Title: Horizon Scale Lepton Acceleration in Jets: Explaining the Compact Radio Emission in M87

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Abstract: It has now become clear that the radio jet in the giant elliptical galaxy M87 must turn on very close to the black hole. This implies the efficient acceleration of leptons within the jet at scales much smaller than feasible by the typical dissipative events usually invoked to explain jet synchrotron emission. Here we show that the stagnation surface, the separatrix between material that falls back into the black hole and material that is accelerated outward forming the jet, is a natural site of pair formation and particle acceleration. This occurs via an inverse-Compton pair catastrophe driven by unscreened electric fields within the charge-starved region about the stagnation surface and substantially amplified by a post-gap cascade. For typical estimates of the jet properties in M87, we find excellent quantitive agreement between the predicted relativistic lepton densities and those required by recent high-frequency radio observations of M87.

Horizon Scale Lepton Acceleration in Jets: Explaining the Compact Radio Emission in M87

Alexander (Sasha) Tchekhovskoy

Einstein Fellow
UC Berkeley

with Avery Broderick and Omer Bromberg

Talk Plan

- What makes jets shine
  - near the black hole?
  - far from the black hole?

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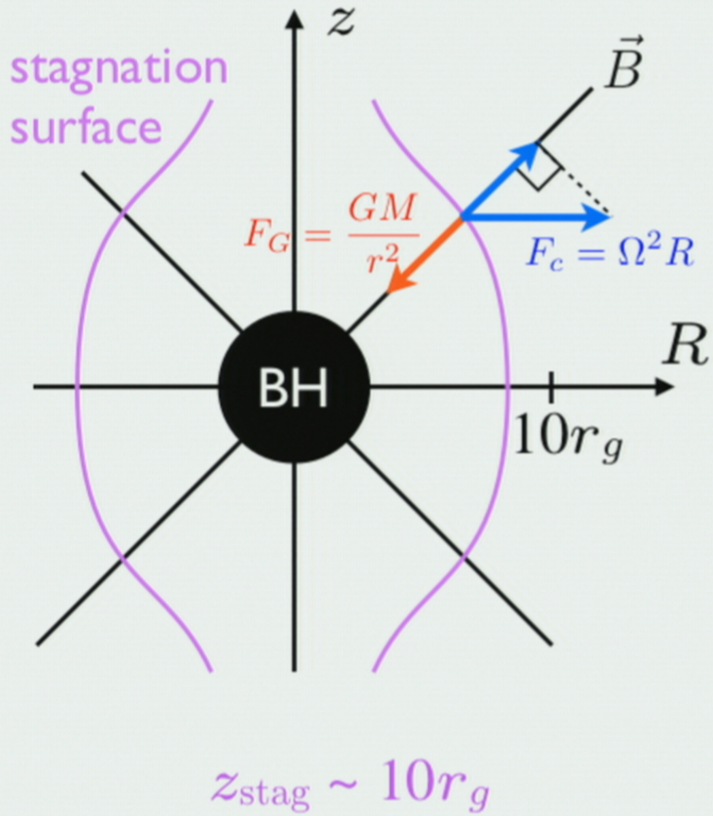
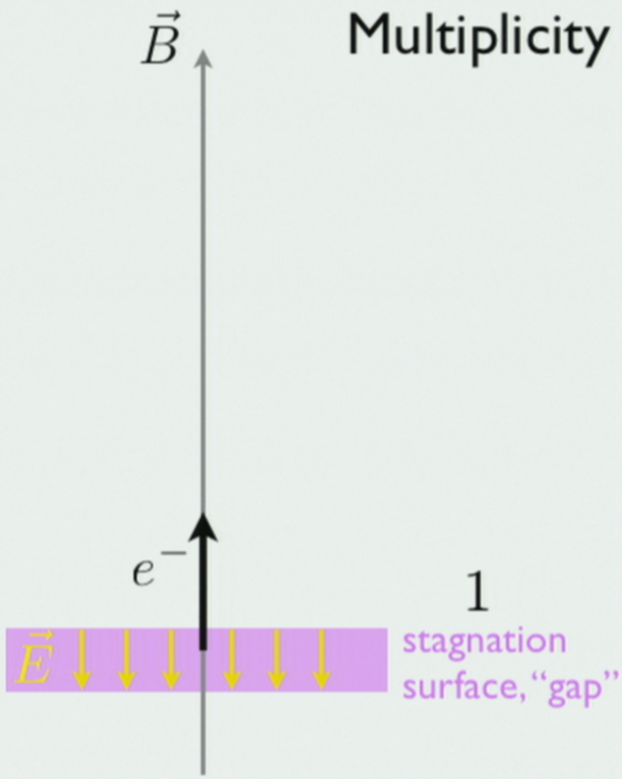
What makes jets shine close-in?

- M87 sub-mm emission extends down to $z \sim 10r_g$
- Same region as *stagnation surface* (see Masa Nakamura's talk): $F_G = F_c$
- Stagnation surface is at the right place (see Avery's talk) to accelerate radiating particles!
- Gas runs away from stagnation surface -> density drops to zero, "gap"?



Post-Gap Pair Cascade in M87

- Mass density and charge density drop to zero
- Electric field emerges and accelerates electrons
- Start with one energetic electron, $\Gamma_e \sim 10^9$
- Get pair catastrophe



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Broderick & Tchekhovskoy, ApJ, subm

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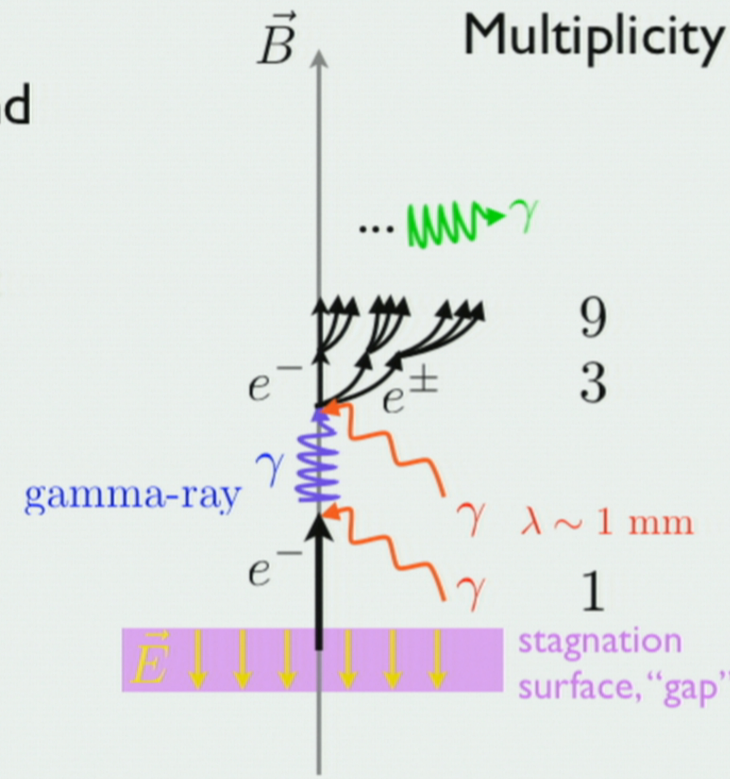

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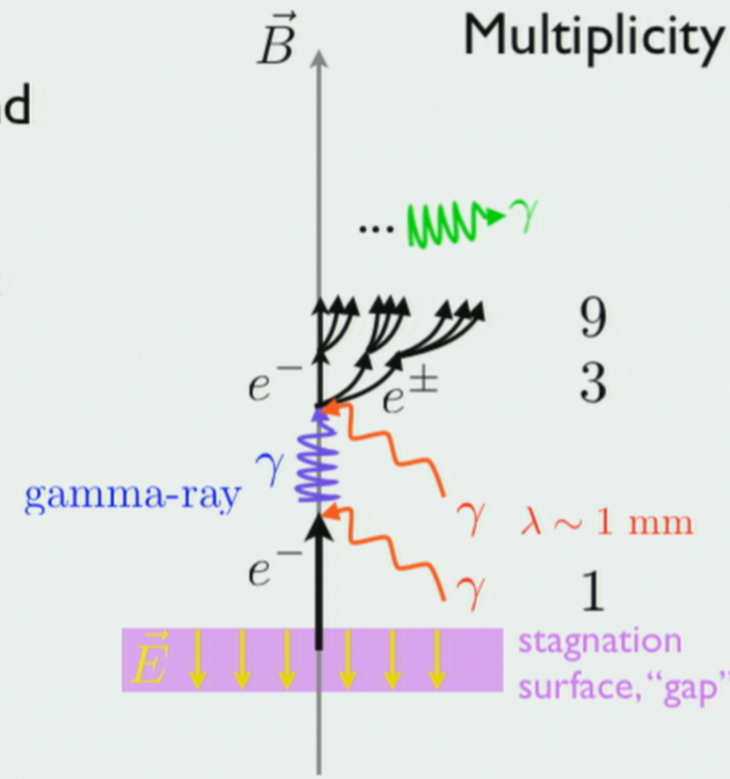

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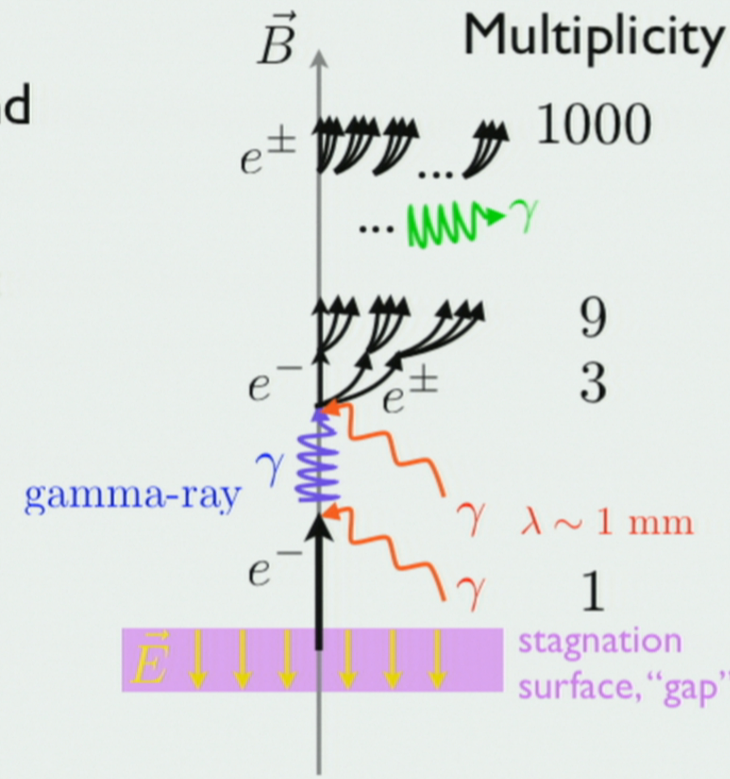

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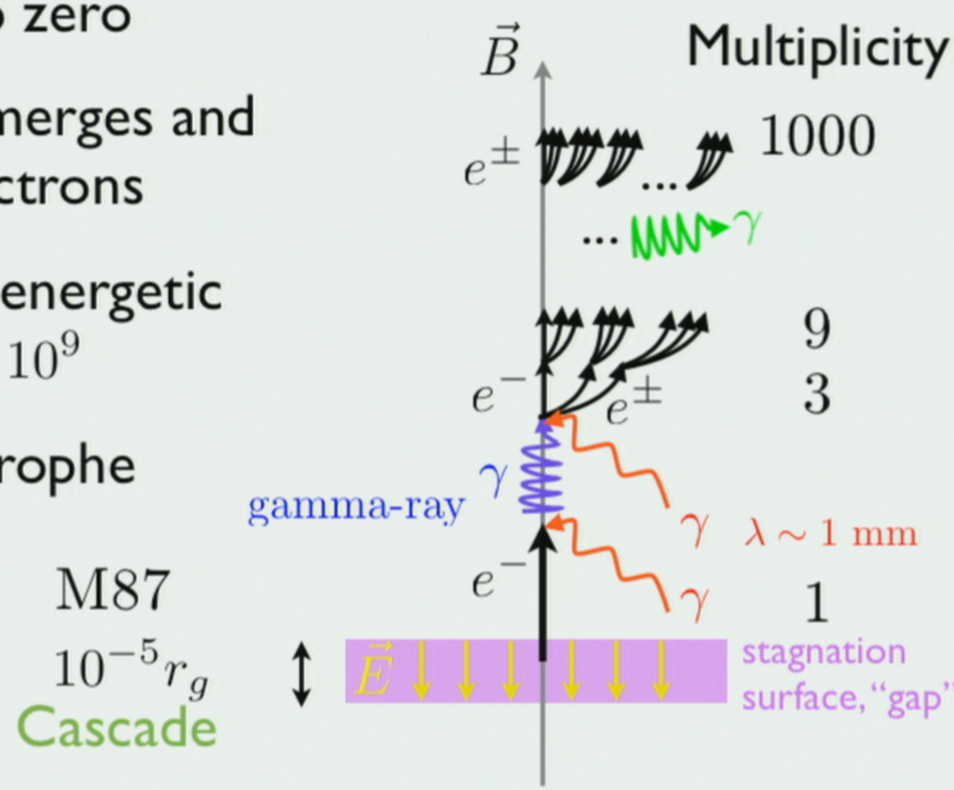

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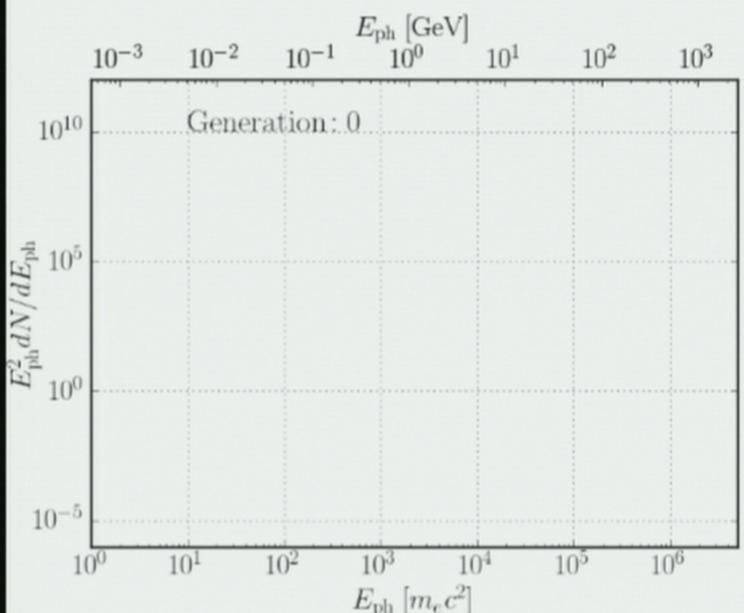
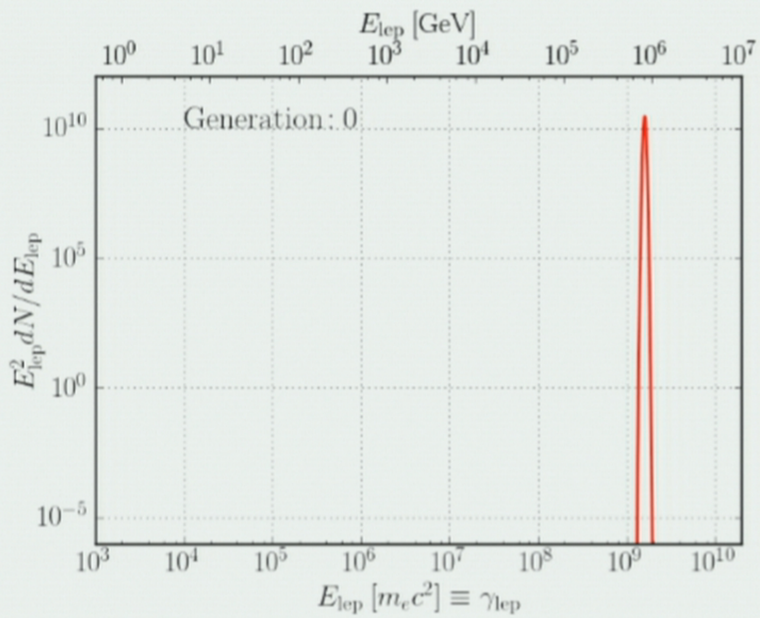
Development of Cascade

- Start with just one electron -> cascade produces leptons and gamma-rays

Escaping gamma-rays



Accelerated $e^{\pm}$ ...



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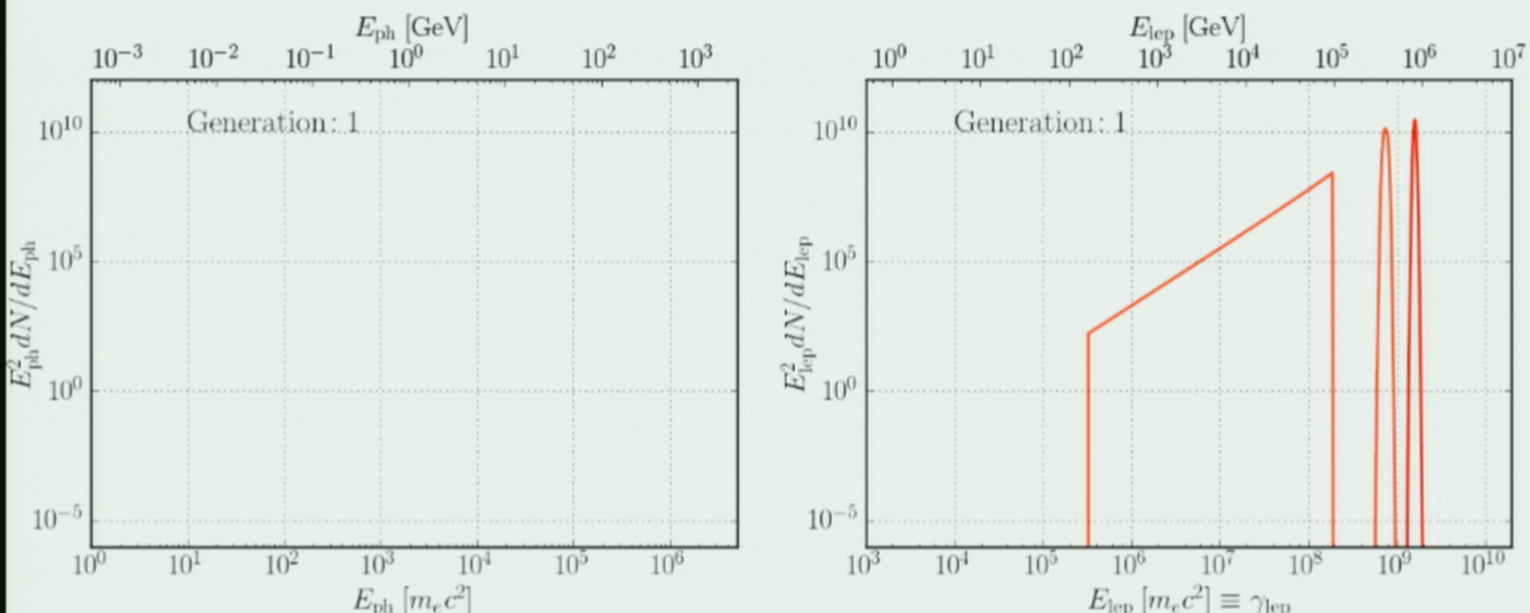

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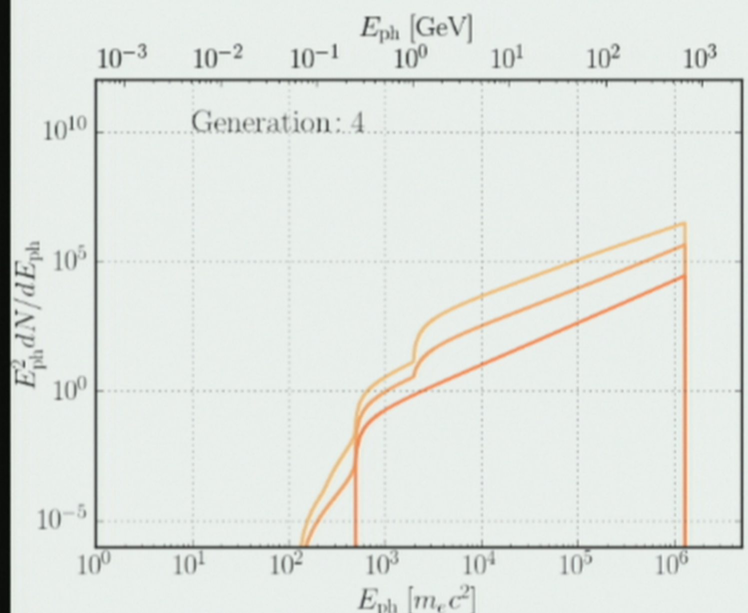

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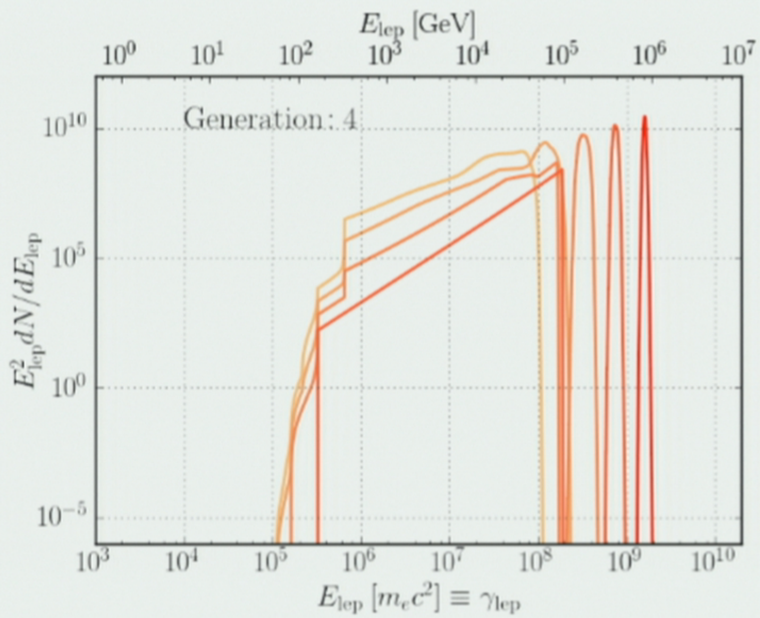

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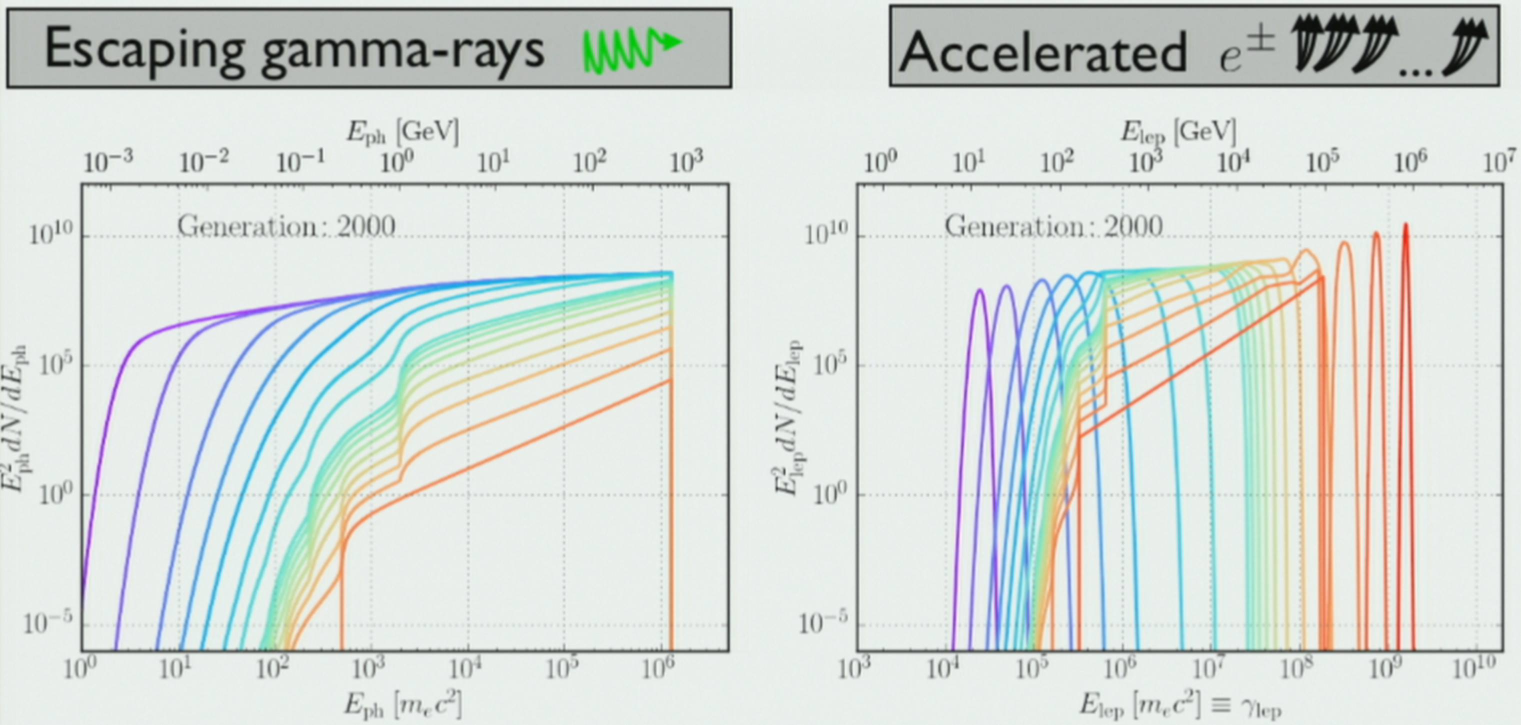

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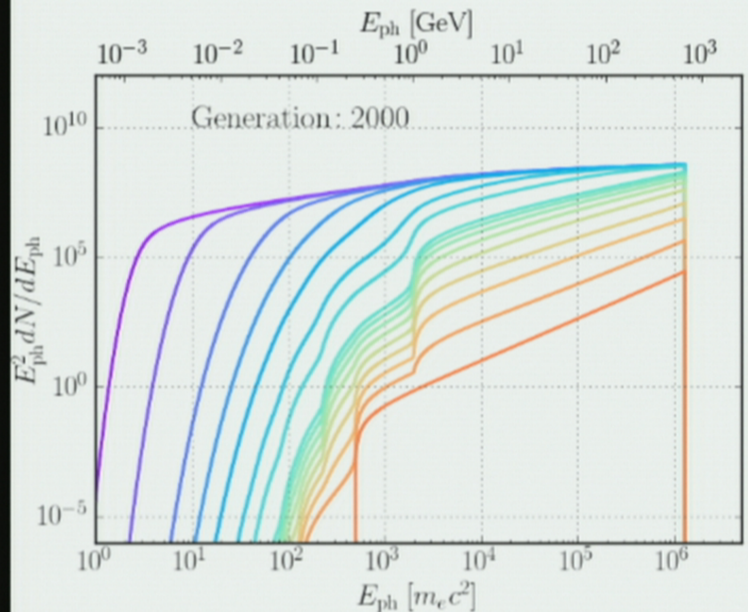

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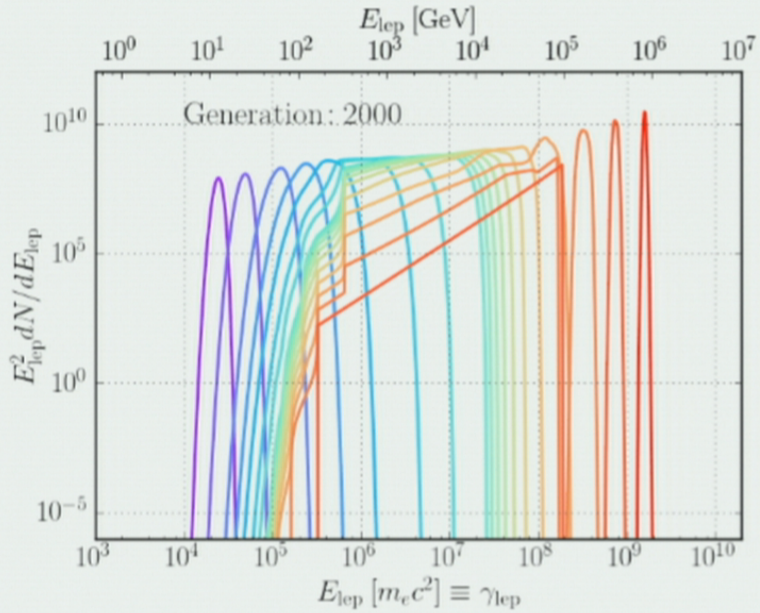

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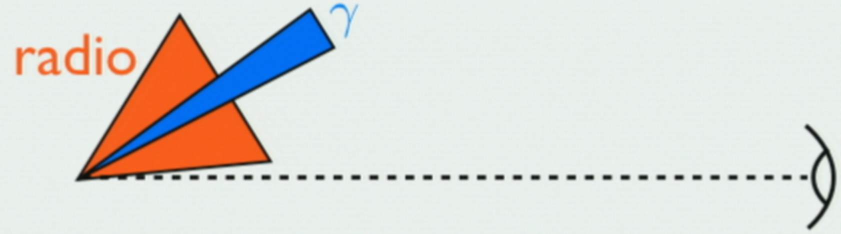
Energetics of M87 emission



Two types of beamed emission in M87:

- Beamed away from us:
  $L_{gamma} \sim 10^{43}$ erg/s = 10% of total jet power
- Beamed toward us:
  $L_{radio} \sim 10^{41}$ erg/s, sufficient to account for observed mm-radio emission
  - ➡ seed photons produced by the jet itself

In SgrA*, gap is too wide ($\sim r_g$) for cascade to operate.

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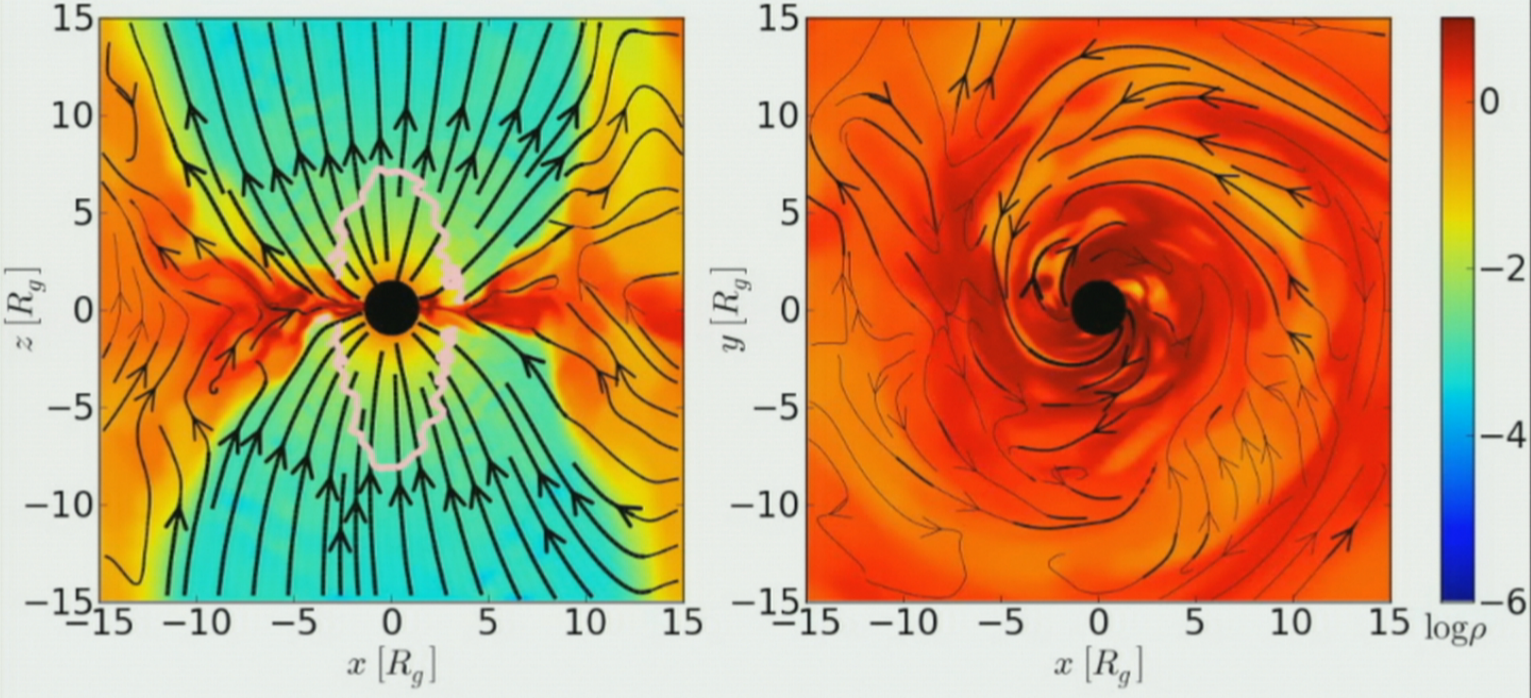
Simulated Stagnation Surface



Simulations add gas to keep density from falling too low.
In reality, a "gap" opens up with uncompensated $\vec{E}$.

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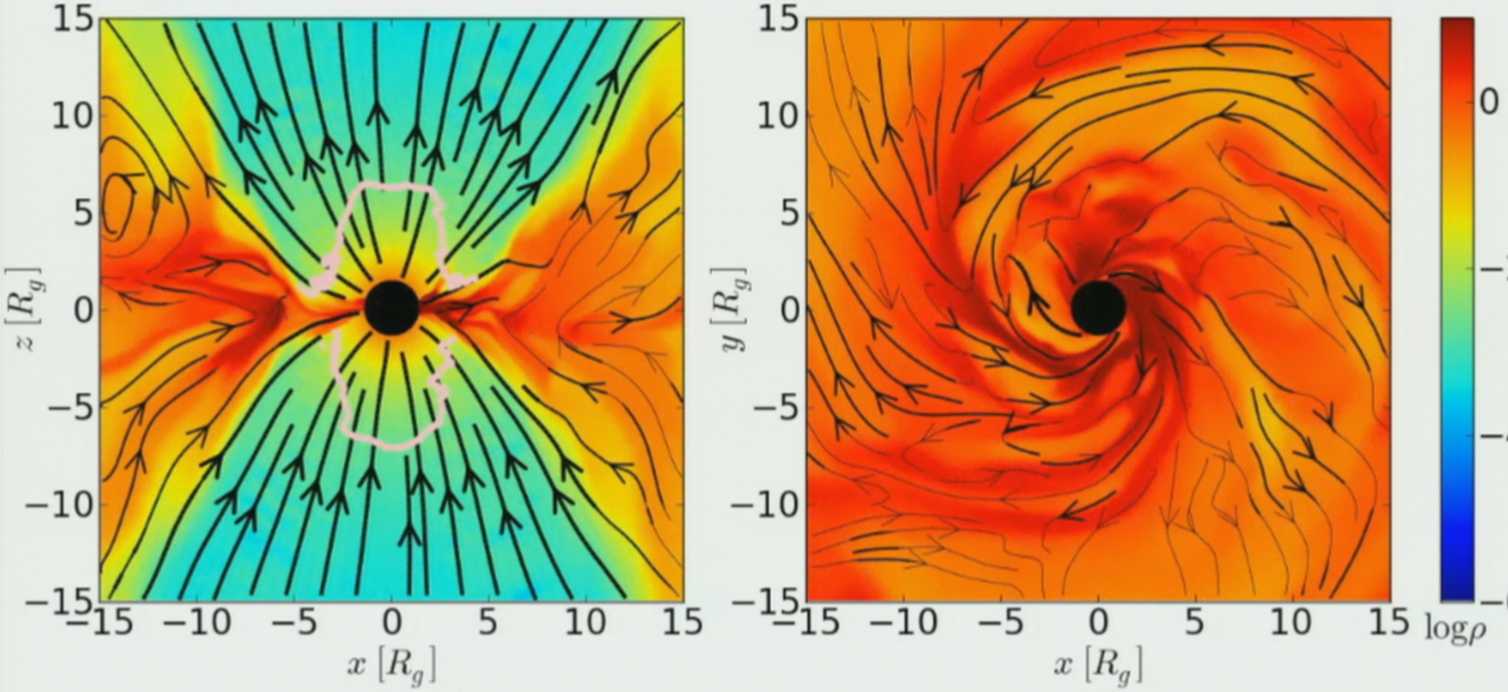

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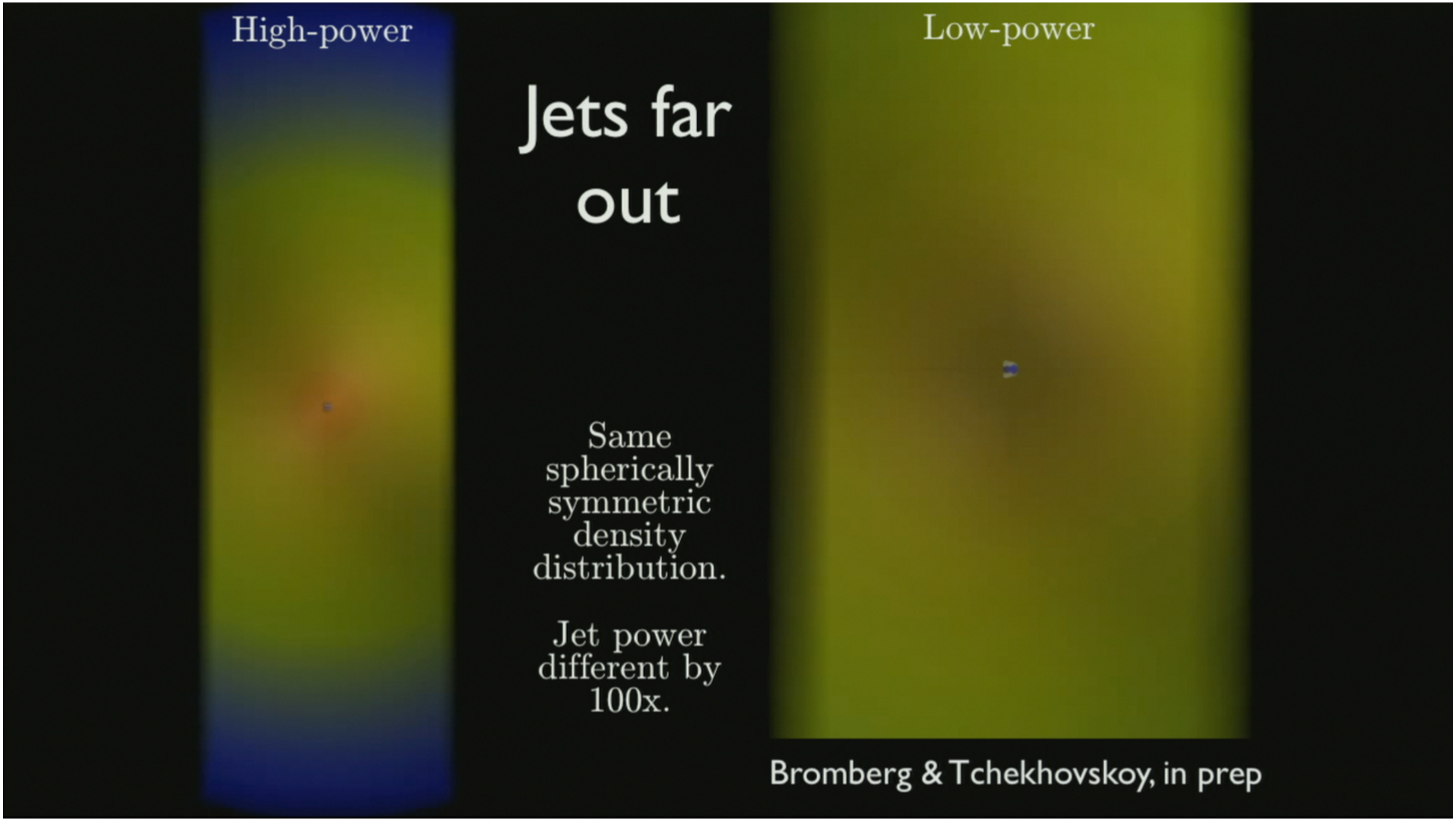
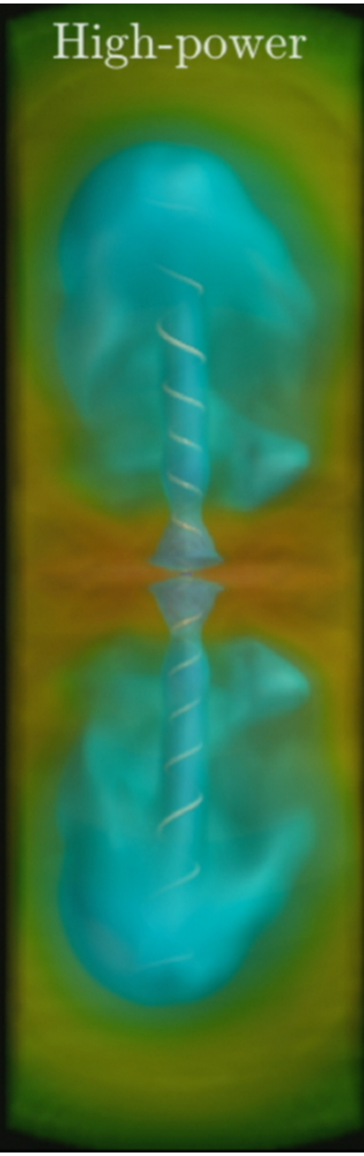
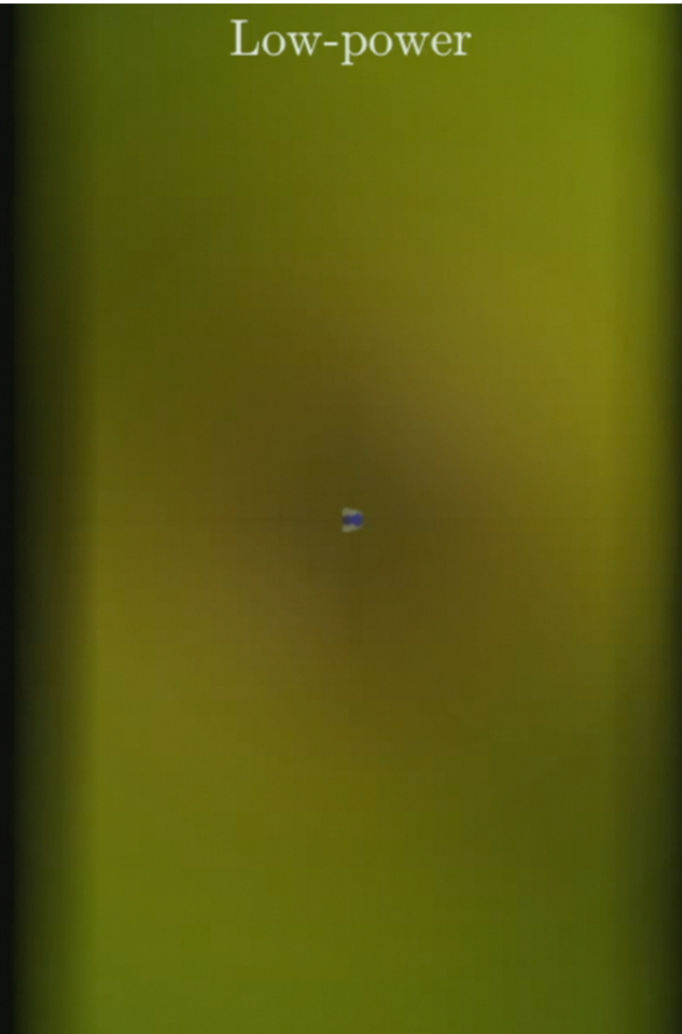

High-power
Low-power
Jets far out
Same spherically symmetric density distribution.
Jet power different by 100x.
Bromberg & Tchekhovskoy, in prep

Jets far out





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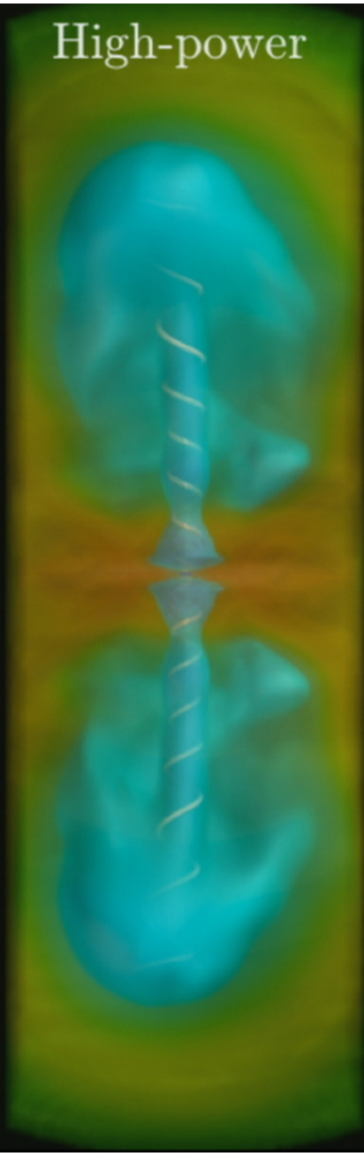

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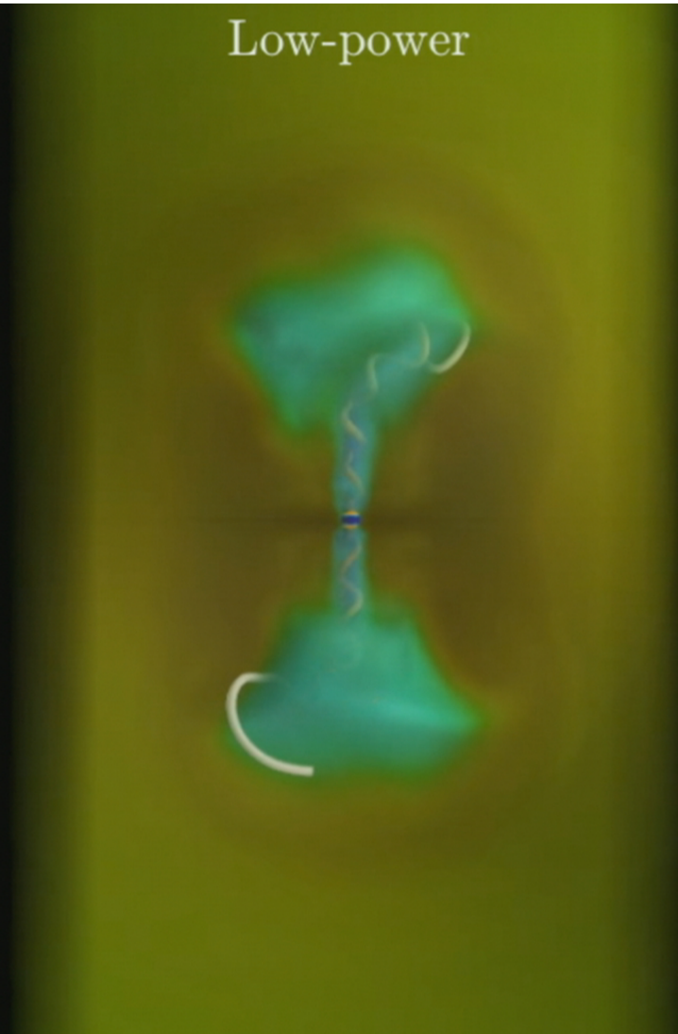

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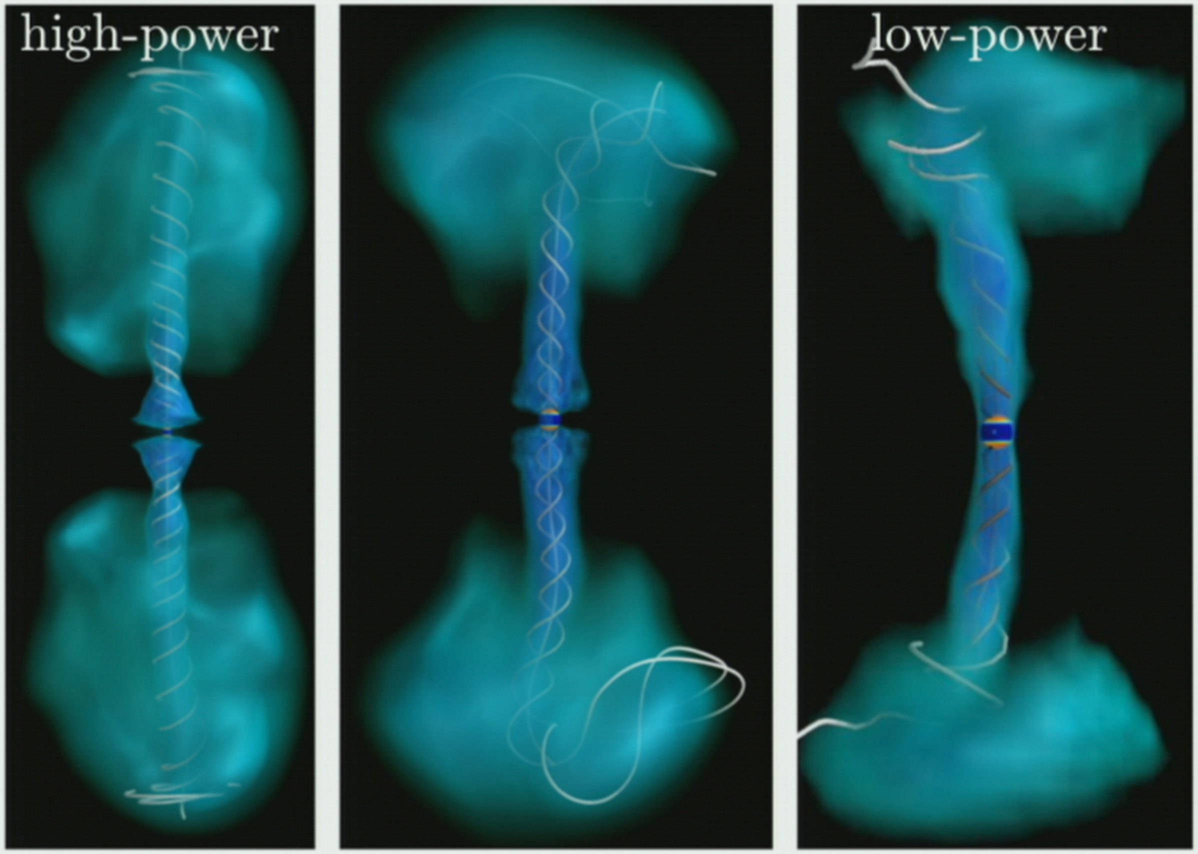
Jet Power Controls the Morphology



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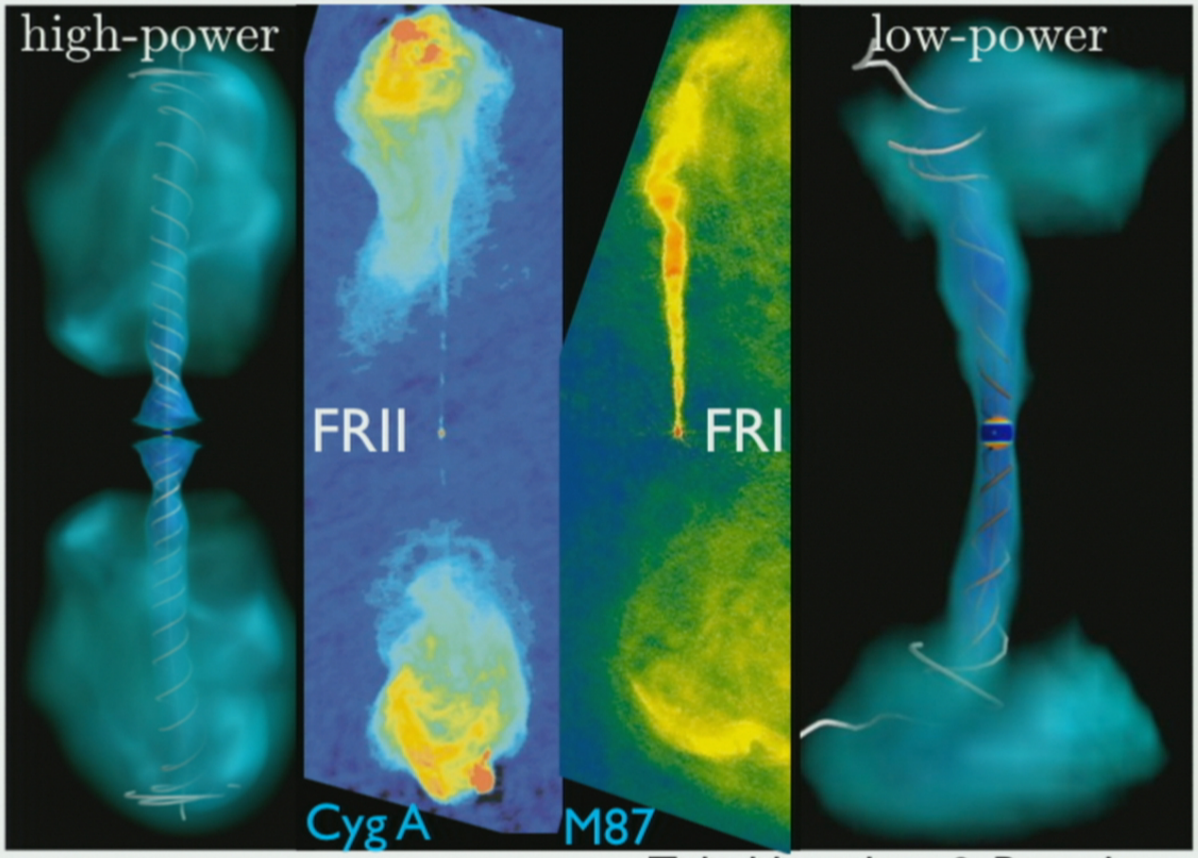

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Conclusions

- Stagnation surface opens a "gap": an ideal location for particle acceleration:
  - *M87*: "gap" accounts for radio and gamma-ray luminosity
  - *SgrA**: no efficient acceleration at the "gap"
- Even though jets shake their heads,
  - both FRI and FRII central engines can be the same
  - jet morphology (FRI/FRII) can be caused by jet power variations (low/high) alone

How strong is B in AGN?

- Radio jet core is where jet becomes transparent to its own synchrotron radiation:

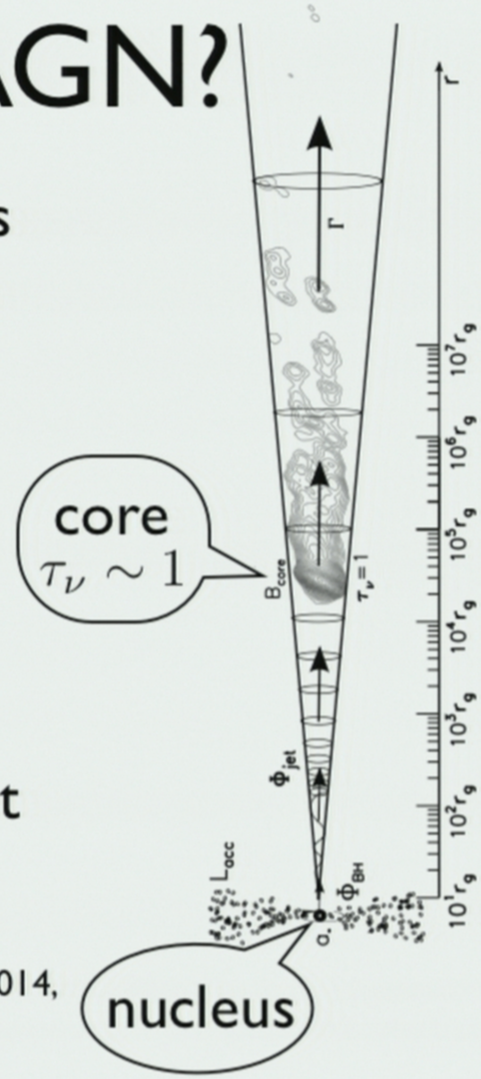
$$\tau_\nu \sim 1$$

- At higher ν, the core shifts inward

$$B \propto (dr_{\rm core})^{3/4}$$

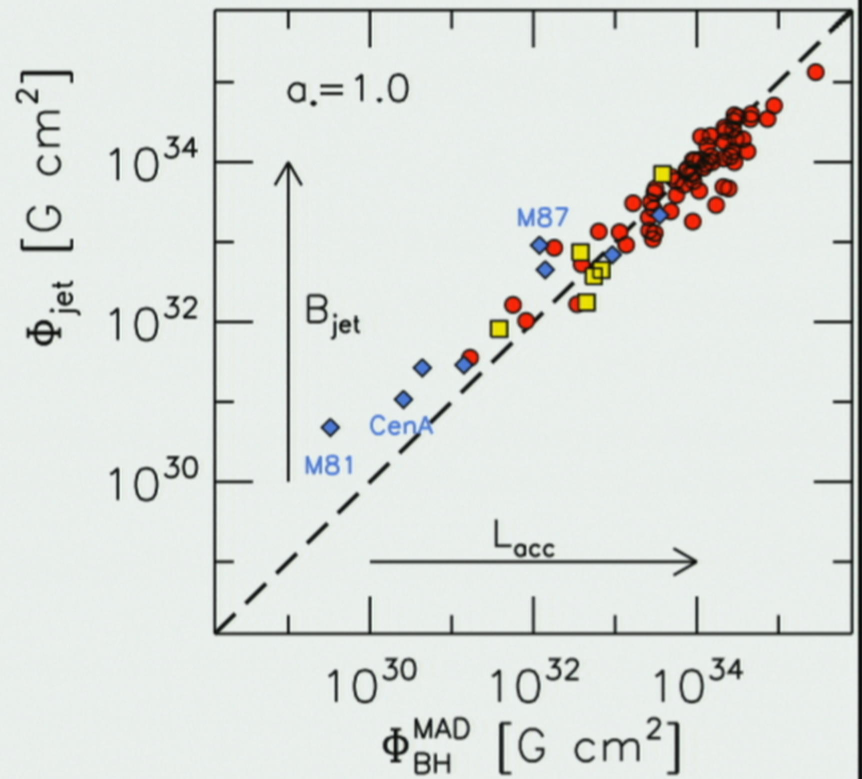
- Can use this to measure B in the jet
- Magnetic flux $\Phi \approx B\pi r_{\rm core}^2\theta_j^2$

(Zamaninasab, Clausen-Brown, Savolainen, Tchekhovskoy, Nature, 2014, Zdziarski, Sikora, Pjanka, Tchekhovskoy, MNRAS, submitted)



MADs in AGN?

- Observed scaling:
  $B_{\rm jet} \propto L_{\rm acc}^{1/2}$
- Magnitude of magnetic flux in *radio-loud* AGN is consistent with MAD expectation (Tchekhovskoy, McKinney, Narayan, MNRAS, 2011)
- Many AGN are MAD
  - their central BHs are surrounded by *dynamically important magnetic field*



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