Acceleration and Collimation of Relativistic Magnetized Jets

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with Ramesh Narayan and Jonathan McKinney

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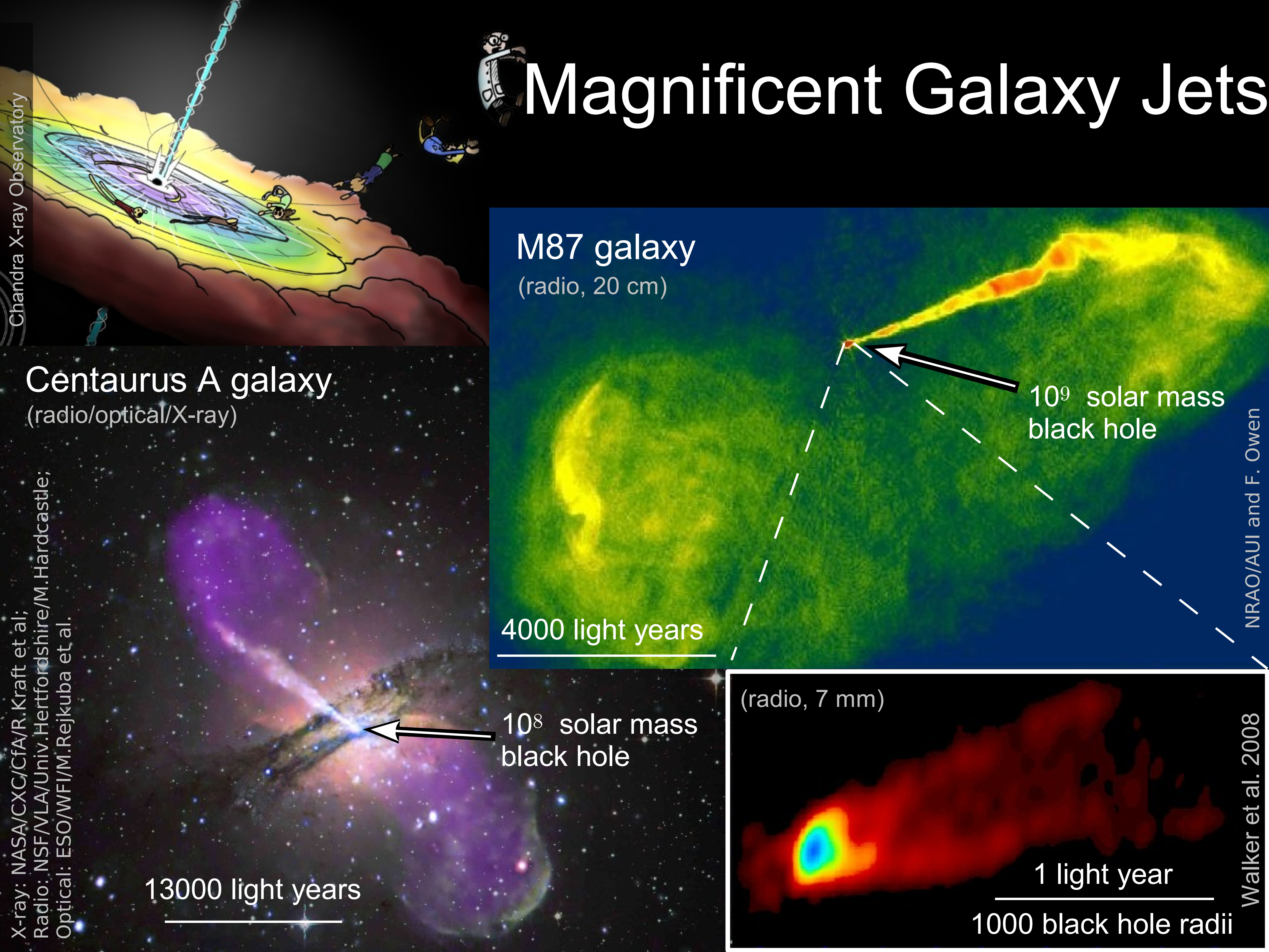
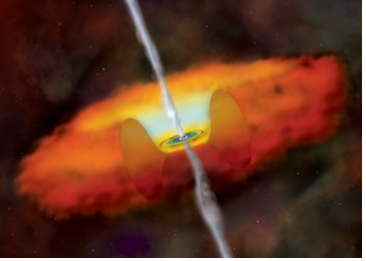
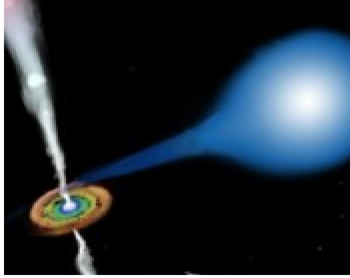
Magnificent Galaxy Jets





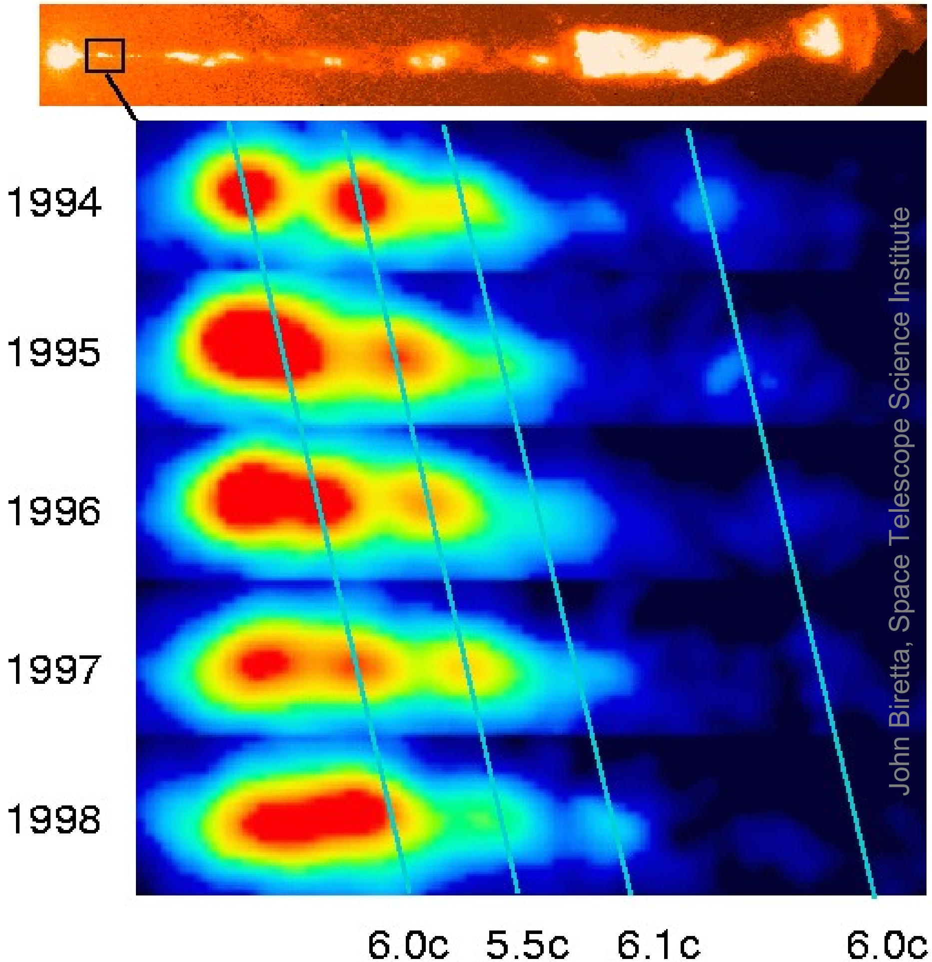
Chandra XRC

Superluminal Motion in Jets: Different Masses, Similar Speeds



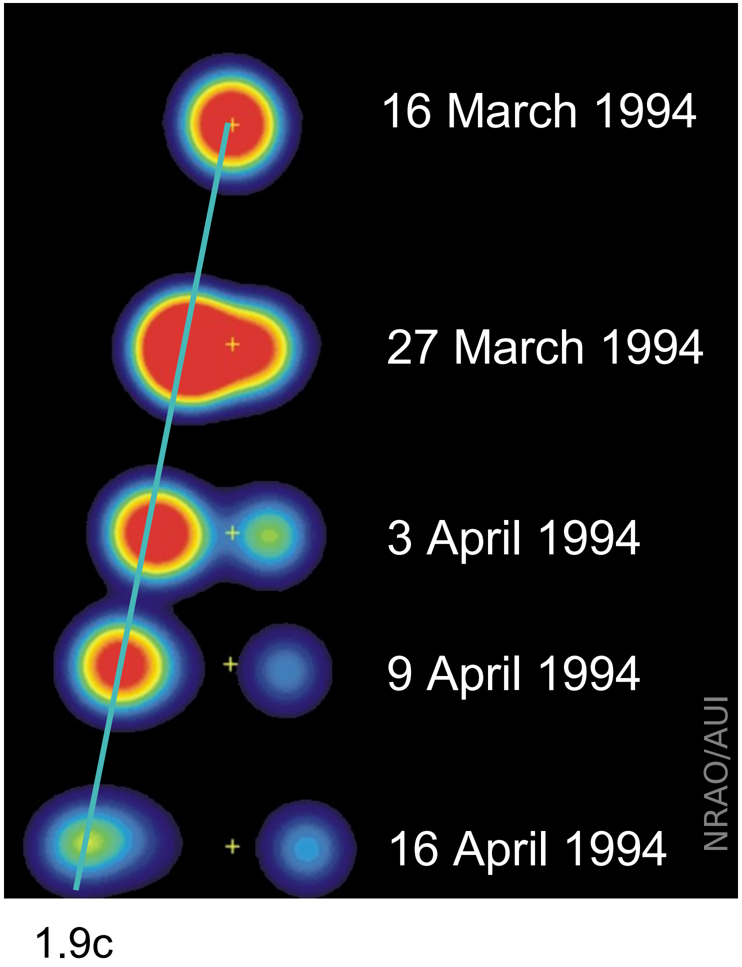
Chandra XRC

Active Galaxy M87 with $M_{BH} = 3 \times 10^9\ M_\odot$:



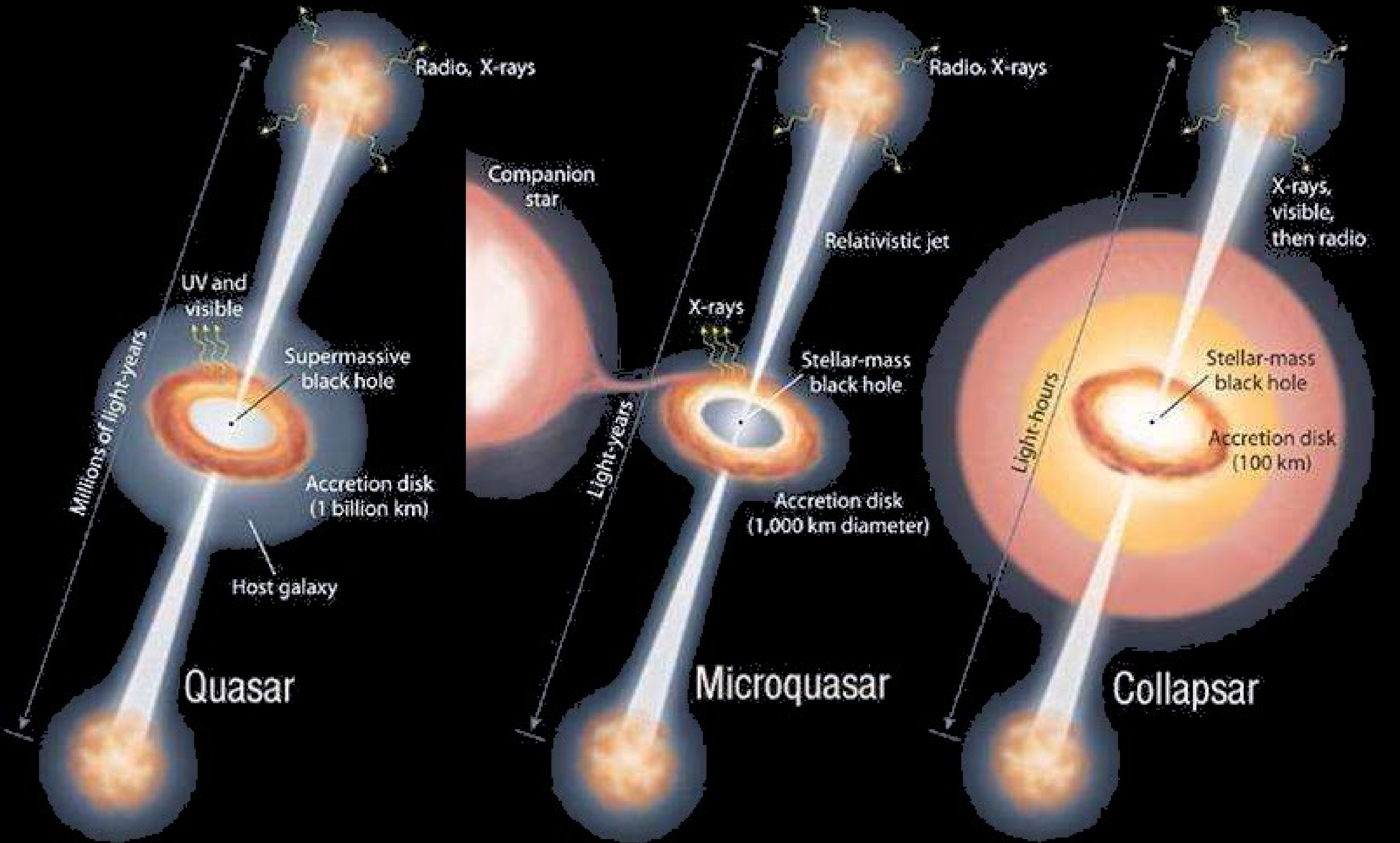
Relativistic jet from a supermassive BH

X-ray Binary GRS 1915+105 with $M_{BH} = 15\ M_\odot$:



Relativistic jet from a stellar-mass BH

Different masses, similar jets



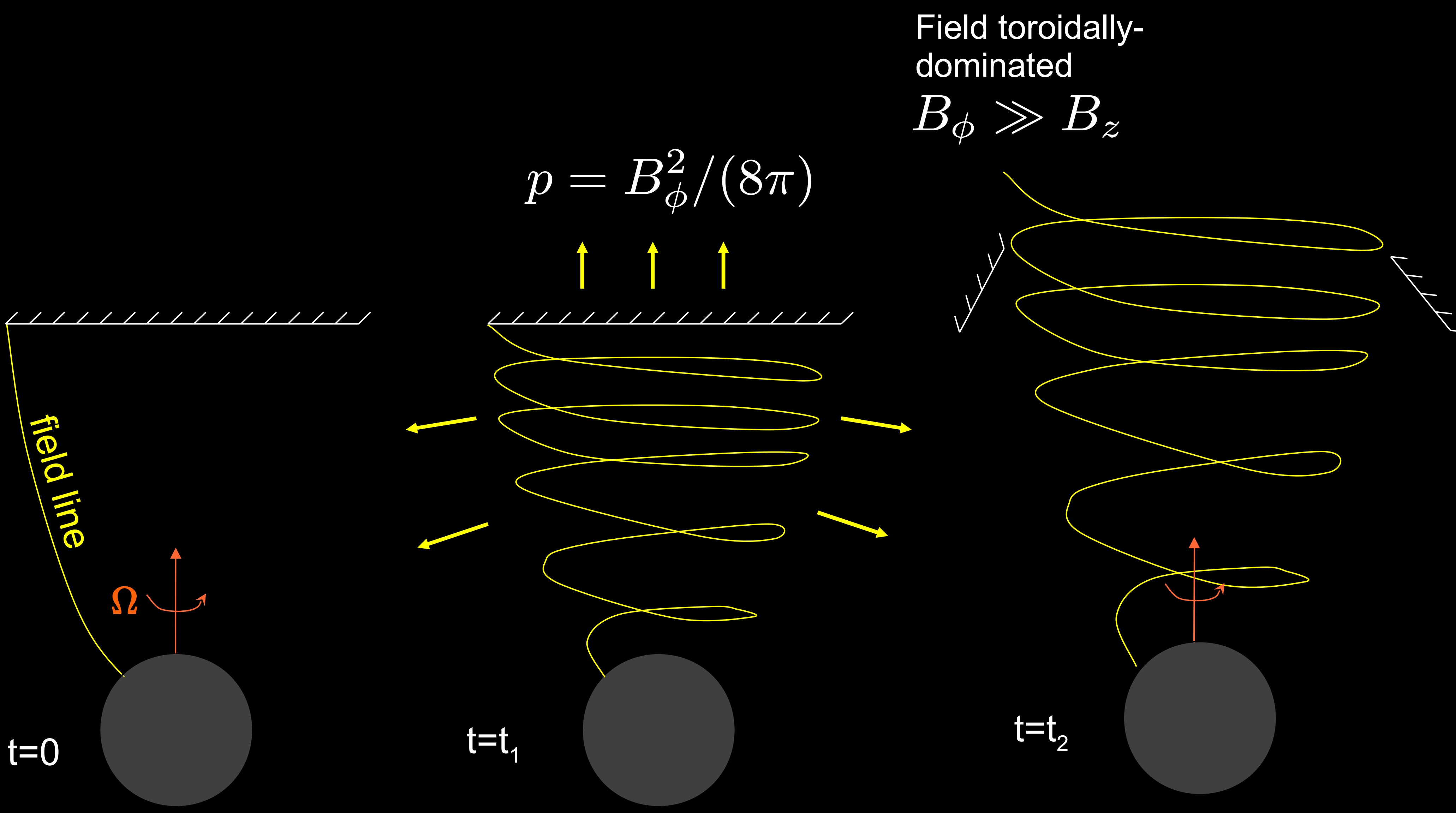
Mirabel & Rodriguez, 2002, Sky and Telescope

Active Galactic Nuclei (e.g., M87, $M_{BH}=3 \times 10^9 M_\odot$)

Black Hole X-ray Binaries (e.g., GRS 1915+105, $M_{BH}=15 M_\odot$)

Gamma-Ray Bursts (e.g., GRBYYMMDD, $M_{BH} \simeq 3 M_\odot$)

How do magnetic jets work?



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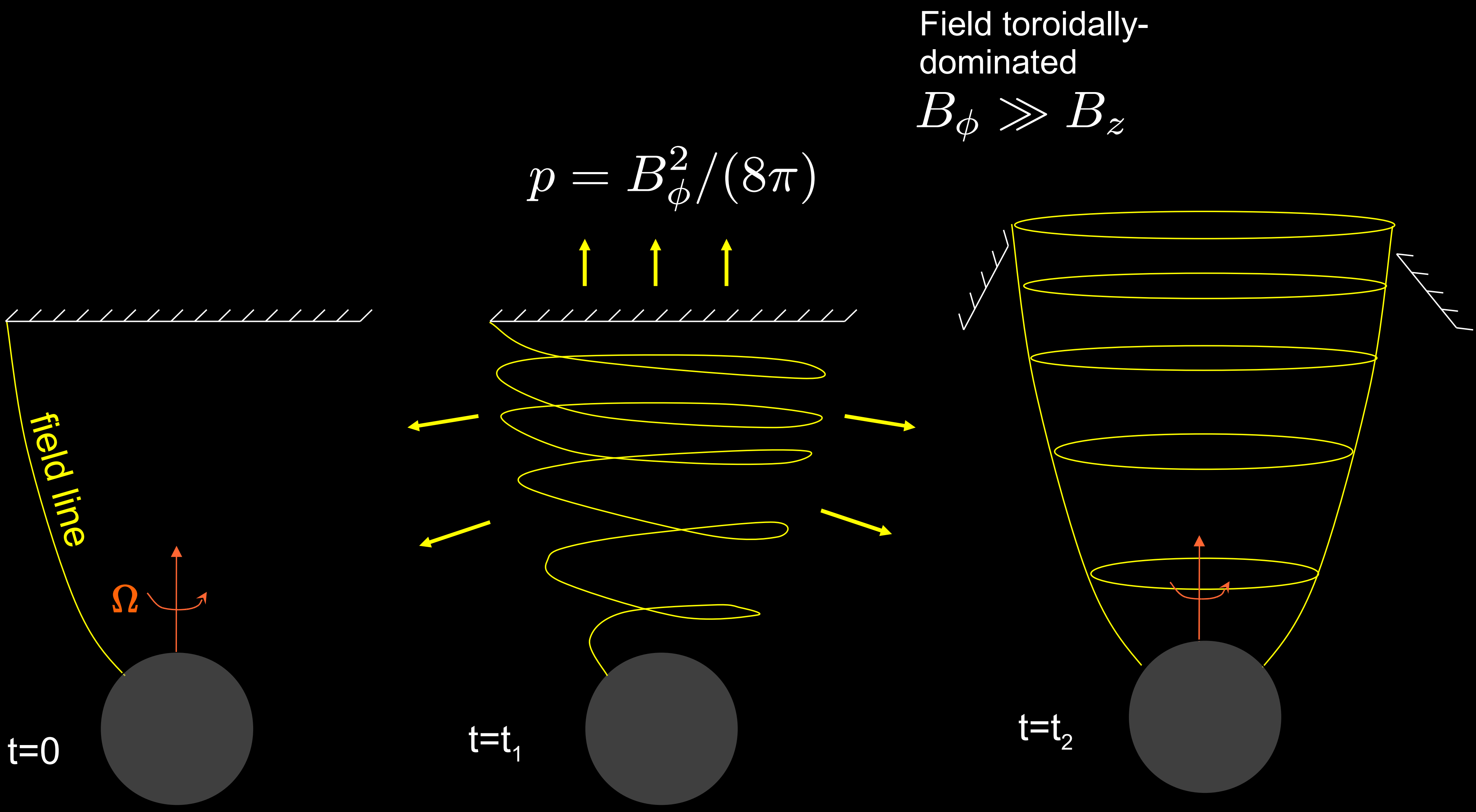

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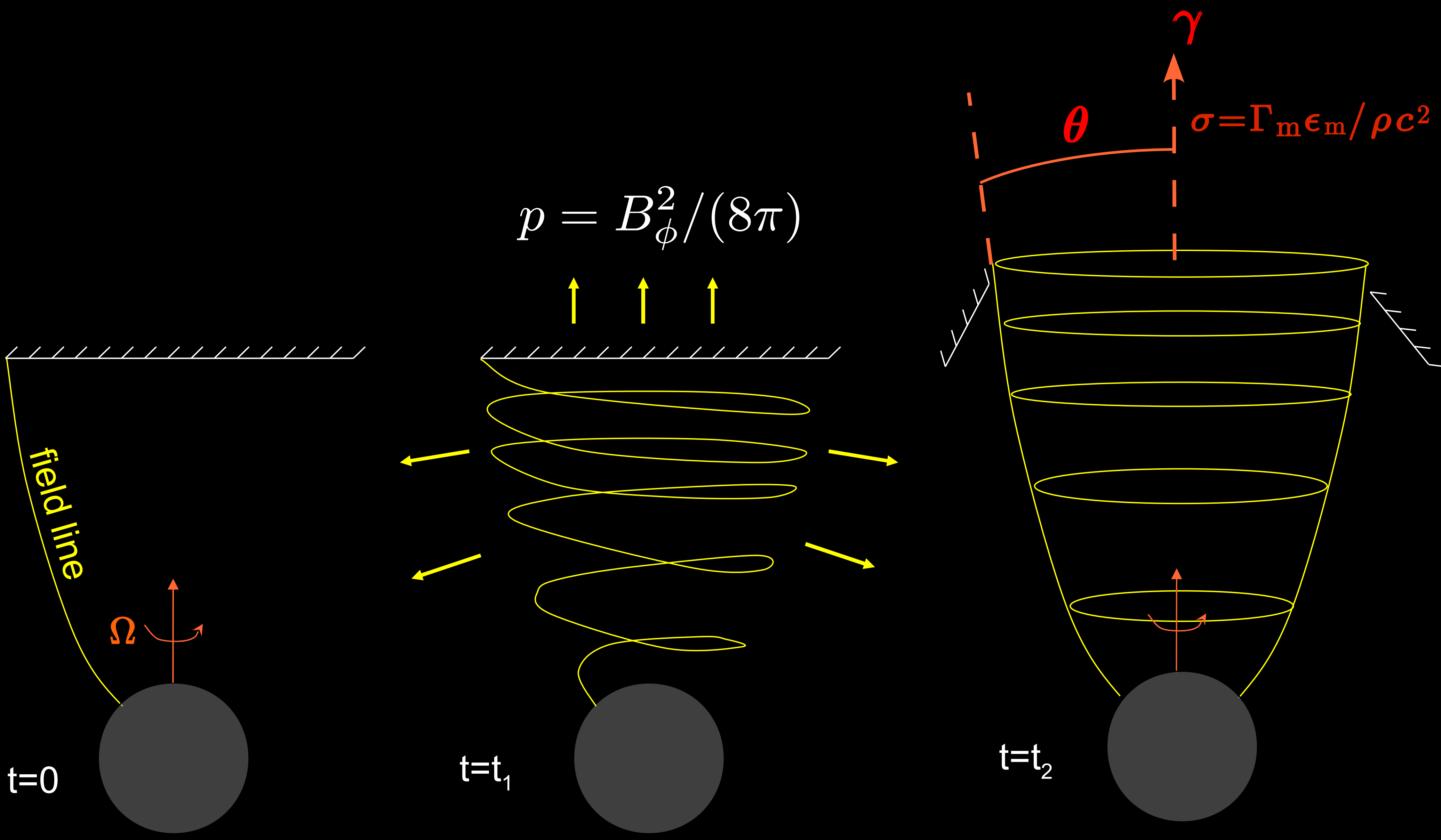


AGN and GRB Jets

AGN:

$\gamma \lesssim 10$

$\theta \lesssim 0.1$

$\gamma\theta \lesssim 1$

$\sigma \lesssim 1$

GRB:

$\gamma \gtrsim 100$

$\theta \lesssim 0.1$

$\gamma\theta \gtrsim 10$

$\sigma \lesssim 1$ ← $\sigma = \Gamma_{\rm m}\epsilon_{\rm m}/\rho c^2$

Simulations of magnetized confined jets:

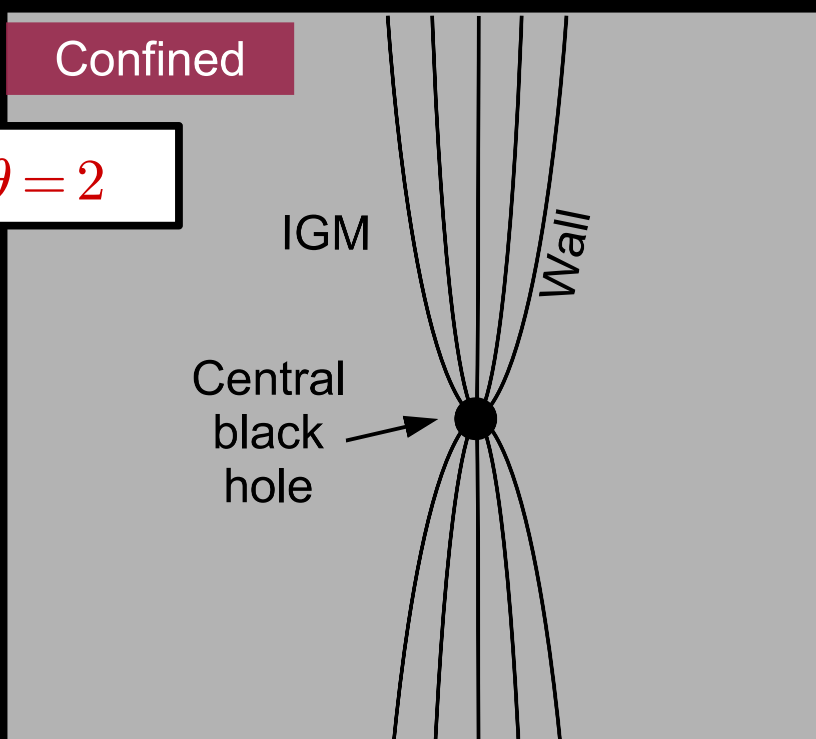
$\gamma\theta \lesssim 1$

(Komissarov et al., MNRAS, 2009)

Is there any hope for magnetized GRB jets?

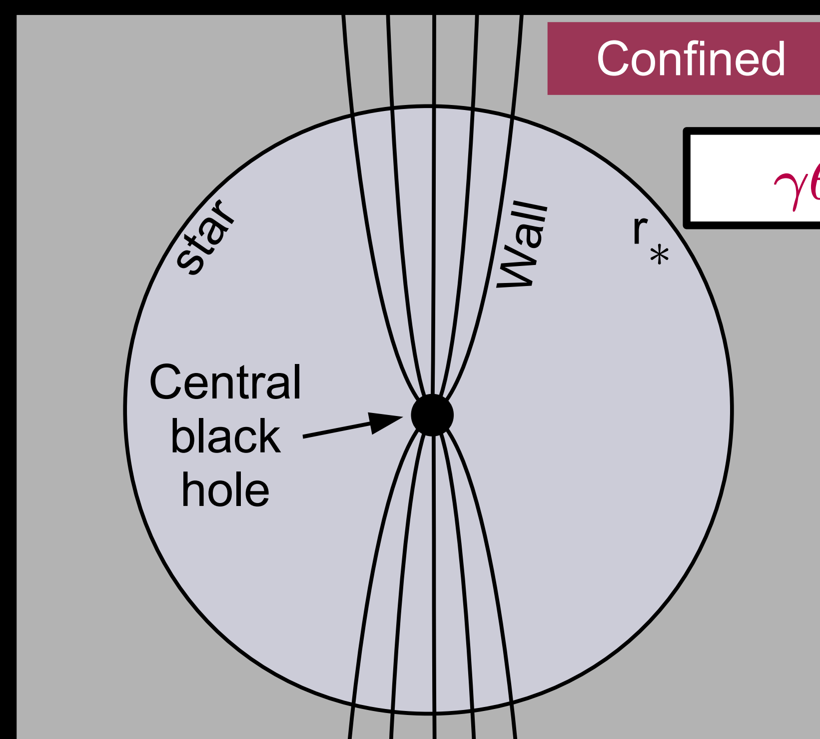
Confined

$\gamma\theta = 2$



Confined

$\gamma\theta = 2$ ✗



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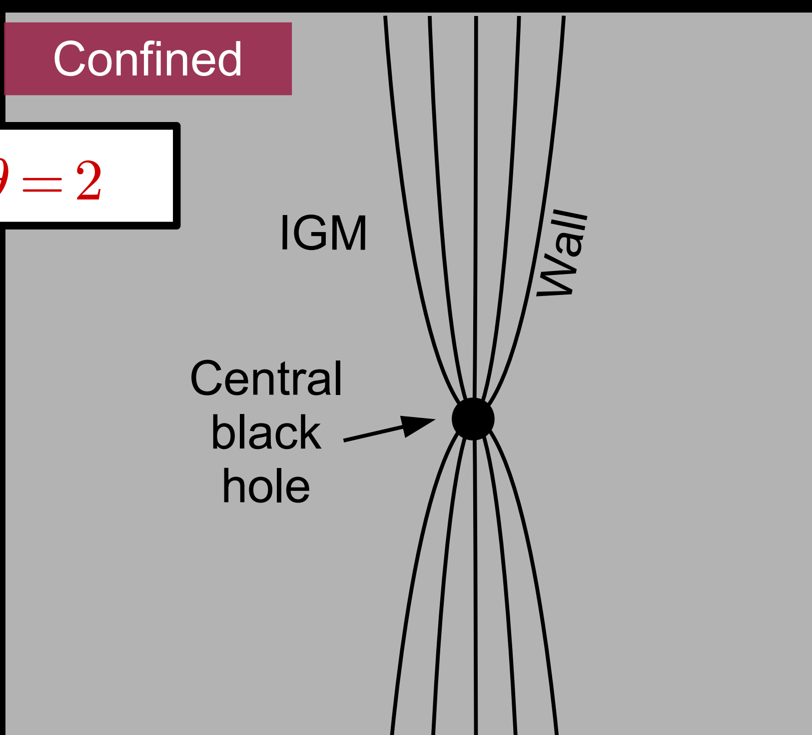
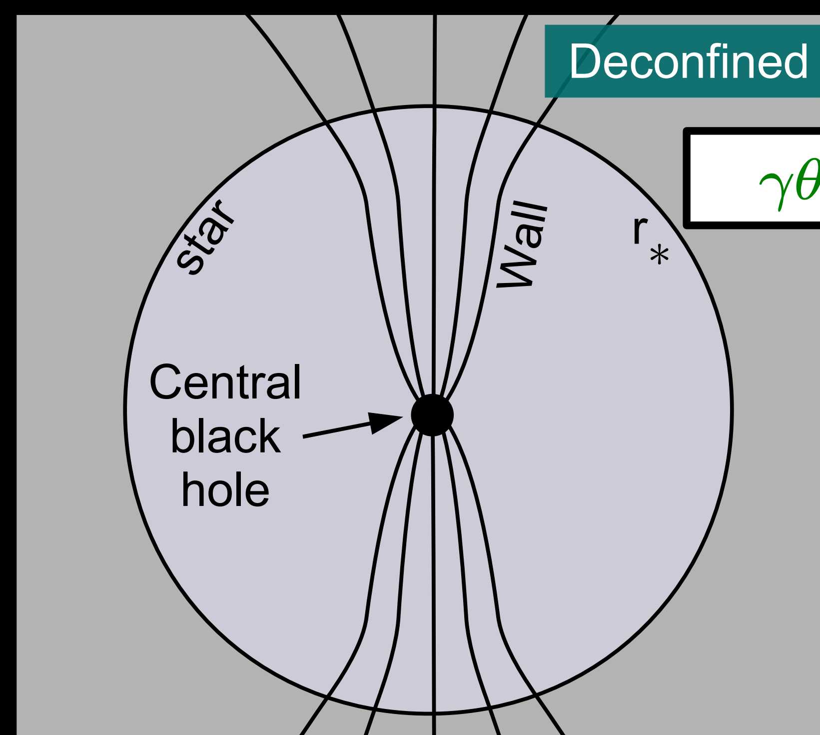
GRB jets are DEconfined:

$\gamma\theta \gtrsim 10$

(Tchekhovskoy, Narayan, McKinney, New Astronomy, 2010)

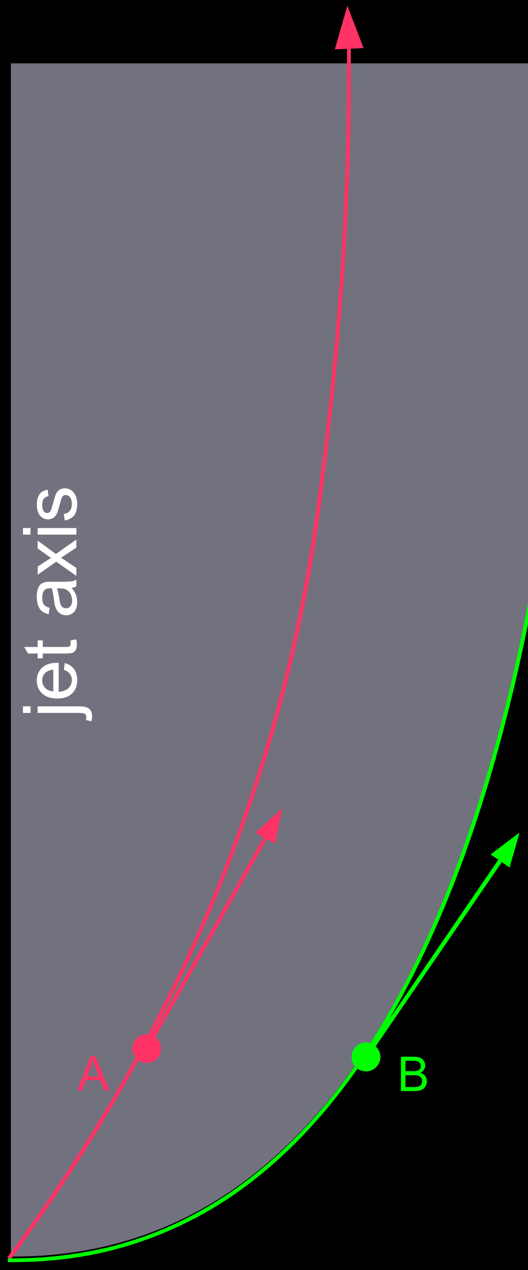
$\gamma\theta = 2$





$\gamma\theta = 20$ ✓

Why is $\gamma\theta \lesssim 1$ in confined jets?



- Communication is essential

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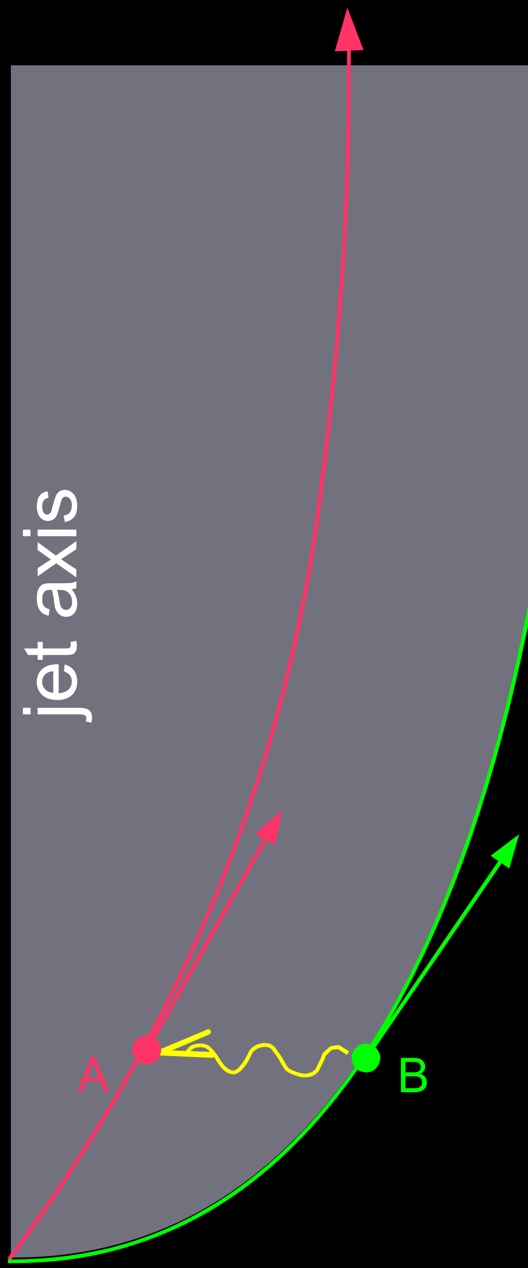

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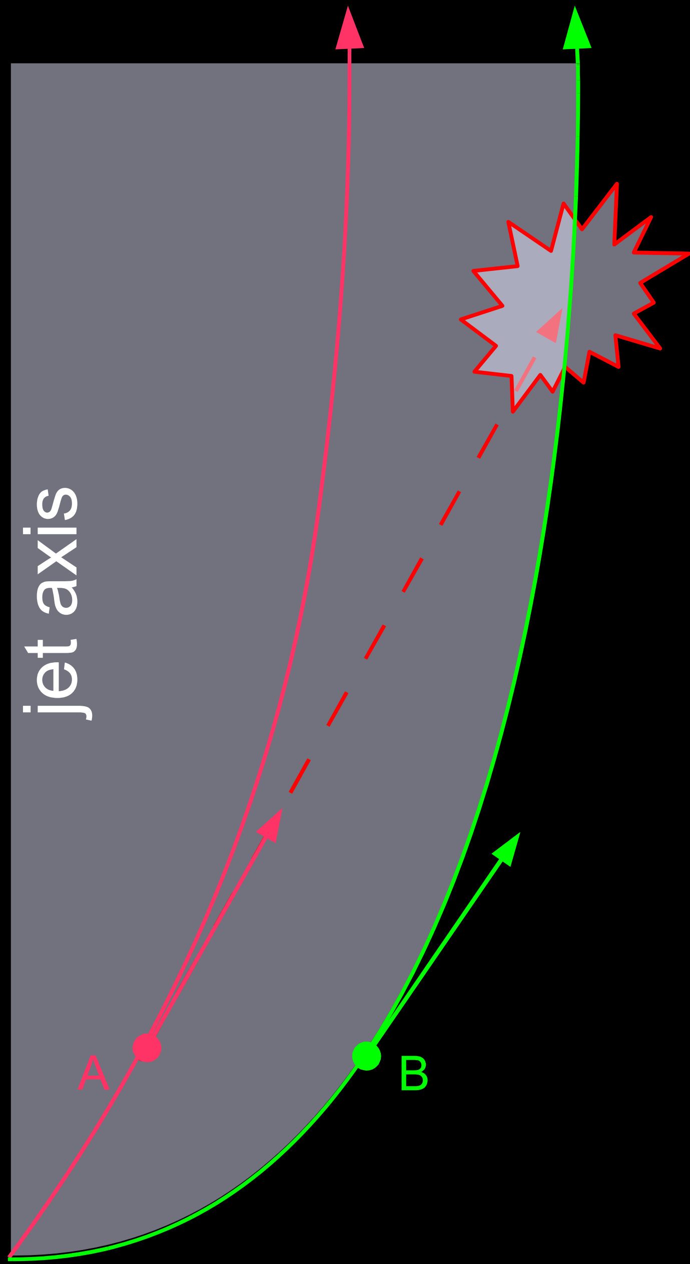

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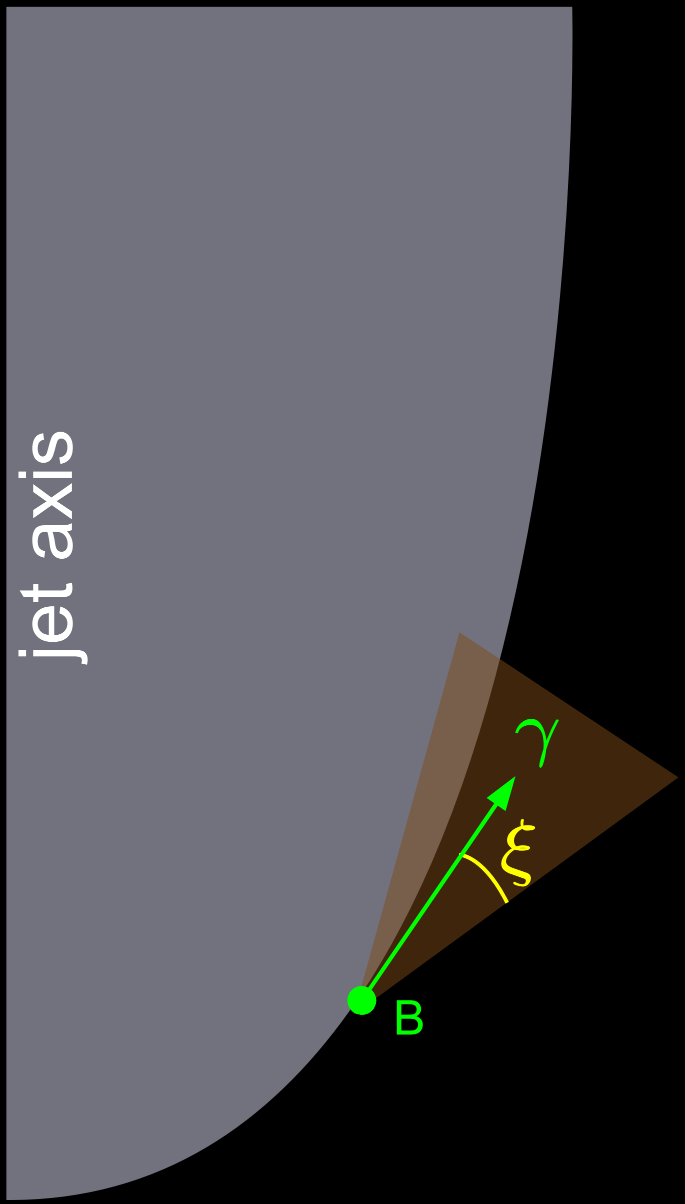

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$$\xi \le \frac{\gamma_s}{\gamma} \approx \frac{(\Gamma_{\rm m} p_{\rm m}/\rho)^{1/2}}{\gamma} = \frac{\sigma^{1/2}}{\gamma}$$

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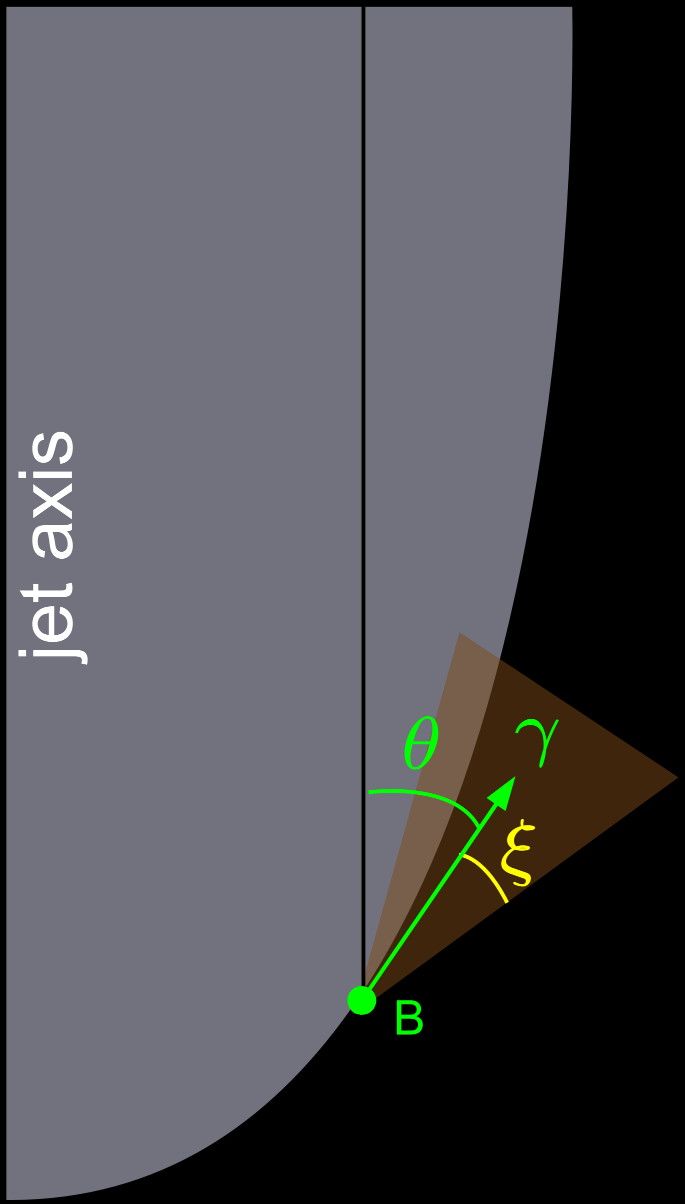

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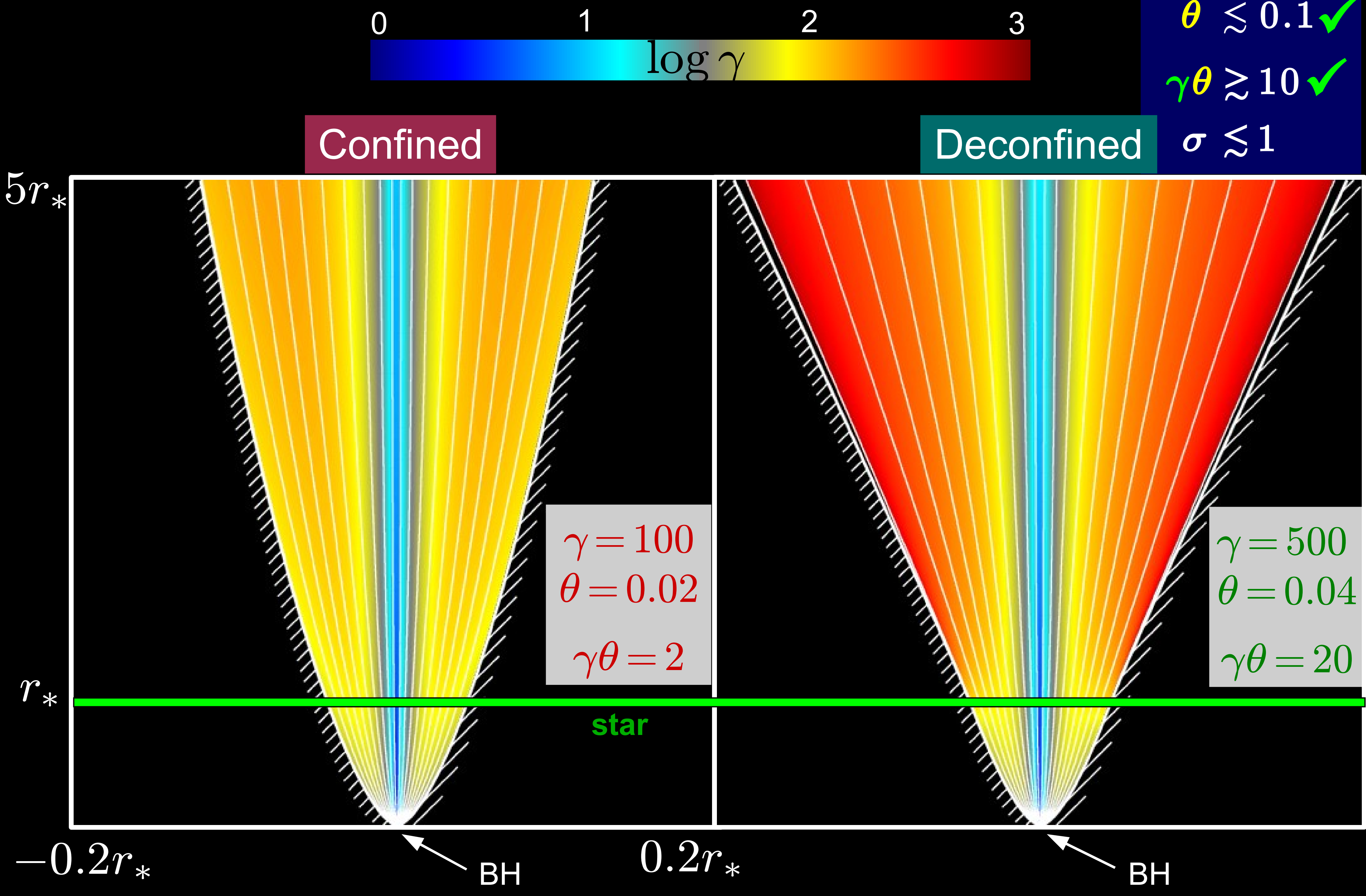
- For communication across jet need $\theta \lesssim \xi$, so $\theta \lesssim \sigma^{1/2}/\gamma$
- Robust conclusion: $\gamma\theta \lesssim \sigma^{1/2} \lesssim 1$

GRB Jets are Deconfined



Understand This Analytically

After jets lose ambient pressure support, they switch from the fully confined solution to the fully unconfined solution.

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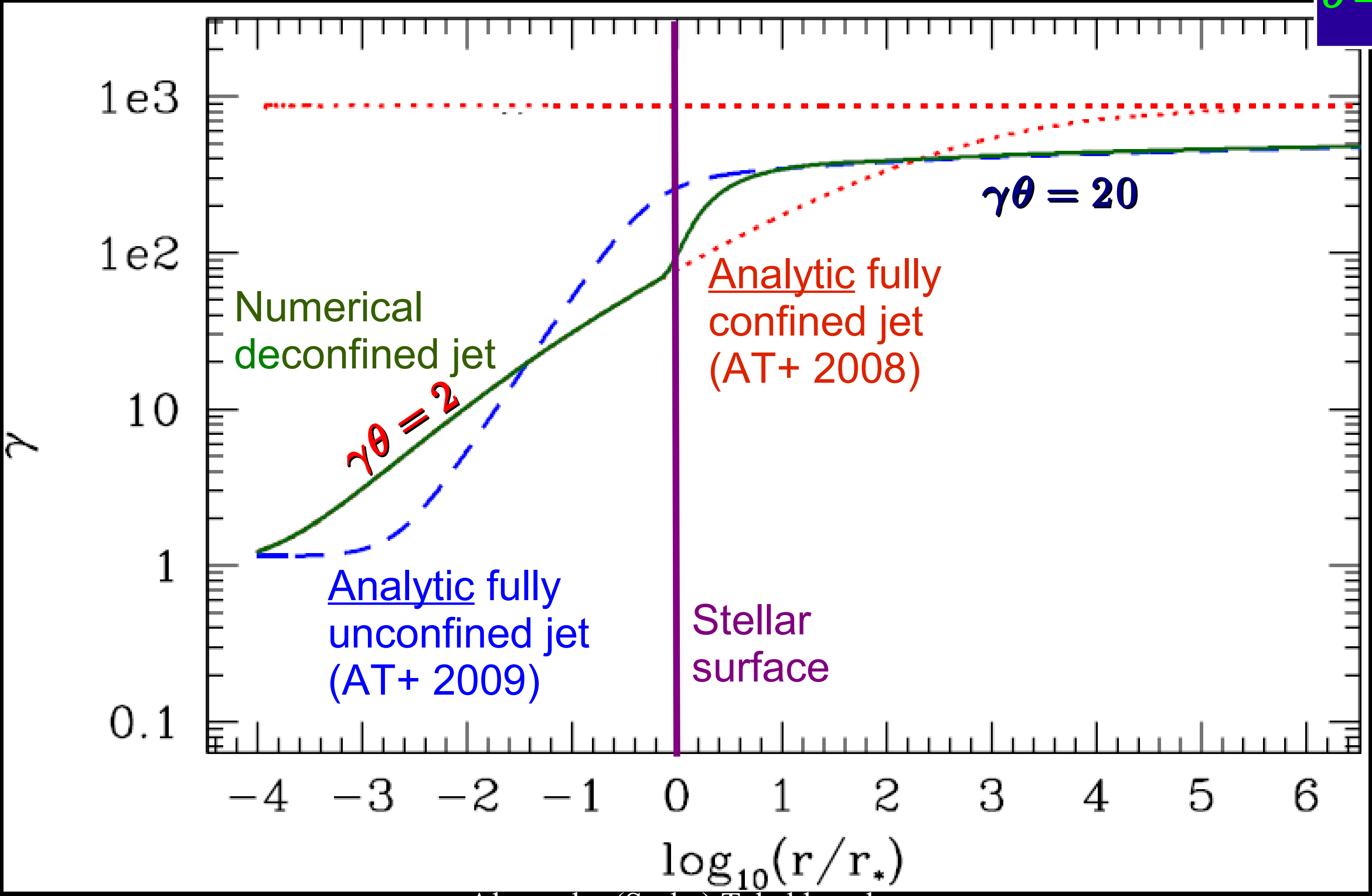

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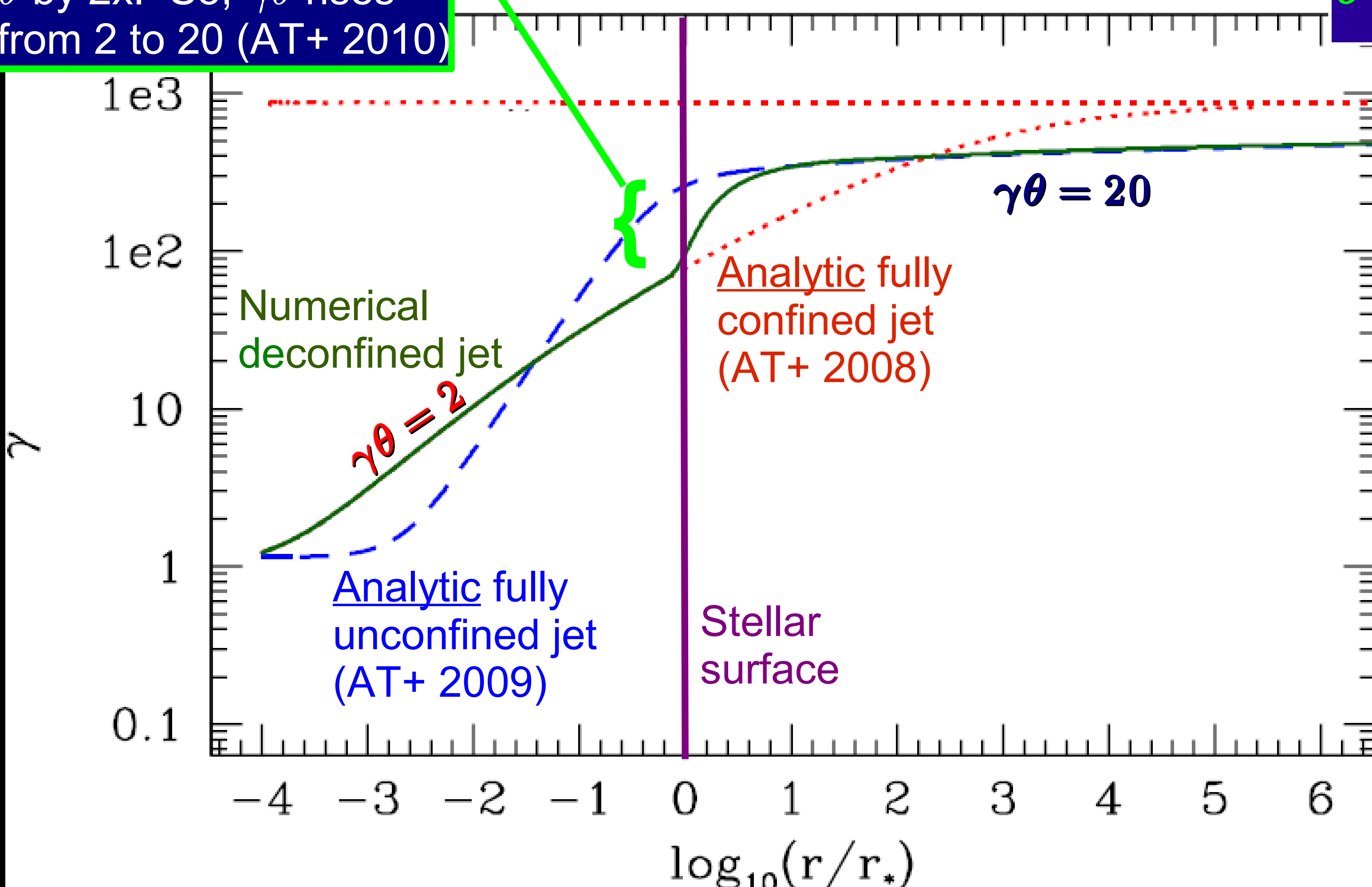
γ increases by 5x and θ by 2x. So, $\gamma\theta$ rises from 2 to 20 (AT+ 2010)



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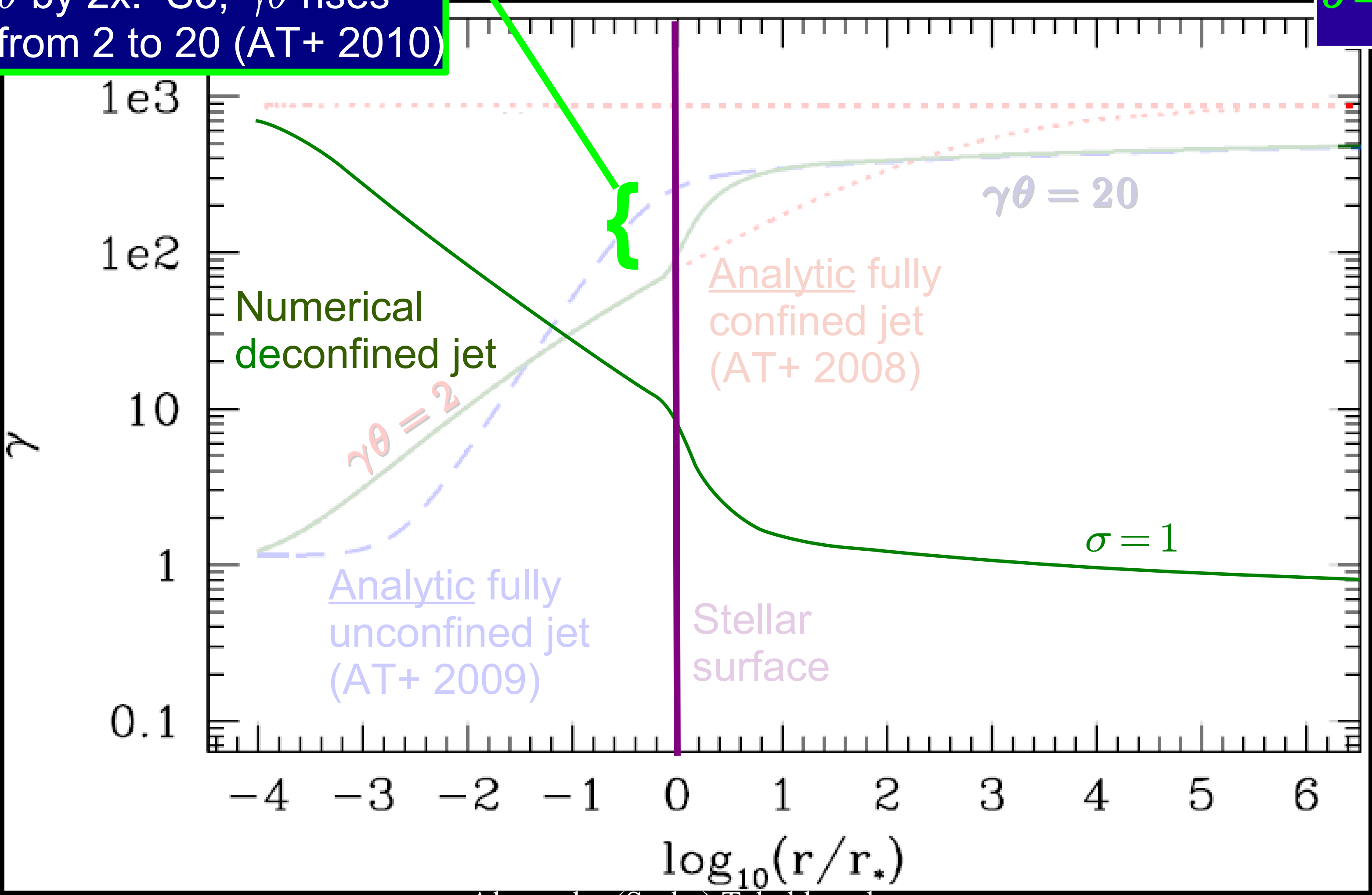

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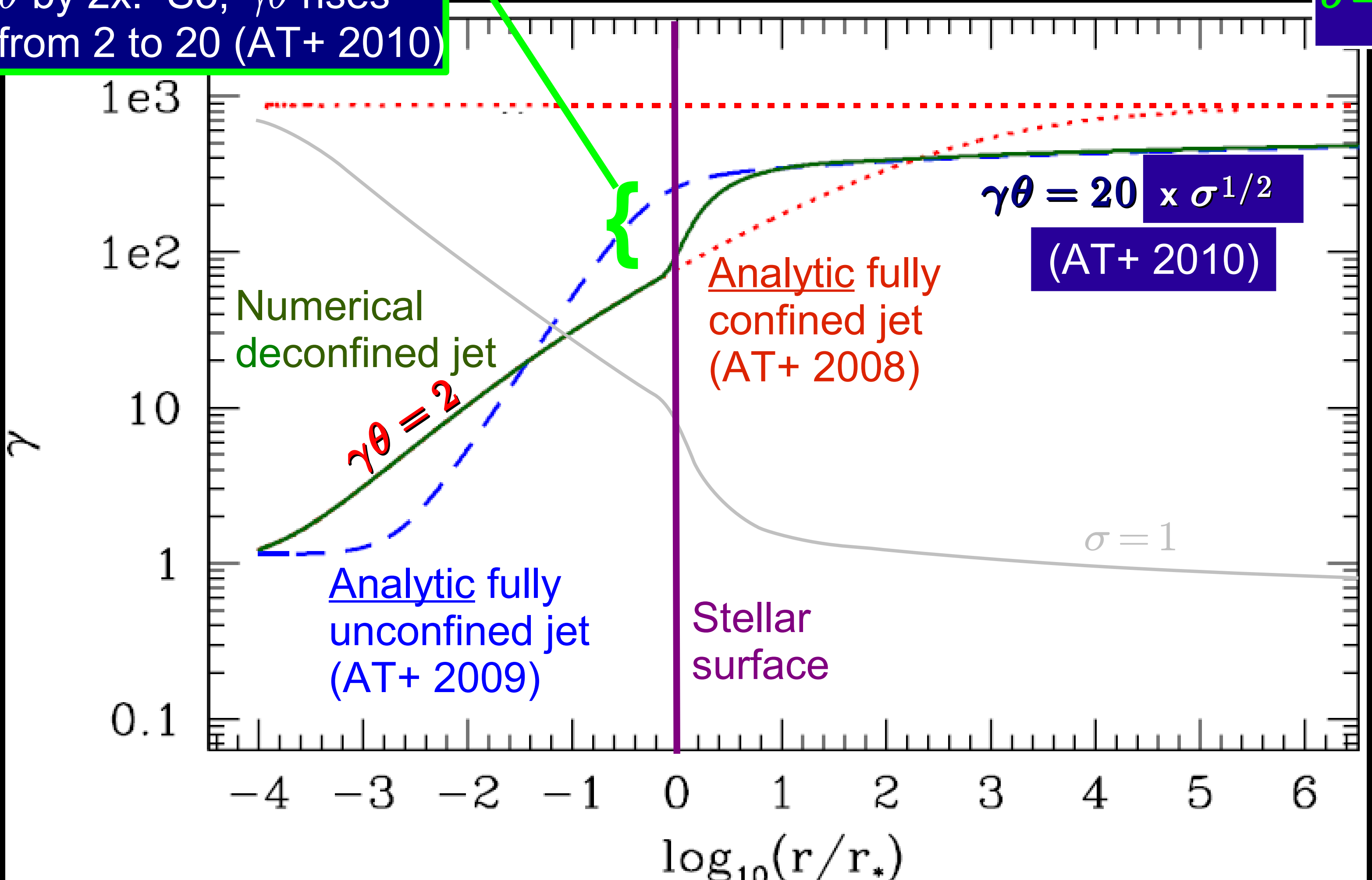

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Acceleration and Collimation

- Relation between jet acceleration and collimation

$$\gamma\theta \simeq C\sigma^{1/2}$$ (AT+ 2010)

  - confined, $C \lesssim 1$
  - deconfined, $C \approx 20$

- What do observations tell us?
  - AGN: $\gamma\theta \lesssim 1$, $\sigma \lesssim 1$ → no indication of deconfinement
  - GRB: $\gamma\theta \sim 10\text{–}30$, $\sigma \lesssim 1$ → jets must be deconfined
    - Some GRBs: $\gamma\theta \sim 100$ → $\sigma \sim 20 \gg 1$
    - If many more GRBs show $\gamma\theta \sim 100$, this will challenge standard GRB emission models that require $\sigma \lesssim 1$.

GRB:
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$\sigma = \Gamma_m \epsilon_m / \rho c^2$

GRB	$\gamma\theta$
970508	47
980519	10
990123	11
990510	7.8
991208	15
991216	7.0
000301c.........	38
000418	78
000926	19
010222	9.2
090323	27
090328	18
090902B	70
090926A	90

Panaitescu & Kumar 2002

Cenko+ '10

Jets: Required Ingredients

- GRB Jets:

  Both propagation inside and outside the star required

  1) Fully confined jets are too slow for their opening angles:

  $$\gamma\theta \lesssim 1$$

  2) Fully deconfined jets have too large opening angles:

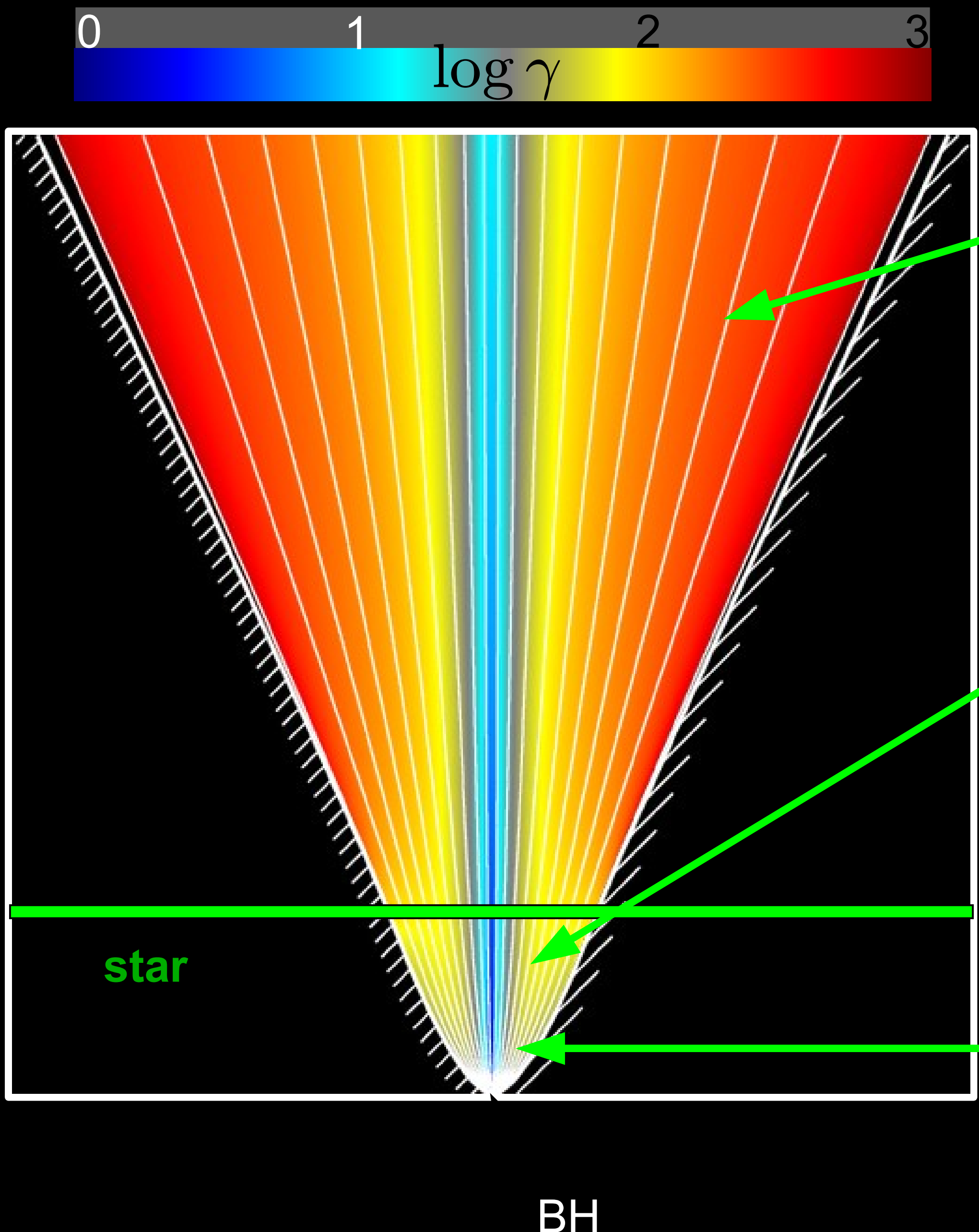
  $$\theta \sim 1$$

  Bottom line: need
  1) confinement to collimate the jet initially and
  2) deconfinement to accelerate the jet

- AGN Jets:

  Either confined or deconfined jet scenarios allowed

Jet Structure Summary



Fully unconfined jet:

$$\gamma\theta \simeq 20\sigma^{1/2}$$ (AT+ 2010)

Fully confined jet, large distance. Centrifugal force limits jet velocity (AT+ 2008):

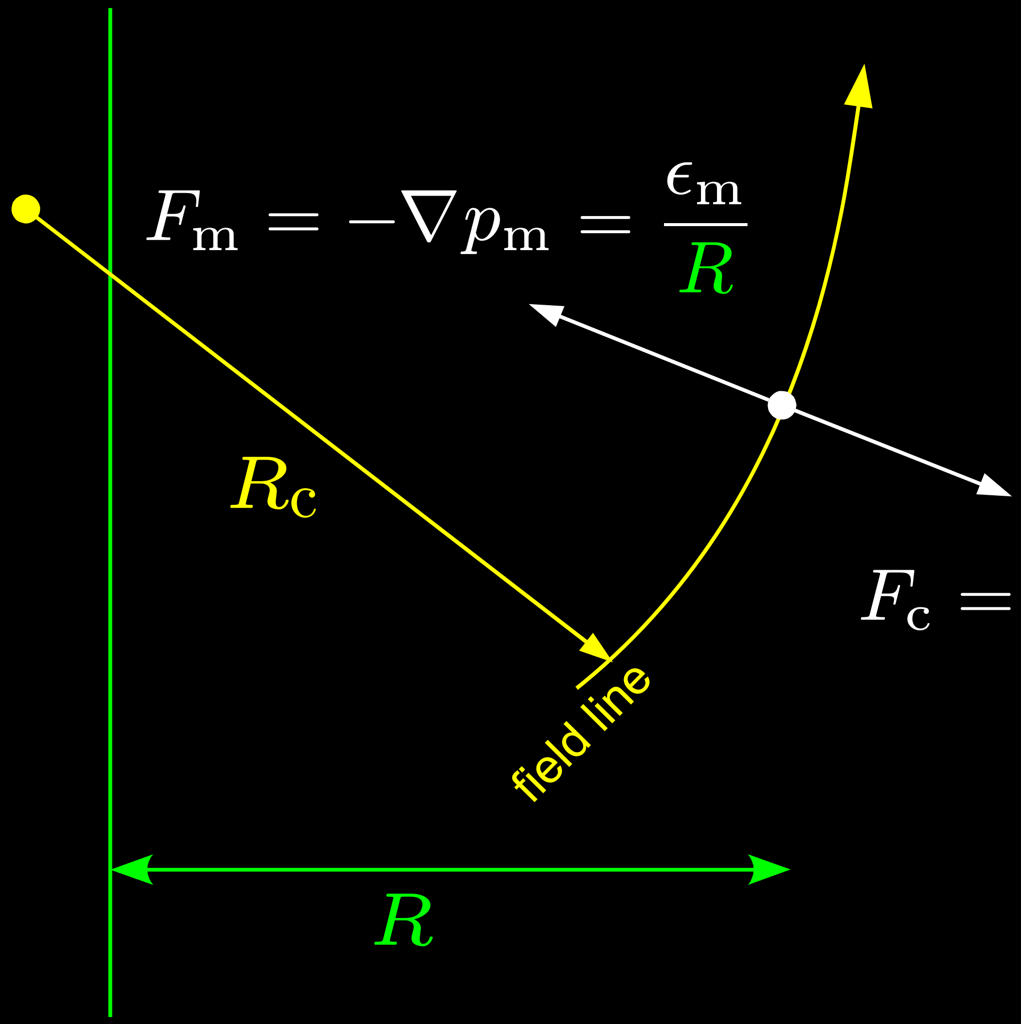
$$\gamma \approx \left(\frac{3R_c}{R}\right)^{1/2}$$

Fully confined jet, small distance. Linear increase:

$$\gamma \approx \Omega R$$ (Michel 1969)

Understand this analytically

Centrifugal force slows jet down (approximate)



$$F_m = -\nabla p_m = \frac{\epsilon_m}{R}$$

$$F_c = \frac{\epsilon_m \gamma^2}{R_c}$$

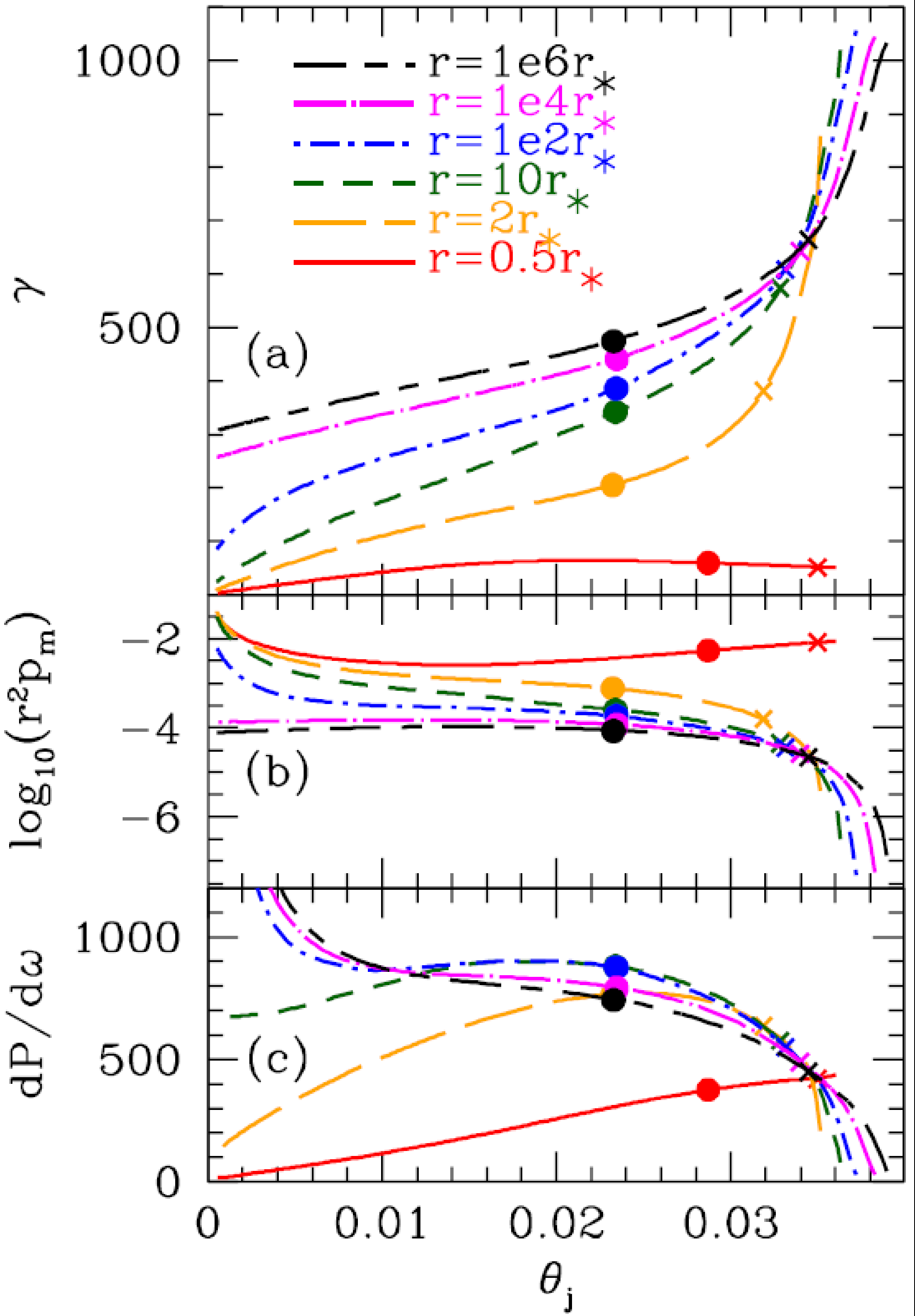
$$F_m = F_c$$

$$\frac{\epsilon_m}{R} = \frac{\epsilon_m \gamma^2}{R_c}$$

$$\gamma = \left(\frac{R_c}{R}\right)^{1/2}$$

Jet cross-section

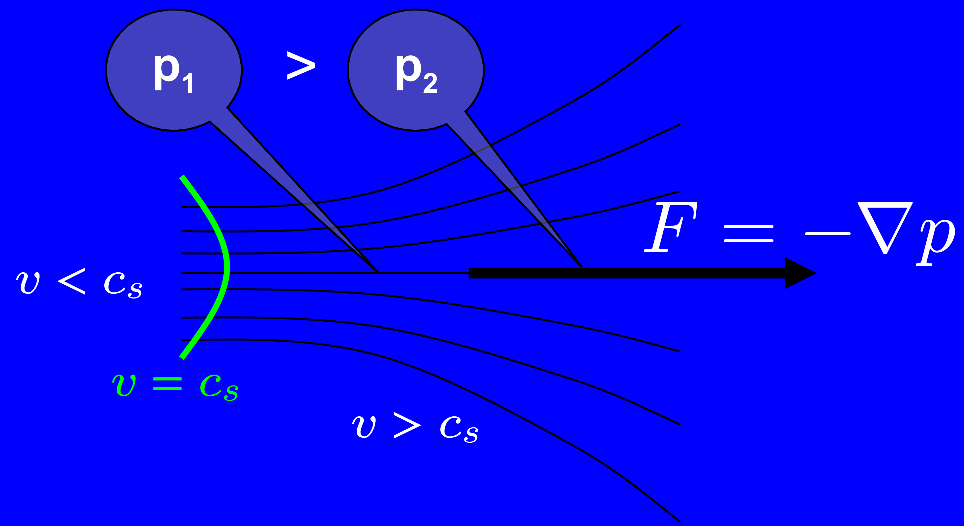
- The further the jet propagates, the more uniform it becomes
- Jet is surrounded by vacuum (p = 0)

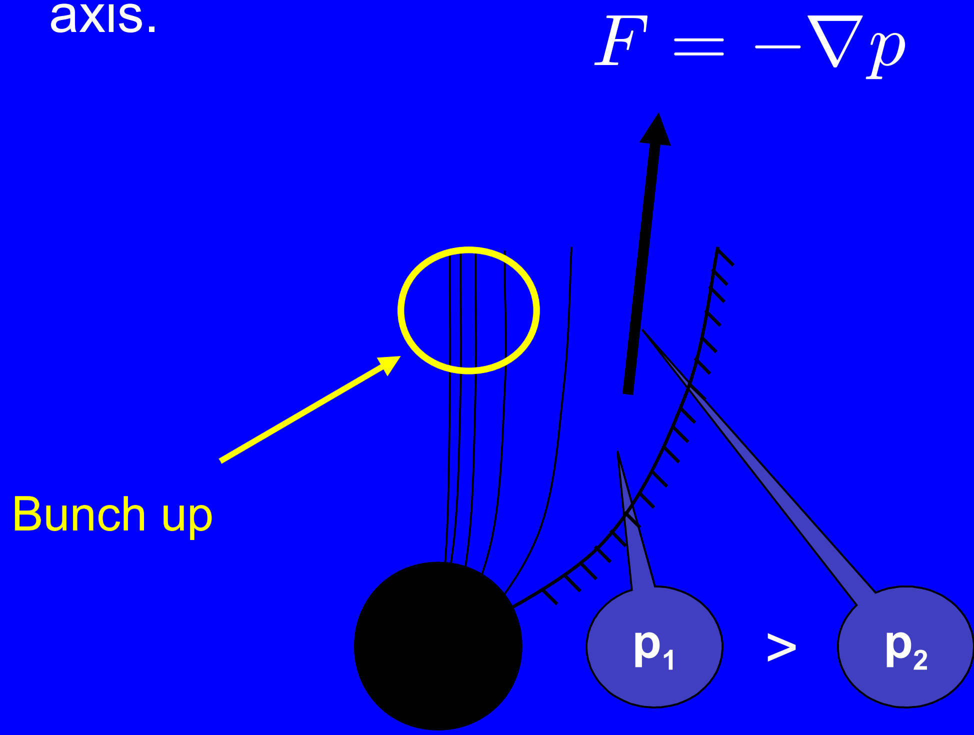


Magnetic nozzle for field lines

Hydro: de Laval nozzle: flow opens up after sonic surface → pressure drops → ∇ p accelerates flow:

MHD: reduction in field line density as the rest of field lines bunch up at the jet axis.





(Begelman & Li 1994, Komissarov 2009, AT+ 2009)