Astronomical Plate Archives and Supermassive Black Hole Binaries

René Hudec

Astronomical Institute, Academy of Sciences of the Czech Republic, Ondřejov, Czech Republic

Czech Technical University in Prague

Motivation

- Numerous HE/VHE/UHE sources are also emitters of optical light
- Many of them are variable
- The astronomical plate archives represent the only method how to study the behaviour of the objects over very long (100 years or even more) time intervals
- In addition, huge monitoring times allowing to detect and to study rare events such as flares

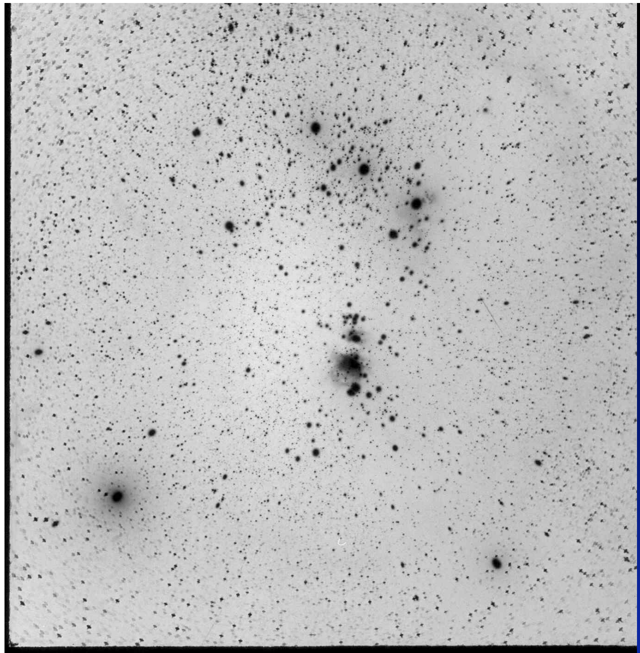
The Astronomical Photographic Plate Archives

There are more than 5 millions astronomical plates in the world, lim mag up to 23, > 5 x 5 deg in most cases

Importance of astronomical plates in HE/VHE/astroparticle astrophysics

Providing supplementary observational data for objects with optical counterparts on:

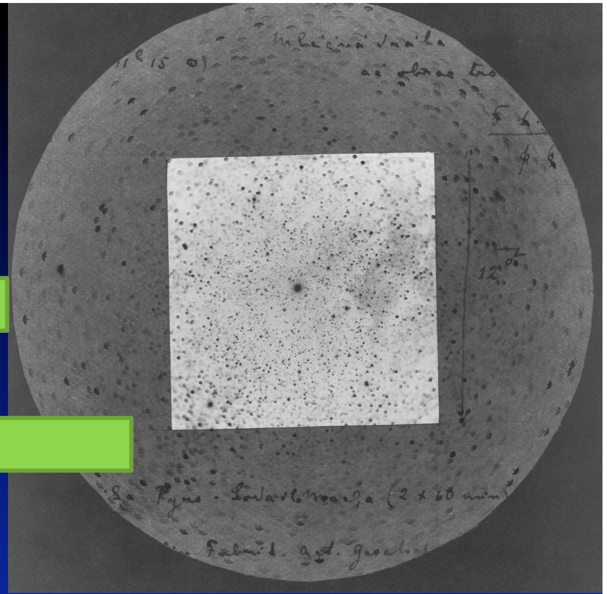
- **long-time evolution up to > 100 years**
- **flaring activity**
- **In some cases fine sensitivity (mag 20-23)**
- **In some cases spectra (up to mag 18)**
- **In some cases ability to study short-term time variations ~mins**
- **Huge amounts of measurements: typical plate has ~ 1 mil. objects, several millions of plates… ~ 10^{12} data points**
- **Huge amounts of continuous monitoring of particular object e.g. to detect rare flares (recently ~26 000 hrs)**
- **Data are (almost) free of charge**

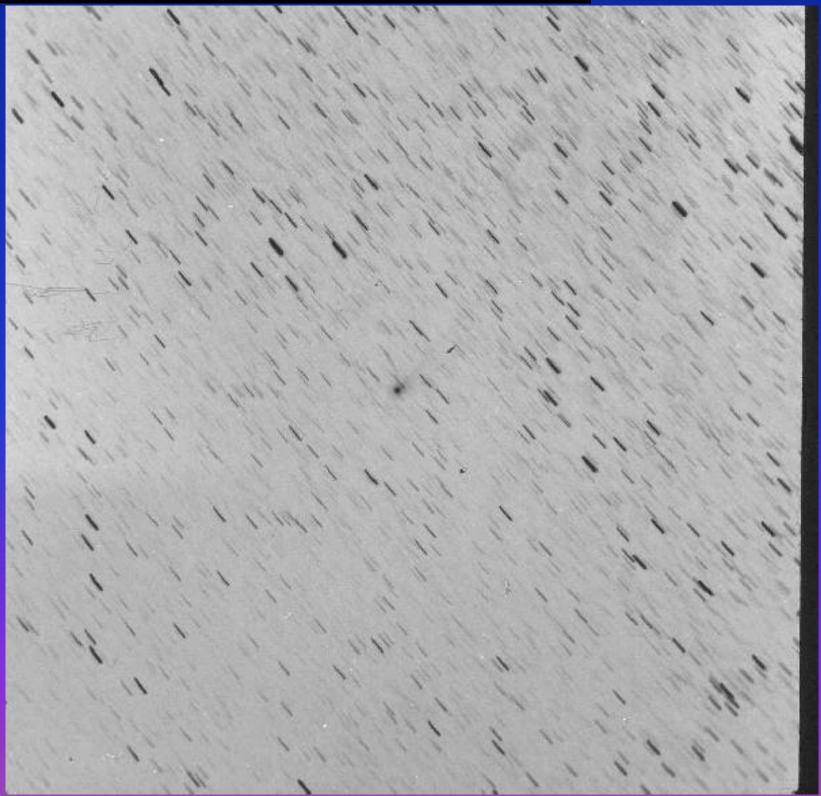


Historical photographic plates, around 1895, Ondřejov Observatory

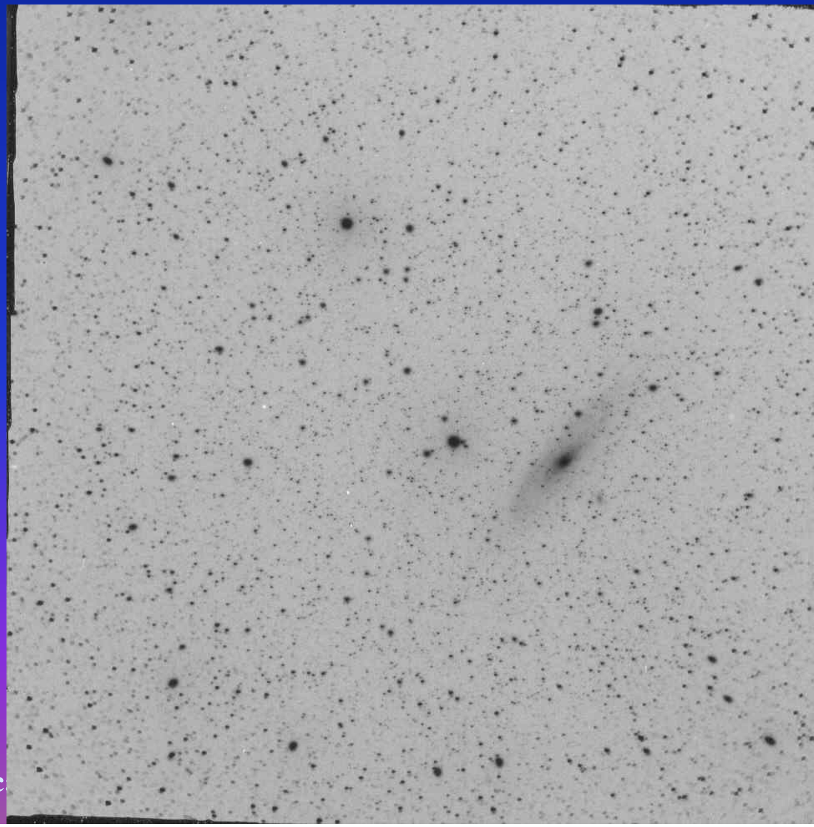
Time machine

Sky 117 years ago





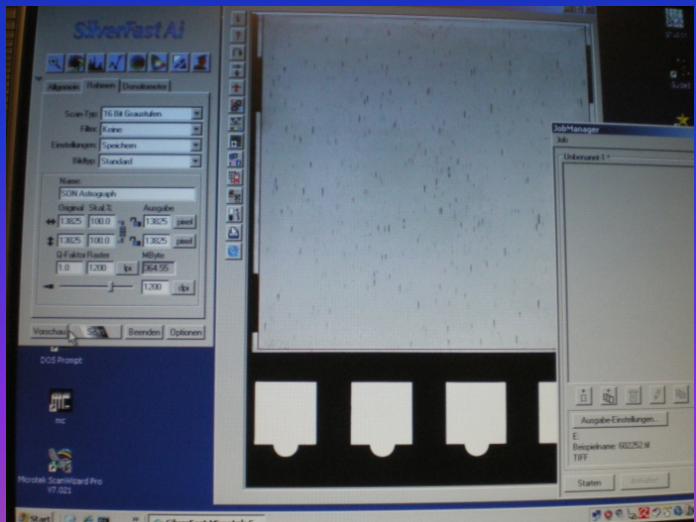
Vulc



Norbert Polko: 240 000 plates scanned: worlds record

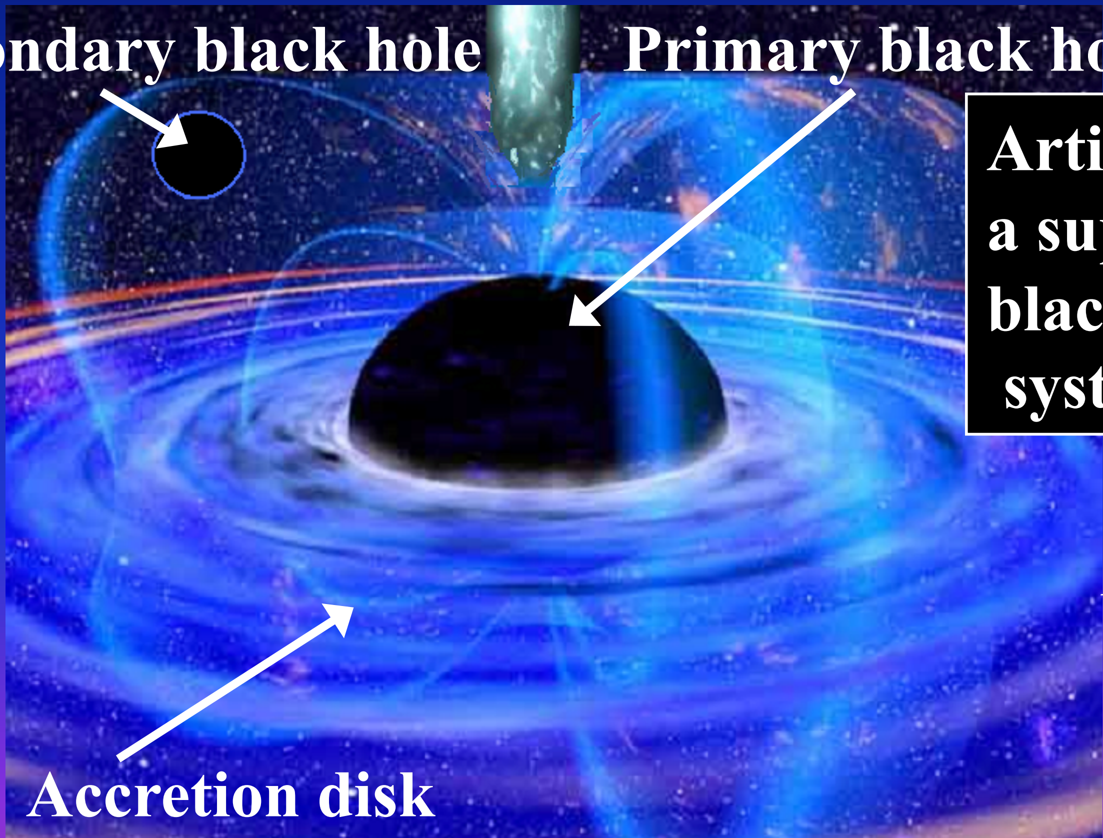
Scanning efforts at Sonneberg Observatory more than 240 000 plates already scanned

Converting plates to image files




Binary Blazars - Objects with
Binary Supermassive
Black Hole

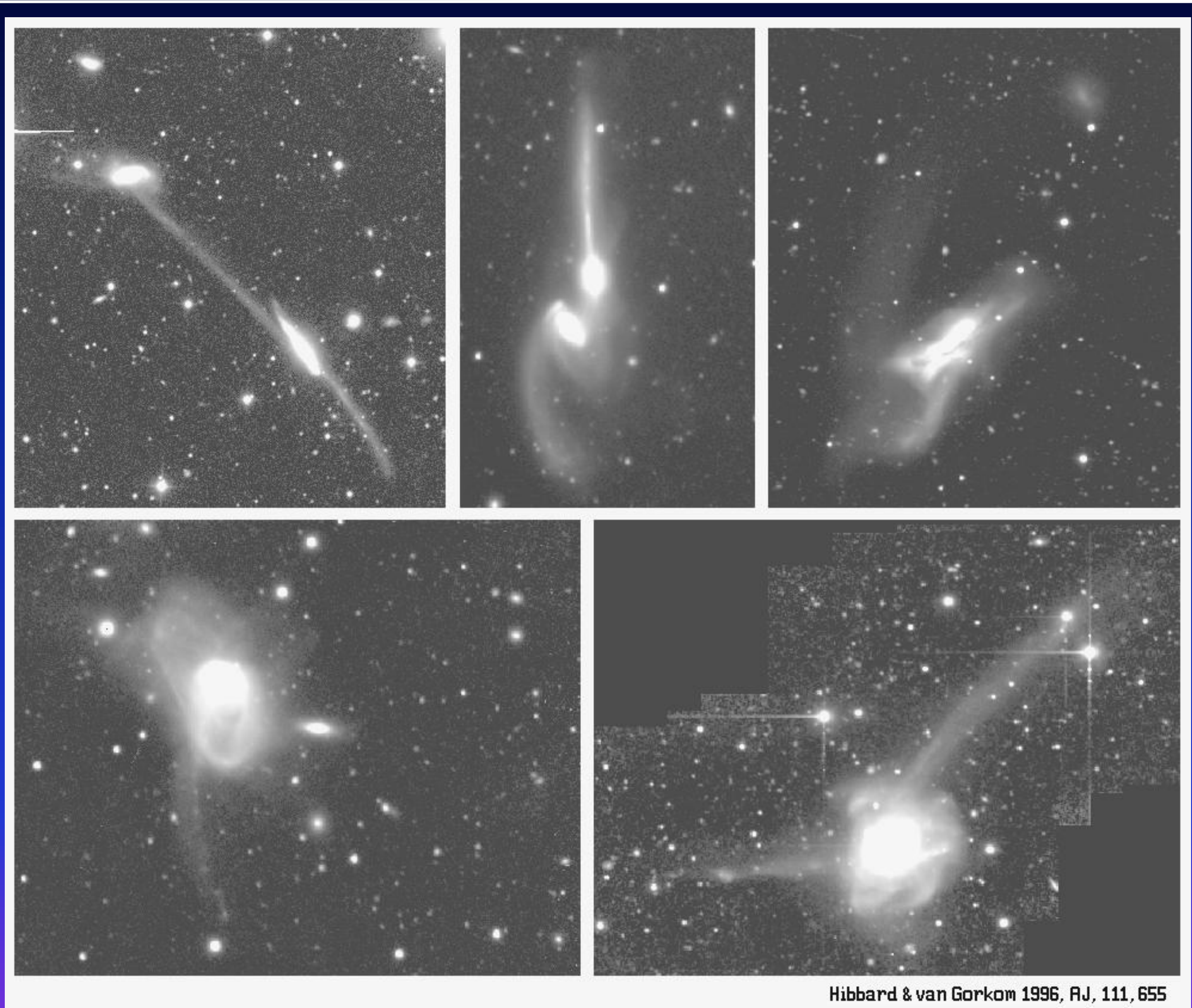
There are quite a lot of suggestions that not ONE black hole but TWO are present in some blazars . . .



Artist's conception of a supermassive binary black hole (= BBH) system

- *Volonteri et al., 2003* *BBHs should be common*
- *There is observational evidence for BBHs*

Origin of Binary Black Holes (= BBHs)



Hibbard & van Gorkom, 1996

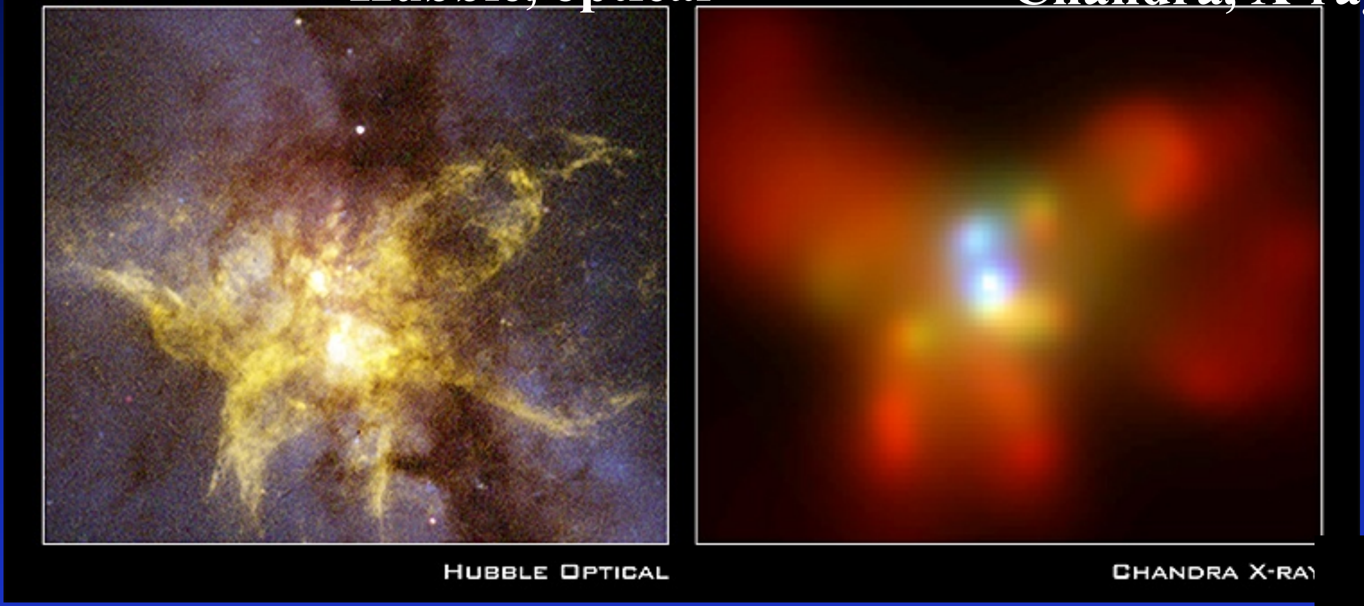
The origin of the binary black hole system is in the merging of galaxies

If each galaxy contains a supermassive black hole → a binary black hole system is formed (frequent in clusters)

Observational evidence for BBH systems

- **NGC 6240**

Hubble, optical **Chandra, X-ray**

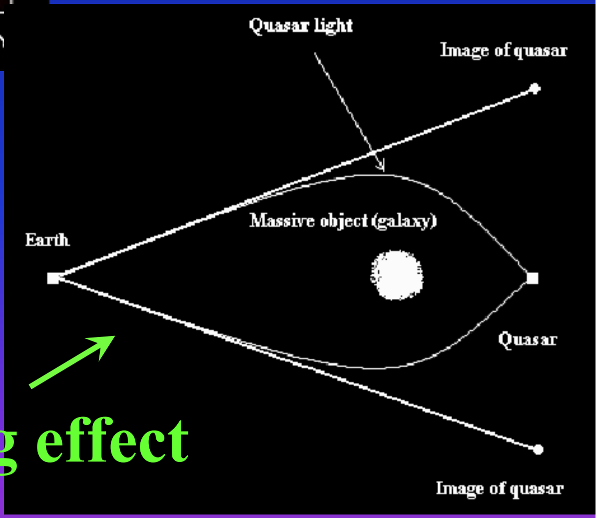


Komossa et al., 2003

- **High-redshift quasars observed in pairs**

Q1343.4+2640, LBQS0103-2753, UM425,...

Komossa, 2003



True pairs x Chance alignments x Lensing effect

Our blazar sample - suspected periodicity (Part I)

Within the following blazars indications for periodicity were found

1. ON 231

Possible periodicities:

- 13.6 years in optical (Liu et al., 1995)

2. Mkn 421

Possible periodicities:

- 23 years in the optical band (Liu et al., 1997)
- 10^4 second variations in the X-ray band (Marashi et al., 1999)

3. 0109+224

Possible periodicities:

- Long-term oscillations of the base-level flux on a timescale of about 11.6 years (Smith & Nair, 1995)

4. Mkn 501

Possible periodicities:

- 23 days in the X-ray and TeV band (Nishikawa et al., 1999)

Our blazar sample (Part II)

Several of the candidates are TeV sources

5. **Mkn 766**

Possible periodicities:

- **4200 seconds in the X-ray band (Boller et al., 2001)**

6. **3C 345**

Possible periodicities:

- **5 and 11 years in the optical band (Caproni & Abraham, 2004)**

7. **AO 0235+16**

Possible periodicities:

- **5.7 years in the radio light curve (Raiteri et al., 2001)**
- **2.95 years in the optical light curve (Fan et al., 2002)**

8. **3C 279**

Possible periodicities:

- **7.1 years in the long-term near infrared light curve (Fan, 1999)**
- **22-year period from movement of jet components (Abraham & Carrara, 1998)**

Our blazar sample (Part III) - except OJ287

9. PKS 0420-014

Possible periodicities:

- 13-months between optical major outbursts (Wagner et al., 1995)

10. 0716+714

Possible periodicities:

- 0.7-year quasi-periodic ejection of VLBA components (Jorstad et al., 2001)
- 12.5, 2.5 & 0.14-day periodicity of polarization in the optical band (Impey et al., 2000)
- 4-day periodicity in the optical band (Heidt & Wagner, 1996)

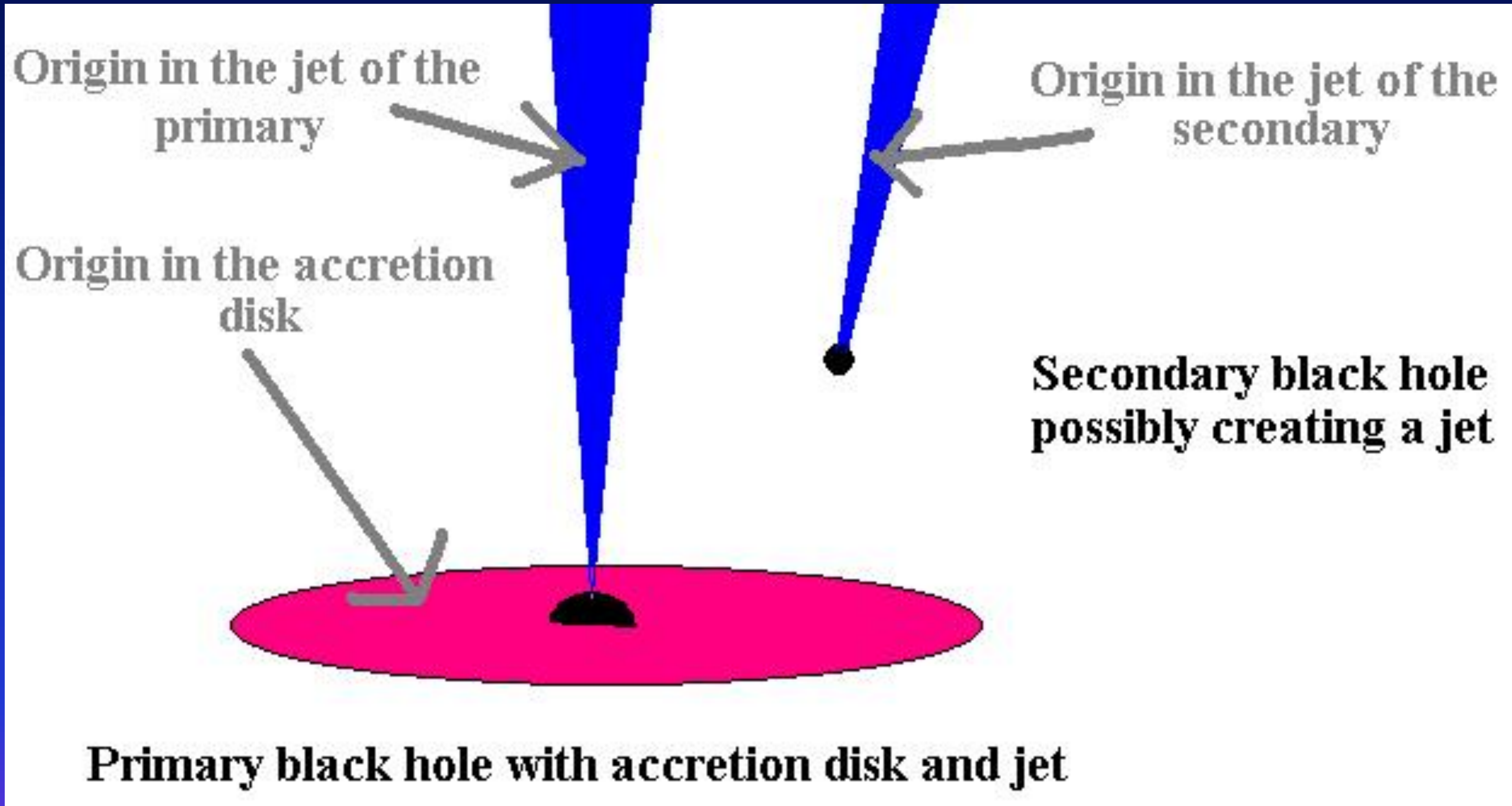
11. 3C 66a

Possible periodicities:

- 2.5 years (Belokon & Babadzhanyants, 2003), 275 and 64 days in the optical band (Marchenko, 1999; Lainela et al., 1999)

The periodicity in blazars may be an indication for a binary black hole nature

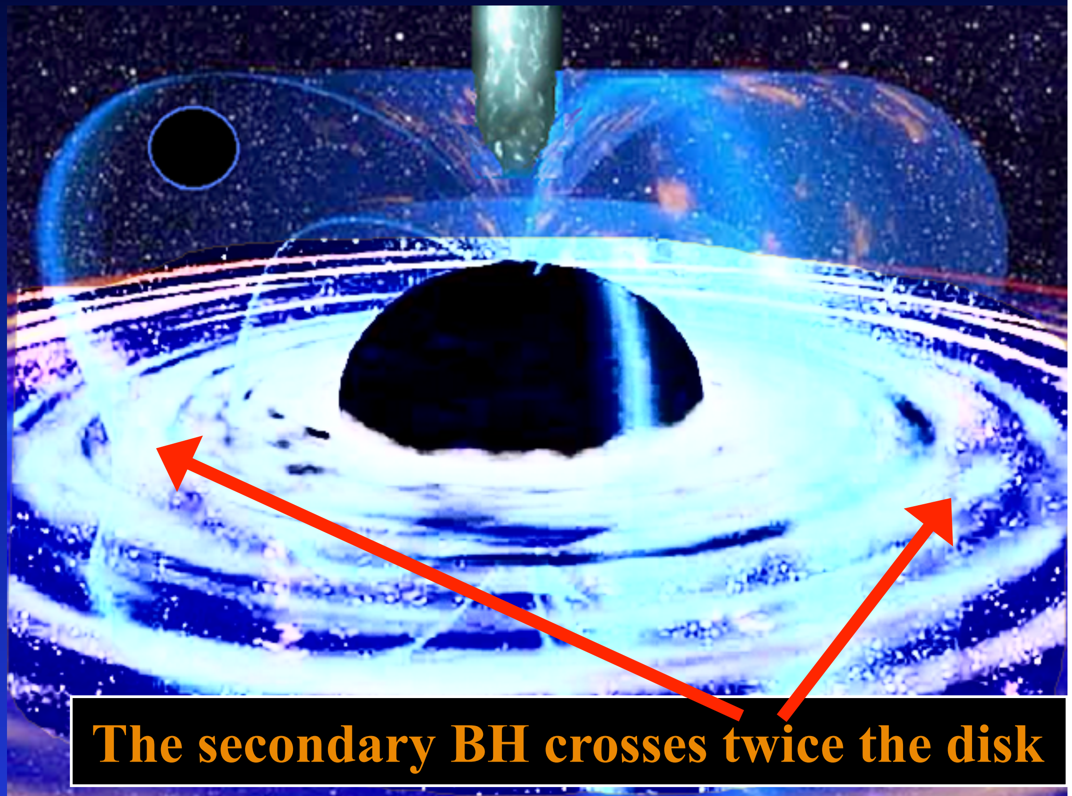
Possible origin of periods in blazars: many alternative models



It is necessary to observe the whole spectrum behavior and the behavior of colors and flares to be able to distinguish between different origin of periods in blazars.

Periodicity interpretation – origin in the accretion disk

- While the secondary is piercing a channel into the accretion disk of the primary the gas gets heated and radiates.
- Timing of the outbursts enables the determination of the orbital period.
- Color behavior may support or reject the origin of the periodicity in disk!!



The origin of the period in disk may be the case of blazar OJ 287:
"Predicting the next outburst of OJ 287", Valtonen, M.; Lehto, H., Hudec, R.; Basta, M. et al., 2006

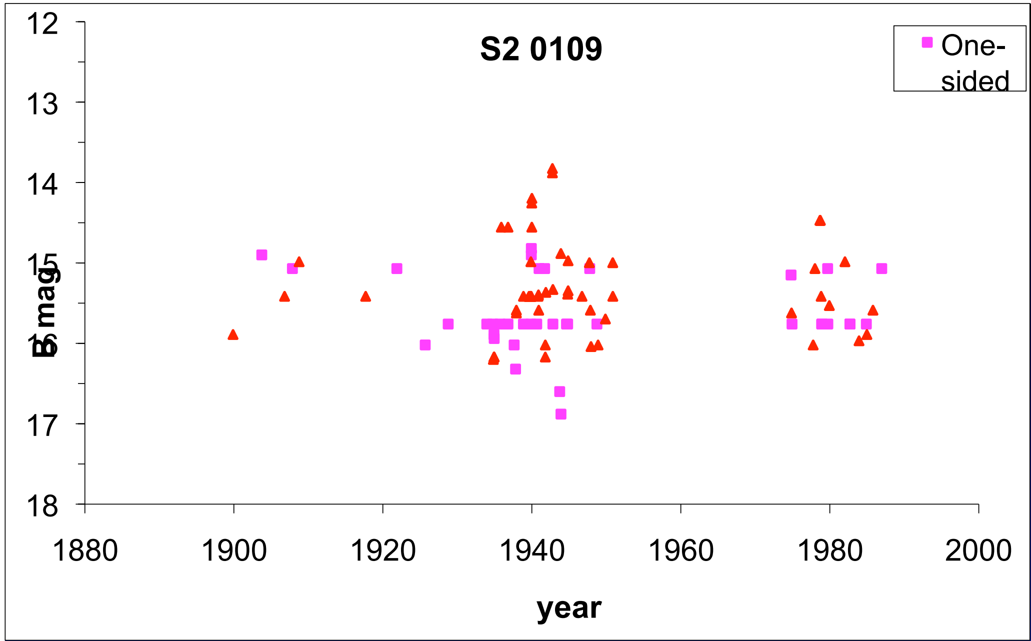
Harvard HCO Data Mining

The largest plate archive is suitable for data mining in the plate stacks with the intention to gather new historical data points for various astronomical objects (mainly blazars). During our stay we explored about 8,000 plates and obtained altogether more than 4,000 new data points including upper limits for 9 blazars (extragalactic objects), 3 cataclysmic variables and the McNeil's nebula star:

•Blazars (extragalactic objects):

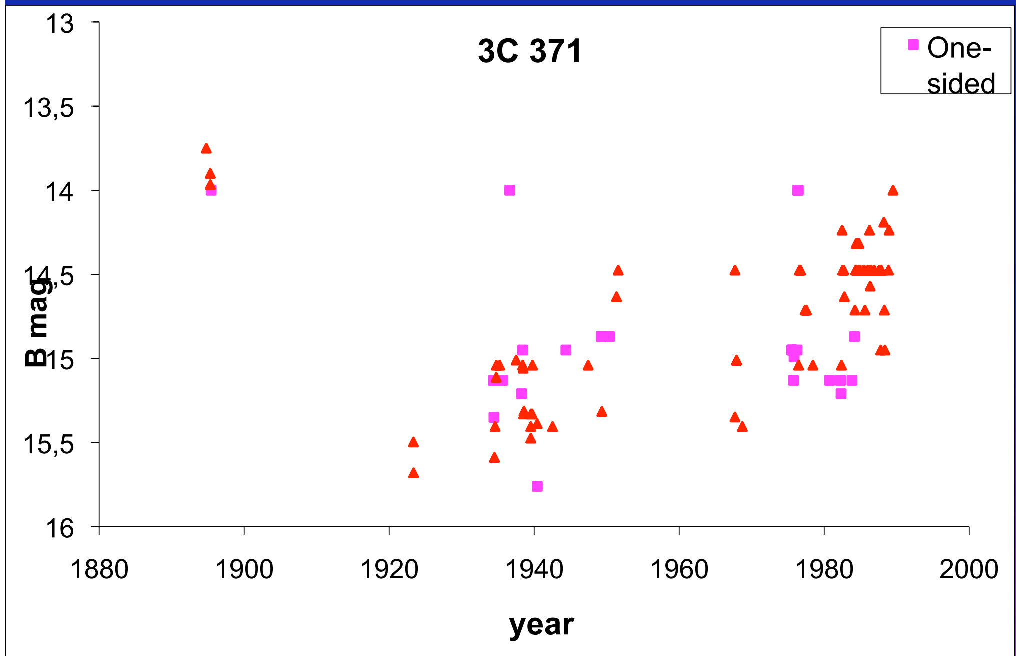
- **OJ287 (~ 550 recorded data points)**
- **3c66a (~ 400 rec. data p.)**
- **S20109+22 (~ 450 rec. data p.)**
- **S50716+71 (~ 450 rec. data p.)**
- **ON231 (~ 500 rec. data p.)**
- **Mrk421 (~ 550 rec. data p.)**
- **PKS2155-304 (~ 550 rec. data p.)**
- **3C371 (~ 250 rec. data p.)**
- **BL Lac (~ 150 rec. data p.)**

HCO plate stacks



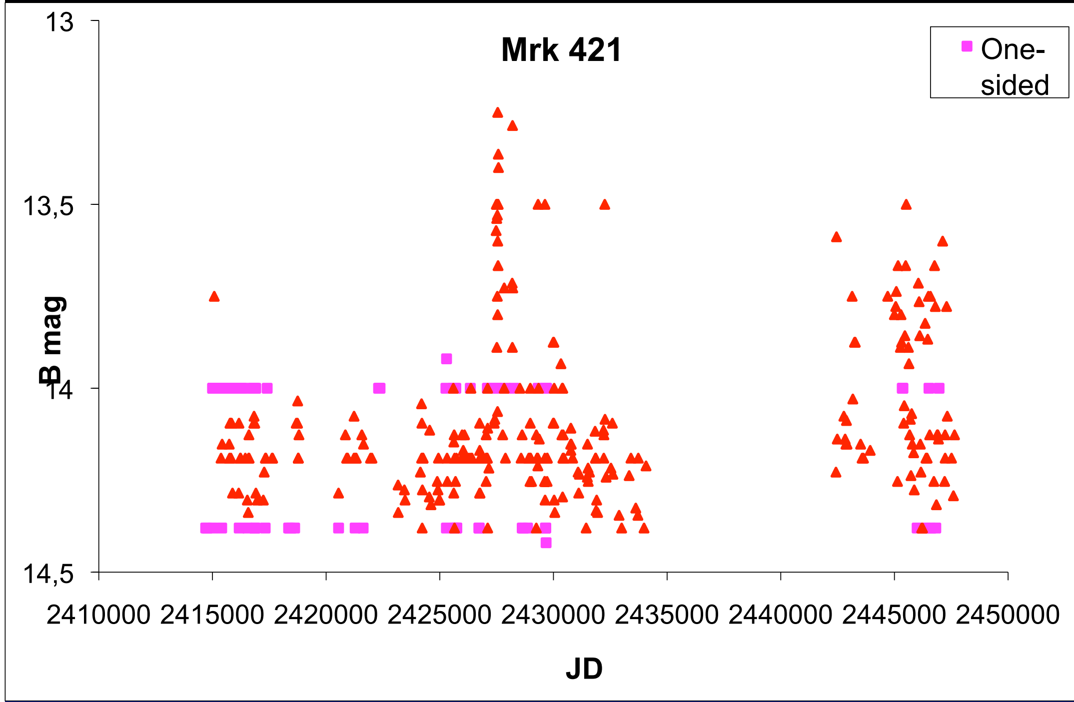
S2 0109

Two large flares revealed, separated by ~ 40 years, amplitude ~ 3 mag



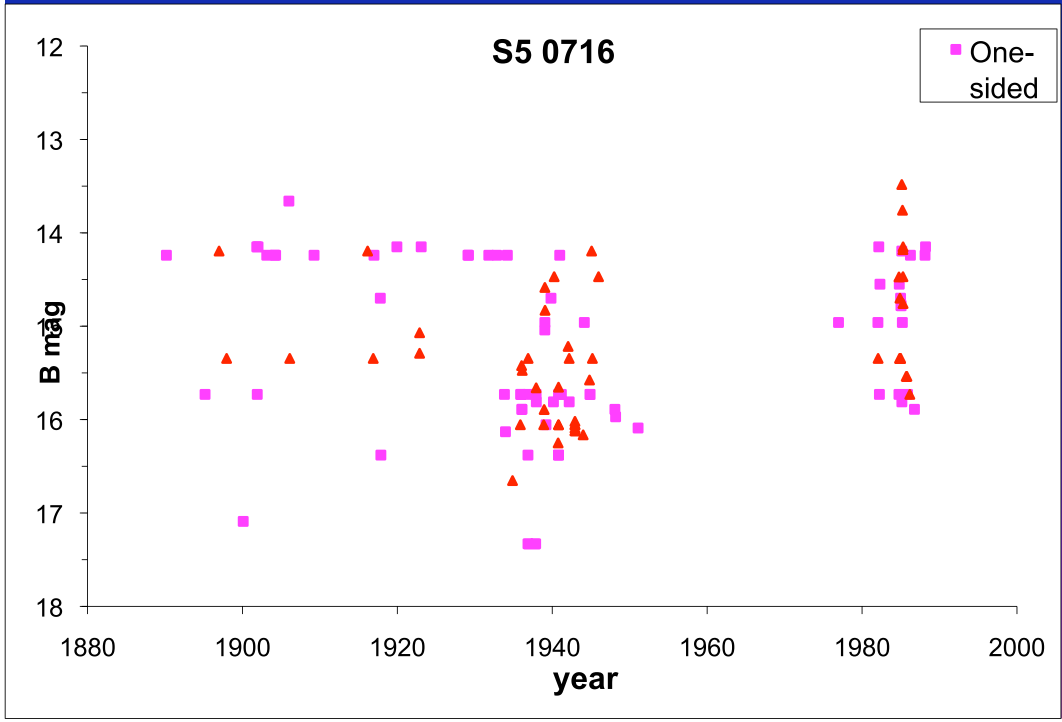
3C 371

4 flaring episodes revealed over ~100 years, amplitude ~2 mag



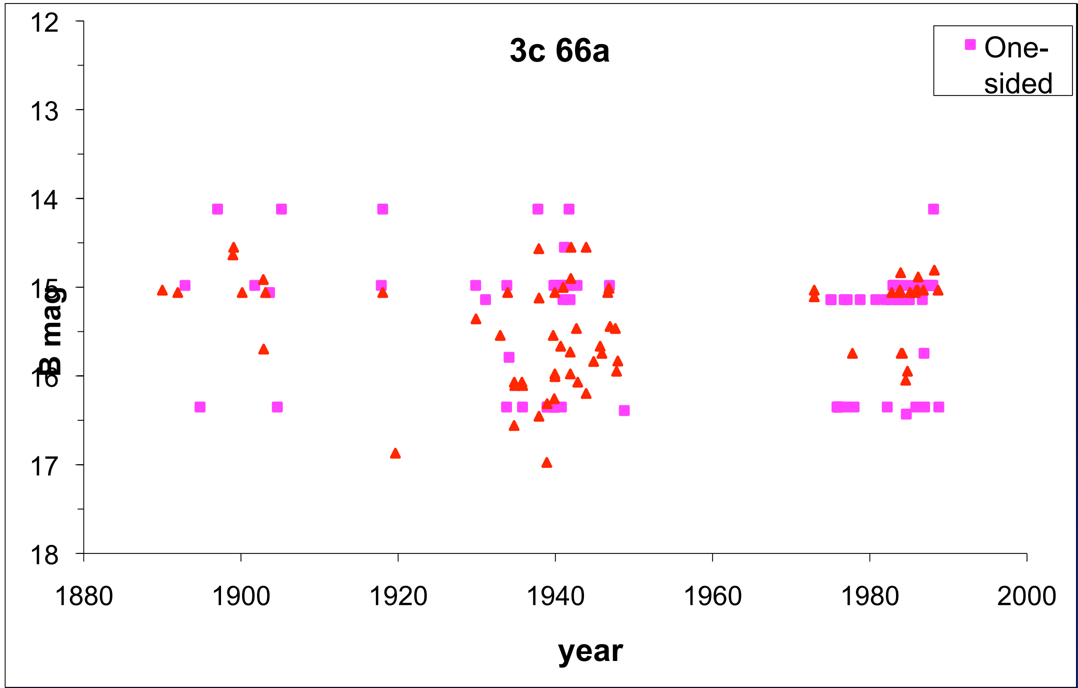
Mrk 421

7 sharp large flaring episodes revealed with fast rise and decline, one with large (~1.5 mag) amplitude



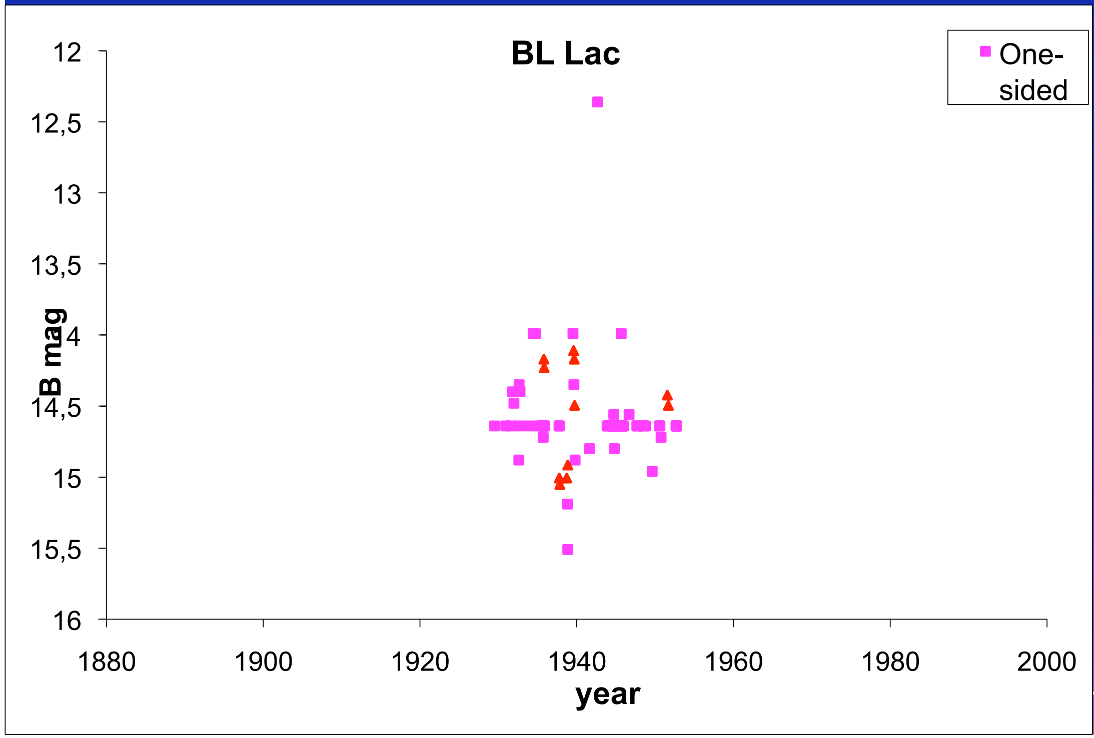
S5 0716

Violent long-term optical variability revealed, with at least 5 large flaring episodes



3C 66a

Several flaring episodes, amplitudes ~2 -3 mag

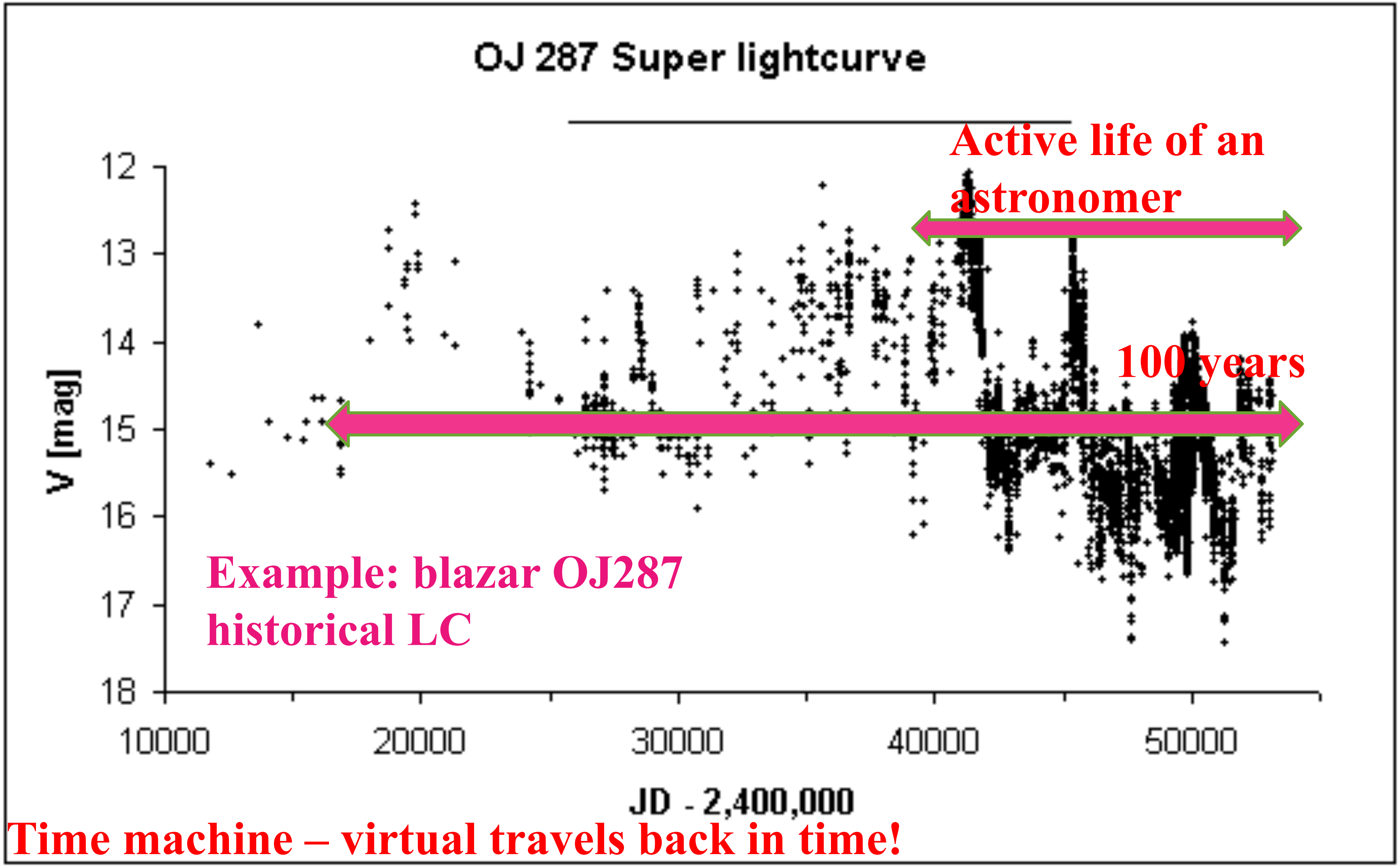


BL Lac

One large flaring episode after JD 2425000, none before (but bad sampling)

The OJ287 case

Blazar OJ287, the best candidate for supermassive black–hole binary



OJ287 - long term light curve (> 100 years), the only well studied case so far …. > 100 years coverage

The NEW (not yet published) OJ287 photometry from HCO patrol plates

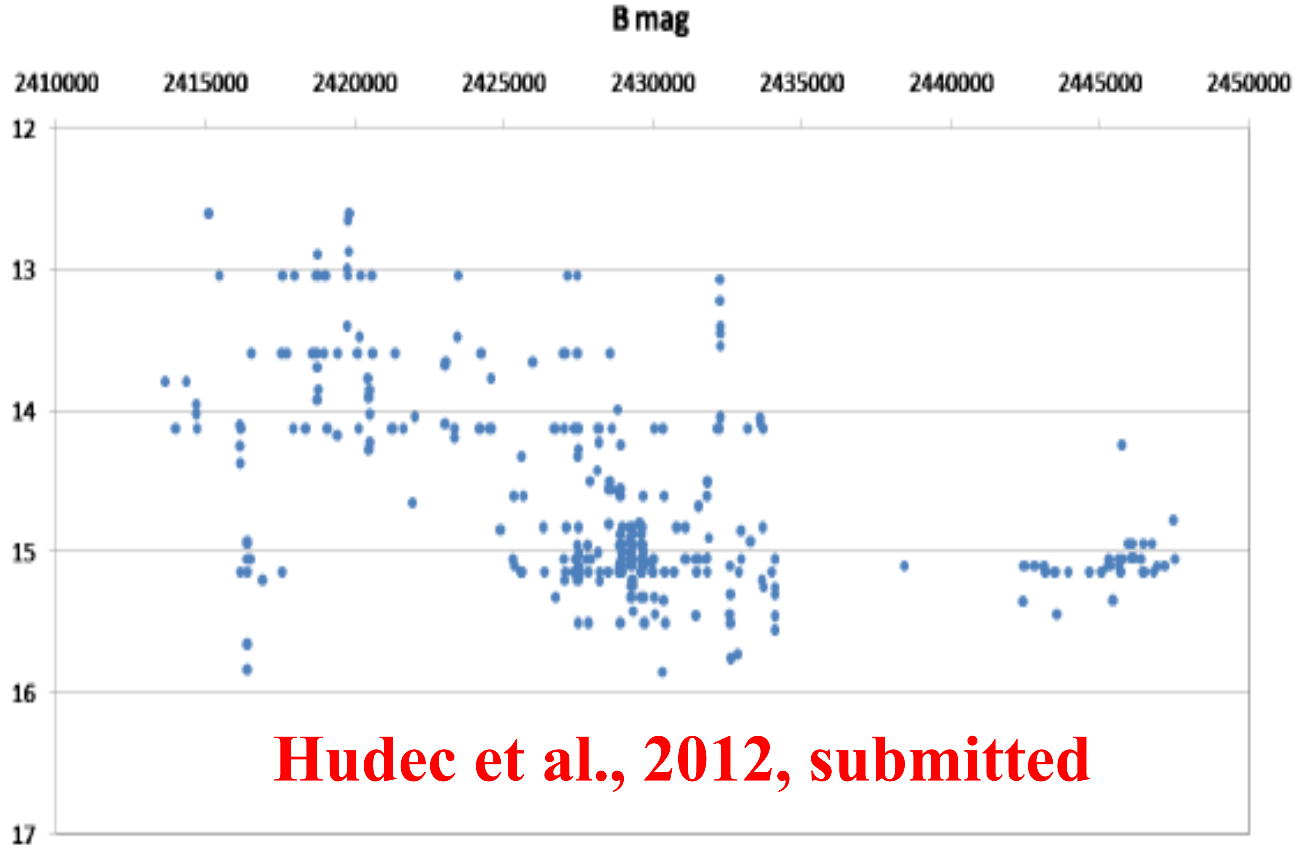
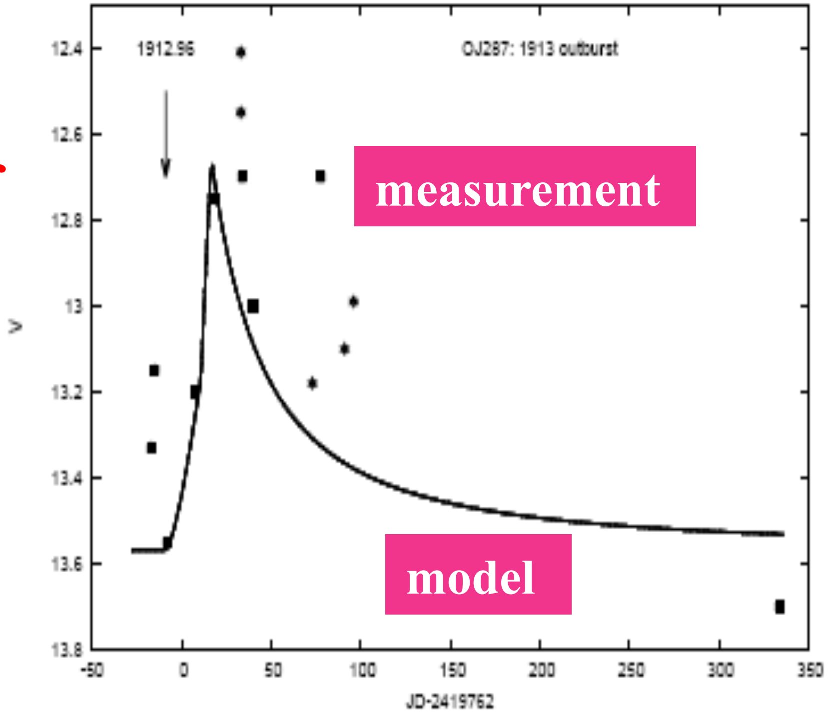


Fig. 2. The new measurements (B-mag) of OJ287 from HCO sky patrol plates, reported in this paper, plotted as light curve B-mag versus JD

Demonstrating power of historical data: the 1913 flare

Hudec et al., 2012, submitted

Outburst arising from the impact of the secondary black hole on the accretion disk of the primary black hole



consistent with the latest orbit solution in the precessing binary model

Fig. 5. The light curve of the 1913 flare in OJ287. The V-band light curve combines old (stars) and new (squares) measurements. Also the theoretical light curve of 46 day duration at half-maximum is shown. The starting point of the outburst is at 1912.96 in this fit.

The large 1900 flare: unknown before & the eldest OJ287 flare

outburst from increased accretion rate when the two black holes are close to each other

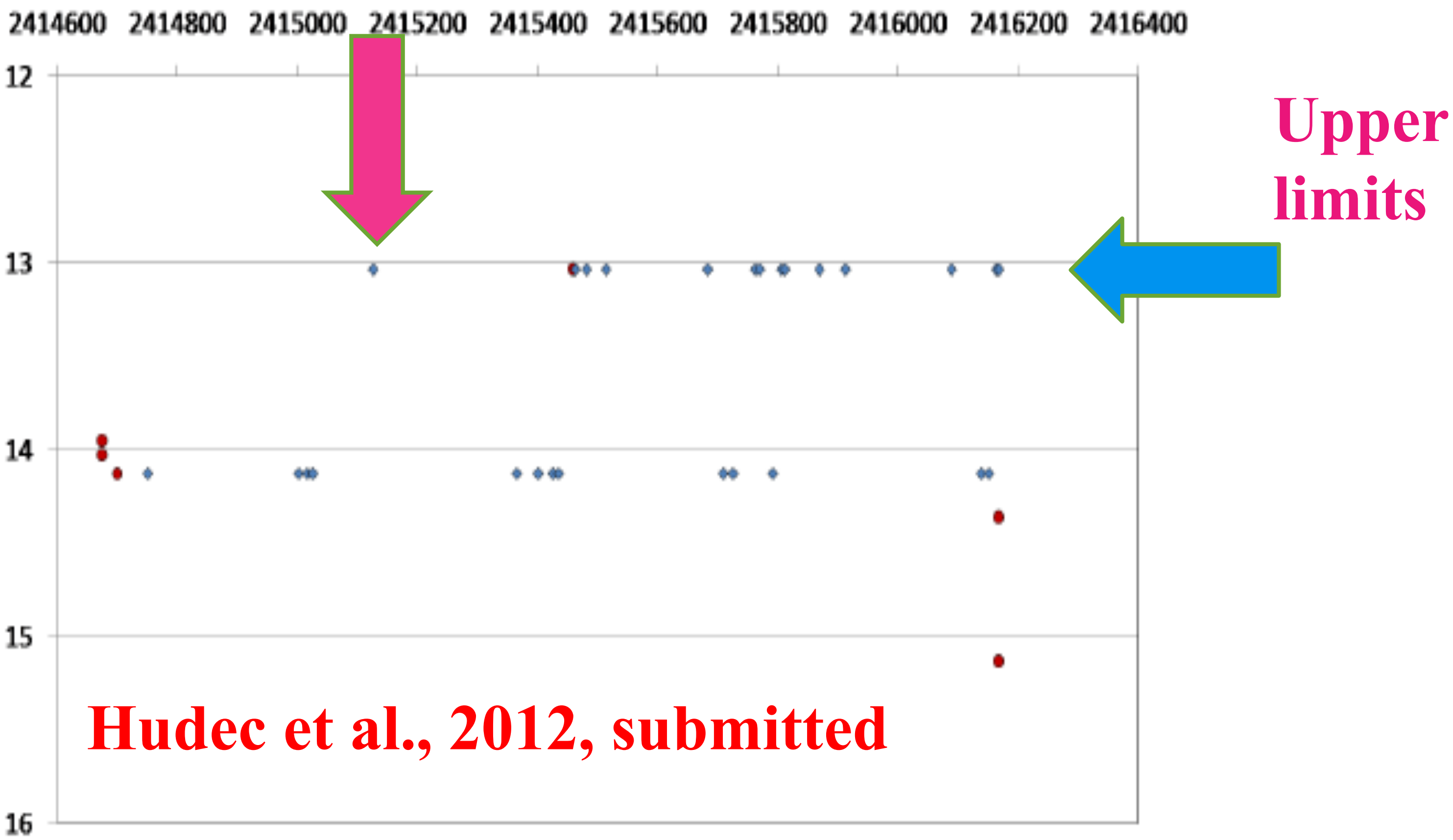


Fig. 6. Light curve (B-mag versus JD) of the 1900 OJ287 flare, reported for the first time. The circles represent measurements, the squares represent the upper limits, both for HCO sky survey plates.

With the precessing binary black hole model one can understand the systematics of outburst timings

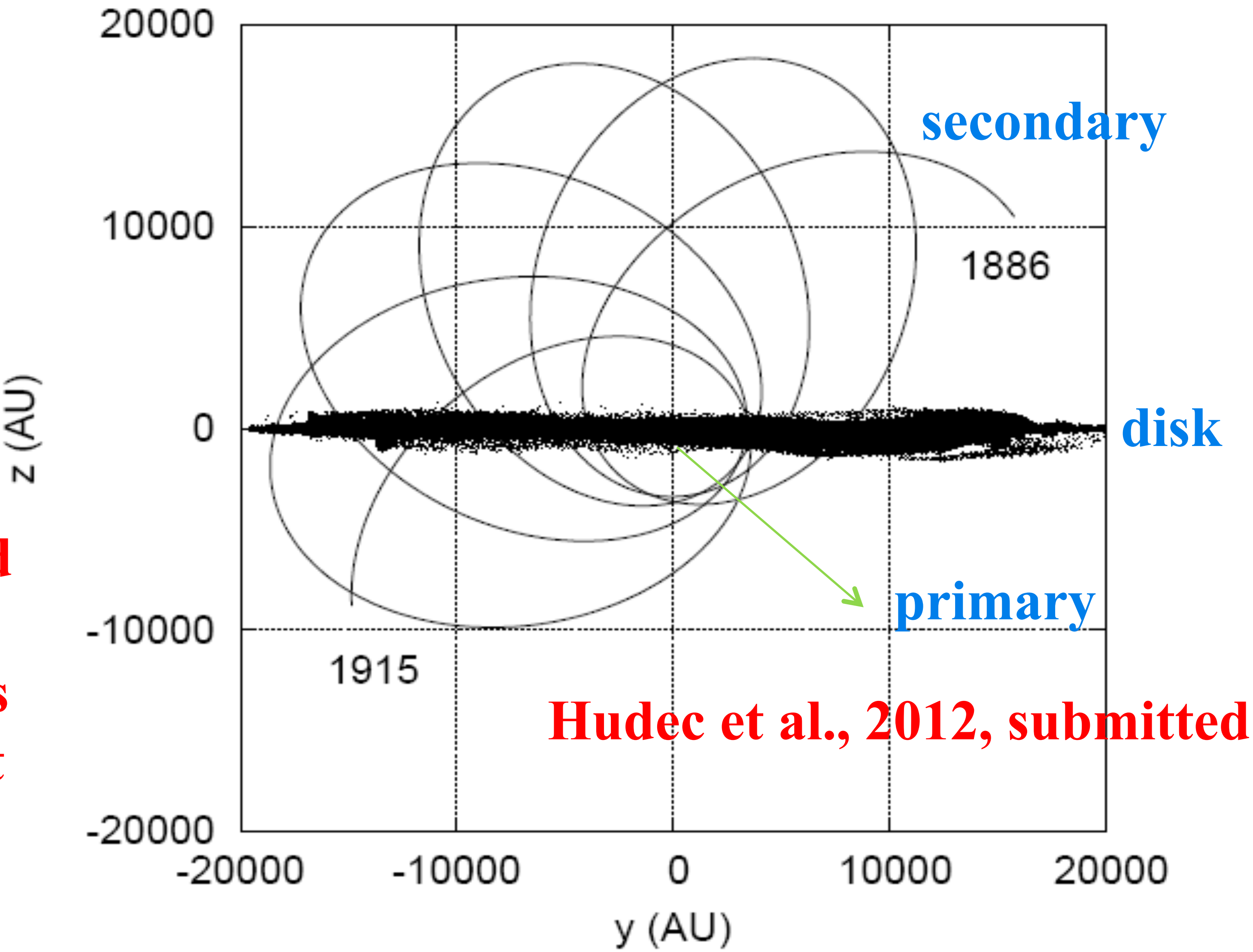
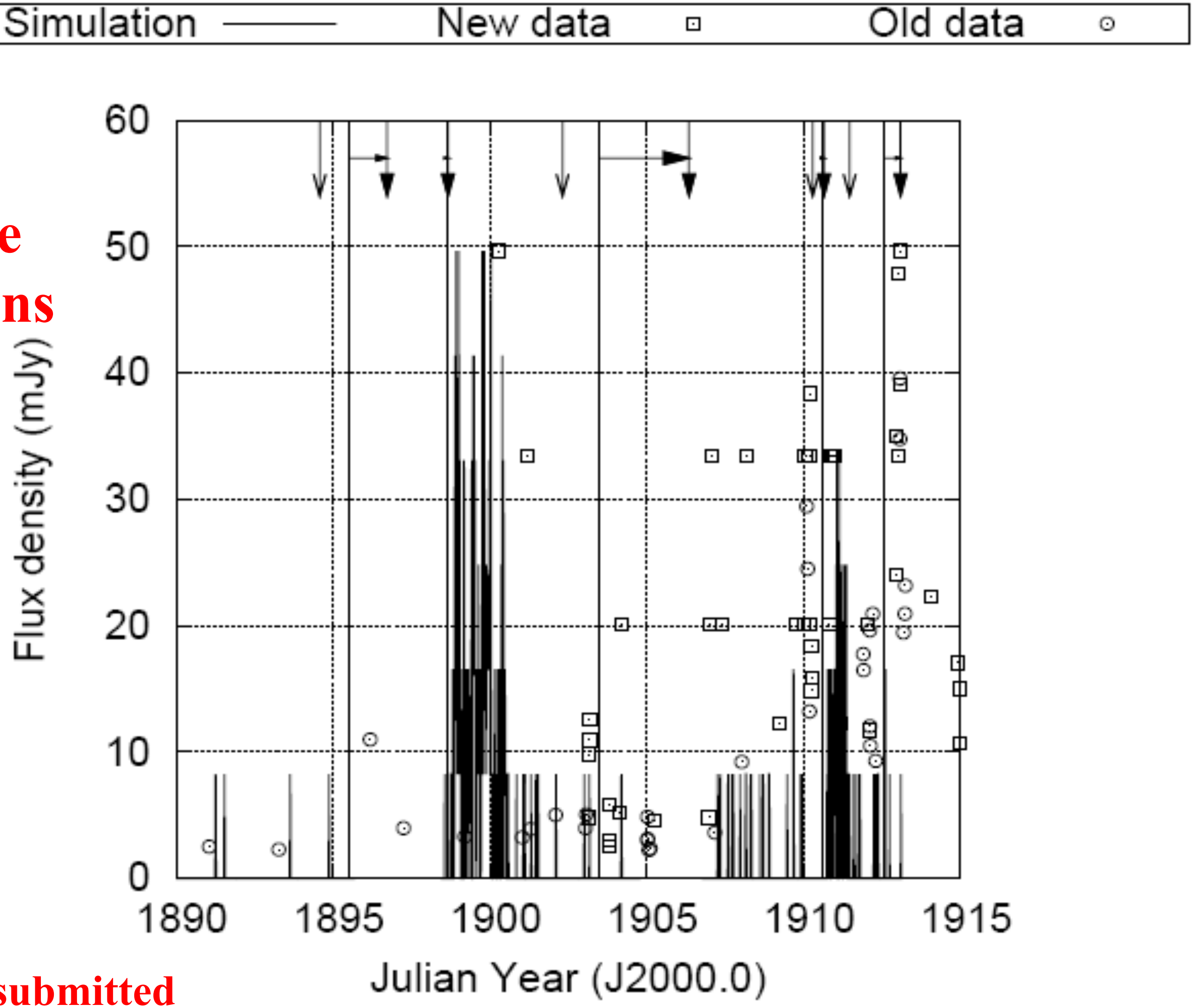


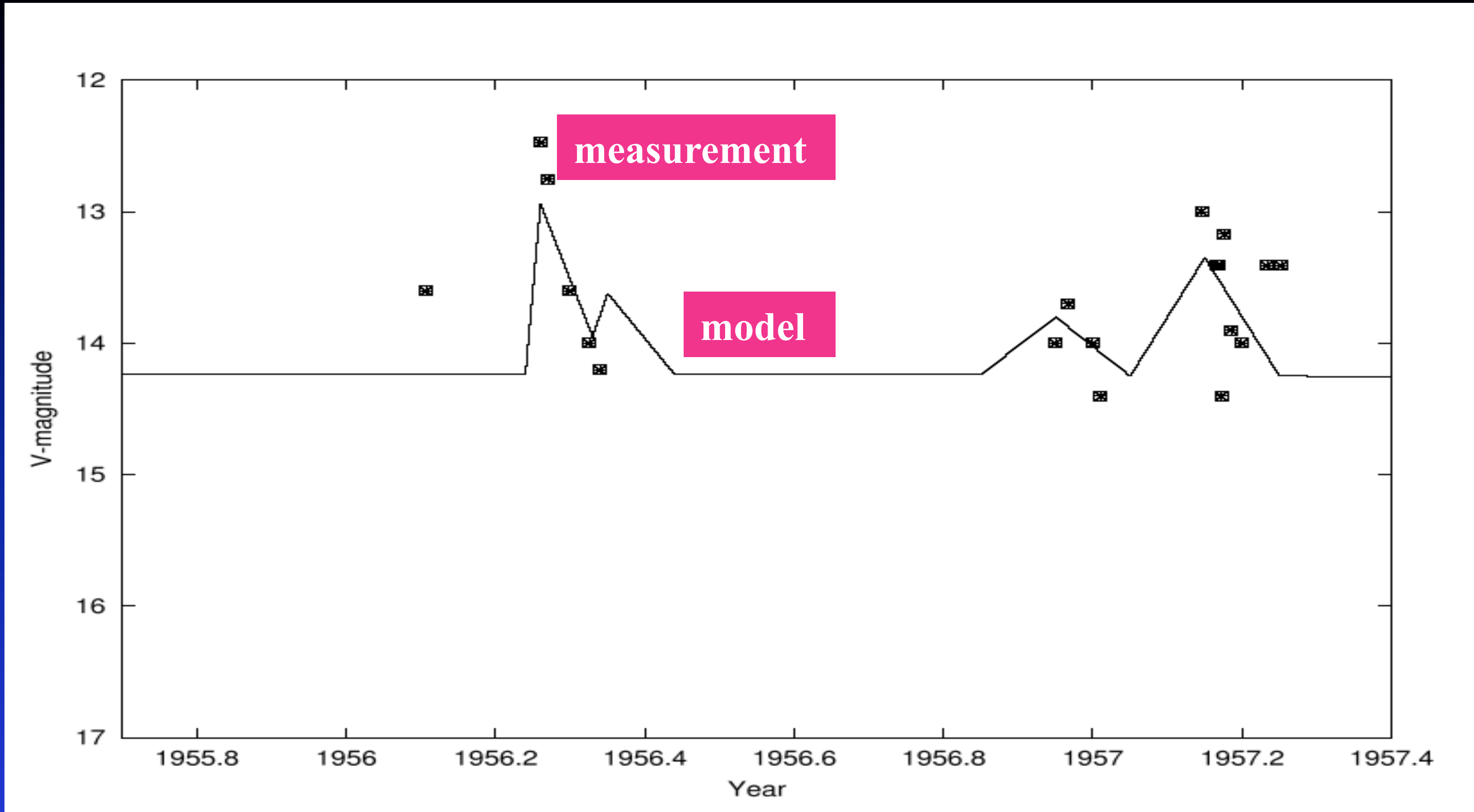
Fig. 8. The orbit of the secondary around the primary which is approximately at the point (0,0). The coordinate units are AU. The disk is seen edge–on. The secondary orbits the primary in counter-clockwise sense. The last point in the orbit is in the year 1915; the previous disk crossings occur in 1912 and 1910. The disk crossing furthest to the left happens in 1903, and prior to that the crossings are in 1898 and 1895. Because of precession the intervals between disk crossings vary greatly.

Predicted accretion rate & observations



Hudec et al., 2012, submitted

Fig. 9. The accretion rate in the precessing binary black hole model (vertical lines) compared with the observed brightness of OJ287 (squares: data from this paper, circles: previously published data) in linear scale. The vertical arrows mark the expected times of outbursts arising from the disk crossings by the secondary, while the horizontal arrows indicate the time delays between the disk impacts and the related outbursts.



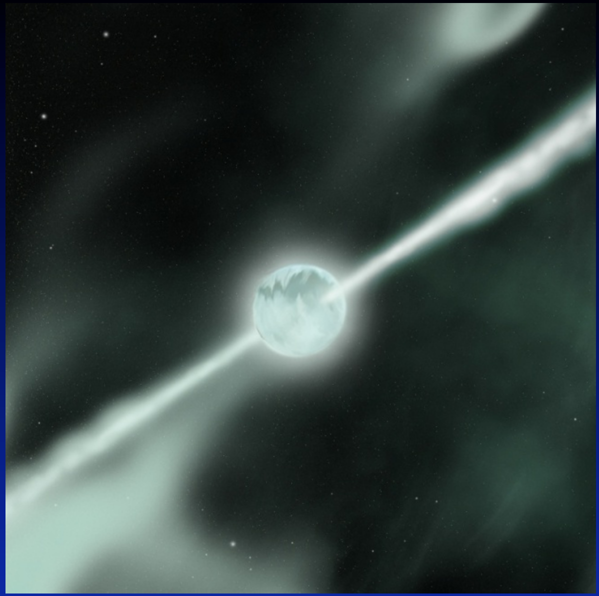
The giant flare of OJ287 on Sonneberg archival plates in 1956 (points, Hudec, 2001) and model prediction by Valtonen et al. (2004) (line)

Other Examples of HE/ VHE/UHE Science with Plate Archives

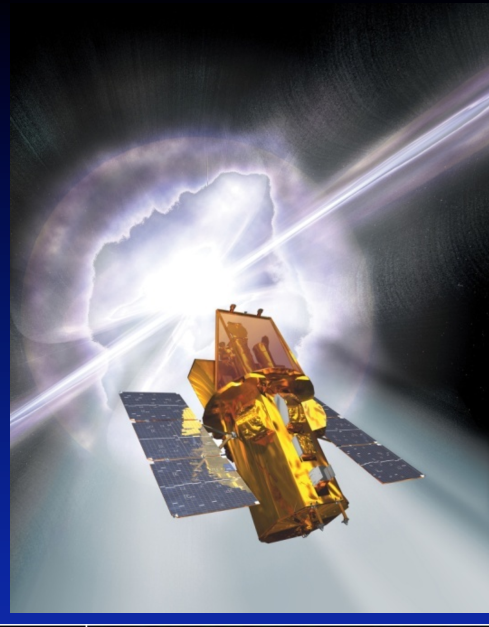
- Examples of other applications: TeV blazars, gamma-ray binaries, GRBs, magnetars, etc
- If the (new) PeV and EeV sources going to be detect with new instruments will have persistent and/or flaring optical emission brighter than mag 20, then they can be also studied on astronomical archival plates

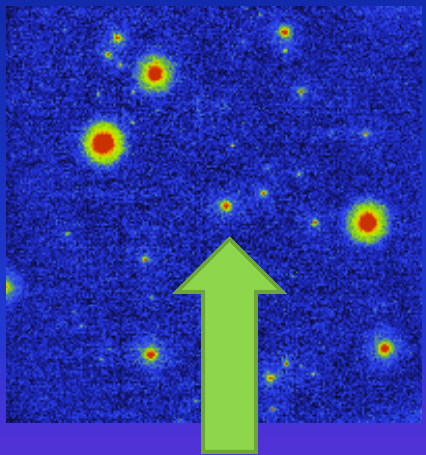
Gamma Ray Bursts and Astronomical Plates

- There is a population of GRBs with bright prompt optical emission of GRBs
- These OTs achieve optical brightness of mag 6-12, and perhaps even brighter, lasting of ~1 min
- These OTs can be recorded on astronomical plates
- The obvious question: how to find them?
- In addition, orphan OTs and OAs

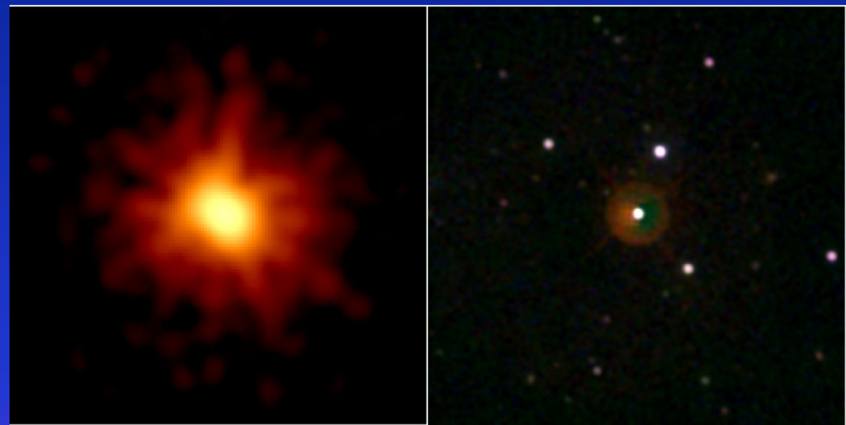


GRB080319B
For ~ 1 minute
Brighter in optical light than mag 6

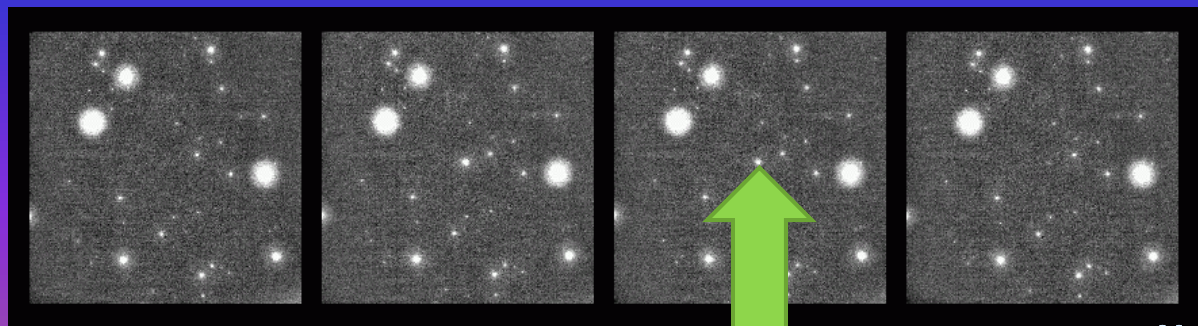


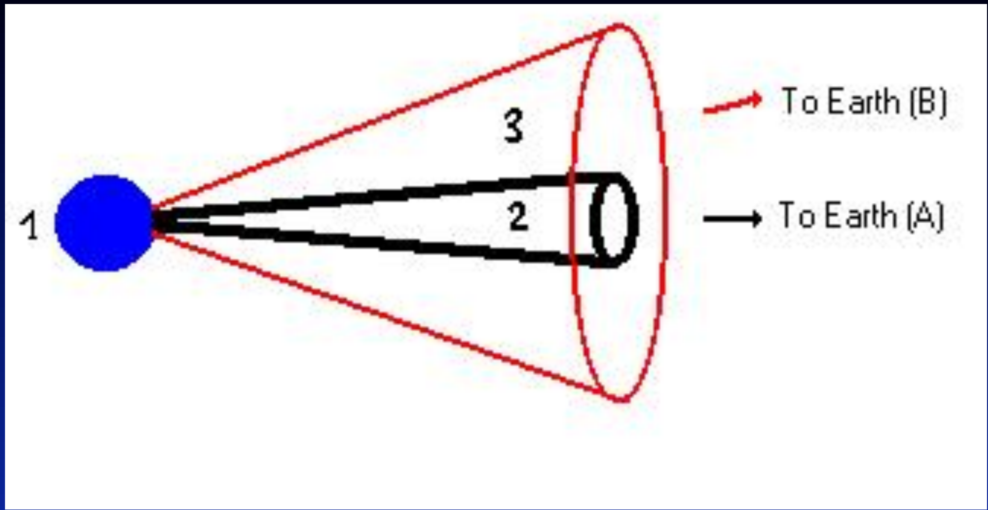


Naked eye visibility
At z ~ 0.75



GRB belongs to objects seen on the night sky by naked eye!





Orphan afterglows/ transients of GRBs …. GRBs visible only in optical light

- Orphan afterglow – optical afterglow without detectable Gamma ray emission (due to different beaming)

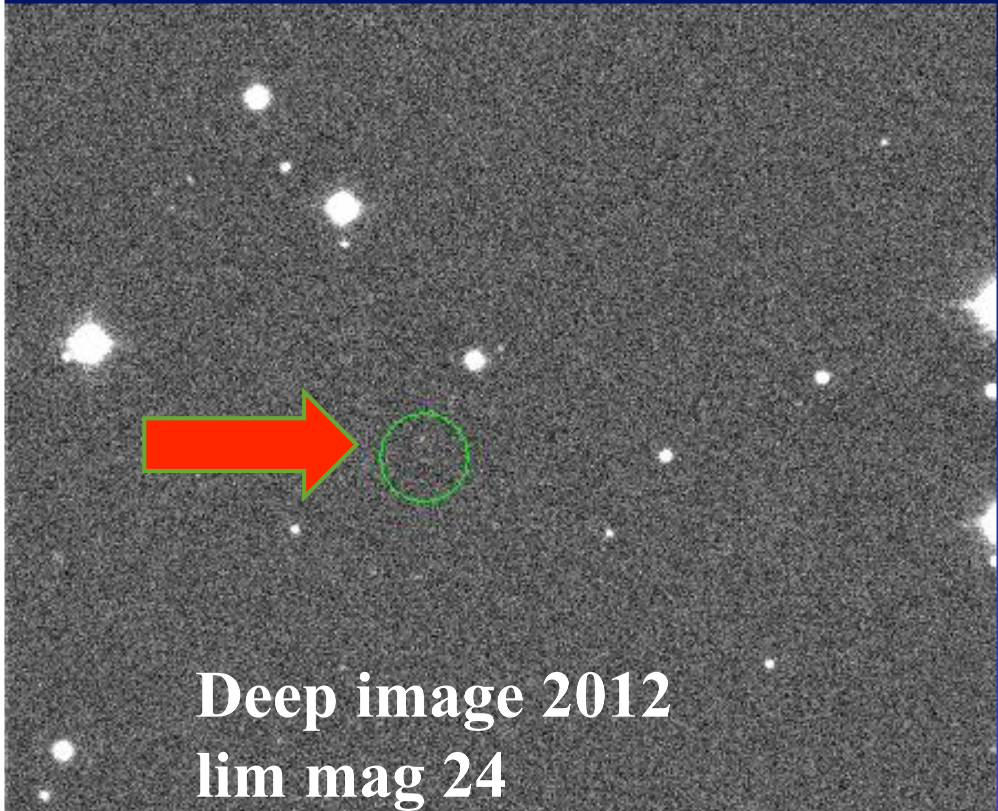
- Predicted by theory but not yet confirmed by observation

- The rate of Orphan Optical Afterglows (OOAs) is expected to exceeds the GRB rate, hence the improved GRB statistics is expected with numerous consequences such as improved statistics of host galaxies, redshift distribution, cosmological conclusions, etc.

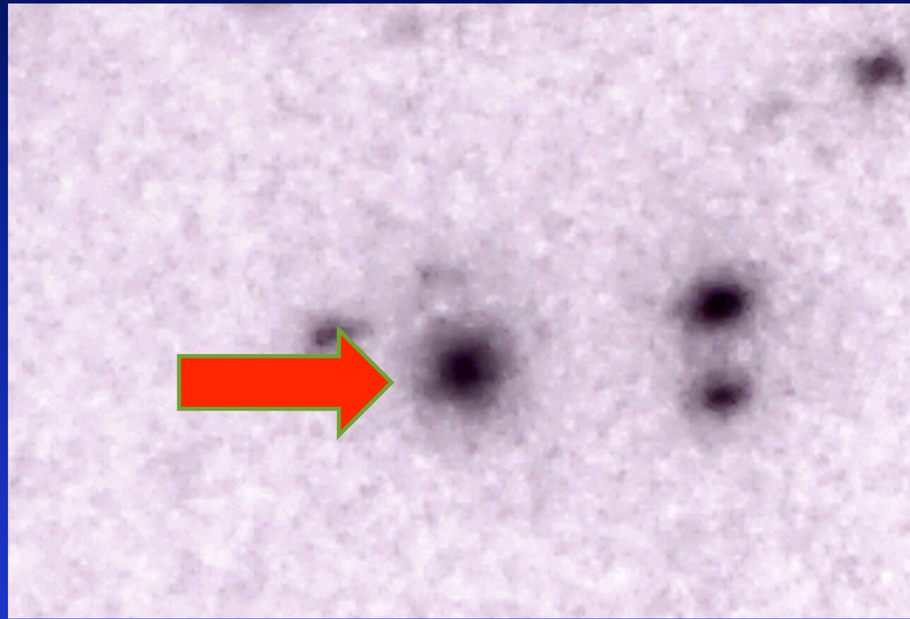
Recent Bamberg GRB Project

- 5000 selected high-quality sky patrol plates investigated for flaring GRB/OT candidates (including orphans)
- In total ~50 000 square degrees covered for > 24 hrs, lim mag 15-16
- 6 candidates found, 2 promising – quiet candidates consistent with GRB host galaxy
- Award-winning in German High School Competition Jugend Forscht in 2012

1966 OT0519-5210 1st ever recorded GRB? (1st satellite detected GRB in 1967)



Deep image 2012
lim mag 24



OT image 1966 Nov 13 lim mag 15, duration < 1 day

Faint object at the OT position has colors not in contrast with GRB host galaxy at redshift ~ 3.5

Transportable plate scanning device

Plate collections visited:
Carnegie Observatories Pasadena
Lick Observatory
Yerkes Observatory
Mt Palomar Observatory
PARI NC
KPNO Tucson
CFHT Waimea, Hawaii
IfA Manoa, Hawaii
USNO Flagstaff, AZ
USNO Washington, DC & 7 more

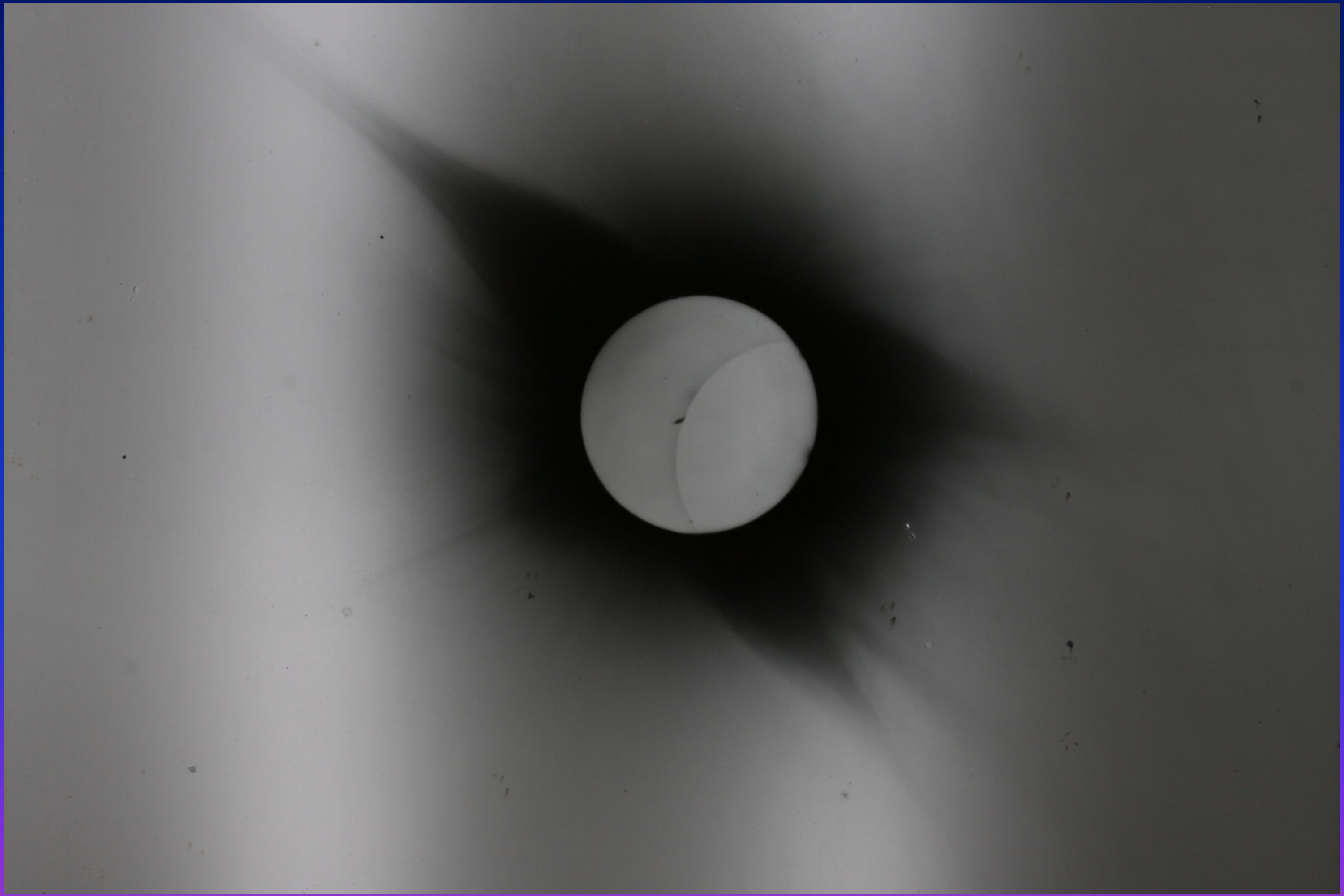
About 1 million plates in these archives

Preferences: transportable, very fast scanning, high repeability (no moving scanner parts)

Used equipment:

Camera: 21 MPx Canon EOS 5D Mark II Lenses: Canon EF 24-70 f/2.8 L USM & Canon 70-200mm F4

Solar Eclipse Einstein relativity theory tests 1919 (Eddington) – original plate digitized by us



Conclusions

- Astronomical Plate Archives represent valuable data source for all optically variable sources including HE, VHE and UHE objects
- Most important: long time evolution, dense sampling, rare flares, spectral changes
- Recent wide digitization and evolution of dedicated software enables evaluation by computers, for the first time
- Fast (<20 sec) and inexpensive (~0.25 $) plate digitization technique developed and tested able to convert glass plates to computer files effectively

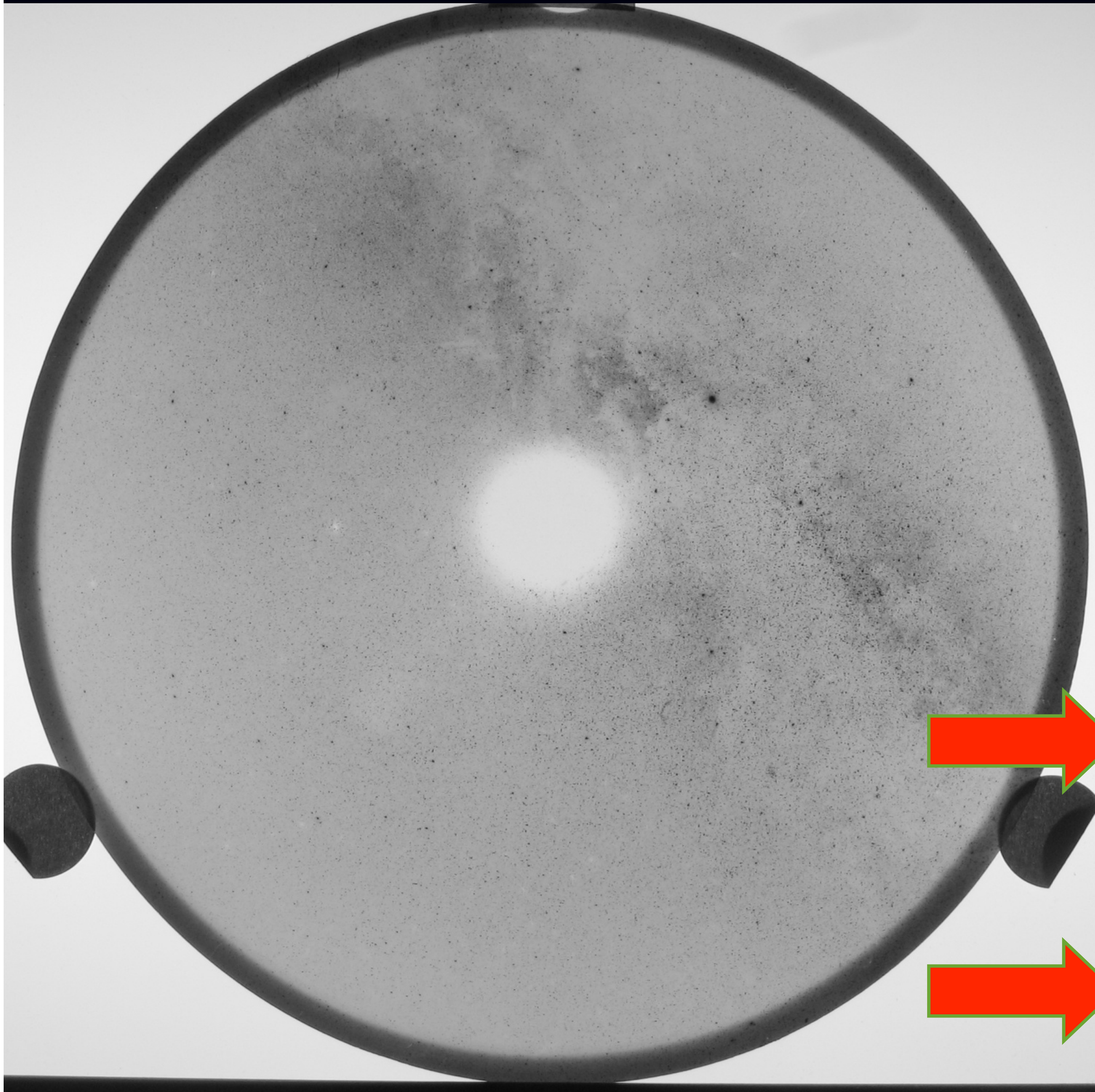
The End

Outline

- Astronomical Plate Archives
- Binary Blazars: Supermassive Black Hole Binaries
- The OJ287 case
- Other applications
- Recent GRB Search in Bamberg
- Hidden treasure: US plate archives

FINDING HIDDEN TREASURES

INVESTIGATIONS IN US ASTRONOMICAL PLATE ARCHIVES



Super-Schmidt Baker Camera

About 100 000 films

Limiting magnitude 15, very sharp images

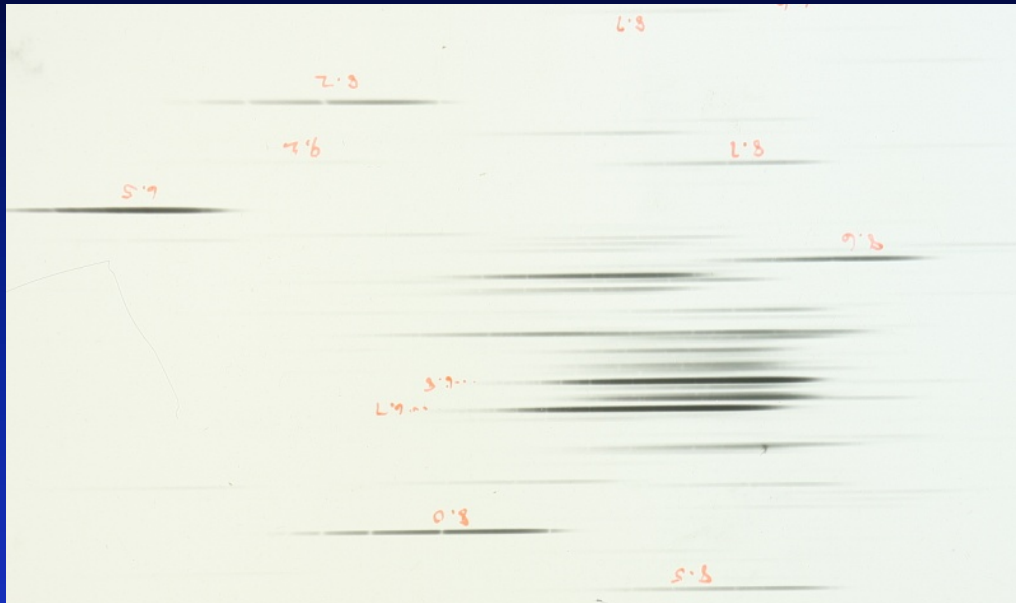
FOV 55 degrees

1950-1960

Very dense (20 minutes) sampling

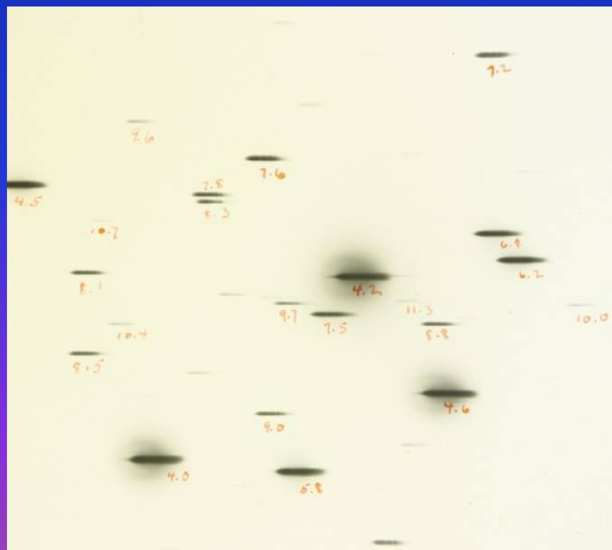
Now deposited at PARI, NC

Carnegie Observatories Pasadena

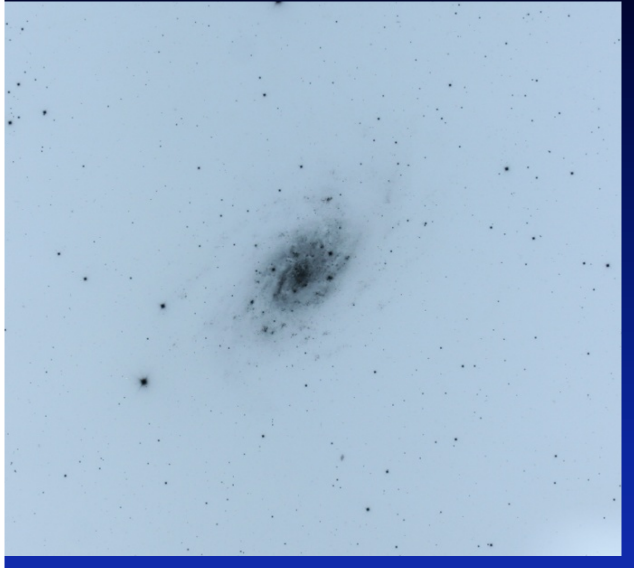


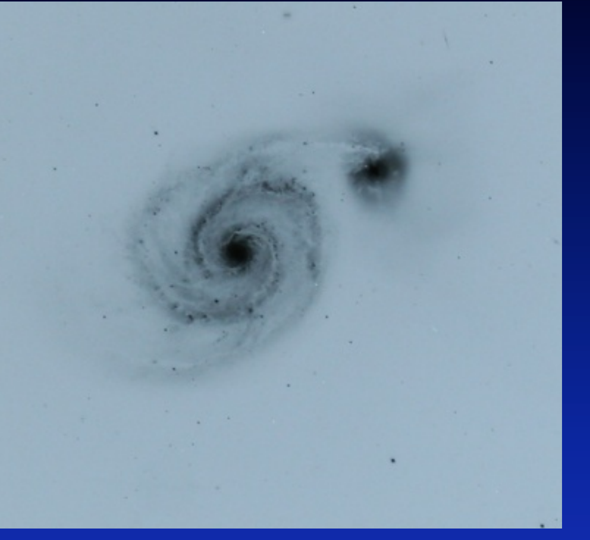
LDS (Low Dispersion Spectroscopy) plates from 1909 at Carnegie Obs, Pasadena, CA, USA

The North Mt Wilson – Michigan Halpha survey plates are deposited here



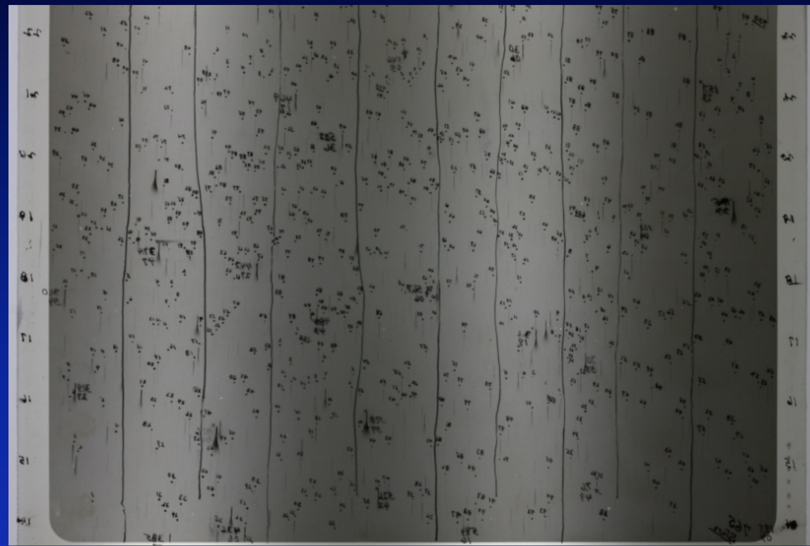
CFHT Waimea Hawaii I





Valuable plates taken by 3.6 m CFHT telescope Very deep lim magn

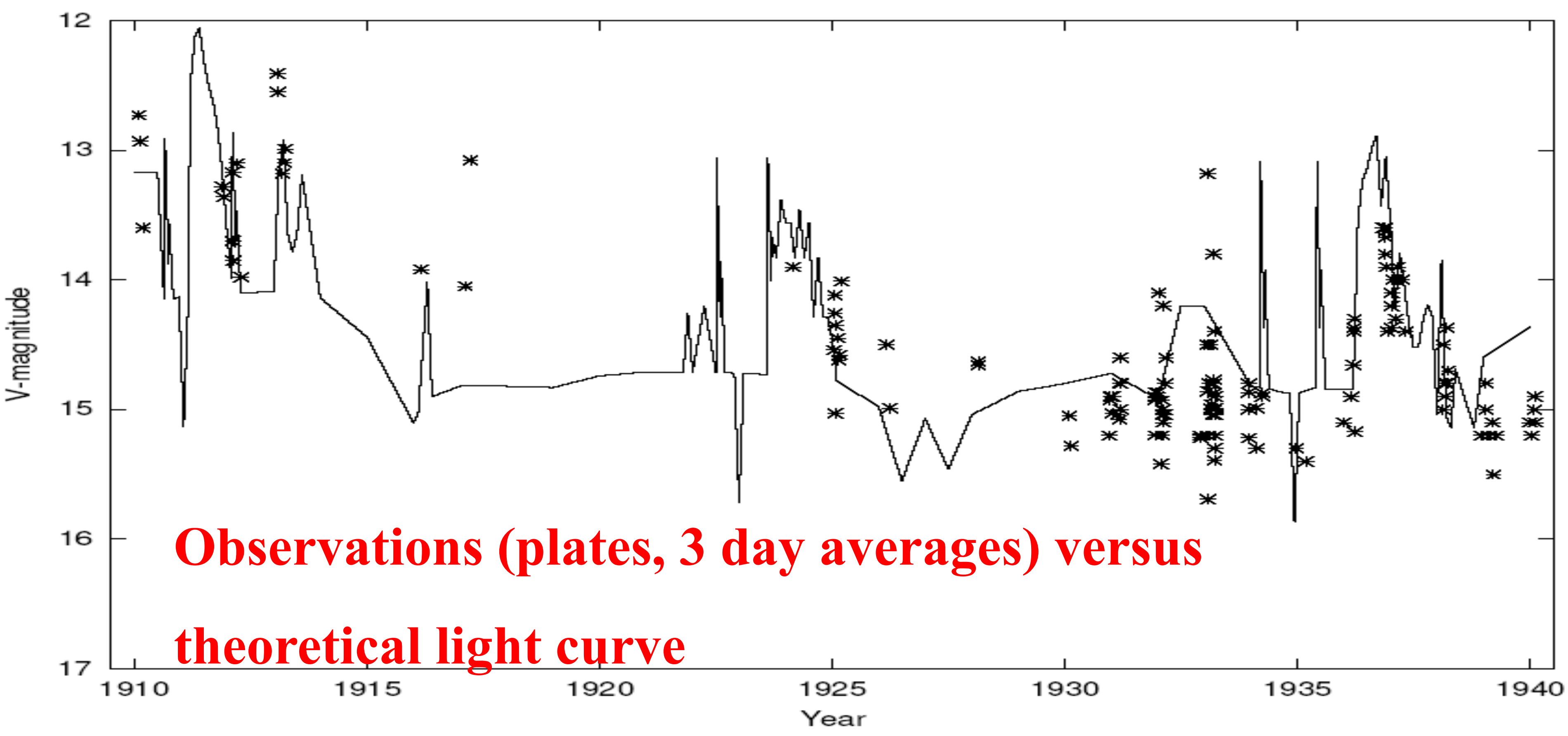
Yerkes Observatory



~ 170 000 astronomical archival plates (including spectra and solar)

The next giant outbursts of OJ287 can be predicted with accuracy of (+- 3 days)

For the prediction the binary precession model by Valtonen & Lehto (1996) has been used and the previously unknown major outburst in 1956 (found on Sonneberg archival plates, Hudec, 2001)



Observations (plates, 3 day averages) versus theoretical light curve

The periods in our sample of 11 blazars are not confirmed as their light curves are not well-sampled and do not involve much historical data.

Our project:

1. **Gathering of optical data**
   - **Photographic plate collections**
     - **Sonneberg Observatory, Germany (280 000 plates)**
     - **Harvard College Observatory, USA (600 000 plates)**
     - **UKSTU plate collection ROE Edinburgh, UK (18 000 plates)**
     - **Observatory Leiden, NL (40 000 plates)**
   - **Papers**
   - **Observational campaigns archives, public archives, internet**
2. **Gathering support data from other energy bands**
3. **Periodicity analysis of the optical light curve**
4. **An overall analysis to adopt a BBH model**
5. **Establishing statistical results based on our sample of 11 blazars**

Optical data gathering & Periodicity analysis

Sonneberg photographic plate

Sextractor (or other) processing

Sextractor screenshot

Modified Argelander method

Thousands of photographic plates

Determination of magnitude of a specific object in individual plates

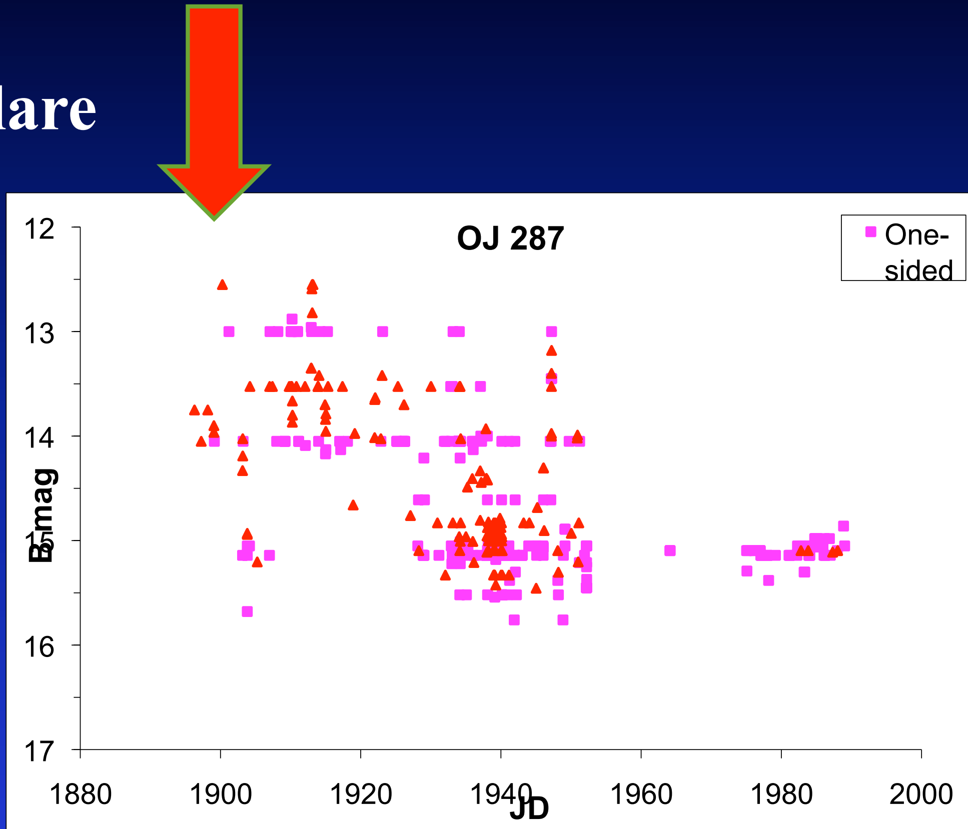
ANALYSIS OF THE TIME SERIES

- **Stellingwerf's method (folded light curves)**
- **Deeming method**
- **CLEAN algorithm**
- **Wavelets analysis**

$$CW_x^{\psi}(\tau, s) = \frac{1}{\sqrt{s}} \int x(t) \psi^* \left(\frac{t-\tau}{s}\right) dt$$

OJ 287: new historical flare found

New flare



Data mining mostly on plates with limit close to the object magnitude

This and next slides: preliminary, still awating better calibration improving the accuracy

One new major, previously unknown, historical outburst in 1900 added. The 2nd historical outburst in 1913 much better covered than before.

OJ287 with our new photometric data added

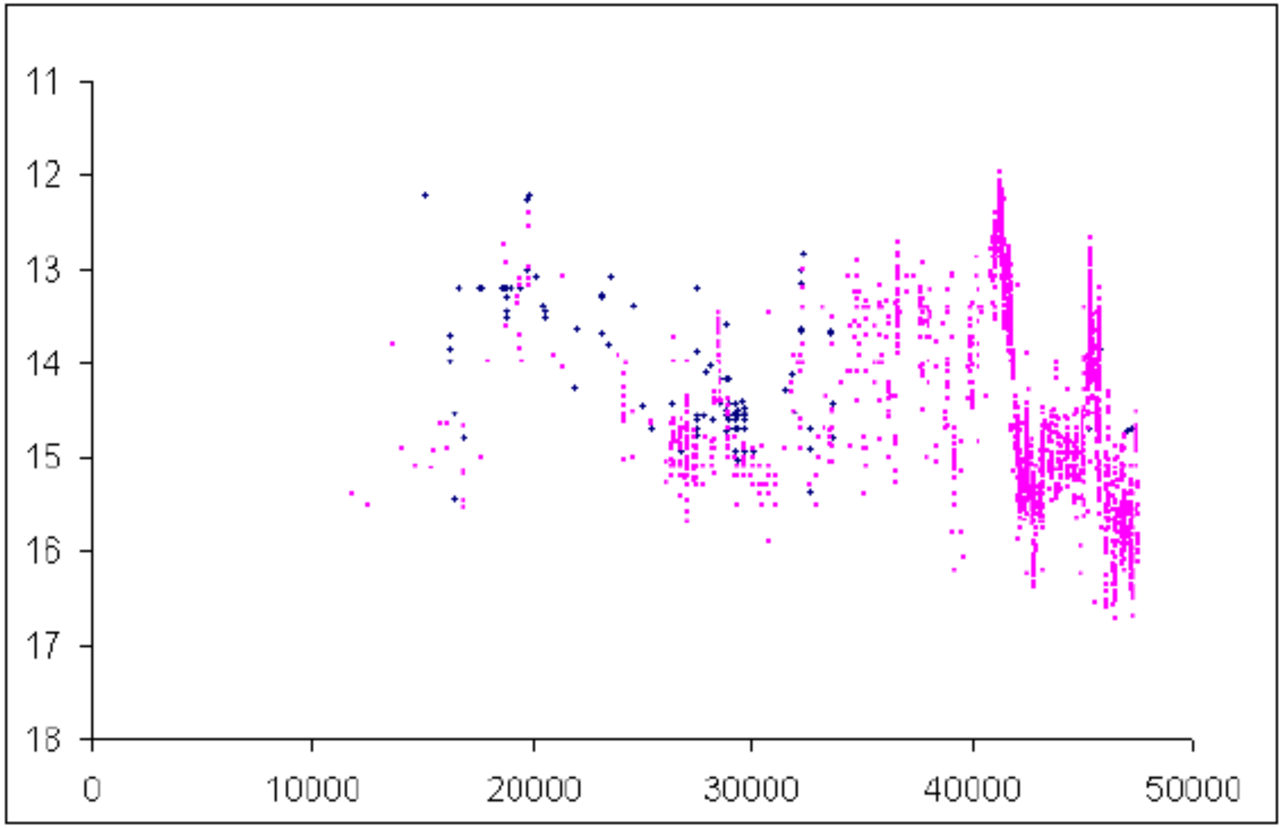


Fig. 1. The long–term (> 100 years) V-mag light curve (V-magnitude versus MJD) of OJ287 based on data referenced by Takalo (1994). The newly added photometric points reported in this paper are marked by crosses.