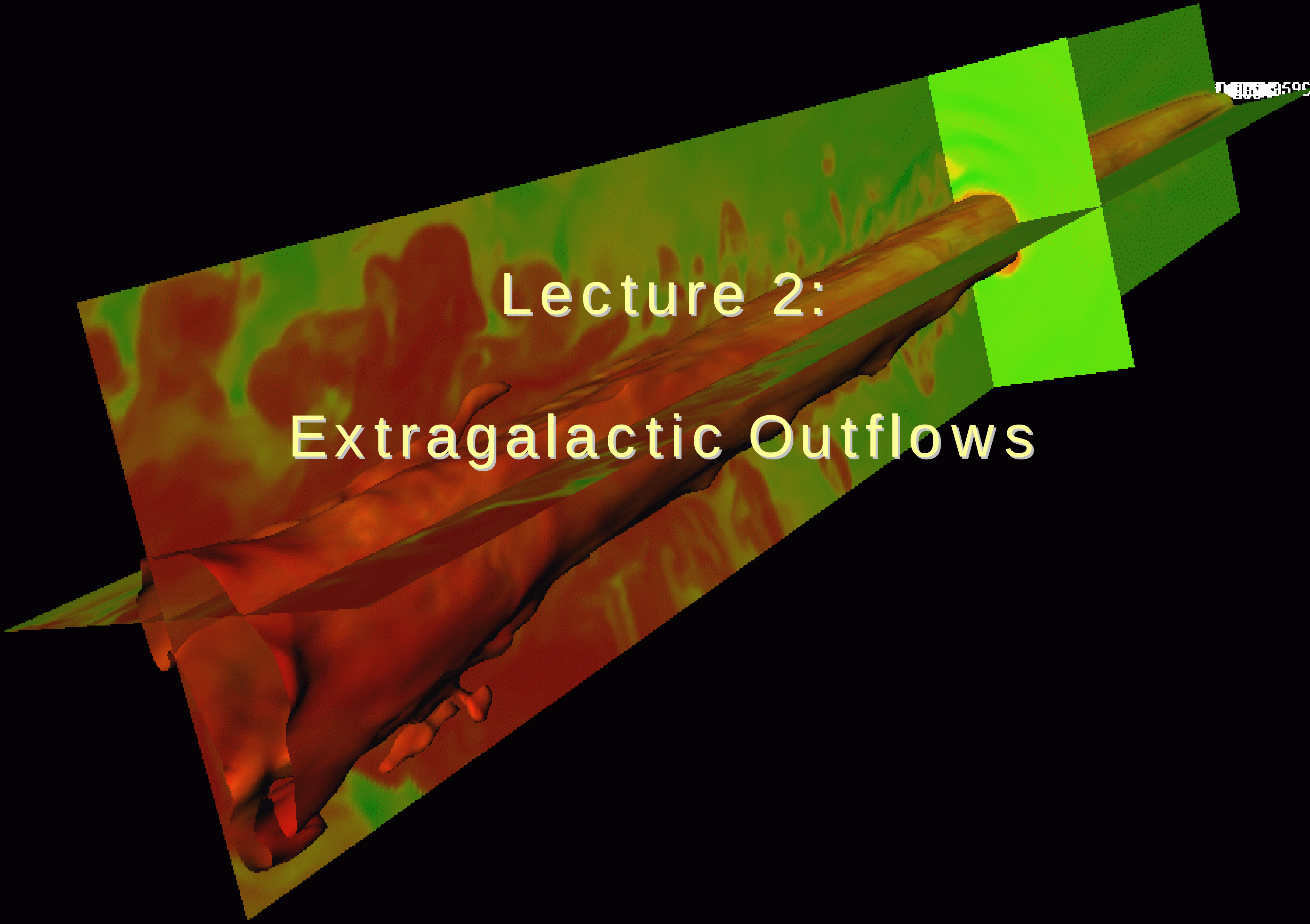
Lecture 2:

Extragalactic Outflows



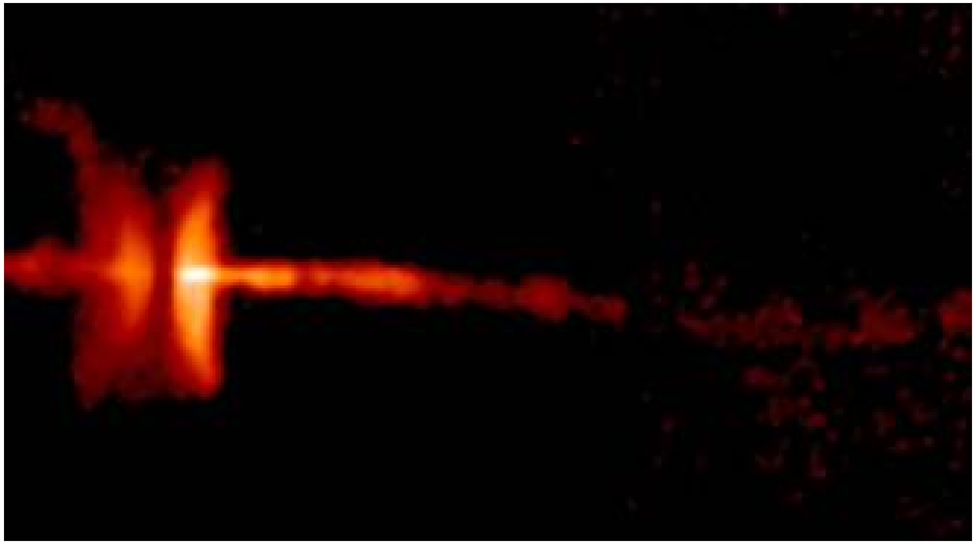
Outline

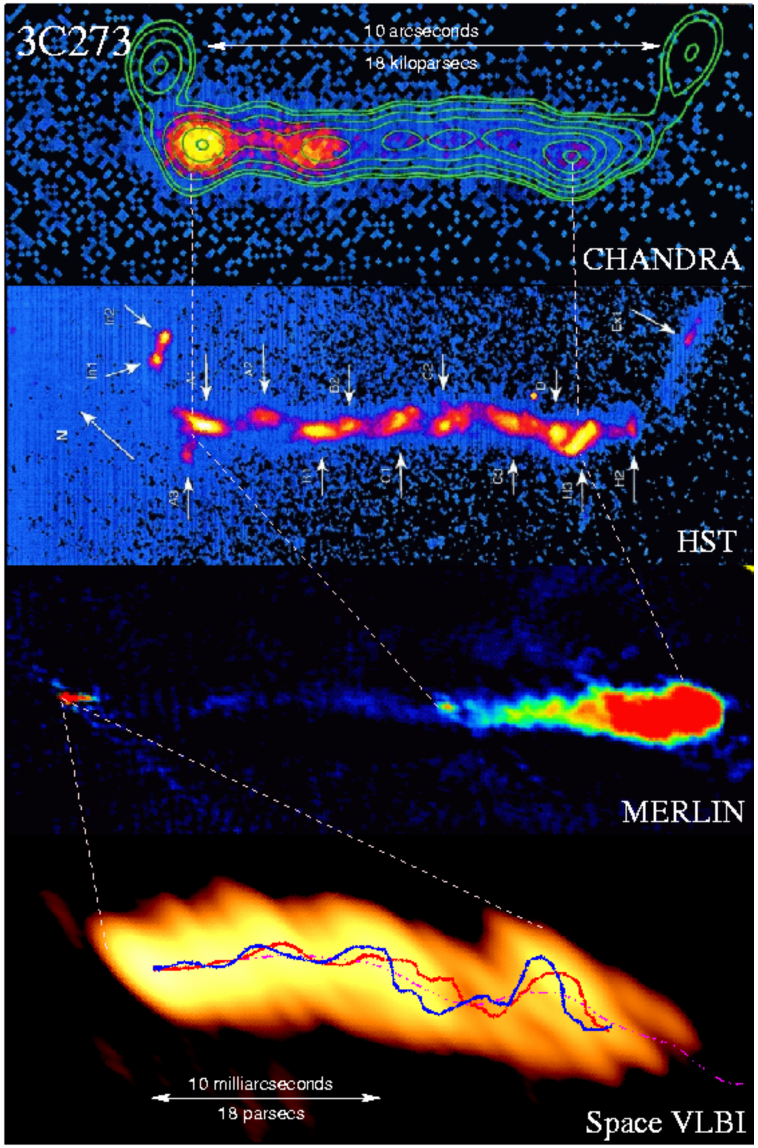
- General aspects of collimated outflows
- Thermal (sub-relativistic) and non-thermal (relativistic) flows
- Thermal outflows and their effect on AGN hosts and IGM
- Formation of relativistic jets, kinematics of compact jets
- Overview of the jet emission
- Jet models versus observables
- Relativistic shocks
- Plasma instabilities
- Nuclear opacity in jets

Collimated outflows

• Jets (bipolar outflows) are common. Range from YSO to QSO, found also in pulsars and even on the Sun.

• Generally: bipolar outflows solve the problem of transporting excess energy and angular momentum from compact, rotating, magnetized objects which accrete external matter

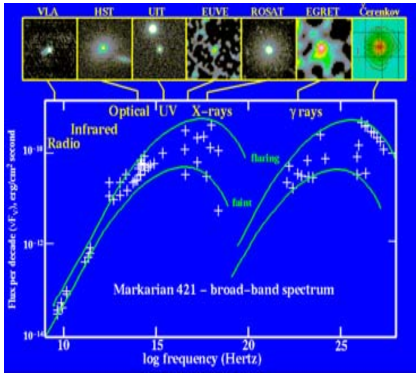




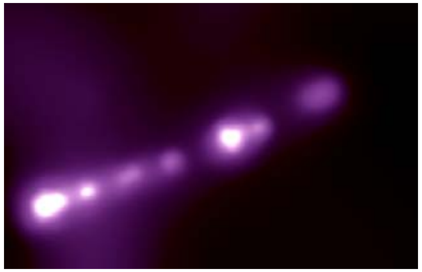
Fundamental jet questions

- Formation and collimation of relativistic jets.
- Matter content of the jets and outflows
- Stability and propagation on spatial dynamic scales of $>10^5$
- Relation to accretion disks and black holes
- Contribution from the jets and outflows to ISM and IGM

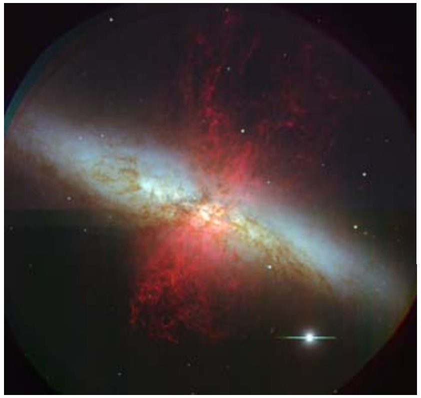
AGN Energy Balance



- ❑ Radiation:
  - – Quasar luminosity: 10^{44} — 10^{47} erg s^{-1}
  - – Luminosity integrated over lifetime: 10^{57}— 10^{62} erg



- ❑ Relativistic jets:
  - – Jet power: 10^{43} —10^{47} erg s^{-1}
  - – Jet power integrated over lifetime: 10^{57} — 10^{62} erg
- ❑ Sub-relativistic outflows (winds):
  - – Total wind power: 10^{43} — 10^{46} erg s^{-1}
  - – Wind power integrated over lifetime: 10^{56} — 10^{61} erg

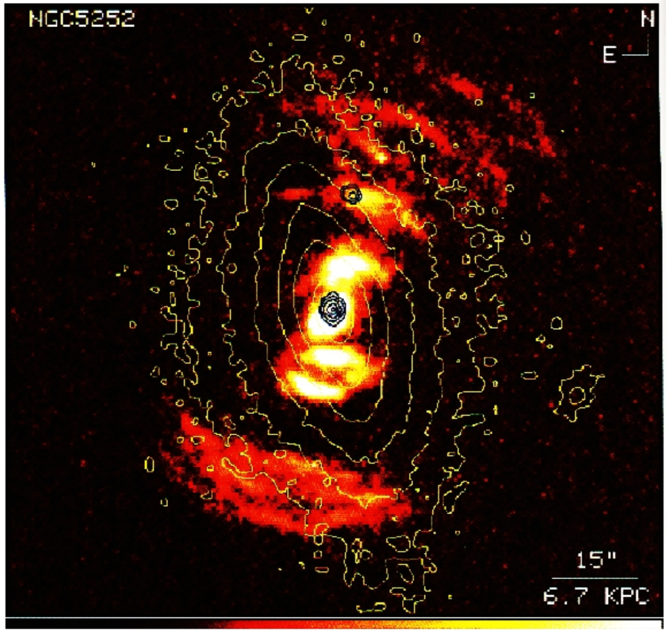


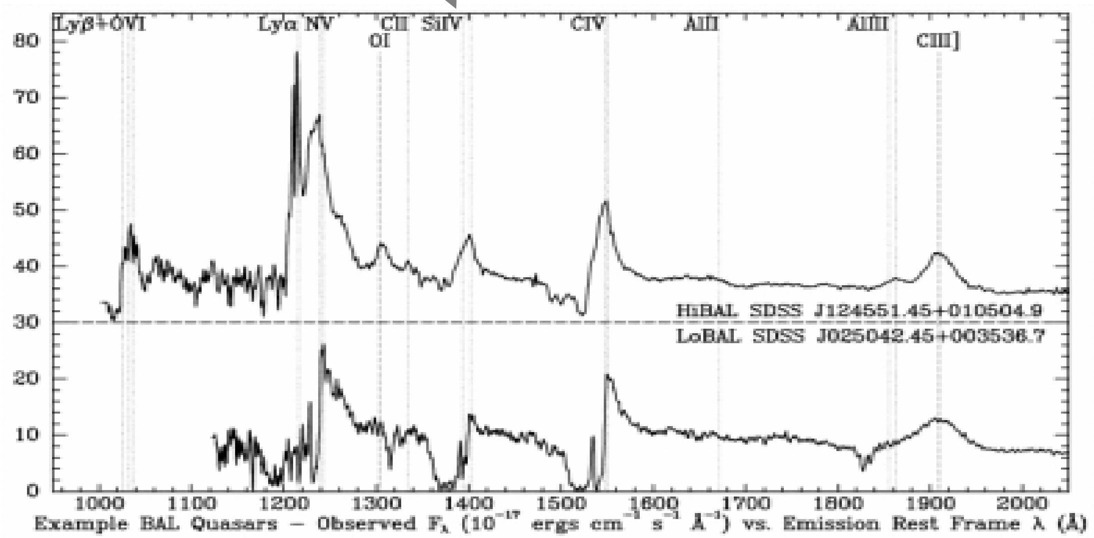
- ❑ Starburst-induced superwinds
  - – Reliable quantitative assessment is difficult

Sub-relativistic Outflows

Outflows

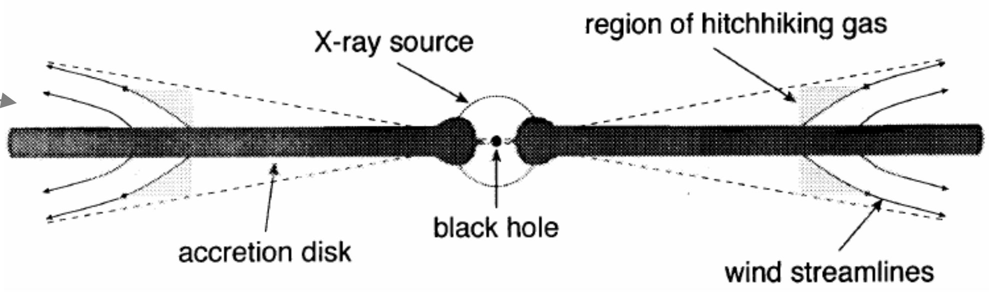
- Jets: non-thermal, relativistic flows: *v* $\lesssim$ *c*, present in ~10% of AGN
- Broad-absorption-line (BAL) outflows: v $\lesssim$ *50000 km/s,* present in ~50% of low-L AGN and ~20% of high-L AGN.
- Wide-angle winds in Seyfert galaxies (OIII cones): ~20-40% of Sy galaxies

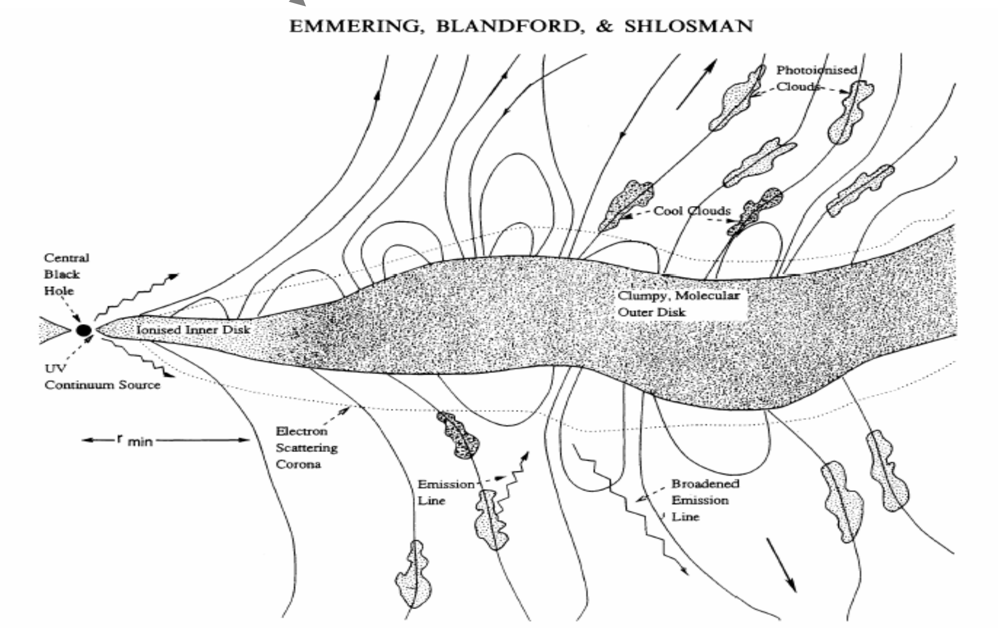


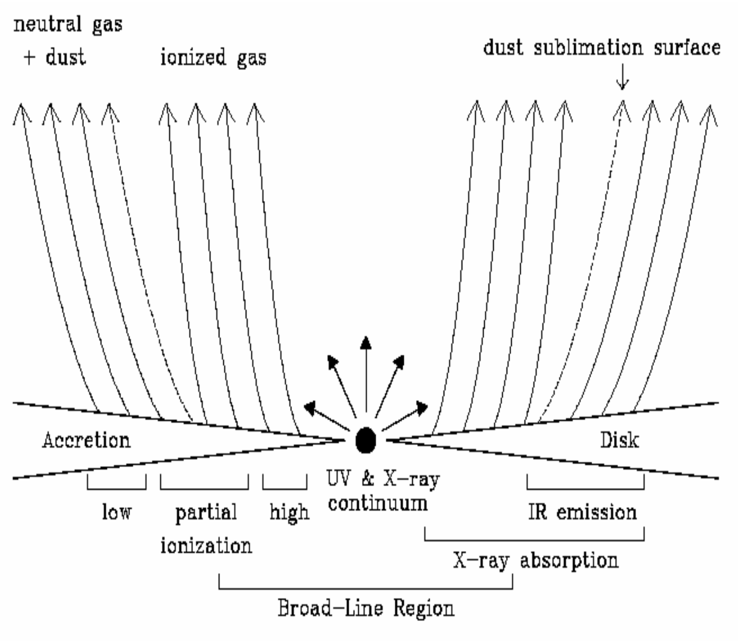


Outflows: Interpretations

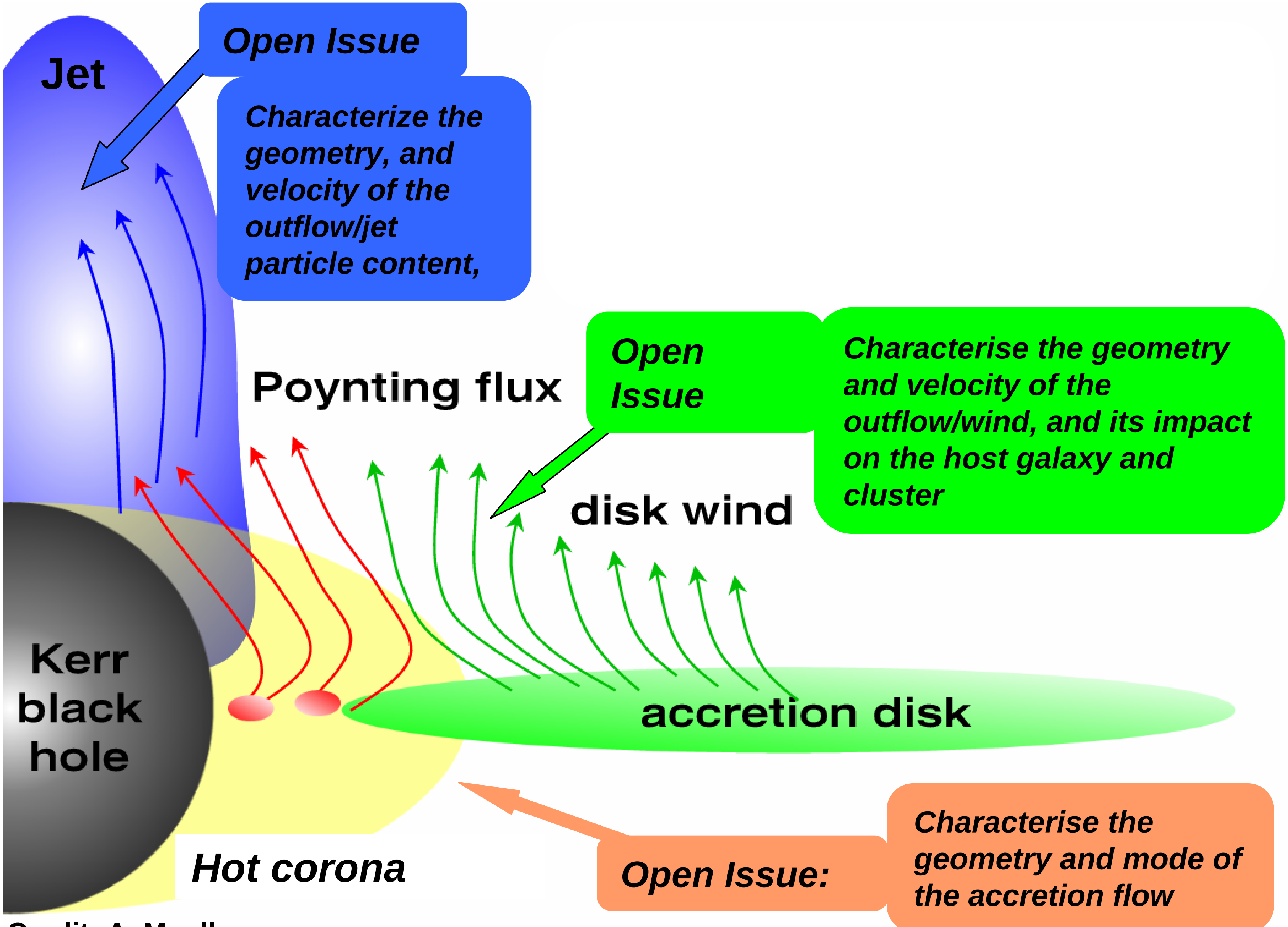
- Radiation-driven winds from accretion disk
- Thermally-driven winds from BLR or torus
- Magnetically-driven winds from accretion disk







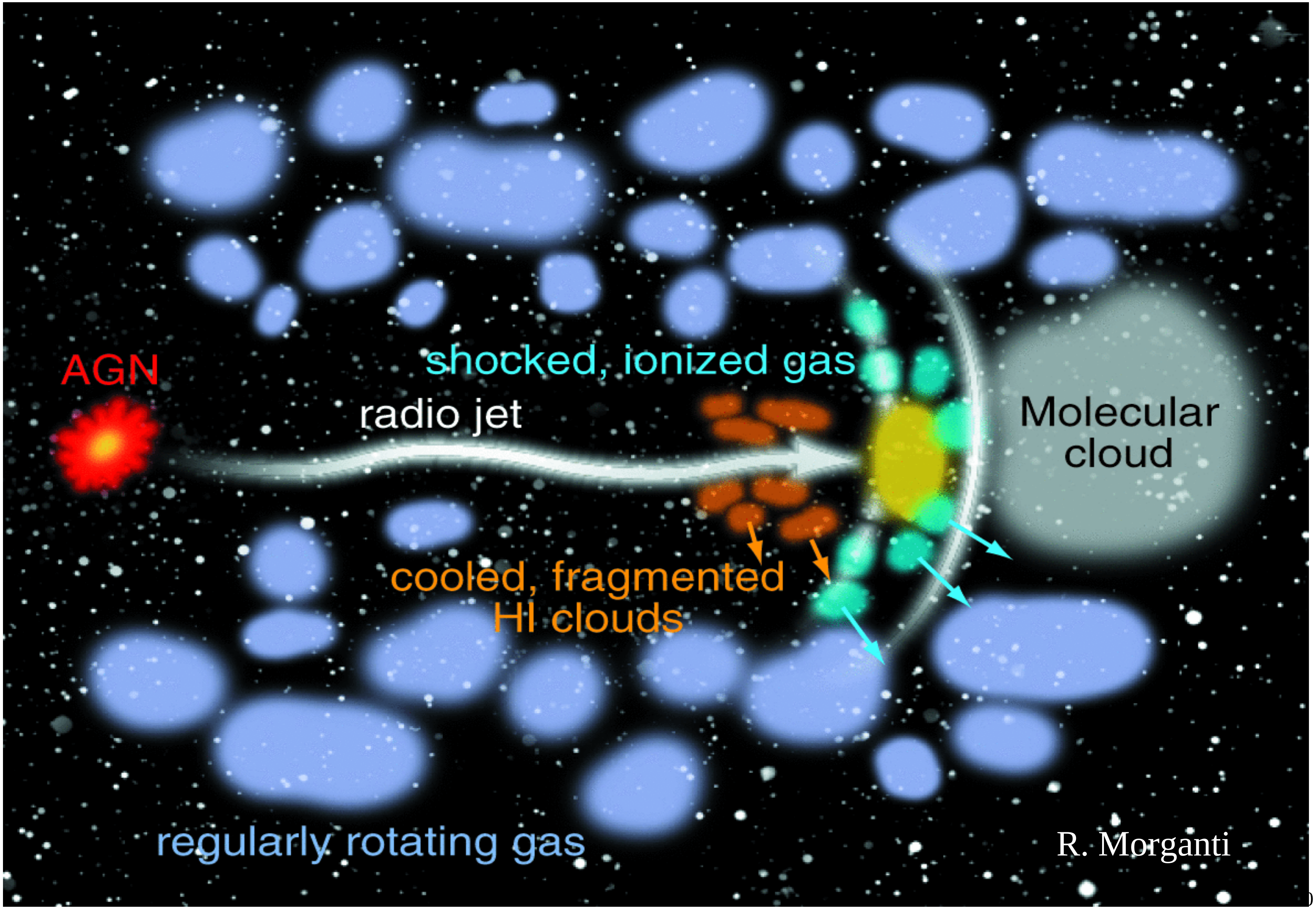
Outflows: Where it all begins



Credit: A. Mueller

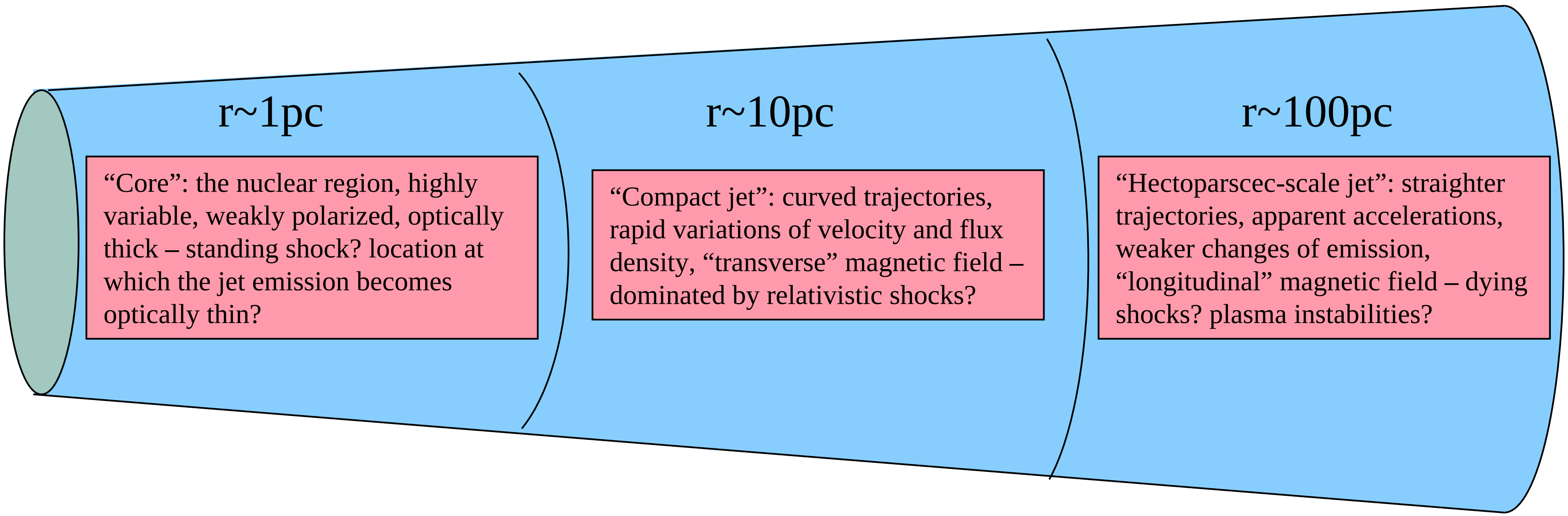
Outflows: How it all ends

A. Lobanov



Relativistic Outflows

Jets: Current paradigm



A. Lobanov

Jet formation

Formation

1. Lorentz factors:

$\gamma_j \sim 10^3 - 10^4, \quad \Gamma_j \le 15$

2. thin/thick accretion disks:

$\dot{M} \le 0.5\dot{M}_E \quad \text{or} \quad \ge \dot{M}_E$

3. MHD and magnetized disks:

$B_G \sim 10^2 - 10^4\ \text{G}$

Collimation and Acceleration

pressure/density/B-field gradients

$z_{col} = \alpha_c R_G, \ R_G = 2GM_{BH}/c^2,$

$\alpha = 10^2 - 10^3$

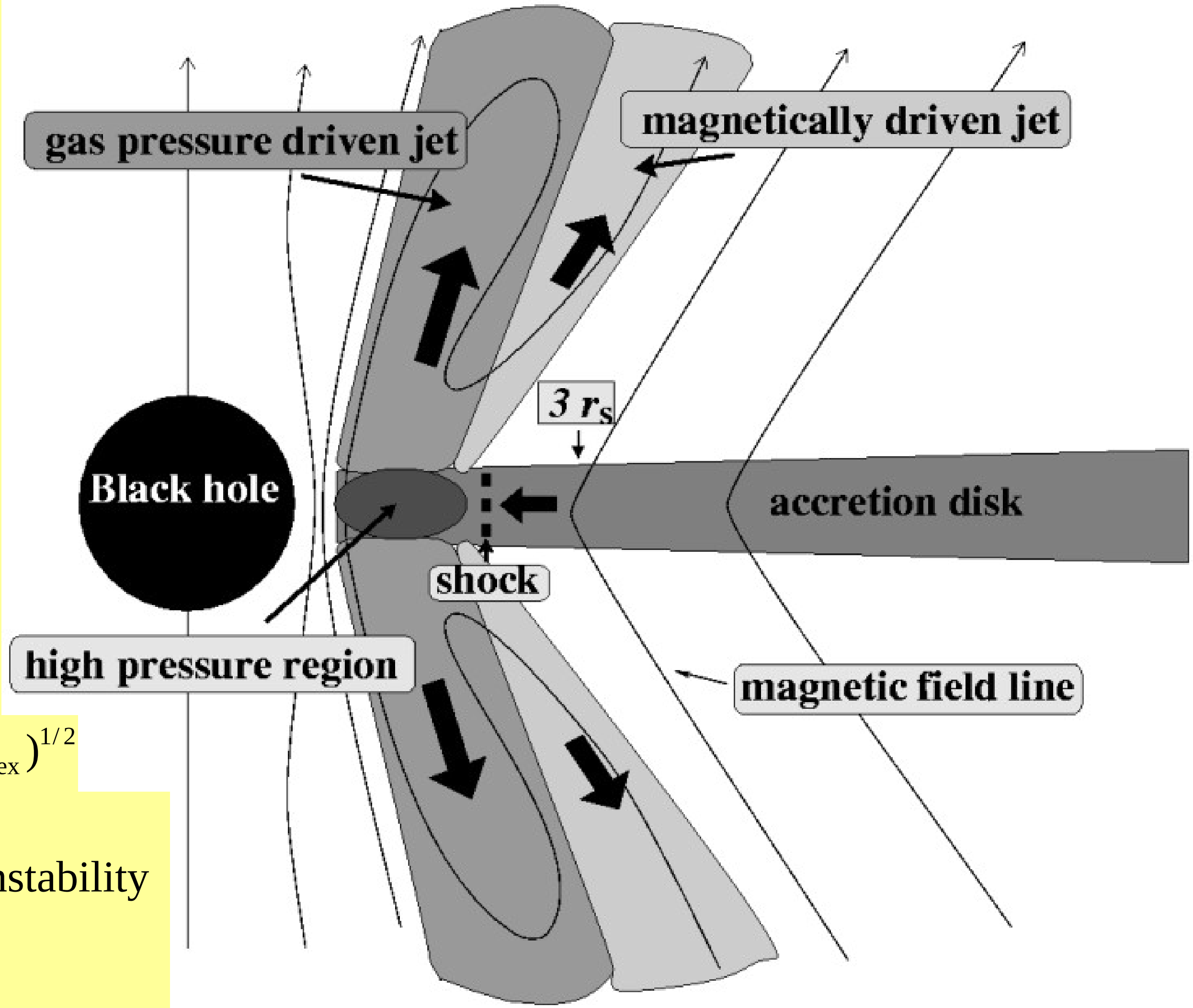
collimated width: $r_{jet} = R_G (B_G / B_{ex})^{1/2}$

Dynamics

stationary flows, shocks, plasma instability

$(\vec{v}\nabla)\Gamma_j p^{1/4} = 0, \quad \Gamma_j(z_{col}) \approx 1.22$

$N(\gamma)d\gamma = N_0 \gamma^{-s} d\gamma, \quad B(z) \propto z^{-m}, \quad N(z) \propto z^{-n}$



Jet kinematics

Superluminal motions and relativistic effects

Apparent speed: $\beta_{\rm app} = \frac{\beta \sin\theta}{1-\beta\cos\theta}$; $\beta = v/c$, $\gamma = \frac{1}{(1-\beta^2)^{1/2}}$

Relativistic transformations:

$t = \delta^{-1} t'$ $\nu = \delta \nu'$ $I_\nu(\nu) = \delta^3 I'_{\nu'}(\nu')$, with $\delta = [\gamma(1-\beta\cos\theta)]^{-1}$

Useful relations for $\beta_{\rm app} = \beta_{\rm app}(t)$

Jet with constant viewing angle ($\theta = const$):

$$\beta(t) = \frac{\beta_{app}(t)}{\sin\,\theta + \beta_{app}(t)\cos\,\theta}$$

Jet with constant rest frame speed ($\beta = const$):

$$\cos\,\theta(t) = \frac{\beta^2_{app}(t) \pm [\beta^2(\beta^2_{app}(t)+1) - \beta^2_{app}(t)]^{0.5}}{\beta(\beta^2_{app}(t)+1)}$$

Minimum kinetic power condition:

$$\gamma_{\rm min} = (1+\beta^2_{\rm app})^{1/2} \qquad \beta_{\rm min} = \cos\theta \qquad \delta_{\rm min} = (1+\beta^2_{\rm app})^{1/2}$$

Jet kinematics

Rest frame kinematics

Luminosity distance

$$D_L = \frac{c}{H_0 q_0}\left\{q_0 z + (q_0 - 1)[(1 + 2q_0 z))^{1/2} - 1]\right\}$$

Apparent speed

$$\beta_{app}(t) = \mu(t) D_L (1+z)^{-1}$$

Distance travelled in the rest frame of the jet

$$R(t) = (1+z)^{-1} \int_{t_0}^{t} \frac{\beta(t)}{1 - \beta(t)\cos\theta(t)} dt$$

Rest frame time

$$\Delta t' = (1+z)^{-1} \int_{t_0}^{t} \delta(t) dt$$

Rest frame viewing angle

$$\cos\theta'(t) = \frac{\beta(t) - \cos\theta(t)}{1 - \beta(t)\cos\theta(t)}$$

Overview of Jet emission

Jet emission: Overview

Radio / optical / X-ray

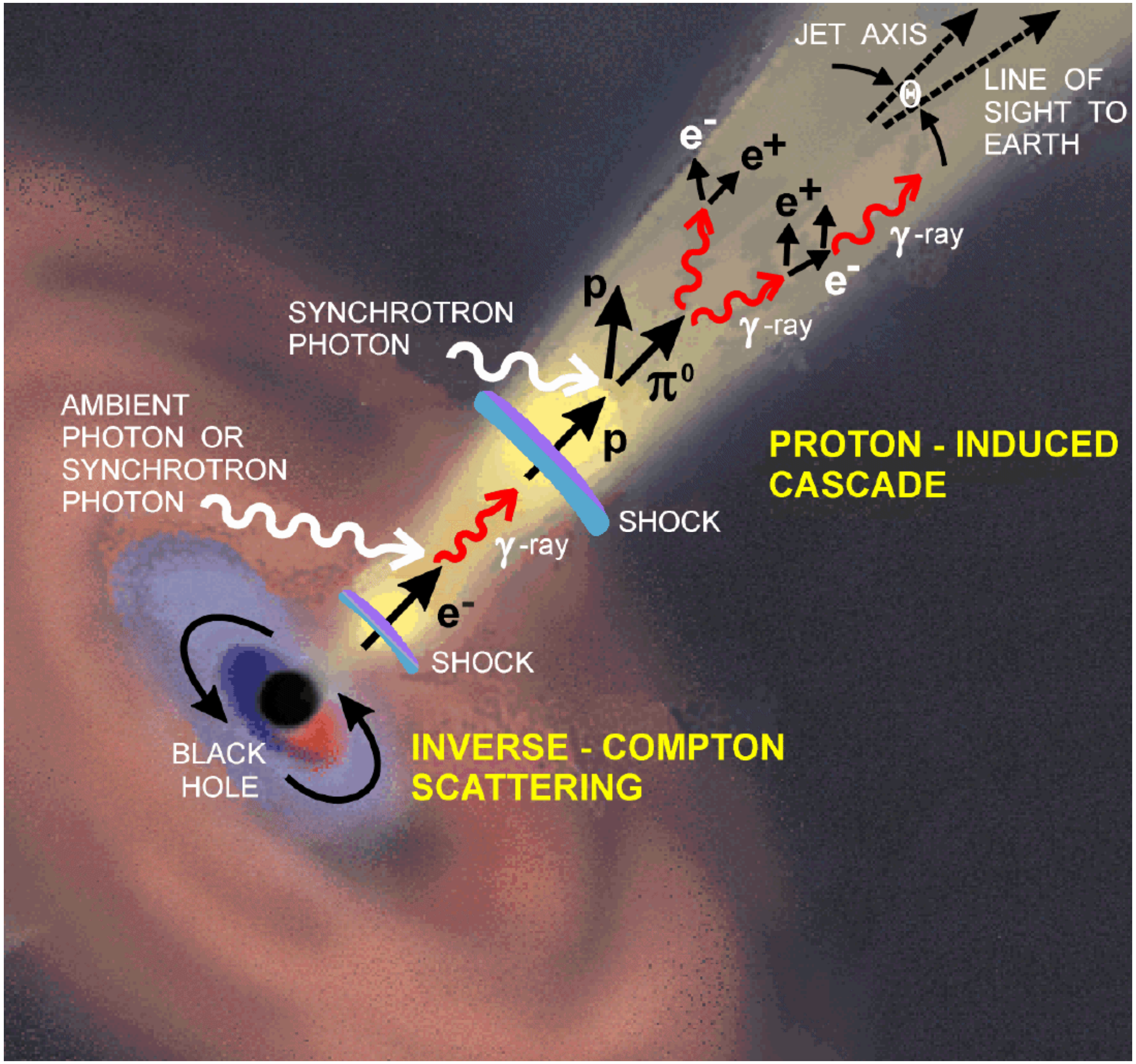
Synchrotron radiation emitted by relativistic electrons and positrons

X-ray / γ-ray

Inverse Compton scattering of electrons and low energy photons

Particle cascades induced by ultrarelativistic protons.

Shock acceleration – additional mechanism for producing energies needed for γ-ray emission



Jet emission: Synchrotron

single electron: $P_\mathrm{s} = 2\sigma_\mathrm{T} c \gamma_\mathrm{e}^2 u_\mathrm{B} \sin^2\psi$

$\sigma_\mathrm{T} = (8\pi e^4)/(3 m_\mathrm{e}^2 c^4)$

particle energy distribution: $N(\gamma)\mathrm{d}\gamma = N(\gamma_0)\gamma^{-s}\mathrm{d}\gamma$

Lorentz factors: $\gamma_\mathrm{l} < \gamma < \gamma_\mathrm{u}$

Frequencies: $\omega_\mathrm{l,u} = \gamma_\mathrm{l,u}\Omega_\mathrm{e}\sin\psi \quad \Omega_\mathrm{e} = (e\,B)/(\gamma\, m_\mathrm{e}\, c)$

emissivity: $j_\nu = c_5(\alpha)(2c_{\gamma 1})^\alpha N_{\gamma_0}(B\sin\theta)^{\alpha+1}\nu^{-\alpha}$

self-absoprtion: $I_\nu = j_\nu/\kappa_\nu[1 - \exp(-\kappa_\nu L)]$

for $\tau \gg 1$, $\kappa_\nu \propto j_\nu \nu^{-5/2}$

$$I_\nu = I_0 \left(\frac{\nu_1}{\nu_0}\right)^\alpha \left(\frac{\nu}{\nu_1}\right)^{5/2} \left(1 - \exp\left[-\left(\frac{\nu_1}{\nu_0}\right)^{5/2-\alpha}\right]\right)$$

$\alpha = \frac{1-s}{2} \quad \nu_\mathrm{m} = \tau_\mathrm{m}^{1/(\alpha-2.5)}\nu_1 \approx 1.097(-\alpha)^{-0.386}\nu_1$

Synchrotron: Spectral turnover

$$S_m = \frac{\pi}{6} C_S(\alpha) N_0 B^{1-\alpha} \nu_m^{\alpha} d_\Omega^3 D_L (1+z)^{\alpha-1} \delta_j^{3-\alpha}$$

$$\tau_m = C_\tau(\alpha) N_0 B^{1.5-\alpha} \nu_m^{-(2.5+\alpha)} d_\Omega D_L (1+z)^{\alpha-4.5} \delta_j^{2.5-\alpha}$$

$$B = 10^{-5} C_B(\alpha) d_\Omega^4 \nu_m^5 S_m^{-2} \delta_j (1+z)^{-1}$$

$$N_0 = C_N(\alpha) D_L^{-1} d_\Omega^{4\alpha-7} \nu_m^{4\alpha-5} S_m^{3-2\alpha} (1+z)^{6-2\alpha} \delta_j^{2\alpha-4}$$

Synchrotron: Spectral turnover

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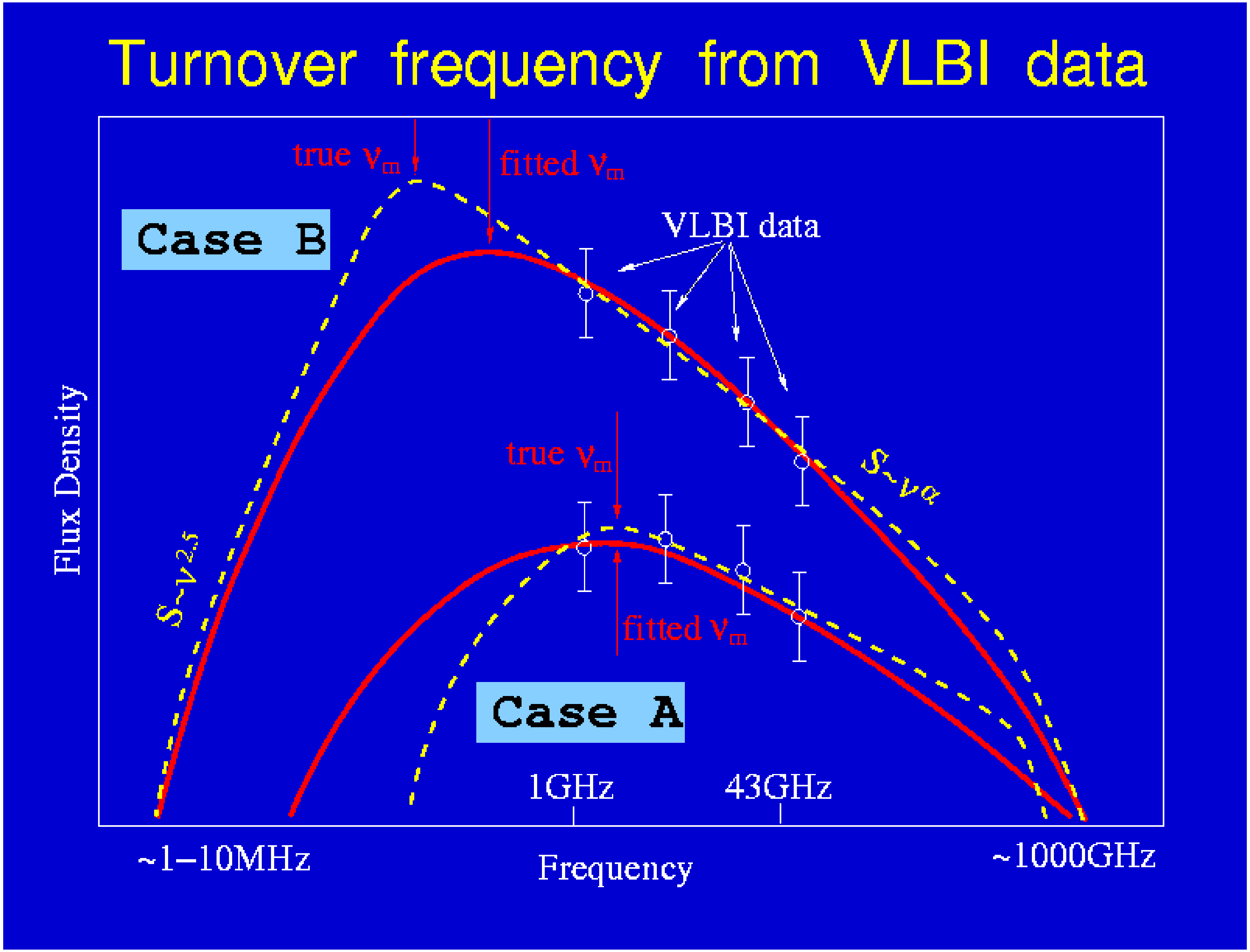
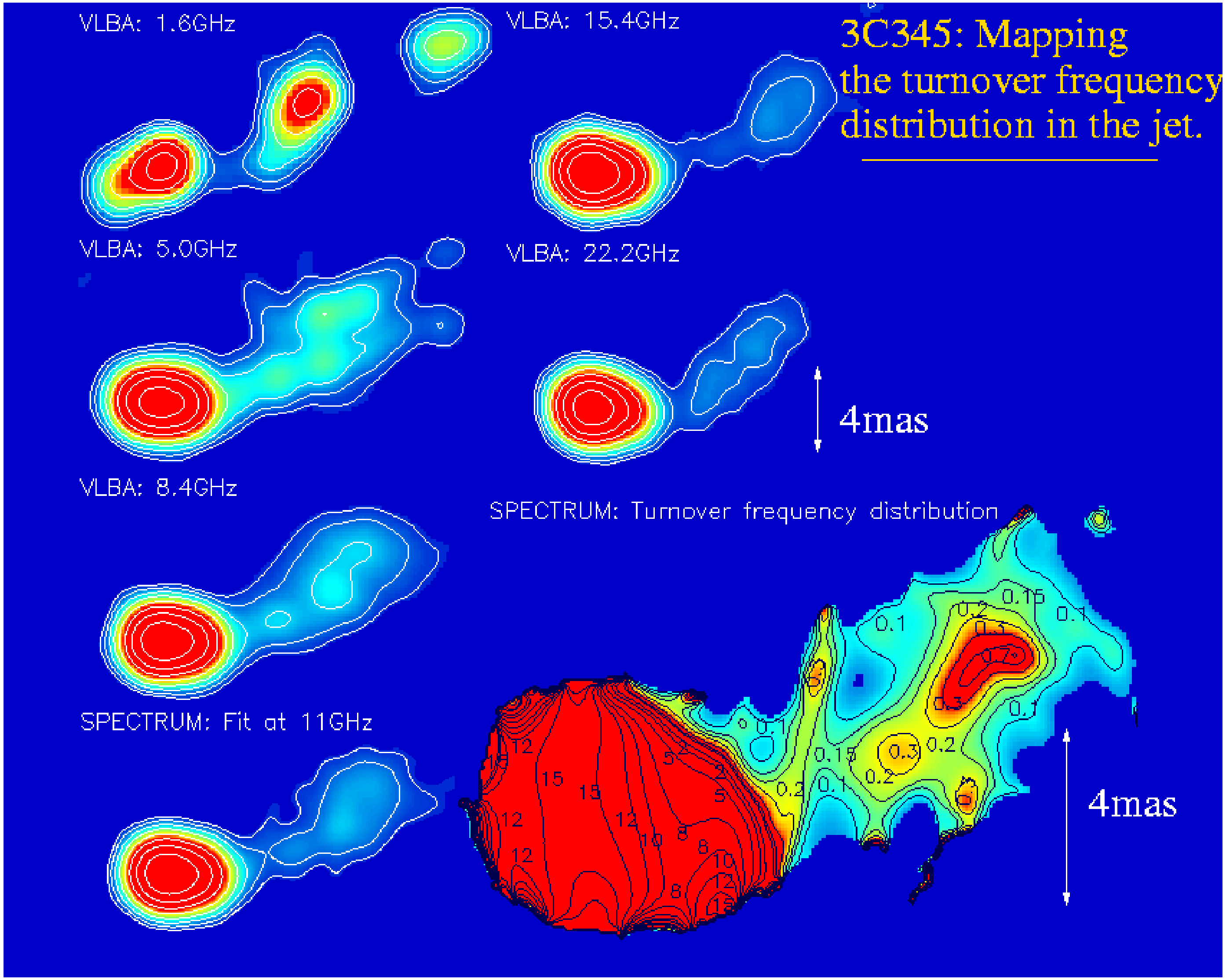


Turnover frequency imaging

- Turnover frequency distribution diagnoses plasma in the jet



Jet models

Information from VLBI images

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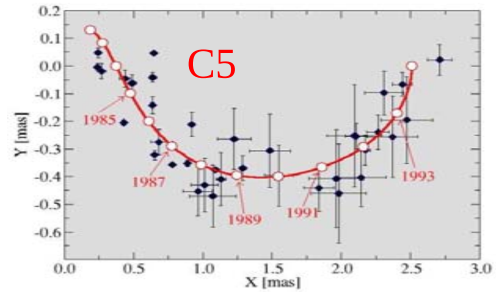
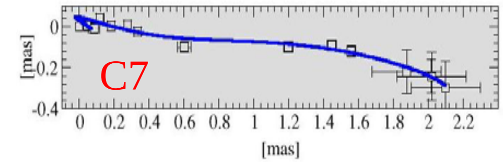
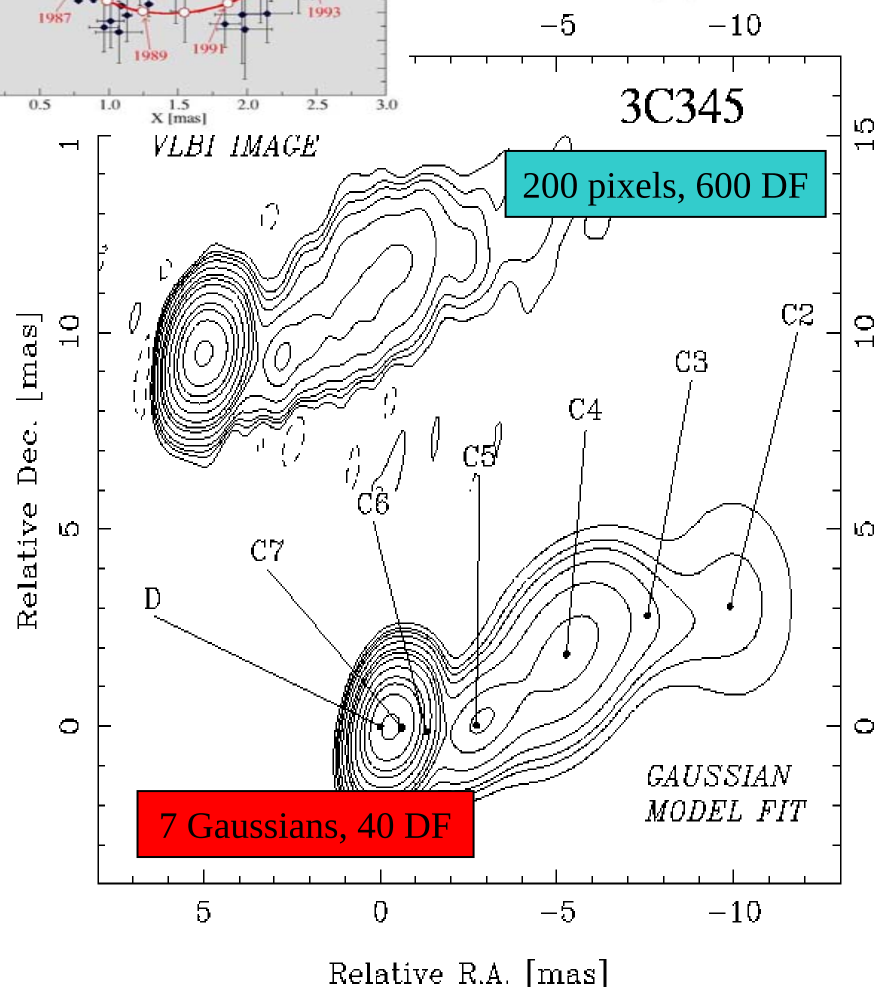
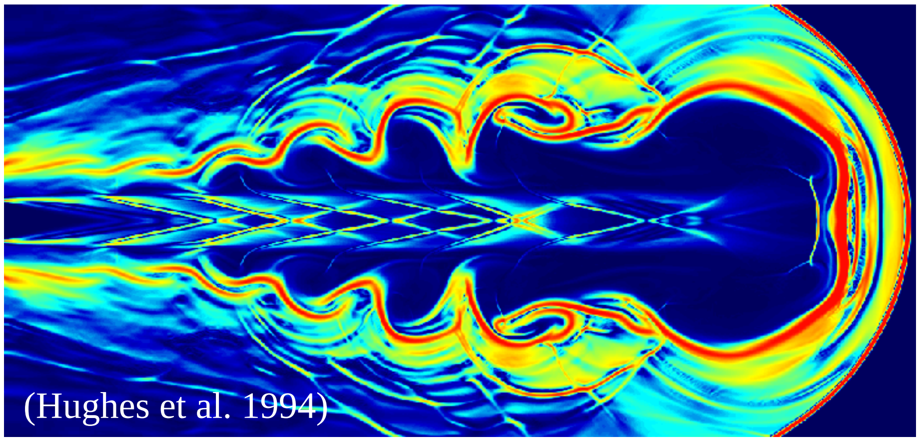
- **Observations:** **1D** (routinely), **2D**(SoA)
- **Models (relativistic).**
  Analytical: **2D** (routinely), **3D(t)** (SoA)
  Numerical: **3D** (routinely), **3D(t)** (SoA)
- **Problems:** connecting predictions (**p**,**v**,ρ) to observables (S_ν, α, β_{app}). Elusive **B** , Γ_j and M_j
- **Solution:** find a way to extract reliable 2D information from images! High-fidelity images and novel reduction and analysis techniques are much needed!

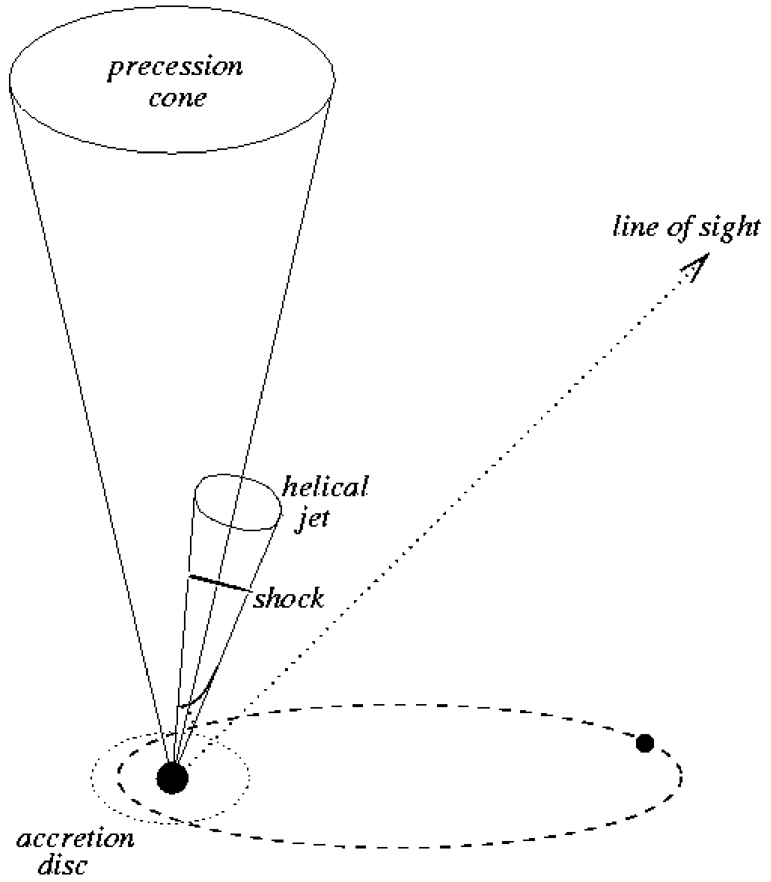







(Hughes et al. 1994)

Models vs. Observations



Model:

$S_\mathrm{m} \propto \nu_\mathrm{m}^\rho;$
$\nu_\mathrm{m} \propto r^\epsilon$
$\delta \propto r^b$
$B \propto r^{-m}$
$N \propto r^{-n}$

Observables:

$\beta_\mathrm{app}(t)$
$S(t)$
$S_\mathrm{m}(t)$, $\nu_\mathrm{m}(t)$

Jet models: Analytical

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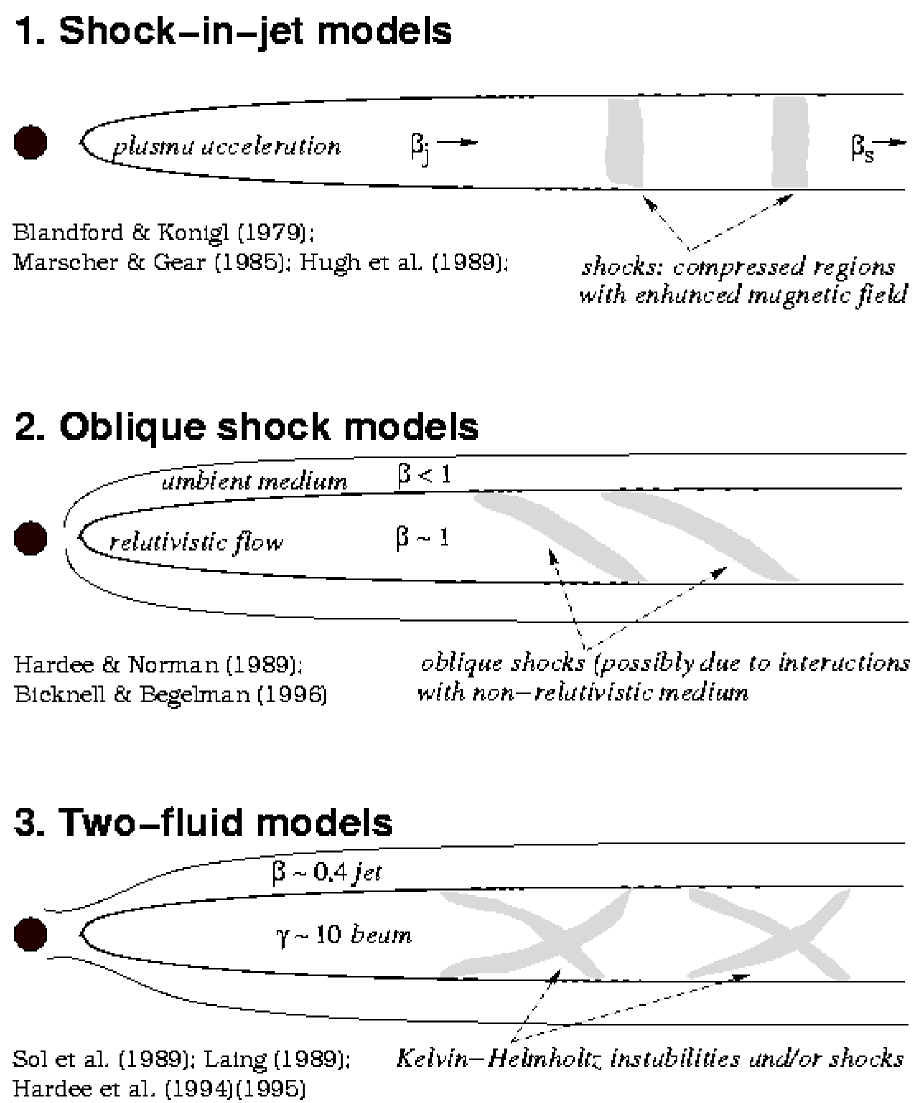
- Relativistic beaming (Shkolvsky 1963)
- Accretion (Linden Bell/Salpeter/Zeldovich 1964)
- Relativistic jet (Rees, 1969)
- Relativistic shock (Blandford & Rees, 1978)
- Plasma instability (Reynolds 1982, Hardee, 1982)
- Shock-in-jet model (Marscher & Gear 1985)
- Two-fluid model (Sol, Pelletier & Asseo 1989)
- Poynting flux jet (Lovelace & Romanova 1992)
- “Electric current” jet (Camenzind 1993)



Jet models: Numerical

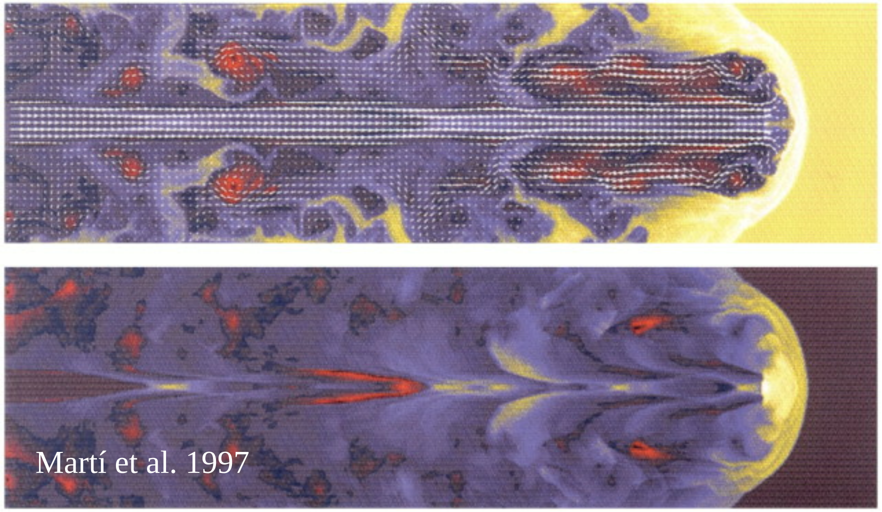
Numerical era:

-- began in late 1960s from essentially 1D works,

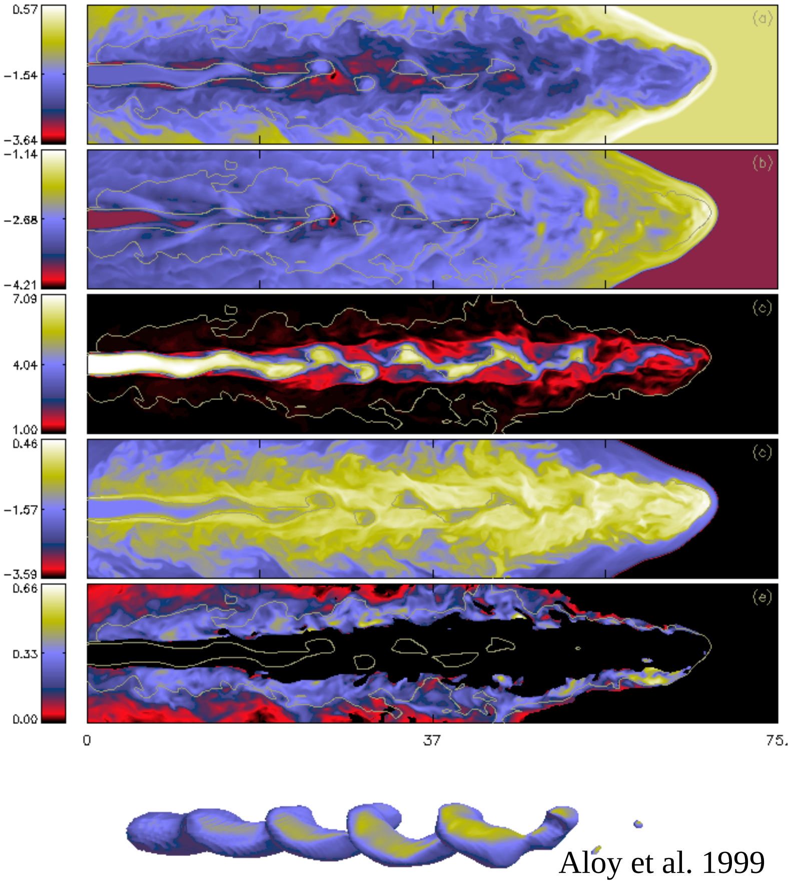
-- continued through 2DMHD and 2DRMHD

-- the goal now 3D RMH(E?)D… + rotating, transversally stratified outflows

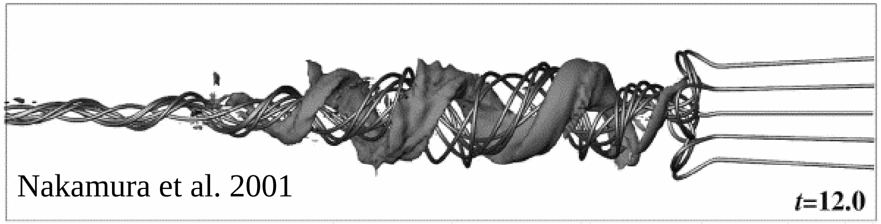
-- problem: detailed comparison to observations



Martí et al. 1997



Aloy et al. 1999



Nakamura et al. 2001

Shocks and Instabilites

Relativistic shocks

Relativistic shocks

Shock in a conical jet with a half–opening angle ϕ. $x \ll R$

Approximations: $B \propto R^{-m}$, $N \propto R^{-n}$, $\delta \propto R^{b}$

Received spectrum: $S(\nu) \propto R^{\xi} \nu^{-\zeta} \delta^{(s+3)/2}$,

ζ and ξ depend in the dominant energy loss mechanism.

Turnover flux density: $S_{\rm m} \propto B^{-1/2} \nu_{\rm m}^{5/2} R^{2} \propto R^{(4+m)/2} \nu_{\rm m}^{5/2}$

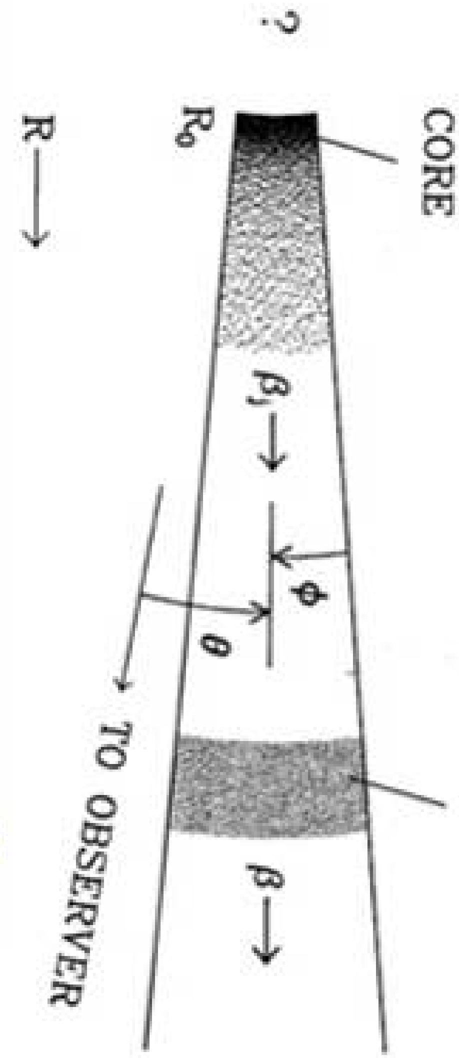
Turnover frequency: $\nu_{\rm m} \propto R^{[\xi-(4+m)/2+b(s+3)/2]/[5/2+\zeta]}$

Stages of shock evolution:

1) Compton–loss stage $\xi = [(11-s) - m(s+1)]/8 \quad \zeta = s/2$

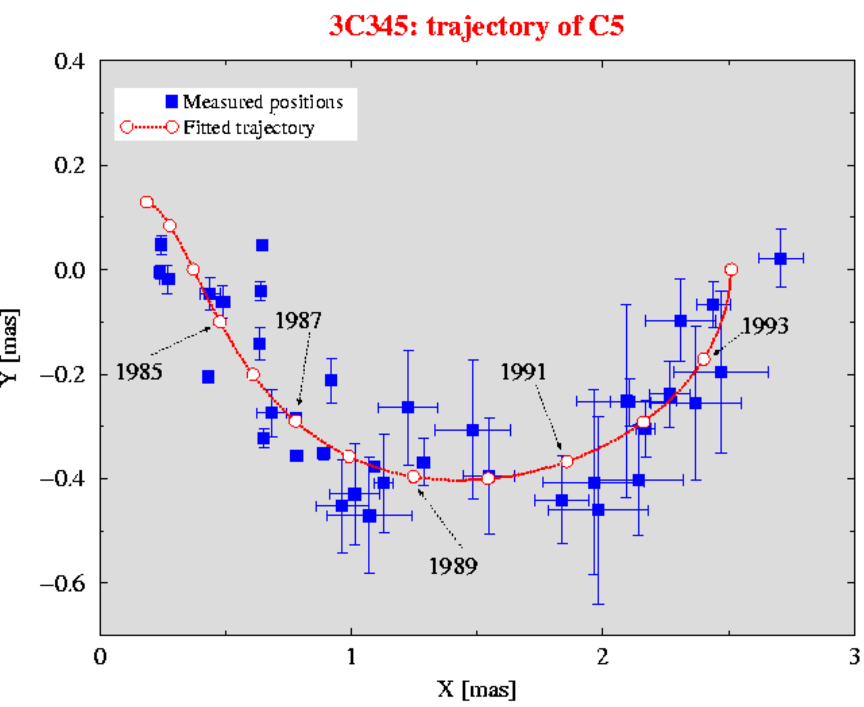
2) Synchrotron–loss stage $\xi = -[4(s-1) + 3m(s+1)]/6 \quad \zeta = s/2$

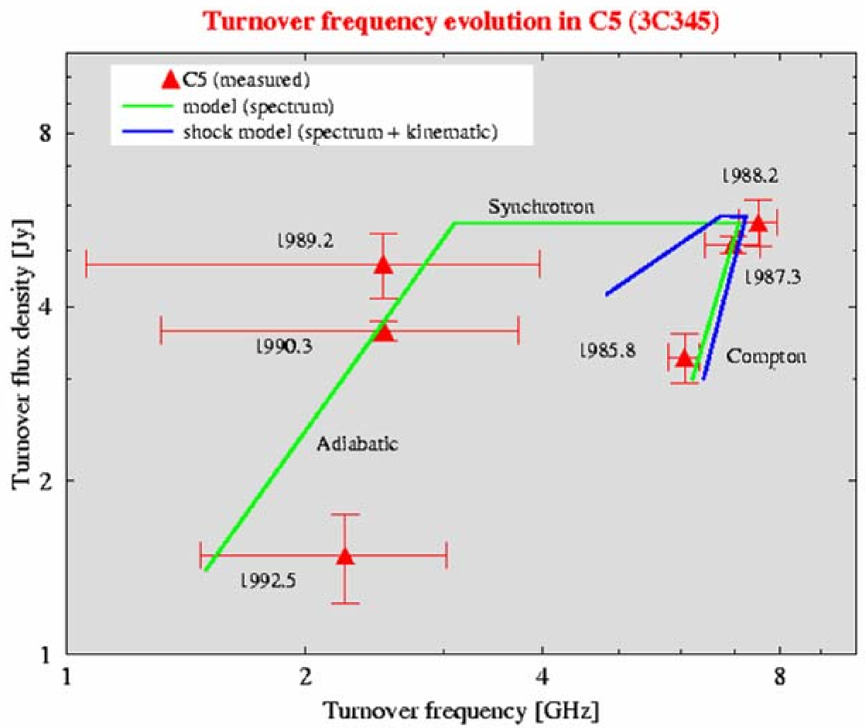
3) Adiabatic–loss stage $\xi = [2(5-2s) - 3m(s+1)]/6 \quad \zeta = (s-1)/2$



Shock model: application

- Shock model explain successfully the spectral evolution in one of the moving features in the jet in 3C345.
- Fitting simultaneously the spectral and kinematic changes is problematic – possibly due to rapid shock dissipation





Jet models: K-H instability

Linear perturbation analysis of dispersion relation (Hardee 1987, 1998, 2000)

Low frequency limit *(longest unstable wavelength)* :

$$\lambda^{l}_{nm} = \frac{4\,n\,\Gamma_j R_j (M_j^2 - 1)^{0.5}}{(n + 2m - 0.5)},$$

High frequency limit *(resonant wavelength)* :

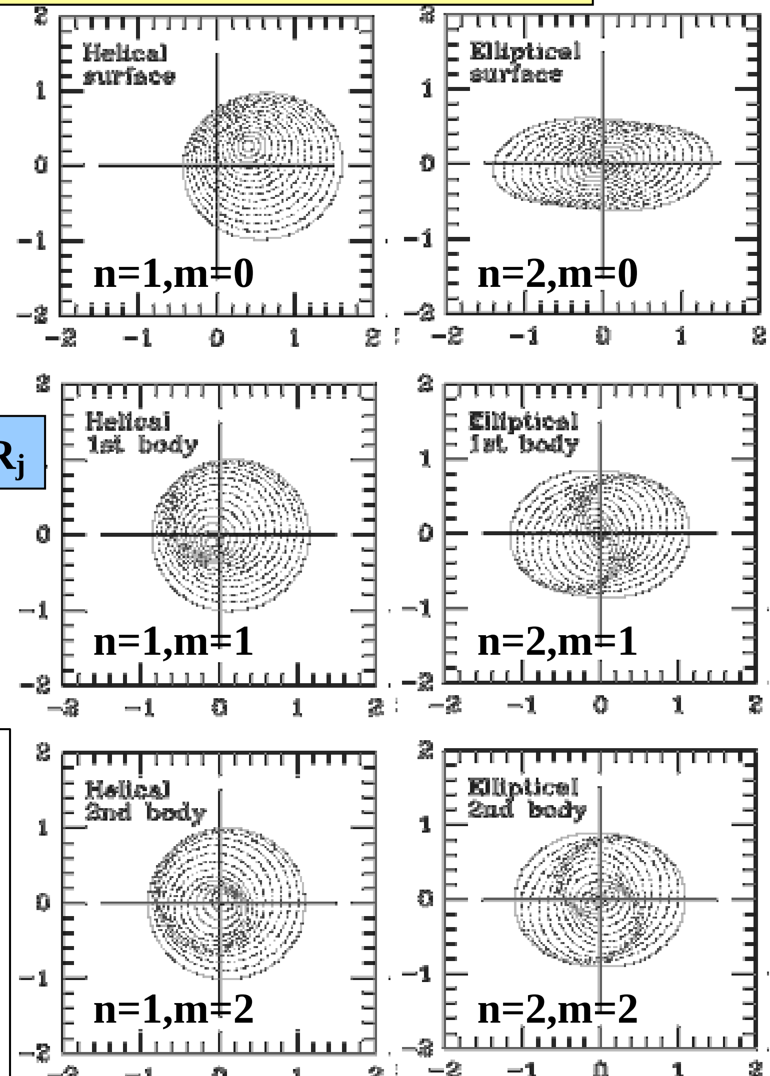
$$\lambda^{*}_{nm} = \frac{4\,n\,R_j M_j \beta^{*}_{w}}{\eta^{0.5} \beta_j (n + 2m + 0.5)}.$$

Resonant modes propagate at:

$$\beta^{*}_{w} = \varepsilon \beta_j\,, \quad \varepsilon = \frac{\eta^{0.5}}{\Gamma_j^{-1} + \eta^{0.5}},$$

In the low and high frequency limits: $\lambda^{*} \propto R_j, \quad \lambda^{l} \propto R_j$

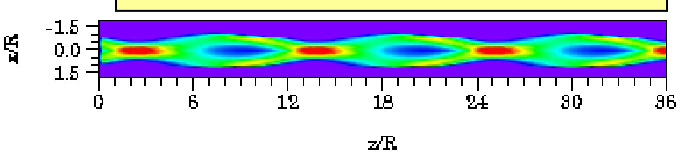
Constant frequency (ω=*const*) regime: $\lambda^{*} \leq \lambda_{\omega} \leq \lambda^{l}$
and λ_{ω} may not depend on Rj.

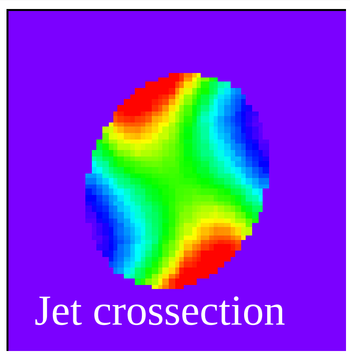


(Hardee 2000)

- Can estimate basic parameters (M_j, a_j, M_x, a_x, η, ρ_j/ρ_x)
- Can also predict the behavior of the instability modes, and reproduce the jet structure.

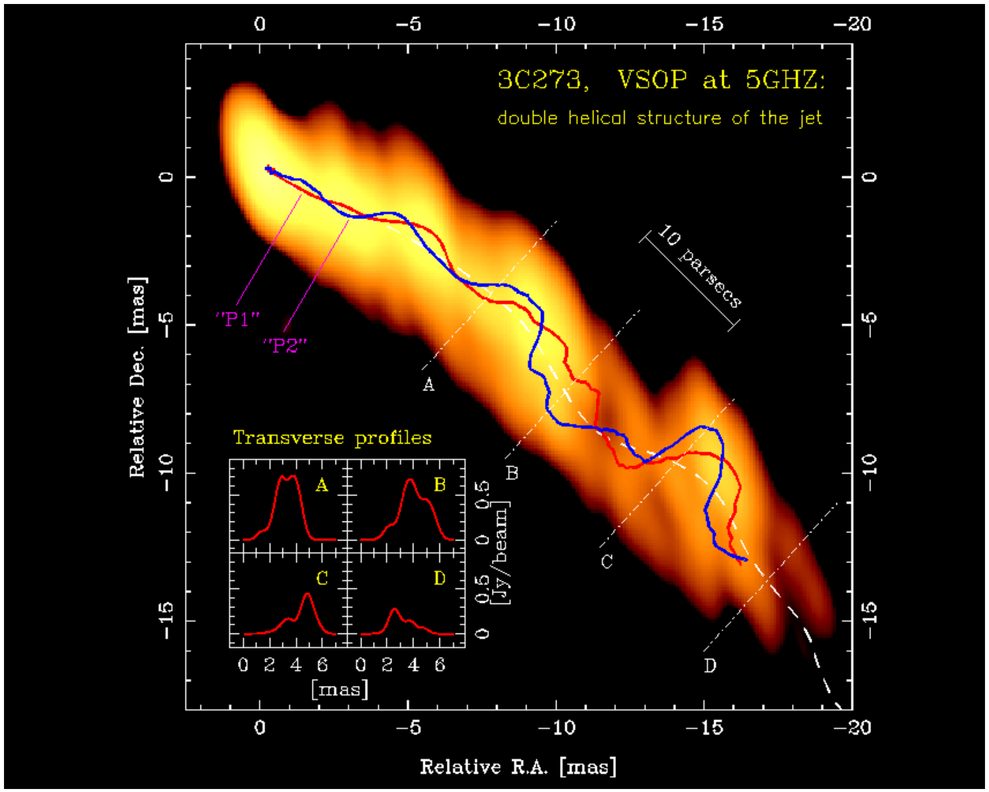
Pressure structure of Es mode

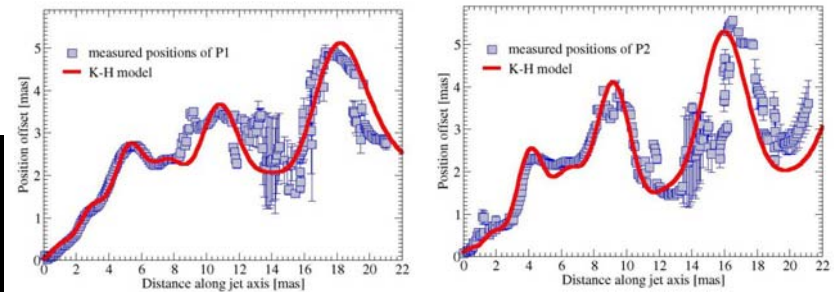




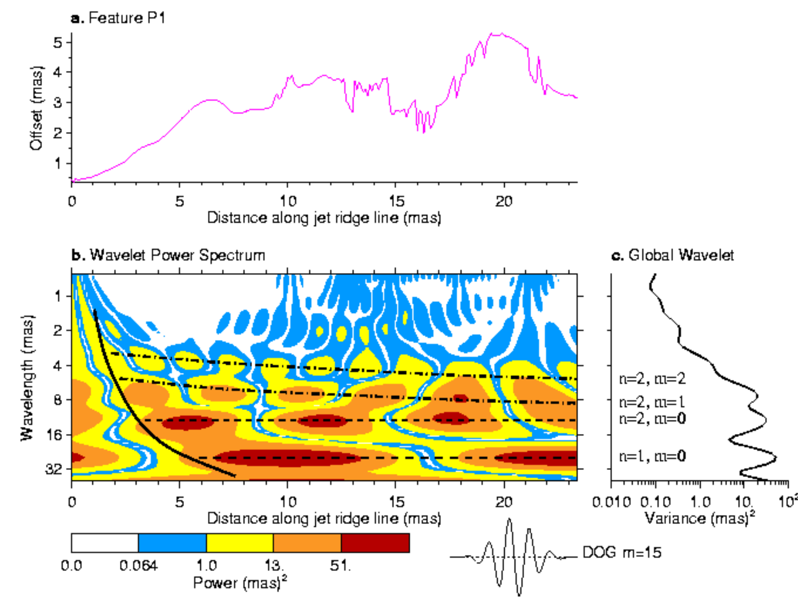
Instabilities on pc scales

- Linear regime of K-H instability





λ_{Hs}=18.0, λ_{Es}=12.0, λ_{Eb1}=4.0, λ_{Eb2}=1.9



G_j=2.1, M_j=3.5, η=0.02, a_j=0.53, v_w=0.21

Lobanov & Zensus 2001, Perucho, Lobanov, Martí 2006

Nuclear Opacity

Compact jet properties

❑ Properties of ultra-compact jets can be described by the following set of condition:

A power-low particle distribution

$$N(\gamma_e) = N_0 \gamma_e^{-s} \text{ for } \gamma_{min}(r) < \gamma_e < \gamma_{max}(r)$$

$$\alpha = (1-s)/2$$

Jet expansion

$$R = a\, r^{\varepsilon} \quad (\varepsilon \leq 1)$$

Magnetic field evolution along the jet

$$B = B_1 (r_1/r)^m$$

Particle density evolution along the jet

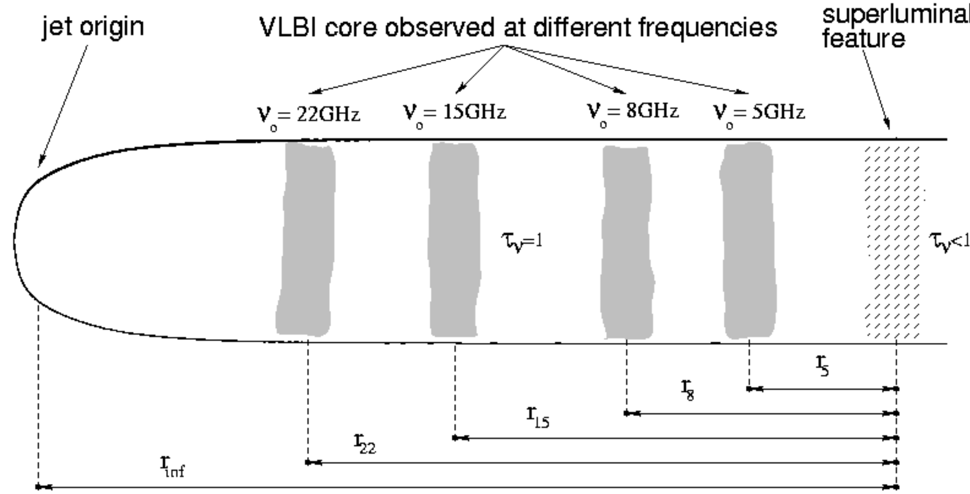
$$N = N_1 (r_1/r)^n$$

The case m=1, n=2 corresponds to the equipartition regime

Physics of VLBI Core

A. Lobanov

- The „core“ of a VLBI jet is located in a region where emission turns optically thin at a given frequency. Hence the core position depends on the observing frequency



Optical depth in the jet

$$\tau_s(r) = C(\alpha) N_1 \left(\frac{eB_1}{2\pi m_e}\right)^{\epsilon} \frac{\delta^{\epsilon}\phi_o}{r^{(\epsilon m + n - 1)}\nu^{\epsilon+1}}$$

The condition τ_s=1 determines the location of the core

$$r[\mathrm{pc}] = (B_1^{k_b} F/\nu)^{1/k_r}$$

$$F = (1+z)^{-1}[6.2 \cdot 10^{18} C_2(\alpha)\delta_j^{\epsilon} N_1 \phi_o]^{1/(\epsilon+1)}$$

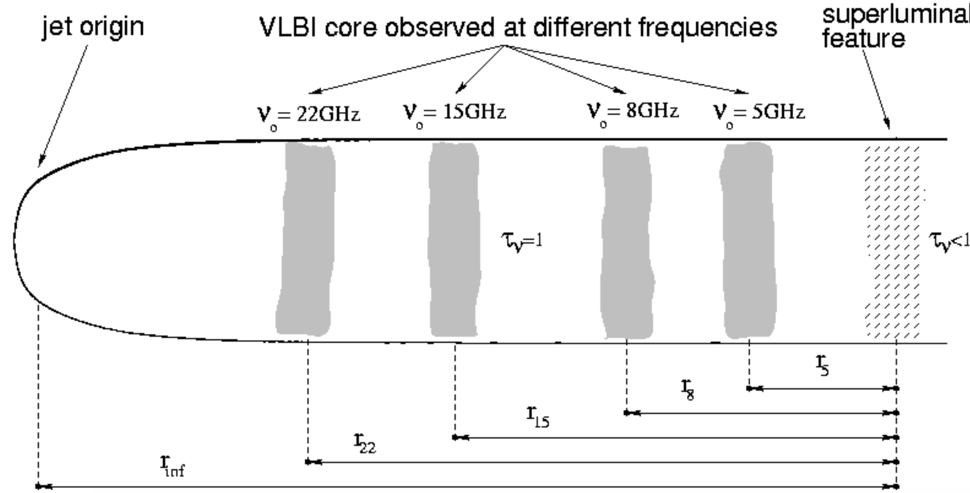
$$k_b = (3 - 2\alpha)/(5 - 2\alpha)$$

$$k_r = ((3 - 2\alpha)m + 2n - 2)/(5 - 2\alpha)$$

Nuclear opacity: Core shift

A. Lobanov

- Position offset of the optically thick „core“ of a VLBI jet can be used to estimate physical conditions in the nuclear region of AGN



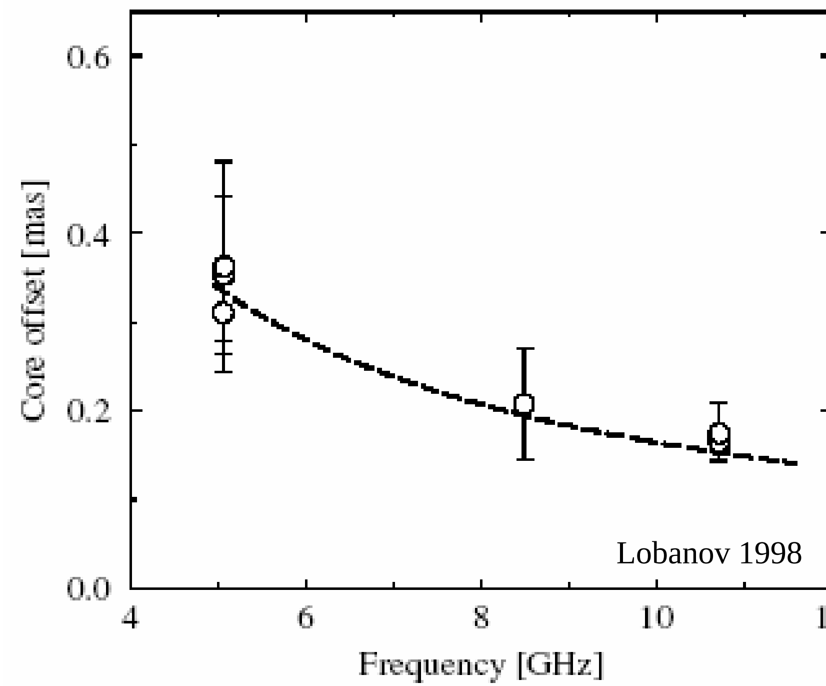
Core location:

$$r[\mathrm{pc}] = (B_1^{k_b} F/\nu)^{1/k_r}$$

(Königl 1981)

Core offset measure:

$$\Omega_{r\nu} = 4.85 \cdot 10^{-9} \frac{\Delta r_{\mathrm{mas}} D_{\mathrm{L}}}{(1+z)^2} \cdot \frac{\nu_1^{1/k_r} \nu_2^{1/k_r}}{\nu_2^{1/k_r} - \nu_1^{1/k_r}}$$



Derived magnetic field and distance from the central engine to the core:

$$B_1 = (\Omega_{r\nu} / \sin\theta)^{k_r/k_b} F^{-1/k_b}$$

$$r_{\mathrm{core}}(\nu) = \Omega_{r\nu} \left[\nu^{1/k_r} \sin\theta\right]^{-1}$$

Summary

- Jets are formed in the immediate vicinity of supermassive black holes.
- Jets transport excess energy and momentum away from SMBH
- Dynamic evolution and emission properties of compact jets are described well by synchrotron emission
- Shocks and plasma instabilities affect strongly the dynamics and emission of the jets.
- Multifrequency studies involving spectral imaging and opacity measurements in the nuclear regions offer a good opportunity to assess physical properties in the jet plasma.