Synchrotron radiation maps from relativistic jet simulations

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Outline

- Motivation (two-component jets & observations)
- Simulations of two-component jets
- Emission from astrophysical jets
- Synchrotron maps of simulated jets
- Summary & future work

Astrophysical jets

- A very common feature in the universe
  - Different scales (AU to kpc – YSO to AGN)
  - Different environments (stellar to galactic)
  - Different origin (but most likely some kind of accretion always present)
  - Different velocities (~100 km/s – γ~100)
  - Different energy output (up to 10^{51} ergs/s)

- Main categories:
  - Young stellar objects (YSO jets)
  - Gamma ray bursts (GRBs)
  - Microquasars (accreting binary systems)
  - Active galactic nuclei (AGN jets)

- Acceleration (HD v MHD v GRMHD + radiation), collimation (self-collimation, role of environment,…)

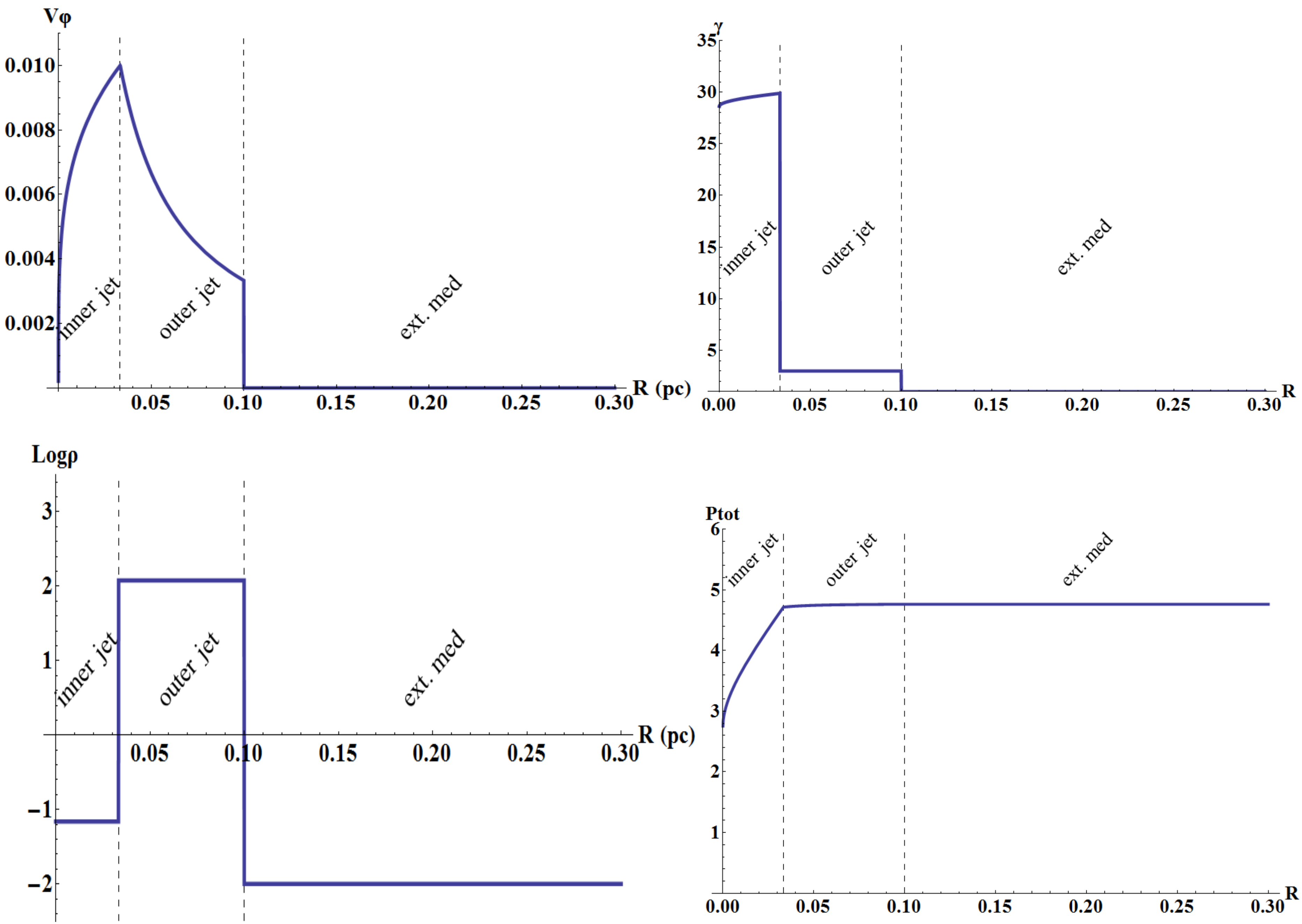
Two-component jets ?

- Indications: brightening, variability in TeV,…
- Variability in TeV:
  - high γ
  - ultra relativistic bulk motion of the jet
- Radio observations of pc-scale structure:
  - broad, slow (but relativistic) motion
- Sometimes (?) :
  - Fast, light inner jet
  - Slow, heavier outer jet
- *Stability ?*

Two different (in terms of velocity) regions !

Relativistic MHD simulations

- Relativistic module of grid adaptive, MPI-AMRVAC code
- Use 3 levels of AMR to resolve regions of interest (interfaces)
- Base resolution 128^2, effective 512^2
- Dimensions: $-0.3\text{pc} < x,y < 0.3\text{pc}$
- GLM method to control divergence of $\vec{B}$
- Duration: 3 rotations of inner jet or ~190 yrs
- VSC cluster (Muk, BrEniac)



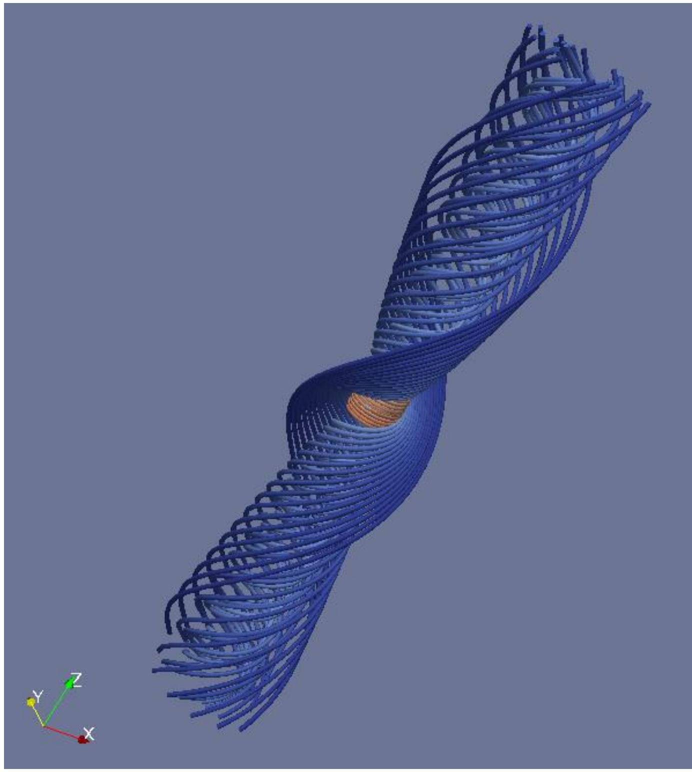
Vφ
0.010
0.008
0.006
0.004
0.002
inner jet
outer jet
ext. med
0.05
0.10
0.15
0.20
0.25
0.30
R (pc)
γ
35
30
25
20
15
10
5
inner jet
outer jet
ext. med
0.00
0.05
0.10
0.15
0.20
0.25
0.30
R
Logρ
3
2
1
−1
−2
inner jet
outer jet
ext. med
0.05
0.10
0.15
0.20
0.25
0.30
R (pc)
Ptot
6
5
4
3
2
1
inner jet
outer jet
ext. med
0.00
0.05
0.10
0.15
0.20
0.25
0.30
R

Magnetic field configuration

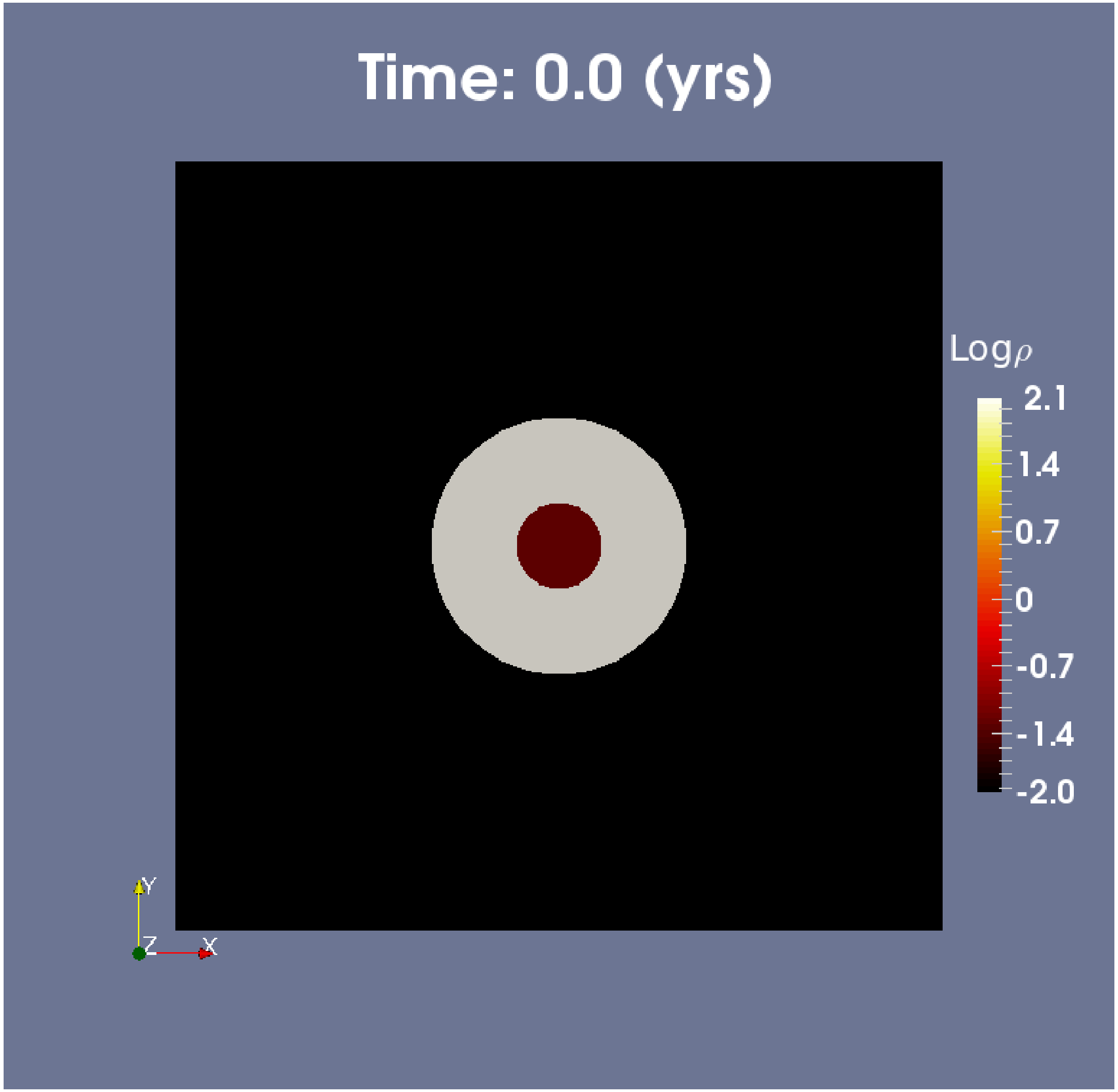
- $$B_\varphi(r) = \begin{cases} \mathrm{B}_{\varphi,\mathrm{in}} \left(\frac{r}{r_{in}}\right)^{a_{in}/2} &, \quad r \leq r_{in} \\ \mathrm{B}_{\varphi,out} \left(\frac{r}{r_{in}}\right)^{a_{out}/2} &, r_{in} < r < r_{out} \end{cases}$$

$$\alpha_{in} = 0.5, a_{out} = -2$$

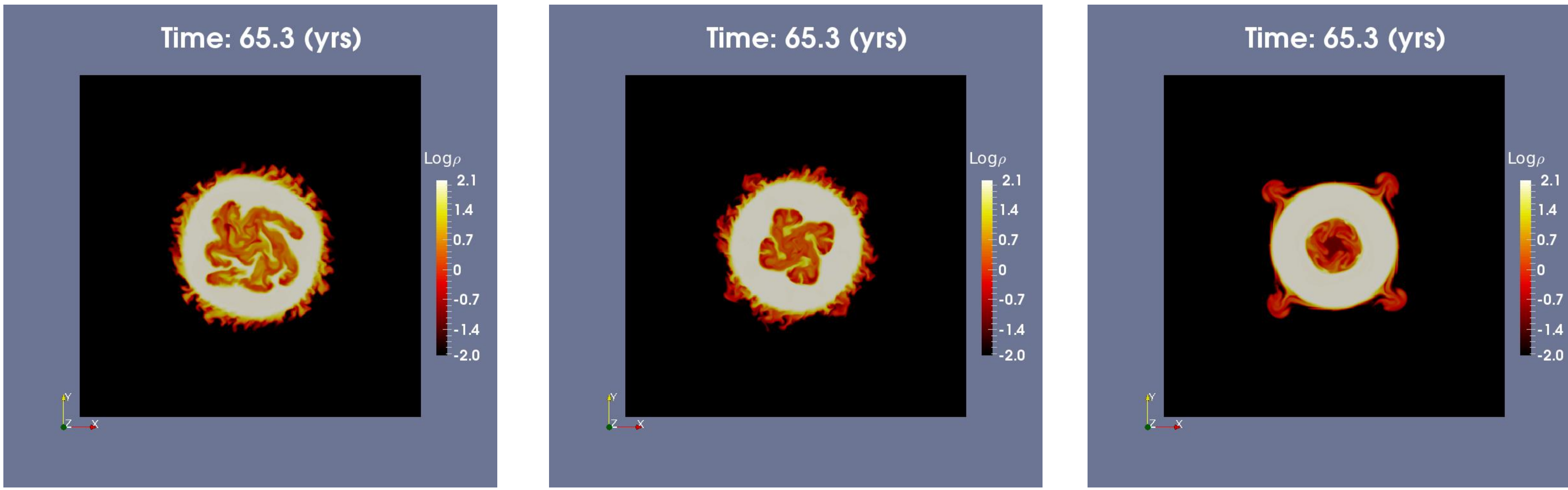
- $$B_z(r) = \begin{cases} B_{z,in}, & r \leq r_{in} \\ B_{z,out}, & r > r_{in} \end{cases}$$



- No discontinuity at the interface, $\mathrm{B}_{\varphi,\mathrm{in}} = \mathrm{B}_{\varphi,\mathrm{out}}$
- $\mathrm{B}_{\varphi,\mathrm{in}}$ defined by fixing the magnetization at $r=r_{in}$ ($\sigma = \mathrm{B}_\varphi^2 / \gamma^2 \rho$)
  - Use values corresponding to kinetically dominated jets ($\sigma < 1$), $\sigma_{max} = 0.1$


Time: 0.0 (yrs)
Logρ
2.1
1.4
0.7
0
-0.7
-1.4
-2.0
Y
Z
X

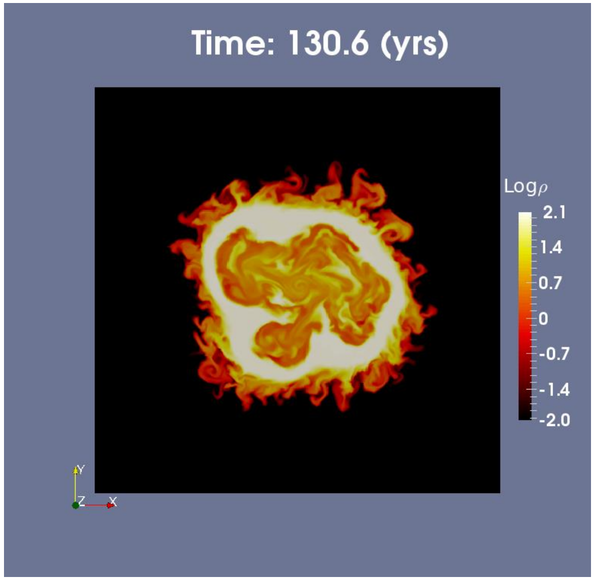
σ



σ = 0.001 **σ = 0.01** **σ = 0.1**

t = 1 rotation

Millas et al., 2017, MNRAS



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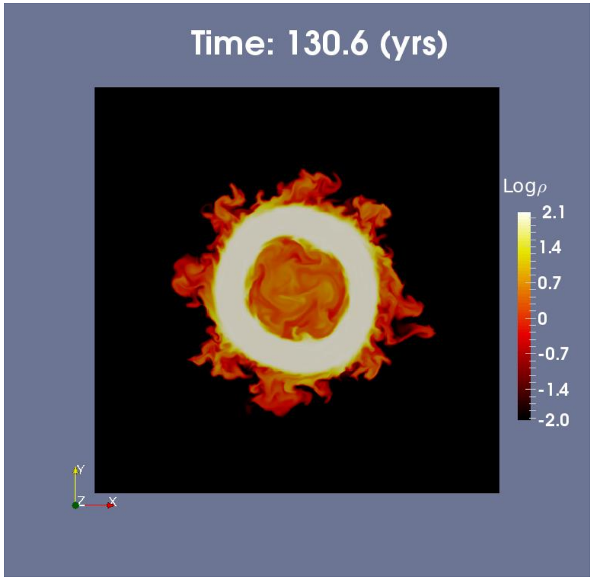
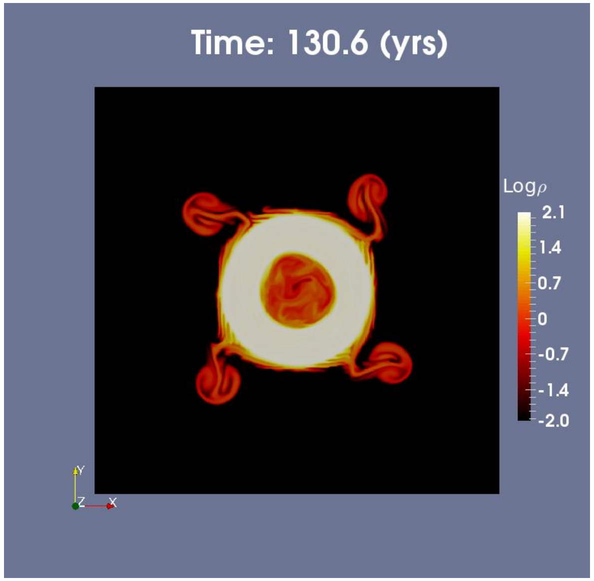


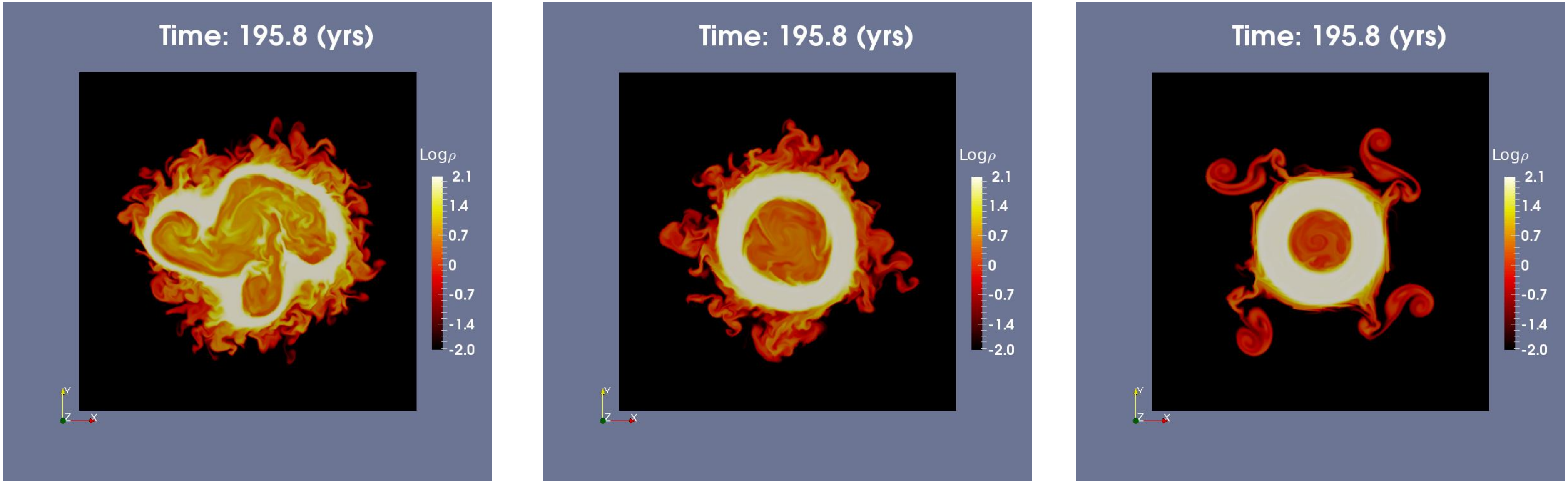
σ = 0.01



σ = 0.1

t = 2 rotations

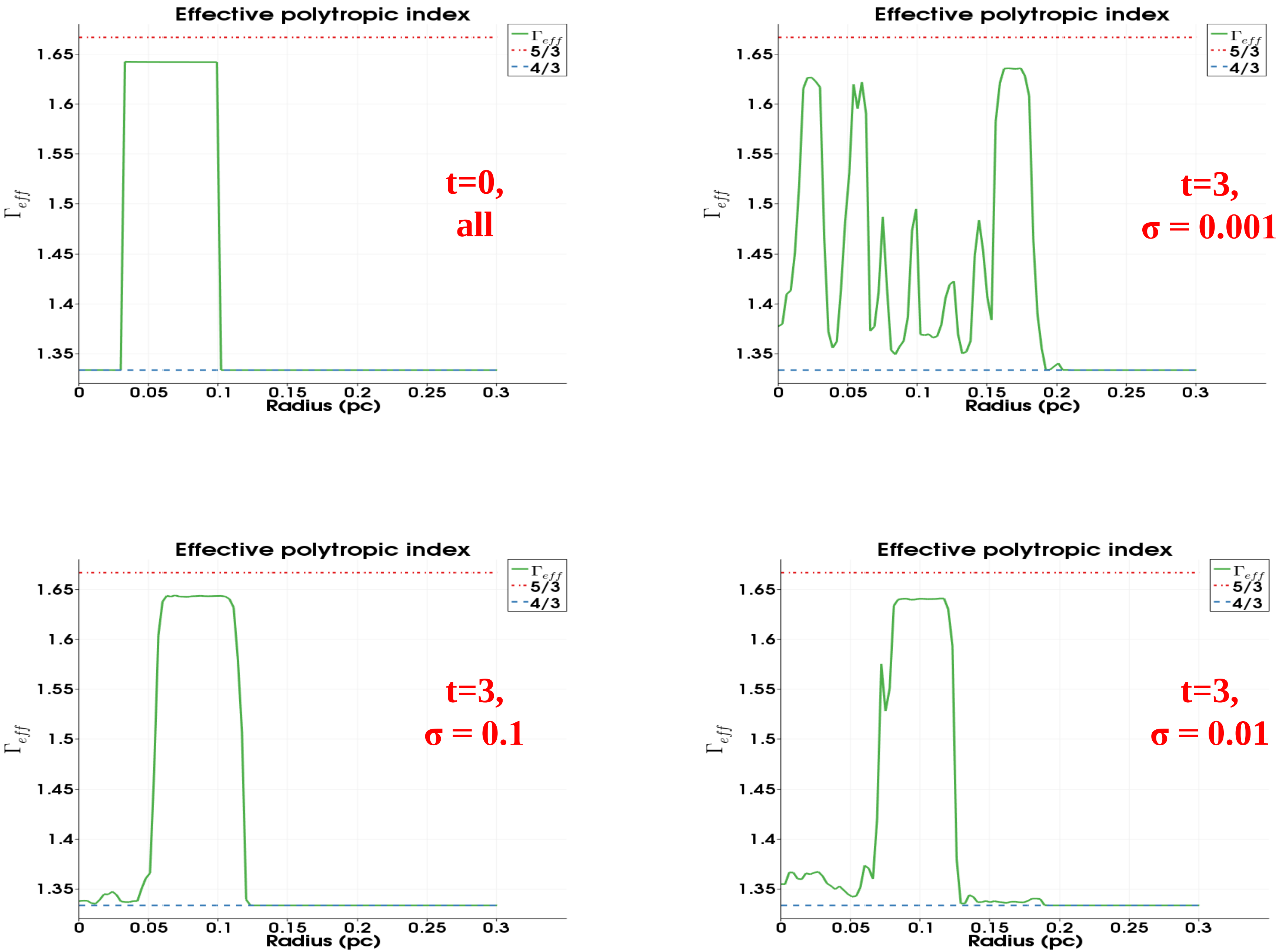
Millas et al., 2017, MNRAS



σ = 0.001 **σ = 0.01** **σ = 0.1**

t = 3 rotations

Millas et al., 2017, MNRAS



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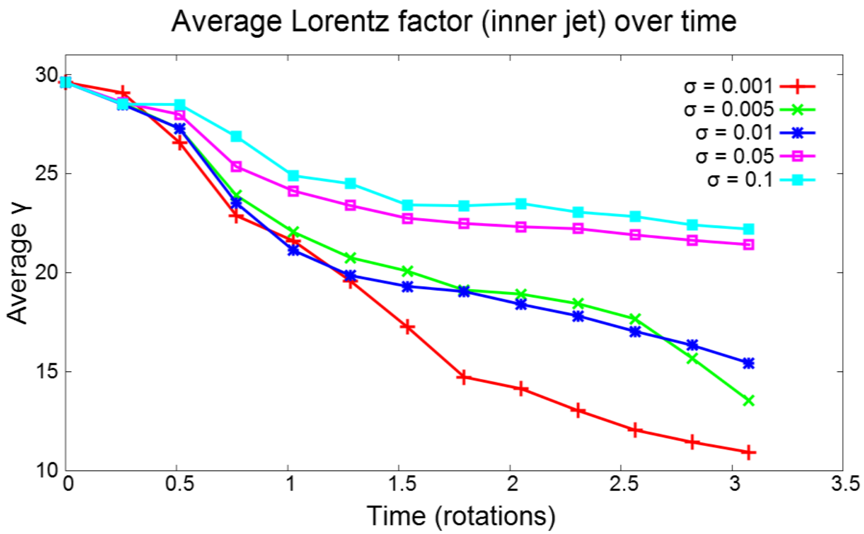

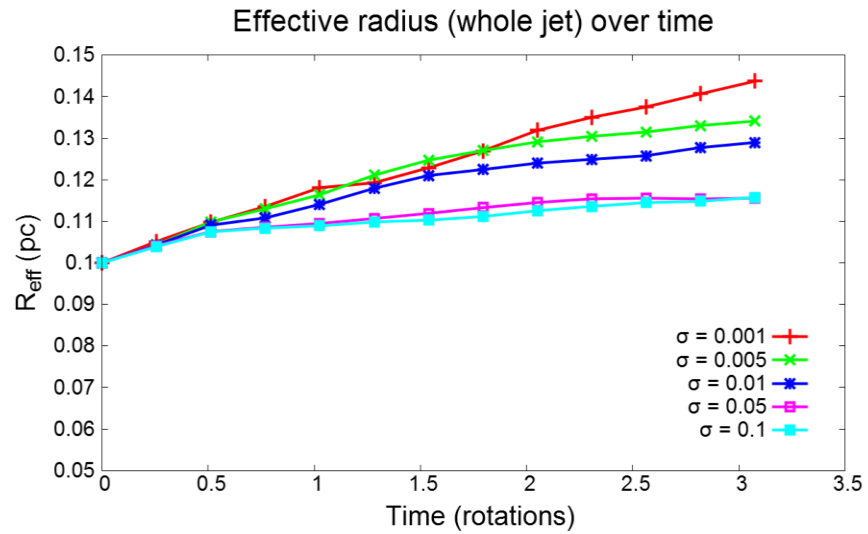

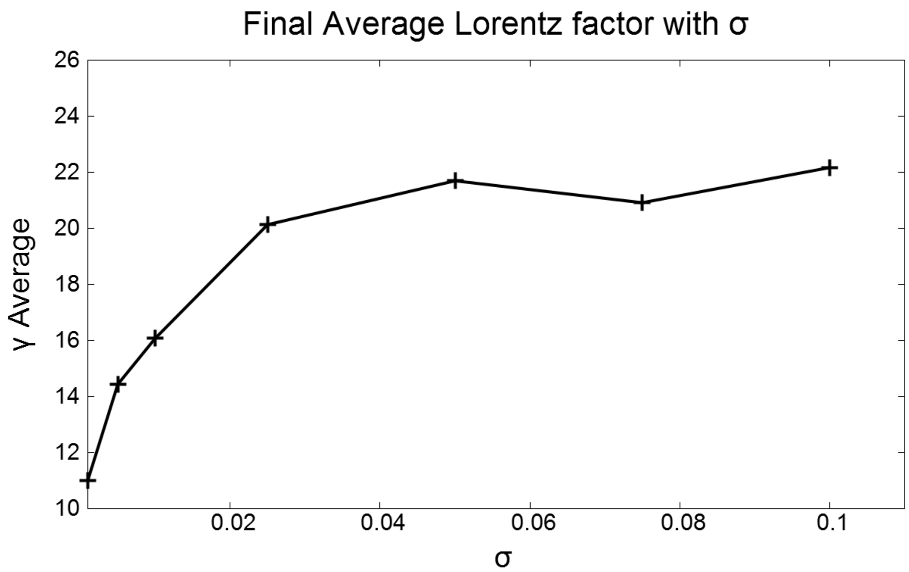

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Intermezzo: Emission from AGN

- Mostly **non-thermal**
- Presence of magnetic field → **Synchrotron**
- Photon field → **Inverse Compton**

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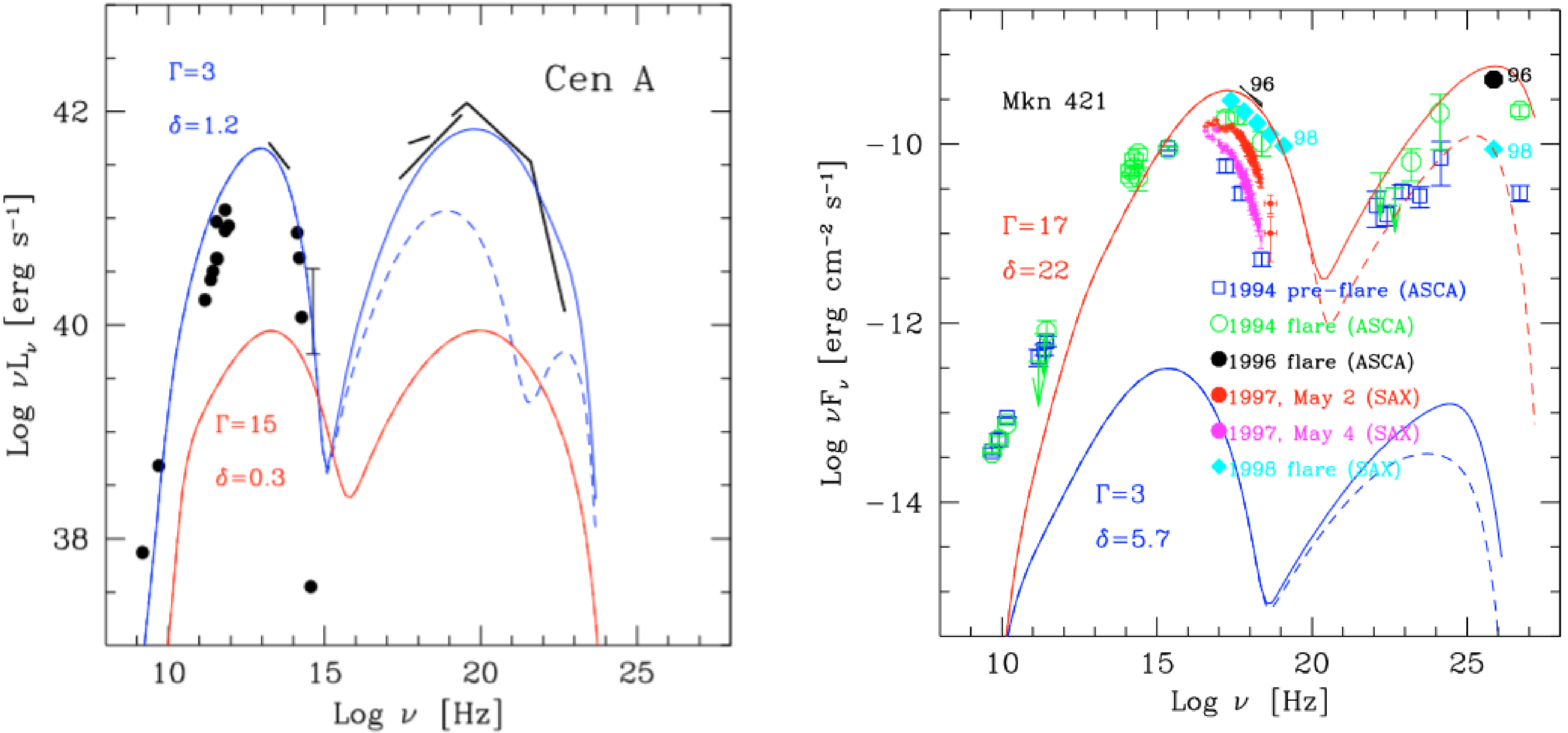
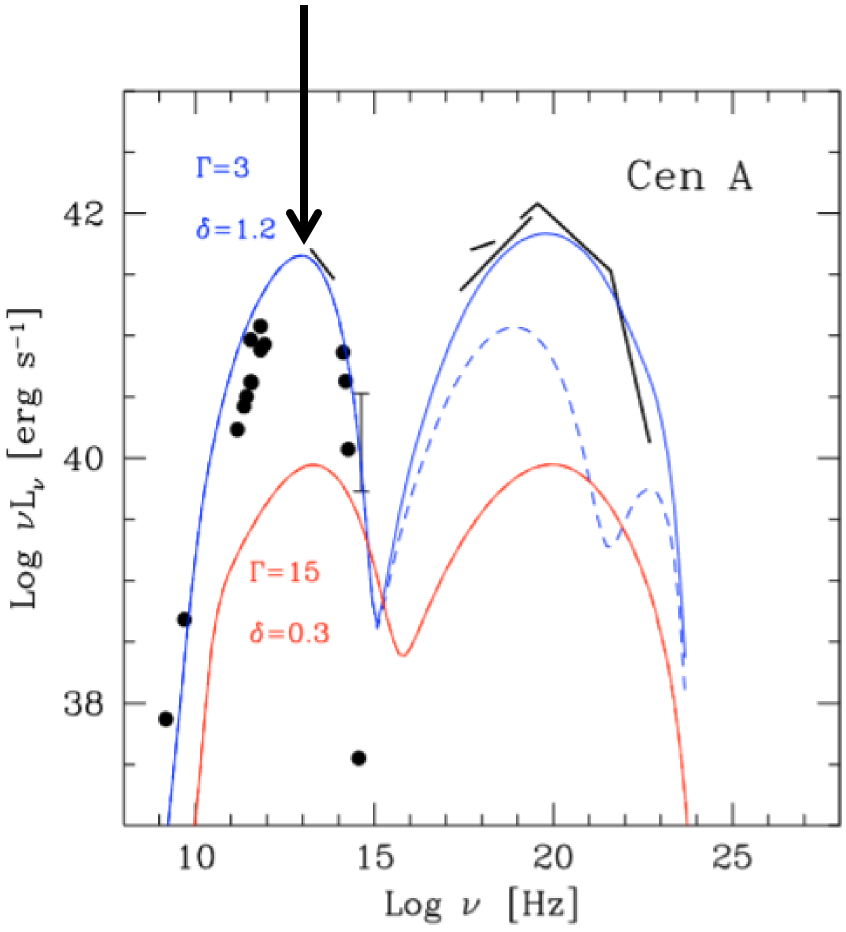
Intermezzo: Emission from AGN

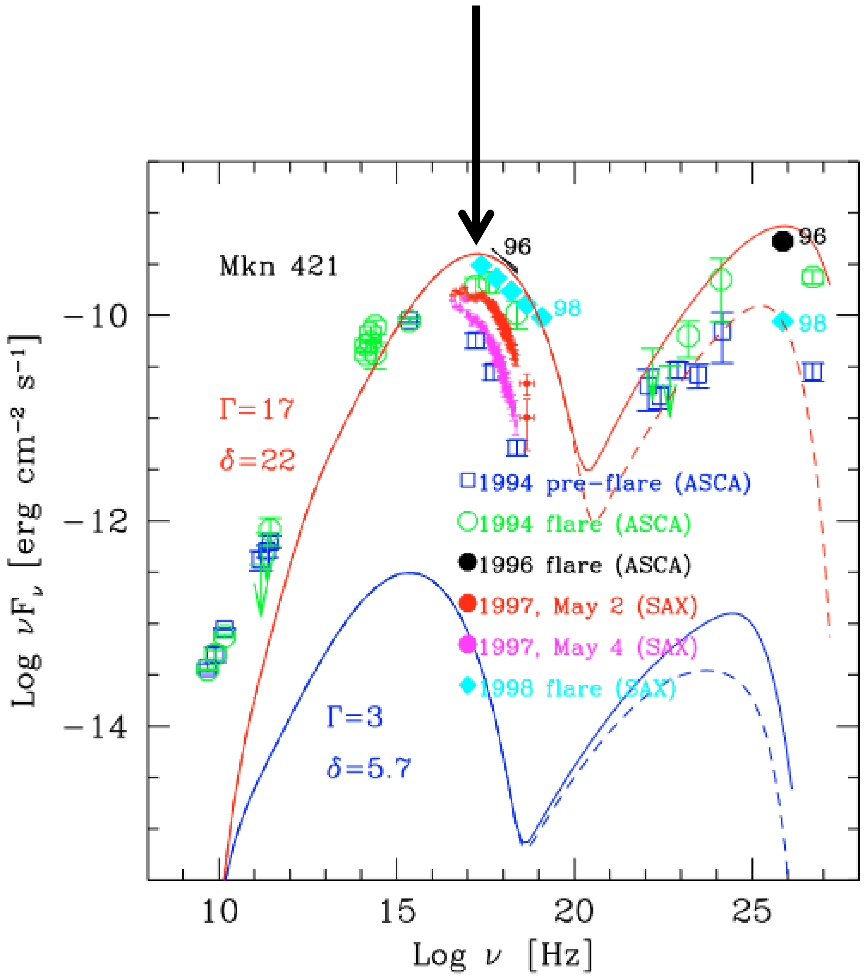
- Mostly **non-thermal**
- Presence of magnetic field → **Synchrotron** (true emission)
- Photon field → **Inverse Compton** (no "new" photons!)
- Characteristic signatures in most observations
- $P_{syn} \sim \gamma^2 U_B$, $U_B = B^2/8\pi$



SED of Cen A , Mkn 421 (Ghisellini et al. 2005)

Synchrotron





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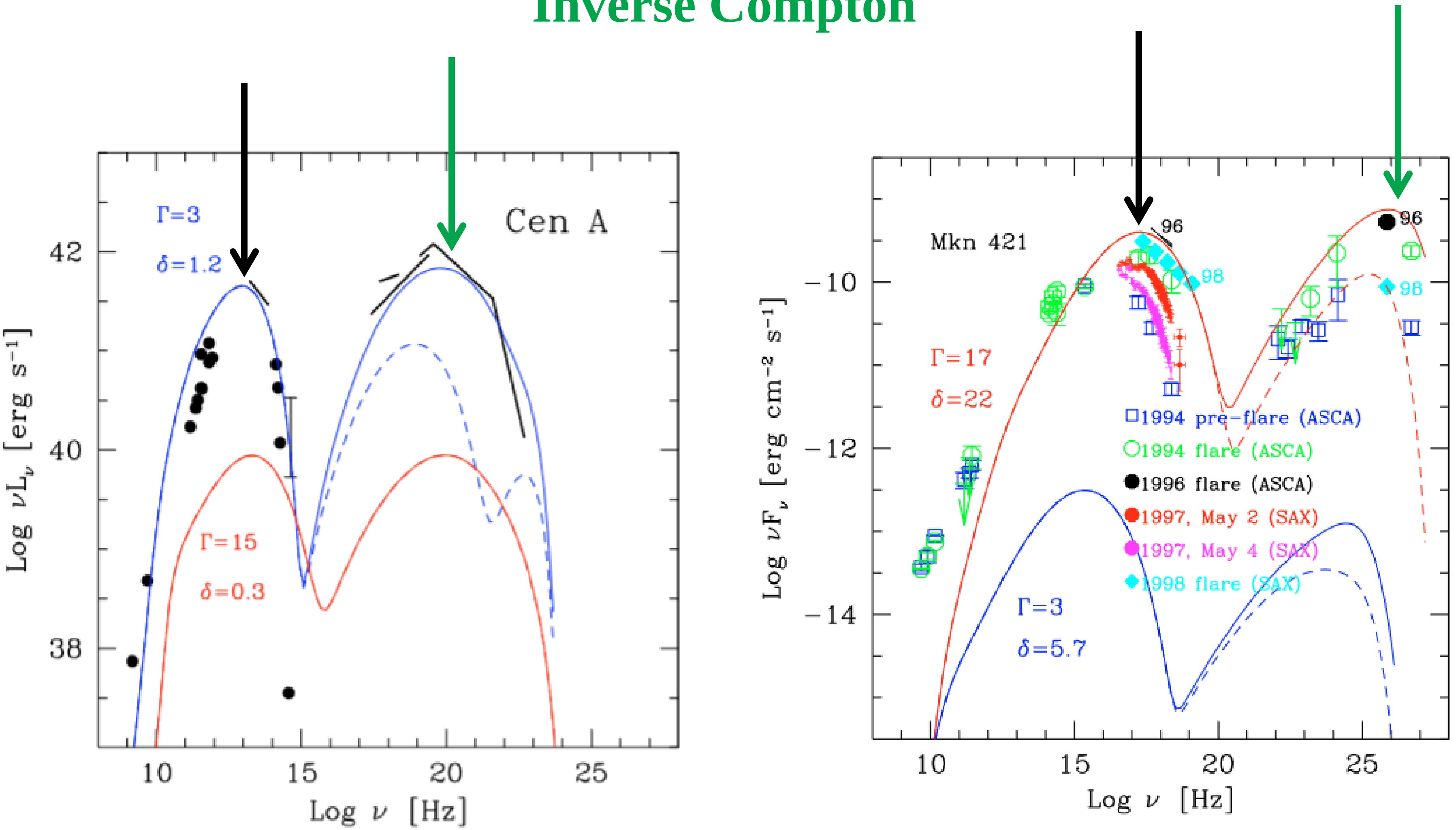
Synchrotron
Inverse Compton



SED of Cen A , Mkn 421 (Ghisellini et al. 2005)

Polarization

- Plane-wave solution of Maxwell's equations in vacuum with arbitrary polarization

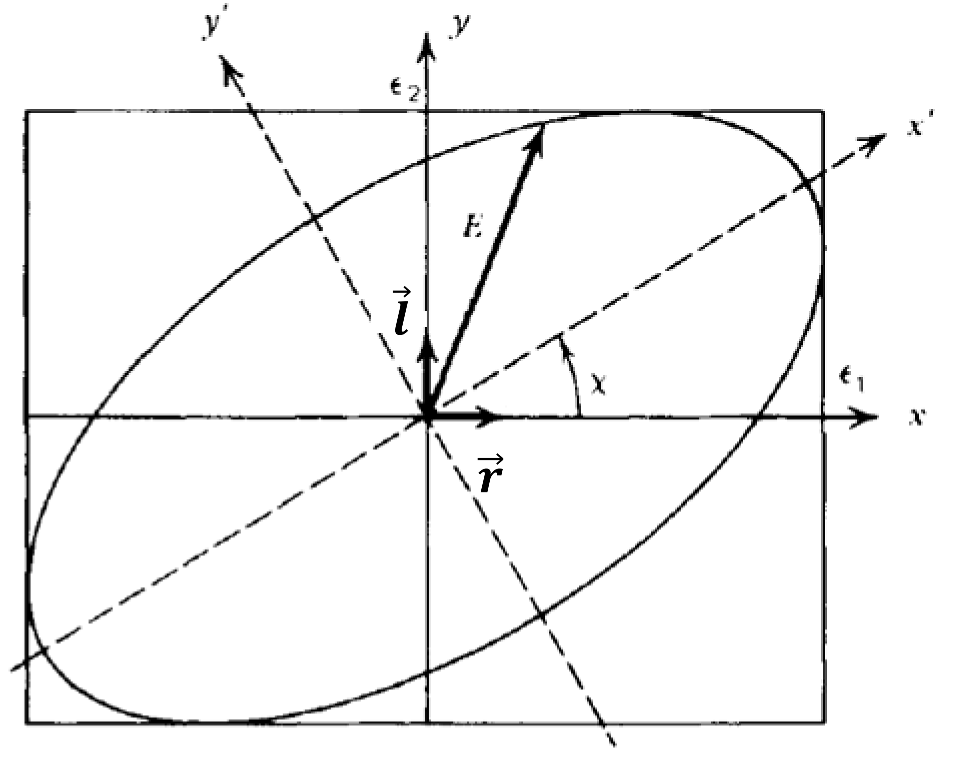
- $\vec{E}$ can be expressed as:

$$\vec{E} = Re\left[E_l \vec{l} + E_r \vec{r}\right]$$

- Direction of propagation:

$$\vec{n} = \vec{r} \text{ x } \vec{l}$$

- Geometrical shape that $\vec{E}$ creates while propagating



Stokes Parameters

- Four quantities that fully define the electric field

- These are usually expressed as:
  - $I = E_l E_l^* + E_r E_r^*$
  - Q= $E_l E_l^* - E_r E_r^*$
  - U= $E_l E_r^* + E_r E_l^*$
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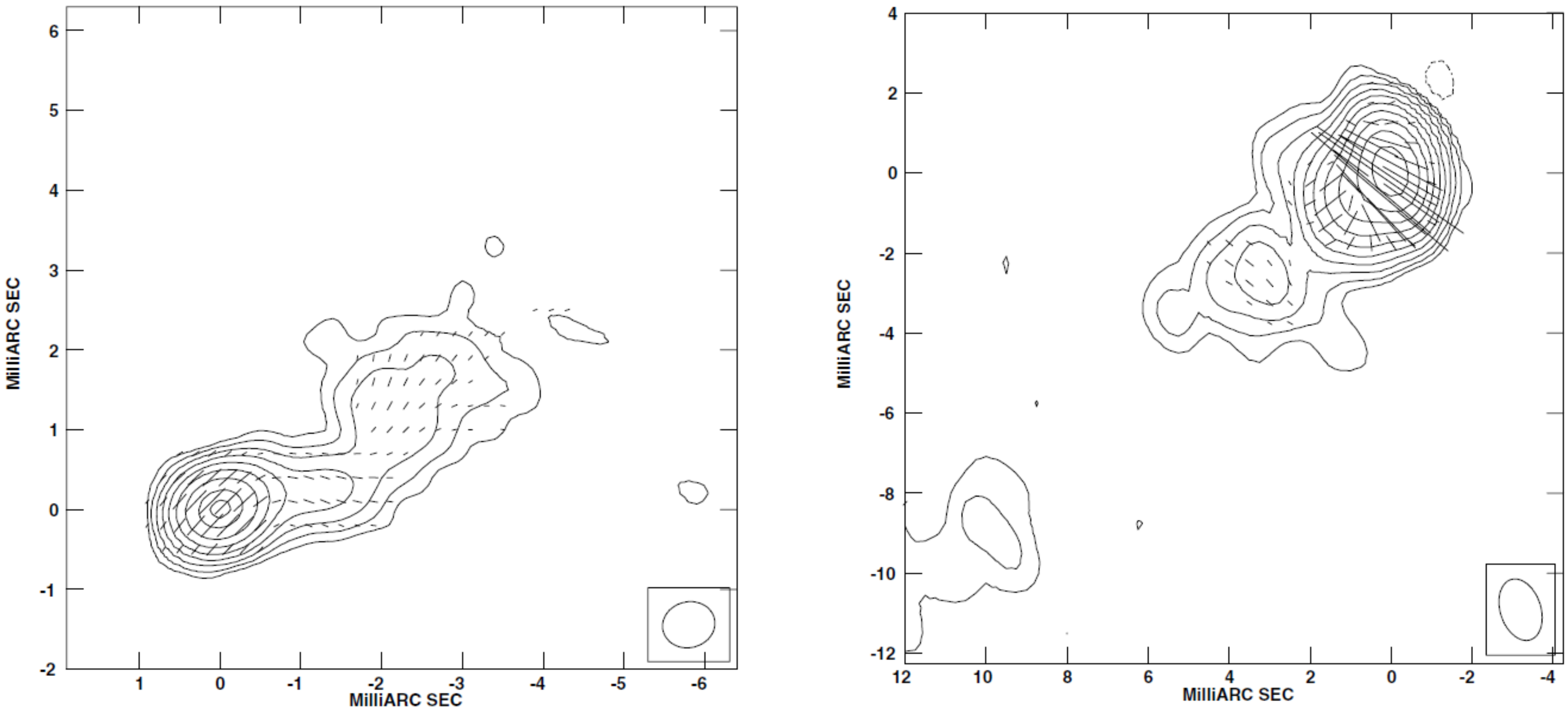
- $I^2 = Q^2 + U^2 + V^2$

Jets & Emission: What is known (?)

- General trends:
  - Roughly bimodial distribution of EVPA (∥ or ⊥ to the jet direction)
  - EVPAs generally follow the jet orientation
  - EVPAs experience ''jumps'' from orthogonal to parallel
  - Faraday rotation frequently observed

- Due to:
  - Large scale magnetic fields + shocks in the jet
  - Large scale helical magnetic fields

Examples



4cm intensity for BL Lac 1749+701 (left) and 6cm intensity for BL Lac 1418+546 (Lyutikov et al. 2005)

Ray-tracing

- Create a “ray-box” on the emitting “object”
- Calculate the Stokes parameters
- Solve the radiation transfer equation

$$\frac{d\boldsymbol{I}}{dl} = \mathcal{E} - \mathrm{A}\cdot\mathbf{I}$$

(or in the unpolarized case)

$$\frac{dI_\nu}{dl} = \varepsilon_\nu - \kappa_\nu \mathrm{I}_\nu$$

Assumptions

- Optically thin emission (no absorption, κ_ν=0)
- Circular polarization ignored (small % in observations)
- Mask the emitting region: use γ and ρ of final state
  - Consider emission from inner jet only
  - No Faraday rotation (polarization plane: constant)
- Power law for e^- distribution, $dn' \sim E'^{-p} dE'$, $p = 2.4$
  - Emissivity: $\varepsilon_\nu \sim \nu^{(p-1)/2}$
- Small viewing angle $\theta_{obs} \sim 5^o$, ν =15GHz

Calculations

- Total Intensity: Stokes I
  - Also the polarized intensity

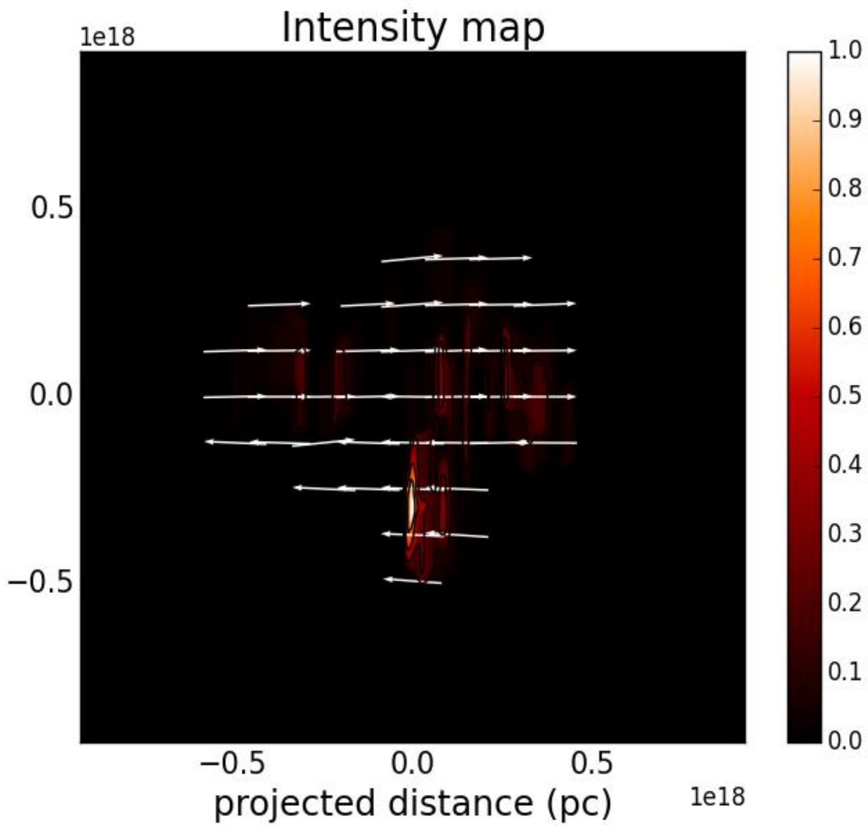
- Intensity distribution across the jet

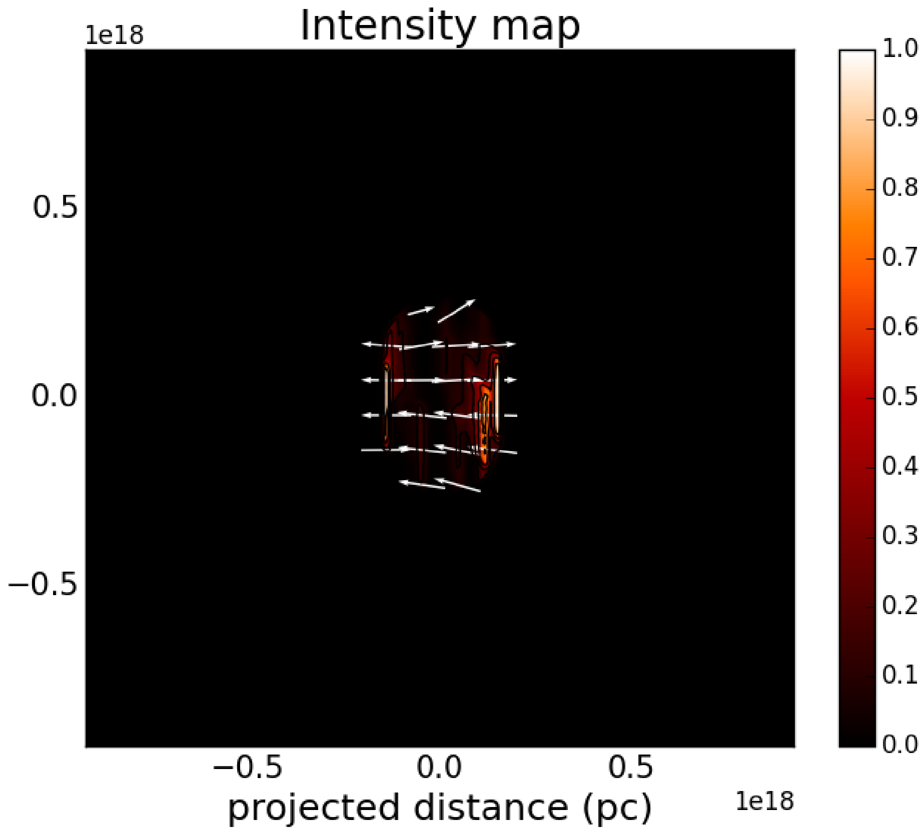
- EVPAs

$$\cos(2\chi) = \frac{Q}{\sqrt{Q^2+U^2}}, \sin(2\chi) = \frac{U}{\sqrt{Q^2+U^2}}$$

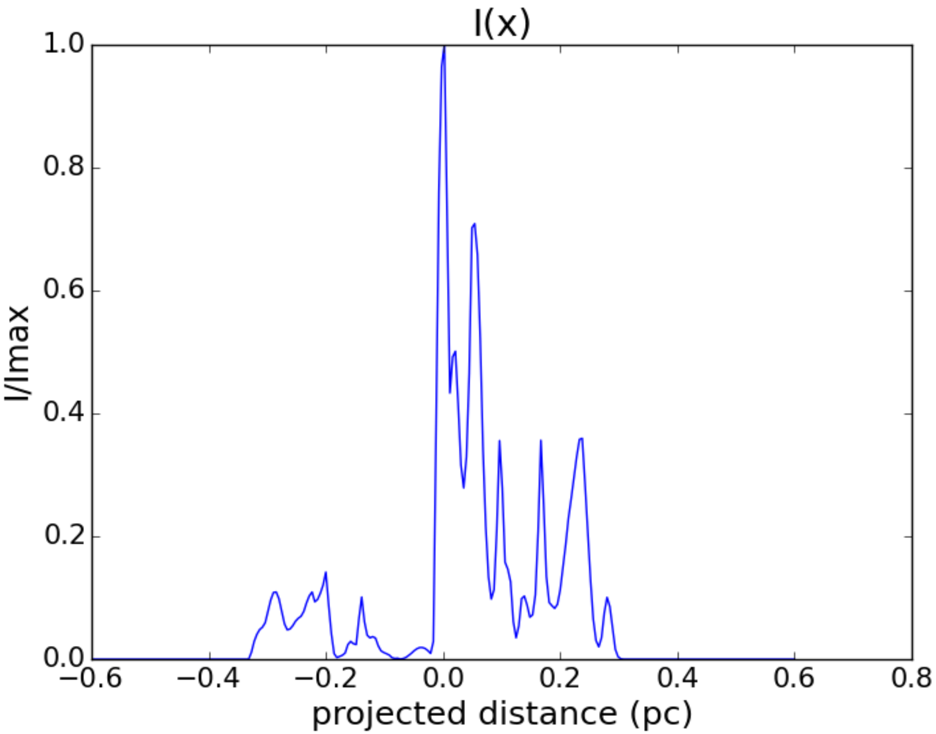
- Polarization fraction $\Pi = \frac{\sqrt{Q^2+U^2}}{I}$

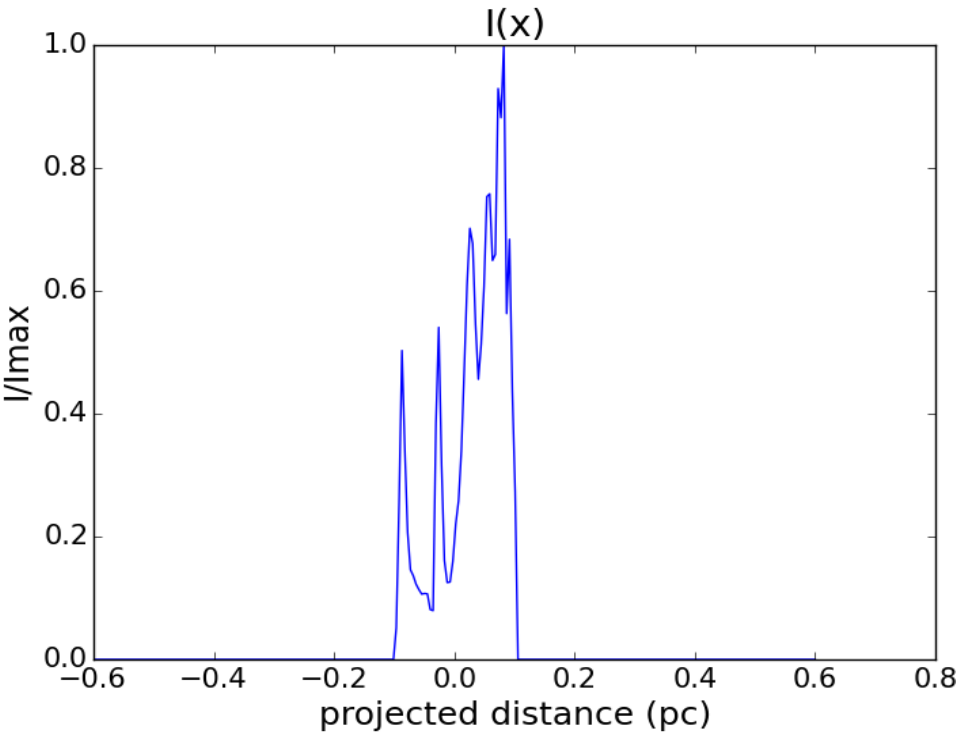
Total Intensity (final state)



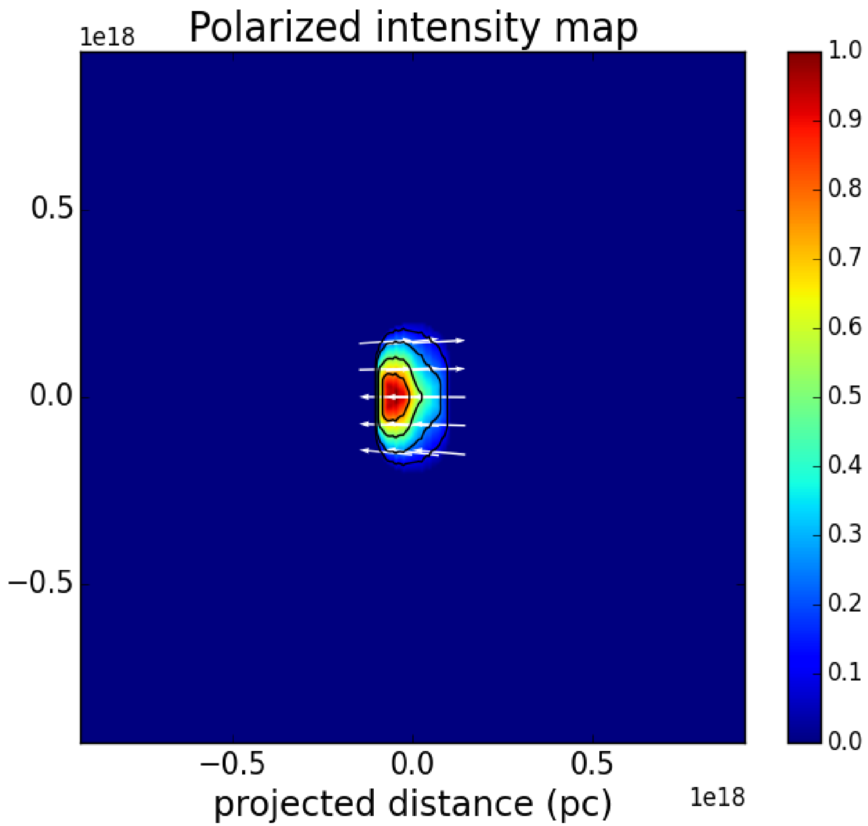


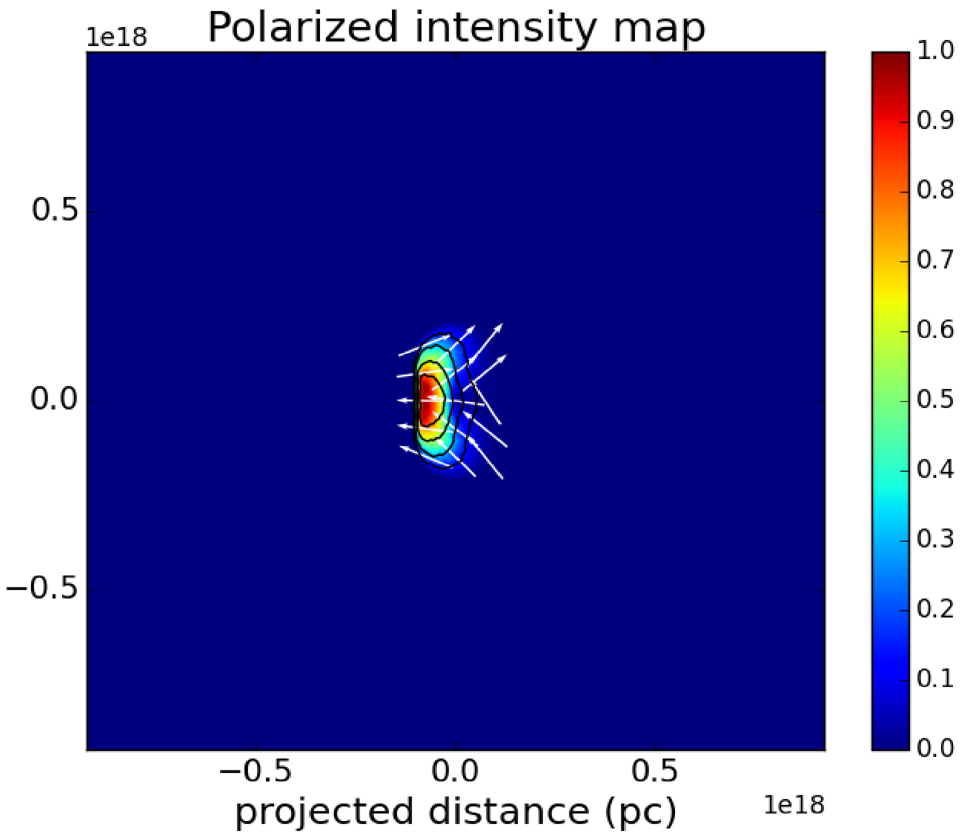
Intensity profile (final state)



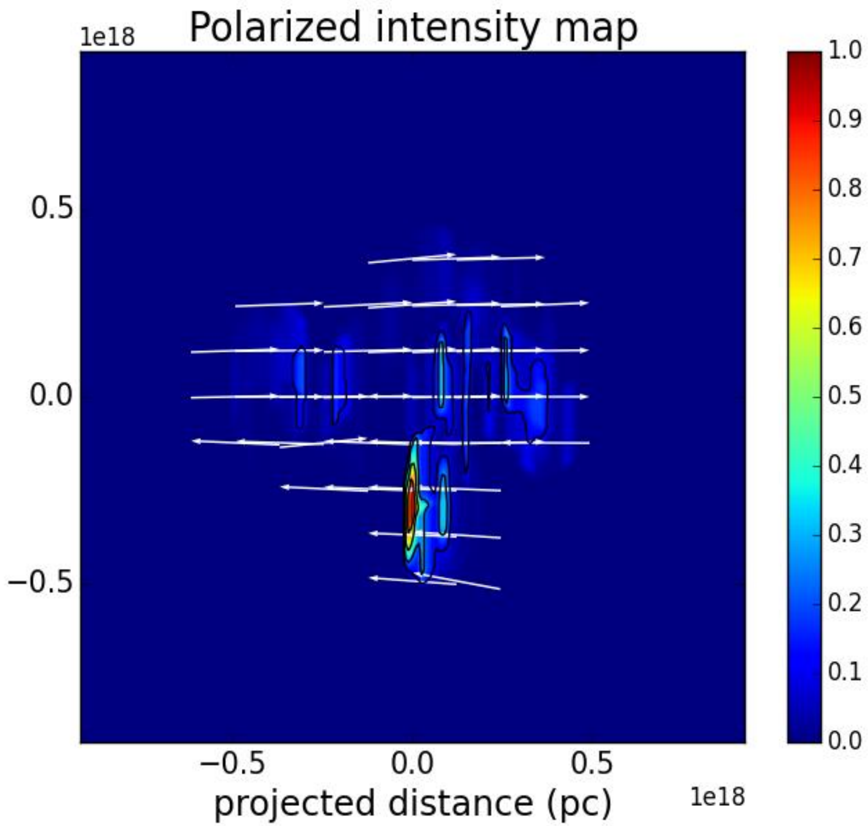


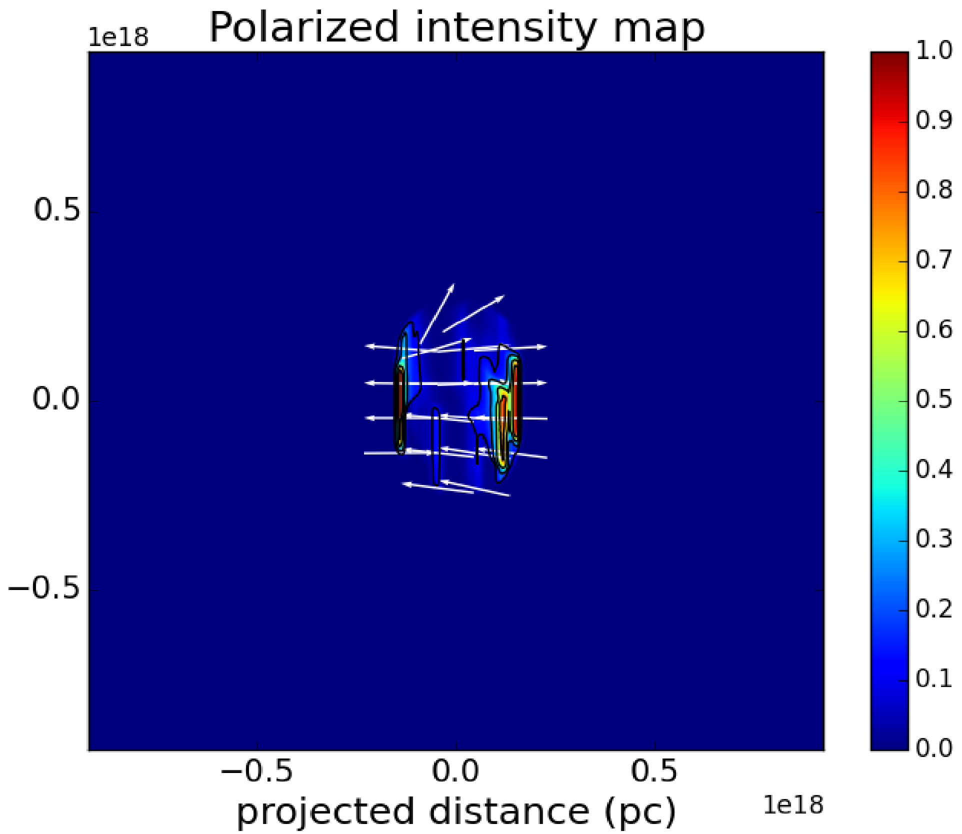
Polarized Intensity (initial state)

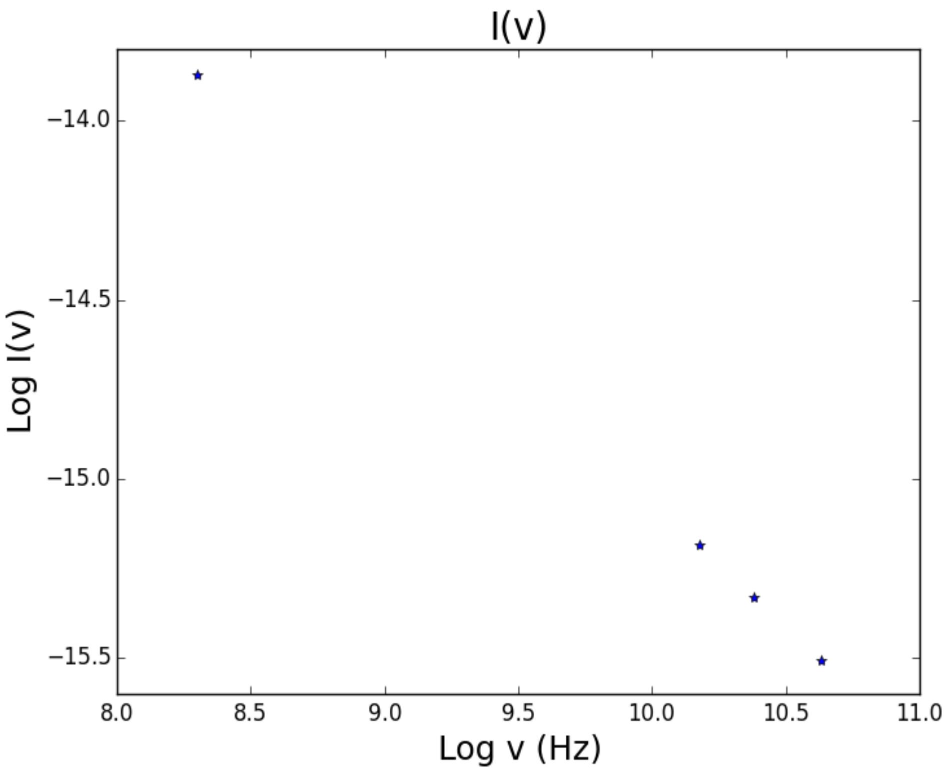


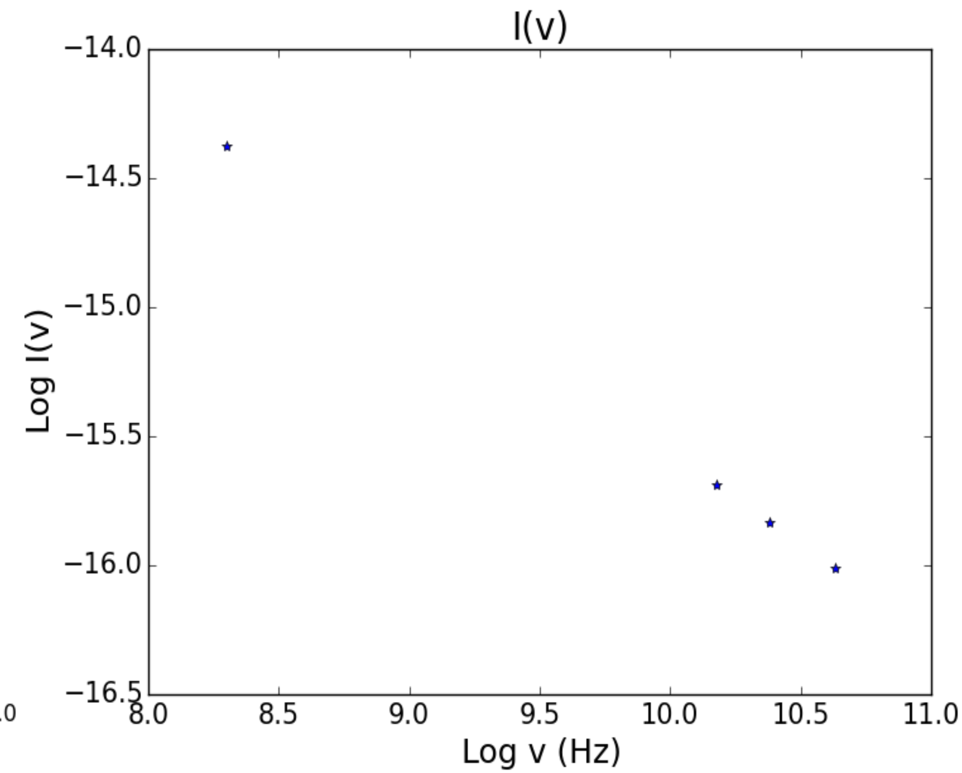


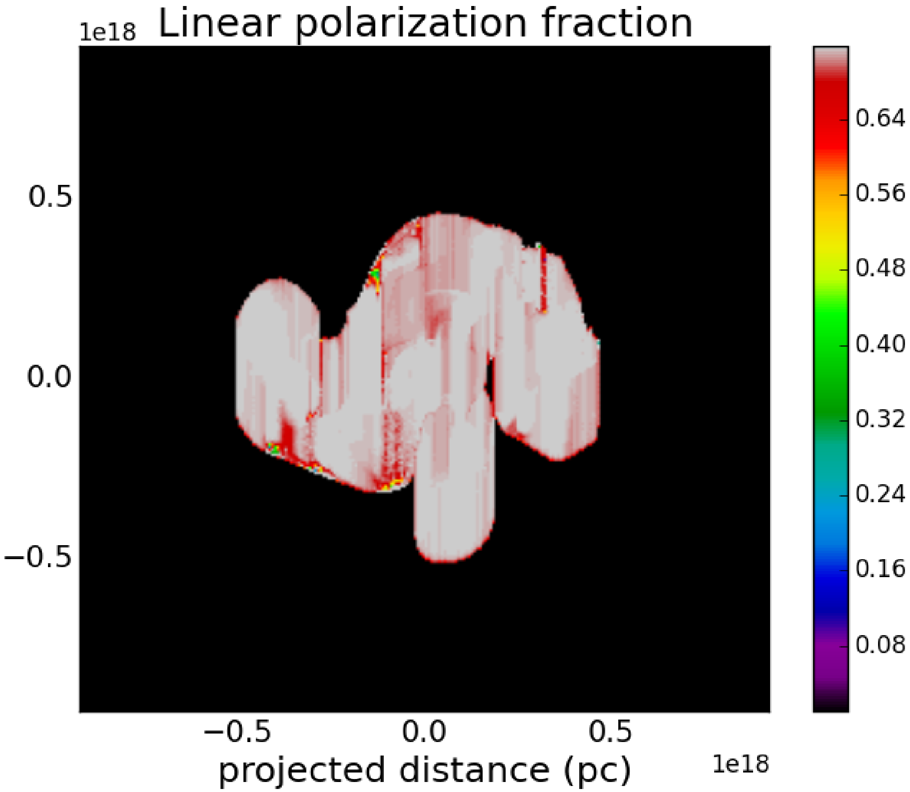
Polarized Intensity (final state)

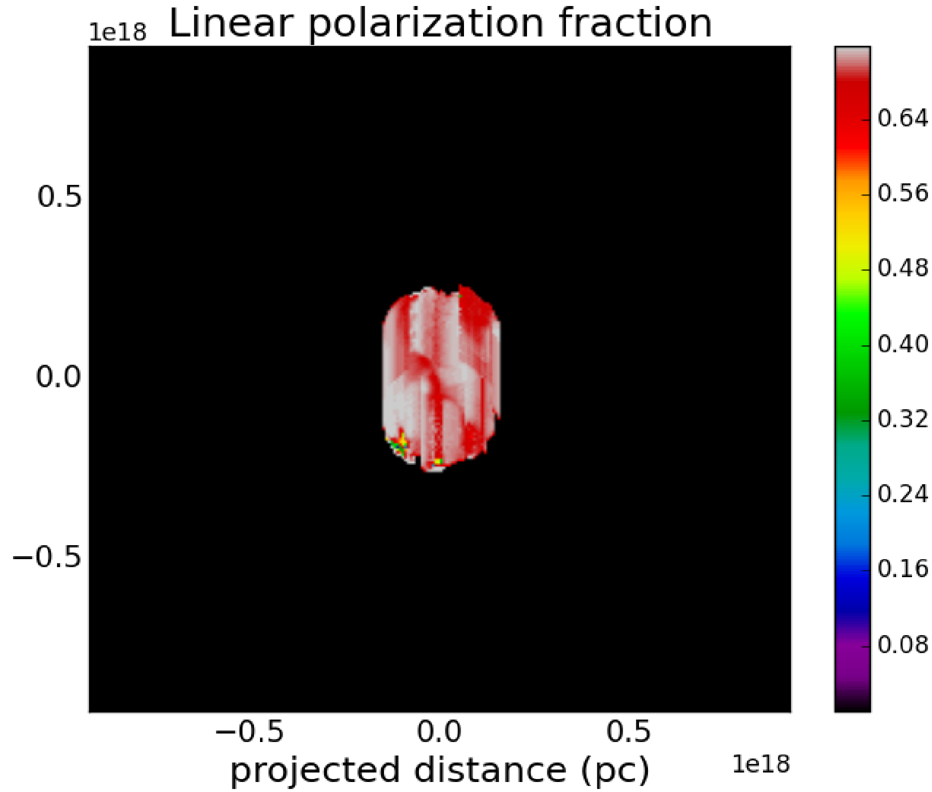





I(v)
Log I(v)
Log v (Hz)
−14.0
−14.5
−15.0
−15.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0


I(v)
Log I(v)
Log v (Hz)
−14.0
−14.5
−15.0
−15.5
−16.0
−16.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0





Close to theoretical max $\Pi \sim 70\%$ (for $p = 2\text{-}3$)
for **ordered** fields

Results

- Stability has an effect on the emission pattern
  - B field remains ~ helical in stable cases
  - Mixing important (extended emitting region in unstable cases)

- General tendencies present also in our radiation maps
  - EVPA mostly **perpendicular** to the jet axis
  - EVPA "jumps", mostly near the interface (for larger θ_{obs})

- Max polarization fraction Π ~ 70%
  - in σ=0.001 (as B_p dominant)
  - in σ = 0.1 (sensitive to mask, θ_{obs} !)

Next steps…

- Include absorption & check spectral index
  - Absorption modifies p !
  - Regions with different optical depth $\tau < 1$, $\tau \sim 1$, $\tau > 1$
  - Thermal absorption vs other mechanisms (e.g. SSA)

- Different masking of emitting regions
  - Changes in Π
  - Use outer jet as "Faraday sheath"

- Examine different distributions (e.g. Kappa ?)

- Implement Inverse Compton & SEDs ?