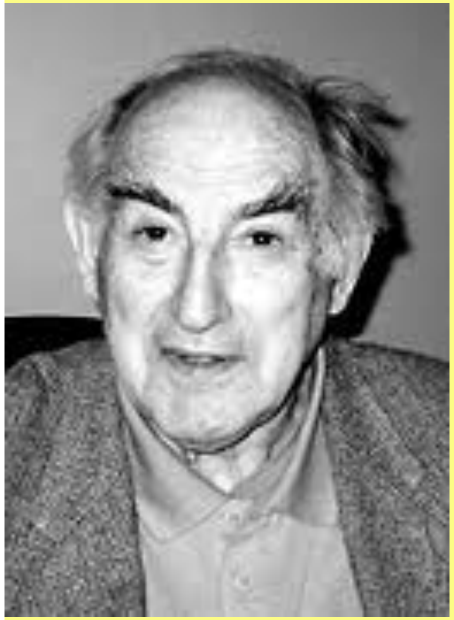
Holes, Jets and Cosmic Rays



Roger Blandford,
KIPAC
Stanford
with
Jonathan McKinney (KIPAC, Maryland)
Sasha Tschekovskoy (Princeton)
Nadia Zakamska (JHU)
Fermi-LAT team…

Accreting Black Holes

- **Characterized by M, a/Ω**
- **Observe as SBH, MBH, IBH, GRB**
  - **SBH ~20, 3-20M_{sun}**
  - **MBH, most galaxies, up to $10^{10}M_{sun}$**
- **"Central Dogma"**
  - **Scaling, L, t ~ M**
  - **Intrinsic properties: $S = t_{Edd} d \ln M_{sup}/dt$, $s = \Omega M$;**
    - Low high S - adiabatic accretion, thick disk, winds
    - Intermediate S – radiative accretion, thin disk
    - High s necessary for relativistic jets
  - **Extrinsic properties: θ, ρ_{nuc}, dust…**
    - cf main sequence stars

Energy Extraction (Bekenstein, Hawking, Penrose…)

Irreducible Entropy, Area Radius (of gyration) Mass

$$r_O = \left[\frac{A}{4\pi}\right]^{1/2} = 2m_O$$

Specific Angular Momentum

$$a = r_O^2\Omega < m;$$

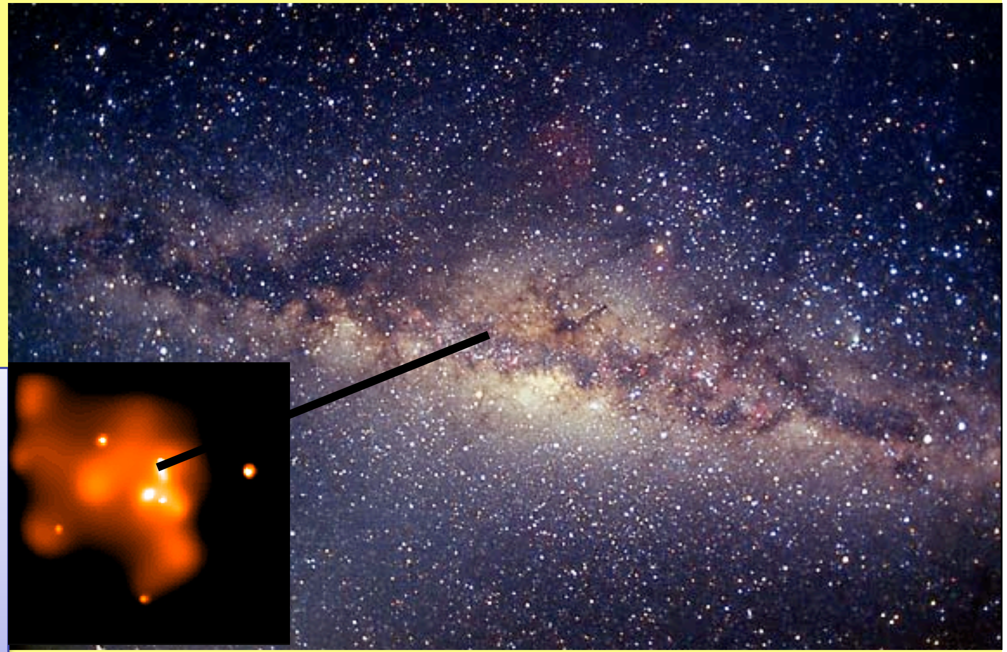
Rotational Speed

$$\beta = \Omega r_O < 0.71$$

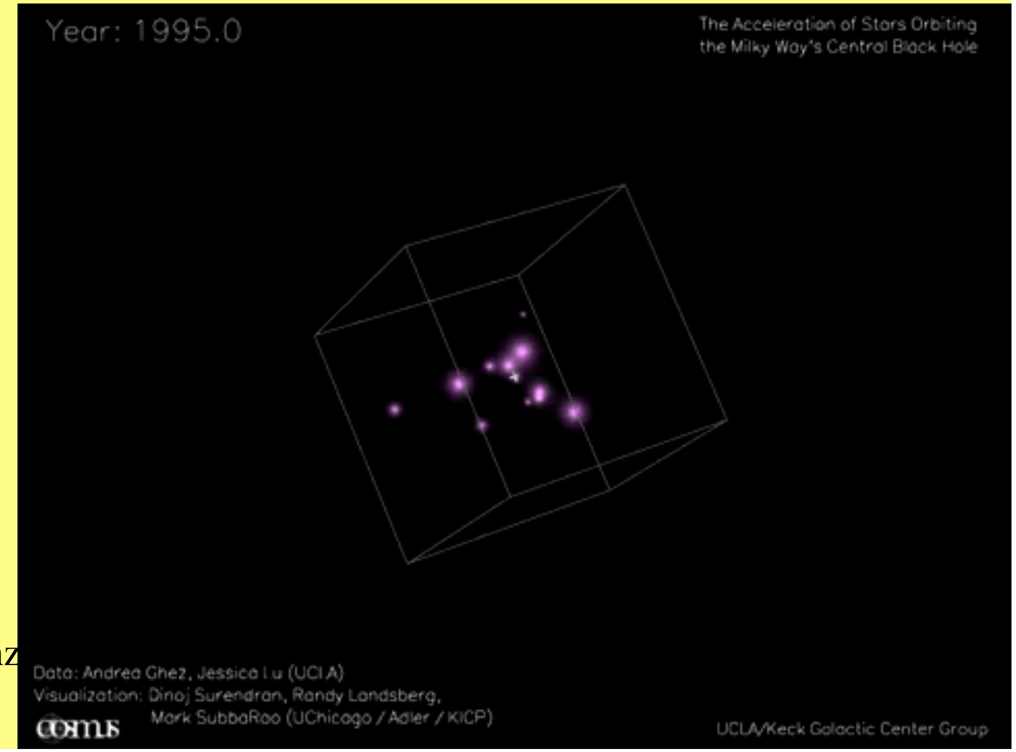
Gravitational mass

$$m = \frac{m_O}{\sqrt{1-\beta^2}}; m_O > 0.71m$$

Stellar Supply

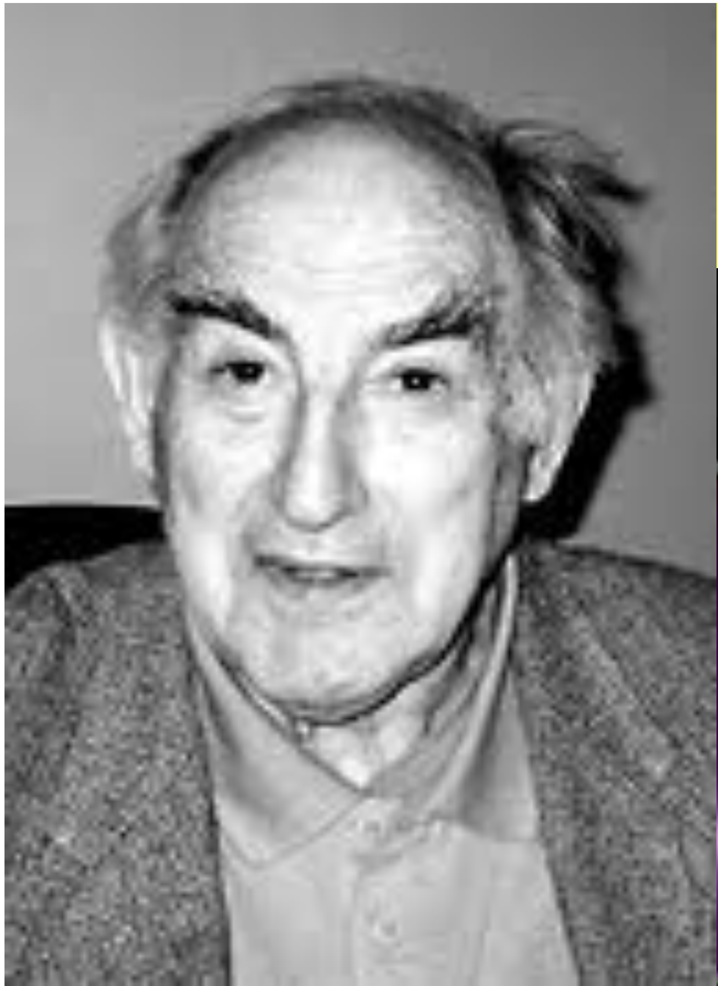


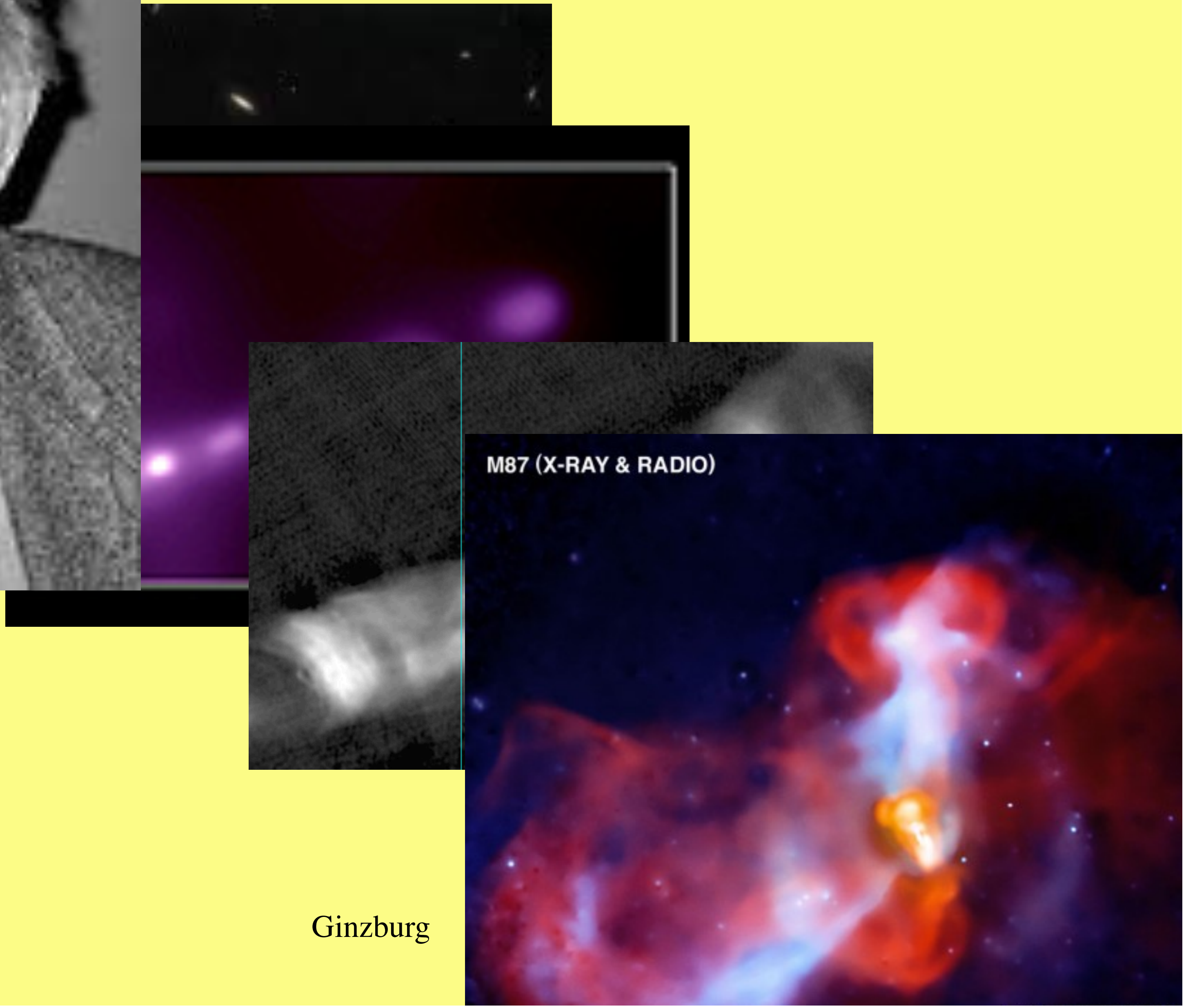
- Our Galactic Center
- Four million solar masses
- Varies in 15 min!



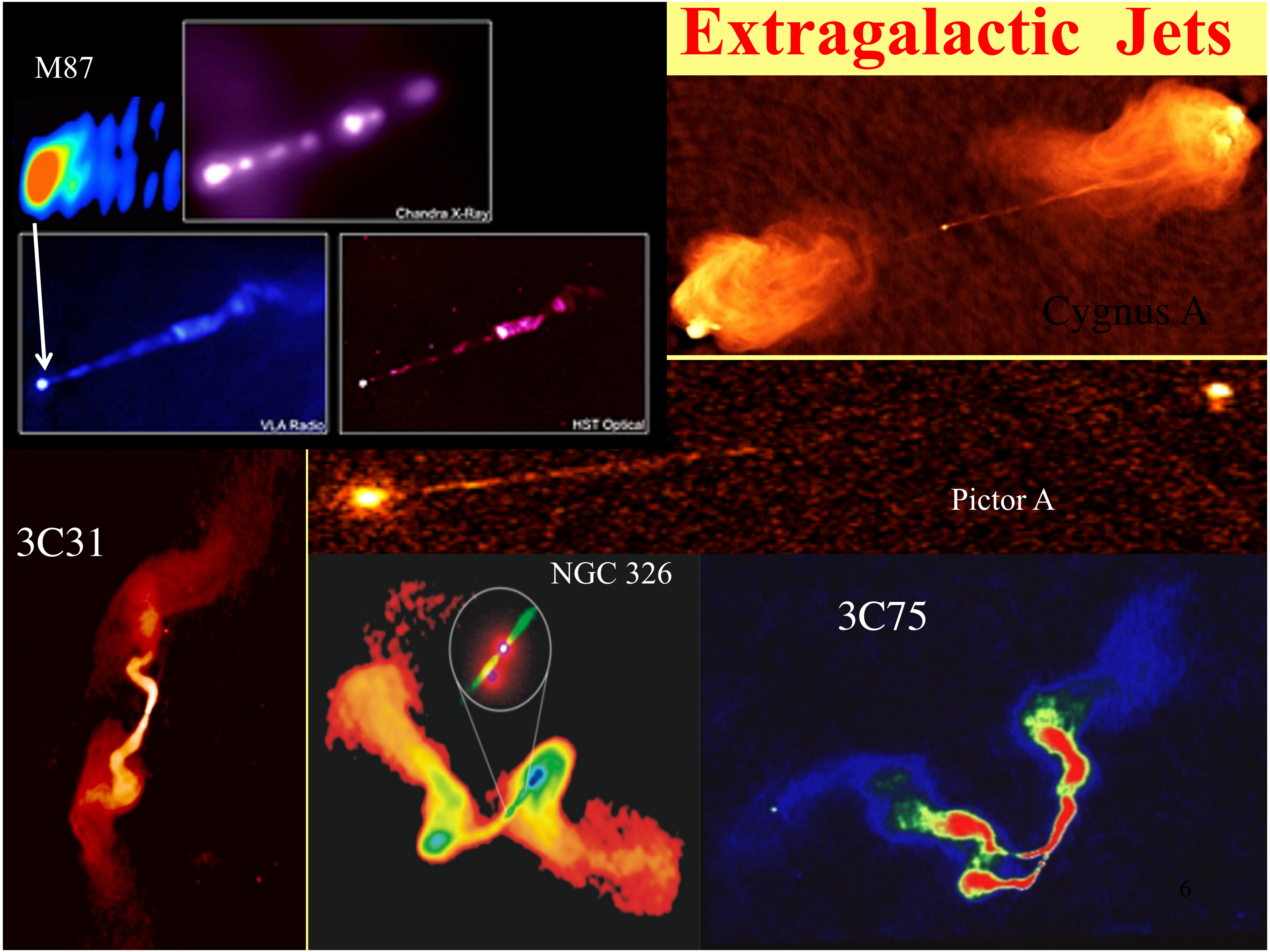
Tidal disruption?
Gas cloud to 3000m in 2013?

M87



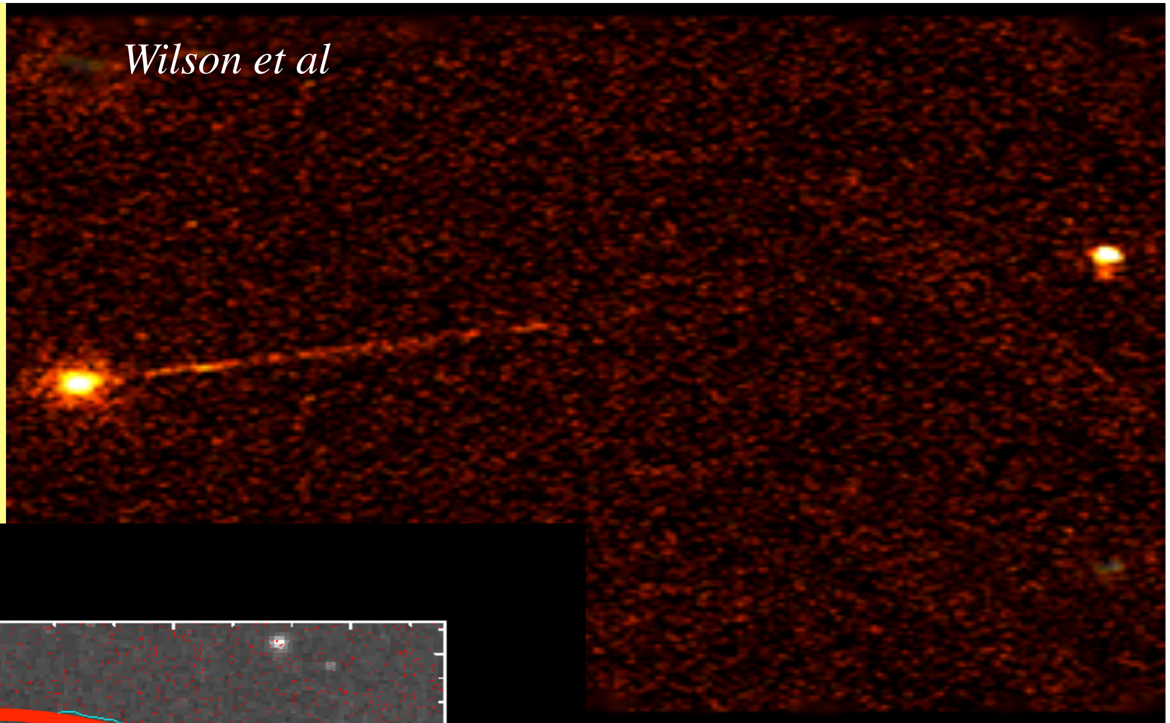


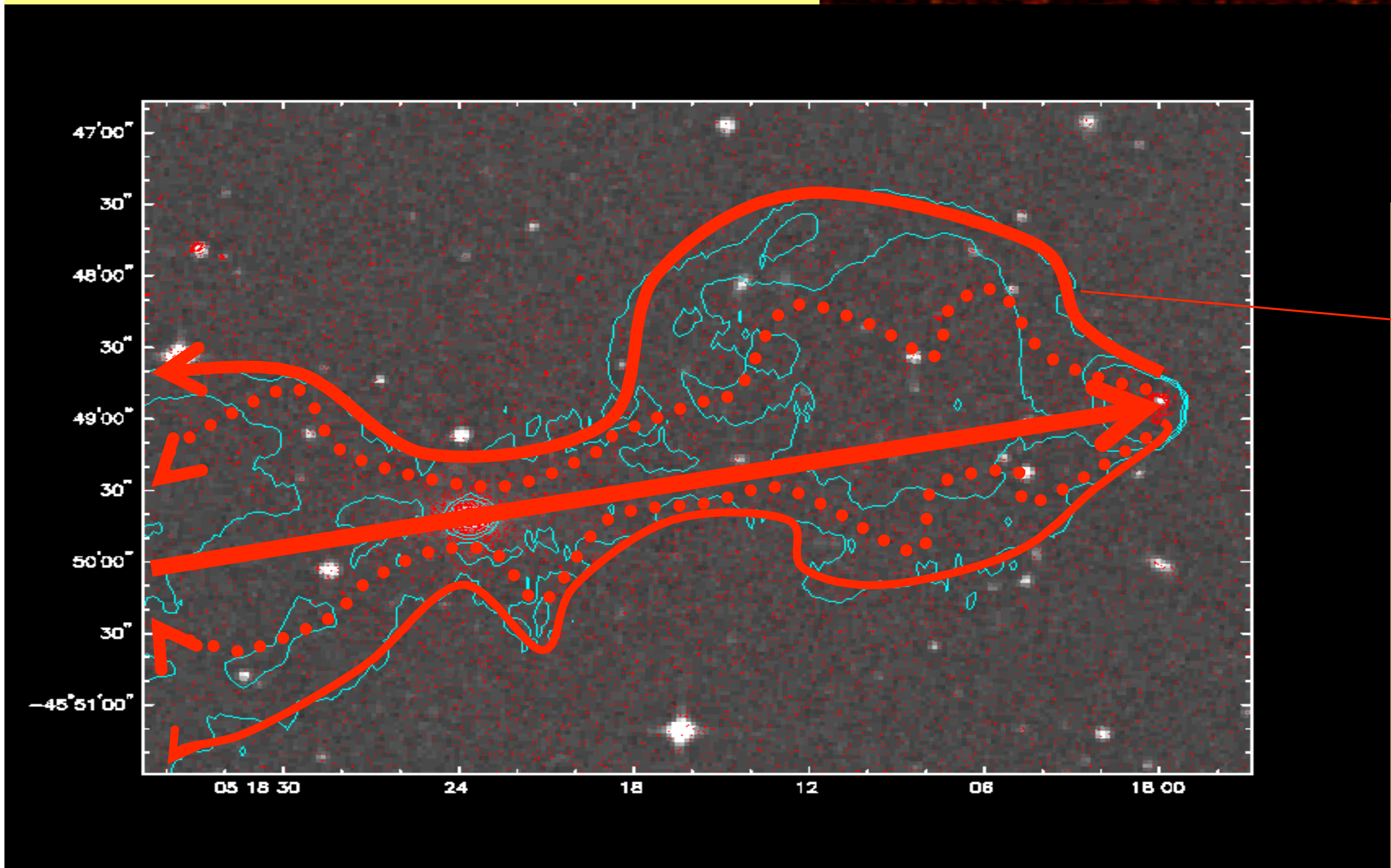
Extragalactic Jets



Pictor A

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





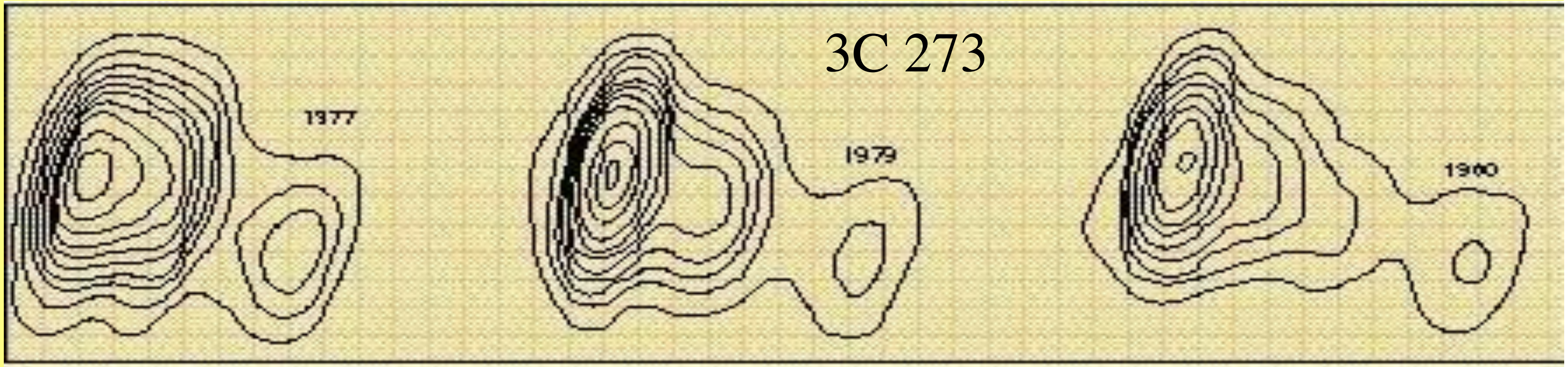
Current Flow

Nonthermal emission is ohmic dissipation of current flow?

Pinch stabilized by velocity gradient

Equipartition in core

SUPERLUMINAL EXPANSION



$\Gamma \sim 10 , \sim 3$ (FR 1)

S ~ Γ^3

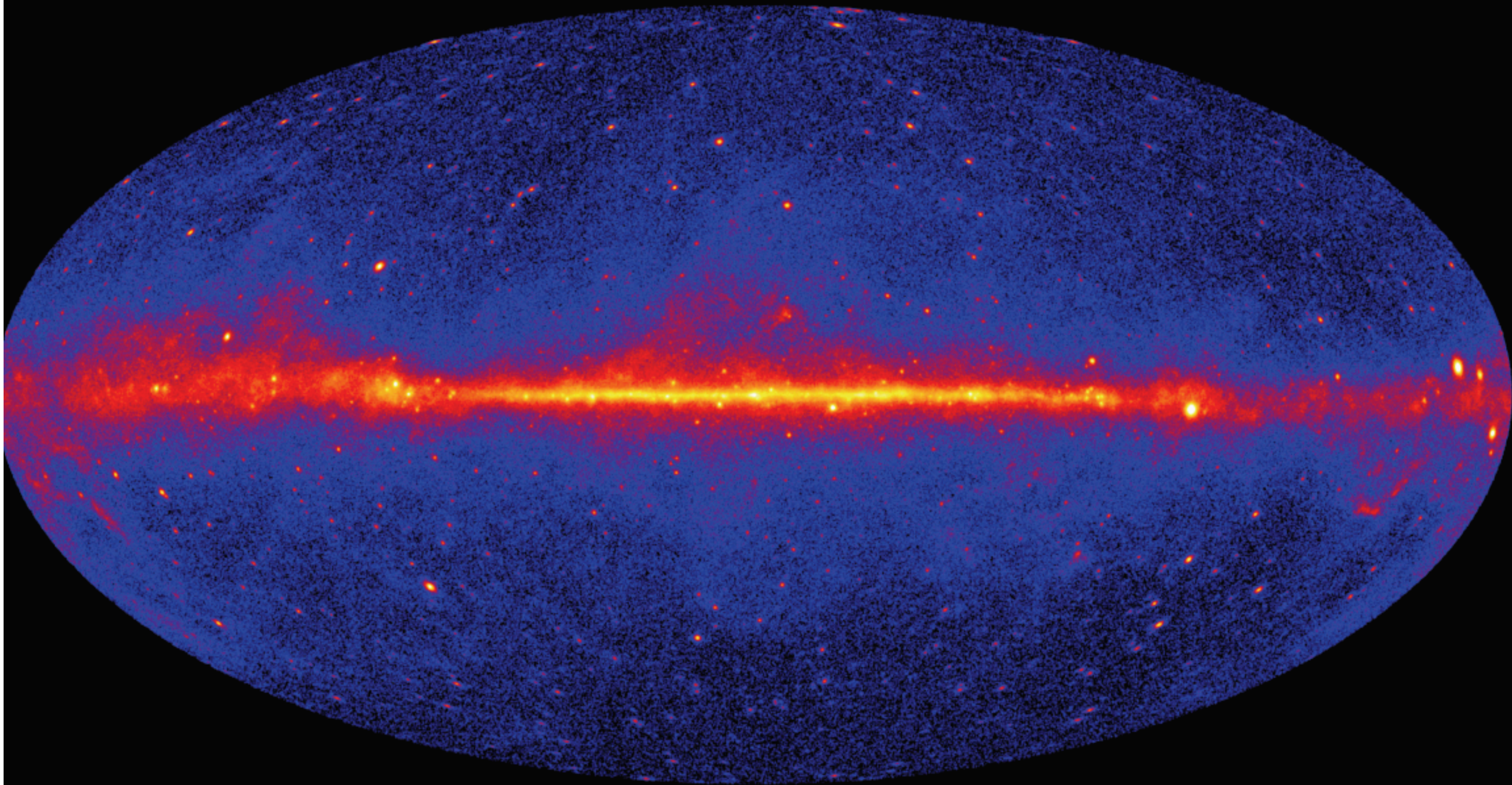
Strong Doppler Beaming

Intraday variability $\Gamma \sim 300$

Coherent emission ?

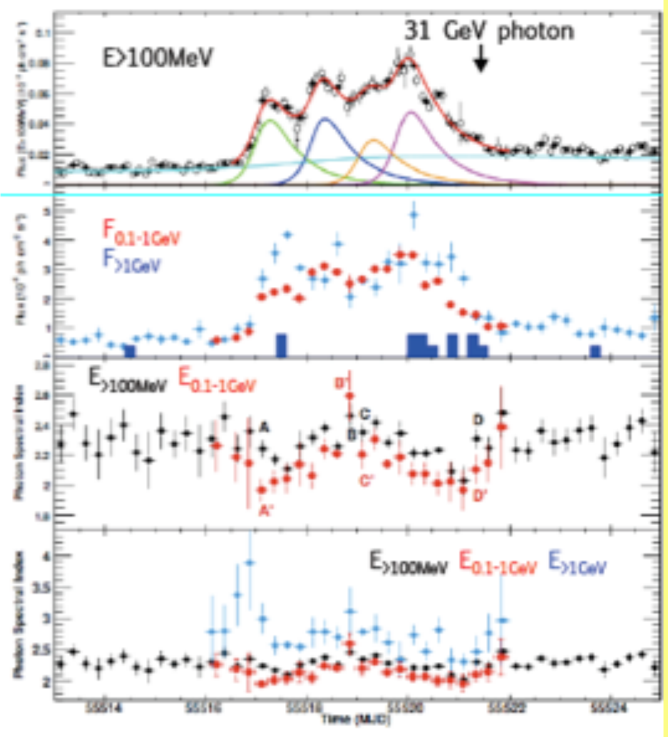
Do we see all the jet?

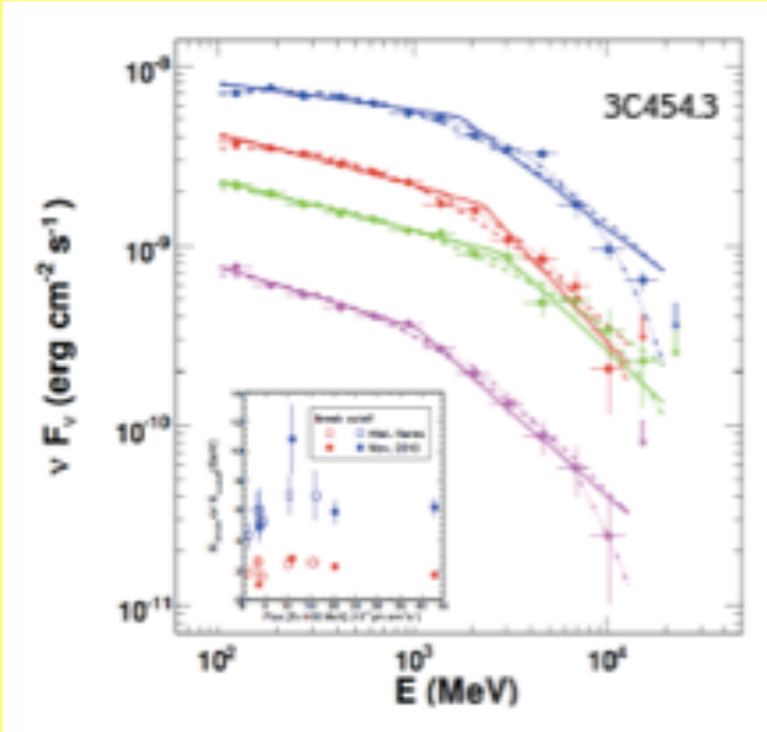
Latest Photon Intensity Map

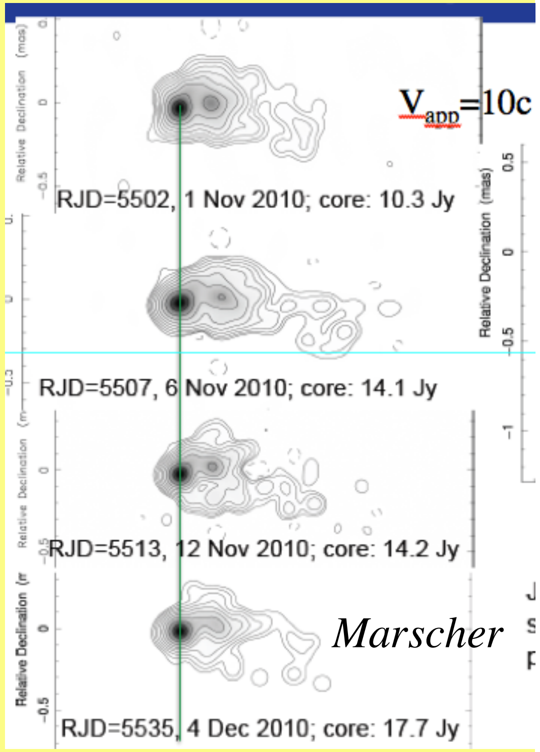


832AGN+268Candidates+594Unidentified!

3C454.3





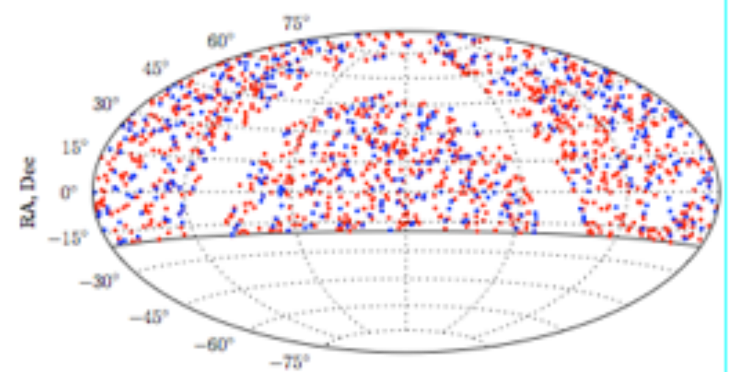


$2x10^{50}$erg s^{-1} isotropic

Breaks due to recombination radiation?

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

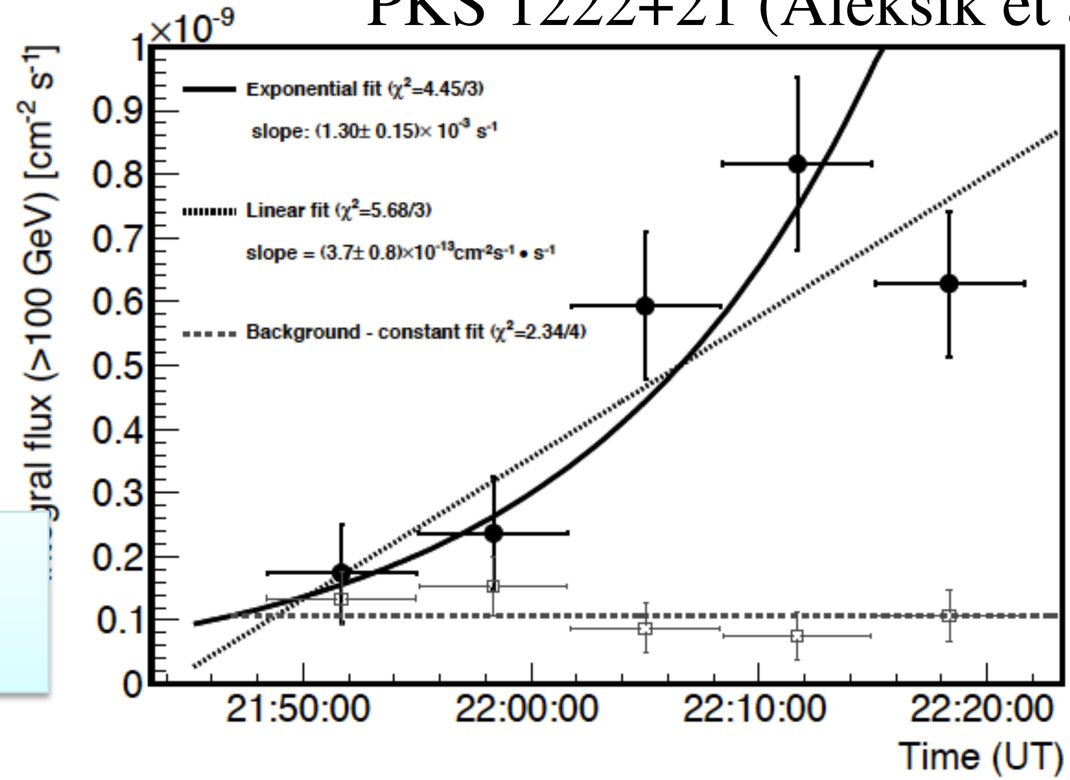
Max-Moerbeck etal

Rapid MAGIC variation

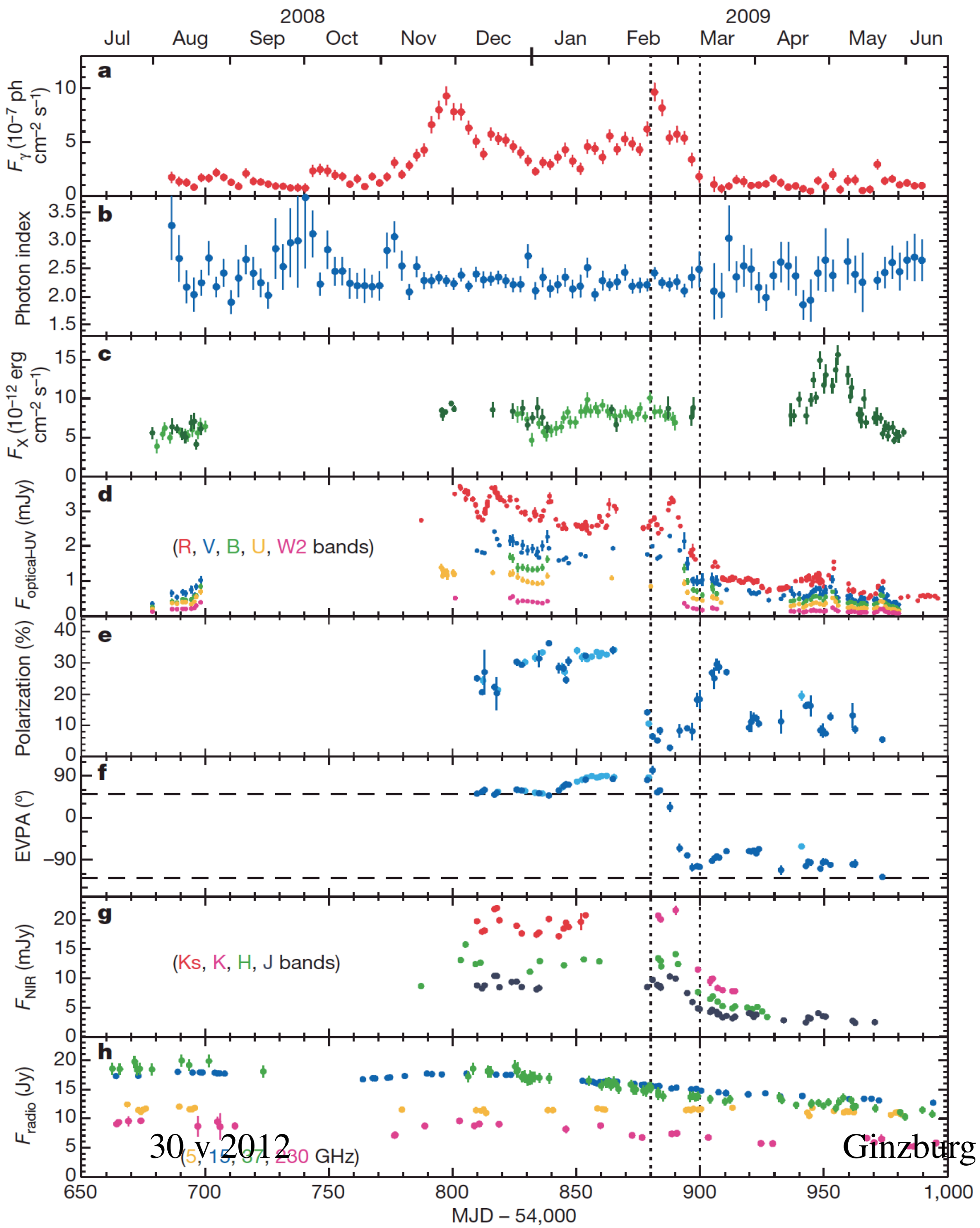
- **PKS 1222+21**
  - 10 min
- **MKN 501**
  - 2min?
- **PKS 2155-304**
  - "Few hr"?

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~$\gamma^2 c\tau$ ~ pc or τ_{disk}?
- Correlated optical variation? => common emission site
- X-ray, radio uncorrelated => different sites
- Rapid polarization swings ~200° => rotating magnetic field in dominant part of source

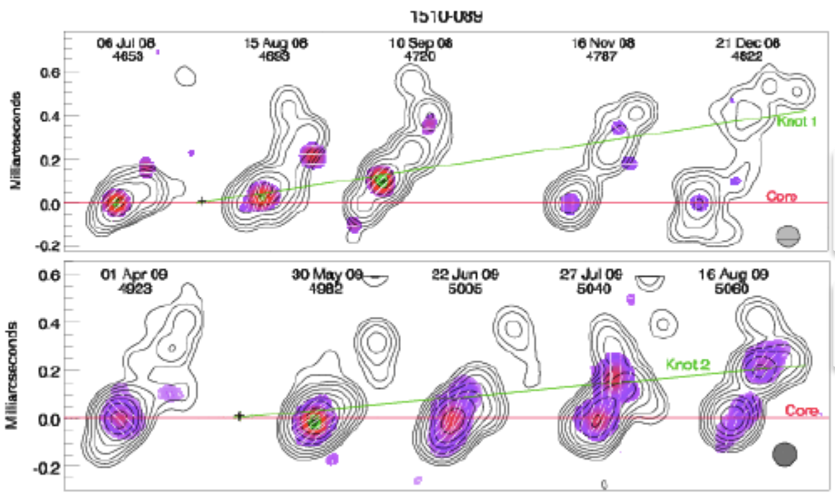
r ~ 100 or 10^5 m?

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

PKS1510+089

(Wardle, Homan et al)

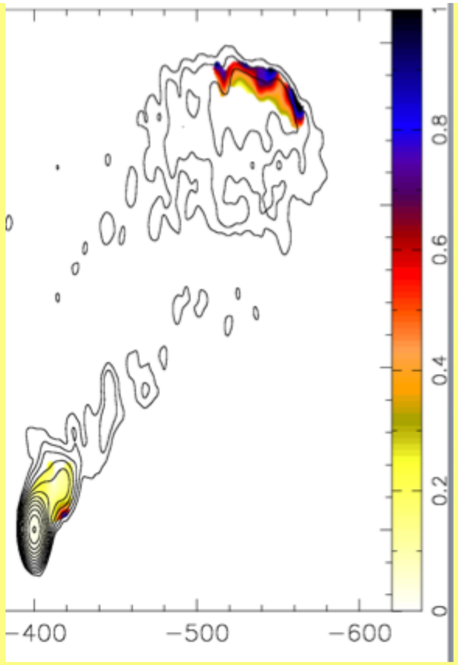
43 GHz VLBA Images of PKS 1510-089

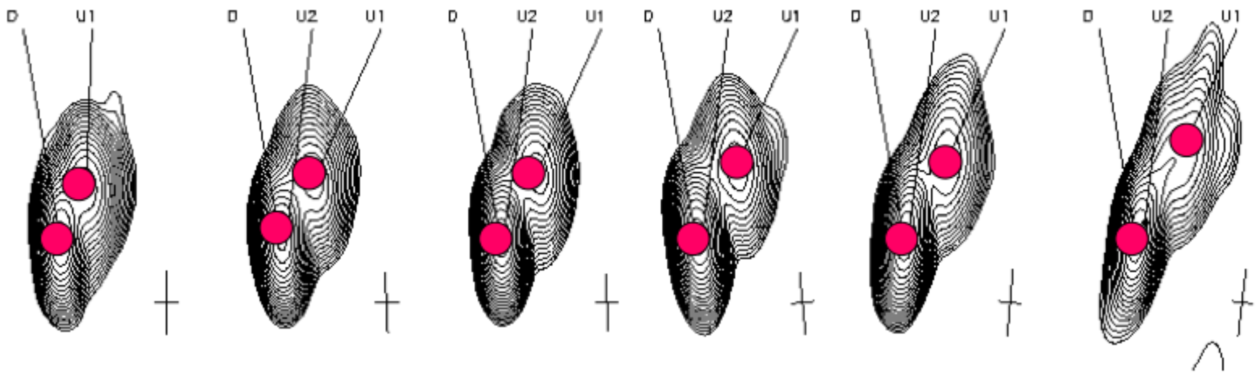


β_{app}=45

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)*

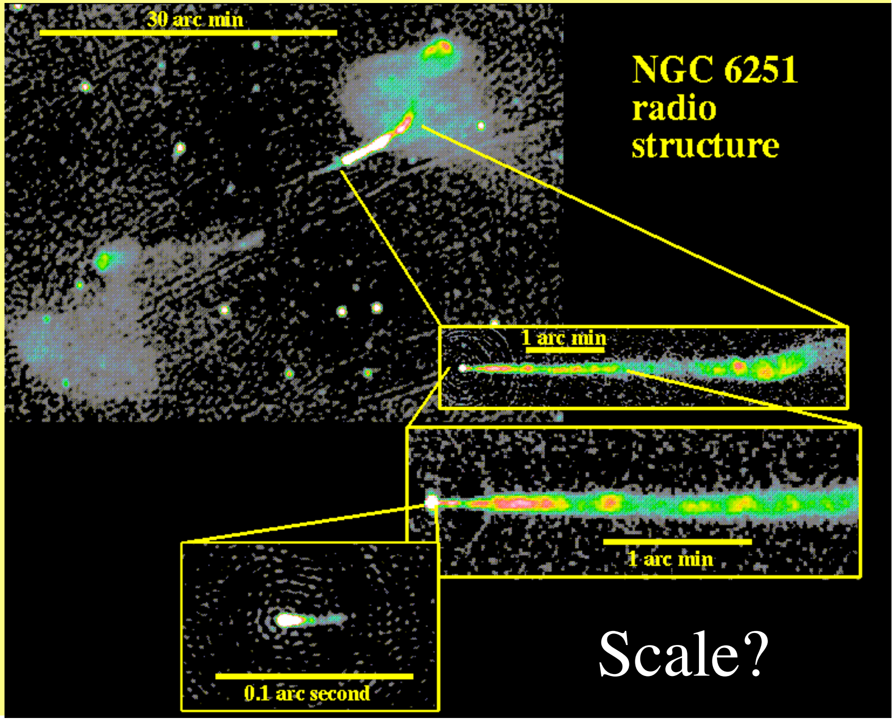
Some Issues

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

The Bigger Picture

Focus on AGN

- Prime Mover?
  - Protostars, stars, superstars, supernovae, pulsars… **holes**
- Black Hole (reverse) 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

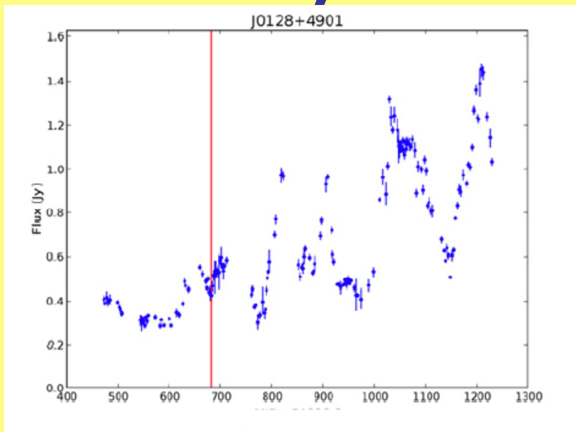
1. Locate the sites of radio, γ emission
2. Map jet velocity fields and causality
3. Verify the emission mechanism
4. Understand the changing composition
5. Measure external pressure
6. Deduce jet confinement mechanism
7. Infer jet powers, thrusts
8. Test Central Dogma
9. BHGRMHD capability
10. Quantify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

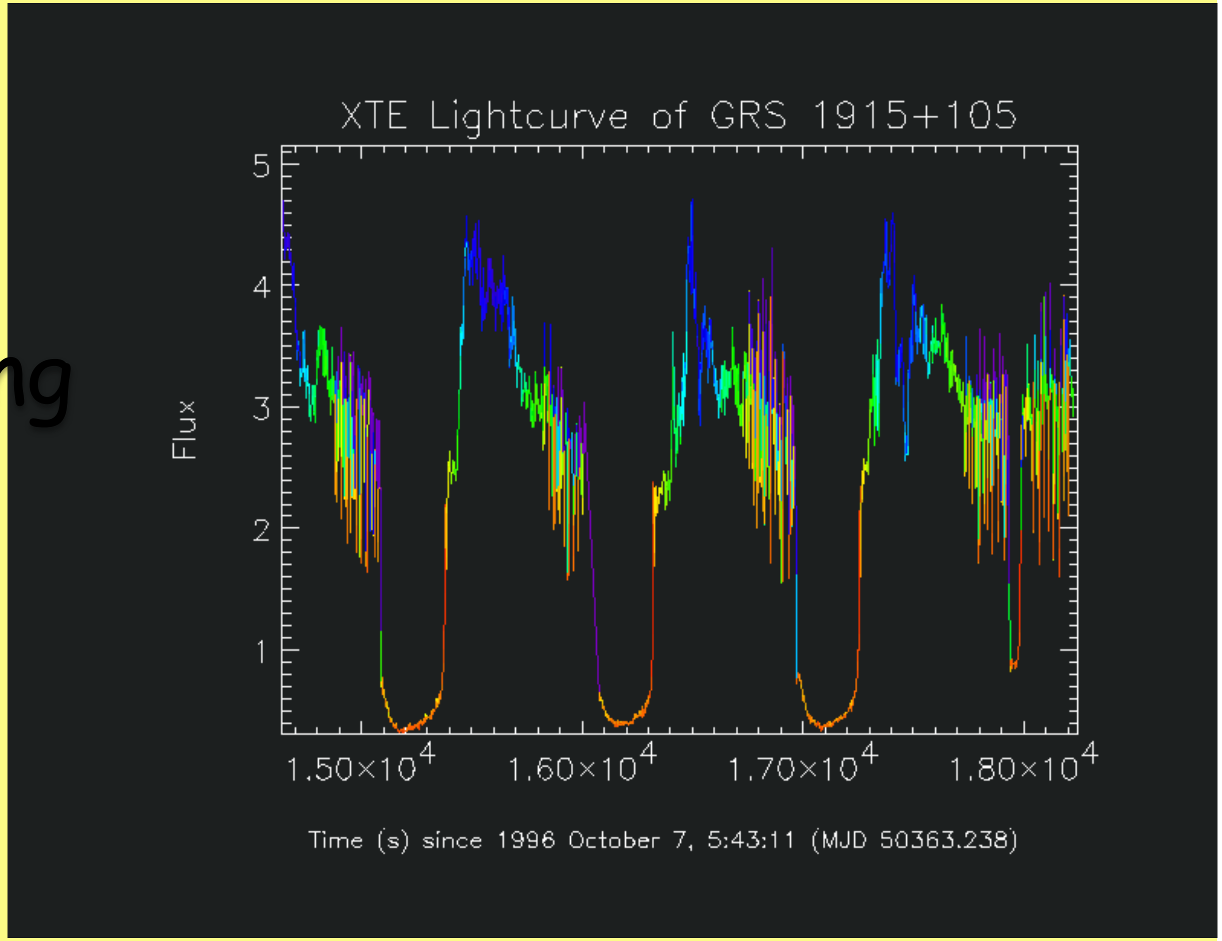


- Account for Extreme Jets
  - Most variable, fast, bright, polarized…
- Modeling must match this increase in sophistication
- Simulations are now becoming available
  - Understand kinematics, QED, fluid dynamics
  - Ignorant about particle acceleration, transport, radiation, field evolution

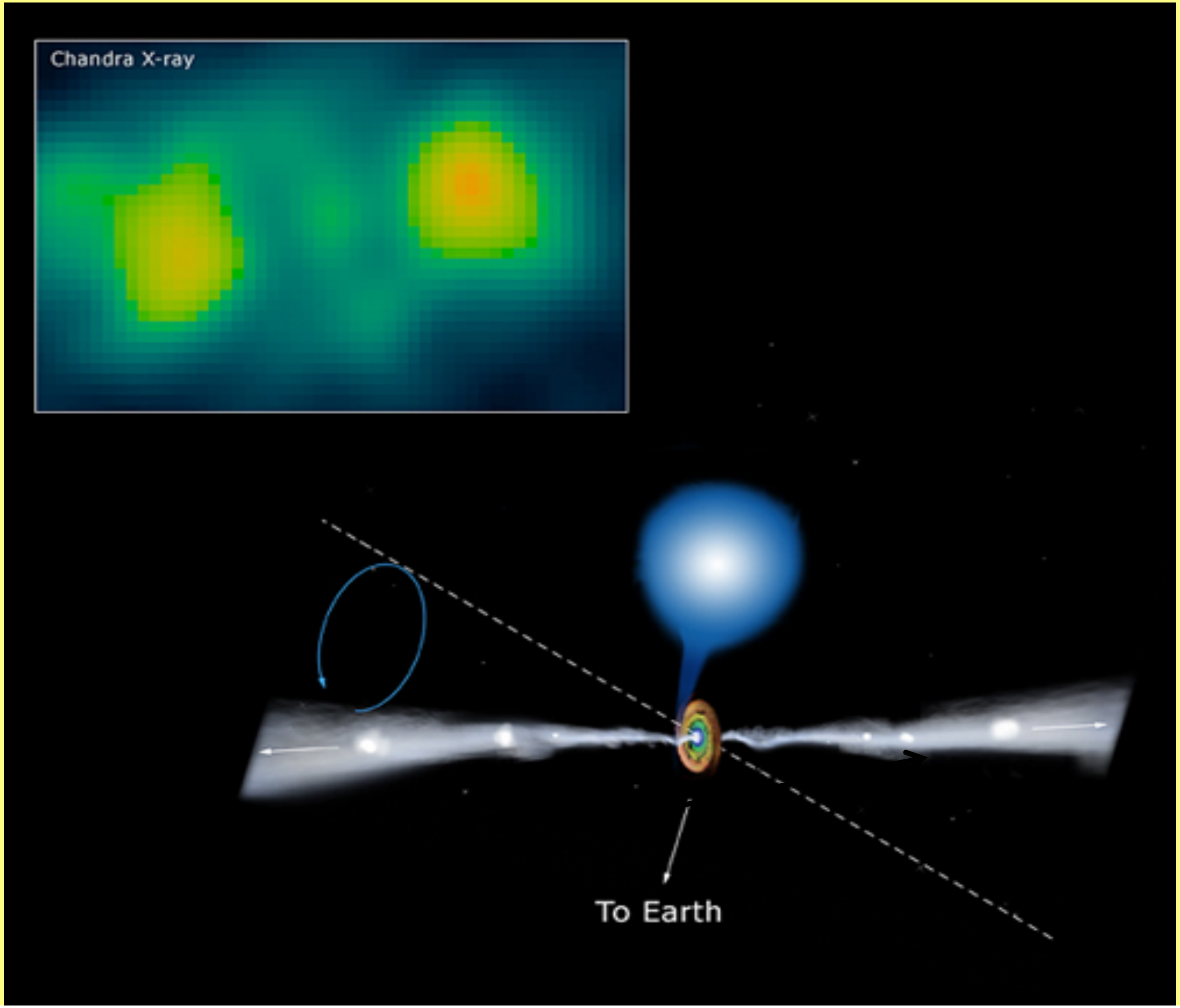
Physical assumptions ⇄ *Simulation* → **Statistics** ← *Analysis* ← Observations

Performing Black Holes

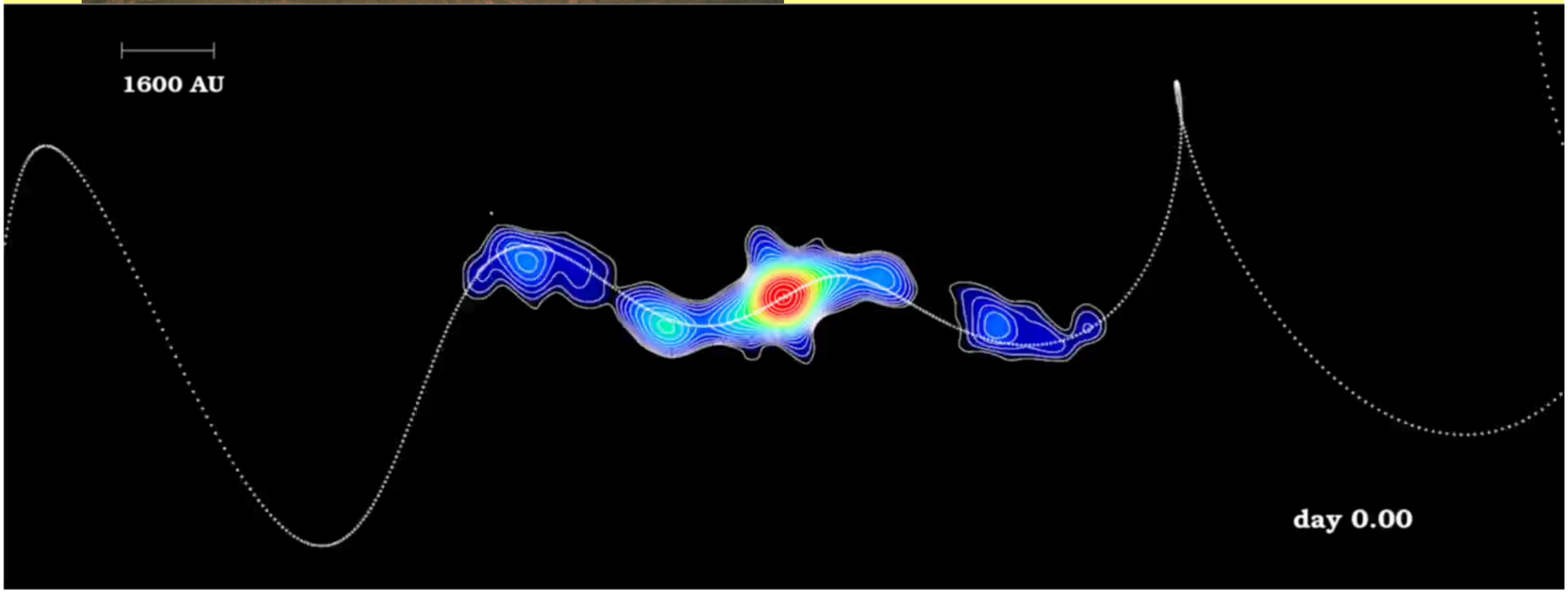
Black Holes can sing



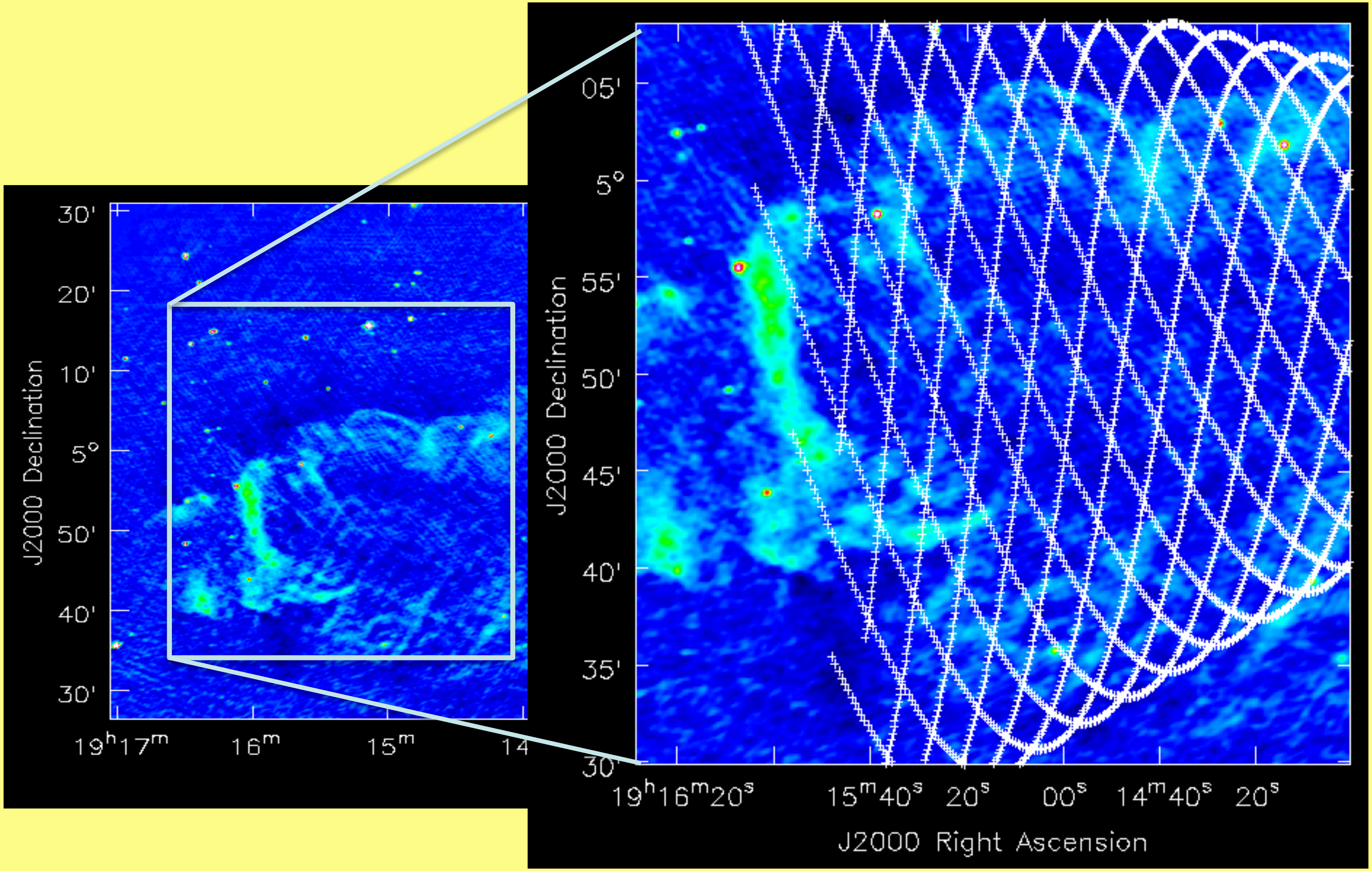
They also "dance"



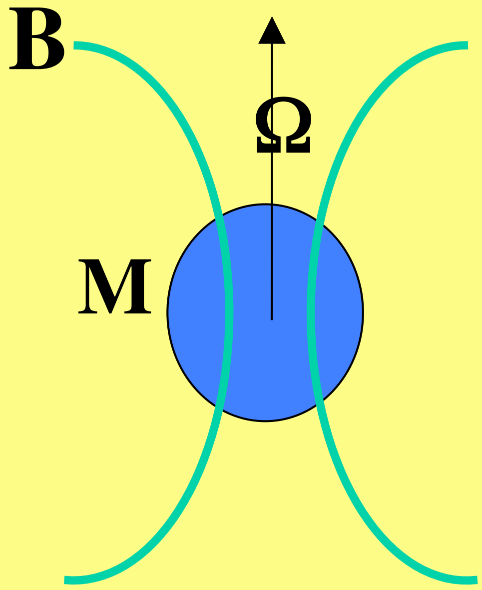
New Radio Telescopes



SS433 and the W50 nebula

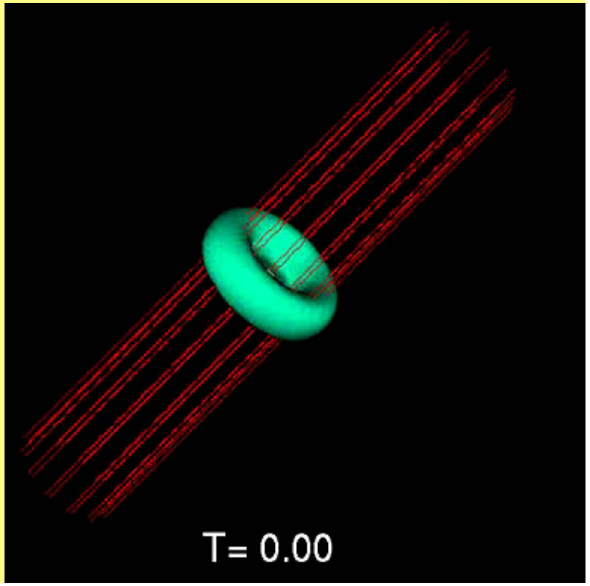


Unipolar Induction



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

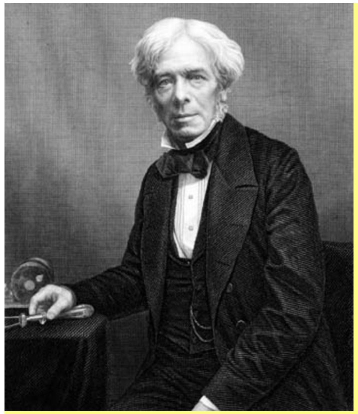
	PWN	AGN	GRB
B	100 MT	1 T	1 TT
$\Omega/2$	10 Hz	10 μHz	1 kHz
R	10 km	10 Tm	10 km
V	3 PV	300 EV	30 ZV
I	300 TA	3 EA	300 EA
P	100 XW	1 TXW	10 PXW



UHECR!

Three Approaches

- Fluid dynamics +passive field
  - Fluid velocity, scalar + ram pressure
- Classical Electromagnetodynamics
  - Maxwell stress tensor + Poynting Flux
- Relativistic Magnetohydrodynamics
  - All of the above



Let there be Light

- Faraday
- Maxwell
- Initial Condition
- Definition

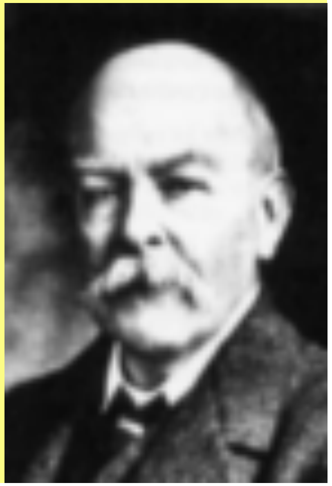
$$\frac{\partial B}{\partial t} = -\nabla \times E$$

$$\frac{\partial E}{\partial t} = \nabla \times B - j$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot E = \rho$$

=>Maxwell Tensor, Poynting Flux



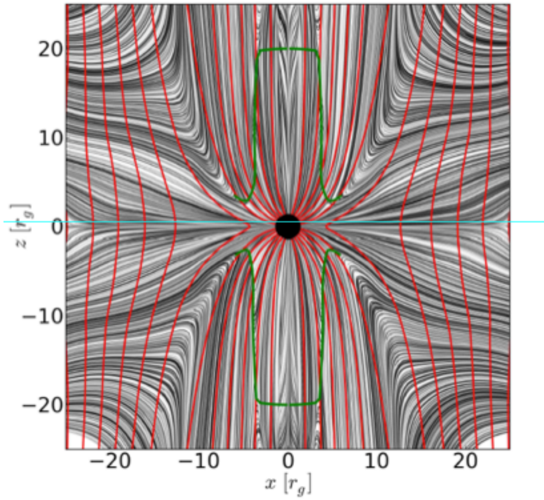
Force-Free Condition

$$\rho E + j \times B = 0 \Rightarrow E \cdot B = E \cdot j = 0$$

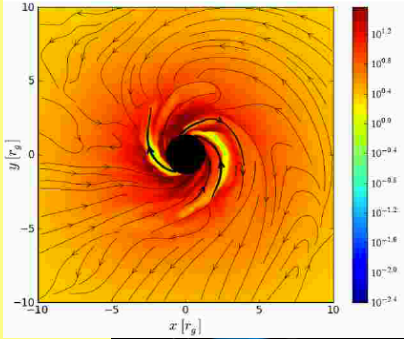
$$j = \frac{(\nabla \cdot E)E \times B + (B \cdot \nabla \times B - E \cdot \nabla \times E)B}{B^2}$$

- Ignore inertia of matter $\sigma = U_M/U_P >> \Gamma^2, 1$
- Electromagnetic stress acts on electromagnetic energy density
- Fast and intermediate wave characteristics,

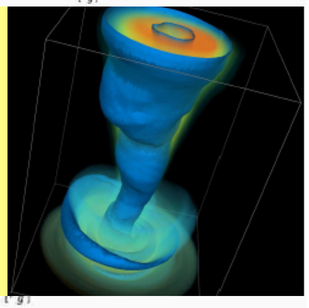
3D GRMHD Simulations



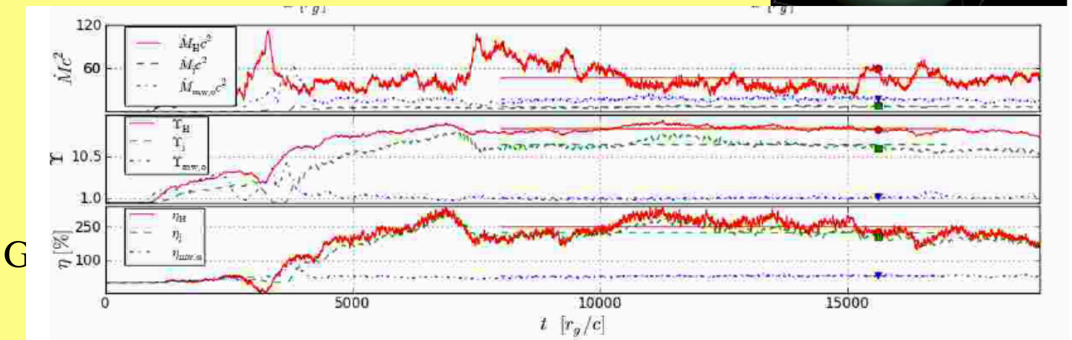
- $>10^5$m Kerr-Schild, HARM, 512x768x64
  - Quasi-steady state
- Build up flux –back reaction
  - Thick spinning disks, suppress MRI
  - Dipolar (not quadrupolar) makes jets



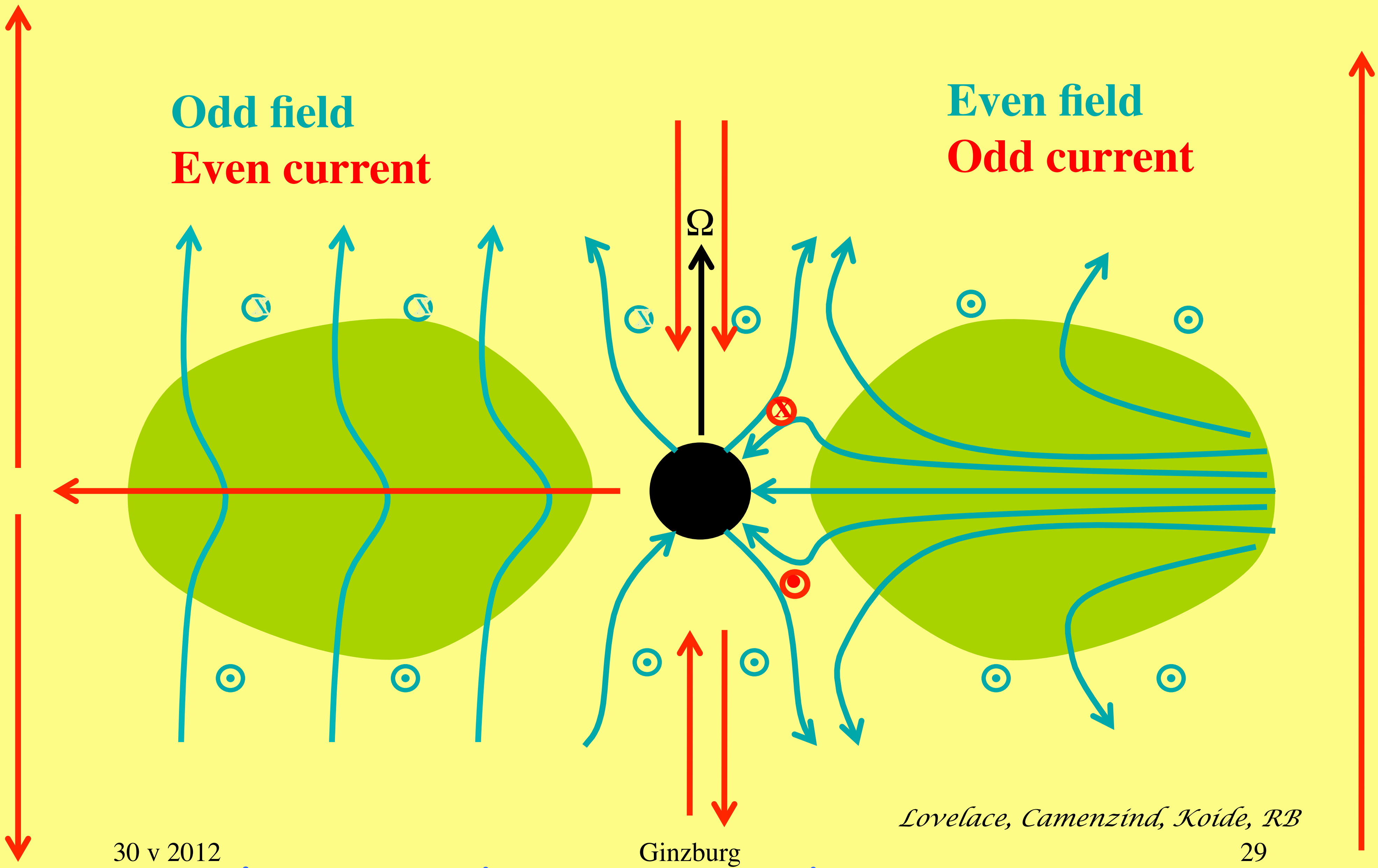
- Efficient extraction of spin energy-> jets
  - Prograde (not retrograde) more efficient
- Wind outflows
  - Poorly collimated, slow



- QPOs,
  - m=1 mode; ν~400(Ω/Ω_{max})($M/10M_{sun}$) ;Q~100 (jet) ~3 (disk),
- Strong intermittency
  - Helical instability

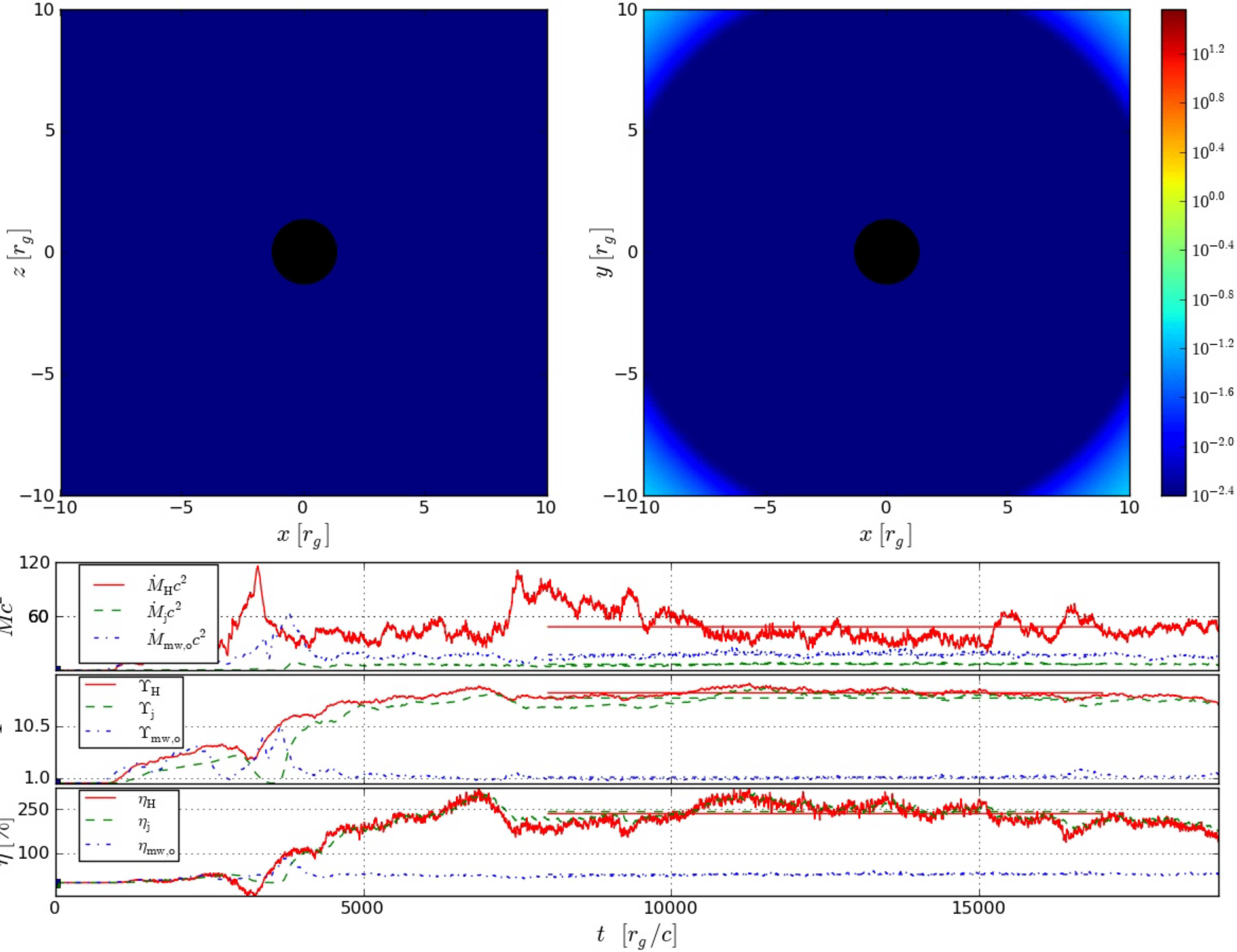


Dipolar or Quadrupolar?



Lovelace, Camenzind, Koide, RB

Also prograde vs retrograde?

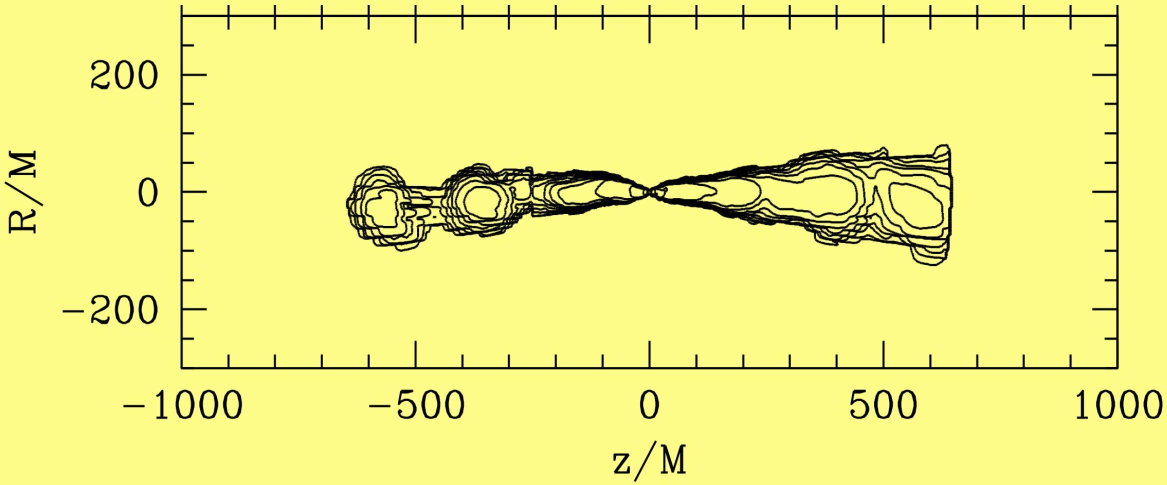


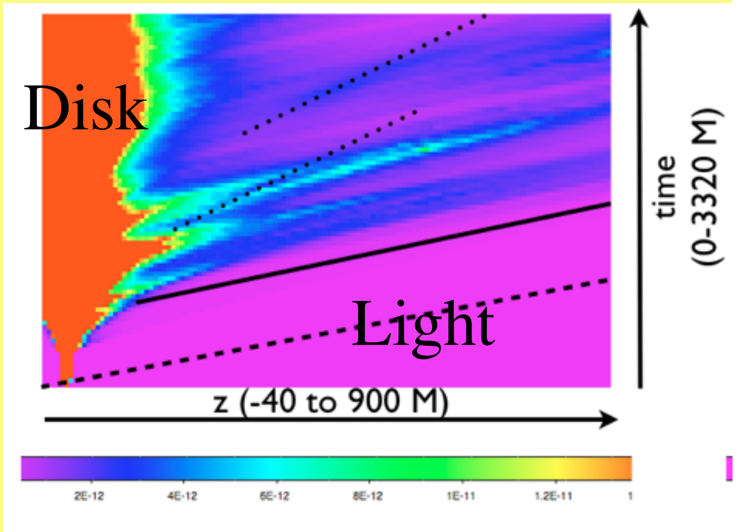
z [r_g]
y [r_g]
x [r_g]
10
5
0
−5
−10
10^{1.2}
10^{0.8}
10^{0.4}
10^{0.0}
10^{−0.4}
10^{−0.8}
10^{−1.2}
10^{−1.6}
10^{−2.0}
10^{−2.4}
Ṁc^2
120
60
Ṁ_H c^2
Ṁ_j c^2
Ṁ_mw,o c^2
Υ
10.5
1.0
Υ_H
Υ_j
Υ_mw,o
η [%]
250
100
η_H
η_j
η_mw,o
0
5000
10000
15000
t [r_g/c]

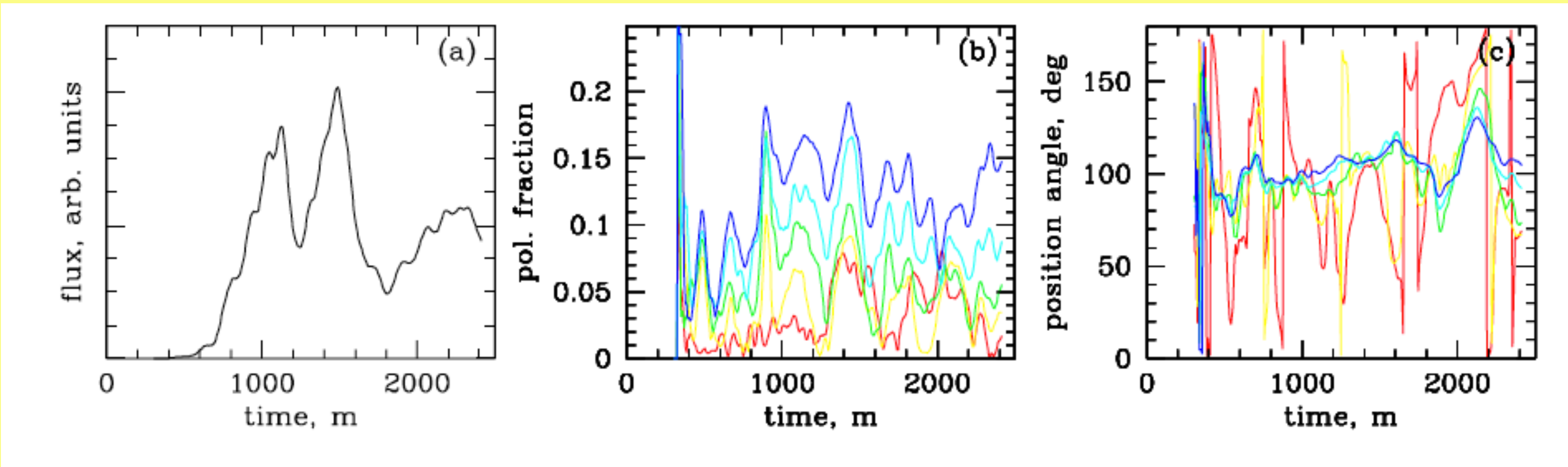
Quivering Jets

- Observe γ-rays (and optical in 3C279)
- Gammasphere $\tau_{\gamma\gamma}$~1, 100-1000m ~ $E\gamma$
- 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 $\gamma \sim 3\text{-}4$

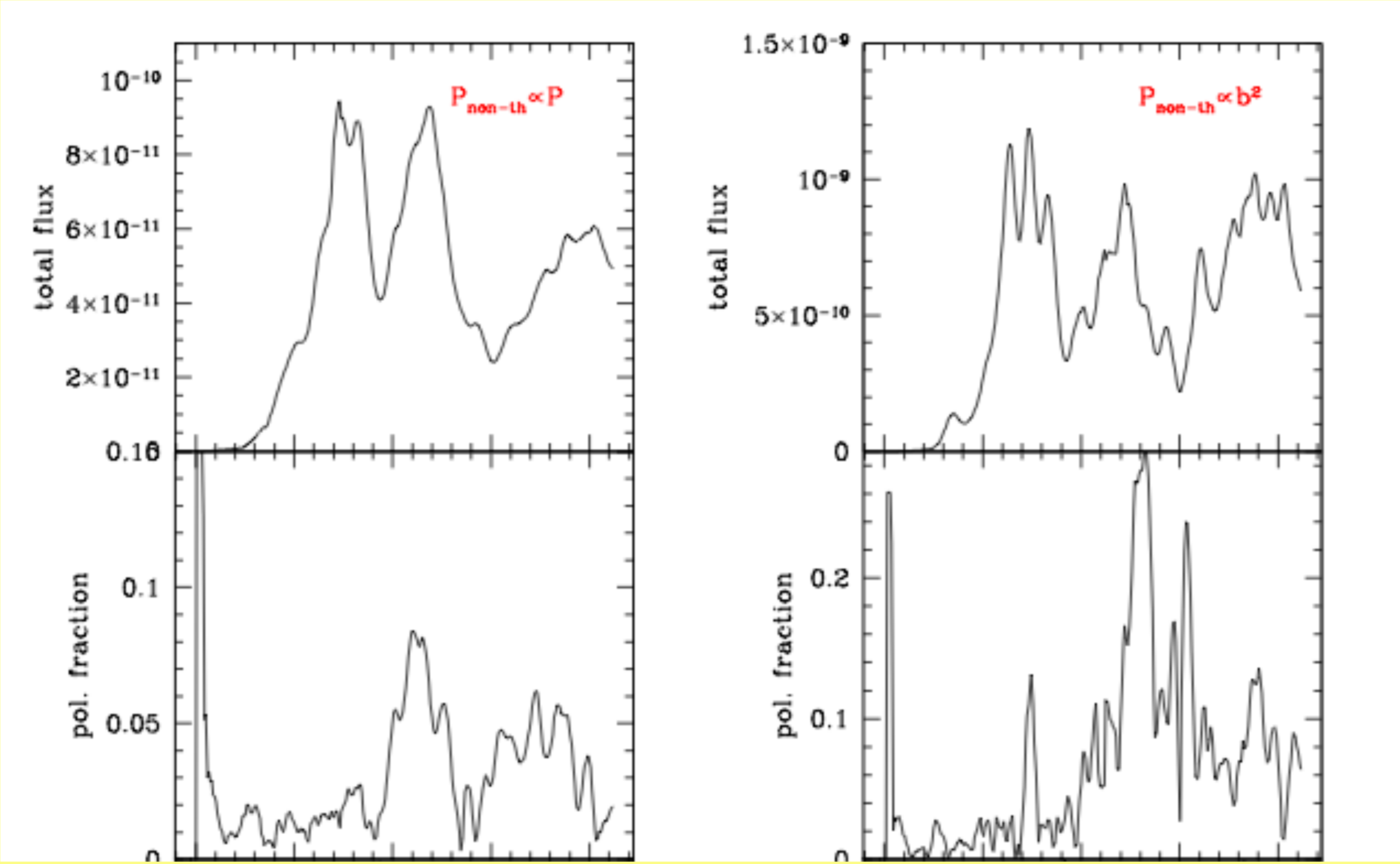






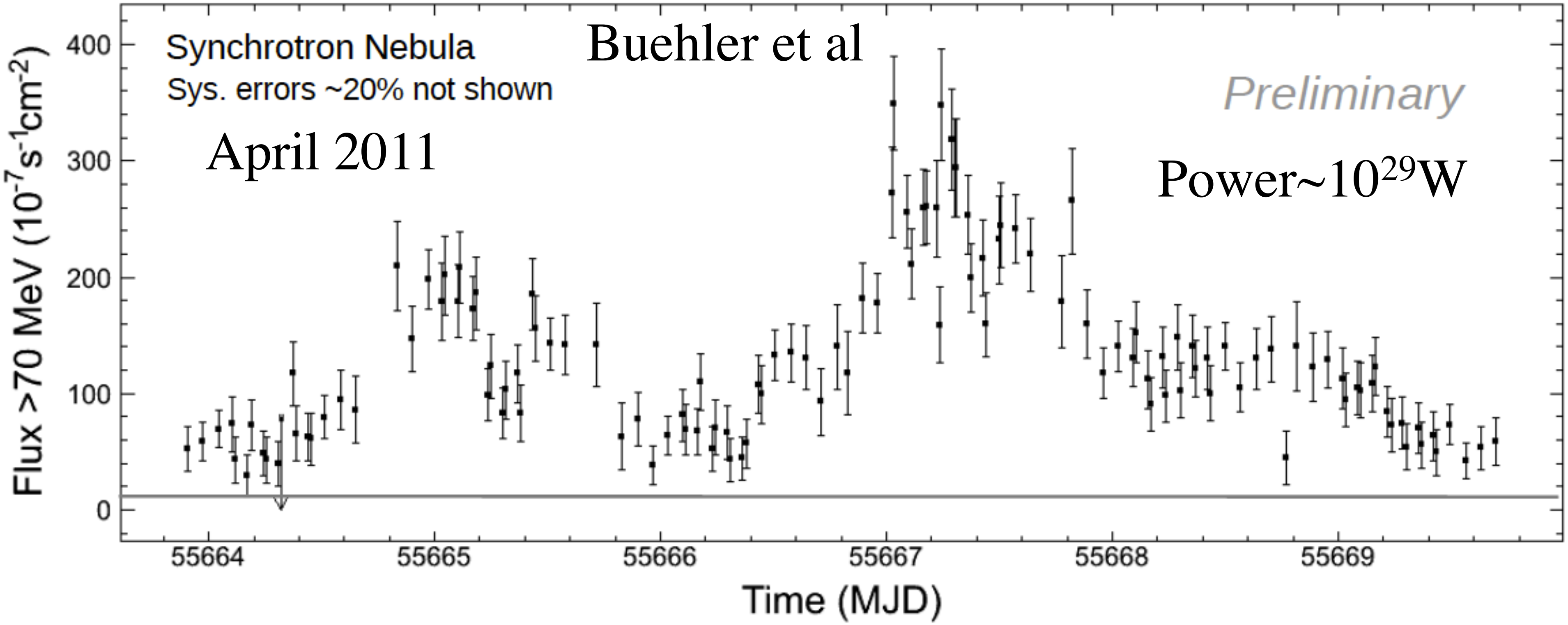
Zakamska, RB & McKinney in prep

Total Flux and Degree of Polarization



PWN Jets

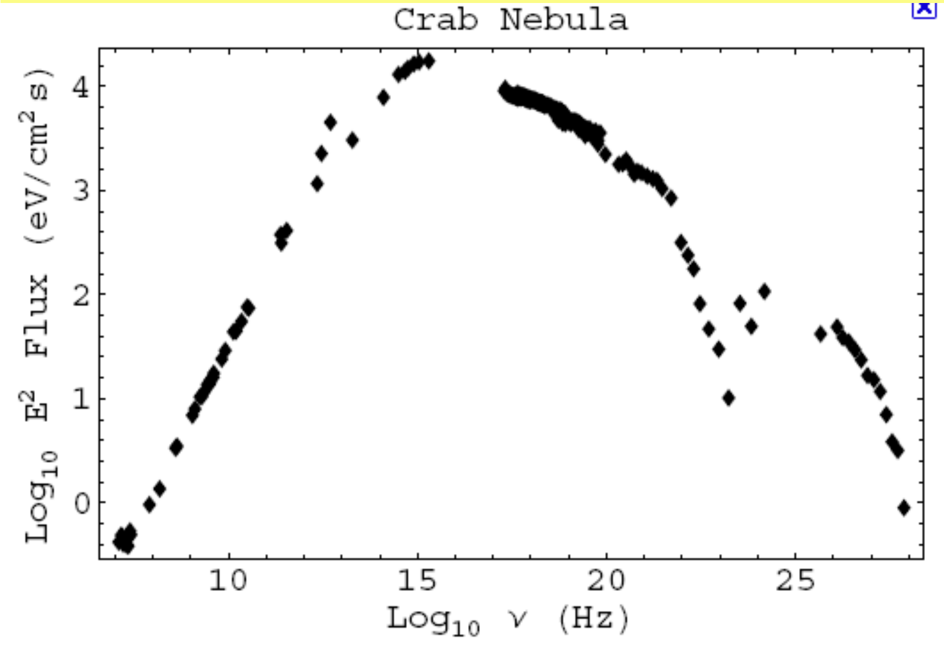
Flaring behavior

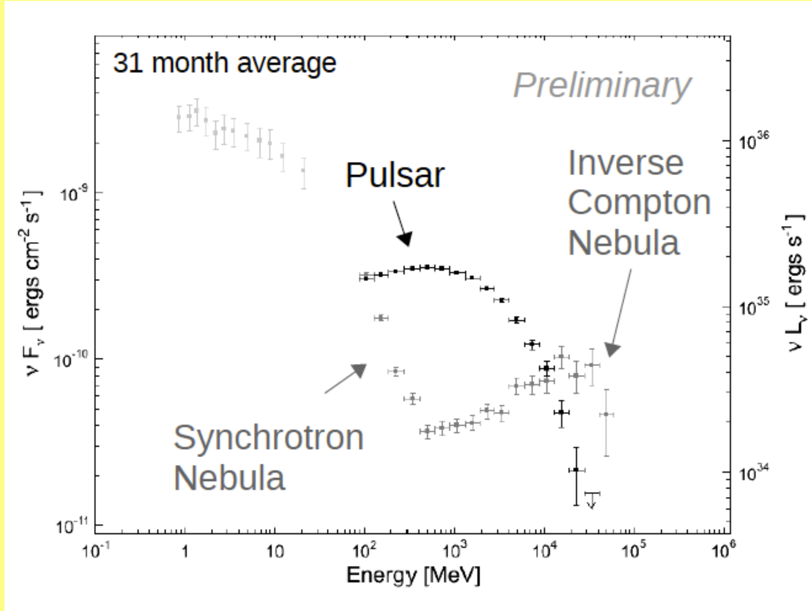


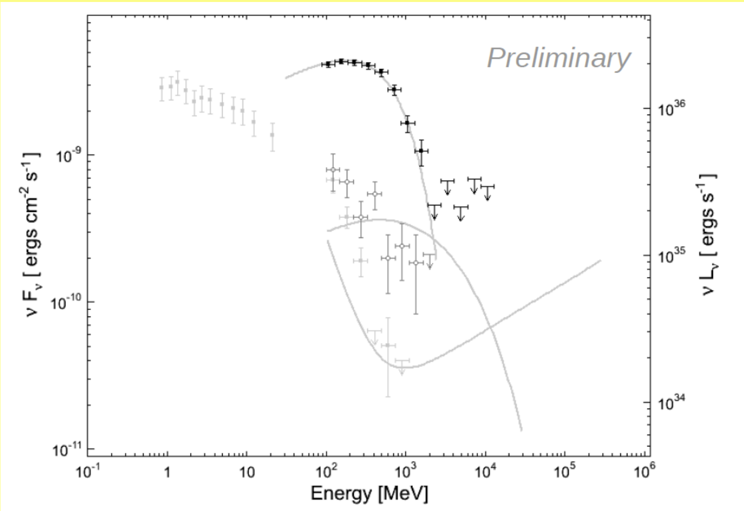
Singular events or power spectrum? No variation seen in other bands

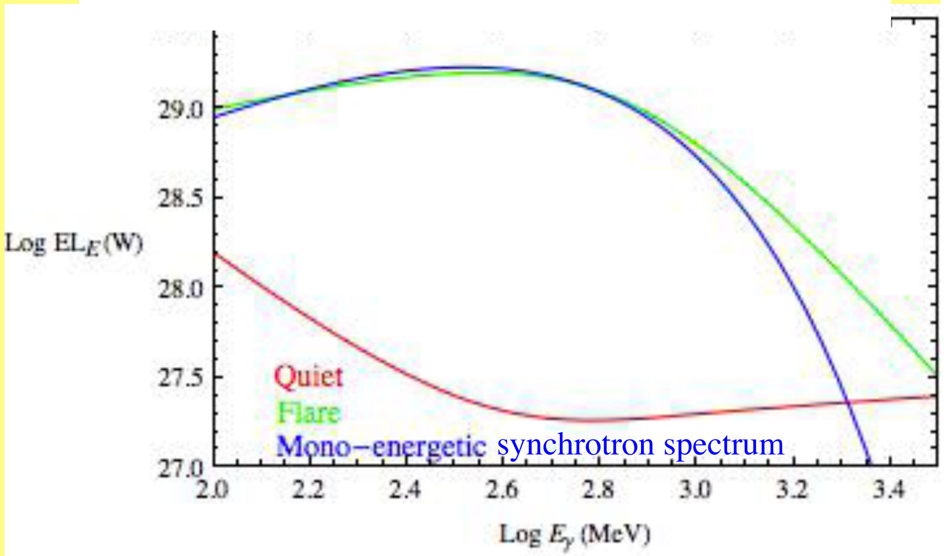
Rapid flux variability <1h

Spectrum of "Flare"



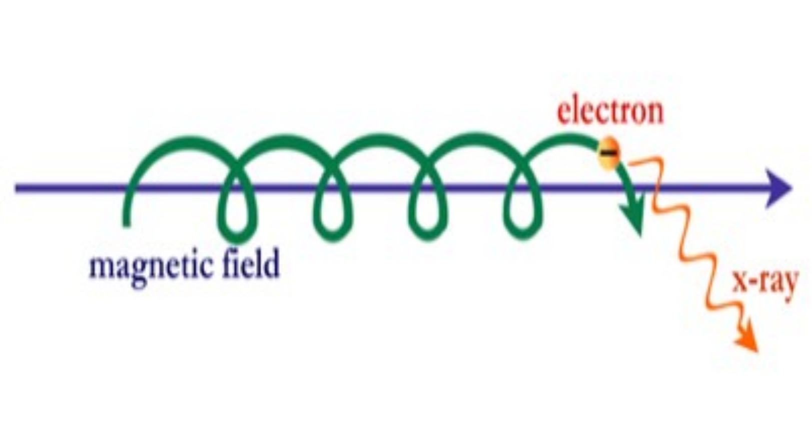






Electron synchrotron radiation: E~PeV, γ~10^9; B~100nT

Equations of Motion



0.011photons emitted in turning through aberration angle γ^{-1}

$$\frac{d\vec{u}}{dt} = \vec{a}_L - \frac{2r_e}{3c}\gamma^2 a_{L\perp}^2 \hat{\vec{u}}, \quad \frac{d\vec{x}}{dt} = \hat{\vec{u}}$$

$$\vec{a}_L = \frac{e}{m}\left(\frac{\vec{E}}{c} + \hat{\vec{u}} \times \vec{B}\right)$$

$$a_{L\perp}(\vec{x}, \hat{\vec{u}}) = \frac{e}{m}B_e = \frac{e}{m}\left[B_\perp^2 + \left(\frac{E_\perp}{c}\right)^2 - 2\frac{\vec{E}\times\vec{B}.\hat{\vec{u}}}{c}\right]^{1/2}$$

$\gamma_9^2 B_{e-7} = (E_{peak}/23\text{MeV})$

Radiation reaction dominates when $E_\gamma > \alpha^{-1} m_e c^2$

If only uniform magnetic field, electron cools in 12^o

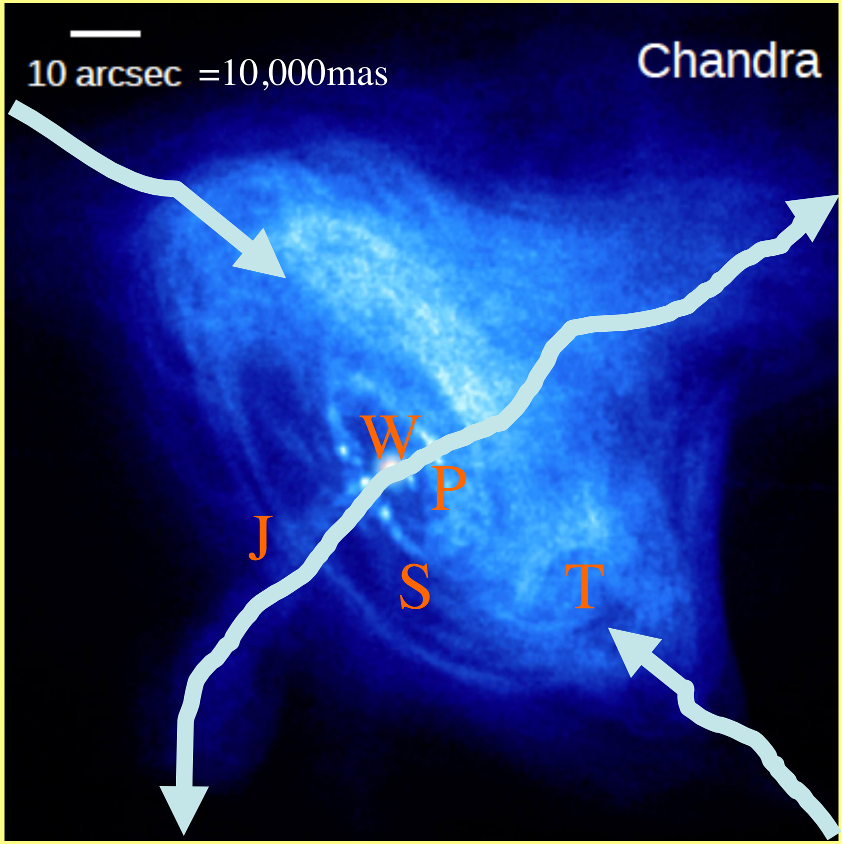
If add electric field, E>5cB to avoid energy loss

If as likely, E>cB, not just relativistic beaming

Where does the variation originate ?

- Long term variation of nebula likely due to changes in magnetic field
- Peak power is ~ 3 percent of nebular power
- Flare energy equals that stored in a region of size

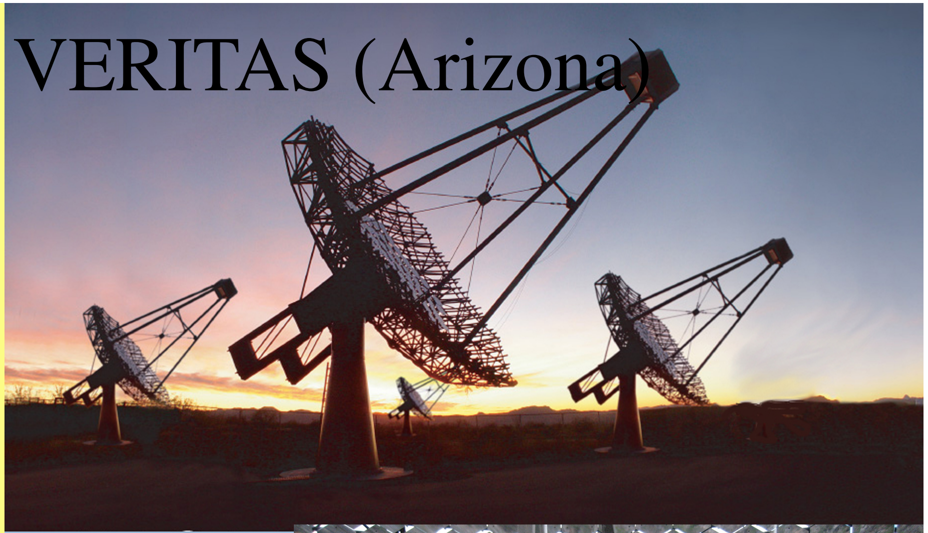
  $L \sim 20B_{-7}^{1/2}$ lt d ~ $2B_{-7}^{1/2}$ arcsec
- We want to learn where and how nature accelerates particles to high energy
- Not the Pulsar
  - No correlation with rotation frequency
- Wind shocks when momentum flux equals nebular pressure
- Wind, Shock, Jet, Torus are all possibilities



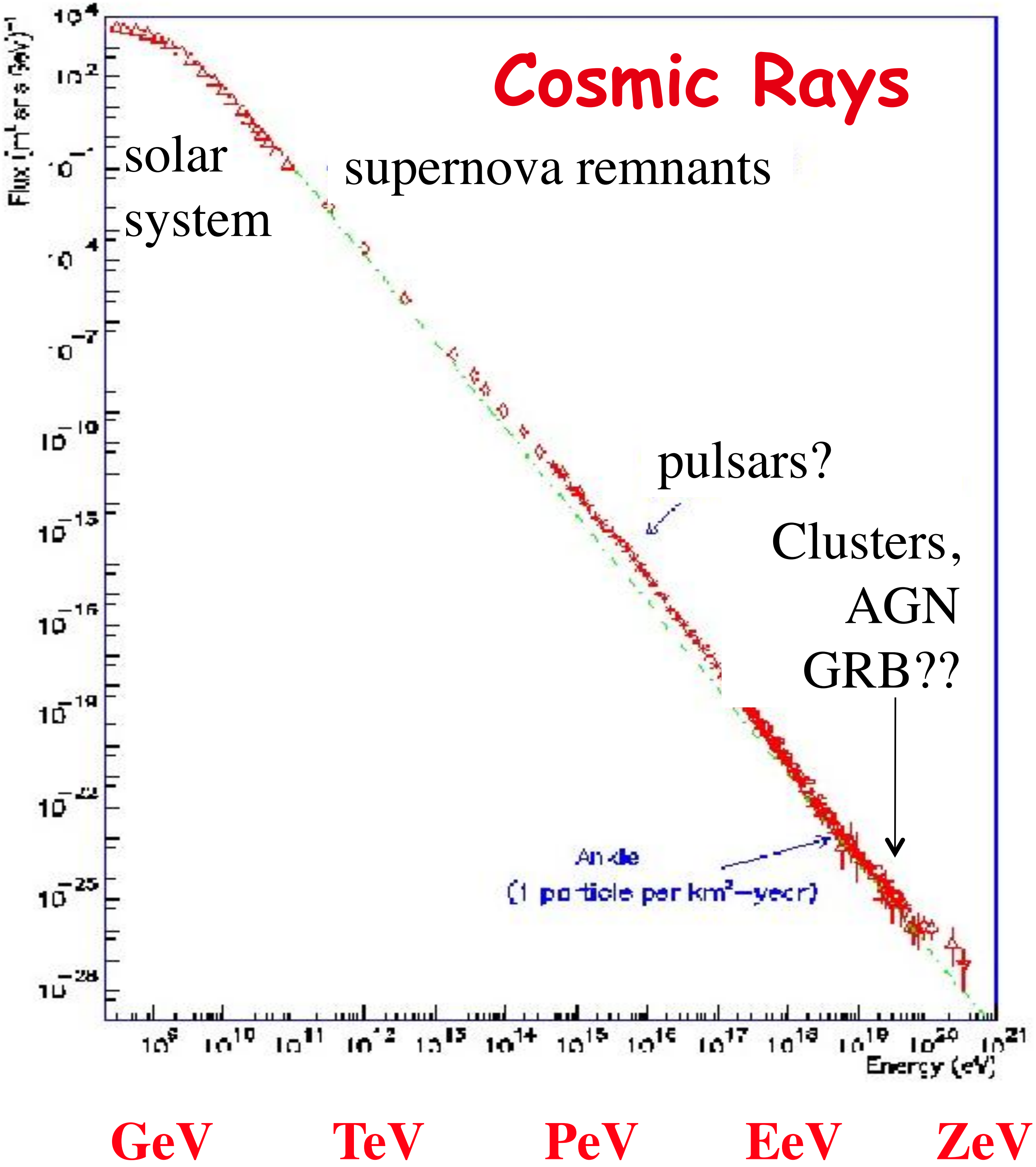
1 lt hr = 3 mas

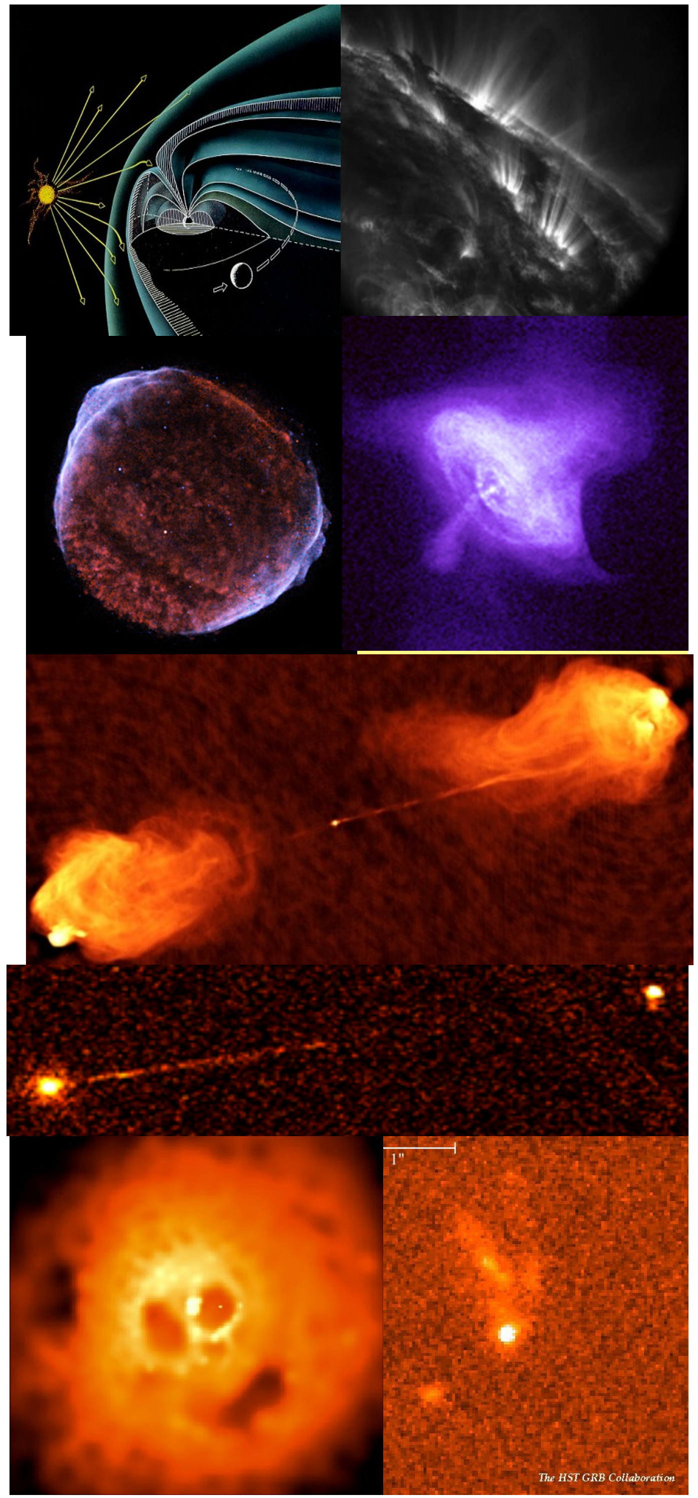
Larmor radius= $60\gamma_9 B_{-7}^{-1}$mas

Very High Energy Gamma Rays



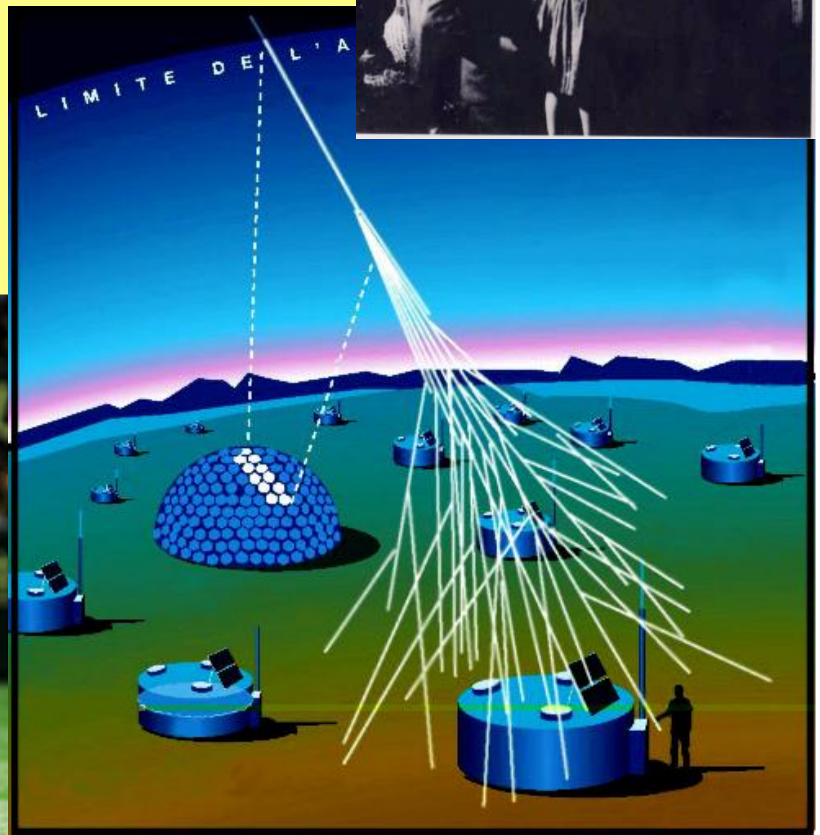
- Energy ~ Uranium nucleus
- Many new sources
  - Black hole jets
  - Supernova remnants
- 3 minute variations


Cosmic Rays
solar system
supernova remnants
pulsars?
Clusters, AGN GRB??
Ankle
(1 particle per km²–year)
Flux (m⁻² sr s GeV)⁻¹
Energy (eV)
GeV
TeV
PeV
EeV
ZeV

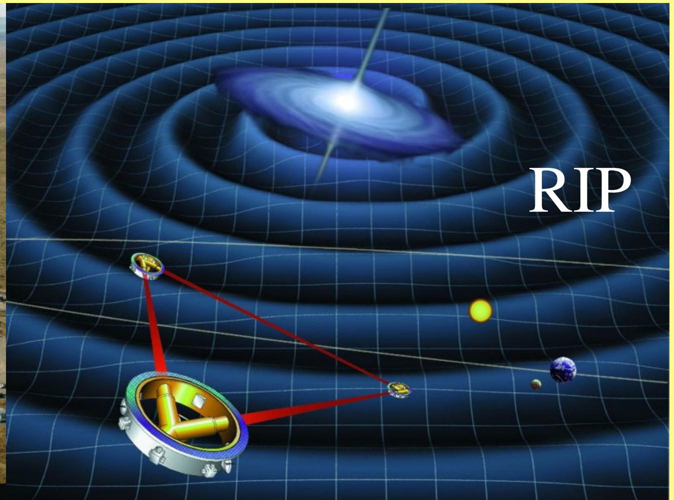

The HST GRB Collaboration

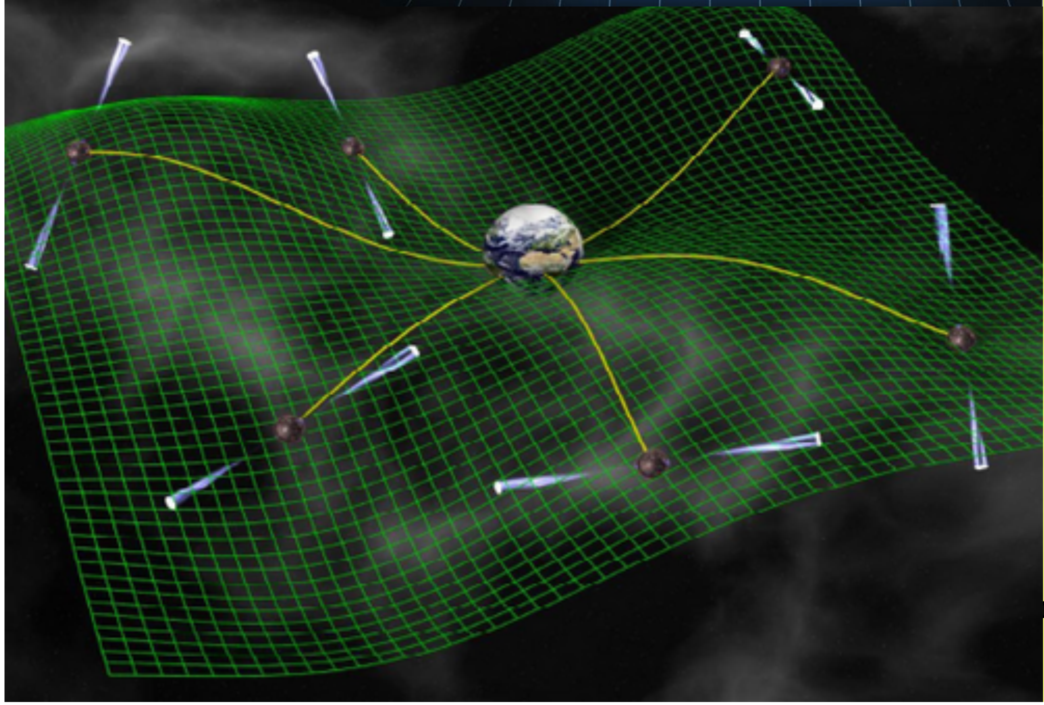
ULTRA HIGH ENERGY COSMIC RAYS

- Ultra High Energy Cosmic Rays
- Energies up to 50 Joule!
- May be seeing black hole sources
- eg Centaurus A



LIGO, LISA, Nanograv…



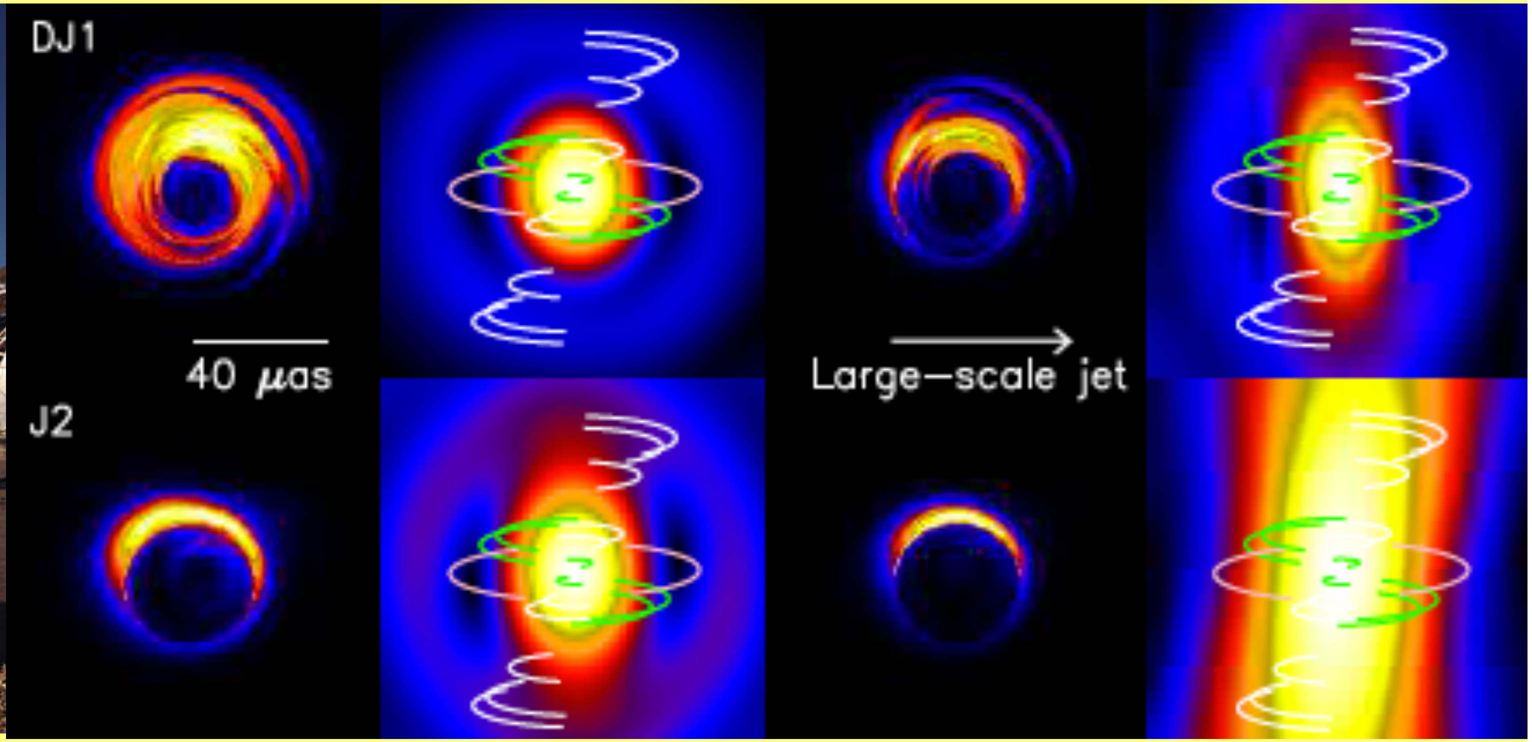


- **Merging Black Holes**
  - Ultimate test of dynamical, strong General Relativity
  - Orbit, plunge…
  - Background
- **Millisecond pulsar array**
  - Fermi + radio (44)
  - 40 ns timing accuracy

Imaging a Black Hole?

- **For M87 and Galactic Center,**
  - **2m ~10μ arcsec ~ 300μ/R_E**
- **Event Horizon Telescope (Doeleman et al)**
  - **ALMA VLBI**

Dexter, McKinney, Agol



Summary

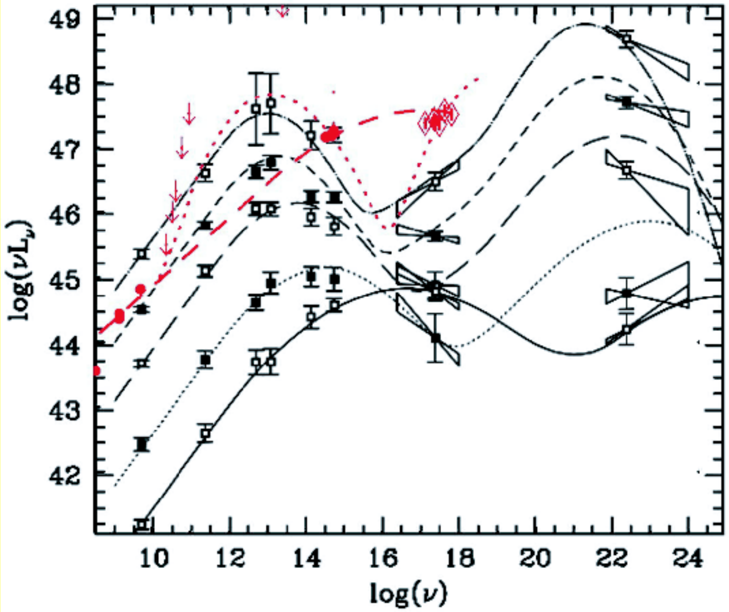
- Black Holes common in Galaxy, AGN, GRB
- Masses and spins can be high
- Multi-λ observations of large jet samples
- 3D RMHD simulations now very powerful
- Parallel issues with PWN
- Magnetic->Leptonic->Hadronic transitions
- MBH jets may accelerate UHECR

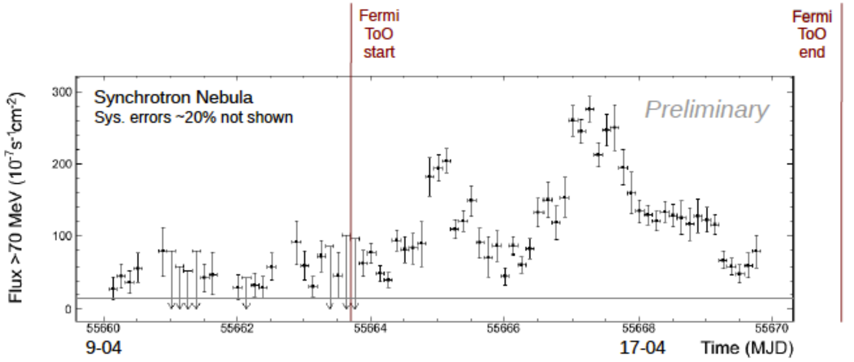
Particle acceleration in high σ environments

- 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

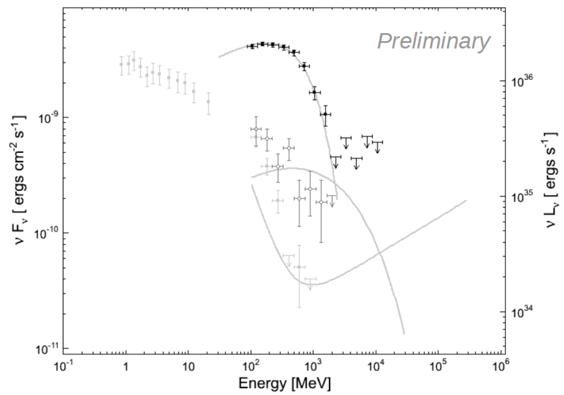
Particle Acceleration

- 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?





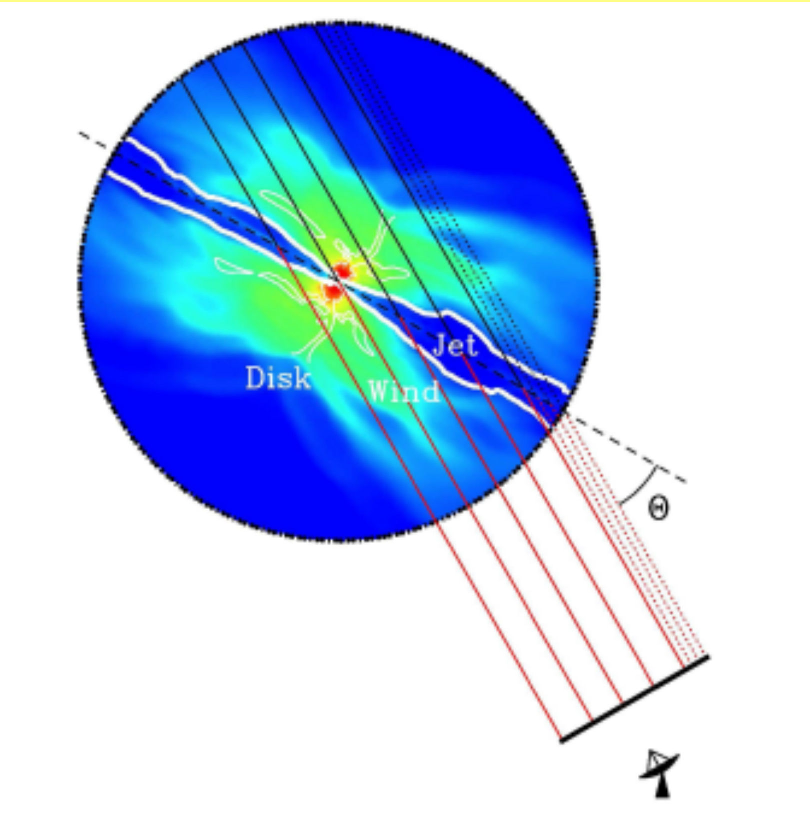
Synchrotron nebula increased by factor ~20
during very good Chandra coverage



Faraday Rotation

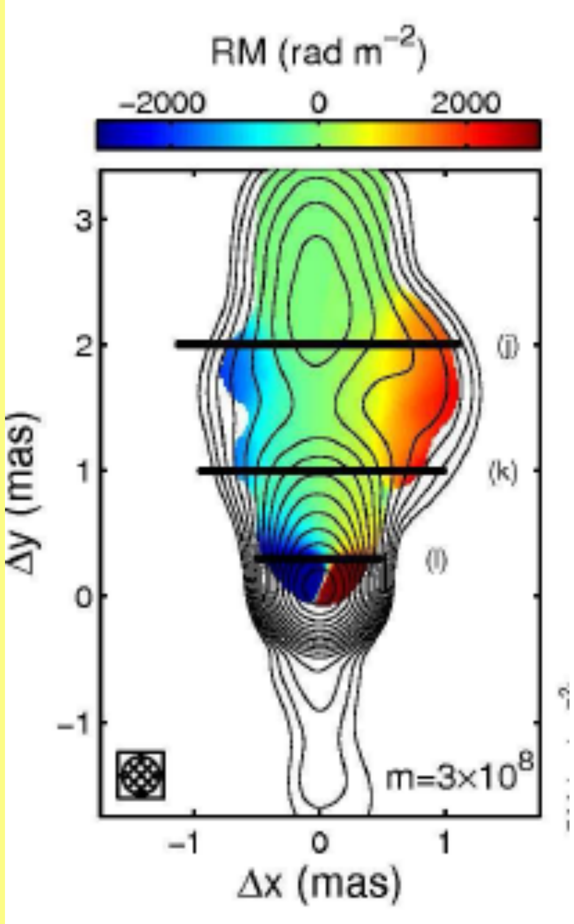
Simulation

Signature of toroidal field/axial current

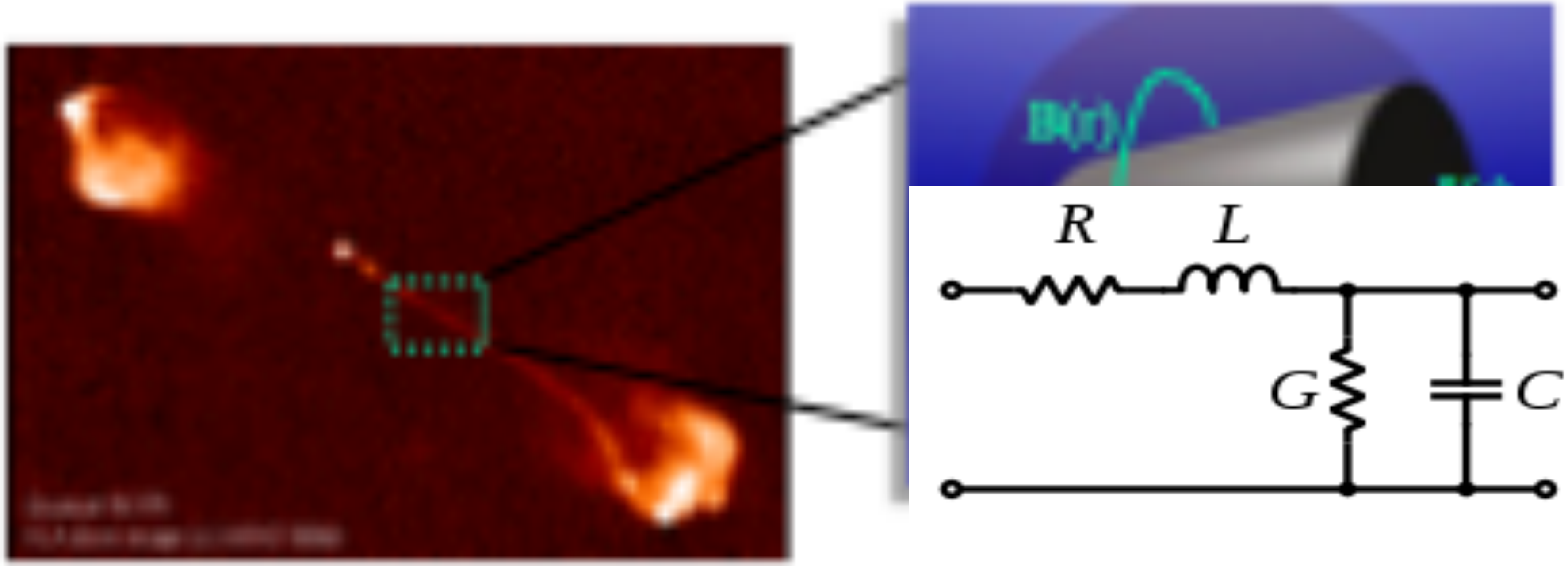


Broderick & McKinney

Rotation from sheath



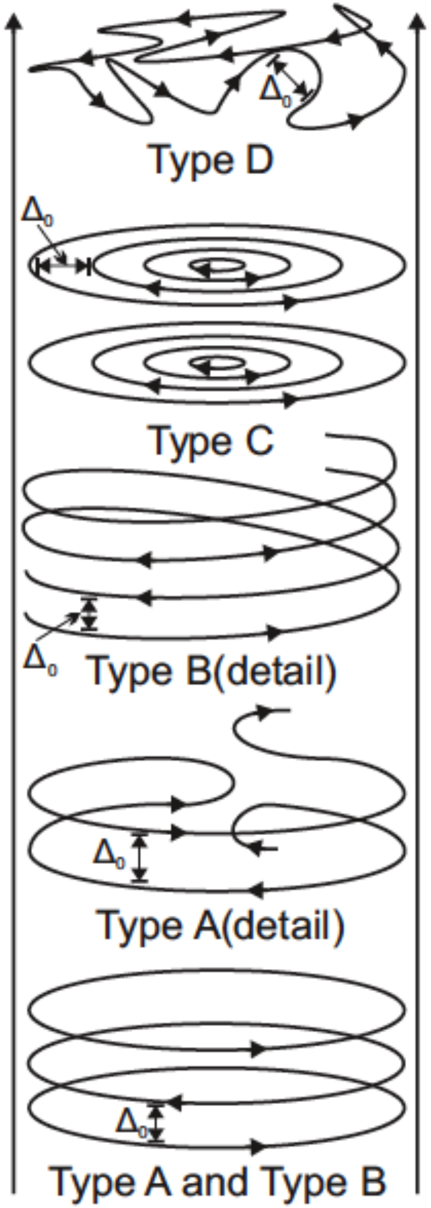
Observations ???



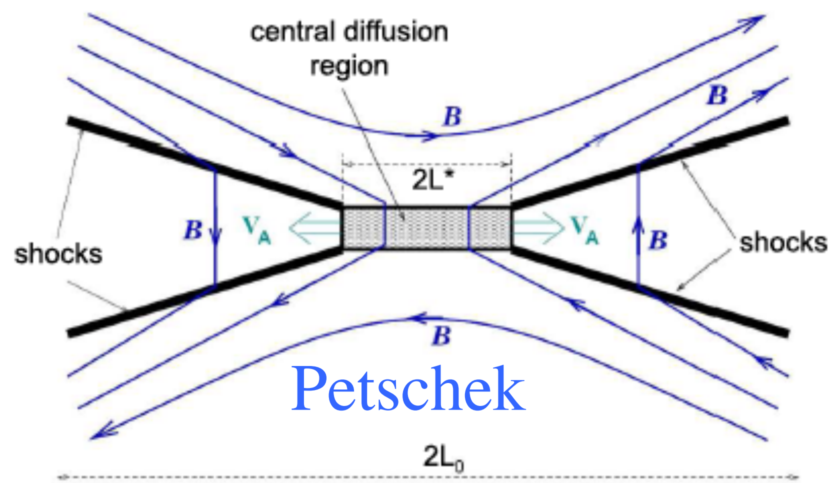
$$\frac{\partial^2}{\partial x^2}V = LC\frac{\partial^2}{\partial t^2}V + (RC + GL)\frac{\partial}{\partial t}V + GRV$$
$$\frac{\partial^2}{\partial x^2}I = LC\frac{\partial^2}{\partial t^2}I + (RC + GL)\frac{\partial}{\partial t}I + GRI$$

Telegraphers' Equations

Relativistic Reconnection

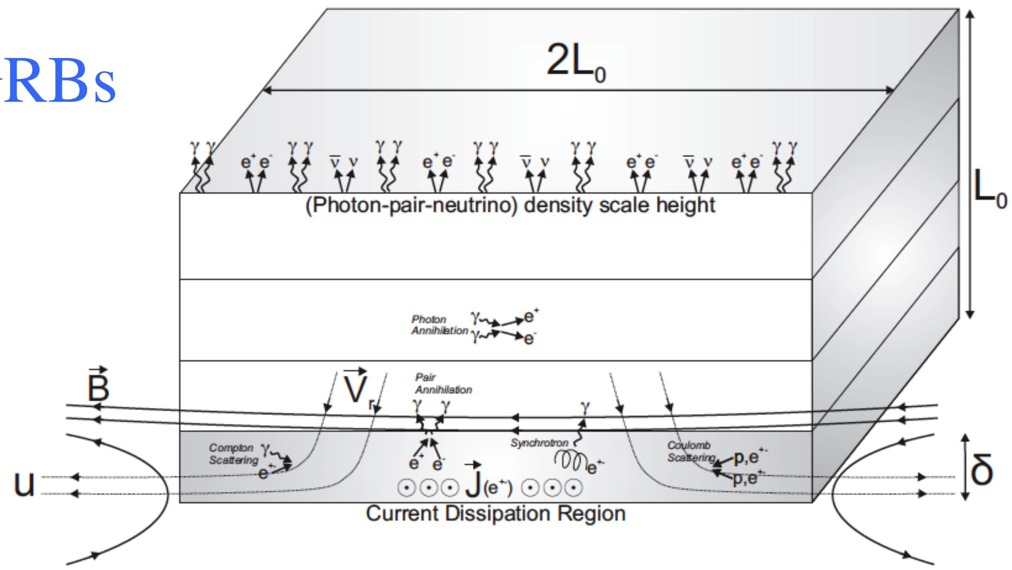


- High σ flow
- Hall effects may save Petschek mechanism
- Anomalous resistivity?
- Also for AGN



Petschek

GRBs ?

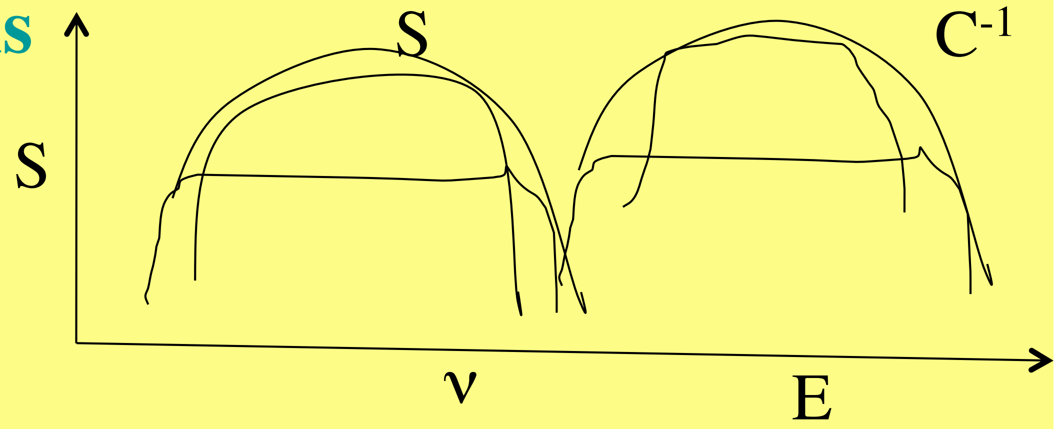


30 v 2012

McKinney & Uzdensky

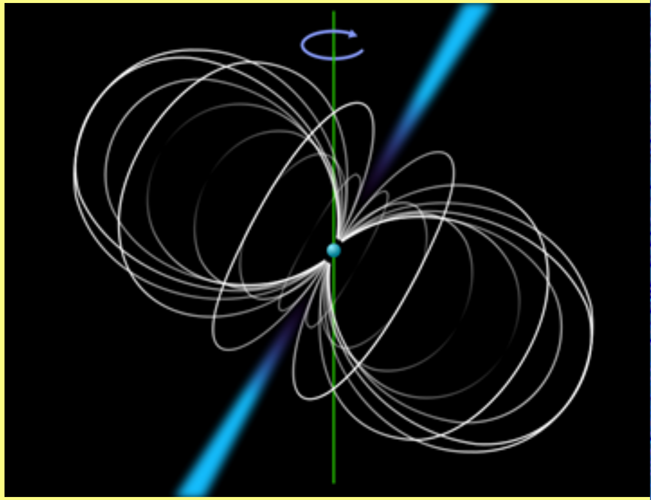
Inhomogeneous Sources

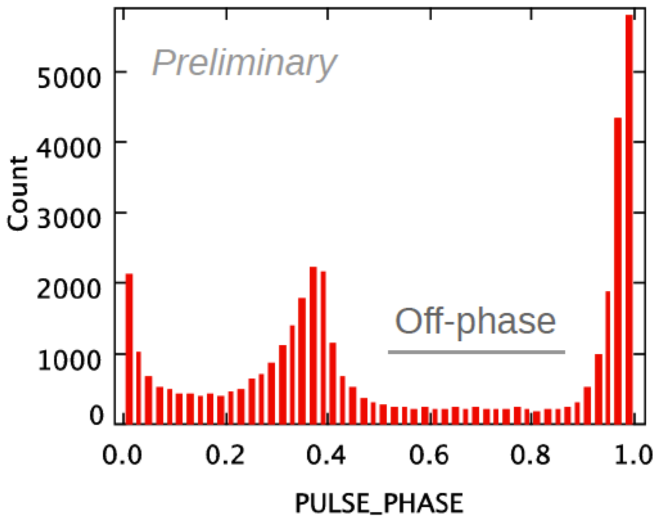
- Radio synchrotron photosphere, r ~ λ
  - Doppler boosting
- Compton gammasphere, r ~ E?
  - Internal, external radiation
  - Test with variability, correlation
- Electron acceleration
  - >100 TeV electrons

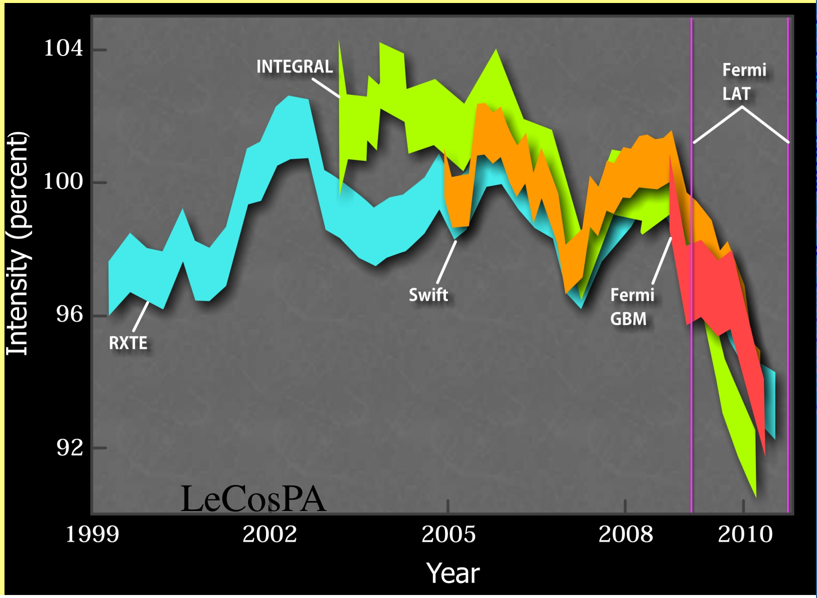


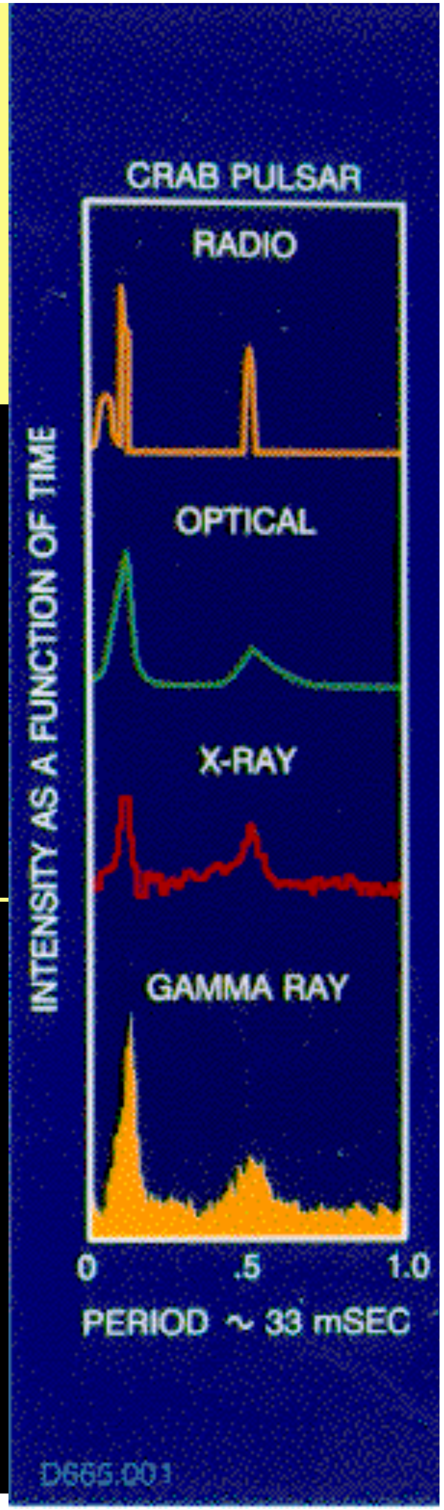
Crab Pulsar

- **Discovered in 1968**
  - Turning point in history of astronomy
  - Spinning, magnetized neutron star
  - Predicted by Pacini
  - 12km radius
  - 30 Hz spin frequency
  - B= 200 MT (2×10^{12}G)
  - Radio through 400 GeV pulses
  - ~ 50PV; 200TA; 2×10^{31}W ~ $-I\Omega\Omega'$
  - Carried off in wind
  - Powers nebula



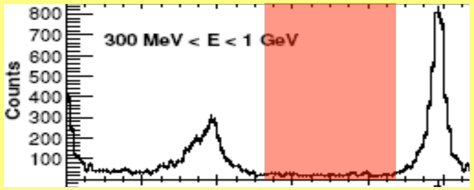


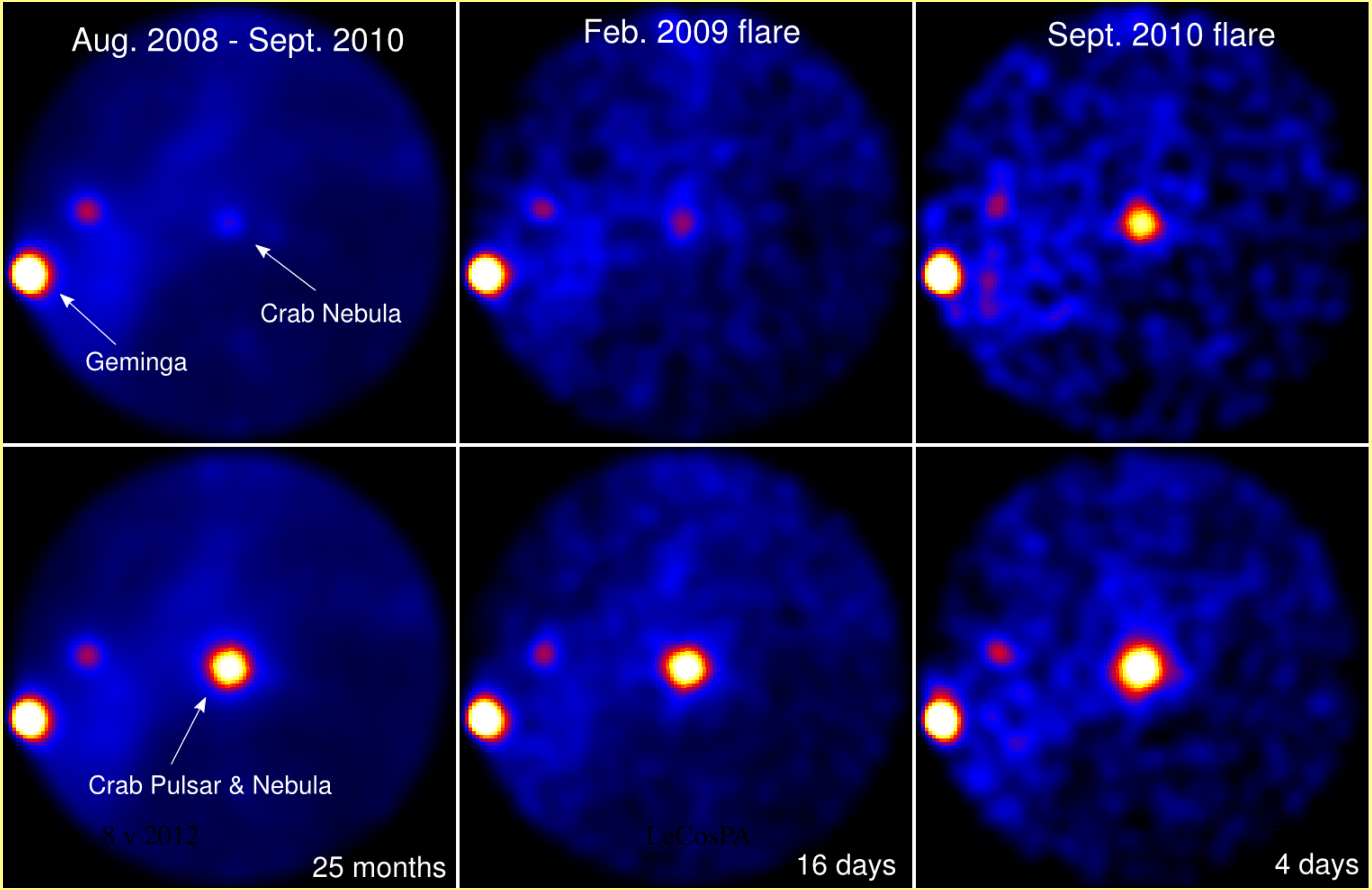




Buehler

GeV Crab Flares





Pair vs Ion Plasmas

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

“Observing” Simulated Jets Pair Opacity

- External and internal radiation
- Internal radiation varies

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