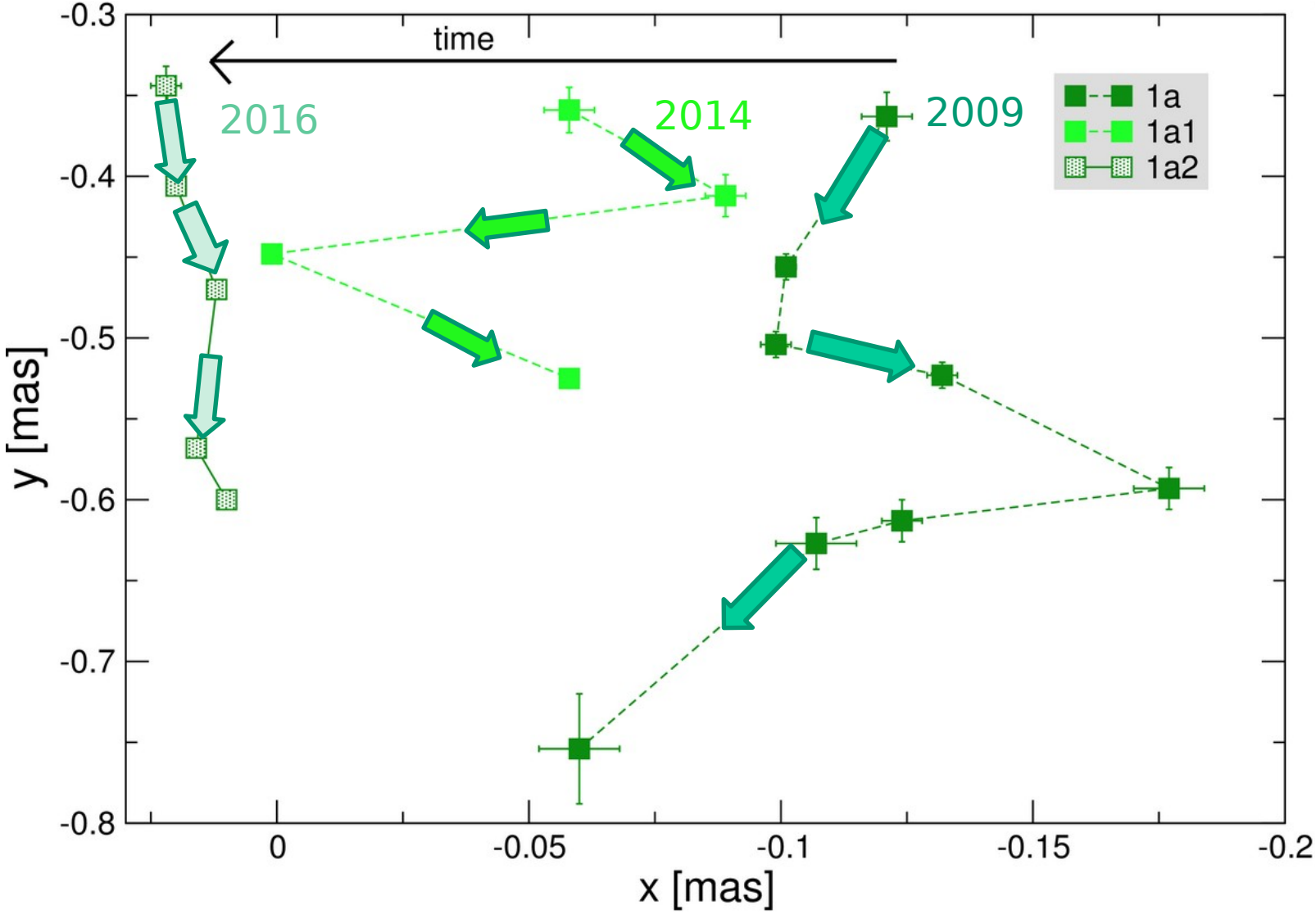
IceCube neutrino generated in a **precessing jet-jet interaction** in TXS 0506+056?





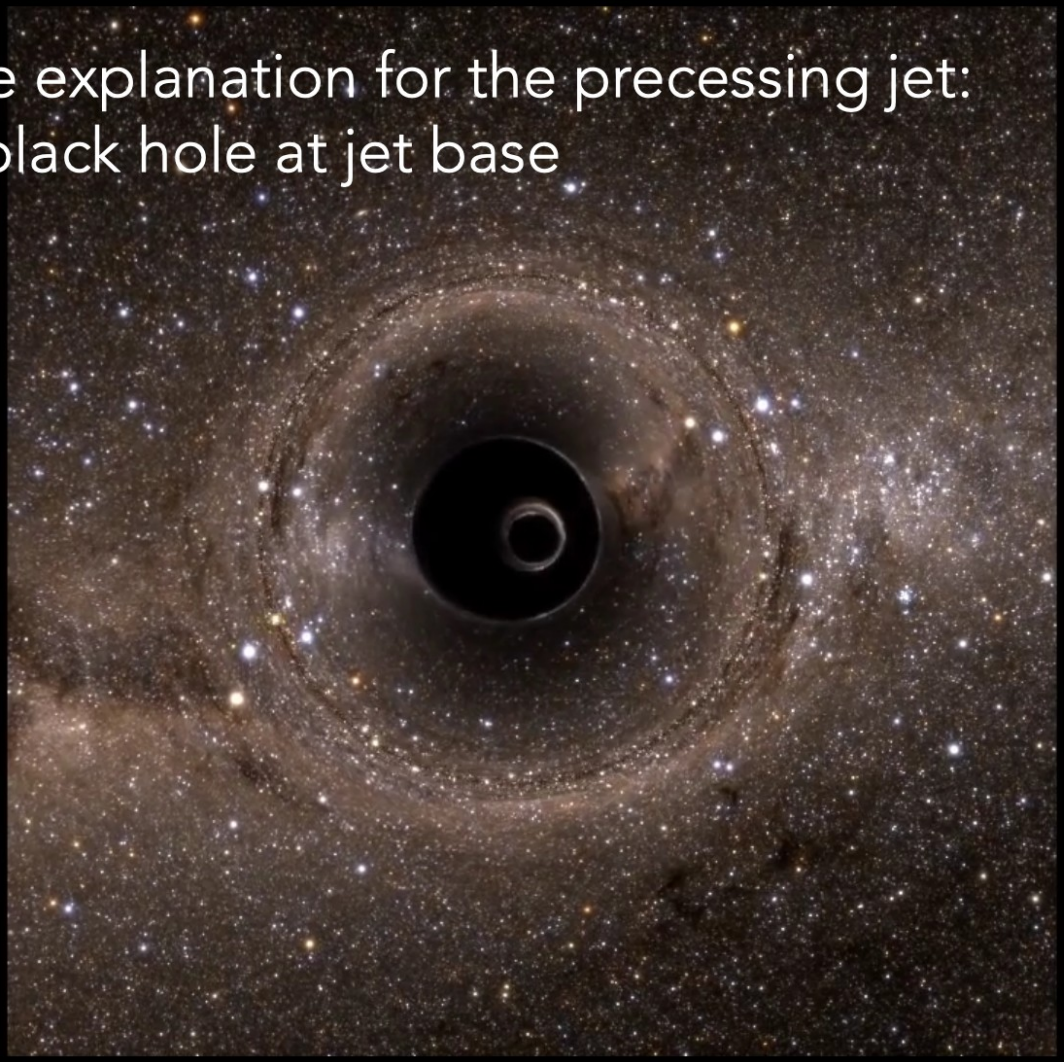
Britzen et al., 2019, A&A, 630, A103

The inner part of the jet – evidence for jet precession

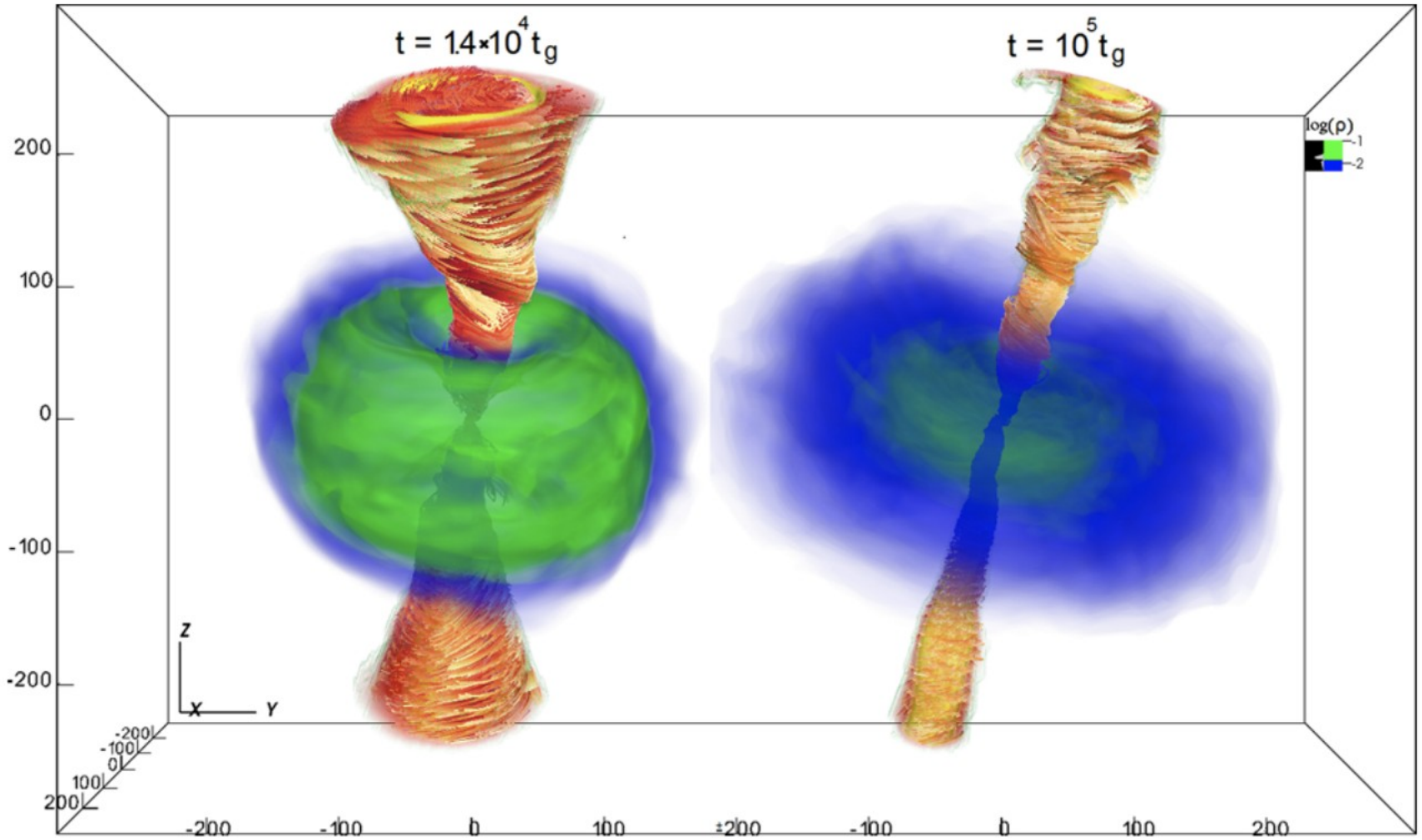


see also: Li *et al* 2020 *ApJ* **896** 63, de Bruijn *et al* 2020 *ApJL* **905** L13

1. Possible explanation for the precessing jet: binary black hole at jet base



SXS collaboration uses the Spectral Einstein Code (SpEC) to simulate compact object mergers, be it with black holes or neutron stars (Taylor et al. 2013)

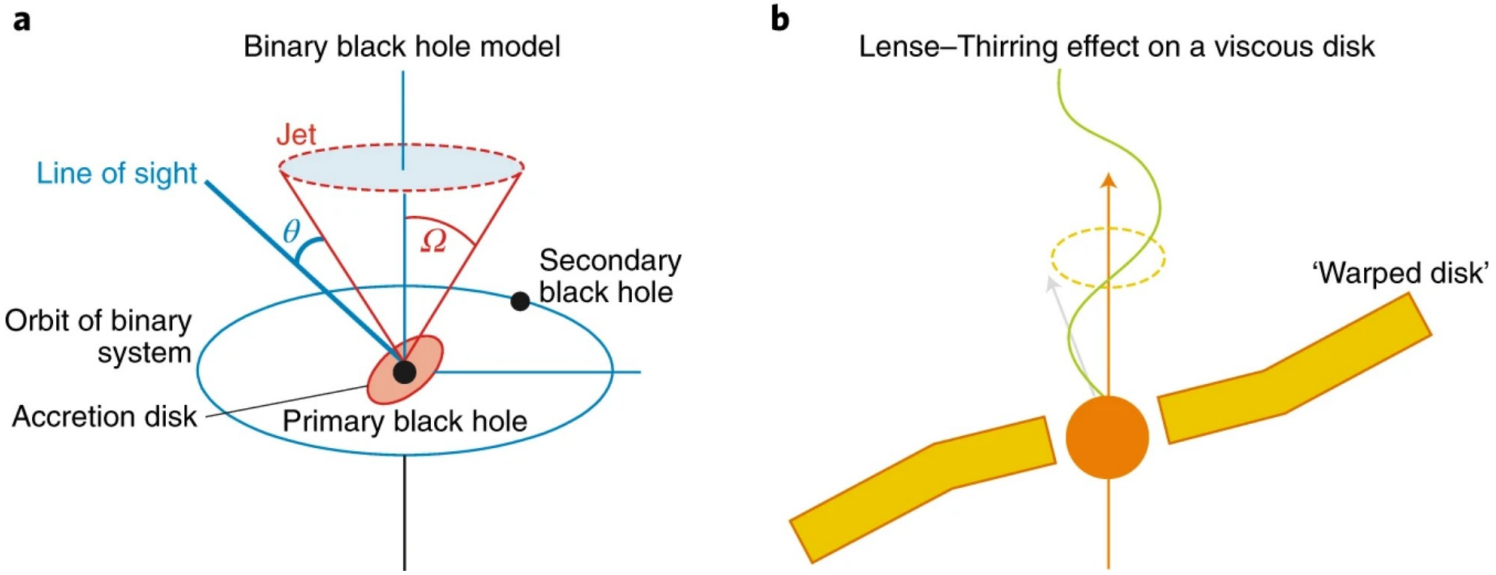


Disk (blue and green), magnetic field lines in the jets are shown with yellow–red lines. The disc–jet system precesses as a whole around the BH spin vector, which is vertical in the figure.

Liska et al. 2018

Precessing jets are game changers

- Jet precession has been found and modeled:
  - e.g., 3C 279 (Abraham & Carrara 1998), 3C 273 (Abraham & Romero 1999), **PKS 0735+178** (Britzen+ 2010), 2200+420 (BL Lac, Caproni et al. 2013), PG 1553+113 (Caproni+ 2017), 3C 345 (Caproni & Abraham 2004), 3C 120 (Caproni & Abraham 2004), 1308+326 (Britzen+ 2017), 3C 84 (Dunn+2006, Britzen+ 2019), **TXS 0506+056** (Britzen+ 2019), **PKS 1502+106** (Britzen+2021), and many more.
  - and **OJ 287** (e.g., Sillanpää+1988; Valtonen+2016, Britzen+2018)

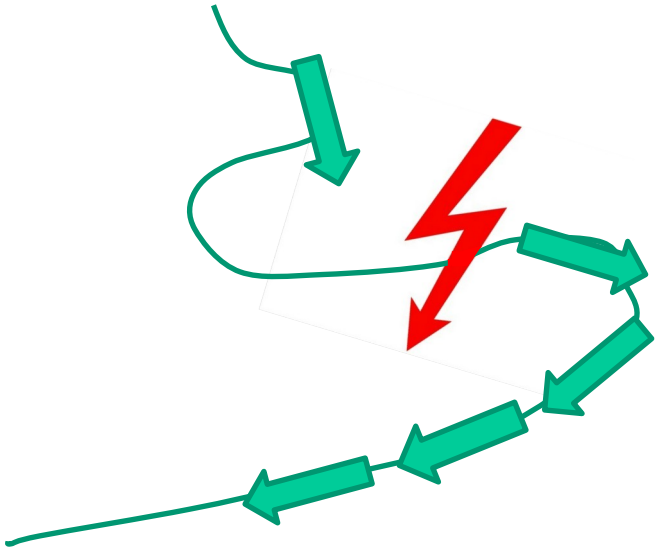


a, The orbital motion of a supermassive black hole binary leads to the precession of the jet on the surface of a cone with opening angle Ω, at an angle θ from the observer's line of sight. **b**, A misalignment of the supermassive black hole spin (orange arrow) with the accretion disk angular momentum (grey arrow) leads to the Lense–Thirring effect and the precession of the relativistic jet (green line).

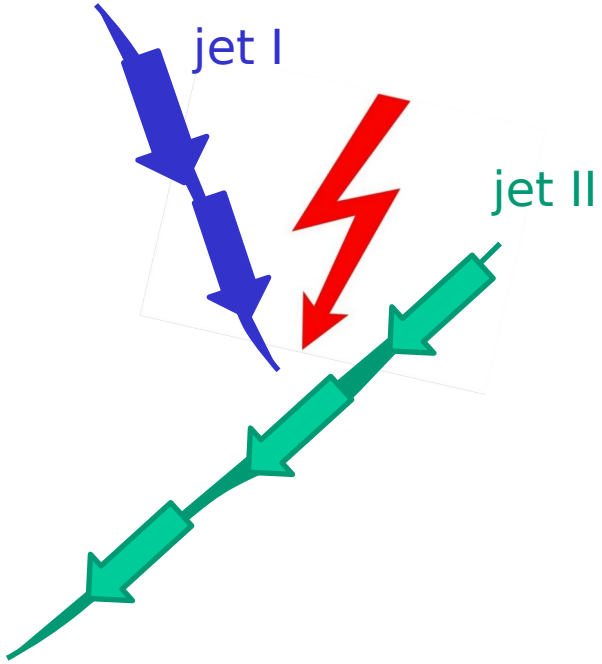
Abraham, Nature Astronomy, 2018

1Jet or 2Jet-scenario ?

In any case: jet collision !!



a strongly curved jet,
very special viewing angle

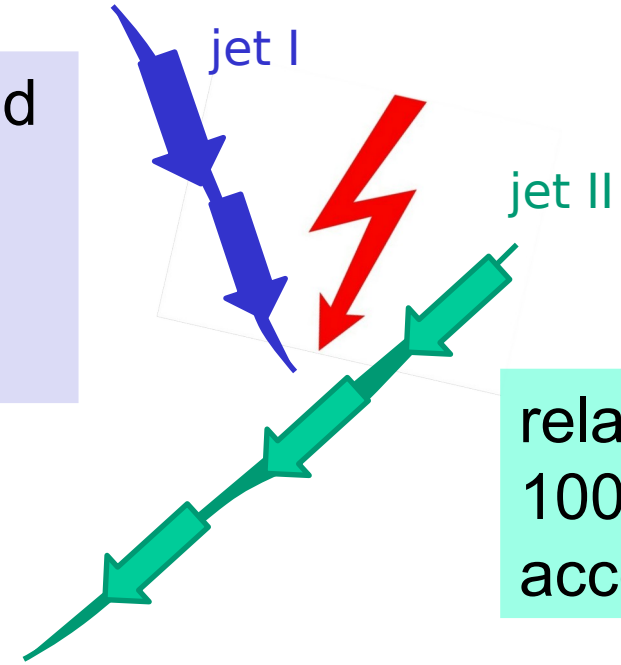


2 jets on a collision-course

Photo-hadronic interactions in the jet(s) of TXS 0506+056

synchrotron photon field (X-rays) of jet I acts as target photon field for

$p\gamma$ pion production

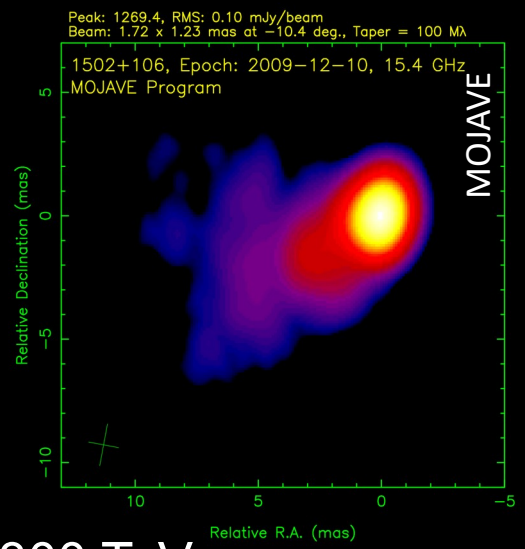


relativistic protons in the 100 TeV-10 PeV range accelerated in jet II

large velocity difference between both jets required to explain 2014/15 neutrino flare

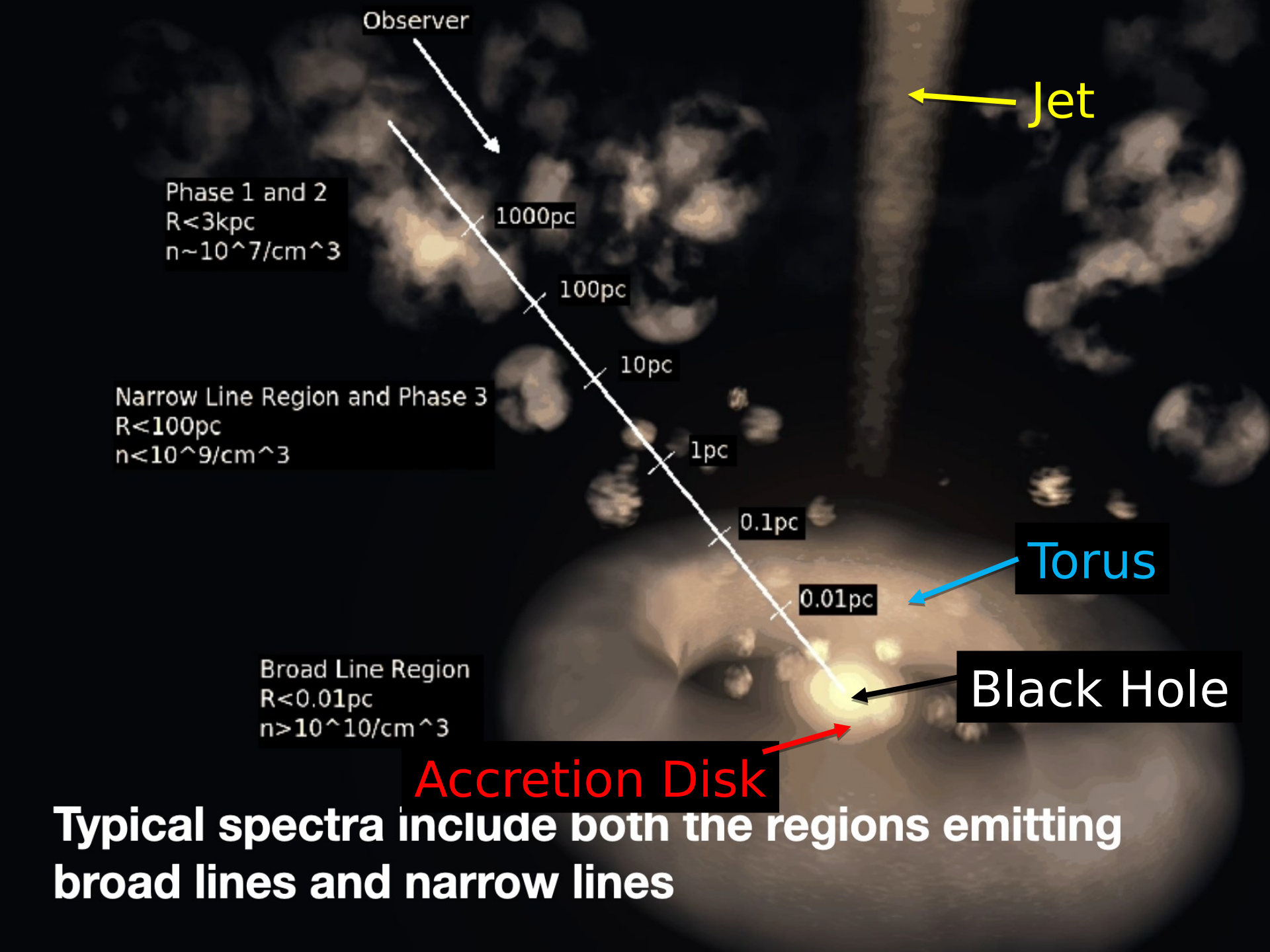
A cosmic laboratory: PKS 1502+106

A spatial coincidence: IceCube190730A with PKS 1502+106

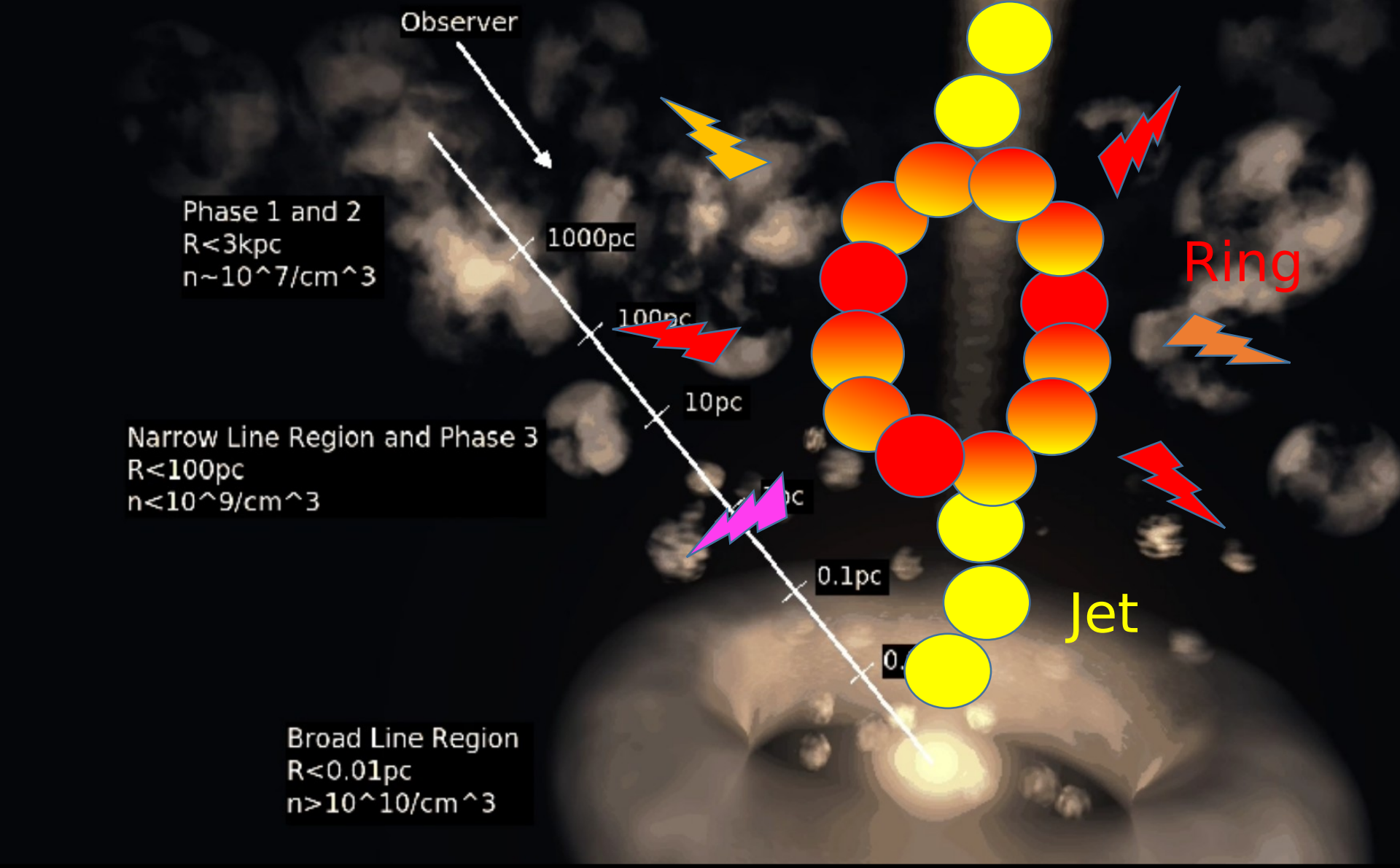


- IceCube-190730 has an estimated neutrino energy of 300 TeV
- the 15th brightest gamma-ray source at > 100 MeV in terms of energy flux (among 2863 sources in the fourth catalog of AGN detected by Fermi-LAT, Ajello et al. 2019)
- large redshift: 1.84 => extremely high intrinsic luminosity
- highly variable in the gamma-ray band (e.g., Abdo et al. 2010)
- broad emission line, flat-spectrum radio quasar, highly polarized
- has been studied across the electromagnetic spectrum (e.g., Zensus et al. 2002, An et al. 2004, Pian et al. 2011, Karamanavis et al. 2016, Ding et al. 2019)

- We had a closer look ...

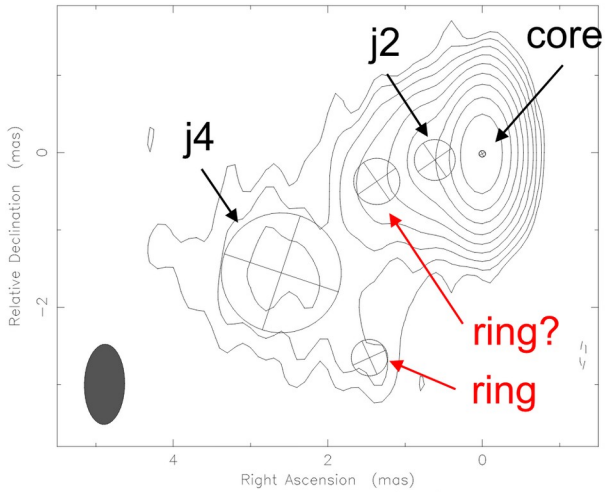


Typical spectra include both the regions emitting broad lines and narrow lines

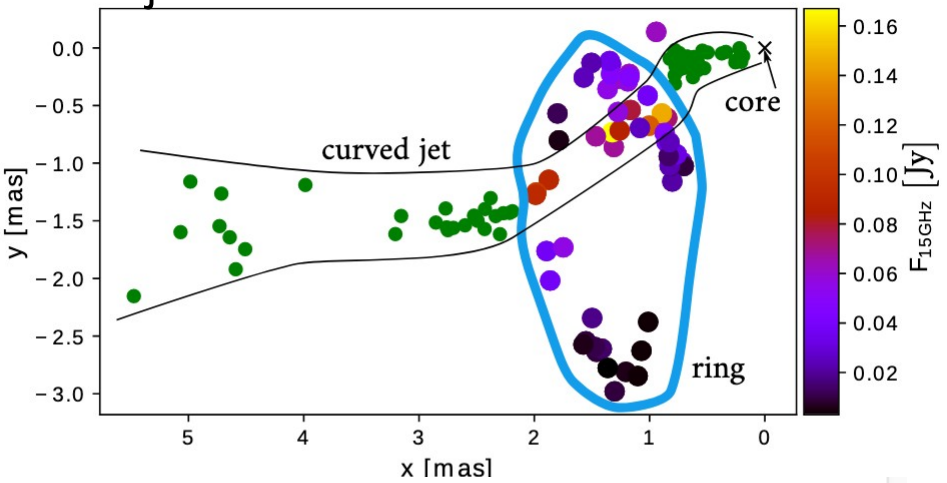


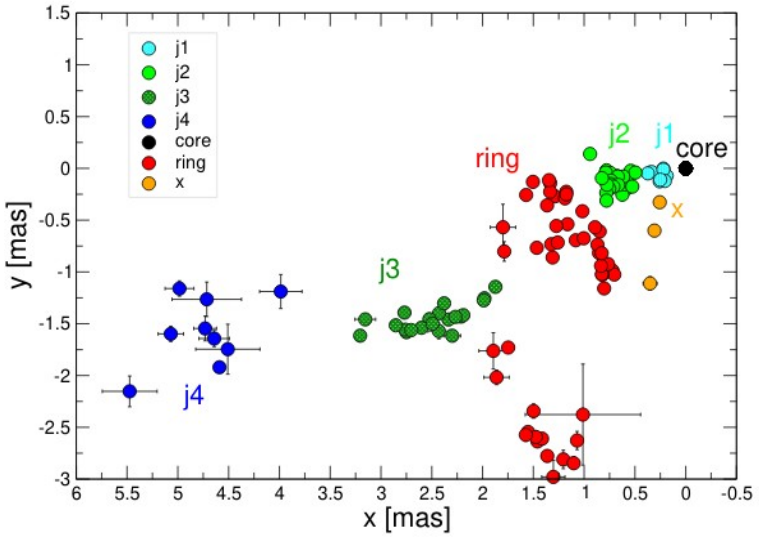
very not-to-scale, just a sketch

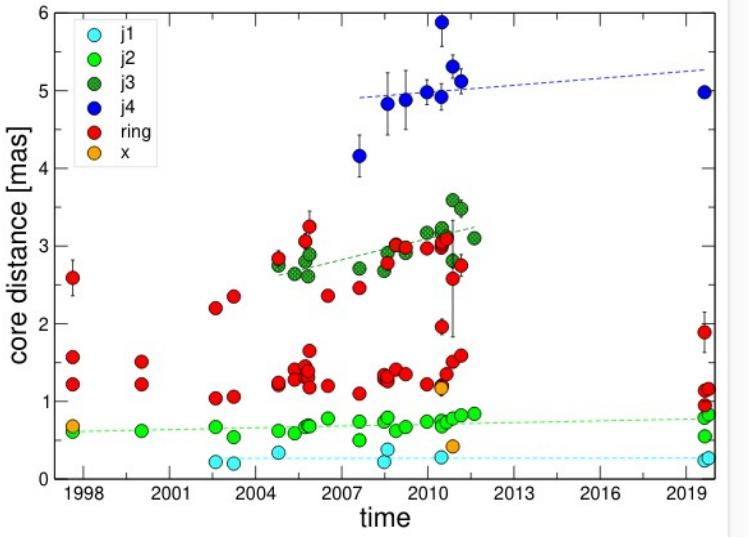
VLBI: Jet kinematics (re-analysis of MOJAVE data)



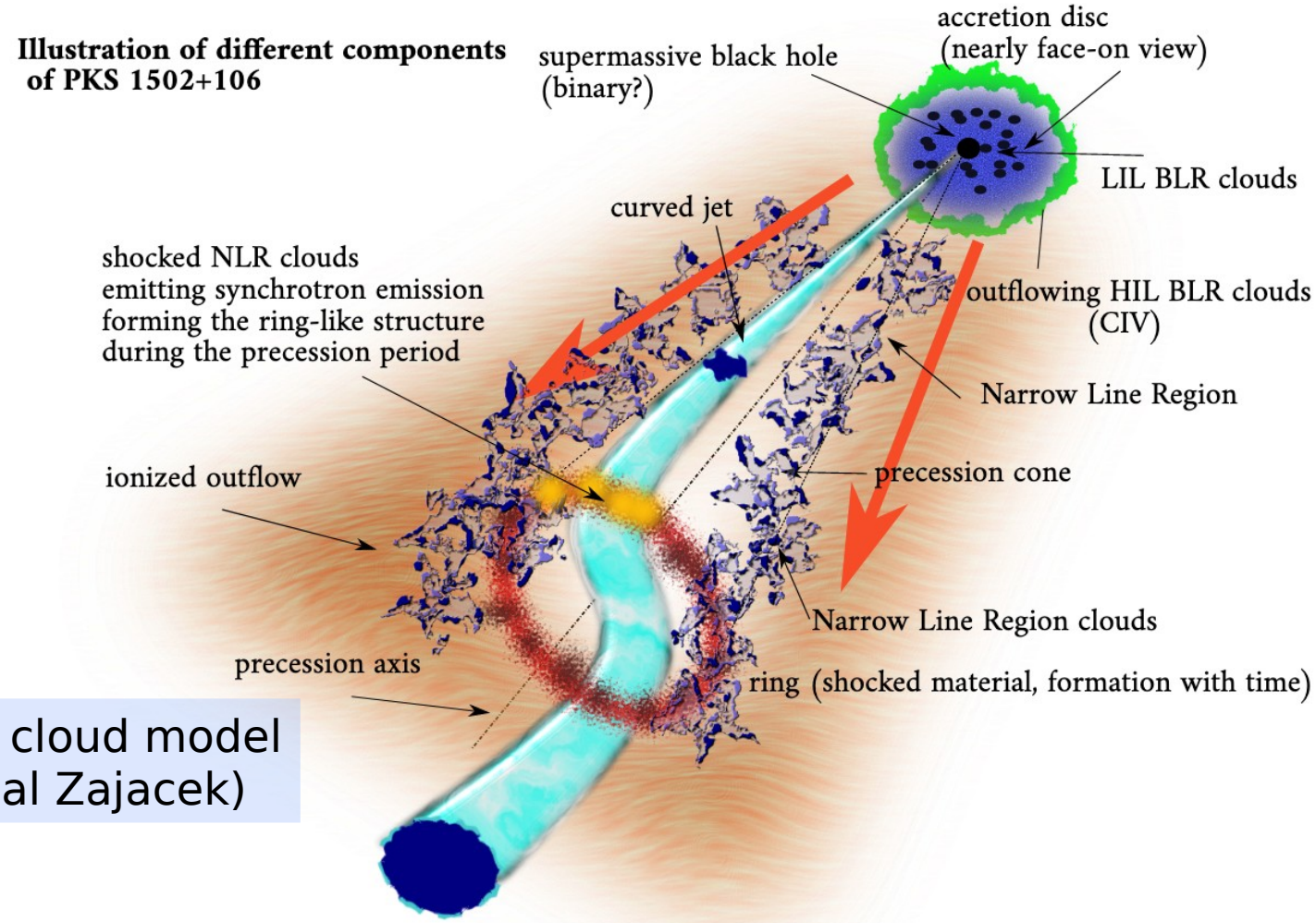
jet evolution: 1997 - 2020







Britzen et al., 2021, arXiv:2103.00292



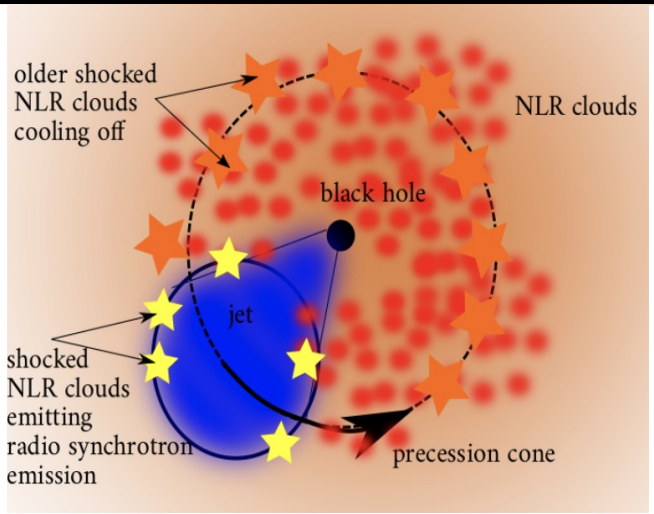
collisional cloud model
(by Michal Zajacek)

Figure 17. Illustration of different components of PKS 1502+106. In particular, we depict a curved jet whose axis is close to the line of sight. The jet as a whole is precessing around a precession axis. The interaction of the curved precessing jet with the ionized outflow, in particular the denser narrow-line region clouds, may be responsible for the formation of the ring structure with time. Closer to the supermassive black hole or potentially a binary black-hole system, we show the narrow line region and the low- and high-ionization broad line region clouds (LIL and HIL BLR clouds). The HIL BLR material traced by C IV broad line is blueshifted and therefore is outflowing.

Britzen et al., 2021, arXiv:2103.00292

Putting the pieces together

The energies are sufficient to produce **neutrinos** via **proton-proton interaction**. In the case of flaring activities and episodic encounters of the jet with dense clouds, the pp-process can be efficient. Confirmed by Wang & Xue 2021.



The outflowing BLR provides the external radiation field for **gamma-ray** production via **external Compton scattering**. The **spine-sheath** scenario supports this **EC emission beyond the BLR**.

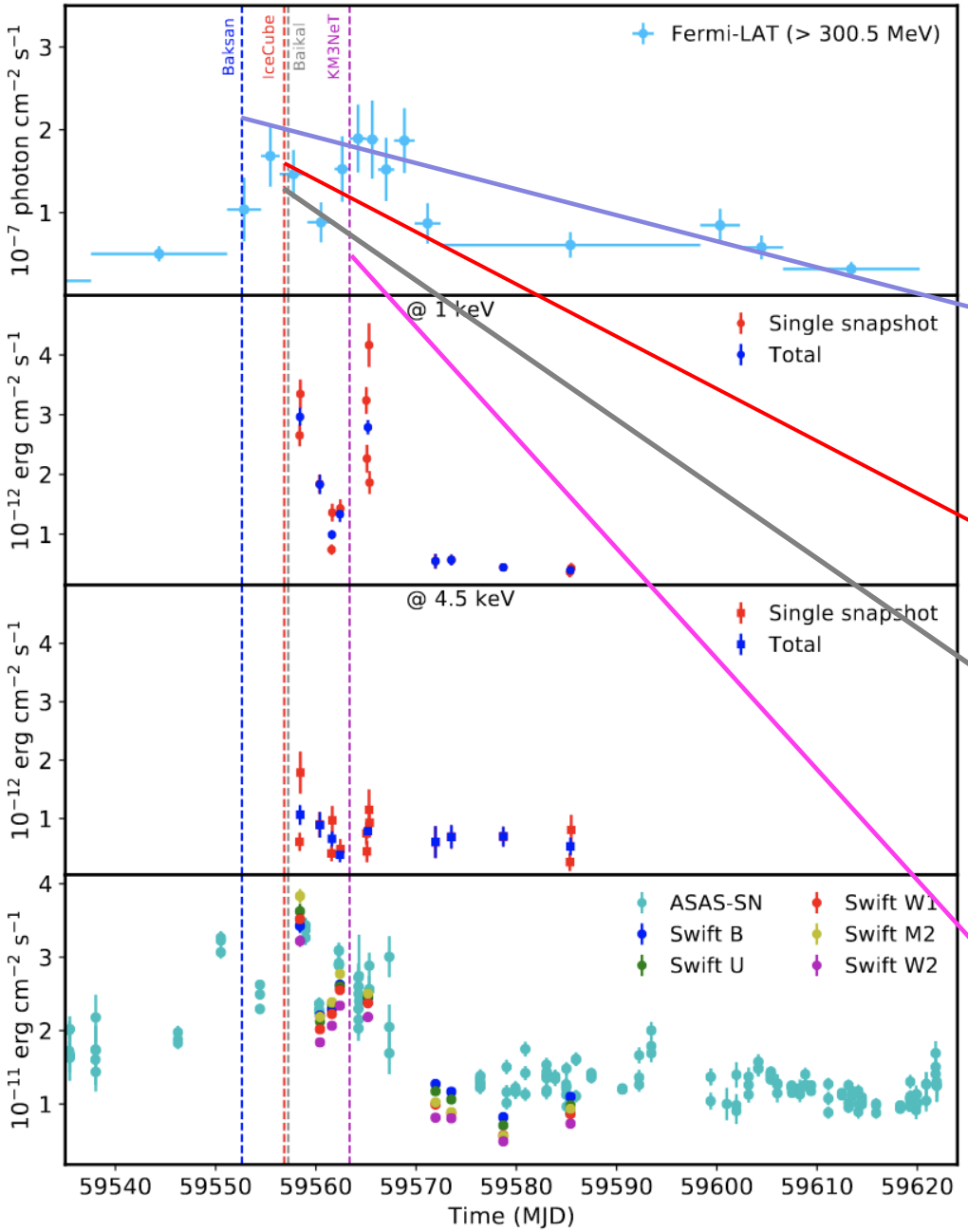
- Based on the gamma-ray variability timescale, we constrain the gamma-ray emission zone to the **BLR** and within the **jet launching region.**

Supported by independent SED-modeling by *Rodrigues et al. (2020).*

- Superposition of **deterministic** and stochastic processes in the light-curves.

Supported by *Bhatta et al. (2020*): PKS 1502+106 is the most **deterministic source** in a sample of 20 gamma-bright AGN.

AGN physics at its best: PKS 0735+178



Baikal-GVD

Figure 2. Multi-frequency light-curves near the time of detection of IceCube-211208A .

Sahakyan et al. 2022, arXiv:2204.05060

PKS 0735+178

- LSP BL Lac
- redshift unknown
- variable
- variable at Gamma-rays
- no TeV-detection
- ...

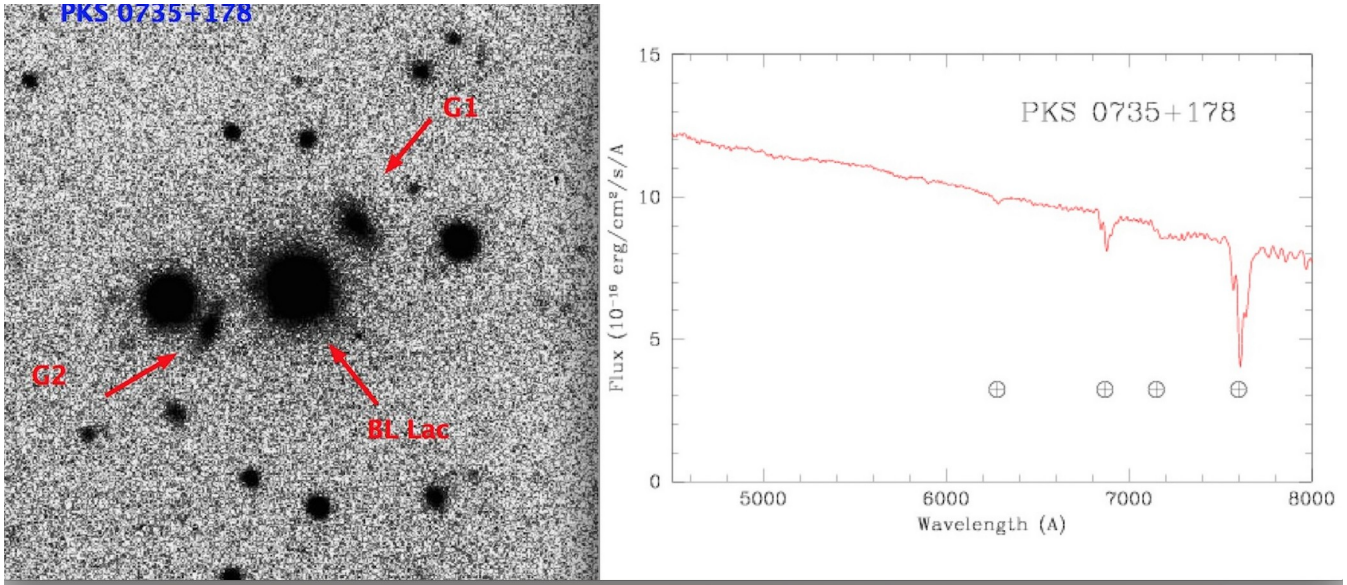
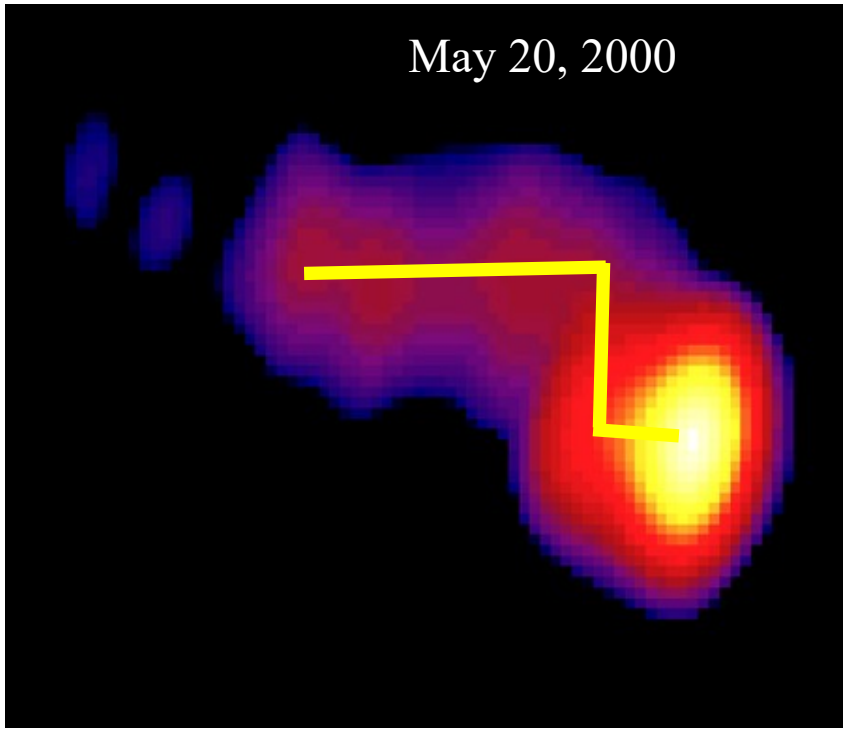
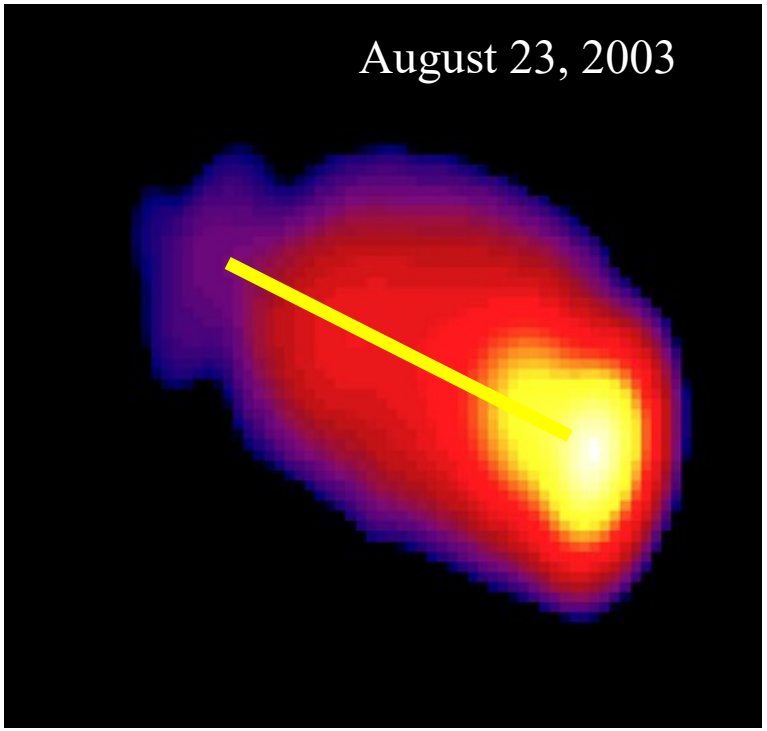


Figure 1 . Left: The BL Lac object PKS 0735+17 imaged by NTT+SUSI (R filter). Two close companion galaxies are clearly detected (G1 is at z =0.65). Field shown is 52 arcsec and North-East is at the top-left side. Falomo and Ulrich 2000) Right: The optical spectrum of PKS 0735+178 obtained at VLT+FORS (Landoni et al 2013) . The spectrum is also available in the database ZBLLAC (https://web.oapd.inaf.it/zbllac/).



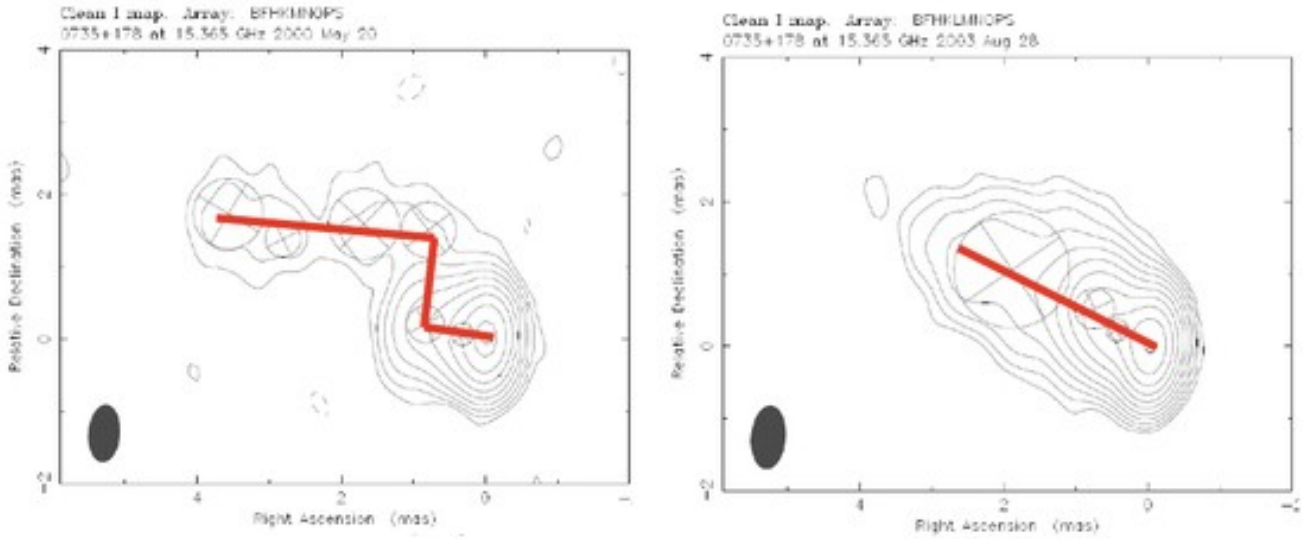


Images from MOJAVE webpage.

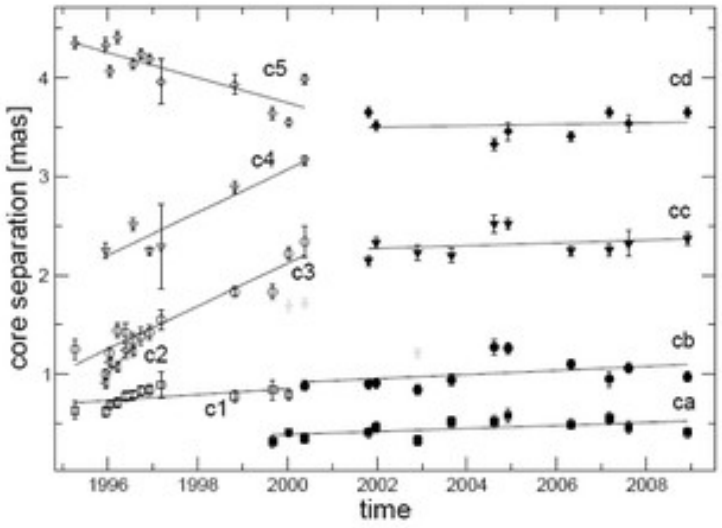
Britzen et al. 201

0735+178 - Switching between apparent stationarity and apparent superluminal motion

Two images of the same Active Galactic Nucleus (a BL Lac Object) at different times.



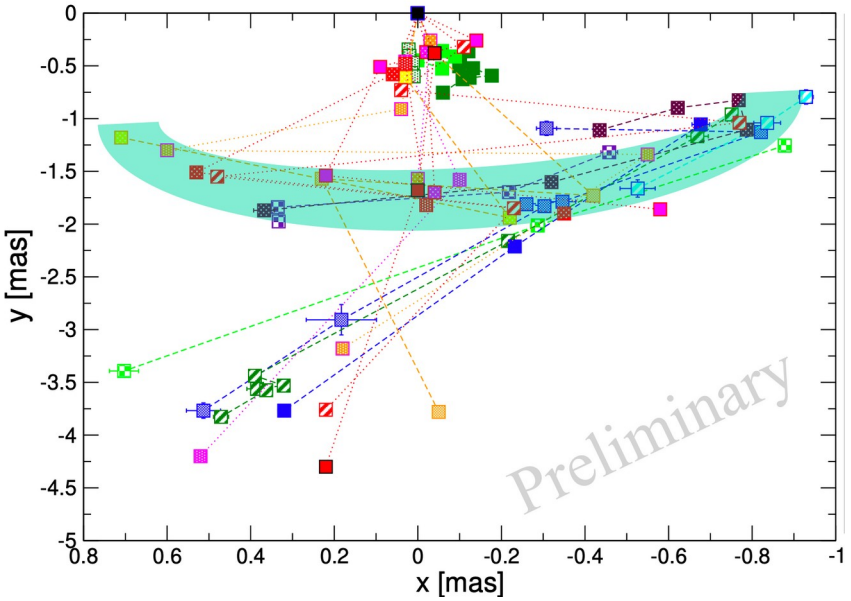
And the corresponding kinematic behaviour of the jet components.



Thus - apparent superluminal motion seems to be a **state/phase** of an Active Galactic Nucleus and can change (Britzen et al., 2010, A&A, 515, 105).

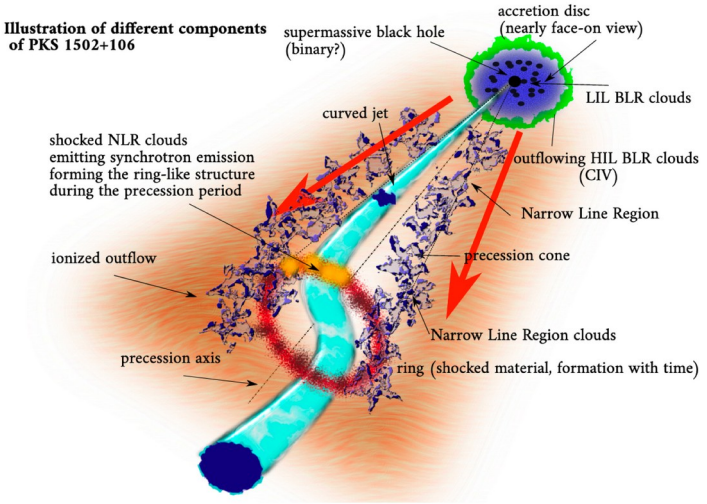
Interaction (jet with something) plays an important role

TXS 0506+056



- untypical VLBI results
- only visible in long-term VLBA data (kinematic) analysis
- Interaction of the jet with jetted material (or another jet)

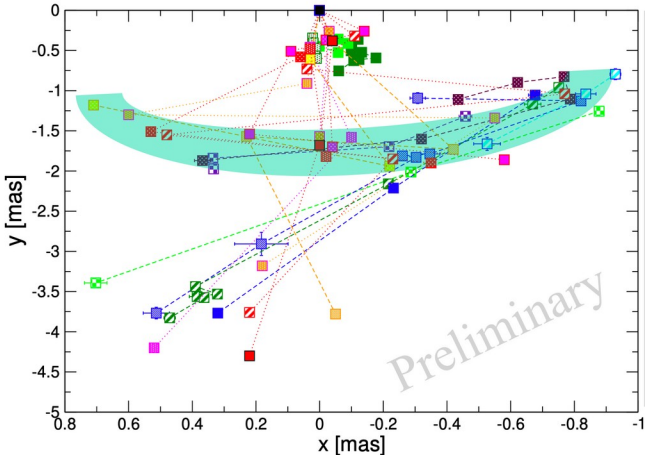
PKS 1502+106



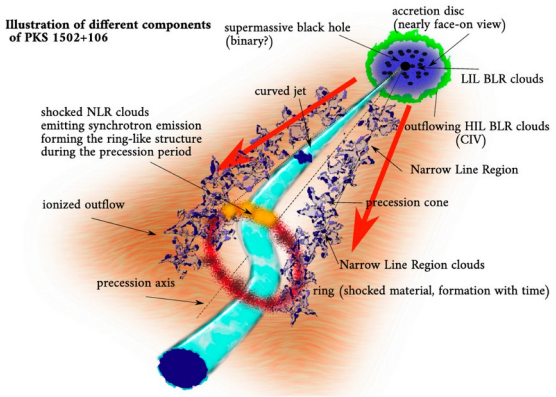
- untypical VLBI results
- only visible in long-term VLBA data (kinematic) analysis
- Interaction of the jet with outflowing BLR, dense NLR clouds

Evidence for precession

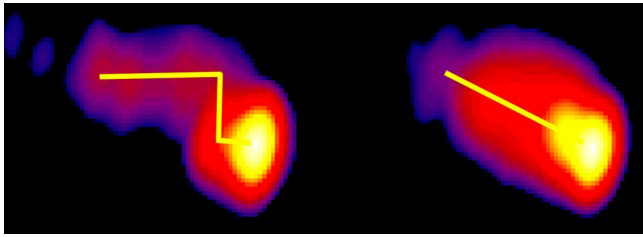
TXS 0506+056

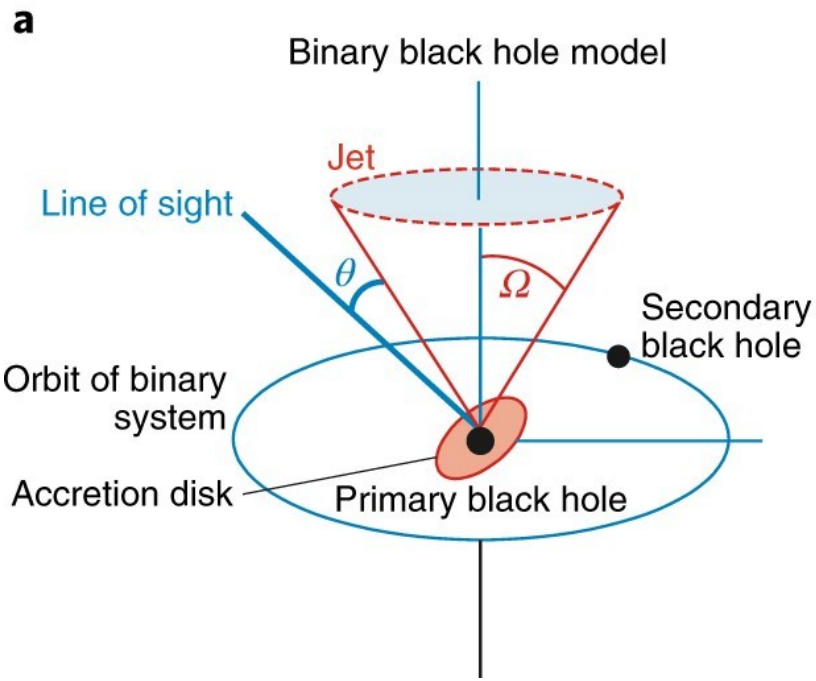


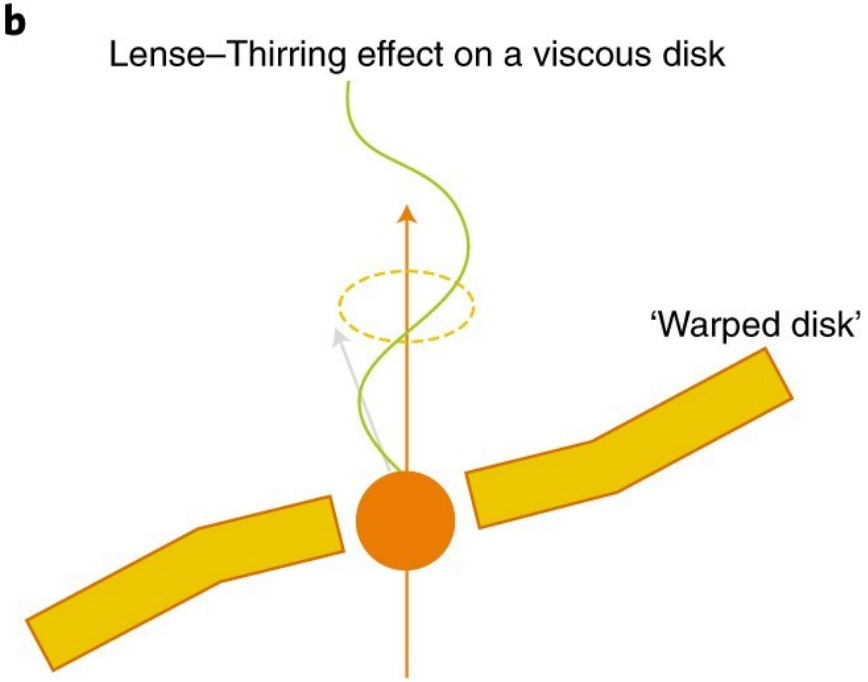
PKS 1502+106



PKS 0735+178







... and a lot more exciting physics to explore !

- Neutrino emission acts as **spotlight** and allows us to explore the astrophysics of jets!

- Those neutrino emitters analysed so far: special and unique (interaction, precession, binary black hole candidates, high polarisation, spine-sheath scenario, etc.) – they might represent extreme representatives of the blazar class.

- AGN variability & AGN kinematics can be predictable. A superposition of **deterministic and stochastic processes** seems to be linked to the neutrino emission.

- **Neutrino-AGN**: High potential for a better understanding of jet and black hole physics ...

Thanks a lot for your attention !