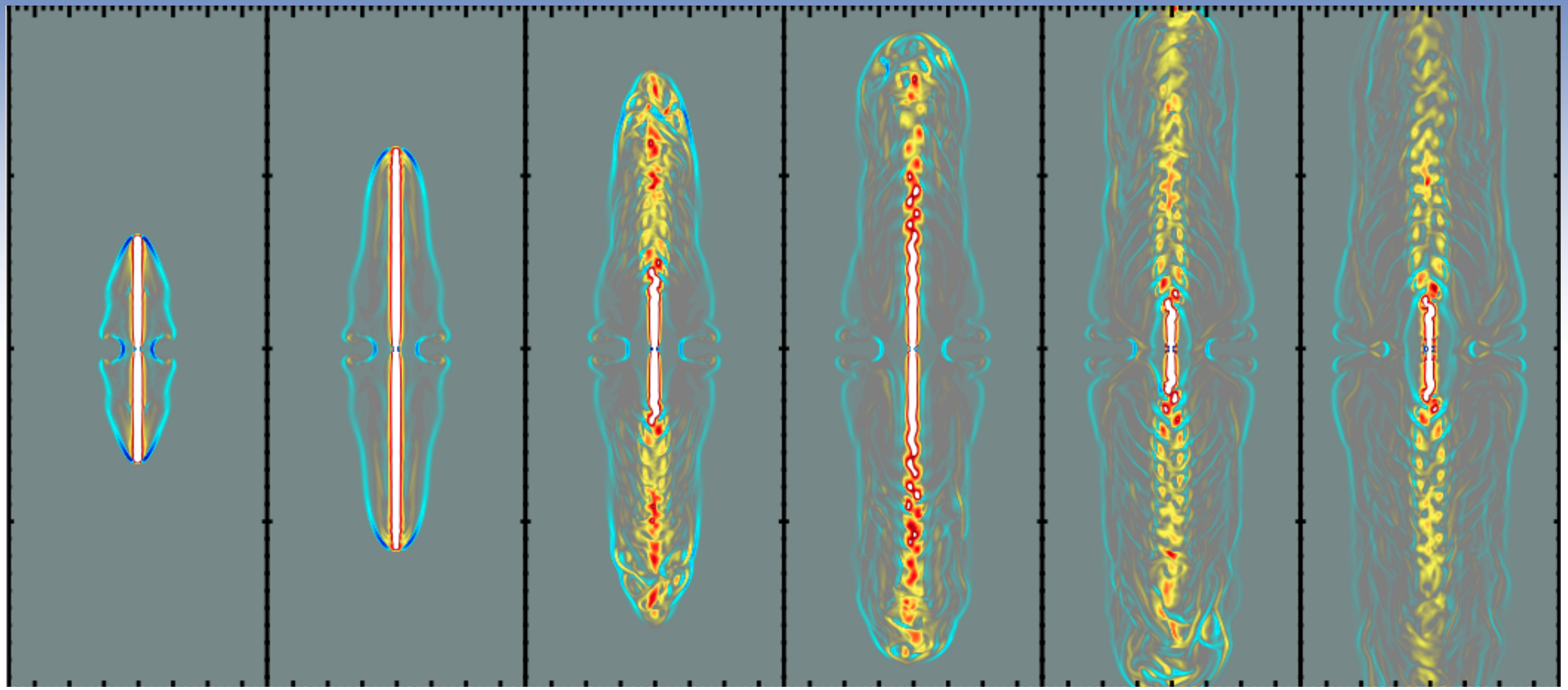
Relativistic MHD Simulations of Magnetic Flux-Driven Jets



Xiaoyue Guan

Los Alamos NATIONAL LABORATORY

TeV PA 2013

Irvine CA • August 2013

Los Alamos NATIONAL LABORATORY EST. 1943

Outline-- AGN Jet Simulations

- Basic Picture
- BH Jet Launching & GRMHD Simulations
- 3D RMHD Jet Propogation

  part of jet modeling efforts at lanl

  - motivations, model assumptions
  - Relativistic MHD code
  - dynamical properties of magnetic flux-driven jet
- What can we do from here?

Jet Launching

- Jets: YSO, micro-quasars, AGN, GRBs
- Need: rotation + B fields
- Blandford & Payne(1982): powered by disk rotational energy

  disk rotation + large-scale poloidal fields
- Blandford & Znajek(1977): powered by rotation of the hole

  frame dragging + radial fields

$$L_{BZ} \propto \Omega_{BH}^2 \Phi_{max}^2, \quad \omega_B \sim 0.5\,\Omega_{BH}, \quad \Omega_{BH} = a\,c/(2r_{hor})$$

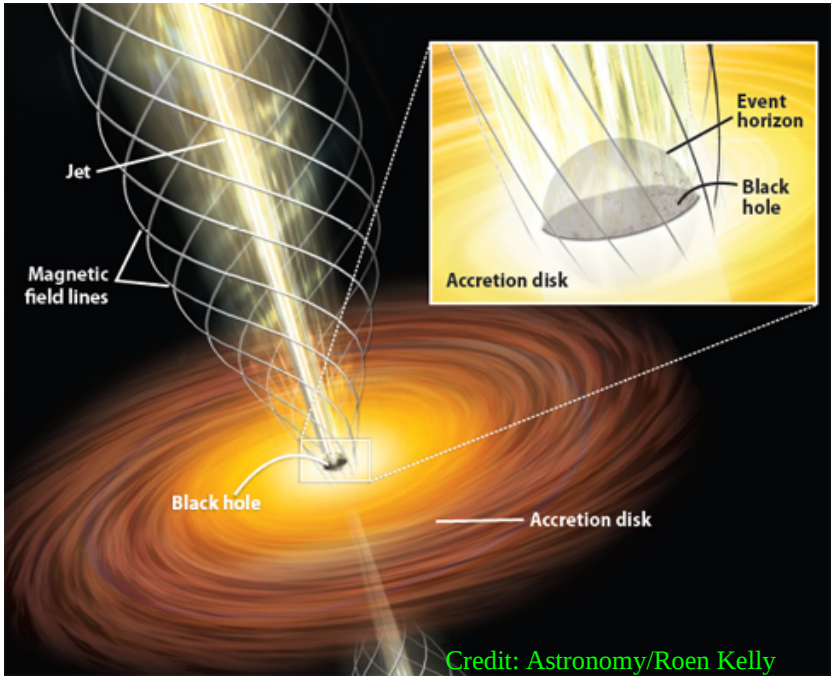
=>produce energetic & relativistic jets

$$cf.\ L_{BZ} \sim B^2 r_{hor}^3/(r_{hor}/c) \sim B^2 r_{hor}^2 c$$

$$\sim 10^{45}\left(\frac{B}{10^5 G}\right)\left(\frac{M}{10^7 M_{sun}}\right) erg/s \sim \left(\frac{B}{10^5 G}\right)\left(\frac{M}{10^7 M_{sun}}\right) L_{edd}$$

$r_{hor} \sim 10$AU, $t_{hor_crossing} \sim$hrs for $10^9 M_\odot$

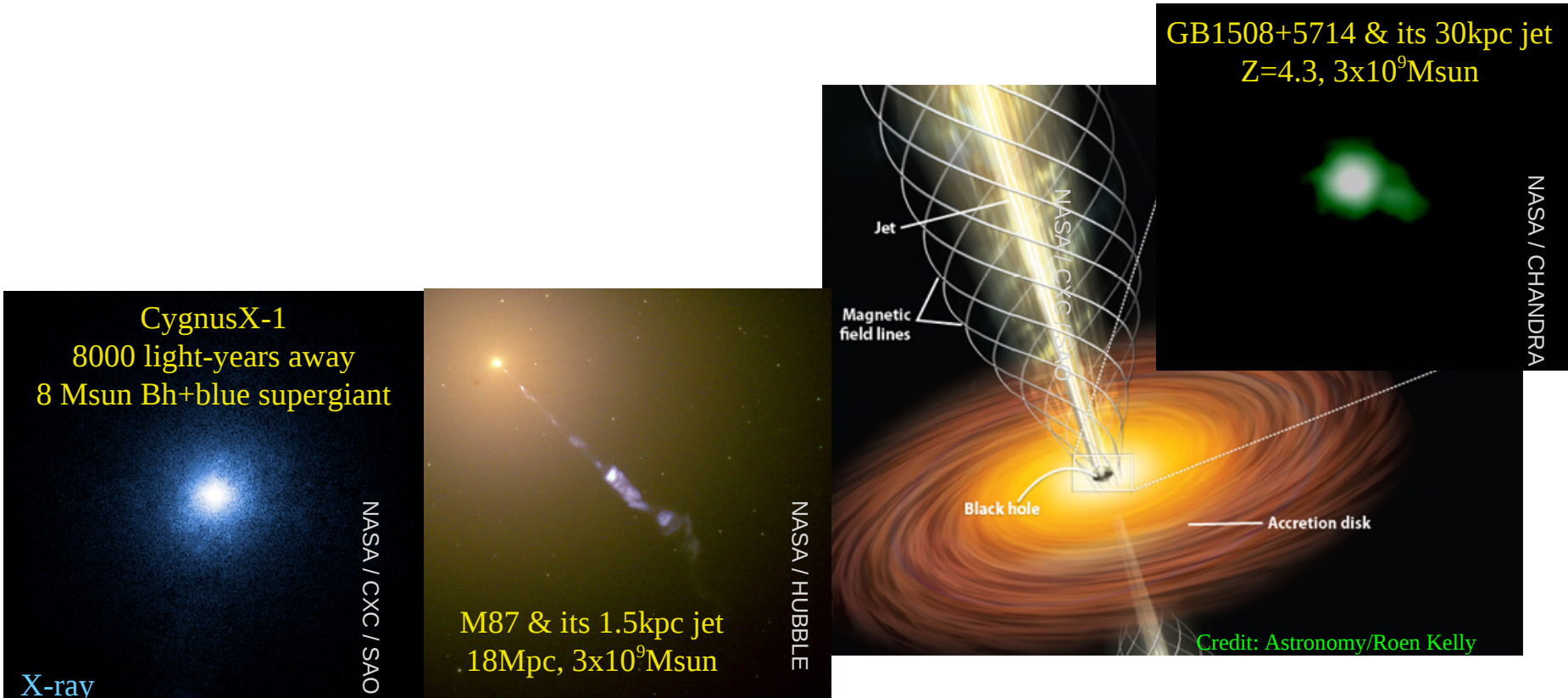
$t_{acc} \sim 10^6$yr, $t_{disk_dyn} \sim$yr



BH Accretion → Relativisitic Jet

- Some X-ray Binaries: $M\sim 3\text{-}20 M_{\odot}$, $L\sim 10^{36}\text{-}10^{38}$ erg/s, $\gamma_{jet}=3\text{-}10$
- All AGN/QSOs: $M\sim 10^{5}\text{-}10^{9} M_{\odot}$, $L\sim 10^{42}\text{-}10^{48}$ erg/s, $\gamma_{jet}=3\text{-}10$
- Some GRBs: $L\sim 10^{45}\text{-}10^{53}$ erg/s, $\gamma_{jet}\sim 10\text{-}100$

$$cf.\ L<L_{edd}\sim 4\times 10^{37}(M/M_{sun})\,erg/s,\quad M>M_{edd}\sim L/L_{38}M_{sun}$$

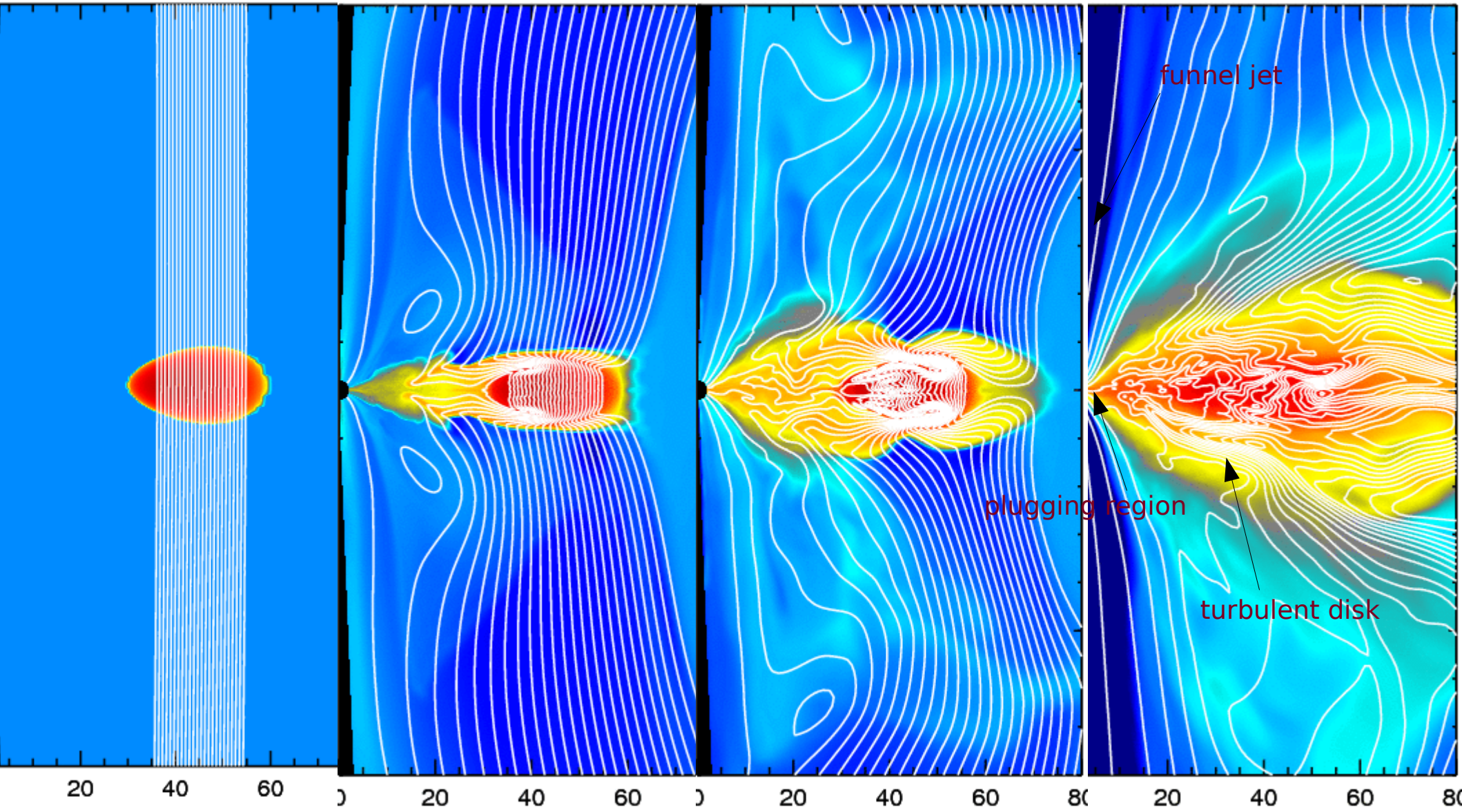


MHD Jet Simulations

- GRMHD/FFEM BH accretion based jet launching (e.g. Komissarov 1999, De Villiers *et al. 2004 , Gammie et al. 2004, Mckinney & Blandford 2009*)
- Local MHD/RMHD jet propogation from an injection boundary/nozzle (e.g. Lery *et al. 2000, Baty & Keppens 2002, Nakamura & Meier 2004, O'Neill 2005, Li et al. 2006, Nakamura et al. 2006, Komissarov 2007, Moll et al. 2008, Mignone et al. 2010, Mizuno et al. 209, O'Neill et al. 2012*) ;

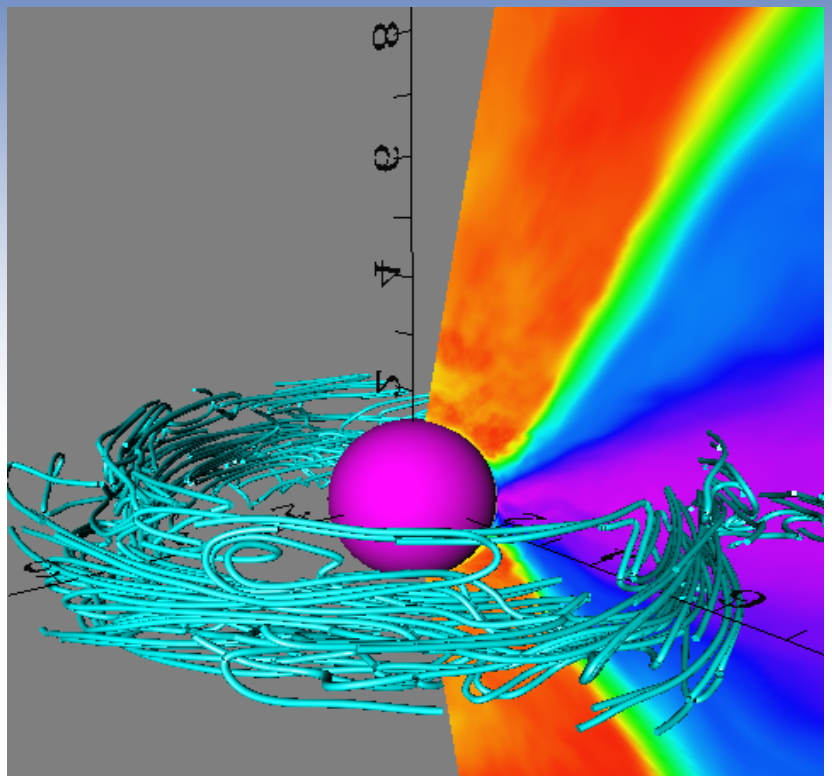
  MHD bipolar jet propogation on large (~kpc) scales (e.g. *Li et al . 2006*)

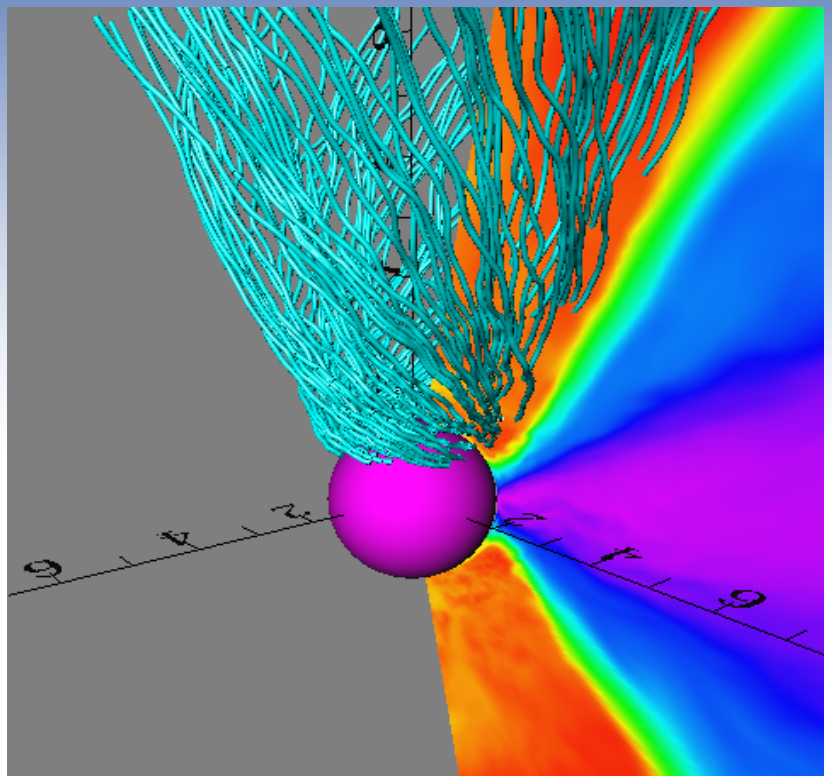
GRMHD BH Accretion Simulations



Beckwith et al. 2009

B Field Near the Hole





Hirose et al. 2004

In the disk:

tangled,mainly toroidal.

In the funnel jet:

poloidal radial (plunging inflow) +

toroidal (spin)

Jets in GRMHD Accretion Simulations

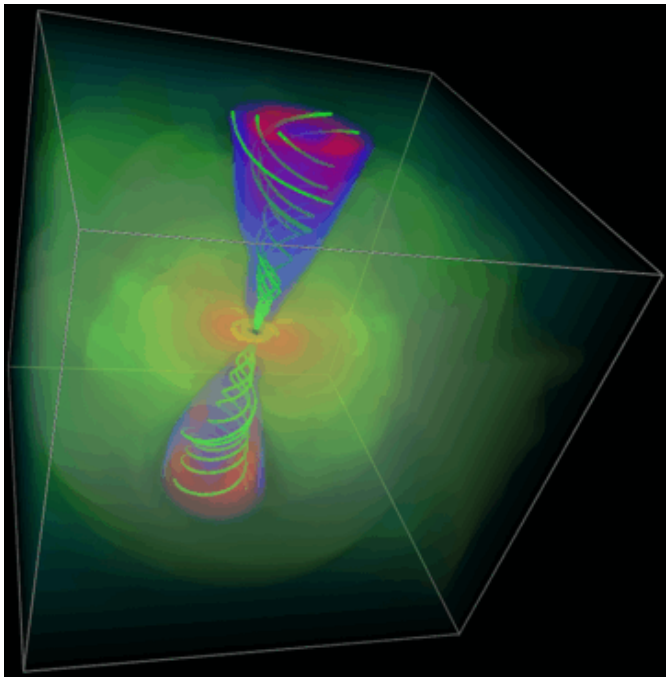
- Poynting flux dominated, stable, outward jet
  - $\gamma \sim$ a few, depending on density floor
  - require: spin $\neq$ 0; initial poloidal and/or verticle field
  - EM power: increase with spin; largest for vertical field, almost none for pure toroidal field

consistant with B-Z predictions

- Largest simulations so far

(marginally) stable, slight hint of m=1 kink

EM dominated jet -> 10^3 r_{grav}



McKinney & Blandford 2009

Relativistic MHD Jets Propogation

- Motivation: instabilities, morphology, σ problem, flares

  & other physics (radiation; particle acceleration)

- Launch jet from accretion disk near r_{hor} ~AU

  + follow jet to observed (>pc) scale: not possible yet

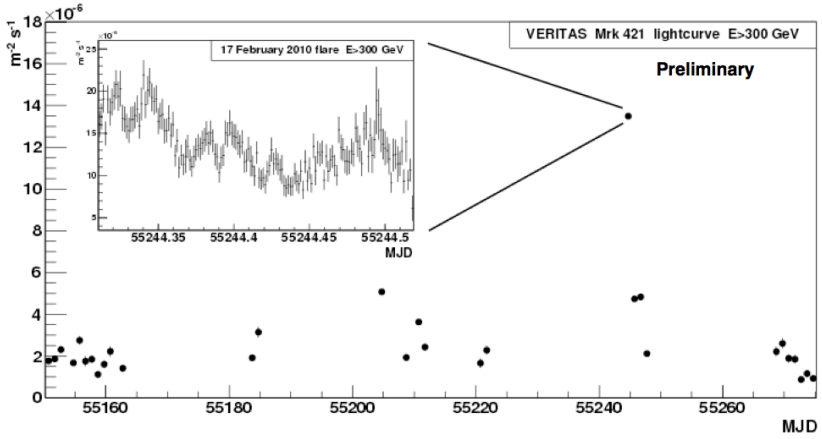
- @LANL Guan et al. 2013

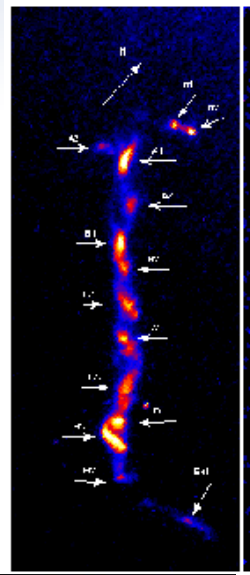
  – assume jet has already been launched from vicinity of the BH

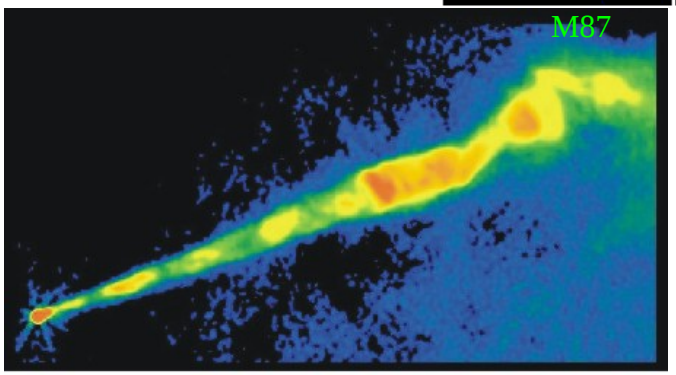
  – inject (possibly BH accretion-powered) EM flux @ $10^3 r_g$

  – propogate Poynting Flux-driven jet to >pc scale

- Relativistic MHD: LA-COMPASS(lanl)







RMHD Code

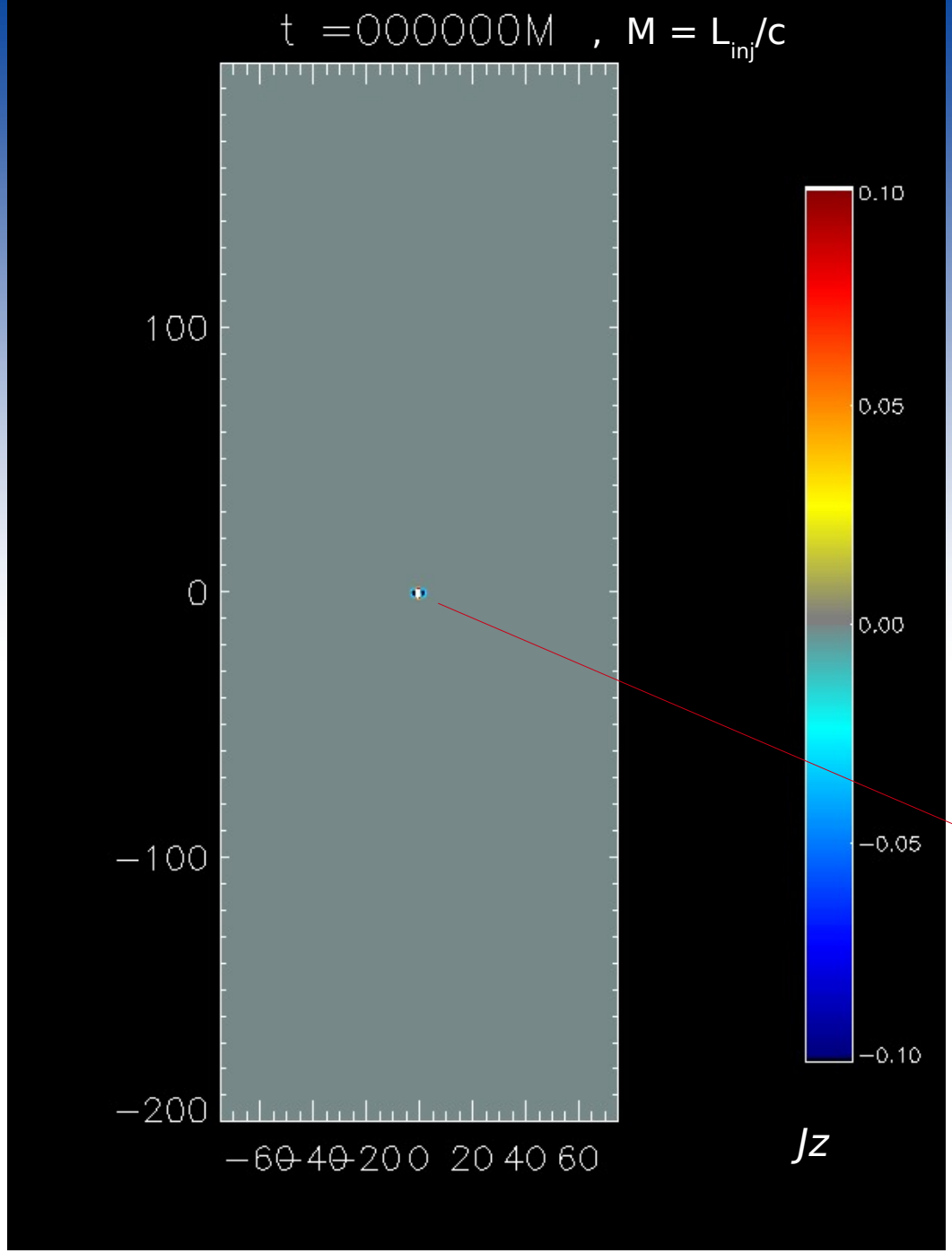
- LA-COMPASS: developed at LANL (*Li & Li 2003*)
  - Higher order conservative scheme
  - HLLE/HLLC/Roe etc. approximate Riemann solver
  - Corner transport upwind + CT for B field
  - Conservative vars → primitive vars: Newton-Raphson
  - 3D Cartesian coords, uniform/non-uniform grid (600x600x1600)
  - Ideal gas $p = (\gamma - 1)\rho\varepsilon$; no explicit dissipation

$$\partial_t \boldsymbol{U} + \partial_x \boldsymbol{F}^x + \partial_y \boldsymbol{F}^y + \partial_z \boldsymbol{F}^z = \boldsymbol{S},$$

$$\boldsymbol{S} = (\dot{D}_{inj}, 0, 0, \dot{S}^z_{inj}, \dot{E}_{inj}, \dot{B}^x_{inj}, \dot{B}^y_{inj}, \dot{B}^z_{inj})^T$$

jet injection

$$\boldsymbol{U} = \begin{pmatrix} D \\ S^x \\ S^y \\ S^z \\ \tau \\ B^x \\ B^y \\ B^z \end{pmatrix} \equiv \begin{pmatrix} \rho W \\ \rho h^* W^2 v^x - b^0 b^x \\ \rho h^* W^2 v^y - b^0 b^y \\ \rho h^* W^2 v^z - b^0 b^z \\ \rho h^* W^2 - p^* - b^0 b^0 - \rho W \\ B^x \\ B^y \\ B^z \end{pmatrix}, \quad \boldsymbol{F}^i = \begin{pmatrix} \rho W v^i \\ \rho h^* W^2 v^i v^x + p^* \delta^i_x - b^i b^x \\ \rho h^* W^2 v^i v^y + p^* \delta^i_y - b^i b^y \\ \rho h^* W^2 v^i v^z + p^* \delta^i_z - b^i b^z \\ \rho h^* W^2 v^i - b^0 b^i - \rho W v^i \\ v^i B^x - B^i v^x \\ v^i B^y - B^i v^y \\ v^i B^z - B^i v^z \end{pmatrix}, \quad \boldsymbol{V} = (\rho, v^x, v^y, v^z, p, B^x, B^y, B^z)^T,$$

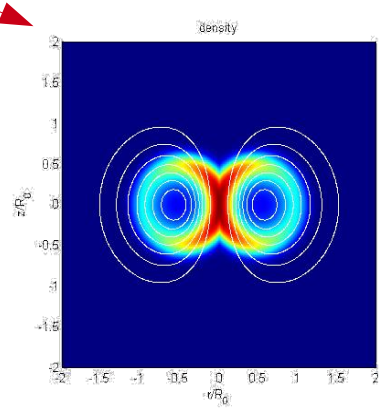


Jz

Uniform background , no rotation

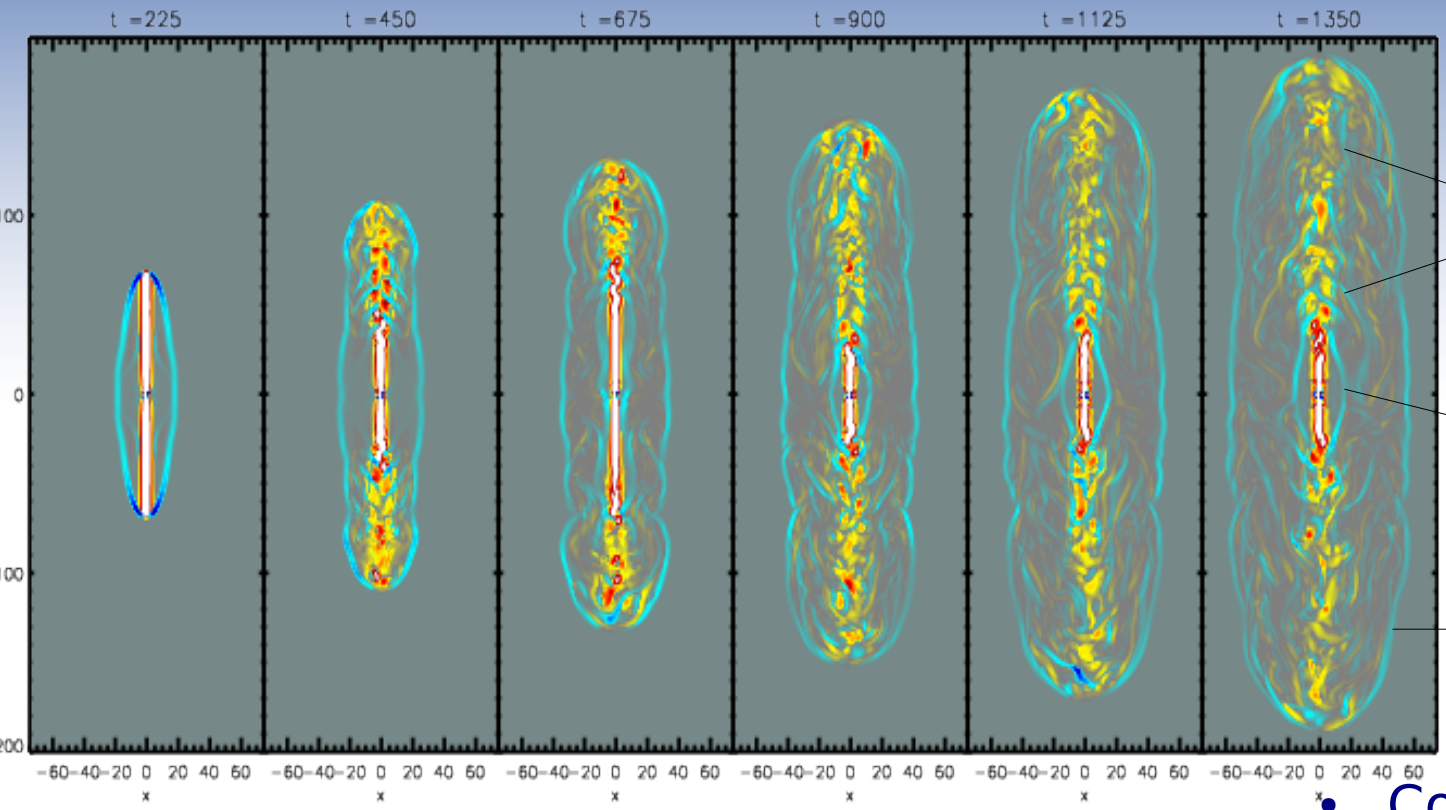
constant field injection:
dipole poloidal $\Phi(r,z)_{inj}$,
toroidal $B_{inj,\phi}=\alpha\Phi/r$

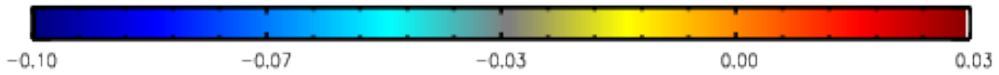
$\alpha=10$



cf. M87(*3x10*^{9}M$_\odot$): L$_{inj}$ ~ *0.1*pc, L ~ *10-100*pc, L$_{inj}$/c ~0.5 yr, T~*10*$^{3-4}$yr; △r~*0.01*pc, △t~20 *days,*
(t$_{acc}$ ~*10*^{6}yr, t$_{disk_dyn}$ ~0.5yr, t$_{hor_crossing}$ ~hrs); B$_{core}$ ~ G, B$_{far}$ ~10^{-3} G, j~10^{18}amp, P$_{inj}$~10^{46} erg/s; n~10^{2}cm^{-3}

Jet at Late Time





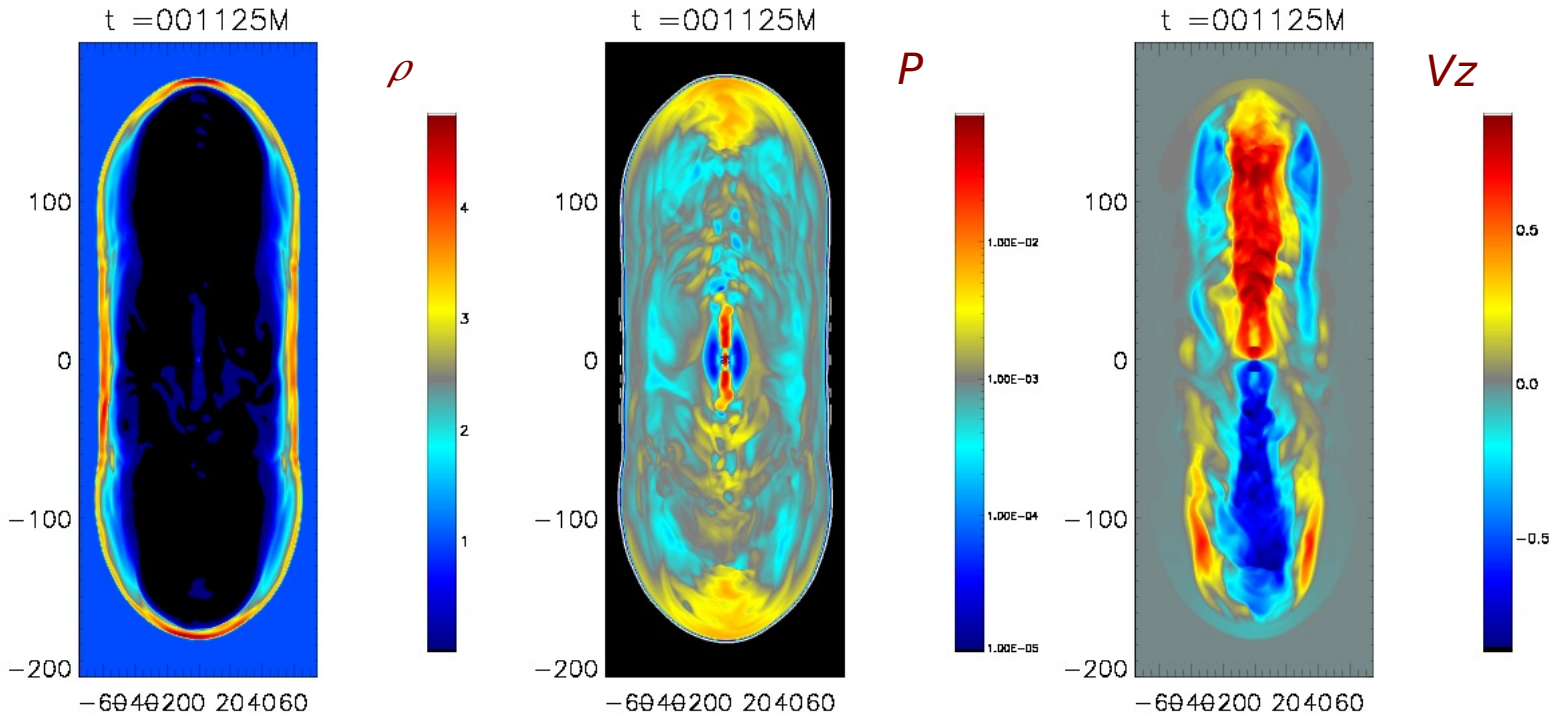
Jz

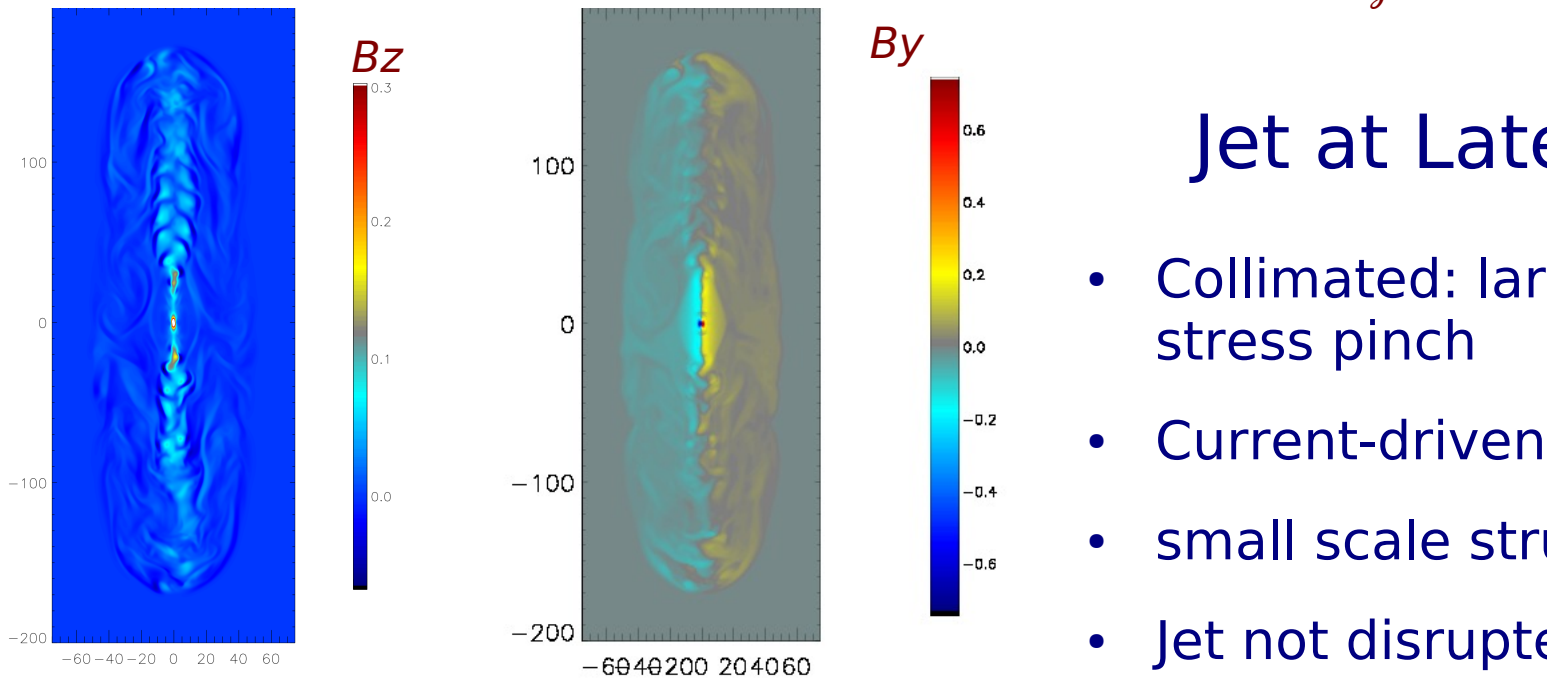
localized current sheets

Collimated jet

return current

- Collimated: large hoop-stress pinch
- Current-driven instabilities
- small scale structures
- Jet not disrupted





Jet at Late Time

- Collimated: large hoop-stress pinch
- Current-driven instabilities
- small scale structures
- Jet not disrupted

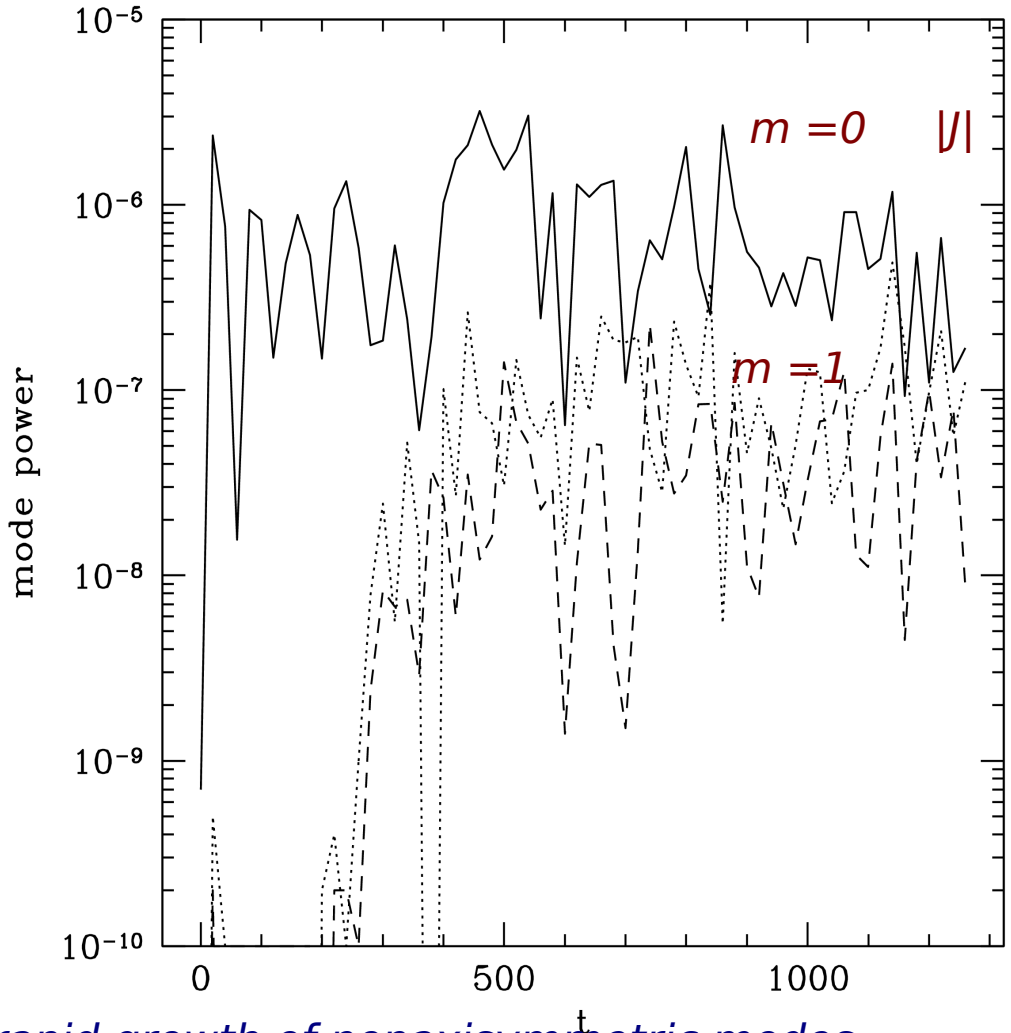
Current Driven Instabilities

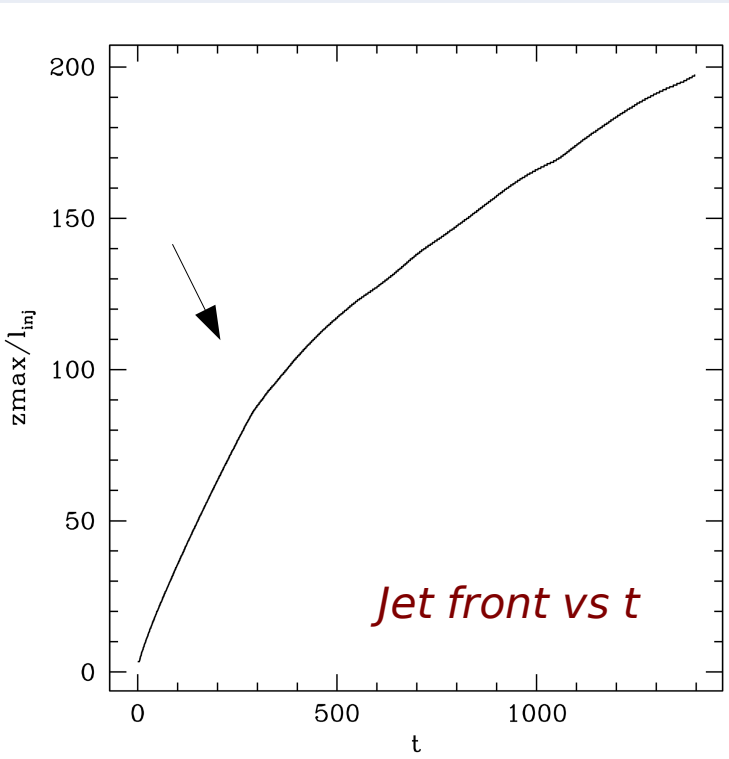
Kruskal-Shafranov: $2\pi rB_z/LB_\phi < 1$

Jet unstable to:

m= 1 kink mode

magnetic K-H



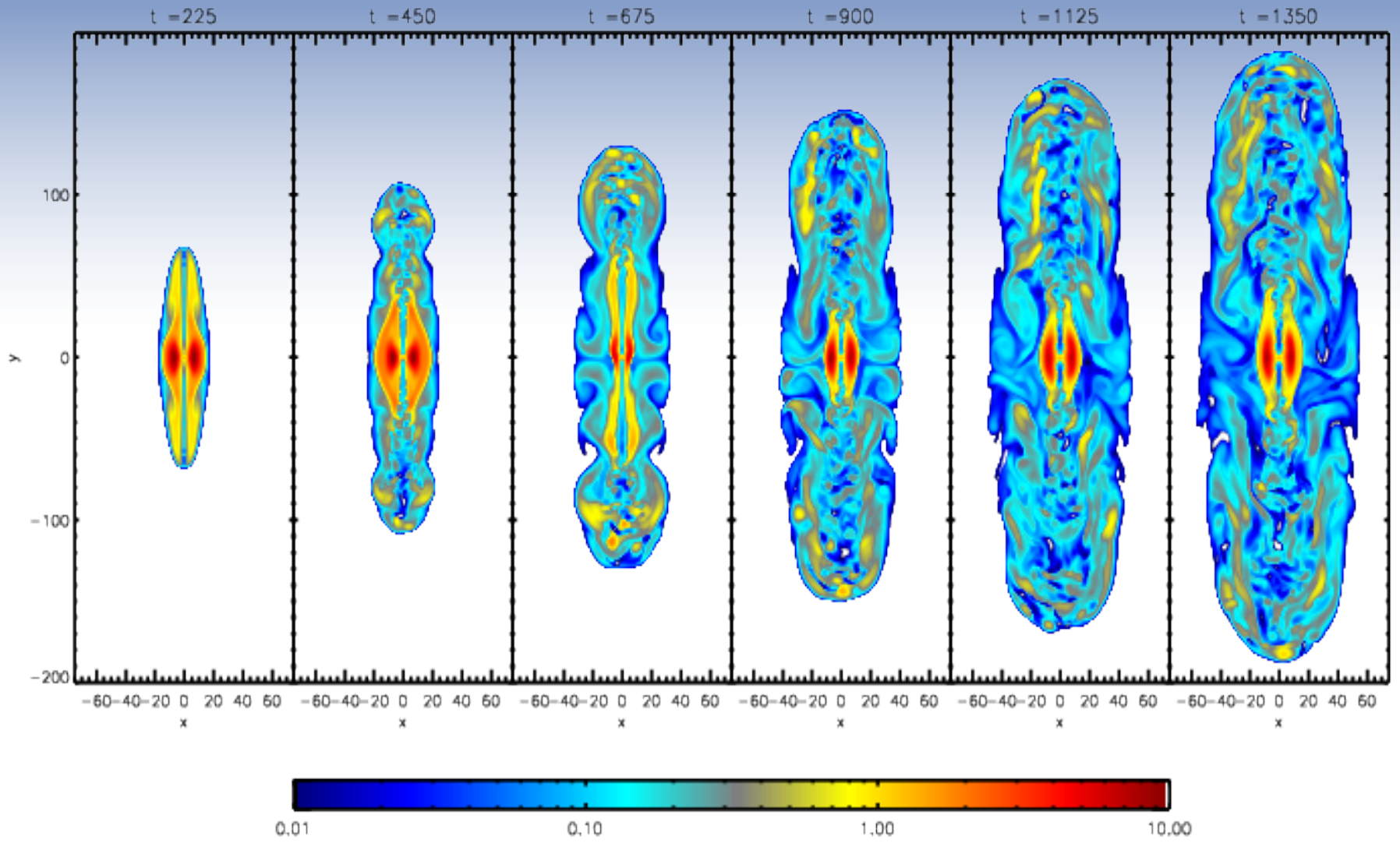


– rapid growth of nonaxisymmetric modes

– axisymmetric mode still dominates

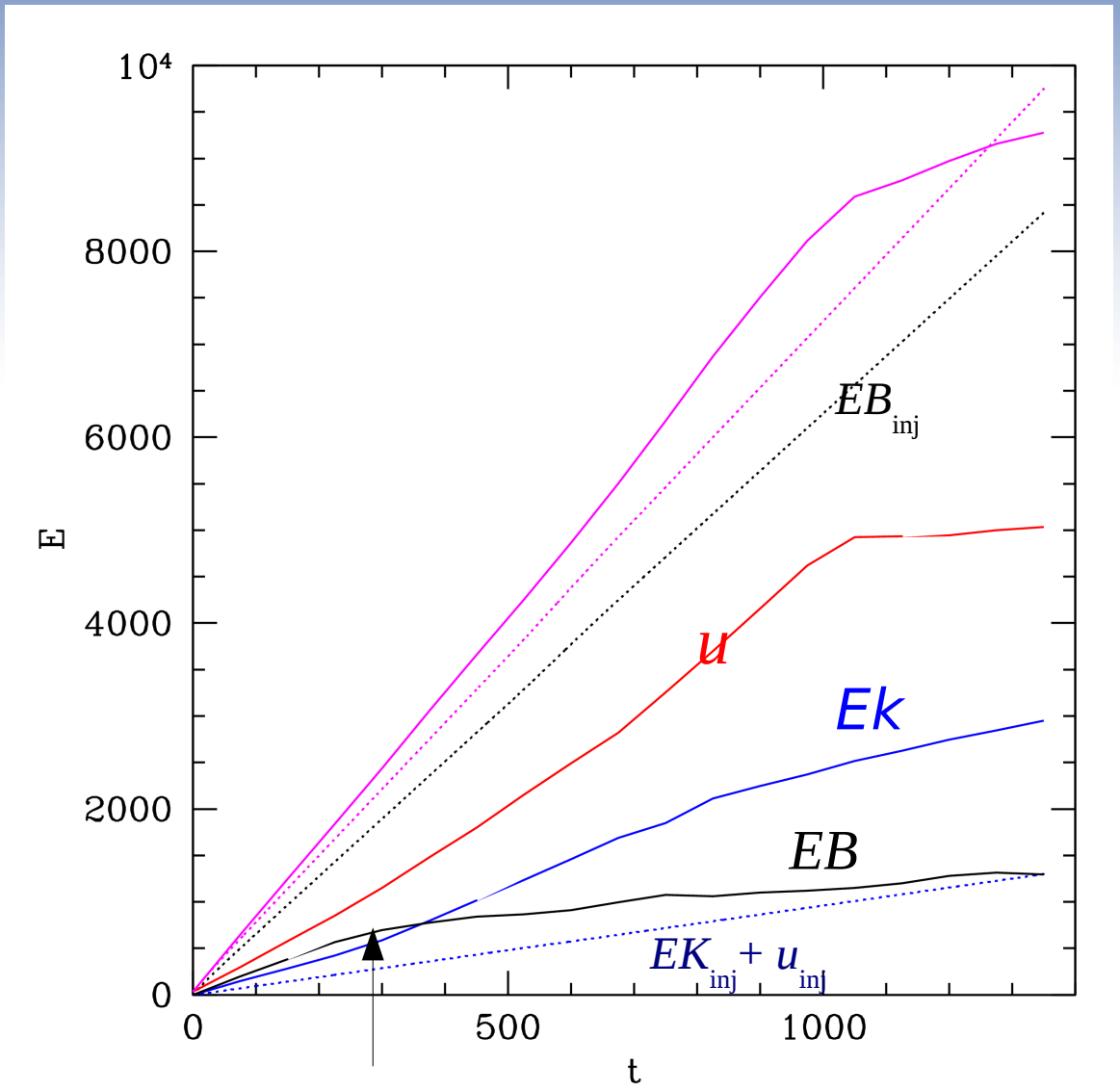
jet slows down, but not disrupted

Energy Transformation



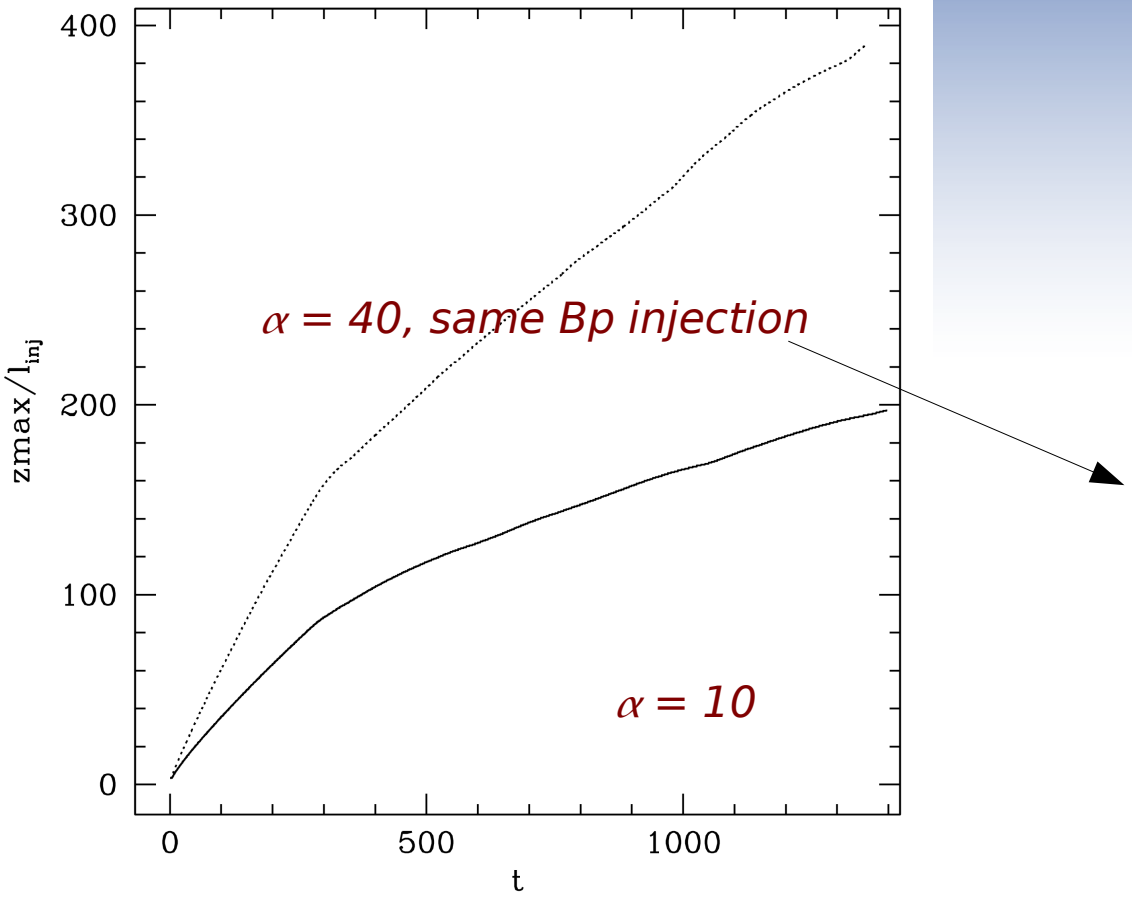
$$\sigma = F_{Poynting}/F_{KE} = B^2/4\pi\gamma^2\rho c^2$$

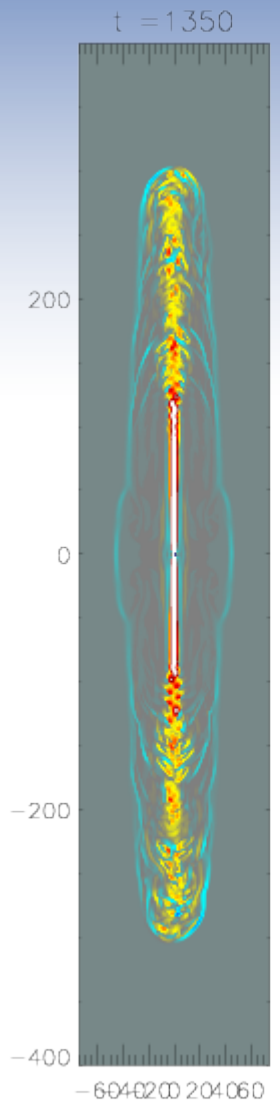
Energetics



EB->EK, as a result of CDI; not saturated yet

Larger Toroidal Flux Case





Jz

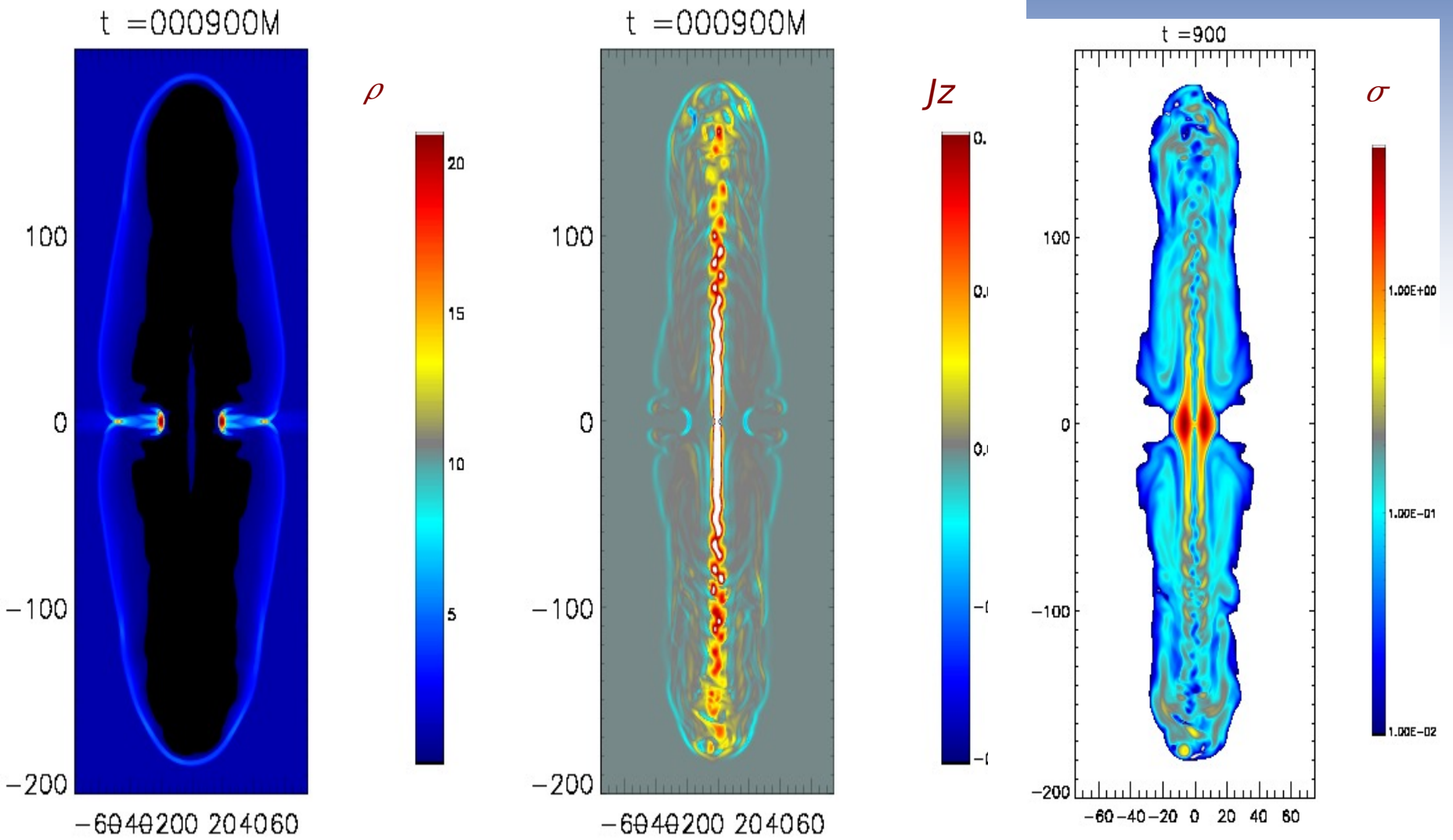
– *more pinch => more elongated jet*

– *different location & time of instability onset*

– *CDIs occurs in all models, so does the energy transformation*

Similar Behaviors with a Disk

Thin Disk

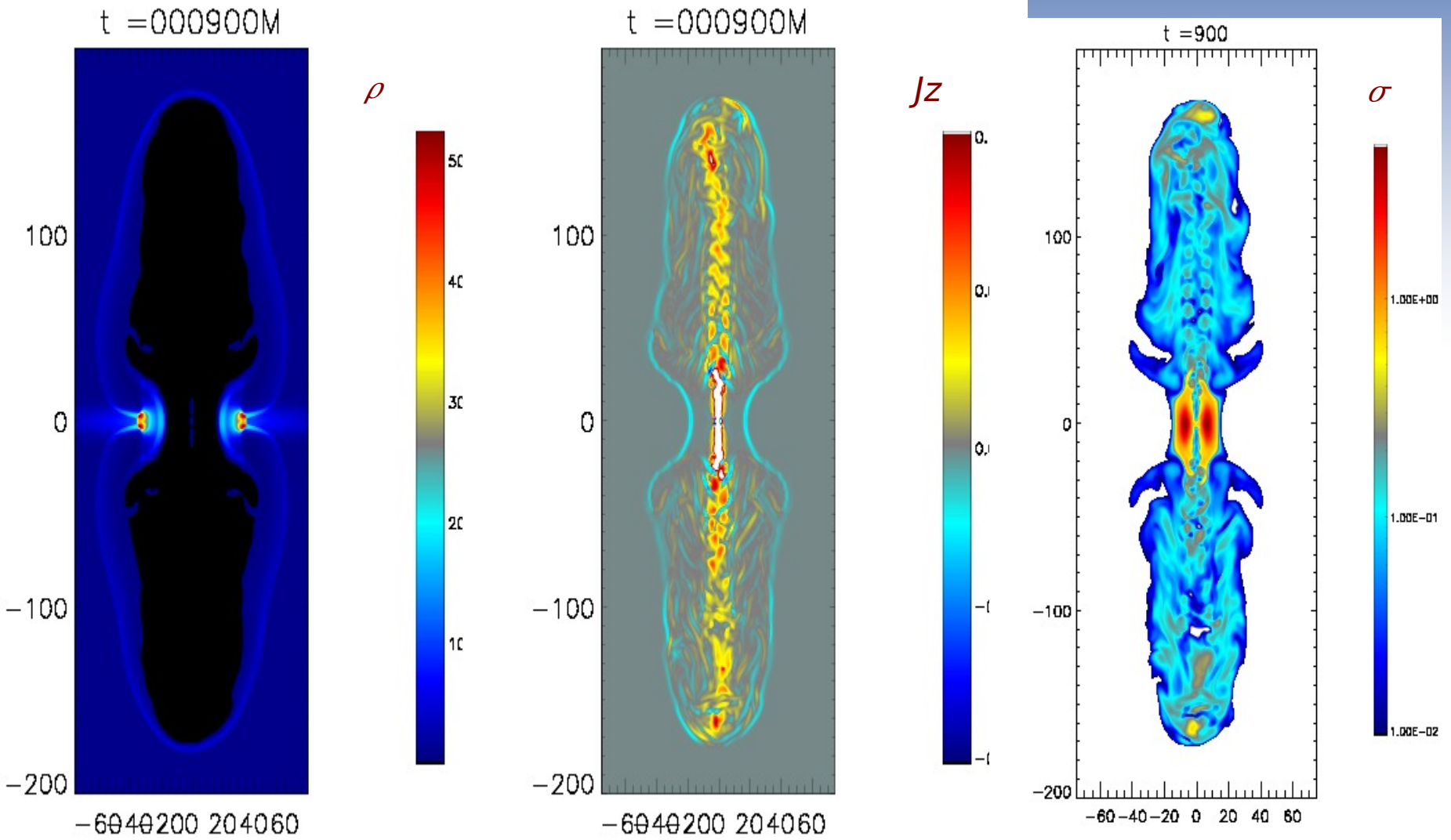


– *disk confinement at the base: opening angle*

– *similar jet behaviors at large distance*

Disk Confinement

Thicker Disk



CDIs & subsequent EB->EK are intrinsic features of EM flux driven jet

Summary & Outlook

- propagate EM jet to ~pc scales

  - jet collimated, subject to current-driven instabilities; not disrupted

  – instabilities transform E_B to E_K

  – detailed jet properties depend on model parameters

  – qualitatively similar behaviors with a gas disk

- Upcoming:

  – states, time-variabilities, disk-jet connections;

  jet interaction with environment

  – time-dependent radiation modeling: light curves, images, spectra (size of TeV emission region: sub-pc)

  – particle acceleration: relativistic PIC simulations in current sheets *Daughton & Li 2013* (10 orders of magnitude difference in scale)

Los Alamos NATIONAL LABORATORY EST. 1943

Summary & Outlook

- propagate EM jet to ~pc scales

  - jet collimated, subject to current-driven instabilities; not disrupted

  – instabilities transform E_B to E_K

  – detailed jet properties depend on model parameters

  – qualitatively similar behaviors with a gas disk

- Upcoming:

=> states, time-variabilities, disk-jet connections;

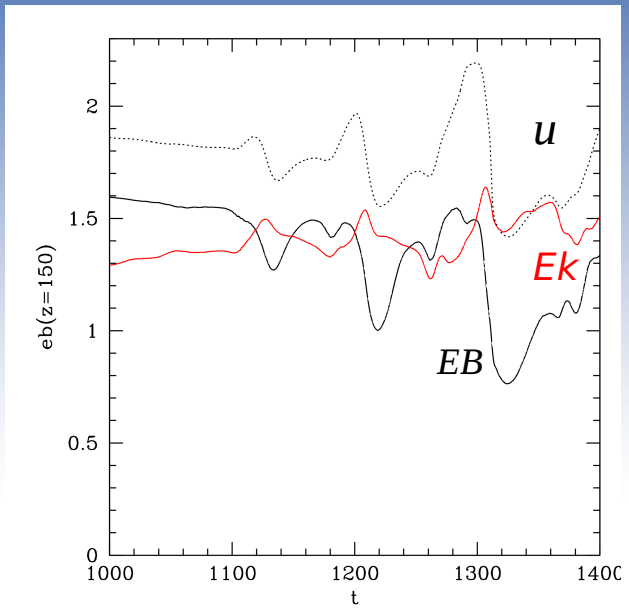
jet interaction with environment

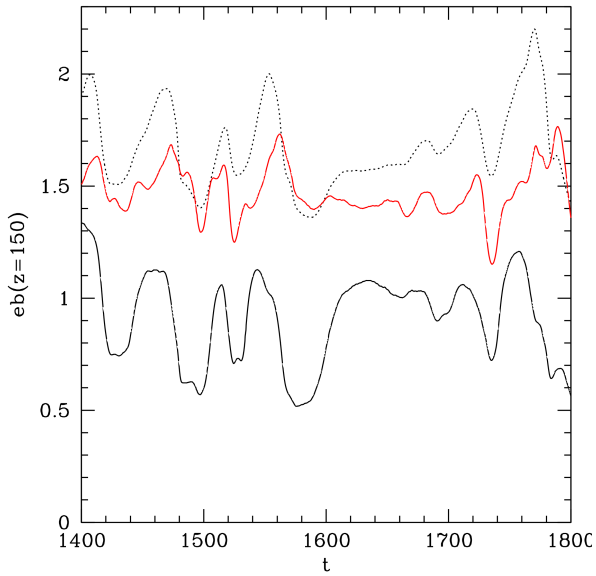
– time-dependent radiation modeling: light curves, images, spectra (size of TeV emission region: sub-pc)

– particle acceleration: relativistic PIC simulations in current sheets *Daughton & Li 2003* (10 orders of magnitude difference in scale)

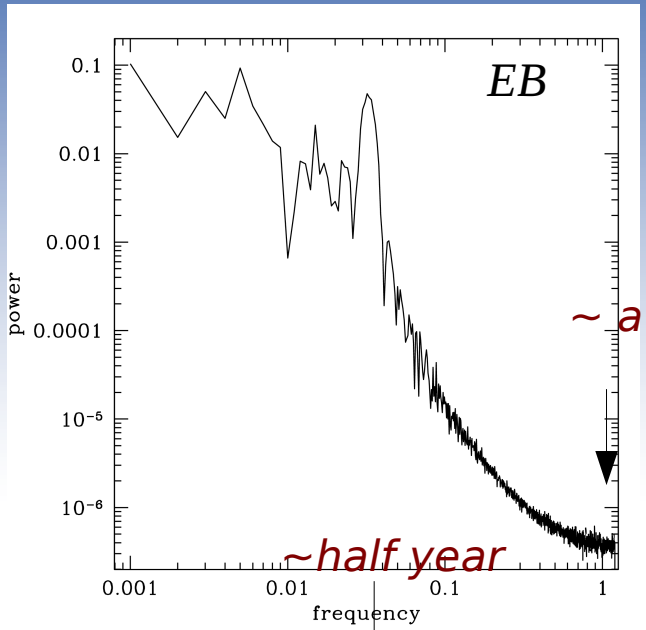
Los Alamos
NATIONAL LABORATORY
EST. 1943

Summary & Outlook





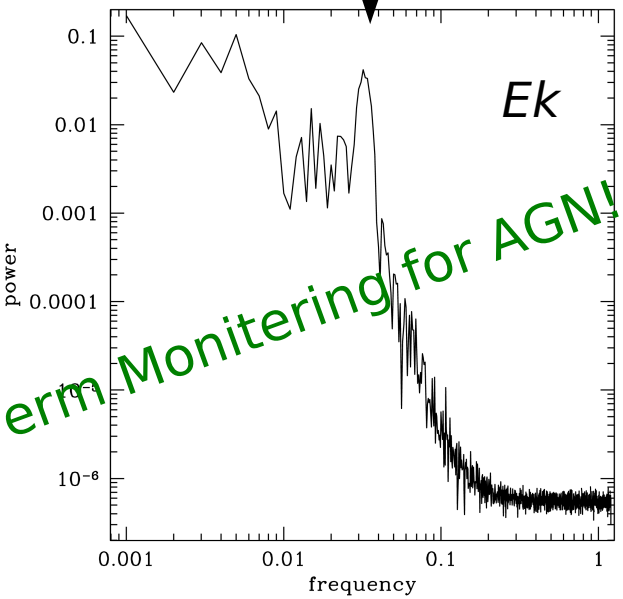
time variabilities @ certain location



~ a few days

$10^8 M_\odot$

~half year



Long Term Monitering for AGN!

power spectra in freq space

Summary & Outlook

- propagate EM jet to ~pc scales

  - jet collimated, subject to current-driven instabilities; not disrupted

  – instabilities transform E_B to E_K

  – detailed jet properties depend on model parameters

  – qualitatively similar behaviors with a gas disk

- Upcoming:

  – states, time-variabilities, disk-jet connections;

  jet interaction with environment

=> time-dependent radiation modeling: light curves, images, spectra (size of TeV emission region: sub-pc)

-- particle acceleration: relativistic PIC simulations in current sheets *Daughton & Li 2013* (10 orders of magnitude difference in scale)

Los Alamos NATIONAL LABORATORY EST. 1943

Summary & Outlook

- propagate EM jet to ~pc scales

  - jet collimated, subject to current-driven instabilities; not disrupted

  – instabilities transform E_B to E_K

  – detailed jet properties depend on model parameters

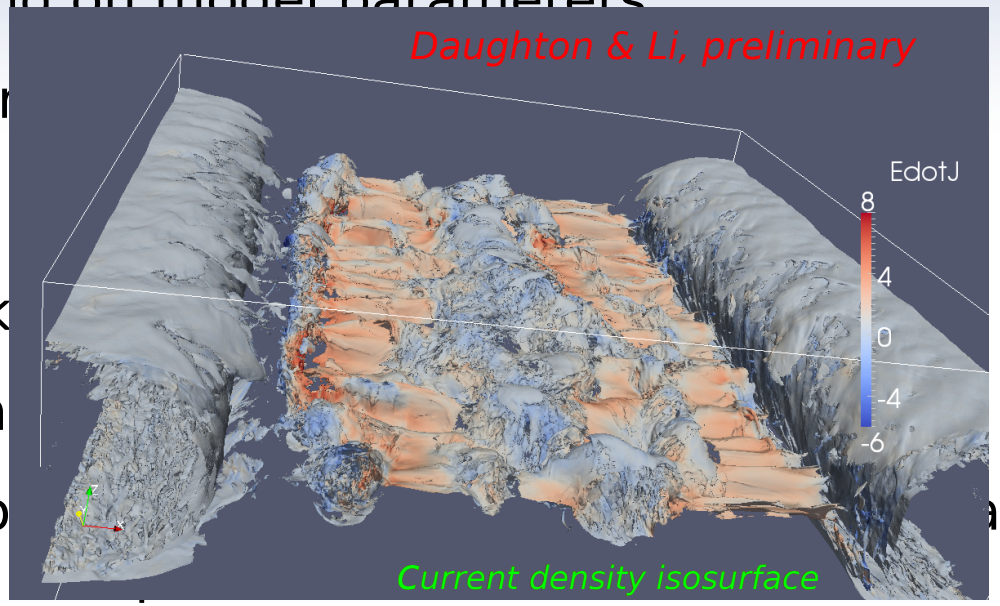
  – qualitatively similar behavior

- Upcoming:

  – states, time-variabilities, disk

    jet interaction with environm

  – time-dependent radiation mo
    (size of TeV emission region:



=> particle acceleration: relativistic PIC simulations in current sheets
Daughton & Li 2013 (10 orders of magnitude difference in scales)

Los Alamos
NATIONAL LABORATORY
EST. 1943