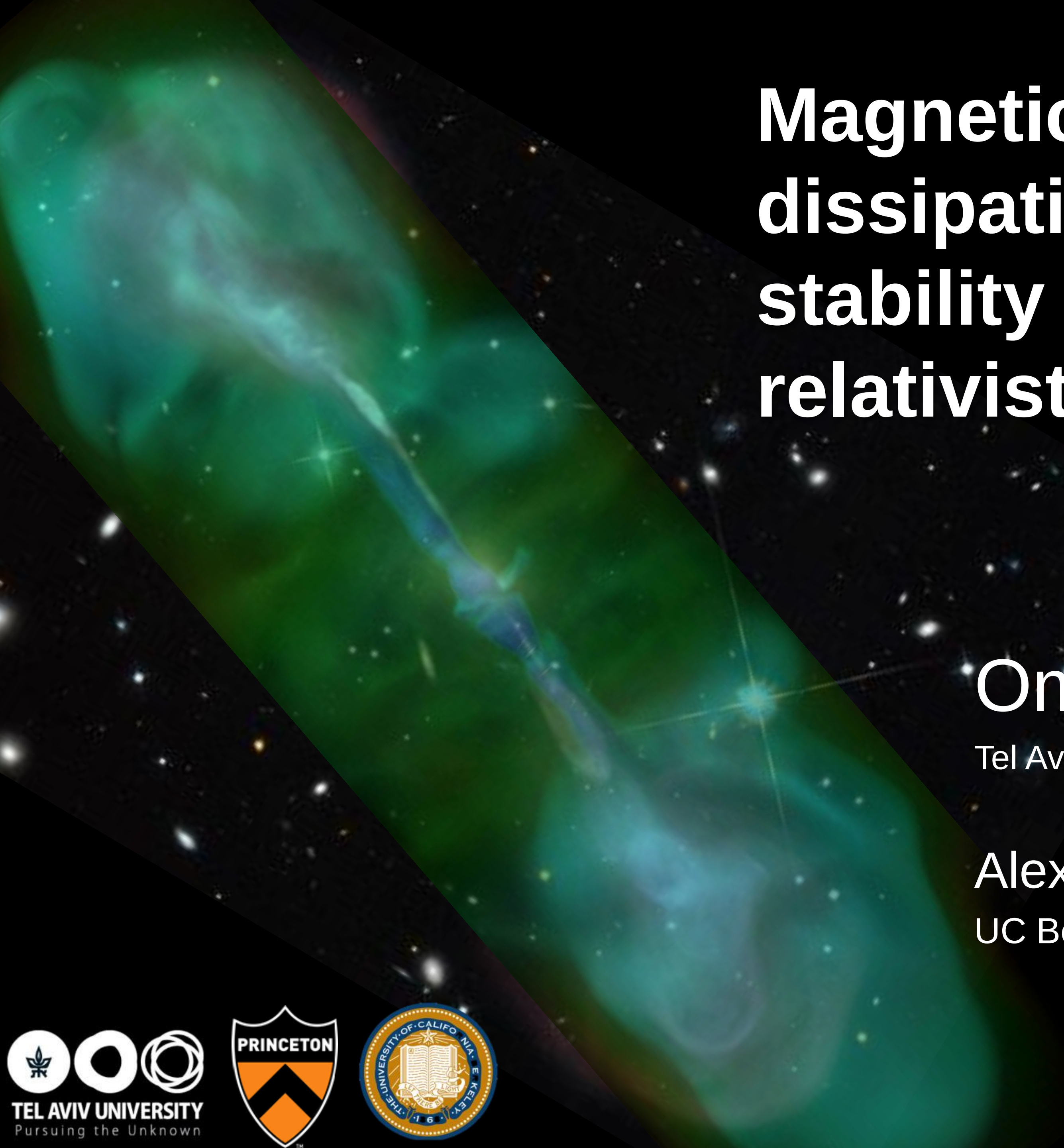
# Magnetic energy dissipation and stability of relativistic AGN jets



Omer Bromberg
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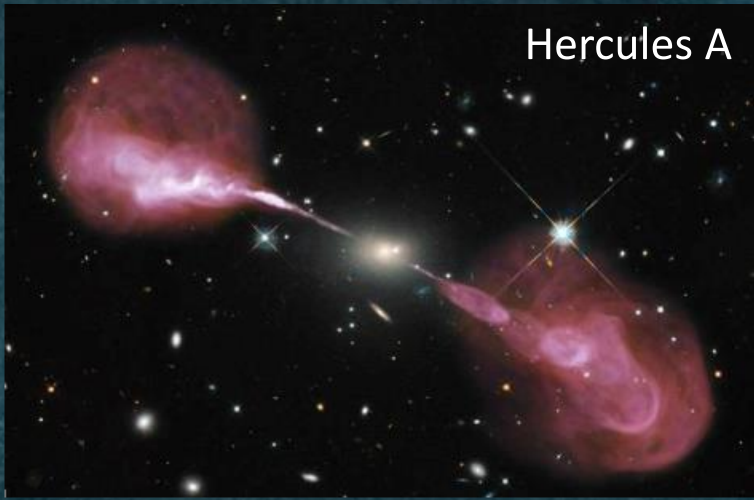
TEL AVIV UNIVERSITY
Pursuing the Unknown

PRINCETON

# Jets in AGNs

- About 10% of all AGNs show evidence for relativistic jets.
- Associate with accretion onto the SMBH.

$$v_{jet} \gtrsim v_{esc} \approx \sqrt{GM/R} \approx c\sqrt{R_{sh}/R}$$

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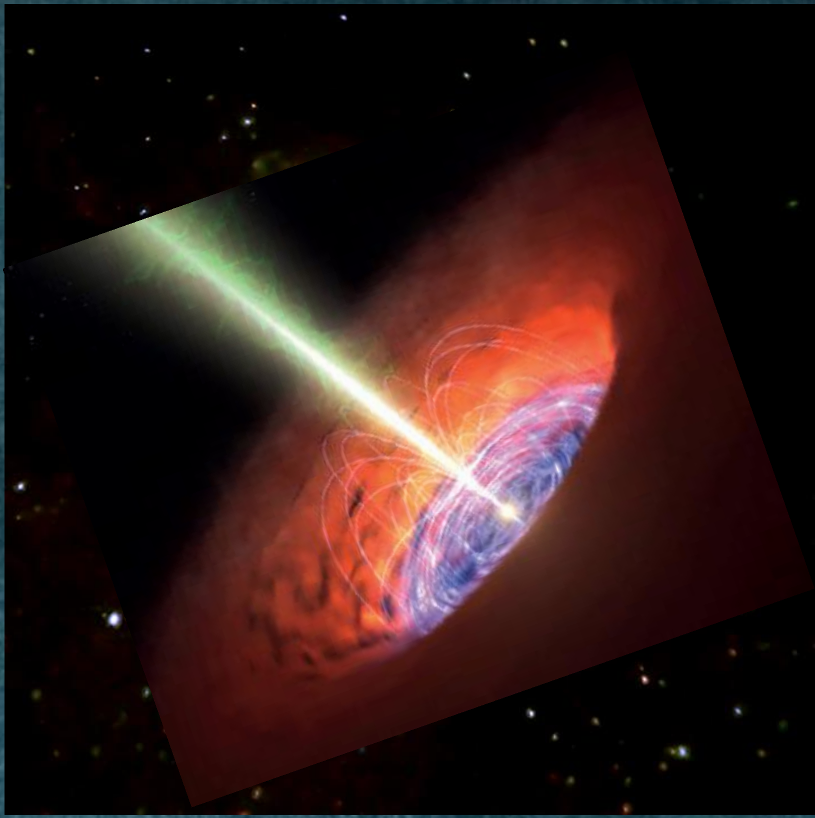

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- Associate with accretion onto the SMBH.

$$v_{jet} \gtrsim v_{esc} \approx \sqrt{GM / R} \approx c\sqrt{R_{sh}/R}$$

- Carry substantial amount of energy from the center

$$L_{jet} = \eta \dot{M} c^2 \approx 10^{46} \eta M_{33} t_7^{-1} \; erg / s$$

$$0.01 < \mu < 1$$

- Dump it at large distances, via extended cocoons, that can heat the CGM / IGM / ICM and affect SFR and the evolution of the galaxy.

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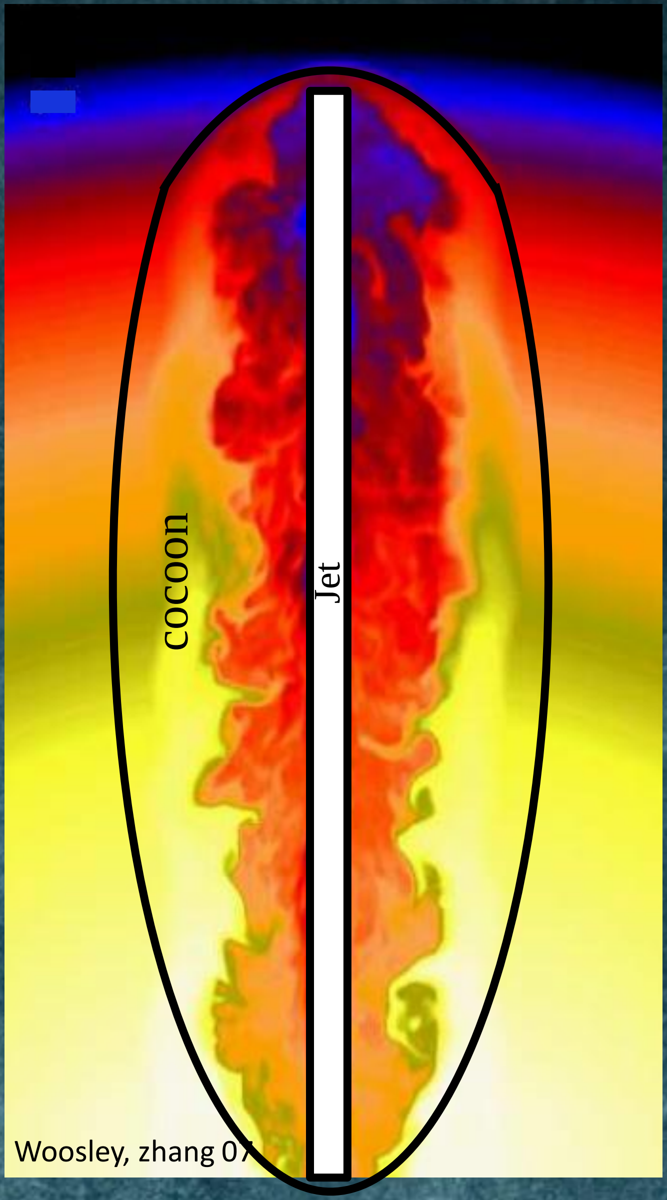
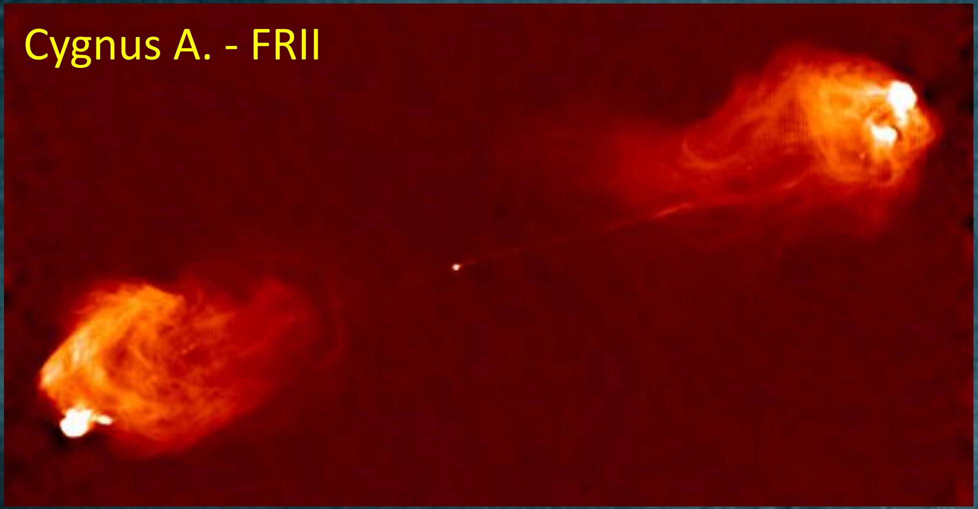
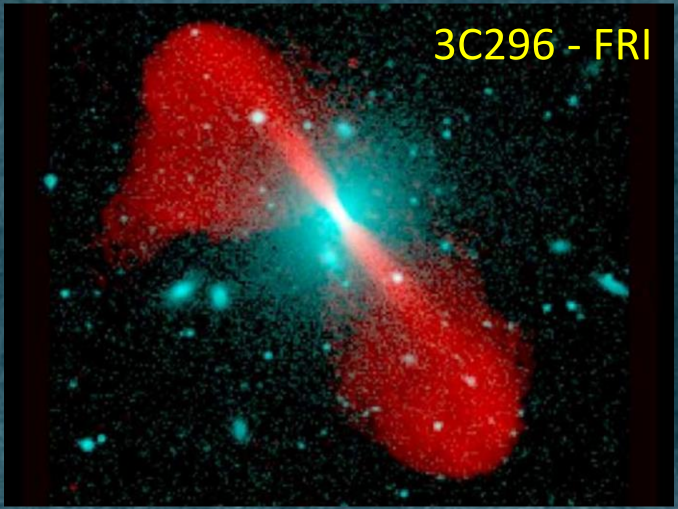


# Morphology: FRI / FRII

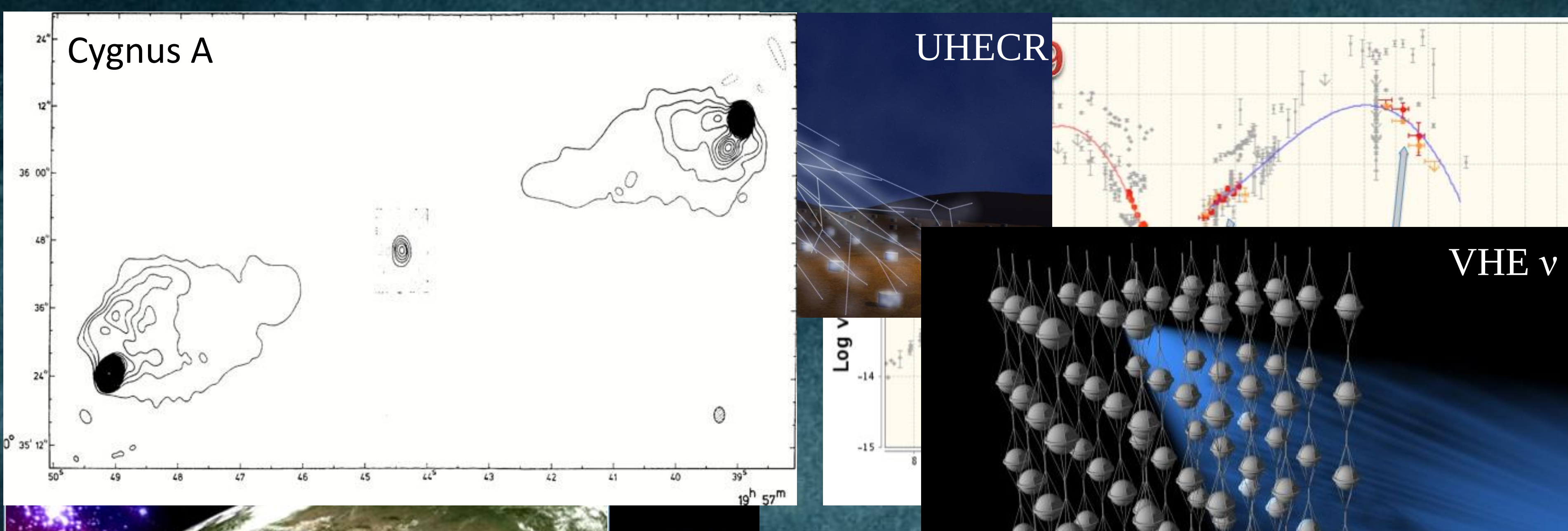
- The jets morphology is very rich.
- Some jets are stable over 100s – 1000s of kpc, and exhibit strong backflows - FRII
- Others break at 10s of kpc away from the galaxy, and blow large cocoons around them – FRI.
- What sets them apart is unclear.



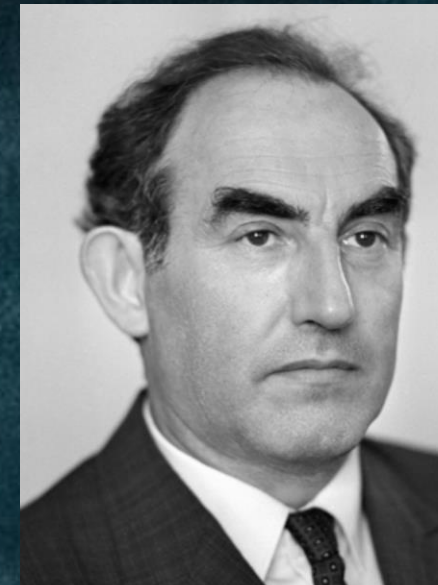
# Spectral range

- Historically detected in radio (“radio galaxies”)
- Radiate over entire spectrum.
- Powerful sources of VHE (>100 GeV) photons, possibly also UHECR and high energy neutrinos.

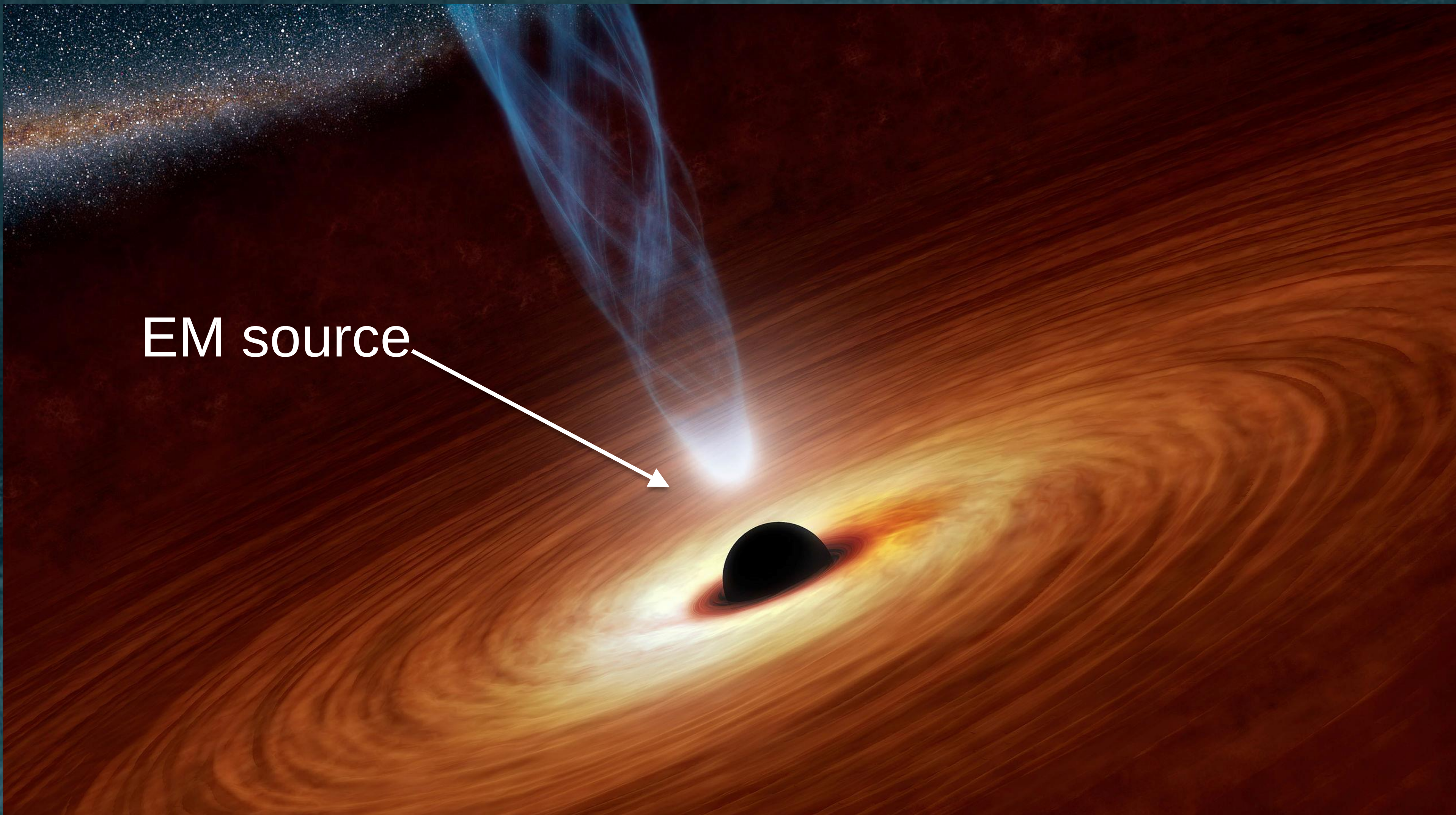


# Vitaly L. Ginzburg

- 1951: Developed the theory of synchrotron radiation to explain non-thermal radio emission.
- The discovery of radio galaxies (late 50's) made them natural candidates together with Sne (Ginzburg & Syrovatsky 61).
- 1964-1966 Ginzburg & Ozeroni: compression of magnetized gas clouds amplifies the magnetic field and could power quasars and AGNs.
- First to suggest that radio jets are powered electromagnetically.



# Powering PFD jets

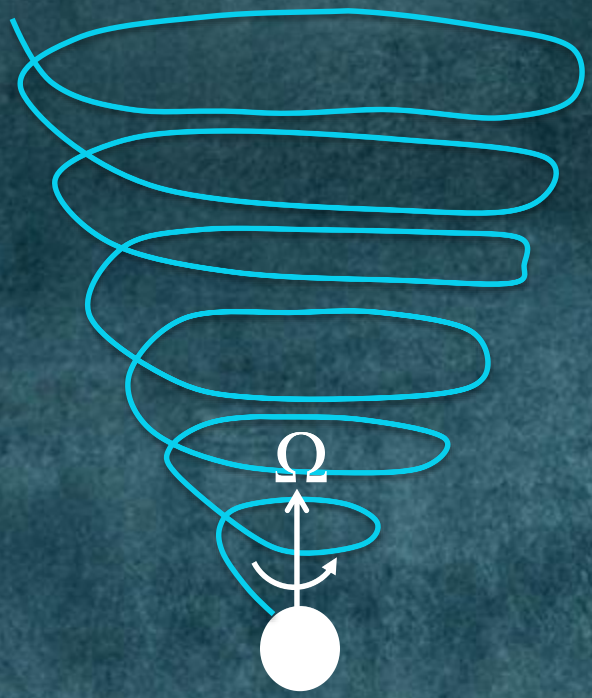


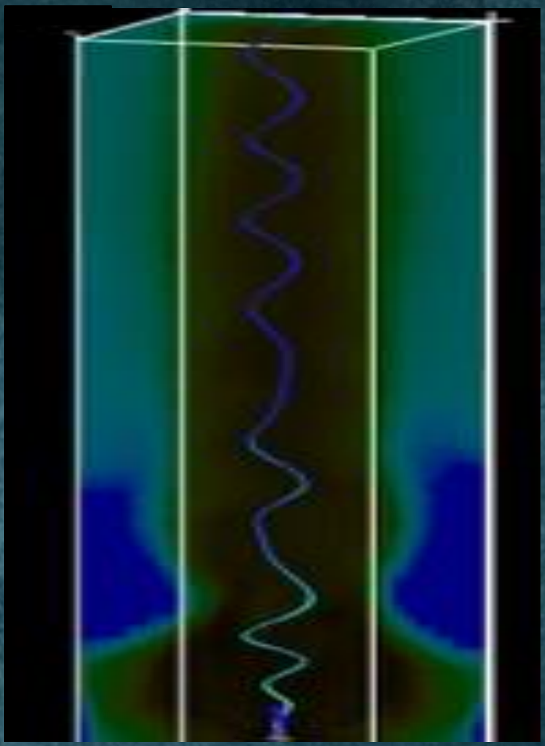
# Powering PFD jets

Poloidal field line connected to a central object

Rotation of the central object winds the field line

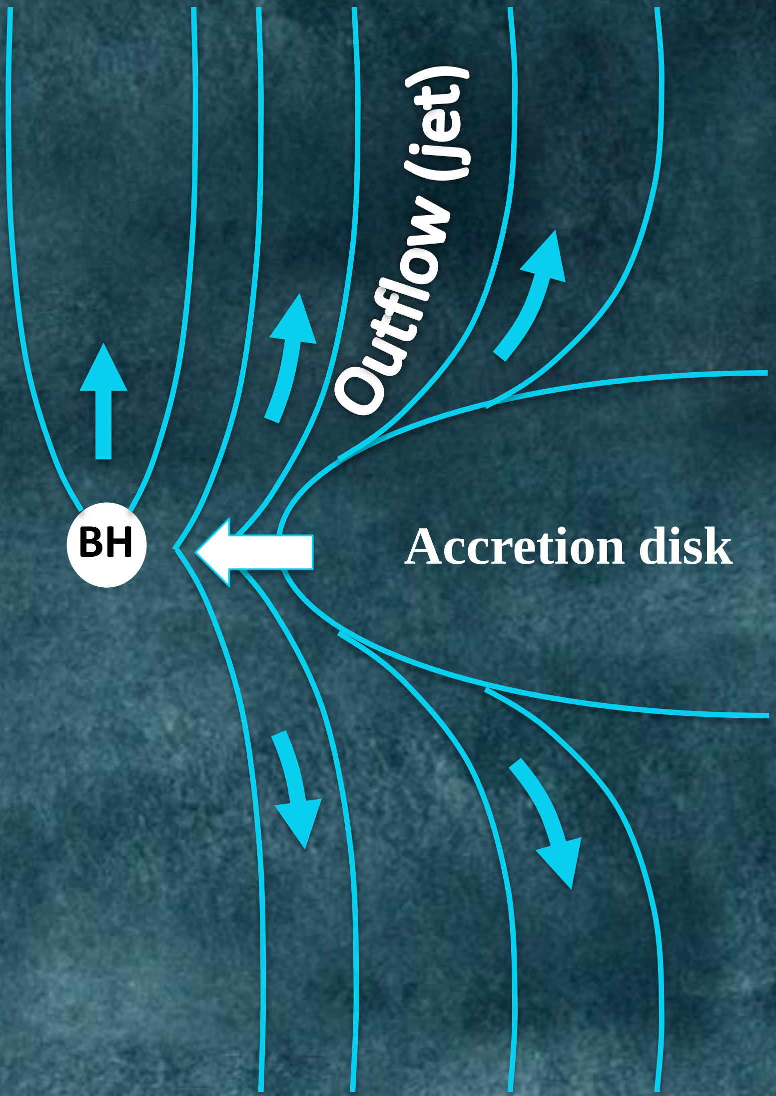
The winding propagates upward carrying Poynting flux

# Powering PFD jets

- Two candidates
  - Accretion disk (Blandford 76;Lovelace 76)
  - BH (Blandford & Znajek 77)
- In the BH scenario magnetic field is supplied by the disk.
- Power is regulated by the accretion rate, (e.g. MAD Tchekhovskoy et. al. 2011).



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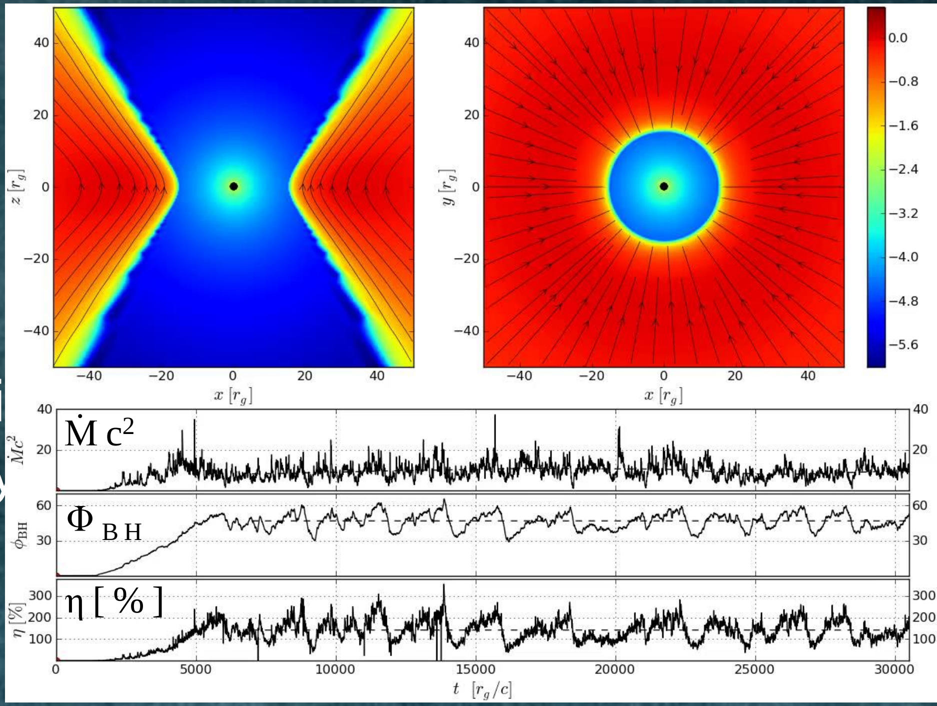


Movie by A. Tchekhovskoy, 2011

# Powering PFD jets

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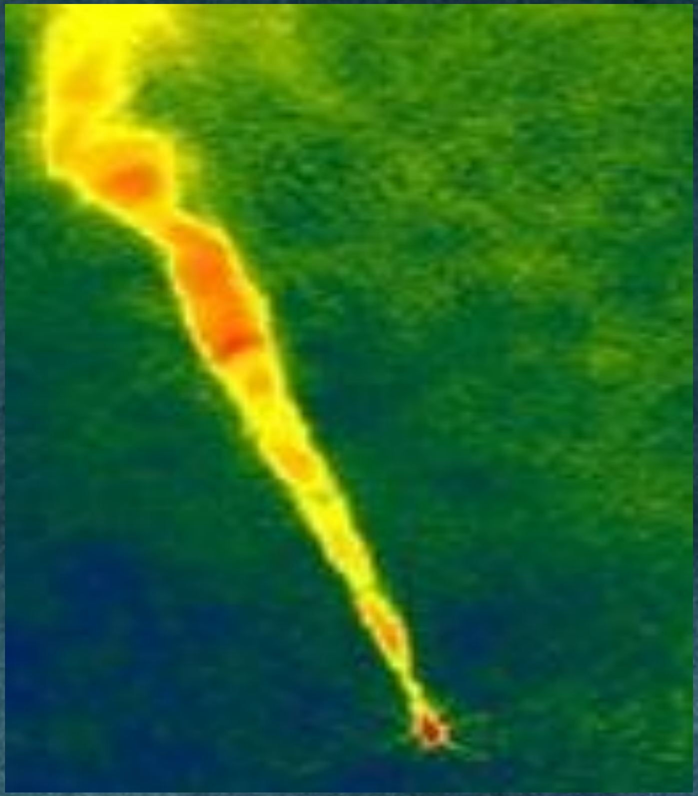
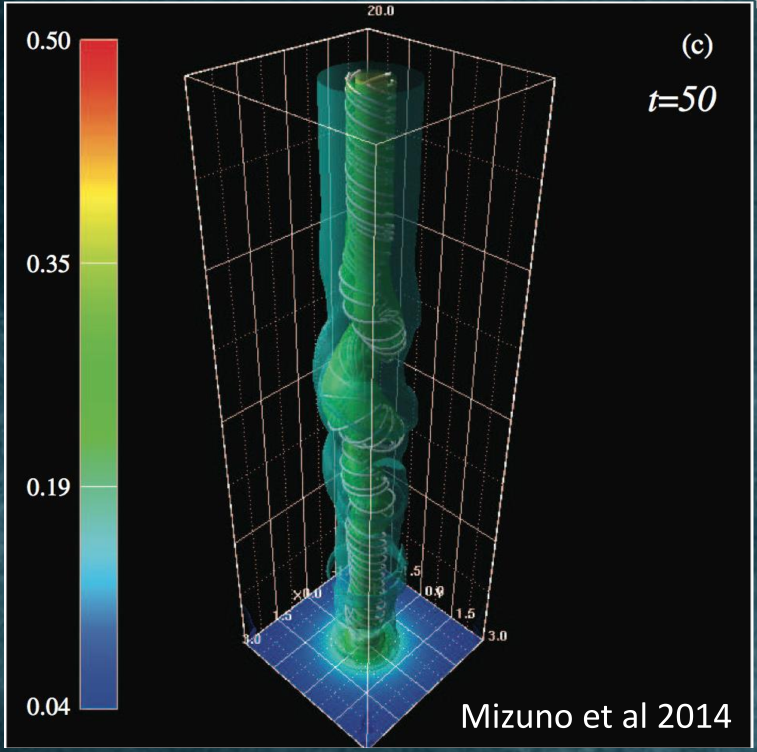
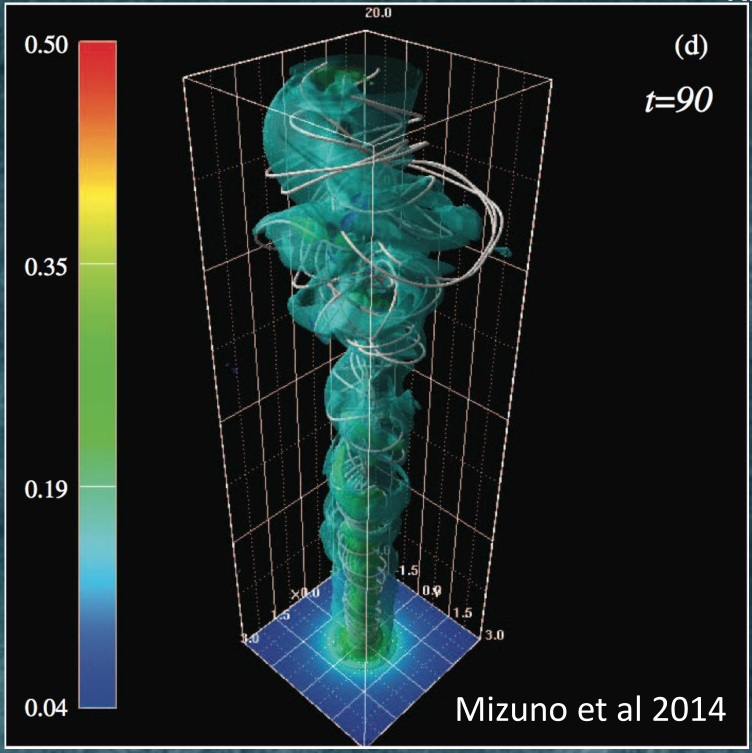
- Power is regulated by the accretion rate, (e.g. MAD Tchekhovskoy et. al. 2011).
- Gives a “clean” EM outflow.
- Need to transform the EM energy into particle motions and radiation.
- The σ problem (e.g. Eichler 93; Begelman & Li 94; Tomimatsu 94; Beskin+ 98; Bogovalov 98; Chiueh+ 98; Bogovalov & Tsinganos 99; Komissarov + 07,09; Lubarsky 09; etc..)



# Magnetic fields are unstable

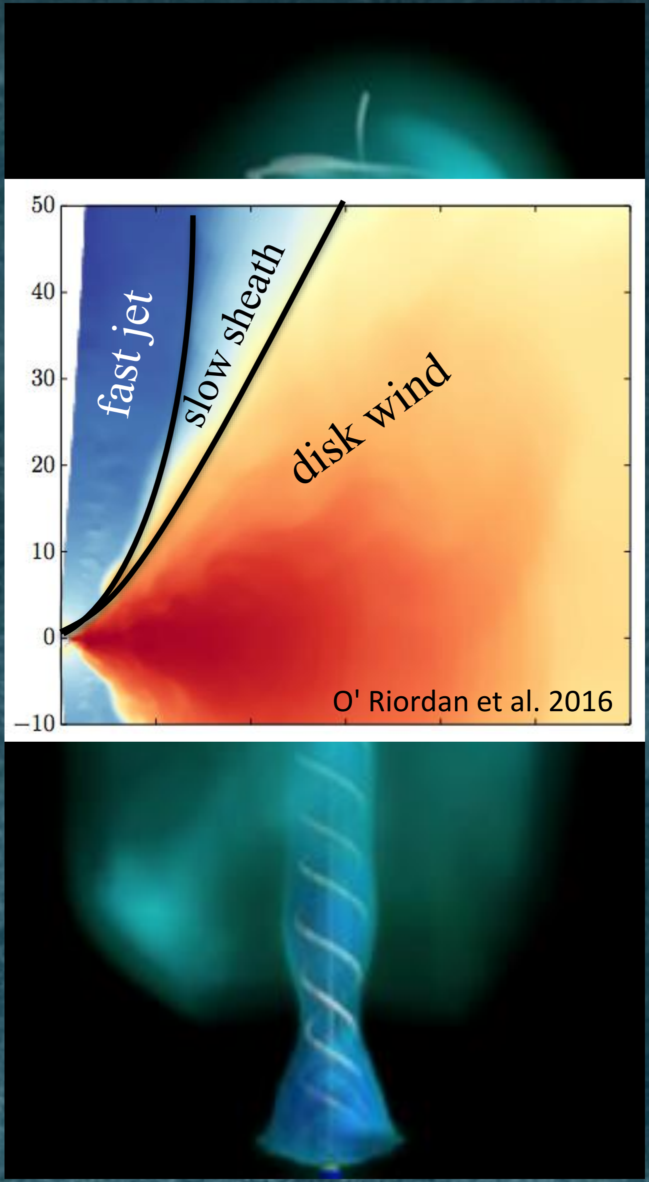
- Toroidal field is unstable to kink modes, and dissipates.
- Basic time unit for kink evolution: $t_{kink} \approx \gamma \frac{2\pi R_j}{v_a} \frac{B'_p}{B'_\Phi}$ 00)
- Typical growth time: 10 circuiting times.
- Narrow jets dominated by $B_\varphi$ become kink unstable in $10t_{kink}$



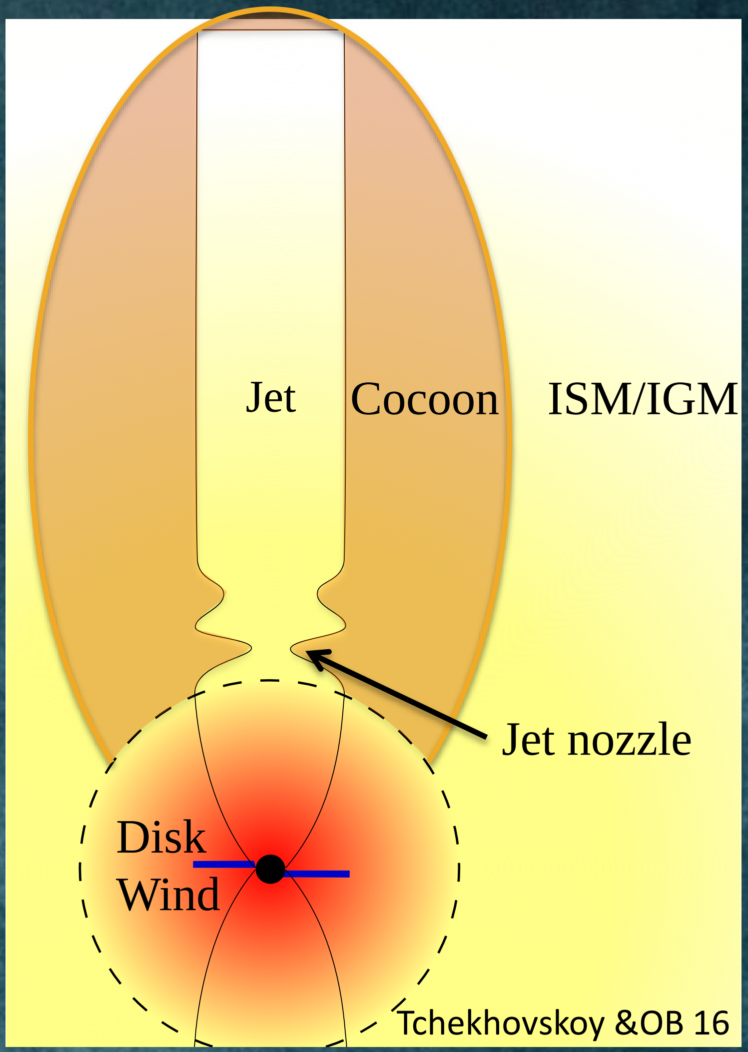
# How do jets become so narrow?

- Relativistic jets need a medium to collimate.
- disk wind:
  - conic or parabolic jets.
  - fast ($\gamma\beta > 1$) stable jets
  - not clear if can give rise to strong dissipation.
- stationary medium:
  - propagation produces a cocoon around the jet
  - uniform pressure, cylindrical jet
  - can get kink unstable

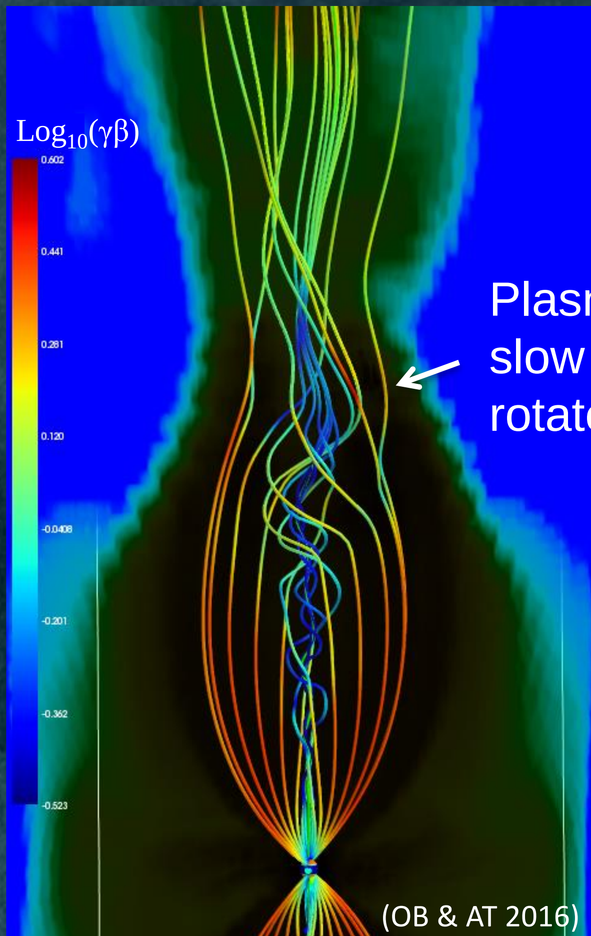


# AGN jet interaction with a medium

- Medium structure is a combination of wind and stationary medium.
- The transition is accompanied by a shift in the jet geometry.
- Field lines become influenced by hoop stressed.
- leads to the formation of a nozzle above the transition region (Lyubarsky 09, komissarov + 15).

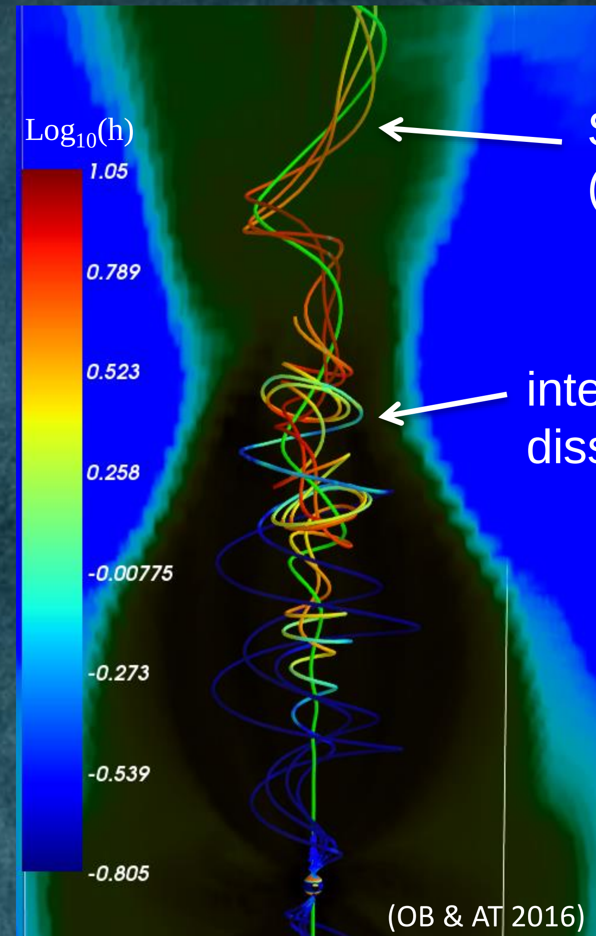


# Energy dissipation at the nozzle




Plasma slow down, rotate

Velocity lines




Smaller twist ($B_\varphi \approx B_p$)

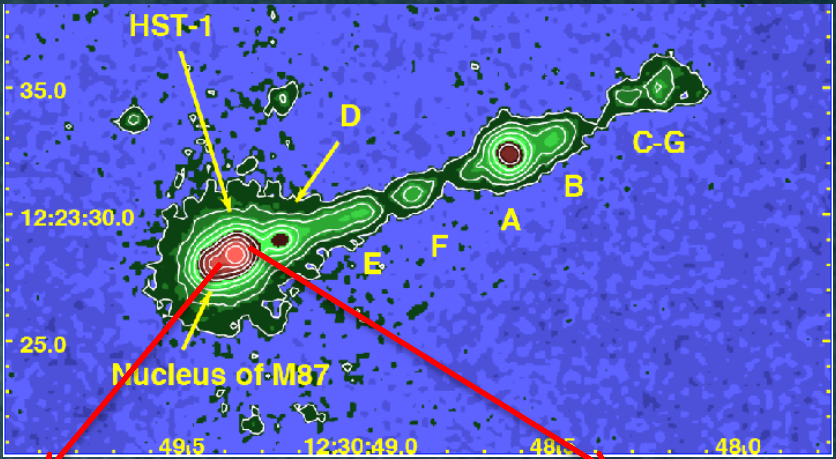
internal kink dissipation

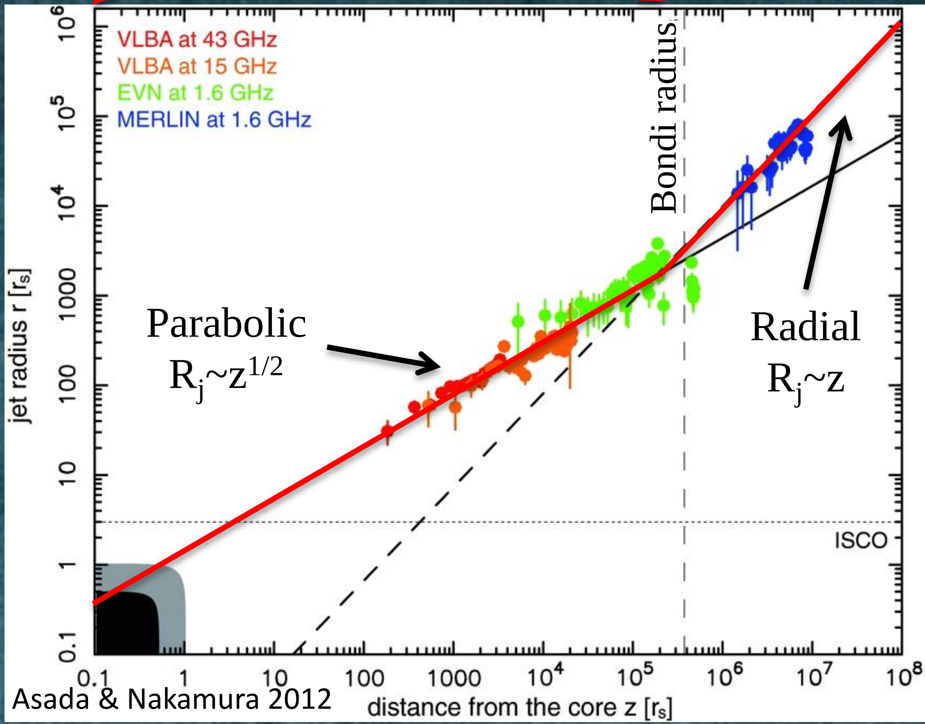
B field lines

Collimation → internal kink → reconnection → emission

# Collimation nozzles as radio knots

- HST-1 knot in M-87
  - Luminous knot: radio - X ray
  - Massive energy dissipation.
  - change in jet geometry.
  - Transition from a wind to a stationary medium ?



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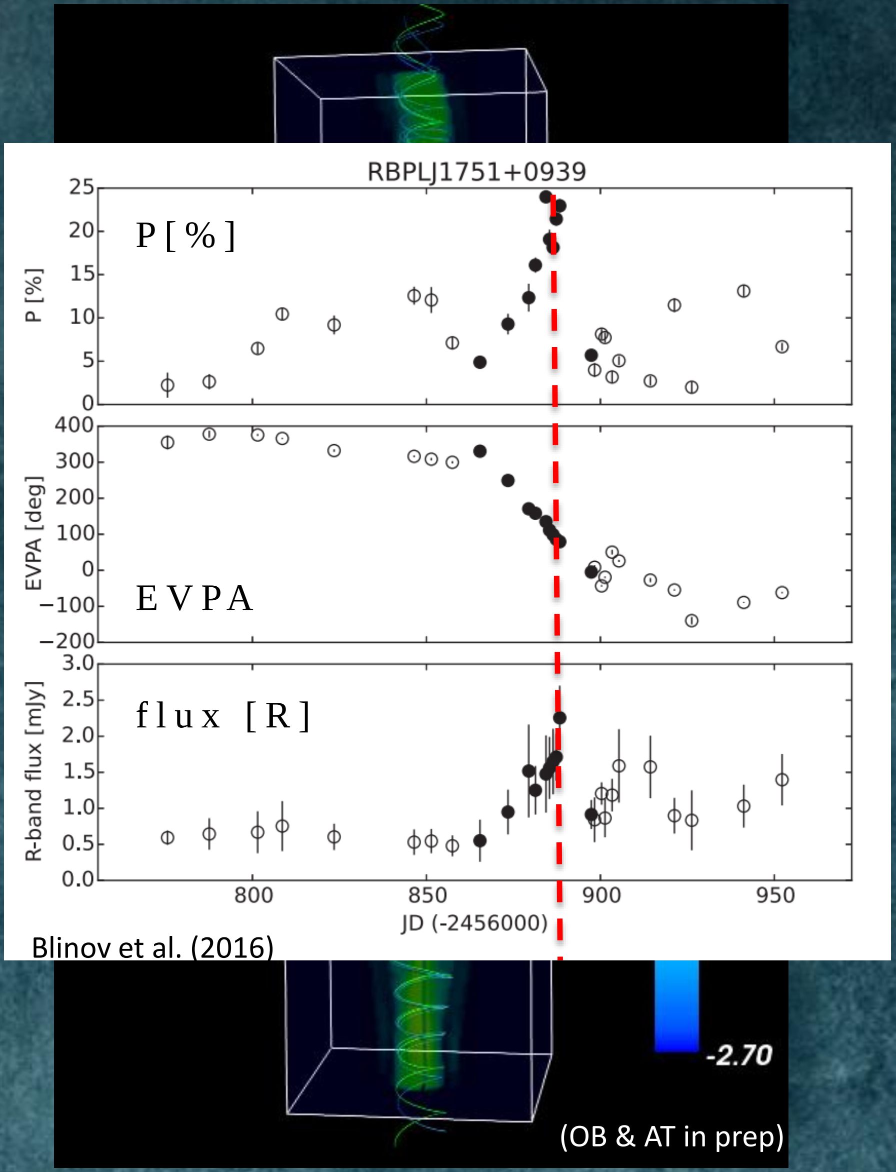
- HST-1 knot in M-87
  - Luminous knot: radio - X ray
  - Massive energy dissipation.
  - change in jet geometry.
  - Transition from a wind to a stationary medium ?
- Rotating flares in Blazars
  - Polarization peak coincides with maximal luminosity.
  - Polarization vector rotates
  - halfway rotation at middle of flare.
  - A passage of a plasma blob through the nozzle ?

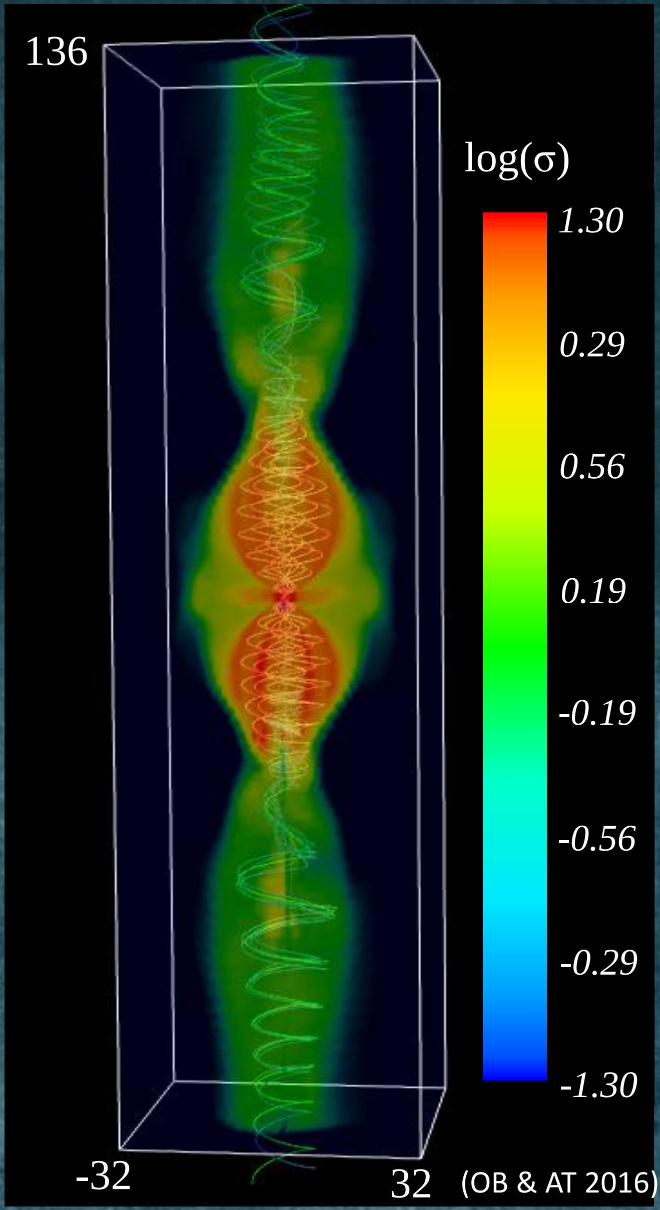


Blinov et al. (2016)

(OB & AT in prep)

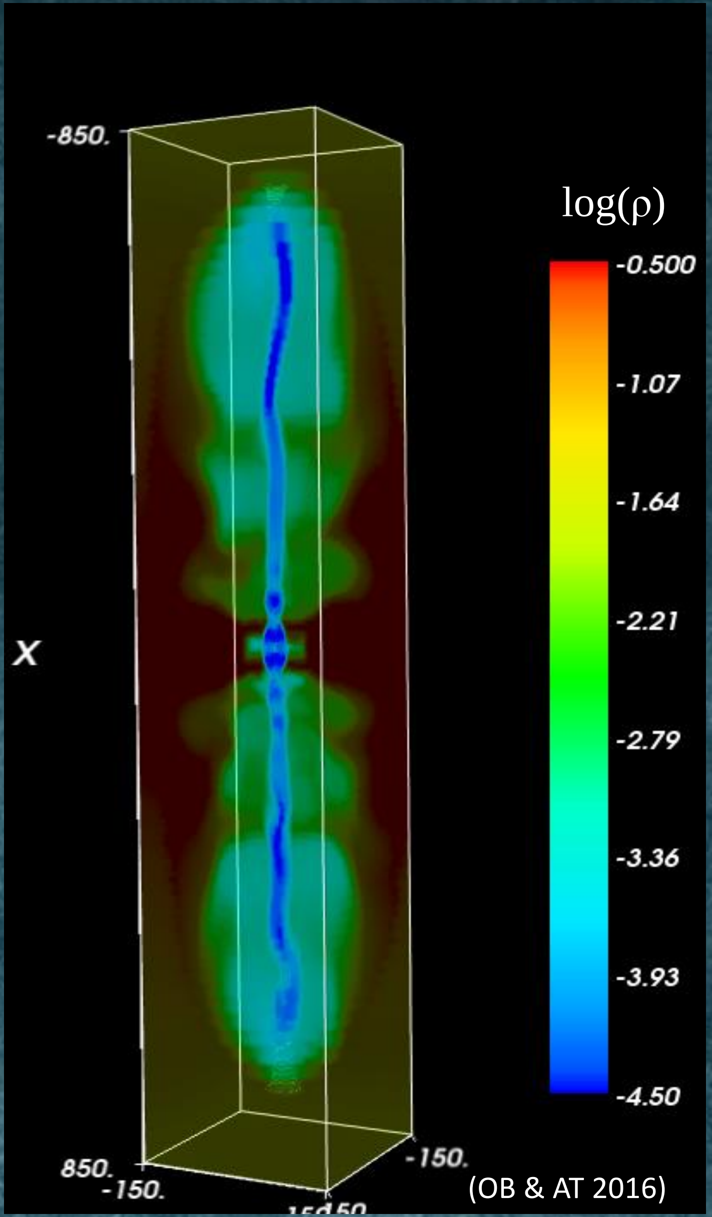
# Jet propagation above the nozzle

- Magnetic dissipation: $P_{th}$ ↑, $B_{\Phi}$ ↓
- Relaxes when: $E_B \approx E_{th}$.
- A "hydrodynamic jet with a tweak":



# Jet propagation above the nozzle

- Magnetic dissipation: $P_{th}$ ↑, $B_{\Phi}$ ↓
- Relaxes when: $E_B \approx E_{th}$.
- A "hydrodynamic jet with a tweak":
- Global kink modes can perturb the jet body.
- Larger effective cross section: jet slows down.

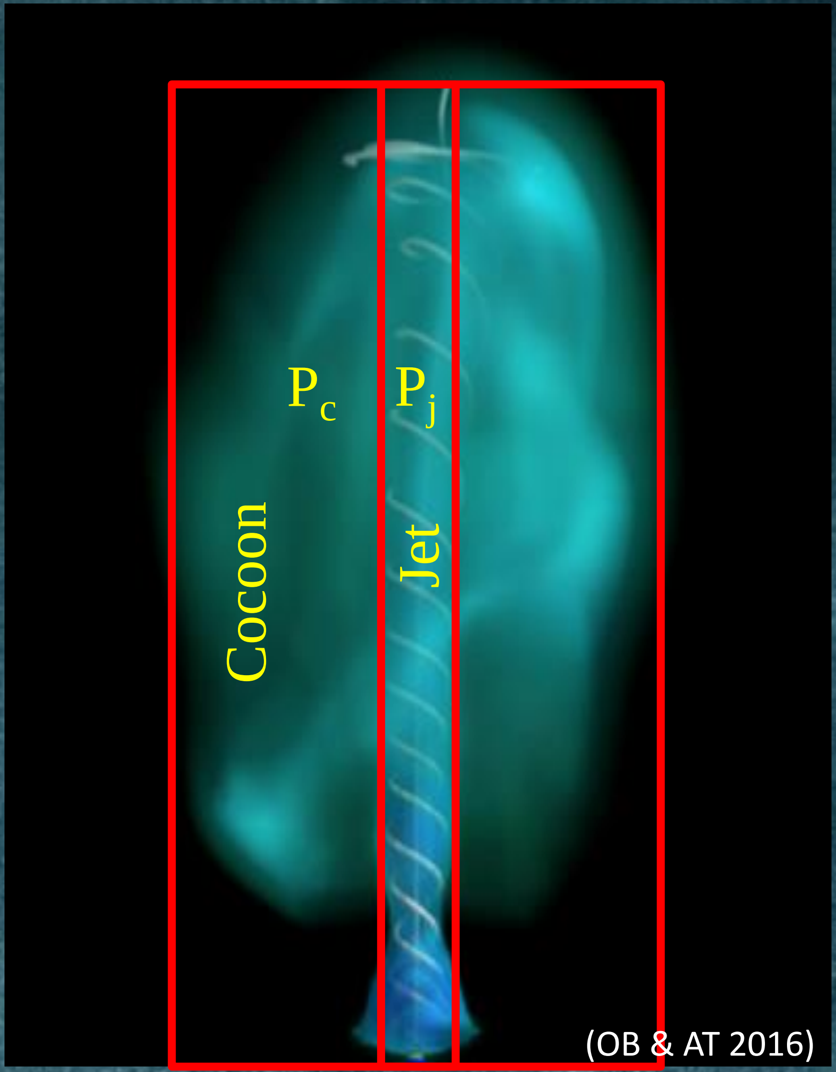


# Analytic scheme for jet stability

- The jet and the cocoon are modeled as rectangles (O.B.+ 11).
- Pressure balance: $P_c = P_j$
- Equipartition: $P_B \approx P_{th}$ ; $B_p \approx B_\varphi$
- $t_{kink} \approx 10 \times (2\pi R_j/c) \times \gamma$
- $t \approx z/c$

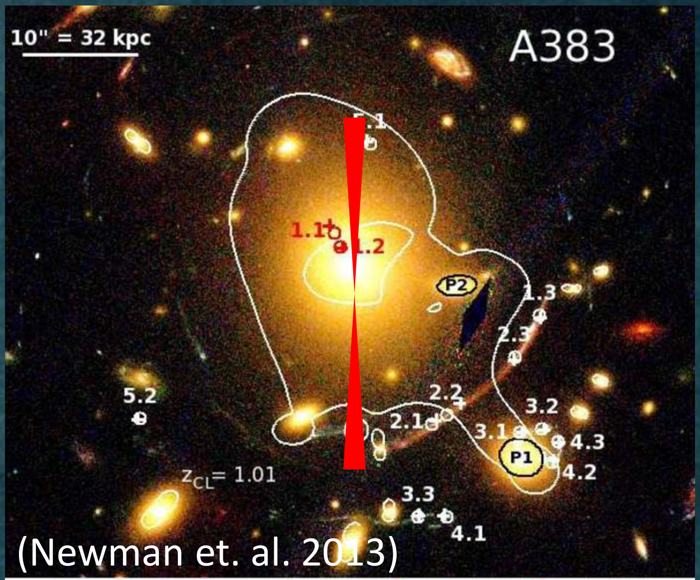
$$\Lambda = \frac{t_{kink}}{t_h} \approx 10\left(\frac{L_j}{\rho z_h^2 \gamma_j^2 c^3}\right)^{1/6} < 1$$

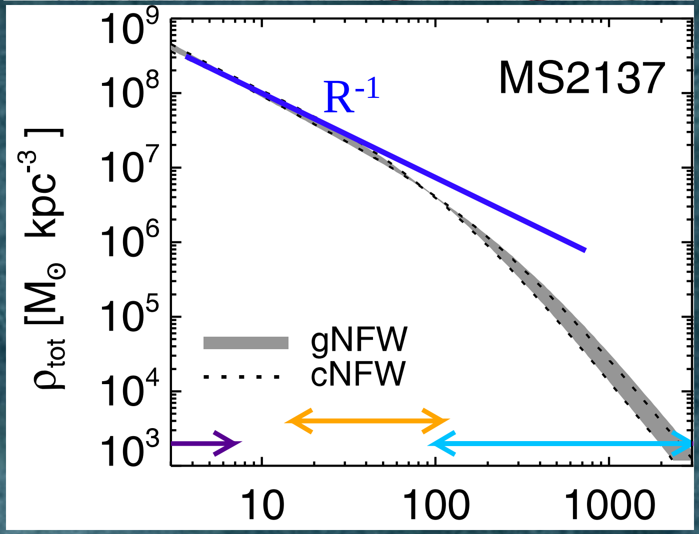
- In density profiles shallower than $z^{-2}$ the jet becomes less stable as it propagates.



# Medium density in galaxy hallows

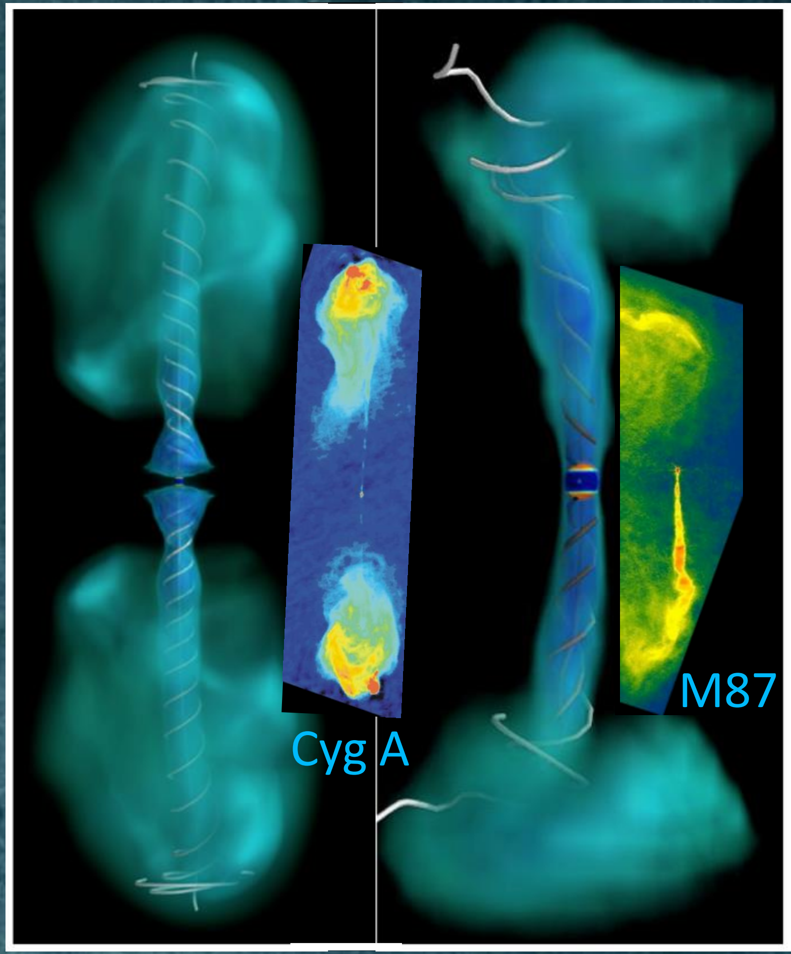
- Galaxy clusters have a shallow density profile at R<100 kpc, becomes steeper at larger radii.
- Jet decelerates & becomes less stable.
- A minimal luminosity for the jet to “break out”: $L_{min} \sim 4\times10^{45}$ erg/s (AT & OB 16)
- If $L < L_{min}$ the jet becomes unstable inside the core and can even stall.



# FRI/FRII dichotomy - indications of external kink

- More energy is dissipated along the jet’s body. The wobbling jet will appear wider and brighter.
- May explain the difference between FR-I and FR-II galaxies.



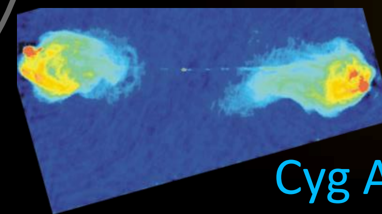

(AT & O.B. 2016)

Cyg A-like

$P_j=10^{46}$ erg $s^{-1}$

t =3 Myr

10 kpc



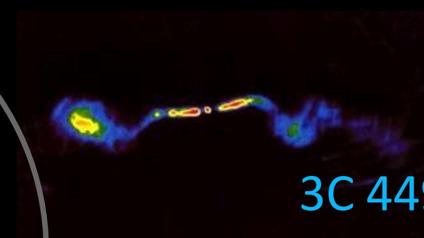
Cyg A

FRII

M87-like

$P_j=10^{44}$ erg $s^{-1}$

t =6 Myr



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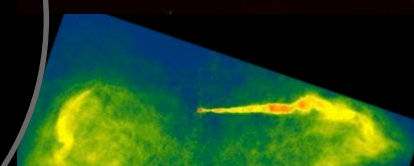


M87

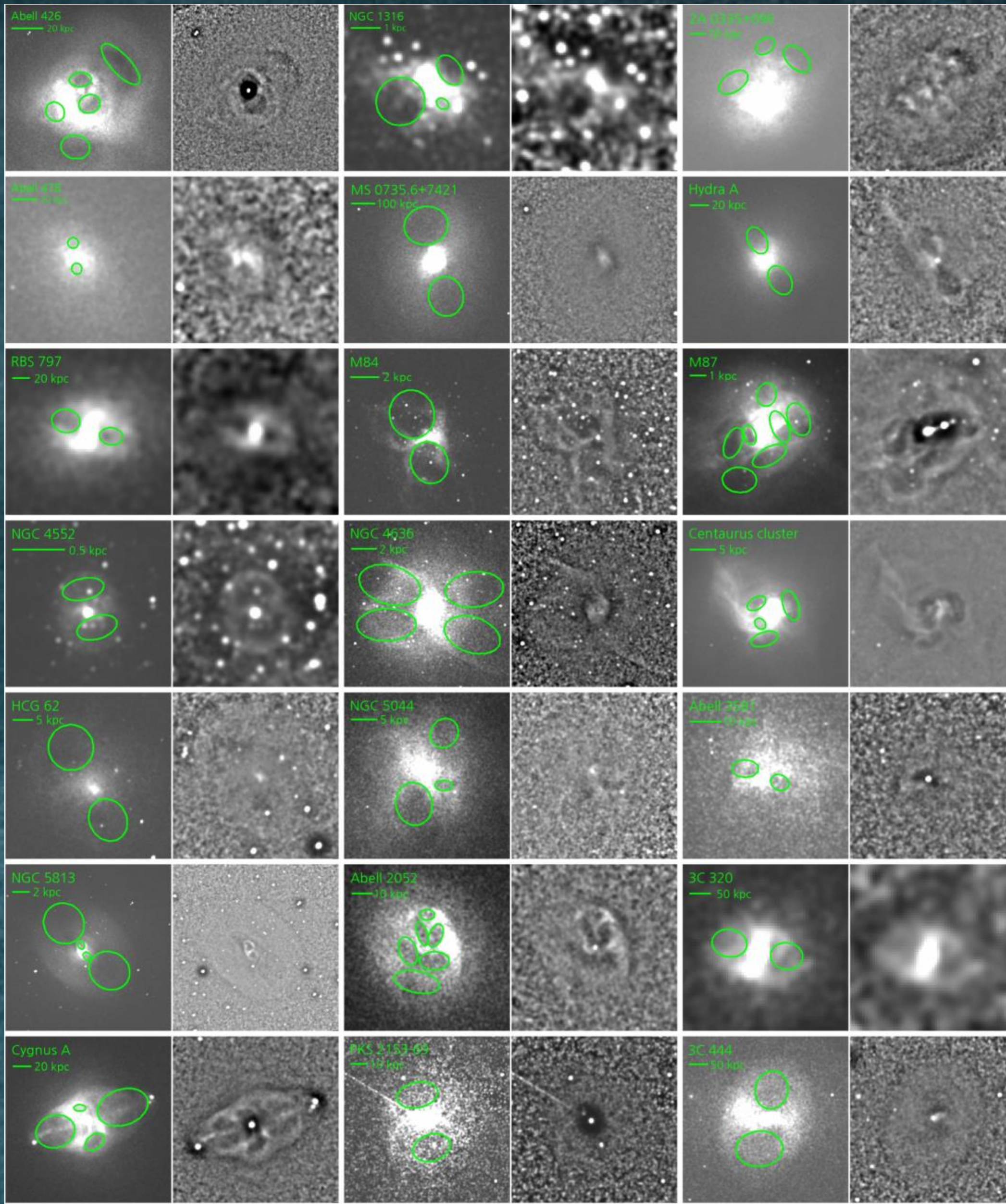
FRI

Tchekhovskoy & O.B. 2016

# X-ray cavities – relics of ancient jets

shin+ 2016

- Deep Chandra images show that many clusters and Elliptical galaxies have elongated cavities.
- X-ray dim, Radio bright.
- Hot, low density gas.
- Energies PV$\sim 10^{55}$ ergs in Eg, to $\sim 10^{61}$ erg in rich clusters – energy was injection by jets.
- Comparing the inferred jets power with medium density can indicate on minimal jet breakout power (FRI / FRII jets)
(OB, medezinski, Can in prep)



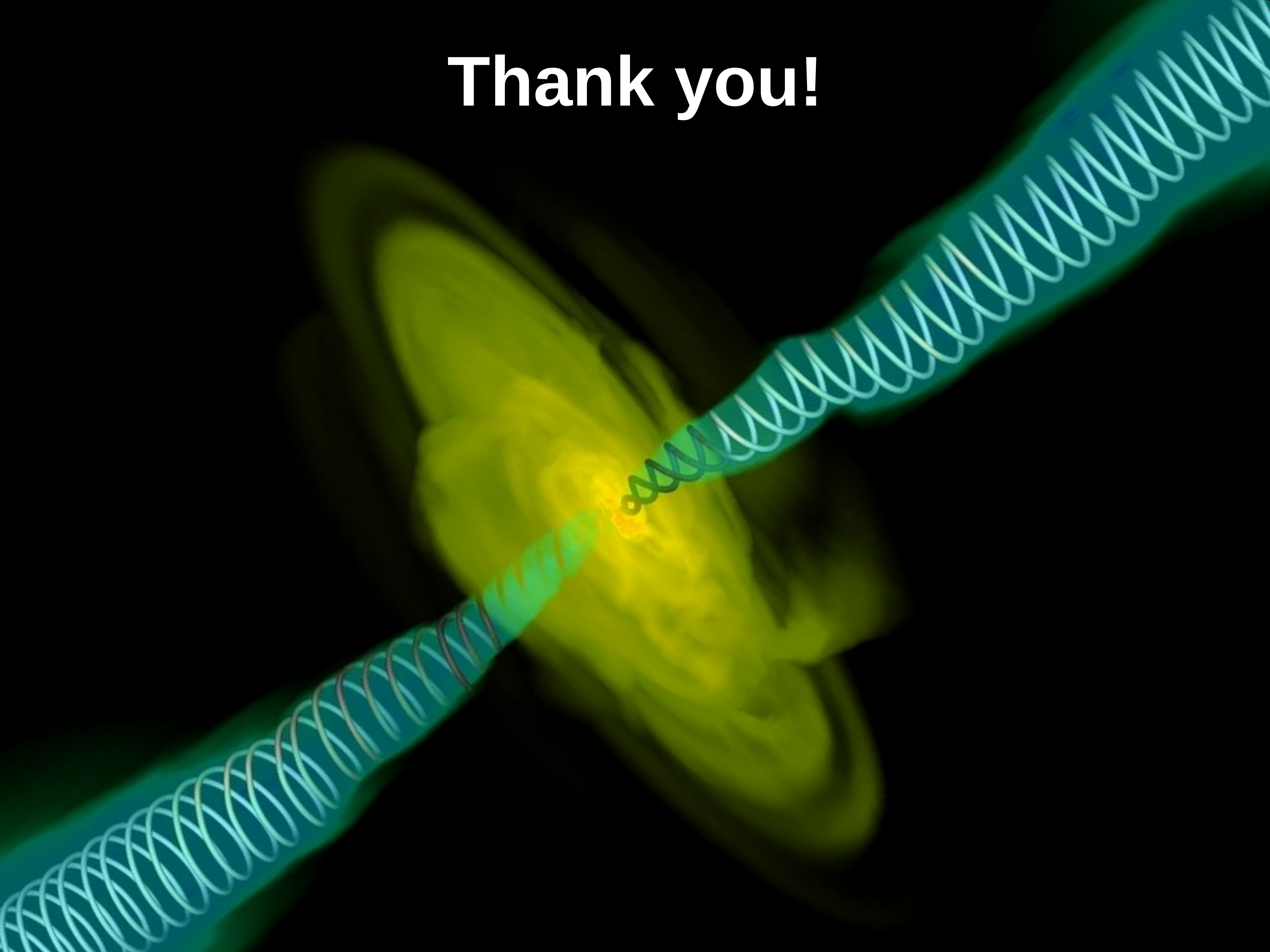
# Summary

- 3D kink instability may control many aspects in AGN jets.
- Internal kink mode:
  - Grows on short time scales.
  - Most effective in collimation nozzles.
  - Dissipates ½ of the jet magnetic energy (σ problem).
  - Massive HST-1 like knots, and some Blazar flares.
- External kink mode:
  - Grows on long time scales.
  - Wobbling motion of the jet body, may cause jet stalling
  - low-power jets more sensitive.
  - FRI/FRII dichotomy could be the result of this instability

# Next

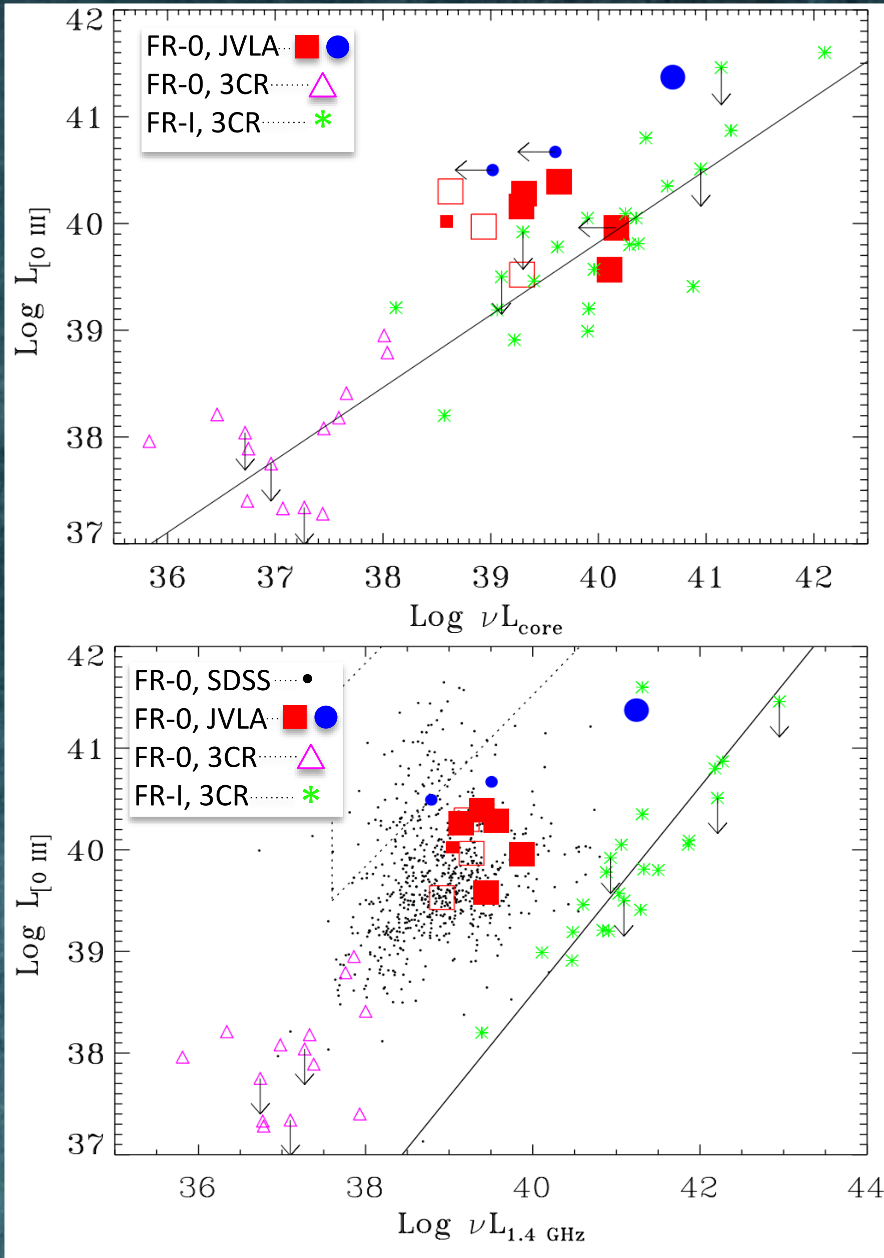
- A thorough investigation of jet collimation by a disk wind, and the effect of transition from a wind to a stationary medium.
- Producing emission and polarization maps from the passage of plasma blob through the nozzle.
- Studying the long time heating effect of the cocoon on the ISM and the IGM.
- Creation of hot cavities by intermittent jets.

# Thank you!



# FR-0 as low power extension of FR-I

- Half of all AGNs show core radio emission similar to FR-I with an extended part <100 times weaker (Baldi+ 16).
- Nature is unclear:
  - Young jets?
  - Unstable, “failed” jets?
- More compact source have higher HI column densities (Chandola + 11).
- Can be tested: obtaining core gas densities (absorption) + jet power (extended radio component) and applying stability model (OB & Horesh in prep).
- Results may show that jets are much more abundant in AGNs.



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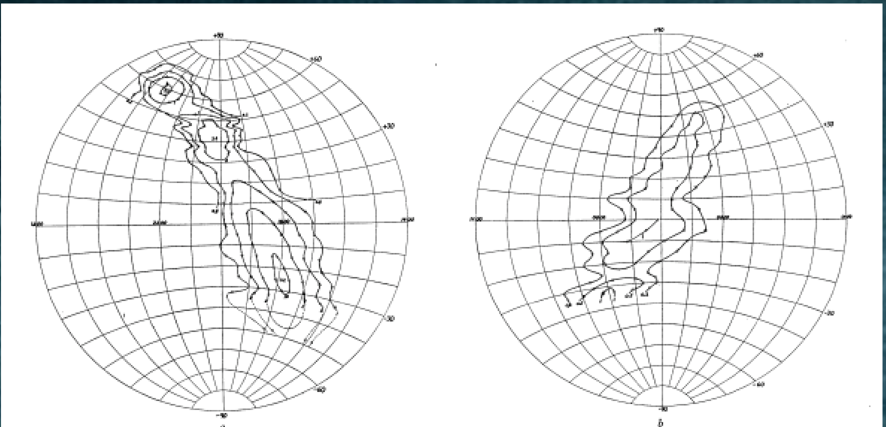

FIG. 4.—Constant intensity lines in terms of $10^{-22}$ watt/sq. cm./cir. deg./M.C. band