From disk winds to relativistic jets

RMHD acceleration / collimation

Oliver Porth - Christian Fendt

porth@mpia.de

Overall goal & method

- Study in detail the acceleration and collimation of disk-winds in the relativistic regime
- Obtain steady state solutions stable for 1000 rotations

Method:

"<u>Disk as boundary</u> " - extended for RMHD

+ follow flow from sub-escape velocity to super-fast

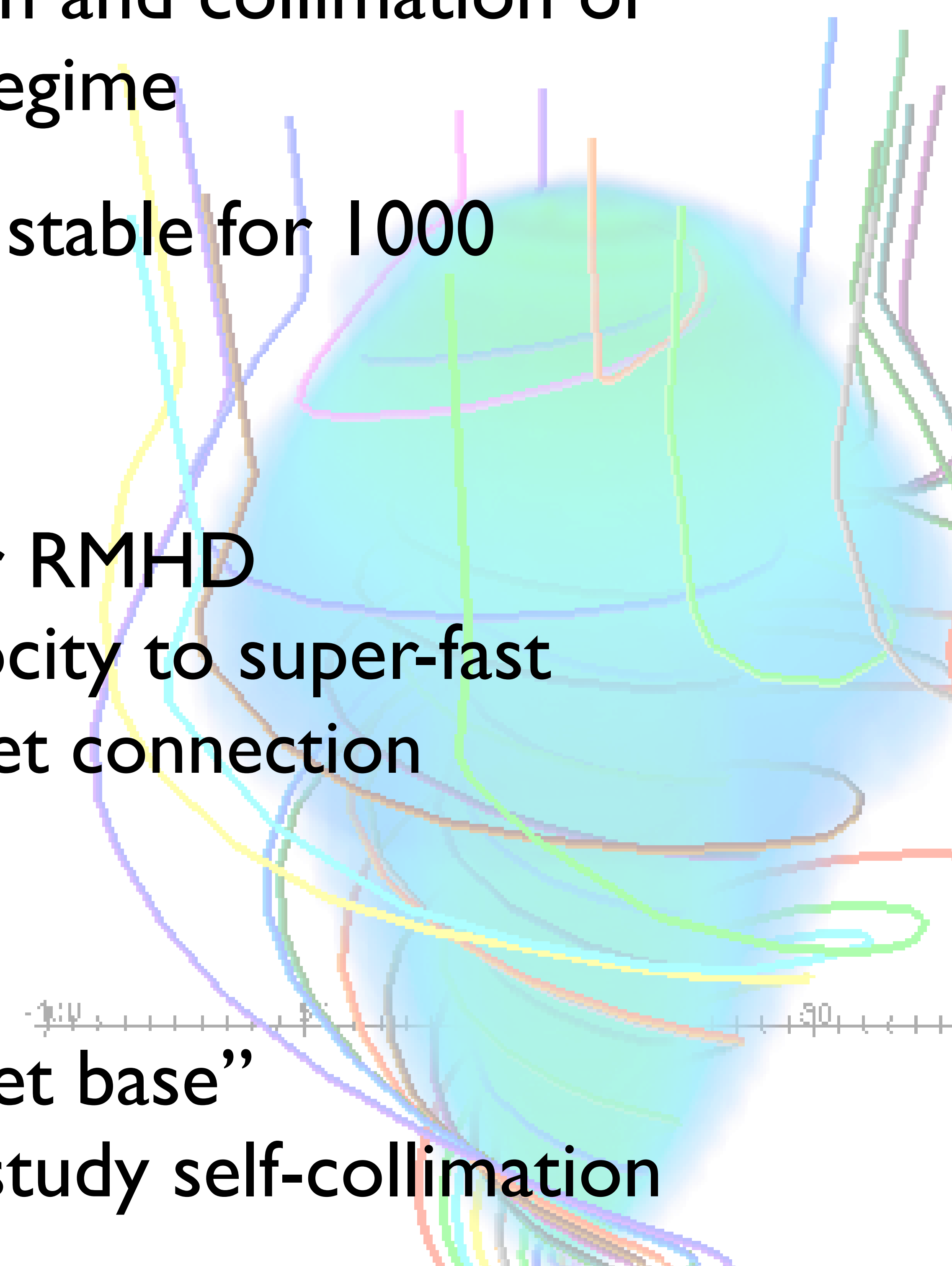
+ can give insight into the disk → jet connection

- limited jet → disk information

We improve on:

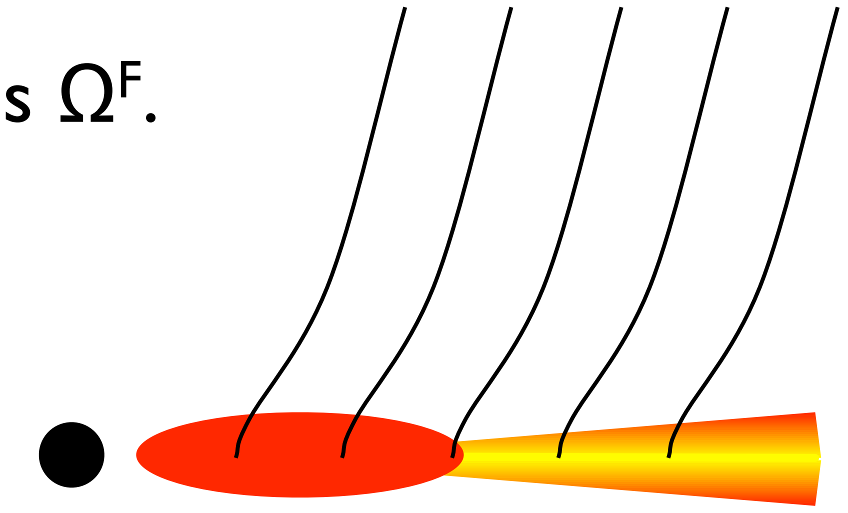
+ realistic boundary close to the "jet base"

+ optimized outflow boundary to study self-collimation



Accretion Disk Corona

- Assumptions:
  - Axisymmetric Ideal (R)MHD
  - Hot (ADAF): $\epsilon = c_s^2/v_\varphi^2 \simeq 1/6 - 2/3$.
  - (radial-) Hydrodynamic equilibrium
  - Large-scale poloidal fields (Blandford & Payne)
- Need:
  - Initially: force-free (Hourglass & Split monopole), steady-state
  - (sub-) Kepler rotation profile of the field-lines Ω^F.
  - Gravity to maintain radial equilibrium

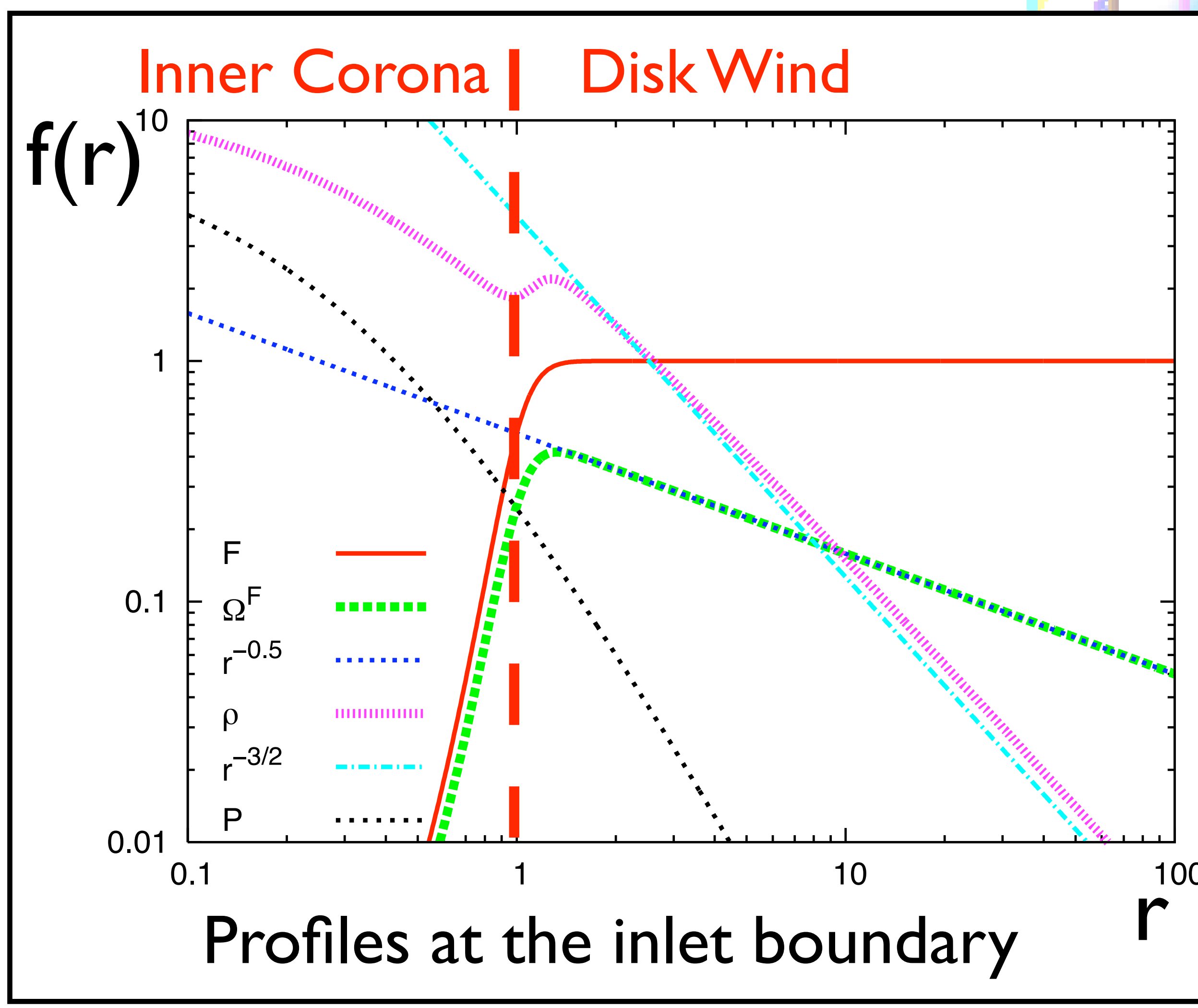


Numerical setup

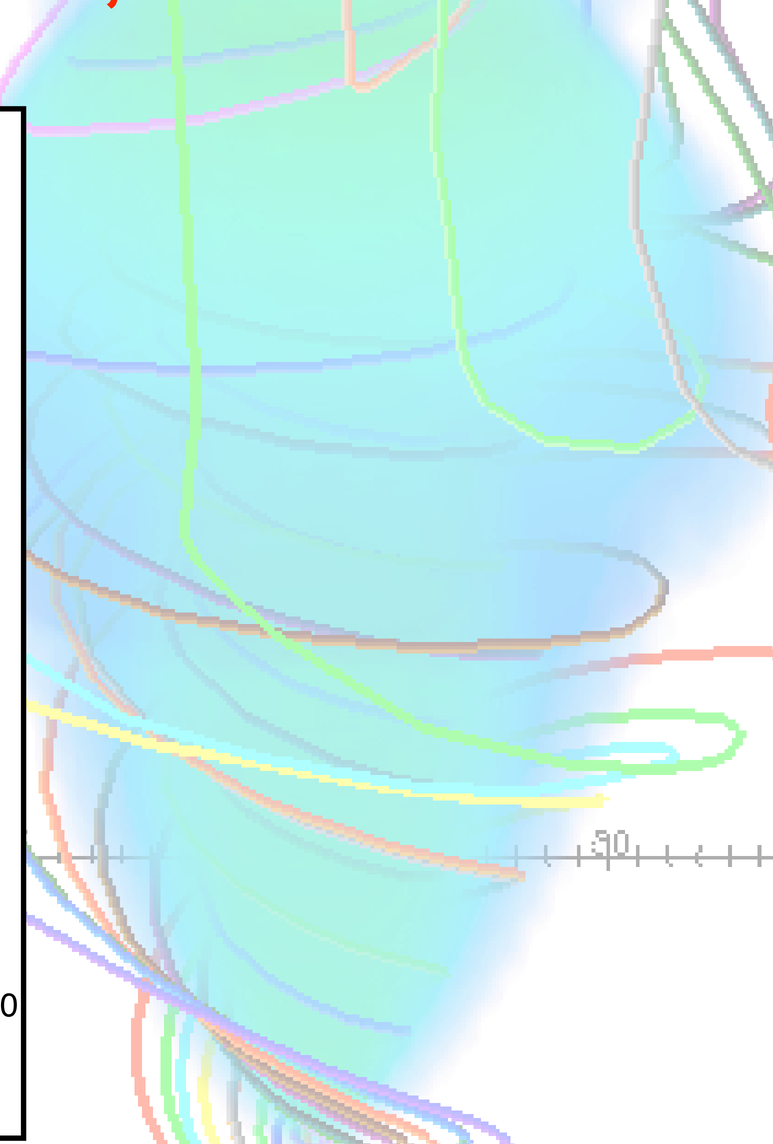
> PLUTO 3.0 RMHD module, hll, constrained transport, RK3 time-integration
> Cylindrical symmetry, 2.5D
> Domain: 300x600 r_S
> 512x1024 stretched cells
> Current-free outflow boundary
> Softened gravitational potential $\phi = -\frac{GM}{R + r_S}$

Inner corona assumed hydrostatic for stability
Sub-slow magnetosonic wind: 4 boundary constraints at the inlet: E_φ, Ω^F, ρ, p

⇒ Poynting & Kinetic energy flux determined by the jet-solution alone!



Profiles at the inlet boundary



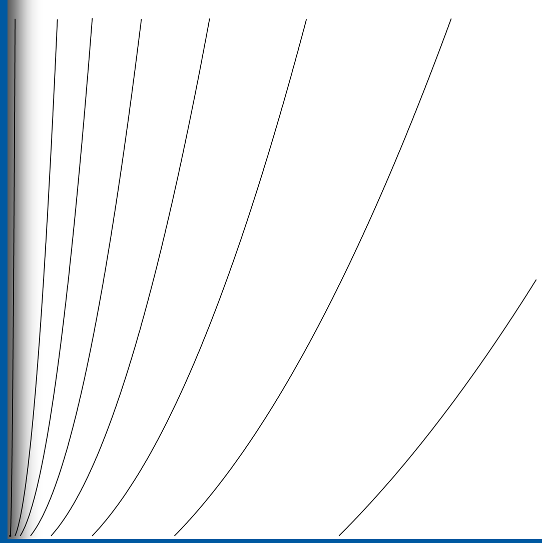
Time evolution

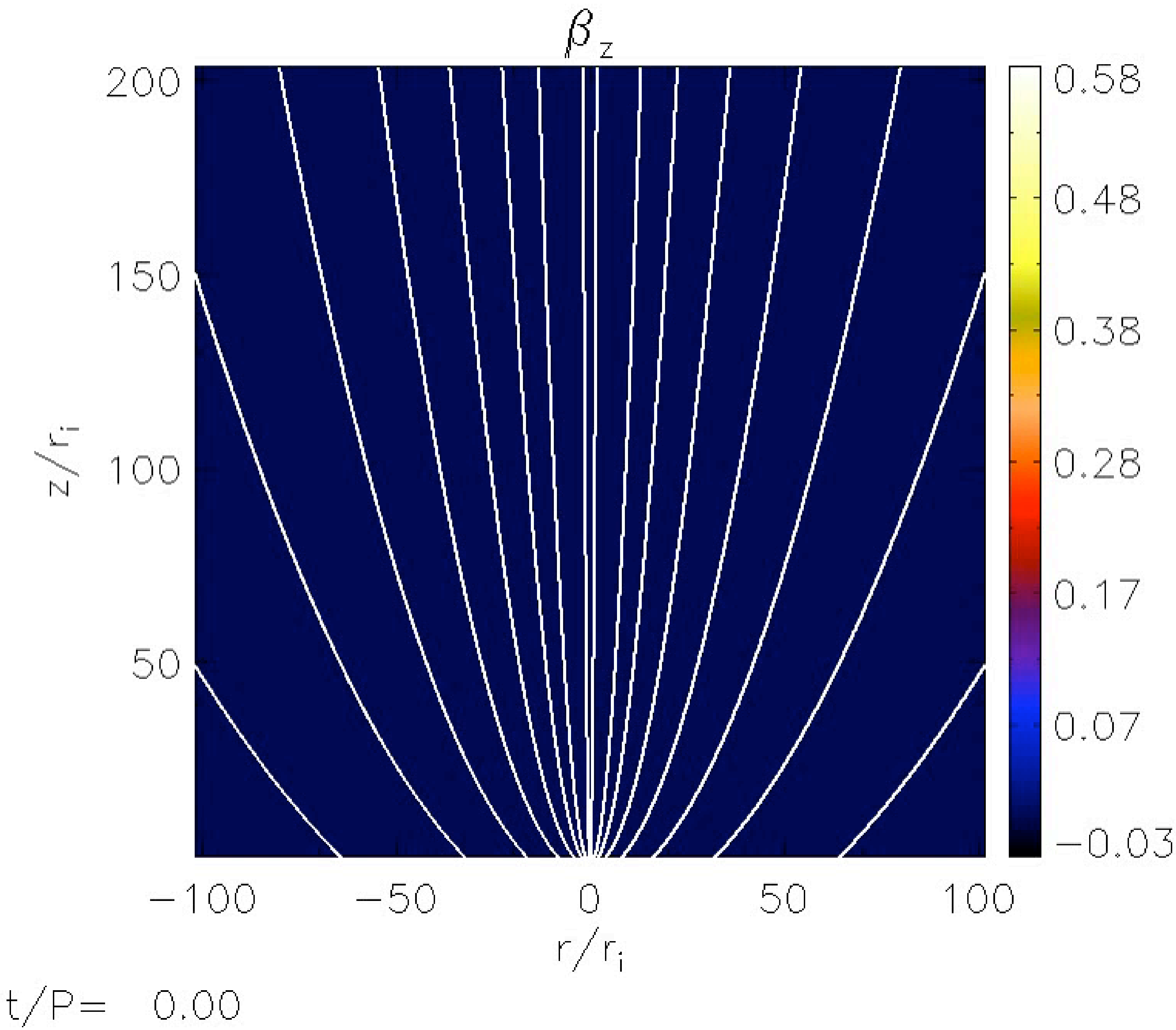
Disk wind simulation with:

v_K=0.5c

ϵ=1/6

β_i=0.2

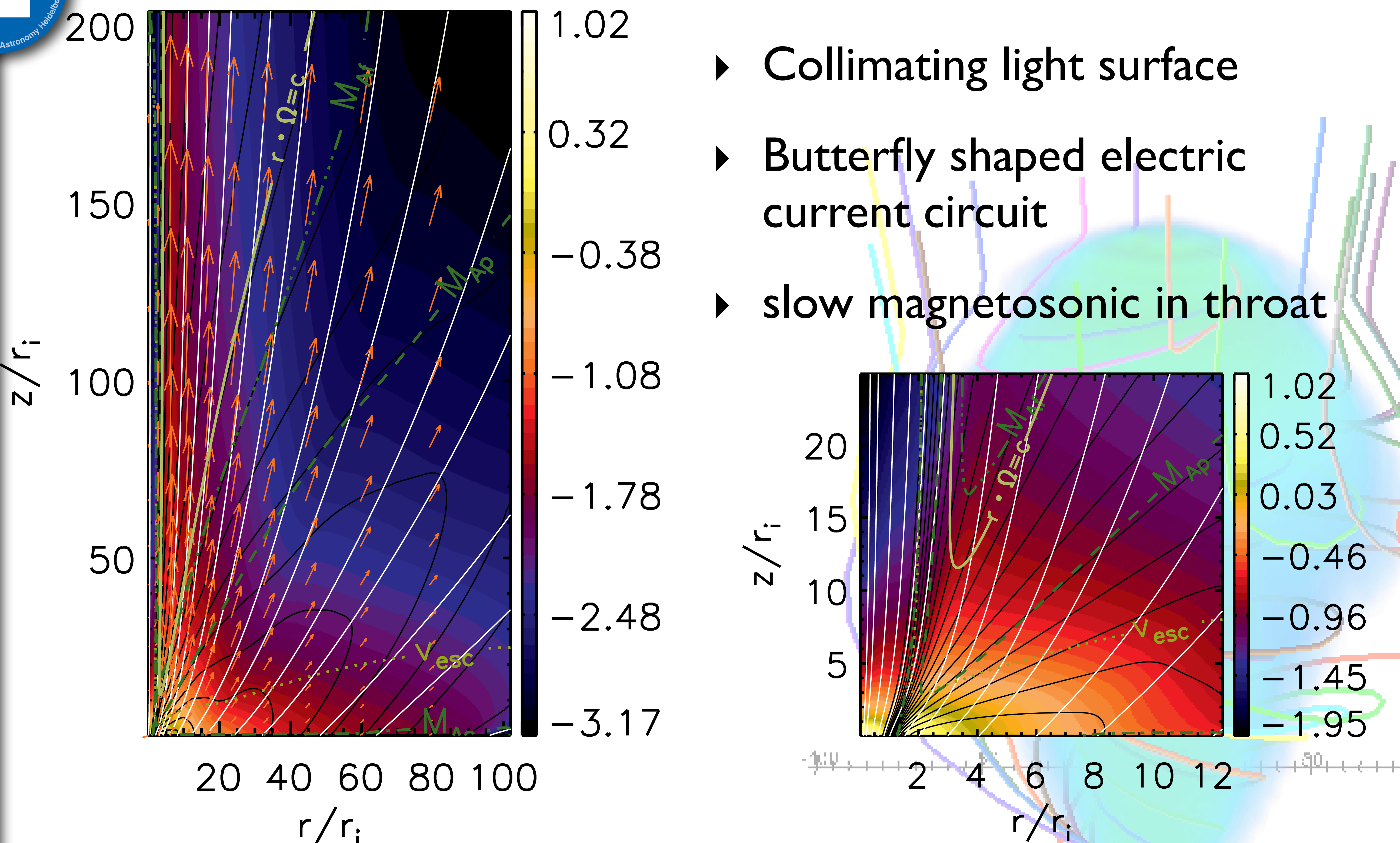




white: field lines; green: electric current; blue: light surface

Steady state solutions

- Collimating light surface
- Butterfly shaped electric current circuit
- slow magnetosonic in throat



Color gradient: logarithmic rest-frame density; white: field lines; red arrows: velocity vectors; green: characteristic surfaces

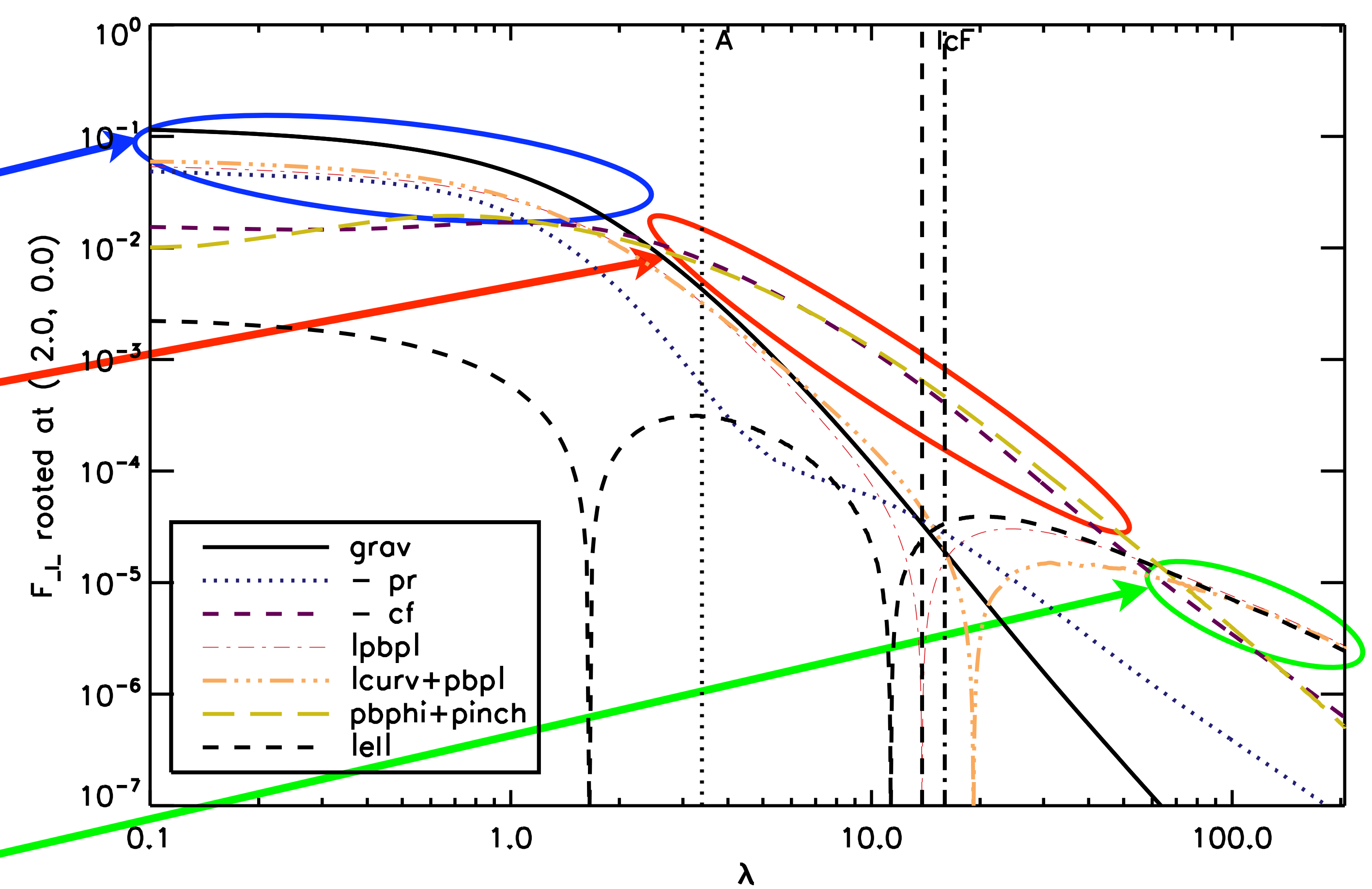
Collimating forces

sub-Alfvèn: Gravity against thermal & poloidal pressure - (magneto-) hydrodynamic

Alfvèn: Pinch against centrifugal force - magnetocentrifugal

Light cylinder: Balance of electric forces - relativistic

$$\mathbf{E} = \frac{r\Omega^F}{c} B_p \mathbf{n}$$



Leading terms in the trans-field direction along r_{fp}=2

Trans-field forces:

$$\kappa \frac{B_p^2}{4\pi}\left(1 - M^2 - \frac{r^2 \Omega^{F^2}}{c^2}\right) = \left(1 - \frac{r^2 \Omega^{F^2}}{c^2}\right) \nabla_\perp \frac{B_p^2}{8\pi} + \nabla_\perp \frac{B_\phi^2}{8\pi} + \nabla_\perp p + \left(\frac{B_\phi^2}{4\pi r} - \frac{\rho h u_\phi^2}{r}\right) \nabla_\perp r - \frac{B_p^2 \Omega^F}{4\pi c^2} \nabla_\perp \left(r^2 \Omega^F\right) + \Gamma \rho \nabla_\perp \phi$$

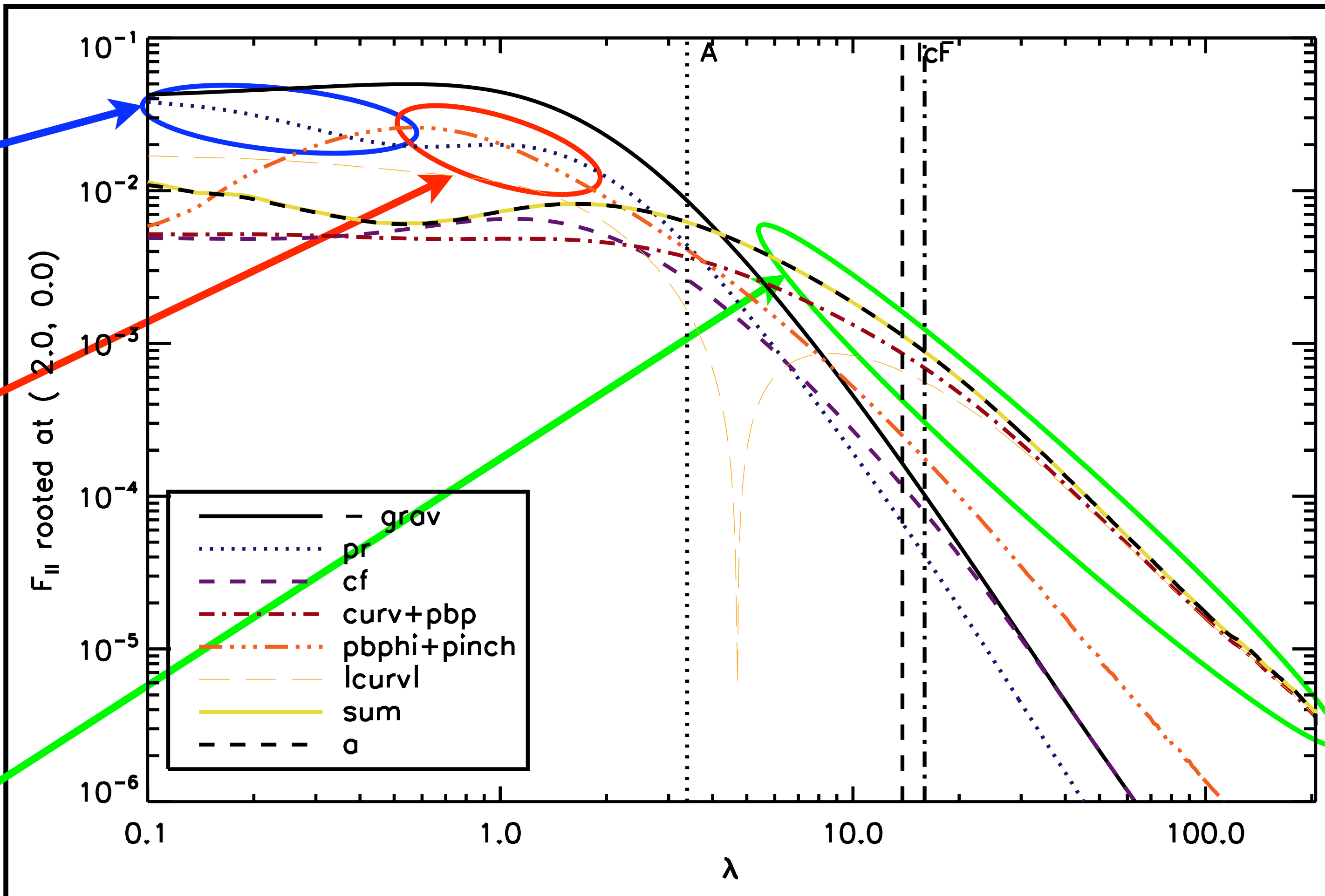
Chiueh+ '91, Appl+ '93

Accelerating forces

Launching: Thermal pressure / centrifugal force (for cool cases)

sub Alfvènic: Toroidal magnetic pressure

super Alfvènic: Poloidal magnetic tension
no electric contribution!



Leading terms in the parallel-field direction along r_{fp}=2

Parallel-field forces:

$$\frac{B_p^2}{4\pi}\nabla_{||}M^2 = \kappa_{||}\frac{B_p^2}{4\pi}\left(1-M^2\right) - \nabla_{||}\left(p+\frac{B_p^2}{8\pi}+\frac{B_\phi^2}{8\pi}\right) - \left(\frac{B_\phi^2}{4\pi r}-\frac{\rho h u_\phi^2}{r}\right)\nabla_{||}r - \Gamma\rho\nabla_{||}\phi$$

Jet acceleration in a nutshell

Cold limit:

$$\sigma = \mathcal{S}/(\mathcal{K}+\mathcal{M})$$

$$\mu = \Gamma\left(\sigma+1\right)$$

$$\Rightarrow \Gamma \underset{(\sigma\to 0)}{\longrightarrow} \mu$$

(μ conserved)

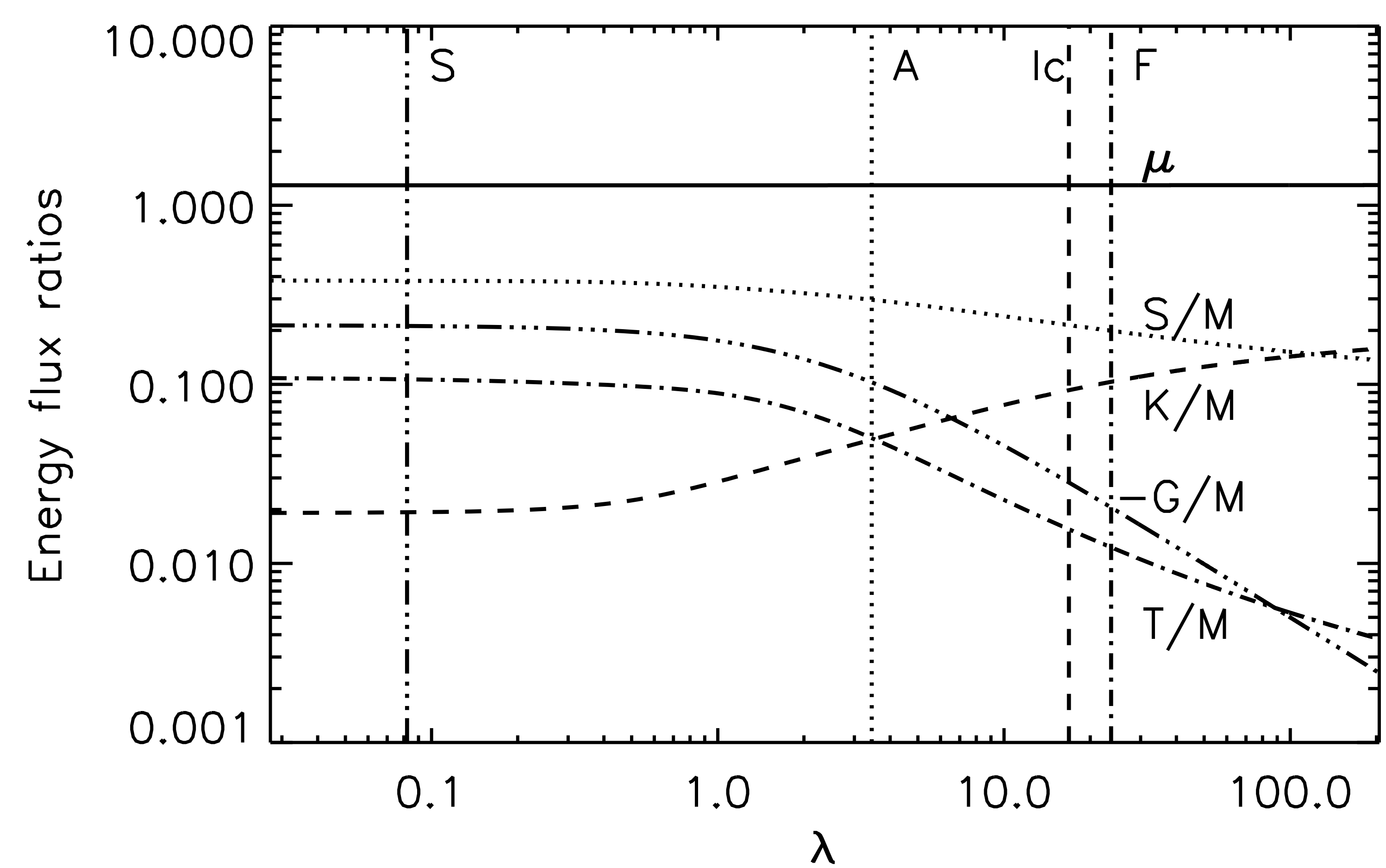
But keep in mind:

$$\Gamma_F \sim \mu^{1/3}$$

(Michel '69, Beskin+ '98)

What dominates disk energetics?

$$\mathcal{K} < \mathcal{T} < -\mathcal{G} < \mathcal{S} < \mathcal{M}$$



Energy fluxes along fl r_{fp}=2

$$\mu \equiv \frac{\mathcal{S}+\mathcal{K}+\mathcal{M}+\mathcal{T}+\mathcal{G}}{\mathcal{M}}$$

Energy conversion

Efficient acceleration,

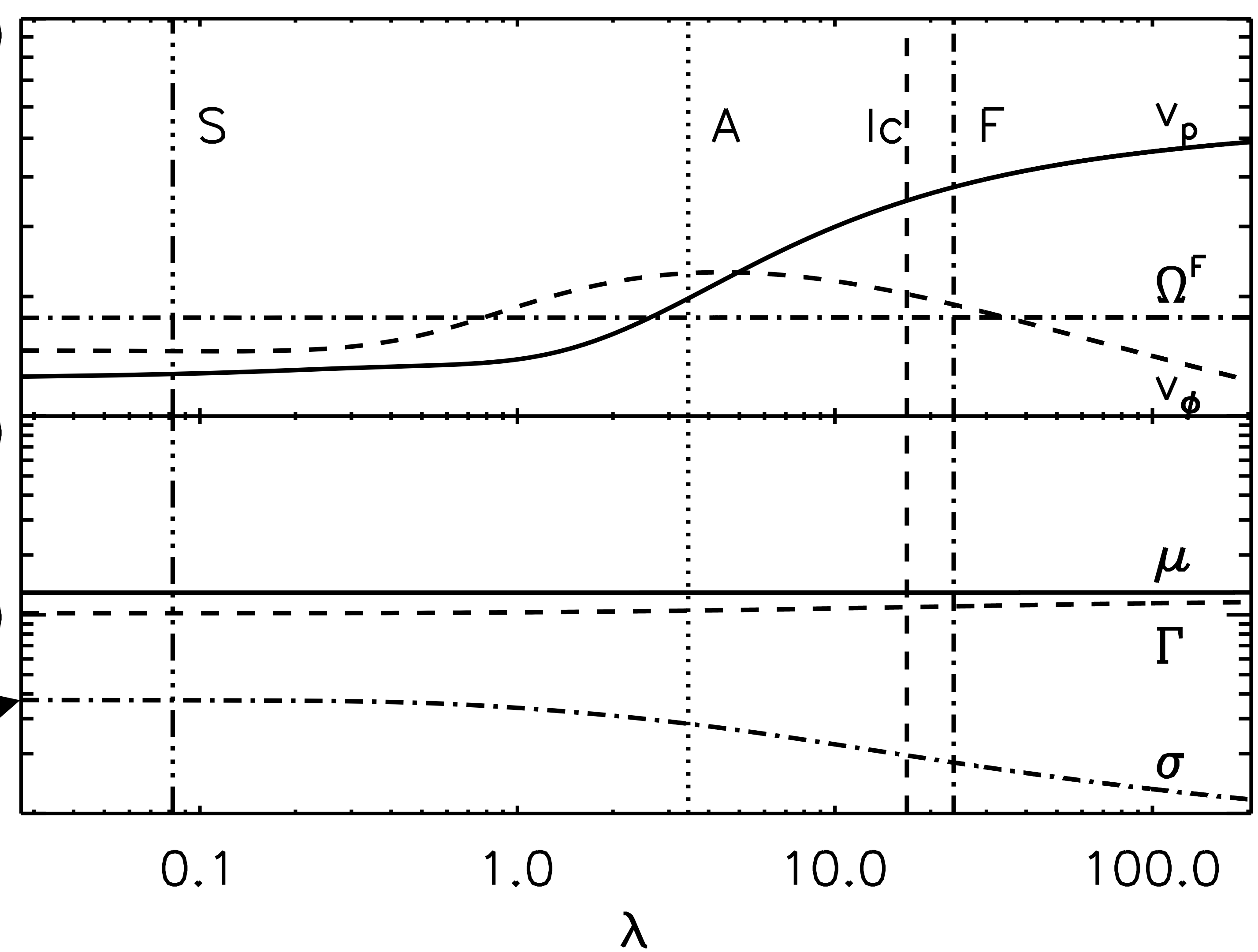
sub-equipartition (σ<1) already at inlet!

v_K=0.5c

ϵ=2/3

β_i=1

$\sigma_{z=0}$<1



Quantities along fl r_{fp}=2

Poynting dominated flows

specify μ via:

$$B_\phi \propto -1/r$$

$$v_z = v_{\rm inj}\; v_\phi(r)$$

$B_{\varphi,i}=2B_{p,i}$

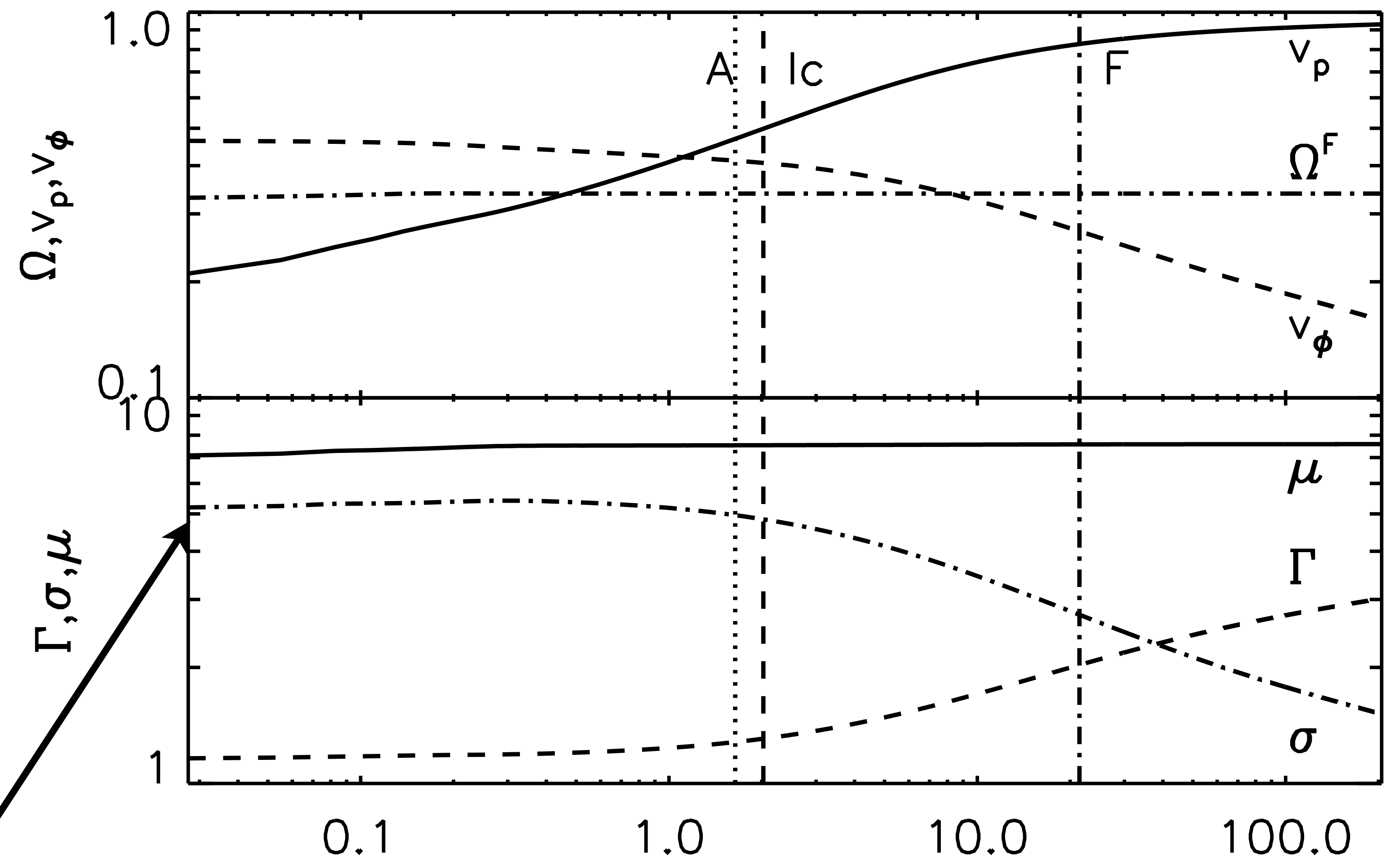
$v_{inj}=0.1$

$v_K=0.5c$

$\epsilon=2/3$

$\beta_i=0.2$

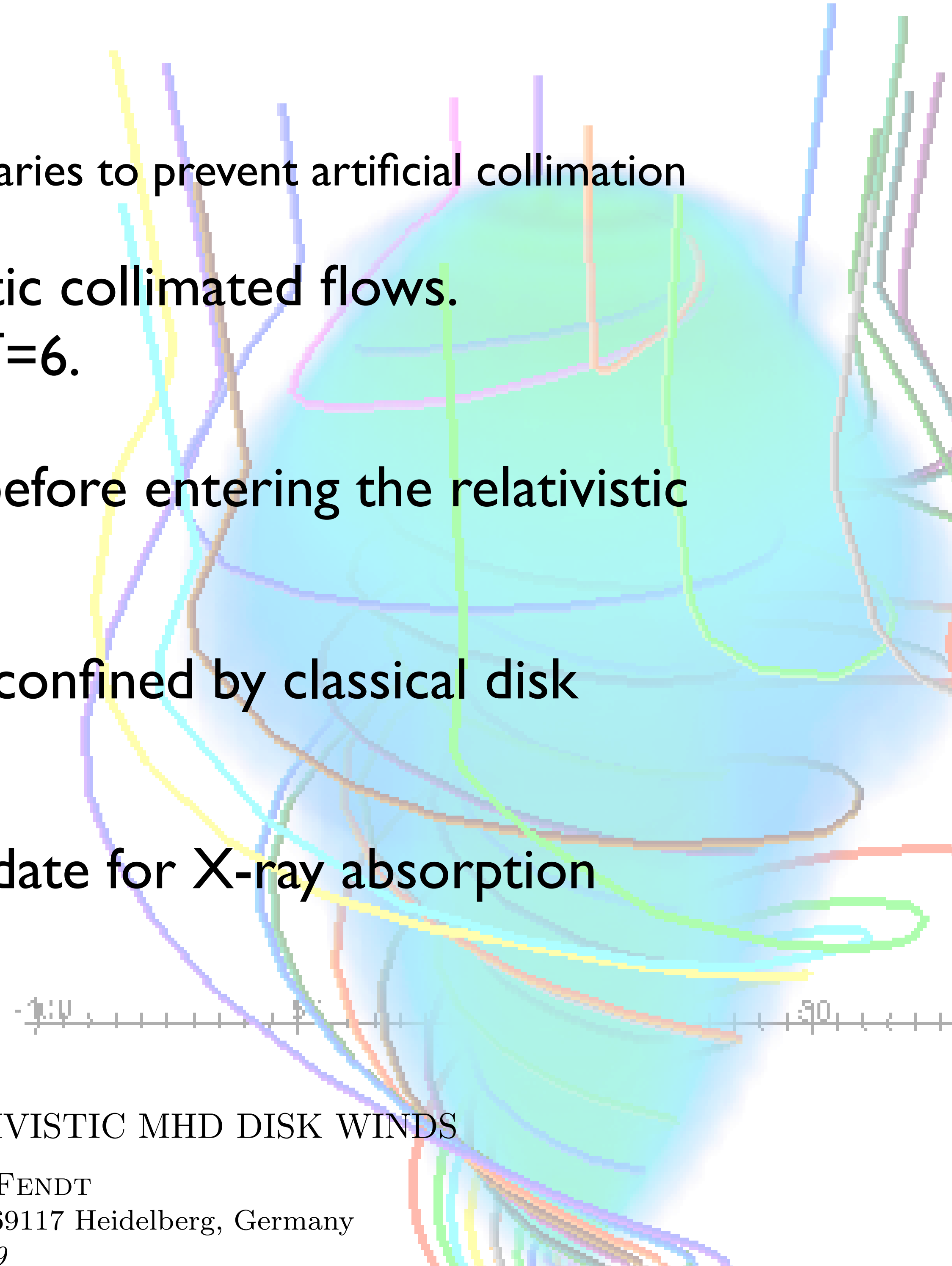
$\sigma_{z=0}=5$



Quantities along fl $r_{fp}=2$

Conclusions

- We investigated the Blandford-Payne mechanism around compact objects (RMHD + Gravity).
  - Physical inlet boundary modeled as disk corona
  - Much efforts put into optimizing outflow boundaries to prevent artificial collimation
- Hot disk coronae produce mildly relativistic collimated flows. Pointing flux dominated cases gain up to $\Gamma=6$.
- Collimation ($3° < \theta_M < 7°$) by pinch forces before entering the relativistic regime.
- Collimating light surface: Relativistic core confined by classical disk wind.
- Outflow from outer disk: Promising candidate for X-ray absorption winds. (Further investigation needed)
- Submitted to ApJ:



ACCELERATION AND COLLIMATION OF RELATIVISTIC MHD DISK WINDS

OLIVER PORTH[1] AND CHRISTIAN FENDT
Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

Draft version October 19, 2009

Time evolution

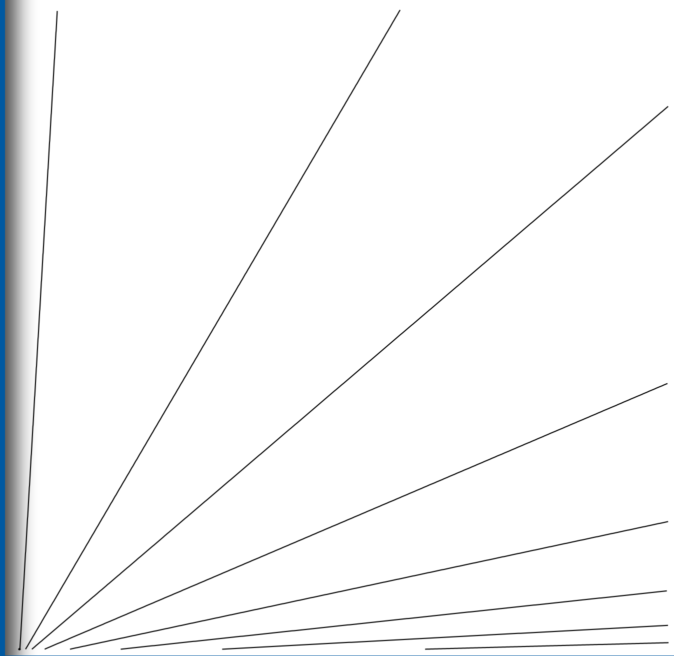
Disk wind simulation with:

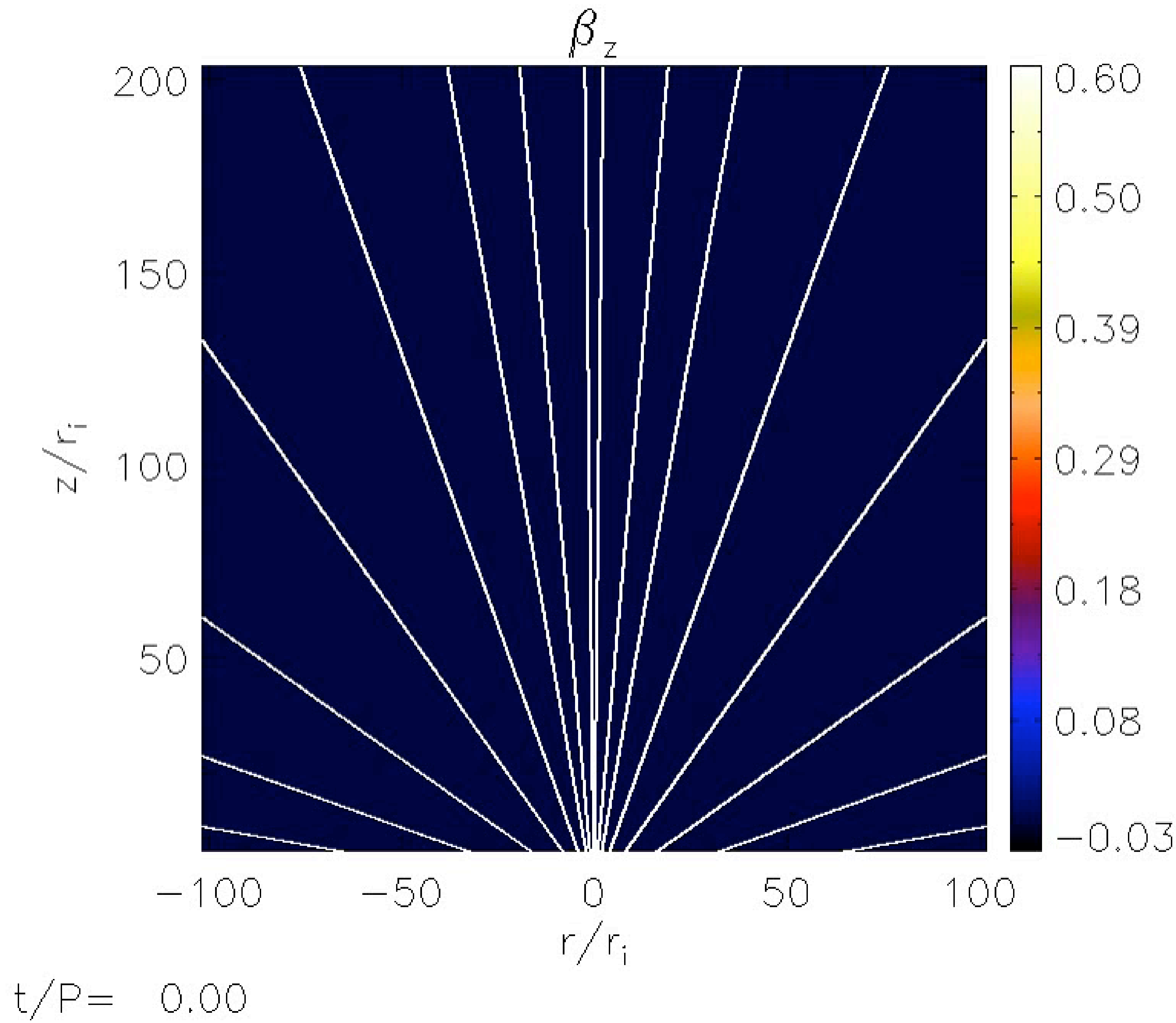
v_K=0.5c

ϵ=2/3

β_i=1

θ_i=85°



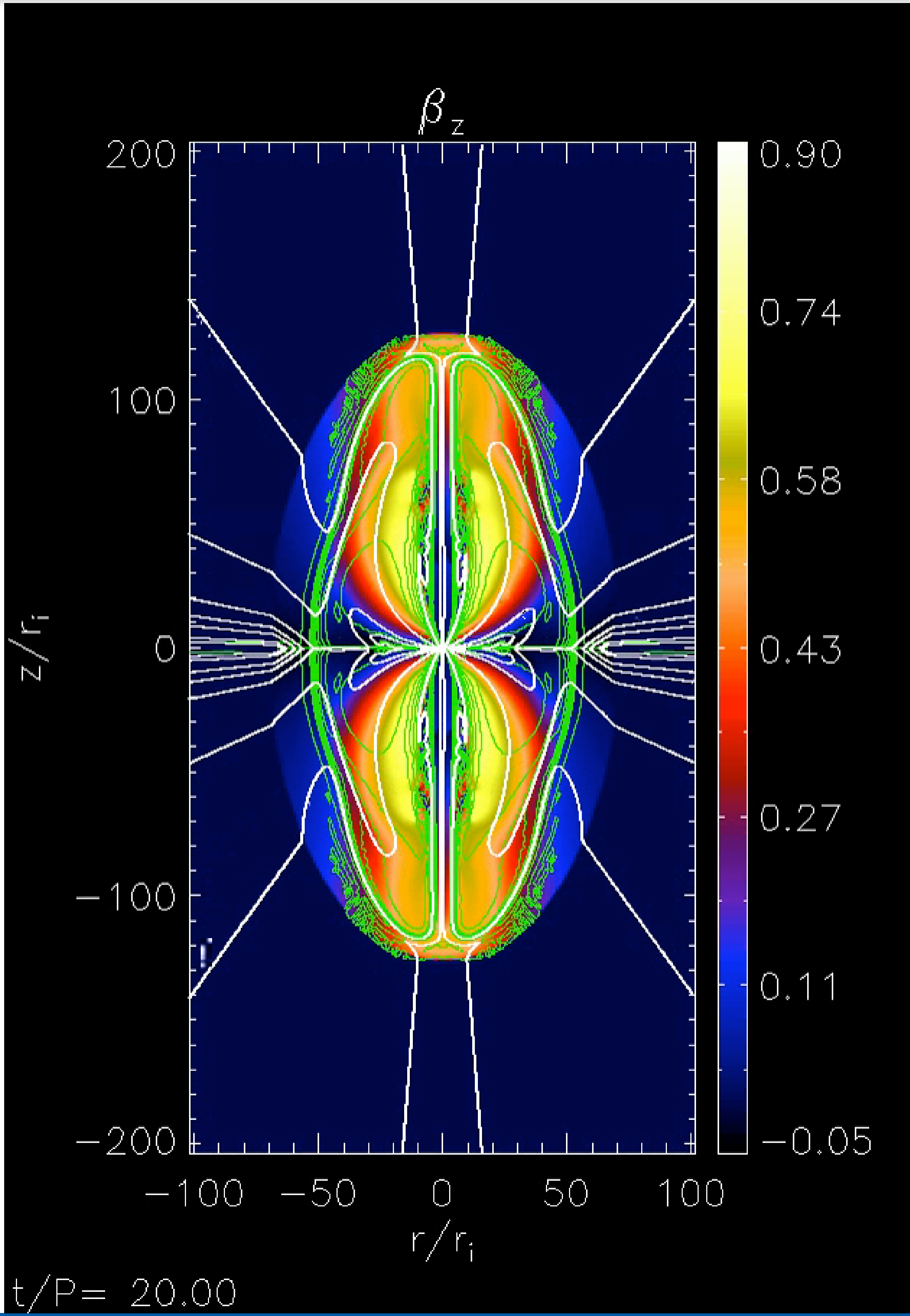


white: field lines; green: electric current; blue: light cylinder

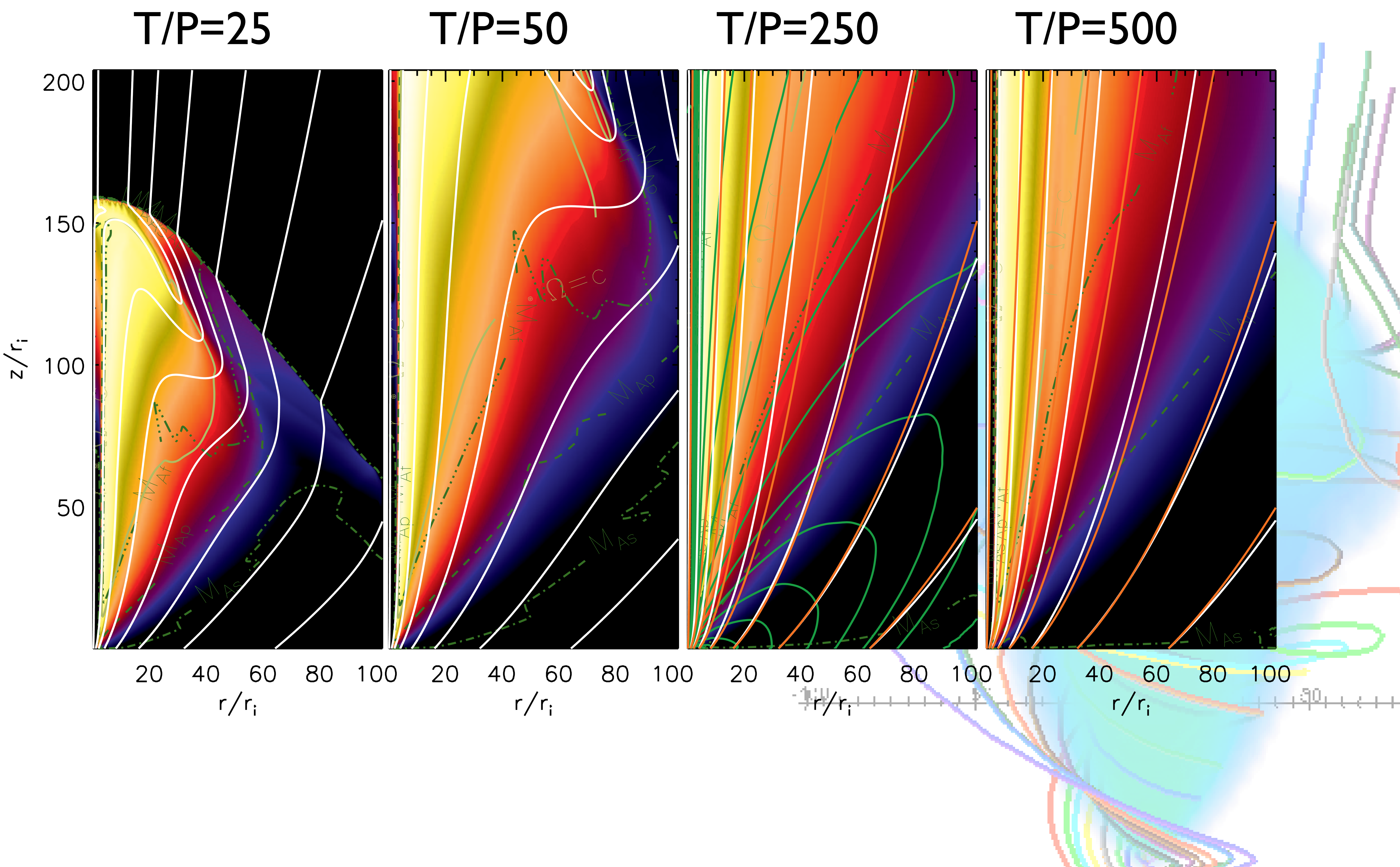
Oliver Porth

MPIA Heidelberg

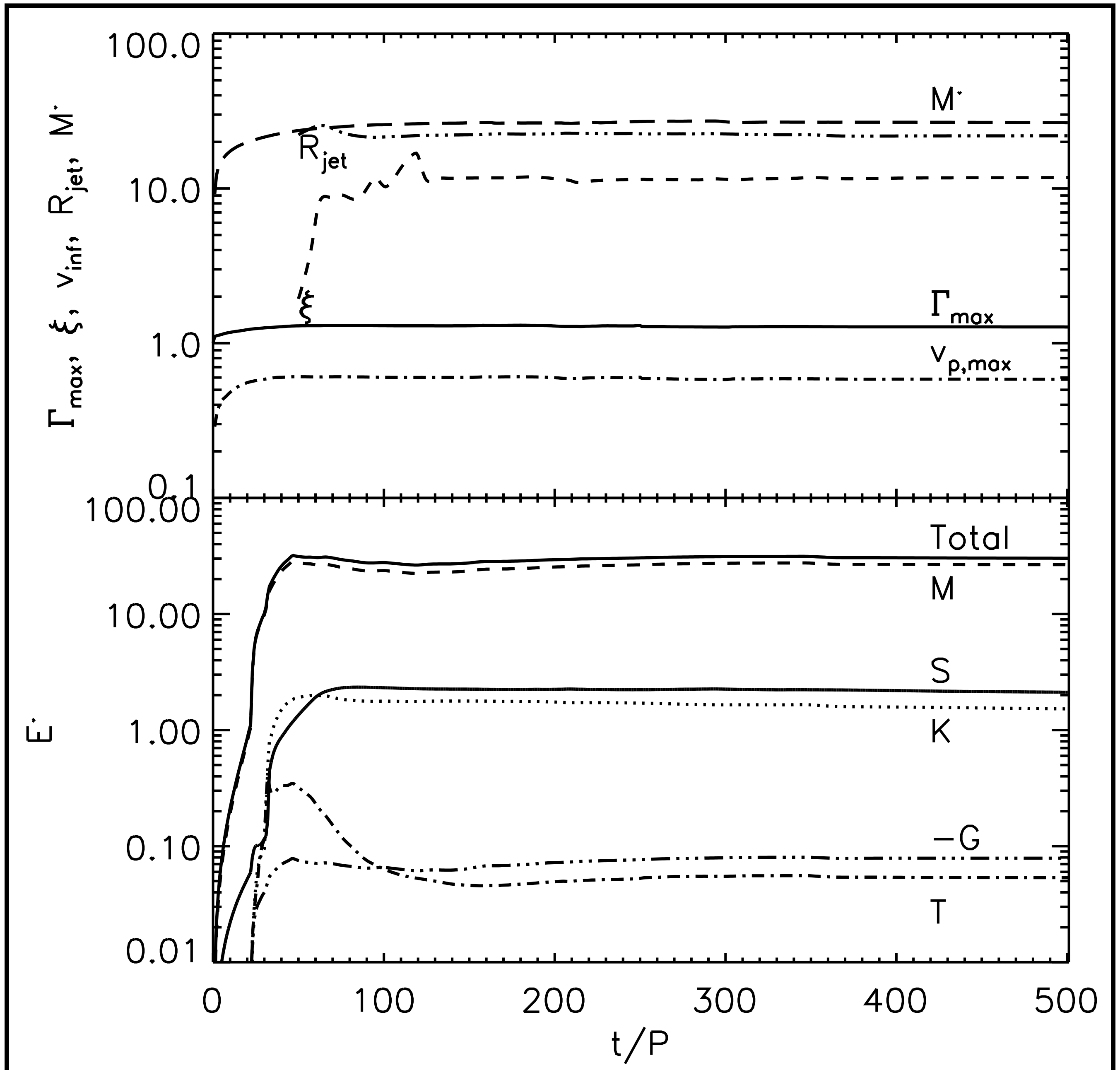
Time evolution



Time evolution



Time evolution



Dynamical parameters & Energy fluxes out of domain

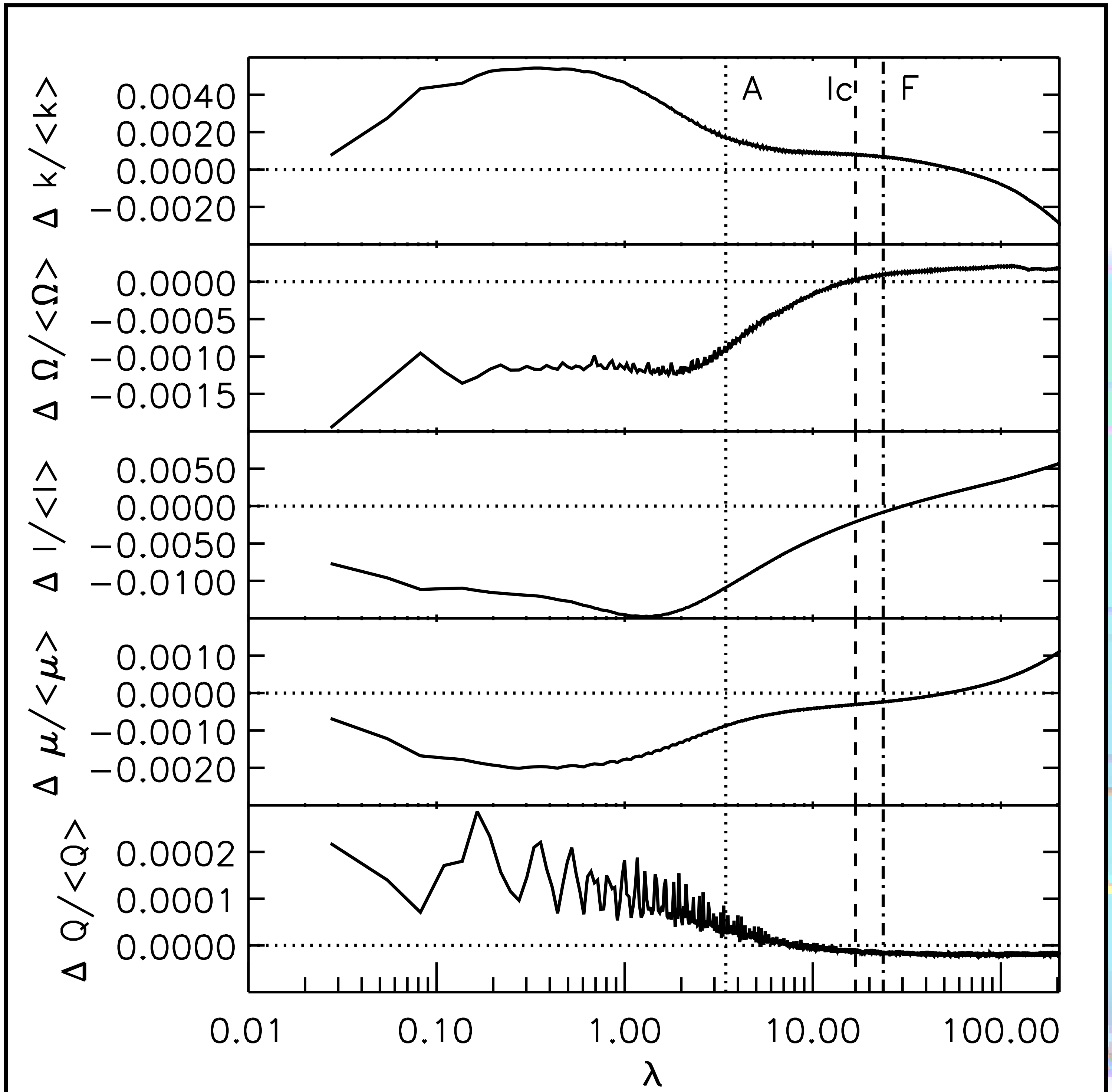
- Simulation reaches quasi steady state in domain after t/P≃200,

  MHD integrals conserved ≃1%

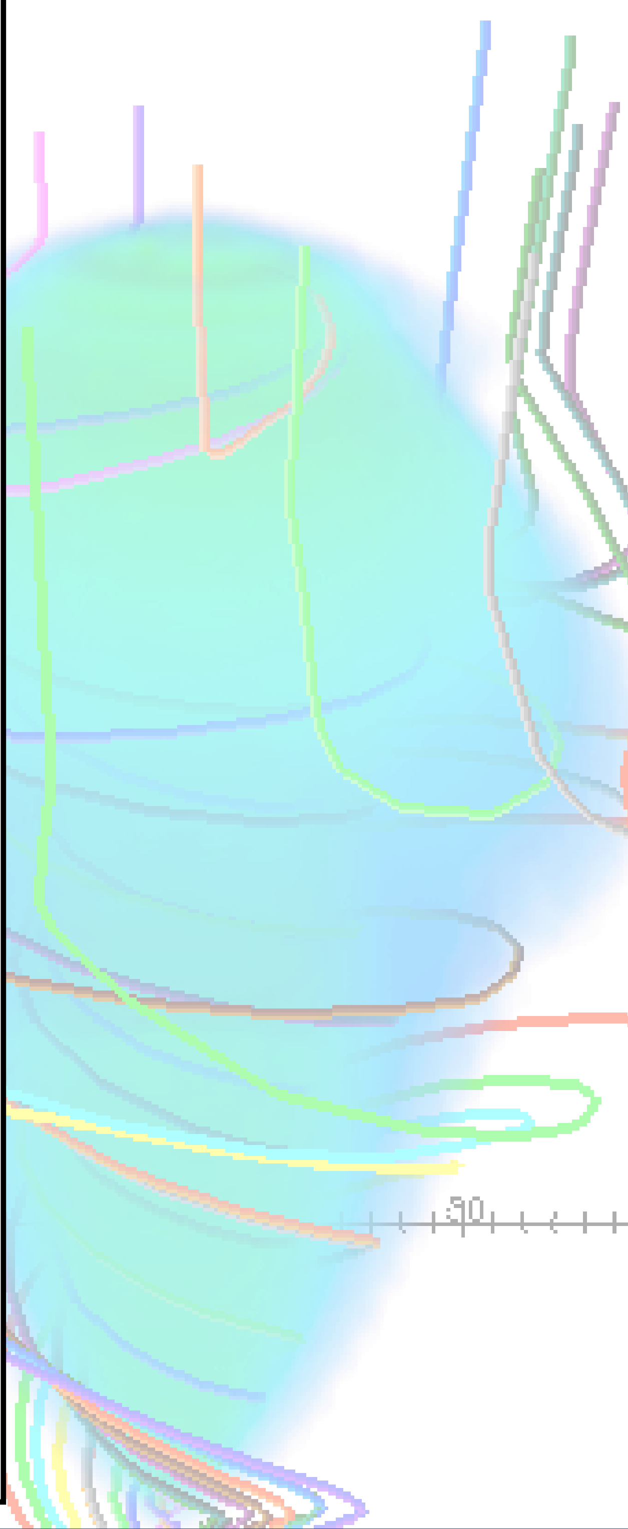
- Main energy flux in terms of rest-mass (heavy wind)

- Thermal and gravitational flux negligible

Field line constants



Constants along field line r_{fp}=2



Jet acceleration in a nutshell

Cold limit:

$$\sigma = \mathcal{S}/(\mathcal{K}+\mathcal{M})$$

$$\mu = \Gamma\left(\sigma+1\right)$$

$$\Rightarrow \Gamma \underset{\sigma\rightarrow 0}{\longrightarrow} \mu$$

(μ conserved)

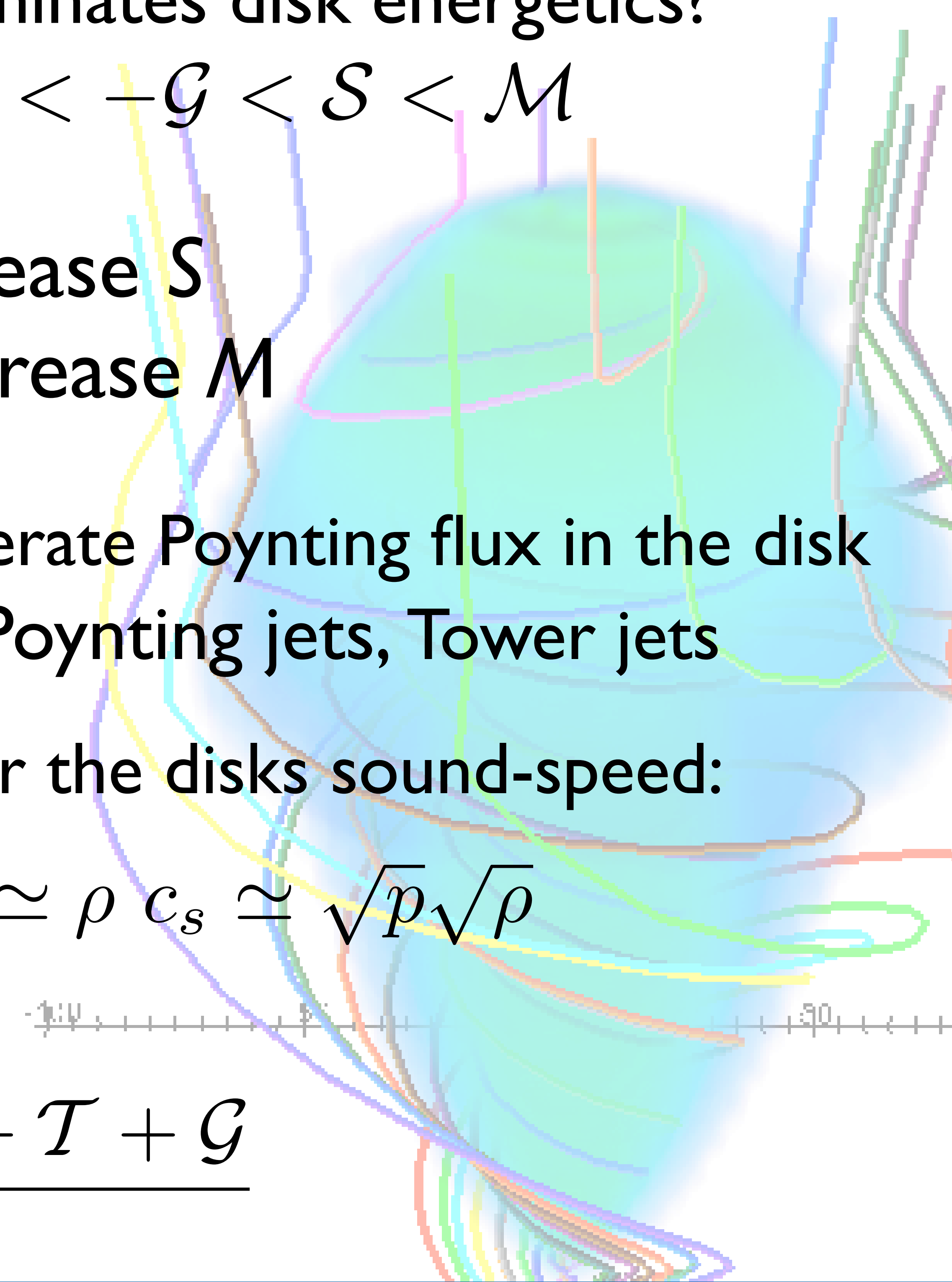
But keep in mind:

$$\Gamma_F \sim \mu^{1/3}$$

(Michel '69, Beskin+ '98)

What dominates disk energetics?

$$\mathcal{K} < \mathcal{T} < -\mathcal{G} < \mathcal{S} < \mathcal{M}$$



1. Increase *S*
2. Decrease *M*

1.: Generate Poynting flux in the disk
→ Poynting jets, Tower jets

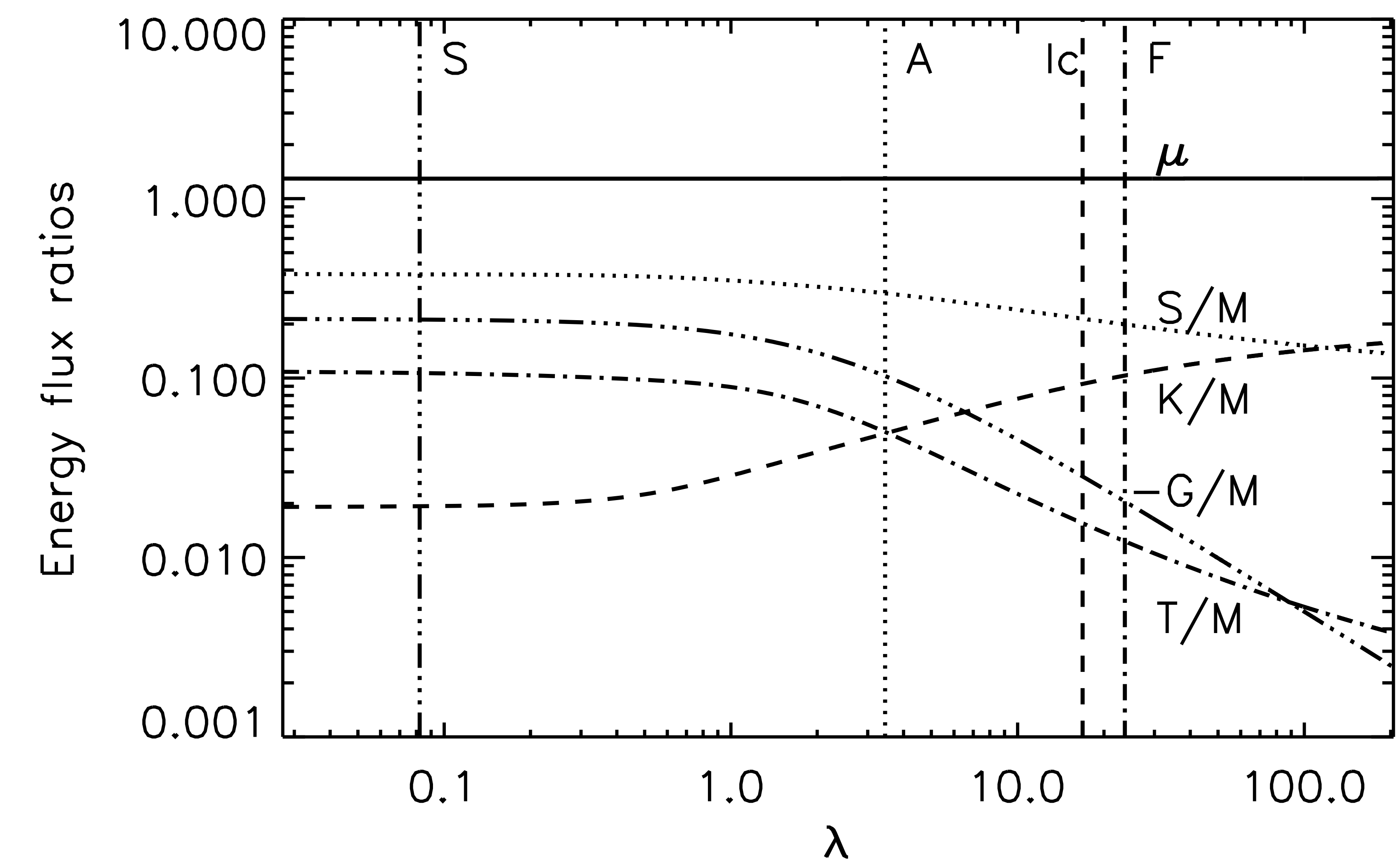
2.: lower the disks sound-speed:

$$\mathcal{M} \simeq \rho\, c_s \simeq \sqrt{p}\sqrt{\rho}$$

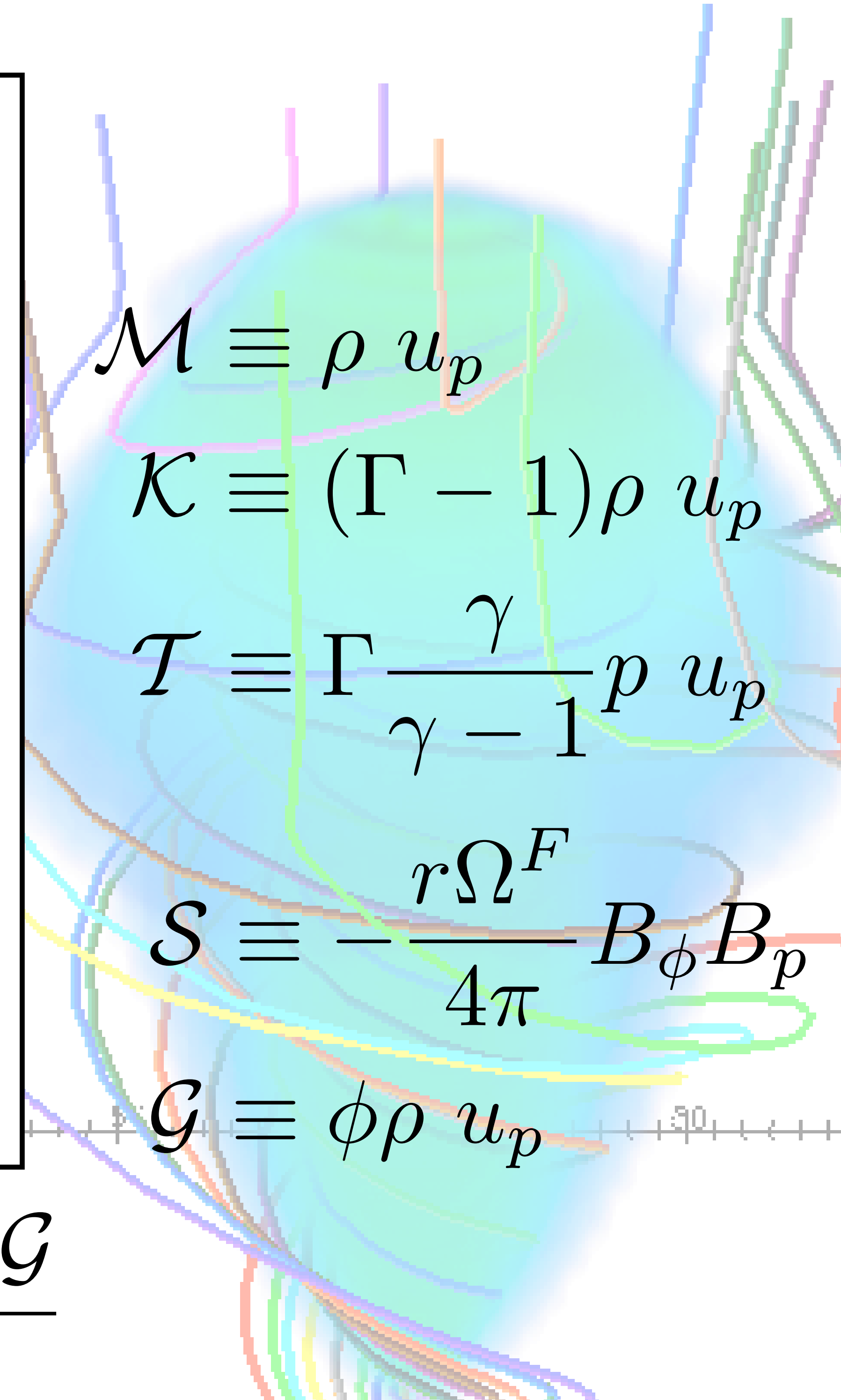
$$\mu \equiv \frac{\mathcal{S}+\mathcal{K}+\mathcal{M}+\mathcal{T}+\mathcal{G}}{\mathcal{M}}$$

Energy conversion

No constraints on energies: Partitioning & conversion alone by jet-dynamics



Energy fluxes along fl r_{fp}=2



$$\mathcal{M} \equiv \rho\, u_p$$

$$\mathcal{K} \equiv (\Gamma - 1)\rho\, u_p$$

$$\mathcal{T} \equiv \Gamma \frac{\gamma}{\gamma - 1} p\, u_p$$

$$\mathcal{S} \equiv -\frac{r\Omega^F}{4\pi} B_\phi B_p$$

$$\mathcal{G} \equiv \phi \rho\, u_p$$

$$\mu \equiv \frac{\mathcal{S} + \mathcal{K} + \mathcal{M} + \mathcal{T} + \mathcal{G}}{\mathcal{M}}$$