Particle Acceleration in γ-ray Sources

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Fermi Collaboration

140 octaves to explore

Electromagnetic

Waves

Particles
Photons

<--- Radio IR UV X-ray Gamma ray---->

Cosmic Rays

Neutrinos

Gravitational Radiation

Dark Matter?

1aeV

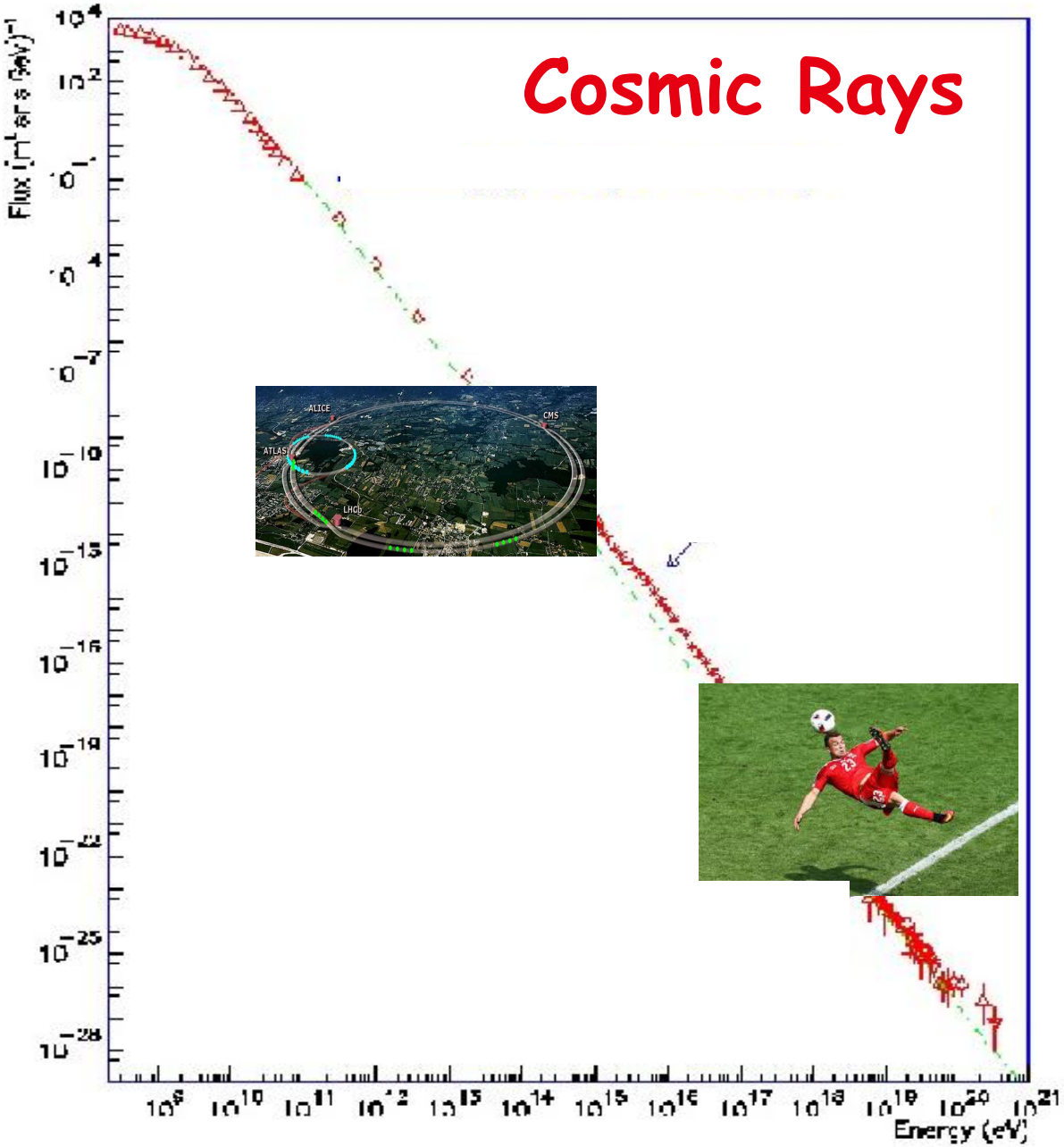
Energy, frequency →

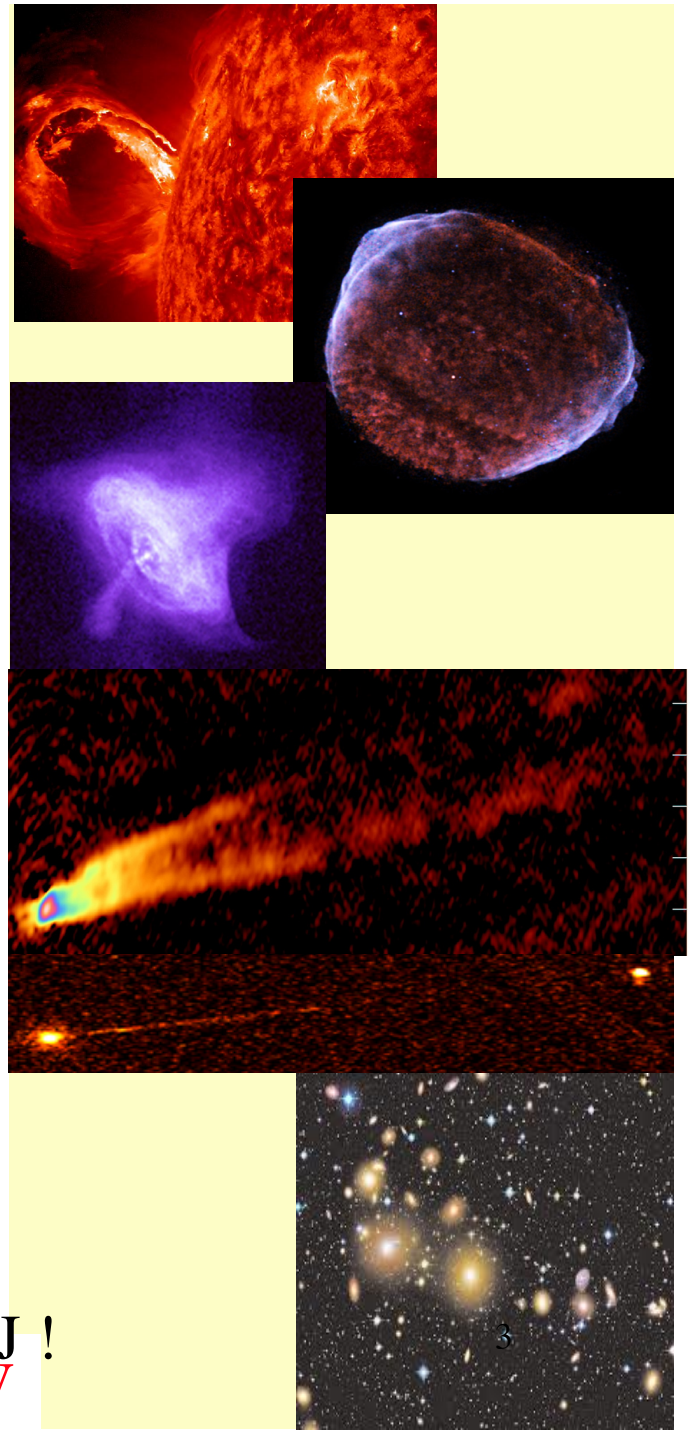
1 ZeV

← Wavelength

+YeV, XeV!

Cosmic Rays





160 J !

GeV TeV PeV EeV ZeV

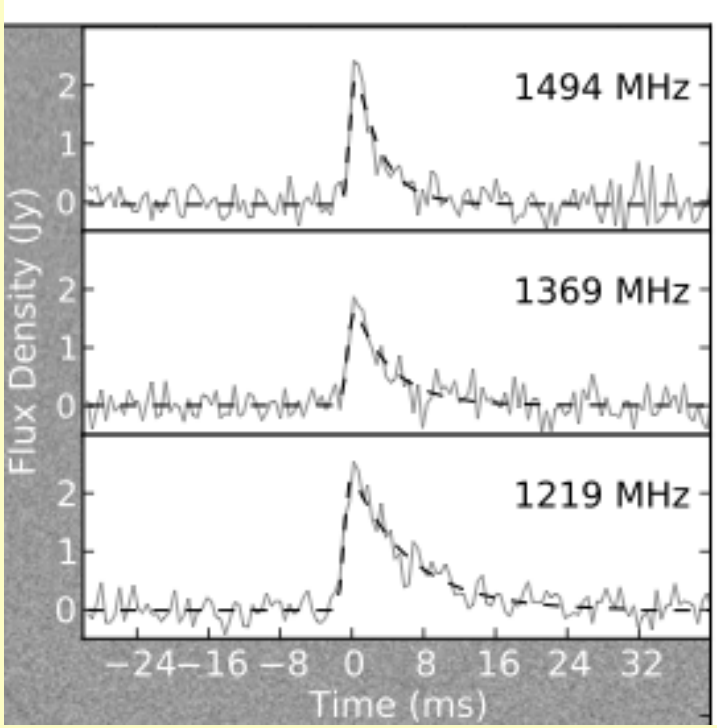
TeV-ZeV Acceleration

- EM/MHD outflows
  - NS, BH, Disks -> Jets and Winds
  - Blazars, GRBs, GSL, PWN, FRB, sun…
  - Magnetic dominance to MHD turbulence
  - Ohmic dissipation is particle acceleration
- Stochastic acceleration in gas flows
  - Shocks, random waves
  - Heliosphere, SNR, Novae, clusters…
  - Plasma dominance?
  - Dynamo action, wave

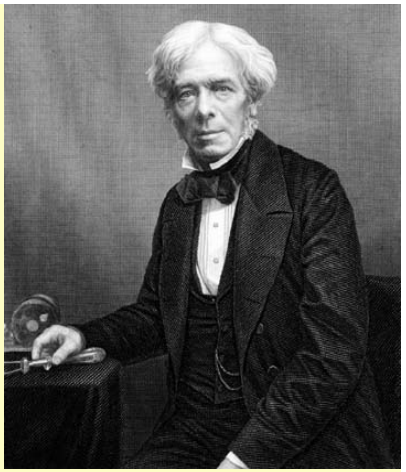
Fast Radio Bursts

- New population of apparently high redshift radio transients
- Identifications unknown but dispersion and scattering consistent with cosmological origin
- ~ 10^{39} erg radio emission in ms
- ~ one every 5-60 minutes
- 10^{30-40}K!
- Many possible sources: WD-WD, NS-NS, NS-BH mergers, magnetar explosions…

(Lorimer et al 2007, Thornton et al 2013)



Unipolar Induction



Unipolar induction by spinning magnetized body

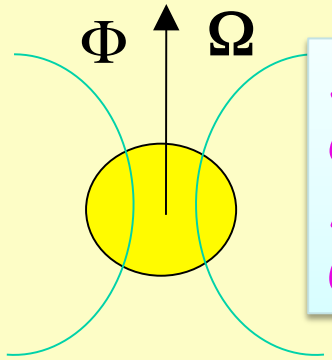
$V \sim \Omega\, \Phi/2\pi \sim E_{max}/e$

$I \sim (V / Z_0)(c/v)$

$Z_0 \sim 100\Omega$

$P \sim V\, I \sim (V^2/Z_0)(c/v)$

p

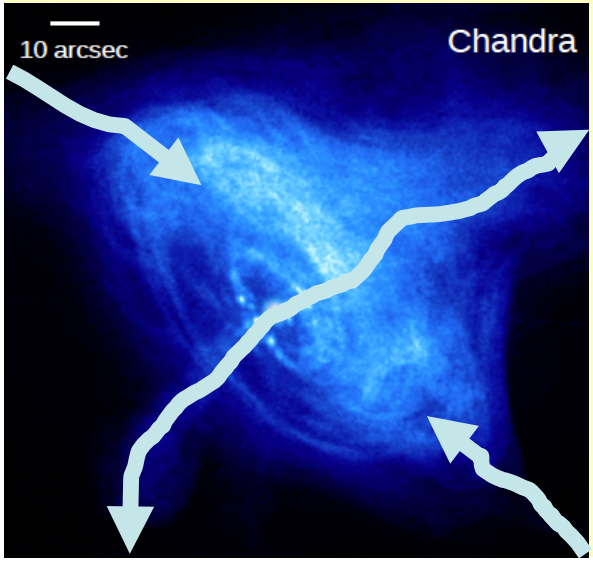


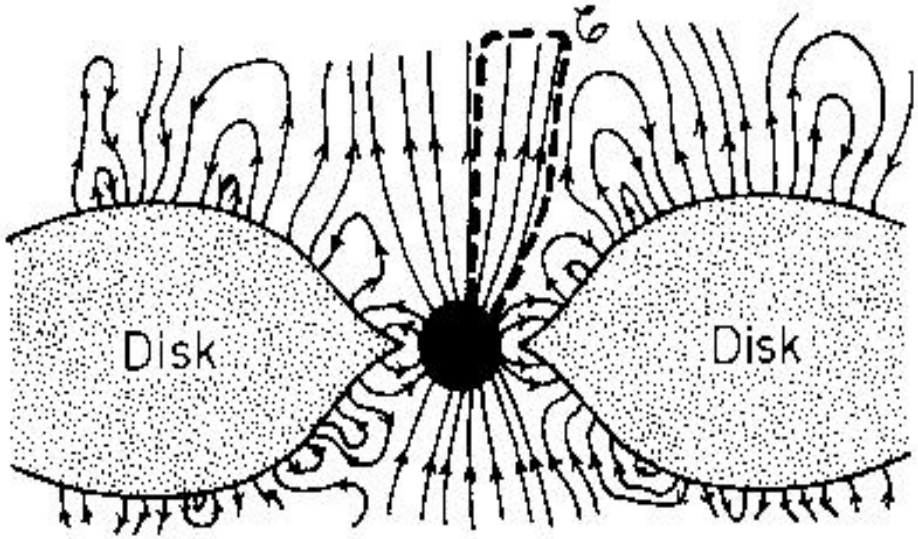
Sun - V ~ 100 MV, I~1 GA, P~100PW

Crab - V~ 30 PV, I~300TA, P~ 10^{31} W

AGN - V ~ 1 ZV, I ~ 10 EA, P~10^{40}W

GRB - V ~ 0.1 YV, I~1 ZA, P~10^{44}W



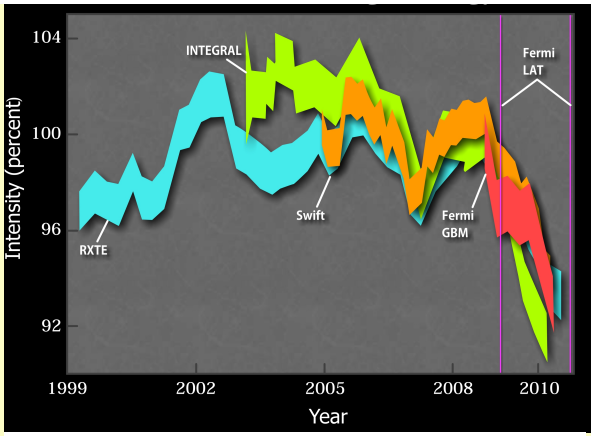


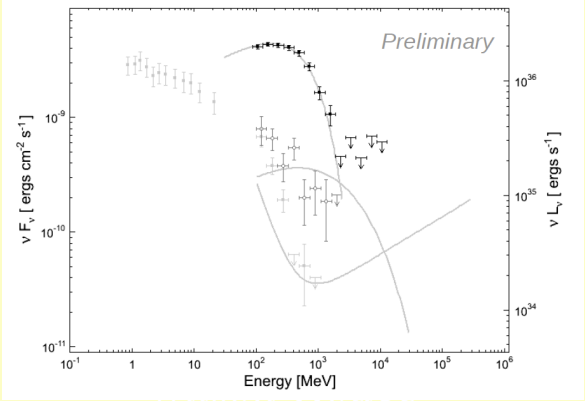
Te

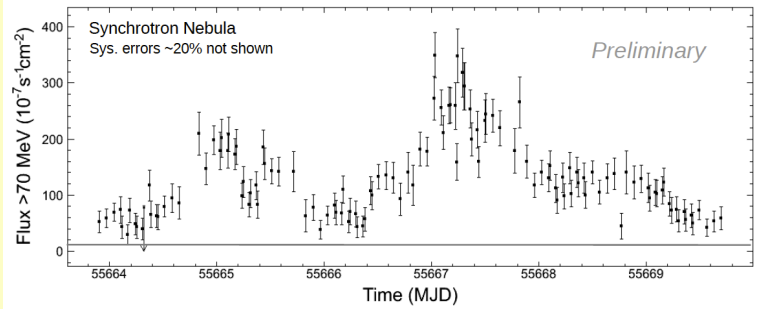
Crab Pulsar and Nebula

XAP Laboratory

- Crab pulsing at ~1TeV
  - ~50 PV EMF
- Unsteady Flux
  - 30 yr timescale in 1000yr source
  - Ordered Magnetic Field
- ~300MeV Crab flares
  - 1-10hr variation in 10 lt yr nebula
  - Synchrotron emission by 3 PeV e
  - B~100 nT
  - r_L ~ 1 lt day





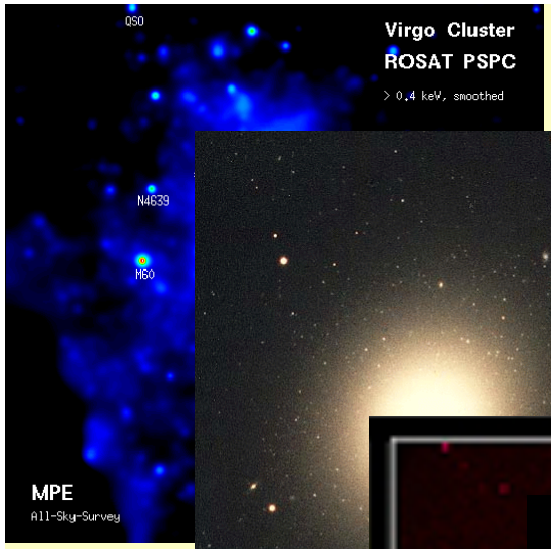


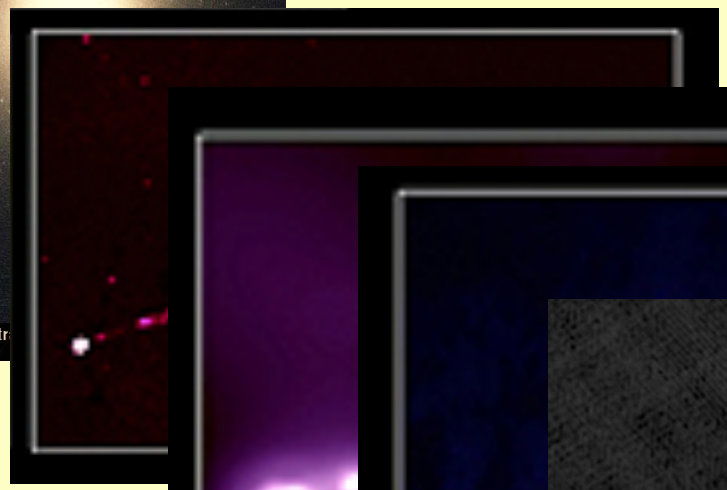
Rapid flux variability <1h

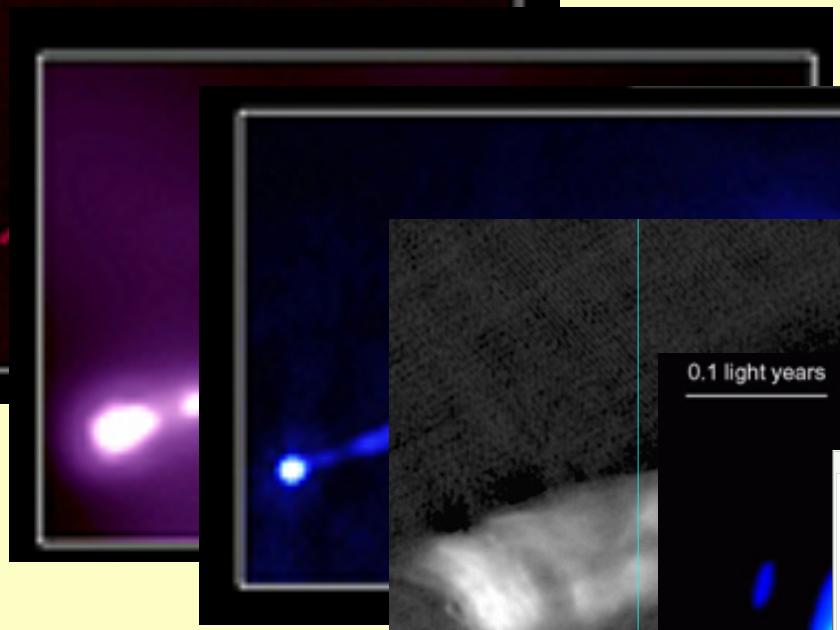
In QED We Trust

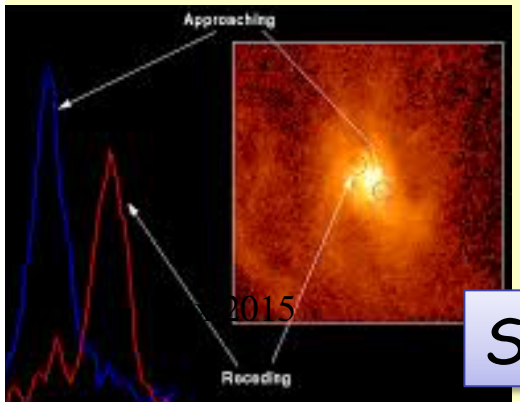
- Synchrotron Radiation
  - $E_\gamma \sim 160\ (E_e/1\mathrm{TeV})^2(B/1\mathrm{T})$ MeV <100 MeV
  - $E_\gamma \sim 20\ (E_p/1\mathrm{EeV})^2(B/1\mathrm{T})$ GeV
    - $t_{cool} \sim 200(E\gamma/1\mathrm{GeV})^{-1/2}(B/1\mathrm{T})^{-3/2}$s
- Compton scattering
  - $\sigma \sim \sigma_T$
- γ–γ pair production opacity
  - $\sigma \sim \sigma_T$
- γ-p pair, pion production
  - $\sigma \sim \alpha\sigma_T$ above threshold
  - p-p pair pion production inefficient

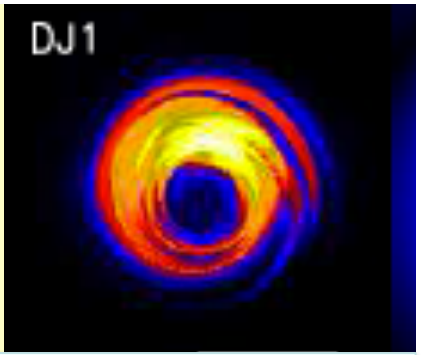
M87



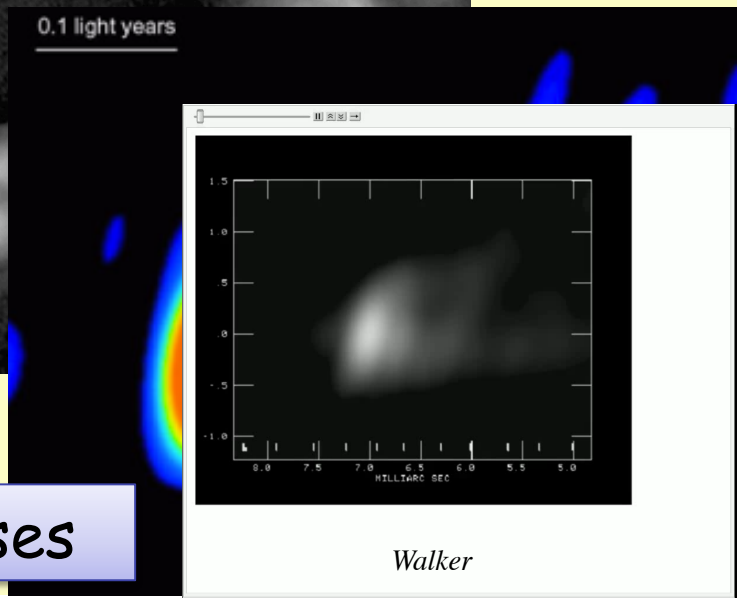








Event Horizon Telescope

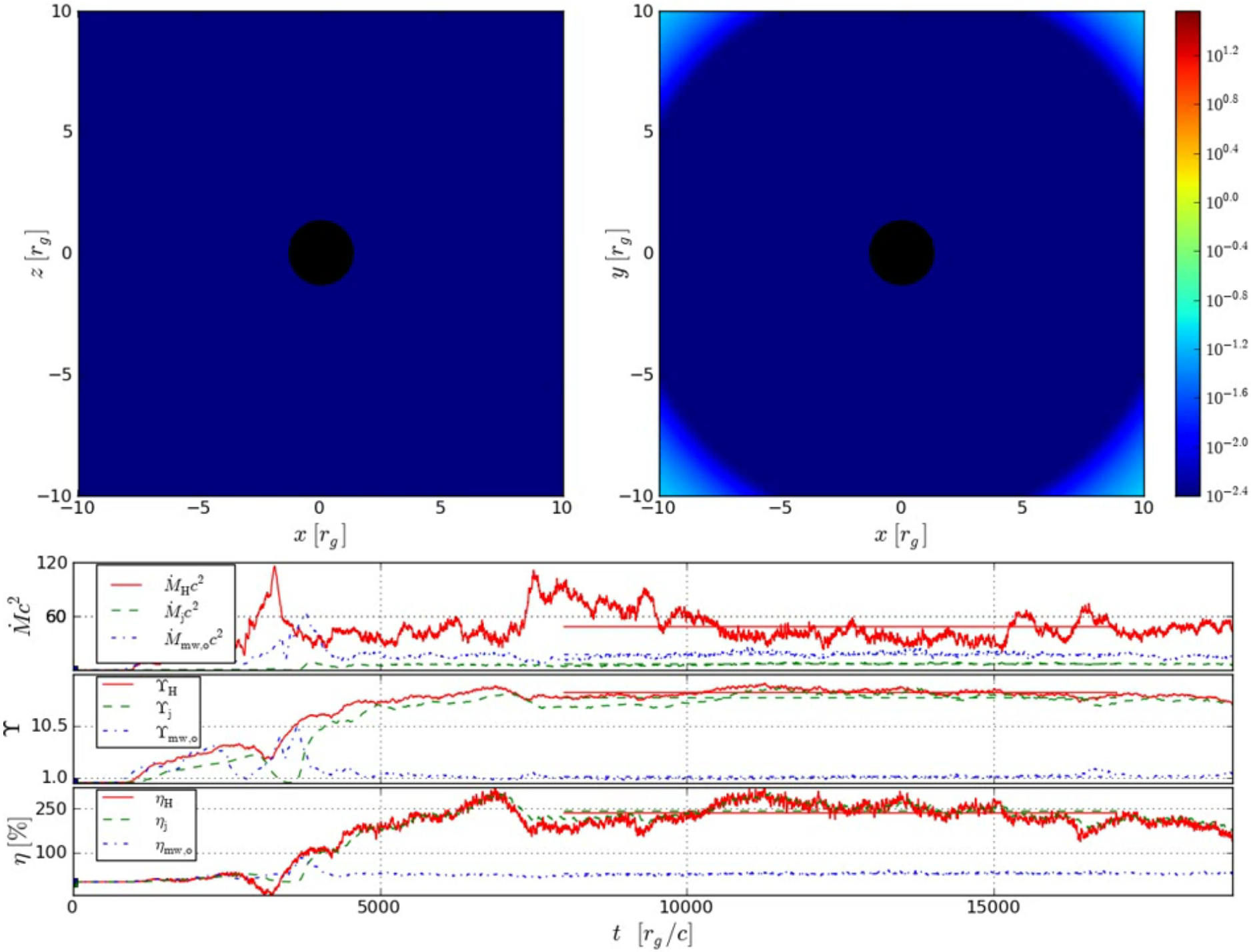


Walker

Seven billion solar masses

Some Inferences for M87

- $m=10^{13}$ m = 4 μas
- $\Omega_H=10^{-5}$ rad s^{-1}
- $\Phi_H=10^{26}$Wb; $L_{EM}\sim 4\times10^{37}$ W
- V = 55 EV; I_{max}=-1.2 EA; B~1mT-1T
- v ~ 0.7-0.95 c
- $M'=1.5 \times 10^{20}$ kg s^{-1}; $\varepsilon_{disk} < 0.002\ c^2$
- Organized Magnetic Field
- Prime Target for EHT


$z\ [r_g]$
$x\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
$10^{1.2}$
$10^{0.8}$
$10^{0.4}$
$10^{0.0}$
$10^{-0.4}$
$10^{-0.8}$
$10^{-1.2}$
$10^{-1.6}$
$10^{-2.0}$
$10^{-2.4}$
$\dot{M}c^2$
$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
Υ
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$t\ \ [r_g/c]$

observing Numerical Simulations

- EM Jet Simulations "Make Sense"
  - Outflows Efficient and Robust
  - Electromagnetic Field prescribed
- Require Confinement
  - Thick Disk and/or Powerful Wind: return current
  - Consequence of Setup
- Entrainment and Hydromagnetic Instablity
  - Sensitive to Code Resolution
  - V, P, U Uncertain
- Particle acceleration quite extraneous
  - Radiative Processes also

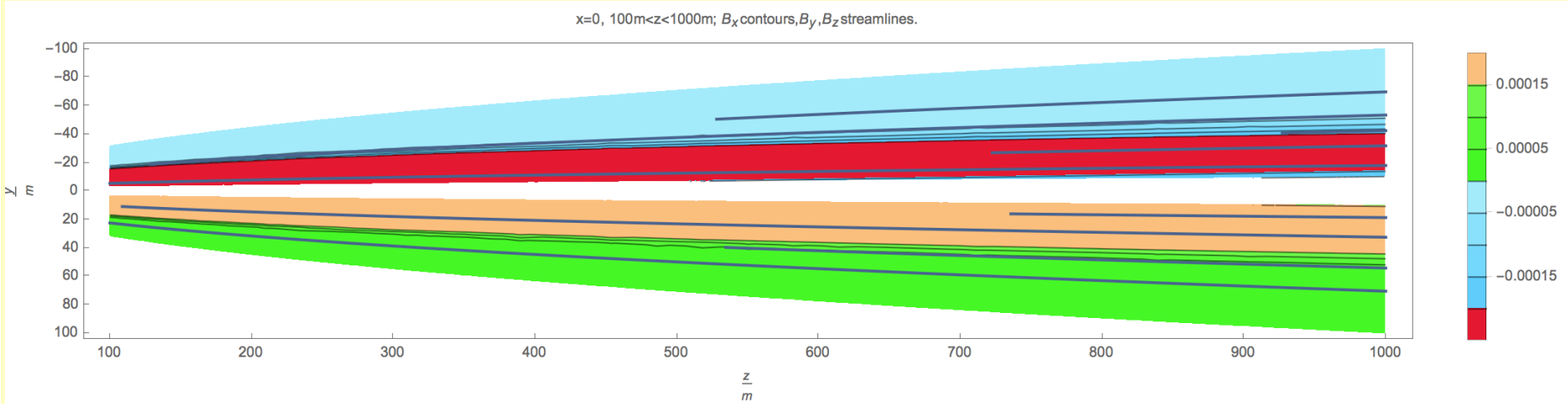
Dark Field???

Anantua

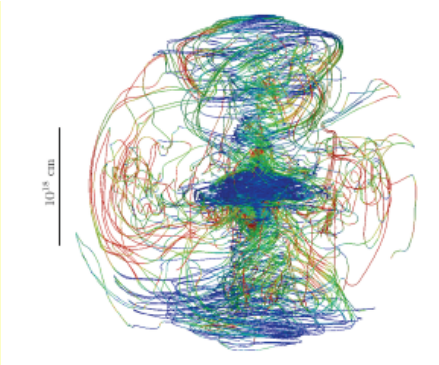
-

Features of the simulation at z=1000m

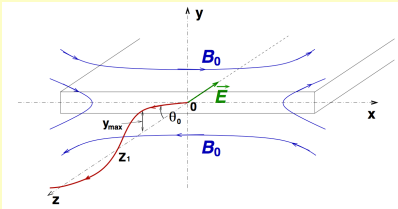
- Thick boundary layer
- Current closure
  - Industrious and Prodigal!
- Entrainment, Velocity shear
- Growth of mechanical power
- Acceleration to $\Gamma \sim 3$

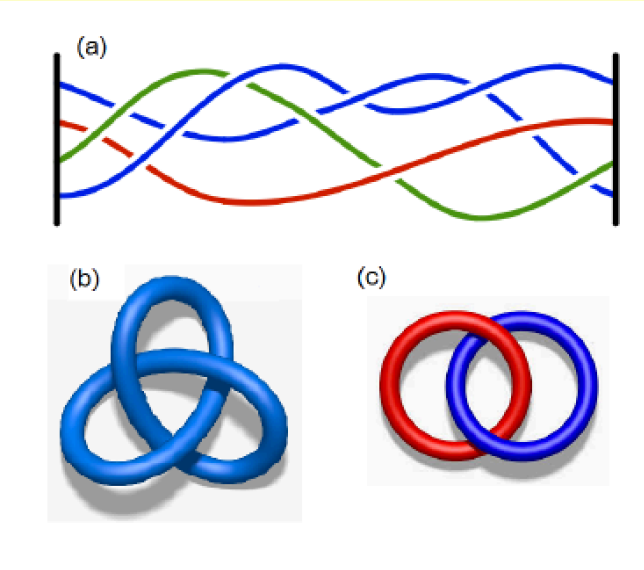


Magnetoluminescence



- EM dominant region->γ-rays
  - Rapid, efficient, volumetric conversion
    - Shocks ineffectual
- Ropes of magnetic flux
  - Evolve to knots
    - Topological structures
    - Measured by **magnetic helicity**
- Relativistic reconnection
  - Untie knots
  - Slow process
  - Change helicity
  - Responsible for steady acceleration

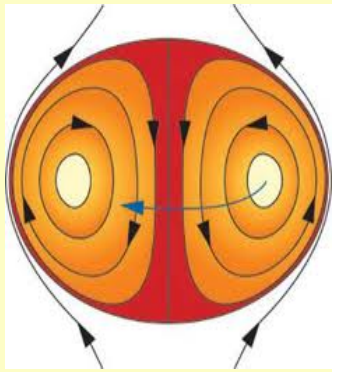


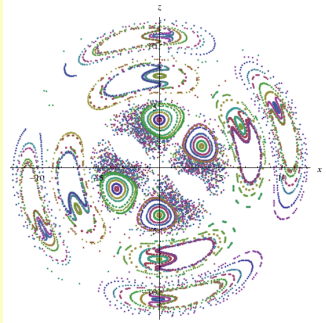


Untangling Magnetic Ropes

- Hairy Ropes
  - Twisted by aligned current
  - Evolve to current sheets
  - Untangle without change of helicity
  - Large inductive electric field?
  - Rapid flaring?
- Followed by instant cooling
  - Implosion not explosion?
  - Emission anisotropic
    - Relativistic beaming
    - Local anisotropic emissivity

Spheromak



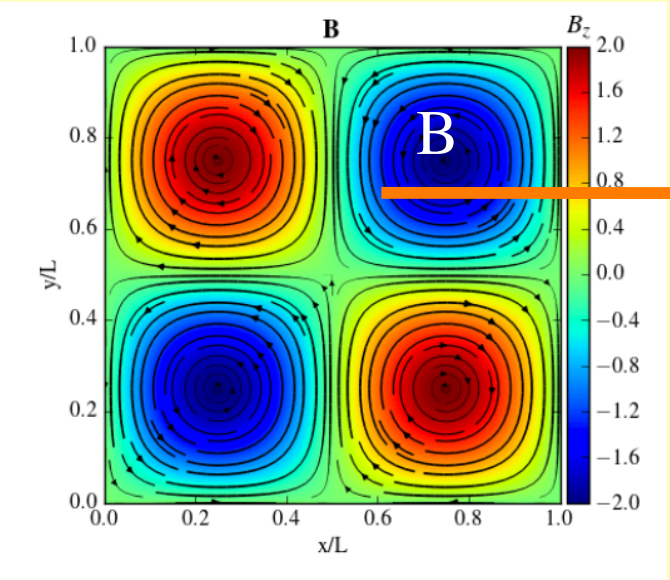


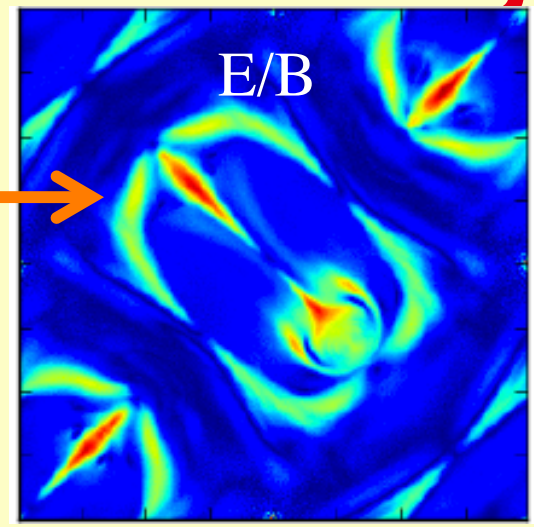
Instability of Force Free Field with Periodic Boundary conditions

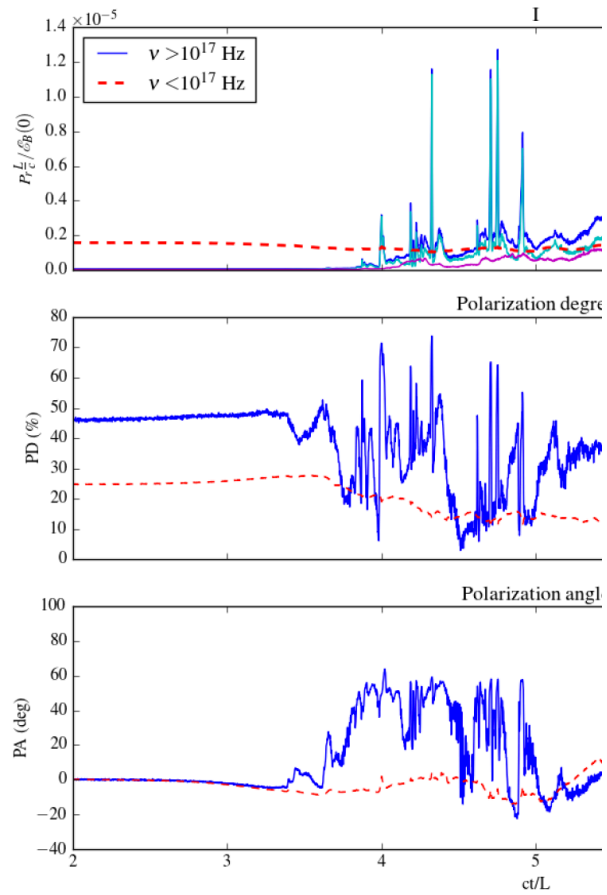
- Equilibrium has j =α B; current ~ flux
- α constant, P=0
- Generically linearly unstable if there is a lower energy state with the same helicity
- Inverse cascade: small-> large scale
- Nonlinear evolution explored using force-free and MHD codes and show E~B
- Volumetric particle acceleration?

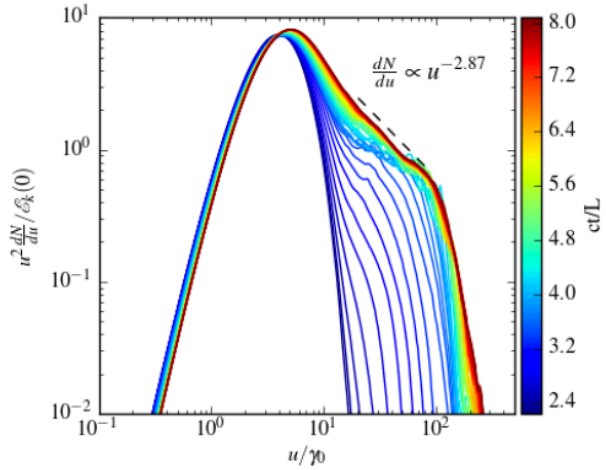
East, Zrake, Yuan, RB

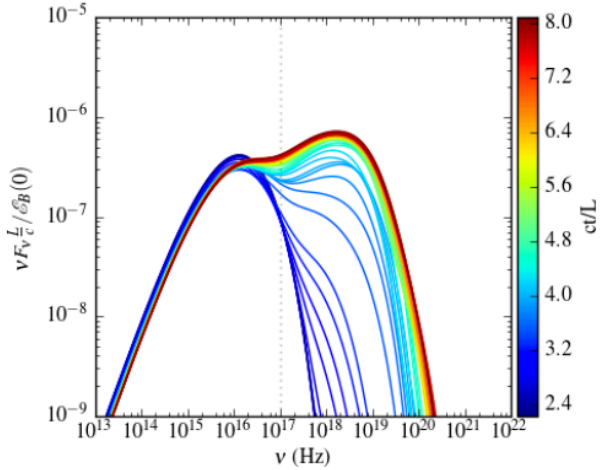
Unstable EM Configurations











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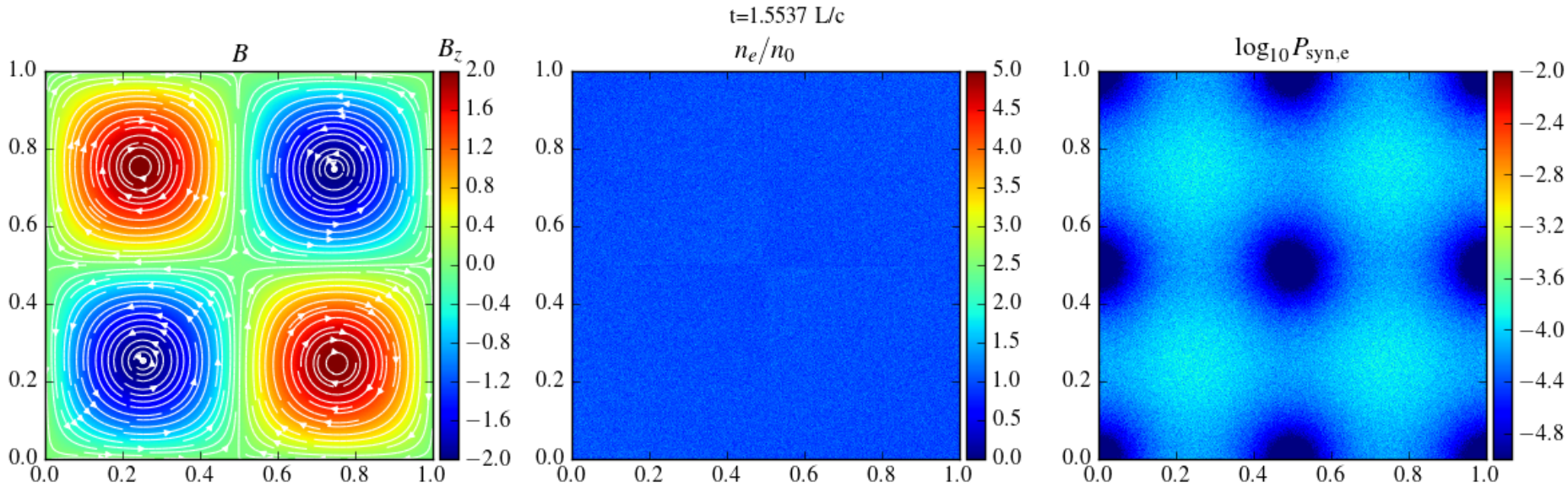
Yuan,Nalewajko, Zrake, East, RB

Yuan et al



Particle Acceleration Location

- β model

$$\beta_e \equiv \tilde{P}_e / P'_M \text{ is constant}$$

- α model

$$W' = \tilde{\alpha}_e P'_M \sigma' \qquad \sigma' = \gamma^2 |dv_z/ds|$$

$$\tilde{P}_e = W' \min[t'_{\rm exp}, t'_{\rm rad}]. \qquad t'_{\rm exp} = \gamma^{-1} |\nabla \cdot (\gamma \mathbf{v})|^{-1}$$

- σ model

$$W' = \mu P'_M \sigma'^2 / c^2 \qquad \mu = cL/3.$$

Limb-brightening

- j^2 model

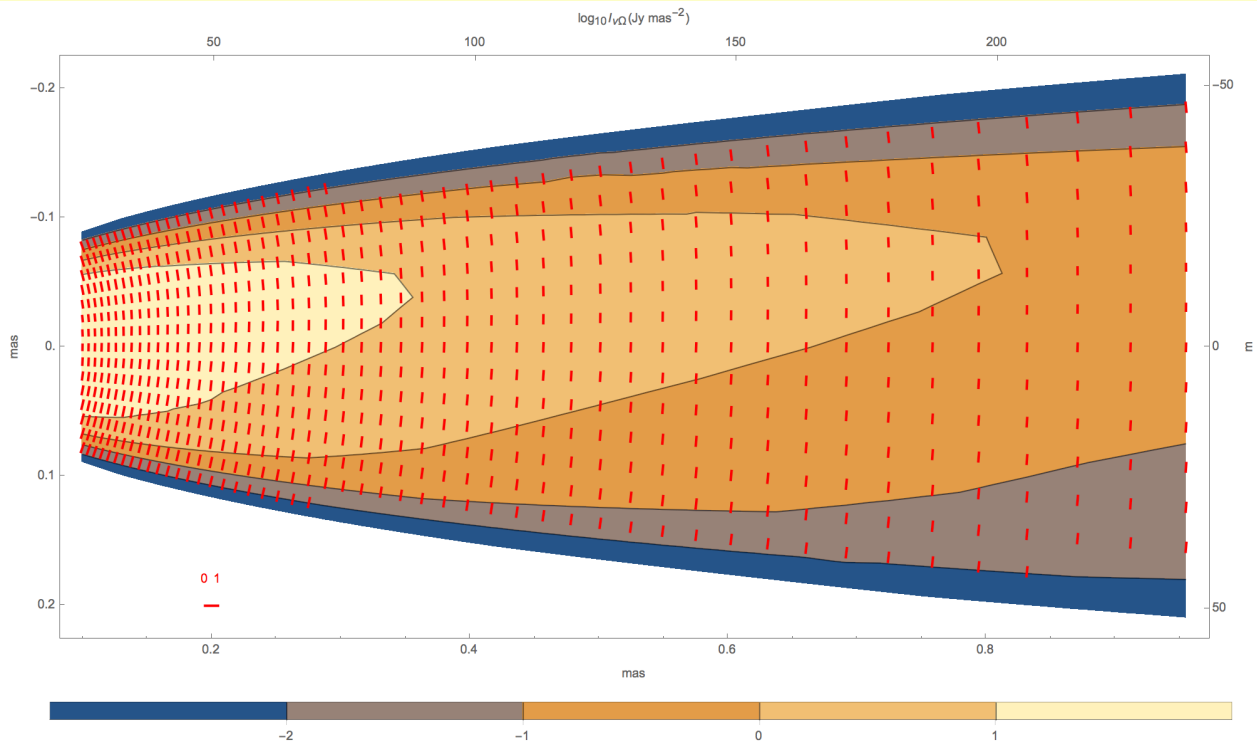
$$W' = \mu_0 c L |j_\alpha j^\alpha|.$$

L is outer scale?

Resistance is Futile

Future M87/EHT Observations

- Toroidal field, transverse shifts -> Ω_H
- Inclination, velocity, V_{obs}
- Pair vs ion plasmas – circular polarization
- Parity
- Acceleration
- Entrainment
- B_{GeV}~10^{-4-2}
- Lateral Shift



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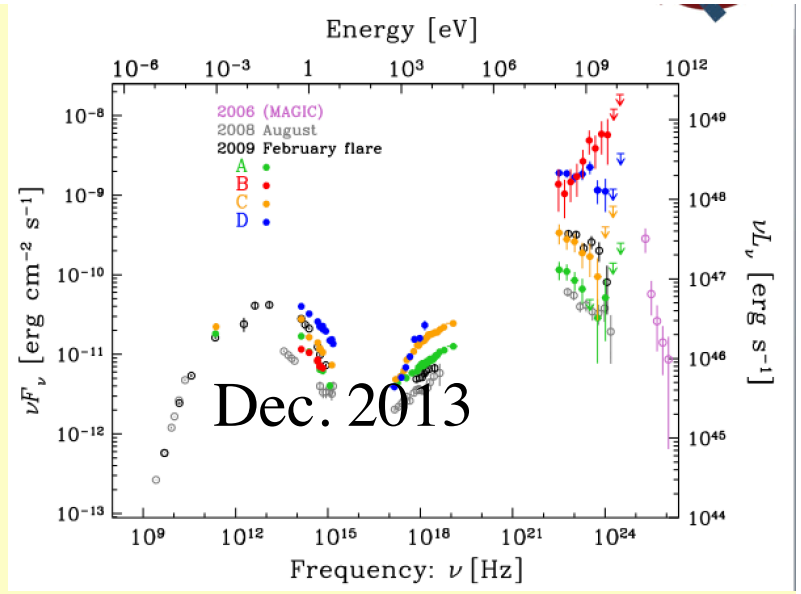
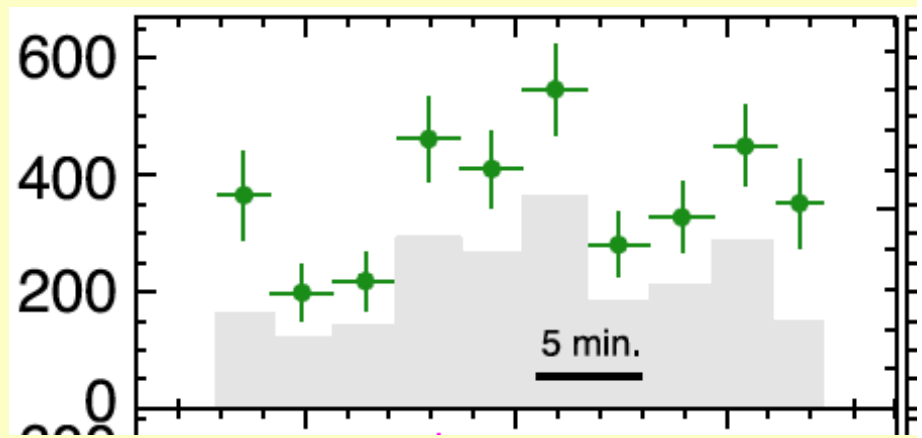
3C279 Observations

- Luminous radio quasar
  - $L_{disk} \sim 3\times10^{38}$ W
- $L_{jetiso} < 3\times10^{42}$ W
  - Doppler-beamed
  - >> L_{synch} => low B?
- $\Gamma_{VLBI} \sim 30$
  - $L_{jet} < 3\times10^{39}$W
  - Marginally radiative?
- $t_{var} > 3$min.
  - $r_{em} \sim r_{\gamma\gamma} \sim 10^{15}$ m?





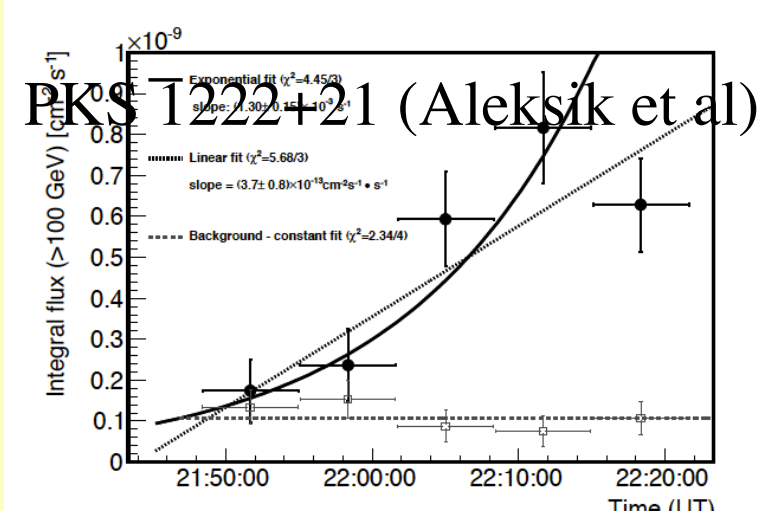
APEX-LMT-SMA fringes

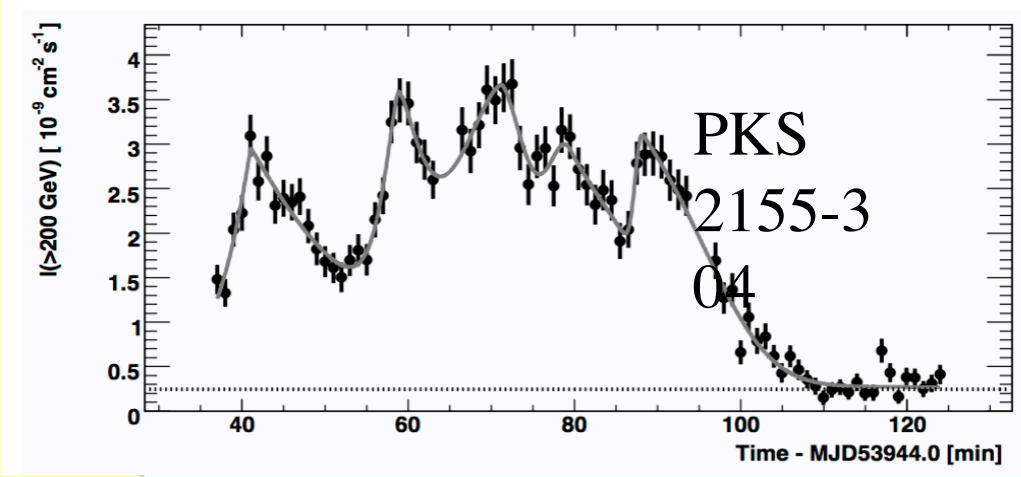
Some Inferences for 3C279

- $M \sim 10^9 M_{sun}$ => $m \sim 1.5$ Tm
- $\Omega_H \sim 7 \times 10^{-5}$ rad s^{-1}
- $L_{jet} \sim 10^{47}$ W => $\Phi_H \sim 500$ YWb
- Accretion Disk
  - BB: T ~ 30,000K, R ~ 25 Tm
  - X-ray: Corona ~ 0.01-0.1 Jet Emission
- Reprocessing/Scattering
  - Broad, emission line clouds
  - Accreting gas, warped outer disk
  - Electron scattering by hot inter-cloud medium

TeV Gamma-ray variation

- M87
  - 1 day
- PKS 1222+21
  - 10 min
- MKN 501
  - 5 min?
- PKS 2155-304
  - 2 min?
- MKN 421
  - Radio –TeV hr – min?





Rapid, efficient, conversion of electromagnetic energy into TeV-PeV pairs, γ-rays

AGN Spectroscopy for Dummies

Bactrian

Dromedary

AGN Spectroscopy for Dummies

Synchrotron
(SL Expansion @10^5m)

Compton
(Low σ @10^{3-7}m)

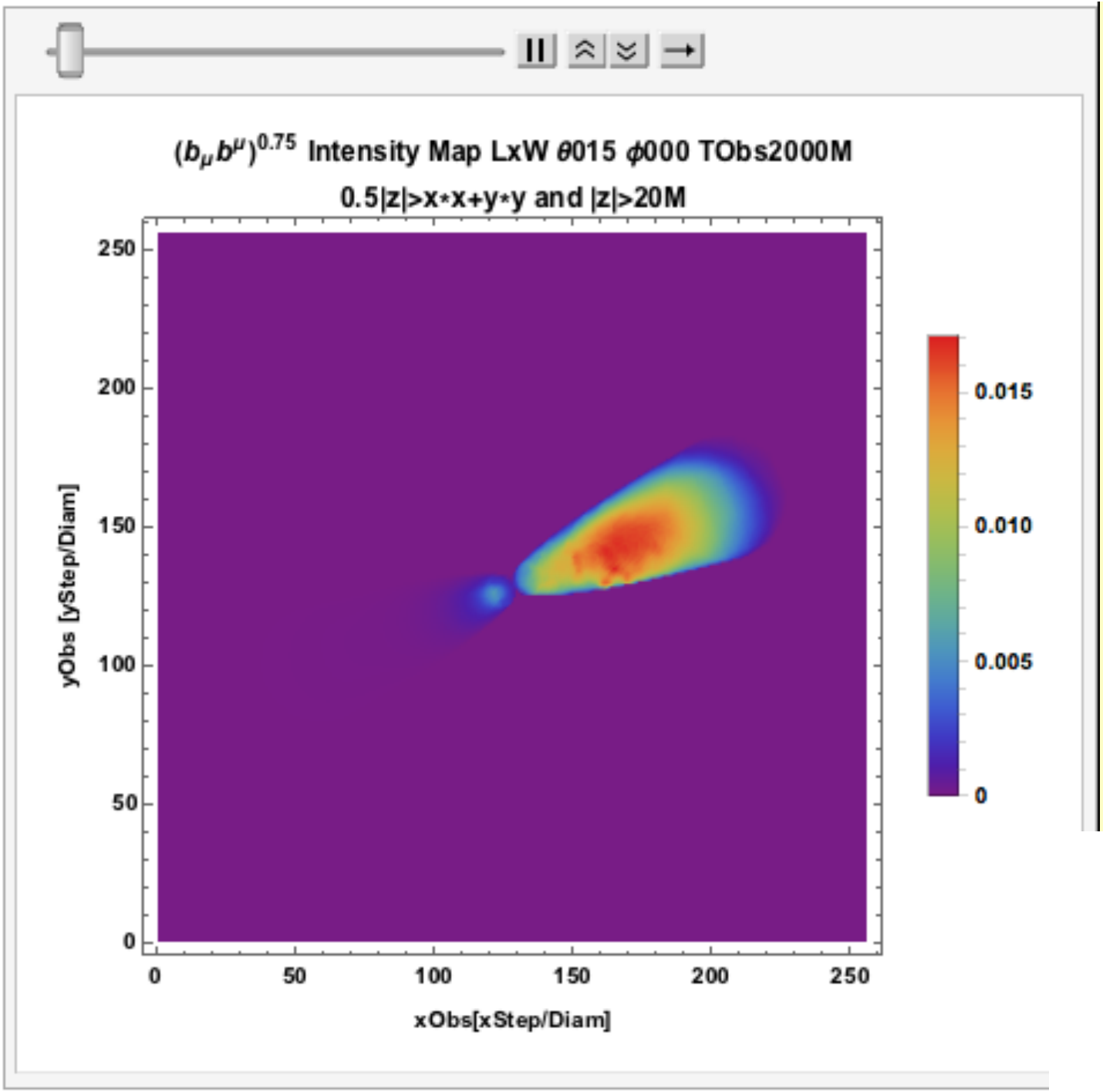
Nose

The Nose of the Camel

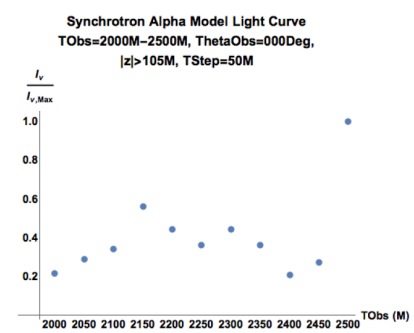
- **Conventional View**
  - **First Hump – Synchrotron**
    - UM << UP
  - **Second Hump – Compton**
    - Outside "γ-sphere", γ−γ pair production, internal/external
- **Controversial View**
  - **GeV γ-rays are synchrotron**
    - E < B (any frame) => $\lambda > r_e$, $E_\gamma < 70$MeV cf Crab Nebula
- **Radical View**
  - **TeV γ-rays are synchrotron**
    - p accelerated to PeV energy; photo-pair production
    - p synchrotron?

Synchrotron γ-rays?

- Minimal Soft Photon Field
- $R_{\gamma\gamma}$ ~100 m at 300 MeV
- Reproduce 100MeV-3 GeV spectrum
- Electron cooling times ~ 10μs
- Predict TeV-PeV! IC spectrum
- Variability still far too slow


$(b_\mu b^\mu)^{0.75}$ Intensity Map LxW θ015 ϕ000 TObs2000M
0.5|z|>x*x+y*y and |z|>20M
yObs [yStep/Diam]
xObs[xStep/Diam]
0
50
100
150
200
250
0.015
0.010
0.005
0

Anantua


Synchrotron Alpha Model Light Curve
TObs=2000M–2500M, ThetaObs=000Deg,
|z|>105M, TStep=50M
$I_\nu / I_{\nu,Max}$
1.0
0.8
0.6
0.4
0.2
2000 2050 2100 2150 2200 2250 2300 2350 2400 2450 2500
TObs (M)

Summary

- BH/NS create relativistic outflows
  - Initially electromagnetic + pair plasma?
- Efficient particle acceleration
  - Variability -> proximity to source
- Untangling and reconnection
  - Flaring and steady acceleration
- Protons may be crucial
  - Radiation reaction limit; photo-pair production?
- Prescriptive observations coming?
  - HAWC, AMS, DAMPE, CTA, EHT, SVOM…