# Relativistic jets shining through their stripes

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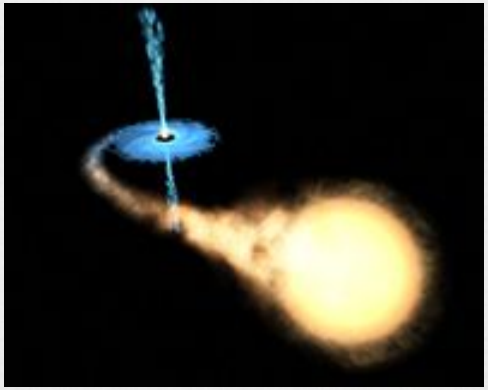
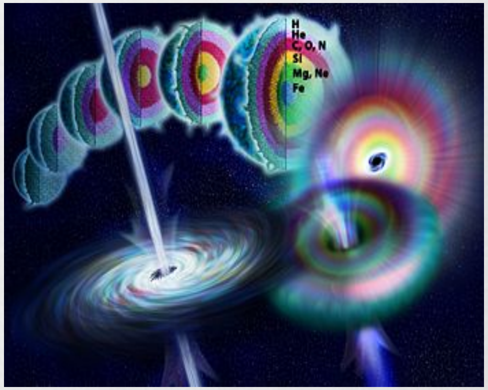
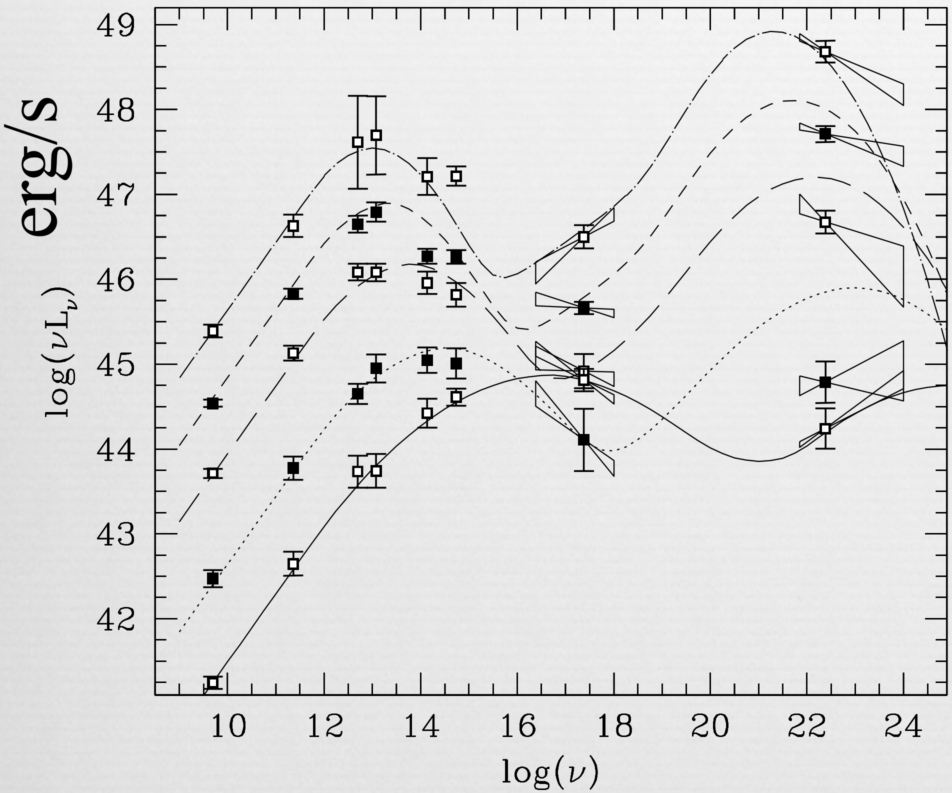
# Relativistic jets are *ubiquitous*

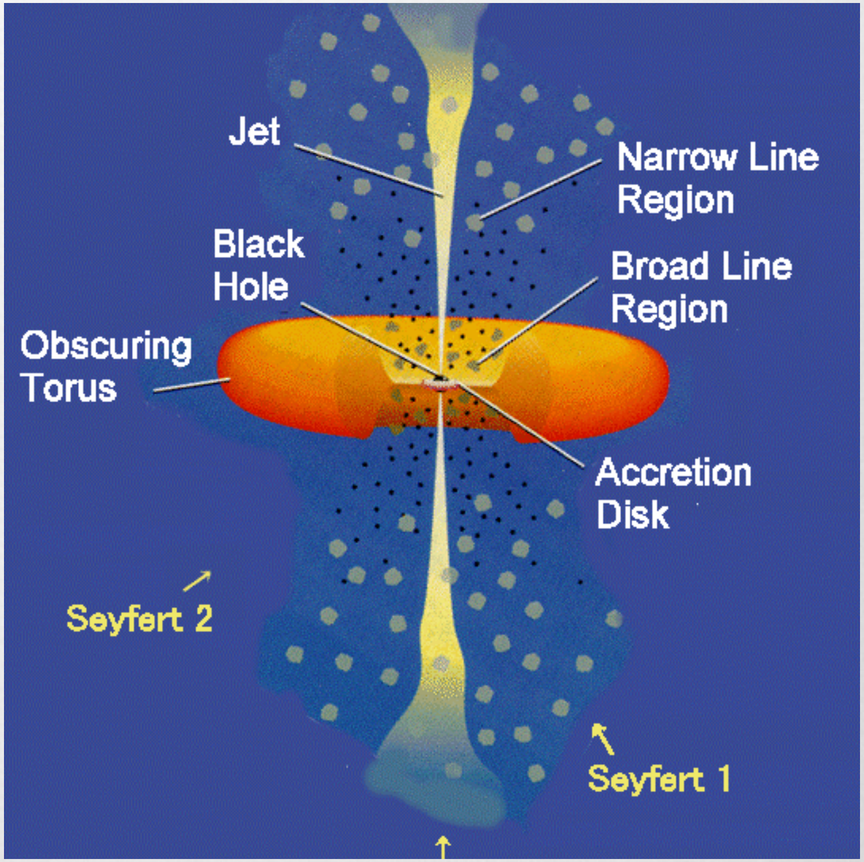
| jets in galactic centers | X-ray binaries | gamma-ray bursts |
|---|---|---|
|  M87; NASA/Hubble |  |   |
| $M_{BH} \sim 10^9 M_\odot$ | $\sim 10 M_\odot$ | $\sim 3 M_\odot$ |
| Power $\sim 10^{44} ... 10^{49}$ erg/s | $\sim 10^{38}$ erg/s | $\sim 10^{52}$ erg/s |

# Blazars:

## Jets from galactic centers moving towards us

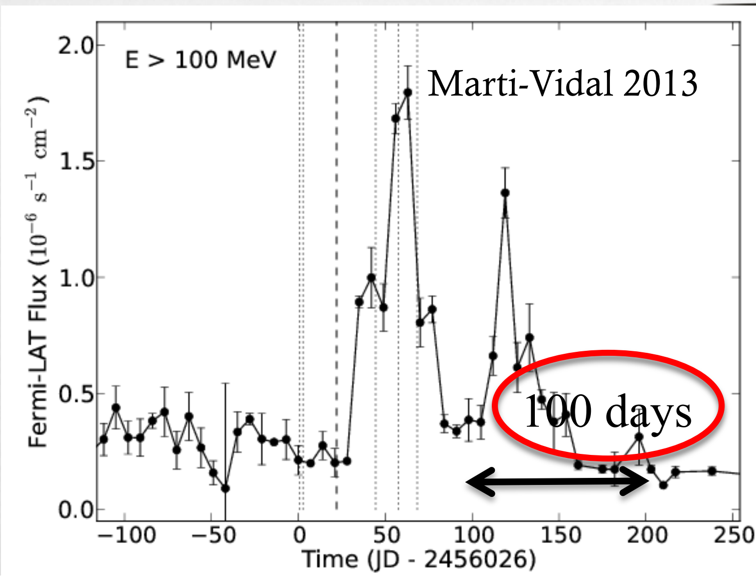


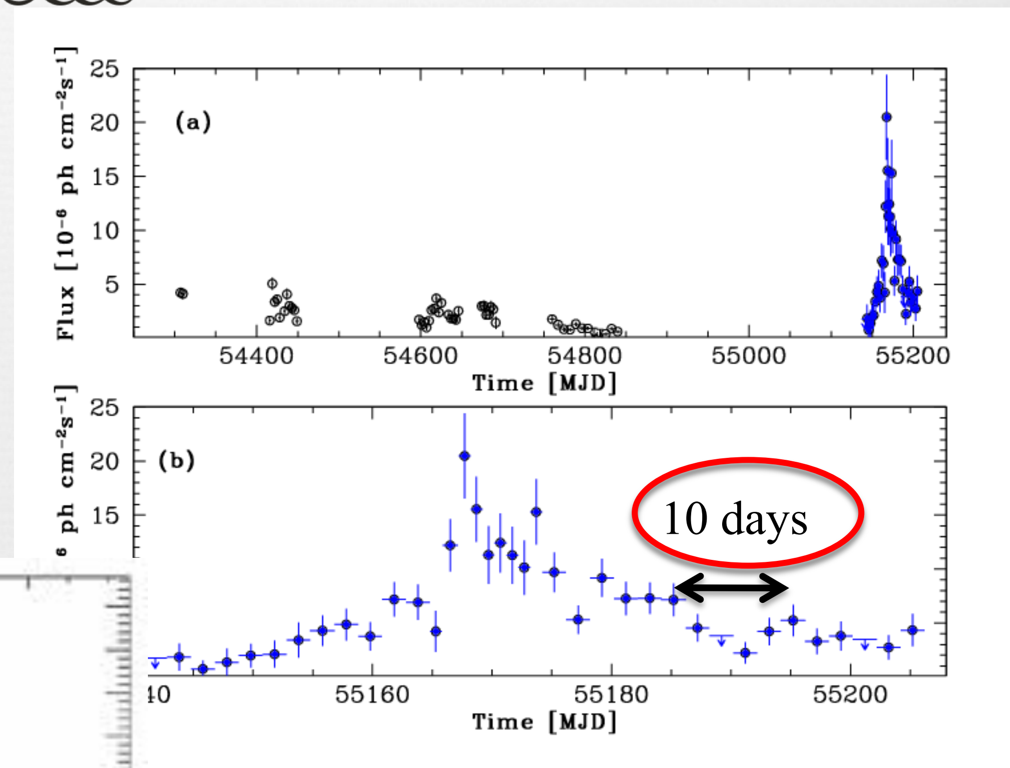

e.g., Fossati et al. 1998



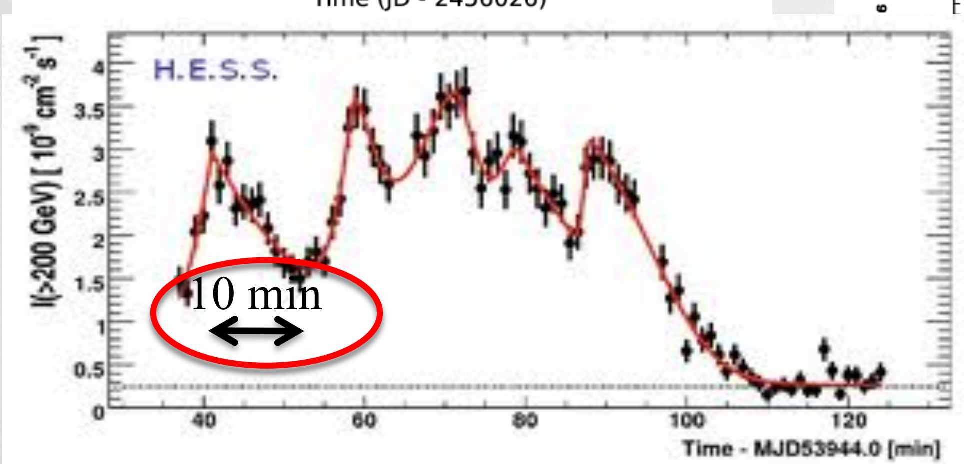

Blazar

# Blazars are variable on timescales: *months*, *weeks*, *days*, even *minutes*!



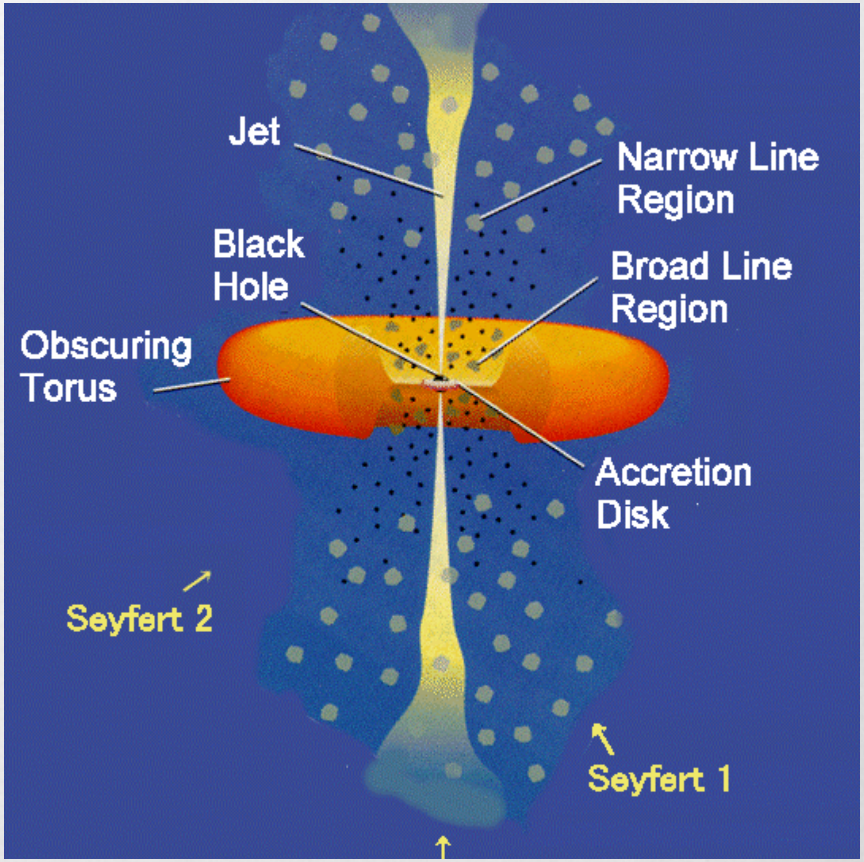

Striani et al. 2010




Aharonian et al. 2007; Albert et al. 2007

# Location of *jet dissipation zone* hotly debated: $0.01 \text{ pc} \lesssim z_{diss} \lesssim 10 \text{ pc}$!

Dermer & Schlickeiser 1994: $z_{diss} \sim 10^{16}$-$10^{17}$cm
Sikora et al. 1994: $z_{diss} < 1$ pc
Ghisellini & Tavecchio 2008: $z_{diss} \lesssim 1$ pc
Agudo et al. 2012: $z_{diss} \sim 10$ pc



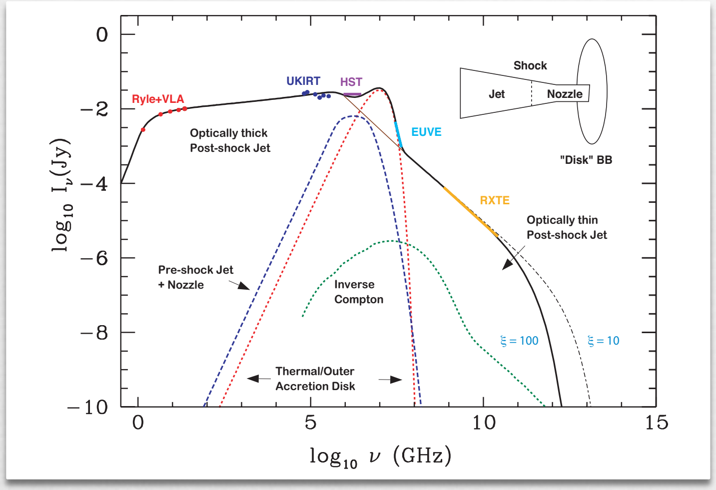

Some big questions:

*Which process accelerates the particles that radiate?*

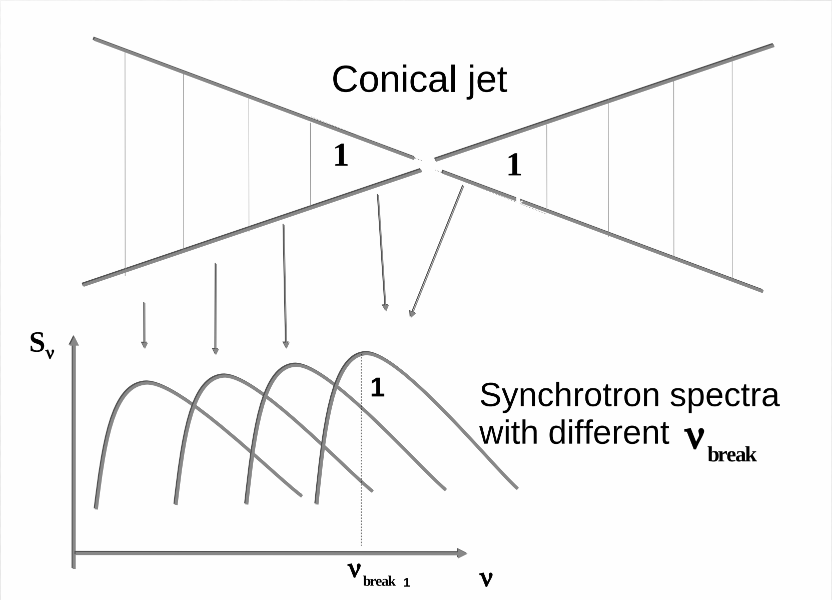
*What determines the distance & size of the emitting region?*

# Flat Radio Spectrum

## Blandford & Koenigl 1979 conical jet model




J1118; Markoff 2010; Giannios 2005

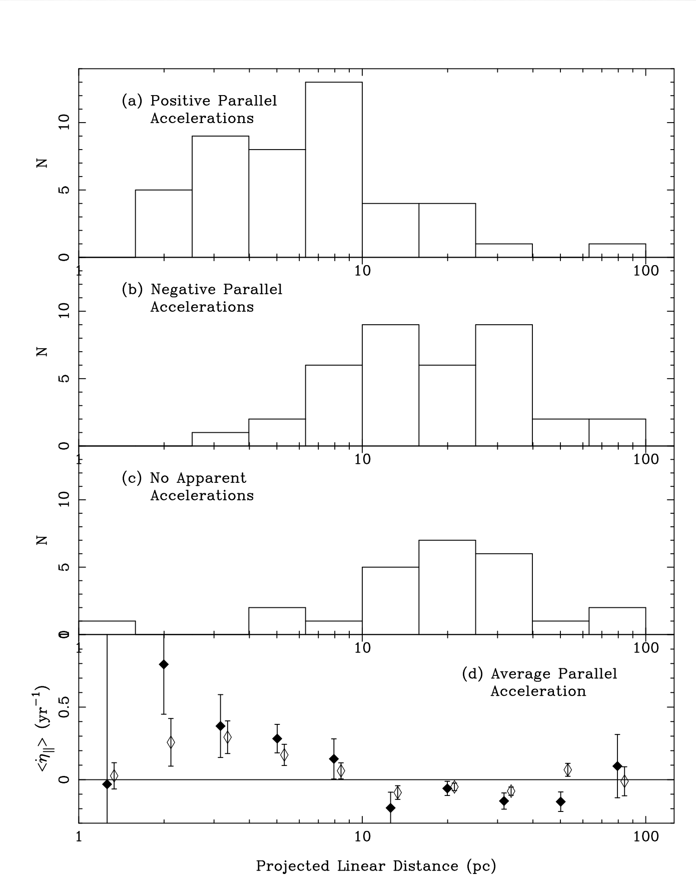



The model requires that electrons are re-accelerated over a broad range of scales

Image Credit: Massi

# Blazar jet bulk acceleration: out to ~100 pc!

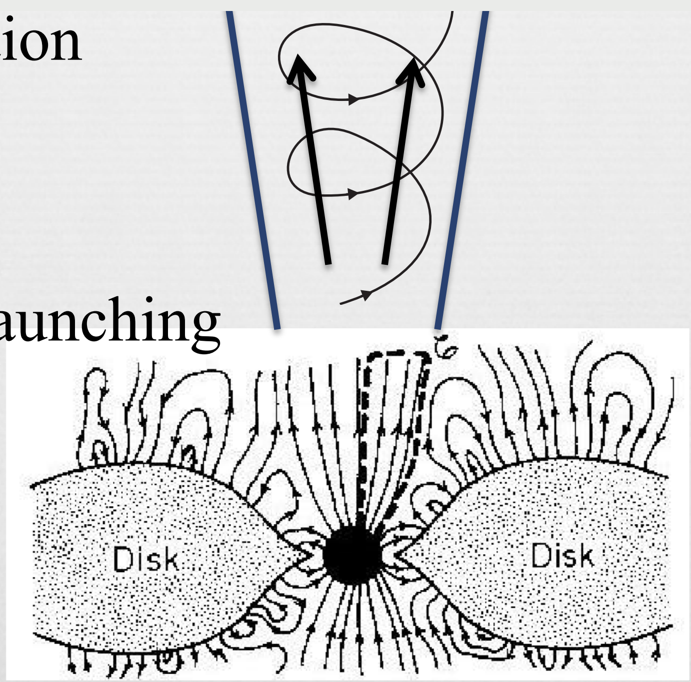
- Homan et al. 2015 report on the acceleration properties of 329 features in 95 blazar jets from the MOJAVE VLBA program
  - acceleration along the jet dominates
  - Blazar jets reach their terminal speed at scales of ~100's pc



# A theorist’s view of jets

acceleration

launching




$$\sigma_{initial} = \frac{B^2}{4\pi\rho c^2} >> 1$$

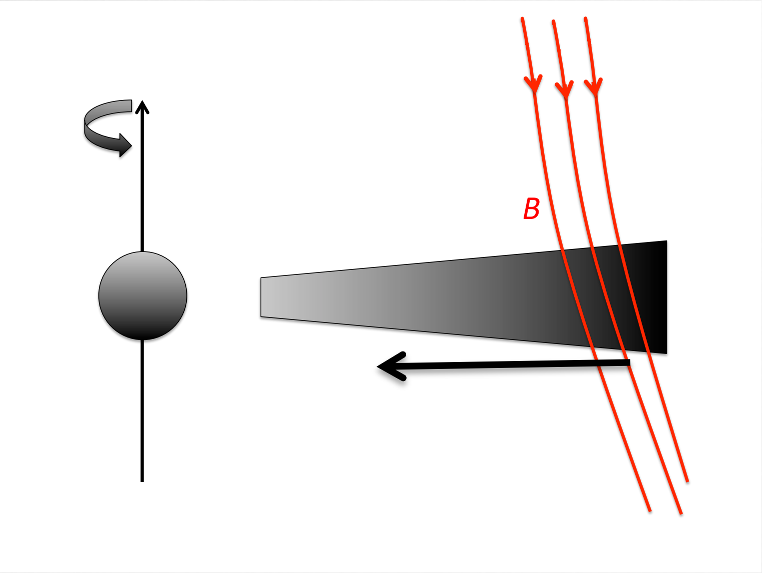
Blandford & Znajek 1977
Begelman & Li 1992
Meier et al. 2001
Koide et al. 2001
Komissarov, Lyubarky,
Barkov, Tchekhovskoy

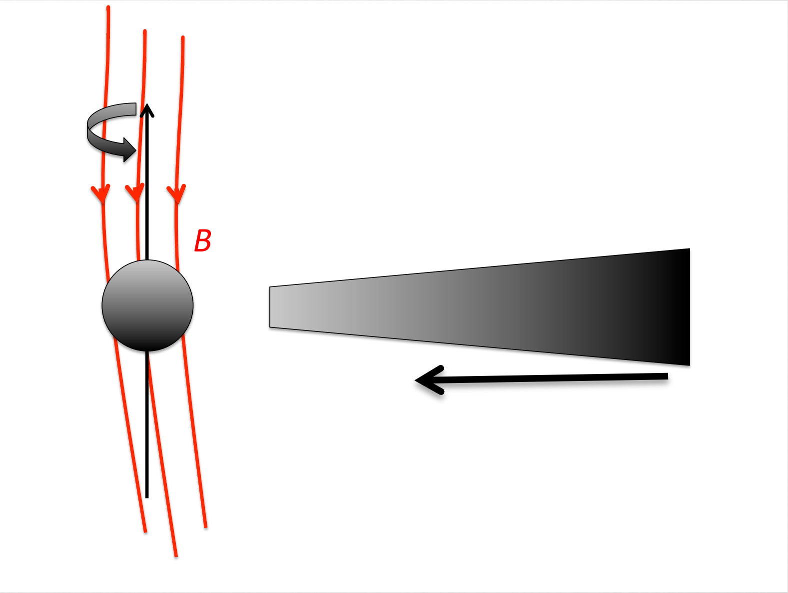
# Origin of magnetic fields

Case I: carried in from large scales

Case II: amplified locally in the disk

# Case I:
# carried in from large scales

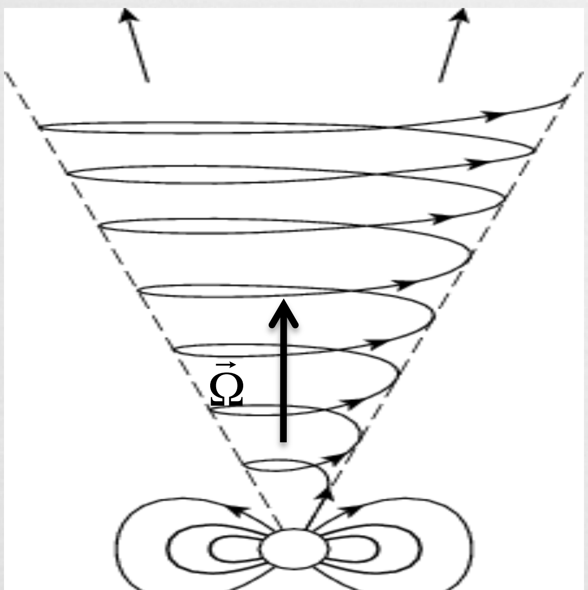


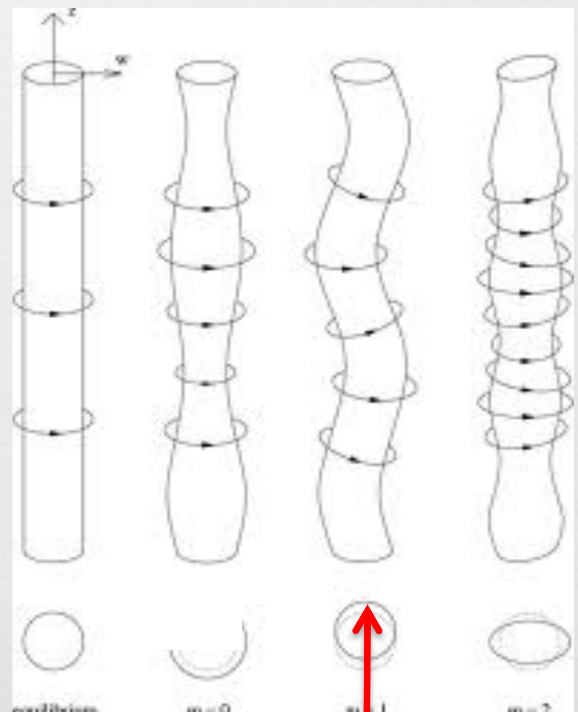



# MHD instabilities in jets: require 3-D studies

## Magnetized jets may be prone to the kink instability

Eichler 1993; Begelman 1998; Nakamura & Meier 2004; Giannios & Spruit 2006; Moll 2009; McKinney & Blandford 2009; Mignone et al. 2010; Porth & Komissarov 2015

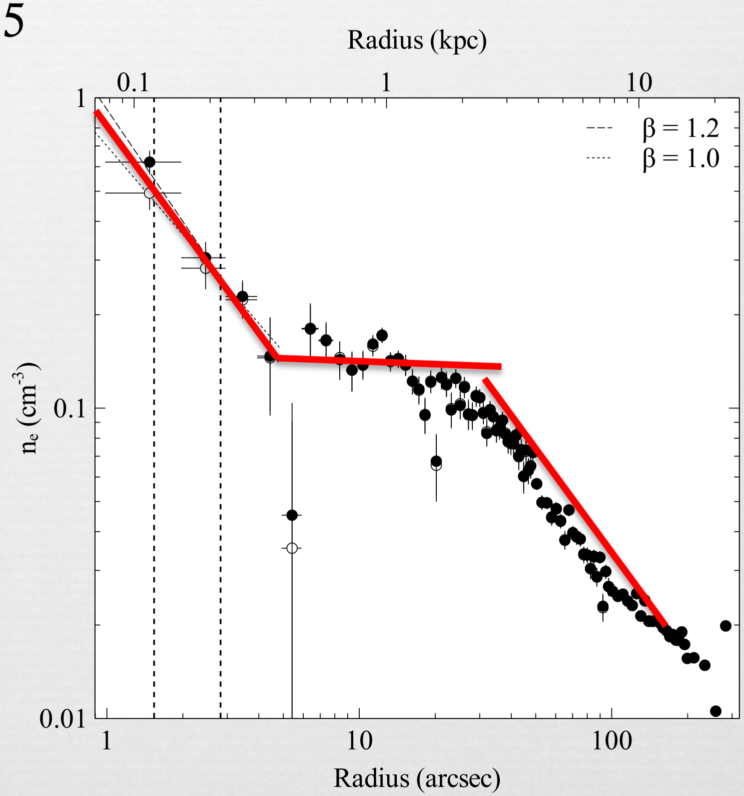


kink instability

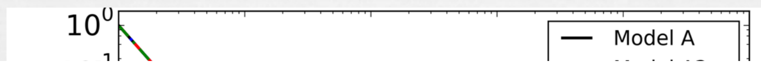
# Jet acceleration and collimation: the role of the surrounding gas

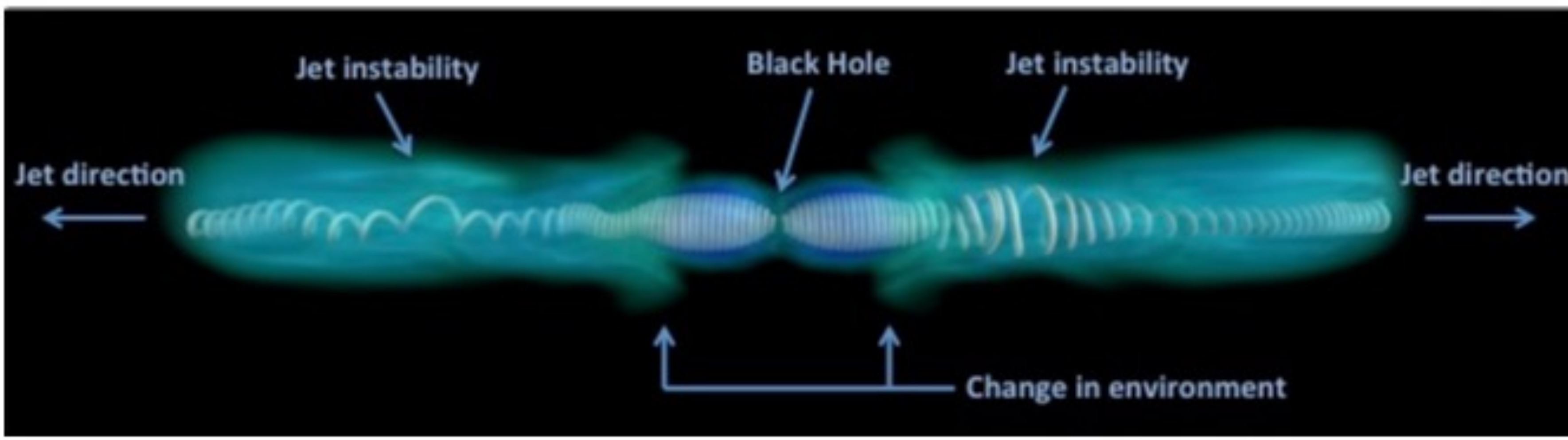
M87 density profile
Russel et al. 2015



# Strong dissipation of magnetic energy triggered by density changes

Barniol-Duran, Tchekhovskoy & Giannios 2017



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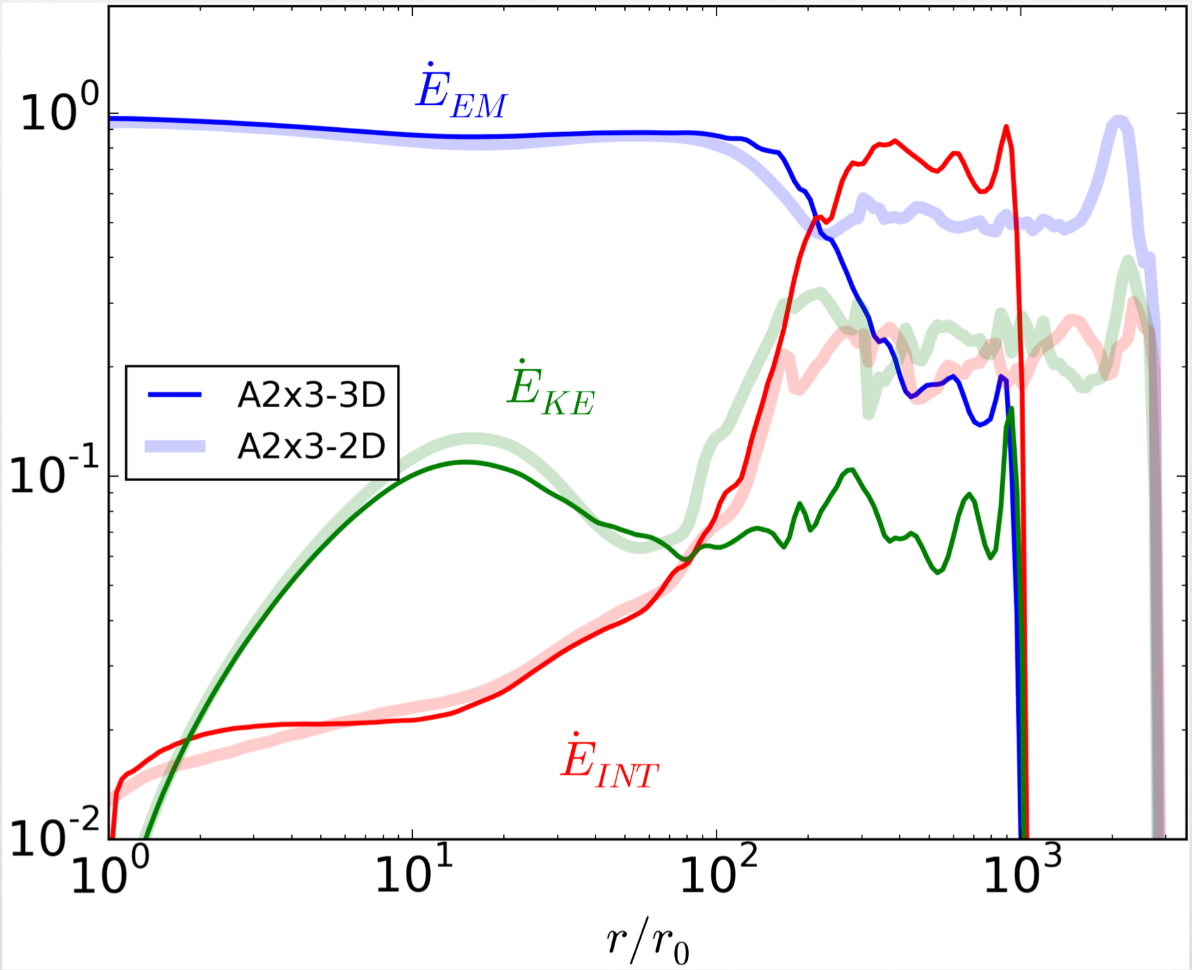
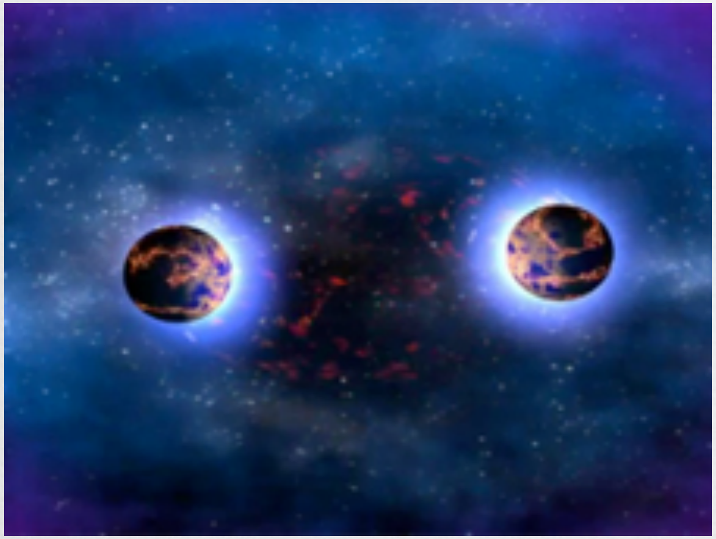
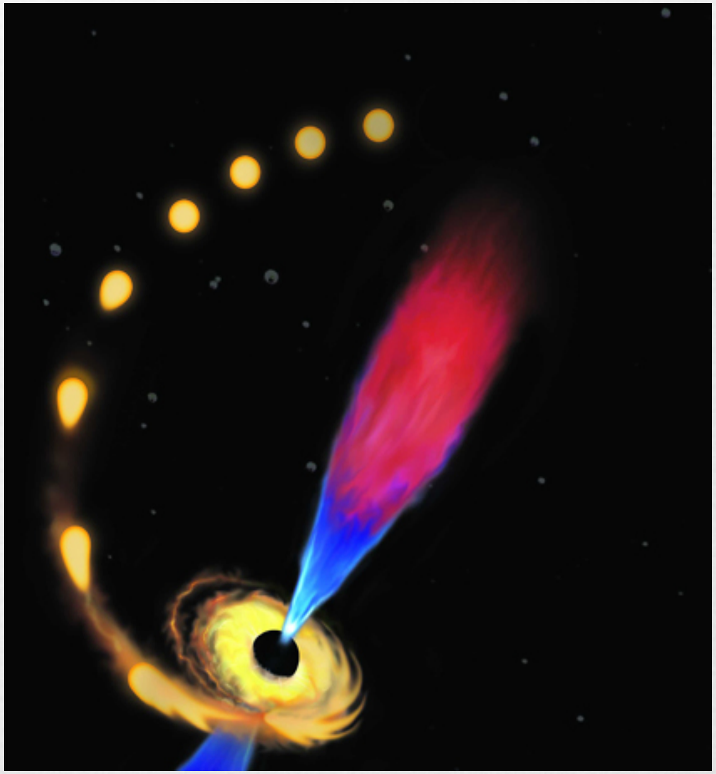


# Magnetic fields at progenitor are *not* always sufficient

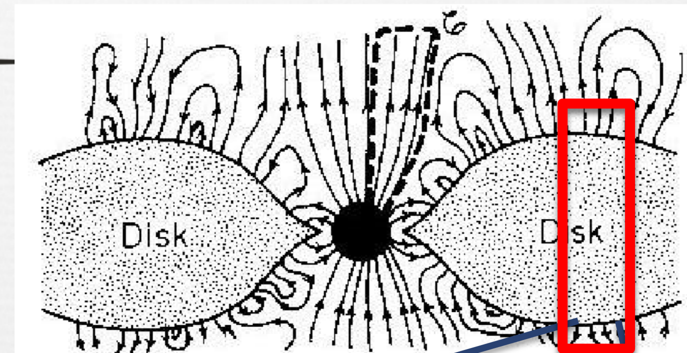


binary neutron star mergers:
Short GRBs



Stellar Tidal Disruption Jets (J1644)
Giannios & Metzger 2011; Bloom et al. 2011

# Case II:
# B-fields amplified locally at the disk

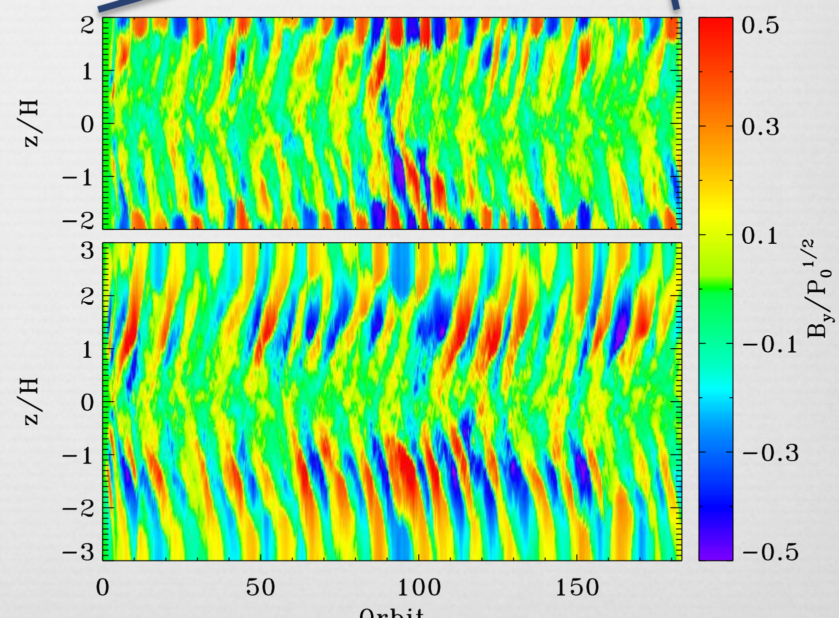



Accretion is likely to be driven by the magnetorotational instability (MRI)

Balbus & Hawley 1992

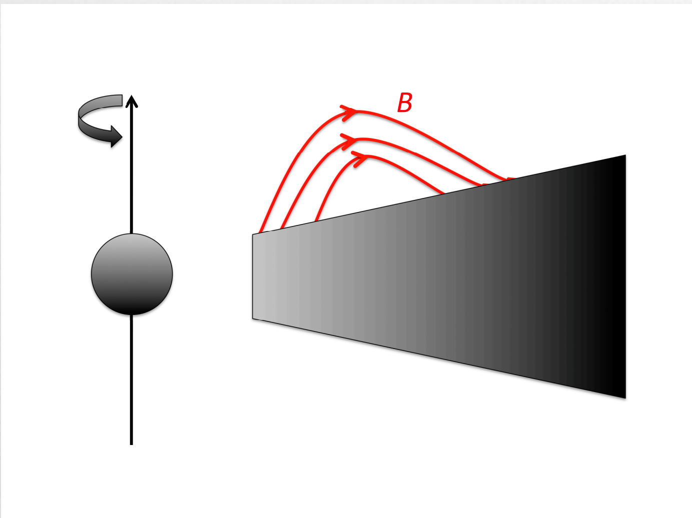
MHD simulations of MRI dynamo in stratified disk show field reversals over $t_{\rm rev} \sim 10 T_{\rm orb} \sim (100\text{-}1000) R_{\rm g}/c$ for inner disk

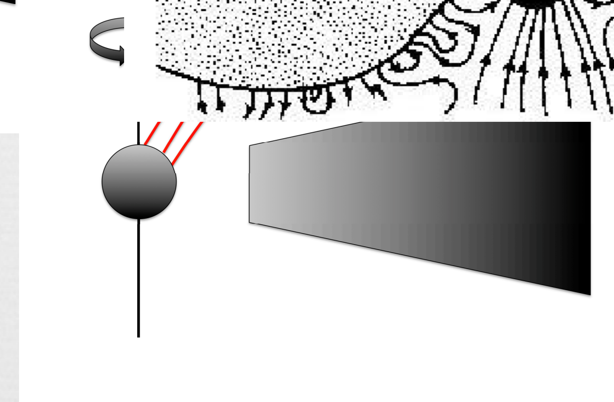
Davis et al. 2010; O'Neil et al. 2011, Simon et al. 2012+++

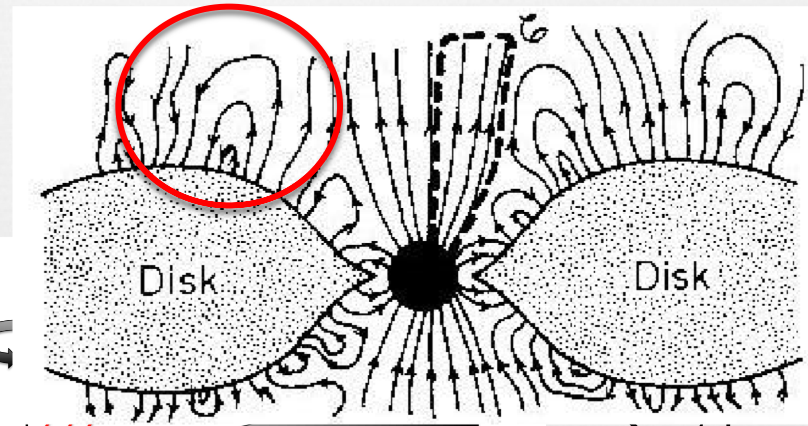



Davis et al. 2010

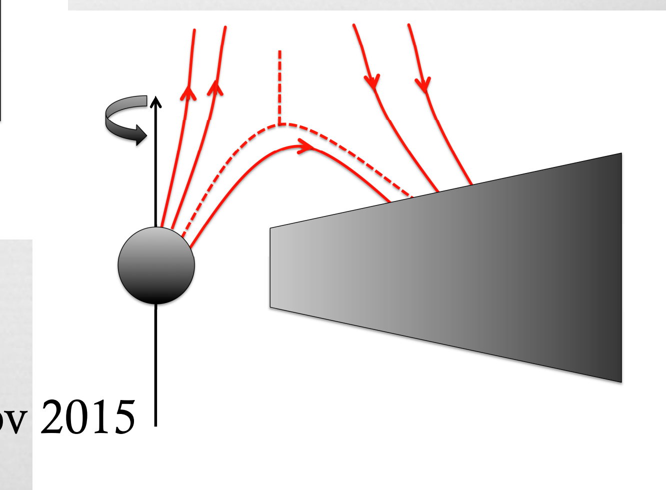
# Case II:
# B-fields amplified locally at the disk






l rotation
p
es open
→ jet forms

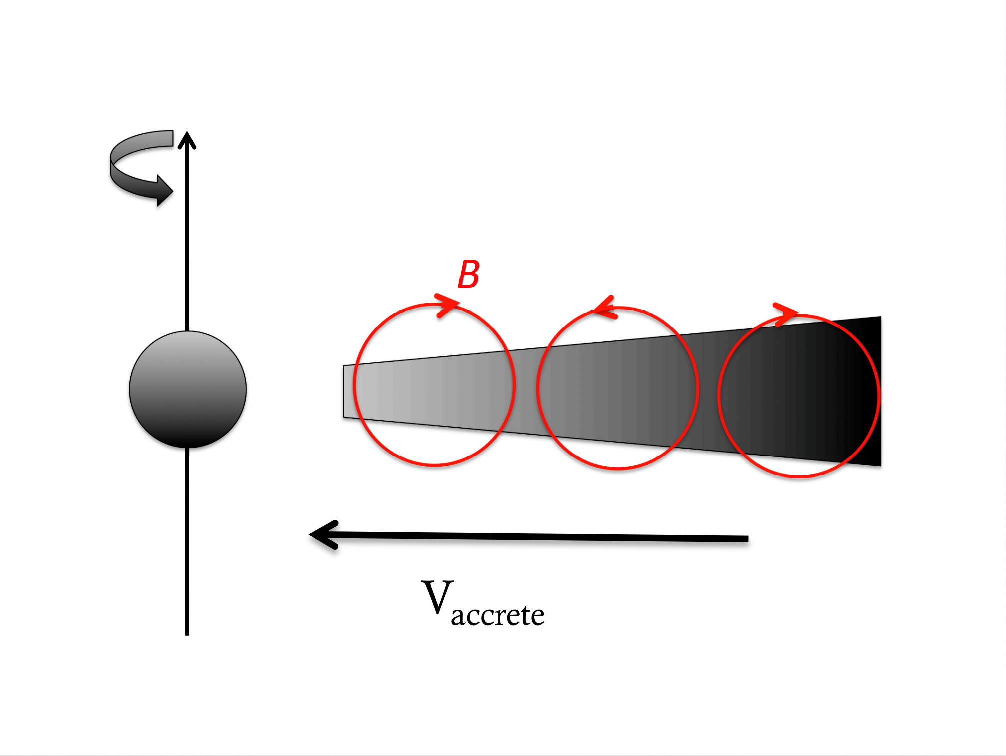


Step I
magnetic loop emerging
from the disk
loop scale ~disk scale
hight

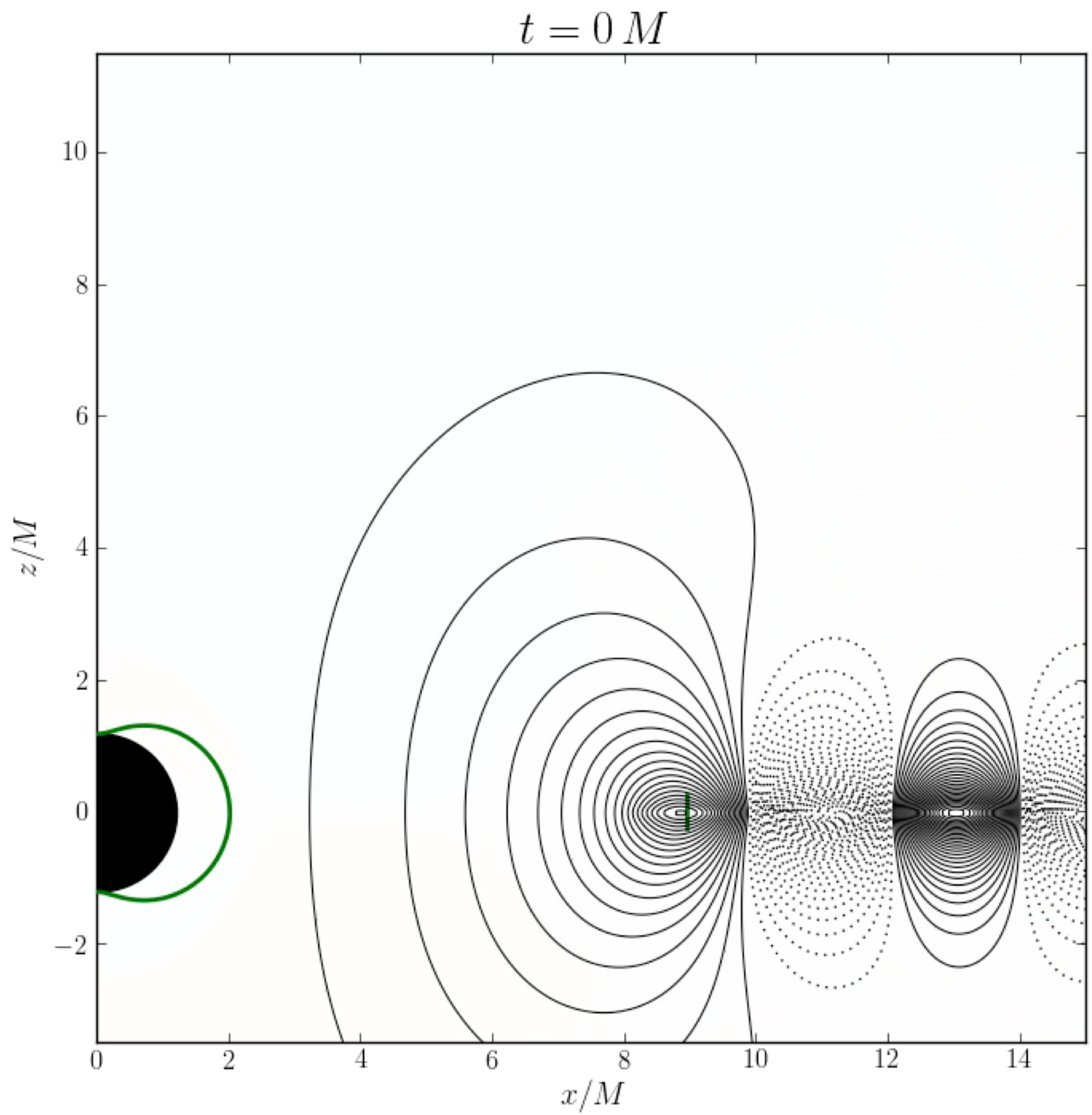
Parfrey, Giannios, Beloborodov 2015

# General relativistic force-free simulations

Parfrey, Giannios, Beloborodov 2015



Parfrey, Giannios, Beloborodov 2015




# Retrograde disc

loop width = 2 $r_g$

loop direction

clockwise

anti-clockwise

Colour: $H_\phi$ positive negative

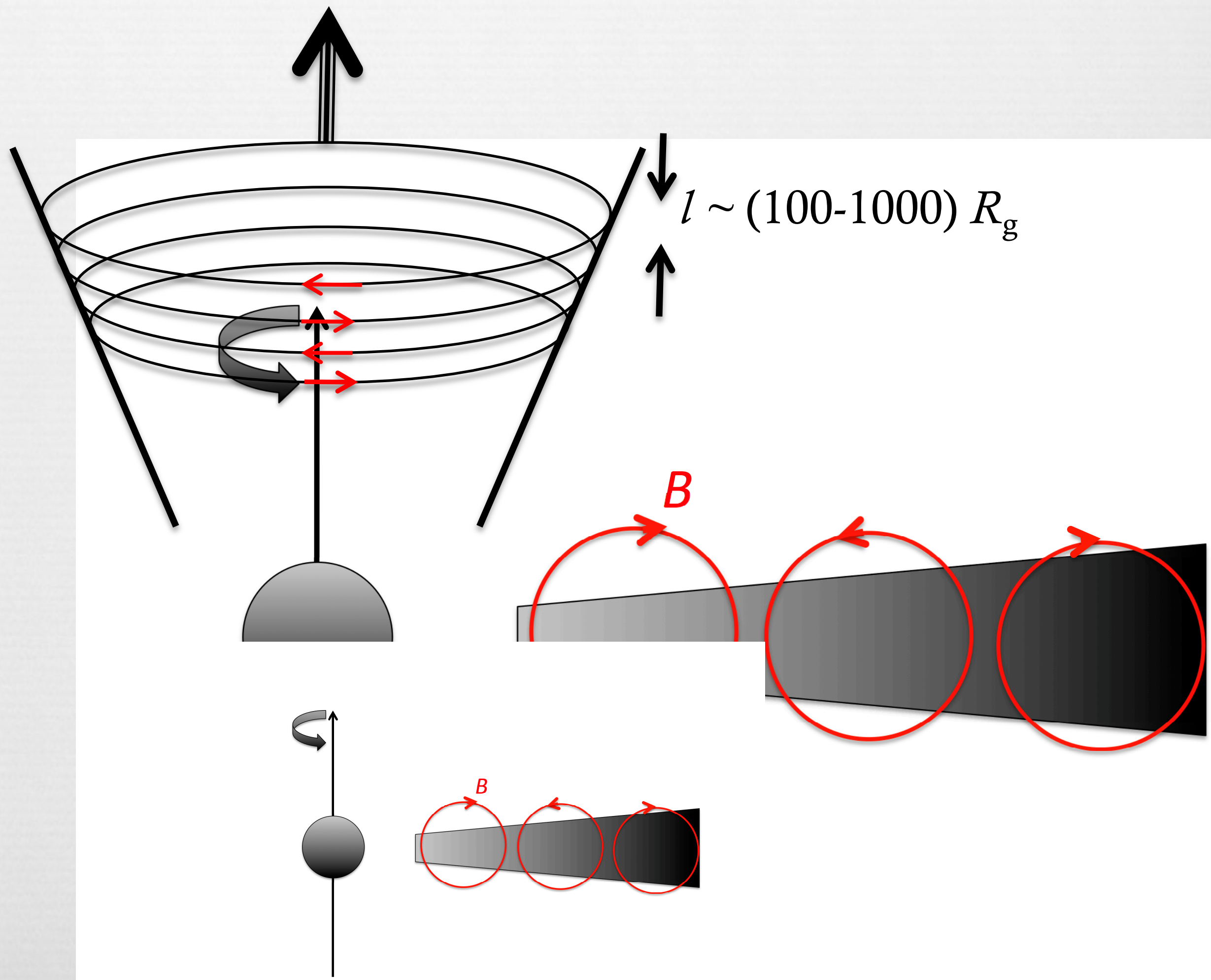
$$v_{\rm accrete} = c/100$$

$$a/M = 0.98$$

# A striped jet

Giannios & Uzdensky 2018

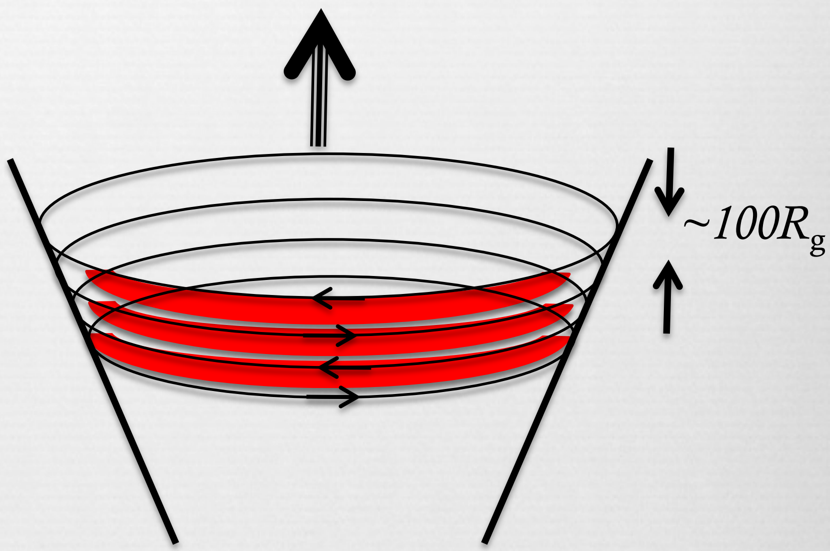
Gives stripes in the jet of width $l \sim (100\text{-}1000)\ R_g$




Reversing the magnetic polarity at the jet base over t ~ (100-1000)$R_g$/c

# Peak dissipation distance in a striped jet

- Jet may contain field reversals on small scale $l \sim (100\text{-}1000)\, R_g$
- magnetic-reconnection becomes effective when




$$t_{exp} \sim t_{rec}$$

where $v_{rec} = \varepsilon c \sim 0.1c$

$z_{rec} / \Gamma_j c \sim \Gamma_j l / \varepsilon c$

$z_{rec} \sim \Gamma_j^2 l/\varepsilon \sim 1\text{pc} \left(\frac{\Gamma_j}{10}\right)^2 \left(\frac{l}{100 R_g}\right)$

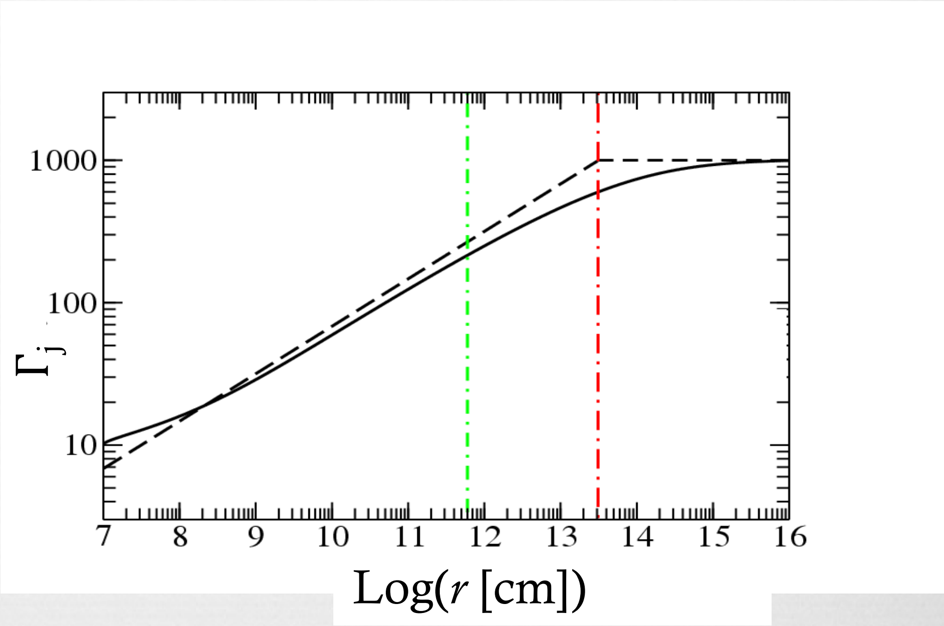
for $M \sim 10^8 M_\odot$

# Striped jet with unique width *l*

- Magnetic field changes polarity on unique scale *l* and reconnects
  Drenkhahn 2002 and Denkhahn & Spruit 2002; see also Lyubarsky & Kirk 2001 for pulsar winds

- Dissipation is *gradual* and leads to bulk acceleration of the flow *and* dissipation

- Dissipation rate rises slows for $z < z_{rec}$ and then drops steeply at larger scale



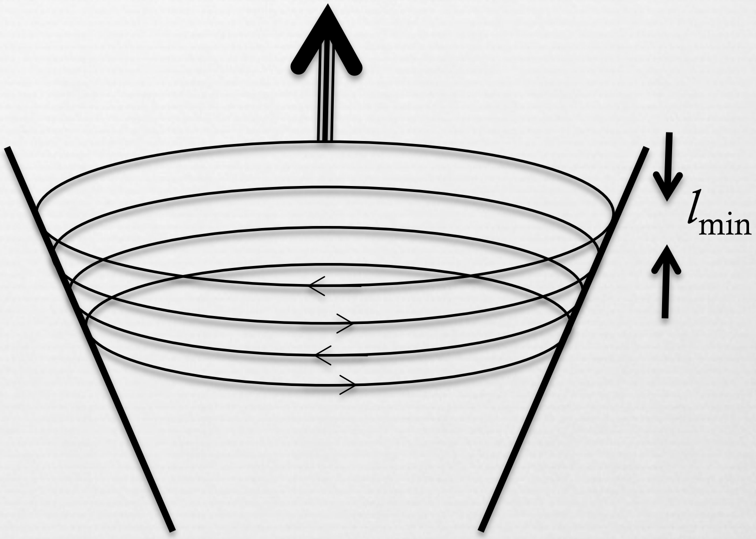

$$\Gamma_j \sim \Gamma_\infty\,(t_{exp}/t_{rec}) \sim \Gamma_\infty\,(z/z_{rec})^{1/3}$$

# Striped jet with a distribution of stripe widths

Distribution of stripe widths $l$

$$\mathcal{P}(l) \equiv \frac{\mathrm{d}P}{\mathrm{d}l} = \frac{1}{(a-1)l_{\min}} \left(\frac{l}{l_{\min}}\right)^{-a}, \quad l \geq l_{\min}$$

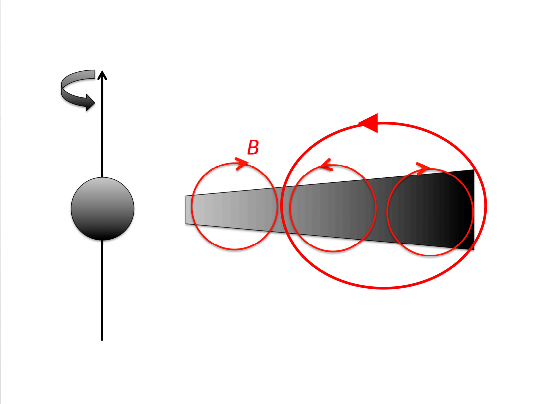
Dominant width scale $l_{\min} \sim 1000\, R_g$




$l = c\,\tau$

$$\mathcal{P}(\tau) \equiv \frac{\mathrm{d}P}{\mathrm{d}\tau} = \frac{1}{(a-1)\tau_{\min}} \left(\frac{\tau}{\tau_{\min}}\right)^{-a}, \quad a > 1, \quad \tau \geq \tau_{\min}$$

Distribution of field reversal timescale at the jet base



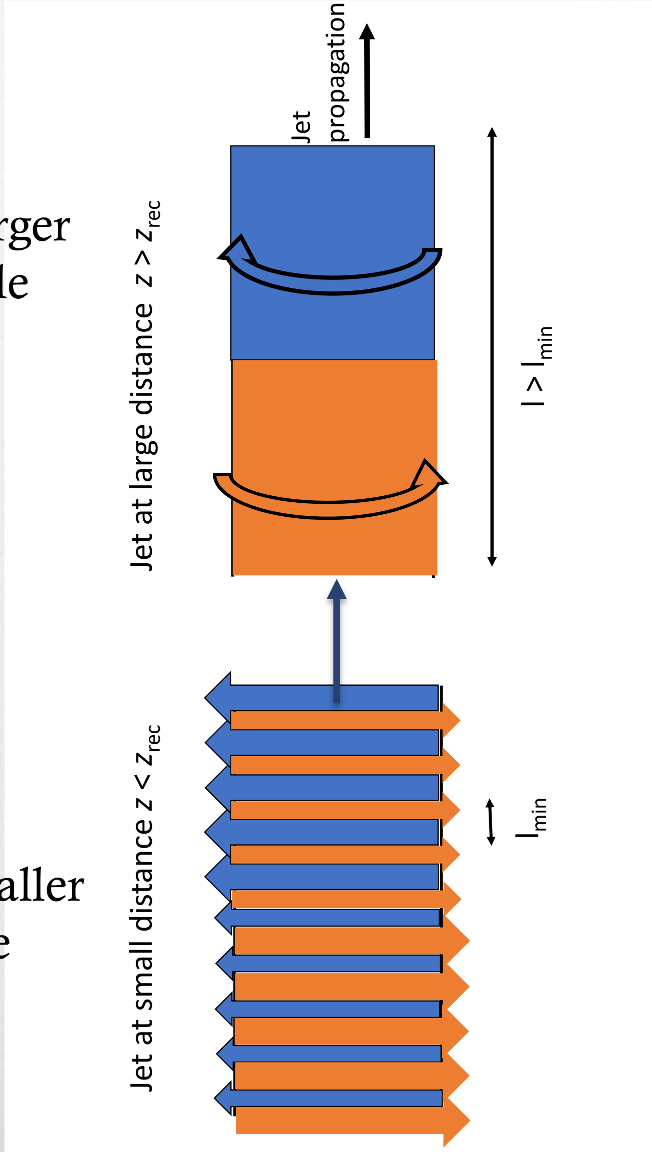
# A multi-width striped jet

Giannios & Uzdensky 2018

Large widths dissipate at larger distances from the black hole

The distribution of widths of the stripes determines the dissipation profile in the jet

Small scales dissipate at smaller distance from the black hole



# Some Math

- The single-width striped jet Drenkhahn & Spruit 2002

$$\frac{\mathrm{d}u}{\mathrm{d}z} = \frac{2\epsilon}{l_{\mathrm{min}}} \frac{(u_\infty - u)^{3/2}}{u^2 u_\infty^{1/2}}$$

- The multi-width stripe jet Giannios & Uzdensky 2018

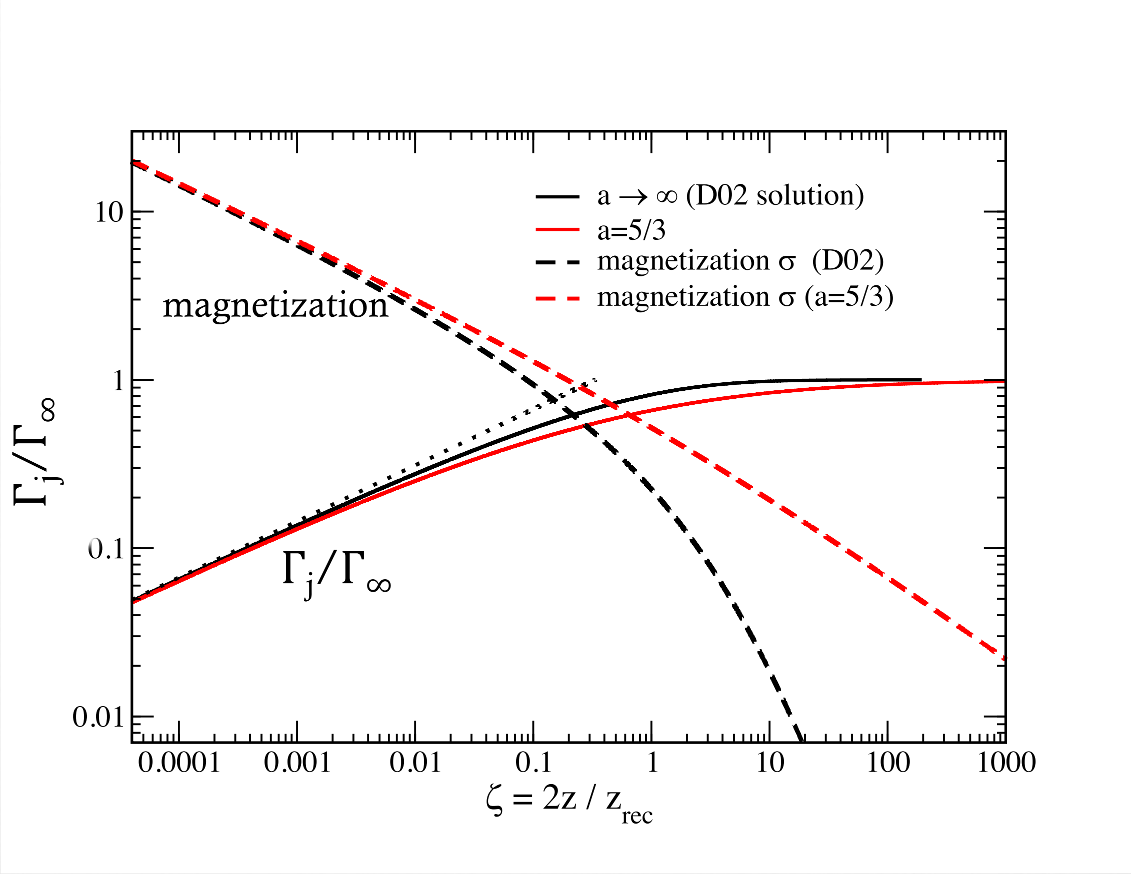
$$\frac{\mathrm{d}u}{\mathrm{d}l_{\mathrm{eff}}} = -u_\infty \mathcal{P}(l_{\mathrm{eff}})$$

$$\frac{\mathrm{d}u}{\mathrm{d}z} = \frac{2\epsilon}{l_{\mathrm{eff}}(u)} \frac{(u_\infty - u)^{3/2}}{u^2 u_\infty^{1/2}}$$

$$\mathcal{P}(l) \equiv \frac{\mathrm{d}P}{\mathrm{d}l} = \frac{1}{(a-1)l_{\mathrm{min}}} \left(\frac{l}{l_{\mathrm{min}}}\right)^{-a}, \quad l \geq l_{\mathrm{min}}$$

# Acceleration/Dissipation

Examples:
i) single stripe width
ii) multi scale with $a$=5/3




Acceleration more gradual for $a$=5/3

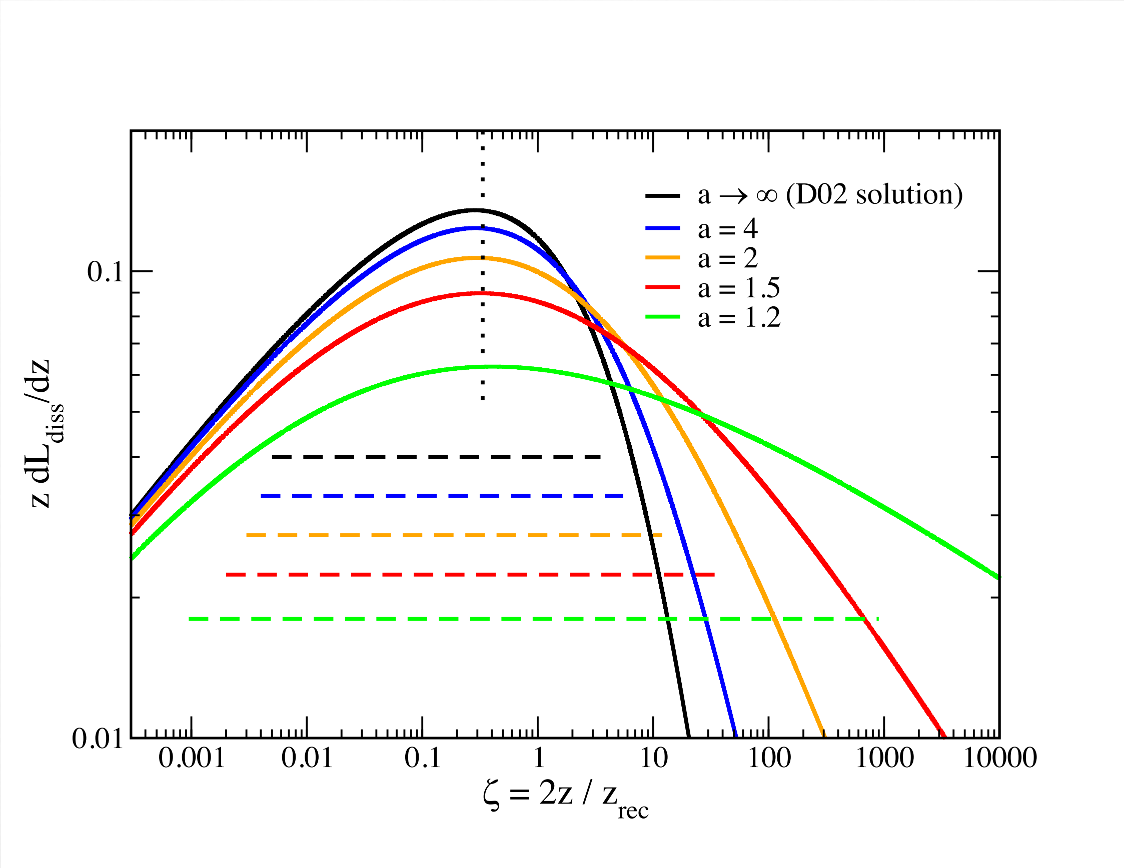
Jet magnetization drops much more smoothly for $a$=5/3

# Jet dissipation profile: very flat

A very extended jet dissipation zone

Extending from ~0.01 $z_{rec}$ to ~100 $z_{rec}$

The smaller *a* the broader the dissipation zone



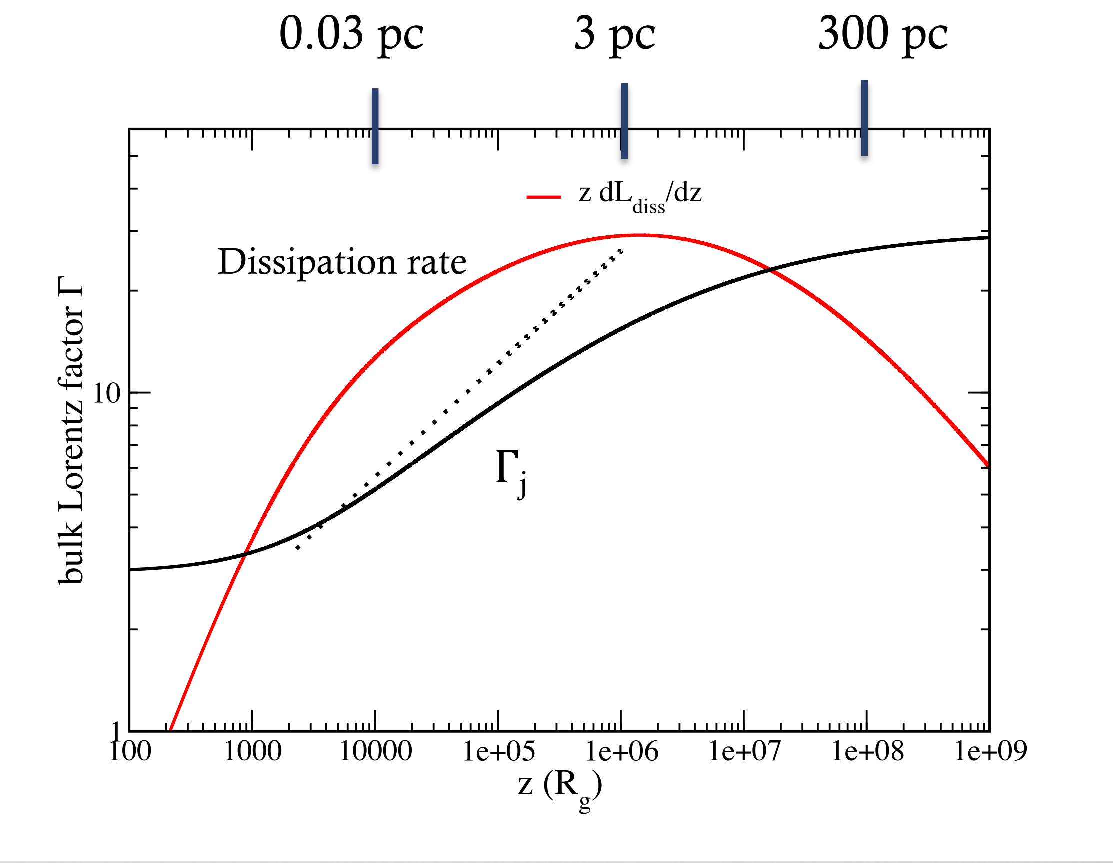
# Implications: Blazars

Inject jet at: $z_o$=100 $R_g$, $\Gamma_o$=3, $l_{min}$ = 1000$R_g$, $\Gamma_\infty$=30

Dissipation region: ~$10^4$ … $10^8$ $R_g$
~0.03pc … 300pc

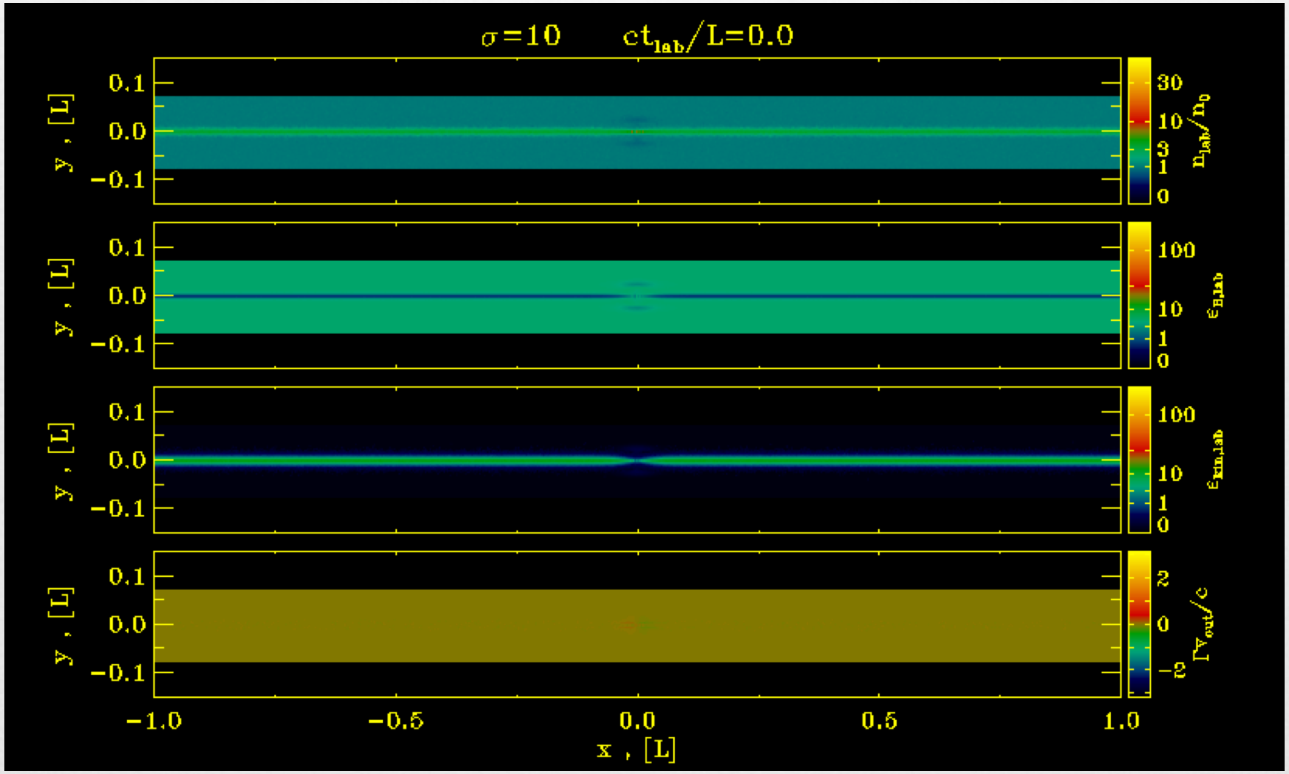
Observed variability timescales:
$t_v \sim z_{diss} / 2\Gamma^2 c \sim (0.1\ldots100) l_{min}/c$
~ days to years!

Jet keeps accelerating out to ~100's pc as seen with VLBI



# From first principle simulations to lightcurves

Sironi, Giannios & Petropoulou 2016

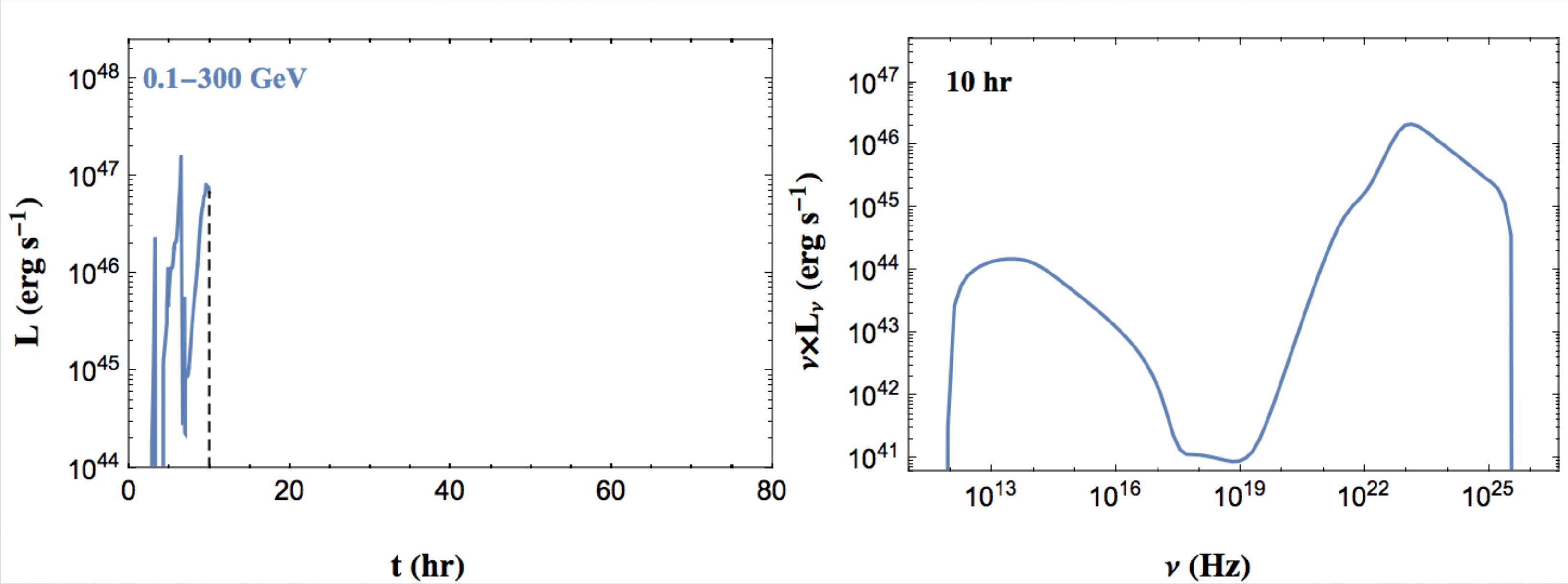


# From simulations to lightcurve: the whole reconnection layer

Christie et al. 2018, in prep.; Petropoulou et al. 2017

Light curve

Spectrum

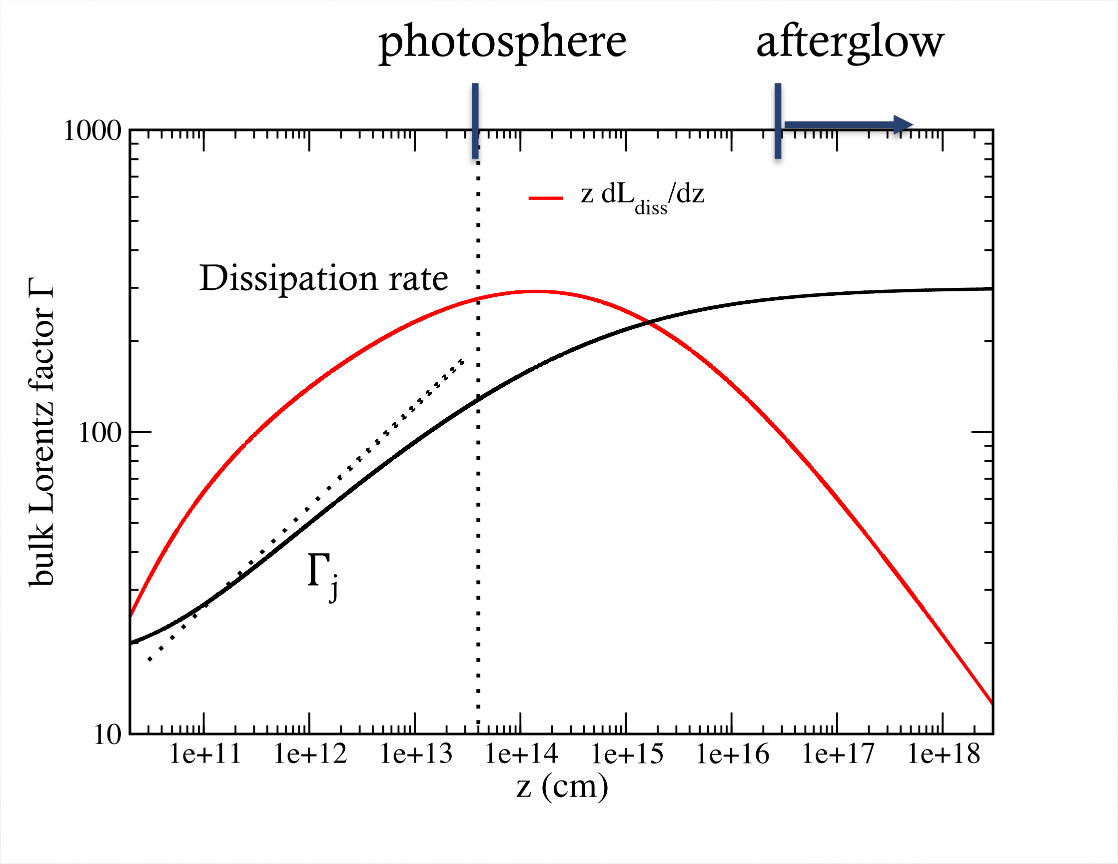


# Implications: GRBs

Inject jet with
$z_o$=3x$10^{10}$ cm, $\Gamma_o$=30,
$l_{min}$ = 1000$R_g$~$10^9$ cm,
$\Gamma_\infty$=300

Dissipation region:
~$10^{12}$ … $10^{16}$cm

~half of the energy is dissipated at optically thick conditions the other half above the photosphere



# Concluding

- A change in the density profile of the ambient gas maybe set the location for blazar jet emission

- The disk may amplify the jet driving B fields
  - The polarity reverses on the inner disk time-scales →

    → a striped jet

- Striped jets have an essentially flat dissipation profile extending over ~4 - 5 order of magnitude in distance

- The model relates the *timescales at the inner disk* with the *length-scales of the jet dissipation zone*