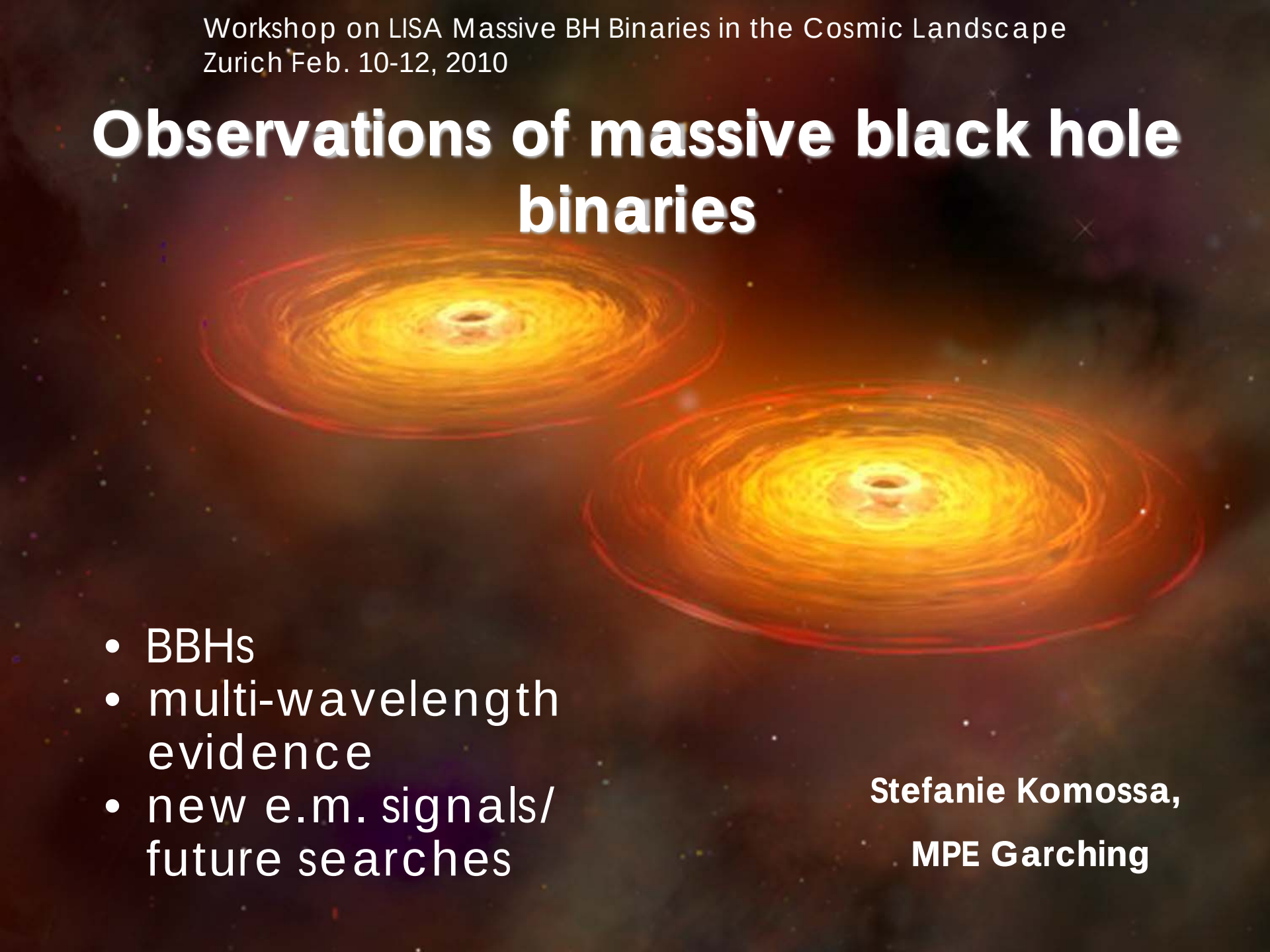
Workshop on LISA Massive BH Binaries in the Cosmic Landscape
Zurich Feb. 10-12, 2010

Observations of massive black hole binaries



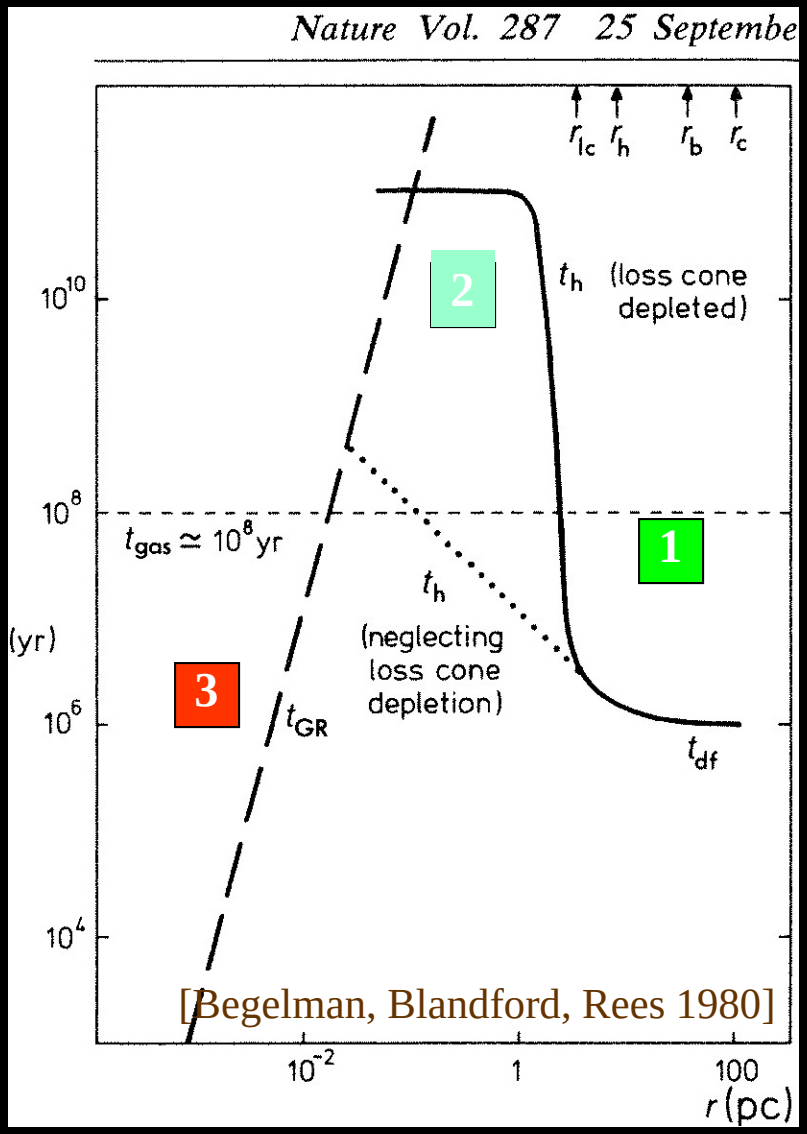
- BBHs
- multi-wavelength evidence
- new e.m. signals/ future searches

Stefanie Komossa,

MPE Garching

evolution of SMBBHs

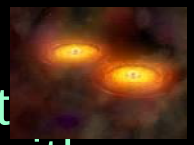
according to hierarchical models of galaxy formation, BBHs should be common



[Begelman, Blandford, Rees 1980]

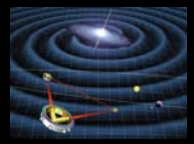
1 **dynamical friction regime**

2 **binary hardening**



e.g., by stellar slingshot effect (loss-cone refilling), interact. with gas, *stalling at ~1-0.1 pc* ?...)*

3 **emission of GWs**



)*[e.g., Saslaw & al. 74, Quinlan & Hernquist 97, Gould & Rix 00, Merritt 01,03, Milosavljevic & Merritt 01,03, Zier & Biermann 01, Ivanov+ 99,04, Yu 02, Blaes et al. 02, Poon & Merritt 02, Haehnelt & Kauffmann 02, Hemsendorf+ 02, Armitage & Natarajan 02,05, Escala+ 03,05, Makino & Funato 04, Berczik+ 05,06, Haardt+. 06, Dotti+ 06, Merritt 06, 07, Matsui & al. 06, Zier 07, Alexander 07, Mayer+ 07, Perets & Alexander 08, Sesana & 08, Berentzen & 08, Mayer+ 09, ...]

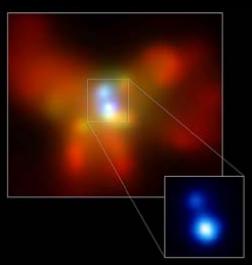
SMBBHs (& galaxy mergers) in astrophysical context

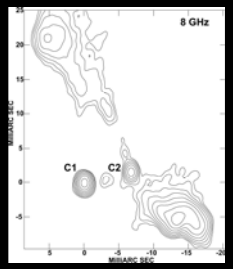
- BH growth + BH-galaxy co-evolution, triggering of quasars, & their lifetimes
- explanations of aspects of AGN & galaxy phenomenology ?
- emission of GWs
- recoiling BHs, and their astrophysical consequences

observational evidence for SMBBHs

- **BH pairs in single galaxies**
  (NGC 6240, 0402+379)

  two accreting BHs, spatially resolved





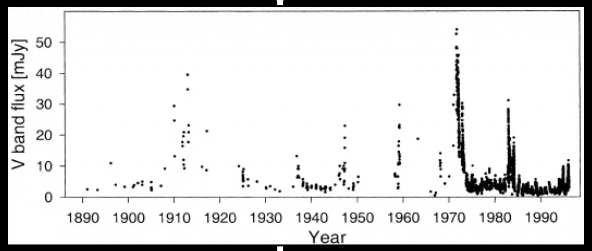
decreasing nuclear separation

- **spatially unresolved BBH candidates**

  - semi-periodic lightcurves (esp. OJ 287)

    2ndary BH hitting disk of primary ?

    2005-2007 monitoring campaign: orbital shrinkage due to GWs



  - helically distorted radio jets (e.g. 3C345)

    jet-emitting 2ndary BH orbiting primary; or precession ?

  (- double-peaked broad lines ?)

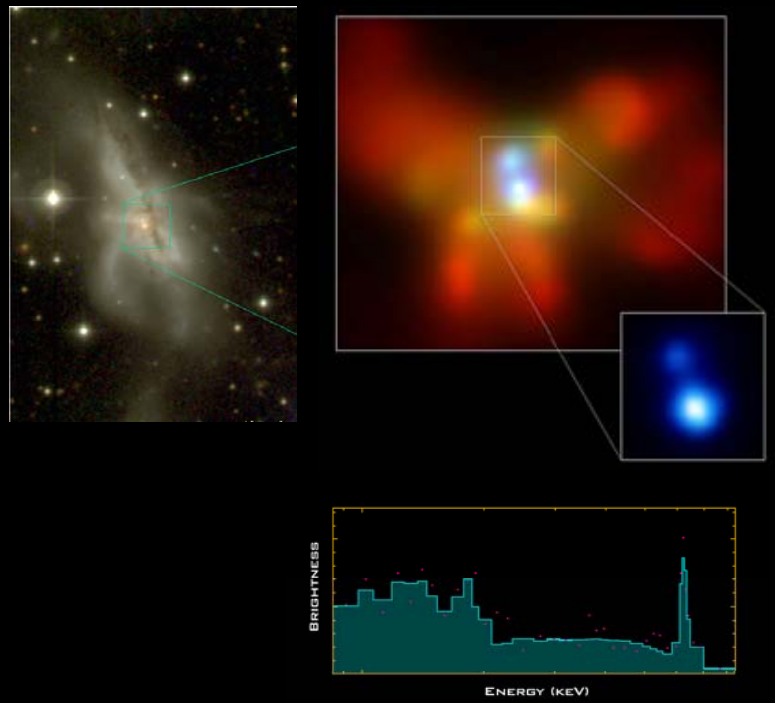
- **post-merger candidates**

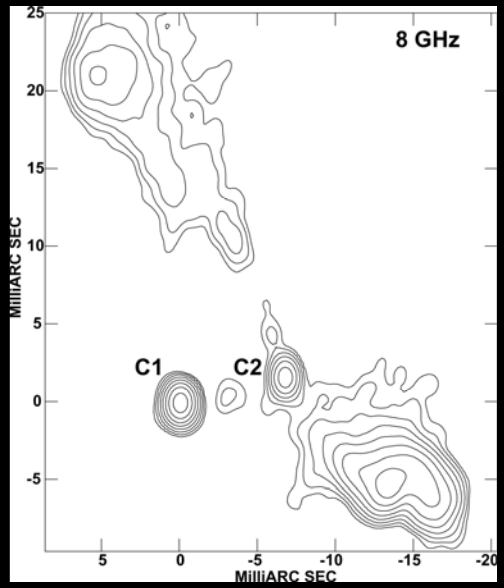
  - double-double radio sources open gap systems ?

  - central light deficits

[e.g., Lehto & Valtonen 96, Silanpää 00, Merritt & Ekers 02, Komossa+ 03, Liu 03, Zhou+ 04, Lobanov+ 06, Rodriguez+ 07, Comerford+ 08, Valtonen+ 07-10, ...]

spatially resolved systems in single galaxies: **NGC 6240 & 0402+379**





- nearby (U)LIRG at z=0.024
- luminous, hard X-ray emission from two cores
- accreting BHs at separation of ~ 1 kpc

[Komossa+ 03]

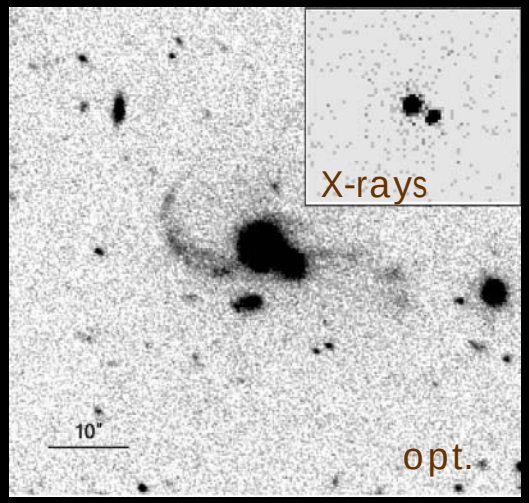
- radio galaxy at z=0.06
- two radio cores C1,C2
- compact, variable & flat-spectrum →
- true nuclei, at 7 pc sep.

[Maness+ 04, Rodriguez+ 07]

spatially resolved systems in single galaxies/ mergers: COSMOSJ1000+0206 & SDSSJ1254+0846

- gal. at z=0.36, in COSMOS survey
- 2 cores with HST
- 1.8 kpc sep.

[Comerford+ 09, Elvis+ 09]



- merger at z=0.4 in SDSS
- two opt. quasars, unabsorberd
- 21 kpc separation

(lensing unlikely)

[Green+ 10]

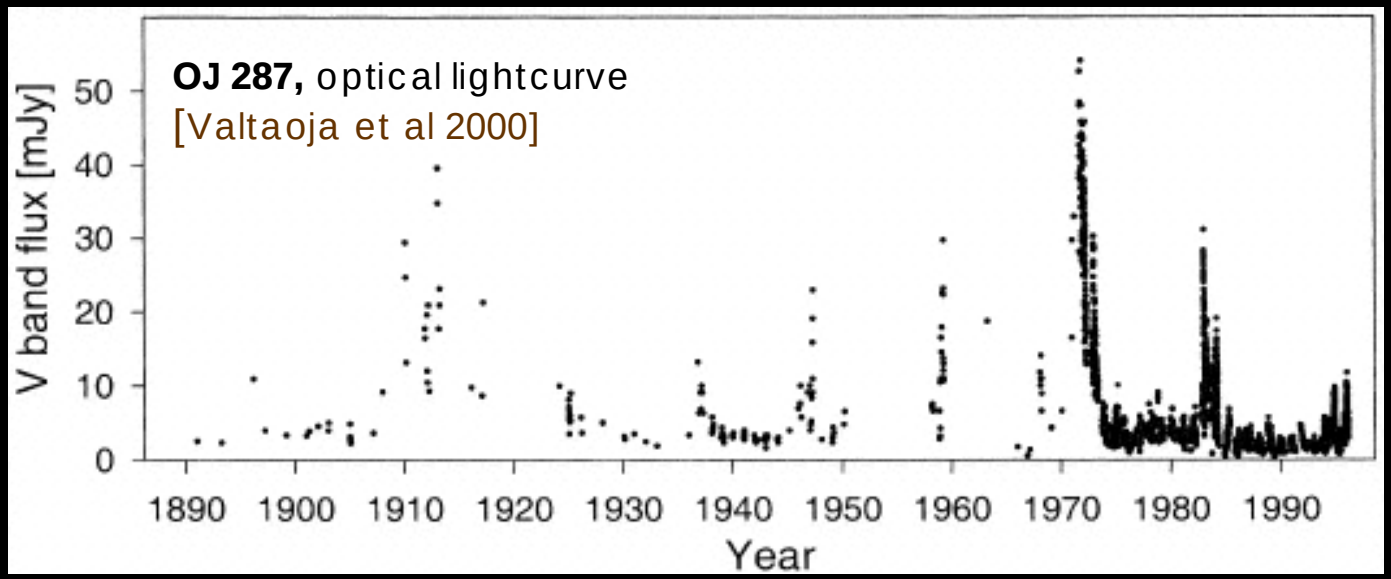
spatially unresolved candidates: **semi-periodic variability & OJ287**

- semi-periodic optical variability of the blazar **OJ 287;** maxima with period of ~12 yr

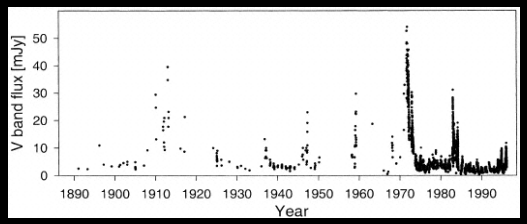
  [e.g., Silanpää et al. 88, 96, Lehto &Valtonen 96, Sundelius+ 97, Pietilä+ 98,Valtaoja 00, Valtonen+ 06, 07.....]

- also seen in other blazars, and in other λ bands (e.g.,**3C345, Mrk 501, ON231,3C273,PKS0420-014,BL Lac, AO0235+16;** periodicities less pronounced, they „come & go", various t-scales)

  [e.g., Fan+ 98,01,02, Rieger & Mannheim 00, Roy+ 00, Webb+ 00, De Paolis+ 02, Xie+ 02, Liu & Wu 02, Rieger 04, Liu+ 06, and many others]



spatially unresolved candidates: **OJ287**

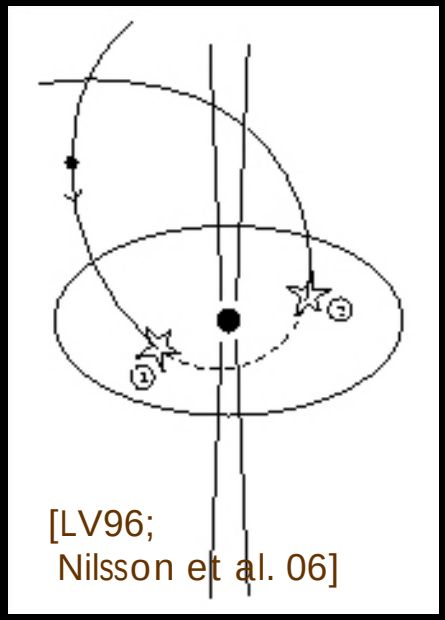


- BBH model: burst interval = orbital period
- double-peak structure: 2ndary in pre-cessing orbit impacts warped, thick disk *twice*
- essential for finding orbital solutions: *timing* of all prev. peaks
- orbital parameters:

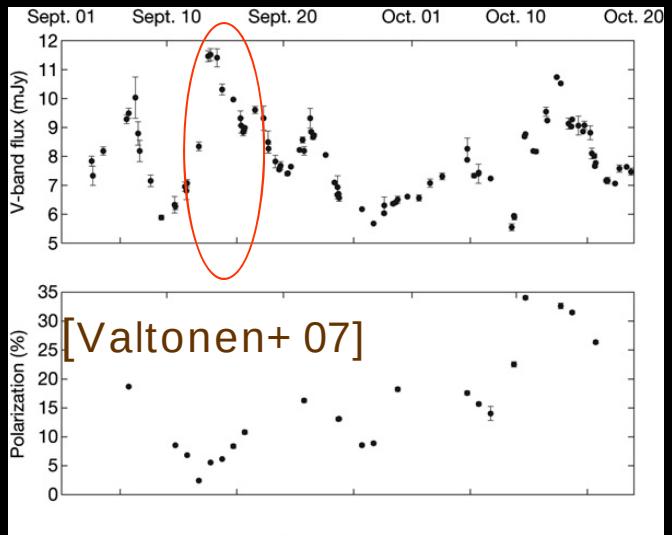
  M_1 = 1.8 10^{10} M_{sun})*

  M_2 = 1.4 10^{8} M_{sun}

  ε = 0.7, $\Delta\phi$ = 40° /orbit



- „ shift“ in Sept. 2007 maximum: interpreted as **orbital shrinkage** due to emission of gravitational waves (ΔT_{GW} = 0.01 yr/period)

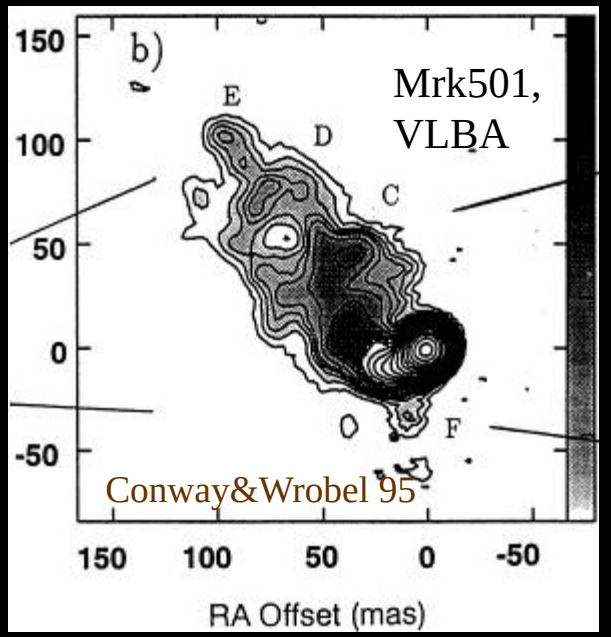


)* but note that the host galaxy appears to imply lower mass – Liu&Wu 02

[e.g. Silanpää et al. 88, 96, Lehto &Valtonen 96, Sundelius+ 97, Pietilä+ 98, Liu & Wu 02, Valtonen+ 97,06, 07,10.....]

spatially unresolved candidates: **helical radio jets**

- **observation:** jets sometimes show (semi-periodic) deviations from straight line **(e.g., 3C345, 3C449, Mrk 501, 4C73.18, 3C120, 3C273, PKS0420-014, BL Lac, ...)**



- **interpretation:**
  presence of BBH leads to
  - modulation due to *orbital motion* of jet-emitting secondary BH around the primary
  - or *precession* of jet

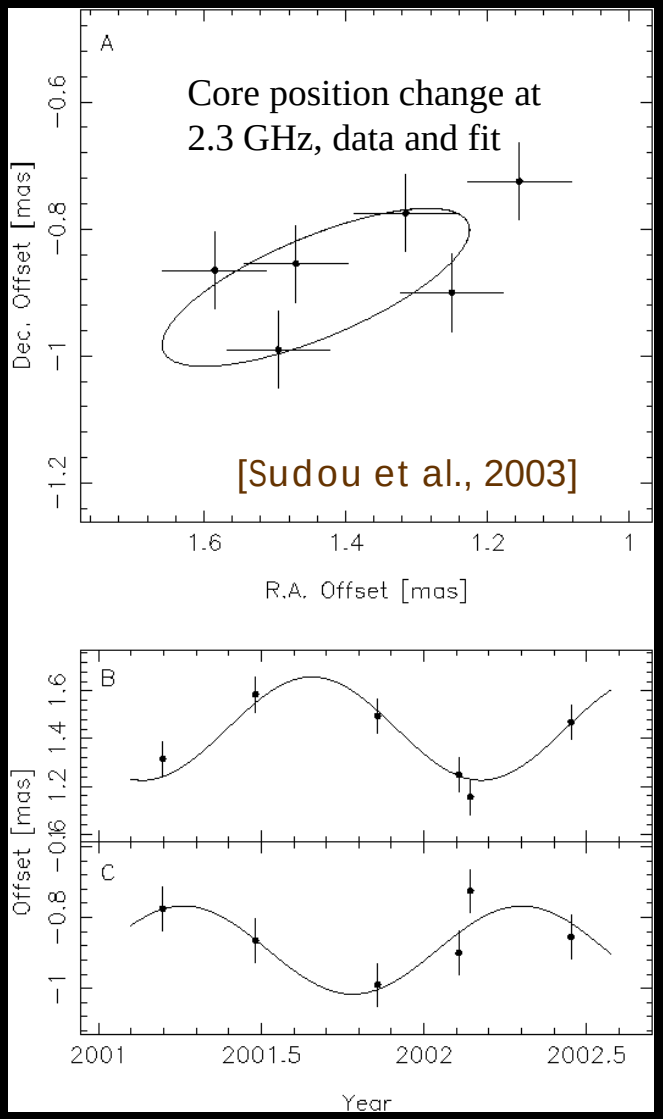
[e.g. Begelman,Blandford,Rees 80, Kaastra & Roos 92, Roos+ 93, Hardee+ 94, Conway & Wrobel 95, Tateyama+ 98, Romero+ 00, Britzen+ 01, Rieger 04, Caproni & Abraham 04a,b, Lobanov & Roland 05, Liu & Chen 07, ...]

spatially unresolved candidates
radio-BBH in 3C66B ?

- **observation:** VLBA imaging → unresolved radio core of 3C66B (z=0.02) shows syst. shifts in position
  period: 1.05 yr
- **interpretation:** elliptical orbital motion of BBH,
  with $M_t \sim 5\ 10^{10}\ M_{sun}$, q ~ 0.1

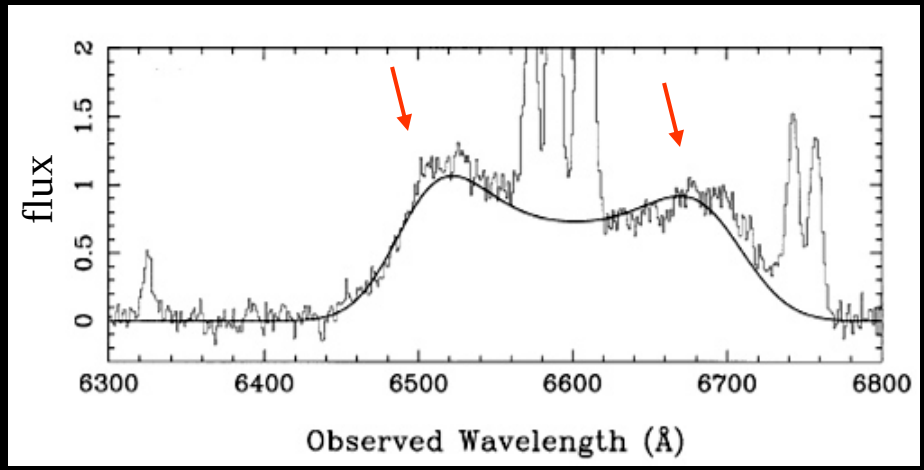
orbital period not confirmed, so far
& part of parameter space excluded by current PT constraints [Jenet+ 05],
with $M_t < 0.7\ 10^{10}\ M_{sun}$

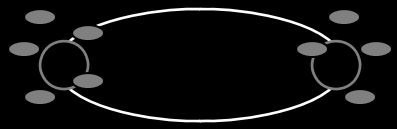
but *method itself potentially* very powerful



interlude:
no BBHs in „broad double peakers“, so far

- a few % of all quasars show broad double-peaked emission lines
- one early idea: BBH systems; gas clouds bound to each BH
- strong prediction: should see orbital motion on timescale of years
- *not detected*
- instead, processes in outer warped accretion disk around a single BH





[e.g., Gaskell 83, 88, 96, Halpern & Filippenko 88, Eracleous et al. 97, Halpern & Eracleous 00, Gaskell 10]

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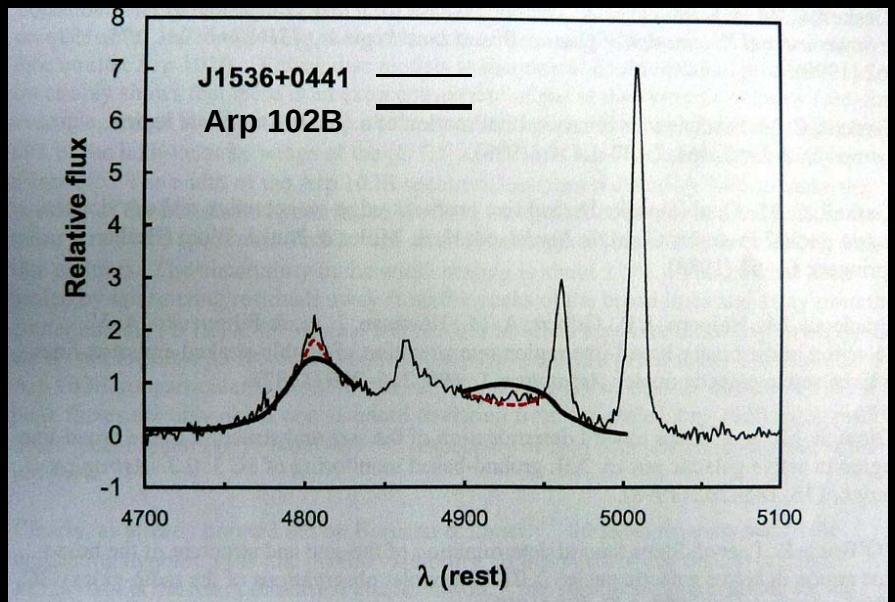


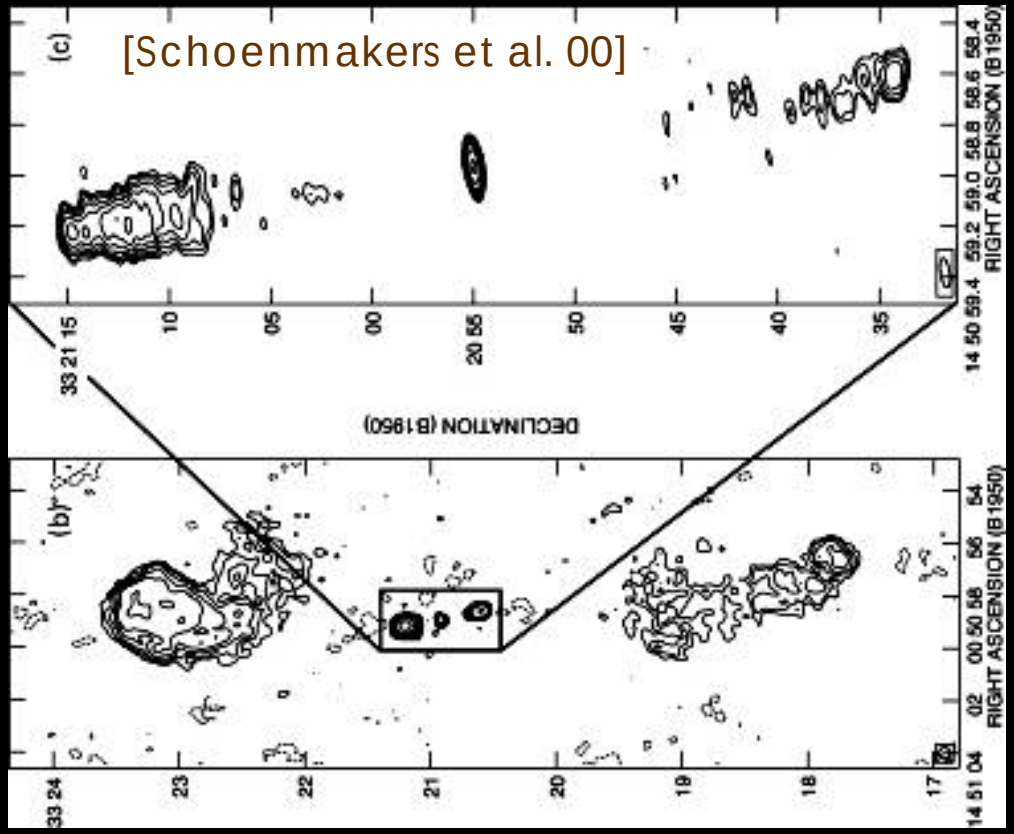
Figure 1 – Comparison of the continuum-subtracted SDSS spectrum of the Hβ region of J1536+0441 (thin black line) with the mean Hα profile of Arp 102B from 1992-1996 (smooth thick black line). The latter is taken from the mean spectrum shown in Fig. 3 of

- **SDSS1536+04** [Boroson & Lauer 09] turned out to be another double-peaker; no orbital motion detected so far [v < 70 km /s /yr; Chornock+ 09, 10]

post-merger candidates: **„open-gap“ systems**

- **double-double radio galaxies**

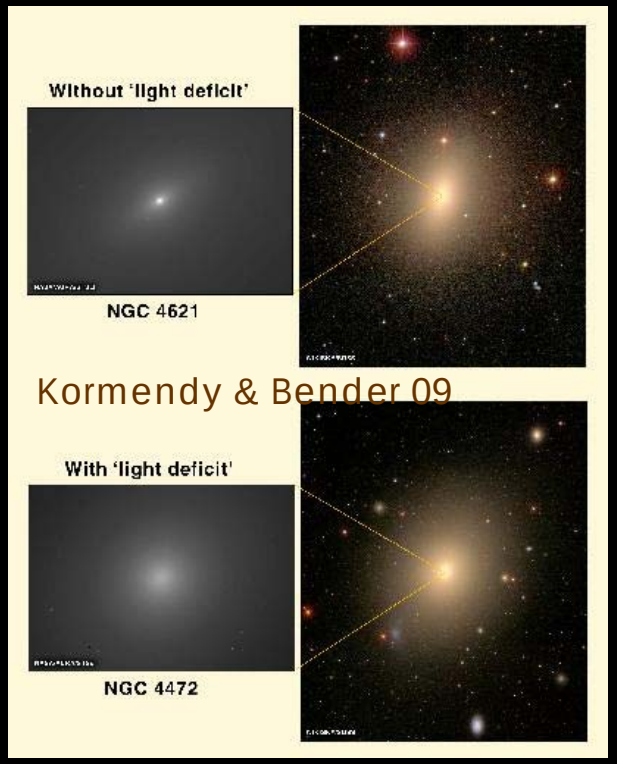
interpret.: inspiralling 2nd BH temporarily removed inner parts of accretion disc of primary BH; after coalescence, accretion activity restarted
[Liu+ 03, Liu 04]

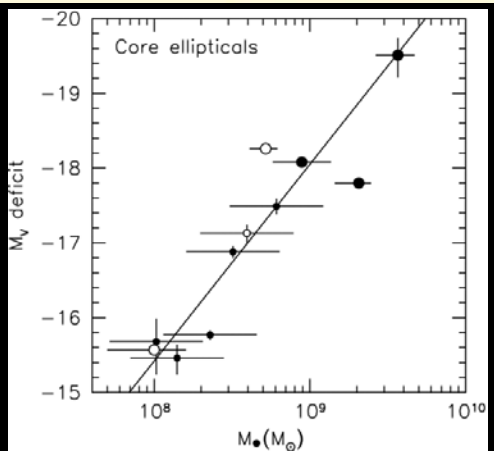


post-merger signature: **galaxies with central mass deficits**

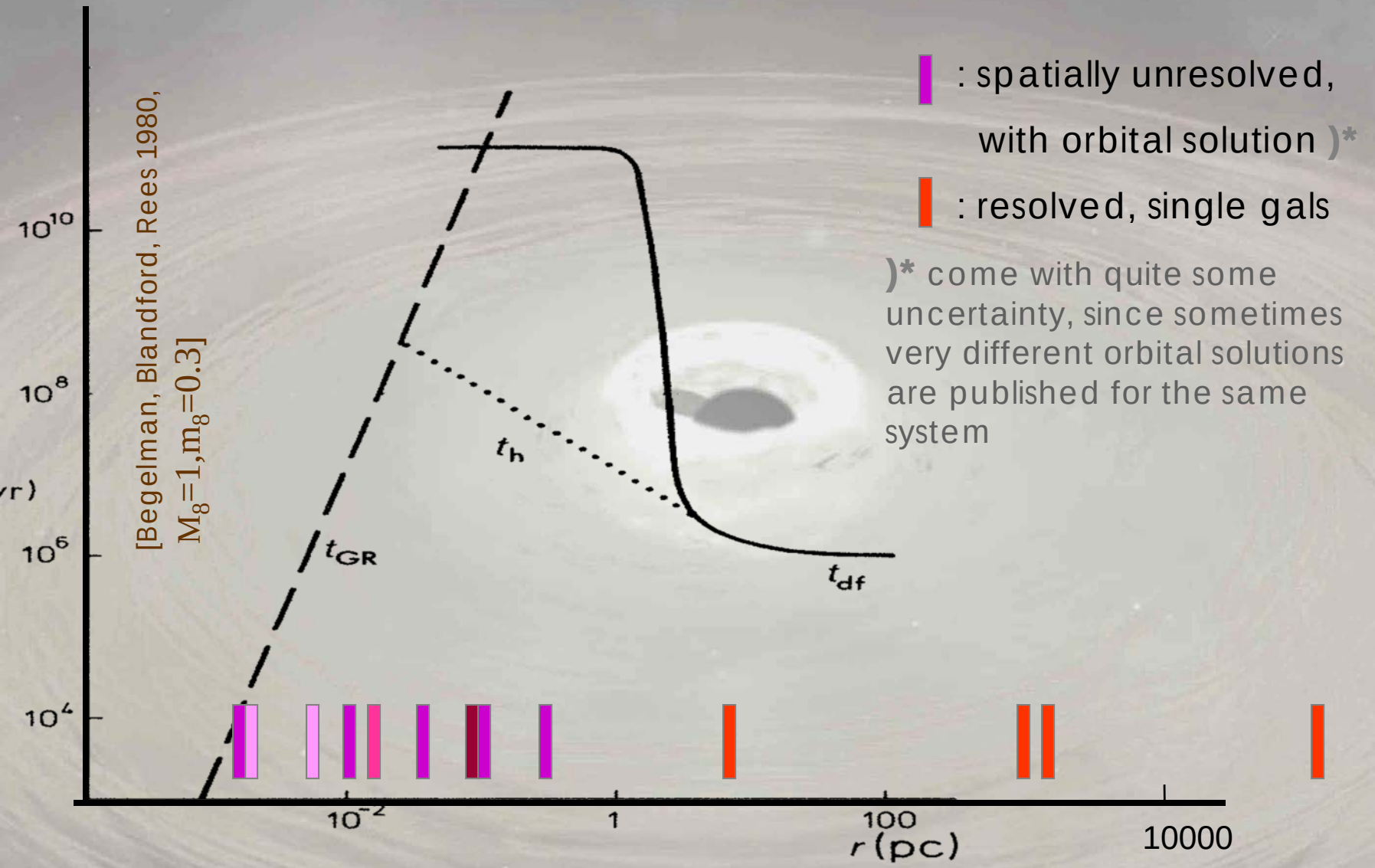
- **observation:** central mass deficits in luminous elliptical galaxies
  [e.g., Faber 97, Ravindranath et al. 02, Lauer et al. 02, Milosavljevic et al. 02, Graham 04, Kormendy & Bender 09]
- size of core, and central mass deficit, correlate with final BH mass

- **explained as**: BBH shrinks by ejecting stars, so the initial cusp is weakened, the core expands
  [e.g., Quinlan & Hernquist 97, Nakano & Makino 99, Milosavljevic & Merritt 01, Milosavljevic et al. 02, Merritt 06]





SMBBHs: summary of separations



: spatially unresolved, with orbital solution)*

: resolved, single gals

)* come with quite some uncertainty, since sometimes very different orbital solutions are published for the same system

future e.m. search for SMBBHs prior to, and quasi-simultaneous with, coalescence

- **wide pairs:**
  - radio, X-ray & optical imaging spectroscopy
- **close pairs:**
  - Fe-line spectroscopy and variability (IXO)
  - periodic shifts in radio position (space-VLBI)
  - acceleration of precession rate
  - t-dependent accretn signatures
- **non-active pairs:**
  - tidal disruption rate (dramatically enhanced rate, temporarily, when one BH refills loss-cone of the other) /accretion interrptn)

- **pre/post-coalescence:**
  - e.m. precursors or afterglows; e.g. when inner disk reforms
  - other effects (shocks in disk) related to recoil
  - GW heating of disk
  - GW emission itself

talks by Centrella, Liu, Haiman, Dotti, Cuadra

[e.g., Milosavljevic & Phinney 05, Armitage & Natarajan 02, Liu 03, Yu & Lu 02, Torres+ 04, Dotti+ 06, Kocsis+ 08, Shields+ 08, Liu & Chen 07, Tao+ 07, Hayasaki+ 08, Lippai + 08, Schnittman+ 08, Haiman+ 08, 09, Loeb 09, Palenzuela+ 09, van Meter+ 09, Megevand+ 09, Chen+ 09, Liu+ 09, ...]