Two Years (1983-1985) in Heaven

(aka Caltech Theoretical Astrophysics)

TAPIR

Numerical Simulations of Relativistic Jets

WITH

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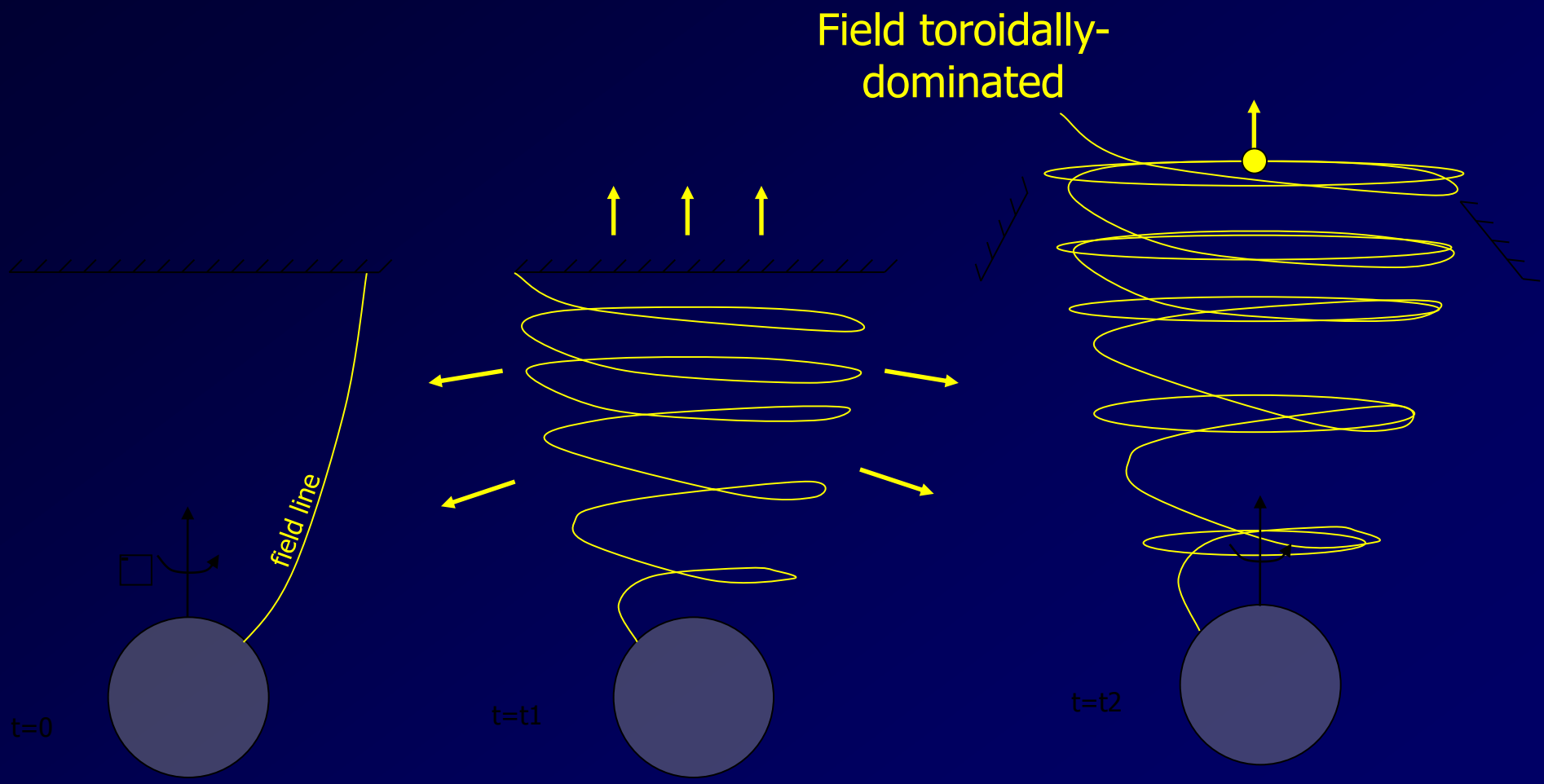
In the Beginning
Darkness was upon the face of
all astrophysicists
Then Blandford & Znajek said:
Let there be
Electromagnetic Extraction of
Energy from Kerr Black Holes
and there was light and joy
among all astrophysicists
and B&Z saw the light and joy,
that it was good

On the seventh day
Blandford rested
and on the eighth day he
sought new worlds to conquer
and relativistic jets sank back
into the mud of
misery and mystery
and there was great wailing
and gnashing of teeth among
the lost tribe of astrophysicists

Making a Relativistic Jet

- Required elements:
  - organized magnetic field
  - rotation at the base (BH/NS/Disk)
- Result:
  - helical outgoing wave
  - accelerates frozen-in gas

How Magnetic Jets Work

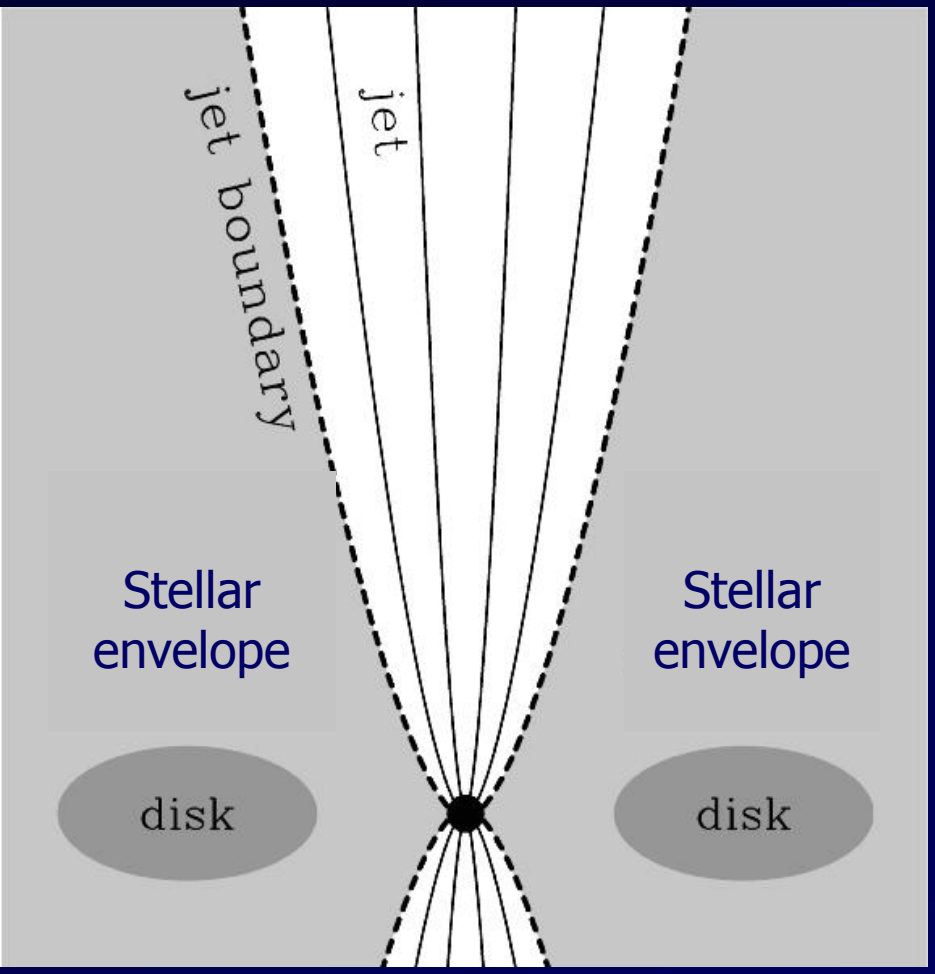


Alexander Tchekhovskoy

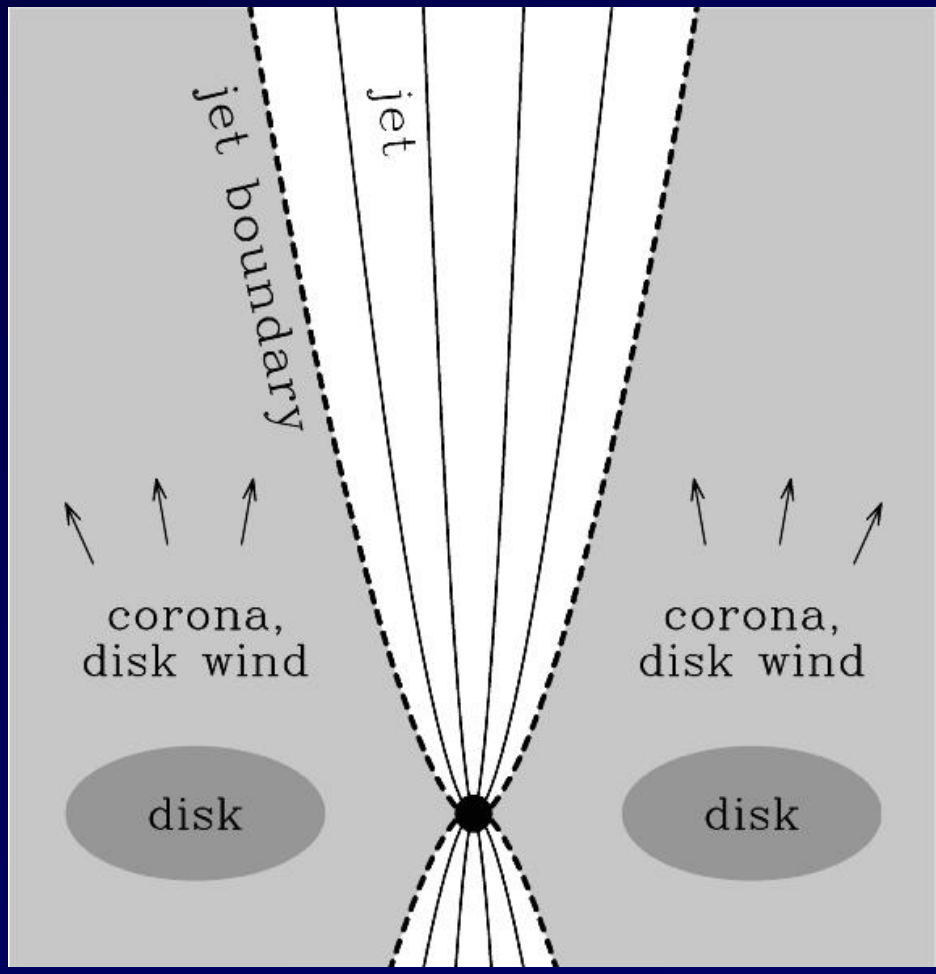
Jet Collimation

- A Poynting-dominated relativistic jet does not self-collimate
- "Hoop stress" is powerless in RMHD
- We need an **external medium** to **collimate** the spinning magnetic field

Possible Geometries

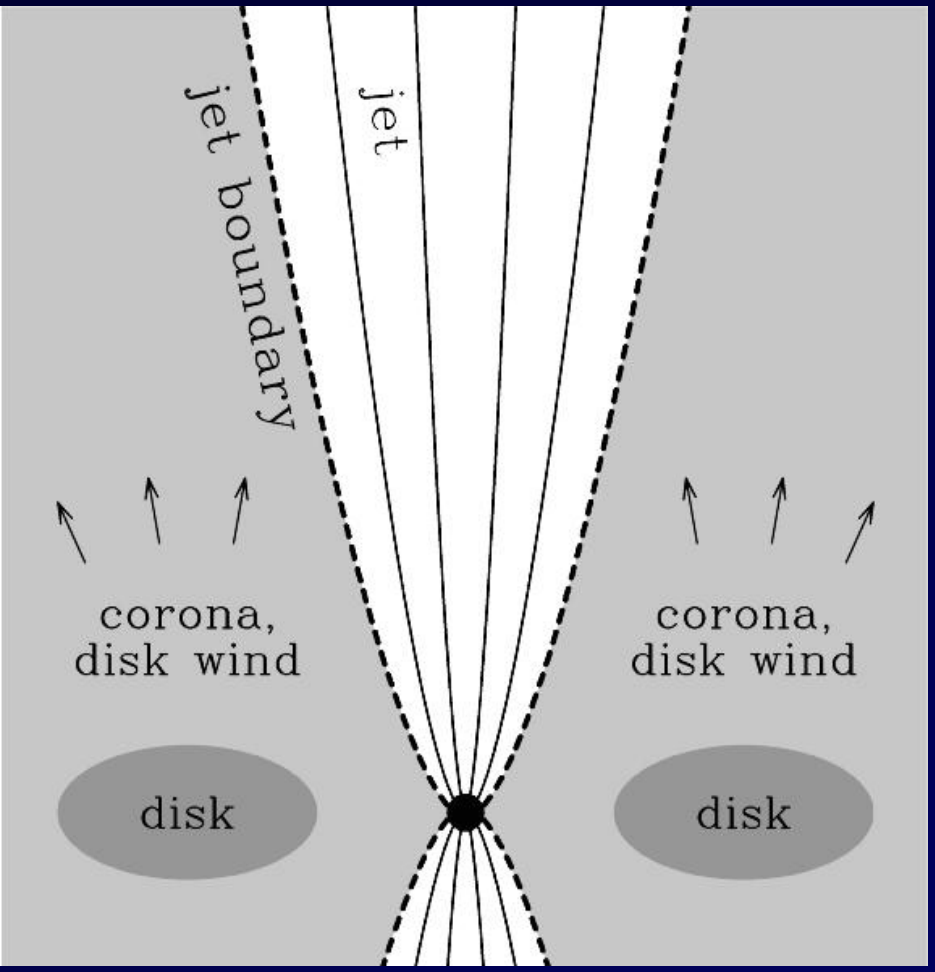


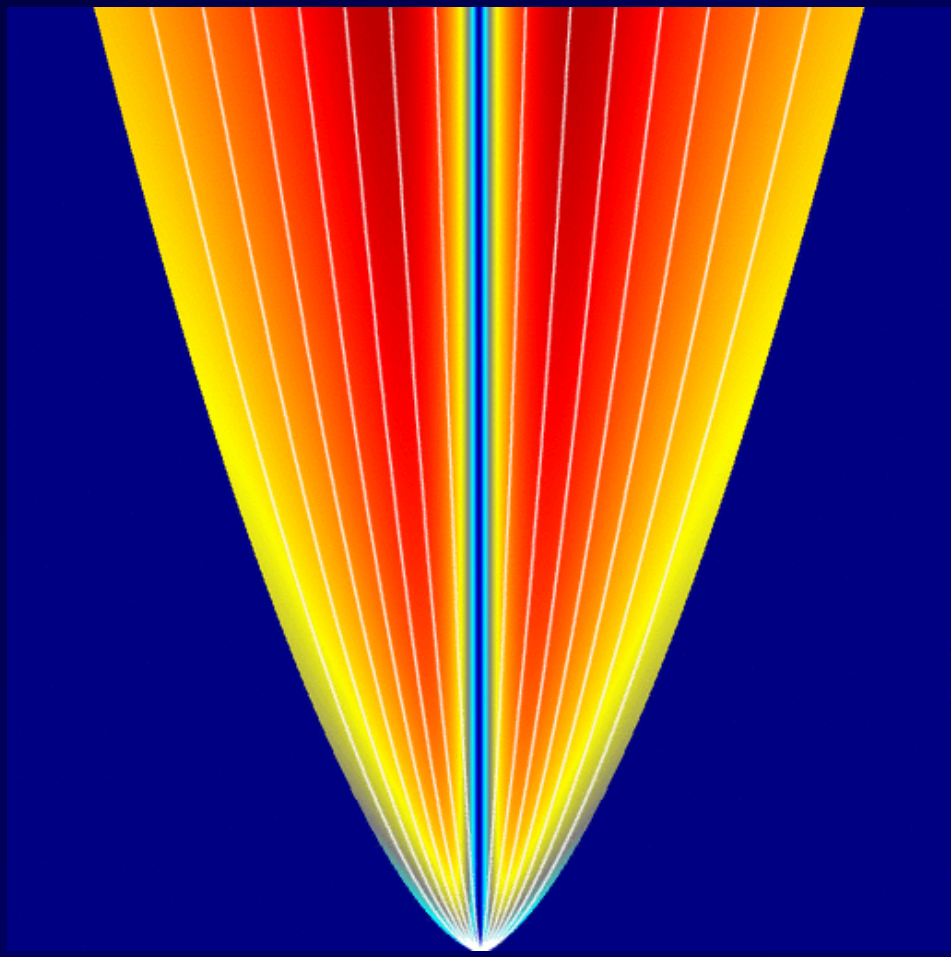
GRB: Collapsar Model



AGN or X-ray Binary

Numerical Simulation of a Collimated Jet





Replace pressure boundary condition due to the star or disk ($P \sim r^{-2} - r^{-5/2}$) with a rigid wall of the appropriate shape ($R \sim z^{1/2} - z^{5/8}$)

Two "Problems"

- AGN: radio-loud vs radio-quiet
  - Does BH spin explain the difference?
  - Spin alone may not be enough… (Tchekhovskoy et al. 2009b)
- GRBs: observations → $\gamma\,\theta_j \sim 10$—30
  - At first sight looks problematic for MHD
  - But no problem within collapsar model (Tchekhovskoy et al. 2009a)

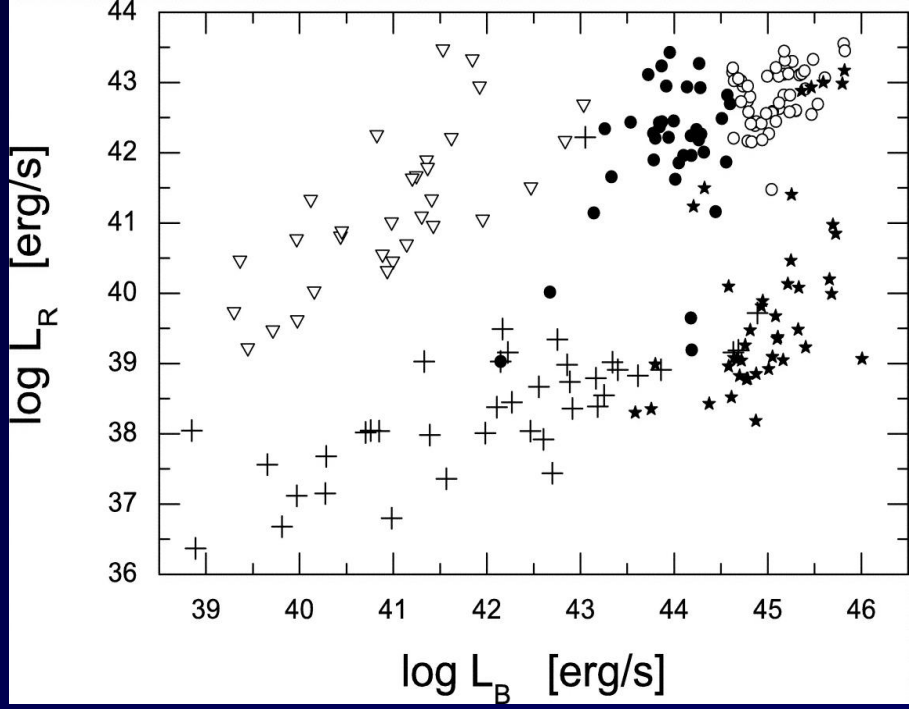
Radio Loud/Quiet Dichotomy

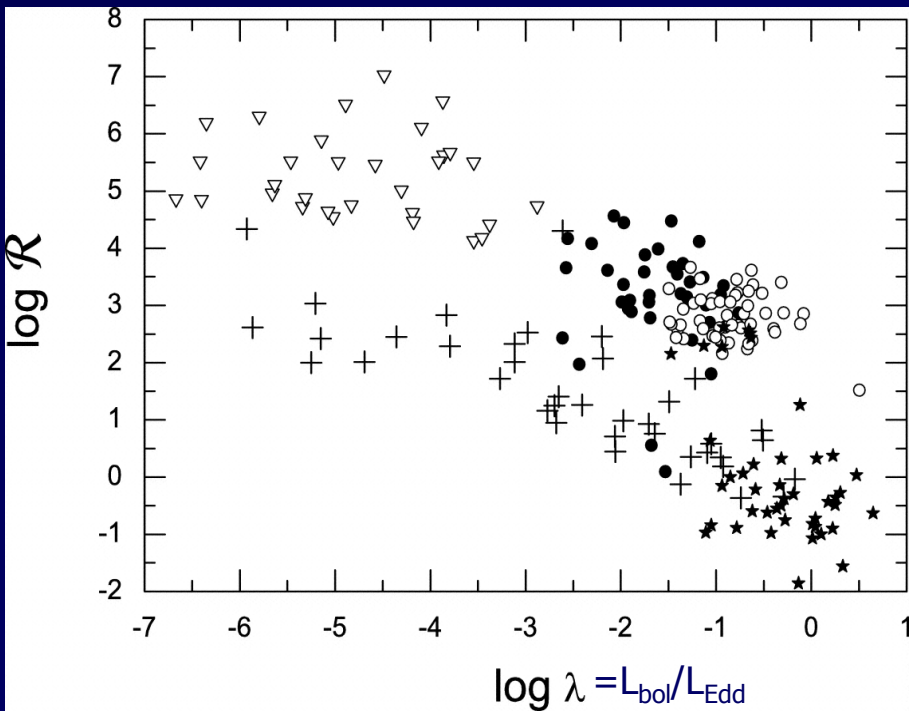
The dichotomy is real: Sikora, Stawarz & Lasota 2007 ➔

Two well-separated classes of objects, with **~10^3** difference in radio loudness

The two classes may be distinguished by BH spin …

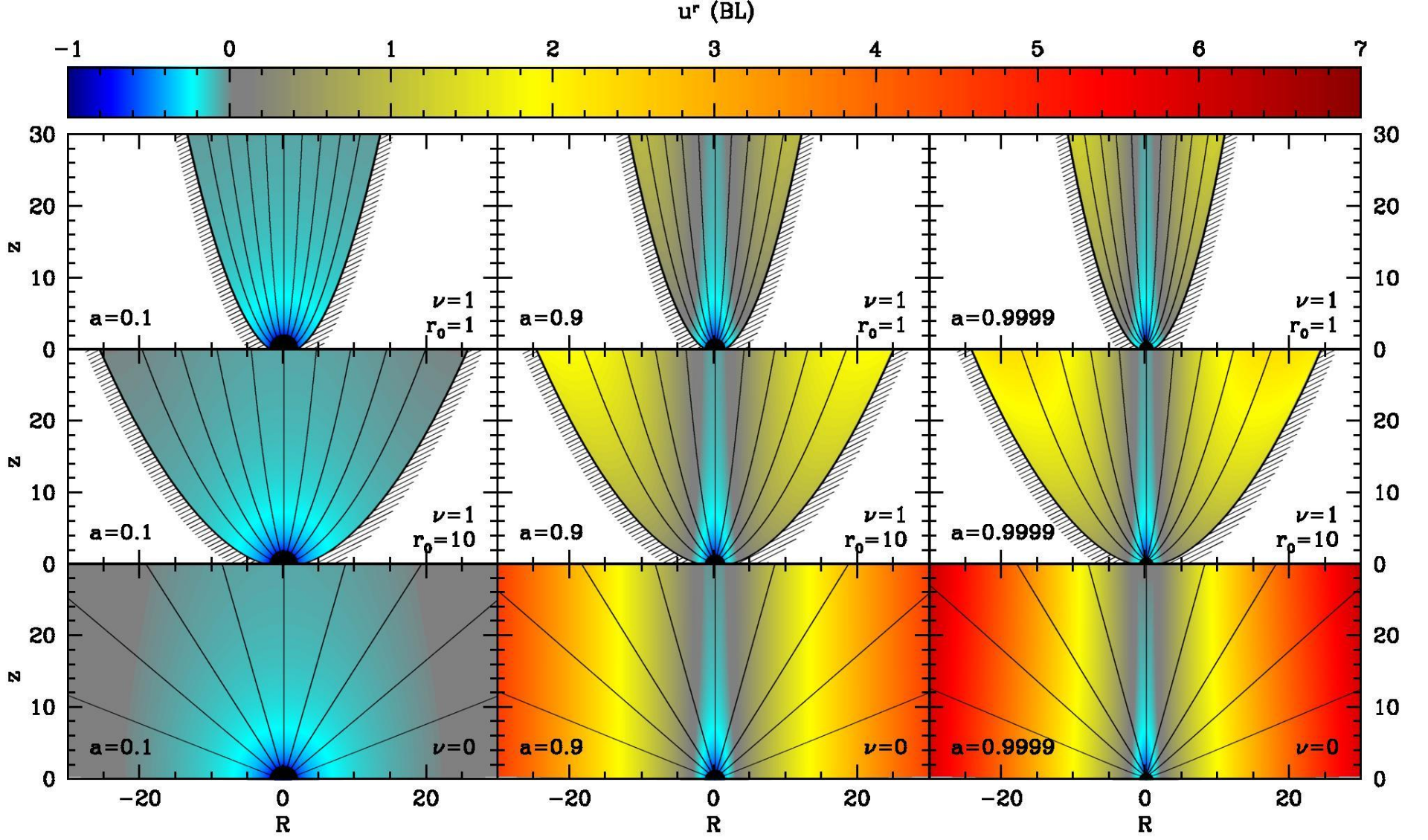
But how can spin have such a large effect on jet power?



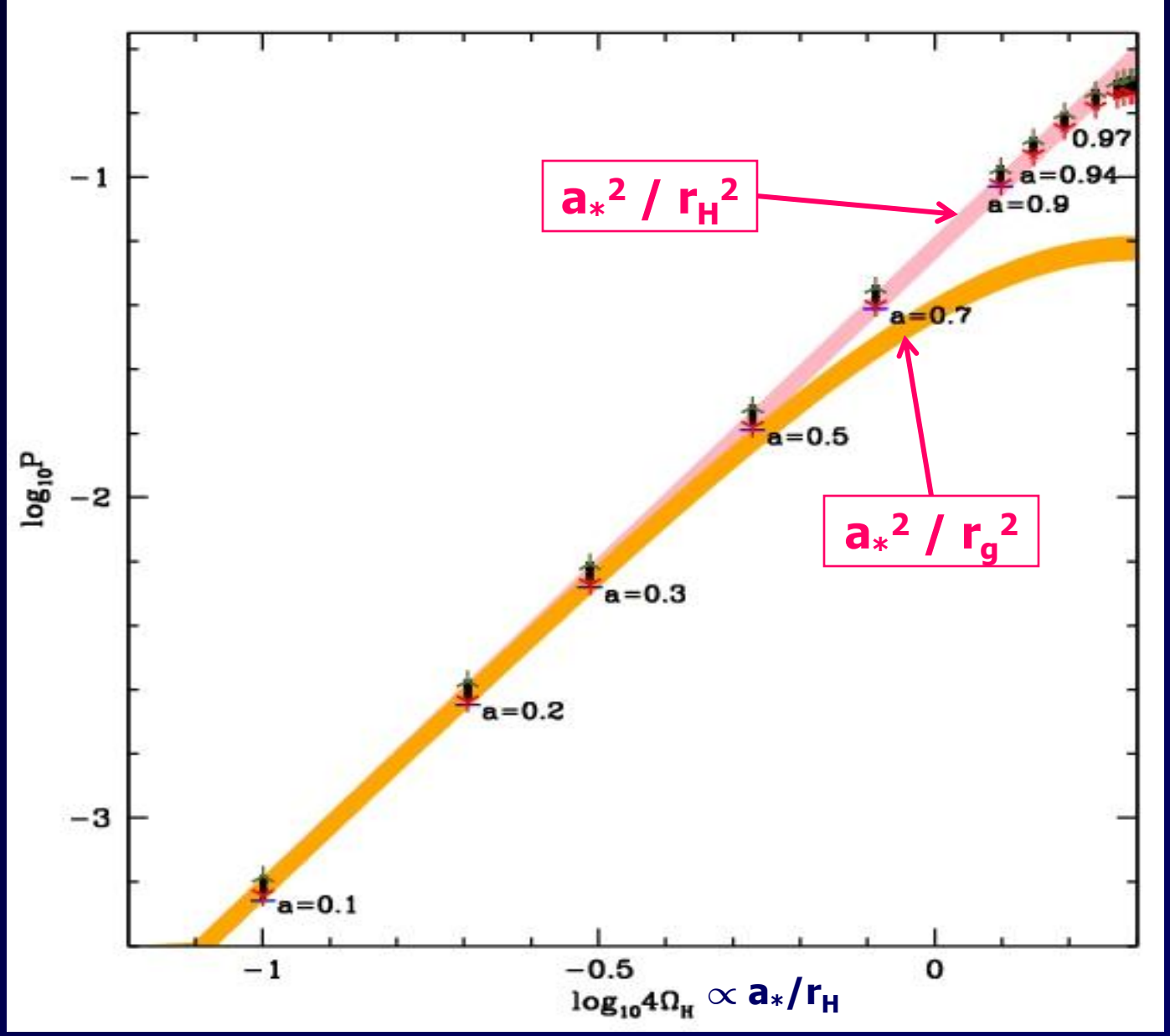


The Gospel According to B&Z

- In the limit of low spin ($a^* \ll 1$):
  $P_{jet} \propto c\, B_p^2\, r_g^2\, a_*^2 \propto c\, \Phi^2\, a_*^2 / r_g^2$
  a_*: Kerr parameter, Φ: magnetic flux,
  $r_g = GM/c^2$: gravitational radius
- a_*^2 scaling seems too weak to explain the huge dichotomy
- Perhaps the scaling becomes steeper as a_* approaches unity?



We tried a variety of collimating geometries with different a_* (Tchekhovskoy et al. 2009b)



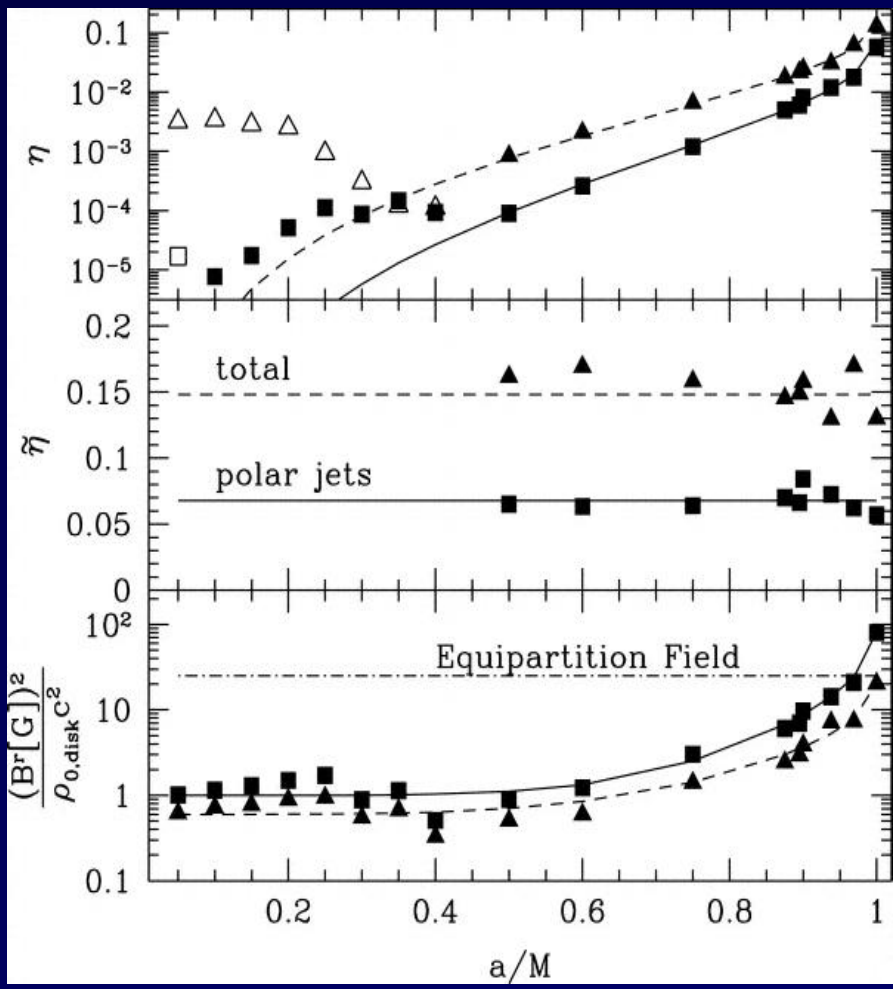
Fixed Φ, **M**, varying a_*, force-free simulations in the **Kerr metric**

Results

- Jet power varies with BH spin as $P_{jet} \propto c\, \Phi^2\, a_*^2 / r_H^2 \propto \Phi^2\, \Omega_H^2 / c$
- Not strong enough to explain radio loud/quiet dichotomy
- If radio loud $a_* \sim 0.9$, quiet $a_* \sim 0.3$, expect only factor ~ 20 change in P_{jet}
- How do we get a factor of 10^3?
- Could radio quiet AGN have $a_* \lesssim 0.05$?!
- Implausible – need other ideas …

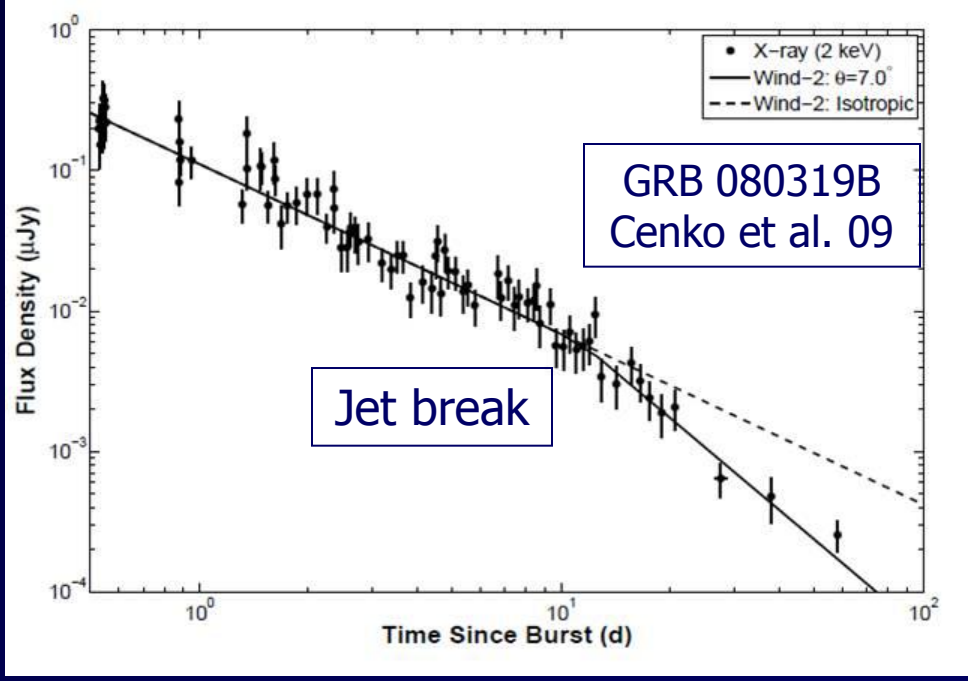
Other Ideas?

- GRMHD disk-jet simulations find much stronger dependence of jet power on BH spin: $P_{jet} \propto a_*^5$ (McKinney 2005)
  - Magnetic flux seems to correlate with a_* – why?
- Is there some kind of a switch at a critical a_*?
- Radio power vs jet power



McKinney (2005)

GRB Jets



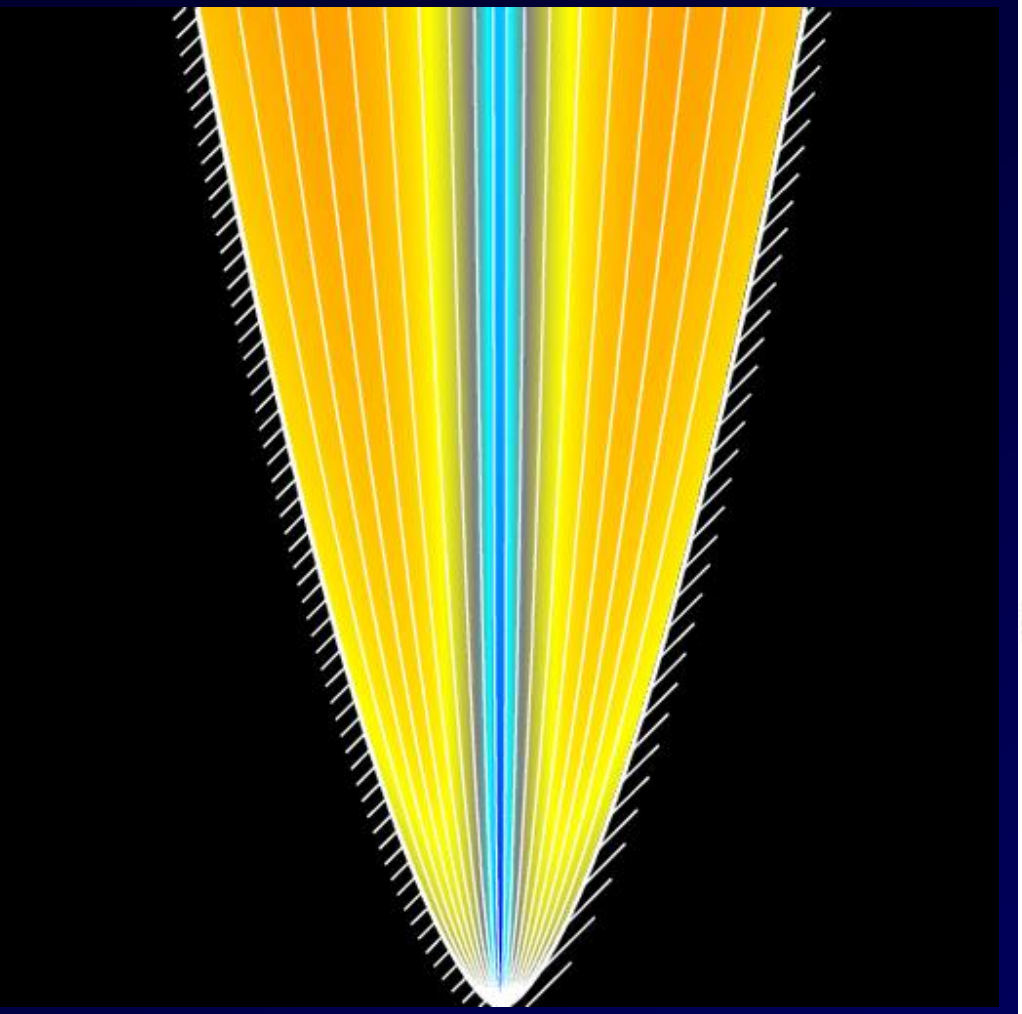
- Very energetic: $E \sim 10^{51}$ erg
- Ultra-relativistic: $\gamma \gtrsim$ few 100 (to avoid compactness problem)
- Collimated: $\theta_j \lesssim 0.1$ (from jet break in afterglow lightcurves)
- Observations imply: $\gamma\, \theta_j \sim 10$—$30$

Jet Acceleration

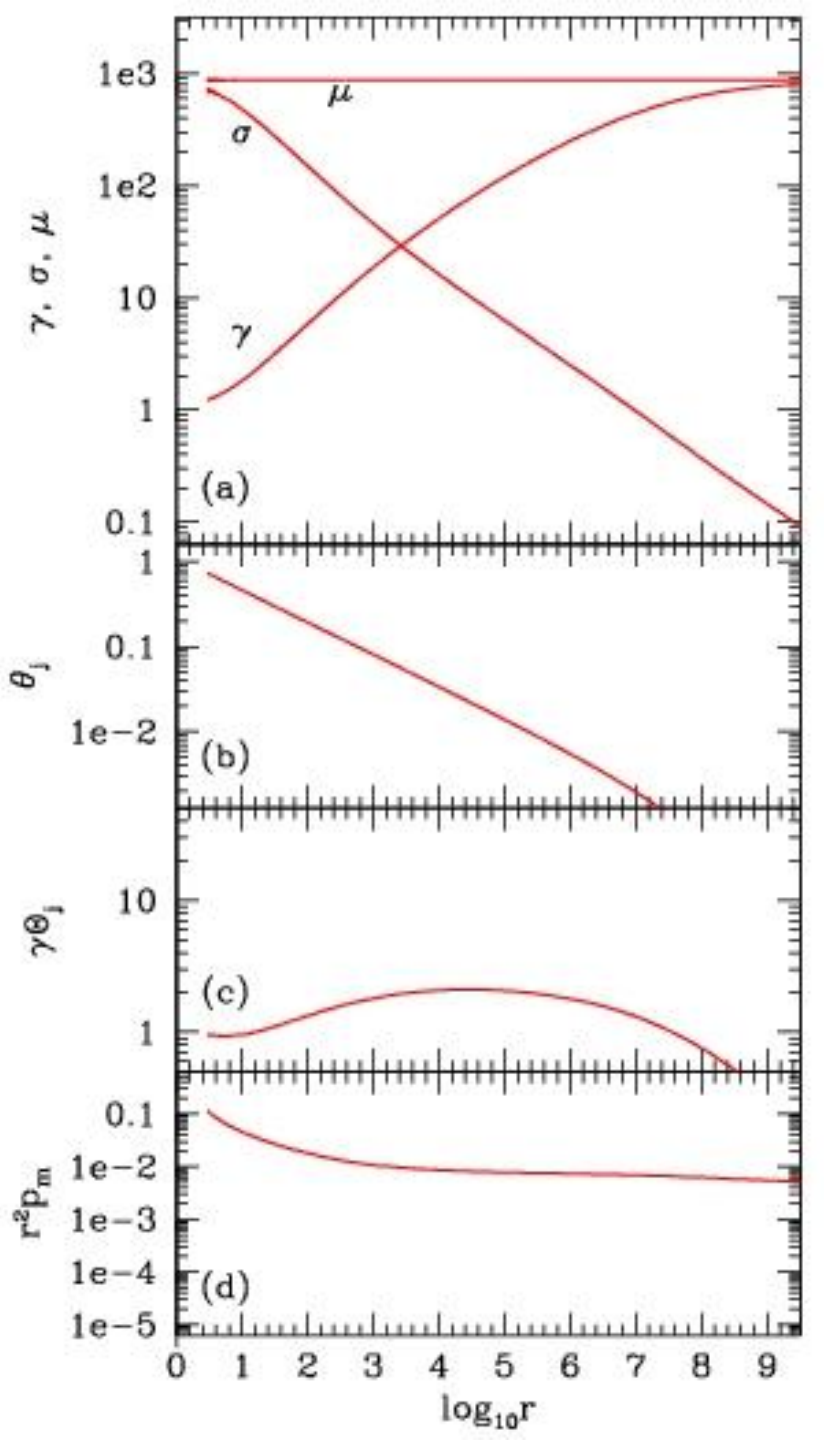
- A relativistic jet starts off Poynting–dominated at the base:
- σ = EM energy flux/kinetic energy flux $\gg 1$
- As the jet moves out, acceleration converts EM energy to matter kinetic energy and σ decreases
- Ideally, the conversion would be efficient and at large distance we would have $\sigma \lesssim 1$
- Surprisingly difficult: the σ problem

No σ Problem for GRB Jets

- Most GRB models require the jet to be matter-dominated, i.e., $\sigma \lesssim 1$, where the observed radiation is produced
- Good news!! There is no σ problem for flow lines near the axis
- Collimated jets can reach large γ and convert Poynting flux to kinetic energy efficiently (Tchekhovskoy et al. 2009)



Confined jet
(Tchekhovskoy et al. 2009a)

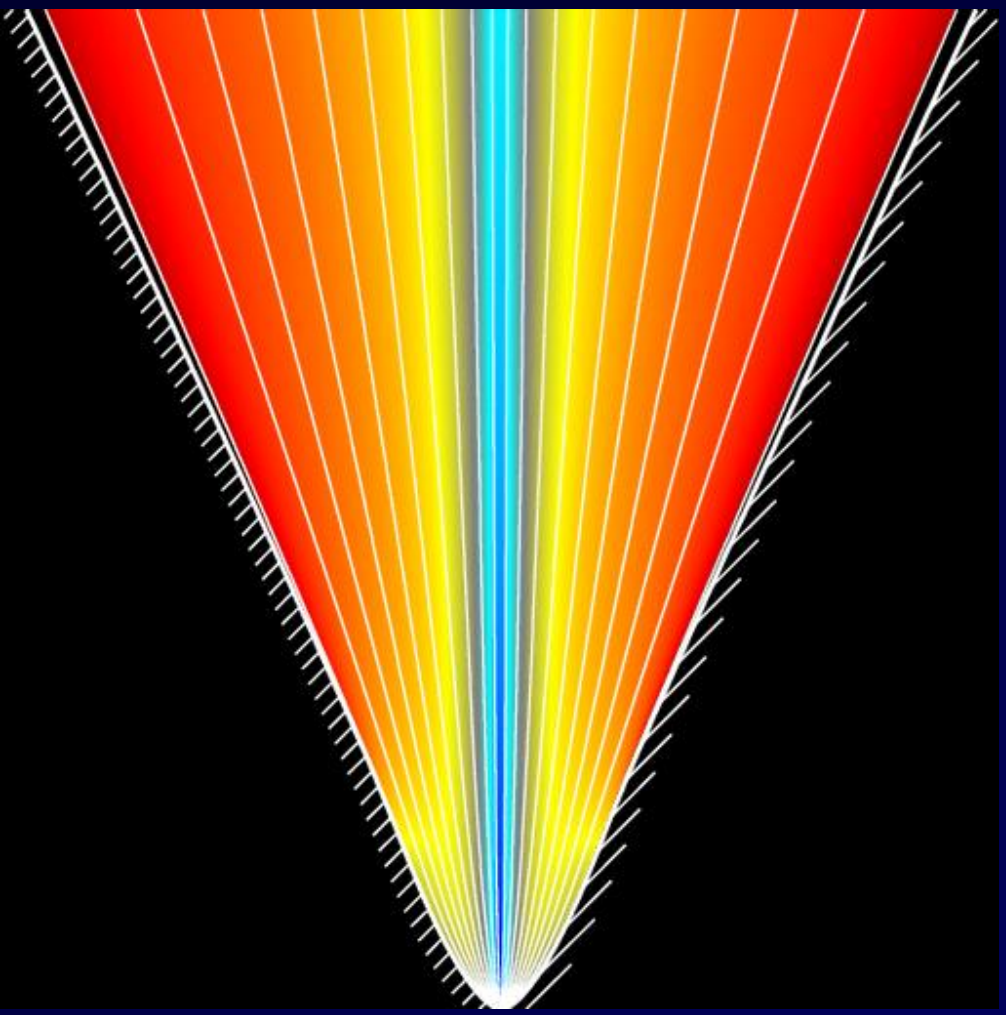


However There May be a $\gamma\,\theta_j$ Problem

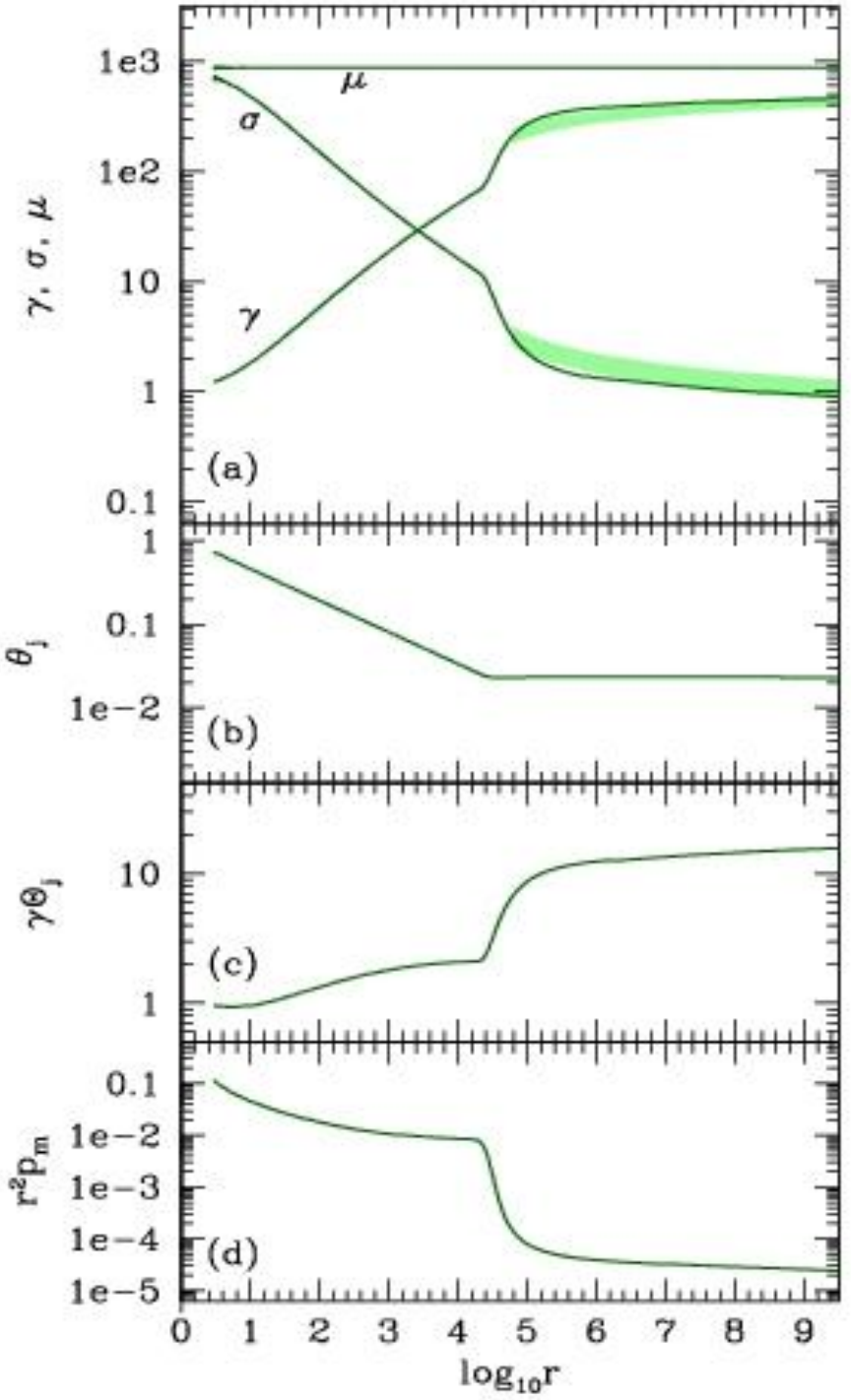
- While collimated jets do not have a σ problem, it is predicted that asymptotically they would have $\gamma\,\theta_j \sim \sigma^{1/2} \lesssim 1$ (Komissarov et al. 2009, Tchekhovskoy et al. 2009a)
- But GRB observations clearly demand $\gamma\,\theta_j \sim 10\text{—}20$
- Looks like we are stuck…

Fortunately, There is a Solution

- A GRB jet is not confined throughout its length
- In the collapsar model, the jet is confined by the star only for a certain distance, and the jet then becomes free once it is outside the star
- Jets that are initially confined and then become deconfined give large $\gamma\ \theta_j$

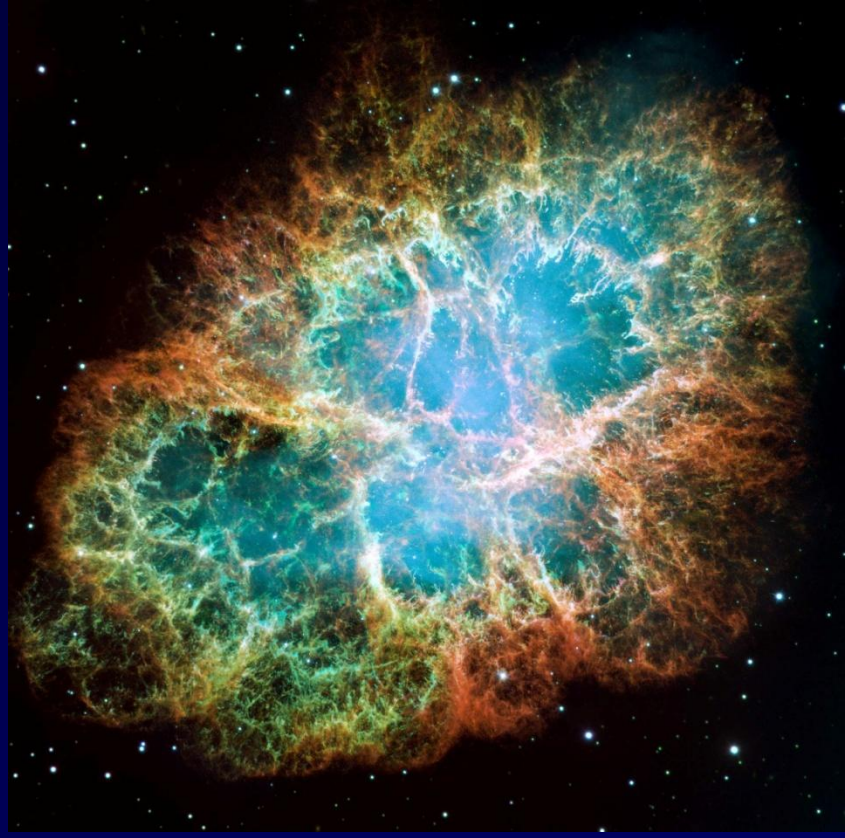


A jet that is confined up to $r \sim 10^4$-10^5 and then deconfined works very well:
$\gamma \sim 500$, $\theta \sim 0.03$, $\gamma\,\theta_j \sim 15$
Good match to GRB observations
(Tchekhovskoy et al. 2009a)



Before We Get Too Excited

- We do seem to have a reasonable explanation for the characteristics of GRB jets
- But a severe problem remains for some other sources
- Crab Nebula: $\gamma\,\theta_j \sim 10^6$!!
- Still have a long way to go…



Roger, We Need You!

- It is **10^n days** **(n ~ 4)** since you had your day of rest and went on to conquer other worlds
- You have had your fun, but now
- please come back to relativisitc jets
- The lost tribe needs you