The Jet Recollimation Shock: A Dramatic Altering of Jet Magnetic and Kinematic Structure On Difficult-to-Observe Scales

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Conclusions

- Launching, acceleration, & collimation are NOT the whole jet formation story

- It appears that in at least most strong AGN jets there is a significant feature/event in the propagation of a super-magnetosonic jet: a quasi-stationary (re-)collimation shock (RCS)

- The RCS appears to convert the pinch-unstable flow into a stable one that continues out to the ~100 kpc lobes

- This feature occurs on scales intermediate between black hole and lobes
  - It is very far from the BH in rg (104−6) but well within the galactic core
  - However, it is very difficult to distinguish on the sky from the BH itself:
    - Nearby (z ~ 0.1): 40 – 4000 μas (foreshortened blazar); 400 – 40,000 μas (if jet is in plane of sky)
    - Far (z ~ 1.0): 10 – 1000 μas (foreshortened blazar); 100 – 10,000 μas (if jet is in plane of sky)

- The RCS in M87 (HST-1) appears to be responsible for the jet "break" (cf. Nakamura)

- The RCS also may play an important role in the FR I / II dichotomy

- The only telescopes that can distinguish RCS activity from BH activity are: the EVN (>5000 μas), the VLBA (>100 μas), and the EHT (> 10 μas)

- VLBI IS ABSOLUTELY CRUCIAL TO UNDERSTANDING JET FORMATION

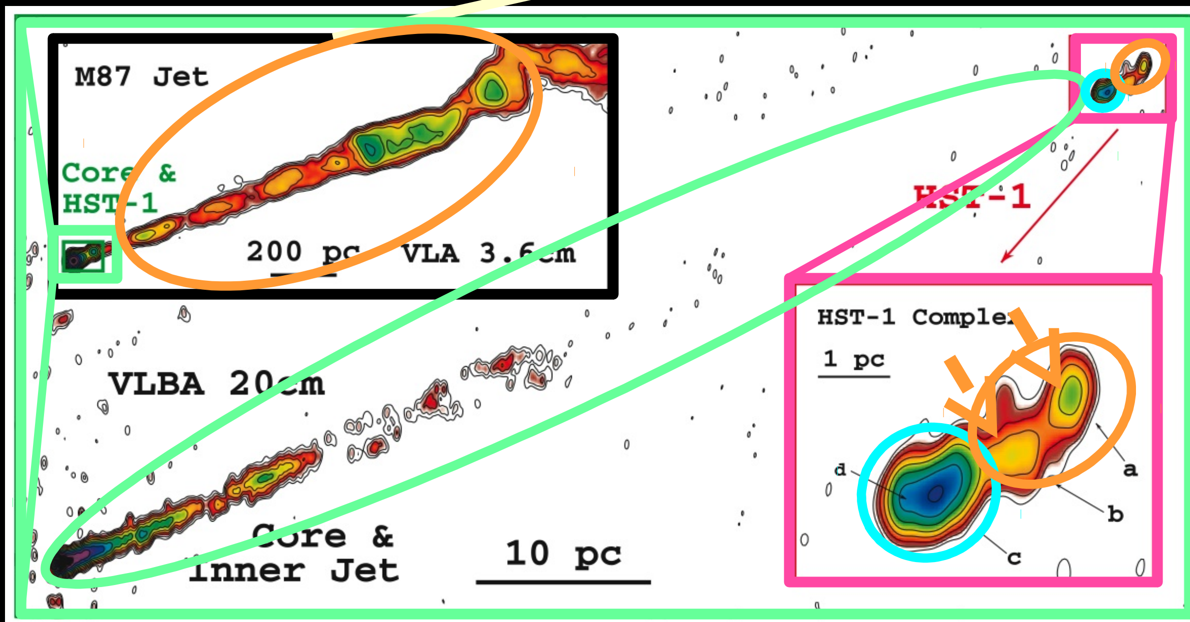
M87: The Rosetta Stone

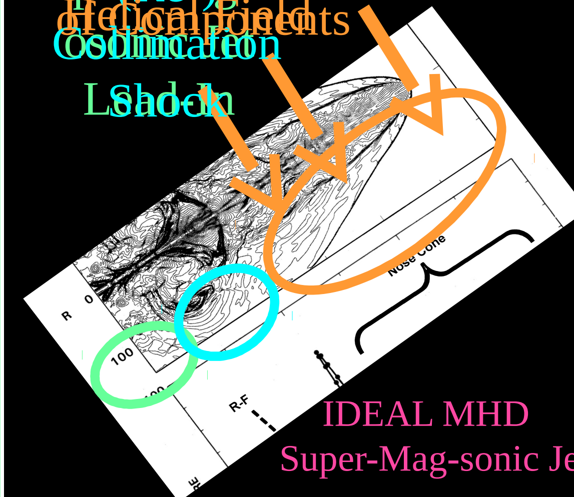
M 87
VLA & VLBA
(Cheung, Harris, Stawarz 2007)

Standard VLA View

VLBA Blowup of Core & HST-1 Region

Trans-Magnetoso





IDEAL MHD
Super-Mag-sonic Jet

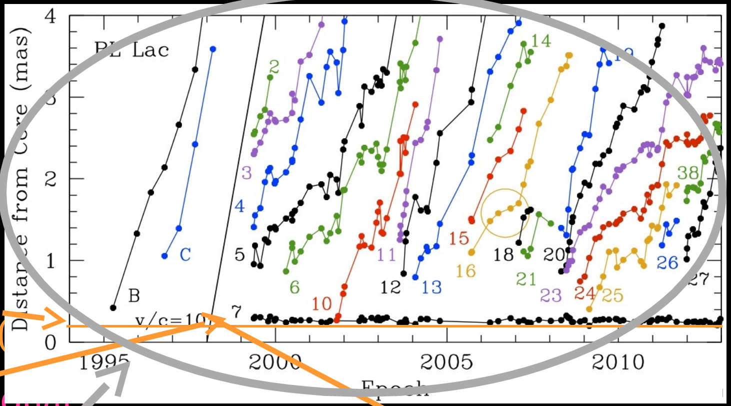
Lind, Payne, dlm, & Blandford (1989); Komissarov (1999) also Nakamura & dlm (2014)

- Similar recollimation shock systems are seen in other BL Lac / FR I-type sources (BL Lac, OJ 287, 3C 120, *etc*.)
- IDEAL MHD flow of a super-magnetosonic jet, without Ohmic dissipation, seems to be a good model for flow near FR I (BL Lac) recollimation shocks

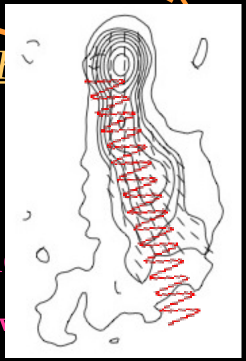
BL Lac: Confirmation of RCS (Quasi-) Stationarity (Cohen, dlm, et al. 2014)

- BL Lac *vs.* M87
  - Smaller black hole ([~0.1– 0.3 *vs.* ~6] × 109 M⦿)
  - Pointed more toward Earth (~6° *vs.* 14° to line-of-sight)
  - Further away (~270 *vs.* 15 Mpc [ang. size distance])

  ⇒RCS should be ~0.3 pc from BH or ~ 0.2 mas from core (
  - Of all BL Lac components, only C7 & core are statio
  - Moving components emanate from C7 (not the core), *like HST-1*
  - So, we suggest that C7 is the BL Lac jet recollimation shock, *just like H*



Cohen & the MOJAVE VLBA team (2014)



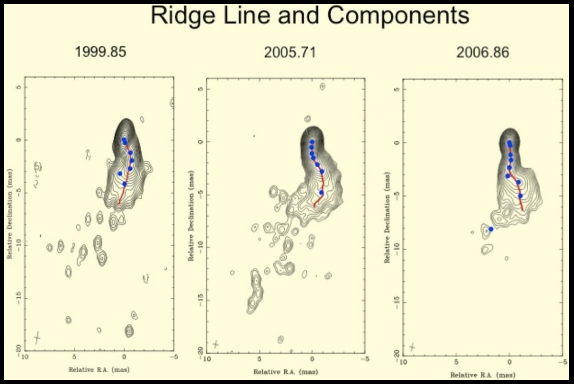
Electric Vector Polarization Angle plot

- The Post-RCS Jet ("current-carrying")
  - EVPA is primarily longitudinal in BL Lac (objects) ⇒X-verse magneti
  - Fractional polarization increases with distance from core ⇒conical flo

- The Moving Components in BL Lac
  - All are relativistic (2c < *V*app < 10c)
  - We modeled the slowest component as a slow MHD wave and fastest as a fast MHD wave
  - Assuming *V*S ~ 0 in jet frame, we find ΓFjet ≈ 1.7 in jet frame and Γjetgal ≈ 3.5, *in galaxy frame*
  - This model does not allow us to determine relative magnetic field strength, VA or ems in jet frame, but Γjet results similar to Nakamura's HST-1 simulations

ALL VLBA DATA

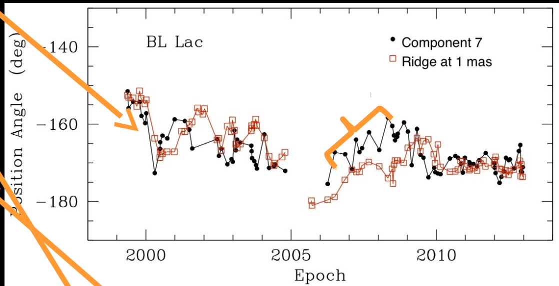
BL Lac: Confirmation of Strong Helical Magnetic Field In Post-RCS Flow (Cohen, dlm, et al. 2015)



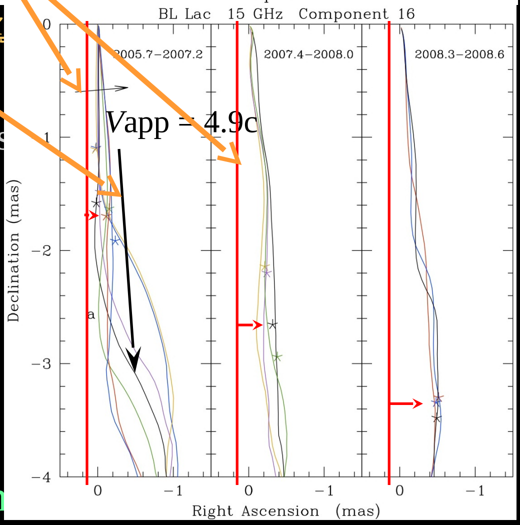
- BL Lac displays RELATIVISTIC Transverse Waves !!
  - Wiggles that propagate down the jet with time
  - These waves seem to be generated by transverse shifts in the RCS *w.r.t.* the core and, hence, in the inner jet position angle
  - Speed of the wave is between slowest & fastest components:

    2c < [Vapp,wave = 4.9c] < 10c

    - Moving components (e.g., C16) is drawn aside by wave
      - Components are not ballistic "blobs"



- We modeled the transverse waves as Alfven waves on
  - Specific model:
    - *Vjet* ~ cms (trans*magneto*sonic flow; *cf.* LPMB, Bicknell) *in galax*
    - *Vwave* = *VA* cos χ in jet frame (*i.e.*, assume helical field)
    - Slowest & fastest components are cs cos χ & *VF* in jet frame, res
  - Model results: Γjetgal ≈ 2.8 *in galaxy frame;*
    - In jet frame cs = 0.3c, *VA* = 0.857c, cms = 0.870c, *M*ms = 1.5, χ =
    - *VS* = 0.22c (ΓSjet ≈ 1.025)
    - *V*wave = 0.63c (Γwavejet ≈ 1.29)
    - *VF* = 0.86c (ΓFjet ≈ 2.0)
  - NOTE: pitch angle derived from MHD wave models (43°) is sm than derived from BL Lac pol obs (>60°), but this implies *M*ms ~ 5



ALL VLBA DATA

What Would Cause a Recollimation Shock to Form So Far from the Black Hole?

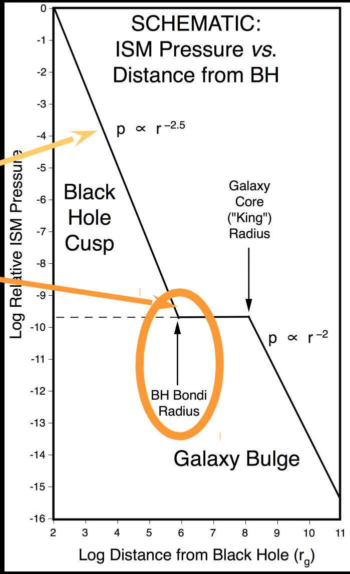
- External collimation: change in ISM pressure profile at BH Bondi radius (Asada & Nakamura 2012; Nakamura & Asada 2013)
  - Jet accelerates & collimates in a decreasing BH cusp pressure gradient
  - Near the Bondi radius, jet enters uniform pressure region and overcollimates
  - Problem?: FR II-type RCSs may occur 100x closer than rB (Cohen et al. 2014)

Table 2
Distance to Recollimation Shock

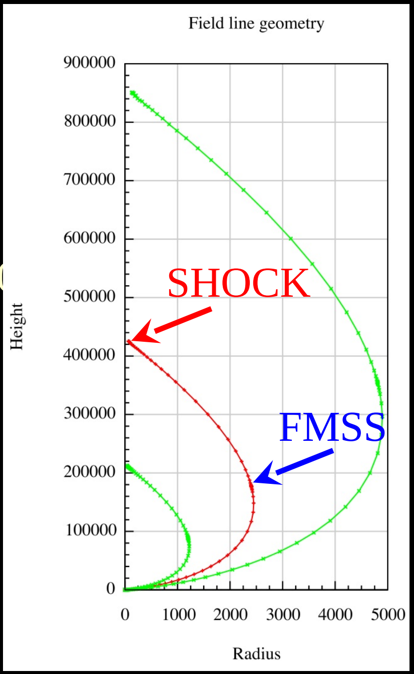
Name	z	Class	pc/mas	theta	Dist to Shock	log M_{BH}	log R	Ref.
BL Lac	0.0686	BLL	1.29	6	0.26	8.2	5.6	1, 2
M87	0.00436	FR I	0.08	13	860	9.8	5.7	1, 3, 4
3C 120 S1	0.033	FR I	0.65	16	0.7	7.8	5.7	5, 6
3C 120 C80	...	...	...	...	80	...	[illegible]	6, 7
3C 273	0.158	FSRQ	2.70	6	0.15	9.8	4.1	8, 9
3C 390.3 S1	0.0561	FR II	1.09	50	0.28	8.6	4.3	10, 11

FR I-type

FR II-type



- Self-collimation: magnetic focusing beyond the Fast Magnetosonic Separatrix Surface (Achterberg, Blandford, Goldreich 1983; Vlahakis *et al.* 2000; Polko, dlm, Markoff 2010, 2013, 2014)
  - Specific model: self-similar axisymmetric relativistic MHD, with 3 critical points applied (Alfven, modified fast [FMSS], modified slow [SMSS])
  - Requiring an FMSS (magnetosonic horizon) produces jet focusing
- More careful measurements of BH – RCS distances are needed in many AGN in order to understand the over-collimation mechanism



Polko et al. (2010,13,14)

Length Scales of ~rB and 10^4.2 rg are Difficult to Discern in AGN

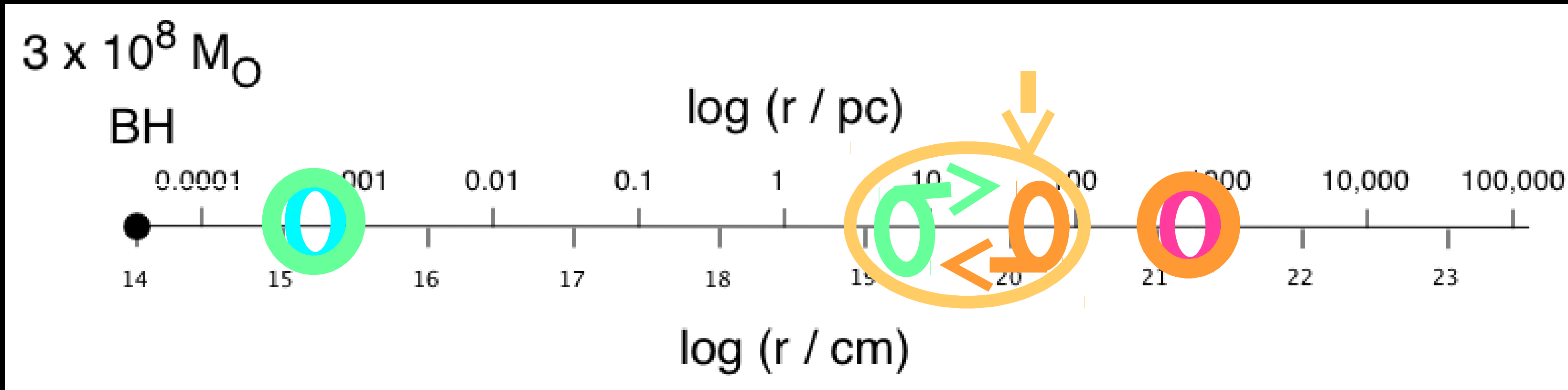
- EXAMPLE: 10^9 M$_\odot$ black hole
  - Case 1: $r_{RCS} \approx r_B \approx 84$ pc ⇒ mas separation (certainly FR I / BL Lacs; maybe FR II also)
    - Nearby ($z = 0.1$): 45 mas (jet in plane of sky) ⇒ < 5 mas (foreshortened in blazar)
    - Far ($z = 1.0$): 10 mas (jet in plane of sky) ⇒ ~ 1 mas (foreshortened in blazar)
  - Case 2: $r_{RCS} \approx 10^{4.2}\ r_g = 0.75$ pc ⇒ μas separation (maybe some/all FSRQs & FR IIs?)
    - Nearby ($z = 0.1$): 400 μas (jet in plane of sky) ⇒ 40 μas (foreshortened in blazar)
    - Far ($z = 1.0$): 90 μas (jet in plane of sky) ⇒ 9 μas (foreshortened in blazar)

- *** Most Telescopes Cannot Distinguish Between BH and RCS activity ***
  - Fermi LAT: angular resolution ~ 10^{6-7} mas
  - NuSTAR / PolSTAR (X-Calibur) ~ 10^{4-5} mas
  - HST / JWST ~ 50 – 100 mas
  - ALMA ≥ 5 mas

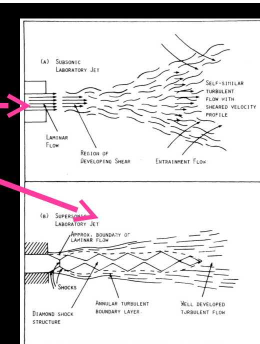
- Only VLBA, maybe EVN, and eventually EHT
  - EVN ≤ 0.5 mas
  - VLBA ~ 0.1 mas (super-resolution mode; $\delta\theta \sim [S / N]^{-1/2}$)
  - EHT ≤ 10 μas

- In order to identify where the source activity is occurring, *** Most Telescopes will Need to Correlate Time-Dependent Activity with VLBA or Other VLBI Telescope Images ***

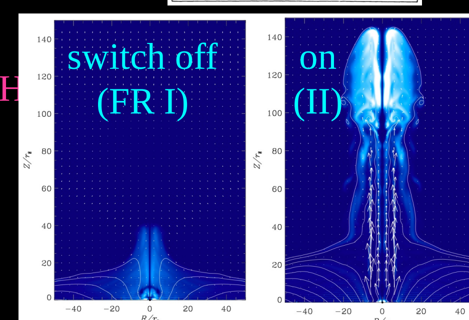
Where in its Travels Does a Jet Decide to be an FR I or II?



- Bicknell (1985, 1995) identified
  - FR Is as tran*sonic* jets that decelerate
  - FR IIs as super*sonic* jets that continue so out to the hot spots and radio lobes
  - Geoff put the radius where this occurs at ~600 pc (galaxy "core" radius)

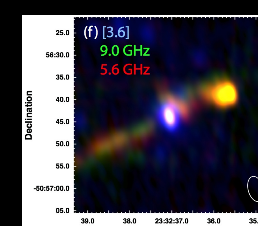


- But, unified schemes (Urry & Padovani 95) indicate that (at low-mid redshift)
  - FR Is (> kpc scale) = BL Lacs (10-100 pc scale, deprojected)
  - FR IIs (> kpc scale) ≈ FSRQs (10-100 pc scale, deprojected)
  - ***So, jets know they will be an FR I or FR II < 10-100 pc from the BH



- Meier et al. (1997) suggested the "magnetic switch" mechanism
  - Like an "Eddington limit" for magnetic fields
  - Occurs in inner accretion disk at ~10-20 rH (< 10–3 pc)
- Gopal-Krishna & Wiita (2000): the HYMOR test
  - HYbrid MORphology objects have one FR I jet & one FR II jet !
  - Such sources appear to exist for ≥ (jet travel time to the lobes) ≈ 3 x 105 yr.
  - Time for galactic ISM weather to alter the 2 jets should be τweather ≥ 10 τdyn = r
  - At 10-20 rH, 10 τdyn ~ 6 wks! So, magnetic switch cannot be FR I / II process

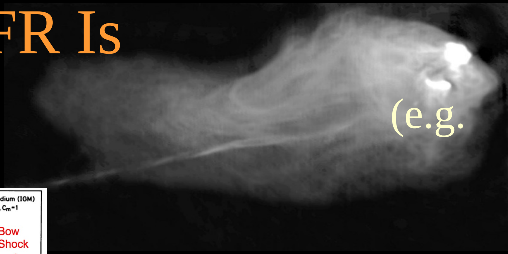
Tsai et al. (2013)



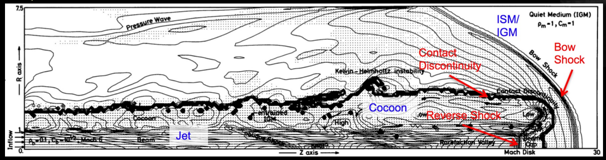
How Could RCS Determine FR I / II Nature?

Application of RESISTIVE MHD to FR II (FSRQ) Sources

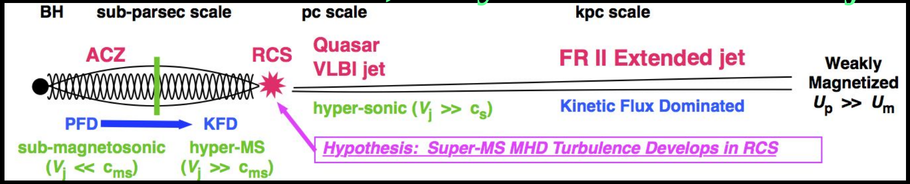
- Magnetic Properties of FR II Sources Differ from FR Is
  - FR II morphology can be reproduced with HD alone (e.g. Blandford & Rees 1974; Norman *et al.* 1982)



Cygnus A with VLA (Dreher *et al.* 1987)



  - More importantly, FR II Hot Spots are weakly magnetized (Werner, Murphy *et al.* 2012) $P_{mag} = B^2 / 8\pi \sim 1\% \; P_{plasma}$
  - If FR II jets are launched like FR Is, why are FR II outer jets de-magnetized?



- Hypothesis: Very Powerful (FR II) Sources Develop Super-magnetosonic MHD Turbulence in the Recollimation Shock (dlm 2013)
  - Super-MS Turbulence has a very fast magnetic field reconnection rate (Lazarian & Vishniac 1999)

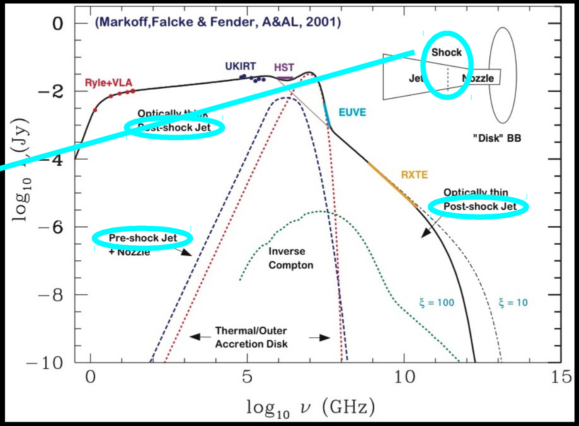
$$t_{recon} / t_{flow} \sim M_{jet} / M_{turb}^2 \ll 1$$

    - Resistivity reconnects and dissipates magnetic field into HEAT in RCS

Other Types of Jetted Sources

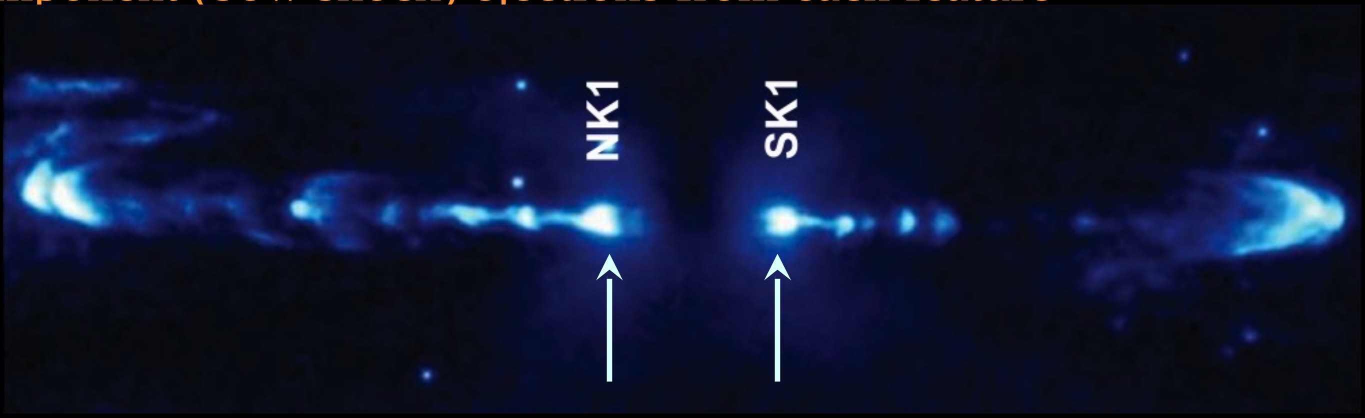
- GRBs: Dissipation in shocks below GRB photosphere (Bromberg 2011; Levinson 2010, 2012)

- X-ray Binary Jets: Models of broad-band emission require a strong shock after jet collimation (Markoff *et al*. 2001 *etc*.)



- Protostellar Jets: HH 212 shows (Correia et al. 2009):
  - (Non-relativistic) pair of strong shocks flanking central source
  - Multiple component (bow shock) ejections from each feature

Correia *et al*. (2009)



Conclusions

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