Theoretical Review of Outflow Phenomena from High Energy Systems

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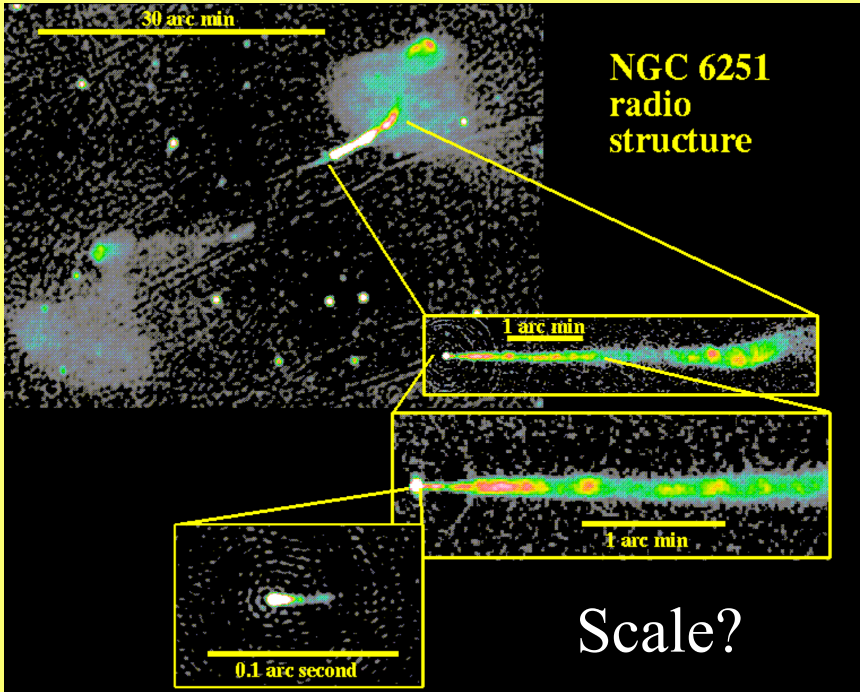
Phenomenology

Some Issues

- **Anatomical**
  - Multi-frequency jet structure
  - Kinematics
  - Composition
- **Physiological**
  - Emission mechanisms
  - Pressures and powers
  - Confinement
- **Sociological**
  - Counts, LF, multivariate properties
  - Backgrounds

The Bigger Picture

- Prime Mover?
  - Protostars, stars, superstars, supernovae, pulsars… holes
- Black Hole Engineering?
  - Energy flow: disks or holes to jets
  - Mechanism: (Electro)magnetic vs gas, Accretion vs spin?
- Galaxy Formation, Evolution/Feedback
  - Major vs Minor mergers
  - Gas vs Stars
  - AGN vs Starbursts
  - Jets vs Winds
- Environmental impact
  - (Re-)ionization
  - Cluster evolution…



Ten Challenges

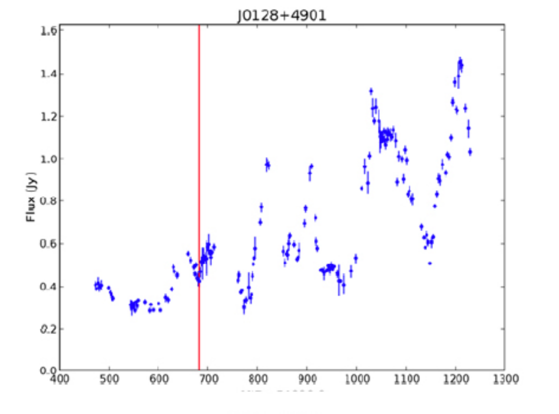
1. Locate the sites of radio, γ emission
2. Map jet velocity fields and causality
3. Verify the emission mechanism
4. Understand the changing composition
5. Measure external pressure
6. Deduce jet confinement mechanism
7. Infer jet powers, thrusts
8. Test Central Dogma
9. BHGRMHD capability
10. Quantify role in clusters

Ten Challenges

1. Locate the sites of radio, γ emission -10-10^6m!
2. Map jet velocity fields and causality – $\gamma\,\theta$=?
3. Verify the emission mechanism – S, C^{-1}, maser?
4. Understand the changing composition – EM -> L -> H
5. Measure external pressure – ISM, CGM, IGM
6. Deduce jet confinement mechanism – B or P?
7. Infer jet powers, thrusts – L_{jet} , L_{wind} / L_{bol}?
8. Test Central Dogma - M, M'/M, ΩM => intrinsic properties
9. BHGRMHD capability – add microphysics
10. Quantify role in clusters – environmental impact

Observation and Simulation

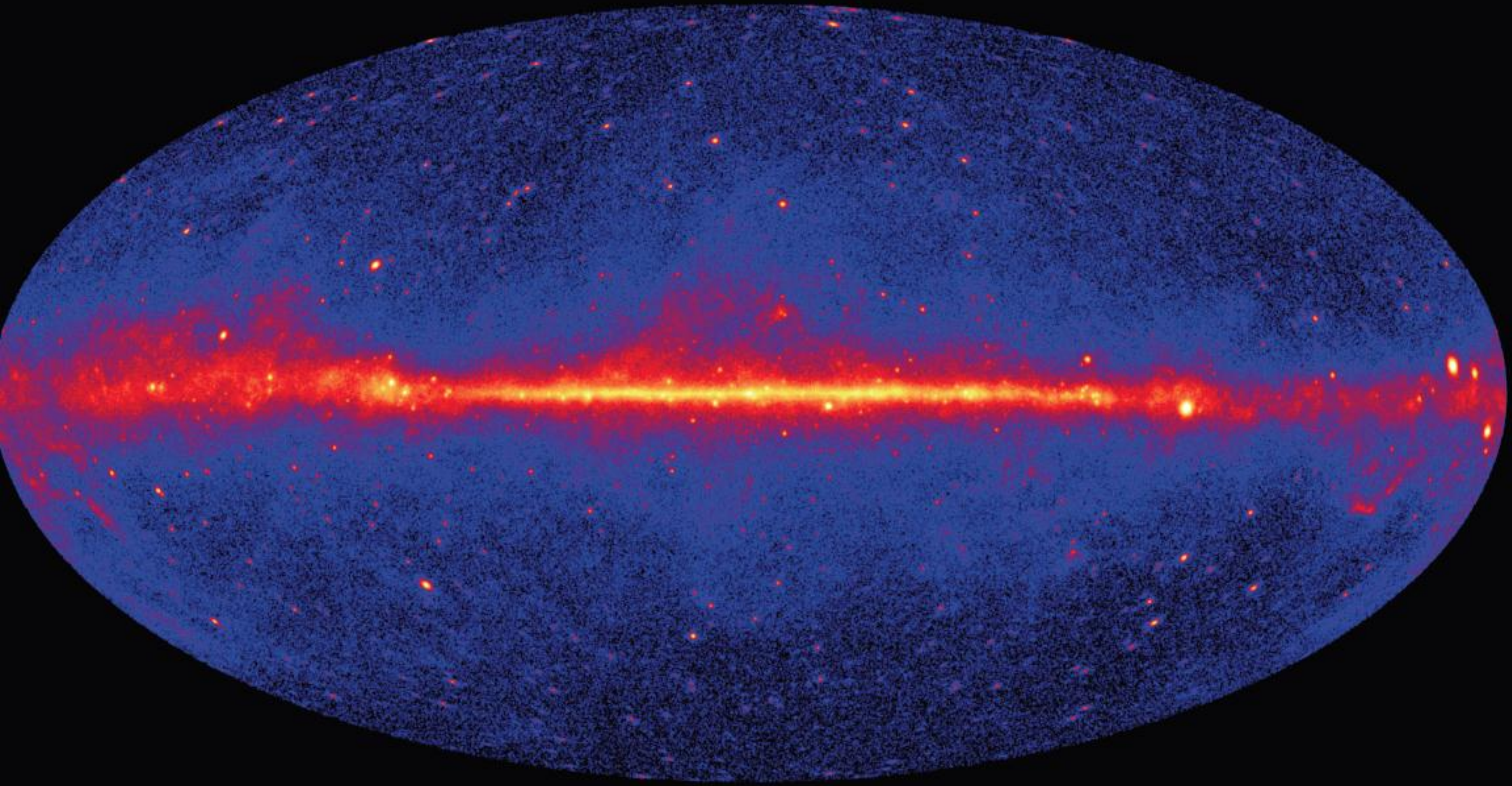
- FGST, ACT…OP…Radio, ν all working well
- N~1000 sources sampled hourly-weekly
- Large data volumes justify serious statistical analyses of multi-λ data
  - Irregular sampling, selection effects
  - Work in progress



- Account for Extreme Jets
  - Most variable, fast, bright, polarized…
- Modeling must match this increase in sophistication
- Simulations are now becoming available
  - Understand kinematics, QED, fluid dynamics
  - Ignorant about particle acceleration, transport, radiation, field evolution

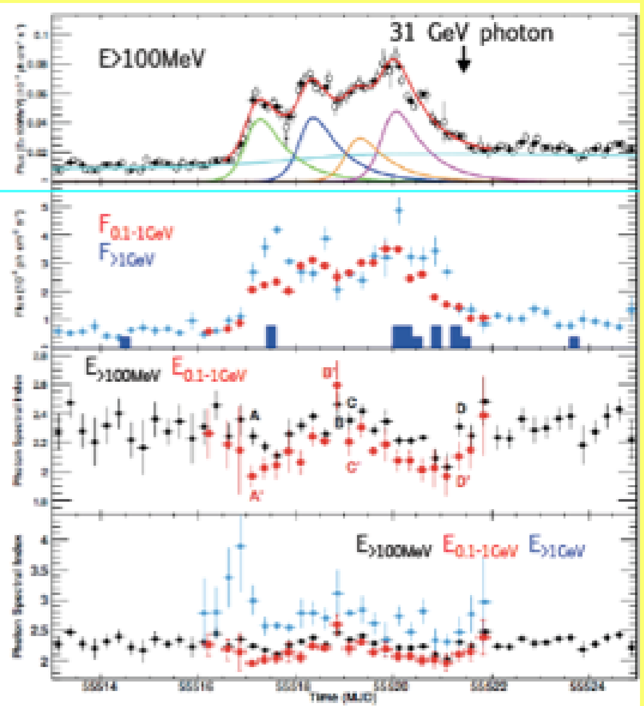
Physical assumptions ⇄ *Simulation* ⇄ **Statistics** ← *Analysis* ← Observations

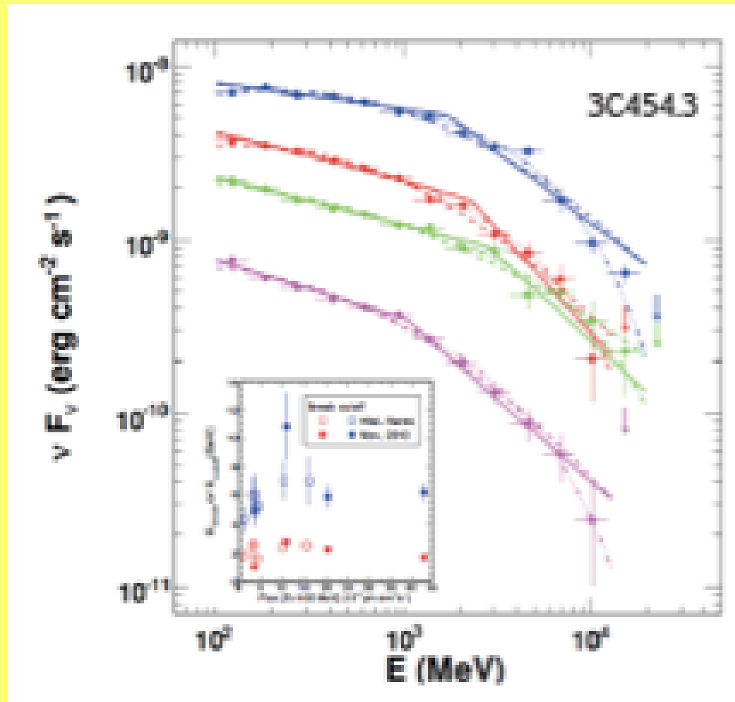
Latest Photon Intensity Map

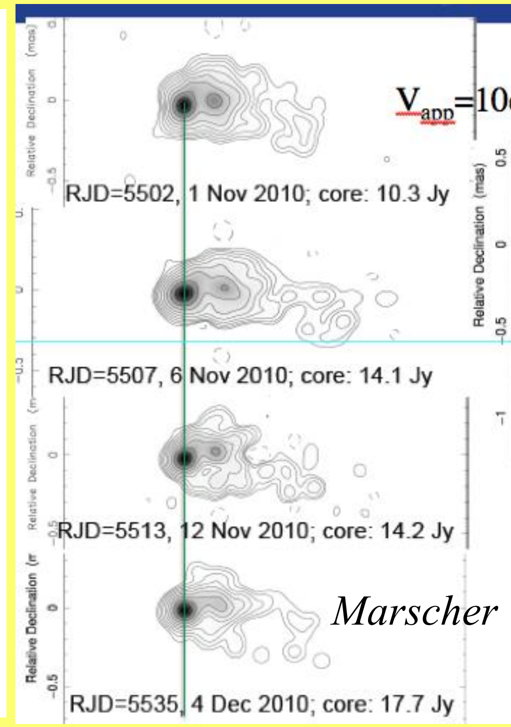


832AGN+268Candidates+594Unidentified!

3C454.3



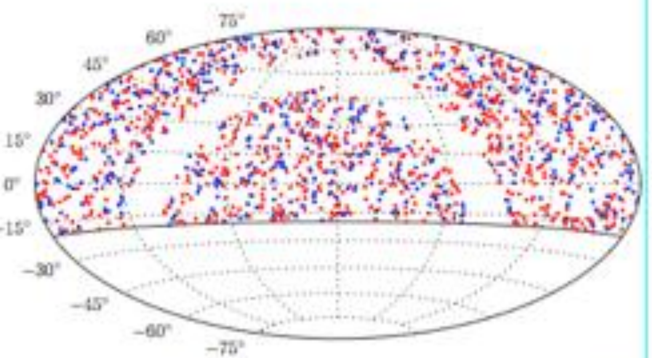




$2\mathrm{x}10^{50}$erg s^{-1} isotropic

Radio Monitoring (OVRO 40m)

- ~1500 sources
- Radio and γ-ray active
- Spectrum, polarization



Distribution of CGRaBS sources in equatorial coordinates.
Red circles CGRaBS, Blue circles 1LAC

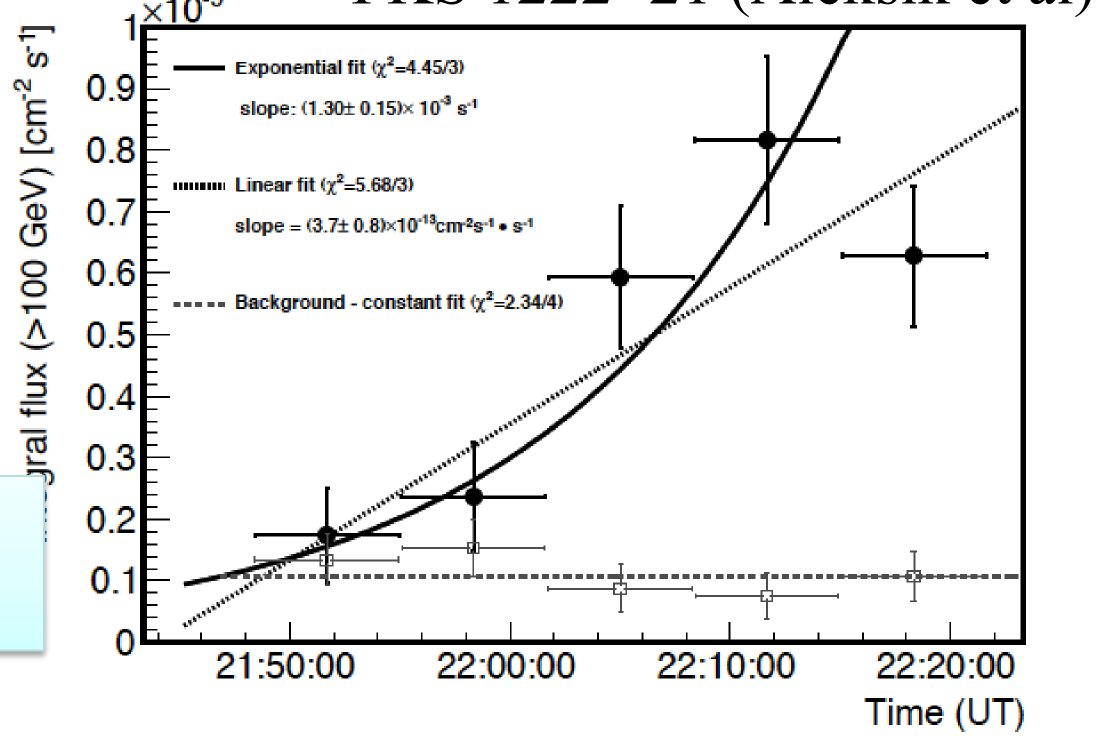
Max-Moerbeck etal

Rapid MAGIC variation

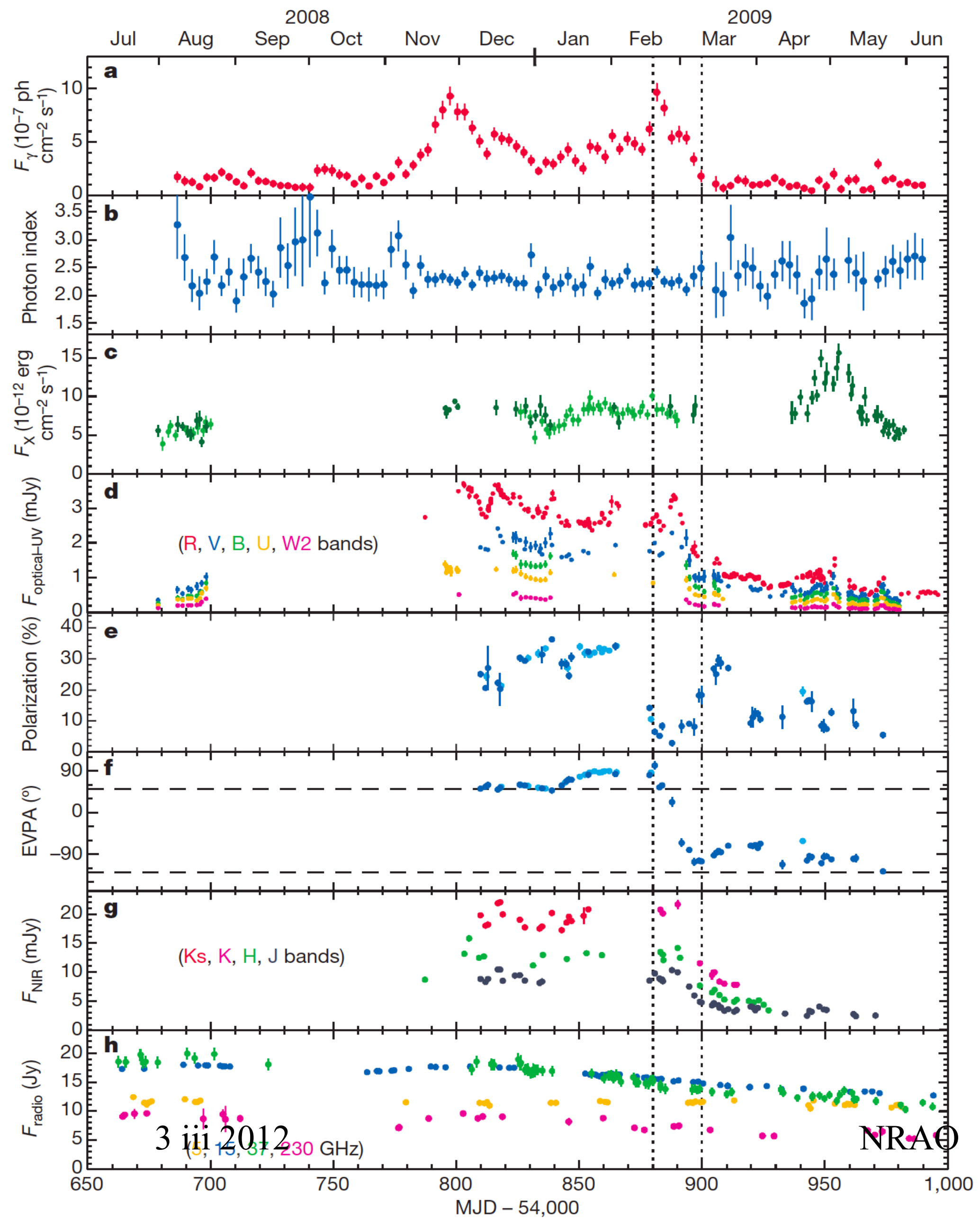
- **PKS 1222+21**
  - 10 min
- **MKN 501**
  - 2min?
- **PKS 2155-304**
  - "Few hr"?

How typical?
How fast is GeV variation?

PKS 1222+21 (Aleksik et al)



3C 279: multi-λ observation of γ-ray flare



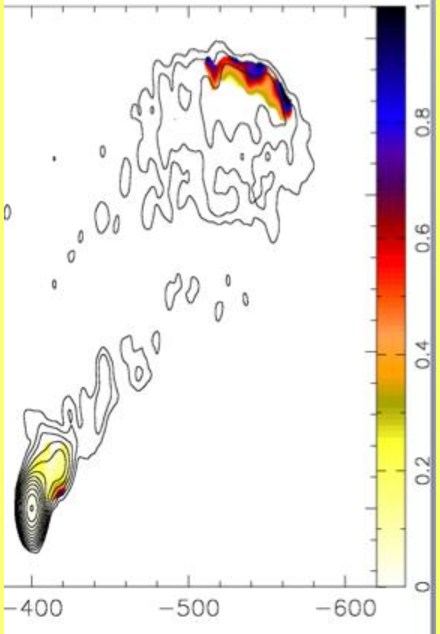
- ~30percent optical polarization => well-ordered magnetic field
- τ~ 20d γ-ray variation
  => $r \sim \gamma^2 c\tau$ ~ pc or τ_{disk}?
- Correlated optical variation? => common emission site
- X-ray, radio uncorrelated => different sites
- Rapid polarization swings ~200^o => rotating magnetic field in dominant part of source

r ~ 100 or 10^5 m?

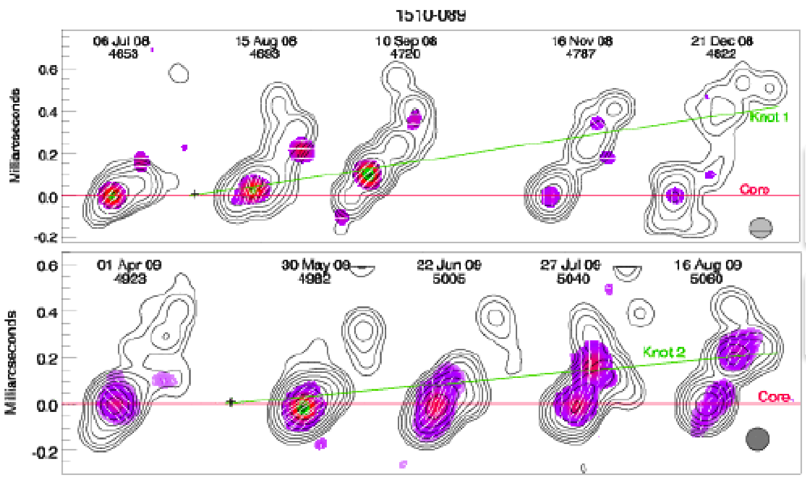
Abdo, et al Nature, 463, 919 (2010)

PKS1510+089

(Wardle, Homan et al)



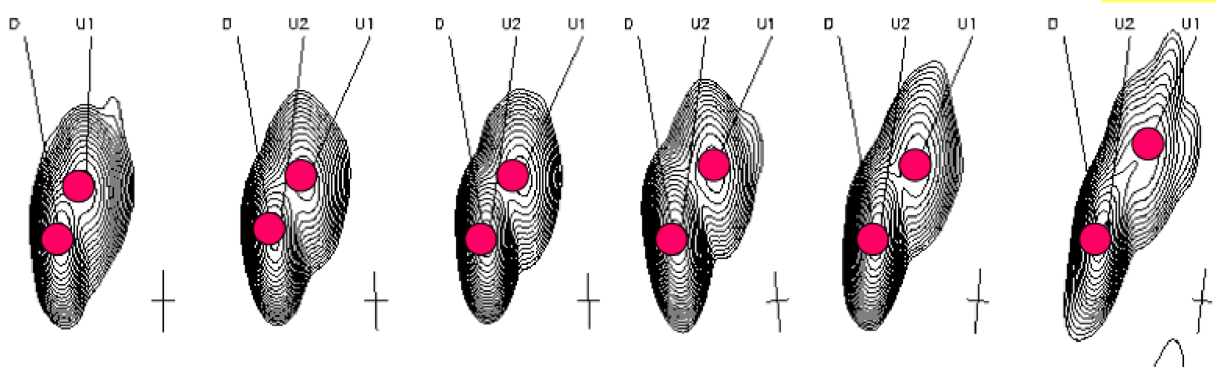
43 GHz VLBA Images of PKS 1510-089



$\beta_{app}=45$

z=0.36

Two bright superluminal blobs emerged during the outbursts in brightness during the 2nd half of 2008 & the 1st half of 2009



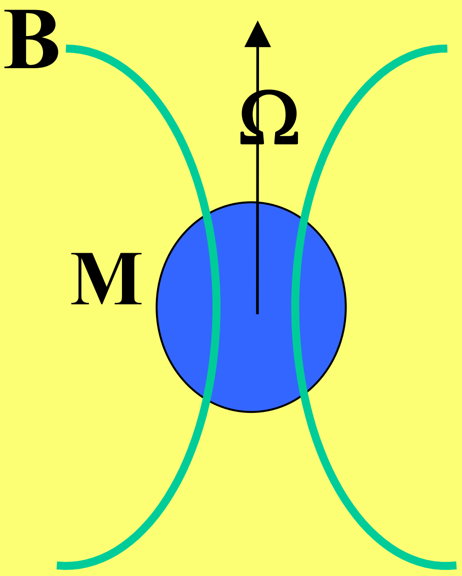
- Rapid swings of jet, radio position angle
- High polarization ~720° *(Marscher)*
- Channel vs Source
- TeV variation *(Wagner / HESS)*
- EBL limit
- r_{min} ; $r_{TeV}>r_{GeV}$ *(B+Levinson)*

Theory and Simulation

Flow Descriptions

- Hydrodynamics
  - Inertia, isotropic P, strong shocks,
  - Efficient impulsive acceleration
- Force Free
  - No inertia, anisotropic P, no shocks
  - Electrostatic and stochastic acceleration
- Relativistic MHD
  - Mixture of both,
  - Relativistic reconnection acceleration

Unipolar Induction



- Rules of thumb:
  - $\Phi \sim B R^2$; $V \sim \Omega \Phi$;
  - $I \sim V / Z_0$; $P \sim V I$

	PWN	AGN	GRB
B	100 MT	1 T	1 TT
Ω/2	10 Hz	10 μHz	1 kHz
R	10 km	10 Tm	10 km
V	3 PV	300 EV	30 ZV
I	300 TA	3 EA	300 EA
P	100 XW	1 TXW	10 PXW

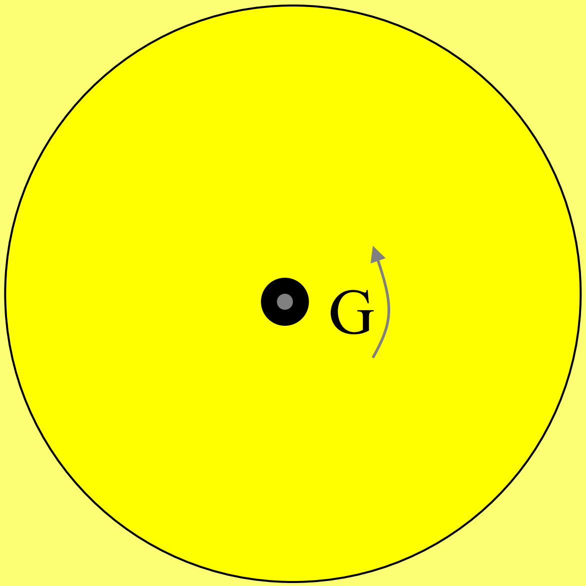
UHECR!

Intermediate Mass Supply

- Thin, cold, steady, slow, radiative disk
- Specific energy e = -Ωl/2

$$G - M'\ell = const \approx 0$$

$$\frac{dL}{dr} = \frac{d(\Omega G - M'e)}{dr} \approx 3M'\frac{de}{dr}$$



Energy radiated is 3 x the local energy loss

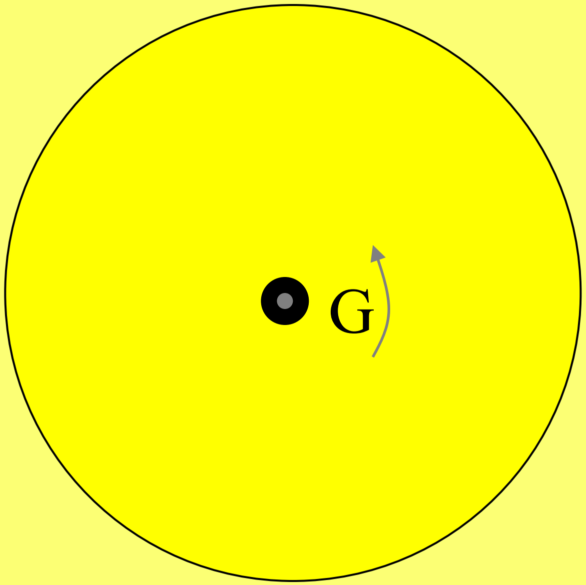
Low, High Mass Supply

- M'<<M'$_E$, tenuous flow cannot heat electrons and cannot cool
- M'>>M'$_E$, dense flow traps photons and cannot cool
- Thick, hot, steady, slow, adiabatic disk
- Bernoulli function: b =e+h

$$G - M'\ell \approx 0$$

$$\Omega G - M'b \approx 0$$

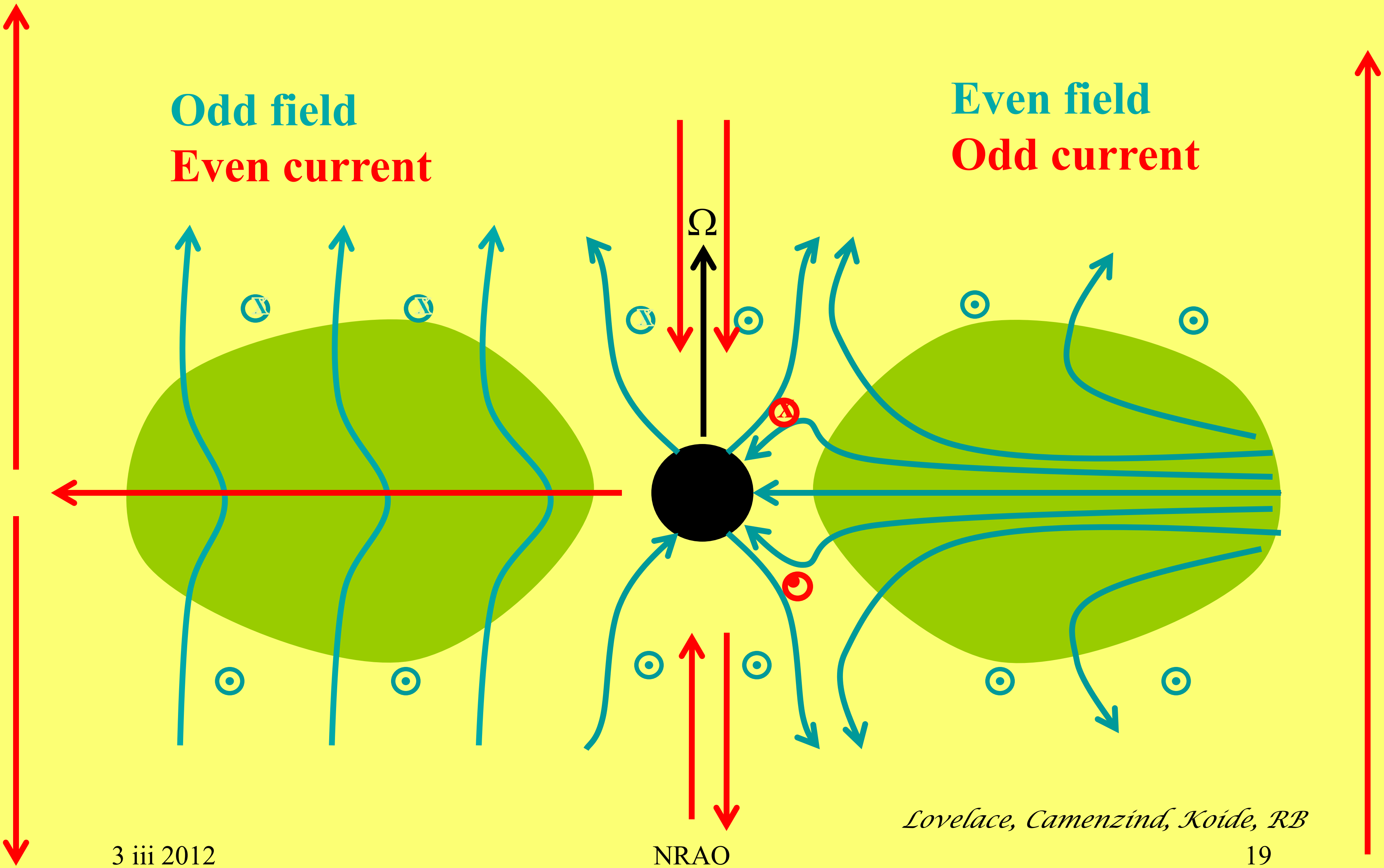
$$\Rightarrow b \approx -2e > 0$$



Energy transported by torque unbinds gas => outflow

ADiabatic Inflow-Outflow Solution

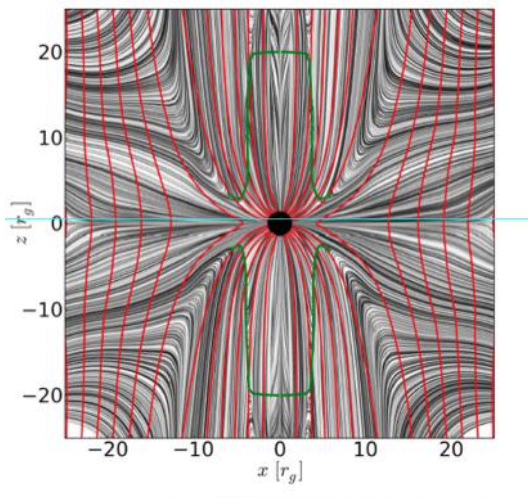
Dipolar vs Quadrupolar

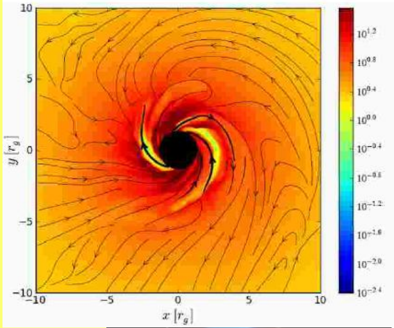


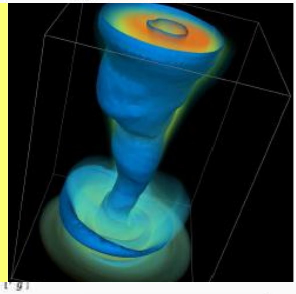
Lovelace, Camenzind, Koide, RB

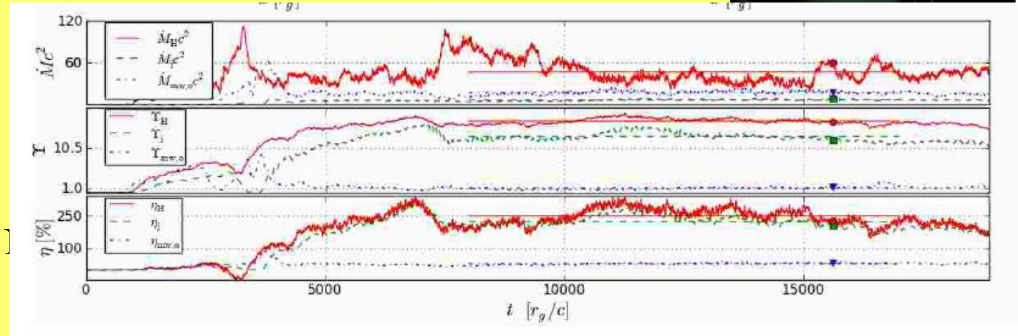
3D GRMHD Simulations

- $>10^5$m Kerr-Schild, HARM, 512x768x64
  - Quasi-steady state
- Build up flux –back reaction
  - Thick spinning disks, suppress MRI
  - Dipolar not quadrupolar
- Efficient extraction of spin energy-> jets
  - Prograde not retrograde
- Wind outflows
  - Poorly collimated, slow
- QPOs,
  - ~70m, a~ 0.9; Q~100 (jet) ~3 (disk)
- Strong intermittency
  - Helical instability m=1









3 iii 2012

McKinney, RB;
McKinney, Tschekovskoy, RB

General Inferences

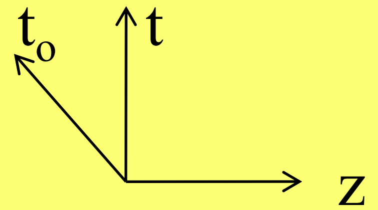
- FRII/FSRQ?
  - a>0.9
    - Hole powered
  - Long range order in field
    - Groups not clusters, few mergers
  - Thick disk?
    - Large mass relative to mass supply rate
  - Low gas density
    - Ellipticals not spirals

What happens to radial/horizontal field?
Is polarity maintained along jet?

General Inferences II

- **FRI/BL Lac**
  - **a<0.9**
    - Disk powered
  - **Short range order in field**
    - Many mergers, spin according to FP equation with deceleration (Hughes & B)
  - **Thick disk**
  - **Low gas density**

"Observing" Simulated Jets Synchrotron Radiation

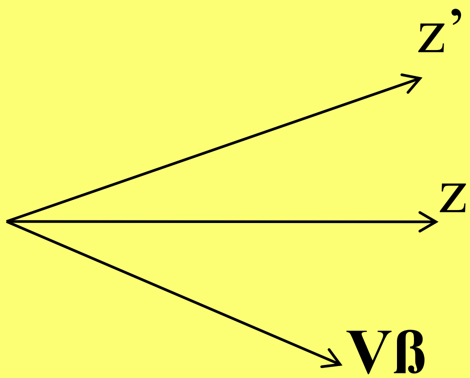


- We know P', B', N', V on grid
- Work in jet frame
- Rotate spatial grid so that observer along z direction
- Shear in t – z space introducing t_o=t-z

$$I_{\nu\Omega}(\nu,t_o) = \int dz\,\delta^2 j'_{\nu'\Omega'}(\nu/\delta,t_o)\,e^{-\int dz\,\delta^{-1}\kappa'(\nu/\delta,t_o)}$$

$$\delta = \frac{1}{\gamma(1-V_z)}$$

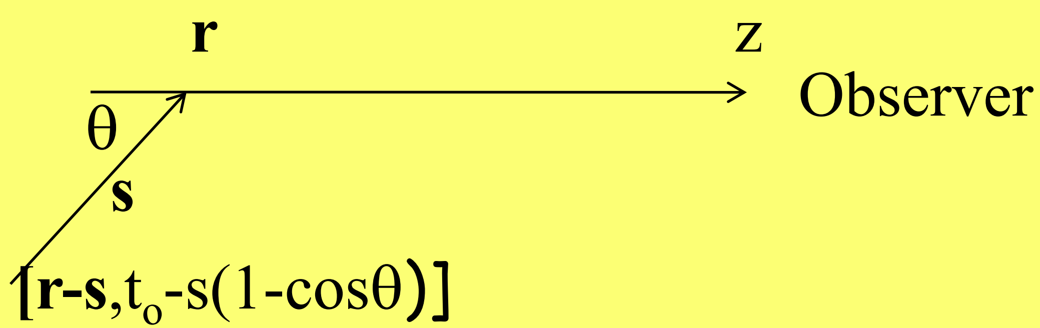
$$S_\nu(\nu,t_o) = \frac{1}{ad^2}\int dxdy\,I_{\nu\Omega}(\nu,t_o)$$



- Make emission model
  - eg $j' \sim P'\,B'^{3/2}\nu\square^{-1/2}$; $\kappa\square \sim P'B'^{2}\nu\square^{-3}$
- Polarization – perpendicular to projected field in cm frame

"Observing" Simulated Jets Inverse Compton Radiation

- Work in jet frame
- Compute incident radiation along all rays from earlier observer times
- Compute $j_{\nu\Omega}$ directly



"Observing" Simulated Jets Pair Opacity

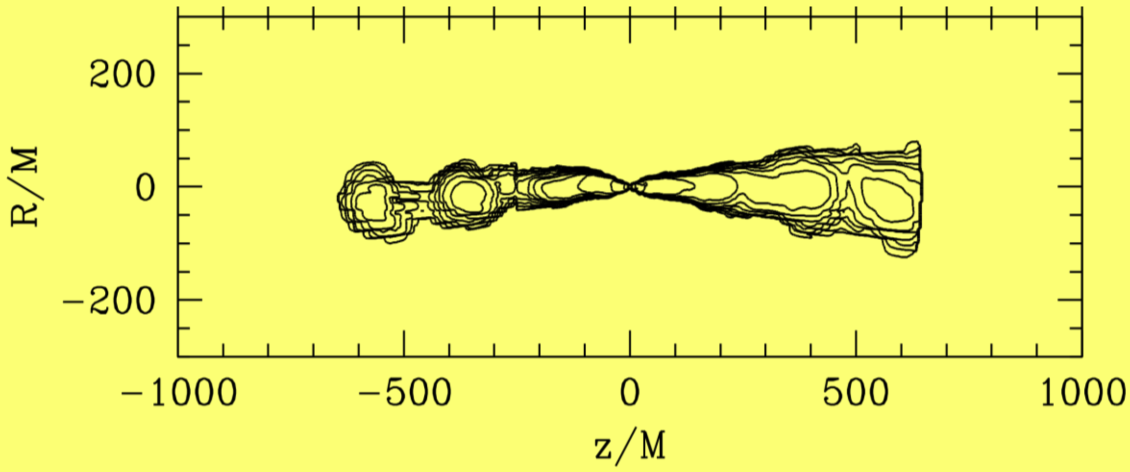
- External and internal radiation
- Internal radiation varies

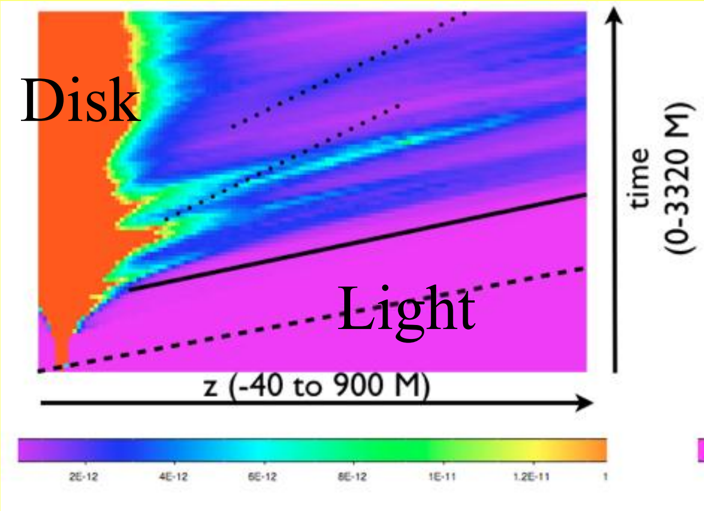
$$\kappa = \int ds\, d\Omega\, d\nu\, N_{\nu\Omega}(\vec{r} - \vec{s}, t_o - s(1 - \cos\phi), \nu)\, \sigma_{PP}(1 - \cos\phi)$$

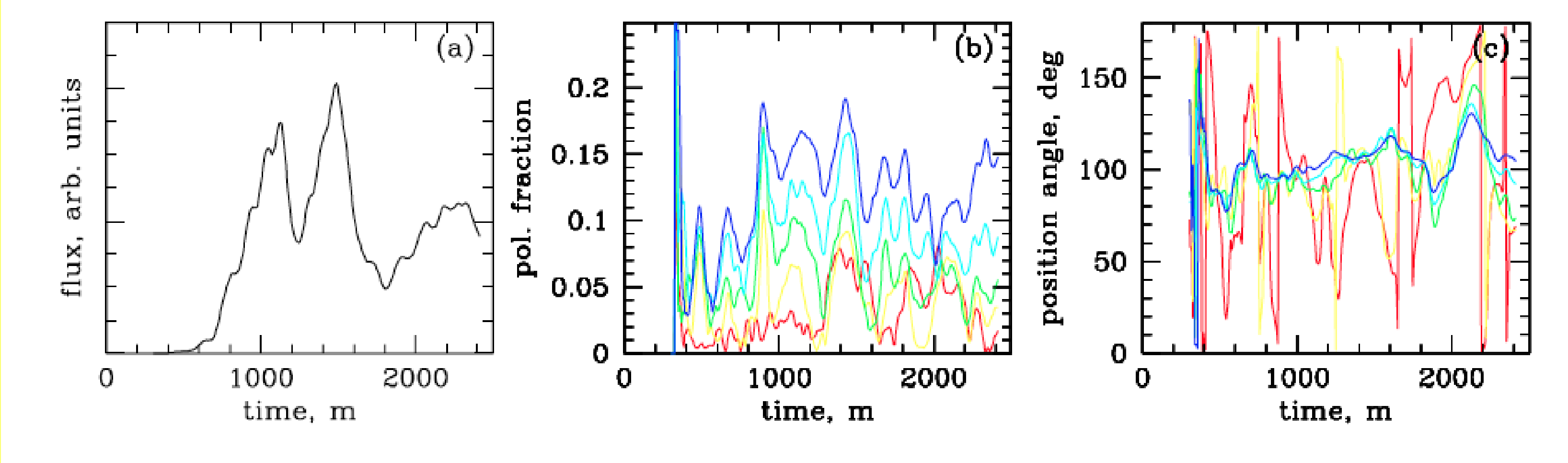
Quivering Jets

- Observe γ-rays (and optical in 3C279)
- Gammasphere $\tau_{\gamma\gamma}$~1, 100-1000m ~ Eγ
- Rapid variation associated with convected flow of features (2min in Mkn 501)
- Slow variation associated with change of jet direction on time scale determined by dynamics of disk (precession?) or limited by inertia of surrounding medium or both as with m=1 wave mode.

Optical emission from jet with $\gamma \sim$ 3-4

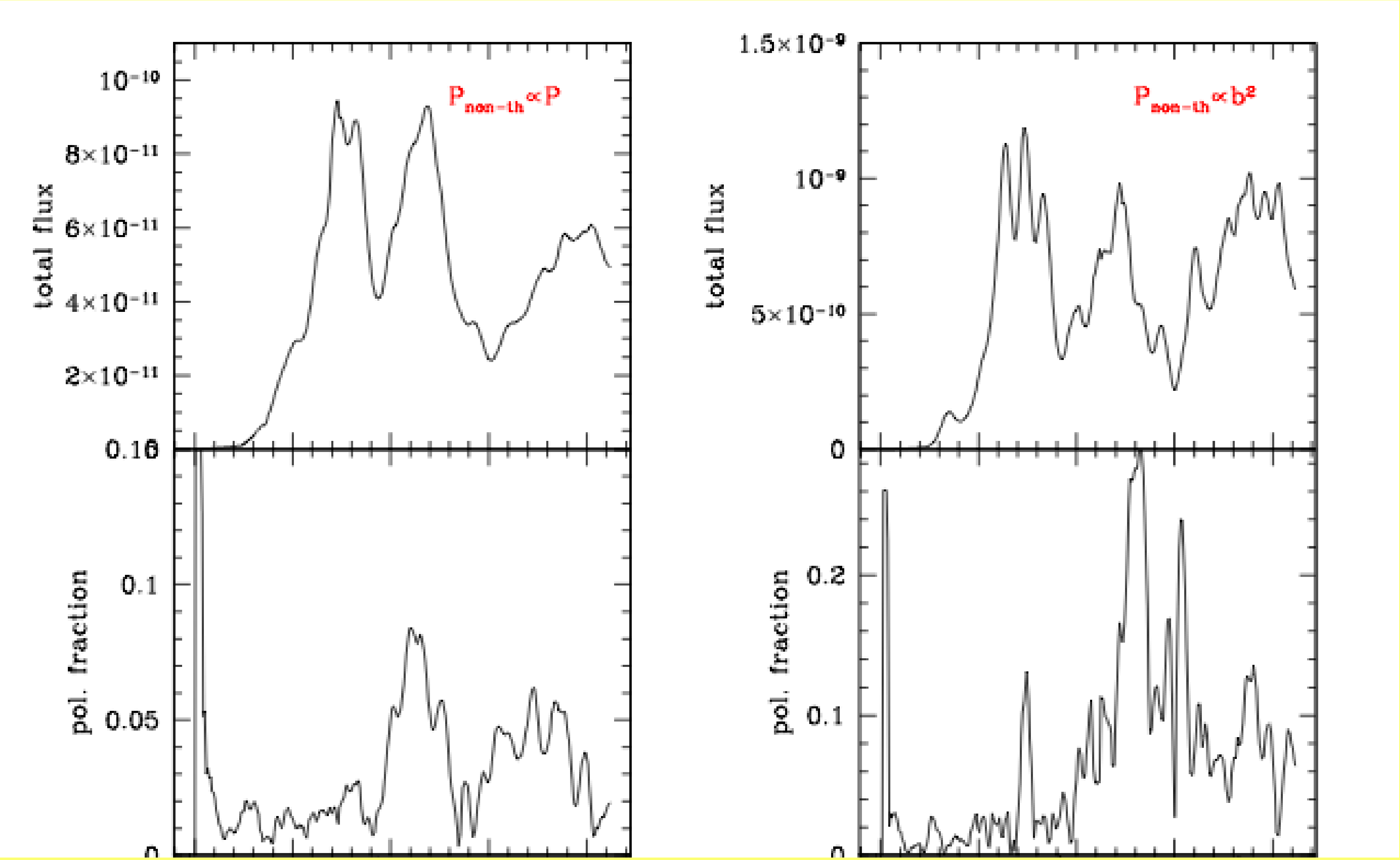






Zakamska, RB & McKinney in prep

Total Flux and Degree of Polarization



Dynamical elements

- Bulk flow
- Shocks
- Shear flow
- Plasmoids, flares, minijets,magnetic rockets…
  - Lorentz boosting
- Precession
  - Disk
  - m=1 instability
- Turbulence

Each of these elements changes the field and the particles

Pair vs Ion Plasmas

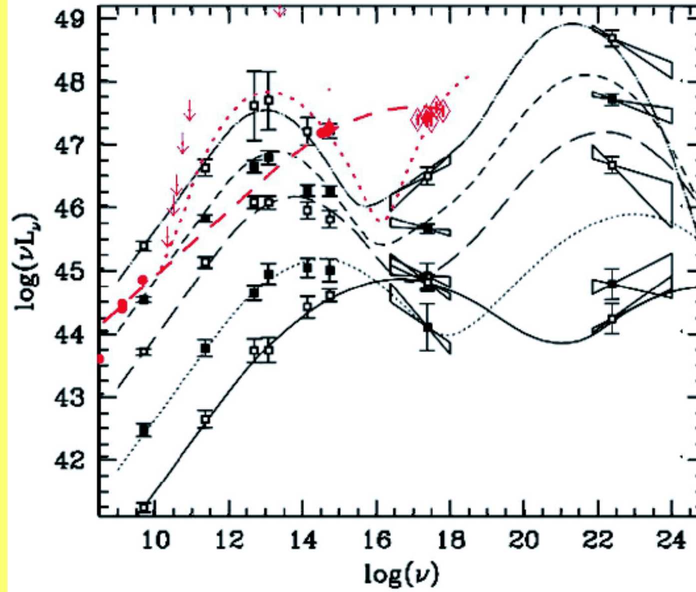
- Pairs must be heavily magnetized to avoid radiative drag
- Circular polarization, Faraday rotation/pulsation
- Expect? pairs, field todecrease, ions to increase along jet

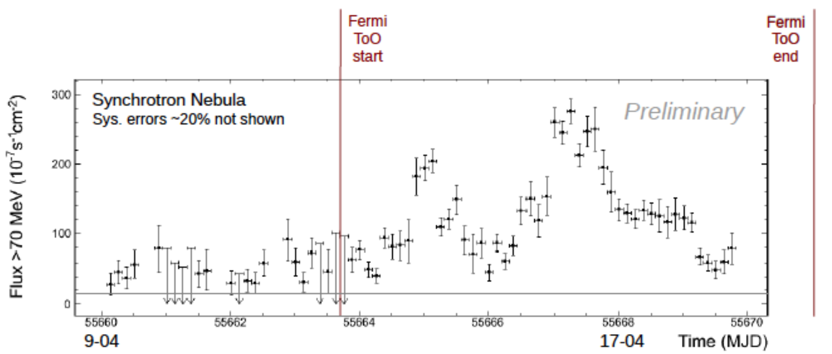
Particle acceleration in high σ environments

- Internal shocks are ineffectual
- Reconnection can be efficient
  - E>B??
- Shear flow in jets
  - Full potential difference available particles accelerated when undergo polarization drift along E
  - UHECR (eg Ostrowski & Stawarz, 2002)
- Fast/intermediate wave spectrum
  - Nonlinear wave acceleration(Blandford 1973…)
    - Mutual evolution of wave cascade and particle distribution function
  - Charge starvation (eg Thompson & Blaes 1997)
- Force-free allows E>B - catastrophic breakdown

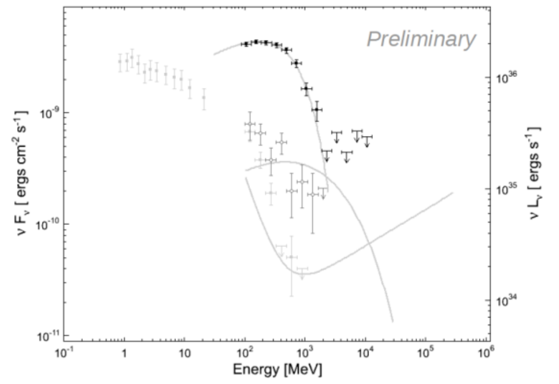
Particle Acceleration

- S-C^{-1} transition quite high in BLLacs
- "Theoretically" $E_\gamma < \alpha^{-1} m_e c^2 \sim 60$MeV
- cf Crab Nebula, UHECR
- Large scale electric fields
- Lossy coax??
- Follow particle orbits.
- Which particles carry the current
- Is the momentum elctromagnetic?



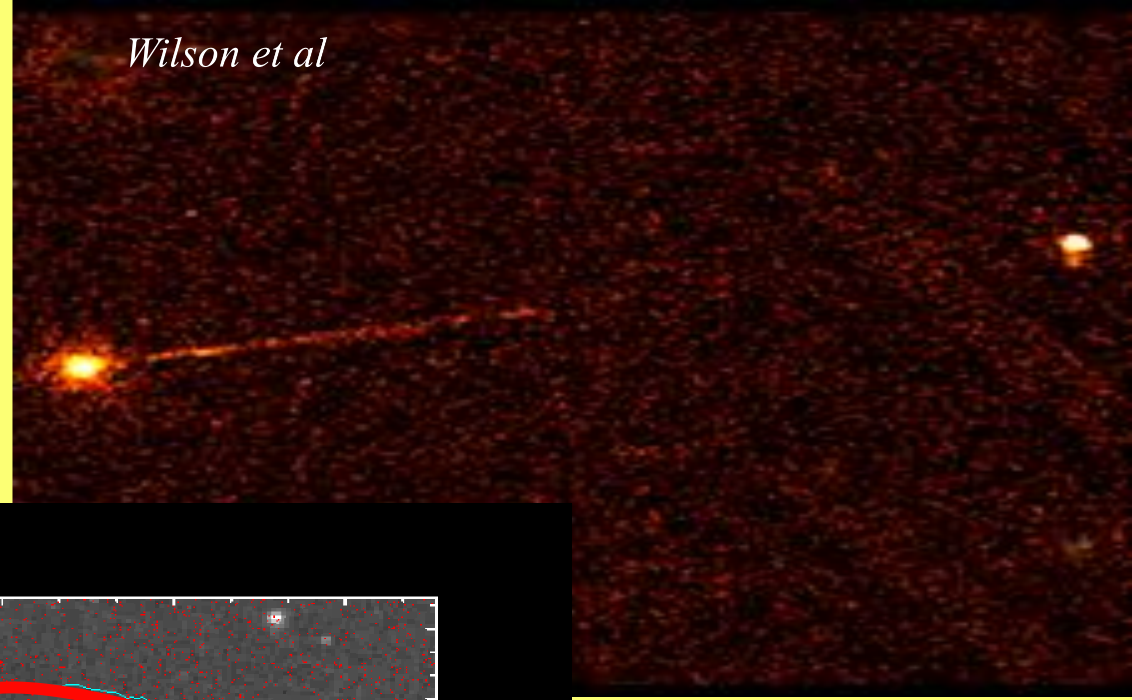


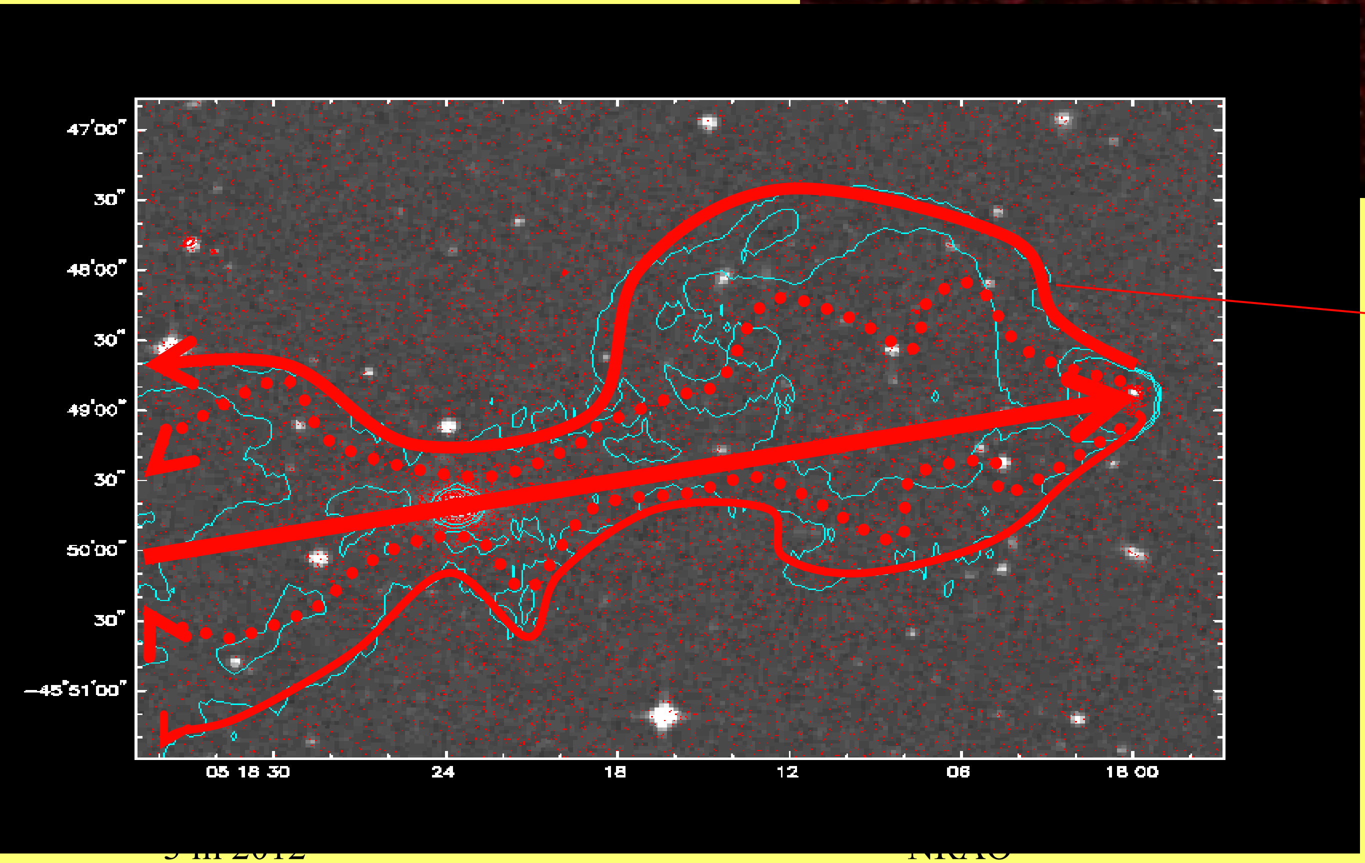
Synchrotron nebula increased by factor ~20
during very good Chandra coverage



Pictor A

Electromagnetic Transport
10^{18} not 10^{17} A
DC not AC
No internal shocks
New particle acceleration mechanisms





Current Flow

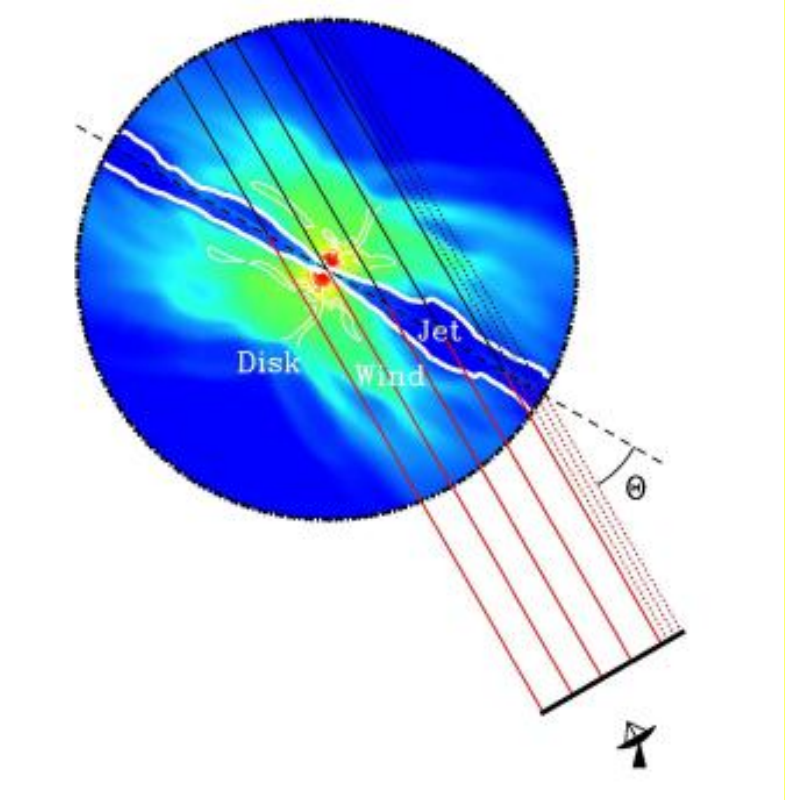
Nonthermal emission is ohmic dissipation of current flow?

Pinch stabilized by velocity gradient

Equipartition in core

Faraday Rotation

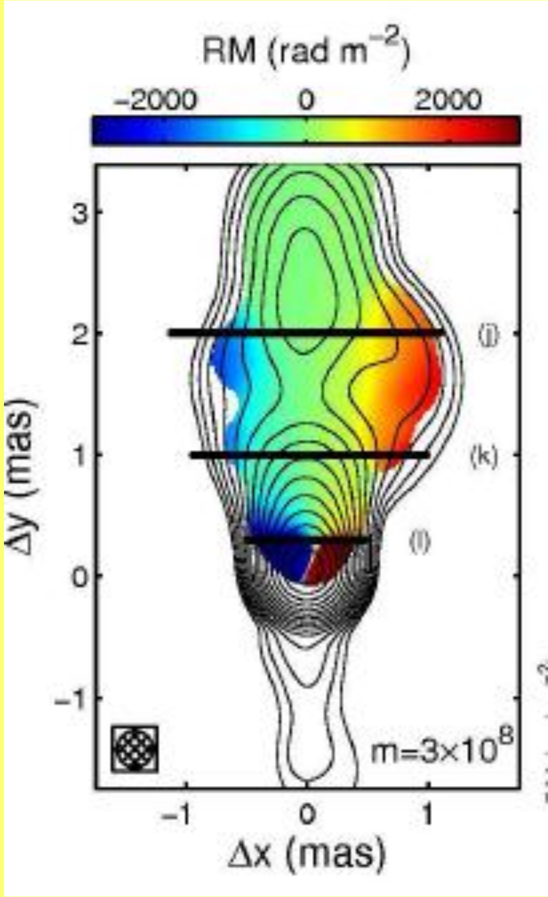
Signature of toroidal field/axial current



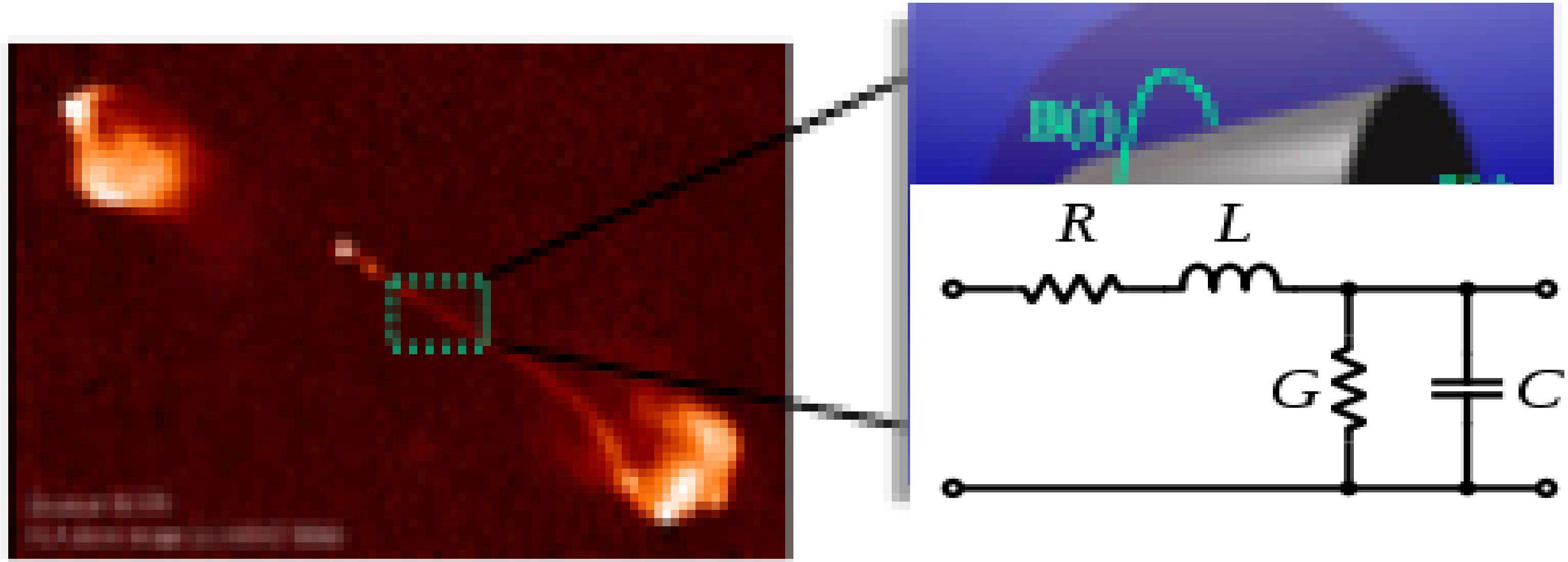
Broderick & McKinney

Rotation from sheath

Simulation



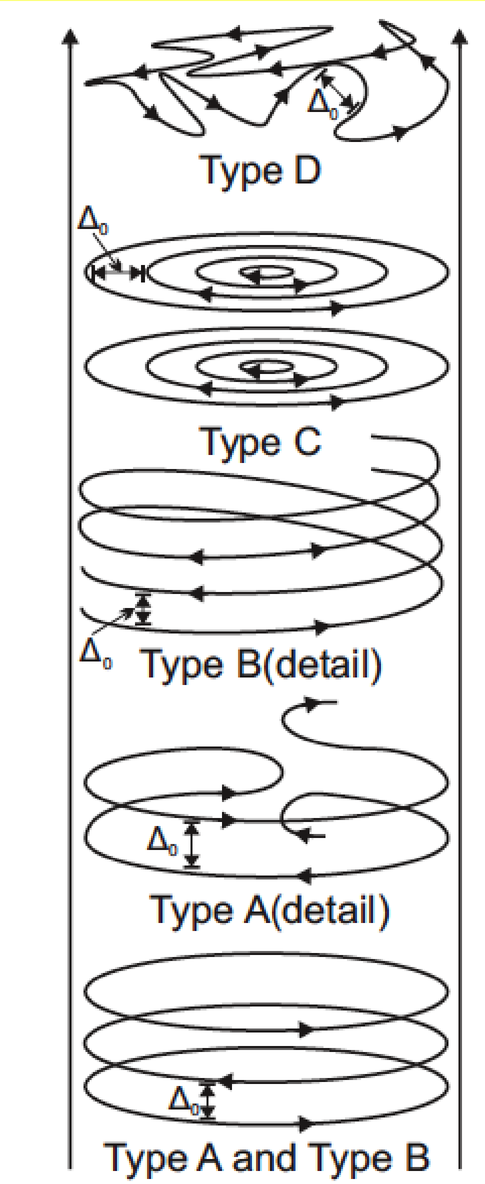
Observations ???



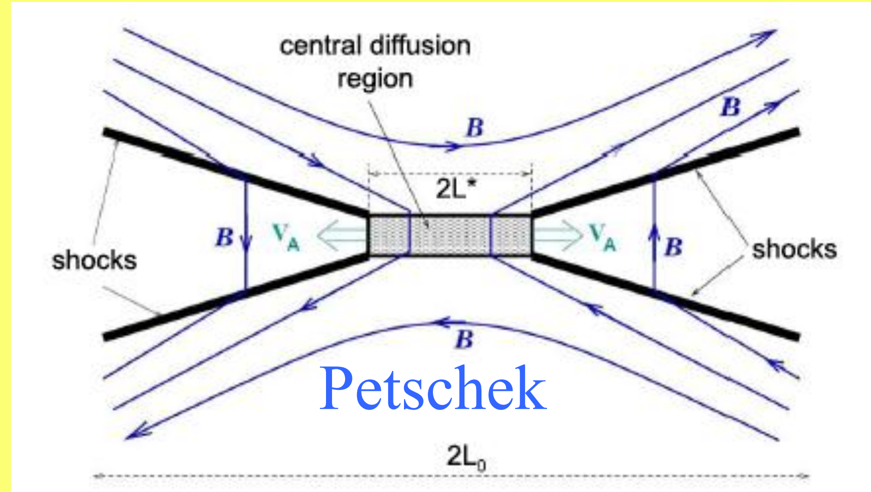
$$\frac{\partial^2}{\partial x^2}V = LC\frac{\partial^2}{\partial t^2}V + (RC+GL)\frac{\partial}{\partial t}V + GRV$$
$$\frac{\partial^2}{\partial x^2}I = LC\frac{\partial^2}{\partial t^2}I + (RC+GL)\frac{\partial}{\partial t}I + GRI$$

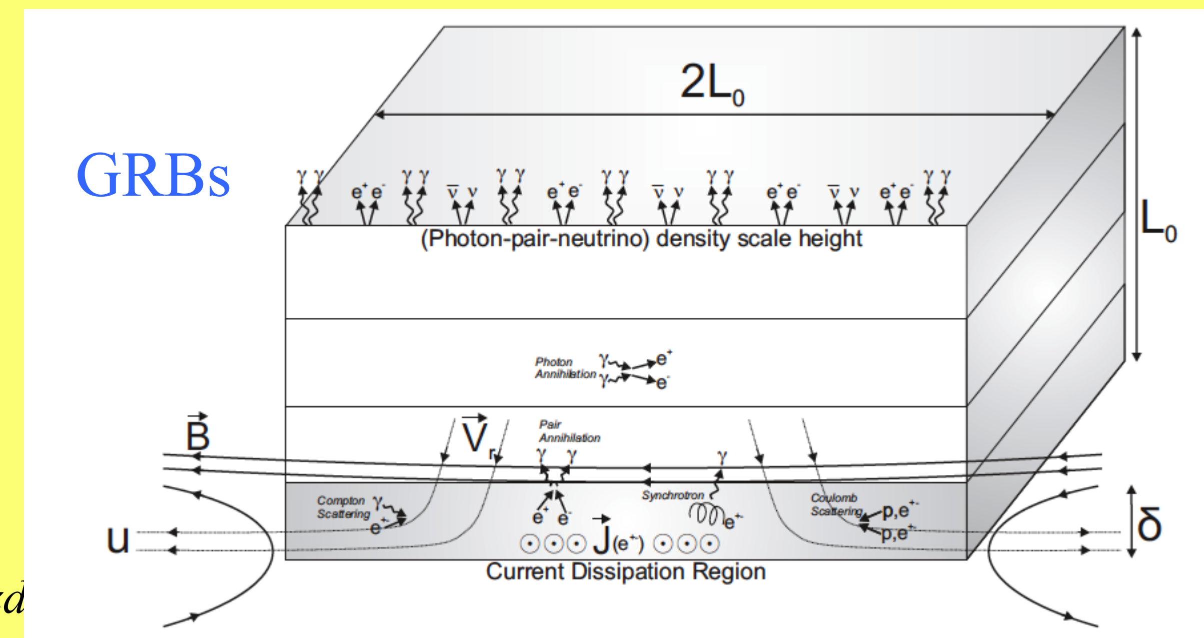
Telegraphers' Equations

Relativistic Reconnection



- High σ flow
- Hall effects may save Petschek mechanism
- Anomalous resistivity?
- Also for AGN





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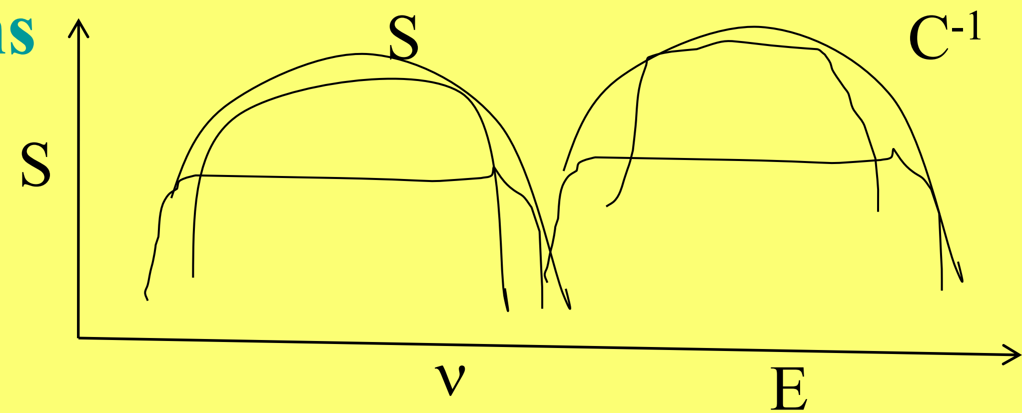
McKinney & Uzd

Inhomogeneous Sources

- Radio synchrotron photosphere, r ~ λ
  - Doppler boosting
- Compton gammasphere, r ~ E?
  - Internal, external radiation
  - Test with variability, correlation
- Electron acceleration
  - >100 TeV electrons



Summary

- Protostars->GRBs->Quasars
- Location, mechanism, collimation, origin…?
- FGST+TeV+multi-λ observations of blazars
- Major monitoring campaigns
- Rotating polarization, rapid variation
- GRMHD simulations answering basic questions about flows, dynamics
- "Observations" of simulations now possible to (in)validate simple phenomenological models and test against data and "best" examples.