Macroscopic & Microscopic Instabilities in Relativistic Jets

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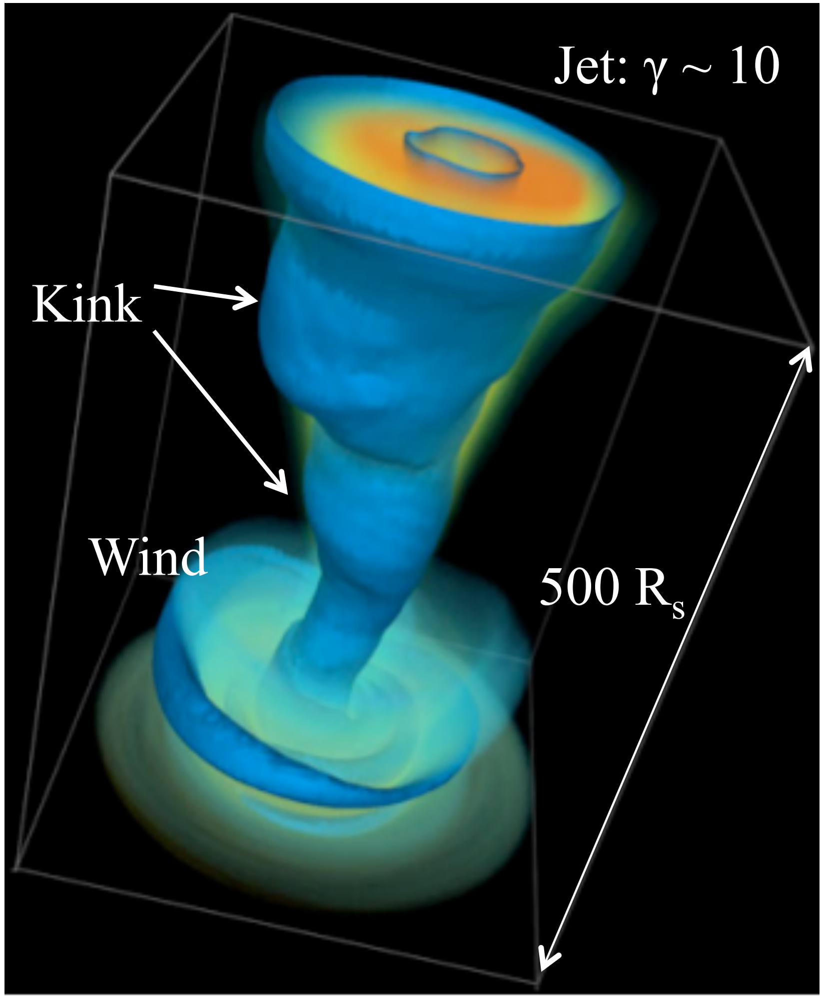
The Innermost Regions of Jets & Their Magnetic Fields
Granada, Spain , June 2013

Introduction

- *Macroscopic Instabilities*
  - KHI (velocity shear driven)
  - CDI (current driven)
- *Macroscopic Observables*
  - Pinch/Twisted structures
  - Flow & Pattern speeds
  - B-field structure via polarization
- *Microscopic Instabilities*
  - Filamentation (2-stream)
  - KKHI (velocity shear)
  - Reconnection
- *Microscopic Observables*
  - Spectrum (Synchrotron/Jitter/IC)
  - Energy distribution
- *M87* – Implications

McKinney & Blandford (2009)

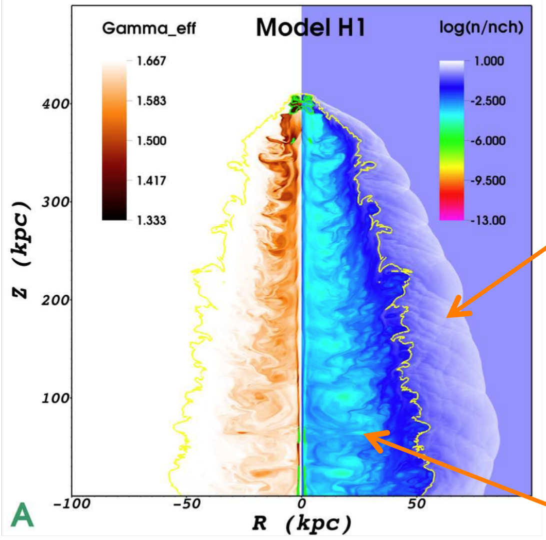


Kinked jet basically stable structure

KHI Spine Sheath Mixing

(Walg et al. 2013)

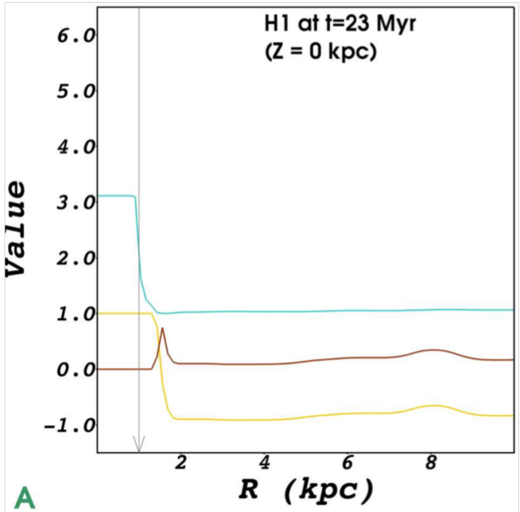
Uniform Jet

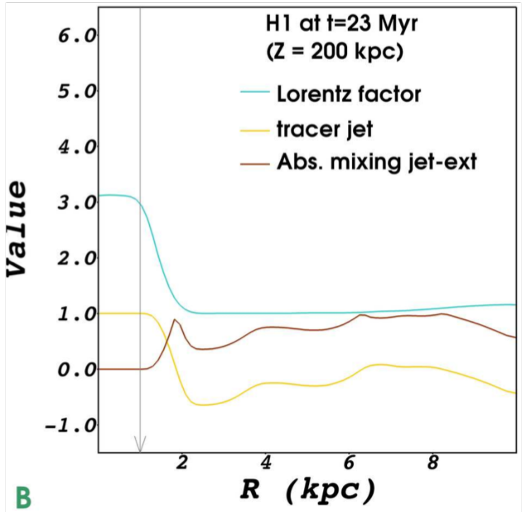


Shocked Ambient Material

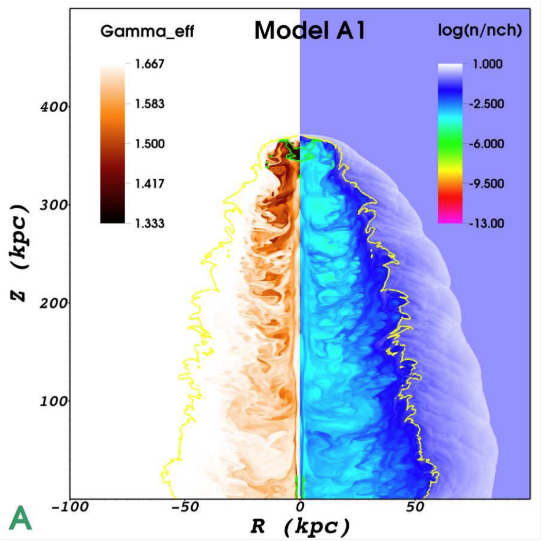
Tenuous Shocked Jet Material

Uniform Jet & Tenuous Cocoon

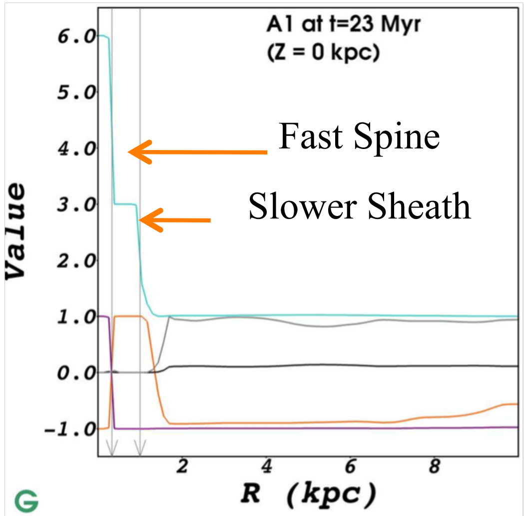


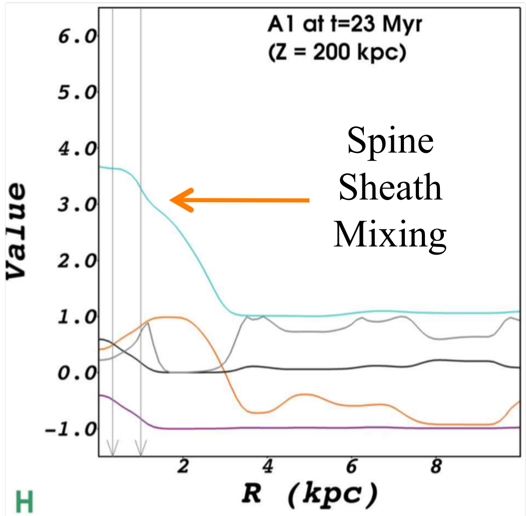


Spine Sheath Jet



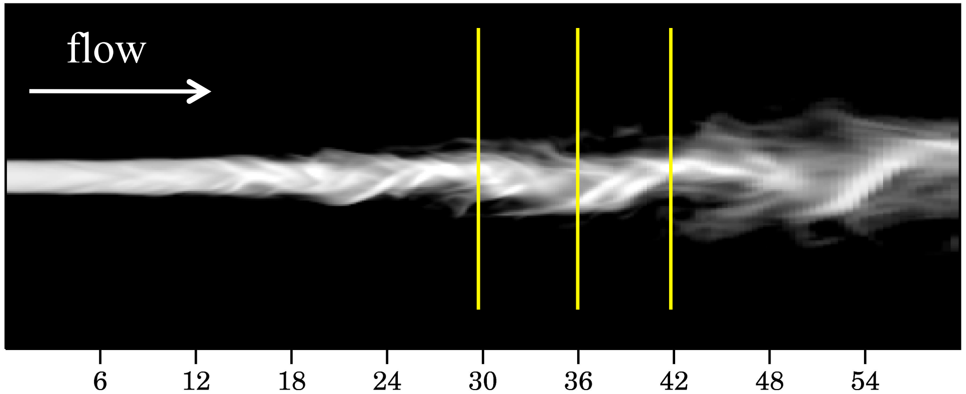
Fast Spine & Denser Slower Sheath



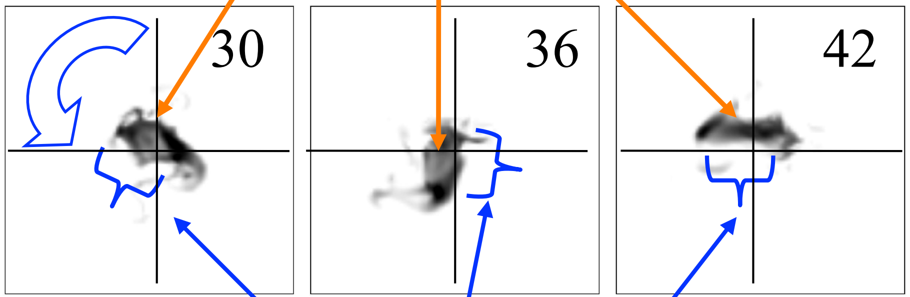


The KH Normal Modes

Intensity Image & Magnetic Pressure
Cross Sections (Hardee et al. 1997)



Helical (S) Mode Twist Offset



Elliptical (S) Mode Twisted Filaments

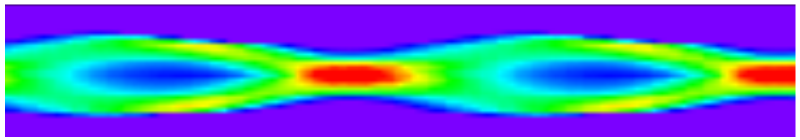
Pinch
(F)undamental & (B)ody
Modes

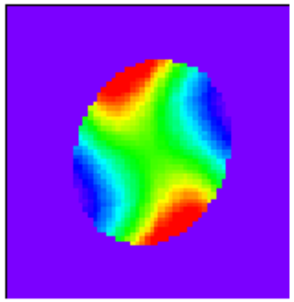
Helical, Elliptical, ...
(S)urface & (B)ody Modes

Fastest Growing: $\lambda^* \alpha \ \gamma M R$

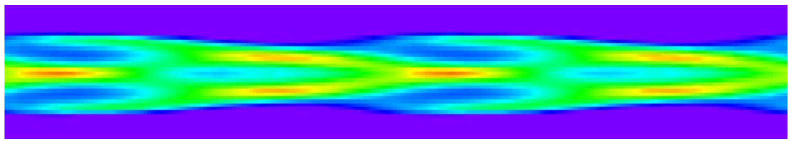
Growth length: $l^* \alpha \ \gamma M R$

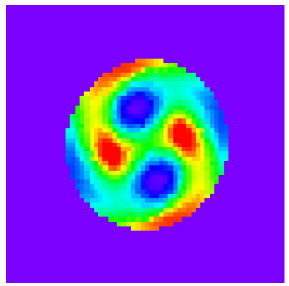
Pressure structure of Elliptical (S) mode





Pressure structure of Elliptical (B) mode

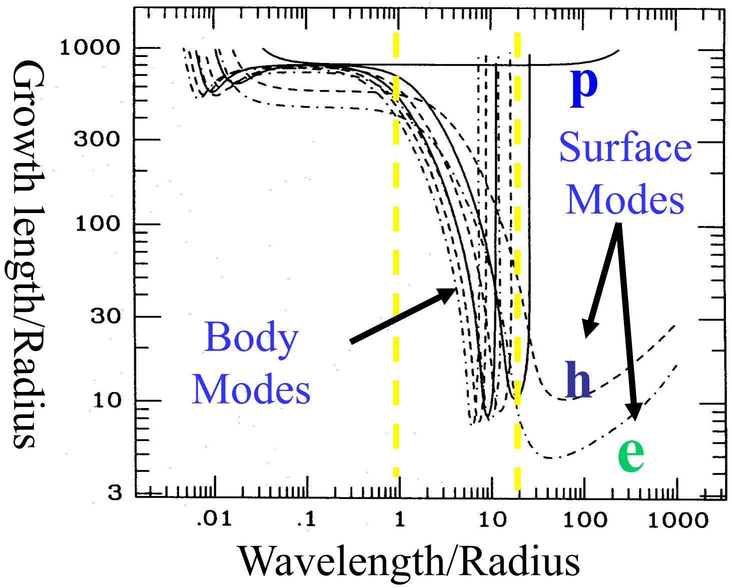




Shear Layer Stabilization

(Birkinshaw 1991)

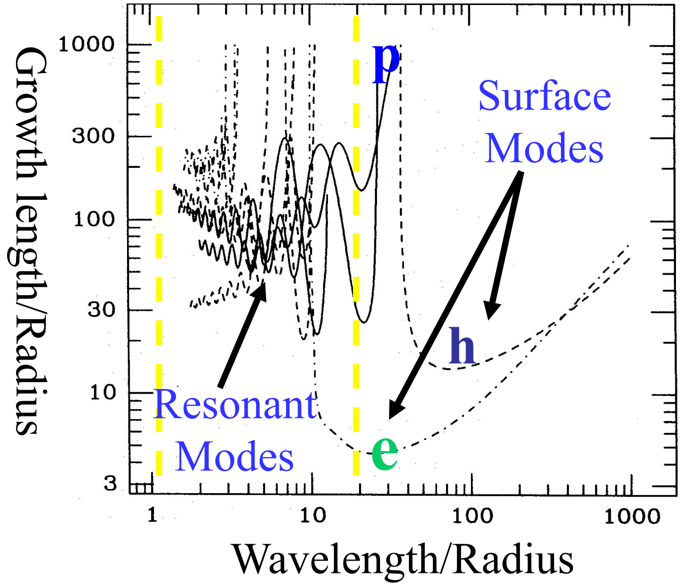
3D: No Shear Layer



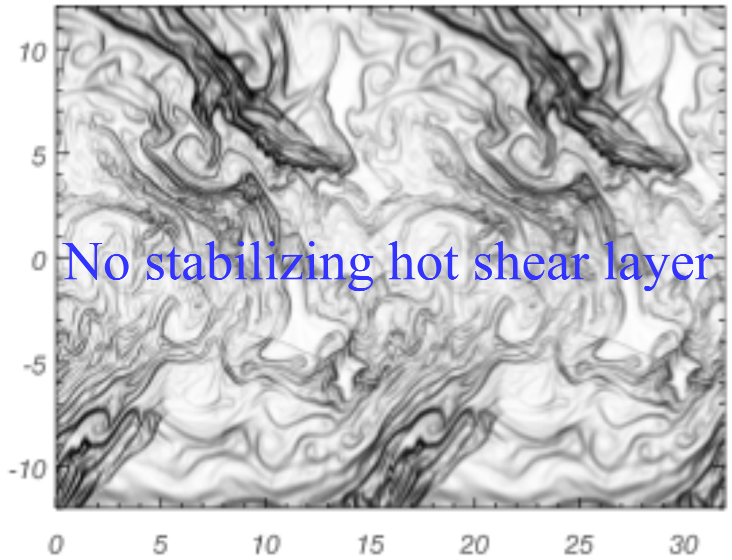
Minor effect:
H & E (S)
modes

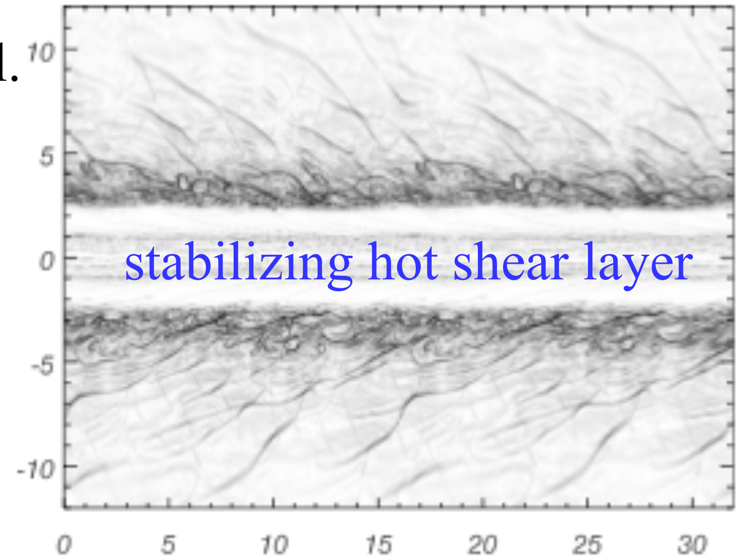
Major effect:
shear
resonances

3D: Shear Layer



(Perucho et al.
2005, 2007)



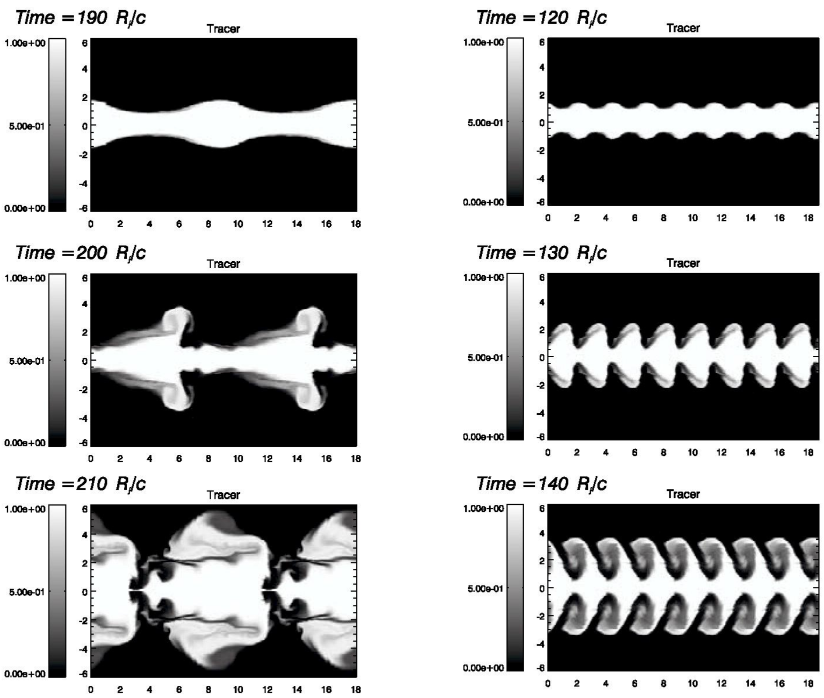


Short λ Saturation/Stabilization

(Pinch Mode - Perucho et al. 2004 ; Helical Mode – Xu et al. 2000)

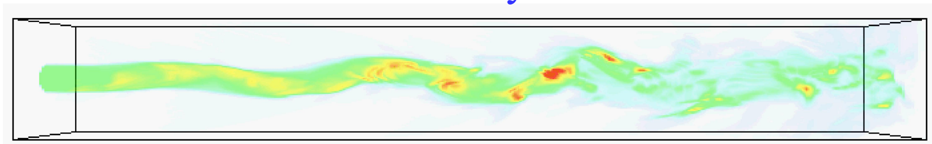
Pinch Mode:

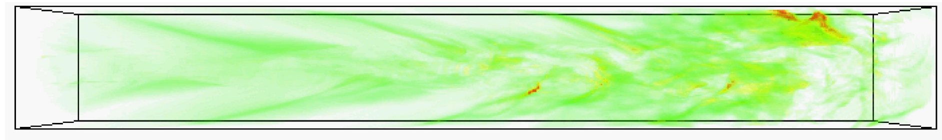
Long λ Disruption ; Short λ Saturation



Helical Mode: Long λ Disruption

Density

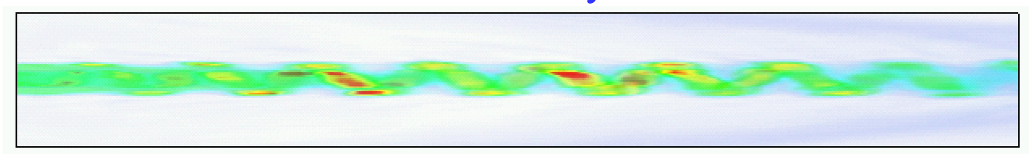




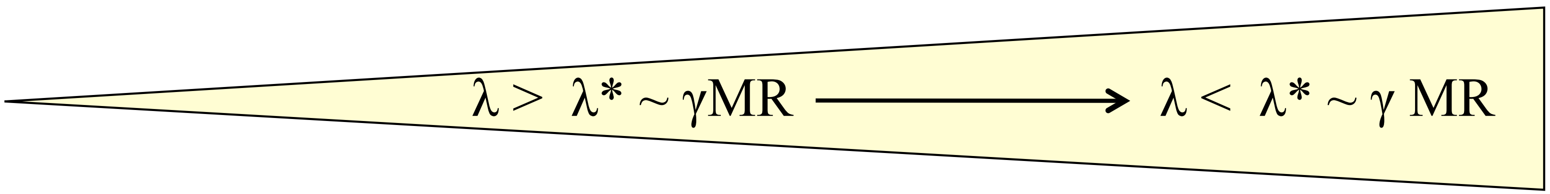
Temperature: box of shocklates

Helical Mode: Short λ Saturation

Density



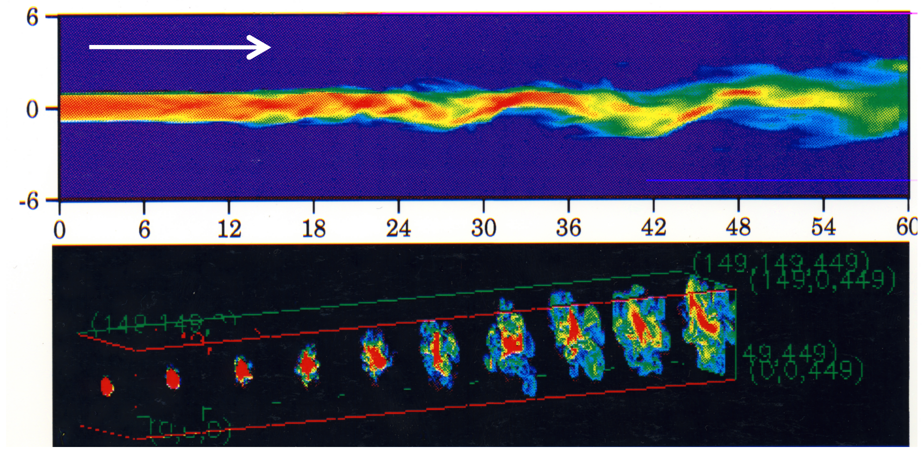
Wave Advection along expanding jet



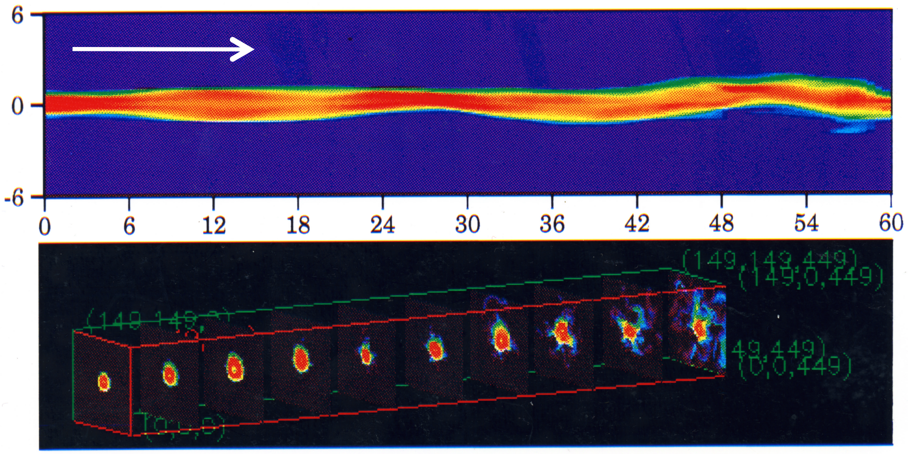
Magnetic Fields & KHI

(Rosen et al. 1999)

Poloidal B

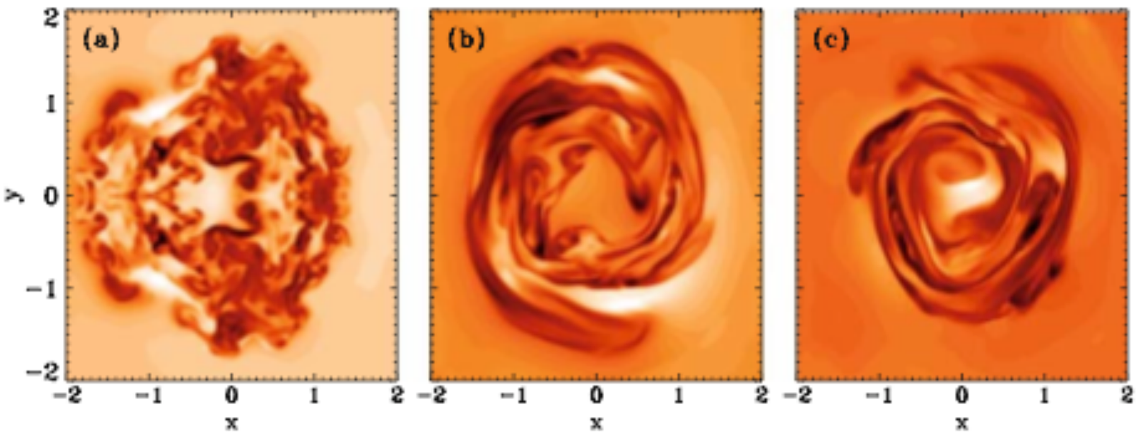


Helical B



Magnetic tension suppresses KHI higher order modes

Poloidal B   Increasing Helicity ➔



Magnetic field suppresses KHI induced vortices

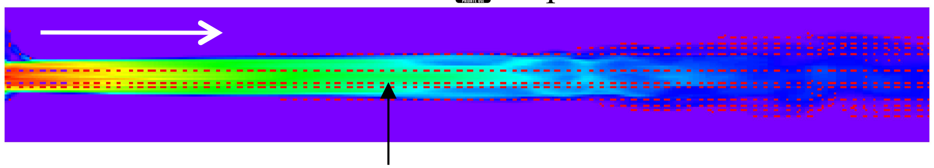
(Baty & Keppens 2002)

Helical Field Helps Maintain Spine Sheath Configuration

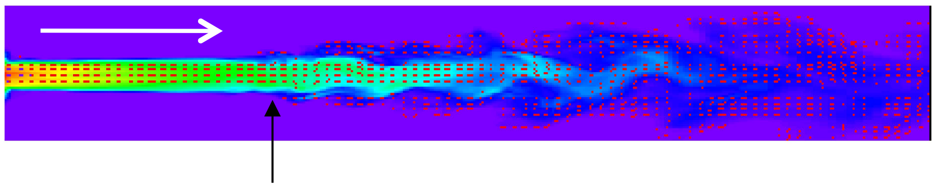
Sub-Alfvénic KH Stabilization

Hardee & Rosen (1999, 2002)

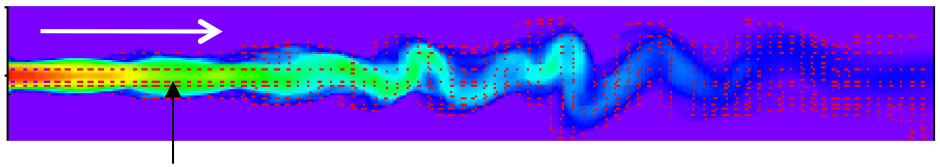
Poloidal: $B_{\phi}/B_p \sim 0$



$B_{\phi}/B_p \sim 0.05$



$B_{\phi}/B_p \sim 0.4$

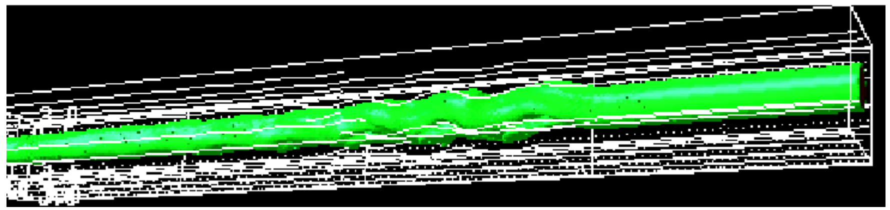


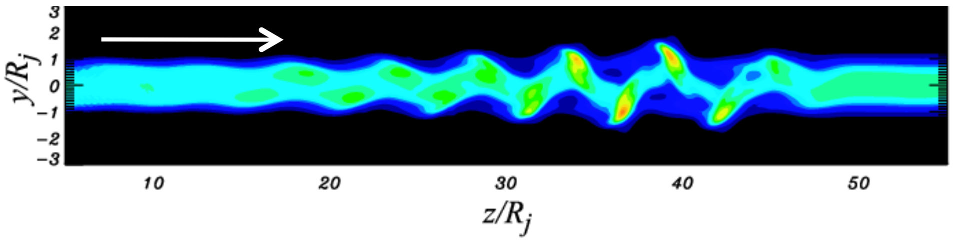
Alfvén point transition

KH Stable when sub-Alfvénic

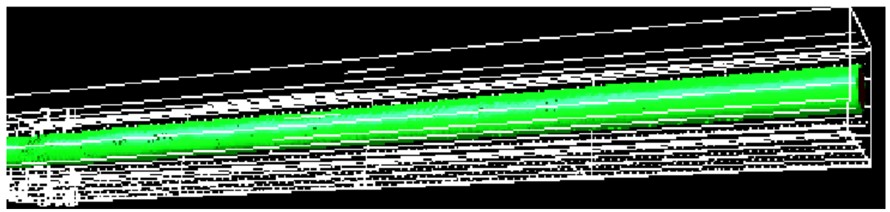
Mizuno et al. (2007)

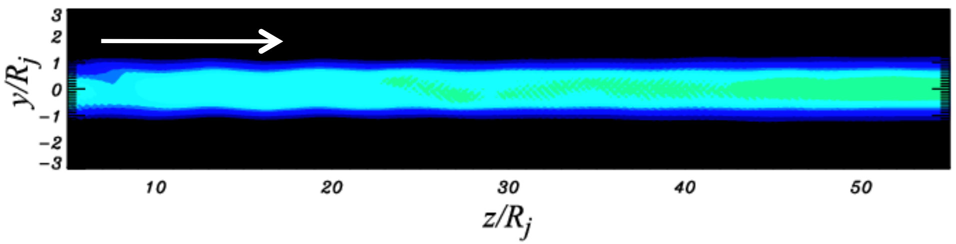
Super-Alfvénic velocity shear





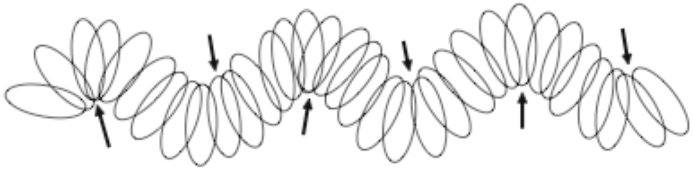
Sub-Alfvénic velocity shear

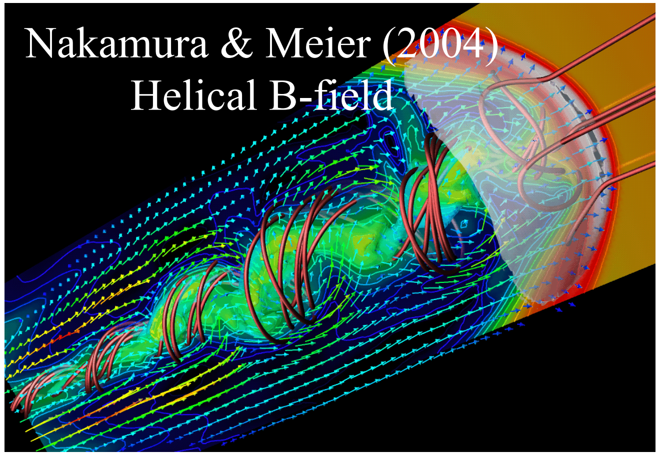




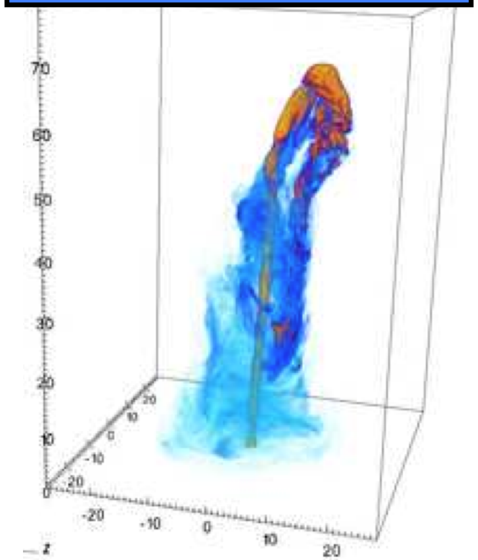
Current Driven Instability

Magnetic pressure (Baty 2005)

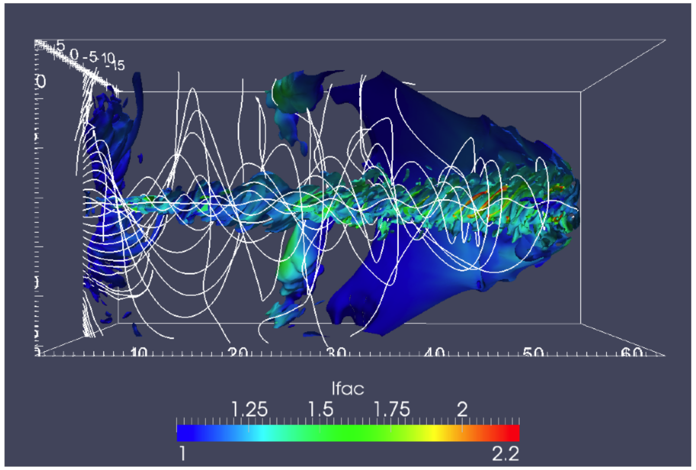




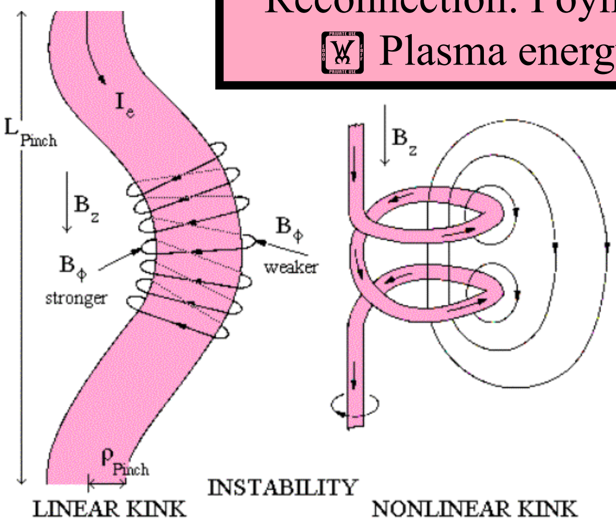
Mignone et al. (2010)
Toroidal B-field



Porth (2013)
B-Field helicity radial decrease
More stable



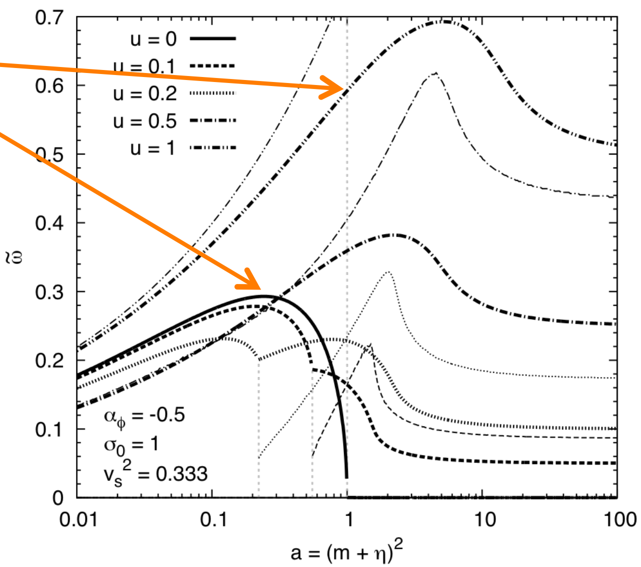
Reconnection: Poynting flux
Plasma energy flux



CDI Growth:
Velocity shear
Static no shear

Analytical Analyses:
Istomin & Pariev (1994, 1996)
Begelman (1998)
Lyubarskii (1992, 1999)

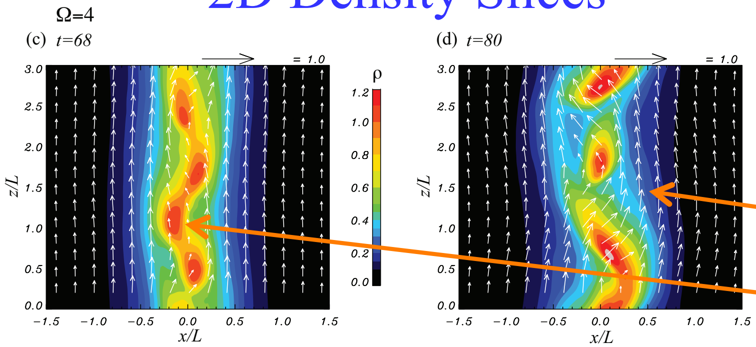
Nalewajko & Begelman (2012)



CDI Kink Destabilzation/Stabilization

(Mizuno et al. 2009,2012)

2D Density Slices



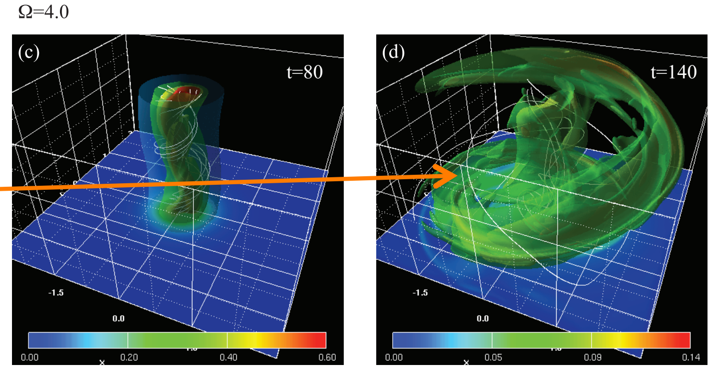
Increased inner helicity

Multiple Kink Modes

Outer Kink

Inner Kink

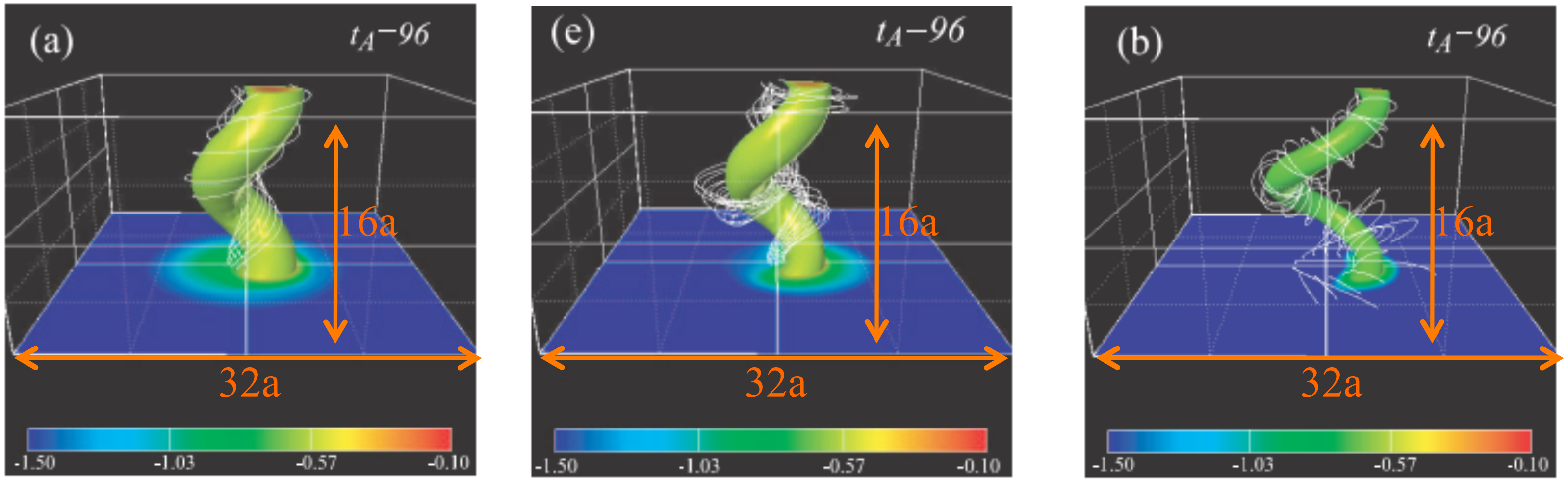
3D Density Isosurfaces



a = radius ~ $(B_{\varphi})^{Max}$

Helicity Decreasing | Constant | Increasing with radius

Periodic



Helicity decreasing & Density increasing with radius ➔ Slower growth

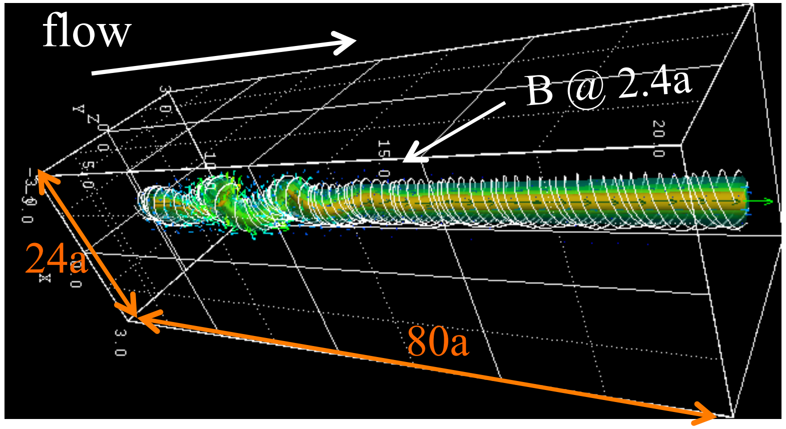
[Agrees with non-relativistic results of Appl et al. (2000); Lery et al. (2000)]

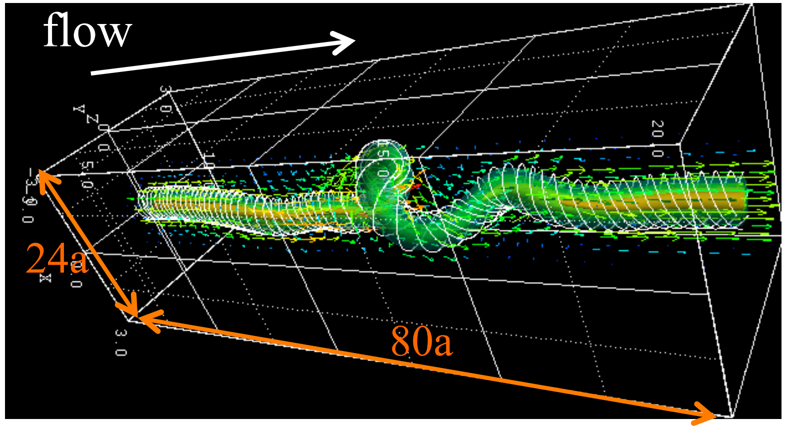
CDI kink: Spatial Growth

(Constant pitch, density decrease: $v_j = 0.2\ c$, $v_A \leq 0.36\ c$)

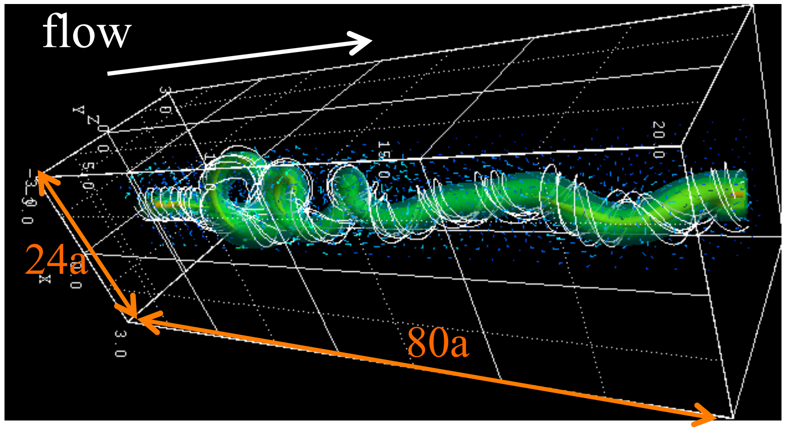
R_j = velocity shear radius   a ~ radius B_φ maximum

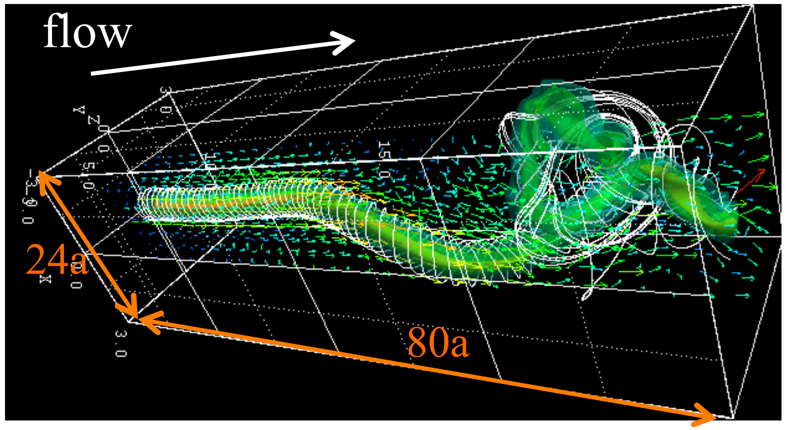
$R_j = a/2$ (flow through kink) $R_j = 4a$ (kink moves with flow)





t = 55



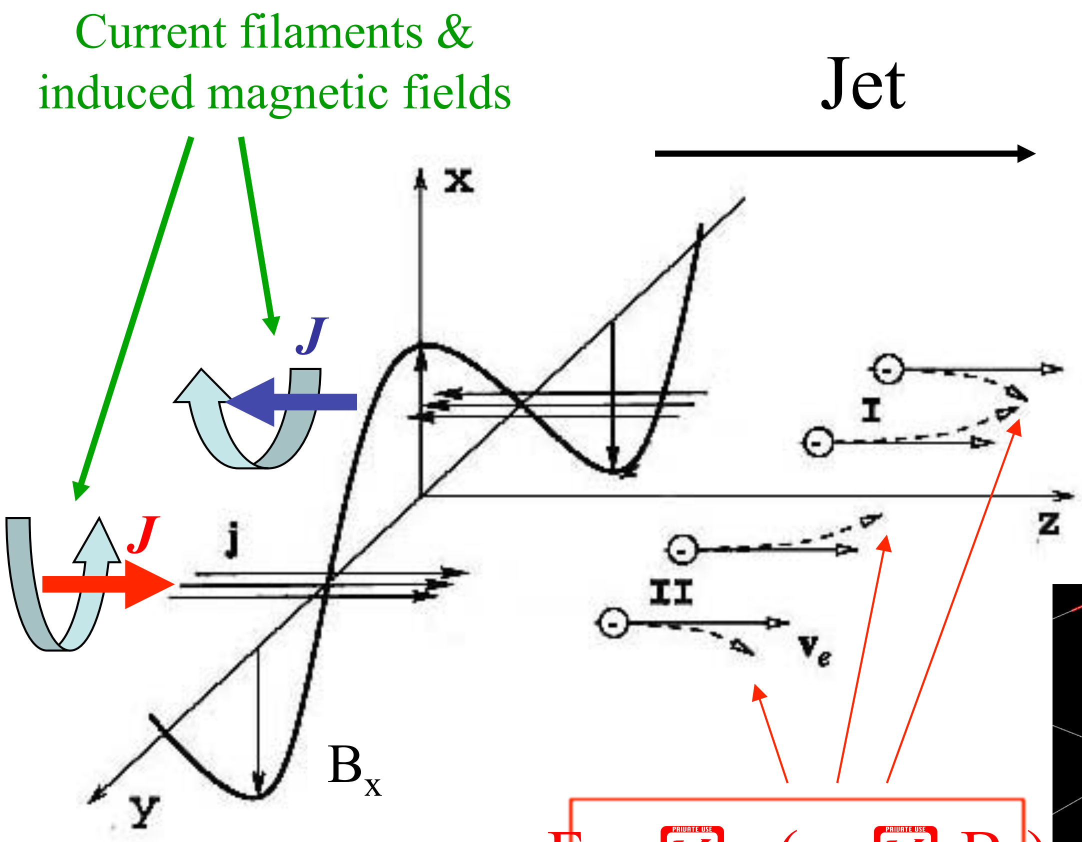


t = 100

Partial stabilization by kink advection with flow

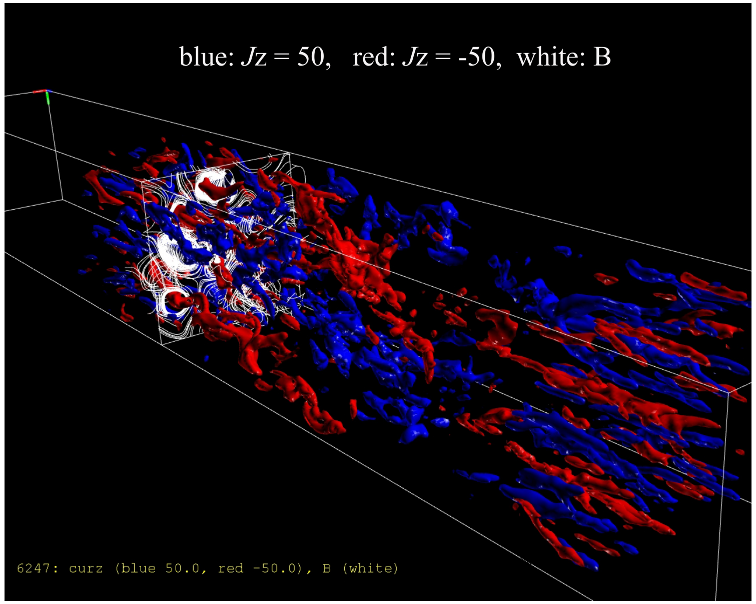
(Mizuno et al. in progress)

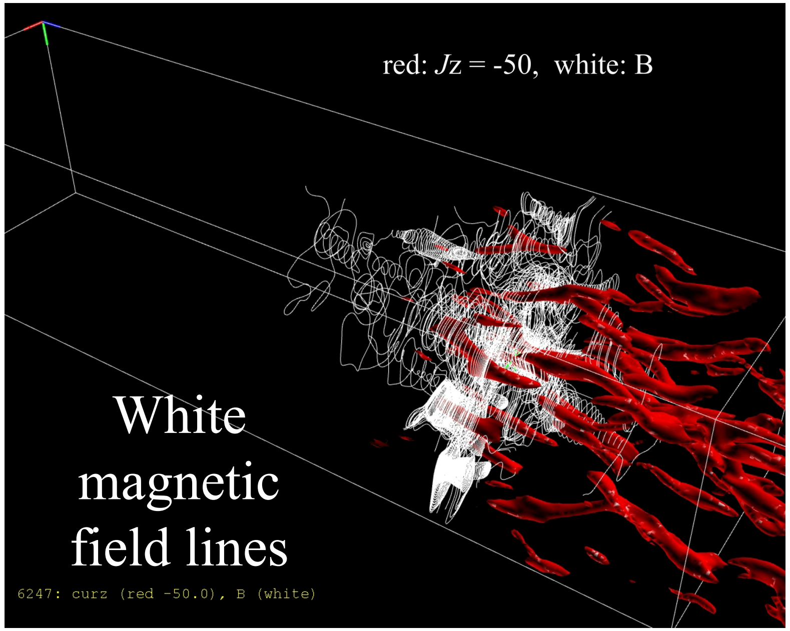
Filamentation Instability - Shocks



$F = -e\,(v_z \times B_x)$

Acceleration timescale ~ few $1000(\omega_p)^{-1}$

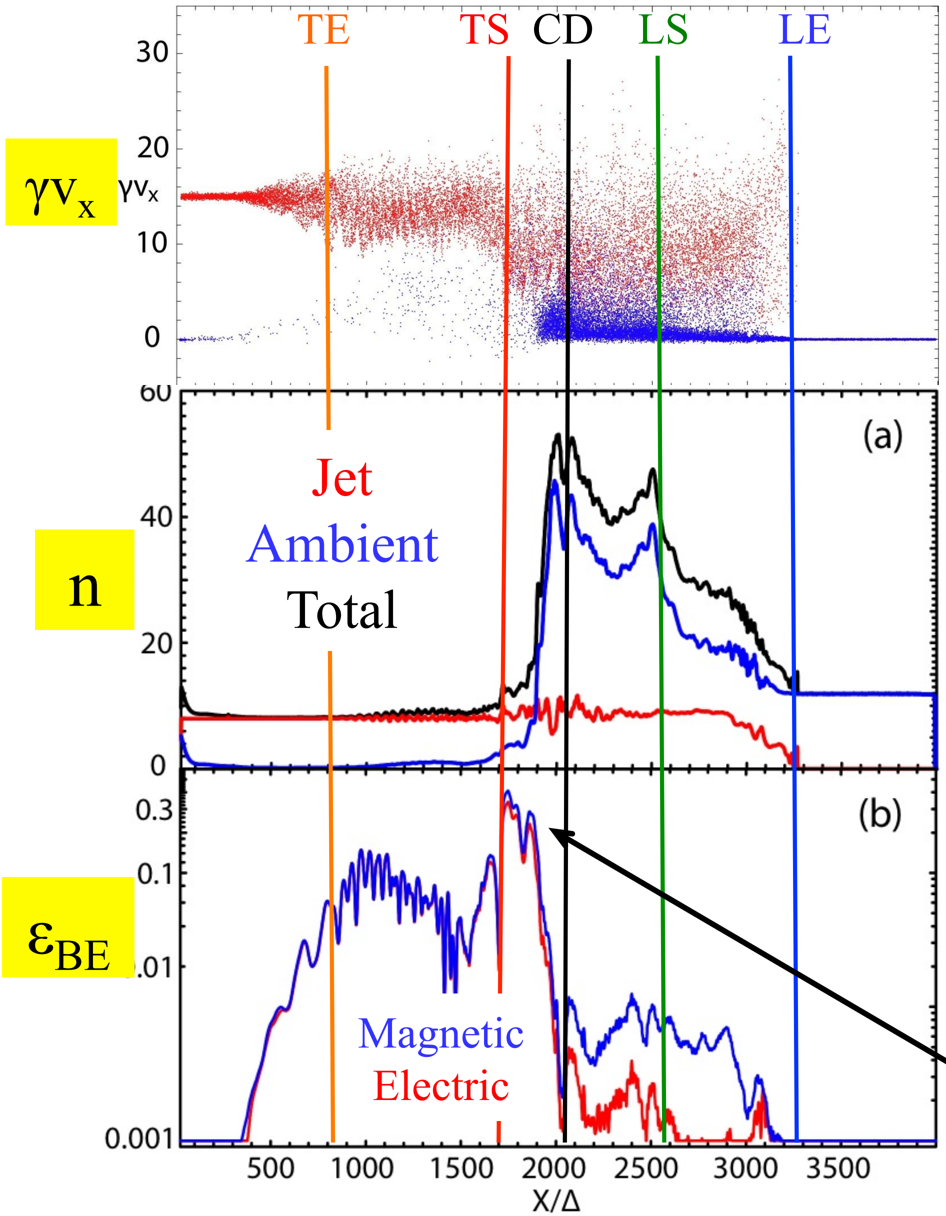


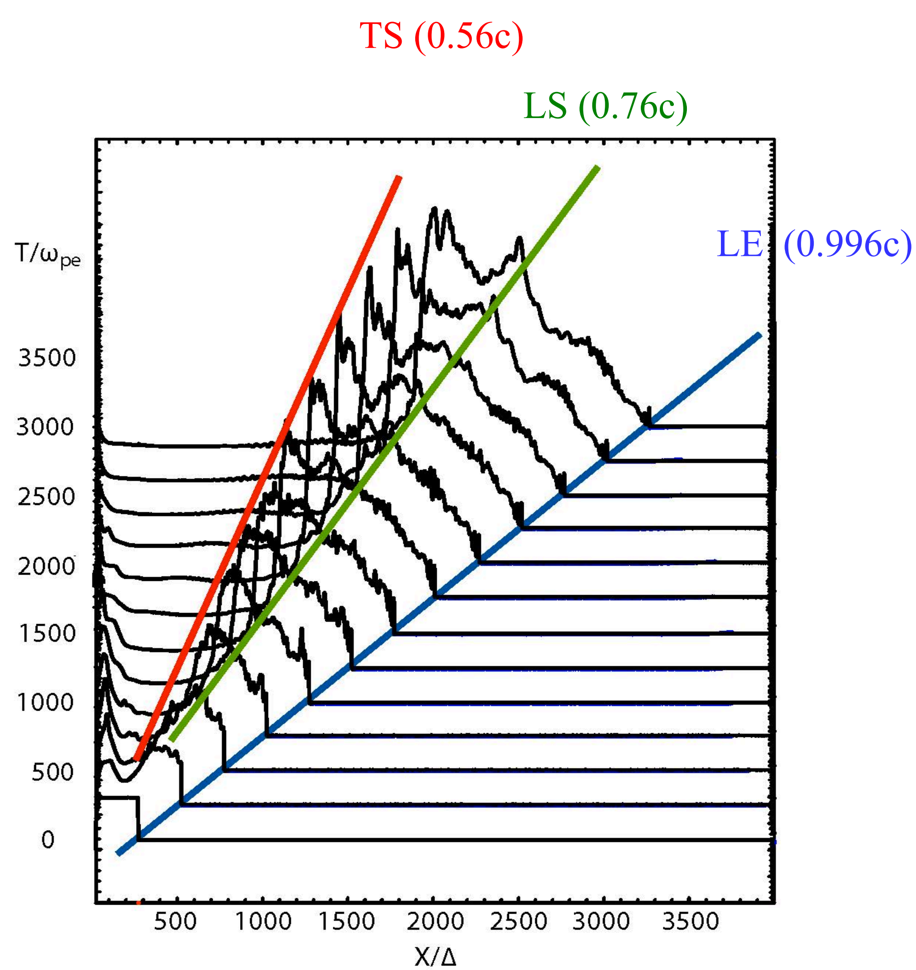


Filamentation Instability & Shock Structure

Jet & Ambient ($e^{\pm}$) Particles

Nishikawa et al (2009)

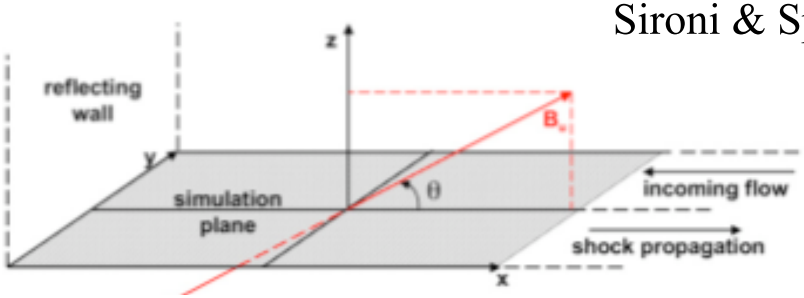




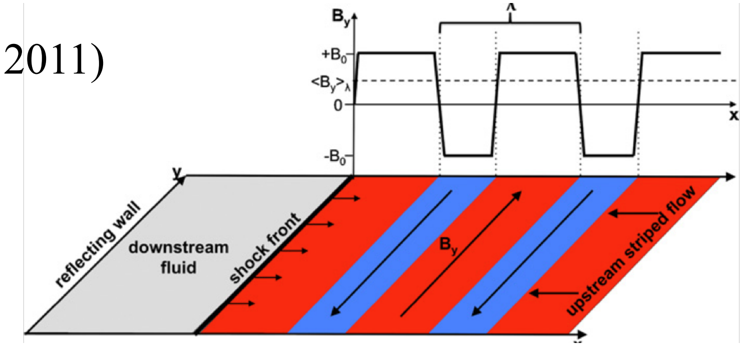
$\varepsilon_{BE} = \rho_{BE}/\rho_{KE} \sim 0.3$

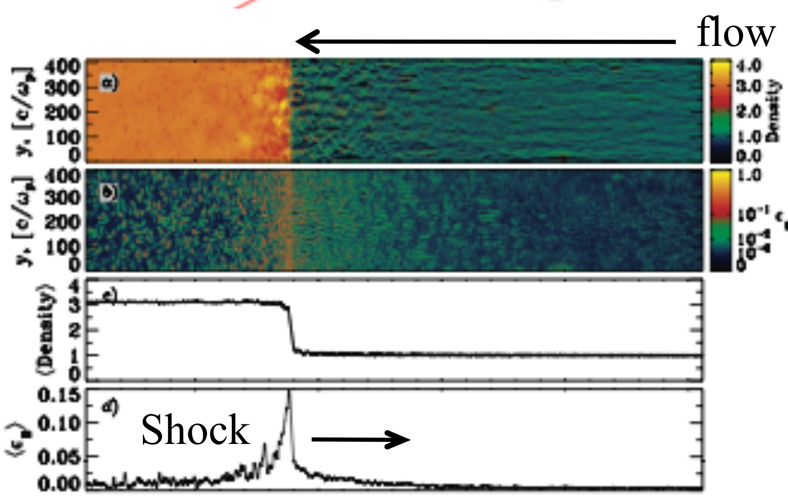
Emission & Reconnection

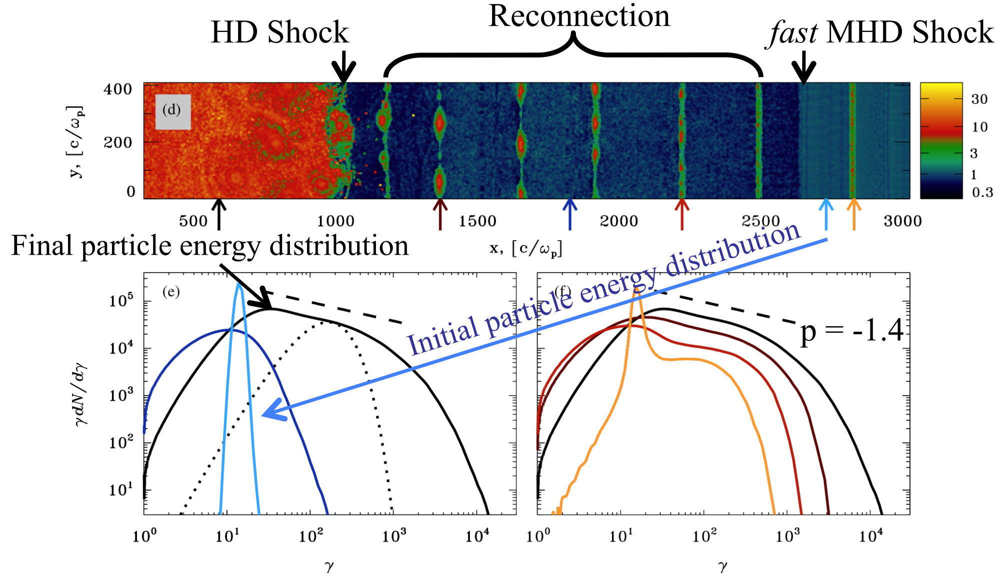
Sironi & Spitkovsky (2009a,b; 2011)



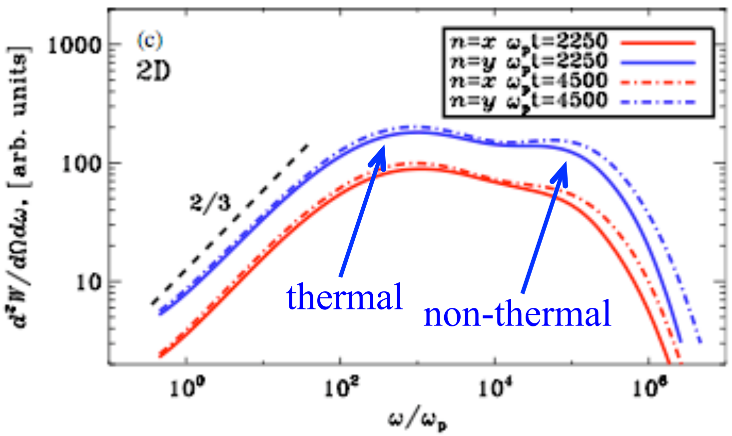
$\gamma_{\rm flow} = 15$



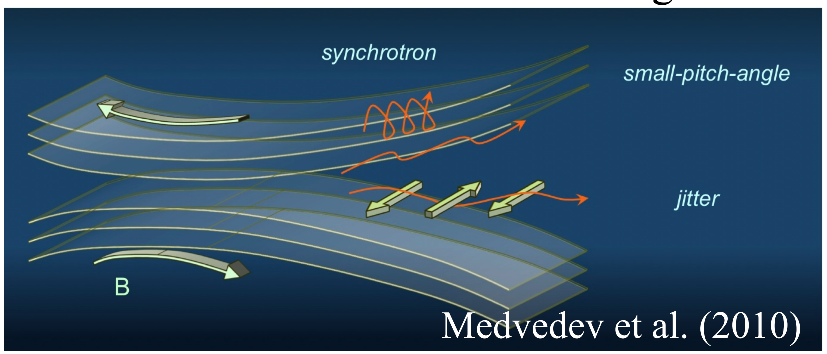




Synchrotron spectrum

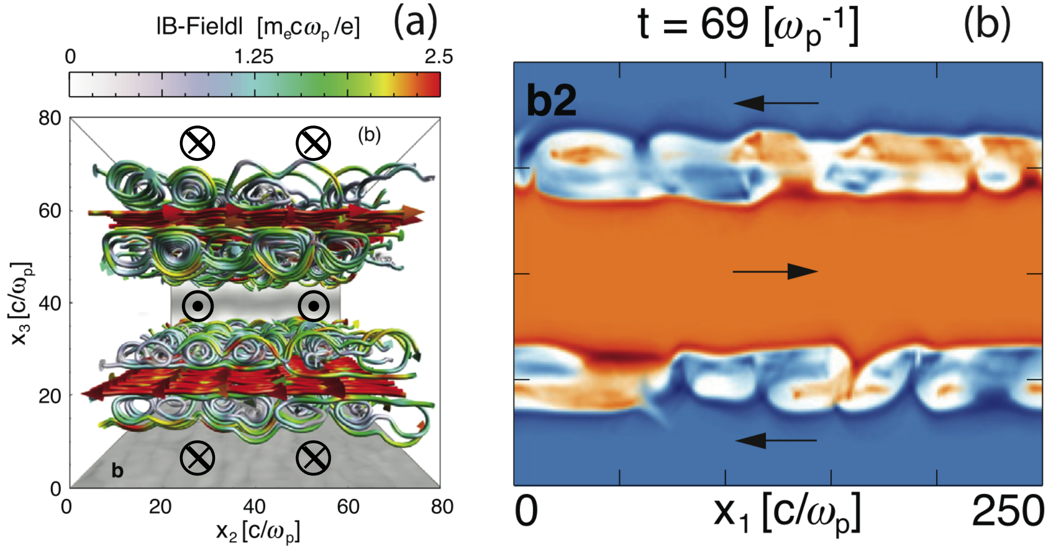


Emission from Reconnection Region

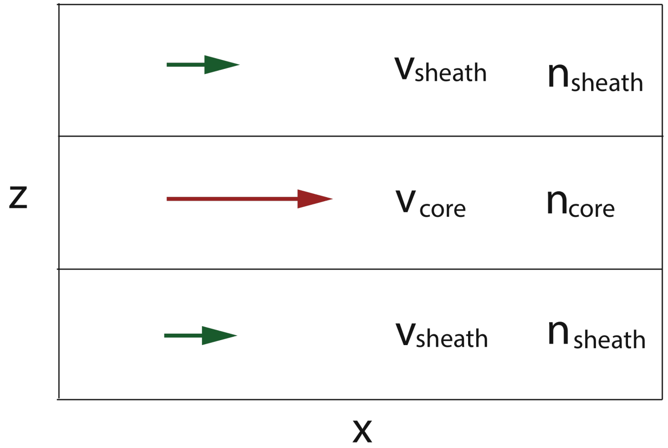


Kinetic Kelvin Helmholtz Instability

Alves et al. 2012: counter-streaming

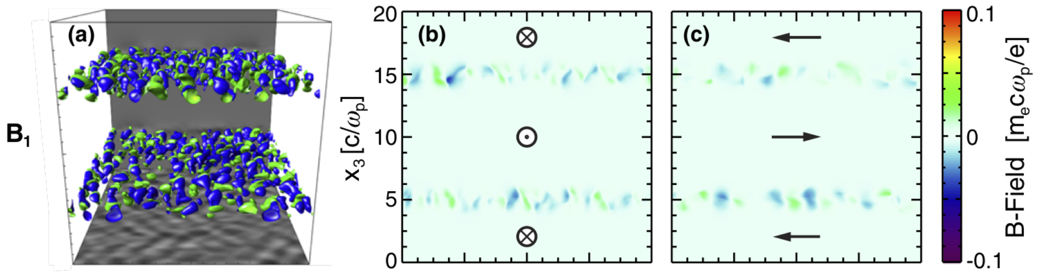


Nishikawa et al. in prep; core-sheath

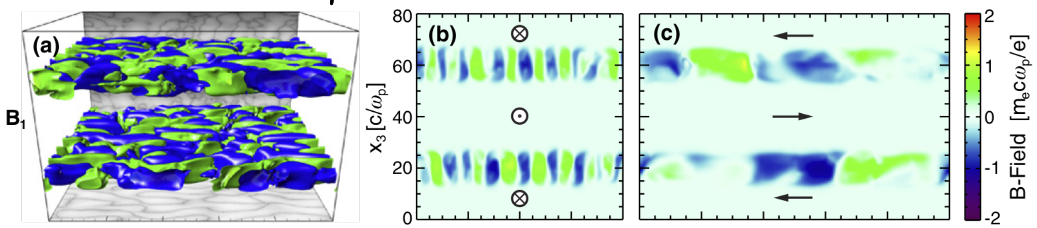


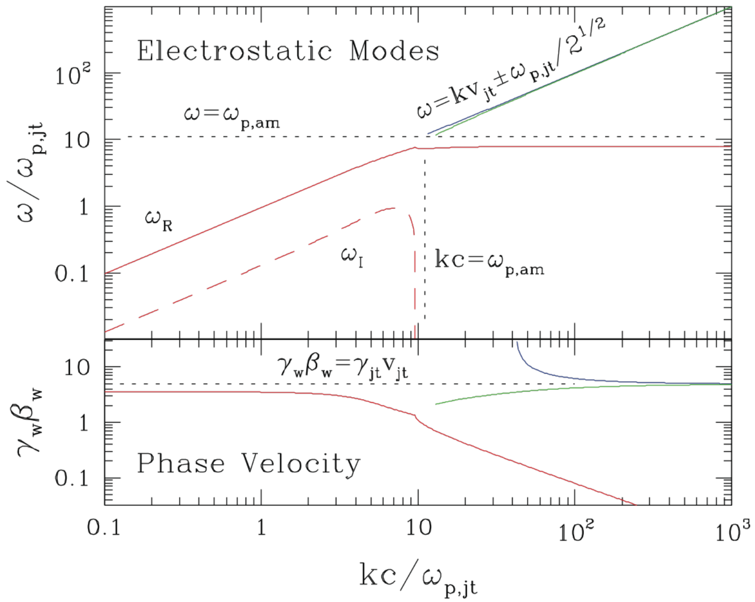
$$\omega \sim \frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt} \pm i\frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})^{1/2}}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt}.$$

Non-Relativistic γ ~ 1



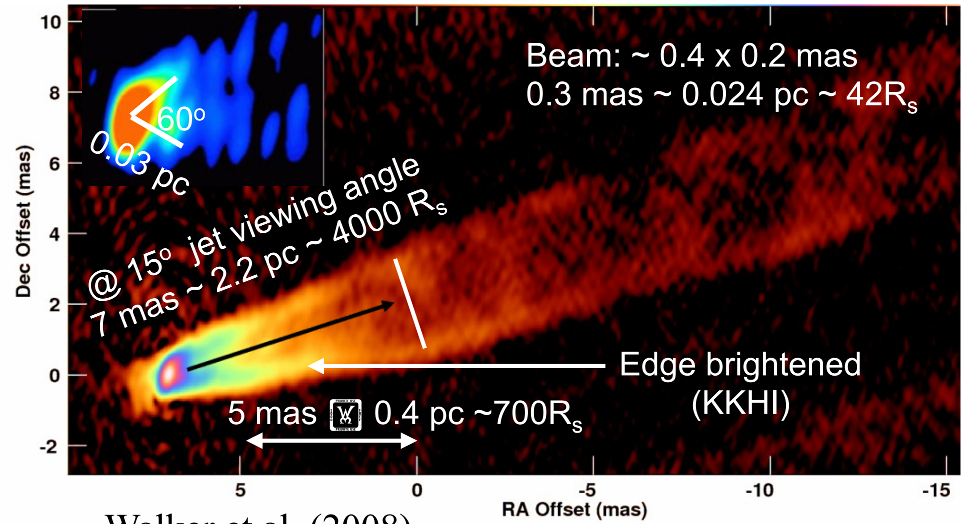
Relativistic γ = 3





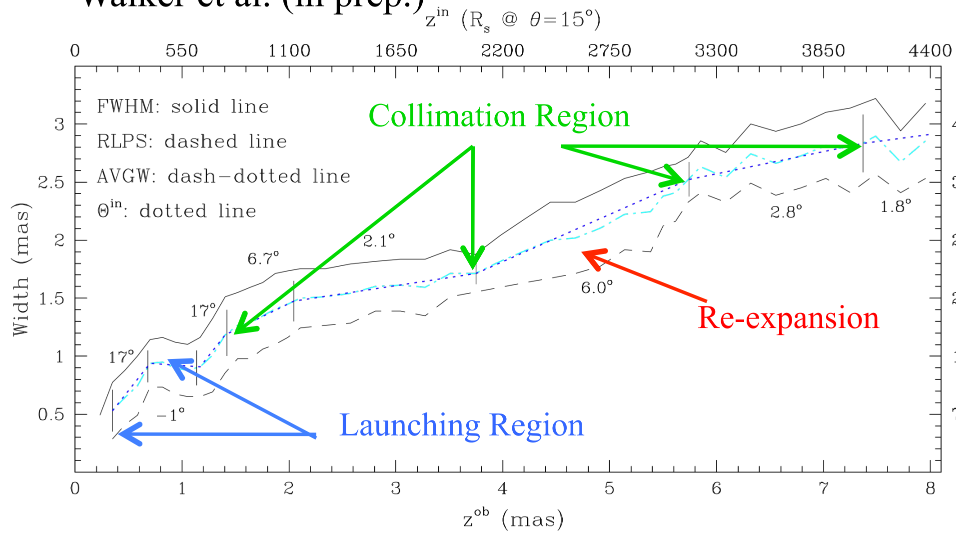
M87: Collimation, Propagation & CDI/KHI

Junor et al. (1999)

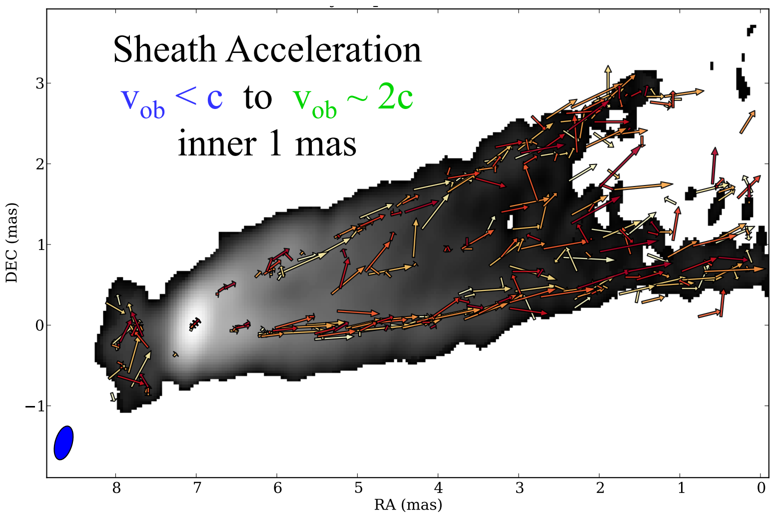


Walker et al. (2008)

Walker et al. (in prep.)

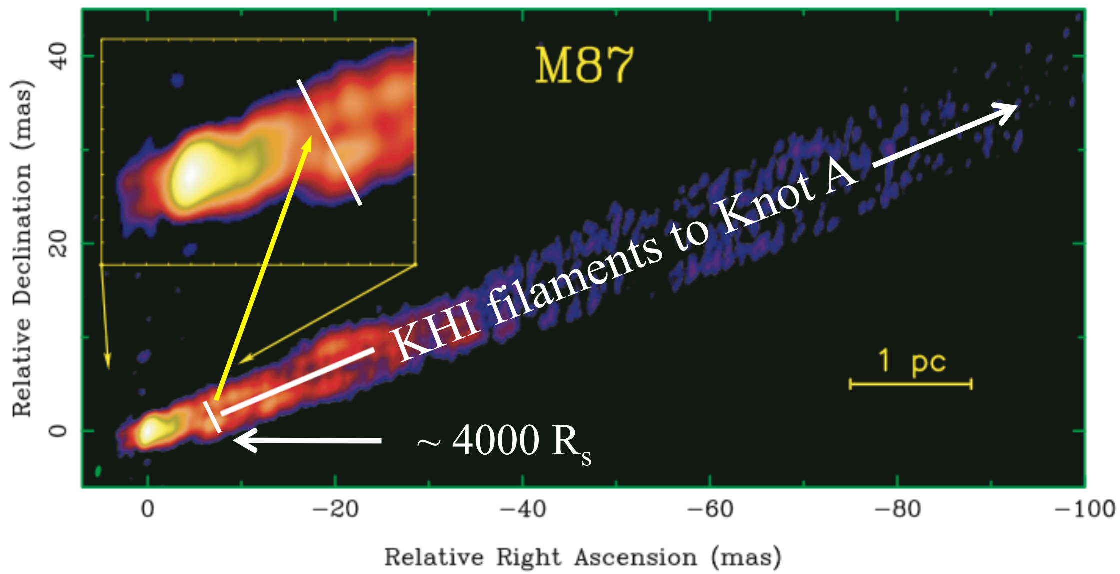


Wavelet analysis (Mertens & Lobanov)



Propagation (KHI) Region

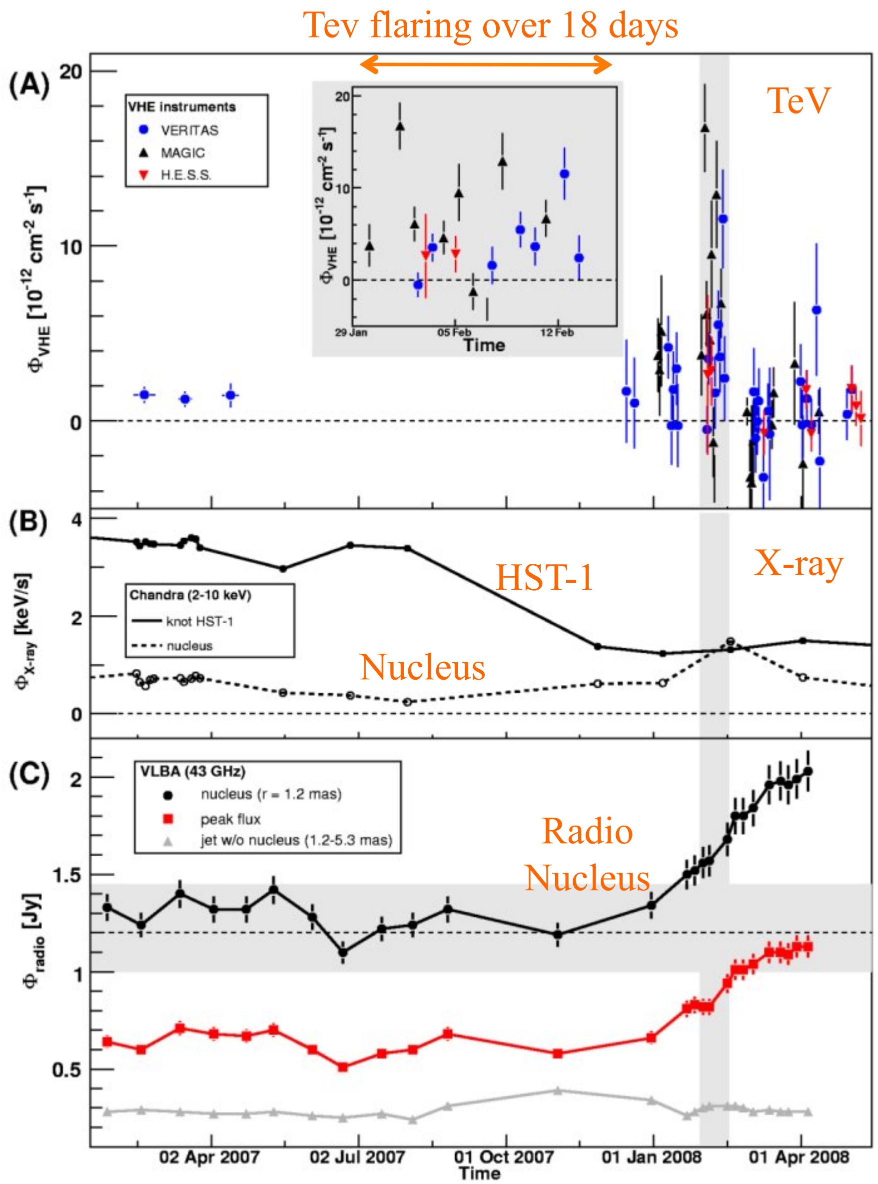
Kovalev et al. (2007)



Launching Region (few 100s R$_s$) ; Collimation (CDI/KHI) Region ; Propagation (KHI) Region

M87: Launching Region & Microphysics

Global Jet Processes too slow for < 1 day Tev variability ⇒
small scale structures for CDI , KKHI , Filamentation, Reconnection & rapid particle acceleration



TeV from core < 1 day variability ⇒
processes on scales <<< 25 $R_s \sim \delta_{max} \Delta t_{obs}$ c

(Poynting domain < few 100 R_s)

Small scale CDI magnetic reconnection & particle acceleration

"Jet-in-a-jet"
[Giannios et al. (2009)]

(Kinetic domain > few 100 R_s)

Small scale shock/shear (Filamentation/KKHI & Reconnection) particle acceleration

"Knots-in-a-jet"
[Lenain et al. (2008)]

"Needles"/spine-sheath
[Ghisellini & Tavecchio; Tavecchio & Ghisellini (2008)]

"Knot"/needle deceleration
[Georganopoulos et al. (2005); Levinson (2007)]

M87: Summary & Conclusion

Jet angle: $\theta \sim 15°$, Global Spine-Sheath: $\gamma_{spine} \sim 7$, $\gamma_{sheath} \sim 3$, Doppler: $\delta \lll \delta_{max} = 2\,\gamma_{spine}$

Launching (sub-pc scales): (⊠$_A$ $v_{Alfvén}$ > ⊠$_{jt}$ v_{jt})

Simulation/M87 ⇒ Global CDI stabilized (expansion, acceleration, radial structure)

M87 ⇒ Poynting to plasma energy conversion (small scale CDI/Reconnection)

Microphysics ⇒ Particle acceleration (Reconnection, KKHI)

Collimation (~ pc scales): (⊠$_{jt}$ v_{jt} ~ ⊠$_A$ v_A)

Simulation/M87 ⇒ CDI/KHI generation global structures

Microphysics ⇒ Shock acceleration/jet knot emission, KKHI acceleration/jet edge brightening

Propagation (> few pc scales): (⊠$_{jt}$ v_{jt} > ⊠$_A$ v_A)

Simulation/M87 ⇒ KHI partial stabilization (expansion, advection, radial structure, magnetic fields)

Microphysics ⇒ shock & shear driven acceleration