The black hole binary model of OJ 287 as witness of the validity of the General Relativity

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Based on a collaborative research performed at
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Jagiellonian Univ., Poland,   ASDC Rome Italy,
Osaka Kyoiku University, Japan
and MW campaing involving many other institutes
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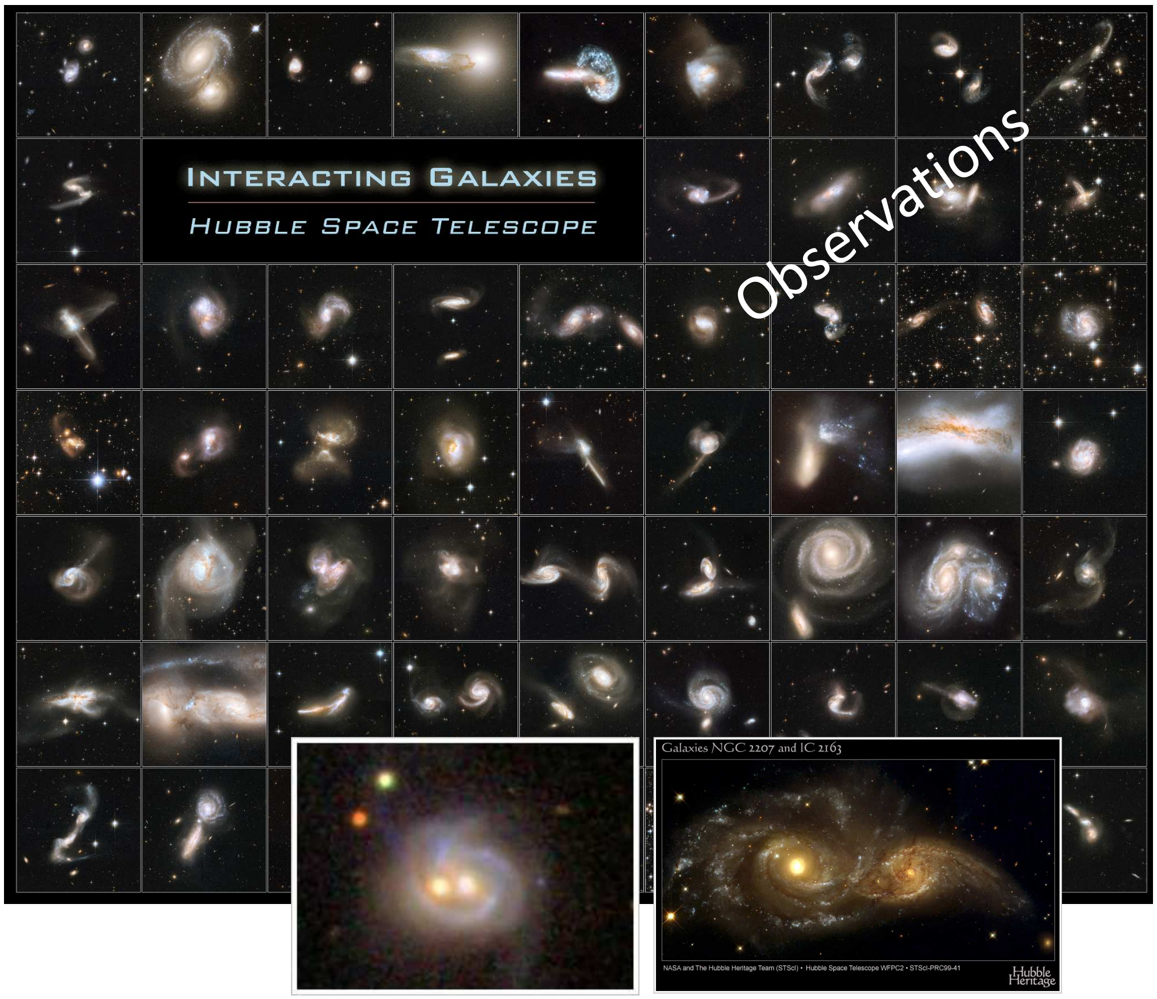
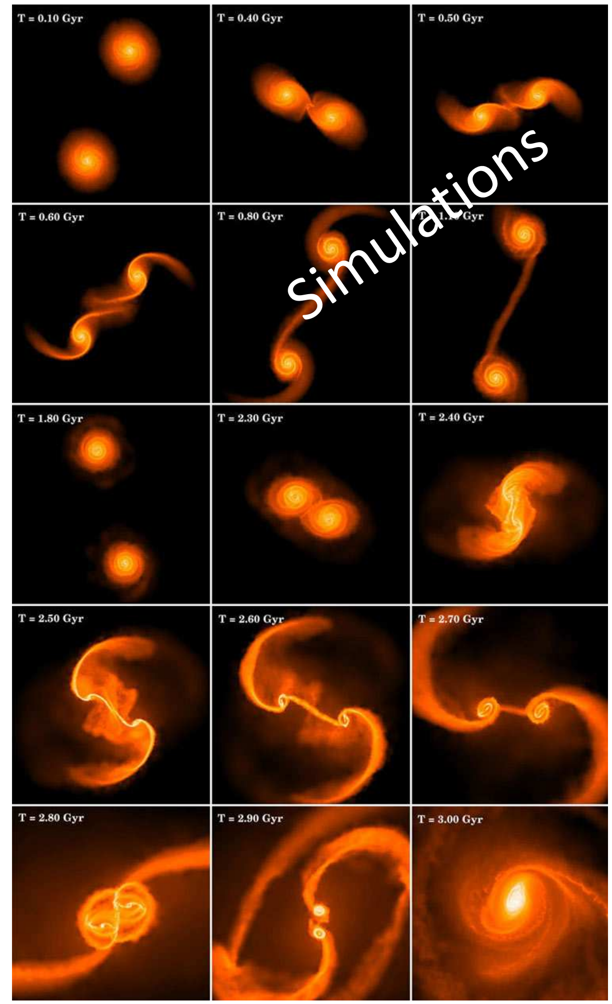
Galaxy encounters/mergers

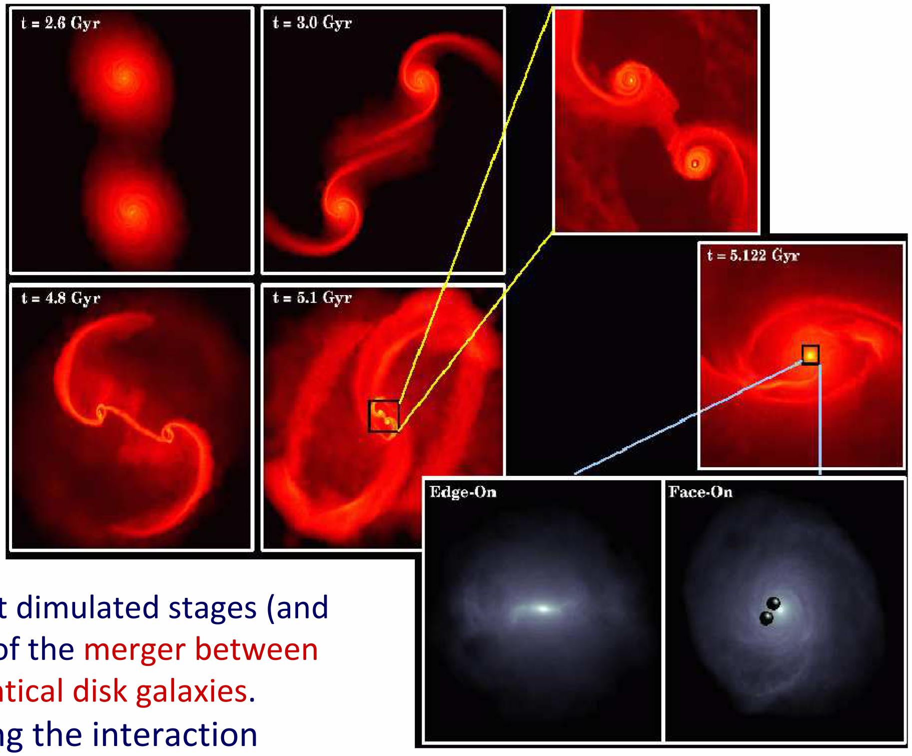
- History of the Universe: hierarchical structure formation, galaxy mergers, SMBH pairs and SMBH binaries.



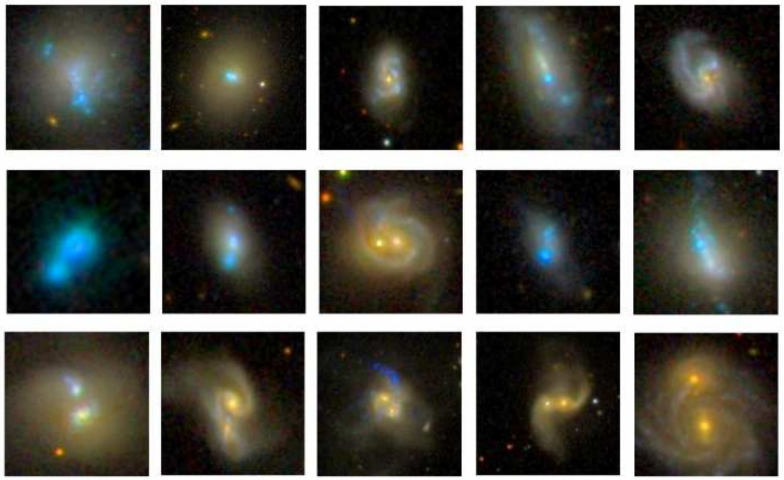


Supermassive BHs pairs/binary

❑ Supermassive black holes (SMBHs) are a ubiquitous component of the nuclei of galaxies and AGN. Following the merger of two massive galaxies, a SMBH binary will form, shrink due to stellar or gas dynamical processes and ultimately coalesce by emitting a burst of gravitational waves.



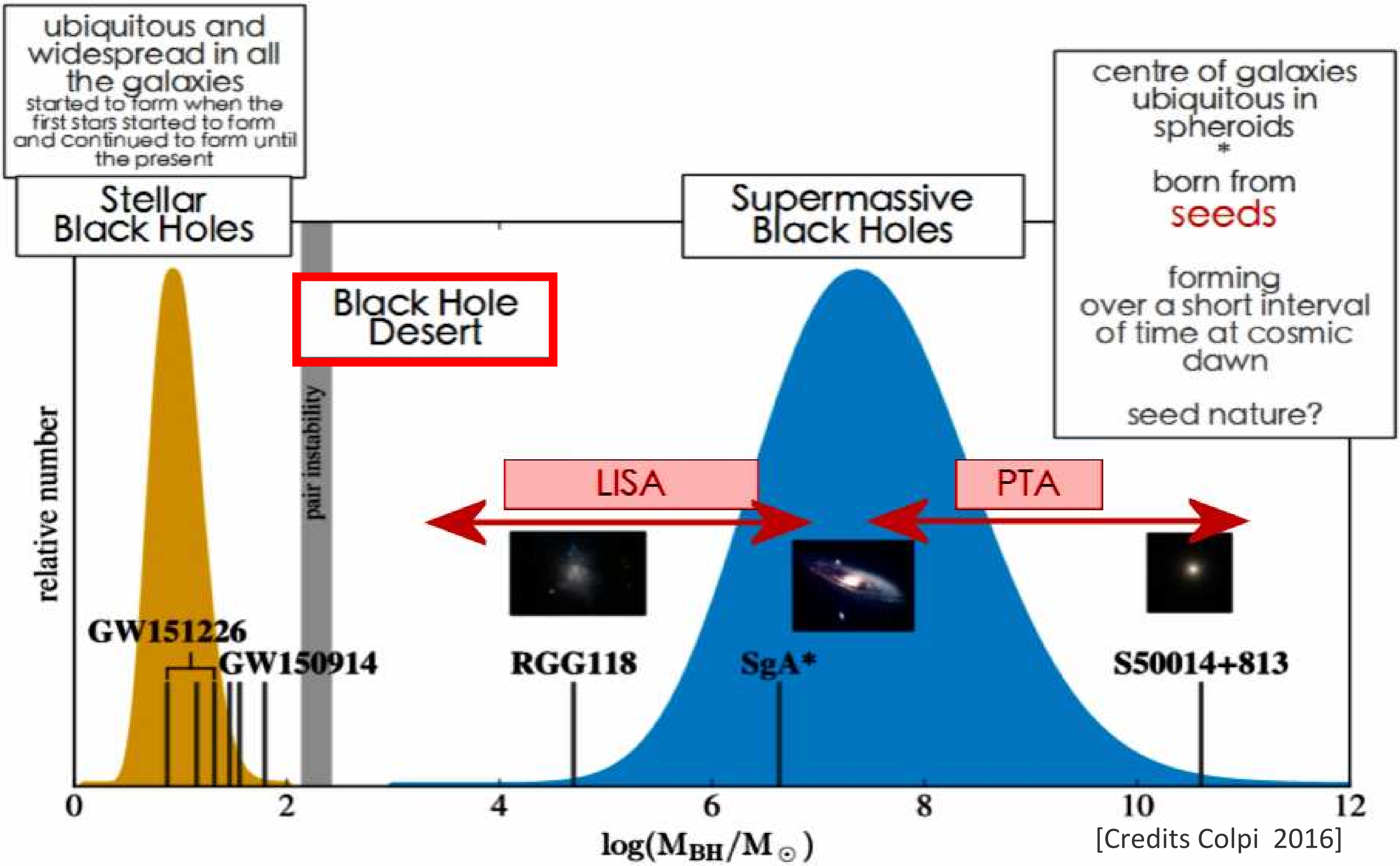
❑ Close (sub-parsec systems) binary SMBHs
→ Indirect searches:
– Double or asymmetric spectral lines (but Liu+2015).
– Helical, distorted jets; tidal disruption events (TDE) as dips in light curves.
– Periodic/quasi-periodic oscillations (long-living) in flux light curves.



Different dimulated stages (and zooms) of the merger between two identical disk galaxies.

❑ During the interaction tidalforces tear the galactic disks apart, generating spectacular tidal tails and plumes. Simulations show that the two SMBHs form an eccentric binary in the disk in less than a million years as a result of the gravitational drag from the gas rather than from the stars (Mayer et al. 2007).

BHs: two flavors, Stellar/Supermassive BHs



[Credits Colpi 2016]

Supermassive BHs pairs/binaries

SciNeGHE 2016

Observational evidence for SMBH pairs and gravitationally bound binary systems:

r/pc

1000 ❑ quasar pairs, AGN in clusters of galaxies

❑ pairs of active galaxies, interacting galaxies in early phase of interaction/merging
100 (double-peaked narrow optical emission lines, if both galaxies have NLR)

❑ SMBH pairs in "single" galaxies and advanced
10 mergers, kpc/100-pc scales
(ex.: two accreting SMBHs spatially resolved, often heavily obscured --> X-ray/radio observations)

1

❑ spatially unresolved binary-SMBHs candidates
(1. pseudo/quasi/semi-periodic signals in radio/optical flux light curves; 2. pc-scale spatial radio-structures
0.1 distorted/helical-patterns in jets; 3. double-peaked broad lines)

0.01 ❑ a few post-merger candidates
(X-shaped radio sources, galaxies with central light deficits, double-double radio sources, recoiling SMBHs)

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Massive black hole binaries in active galactic nuclei

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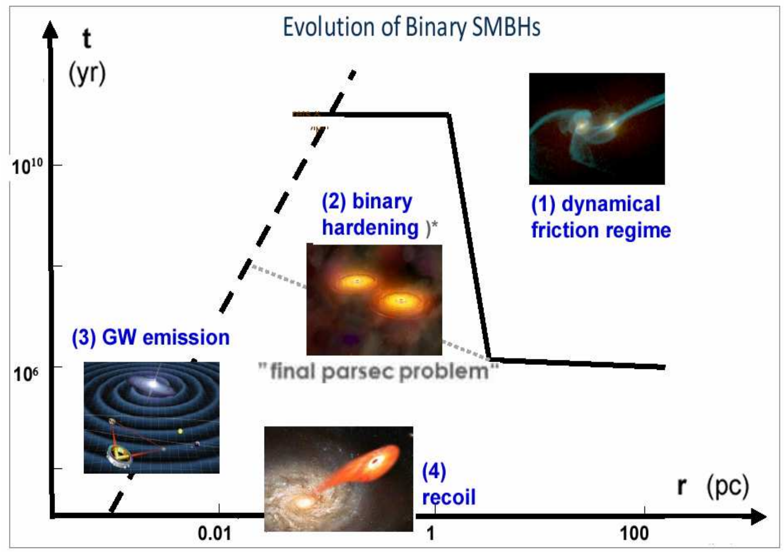


[Credits S. Komossa 2014] Komossa et al.

• Galaxy mergers. Sites of major BH growth & feedback processes.
• Coalescing binary SMBHs. Powerful emitters of GWs and e.m. radiation.
• GW recoil. SMBHs oscillate about galaxy cores or even escape.

Evolutionary track and timescales of binary SMBHs

Little evidence for widespread binary SMBHs → they need to merge rather efficiently. Merger is a natural way of producing SMBHs from smaller seeds.

- ❑ Merger of two galaxies creates a common nucleus; dynamical friction rapidly brings two black holes together to form a gravitationally bound binary (r~10 pc).
- ❑ Three-body interaction of binary with stars of galactic nucleus ejects most stars from the vicinity of the binary by the slingshot effect; a "mass deficit" is created and the binary becomes "hard" (r~1 pc).
- ❑ The binary further shrinks by scattering off stars that continue to flow into the "loss cone", due to two-body relaxation or other factors.
- ❑ As the separation reaches 0.01 pc, GW emission becomes dominant in carrying away the energy.
- ❑ Reaching a few Schwarzschild radii (~10^–5 pc), the binary finally merges.

- **Dynamical friction timescale:** $t_{\rm DF} \sim 10^6\ {\rm yr} \left(\frac{r}{100\ {\rm pc}}\right)^2 \left(\frac{\sigma}{200\ {\rm km/s}}\right) \left(\frac{m_2}{10^8\ M_\odot}\right)^{-1} \left(\frac{\ln\Lambda}{15}\right)^{-1}$
- **A binary is called hard if its orbital velocity exceeds that of the field stars, or the separation is less than a_h:**

$$a_h = \frac{G\mu}{\sigma^2} \approx 2.7{\rm pc}(1+q)^{-1} \left(\frac{m_2}{10^8\ M_\odot}\right) \left(\frac{\sigma}{200{\rm km/s}}\right)^{-2}, \qquad \mu \equiv \frac{m_1 m_2}{m_1+m_2},\ q \equiv \frac{m_2}{m_1}$$

- **The timescale for coalescence due to GW emission is (Peters 1964)**

$$t_{\rm GW} = \frac{5}{256\,F(e)}\frac{c^5}{G^3}\frac{a^4}{\mu(m_1+m_2)^2} \approx 7\times10^8{\rm yr}\frac{q^3}{(1+q)^6}\left(\frac{m_1+m_2}{10^8\ M_\odot}\right)^{-0.6}\left(\frac{a}{10^{-2}a_h}\right)^4$$

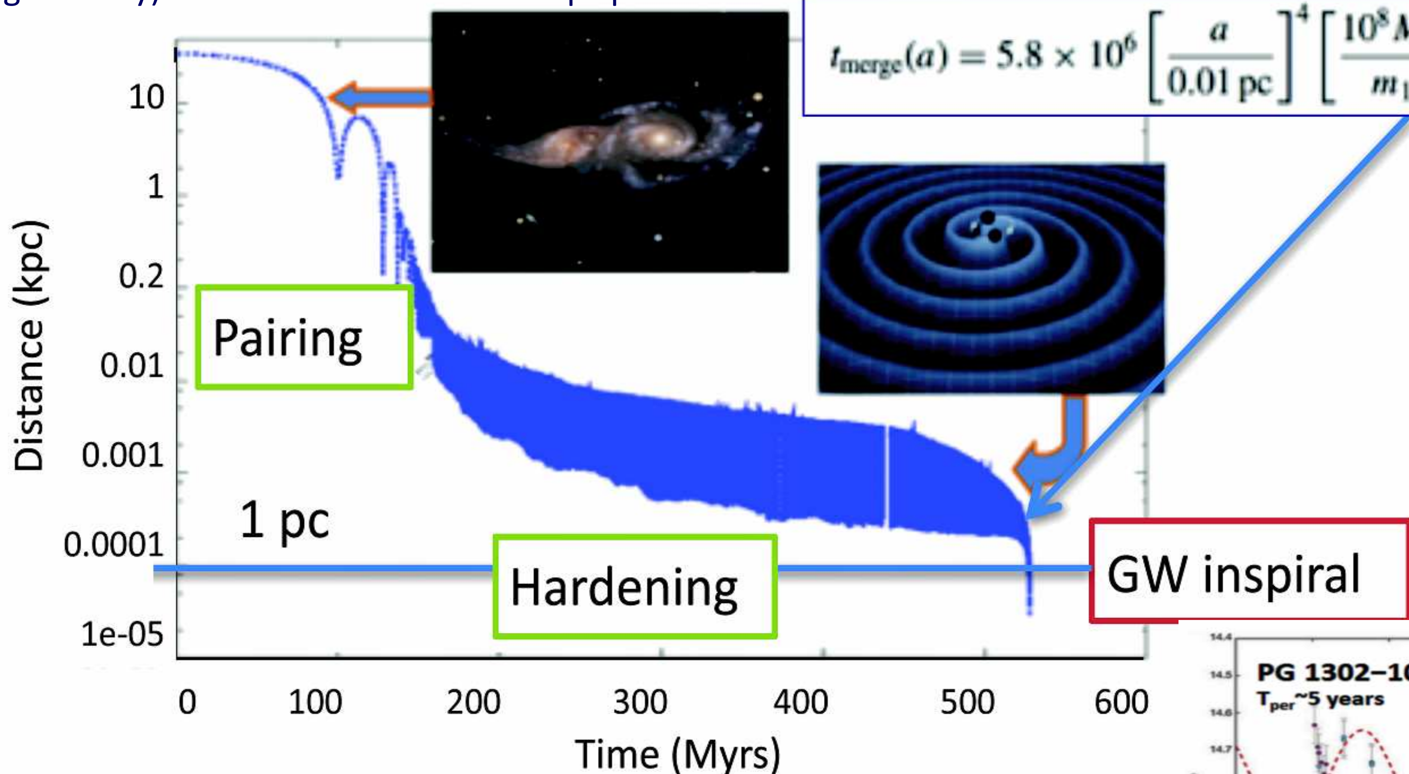
[Credits E. Vasiliev]

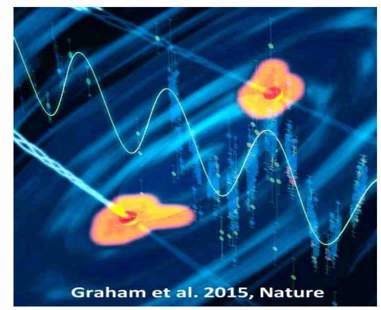
$$F(e) \equiv (1-e^2)^{7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

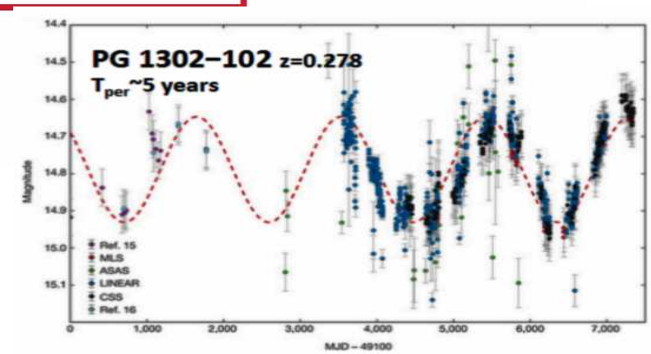
Supermassive BHs pairs/binaries

❑ Observational evidence is important to solve the theoretical "final parsec problem" in GR (solved by non spherical geometry). There is also the final 0.1 pc problem.

$$t_{merge}(a) = 5.8 \times 10^6 \left[\frac{a}{0.01\,\mathrm{pc}}\right]^4 \left[\frac{10^8 M_\odot}{m_1}\right]^3 \frac{m_1^2}{m_2(m_1+m_2)}\ \mathrm{yr}$$





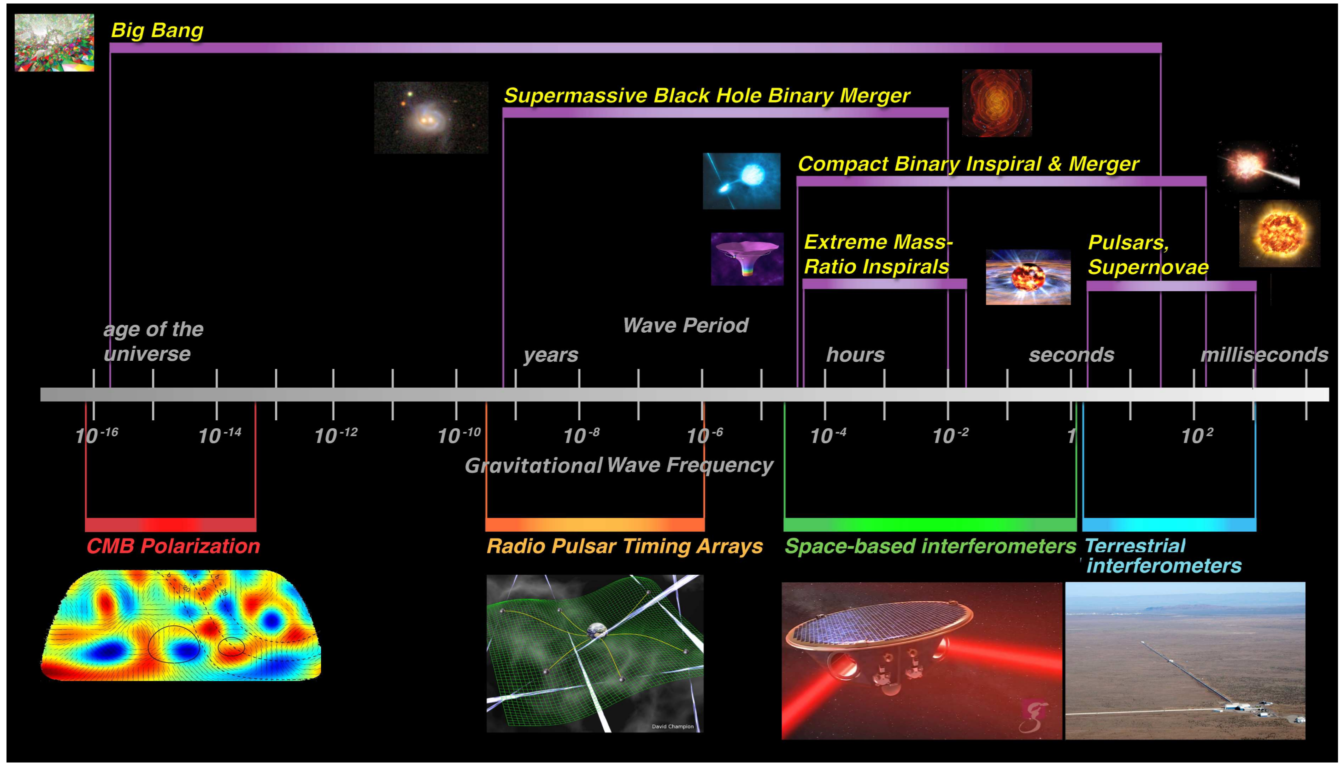


Graham et al. 2015, Nature 518
Binary SHBH 0.01 parsec (2X10^4 AU) separation

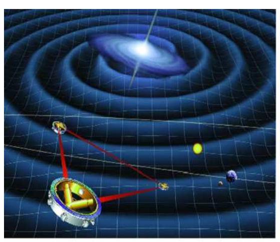
Timescale from two galaxy merger to their central SMBH merger in the range 10^8-10^9 years

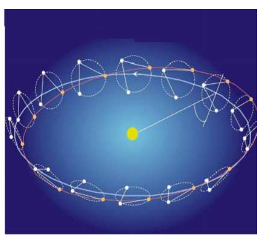
SMBH binaries and GWs

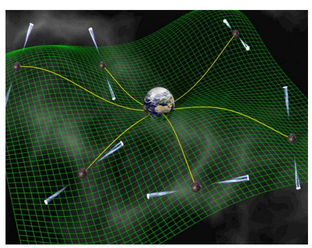
Instruments capable of detecting gravitational waves (GWs) and their sources in the next years: ground-based interferometers like aLIGO (it already discovered them), aVIRGO, KAGRA, Geo600, etc.; the Pulsar Timing Arrays (PTAs), the Square Kilometer Array (SKA); the LISA space mission, the 3rd gen. Einstein GW Telescope.



Binary IMBHs & SMBHs

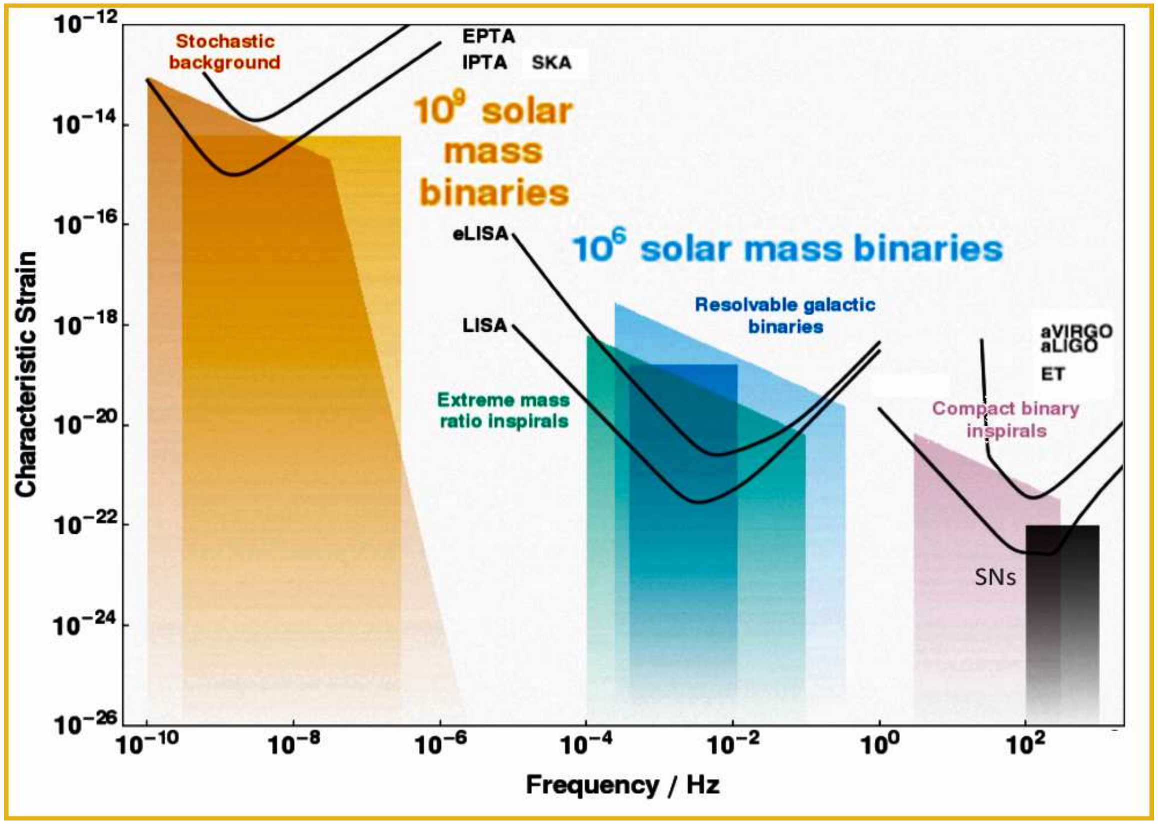




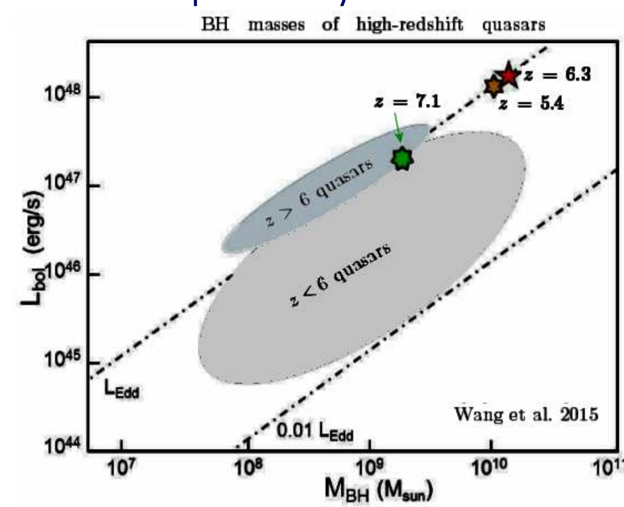


- Binary intermediate/massive black hole (IBH/MBH) binaries with BH masses between 10^4 Msun and 10^7 Msun and extreme / intermediate mass ratio inspirals (EMRI/IMRI) are expected to be detected by eLISA, To explore for the first time the low-mass end of the SMBHs hole population at cosmic times as early as z~10.
- Ultra-low GW frequency domain (nHz) is probed by PTAs
  . → possibly binary SMBHs.

SMBH binaries and GWs



- ❑ Pulsar timing arrays (PTAs) started to place constraints on galaxy merger history from limits on the stochastic Gravitational Wave (GW) background.
- ❑ Coalescing binary SMBHs → loudest sources of very-low frequency (micro-Hz to nano-Hz) GWs in the universe. Subsequent GW recoil has potential astrophysical implications (SMBHs oscillate/even escape).
- ❑ Importance of accretion, merging and stellar captures in growing black holes, and on the BH spin history.



- ❑ Possibilities for future GW astronomy: new research window on structure formation and galaxy mergers, direct detection of coalescing binary SMBHs, high-precision measurements of SMBHs masses and spins, constraints on SMBHs formation and evolution.

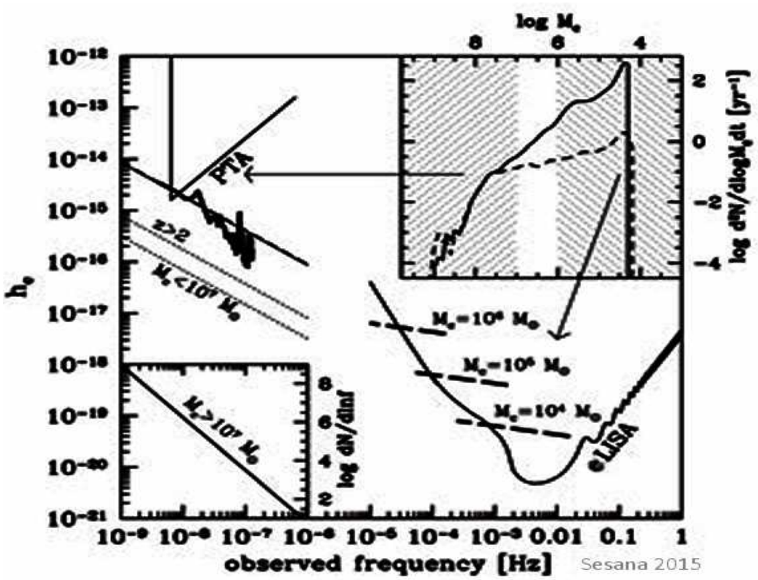
SMBH binaries and GWs

GWs frequency domains probed by LISA and PTAs and expected GW signals from binary IMBHs/SMBHs.

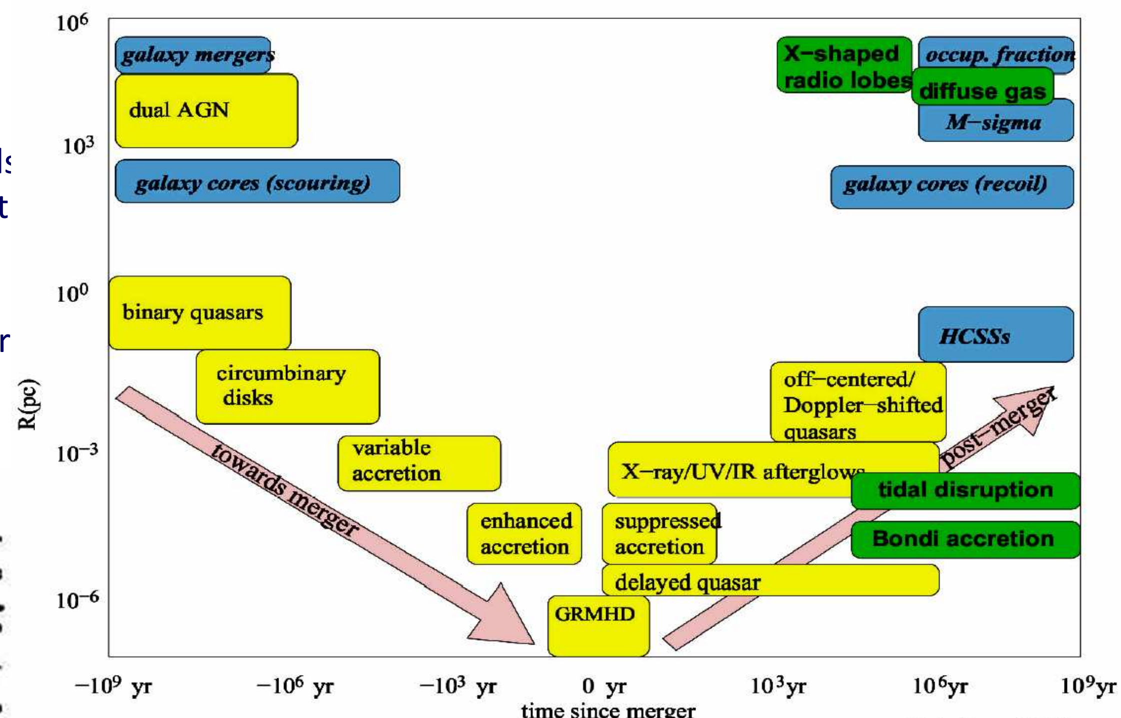
❑ Nano-Hz GW regime: superposition of signal coming from many stationary sources (stochast background).

❑ Milli-Hz GW regime: extreme-mass ratio inspirals (EMRI) at a rate of few events per year Intermediate-mass (exist?) BHs.

❑ Micro/Nano-Hz GW regime: SMBH binaries.



Sesana 2015



[Schnittman 2013]

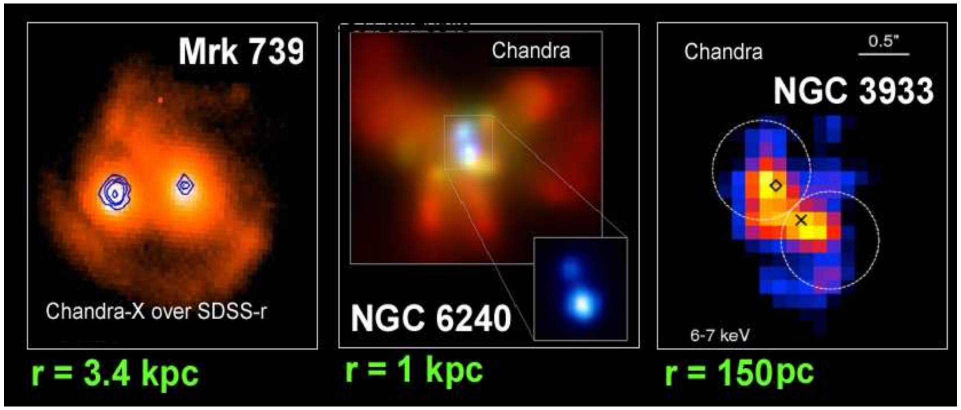
Selection of potential EM sources for astrophysical manifestations/siugnals of binary SMBH mergers, sorted by timescale, typical size of emission region, and physical mechanism (blue/italic = stellar; yellow/times-roman = accretion disc; green/bold = diffuse gas/miscellaneous). The evolution of the merger proceeds from the upper-left through the lower-center, to the upper-right [Schnittman 2013].

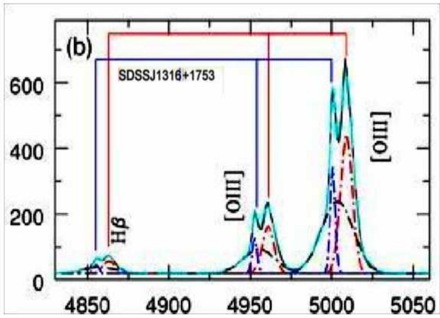
Observational evidence for SMBHs pairs/binaries

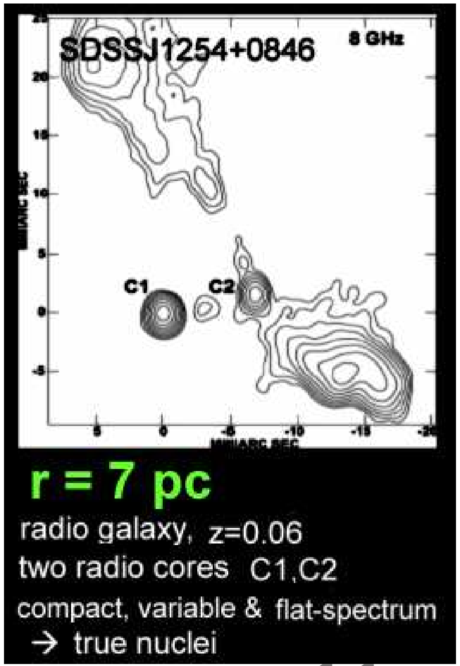
Pair of accreting SMBH in "single" galaxies (spatially resolved 10-pc to 100-pc): NGC 6240; 4C+37.11 NGC 3933, LBQS 0103-2753, Mkn 739, ESO 509-IG 066…

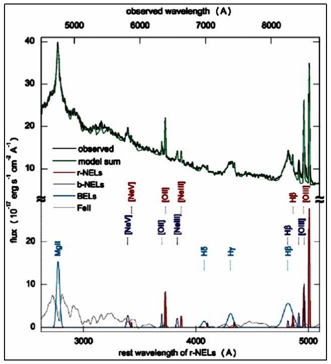
Spatially unresolved (close if <0.1pc) binary SMBHs:

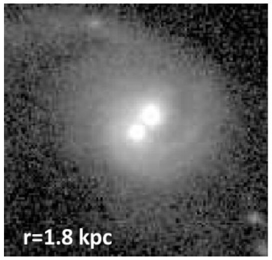
- ❑ from claims of quasi-periodic variability signatures: OJ 287, PG 1302-102, 3C 345, PSO J334.2028+01.4075, AO 0235+16, 3C 273, etc… (still very debated topic).
- ❑ from observed helical distorted radio jets (jet-emitting 2ndary SMBH orbiting primary, precession, jet reorientation in X-shaped radio galaxies): 3C 345, NRAO 530/PKS 1730-13, 3C 120, 3C 66B, Mkn 501, etc…
- ❑ from observed double-peaked broad lines: SDSS J0927+2943, SDSS J1316-1753, SDSS J150243.1+111557, PG 1302-102 (non-double but asymmetric). Only small fraction of all "double-peakers" are good candidates; only a few confirmed as "detections".
- ❑ other evidences: some candidate TDEs (SDSS J120136.02+300305.5), recoils (anisotropic emission of GWs from coalescing binary SMBHs leads to recoil of the newly formed single SMBH) and more exotic ones.



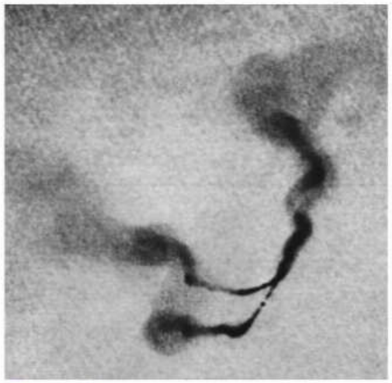




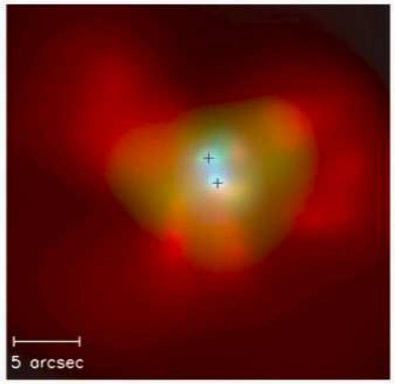




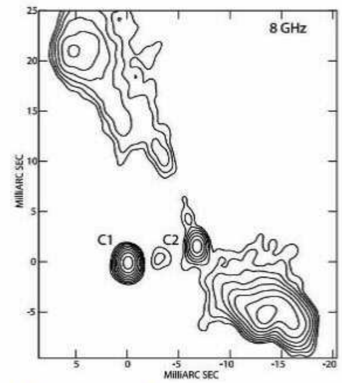
Observational evidence for SMBHs pairs/binaries



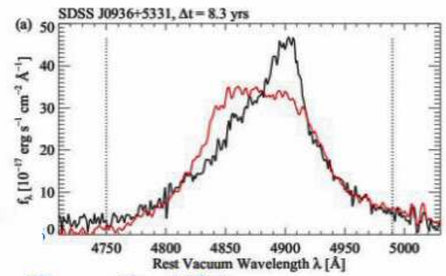
Dual jets (3C 75, a~7kpc) [Owen+ 1985]



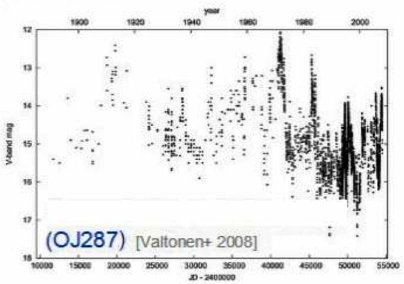
Dual X-ray sources (NGC 6240, a ~ 1.5 kpc) [Komossa+ 2003]

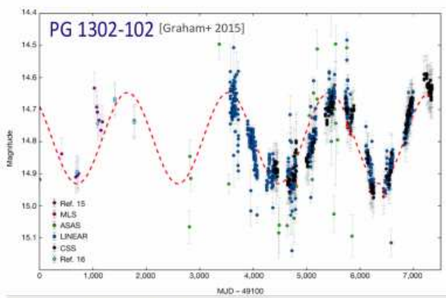


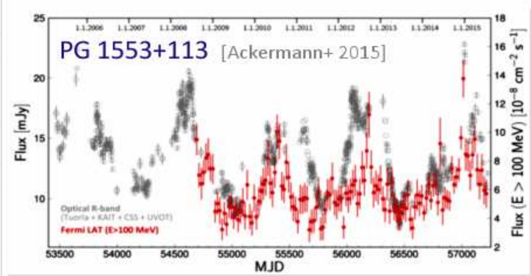
Binary radio sources (0402+379, a ~ 7pc) [Owen+ 1985]

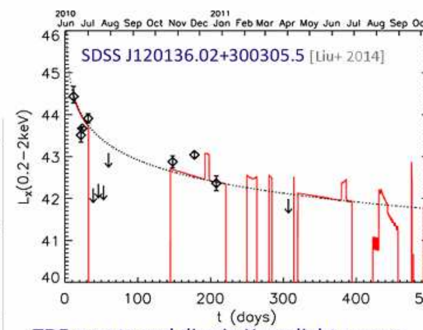


Kinematic shift in multi-epoch observations [Liu+ 2013]









TDE events and dips in X-ray light curves

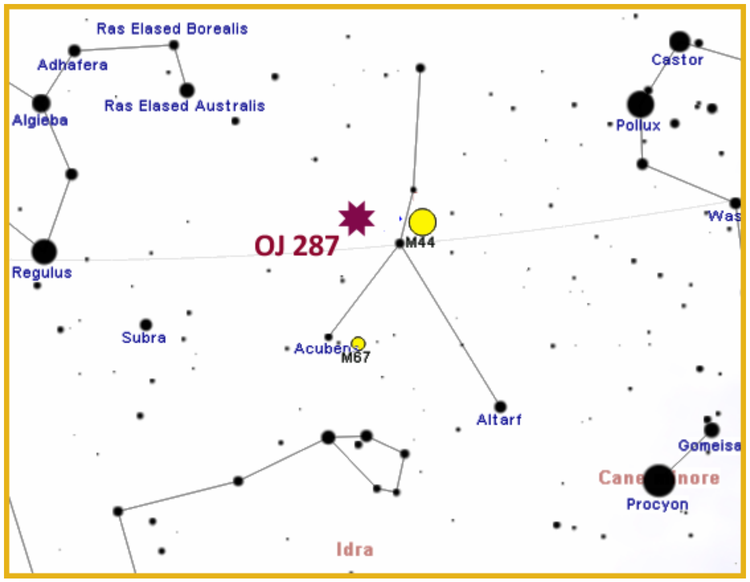
Quasi periodicity in light curves (still controversial topic)

- Many binary SMBHs candidates but few non-controversial confirmations! Why so few ?

Large distances (difficult to resolve). Perhaps obscured. Need to distinguish other phenomena (in-jet knots, lensing, ...). In close pairs most current methods require at least one SMBH to be active (many may not be).

- Perhaps the greatest challenge is to identify the inactive binary SMBHs which might be the most abundant, but are also the most difficult to identify. Most binary SMBHs may form quiescently either in gas-poor or minor galaxy mergers without driving AGN activities.

OJ 287: quasi-periodicity and binary scenario



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OJ 287: BINARY PAIR OF SUPERMASSIVE BLACK HOLES

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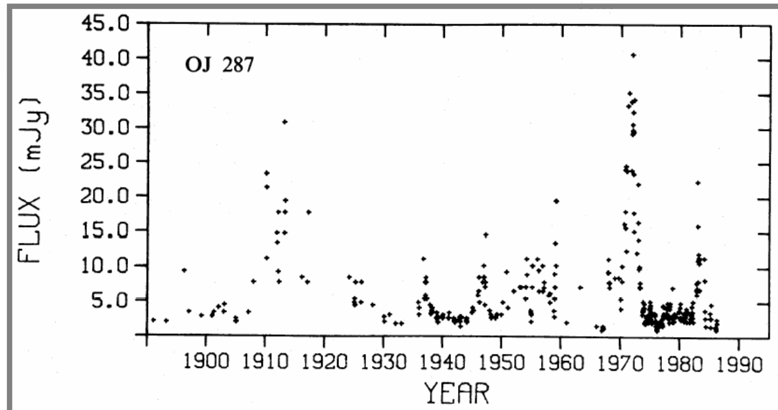

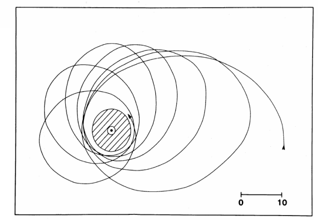

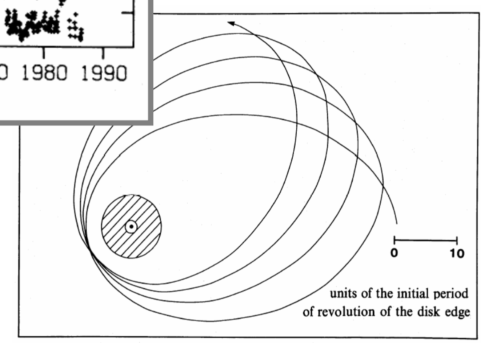

Letters to Nature

Nature 314, 148-149 (14 March 1985) | doi:10.1038/314148a0; Received 6 November 1984;

A 15.7-min periodicity in OJ287

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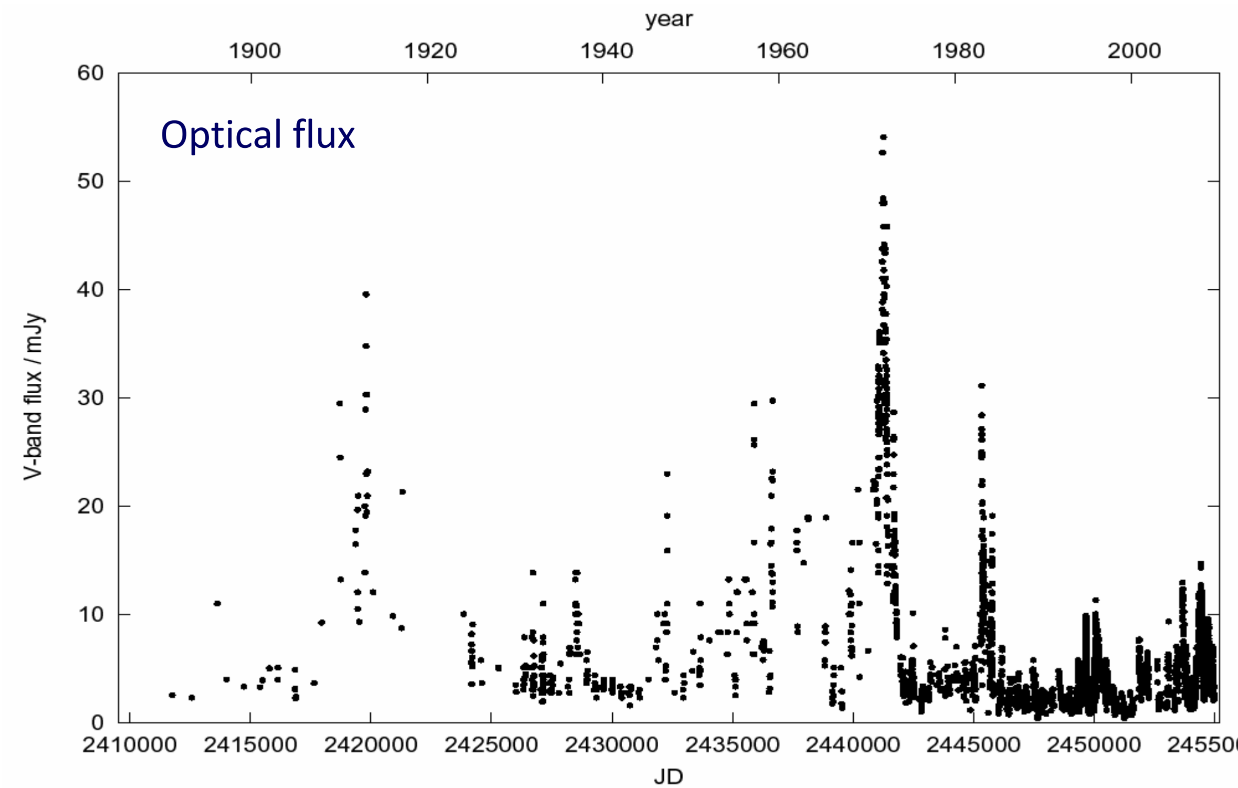
Mauri J. Valtonen

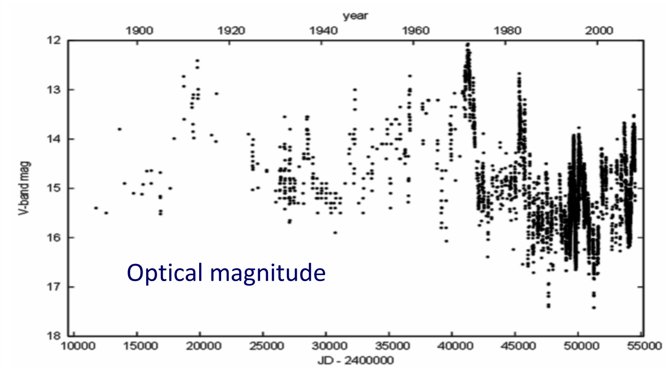
Aimo Sillanpää

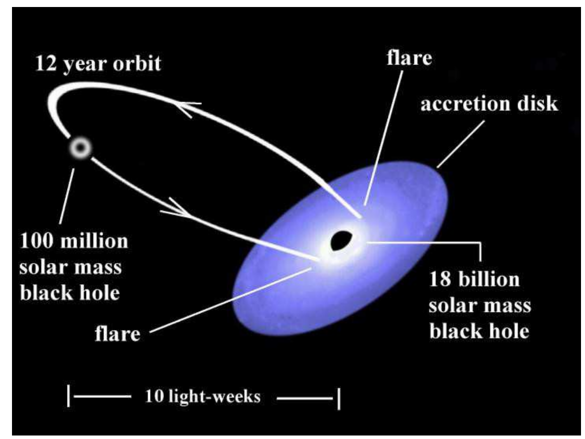
- ❑ 12-year quasi-periodic optical outbursts in the famous BL Lac object OJ 287 (optically bright, and X-ray and GeV gamma-ray emitter). >100-year optical light curves thanks to archival photograpic plates (source close to the ecliptic plane, M44 and M67 nearby).
- ❑ Binary BH model proposed from '80s based on optical quasi-periodicity (Valtonen, Haarala, Sillampaa et al. 1988 ApJ). Other, very short term intra-day periodicdities claimed also in the radio (Valtaoja et al. 1985 Nature).

OJ 287: 100-year optical light curve



One hundred year optical light curve of OJ287 in linear scale

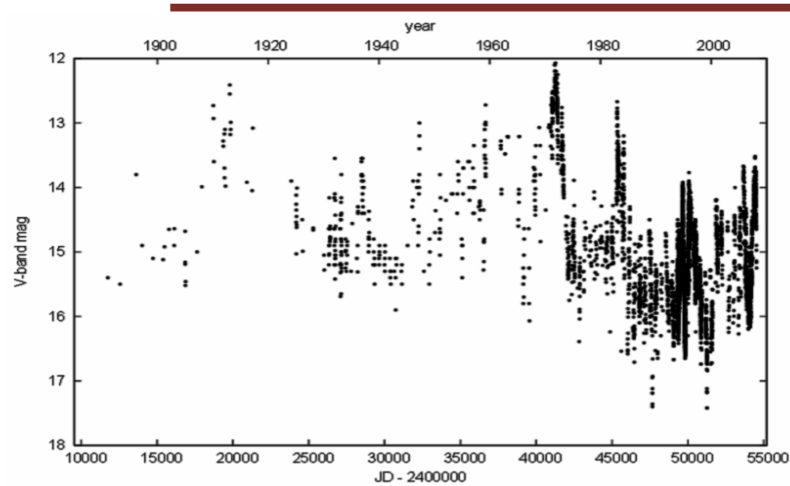




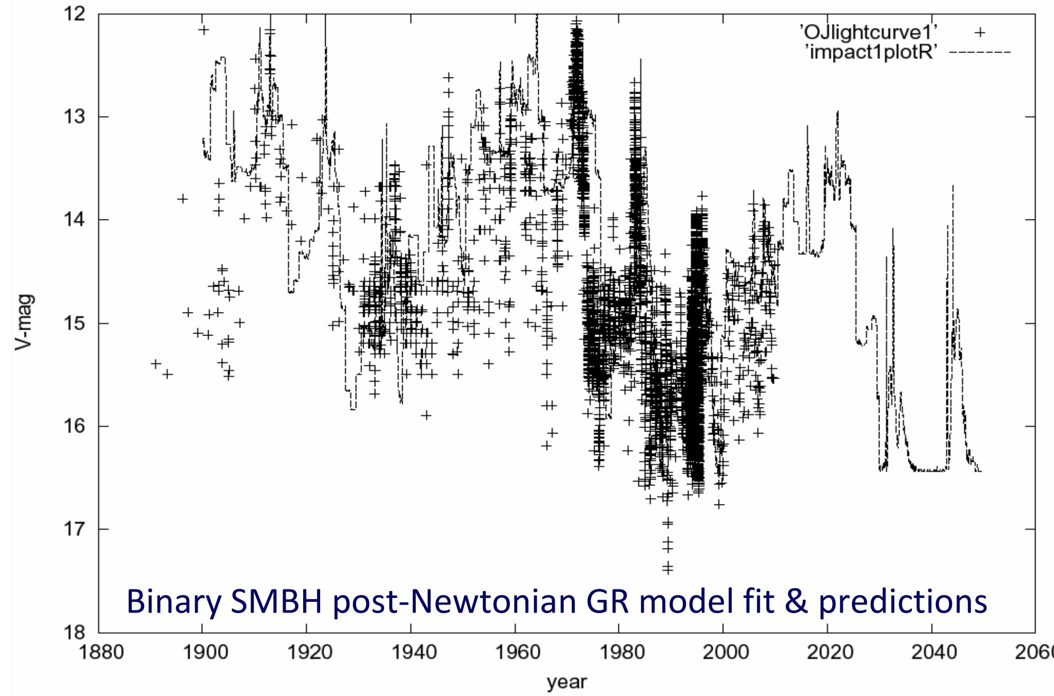
❑ Quasi-periodic pattern of prominent optical outbursts: 12 identified outbursts and several probable secondary outbursts. Because the outbursts seem to come in pairs separated by one to two years, and the pairs occur about 12 years apart, a sub-parsec binary SMBH model is proposed for OJ 287 .

❑ 10^8-10^9 years timescale from two galaxy merger to their central SMBH merger. OJ 287 sub-parsec system, <10^5 years to merge

OJ 287: 100-year optical light curve



Parameter	Value
$\Delta\phi$	$(39.1 \pm 0.1)^\circ$
m_1	$(1.84 \pm 0.01) \times 10^{10}\ M_\odot$
m_2	$(1.40 \pm 0.03) \times 10^{8}\ M_\odot$
χ	0.313 +/- 0.01
ϕ_0	$(56.3 \pm 1.0)^\circ$
e	0.658 ± 0.001
q	1.0 ± 0.9
t_d	0.74 ± 0.04



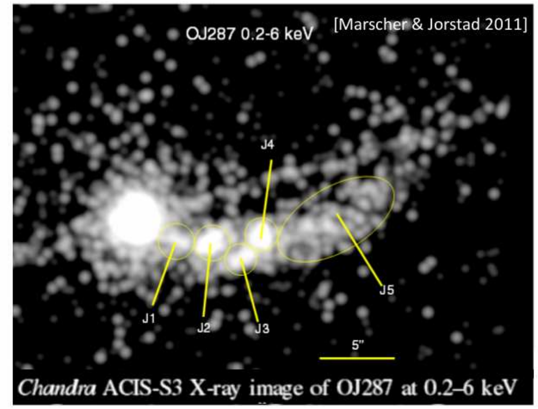
- The last, and best monitored, optical outbursts were at the end of 2005 with secondary activity in 2007, and at the end of 2015.
- Prominent optical outbursts predictable in a binary black hole model. OJ 287 is the most promising candidate for a binary SMBH inspiralling under the action of low frequency gravitational radiation reaction. A promising system for testing the General Relativity (GR) through like curve timing/clocking.

OJ 287: radio/X-ray structure

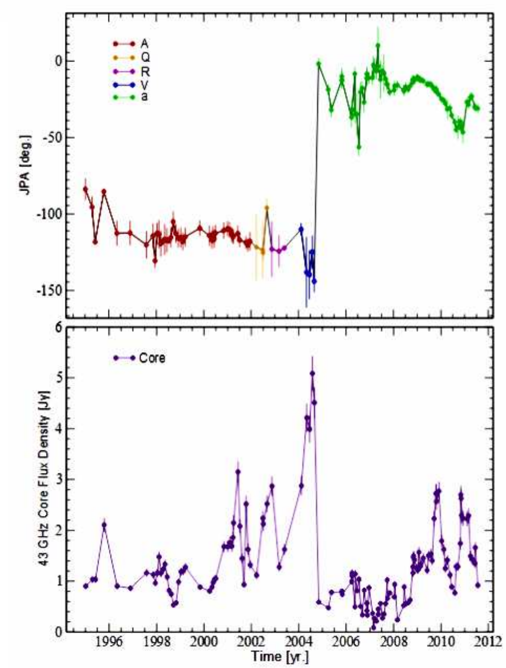
❑ Knotty X-ray jet structure observed in OJ 287 by the Chandra satellite can arise from some thousand-year variationss in jet flow.
❑ [Agudo+ 2011] Ultra-high-resolution VLBA imaging at 7mm of the OJ 287 jet from 1995 to 2011 (136 images) revealed sharp jet-position-angle swing by >100 deg in 2004 2006 and erratic wobbling behavior of the innermost, 0.4mas, jet.

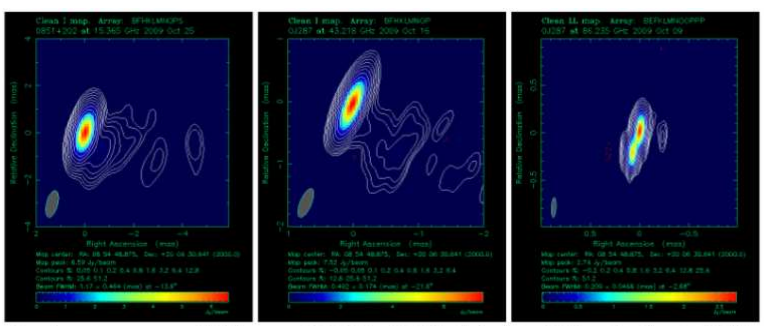
❑ Erratic variations + short timescales → scenarios such as binary SMBH system, accretion disk precession, interaction with the ambient medium ruled out.
It implies turbulence in the accretion disk coupled with HD instabilities.
❑ Binary SMBH scenario indeed is expected to cause longer-term modulation of the jet direction. Wobbling modulation of the jet with periodicity >100 years and a modulation of the jet position angle (JPA) of about 12 years as driven by changes in orientation of the primary inner accretion disk [Valtonen+ 2011].

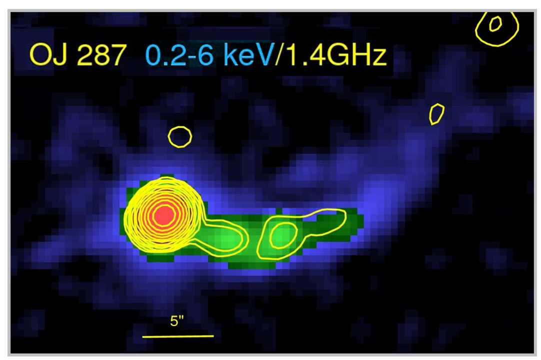
❑ [Moor+ 2011] weak hints for 12-year modulation of the JPA at 3.5cm. At high resolution scales OJ 287 jet exhibits a feature resembling double streams, suggestive of a helical structure [Tateyama+ 2013]



Chandra ACIS-S3 X-ray image of OJ287 at 0.2–6 keV

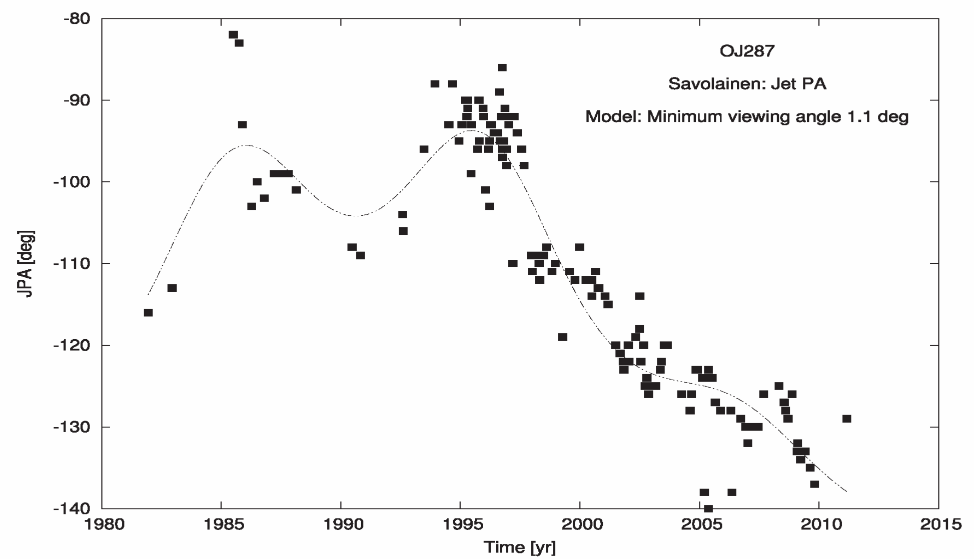


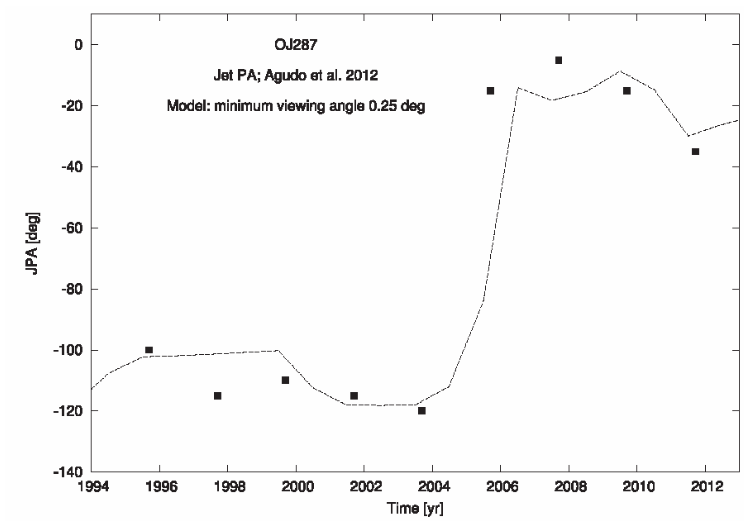

Quasi-contemporanous VLBI maps of OJ287 at 15 GHz (left; data: Mojave data base), 43 GHz (center, data: Boston group), and 86 GHz (right, data: GMVA) of October 2009.



OJ 287: radio/mm jet polarization in BH scenario

- Long-term polarization angle (PA) observations of the jet as a function of time in cm and mm radio bands.
- Expected variation in the PA of the jet if the jet is connected to the primary SMBH accretion disk and follows the wobble of the disk in a binary SMBH model scenario.
- Wobble is modelled by a doubly periodic sinusoidal function of time t (in yers) [Valtonen+ 2014].
- Main contribution to the jet wobble by the orbital motion of the secondary SMBH and erratic contribution to the wobble is small.
- Variations in the orientation of the accretion disk due to the binary system influence → transmitted to the central component in about 10 years → variation is communicated to the jet, starting from the near jet and proceeding outwards with an about 80/70 year unbeamed delay with respect to the optical core.
- The usual in-jet erratic variabolity knots have Lorentz factors in the range 10-20. The binary SMBH kink perturbation in the jet proceeds more slowly (Lorentz factor in the range 3-10) and reaches the mm-wave jet before the cm-wave jet





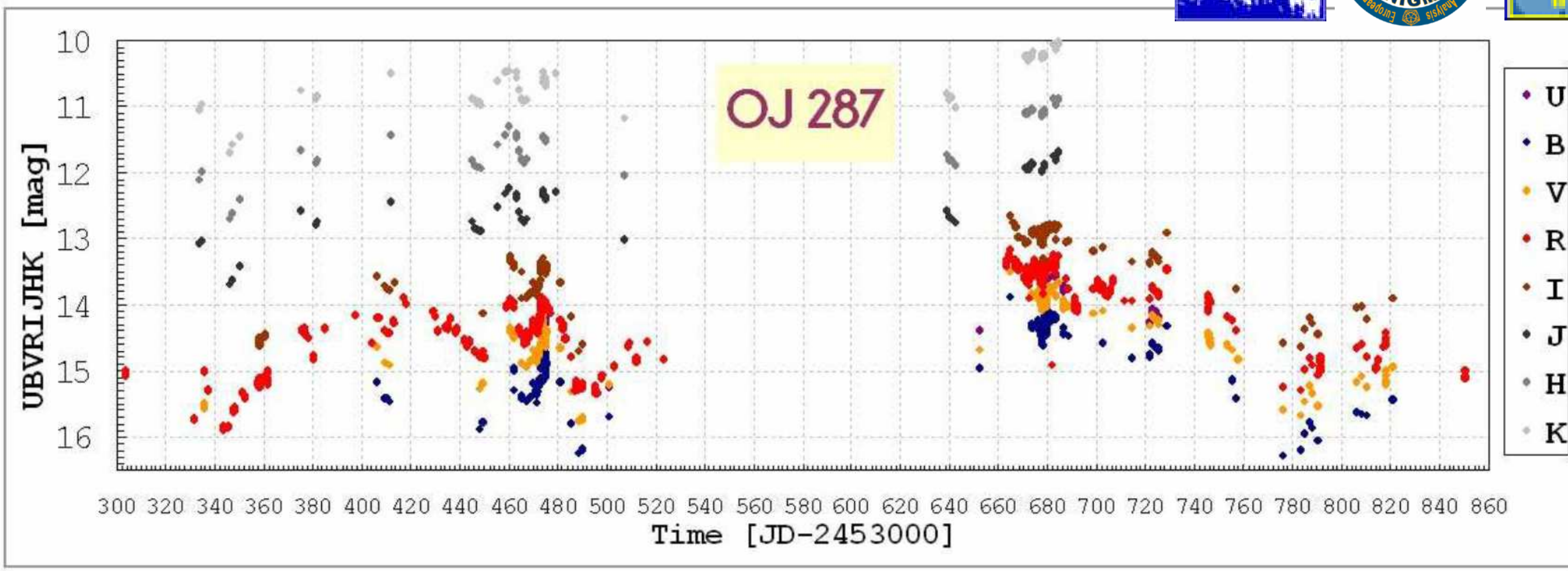
OJ 287: intensive & estensive MW campaigns

Multiwavelenght (MW) observing campaigns: long-term flux monitoring (optical and radio bands) programs ongoing from '90s (the OJ-'94 project), mainly with optical and near-IR flux monitoring (many telescopes, collaborations and consortia, for example the XMM+WEBT+ENIGMA intensive+longterm MW campaign in 2005-2007 campaign manager S. Ciprini, the long-term optical flux/polariz. monitor campaing 2007-2016 campaing manager S. Zola, A. Gopakumar, M. Valtonen) and radio-band flux/structure monitoring. Several X-ray satellite (ex. Swift) pointings (for example the recent winter 2015/2016 Swift timing experiment campaign PI S. Ciprini).

OJ 287: intensive/extensive MW campaign of 2004-2006

A radio, near-IR, optical and X-ray (3 XMM pointings). Light curve: Oct. 2004 – April 2006.

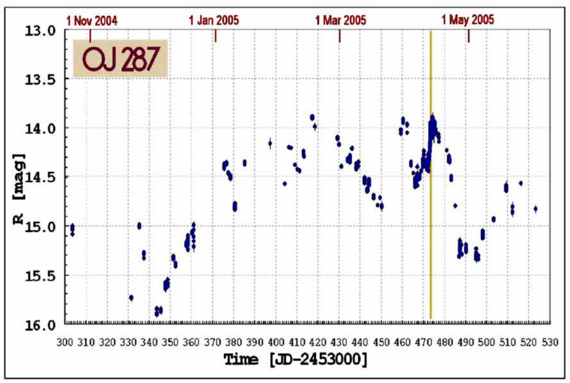
- Data from: WEBT intensive & coordinated campaign and long-term monitoring (from ENIGMA European research training newtwork institutes/observatories + further independent observations).

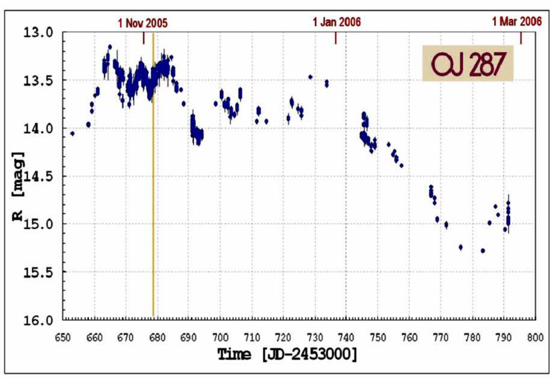


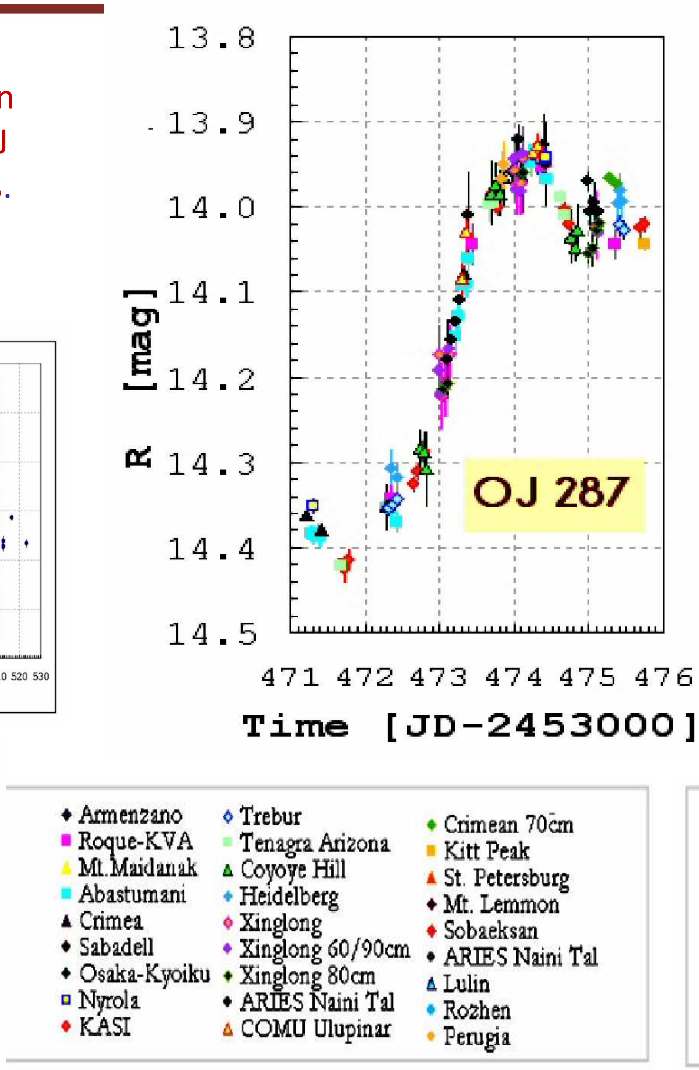
- About 3700 data points collected only in the R-band.
- XMM-Newton observed OJ 287 during two active optical states of the source.
- An enduring, symmetrical, and time structured optical outburst observed in Oct.-Nov. 2005, around the 2nd XMM pointing. Broken power law component (break ~0.7 keV, synchrotron tail/thermal component +IC) X-ray break signature typical of intermediate energy peaked blazars.
- Radio flux on the average and any outburst observed. Radio IDV (3%) found. Frequency dependence of the mean structural position angle of the radio-jet in VLBA maps, consistent with jet precession model.

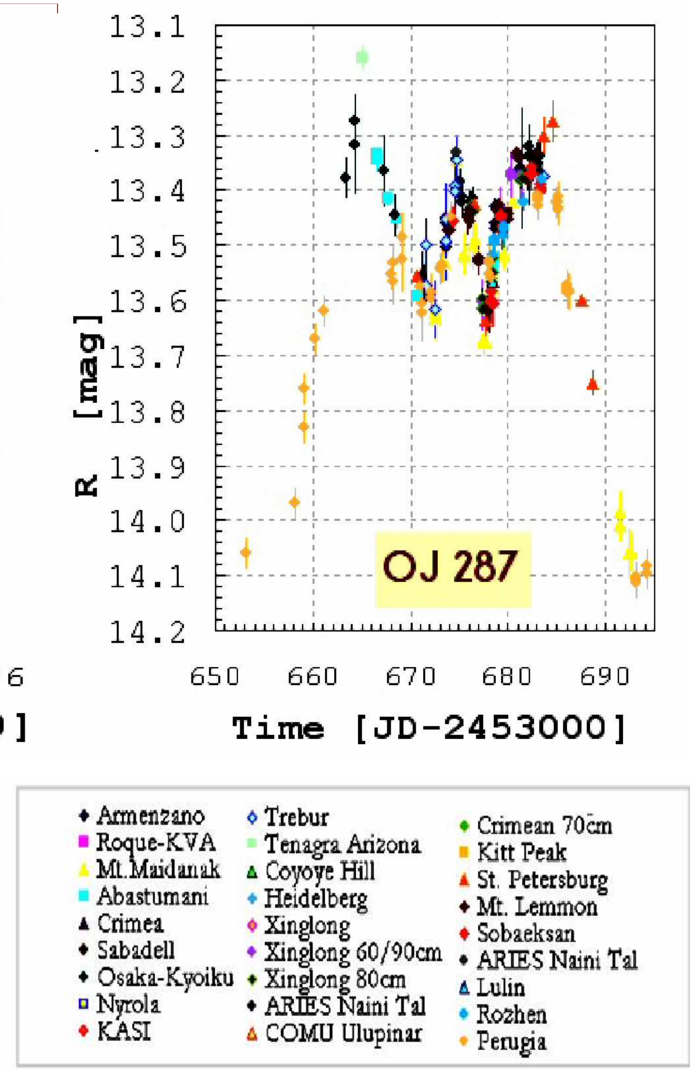
OJ 287: MW campaing of 2004-2006

R-band best sampled light curve.
During both the 2 GO XMM-Newton observations performed in 2005, OJ 287 was flaring in the optical bands.
(…*The source was not shy when observed by XMM).*



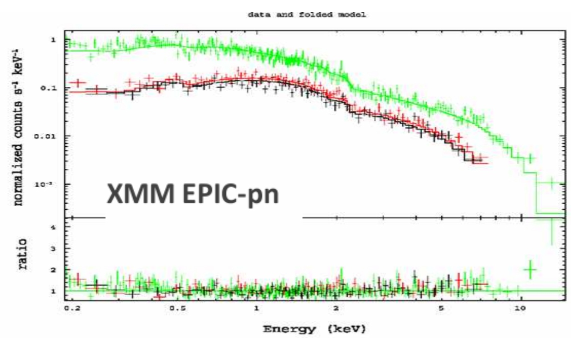






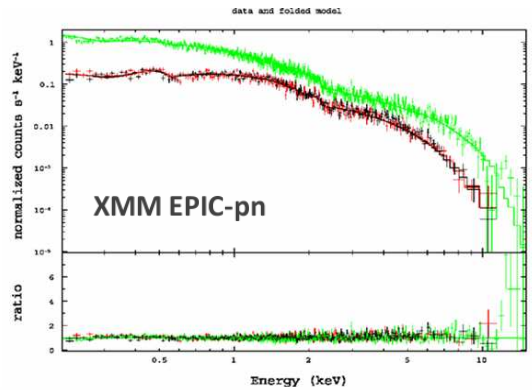
OJ 287: XMM-Newton results

Date: April 12, 2005 - OJ 287, z=0.306.
XMM-Newton *EPIC: PN* + *MOS1* + *MOS2* spectra
Model: single power law + galactic absorption in the 0.2-10 KeV range



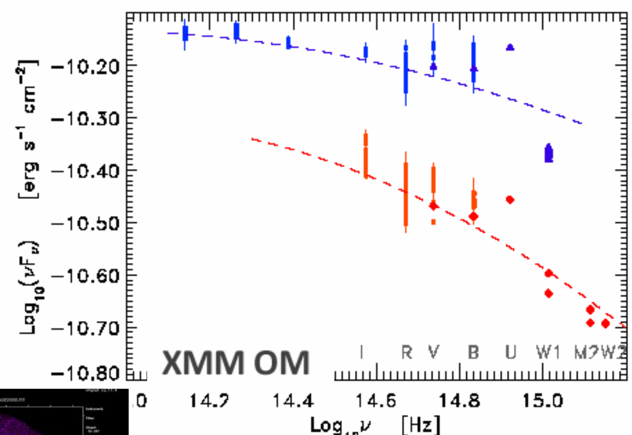
H column density:
N_H=3.09 x 10^{20} cm^{-2}
Power-law photon index:
Γ=1.63 ± 0.02
Reduced chi-squared:
χ_r^2 =1.03, d.o.f.=367
Flux density (2-10 KeV):
$F_{2-10keV}$=(2.5±0.8) $x10^{-12}$erg s^{-1} cm^{-2}

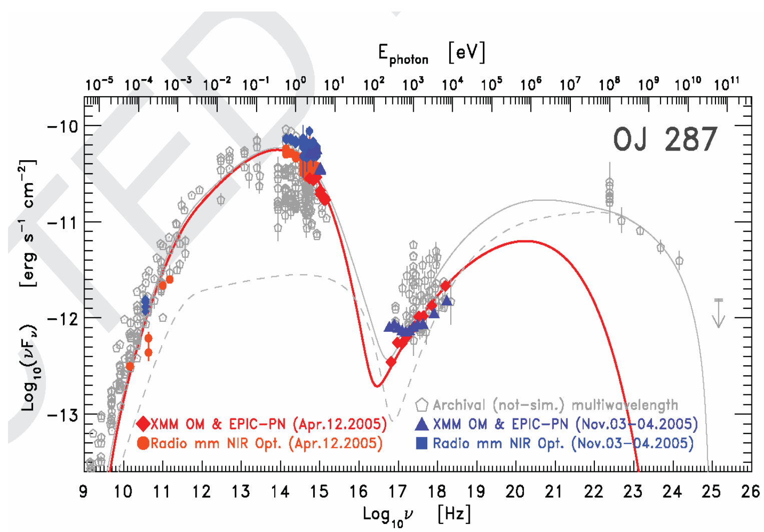
Date: November 3-4, 2005 - OJ 287, z=0.306.
XMM-Newton *EPIC: PN* + *MOS1* + *MOS2* spectra
Model: broken power law + galactic absorption in 0.2-10 KeV range

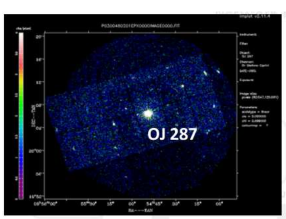


H column density:
N_H=3.09 x 10^{20} cm^{-2}
Broken power-law photon indexes:
Γ_1=2.65(-0.07/+0.12)
Γ_2=1.79 ± 0.02
E_break: 0.69 KeV (-0.05/+0.04)
Reduced chi-squared:
χ_r^2 =1.03, d.o.f.=927

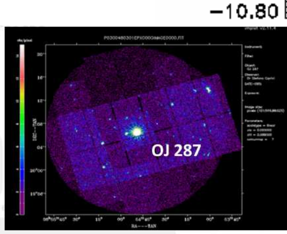
Flux density (2-10 KeV):
$F_{2-10keV}$=(1.82±0.07)$x10^{-12}$erg s^{-1} cm^{-2}







April 12, 2005



Nov. 3-4, 2005

Three-body problem

- ❑ SMBH are prevalent in centers of galaxies → many proto-galaxies merges and piling up, and bringing in new BHs → should we then get clusters of dozens of black holes in galactic nuclei ? NO. As soon as three black holes have come together, we have an unstable threebody system.
- ❑ Three-body problem ancient (motions of Earth, Sun, Moon, planetary motion, predict solar eclipses).

It covers both solvable problems by numerical computations and unsolvable ones (chaos theory). Practical interest but also beauty in the solutions.

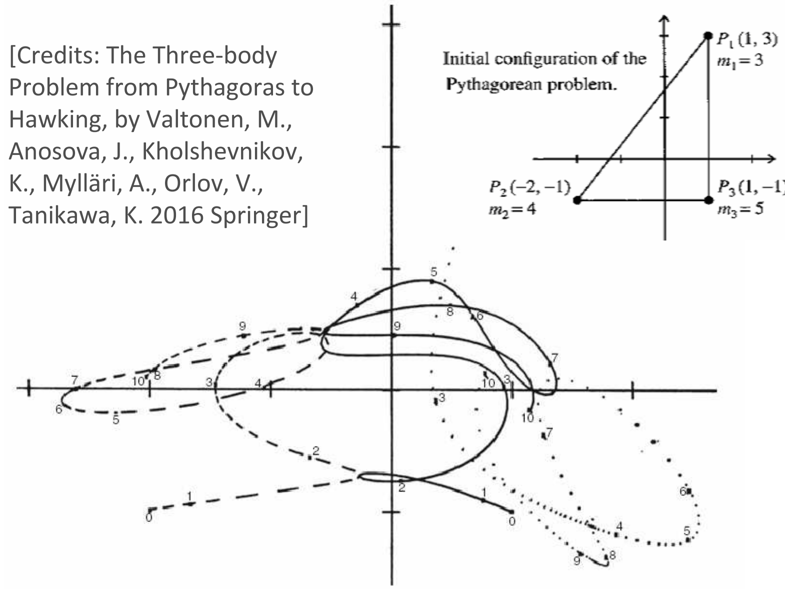
- ❑ Pythagoras: use numbers → expansion in convergent series.

Poincare: simplest form of the three-body problem found no solution.

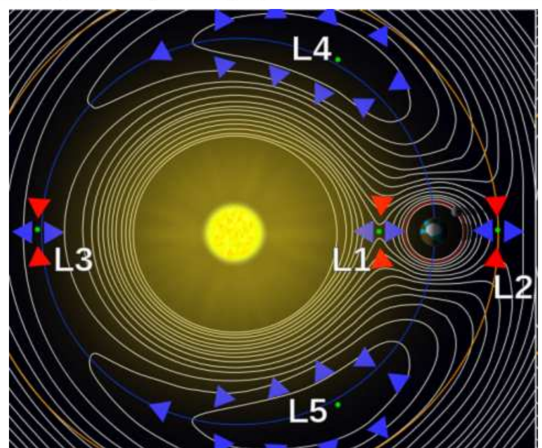
Euler and Lagrange first to solve the problem in two special cases.

- ❑ From '70s Heggie, Valtonen, Mikkola, first studies of the general three-body problem in General Relativity using Newtonian regularization. Levi-Civita introduced regularization using complex numbers and algebraic computation. The use of quaternions (complex number with three imaginary parts) made easier to calculate orbits (Kustaanheimo-Stiefel regularization, also used in astrodynamics).

[Credits: The Three-body Problem from Pythagoras to Hawking, by Valtonen, M., Anosova, J., Kholshevnikov, K., Mylläri, A., Orlov, V., Tanikawa, K. 2016 Springer]



Initial orbits (10 time units) in the Pythagorean problem. Burrau was able to complete them only half-way, and the complicated orbits still continue 6 times longer. From Szebehely and Peters 1967 work (Credit: see previous figure)



Three-body problem in GR

- In strong gravitational fields General relativity), i.e. close two, three, more BHs, they emit gravitational waves and go to the inspiral phase (more complex problem than the 3-body Newtoninan problem). Energy losses which depends on the masses.
- The typical end result of all the complicated and chaotic three-body dynamics in General Relativity is two black holes receding away from their galaxy of origin in opposite directions ("slingshot theory" of double radio sources, alternative to the commonly accepted theory of Blandford-Rees theory for large scale jets and accretion).

- Useful three-body model to study how a stellar system in the AGN reacts to the merging black hole binary.
- Blazar OJ 287: three-body simulations in GR demostrates that a SMBH surrounded by a gas disk (the third body) and possessing a companion SMBH can create a quasi-periodic signal.

By calculating the orbit for every particle in the disk, we get in combination an image of the whole disk and how it reacts to the SMBH binary. The optical light curve signals allow us to determine the orbit of the binary and parametrers of the SMBHs.

- The orbital motion is measurably different if the primary BH has no "hair" (no-hair theorem of GR) or if it has some "hair".

Astron. & Astrophys. 46, 435—440 (1976)

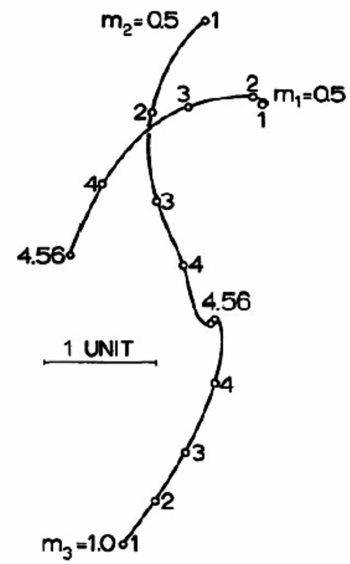
Ejection Speed in the Slingshot Theory of Radio Sources

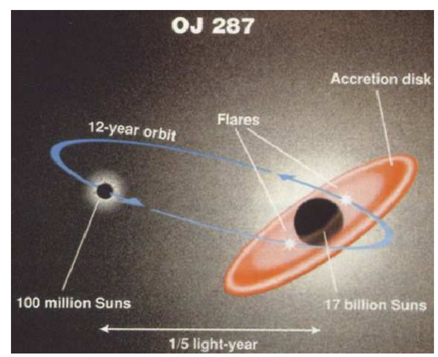
II. General Relativistic Approximation

Mauri J. Valtonen

Research Institute for Theoretical Physics, University of Helsinki

Three black-hole orbit calculation in the first solution of the relativistic three-body problem. The positions of the black holes are marked at times 1, 2, 3 and 4. At time 4.56 two black holes collide and the third black hole flies out with a speed of about 24,000 km/s. By recoil, the merged black hole flies out with speed of about 8000 km/s. If this process happened in the center of a galaxy, a double escape in two opposite directions would be seen (Credit: Valtonen, A&A, 46, 435, 1976, reproduced with permission of ESO)





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Post-Newtonian theory

- The study of the three-body problem in General Relativity (GR) was initiated and continued in '70s through '90s by Valtonen and Mikkola at Turku Univ. (Finland). In the relativistic three-body problem the force law between two bodies is slightly modified from Newton's force law (called the Post-Newtonian force law).

$$\partial_{\mu\nu} H^{\alpha\mu\beta\nu} = \frac{16\pi G}{c^4}(-g)\left(T^{\alpha\beta} + t^{\alpha\beta}_{\rm LL}\right)$$

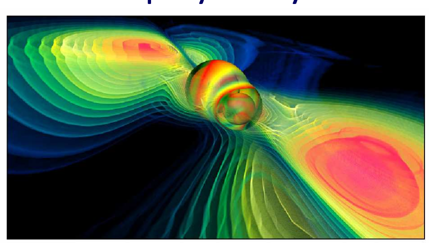
$$H^{\alpha\mu\beta\nu} = \mathfrak{g}^{\alpha\beta}\mathfrak{g}^{\mu\nu} - \mathfrak{g}^{\alpha\nu}\mathfrak{g}^{\beta\mu} \qquad \mathfrak{g}^{\alpha\beta} = \sqrt{-g}\, g^{\alpha\beta}$$

$$t^{\alpha\beta}_{\rm LL} \sim \partial\mathfrak{g}\cdot\partial\mathfrak{g} = \text{field energy-momentum}$$

- Post-Newtonian (PN) theory is a method for solving GR Einstein's field equations that applies when the gravitational field is weak and the motion of the matter is slow. A robust starting point for the PN approximation is the Landau-Lifshitz (LL) formulation of GR.

- PN theory successfully describes the gravitational field of the solar system, but it can also be applied to situations involving compact bodies with strong internal gravity, provided that the mutual gravity between bodies is weak. PN theory has proven to be remarkably effective in describing certain strong-field, fast-motion systems (including binary pulsars, binary BH systems) inspiraling toward the final merger with the calculation of GW emitted. When carried to high orders in the PN sequence, predictions for the GW signal from inspiraling compact binaries play a key role for laser-interf

Neutron stars spiral and coalesce



Black holes spiral and coalesce

Post–Newtonian expansion

$$\epsilon = \max\left\{\left|\frac{T^{0i}}{T^{00}}\right|, \left|\frac{T^{ij}}{T^{00}}\right|^{1/2}, \left|\frac{\phi}{c^2}\right|^{1/2}\right\} \sim \frac{v}{c} \ll 1,$$

In Donder coordinates

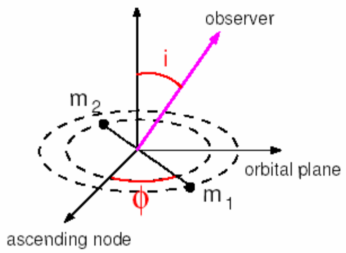
$$h^{\mu\nu} = \sqrt{-g}\, g^{\mu\nu} - \eta^{\mu\nu} \qquad g = \det(g_{ab}) \qquad \partial_\mu h^{\alpha\mu} = 0$$

h^{ab} tensor field of perturbations

field equations $\Box h^{\mu\nu} = 16\pi G \tau^{\mu\nu}$

$$\Box = \eta^{\mu\nu}\partial_\mu\partial_\nu \qquad \tau^{\mu\nu} = |g| T^{\mu\nu} + \frac{1}{16\pi G}\Lambda^{\mu\nu}$$

PN theory: a method to compute GW waveform templates



$$\phi(t) = \phi_0 - \frac{1}{32\eta}\left(\frac{GM\omega}{c^3}\right)^{-5/3}\left\{1 + \frac{1\mathrm{PN}}{c^2} + \frac{1.5\mathrm{PN}}{c^3} + \cdots + \frac{3\mathrm{PN}}{c^6} + \cdots\right\}$$

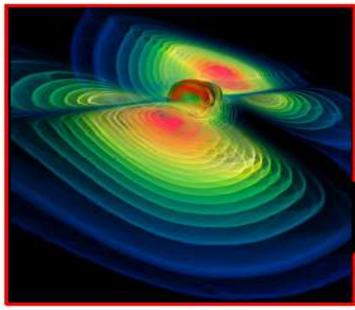
Orbital phase

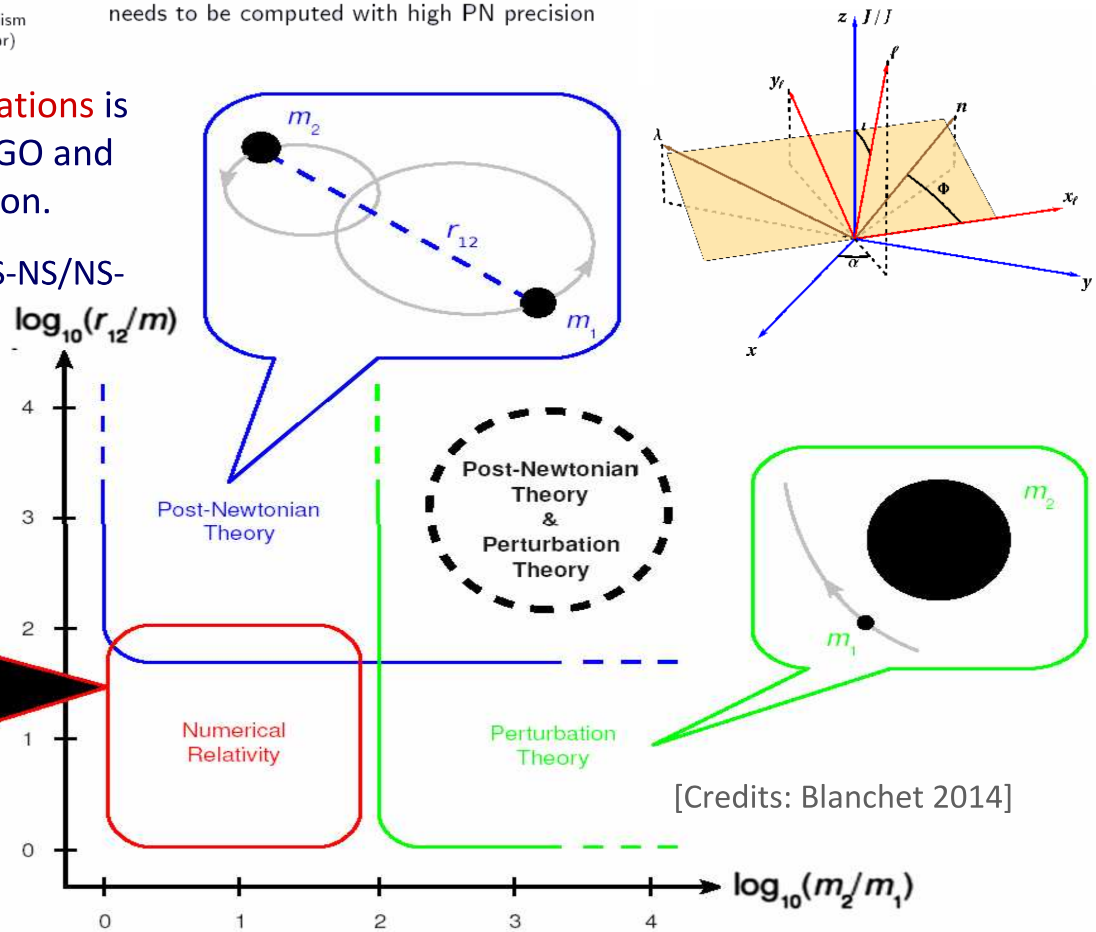
result of the quadrupole formalism (sufficient for the binary pulsar)

needs to be computed with high PN precision

- The required precision for PN theory computations is at least 2PN for detection of GW by aLIGO/aVIRGO and 3PN for GW physical system parameter estimation.

- The equations of motion of compact binaries (NS-NS/NS-BH/BH-BH) are written in Newtonian-like form (with t=x0/c playing the role of Newton's "absolute time").
- High-order Lagrangian/Hamiltonian formalism
- Effects like radiation reaction back onto the GW source.
- Interesting predictions for eccentric compact binaries.
- BHs spins play an important role in the definition of the gravitational wave templates. Post-Newtonian spin precession. Induced precession of the orbital plane.

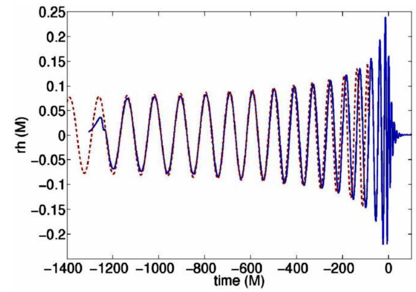


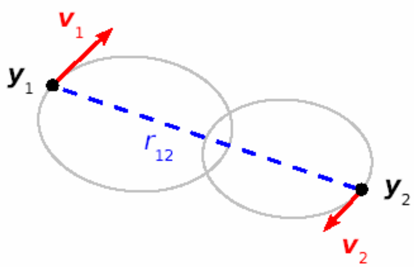


[Credits: Blanchet 2014]

Post-Newtonian theory for compact binaries

- ❑ Advances in theory calculations (PN orders): 1PN (‘20s, ’30s), 2PN and 2.5PN ('80s), 3PN ('90s, 2000s), 3.5PN (2000s).
- ❑ Current precision of the PN inspiral waveform is 3.5PN and it is now matched to the numerical-relativity merger waveform.
- ❑ PN theory has proved to be the appropriate tool to describe the inspiral phase of compact binaries up to the innermost stable circular orbit ISCO (see next slides).
- ❑The 3.5PN templates are though sufficient for detection and analysis of NS-NS binary inspirals in aLIGO/aVIRGO.



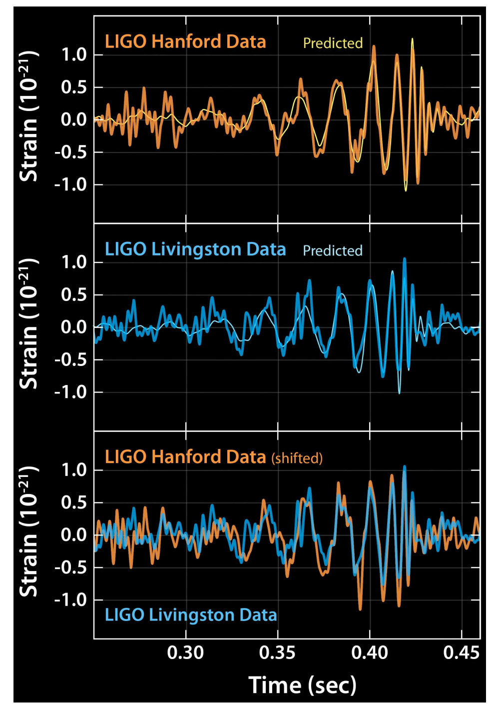


The equations of motion are written in Newtonian-like form (with $t = x^0/c$ playing the role of Newton's "absolute time")

$$\frac{d\mathbf{v}_1}{dt} = \mathbf{A}_1^{\mathrm{N}} + \frac{1}{c^2}\mathbf{A}_1^{1\mathrm{PN}} + \frac{1}{c^4}\mathbf{A}_1^{2\mathrm{PN}} + \underbrace{\frac{1}{c^5}\mathbf{A}_1^{2.5\mathrm{PN}}}_{\text{radiation reaction}} + \overbrace{\frac{1}{c^6}\mathbf{A}_1^{3\mathrm{PN}}}^{\text{very difficult term to compute}} + \underbrace{\frac{1}{c^7}\mathbf{A}_1^{3.5\mathrm{PN}}}_{\text{radiation reaction}} + \mathcal{O}\left(\frac{1}{c^8}\right)$$

1PN	[Lorentz & Droste 1917; Einstein, Infeld & Hoffmann 1938]
2PN	[Damour & Deruelle 1981, 1982]
2.5PN	[Damour 1983; LB, Faye & Ponsot 1998]
3PN	[Jaranowski & Schäfer 1999; LB & Faye 2000, 2001; Itoh & Futamase 2003]
3.5PN	[Pati & Will 2002; Nissanke & LB 2005]

[Credits: L. Blanchet]

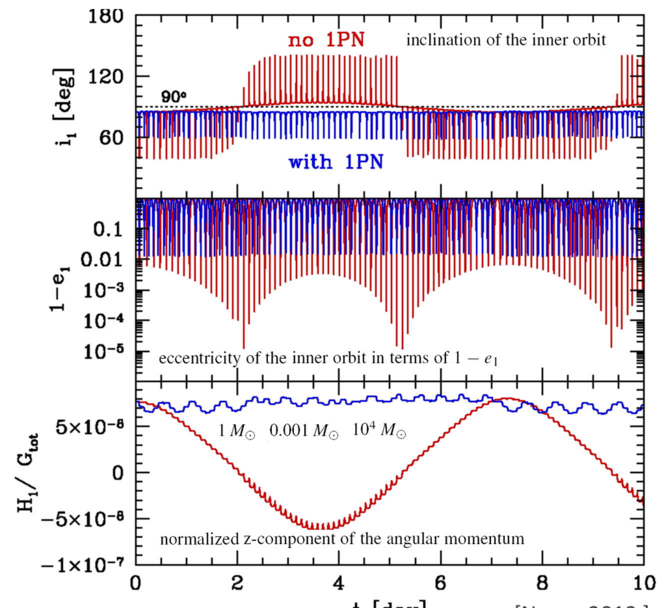


PN theory + 3-body system = Kozai-Lidov resonance

❑ Expansion of the first-order post-Newtonian Hamiltonian to leading-order + hierarchical three-body problem → Kozai-Lidov mechanism [Kozai 1962, Lidov 1962]: a highly inclined perturber can produce large-amplitude oscillations in the eccentricity and inclination of the three-body system. Resonant-like eccentricity excitation.

❑ Kozai–Lidov resonance is a secular (coherent and long interaction compared to orbital period) effect common in hierarchical triple systems but absent from two-body dynamics. It has been suggested to play an important role in both the growth of BHs at the centers of dense stellar clusters and the formation of short period BH X-ray binaries [Miller & Hamilton 2002, Ivanova+ 2010, Naoz+ 2013].

$$T_{\rm Kozai} = 2\pi \frac{\sqrt{GM}}{Gm_2} \frac{a_2^3}{a^{3/2}} \left(1 - e_2^2\right)^{3/2} = \frac{M}{m_2} \frac{P_2^2}{P} \left(1 - e_2^2\right)^{3/2}$$

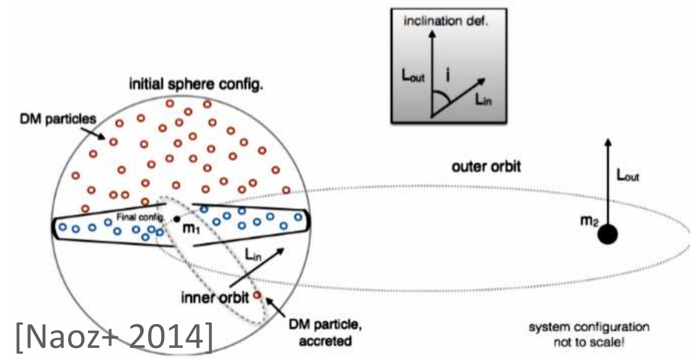


[Naoz+ 2013]

❑ Beyond the semi-regular 12 year cycle in OJ 287 there are hints for the first harmonic of the Kozai resonance at the inner edge of the primary accretion disk at a period of 60 years. Test mass (parcel of gas at the inner edge of the accretion disk) periodically perturbed by the other two massive bodies (the two SMBHs).

❑Furthermore eccentricity excitations are particularly interesting for GW detections [Armitage & Natarajan 2005, Sesana+ 2010]. GWs emitted during Kozai–Lidov-induced, highly eccentric orbits of compact, star-mass system, binaries might be detectable by aLIGO/aVIRGO.

❑ More: Dark Matter could form torii around SMBHs via the eccentric Kozai-Lidov mechanism [Naoz+ 2014]



[Naoz+ 2014]

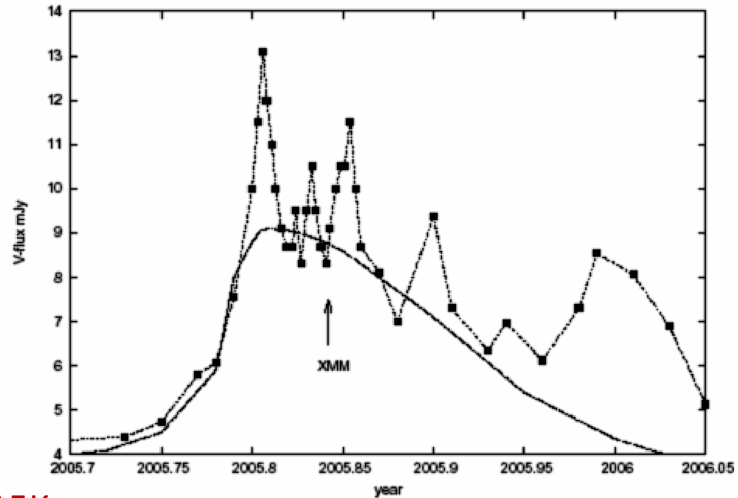
OJ 287 binary SMBH masses estimation

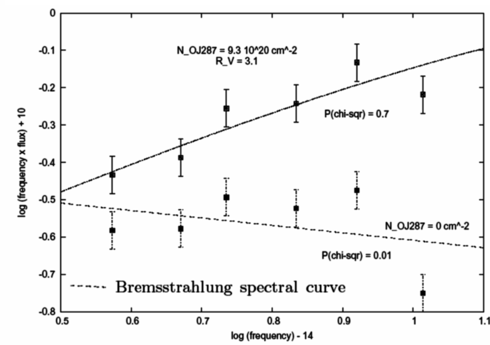
2005 optical outburst and XMM + multifrequency campaign data interpretation:

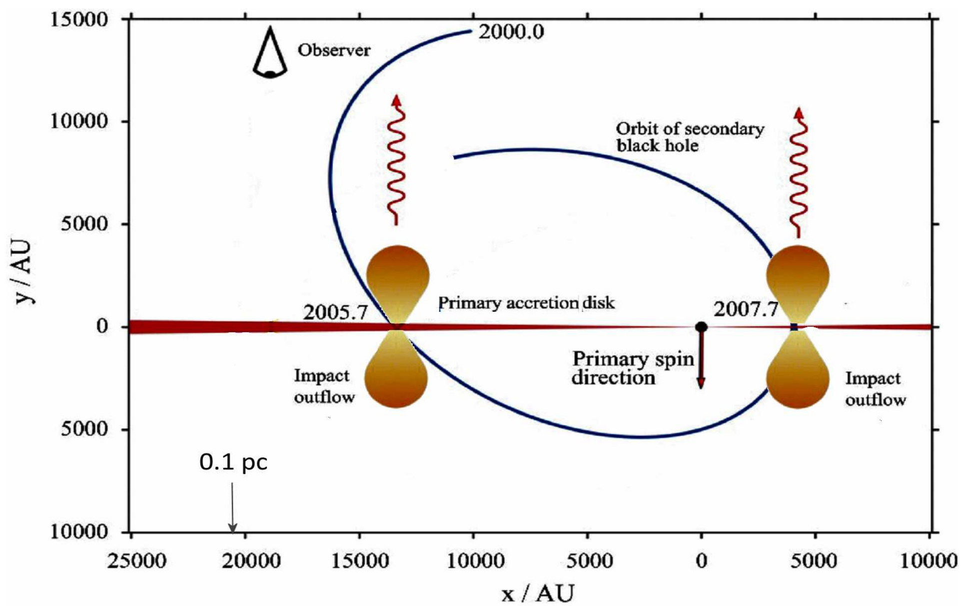
❑ April 2005: an optical pre-outburst state. November 2005: the main 12 year cycle outburst.

❑ Optical-to-UV range has a Bremsstrahlung spectral energy distribution consistent with gas at 3×10^5K temperature. Hot bubble of gas which is torn of the accretion disc by the impact of the secondary, not s not Doppler boosted.

❑ The requirement that the disc is stable inspite of the binary action puts a lower limit on the mass of the primary.
→Binary SMBH masses: 1.5X10^8 M_sun, 1.8X10^10 M_sun, orbital eccentricity (using apocentre/pericentre ratio) 0.7 (Valtonen, Ciprini, Lehto 2011).







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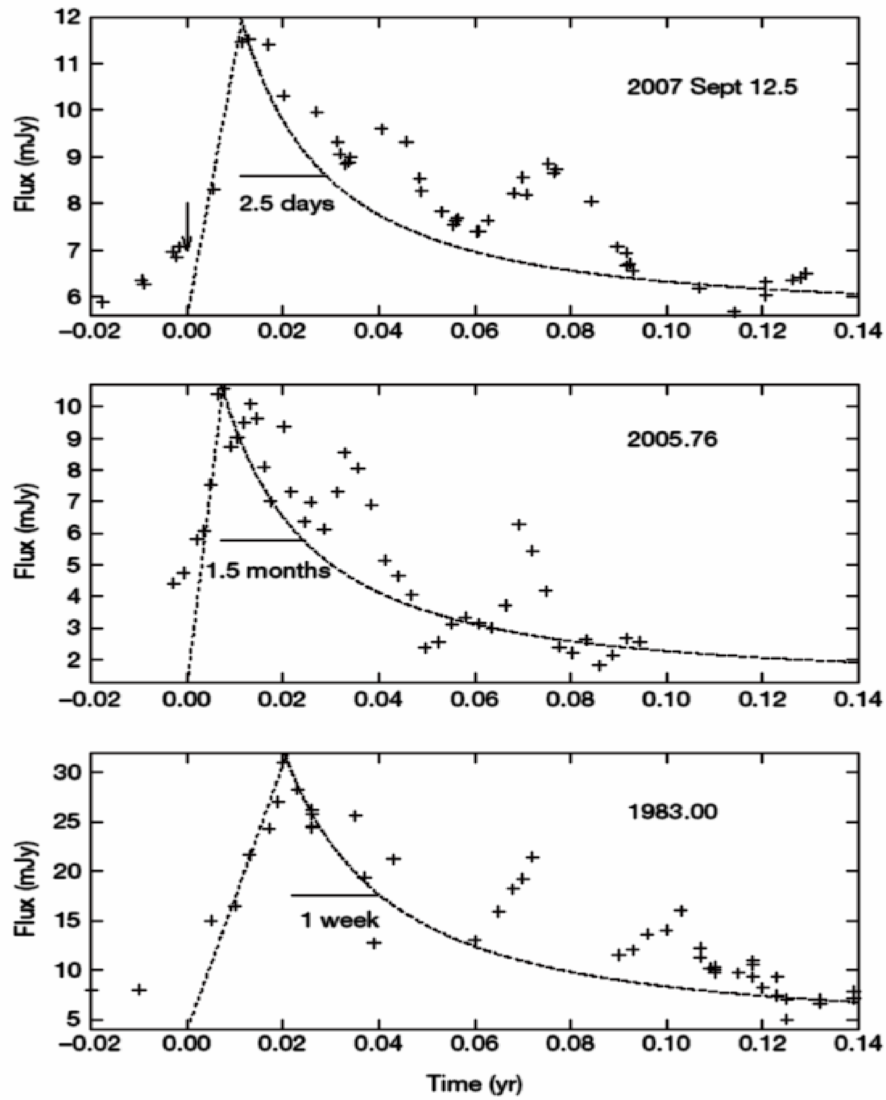
OJ 287: orbital energy losses and precession

GR tests mostly carried out in weak gravitational fields → space-time curvature effects are first-order deviations from Newton's theory. Binary pulsars provide a means of probing the strong gravitational field around a NS, but strong-field effects may be best tested in systems containing BHs.

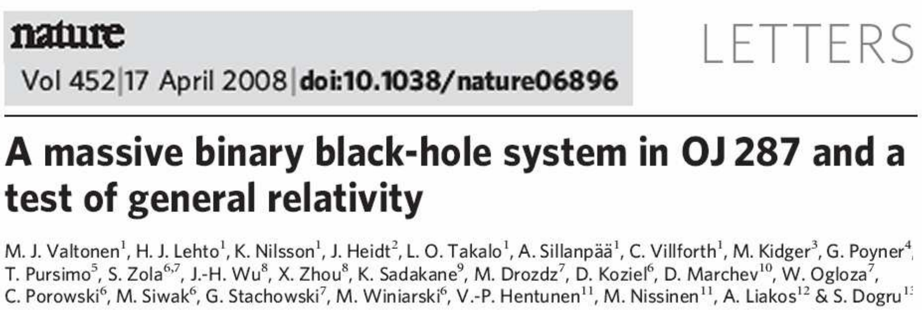
- Thanks to the >100-year long record of past variability and the last well sampled outbursts, it is possible to give a unique mathematical description for the orbit in the post-Newtonian approximation to GR.
- Evidence for the loss of orbital energy. This first test of general relativity with OJ 287 (Valtonen et al. 2008, Nature, 452, 851).



Outburst binary SMBH model fit.
Timescales different because the speed of impact and internal radiating bubble sound speed varies with impact distance from the primary SMBH (13300AU in 2005, 4800AU in 1983, 3400 AU in 2007).

OJ 287: orbital energy losses and precession

- ❑ The Oct.2005 optical-UV outburst came at the expected time, thus confirming the GR precession in the SMBH model system.
- ❑ The nature of the radiation of the Oct. 2005 outburst is well modeled by bremsstrahlung from hot gas at the temperature of 3X10^5 K, confirmed using XMM-Newton OM data.
- ❑ Secondary outburst of the same nature expected and observed in Sept. 2007. Here evidence for the loss of orbital energy, shrinkage in agreement (within 10%) with the emission of gravitational waves.
- ❑ This first test of general relativity with OJ 287 demonstrates the correctness of GR up to the 3rd Post-Newtonian expansion (Valtonen et al. 2008, Nature, 452, 851).


nature LETTERS
Vol 452 | 17 April 2008 | doi:10.1038/nature06896

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]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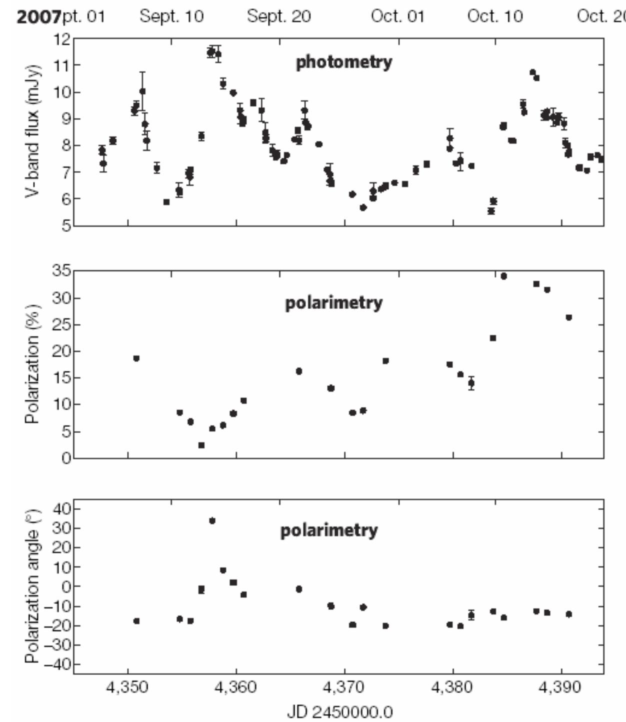
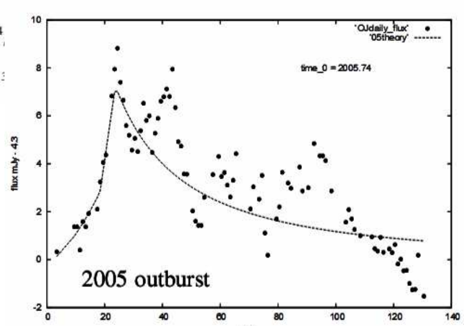
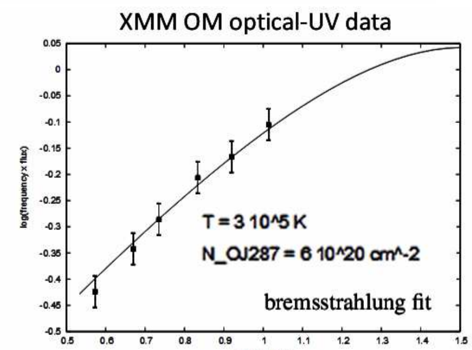
Memorie della

OJ287 binary black hole system

M. Valtonen[1] and S. Ciprini[2]







OJ 287: orbital energy losses and precession

- Loss in gravitational binding energy caused by low frequency gravitational wave emission and the Lense-Thirring (again GR) effect. → Binary SMBH orbital plane to precess, mainly due to the spin of the primary SMBH.
- From 12-year periodicity → to non-truly/strict periodicity model and double outburst model

Precession of the pericenter

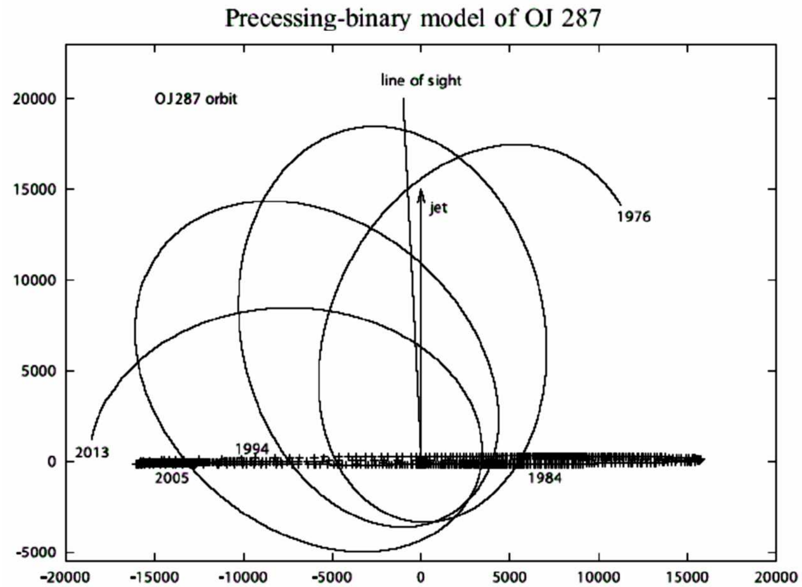
$$P = \frac{(1-e^2)a}{GM} = \frac{2(1+e)r_p}{r_{\rm Sch}}, \quad \text{where } r_p = (1-e)a$$

$$A_1 = 6\pi P^{-1} \quad A_2 = 4\pi\chi P^{-3/2} \quad A_3 = -3\pi\chi^2 P^{-2}$$

pericenter precession during one orbit

$$\Delta\omega = A_1 - 3A_2\cos i - \frac{1}{2}A_3(1-5\cos^2 i)$$

$$\Delta\omega_{\rm OJ287} = 29^\circ \text{ per orbit}$$



Precession of the orbital plane

At higher orders, the orbital plane itself precesses.

$$\Delta\Omega = A_2 - A_3\cos i.$$

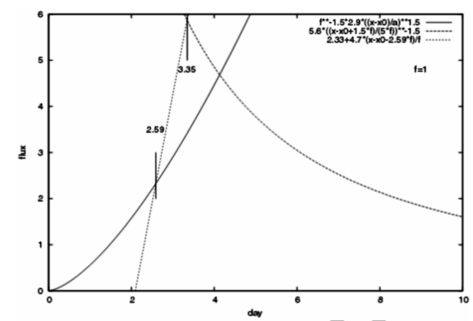
$$\Delta\Omega_{\rm OJ287} = 0.98^\circ \text{ per orbit}$$

OJ 287: test of the GR no-hair theorem

- No-hair theorem of spinning BHs: they are completely smooth (no bumps, not even hair). No possibility of adjusting internal structure. Faster rotation means no BH flattening, but it causes greater flattening in the surrounding space. The BH external gravitational field depends strictly only on the mass and the spin. The other possible property (net electric charge) is not expected in astronomical BHs.

- The No-hair theorem is valid for BHs in GR, but could be violated if GR is not correct. The correctness of the no-hair theorem was proven using the binary black hole system OJ 287. In the study of OJ287 a special kind of three-body problem in GR is solved (binary of two spinning black holes and a gas cloud in the accretion disk, as third body). By calculating the orbit for every particle in the disk, we get in combination an image of the whole disk and how it reacts to the BH binary.

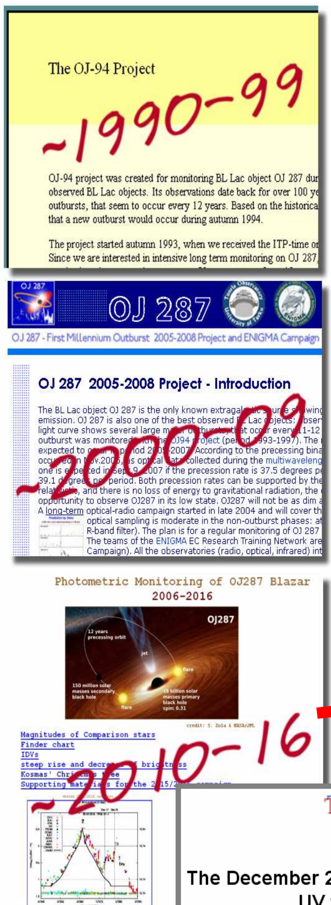
- Observationally the signals obtained from the disk allow us to determine the orbit of the binary. Sharp optical flare signals are obtained every time the secondary black hole impacts the accretion disk. In this way we can follow the orbital motion. The orbital motion is measurably different if the primary black hole has no "hair" or if it has some "hair". Gopakumar (Tata Inst. Fund. Research of Mumbai, India) proposed to test the no-hair theorem in this way with the OJ 287 optical light curves. The test was successful (Valtonen+ 2011, 2016): the primary SMBH in OJ 287 is a BH described by General Relativity with 30% accuracy.



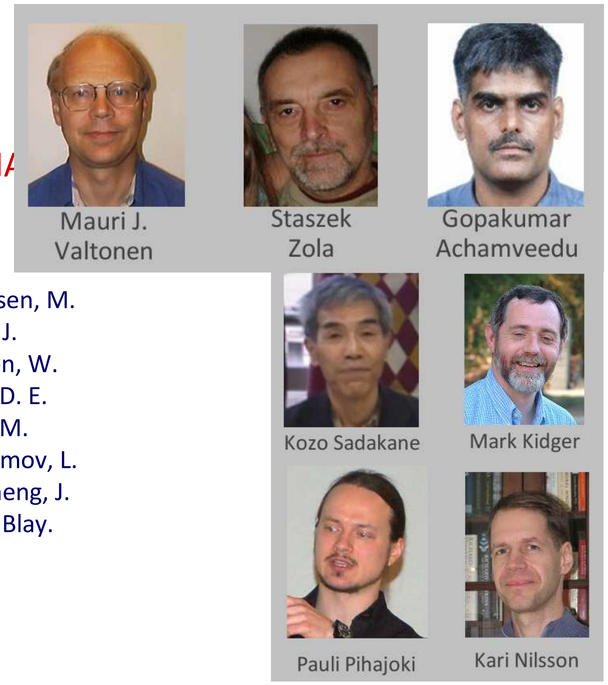
- The occurrence of the optical outburst within the expected time window, using the binary hyphotesis and the data of OJ 287, is consistent with the no-hair theorem at the 2PN order. The clocking of the optical outburst also confirm the loss of energy by gravitational radiation within 2% of the prediction by GR.

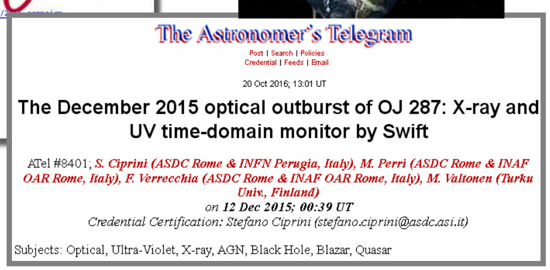
Winter 2015/2016 campaign and outburst

"Decadal" projects



M. Valtonen, S. Zola, S. Ciprini (ASDC/INFN),
A. Gopakumar, K. Matsumoto, K. Sadakane, M. Kidger,
K. Gazeas, K. Nilsson, A. Berdyugin, V. Piirola, H. Jermak,
K. S. Baliyan, M. Perri (ASDC/INAF), **F. Verrecchia** (ASDC/INA
and F. Alicavus, D. Boyd, M. Campas Torrent, F. Campos, J. Carrillo GÓmez, D. B. Caton, V. Chavushyan, J. Dalessio, B. Debski, D. Dimitrov, M. Drozdz, H. Er, A. Erdem, A. Escartin Pérez, V. Fallah Ramazani, A. V. Filippenko, S. Ganesh, F. Garcia, F. GÓmez Pinilla, M. Gopinathan, J. B. Haislip, R. Hudec, G. Hurst, K. M. Ivarsen, M. Jelinek, A. Joshi, M. Kagitani, N. Kaur, W. C. Keel, A. P. LaCluyze, B. C. Lee, E. Lindfors, J. Lozano de Haro, J. P. Moore, M. Mugrauer, R. Naves Nogues, A. W. Neely, R. H. Nelson, W. Ogloza, S. Okano, J. C. Pandey, P. Pihajoki, G. Poyner, J. Provencal, T. Pursimo, A. Raj, D. E. Reichart, R. Reinthal, S. Sadegi, T. Sakanoi, J.-L. Salto González, Sameer, T. Schweyer, M. Siwak, F. C. Soldán Alfaro, E. Sonbas, I. Steele, J. T. Stocke, J. Strobl, L. O. Takalo, T. Tomov, L. Tremosa Espasa, J. R. Valdes, J. Valero Pérez, J. R. Webb, M. Yoneda, M. Zejmo, W. Zheng, J. Telting, J. Saario, T. Reynolds, A. Kvammen, E. Gafton, R. Karjalainen, J. Harmanen, P. Blay.





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20 Oct 2016; 13:01 UT

The December 2015 optical outburst of OJ 287: X-ray and UV time-domain monitor by Swift

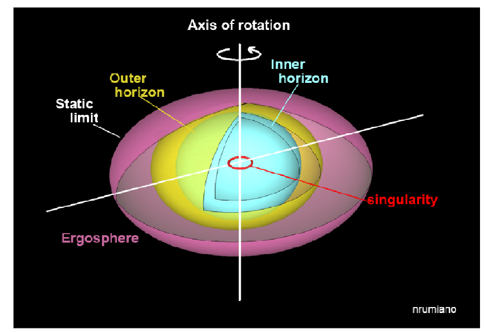
ATel #8401; *S. Ciprini (ASDC Rome & INFN Perugia, Italy), M. Perri (ASDC Rome & INAF OAR Rome, Italy), F. Verrecchia (ASDC Rome & INAF OAR Rome, Italy), M. Valtonen (Turku Univ., Finland)*
on 12 Dec 2015; 00:39 UT
Credential Certification: Stefano Ciprini (stefano.ciprini@asdc.asi.it)

Subjects: Optical, Ultra-Violet, X-ray, AGN, Black Hole, Blazar, Quasar

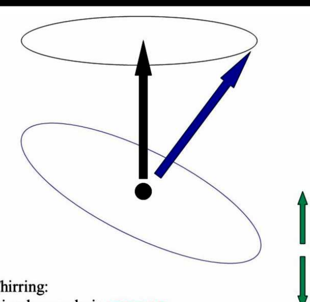
Swift monitor (time experiment) program: Oct.2015-Feb.2016
PI S. Ciprini., accurate and quick XRT/UVOT analysis by M. Perri and F. Verrecchia

OJ 287: the 2015-2016 MW campaign results

- ❑ A promising system for testing the General Relativity (GR) in this decade 2010-2020.
- ❑ Last 2015-2016 data: intensive optical flux monitor, optical polarization monitor, and Swift monitoring program (X-ray from XRT and UV data from UVOT).
- ❑ Swift X-ray measurements (dedicated about daily monitoring in several intervals between end of 2015 and beginning of 2016) and optical polarization data.



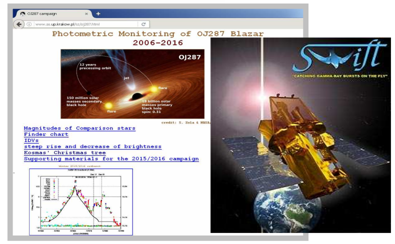
- ❑ Loss in gravitational binding energy caused by low frequency gravitational wave emission and the Lense-Thirring effect. → Binary SMBH orbital plane to precess, mainly due to the spin of the primary SMBH.
- ❑ Recent detailed re-modeling of OJ287 revealed that the primary black hole should spin approximately at quarter of the maximum spin rate allowed in GR. In this scenario, we have a unique mathematical solution and also a unique prediction for the OJ 287 impact flare outburst. It was predicted to occur on 2015 December 6 (+/- 8 weeks).
- ❑ Its timing is spin-sensitive → accurate timing of the secondary BH impact flare allowed us to constrain the Kerr parameter (spinning BH) of the primary BH with a fraction of percent accuracy for the first time.



Lense—Thirring:
plane of circular geodesic precesses
about black hole spin axis: dissipation causes alignment or counteralignment

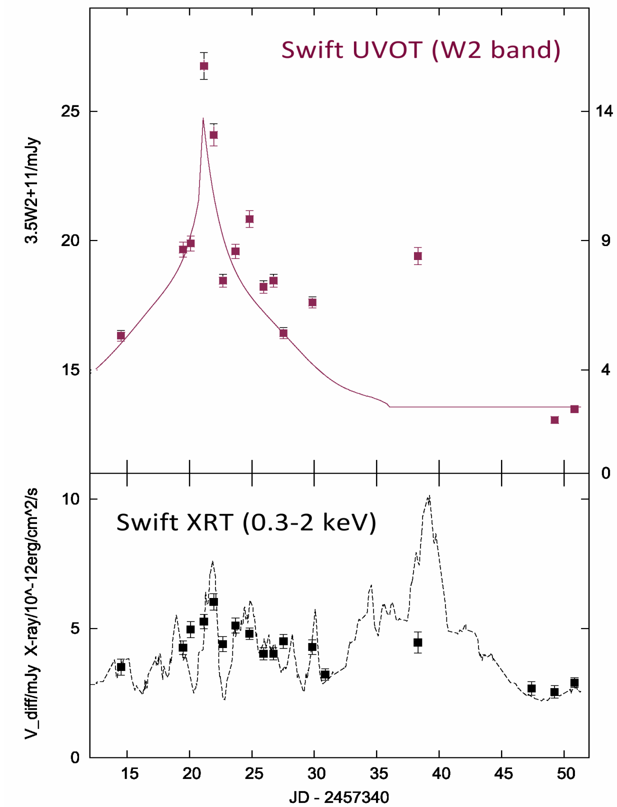
OJ 287: the 2015-2016 MW campaign

For the first time a OJ 287 binary/periodic model outburst was also monitored by a X-ray satellite (i.e. Swift) in both soft X-ray and UV bands.



- ❑ The UV emission measured by Swift UVOT has followed the optical emission rather well in previous campaigns (using a spectral index of 1.35 between the optical R-band and UV-W2 band as based on previous work by Edelson et al. 2015 Switft-Kepler campaign. The optical binary SMBH model line, shifted to the UV-W2 band using this value follows these new UVOT data (UV-W2 band in figure) rather well. UVOT UV-W1 and UV-M2 band light curve are entirely consistent with the binary model line.

- ❑ The model foreseen the separation of the disk impact bremsstrahlung (binary SMBH model) from synchrotron flares (erratic jet variability). X-ray emission modeled as coming entirely from the jet, follow rather well the optical excess emission (optical excess emission is the total optical flux minus the bremsstrahlung flux). The X-ray variability and flare observed by Swift XRT is rather modest and correlates very well with the optical excess flare emission. The non-presence of a simultaneous strong X-ray outburst (orphan optical-UV outburst) strenghten the evidence that there is an extra optical-UV (non-jet) emission component, related to the predicted binary model.



stefano.ciprini@asdc.asi.it - ASDC Rome

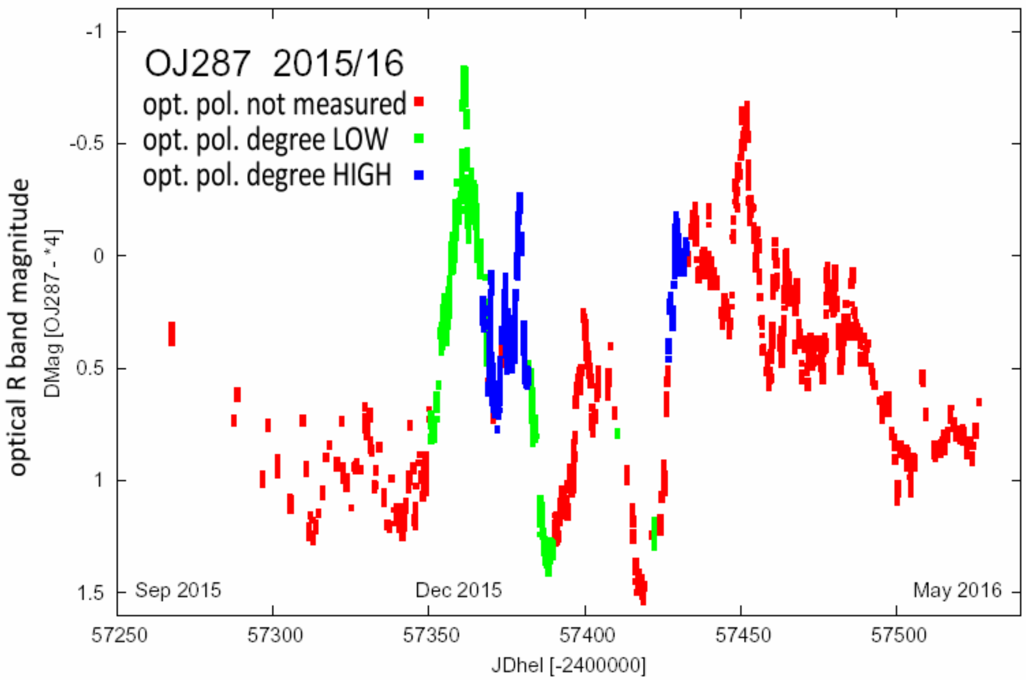
OJ 287: the 2015-2016 MW campaign

❑ The timing signals (clocking) are extracted from the optical light curve by identifying the start of the outburst thanks to the large amount of data and sampling density obtained.

❑ The outburst began on JD 2457342.5*/-2.5 (2015.874, Dec.5 2015). Using the previously calculated correlation with the spin (Valtonen+ 2011) the Kerr parameter of the primary SMBH is obtained (0.313+/-0.01).

❑ For comparison BH spin determinations by X-ray spectroscopy (Reynolds+ 2008, 2014) based on determining the innermost stable circular orbit (ISCO) of the accretion disks in Seyfert nuclei or low-z quasars, or X-ray binaries show that some of the spins are comparable to the spin of OJ 287, others are close to the maximal value of 1, while the LIGO GW burst merger event provides a spin pf 0.67 for the final BH (Abbott et al. 2016).

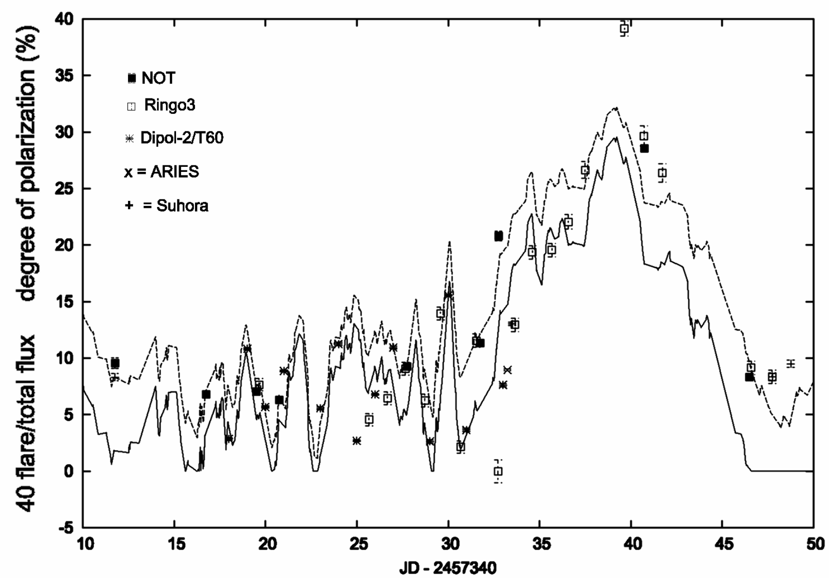
❑ Optical polarization data confirmed the major thermal (low-polarization) component of the predicted binary model outburst.



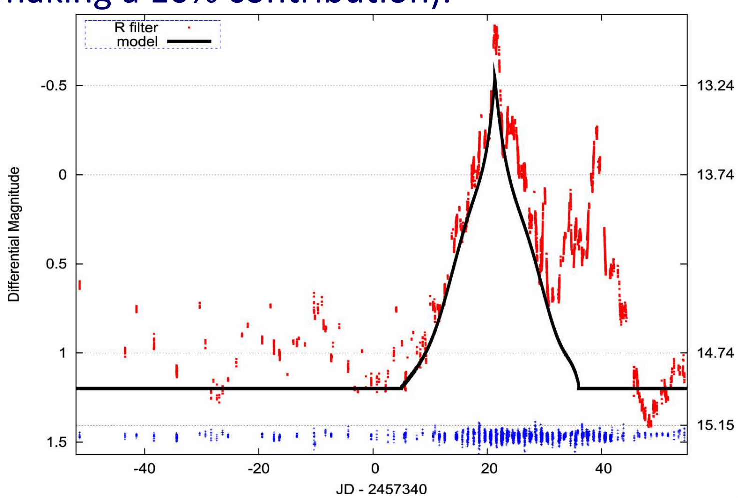
❑ Accurate observing timing (clocking)
→ accurate estimate for the spin of the primary SMBH

OJ 287: the 2015-2016 MW campaign

❑ This Nov-Dec 2015 outburst timing also confirms the correctness of the binary SMBH central engine model for OJ 287 with the specified parameters:
primary BH mass 1.83X10^10 M_sun,
secondary BH mass 1.5X10^8 M_sun,
orbital eccentricity (apocentre/pericentre ratio) 0.7.

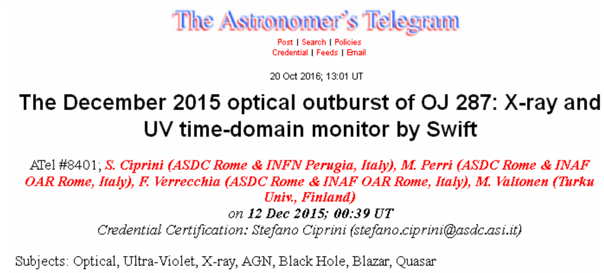


❑ Modeling of the degree of optical polarization of OJ 287 during the outburst is successful
(The plot shows the expected pol. degree curve if the excess non-thermal component, above the line in the magnitude light curve, is 40% polarized and the rest of the radiation is unpolarized. The dashed line is base level pol. flux making a 10% contribution).



OJ 287: the 2015-2016 MW campaign

- ❑ Outburst confirms the established GR properties of the system such as the loss of orbital energy to gravitational radiation at the 2% accuracy level, and it opens up the possibility of testing the black hole no-hair theorem with 10% accuracy during the present decade.



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20 Oct 2016; 13:01 UT

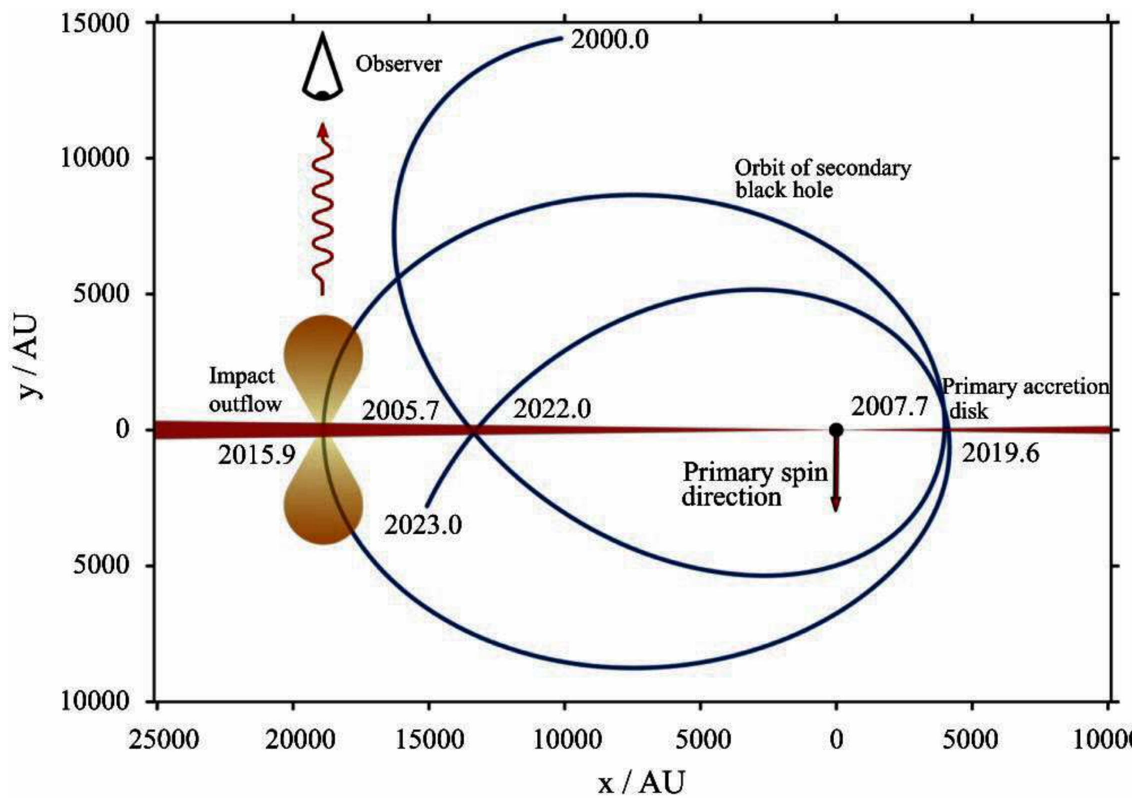
The December 2015 optical outburst of OJ 287: X-ray and UV time-domain monitor by Swift

ATel #8401; *S. Ciprini (ASDC Rome & INFN Perugia, Italy), M. Perri (ASDC Rome & INAF OAR Rome, Italy), F. Verrecchia (ASDC Rome & INAF OAR Rome, Italy), M. Valtonen (Turku Univ., Finland)*
on ***12 Dec 2015; 00:39 UT***
Credential Certification: Stefano Ciprini (stefano.ciprini@asdc.asi.it)

Subjects: Optical, Ultra-Violet, X-ray, AGN, Black Hole, Blazar, Quasar

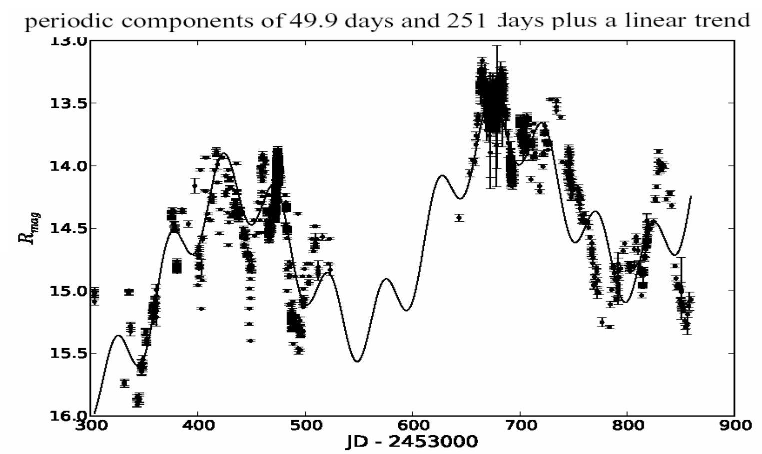
- ❑ This provides the first indirect evidence for the existence of a binary SMBH emitting gravitational waves. This is encouraging news for the PTA efforts that are trying to directly detect GWs from such AGN/galaxies systems.

- ❑ Observing the next predicted July 2019 thermal outburst from the Earth will be difficult owing to the proximity of OJ 287 to the Sun at that time.



OJ 287: ISCO

- Short-term quasi-periodic oscillations linked with accretion disk rotational velocity near the innermost stable circular orbit (ISCO) of the disk.
- In Newtonian gravity, stable circular orbits around a point mass at all radii. This is no longer true in General Relativity. In the Schwarzschild metric, stable orbits allowed only down to R_ISCO=6GM/c^2
- R_ISCO depend by SMBH mass and spin and oscillation observable as a re-emission in the jet → possible indirect detection of the secondary BH jet of OJ 287.

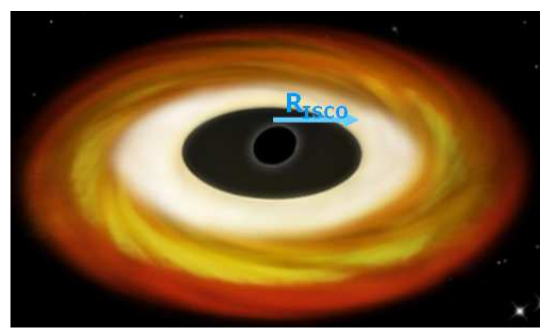


- Short-term variations with 50 day periodic component, presumably related to the half-period of the ISCO of the primary black hole (Pihajoki, Valtonen, Ciprini 2013).

The orbital period P for a test particle on a prograde orbit at a coordinate distance r is (Bardeen et al. 1972)

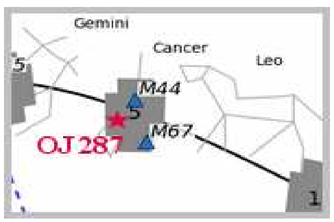
$$P = 2\pi \left(\sqrt{\frac{r^3}{GM}} + \frac{GM}{c^3}\chi \right) = \frac{2\pi r_{\rm Sch}}{c} \left[\sqrt{2} \left(\frac{r}{r_{\rm Sch}} \right)^{3/2} + \frac{1}{2}\chi \right].$$

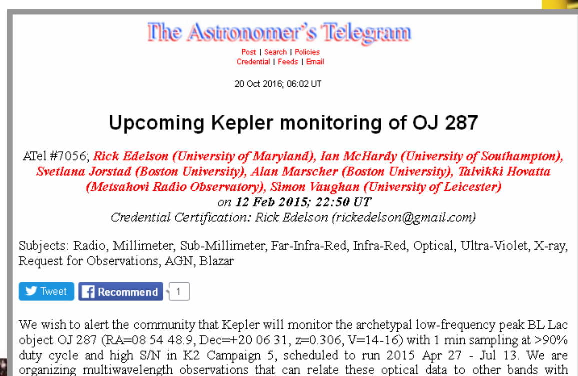
The prograde ISCO for the primary $r \sim 2.52 r_{\rm pri}$ $P_1 \sim 70$ days assuming a primary spin $\chi_1 \sim 0.28$.
The prograde ISCO for the secondary $r \sim 0.618 r_{\rm sec}$ $P_2 \sim 3$ hoursmescale assuming the maximal value $\chi_2 = 0.998$
Corrected for the redshift $z = 0.306$, the observed values become $P_1 \sim 100$ days and $P_2 \sim 4$ hours.



OJ 287: Kepler 3-month campaign

- ❑ Intensive short term camapign. 1 min sampling with Kepler at >90% duty cycle and high S/N in K2 Campaign 5 (Apr.27-Jul.13 2015). Swift almost daily simultaneous monitoring observations.
- ❑ More observations performed by Suzaku, OVRO, Metsahovi. [Campaign managers: R. Edelson, I. McHardy, S. Jorstad, A. Marscher, T. Hovatta, S. Vaughan]





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20 Oct 2016; 06:02 UT

Upcoming Kepler monitoring of OJ 287

ATel #7056; *Rick Edelson (University of Maryland), Ian McHardy (University of Southampton), Svetlana Jorstad (Boston University), Alan Marscher (Boston University), Talvikki Hovatta (Metsahovi Radio Observatory), Simon Vaughan (University of Leicester)*
on 12 Feb 2015; 22:50 UT
Credential Certification: Rick Edelson (rickedelson@gmail.com)

Subjects: Radio, Millimeter, Sub-Millimeter, Far-Infra-Red, Infra-Red, Optical, Ultra-Violet, X-ray, Request for Observations, AGN, Blazar

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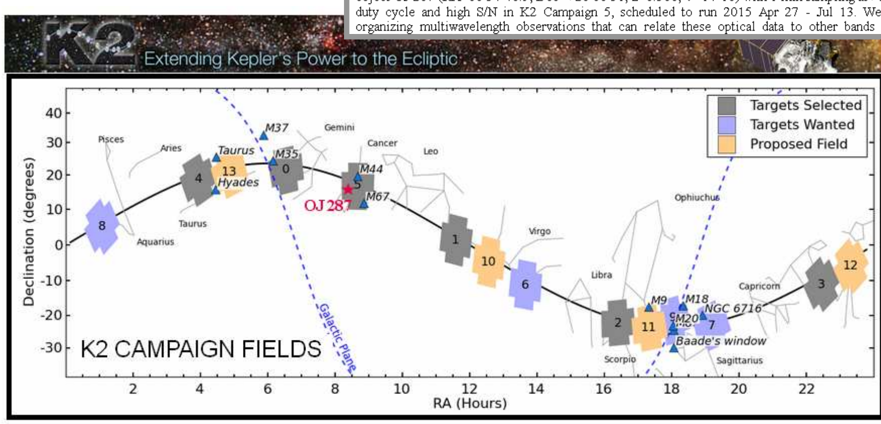
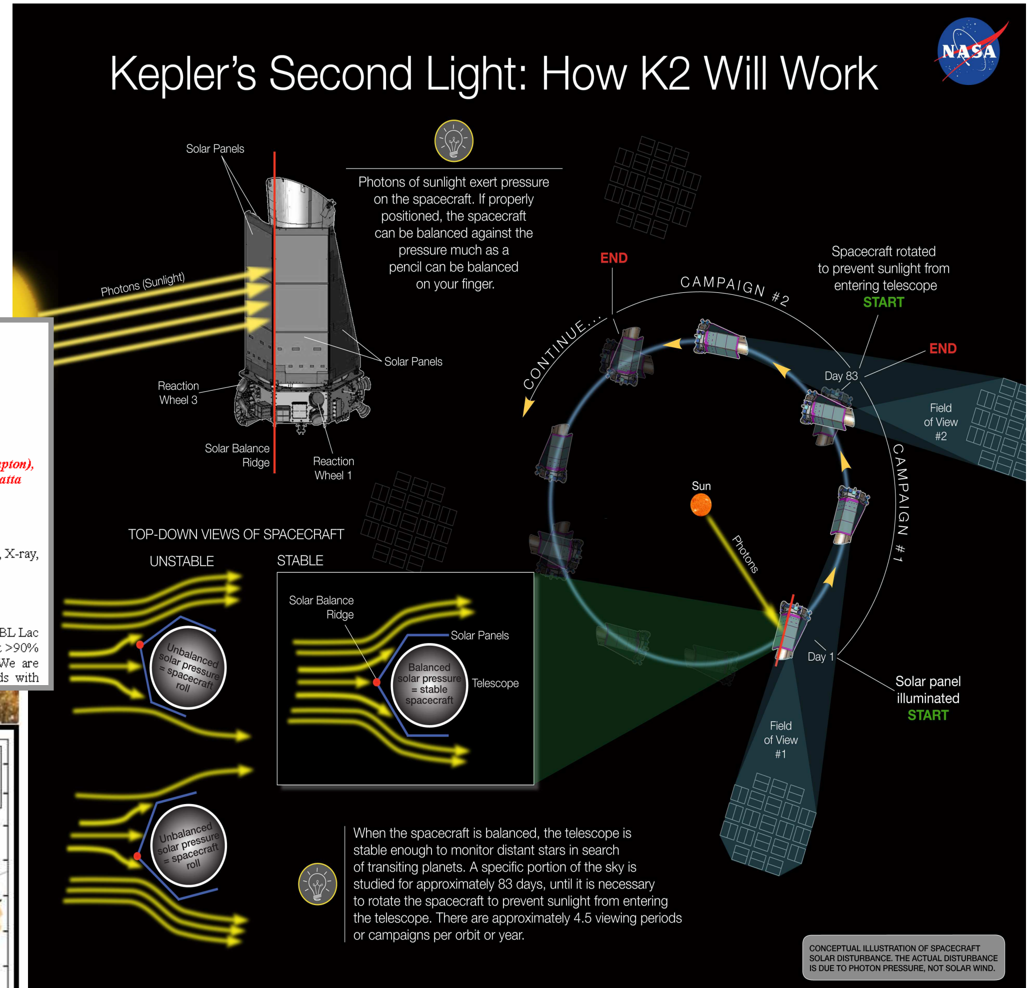
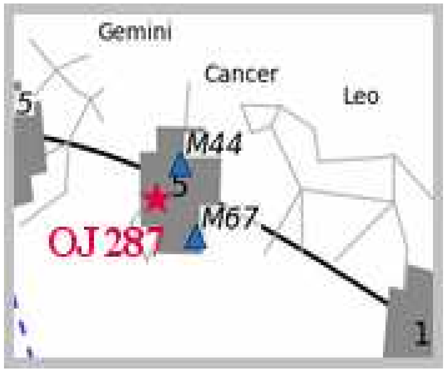
We wish to alert the community that Kepler will monitor the archetypal low-frequency peak BL Lac object OJ 287 (RA=08 54 48.9, Dec=+20 06 31, z=0.306, V=14-16) with 1 min sampling at >90% duty cycle and high S/N in K2 Campaign 5, scheduled to run 2015 Apr 27 - Jul 13. We are organizing multiwavelength observations that can relate these optical data to other bands with

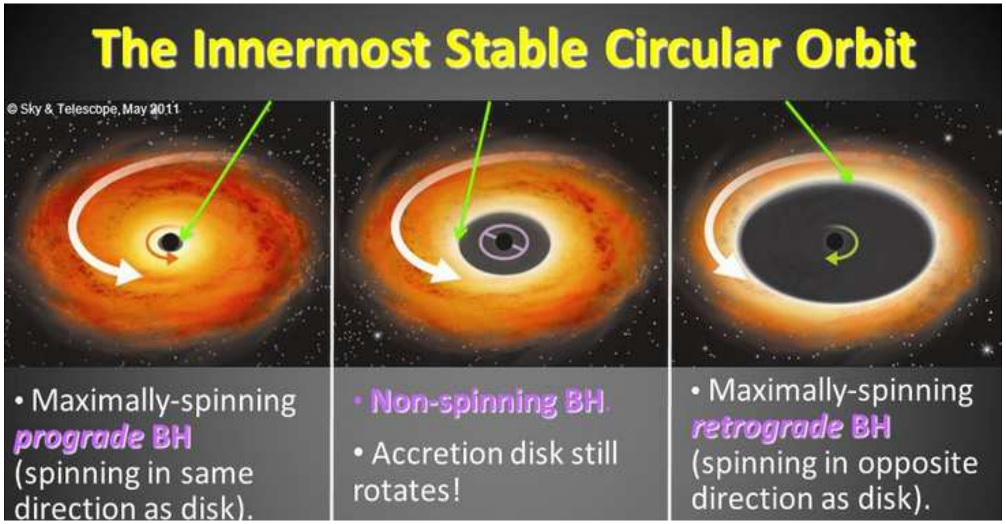


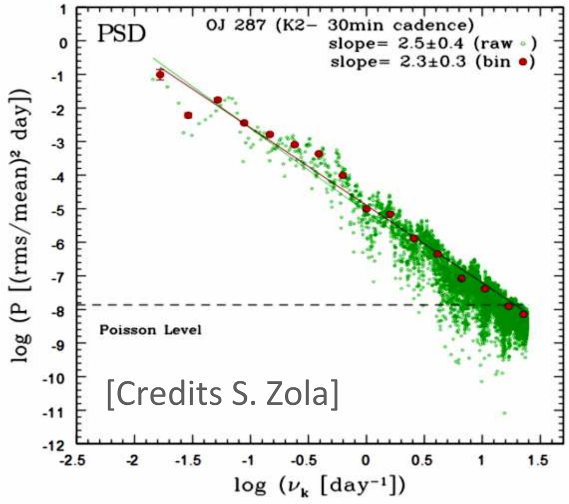


OJ 287: Kepler 3-month campaign

❑ Preliminary Kepler K2 Campaign 5 light curve of OJ 287 analyzed. About 3-month range. There are not statistically significant periodicities detected in the range from minutes to 30 days. ISCO quasi periodic oscillations in the secondary jet (expected to be on the order of 1 day) not detected.







[Credits S. Zola]

OJ 287: AAS press release

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

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THE ASTROPHYSICAL JOURNAL LETTERS, 819:L37 (6pp), 2016 March 10 doi:10.3847/2041-8205/819/2/L37

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],

Dance of Two Monster Black Holes

By Susanna Kohler on 23 March 2016

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

OJ 287 is one of the largest supermassive black holes known, weighing in at 18 billion solar masses. Located about 3.5 billion light-years away, this monster quasar is bright enough that it was first observed as early as the 1890s. What makes OJ 287 especially interesting, however, is that its light curve exhibits prominent outbursts roughly every 12 years.

What causes the outbursts? Astronomers think that there is a *second* supermassive black hole, ~100 times smaller, inspiraling as it orbits the central monster and set to merge within the next 10,000 years. In this model, the primary black hole of OJ 287 is surrounded by a hot accretion disk. As the secondary black hole orbits the primary, it regularly punches through this accretion disk, heating the material and causing the release of ...m the disk. This ... outbursts we see. ...ewtonian orbits ...k hole's crossings ... by when we see ... a model ... on the orbit. ... of these outbursts therefore provide an excellent test of

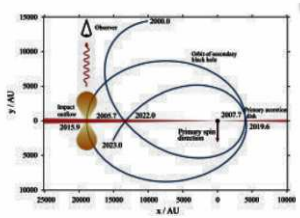
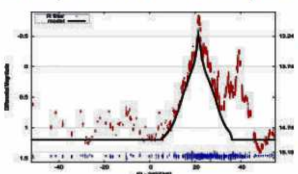
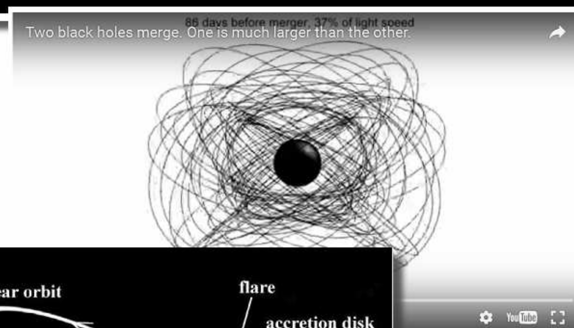


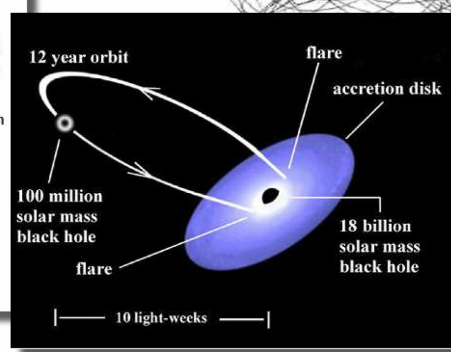
Diagram illustrating the orbit of the secondary black hole (shown in blue) in OJ 287 from 2000 to 2023. We see outbursts (the yellow bubbles) every time the secondary black hole crosses the accretion disk (shown in red, in a side view) surrounding the primary (the black circle). [Valtonen et al. 2016]



Optical photometry of OJ 287 from October to December 2015, showing the outburst that resulted from the secondary black hole crossing the disk. [Valtonen et al. 2016]

Artist's impression of a quasar. In the quasar OJ 287, a secondary supermassive black hole orbits the primary, occasionally punching through the accretion disk surrounding the primary. [ESO/M. Kommesser]





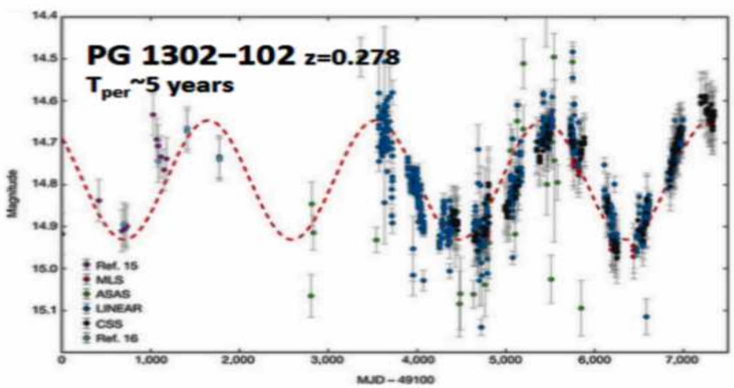
Related

- ASI (Italian Space Agency) news
- INAF (Italian National Institute for astrophysics) news
- TIFR Mumbai India, news
- University of Turku, Finland, news
- Jagiellonian University, Poland, news

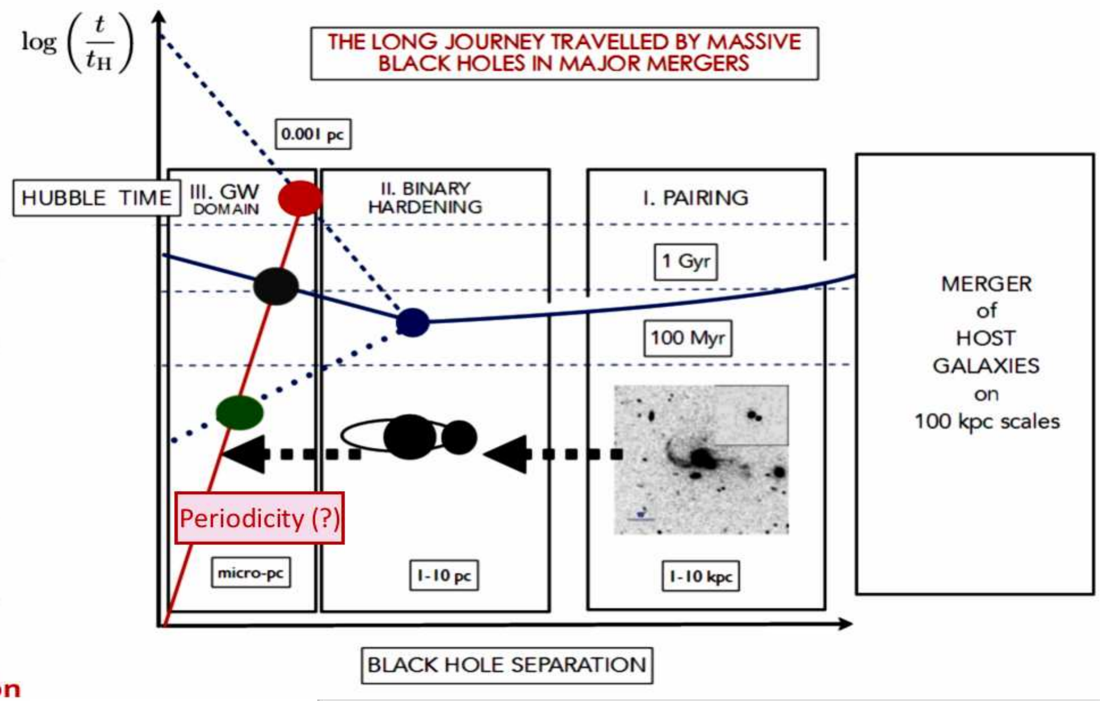
Valtonen, Zola, Ciprini, Gopakumar, et al. 2016, ApJ Lett, 819, 37

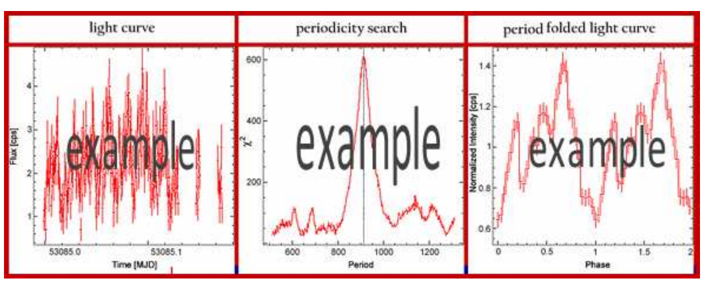
Other cases of AGN periodicity ?

- Periodicity (optical/radio long-term light curves) of AGN is a truly controversial astronomical topic. Skepticism is favorite, even if there is a recurrent ("periodical") enthusiasm and claims from the '70s.

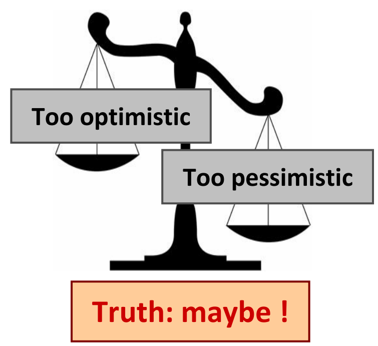


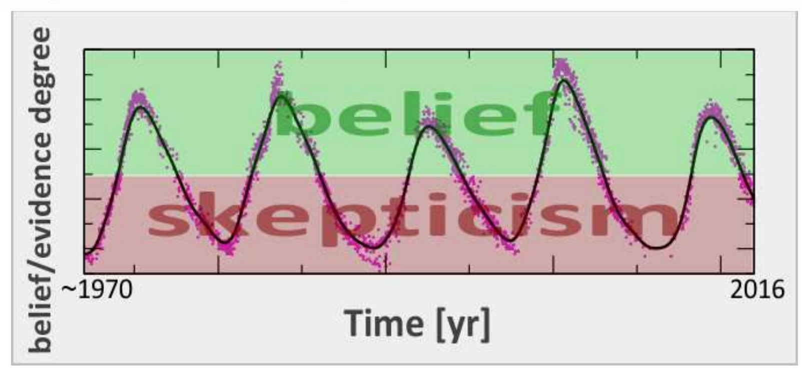
Graham et al. 2015, Nature 518
Binary SHBH 0.01 parsec (2X10^4 AU) separation





A classical 3-step "How-to" periodicity





Possible quasi-periodic signatures in blazars

- Long-term radio/optical light curves of blazars → possible periods several years (OJ 287, PG 1302-102, CGRaBS J1359+401, 3C 345, PSO J334.2028+01.4075, AO 0235+16, 3C 273, TXS 0059+581, BL Lac...)
- Short-term optical/X-ray/TeV light curves of blazars → possible periods of several tens of days (Mkn 501, Mkn 421, PKS 2155-304, 3C 66A, S5 0716+714 , OJ 287, Sy 1 KUG 1031+398/RX J1034.6+3938…)

name	redshift z	periods P_{obs}	$(m+M)/10^8 M_\odot$	P_k [yr]	$d/10^{16}$ cm	$\tau_g/10^8$ yr
Mkn 501	0.034	23.6 d (X-ray) $\sim$ 23 d (TeV)	(2-7)	(6-14)	(2.5-6)	$\leq$ 5.5
BL Lac	0.069	10.06 yr (optical) 13.97 yr (optical) $\sim$ 4 yr (radio)	(2-4)	(13-26.1)	(4.8-9.7)	$\leq$ 29
3C 273	0.158	13.65 yr (optical) 8.55 yr (radio)	(6-10)	(11.8-23.5)	(6.5-12)	$\leq$ 3.5
OJ 287	0.306	11.86 yr (optical) $\sim$ 12 yr (infrared) $\sim$ 1.66 yr (radio) $\sim$ 40 d (optical)	6.2	(9.1-18.2)	(5.5-8.8)	$\leq$ 1.7
3C66A	0.444	4.52 yr (optical) 65 d (optical)	$\geq$1	(3.1-6.3)	$\geq$ 1.5	2.08
0235+16	0.940	2.95 yr (optical)? 8.2 yr (optical)? 5.7 yr (radio)	$\geq$1	(1.5-3.1)	$\geq$ 0.95	$\leq$ 0.3

Candidate BSMBHs in literature based on some reported quasi-periodicity evidence. Associated gravitational lifetime tg is estimated for mass ratios m/M > 1/100 (Rieger 2008, 2007).

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Conclusions

- Multiwavelenght (MW) data (extensive/intensive coordinated observing campaigns, radio/optical telescopes and X-ray satellites like XMM-Newton and Swift) are presented for the famous BL Lac object OJ 287. The 2004-2006 and winter 2015/2016 MW campaign data on OJ 287 represented a test bench for the binary SMBH hypothesis.

- Direct evidence for sub-parsec spatially unresolved binary-SMBHs candidates (quasi periodic signals, pc-scale distorted radio-structures / helical-patterns in jets, double-peaked broad lines, etc.) in general is still a very debated topic in astronomy.

- Periodicity in blazar light curves → caveats.
Strong claims needs strong evidence. MW cross- correlations and polarization data are important. Beware of systematics, data gaps, selection effects, and red-noise.
There are also a variety of mechanisms than might explain the periodicity without the need of a binary SMBH hypothesis.

- Dedicated Swift time-domain experiment (monitoring) during the last outburst of Nov.2015-Jan 2016. There was also a previous intensive campaign (Kepler + Swift) in Apr.-Jul.2015.

- Post Newtonian GR model prediction are observed in the data (tests of GR with massive BHs and strong-fields). Evaluation of the primary Kerr SMBH spin and confirmation of the GR properties of binary SMBH system (masses, orbital parameters, no-hair theorem, precession, GW radiation losses). More tests possible in next years (ex.: the foreseen summer 2019 outburst).