MHD Effects at the Jet Base:

from YSOs to BHs

Elisabete M. de Gouveia Dal Pino
(IAG-USP)

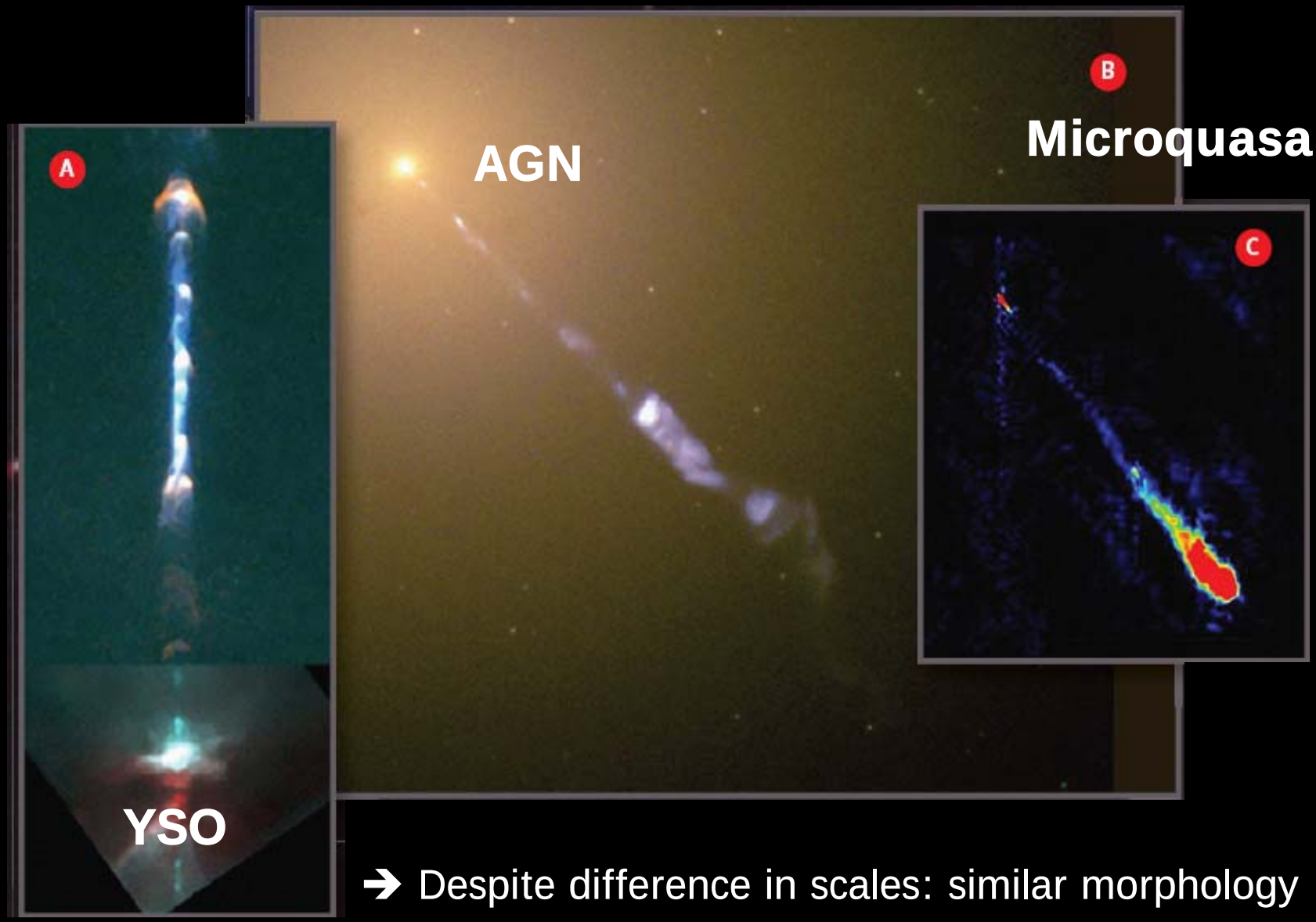
Pamela Piovezan (IAG-USP, MPI-Garching)
Luis Kadowaki (IAG-USP)
Grzegorz Kowal (IAG-USP)
Alex Lazarian (University of Wisconsin)

HERPRO II, Buenos Aires, 2009

JET UBIQUITOUSNESS

- YSOs
- Microquasars and X-ray binaries
- AGNs
- GRBs

ASTROPHYSICAL JETS

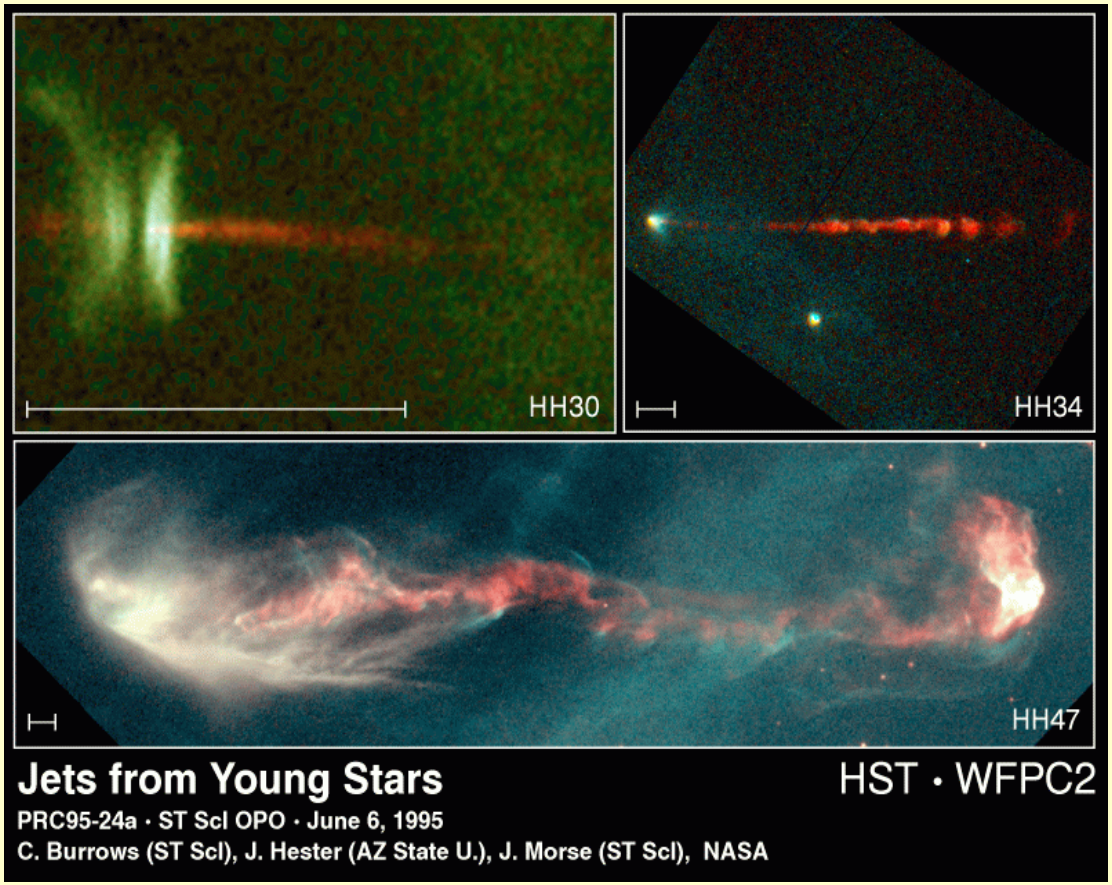


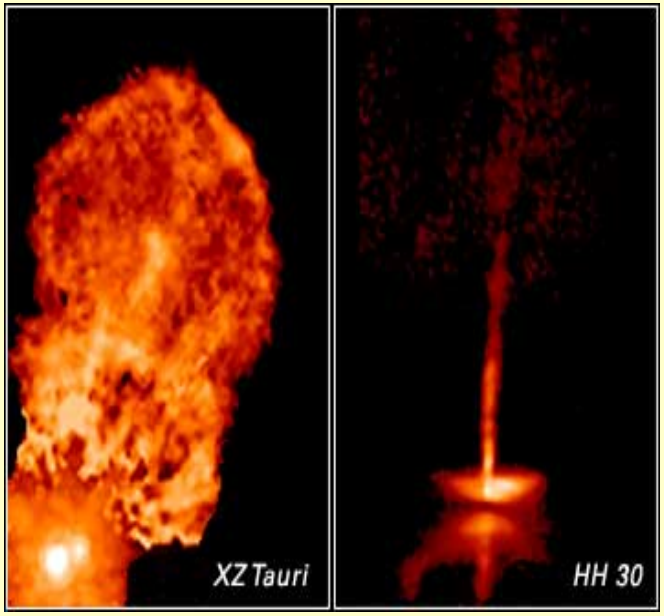
➔ Despite difference in scales: similar morphology

JET UBIQUITOUSNESS

- **GRB, AGN & microquasar jets**: relativistic, chemical composition uncertain (p, e-, e+ ?), light ($\rho_j/\rho_a < 1$)
- **YSO jets**: thermal, forbidden spectral lines, chemical composition known, heavier ($\rho_j/\rho_a > 1$)
- **Despite differences**: similar morphology suggests common mechanism(s) for jet launching
- **YSO jets regarded as excellent laboratories** for jet investigation: numerous & larger proximity (star forming regions)

YSO JETS IN CONTEXT





extension ≤ 1 pc

Source: low mass stars ~1 solar mass

Emitting matter (optical, IR): spectral lines produced by shocks give information on local temperature, density, and jet velocity:

$1\text{-}2\times10^4$ K , $10\text{-}10^5$ cm^{-3}, 100-500 km/s

YSO JETS IN CONTEXT

Key Questions:

- **Small scale < 10 AU**: **Jet launching**
  Is jet rotating? What is the origin of jet knots?

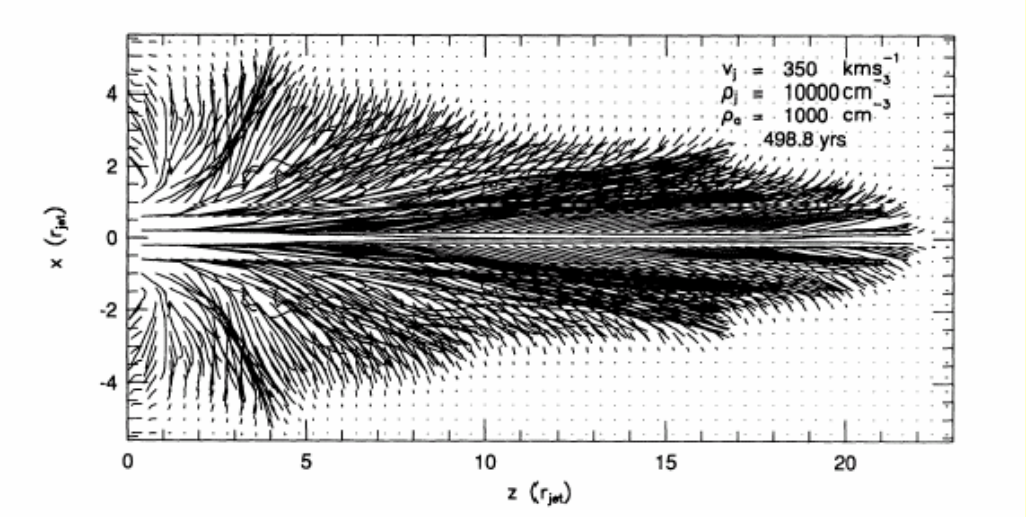
- **Medium scale 10 AU - 1pc**: **Jet propagation**
  How is the jet stabilized?

- **Large scale 1000 AU - 10 pc**: **Interaction with ambient cloud**
  Are jets able to sustain turbulence in molecular clouds?
  Jet feedback on star formation?
  Debating questions

YSO JETS IN CONTEXT

✓ **Large scale 1000 AU - 10 pc**:
Can jets sustain turbulence in molecular clouds?
Debatable !

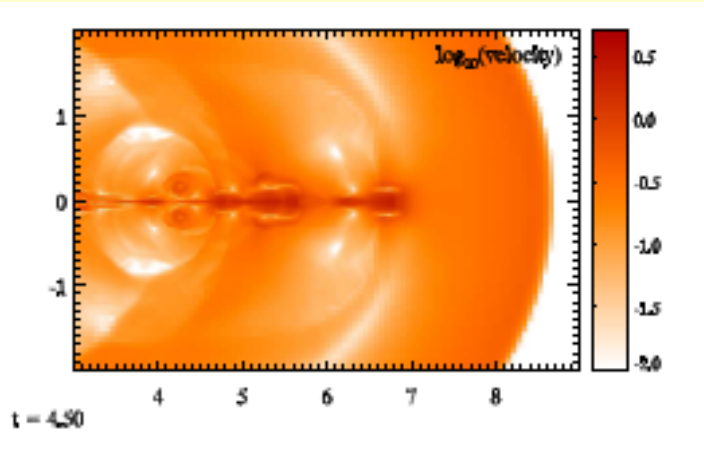
- **Since prompt momentum deposition by bow shock**

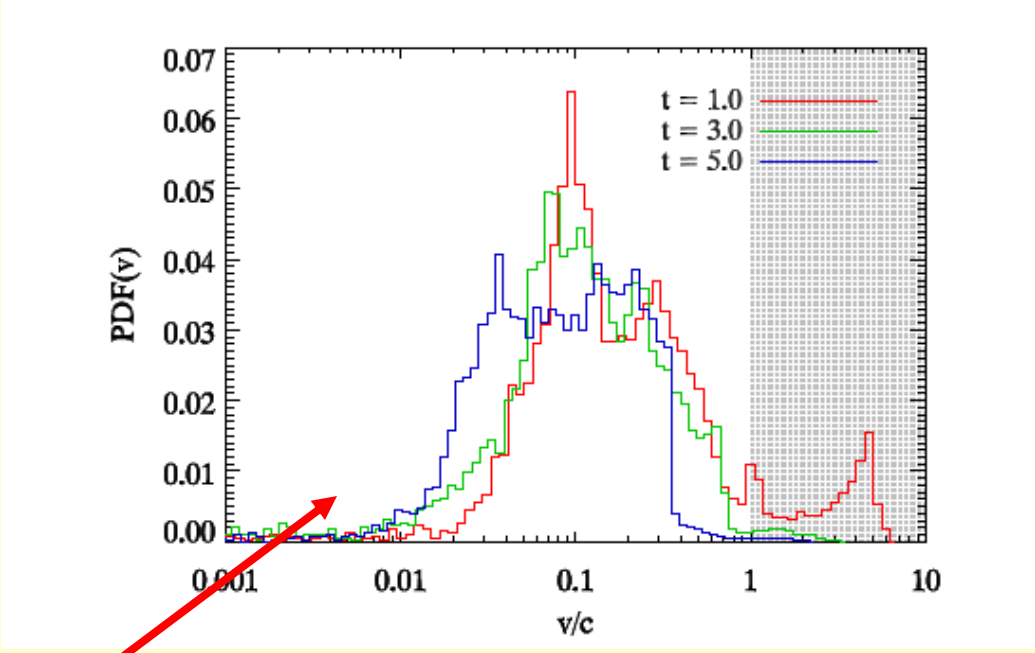


Chernin, Masson, <u>de Gouveia Dal Pino</u>, Benz 1994

YSO JETS IN CONTEXT

Can jets sustain turbulence in molecular clouds?





Banerjee et al (2007): *NO!*

velocity probability density functions: supersonic fluctuations damped quickly and do not spread into the parent cloud

YSO JETS IN CONTEXT

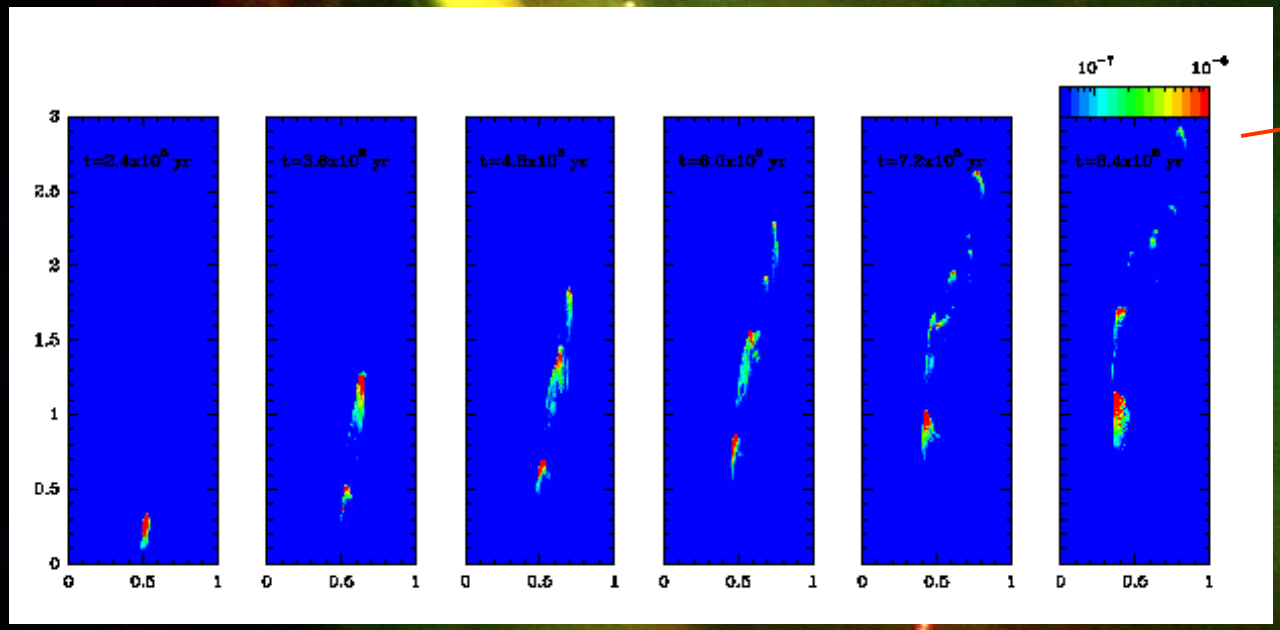
Can jets sustain turbulence in molecular clouds?

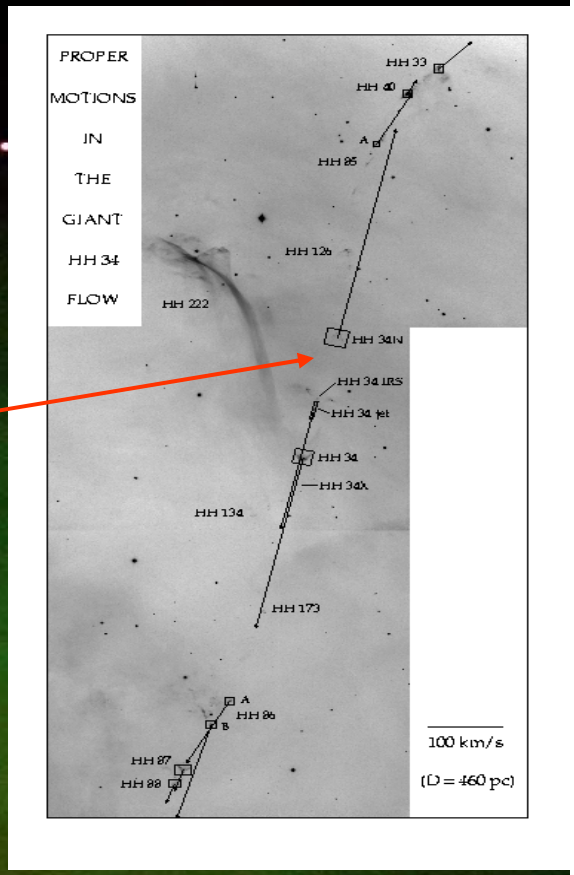
Frank et al: ***YES!***

multiple jets can drive turbulence in initially quiescent media with mean turbulent velocity > 5 times the sound speed (Carroll & Frank 2007; Cunningham et al. 2007, Frank 2009)

PROPAGATION EFFECTS: STABILITY

In **YSO jet HH34**: precession θ_p ~ 6º and P ~ 3170 yrs





Masciadri, de Gouveia Dal Pino, Raga & Noriega-Crespo 2002

YSO JETS IN CONTEXT

Key Questions:

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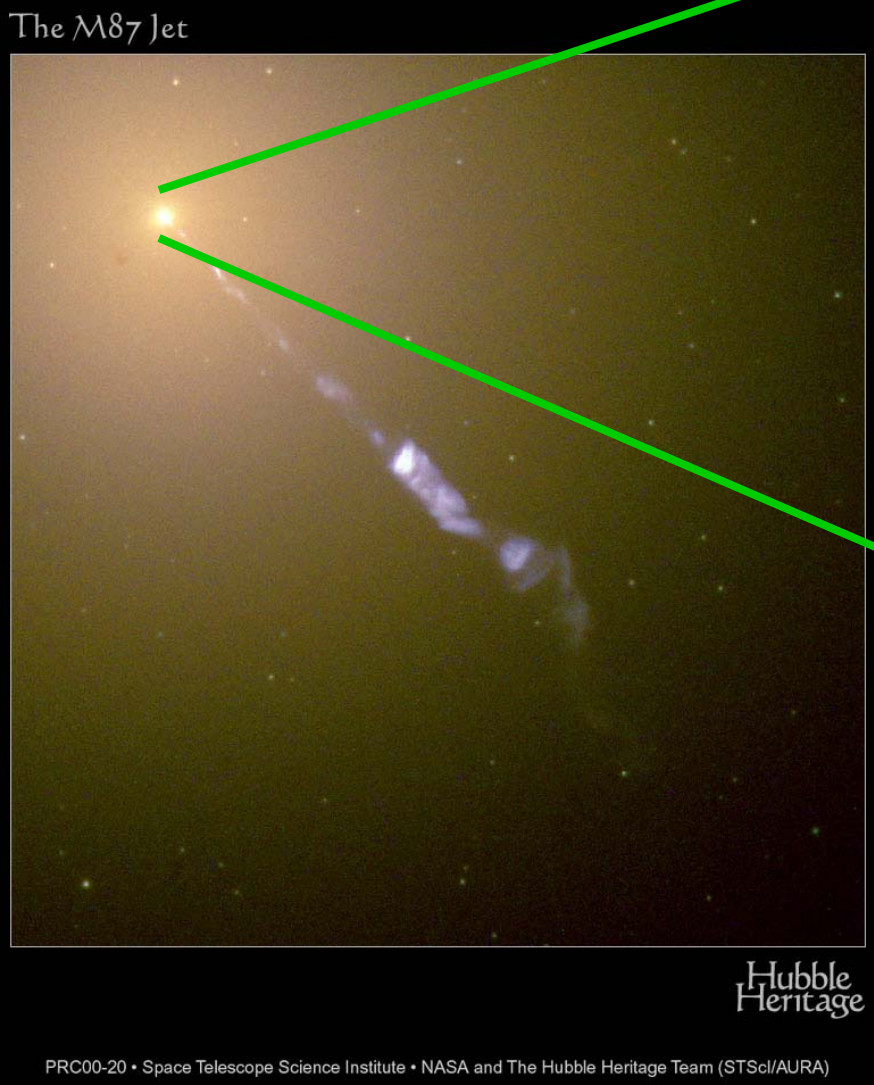
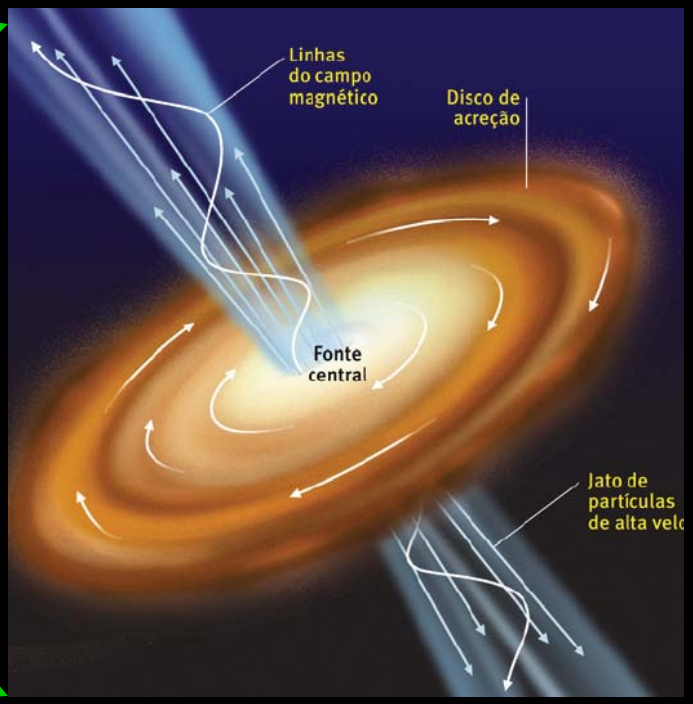
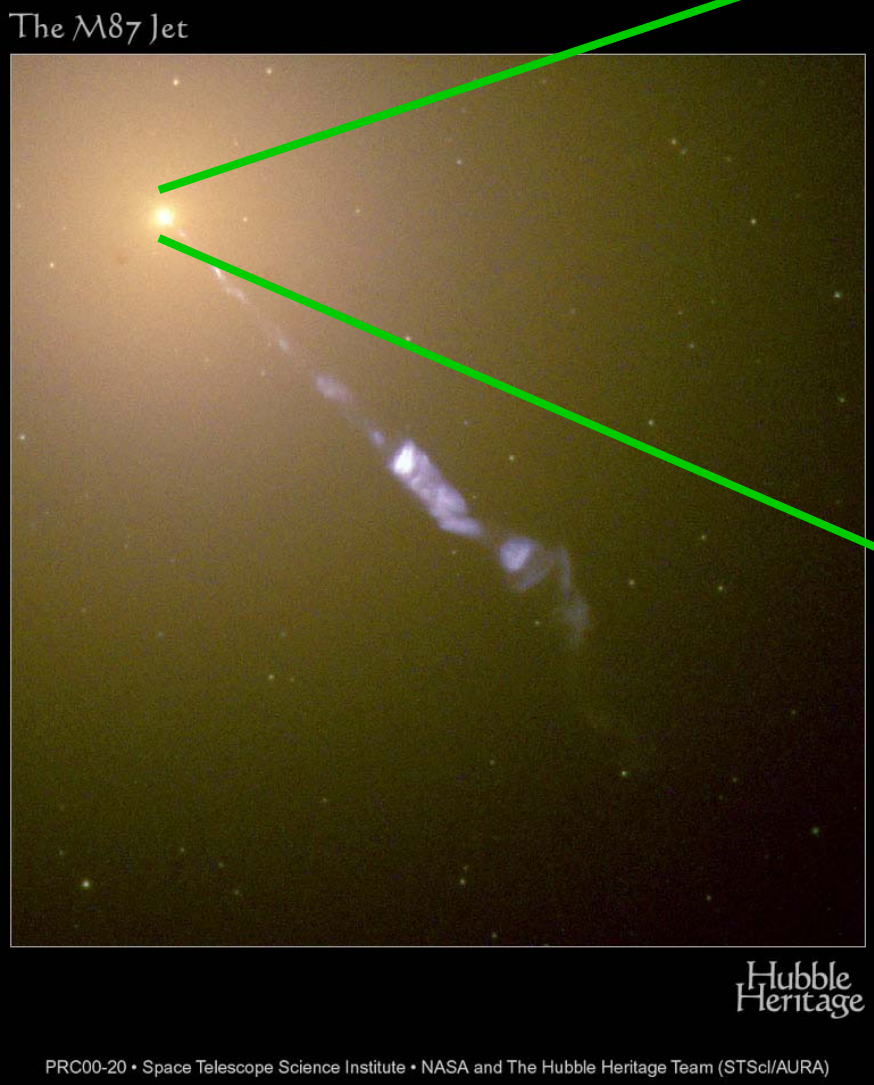
CURRENT FAVOURED MODELS FOR JET ORIGIN?

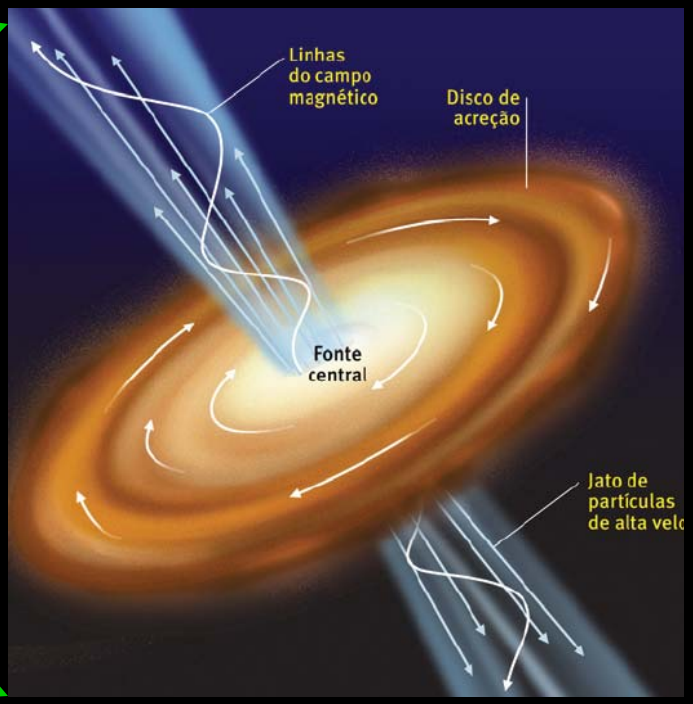




Magneto-centrifugal acceleration out off accretion disk around the source **(Blandford & Payne 1982)** with **B** generated in the disk by MHD turbulence and differential rotation **(Balbus & Hawley 1998)**

CURRENT FAVOURED MODELS FOR JET ORIGIN?





This model does not explain:

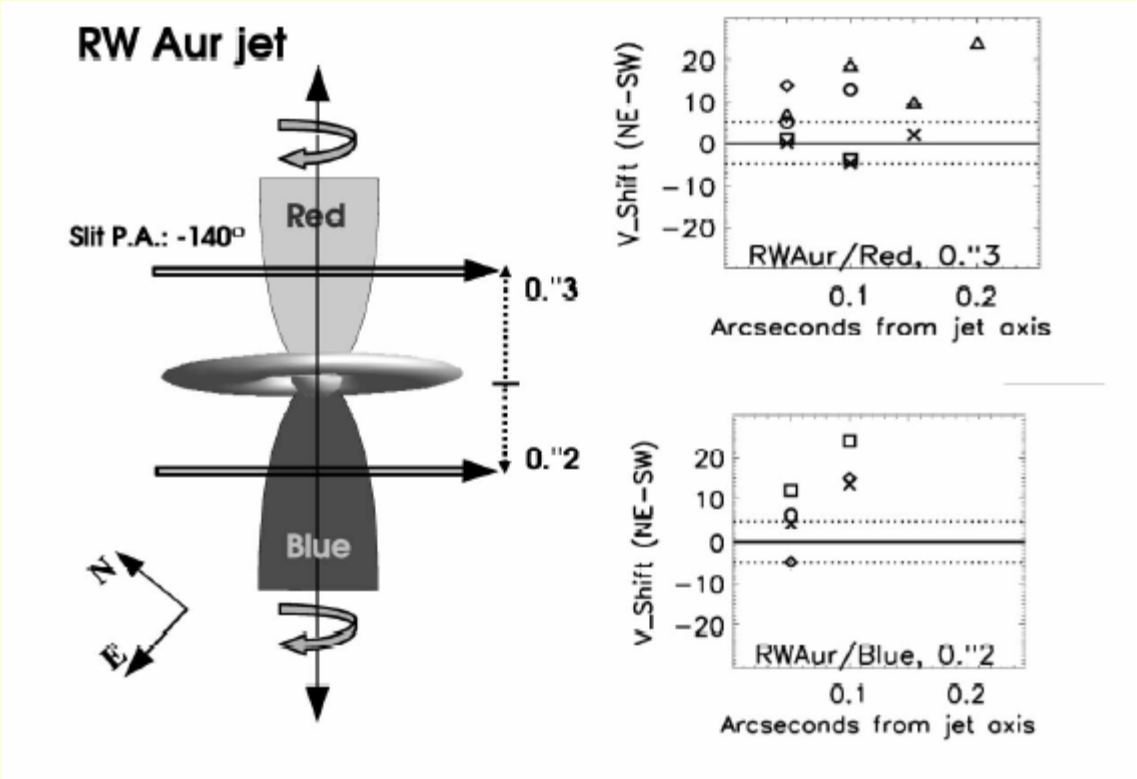
- the nature of the **coupling** between the central source **"magnetosphere" and the disk field lines**

- the **quasi-periodic ejections** that are often associated to these jets

YSO JETS - LAUNCHING

Is jet rotating? (probe magneto-centrifugal mechanism)

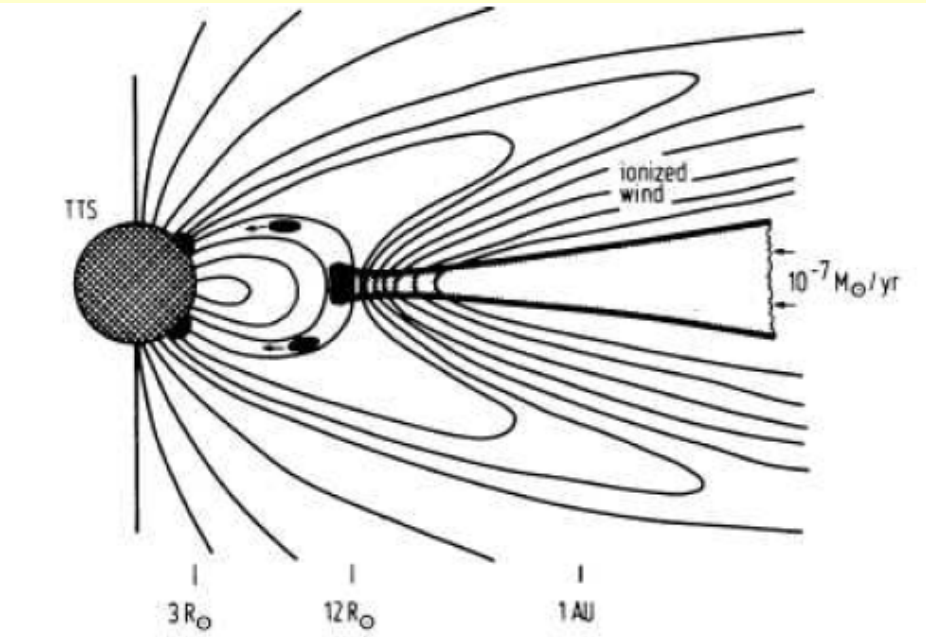
- **Doppler shift asymmetries**: produced by non-rotating precessing jet (Cerqueira et al. 2007) or from interaction of the jet with circumstellar gas (Soker 2009)
- **Jets *do* rotate**, but at << velocity (Soker 2009)
- Wait for **ALMA & LLAMA**



Velocity asymmetries of 10-25 km/s at few 10 AU (Bacciotti et al. 2002)

YSO JETS - LAUNCHING

Nature of Star-Disk Interaction ?



Observational evidence of **dynamical time variable accretion** governed by changes in B

(Alencar, Johns-Krull & Basri 2001; Bouvier et al. 2005; Alencar et al. 2007)

Magnetospheric accretion in funnel flows:
explains main observed characteristics of (T Tauri) YSOs (Camezind 1990)

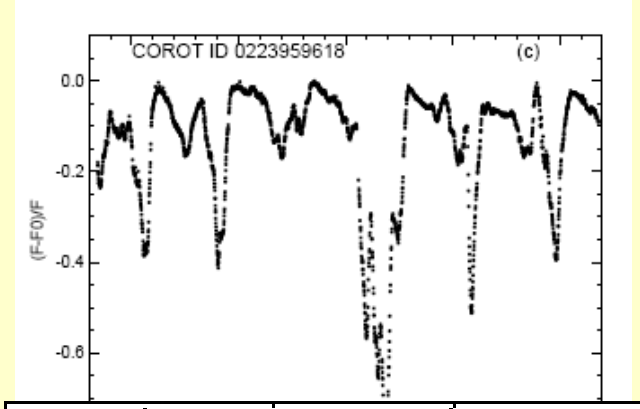
YSO JETS - LAUNCHING

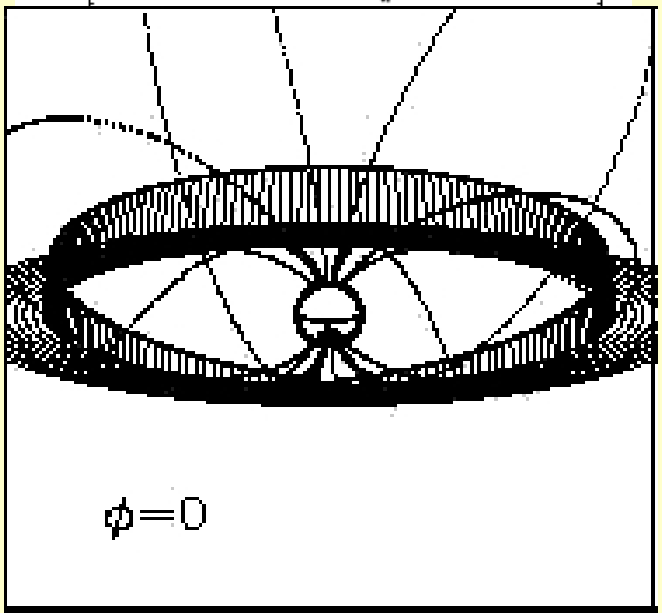
Nature of Star-Disk Interaction ?

Corot light curves + Spitzer data of T Tauri stars (Alencar et al. 2009):

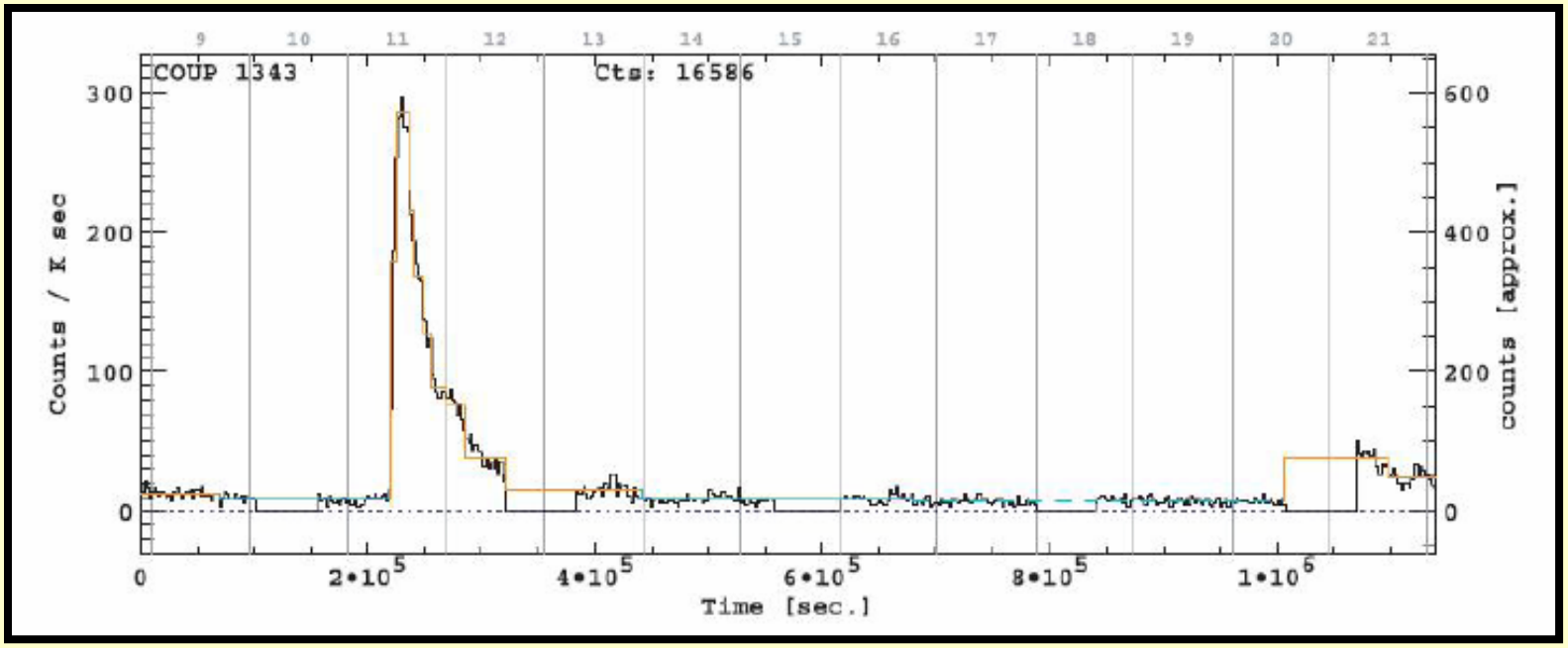
optical variability due to warp disk obscuration

Warp is due to interaction of the disk with inclined stellar field (with respect to rotation axis)





X-RAY FLARES IN YSOS



X-ray flare in YSOs: COUP (Chandra Orion Ultra-deep Project) source (Favata et al. 2005; Bonito et al. 2009)

X-ray flares: often attributed to magnetic activity at stellar corona (e.g. Feigelson & Montmerle 1999)

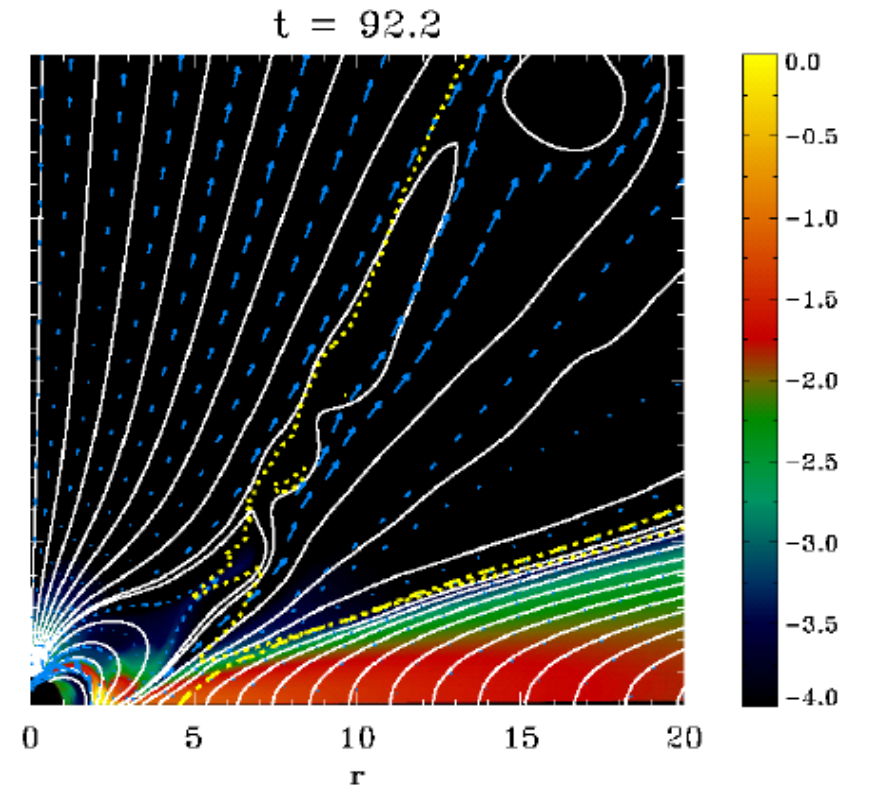
COUP sources: peculiar gigantic magnetic loops $l > R_*$ ➔ link magnetosphere with accretion disk (Favata et al. 2005)

YSO JETS - LAUNCHING

Nature of Star-Disk Interaction ?

Closed stellar field lines anchored beyond corotation inflate and open up: reconnection and plasmoid ejection along current sheet

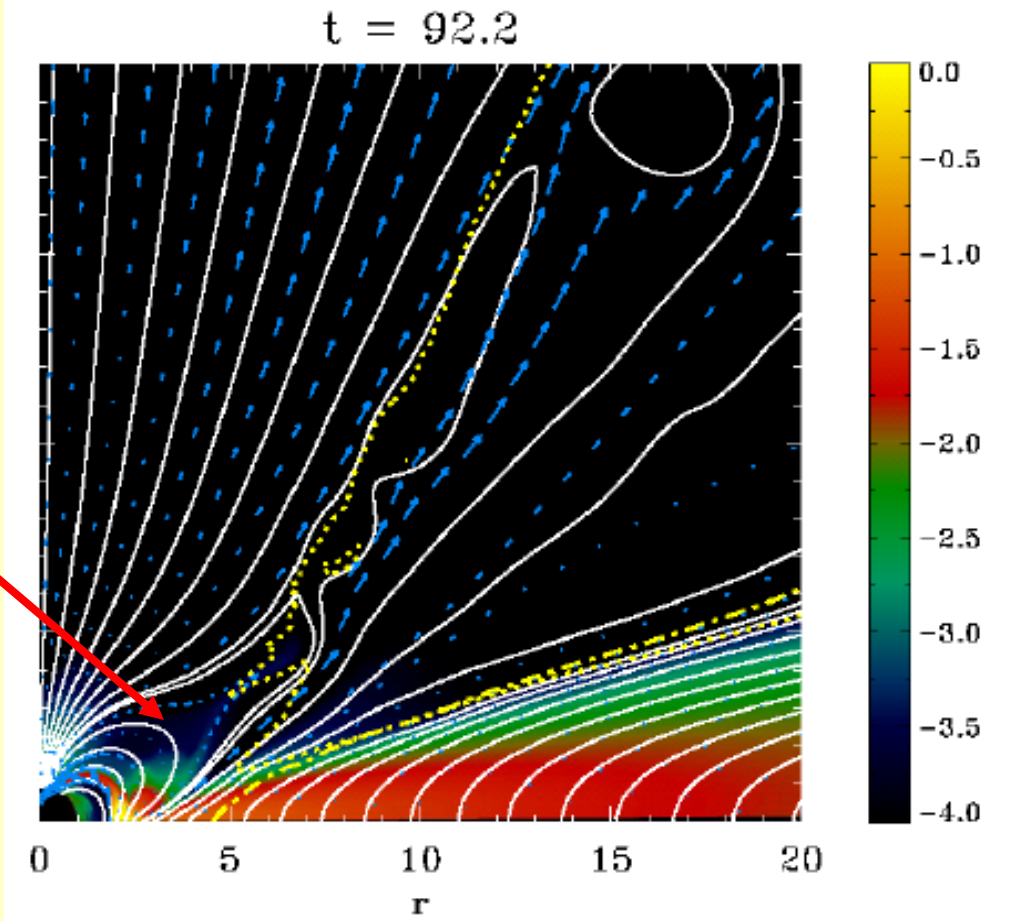
(e.g., Goodson & Winglee 1999, Zanni 2009)



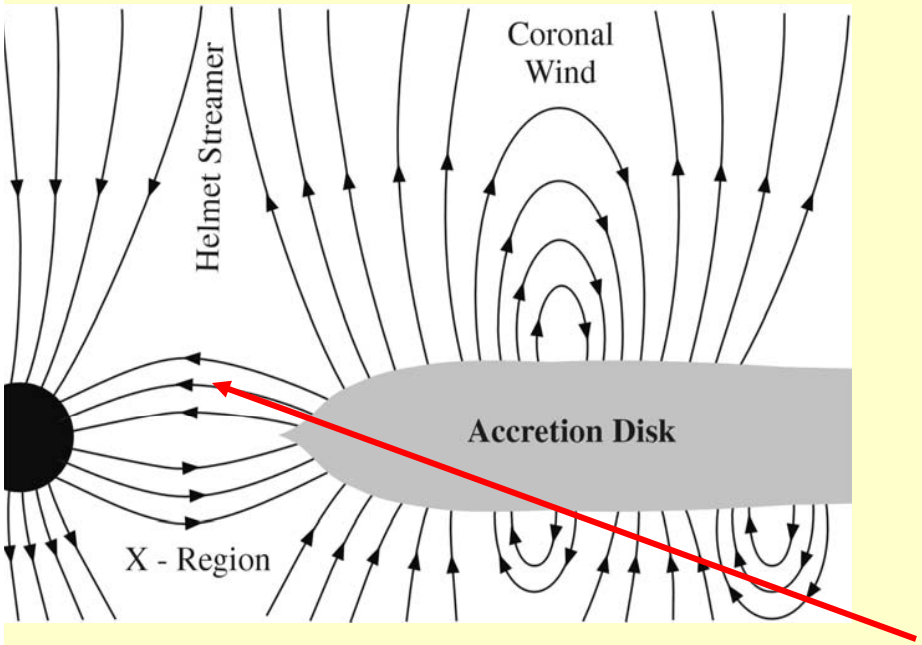
Density and B: $\nu/\eta=10$, $\alpha=\nu/c_s h=1$, $B_*=800$ G, $\Omega_*=10\%$ Kepler (Zanni 2009)

X-RAY FLARES IN YSOS

Episodic violent magnetic reconnection?



X-RAY FLARES IN YSOS



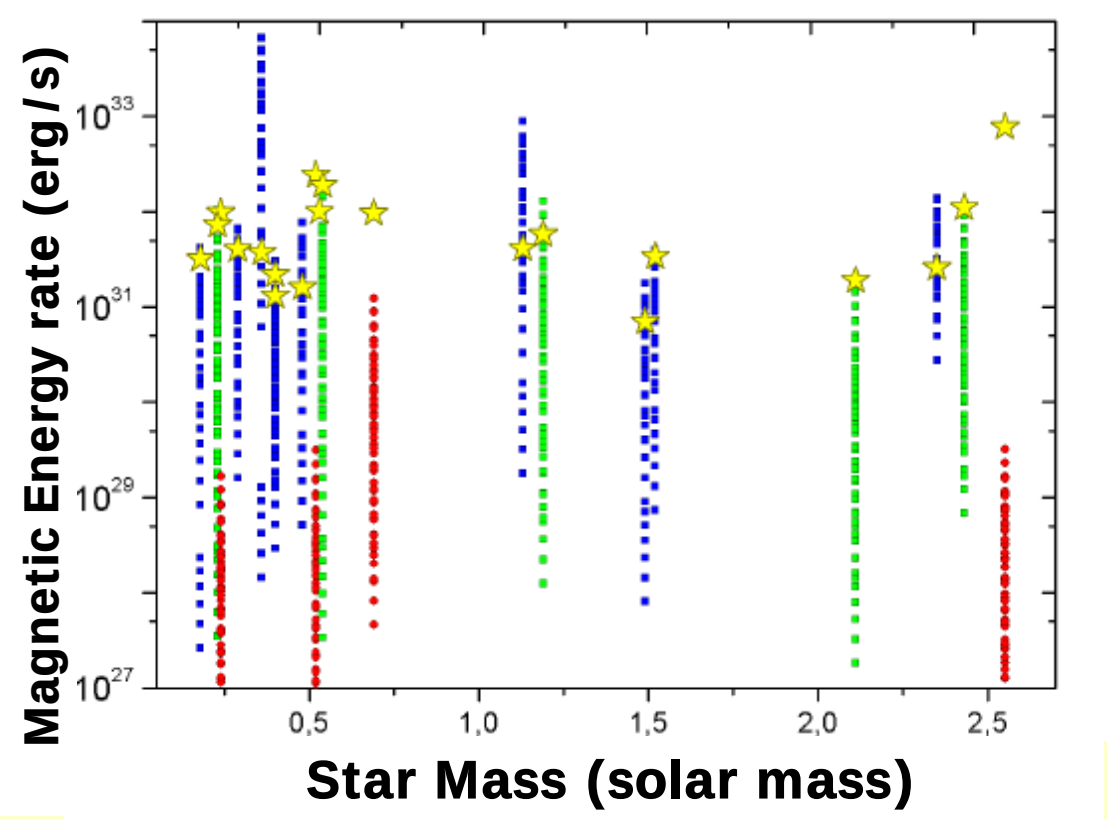
de Gouveia Dal Pino, Piovezan, Kodowaki 2009a, 2009b

X-ray emission connection with magnetic reconnection (Shu et al. 1997)

HH 154: optical knot at the base of the jet coincident with the X-ray source (Bonito et al. 2009)

We examine role of reconnection in the inner disk/corona to explain X-ray flares in the COUP sources

X-RAY FLARES IN COUP YSOS



Yellow Stars: COUP sources

Blue: dM/dt = 0.5-1 x 10^{-4} M_{sol}/yr

Green: dM/dt =2.5-5 x 10^{-4} M_{sol}/yr

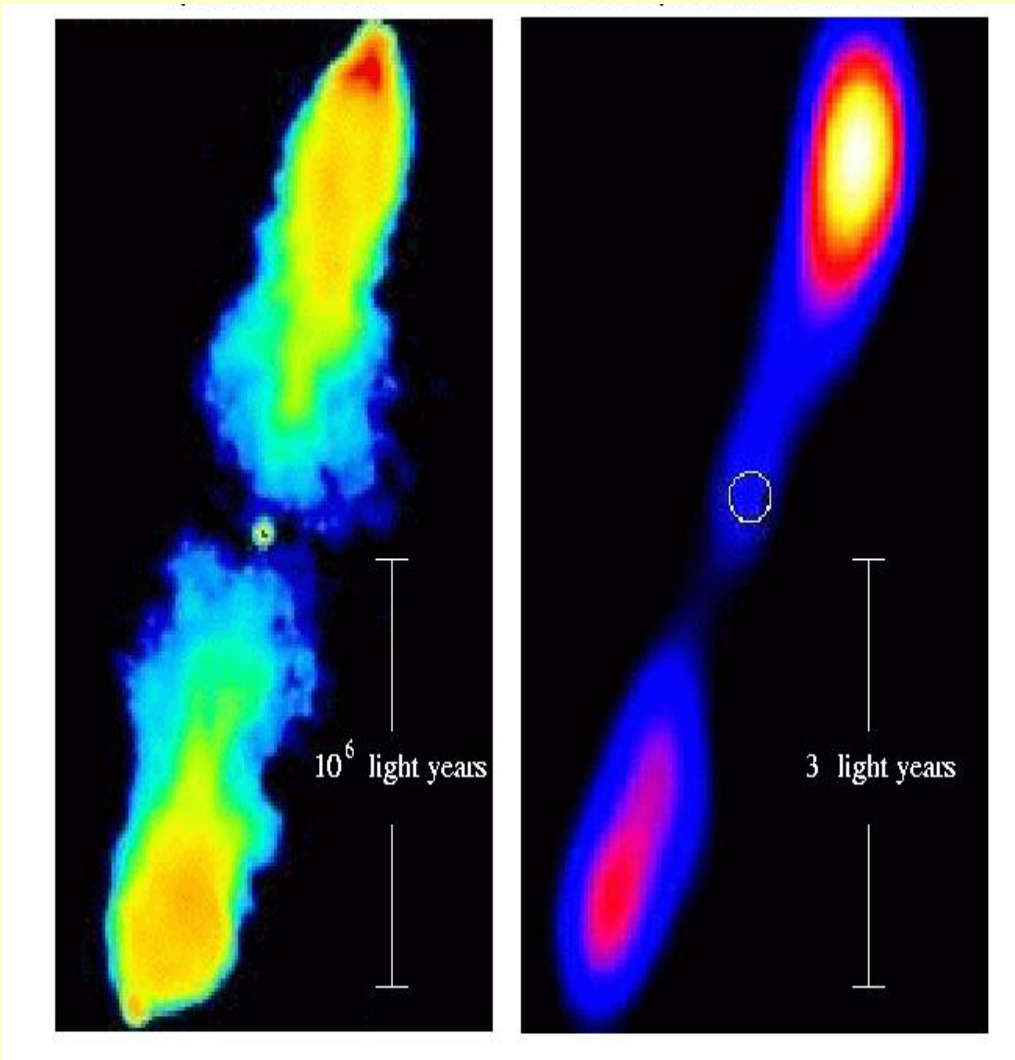
Red: sources require reconnection events with **dM/dt > 5 x 10^{-4} M_{sol}/yr** to explain X-ray emission

$$\dot{W}_{B,max} \cong 1,4 \times 10^{31} \, (\mu B_*)_{5000}^{-16/7} \, M_1^{11/7} \, \dot{M}_{max}^{22/7} R_2^{-48/7} n_{11}^{-3/2} T_8^{-1/2}$$

$$\dot{M}_{max} = 1,12 \times 10^{22} \, (\mu B_*)_{5000}^{2} \, R_2^{5/2} M_1^{1/2} \quad g/s$$

$$\sim 10^{-4} \; M_\odot/\mathrm{ano}$$

MICROQUASARS & AGNS



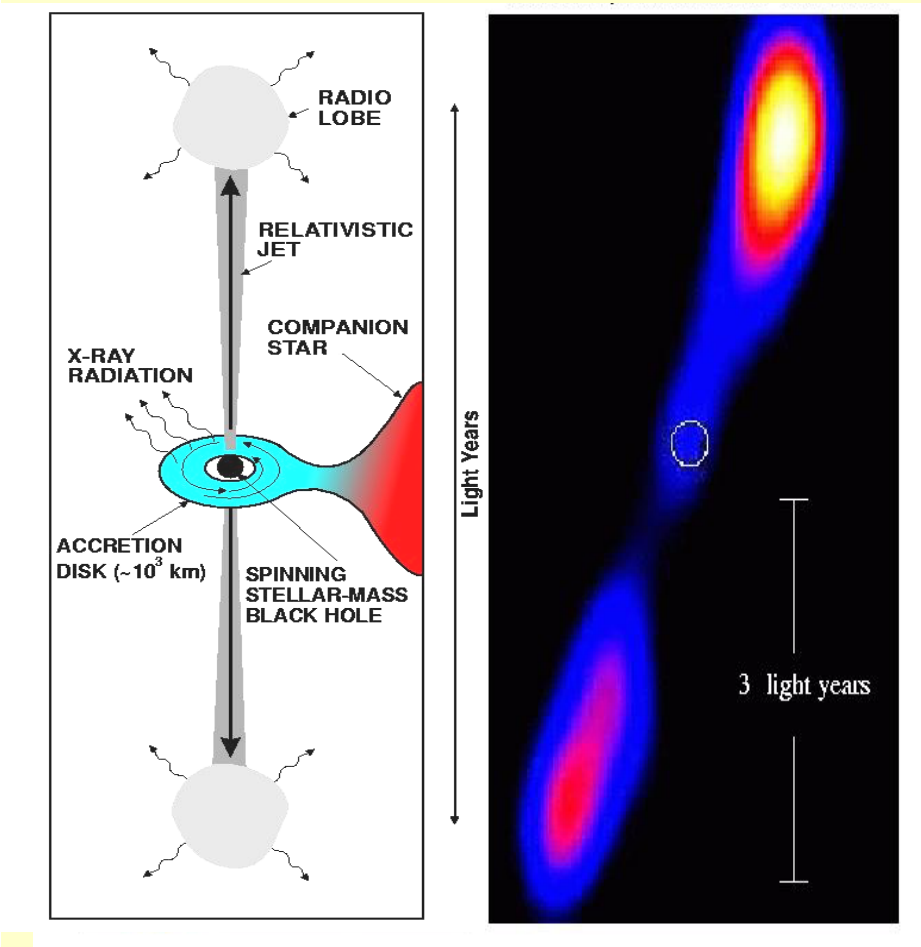
AGN Microquasar

Relativistic jets

different scales

similar morphology

JET LAUNCHING IN MICROQUASARS



Mirabel & Rodriguez

GBHXBs or MICROQUASARS

2 Major States (Remillard & McClintock 2006; Fender et al. 2006):

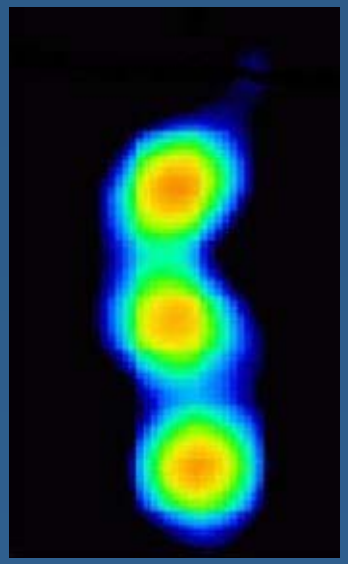
- **Quiescent:** non-thermal, low hard X-ray
- **Outburst**:

  TS (soft X-ray emission from disk)

  HS (hard X-ray by IC)

  SPLS (radio and soft X-ray flares)

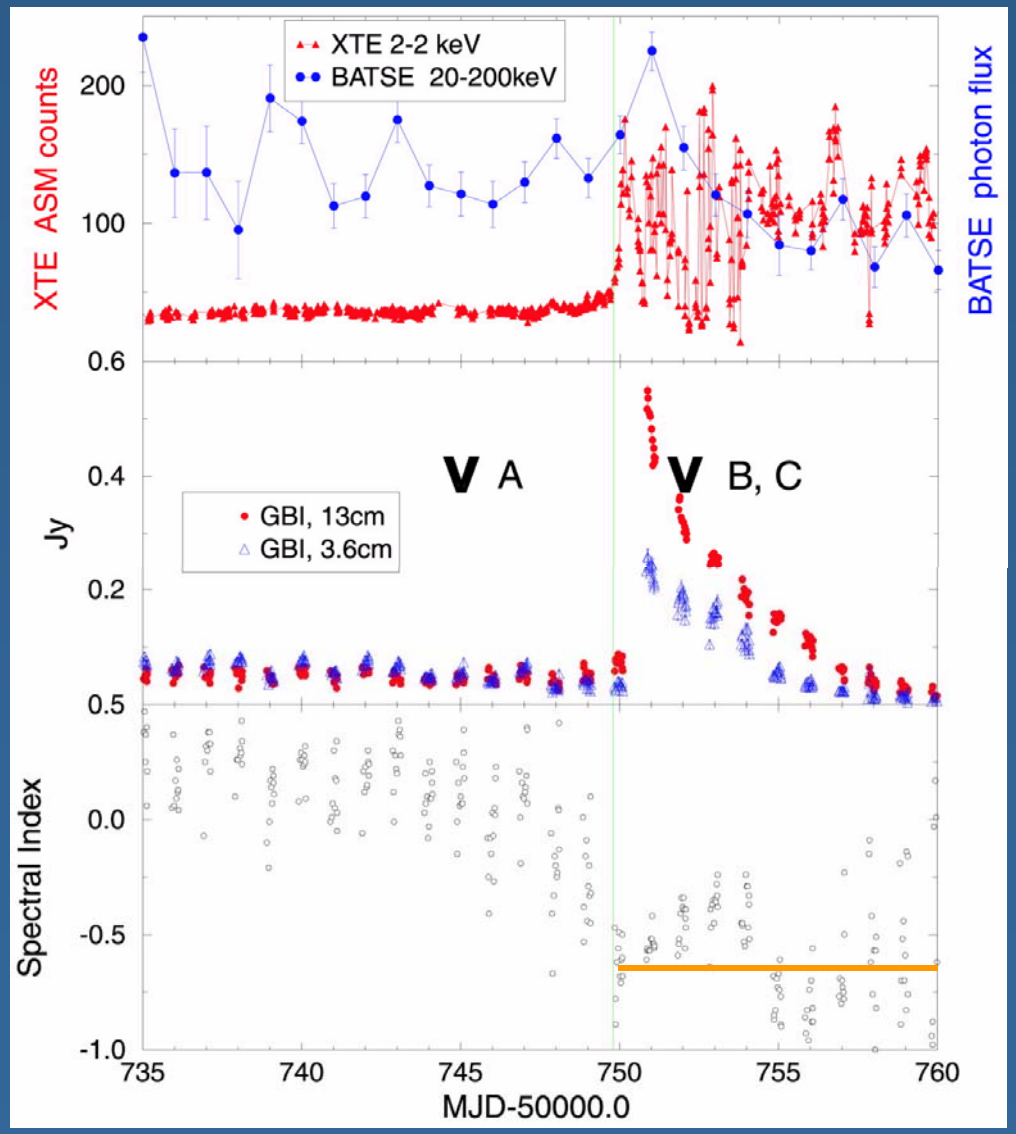
OUTBURST STATE: GRS 1915+105 MICROQUASAR



Compilation of (VLBA) radio + (RXTE/BATSE) X-ray (Dhawan et al. 2000):

➔ **2 PHASES:**

PLATEAU & FLARE

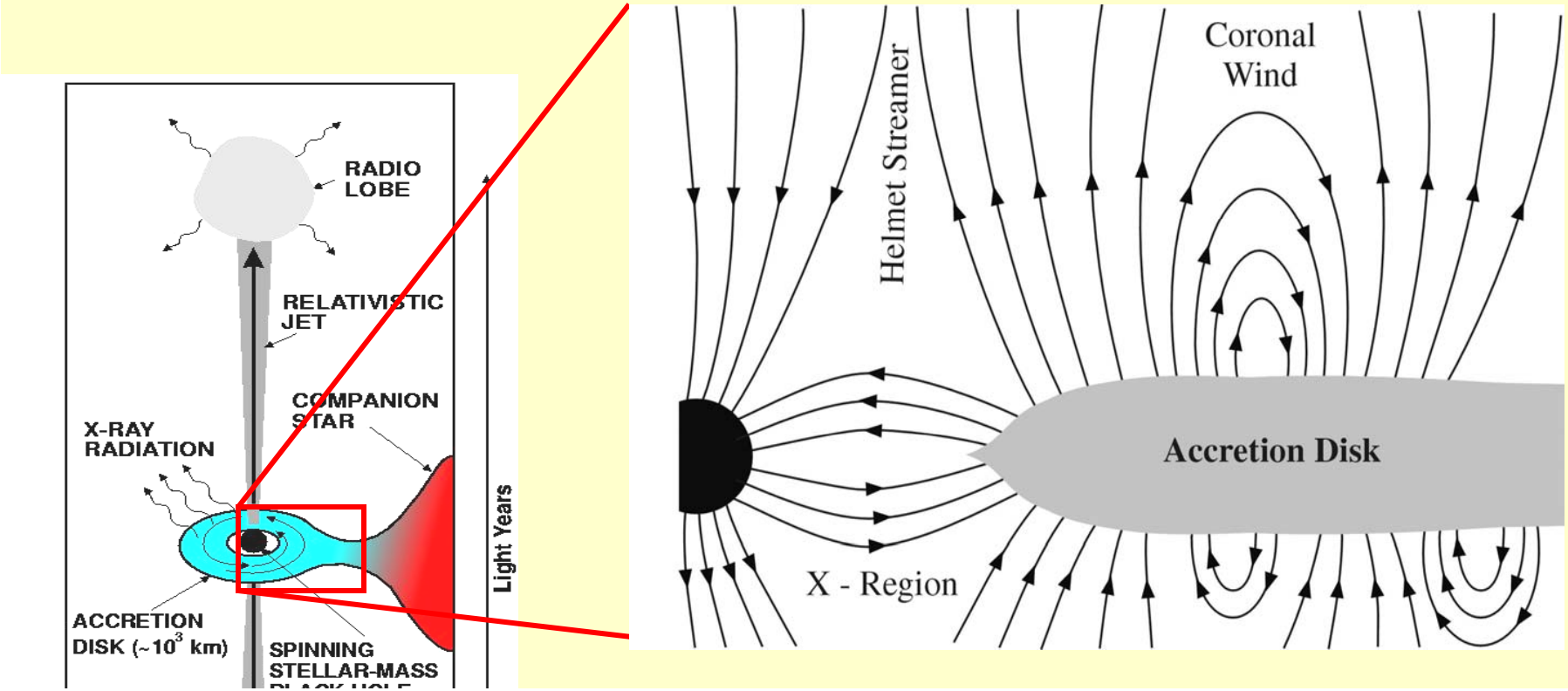


ORIGIN OF LARGE SCALE RADIO FLARE EJECTIONS

Ejections to ~ 500 AU (rise time < 1 day):

Relativistic plasma accelerated during **violent magnetic reconnection** in the magnetized corona

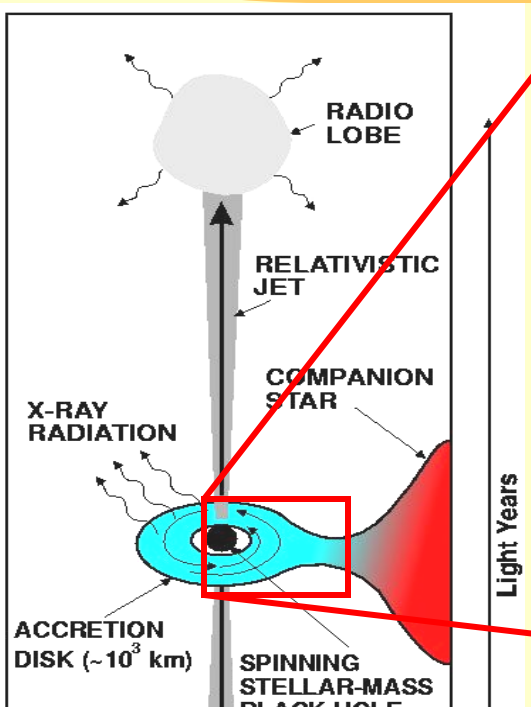
(de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino 2006)

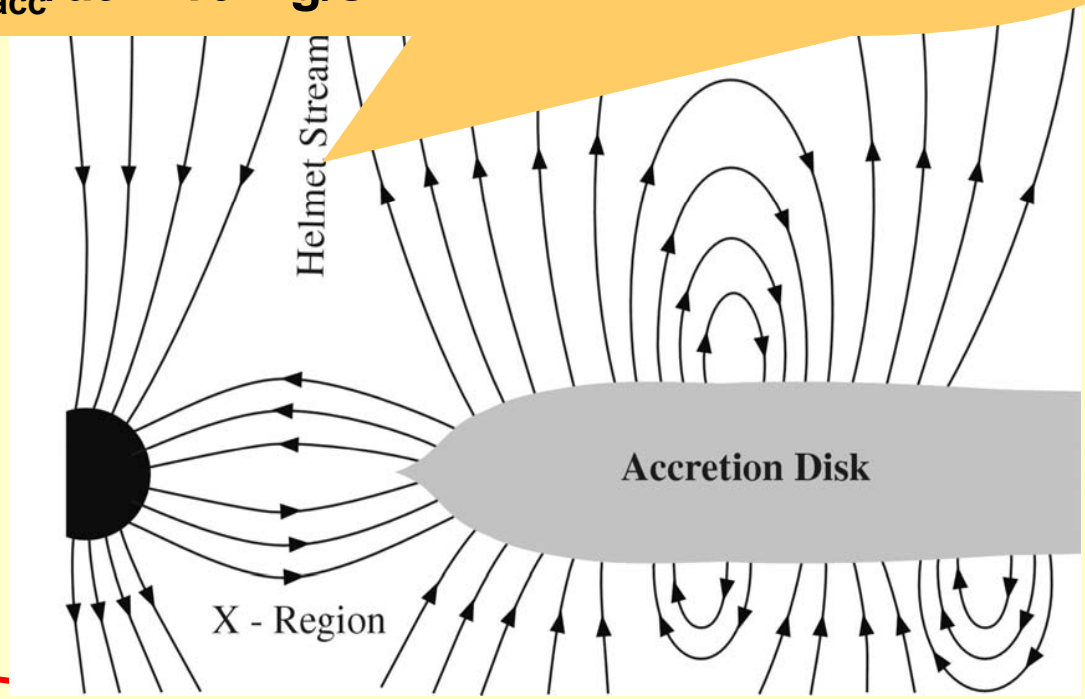


ORIGIN OF LARGE SCALE RADIO FLARE EJECTIONS

Occurs when **large scale B** established by **dynamo** (Balbus & Hawley 1998; Livio et al. 2003, Brandenburg & Subramanian 2004) in inner disk region with $\beta = (p_r + p_g)/p_B \leq 1$

And substantial angular momentum is removed from the disk by wind generated by magnetic flux: increasing disk mass accretion to value near critical $dM_{acc}/dt \sim 10^{19}$ g/s





Magnetic Power from reconnection

$$\dot{W}_B \cong 1,6 \times 10^{35} \alpha_{0.5}^{-19/16} \beta_{0.8}^{-9/16} M_{14}^{19/32} R_{X,7}^{-25/32} l_{100}^{11/16} \ \ erg/s$$

$$t_{rec} \cong \frac{R_X}{\xi v_A} \cong 10^{-4} \xi^{-1} R_{X,7} \ \ s$$

- ✓ heat the coronal gas (T ~ 10^9 K)
- ✓ accelerate the gas to relativistic velocities

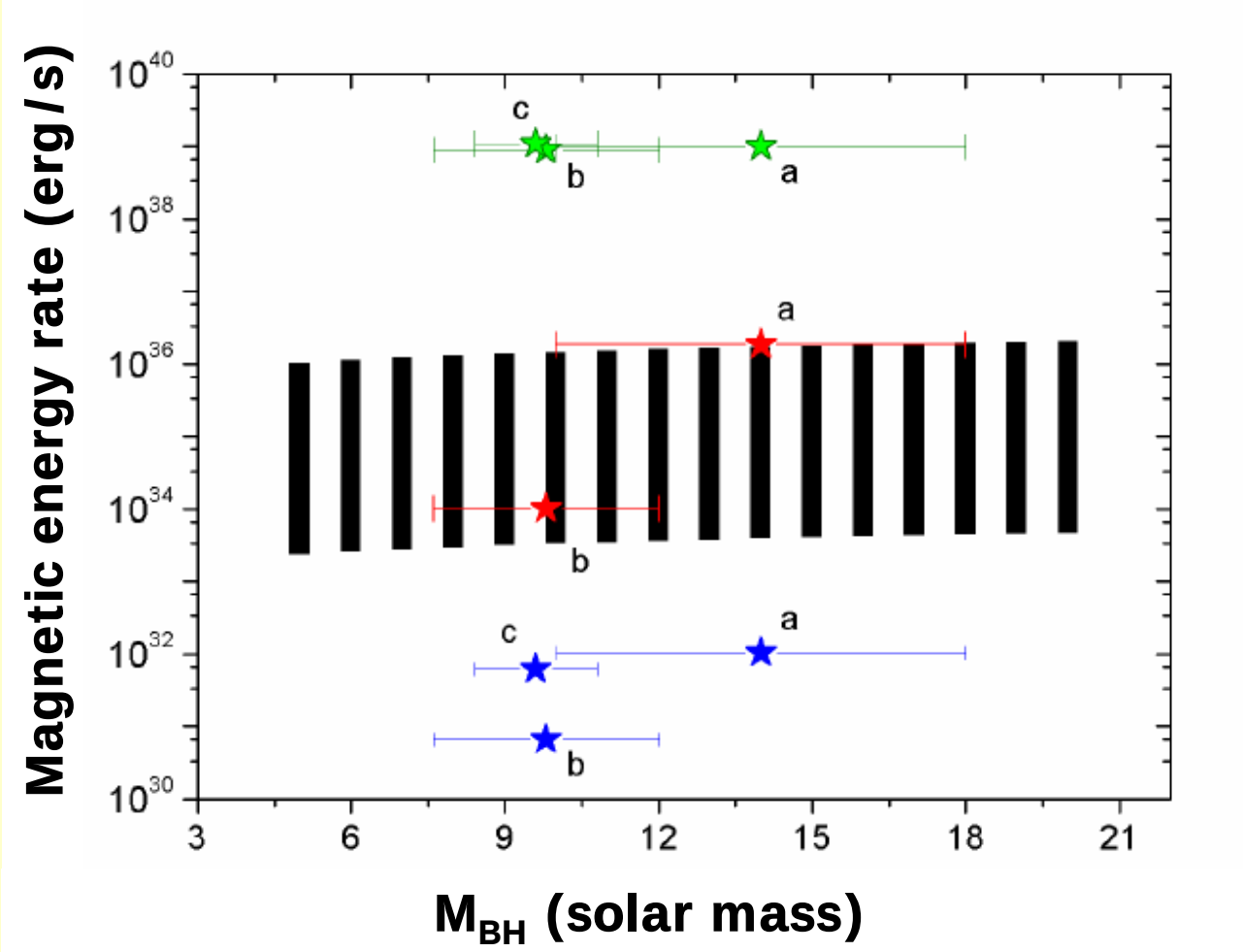
$$\dot{M} \sim 1 \times 10^{19} \beta_{0.8}^{-1} \alpha_{0.5}^{-1} R_{X,7} \ \ erg/s$$

$$\dot{W}_{ac} \cong \frac{G M_{BN} \dot{M}}{R_X} \cong 1.87 \times 10^{39} M_{14} \dot{M}_{19} R_{X,7}^{-1} \ \ erg/s$$

$$L_x \cong \eta \dot{W}_{ac}$$

→ Disk soft X-ray emission during flare

MICROQUASARS: Reconnection Power



a: GRS 1915-105

b: XTE J1859+226

c: XTE J1550-564

$0.05 \leq \alpha \leq 0.5$

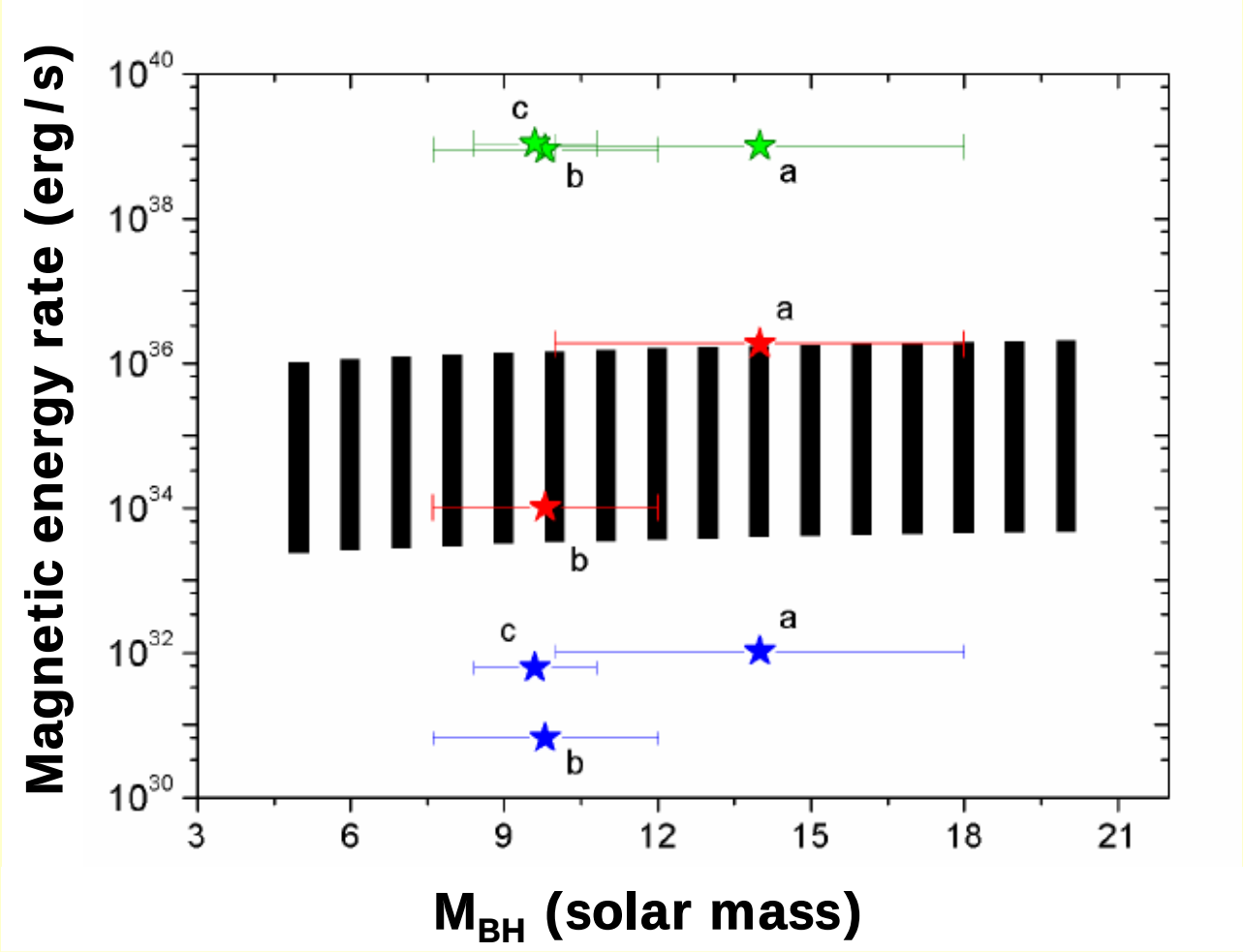
$0.1 \leq \beta \leq 1$

$\dot{M} \lesssim \dot{M}_{Edd}$

$l = 100\ R_{BH}$

de Gouveia Dal Pino, Piovezan, Kadowaki 2009

MICROQUASARS: Reconnection Power



Reconnection flares could be responsible

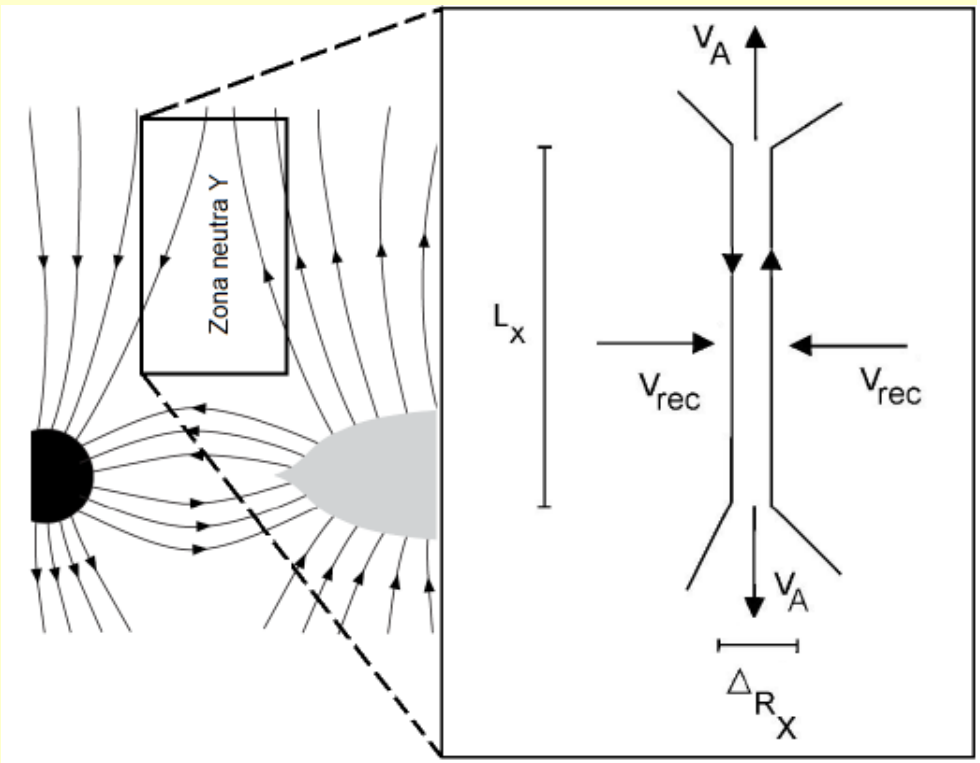
for the transition from the "hard" SPLS to the "soft" SPLS (or even to the thermal state)

de Gouveia Dal Pino, Piovezan, Kadowaki 2009

Particle Acceleration during Flare

:✓ 1st-order Fermi-like

Reconnection site:
left and right parts of the flow move towards each other and particles *see* the other part to approach with $\mathbf{2v_{rec}}$



$$\langle \Delta E/E \rangle = 8v_{rec}/3c$$

➔ **Particle and Synchrotron Spectrum**
(de Gouveia Dal Pino & Lazarian 2005):

$$N(E) \sim E^{-5/2} \rightarrow S_\nu \sim \nu^{-0.75}$$

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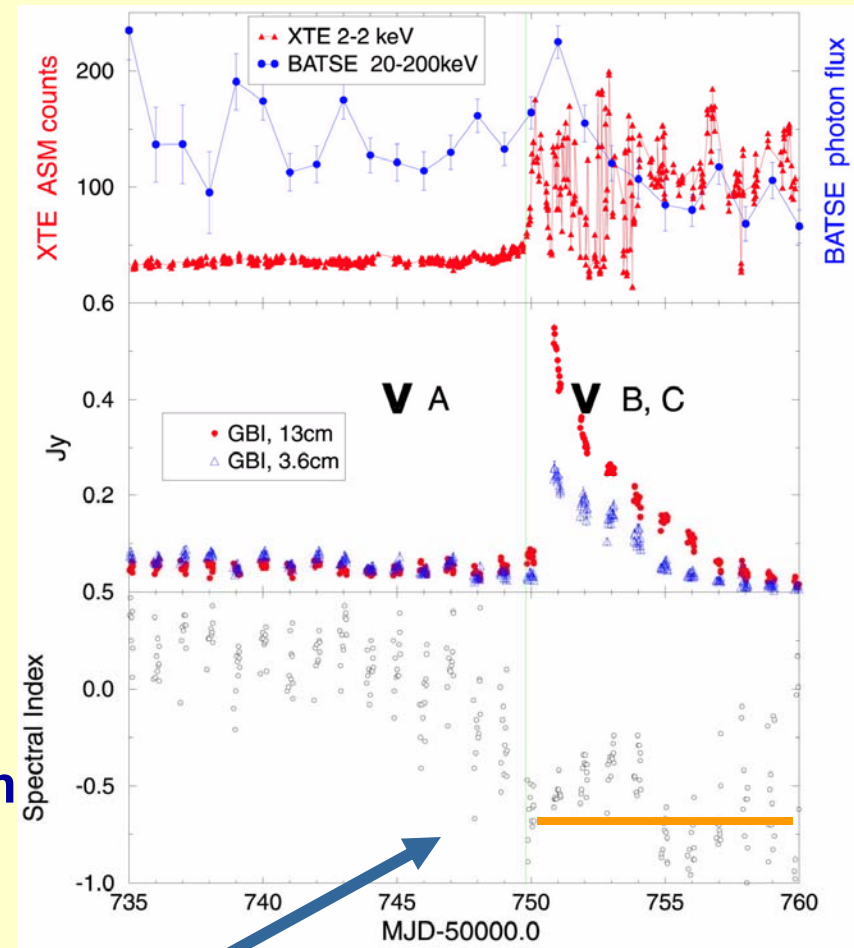
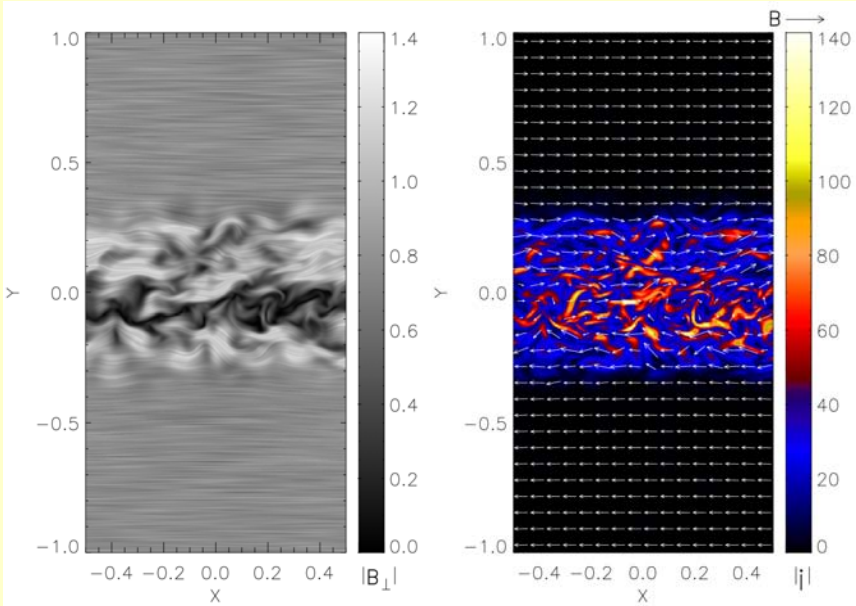
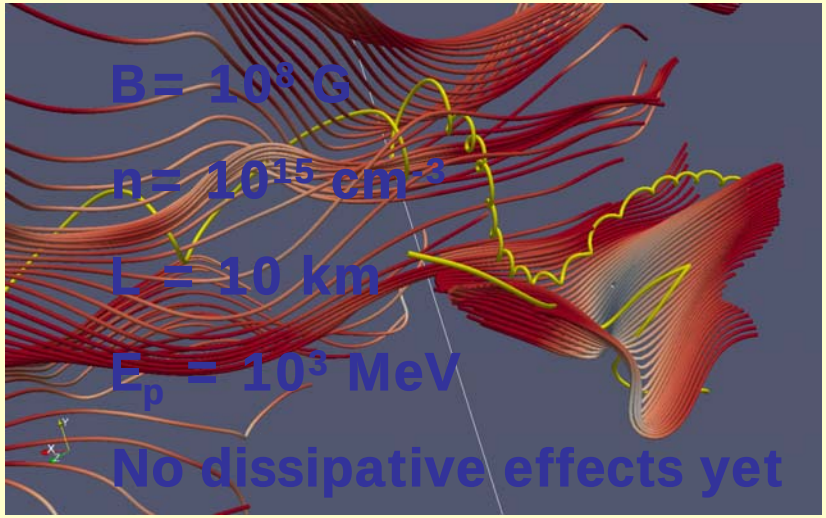
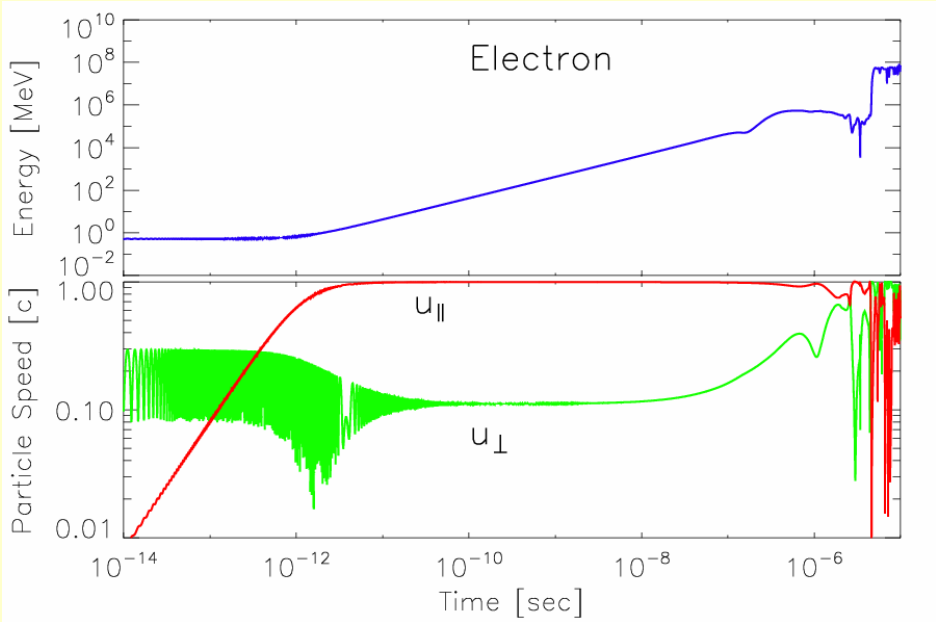


Particle Acceleration within Reconnection site



Kowal, Lazarian, Vishniac, Otmianowska-Mazur 2009





Kowal, de Gouveia Dal Pino, Lazarian in prep. 2009

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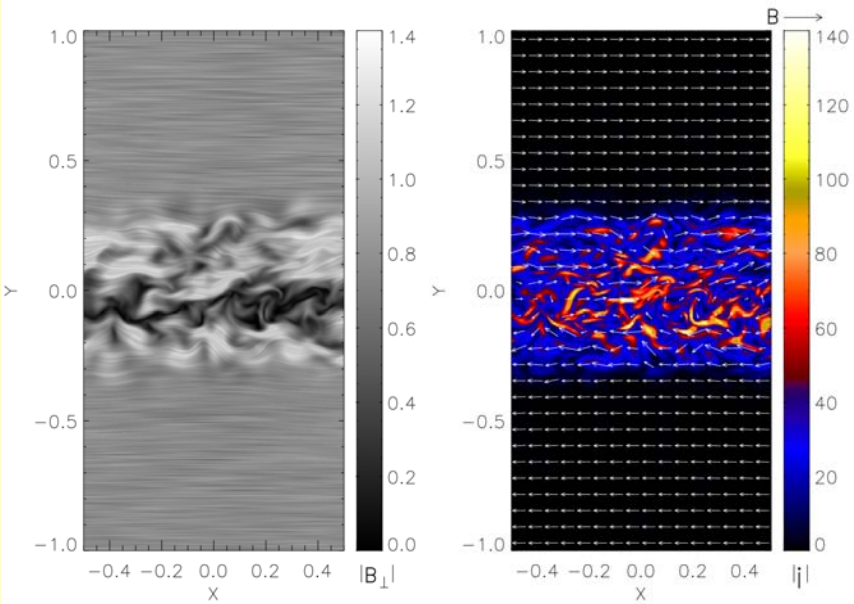
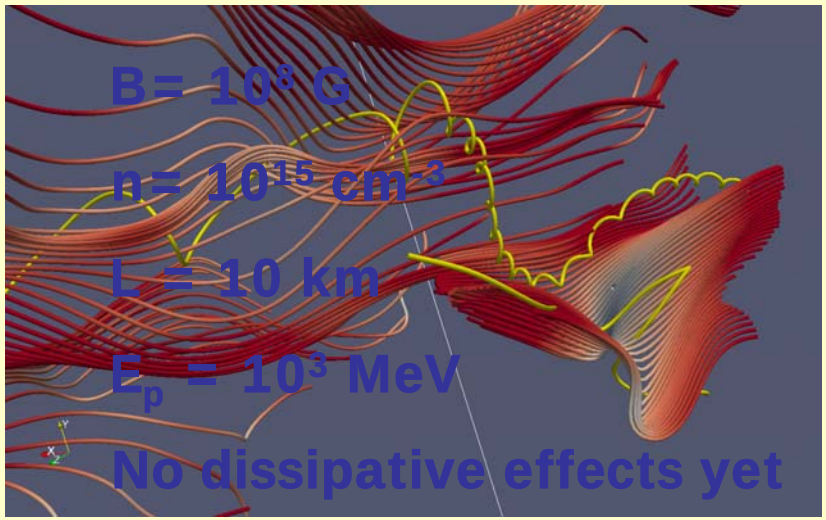
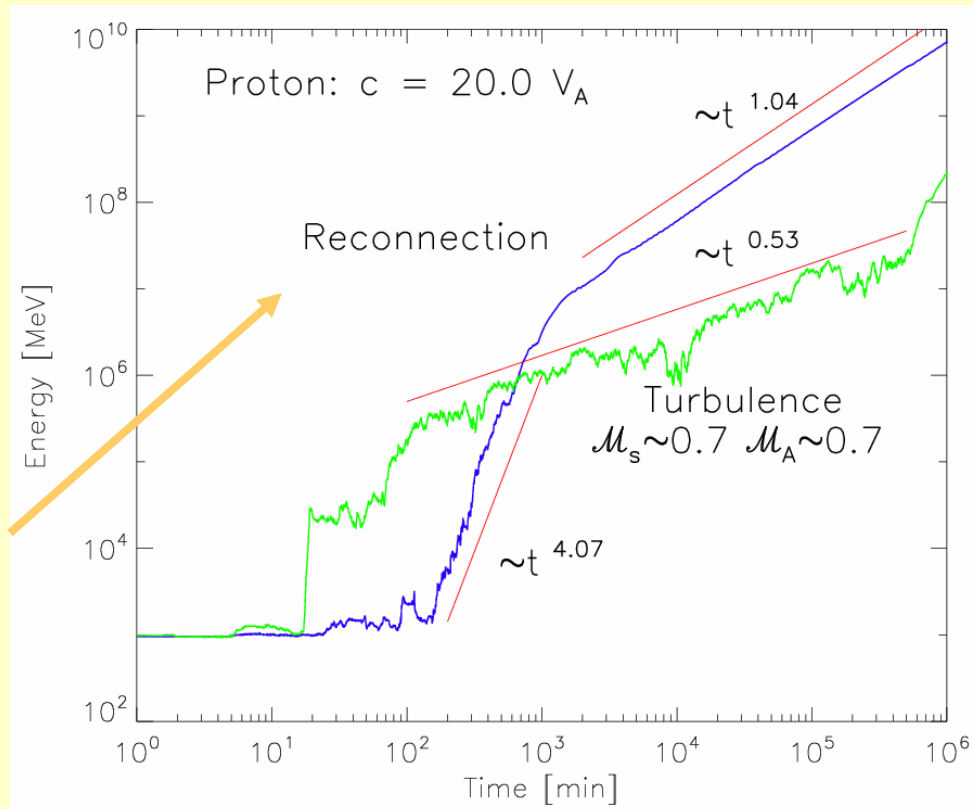


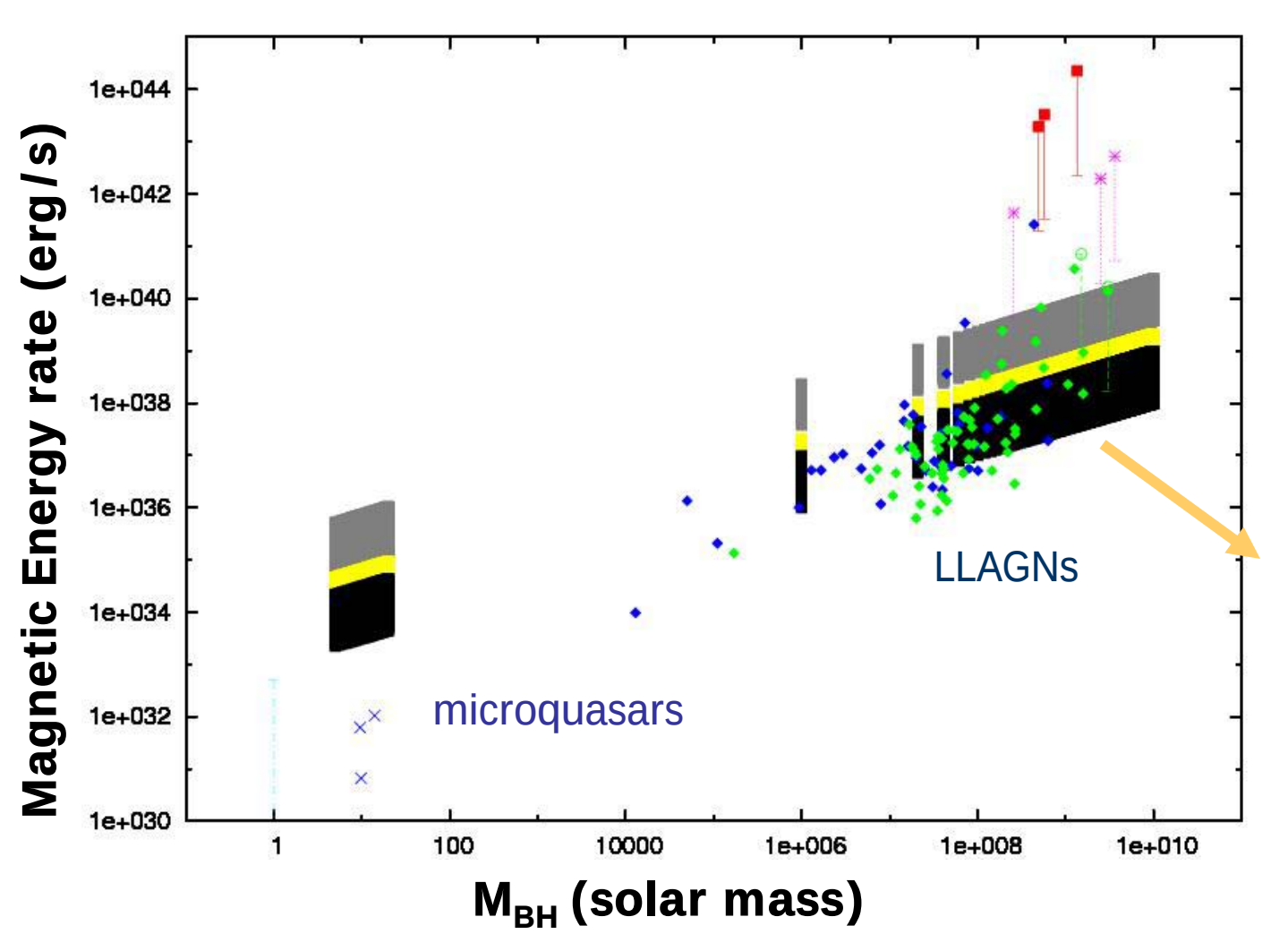
Kowal, Lazarian, Vishniac, Otmianowska-Mazur 2009





Kowal, de Gouveia Dal Pino, Lazarian in prep. 2009

MICROQUASARS X AGNs



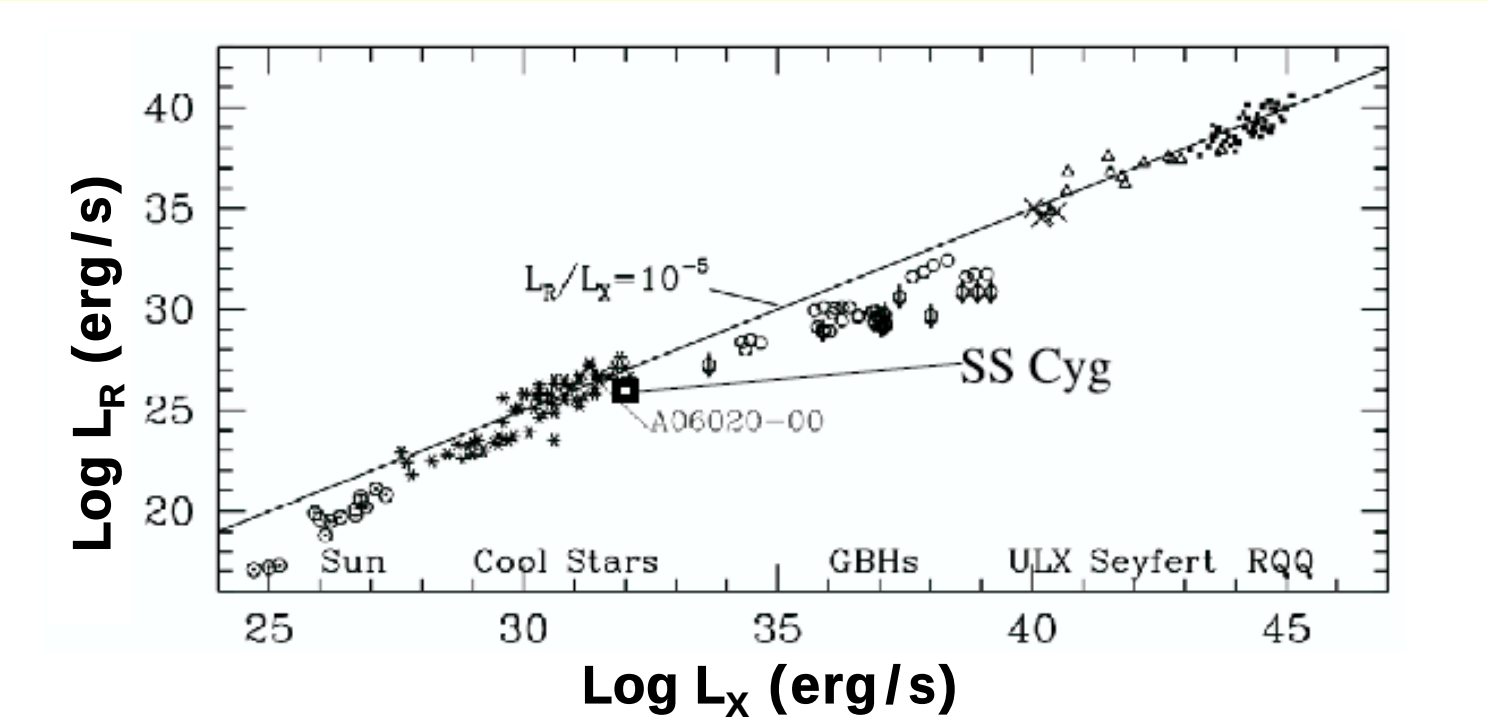
Energy released in reconnection

↓

explains radio outbursts of microquasars and low luminous AGNs

Piovezan, de Gouveia Dal Pino & Kadowaki 2009

Observed correlation: L_R x L_X



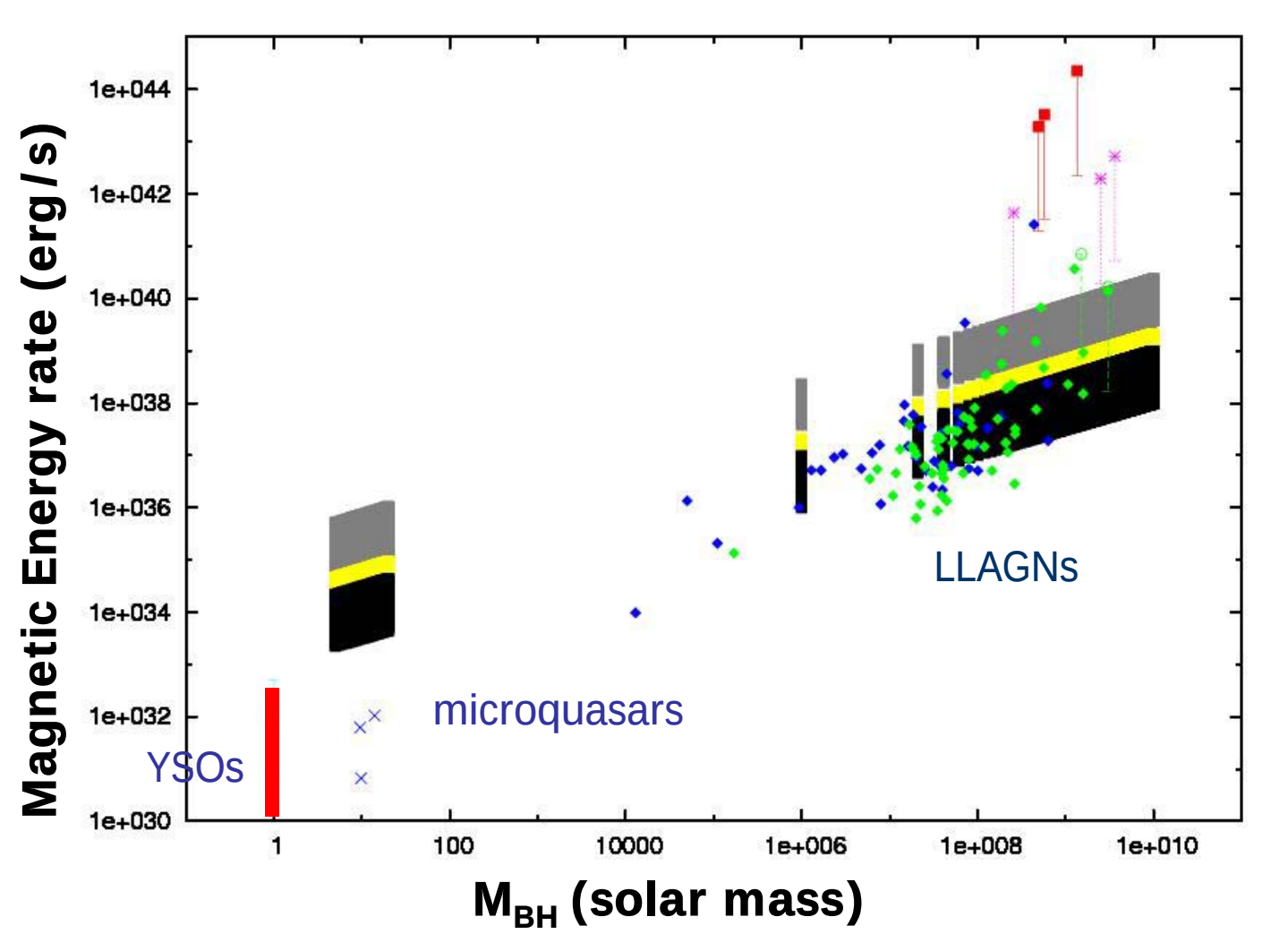
Laor & Behar (2008); Soker & Vrtilek (2009)

(also Merloni et al. 2003, Falcke et al. 2004)

Holds for $L_R/L_X < 10^{-5}$

As in magnetically active stars the radio **emission in GBHBs and radio quiet AGNs**: **from magnetic activity in the coronae** above the accretion disks

MICROQUASARS X AGNs



Energy released in reconnection

↓

explains outbursts from YSOs to microquasars and LLAGNs

(10^9 orders of magnitude)

Piovezan, de Gouveia Dal Pino & Kadowaki 2009

SUMMARY

✓**Reconnection events** could explain radio outbursts from **microquasars to LLAGNs** (over 10^9 orders of magnitude of sources mass)

✓ **Condition for violent reconnection** (flare): when large scale **B** established with $\beta = (p_r + p_g)/p_B \leq 1$ **and dM/dt near critical (Eddington)**

✓ **Reconnection events**: initial particle acceleration to relativistic velocities in the reconnection site through Fermi-like: $\mathbf{N(E) \sim E^{-5/2}}$ **and** $\mathbf{S_\nu \sim \nu^{-0.75}}$ **(**~ observed spectral index during the flares **~ -0.6 to -08)**

✓ **YSOs**: **X-ray flares of most COUP sources** – explained by reconnection events in the magnetosphere-inner disk/corona with dM/dt = 100-1000 <dM/dt> of evolved sources (maximum dM/dt = 10^{-4} – 5 x 10^{-4} M_{sol}/yr (similar to Fu Ori outbursts)

✓ **YSOs:** recconection energy could **heat jet base** (up to 10 AU):

$$\tau_{cond} \sim 10^8 n_{10} T_8^{-5/2} l_{10}^2 \text{ s},$$