



Next Generation Very Large Array



## Astrophysical Jets:

# Formation, Evolution, and Environmental Impact

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# Some collaborations

RB, Meier, Readhead – Annual Review

Meyer, Scargle, RB – Fermi Flares

RB – Black Holes as Cosmic Batteries

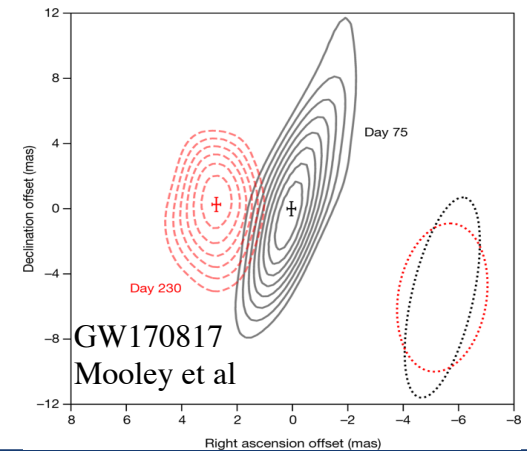
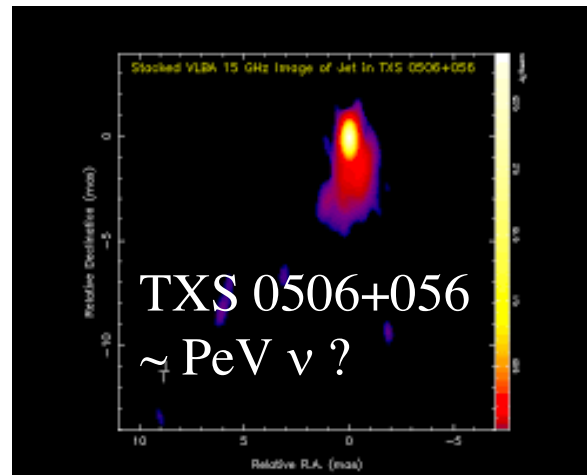
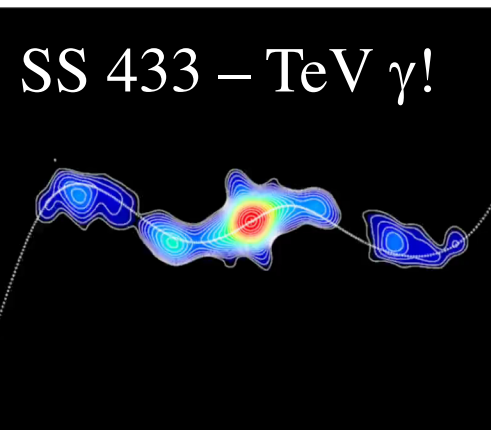
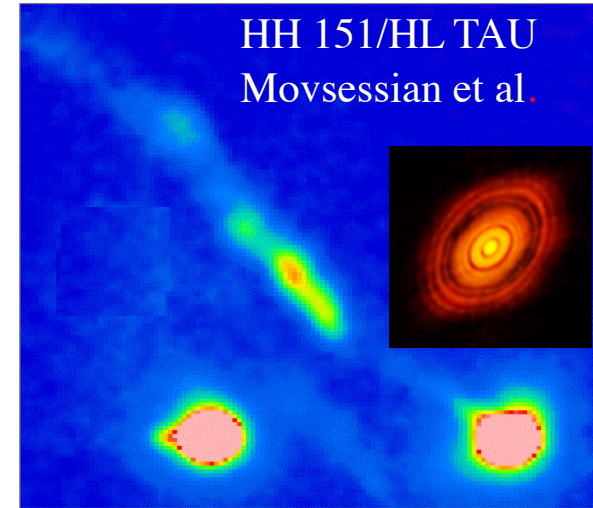
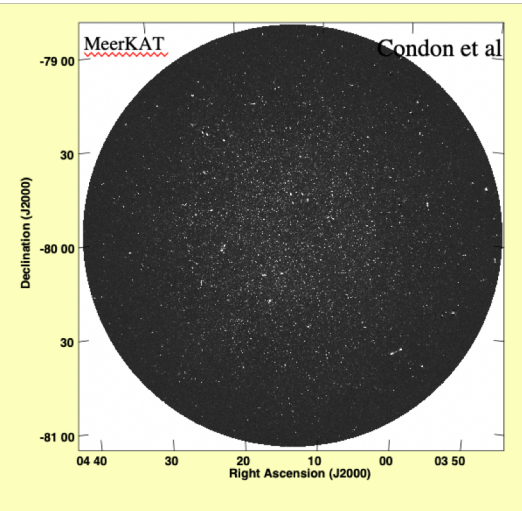
Anantua, RB et al – Observing Jet Simulations

Begelman, RB – Slow Accretion Models

Yuan, RB, Wilkins – Seyfert Lamposts

RB, Yuan, East, Zrake – Magnetoluminescence

# Jets Everywhere



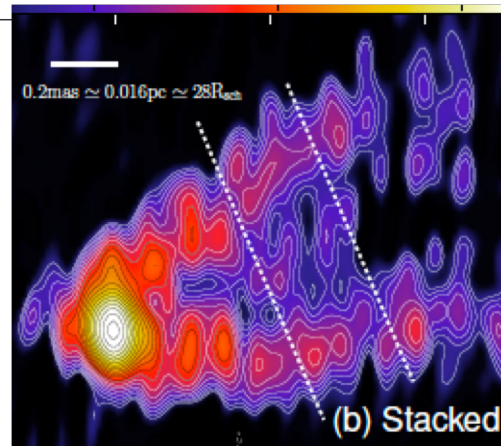
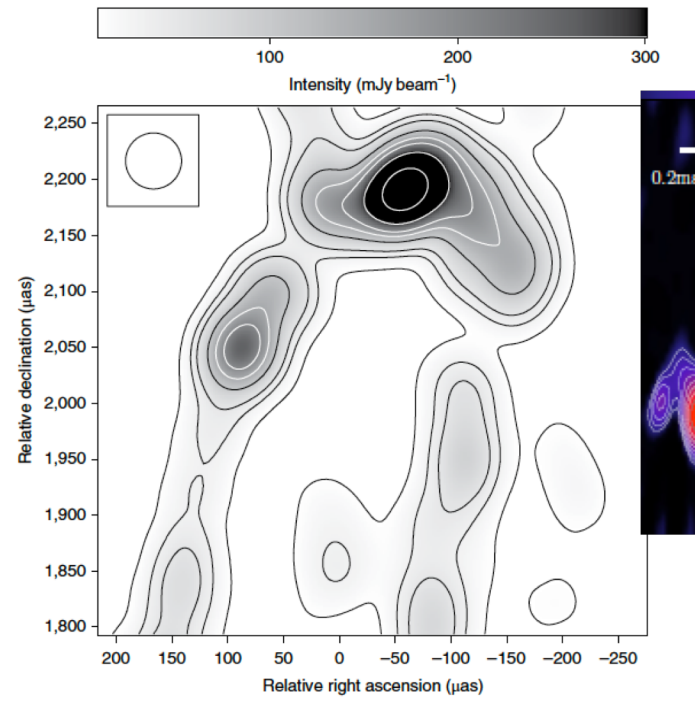
# Some Questions

- Prime mover - disk or spinning hole?
- Working substance - plasma or field?
- Inner confinement - torus or wind?
- Positive particles - pairs or protons?
- Acceleration - reconnection or untangling?
- $\gamma$ -rays - Compton or synchrotron?
- Emission lines - inflow or outflow?
- FR class - hole or environment?
- Radio loudness - hole or field?

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# Prime mover - disk or spinning hole?

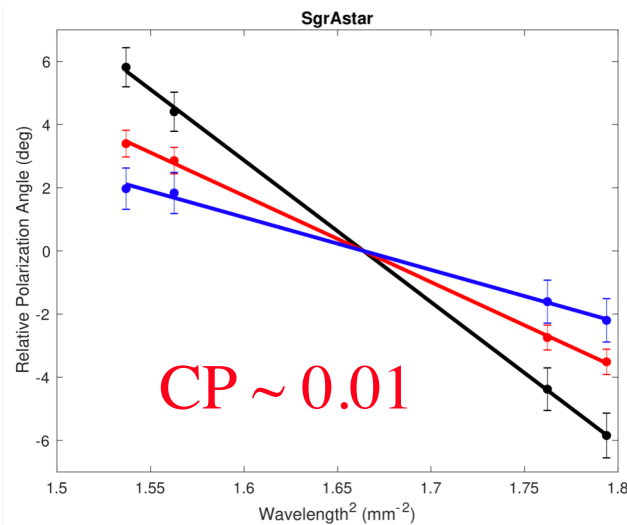


Invisible disk!

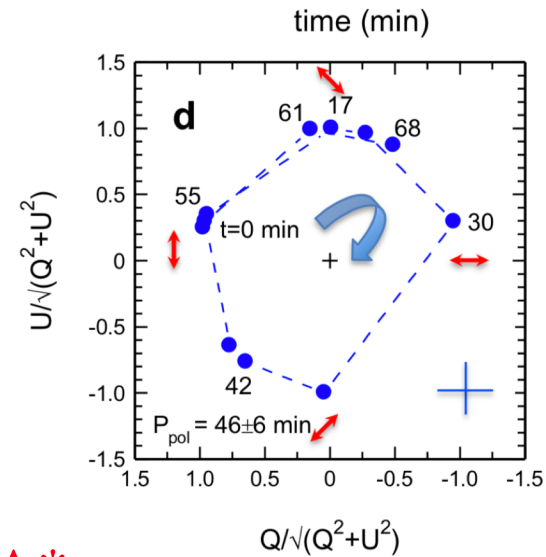
Magnetized, spinning black hole  
 $\sim 10^{20} L_{\text{jet } 45}^{\frac{1}{2}}$  Volt  $\sim 10^{18} L_{\text{jet } 45}^{\frac{1}{2}}$  Amp  
 Initially electromagnetic

# Working substance - plasma or field?

## Bower et al/EHT



## GRAVITY Collaboration

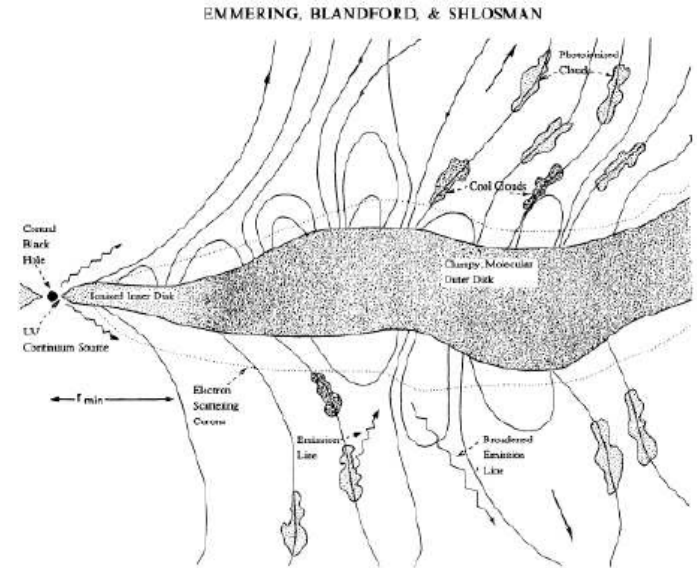
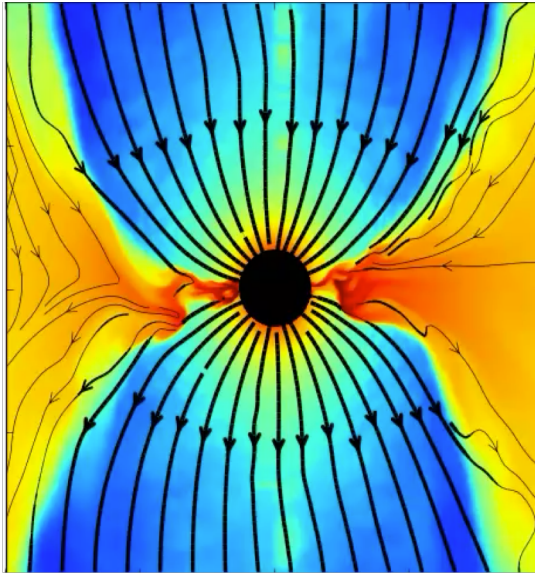


Sgr A\*

Despite evidence for strong field,  
most  $\gamma$ -ray blazar models are weak field

# Inner confinement - torus or wind?


McKinney Tchekhovskoy, RB



Inner jets collimated by nested toroidal magnetic field  
in an MHD wind confined at  $r_{\text{inf}} \sim r_{\text{Bondi}} \sim GM_H/\sigma^2 \sim 10^6 r_g$ ?

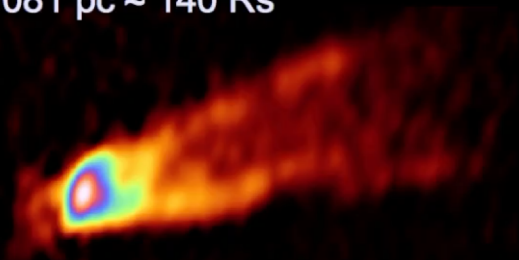


# Positive particles - pairs or protons?

 **M87 INNER JET**

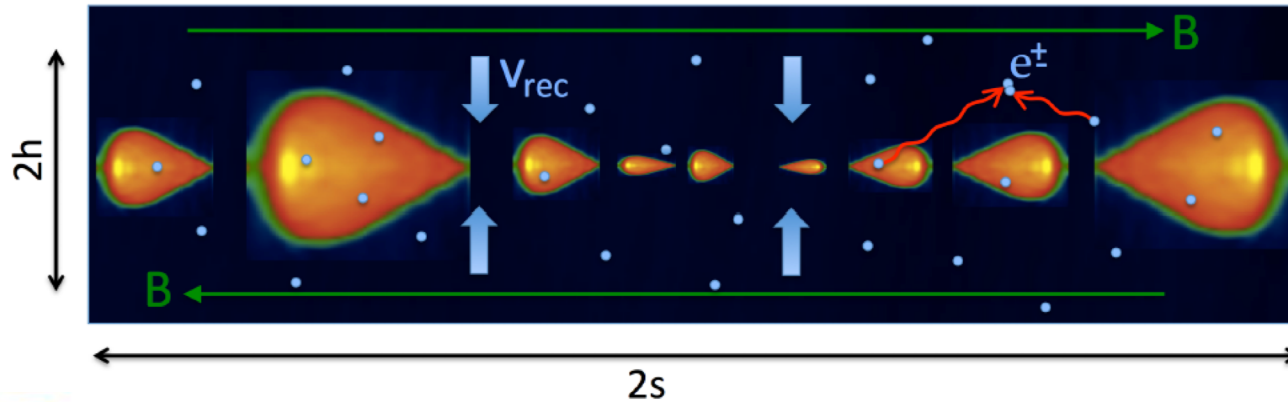
2007: Interval three weeks  
VLBA at 43 GHz  
Resolution 0.21 X 0.43 mas  
Scale: 1 mas = 0.081 pc  $\approx$  140 Rs

Walker, Hardee, Davies,  
Ly, & Junor Ap. J. 2018



Pair production necessary (and easy) close to hole  
Entrainment (from wind?) quickly builds up proton primaries  
Secondary pairs likely

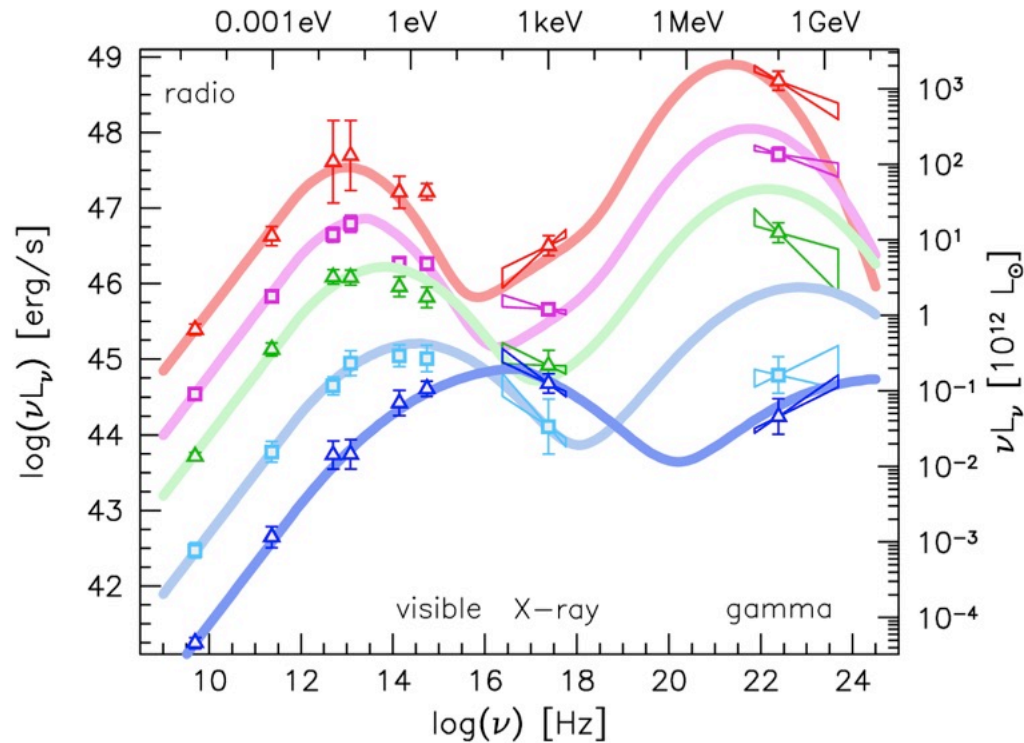
# Acceleration - reconnection or **untangling?**



"Magnetoluminescence"

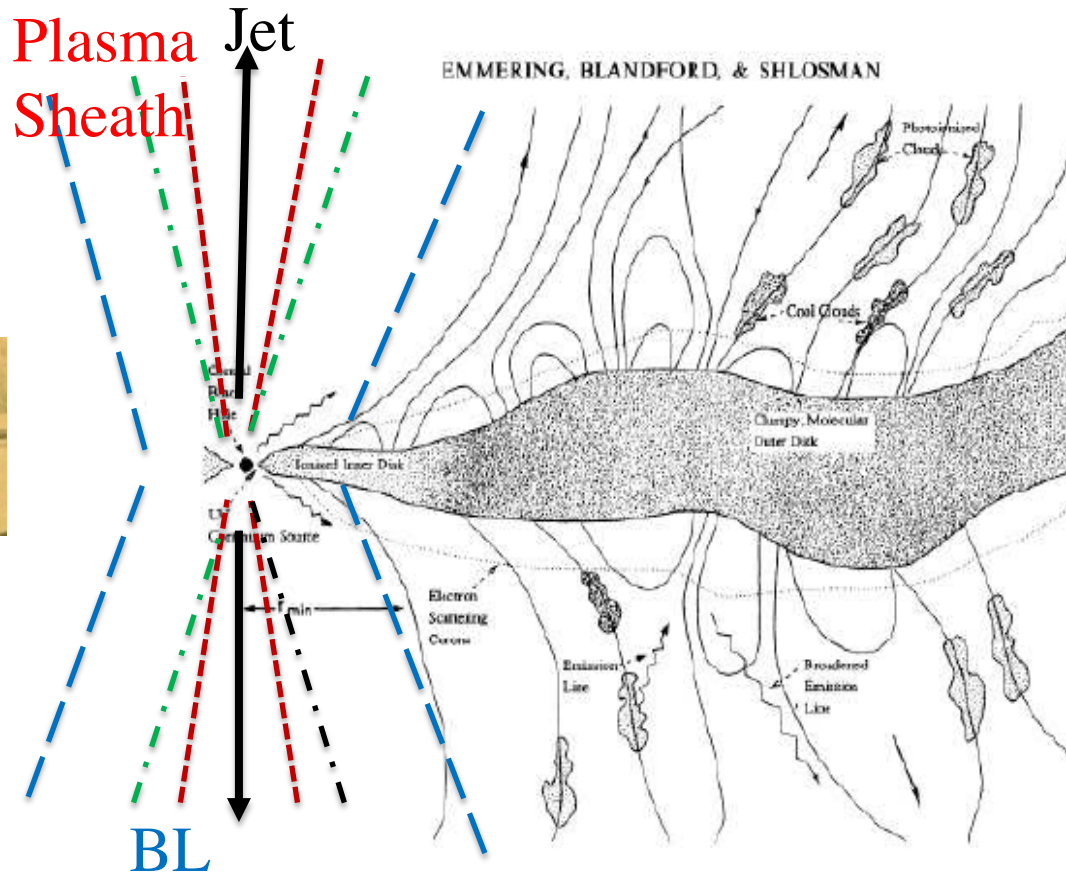
Little magnetic flux in jet  
 Magnetic ropes tangled by instabilities  
 Can untangle relativistically without topological change  
 Accelerate at sliding surfaces if charge-starved

# $\gamma$ -rays - Compton or synchrotron?



Compton model incompatible with strongly magnetized jets  
 Direct electron acceleration limits photons to  $\sim 100\text{MeV}$   
 Protons can be accelerated to PeV-EeV energy  
 Make pair secondaries with very high efficiency

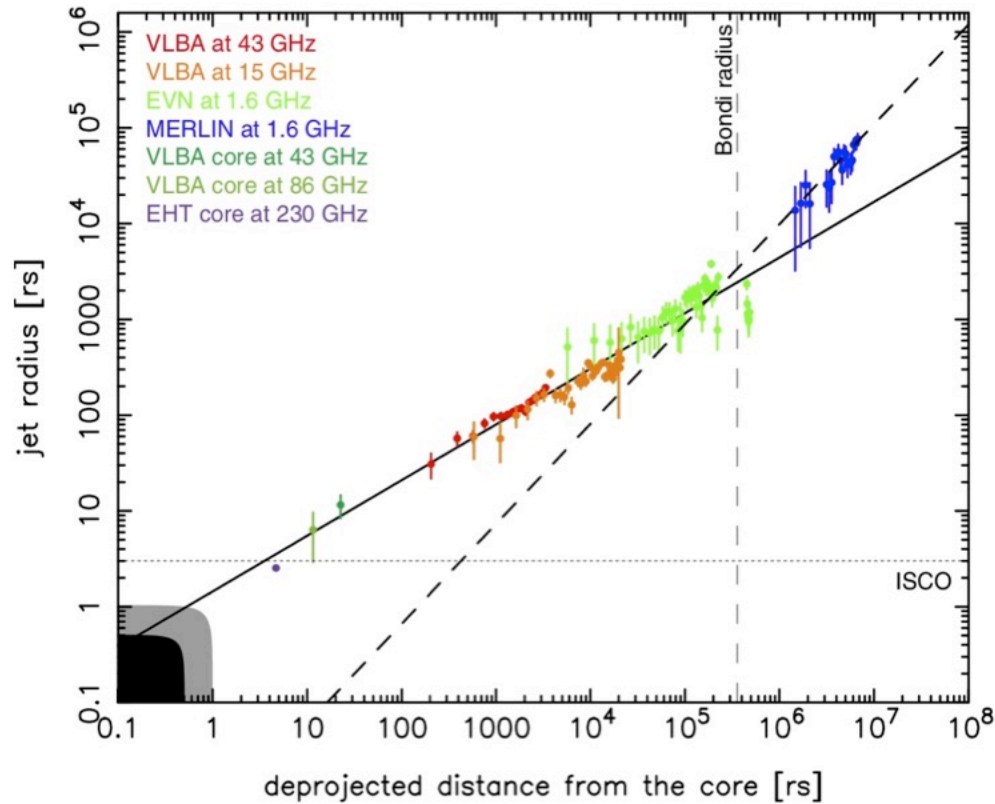
# Emission lines - inflow or outflow?



3C 273  
GRAVITY!

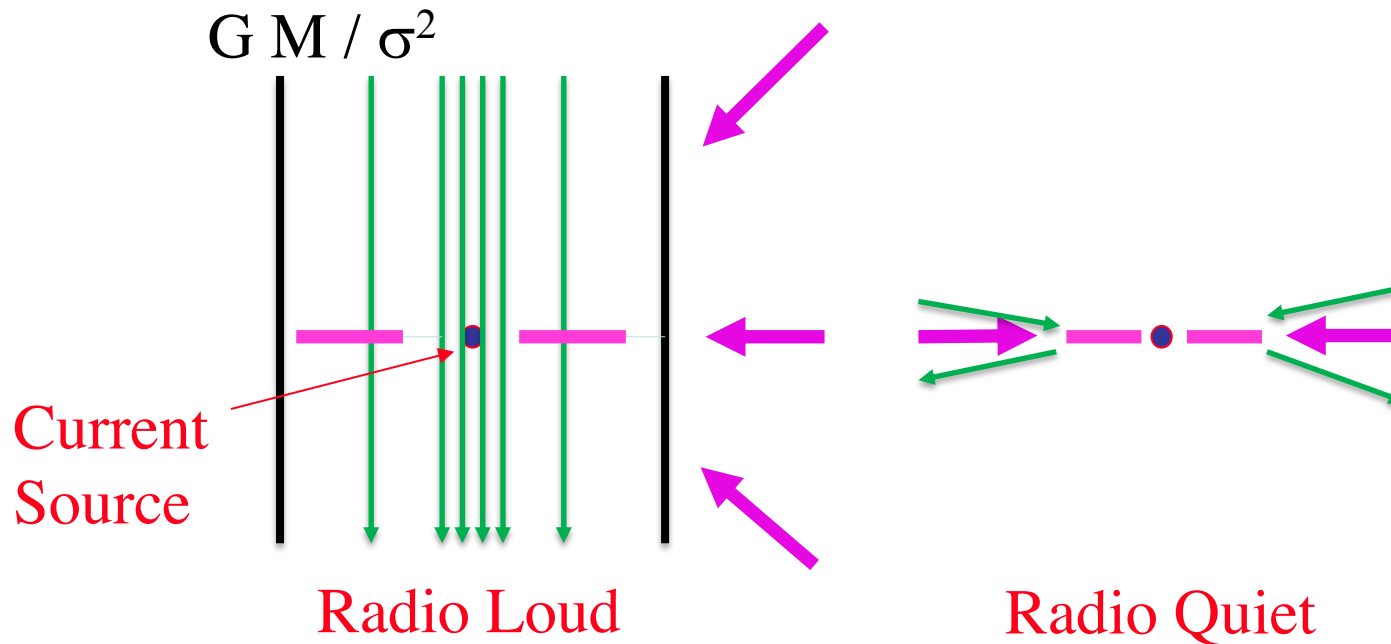
Gamma rays can vary in minutes, even in quasars  
 Shielding  $>13.6\text{eV}$  with plasma sheath avoids pair production  
 Emission line clouds are magnetically-confined disk outflow

# FR class - hole or environment?



Jet collimation breaks, recollimation shocks etc -> dynamics at  $r_{\text{inf}}$   
 FR II: Powerful jets supersonic through  $r_{\text{inf}}$  and propagate to hot spots  
 FR I: Weaker jets breakup into subsonic bubbles and plumes

# Radio loudness - hole or field?



Spinning hole necessary but insufficient for powerful radio jet  
 Need permanent, strong magnetic field concentrated at hole  
 High latitude accretion traps flux; disk accretion does not  
 Magnetic stress balance in wind leads to  $B \sim 1/r$ ;  $L_{\text{jet}} \sim M' \sigma c$

# Summary

- **Multi - source, - wavelength, - messenger**
  - **Integrated approach**
- **Basic questions unanswered**
  - **From prime mover to environmental interaction**
- **Ramsun observations are the key to jets**
  - **Sensitivity, spectrum, resolution**
- **Jets have environmental impact**
  - **Mediate galaxy formation and evolution**