Implications of the predicted General Relativity Centenary flare in Blazar OJ287

Achamveedu Gopakumar,

ASET Colloquium (28/10/2016)

Plan

- Introduction ..why we got some press coverage ? ;-)
- We are NOW confident that the central engine of a special quasar OJ287 involves a massive black hole binary
- Our 2015 efforts & their implications
- Future directions where sophisticated instruments will be crucial

AAS NOVA Research highlights from the journals of the American Astronomical Society

HOME HIGHLIGHTS JOURNALS DIGEST

Dance of Two Monster Black Holes

By Susanna Kohler on 23 March 2016 FEATURES

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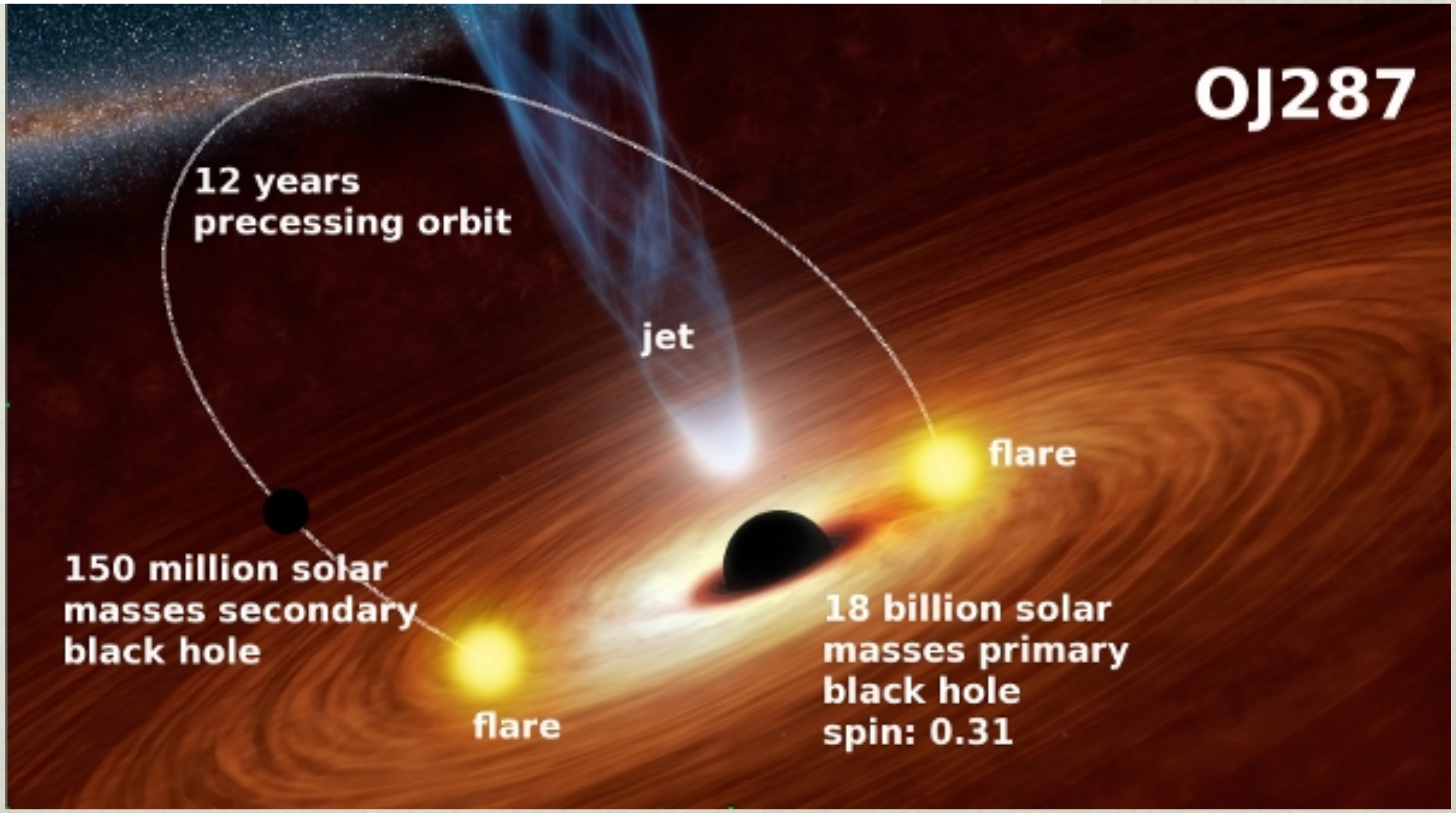
This past December, researchers all over the world watched an outburst from the enormous black hole in OJ 287 — an outburst that had been predicted years ago using the general theory of relativity.

Outbursts from Black-Hole Orbits



PRIMARY BLACK HOLE SPIN IN OJ 287 AS DETERMINED BY THE GENERAL RELATIVITY CENTENARY FLARE

M. J. Valtonen[1,2], S. Zola[3,4], S. Ciprini[5,6], A. Gopakumar[7], K. Matsumoto[8], K. Sadakane[8], M. Kidger[9], K. Gazeas[10], K. Nilsson[1], A. Berdyugin[2] Show full author list

Published 2016 March 10 •

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MEASURING THE SPIN OF THE PRIMARY BLACK HOLE IN OJ287

M. J. Valtonen[1,2], S. Mikkola[1], D. Merritt[3], A. Gopakumar[4,5], H. J. Lehto[1], T. Hyvönen[1], H. Rampadarath[6,7], R. Saunders[8], M. Basta[9], and R. Hudec[9,10]

Published 2010 January 6 •

The Astrophysical Journal, Volume 709, Number 2

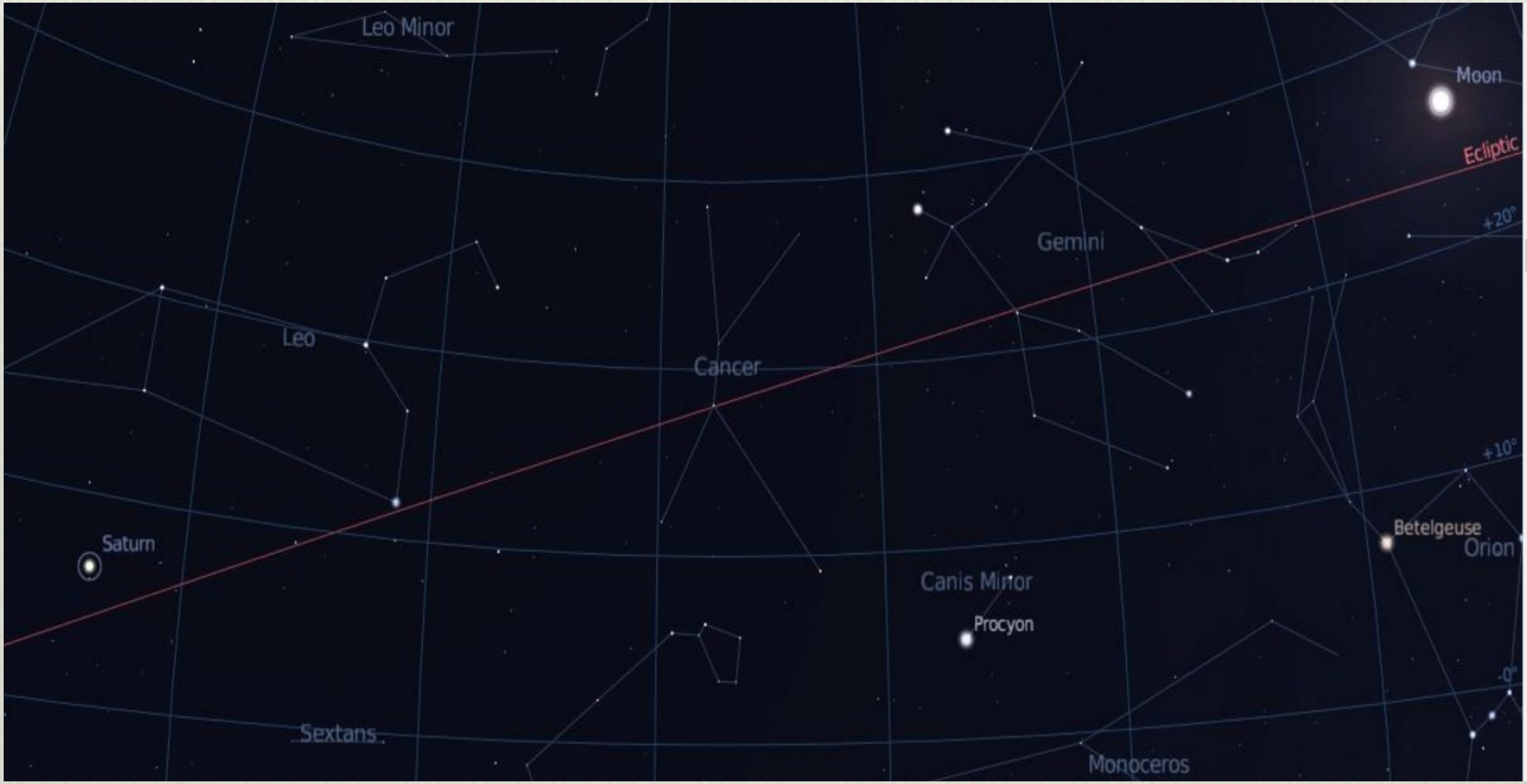
constrain the "no-hair" parameter to be 1.0 ± 0.3, where 0.3 is the 1σ error. This supports the "black hole no-hair theorem" within the achievable precision. It should be possible to test the present estimate in 2015 when the next outburst is due. The timing of the 2015 outburst is a strong function of the spin: if the spin is 0.36 of the maximal value allowed in general relativity, the outburst begins in early 2015 November, while the same event starts in the end of January 2016 if the spin is 0.2.

OJ287 impact flare monitoring campaign during November 2015 to February 2016

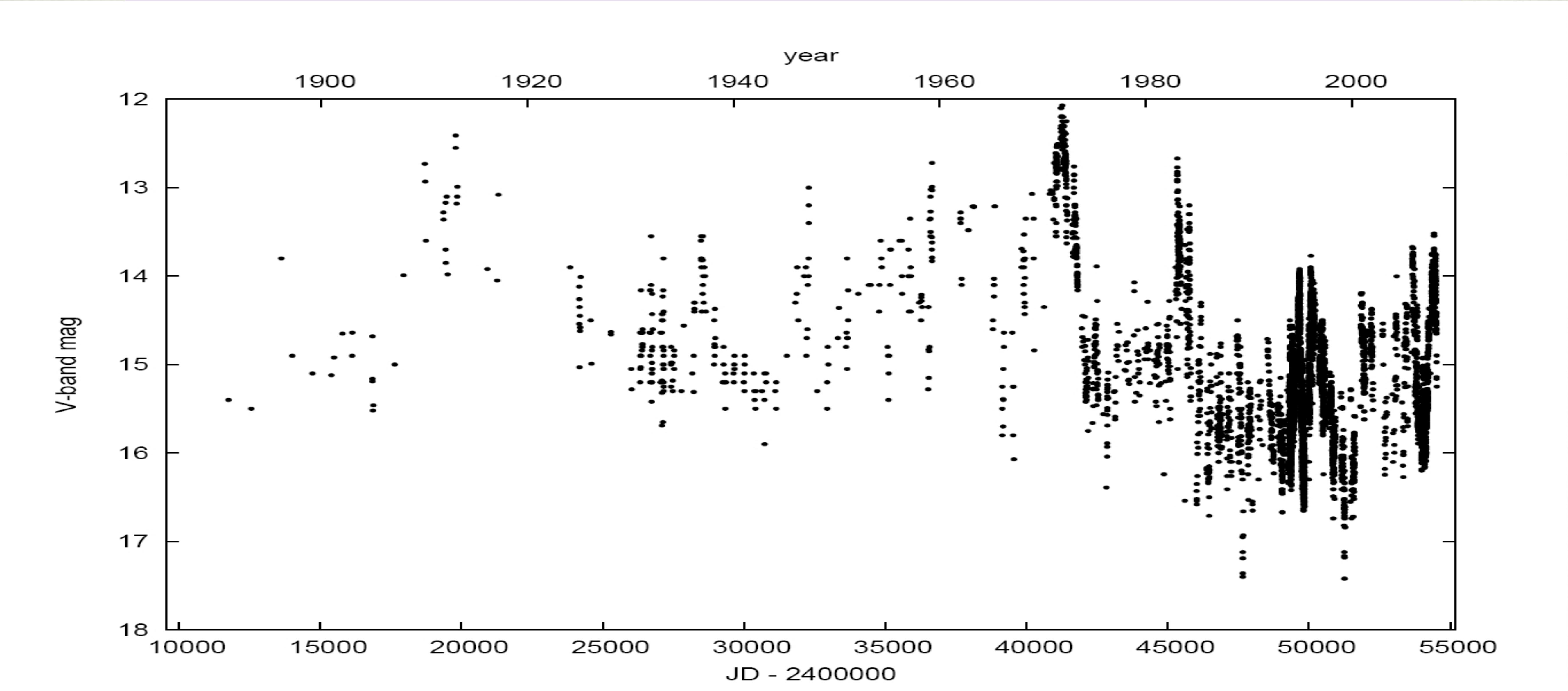
Mauri J. Valtonen[1], Achamveed Gopakumar[2],

OJ287 is a speck of light (14 magnitude) in the constellation of Cancer

OJ287 is a speck of light (14 magnitude) in the constellation of Cancer



What did we predict ?



A stellar object's magnitude is a logarithmic measure of its brightness

Variability in brightness ranges by a factor of >10

We predicted in 2009 the occurrence such an outburst in 2015!!

OJ287: properties

- First discovered as a radio source by the Ohio Radio Survey in 1968
- It is located near the ecliptic, where most of the comet searching were taking place (frequently photographed)
- This is why we have optical observations dating back to 1890 !!
- *Classified as a BL Lac Object, a sub-group of Blazars, and is a sub-group of Active Galactic Nuclei (AGN)*
- $Z = 0.3 \rightarrow 1309$ Mpc

AGN : properties

- High powers: most powerful “non-explosive” sources in the Universe $\sim 10^{13}$ L_{Sun}
  Visible up to large distances: current record z = 7.1

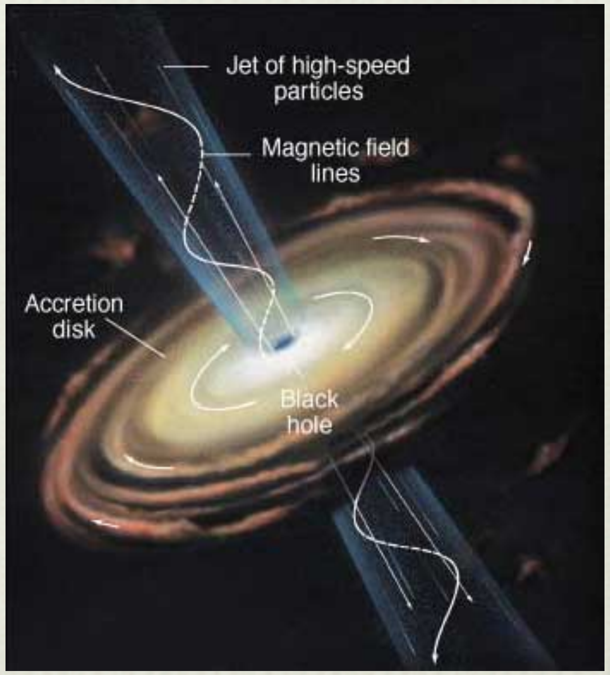
- Small emitting regions: ≈ a few light days
  1 lt -day ~2 x 10^{15} cm ; $R \leq c\, t_{var} / (1+z)$

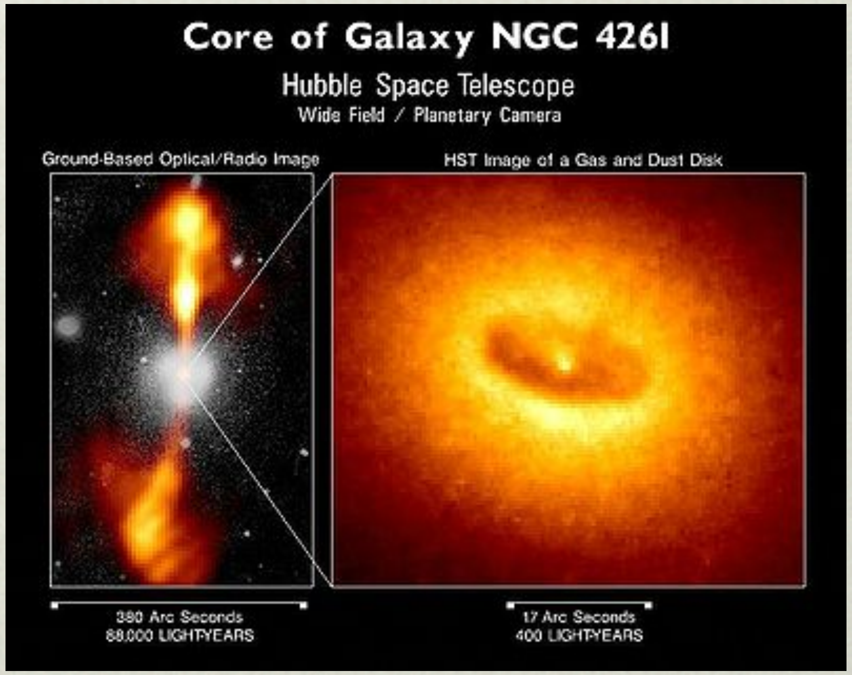
- Broad-band emission: from the radio- to the ϒ-ray band

- AGN phenomenon relatively rare: it affects ≈ 1% of galaxies (at a given time)

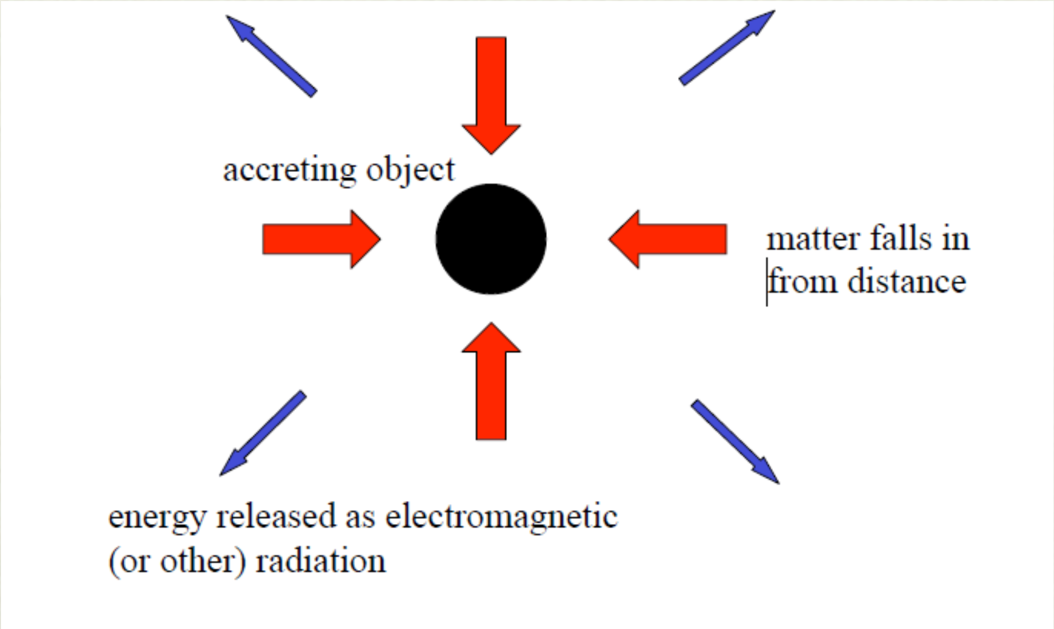
Massive BH as a central engine to AGNs

- AGN shines due to the accretion of matter onto a supermassive black hole at the center of its host galaxy
- Accretion results in the release of gravitational binding energy from infalling matter





Accretion powers AGNs



$$E_{acc} = \frac{GMm}{R} \qquad L_{acc} = \frac{GM\dot{m}}{R} = \frac{GM\dot{m}}{kR_S} = \frac{GM\dot{m}}{\frac{k2GM}{c^2}} = \frac{c^2}{2k}\dot{m}$$

$$\boxed{L_{acc} = \eta \dot{m} c^2}$$

$\eta \approx 0.06$ non-rotating BH
$\eta \approx 0.42$ maximally rotating BH
c.f. $\eta \approx 0.007$ for Hydrogen burning

$$\dot{m} \cong 2 \frac{(L_{bol}/10^{46})}{(\eta/0.1)} M_\odot / yr$$

$$L_{Edd} = 1.3\ 10^{46} (M / 10^8 M_\odot) erg/s$$

AGN Zoo is crowded

Radio-quiet AGN

Type 1 & 2, QSO, QSO2, Seyfert 1, Seyfert 2, Seyfert 1.5, Seyfert 1.8, Seyfert 1.9, Narrow-line Seyfert 1, Liners

Radio-loud AGN

Type 1 & 2, blazars, flat- and steep-spectrum radio quasars, core-dominated, lobe-dominated, optically violent variable quasars, BL Lacertae objects (*high-peaked, low-peaked, radio-selected, X-ray selected*), high- and low-polarization quasars

Radio-galaxies: Fanaroff-Riley I & II, narrow-lined, broad-lined, high-excitation, low-excitation, GHz-peaked

3 parameters to explain full AGN variety !!

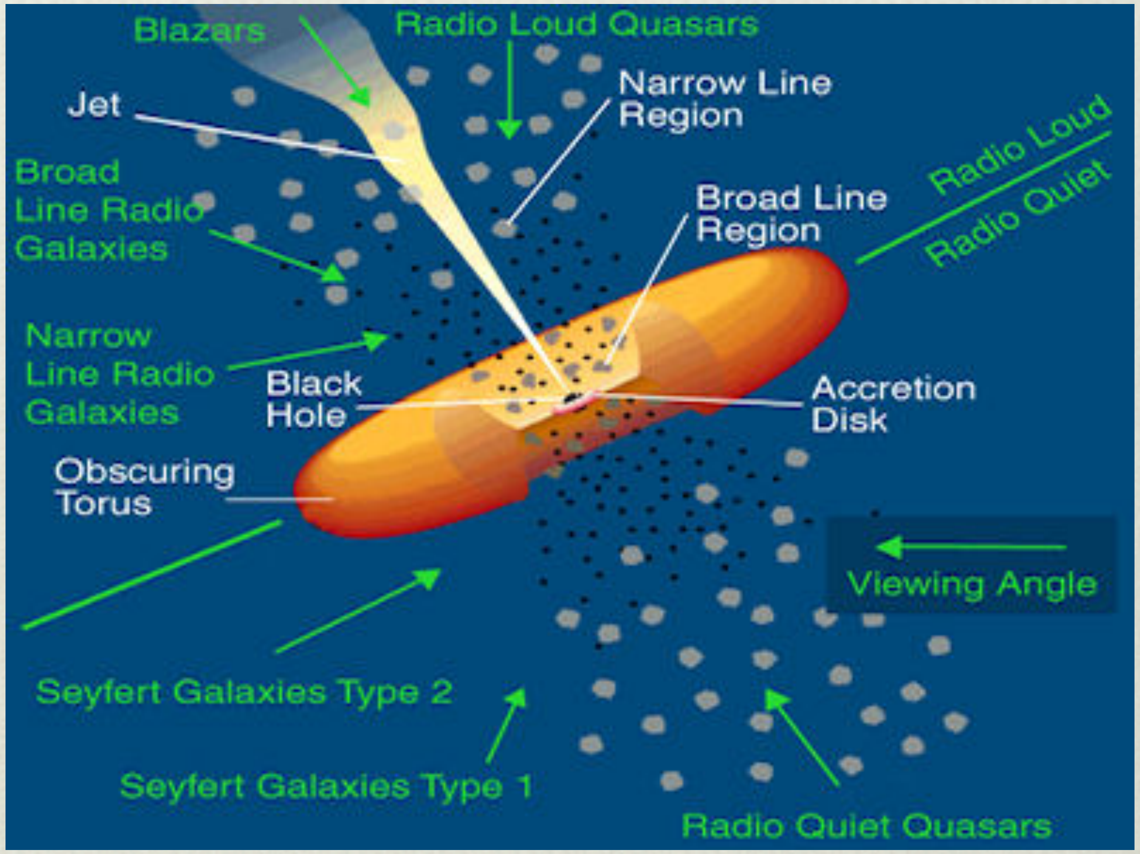
i) viewing angle;

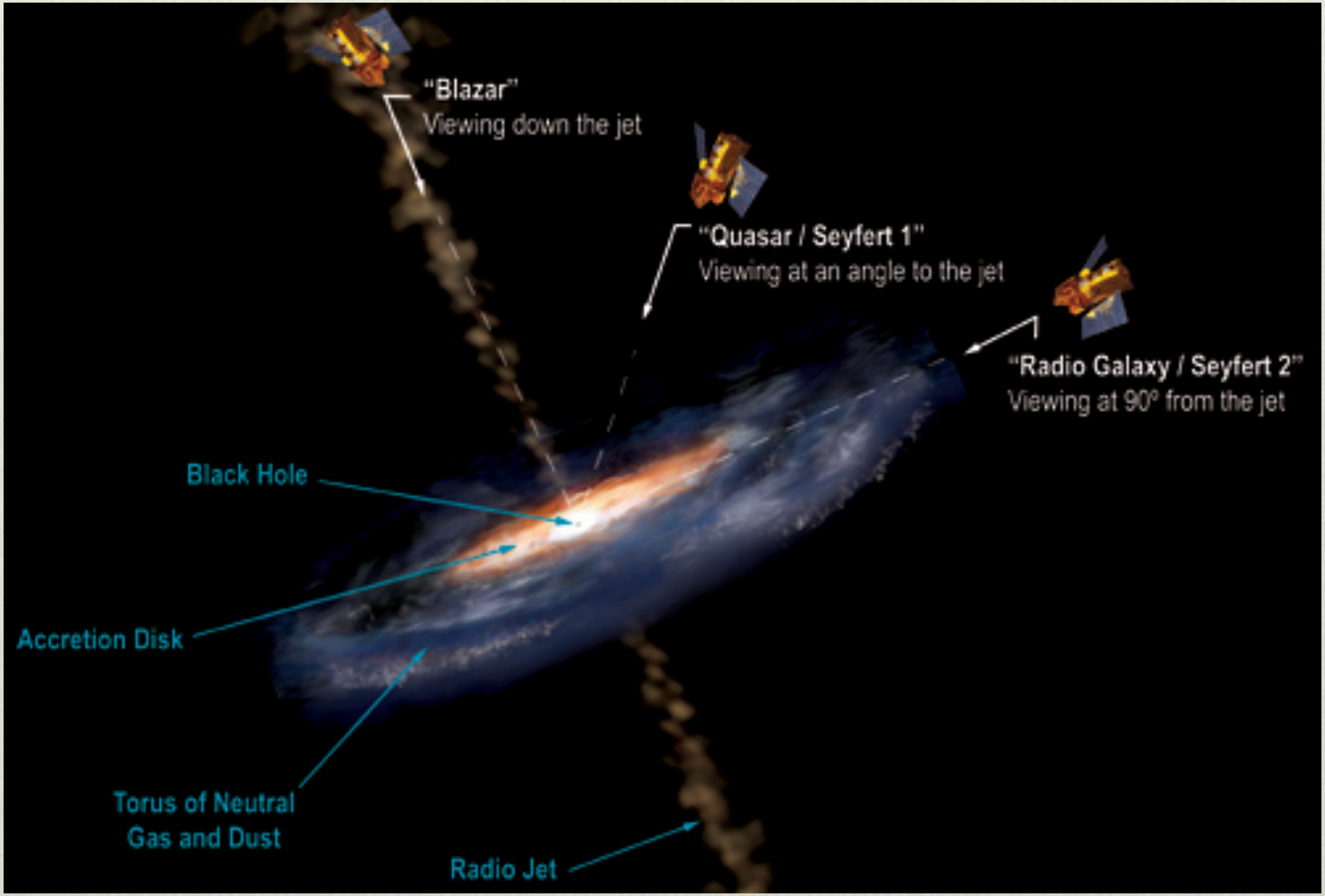
ii) presence (or lack of) jets; radio-loud (radio-quiet)

iii) Accretion rate: $L/L_{Edd} < 0.01$ no broad line region or obscuring torus!

Blazars

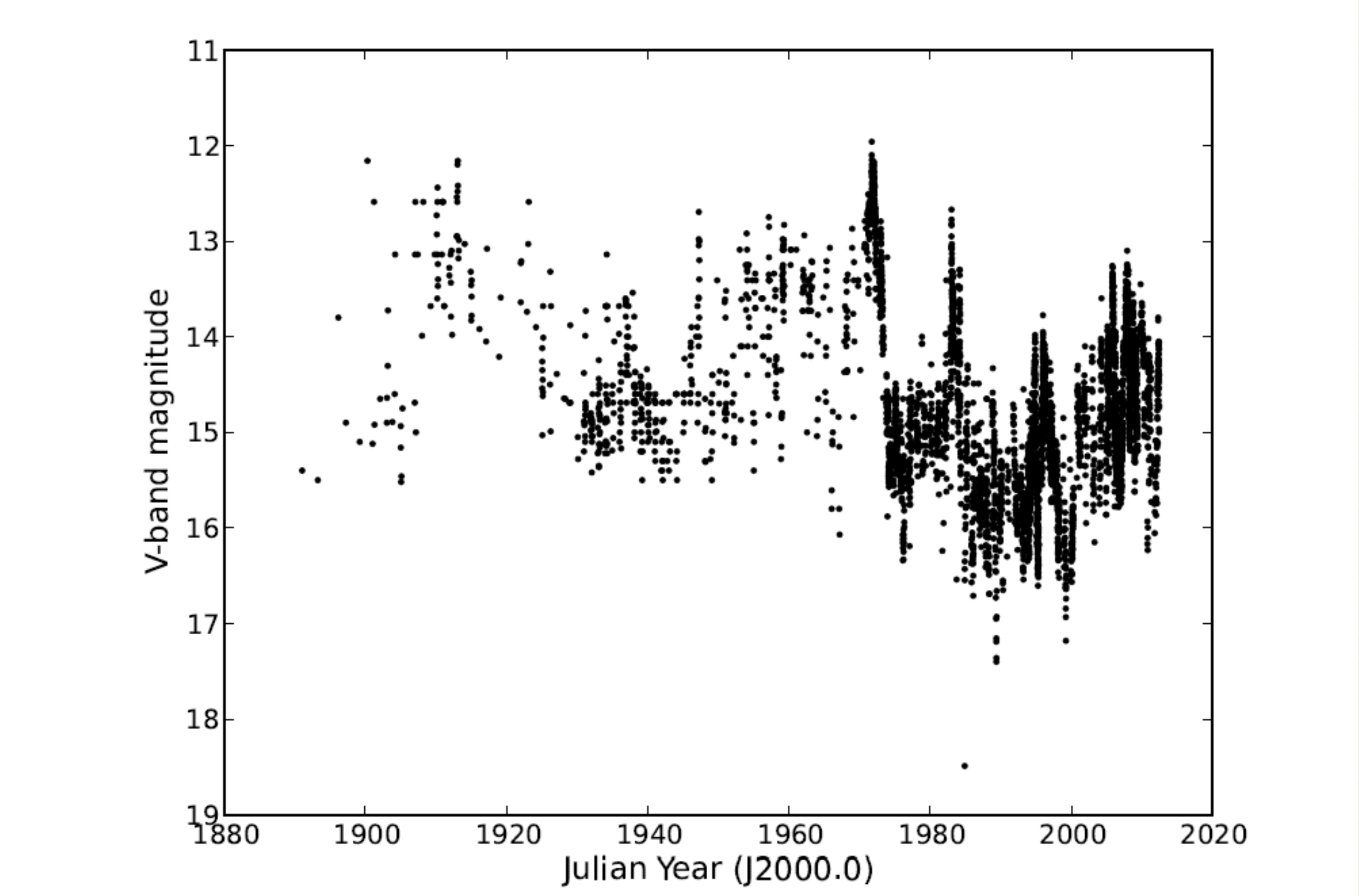
- Smooth, broad, non-thermal continuum (radio to ϒ-rays)
- Compact, strong radio sources
- Rapid variability (high $\Delta L/\Delta t$), high and variable polarization ($P_{opt} > 10\%$)
- Strong indications of “fast” jets forming a small angle with the line of sight




"Blazar"
Viewing down the jet
"Quasar / Seyfert 1"
Viewing at an angle to the jet
"Radio Galaxy / Seyfert 2"
Viewing at 90° from the jet
Black Hole
Accretion Disk
Torus of Neutral
Gas and Dust
Radio Jet

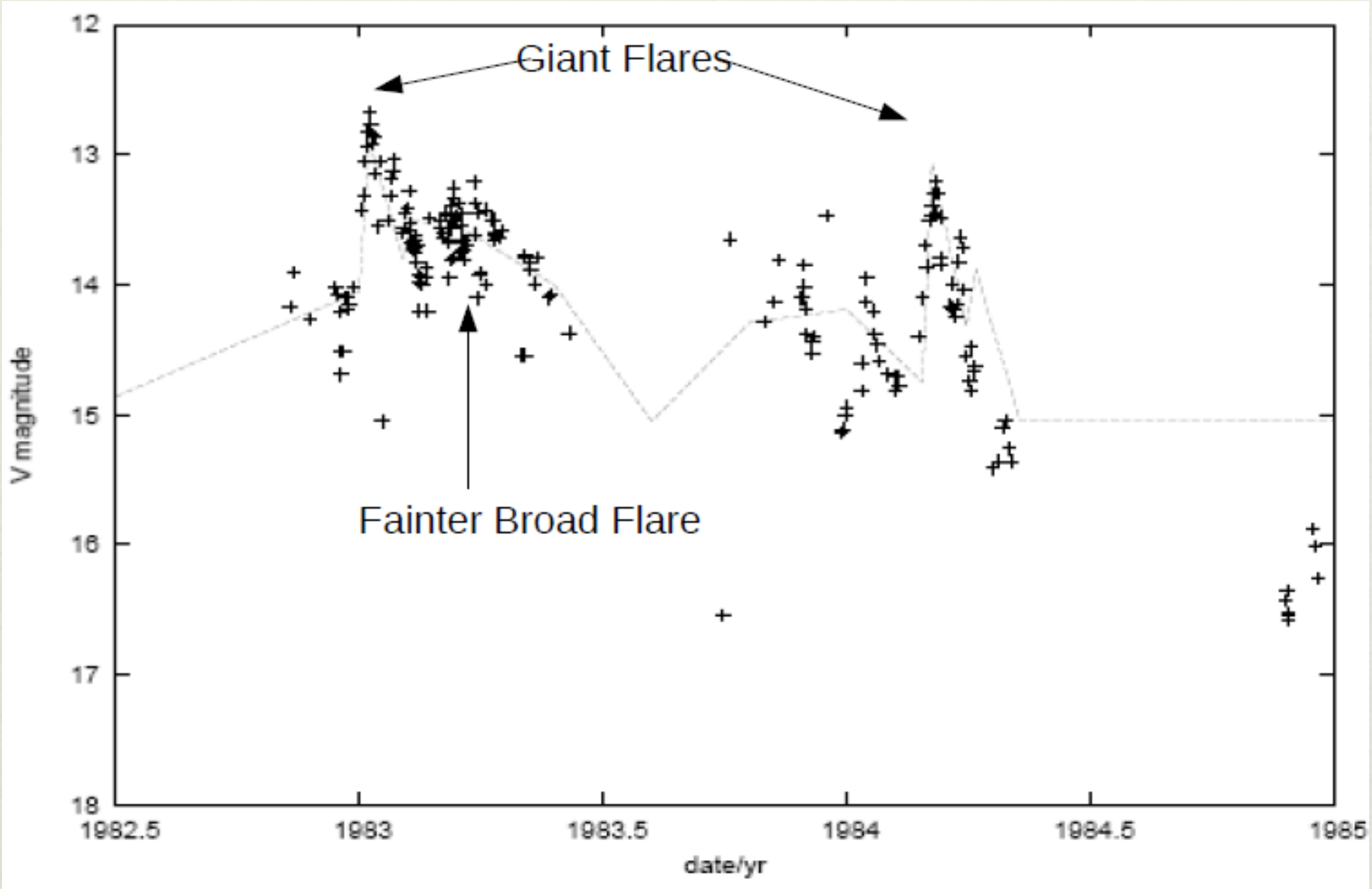
Massive BH binary as the central engine of Blazar OJ287

OJ287: Observations



12 Yr quasi-periodic double peaked outbursts (1913-2007)
Two brightness peaks are separated by 2 + yrs
A long term variations in ~ 60 Yr
Sudden rise of outburst events

OJ287: Observations



Lehto and Valtonen (1996) discovered certain "outburst season"

It is natural to invoke a companion to explain these double peaked quasi-periodic outburst

Lehto-Valtonen model: i

- A simple mathematical rule can be postulated that gives all major outbursts present in the optical light curve
- Take Keplerian orbit and demand that an outburst is produced at a constant phase angle and at the opposite phase angle *(the outburst times can then be easily calculated)*
- This rules provides two outburst peaks arise per period.
- Choose an optimal value of eccentricity
  Allow the semi-major axis of the orbital ellipse to precess in forward direction

These ingredients allowed Lehto & Valtonen to reproduce certain known OJ287 outbursts

Lehto-Valtonen model: ii

- A small black hole in orbit around a massive black hole. The secondary impacts the accretion disk of the primary twice during each full orbit

- The two impacts produce the two flares that are observed ~ 2 years apart

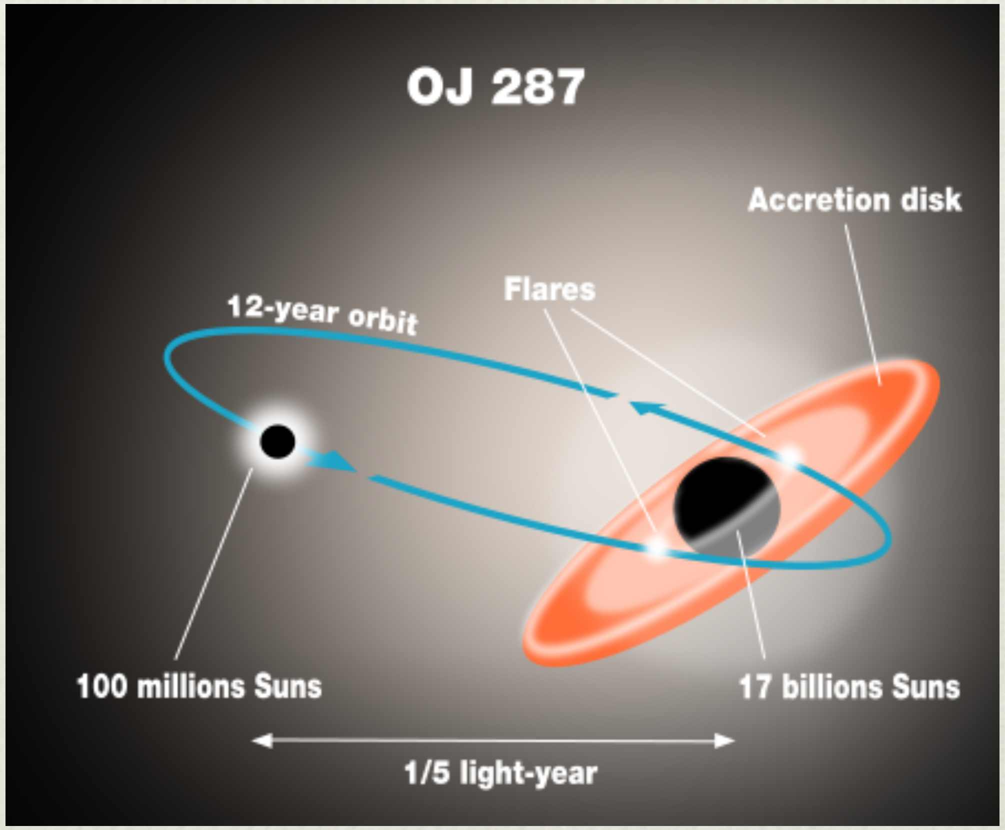
  Flares are repeated in every orbital cycle.

  However, because of relativistic precession, the pattern of flares is not exactly periodic.

  This allows the determination of the precession rate,

- It is NOT necessary to know the inclination of the secondary black hole orbit nor the orientation of the system relative to the observer

Lehto-Valtonen model: iii



This orbit is `defined` using the timing of 5 flares
Five flares have four intervals of time as input parameters
Our unique orbit requires 4 parameters

Primary mass m_1 eccentricity e, orbital precession rate & the initial phase angle (argument of the apo-center)

Astrophysical inputs: i

- *The flares start very suddenly, with the rise time of only about one day* ***(observational inputs)***
- Secondary BH impact on the accretion disk releases hot bubbles of gas from the disk (Ivanov et al. 1998)
- These bubbles expand until they become optically thin & the radiation from the whole volume is seen
- The radiation is thermal bremsstrahlung at the temperature of about

  3×10^5 K

Astrophysical inputs: ii

- ❖ The addition of such an unpolarised component to the emission lowers the degree of polarization

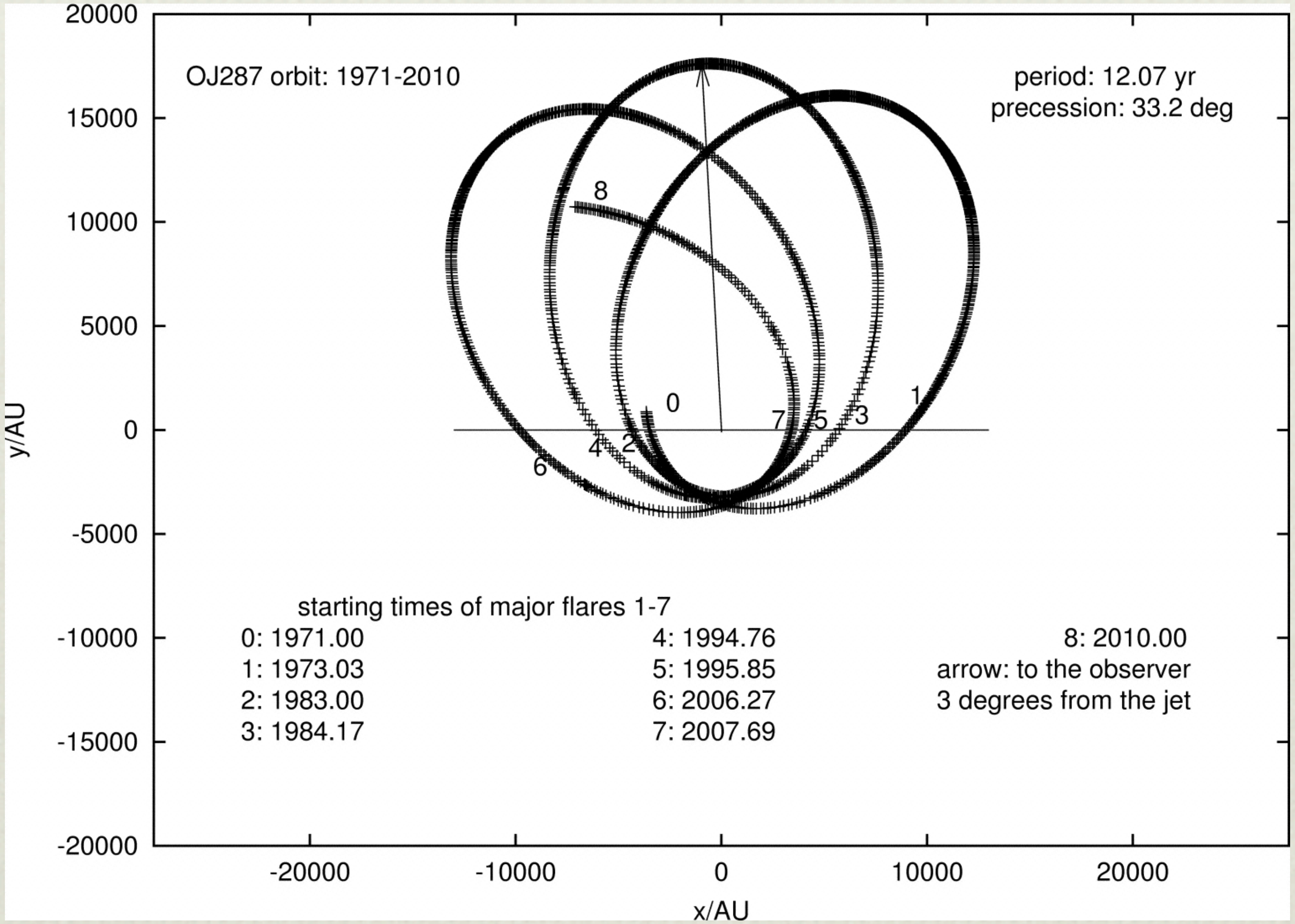
  Another piece of evidence suggesting the presence of bremsstrahlung radiation

- ❖ The astrophysical model introduces a new unknown parameter, the thickness of the accretion disk

  (➔ certain dimensionless time delay)

- ❖ *We have 5 free parameters to fix from observations*

Precessing BBH model for OJ287



Six well timed outbursts; 1947.30, 1972.99, 1983.00, 1984.16, 1994.77 and 2005.76 gave a UNIQUE orbital description

One can make predictions

THE ASTROPHYSICAL JOURNAL, 460:207–213, 1996 March 20

OJ 287 OUTBURST STRUCTURE AND A BINARY BLACK HOLE MODEL

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AND
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Received 1995 April 17; accepted 1995 October 4

ABSTRACT

During the last hundred years, the quasar OJ 287 has experienced several major outbursts as well as numerous smaller brightness fluctuations. The major outbursts occur at intervals of approximately 12 years, the most recent of which is currently underway. Here we analyze the substructure inside the major outbursts and identify well-defined sharp flares. We connect these with a model in which a smaller black hole crosses the accretion disk of a larger black hole during the binary orbit of the black holes about each other. The known flares are numerous enough for a unique determination of the parameters of the binary orbit: eccentricity 0.68, the (redshifted) period 12.07 yr, the (relativistic) precession period 130 yr, and the inclination of the accretion disk in the sky, 4°. A model of the flares is developed which allows us to estimate the mass of the secondary black hole as $10^8\ M_\odot$. The rate of the relativistic precession is used to estimate the mass of the primary black hole as $17 \times 10^9\ M_\odot$ and the current semimajor axis of the orbit as 0.056 pc. It is possible that the system is an eclipsing binary, in which case the next eclipse is expected in the beginning of 1998. The model leads to predictions for the times of occurrence of future outbursts and flares.
Subject headings: accretion, accretion disks — black hole physics — quasars: individual (OJ 287)

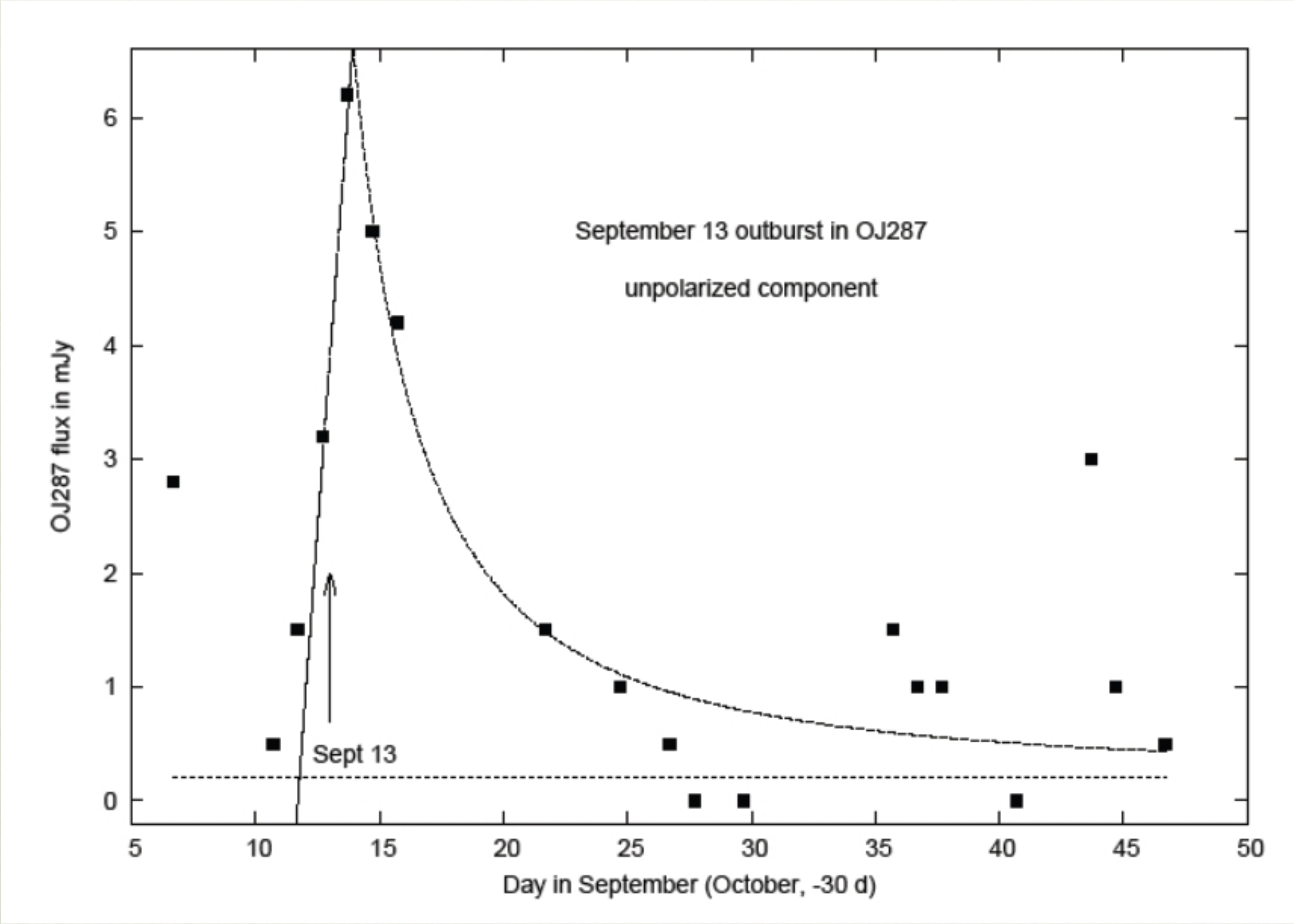
If an astrophysical model fits the observed data, it is the responsibility of a good physicist to make a prediction

Predicting the Next Outbursts of OJ 287 in 2006-2010

M. J. Valtonen[1], H. J. Lehto[1,5], A. Sillanpää[1], K. Nilsson[1], S. Mikkola[1], R. Hudec[2], M. Basta[2], H. Teräsranta[3], S. Haque[4], and H. Rampadarath[4]

The Astrophysical Journal, Volume 646, Number 1

BBH-AD impact model predicted the next outburst on 13/09/2007 ± 2 days (in 2006)



The observed flux rise coincides within 6 hours of the prediction

The accuracy is about the same with which we were able to predict the return of Halley's comet in 1986!

Letter

Nature **452**, 851-853 (17 April 2008) | doi:10.1038/nature06896; Received 1 December 2007; Accepted 6 March 2008

A massive binary black-hole system in OJ 287 and a test of general relativity

M. J. Valtonen[1], H. J. Lehto[1], K. Nilsson[1], J. Heidt[2], L. O. Takalo[1], A. Sillanpää[1], C. Villforth[1], M. Kidger[3], G. Poyner[4], T. Pursimo[5], S. Zola[6,7], J.-H. Wu[8], X. Zhou[8], K. Sadakane[9], M. Drozdz[7], D. Koziel[6], D. Marchev[10], W. Ogloza[7], C. Porowski[6], M. Siwak[6], G. Stachowski[7], M. Winiarski[6], V.-P. Hentunen[11], M. Nissinen[11], A. Liakos[12] & S. Dogru[13]

If Mauri did NOT include the effect quadrupolar order GRR, the September 2007 outburst would have been 20 days later.

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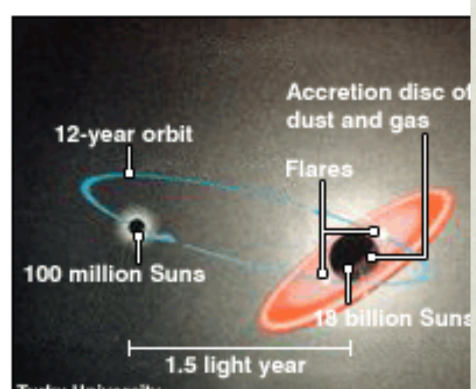
Huge black hole tips the scales

By Paul Rincon
Science reporter, BBC News, Austin

Astronomers have weighed the biggest known black hole in the Universe.

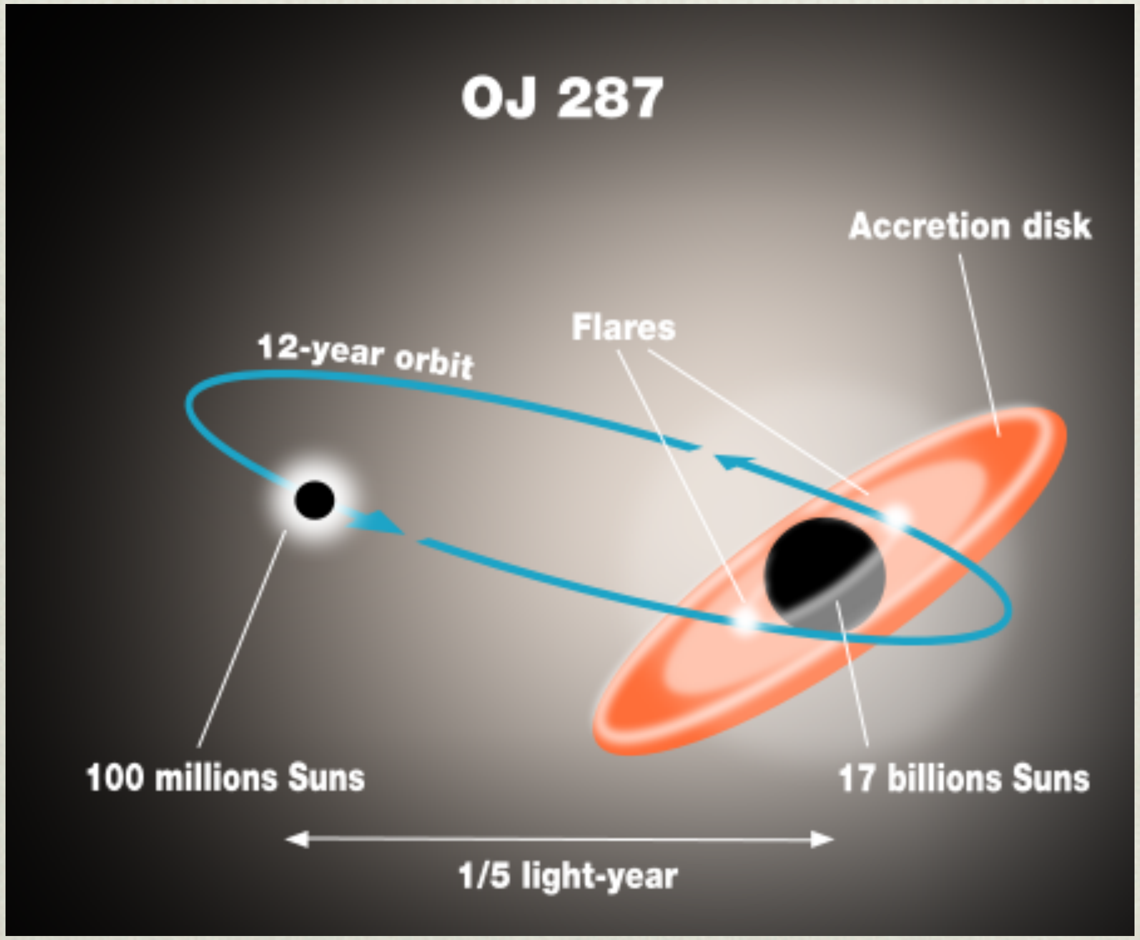


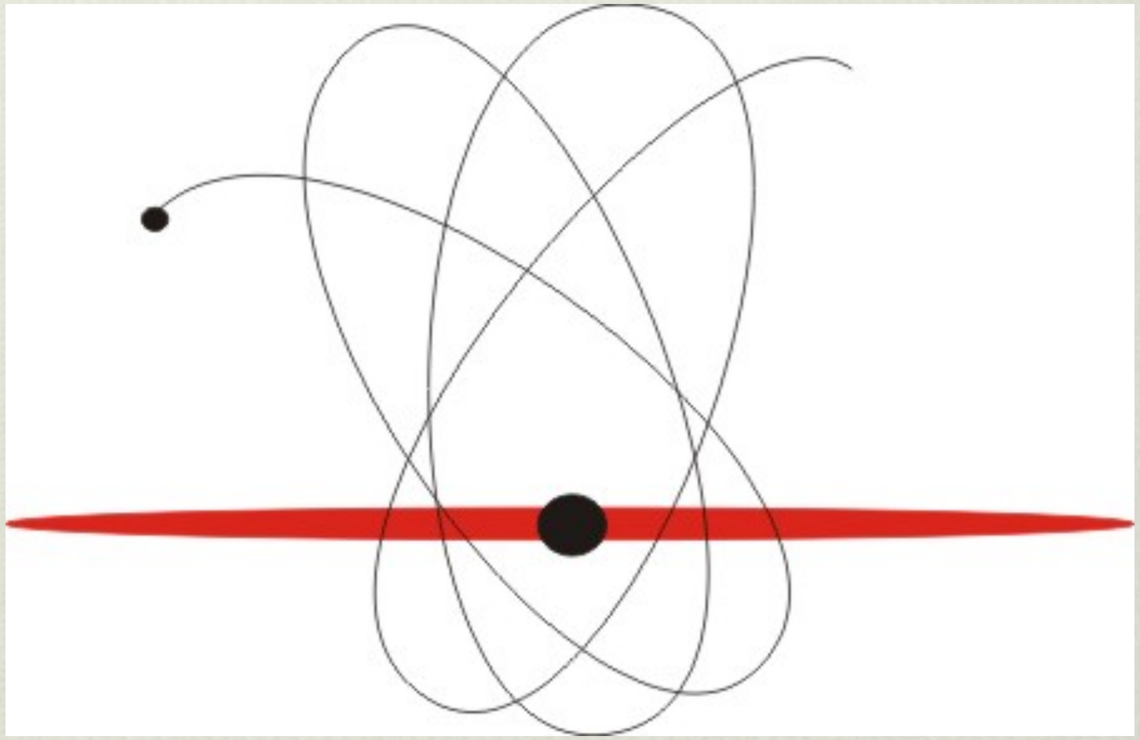
The monster celestial object is 18 billion times more massive than our own Sun, says a team from Finland - six times larger than the previous record.

The object, called OJ287, is orbited by a smaller black hole, which allowed its mass to be measured very accurately.

The finding also enabled the researchers to test Einstein's theory of gravity for the first time in a strong gravitational field

Massive BH binary model for OJ287





Can we probe other properties of the binary black hole in OJ287 ?

Can we do better ?

- Rampadarath et al. discovered an outburst beginning at 1957.07 (tentative observational evidences for 1906 & 1912 outbursts)

Table 6. Outburst times outbursts.

Time	uncertainty
1912.970	$\pm$ 0.010
1947.282	$\pm$ 0.0005
1957.080	$\pm$ 0.020
1972.94	$\pm$ 0.005
1982.964	$\pm$ 0.0005
1984.130	$\pm$ 0.002
1995.843	$\pm$ 0.0005
2005.745	$\pm$ 0.005
2007.692	$\pm$ 0.0005

9 observed outburst times !

Let the primary BH spin

Accurate description of the relativistic orbit is crucial to time the AD impacts

An accurate timing will constrain system parameters more accurately

It will allow us to make accurate predictions of the future impact flares

Accurate GR description for the BH binary

- The Post Newtonian approximation to GR provides dynamics of compact binary as corrections to the Newtonian equations of motion
  in powers of $(v/c)^2 \sim G\,M/(c^2 r)$

$$\frac{\mathrm{d}^2\vec{r}}{\mathrm{d}t^2} = \frac{G(m_1+m_2)}{r^2}\Big[-\vec{n} + c^{-2}\vec{A}_{1\mathrm{PN}} + c^{-3}\vec{A}_{\mathrm{SO}} + c^{-4}\left(\vec{A}_{2\mathrm{PN}} + \vec{A}_{\mathrm{Q}} + \vec{A}_{\mathrm{SS}}\right) + c^{-5}\vec{A}_{2.5\mathrm{PN}} + c^{-6}\vec{A}_{3\mathrm{PN}} + c^{-7}\vec{A}_{3.5\mathrm{PN}} + \mathcal{O}\left(c^{-8}\right)\Big]$$

$$\frac{\mathrm{d}\vec{s}_1}{\mathrm{d}t} = \left[c^{-2}\vec{\Omega}_{\mathrm{SO}} + c^{-3}\left(\vec{\Omega}_{\mathrm{SS}} + \vec{\Omega}_{\mathrm{Q}}\right)\right] \times \vec{s}_1,$$

Orbital plane precesses around the spin vector with a constant angle …

Precessional cone axis aligned with AD axis ..

Predicting the next impact flare

Table 5. Solution parameters.

Parameter	Astrophysics	Orbit
$\Delta\phi$	$38.^\circ6 \pm 1.^\circ0$	$39.^\circ1 \pm 0.^\circ1$
m_1	$(1.8 \pm 0.1) \cdot 10^{10} M_\odot$	$(1.84 \pm 0.01) \cdot 10^{10} M_\odot$
m_2	$(1.4 \pm 0.4) \cdot 10^{8} M_\odot$	$(1.46 \pm 0.1) \cdot 10^{8} M_\odot$
χ_1	0.25 ± 0.04	0.28 ± 0.03
ϕ_0	$56.^\circ0 \pm 4.^\circ0$	$56.^\circ3 \pm 1.^\circ0$
e	0.7 ± 0.03	0.70 ± 0.001
α	0.3 ± 0.2	0.3 ± 0.1
q	–	1.0 ± 0.3

In 2010, we predicted an outburst in late 2015 to early 2016 (easy to detect)

Its timing is spin-sensitive; the exact date will give us a good spin value

2015 impact flare: i

$$\chi_1 = 0.25 - 0.5 \times (t - 2016.0).$$

Here t is the time of the beginning of the outburst in years.

χ1= 0.36 if the outburst begins in early 11/2015 Nov
If it begins by the end of January 2016 χ1= 0.2

Accurate timing of the secondary BH impact flare should allow us to measure the Kerr parameter of a massive BH for the first time

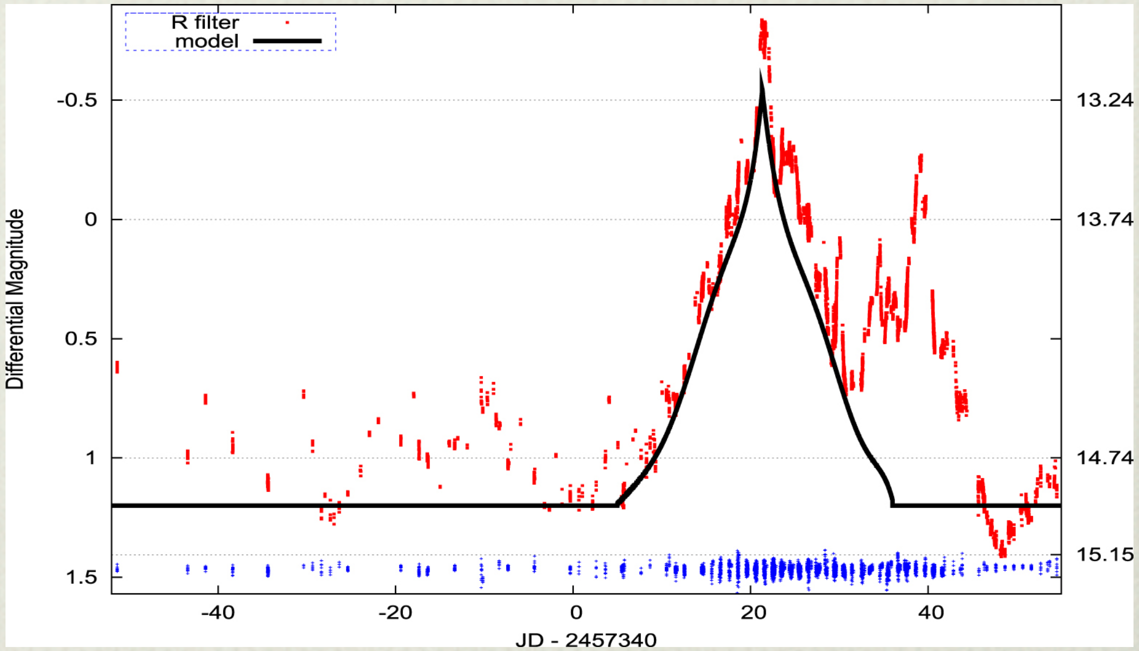
OJ287 impact flare monitoring campaign during November 2015 to February 2016

Mauri J. Valtonen[1], Achamveed Gopakumar[2],

A campaign was initiated

2015 impact flare: ii

- Optical outburst peak occurred within the expected time range, *It peaked on 2015 December 5 at magnitude 12.9 in the optical R-band*



- The major outbursts involve a rapid rise to a narrow peak and then a slower decline with multiple smaller flares

- Additionally, there exists an initial, slowly rising part in the light curve with an additional peak at the maximum.

The model LC is from a uniform expanding sphere of plasma

2015 impact flare: iii

- Swift/XRT observations reveal modest X-ray flare , much smaller than the optical outburst

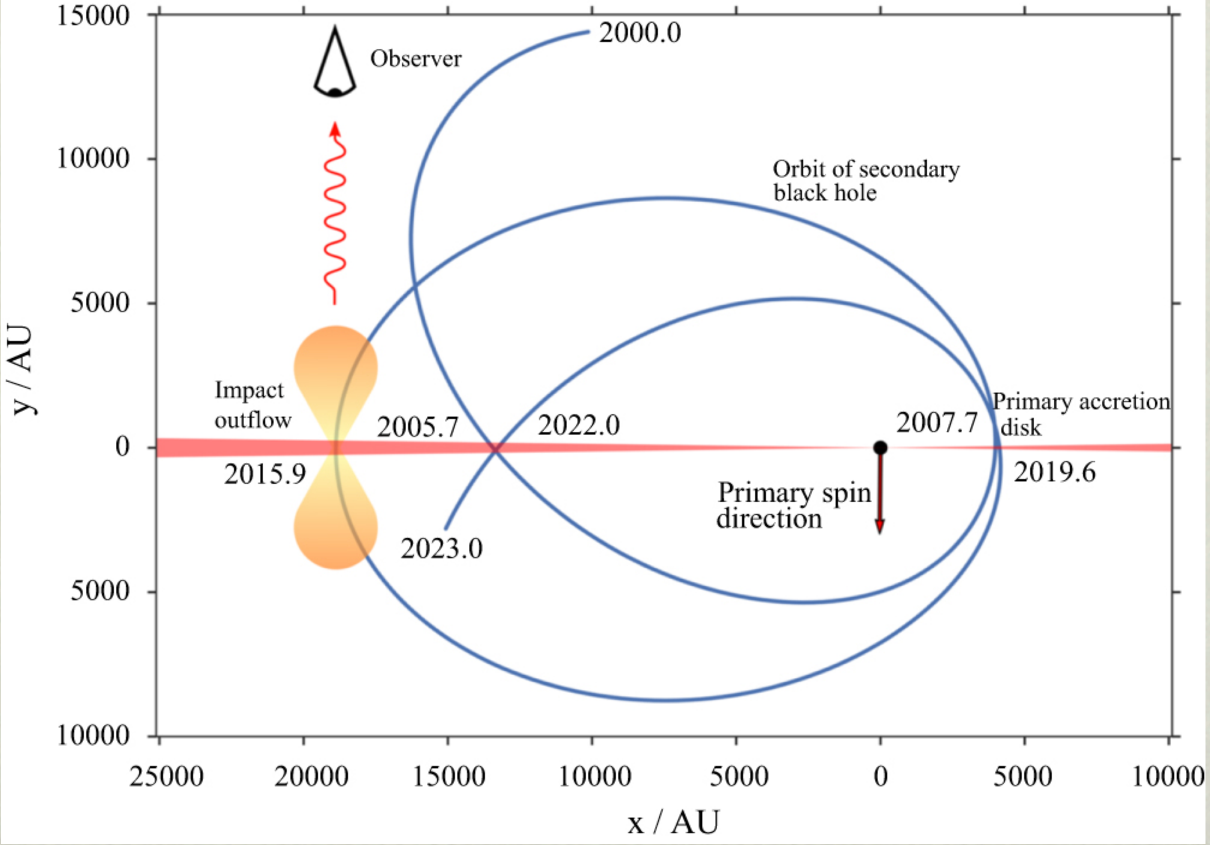
- However, it correlates very well with the excess flare emissions
  The optical excess emission is defined as the total optical flux minus the bremsstrahlung flux (optical polarization data allowed us to estimate it)

- ***Data from Swift/XRT daily monitoring & optical polarization data confirmed the major thermal component of the predicted outburst.***

The timing of the thermal component rise provided ***an accurate measurement*** *for the spin of a massive black hole,* $\chi = 0.313 \pm 0.01$

We confirmed the established general relativistic properties of the system at the 2% accuracy level

May test No Hair theorem during this decade !!



On-going efforts: i

- Do we need to incorporate higher order spin effects ? (both conservative & reactive)

- Can we constrain certain dipole radiation that such a massive BH binary may emit ?

Early estimates suggest that these bounds can be better that LIGO-LISA bounds !!

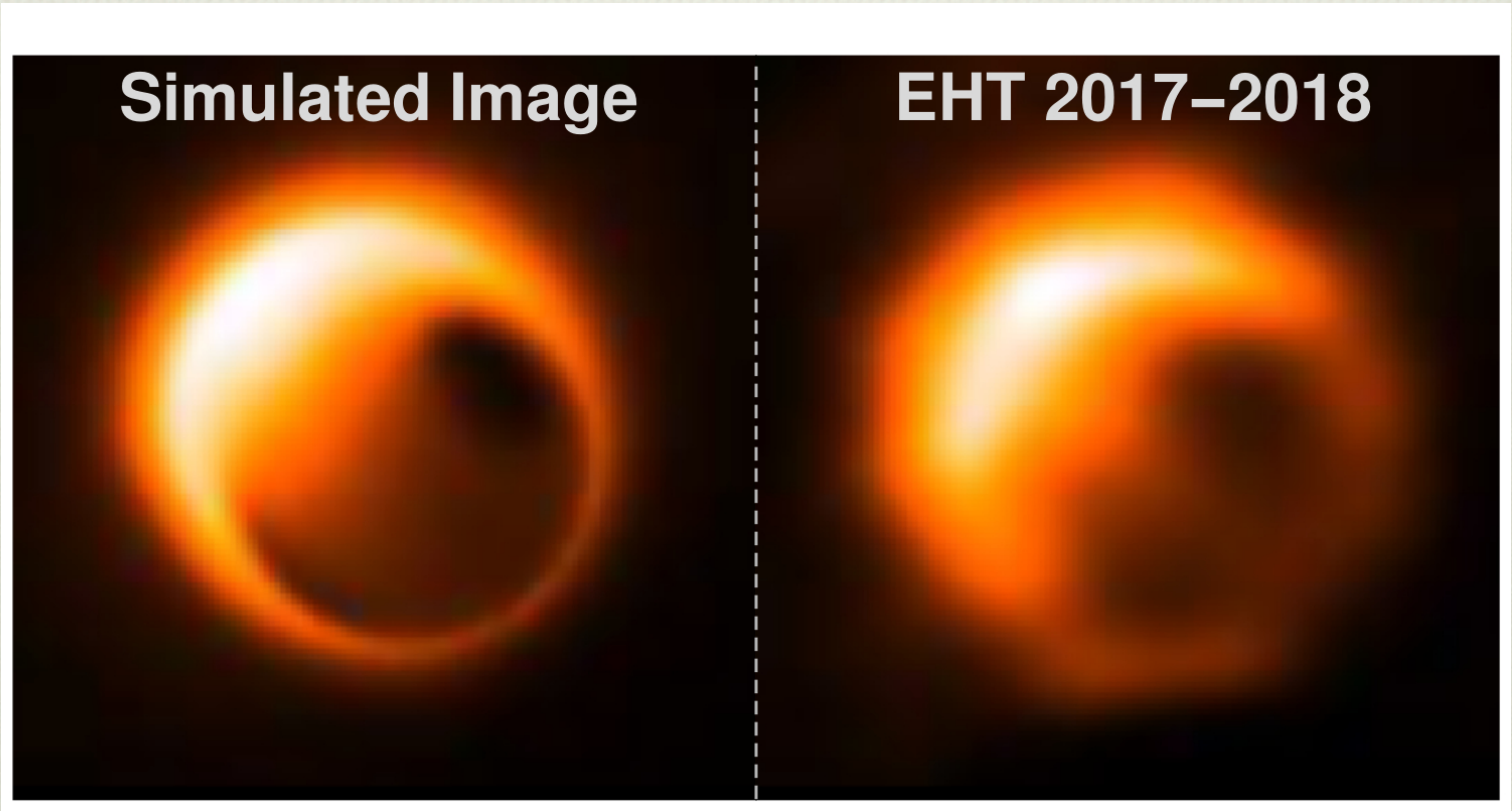
- Variations in G

With Lankeswar Dey & Mauri Valtonen

On-going efforts: ii

- The 2019 outburst timing should allow one to test BH no-hair theorem at below 10 % level
- However, observing OJ287 during the rising flux of the 2019 outburst, predicted to occur July 14 to July 17, is a challenge for ground based observers.
- The angular distance between the Sun and OJ287 is only about 20 degrees during that epoch !
- A real technological challenge for optical astronomers

EHT is expected to resolve objects at the 50 μas level during this decade



Next Generation EHT for OJ287 ?

- Angular diameter of a non-rotating BH ~ $6 \; G M / c^2 d$
- For OJ287, this is ~ 3.5 μas
- The present EHT may not be able to resolve BBH system in OJ287
- However, can EHT measures astrometric displacement when the smaller BH plunges into the primary accretion disk ?

Implications for TATA Pulsar Timing Array (TAPTA)

- ❖ **The present campaign confirmed the first indirect evidence for the existence of a binary SMBH emitting GWs.**

- ❖ **This is an encouraging news for the PTA efforts that will directly detect gravitational waves from such massive BH binaries in the nano-Hz regime**

- ❖ The proposed TAPTA will be the only facility in the world that would make such daily observations of IPTA pulsars for directly detecting nano-Hz GWs

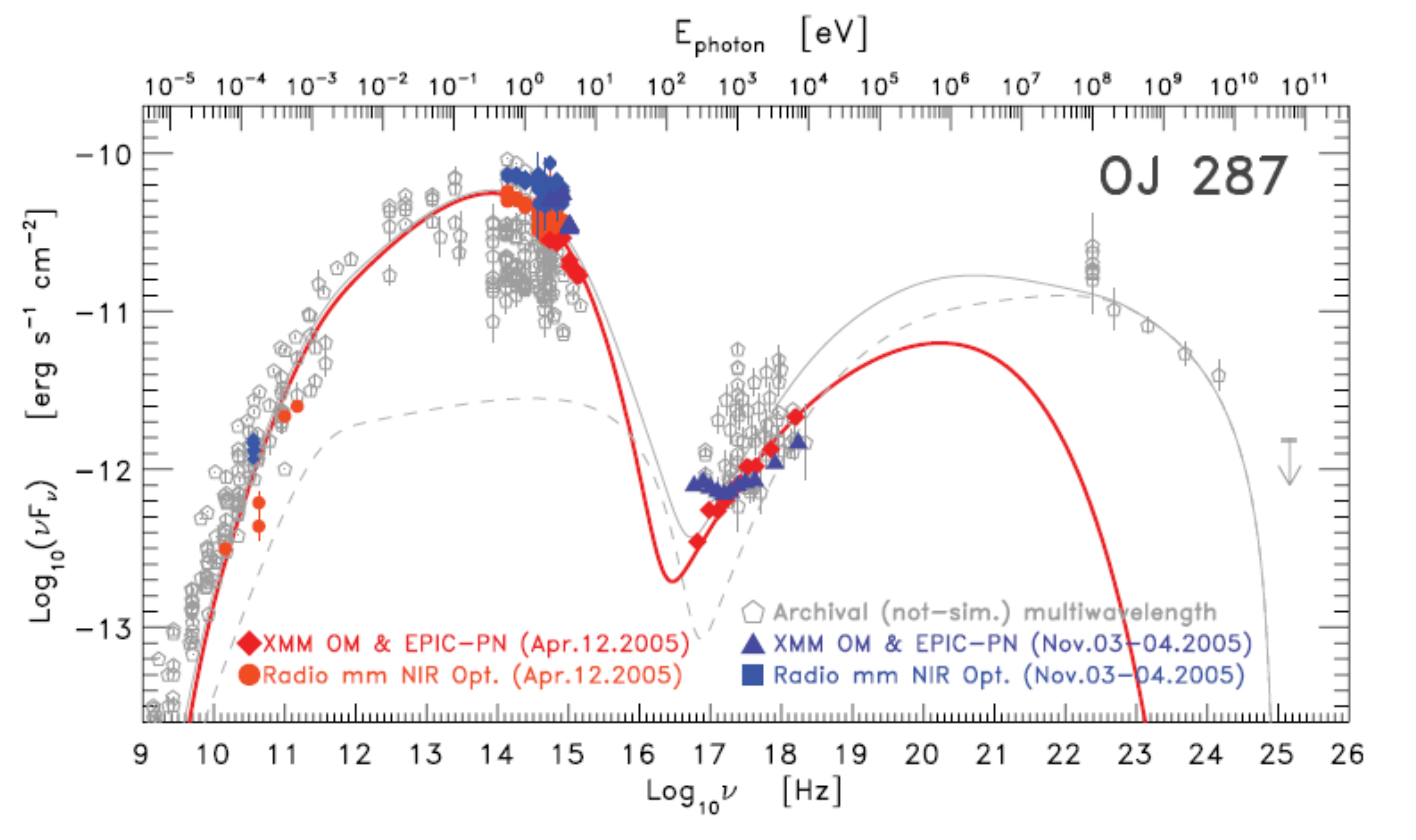
  In principle, TAPTA can also contribute to the world-wide EHT effort

TIFR & India can contribute significantly to these efforts with TAPTA

Summary

- The predicted 2015 impact flare firmly established the presence of a massive BH binary in OJ287
- *We provided **an accurate measurement** for the spin of a massive black hole,* $\chi = 0.313 \pm 0.01$
- ***We confirmed the established general relativistic properties of the system at the 2% accuracy level***

SED for OJ287



Theoretical v-mag for OJ287