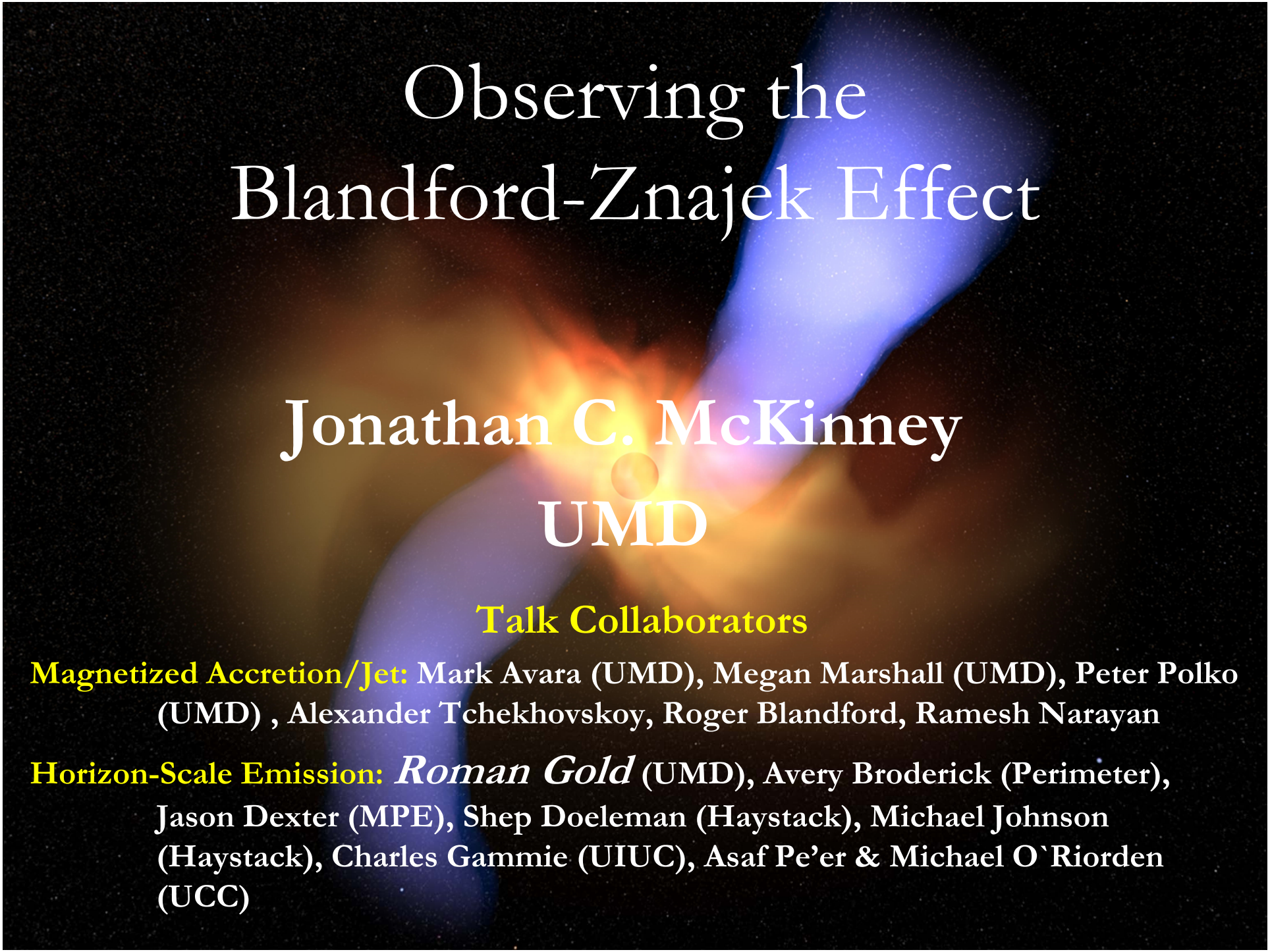


Observing the Blandford-Znajek Effect

Jonathan C. McKinney

UMD

Talk Collaborators

Magnetized Accretion/Jet: Mark Avara (UMD), Megan Marshall (UMD), Peter Polko (UMD) , Alexander Tchekhovskoy, Roger Blandford, Ramesh Narayan

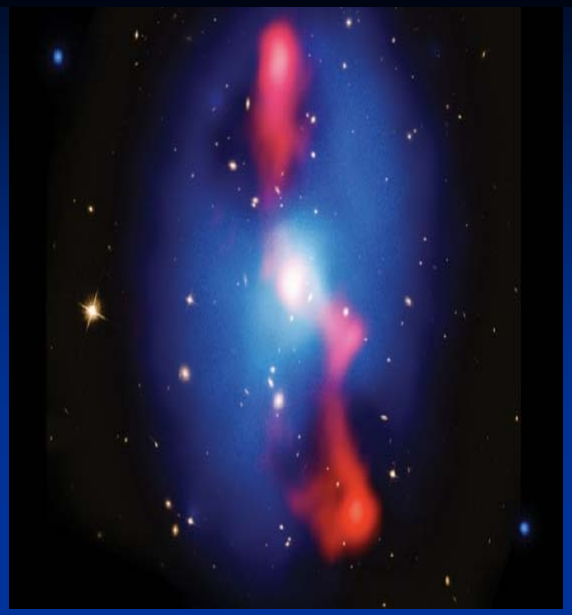
Horizon-Scale Emission: *Roman Gold* (UMD), Avery Broderick (Perimeter), Jason Dexter (MPE), Shep Doeleman (Haystack), Michael Johnson (Haystack), Charles Gammie (UIUC), Asaf Pe'er & Michael O`Riorden (UCC)

Outline

- Disks and Jets

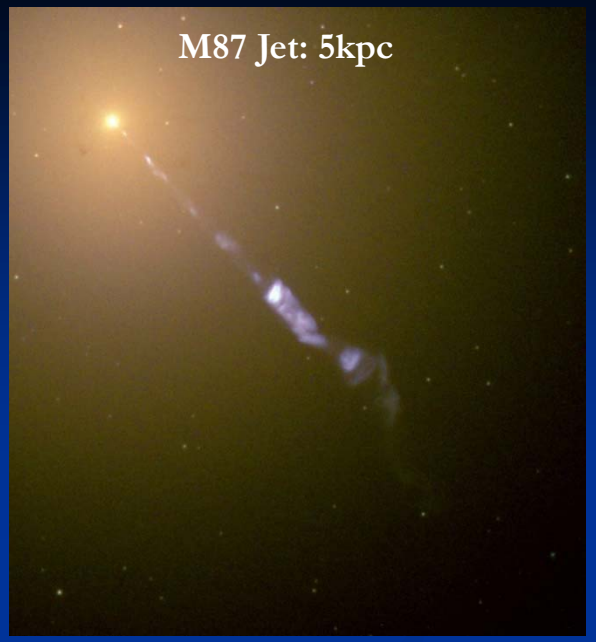
- Horizon-Scale Observations vs. Theory

MS 0735+7421 Cluster Scale: 1Mpc

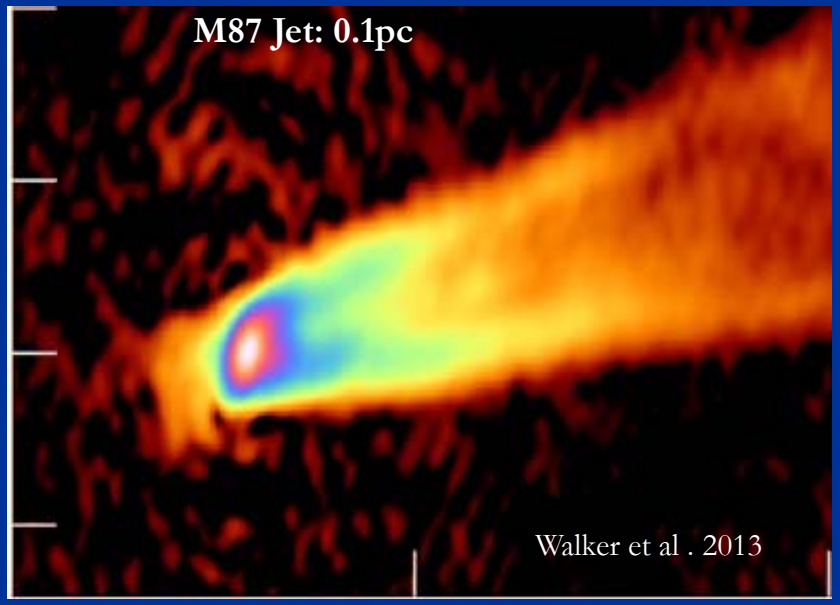


M87 Galaxy: 30-150kpc

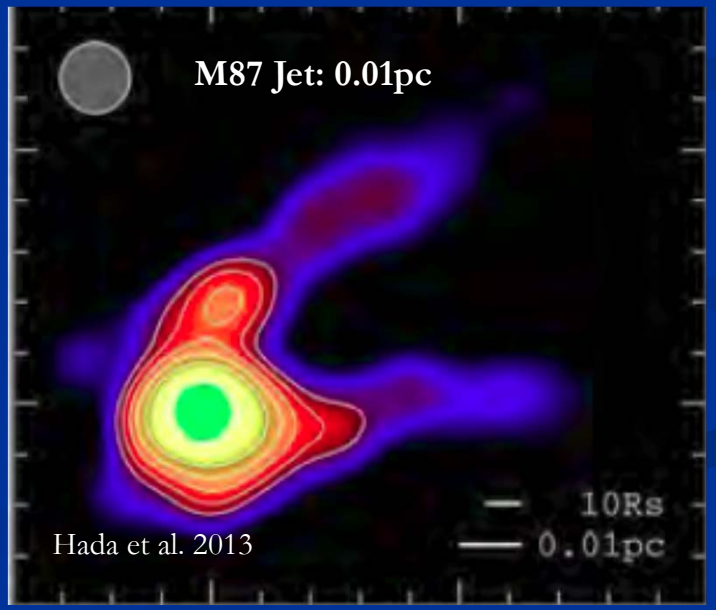
M87 Jet: 5kpc



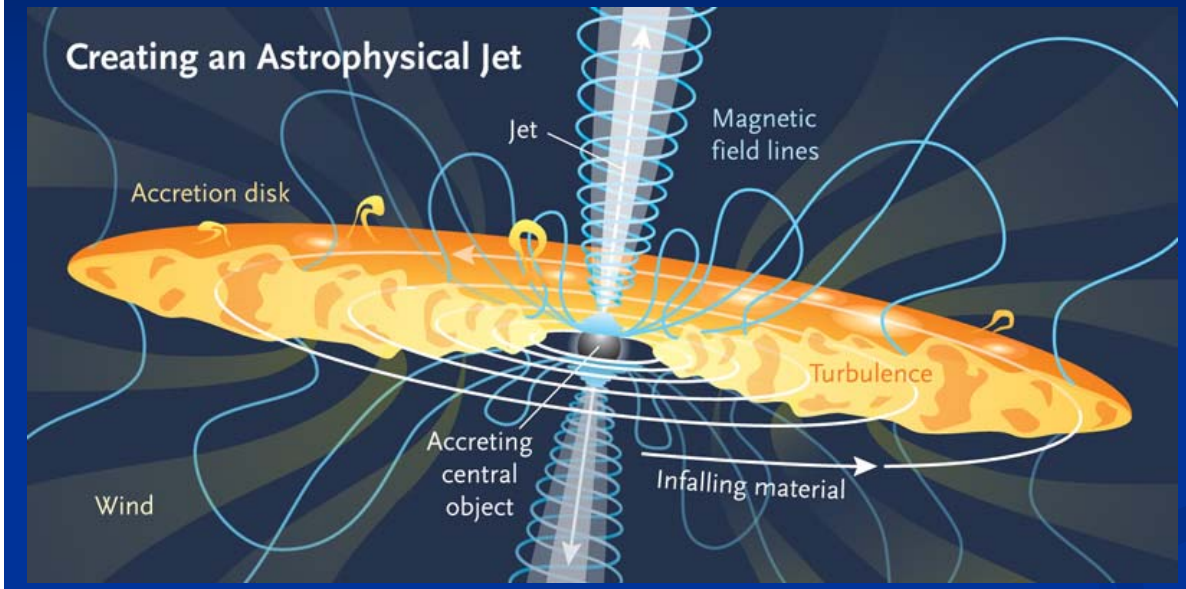
M87 Jet: 0.1pc



M87 Jet: 0.01pc



Accreting Black Holes



Sky & Telescope (Apr 2010)

Accreting BHs:

BH: M, |a|, θ
Magneto-Turbulent Disk
Relativistic Jet and Wind

Plasma:

Thermal p,e
Collisionless Effects on p,e
Non-Thermal e
Shocks (e.g. Fermi Acceleration)
Magnetic Reconnection

Pair Creation Processes:

$\gamma\,\gamma \rightarrow e^+\,e^-$
$\gamma e \rightarrow e\,e^+\,e^-$
$\gamma p \rightarrow p\,e^+\,e^-$

$ee \rightarrow ee\,e^+\,e^-$
$ep \rightarrow ep\,e^+\,e^-$

BZ77: $E + e^+\,e^- \rightarrow N\,e^+\,e^- + M\,\gamma$
Schwinger: $E \rightarrow e^+\,e^-$

Photon Radiation Processes:

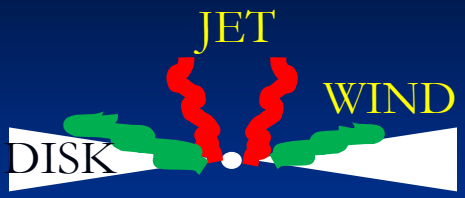
Cyclo-Synchrotron
Comptonization (Scattering)
Bremsstrahlung (free-free, etc.)
Pair Annihilation

Tools

- **HARMRAD:** Brem + Synch + Compt + Photon chem. pot. = Opacity. BUT: Grey M1, Thermal ele. (no pairs)
- **ASTRORAY:** Thermal + Non-Thermal e's in all Stokes Params. BUT: No Compt, Doesn't solve for Te.
- **GRMONTY:** Comptonized Spectra (Thermal e, soon non-th ele). BUT: No Polarization, Thermal ele.
- **Kinetic Codes:** Kinetic Sims. for Te and non-th ele. BUT: Many conditions, including irregular conditions

Disk States (Mdot, M, B?)

Super-Eddington state



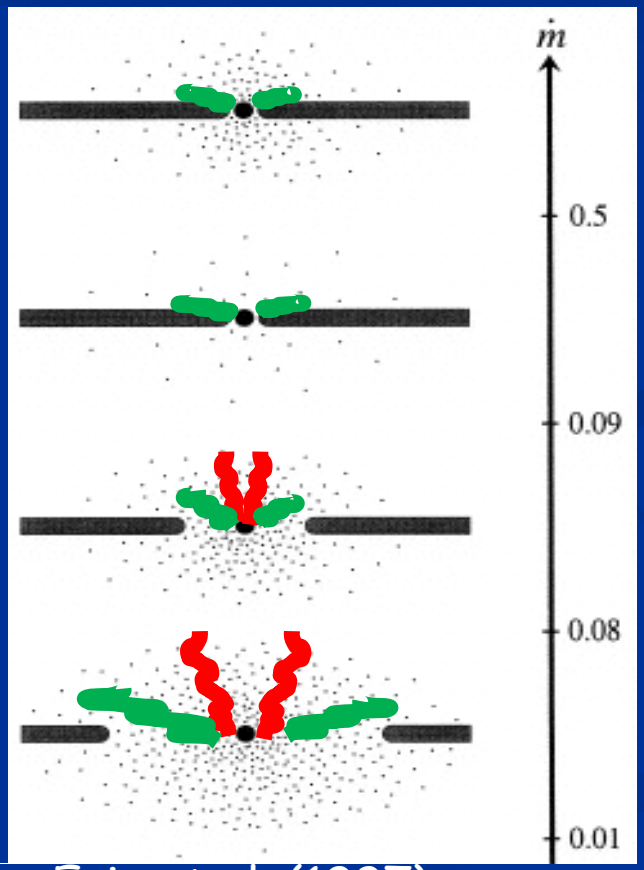
$\dot{m}>1$

Very high state
(standard disk+corona)

High/soft state
(standard disk)

Intermediate state

Low/hard state
(RIAF/ADAF/ADIOS)

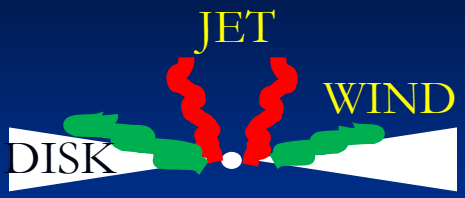


Esin et al. (1997)

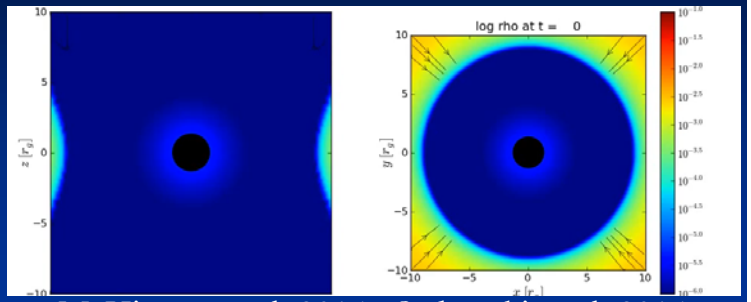
$$\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$$

Disk States (Mdot, M, B?)

Super-Eddington state



$\dot{m}>1$



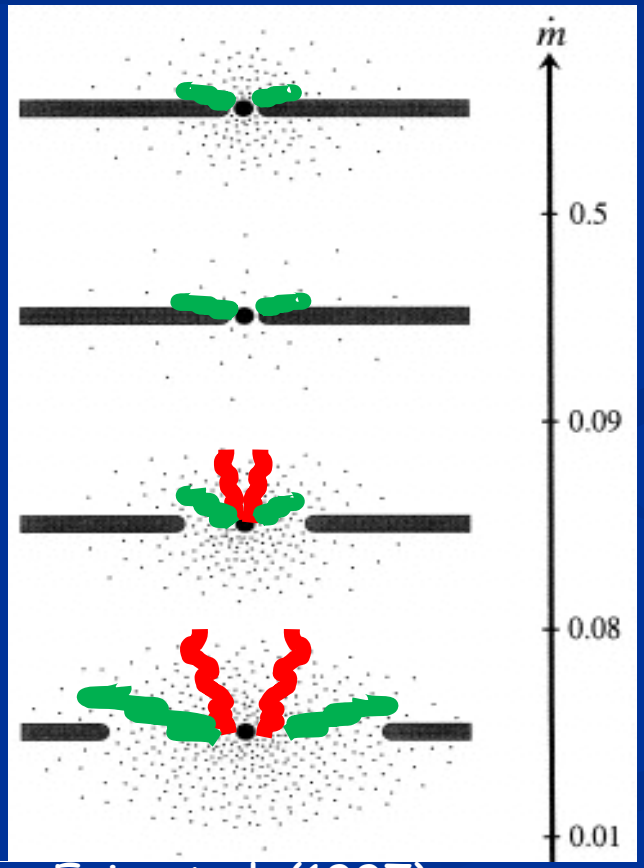
McKinney et al. 2014 ; Sadowski et al. 2014

Very high state
(standard disk+corona)

High/soft state
(standard disk)

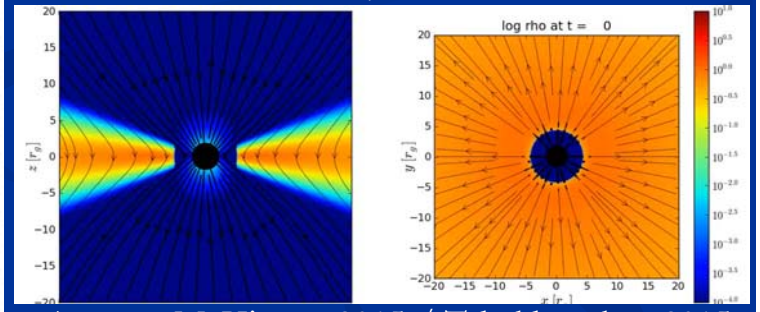
Intermediate state

Low/hard state
(RIAF/ADAF/ADIOS)

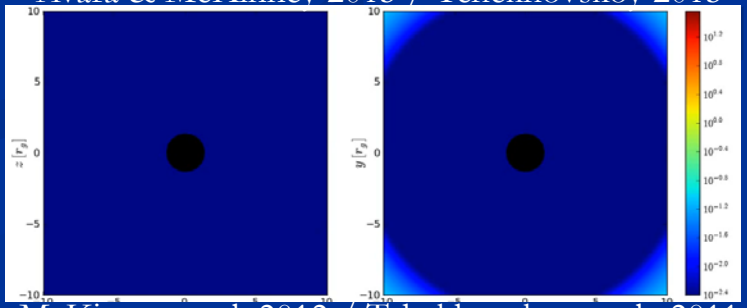


Esin et al. (1997)

Shafee/Penna & McKinney et al. 2009/2010/2011
See also Noble et al. 2009,2010



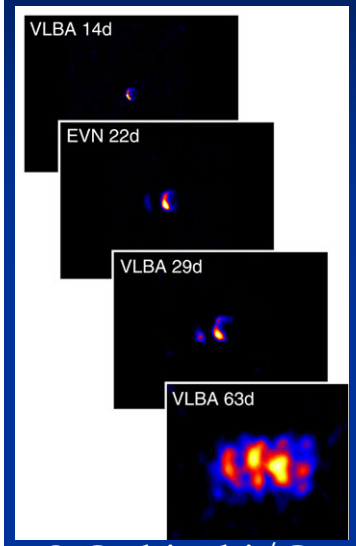
Avara & McKinney 2015 / Tchekhovskoy 2015



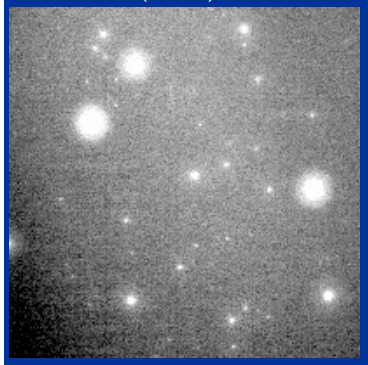
McKinney et al. 2012 / Tchekhovskoy et al., 2011

$$\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$$

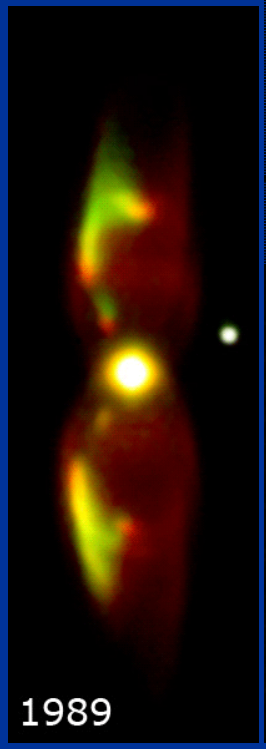
Jets (Collimated Outflows)



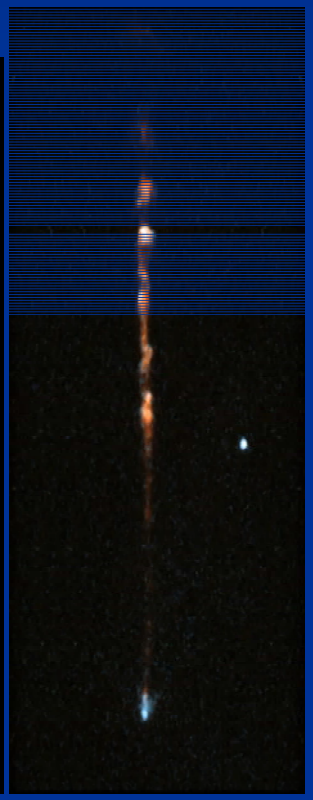
RS Ophiuchi/CV
(radio)



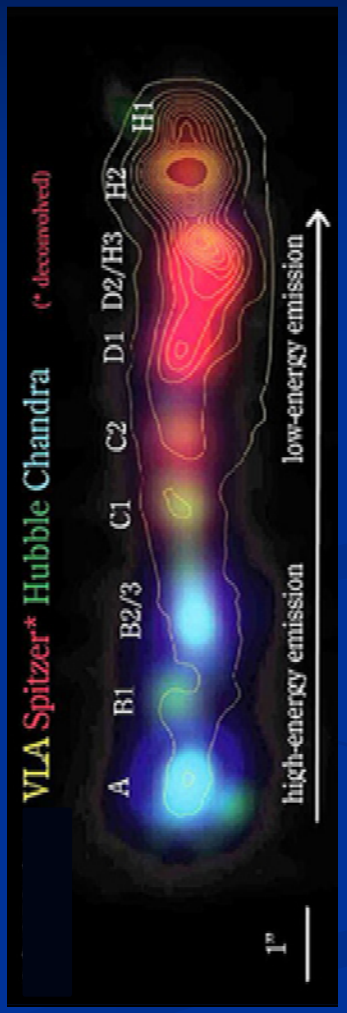
GRB080319B
(optical afterglow)



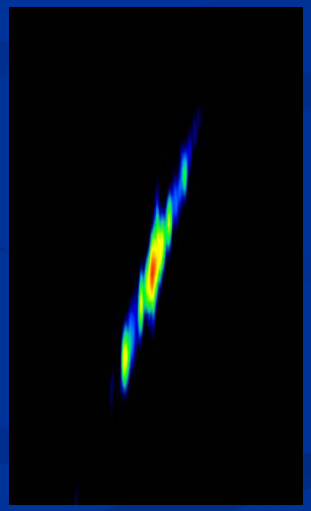
Post-AGB Star
(The "Butterfly" or "Twin Jet" Nebula M 2–9). Green is[OIII], red is [NII]



Protostellar jet
HH34
(optical)

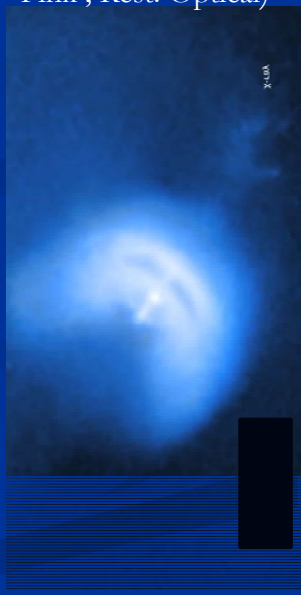


3C273
Spitzer: Red ; HST: Green ; Chandra: Blue ; VLA (2cm): Contours



X-ray Binary
SS433
(Radio 1-5Ghz)

Circinus X-1
(X-ray: Blue ; Radio: Pink ; Rest: Optical)



Vela Pulsar
(X-ray)

Jets (Power/Velocity)

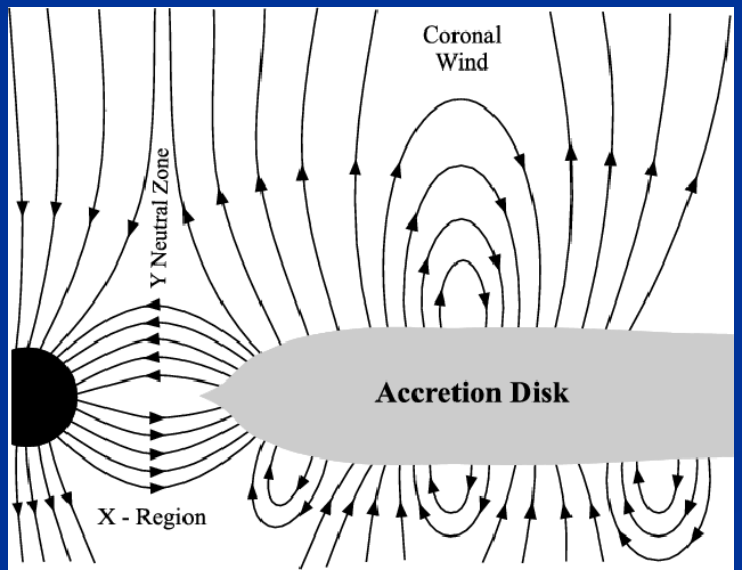
Blandford-Payne / Blandford-Znajek Wind/Jet:

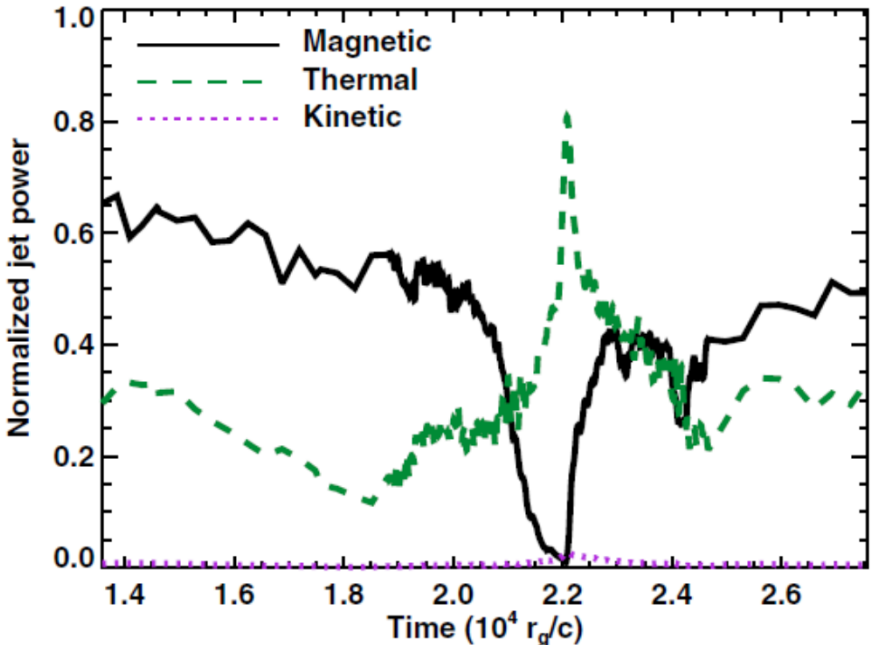
Pjet 2 #B^2 v^2 vjet~ v_{esc}

Magnetic Dissipation Wind/Jet: Pjet 2 #B^2 v_r

(Dexter, McKinney, Markoff, Tchekhovskoy 2014)

Lovelace, Newman, Romanova (1997)
de Gouveia dal Pino, Lazarian (2005,2010), Igumenshchev (2009)
Tagger & Pellat (99), Livio et al. (03), King et al. (04),
Begelman & Armitage (14)





Jets (Power/Velocity)

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Pjet 2 #$B^2 v^2$ vjet~ v_{esc}

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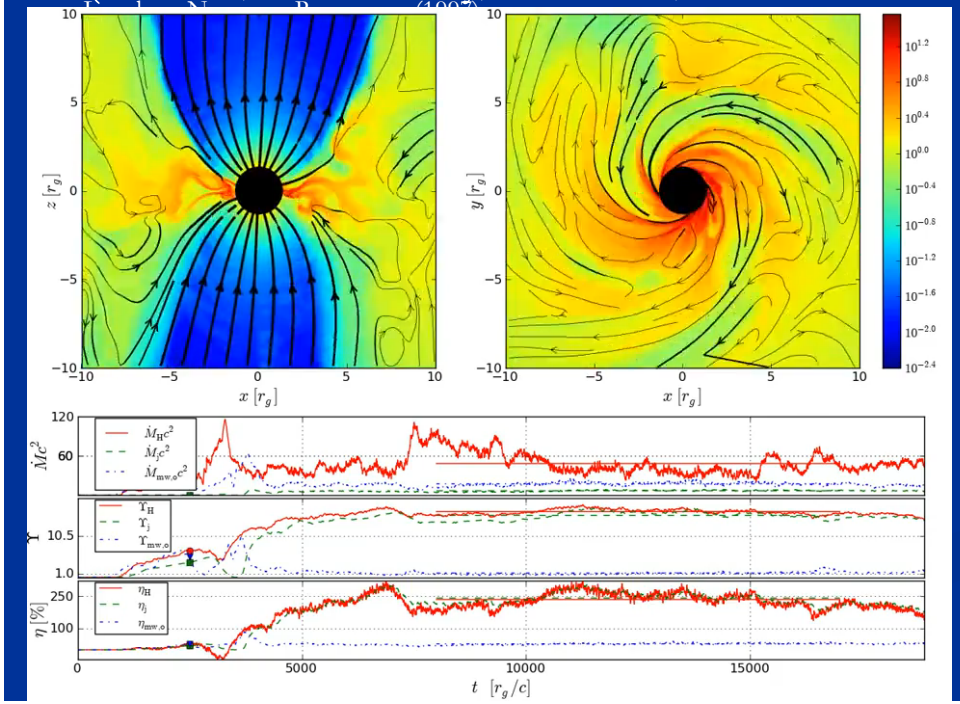
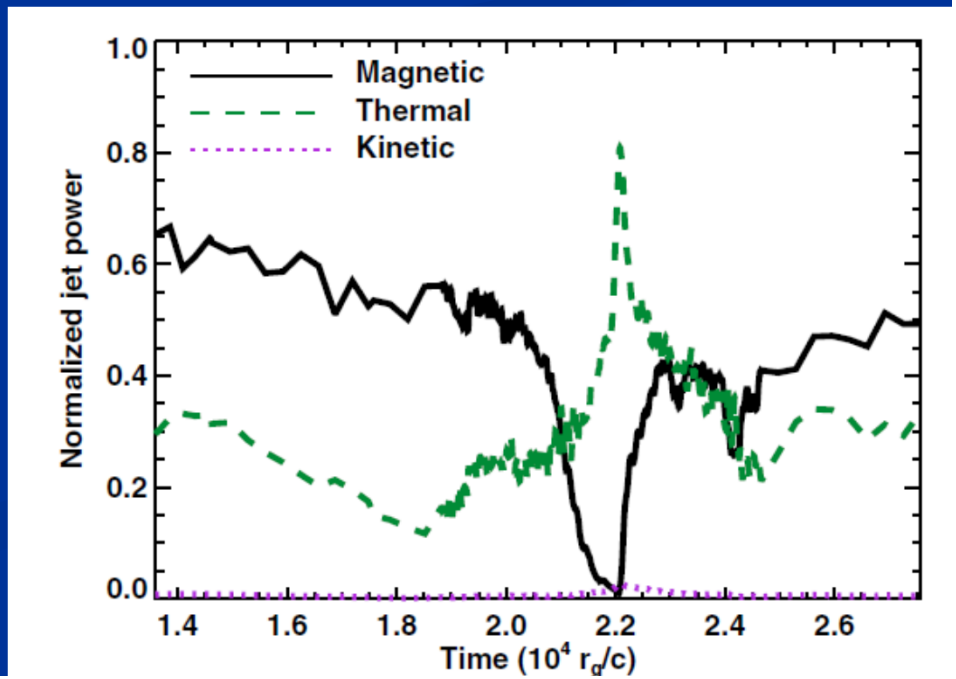
(Dexter, McKinney, Markoff, Tchekhovskoy 2014)





Testing BZ Effect

- <~45° pitch angle (wind much more toroidal)
- Relativistic Jet (but NS Circ X-1)

- Power vs. spin dependence (Narayan & McClintock (2012-2015) But see Russell & Fender (2013-2014))
- Power magnitude or MADs

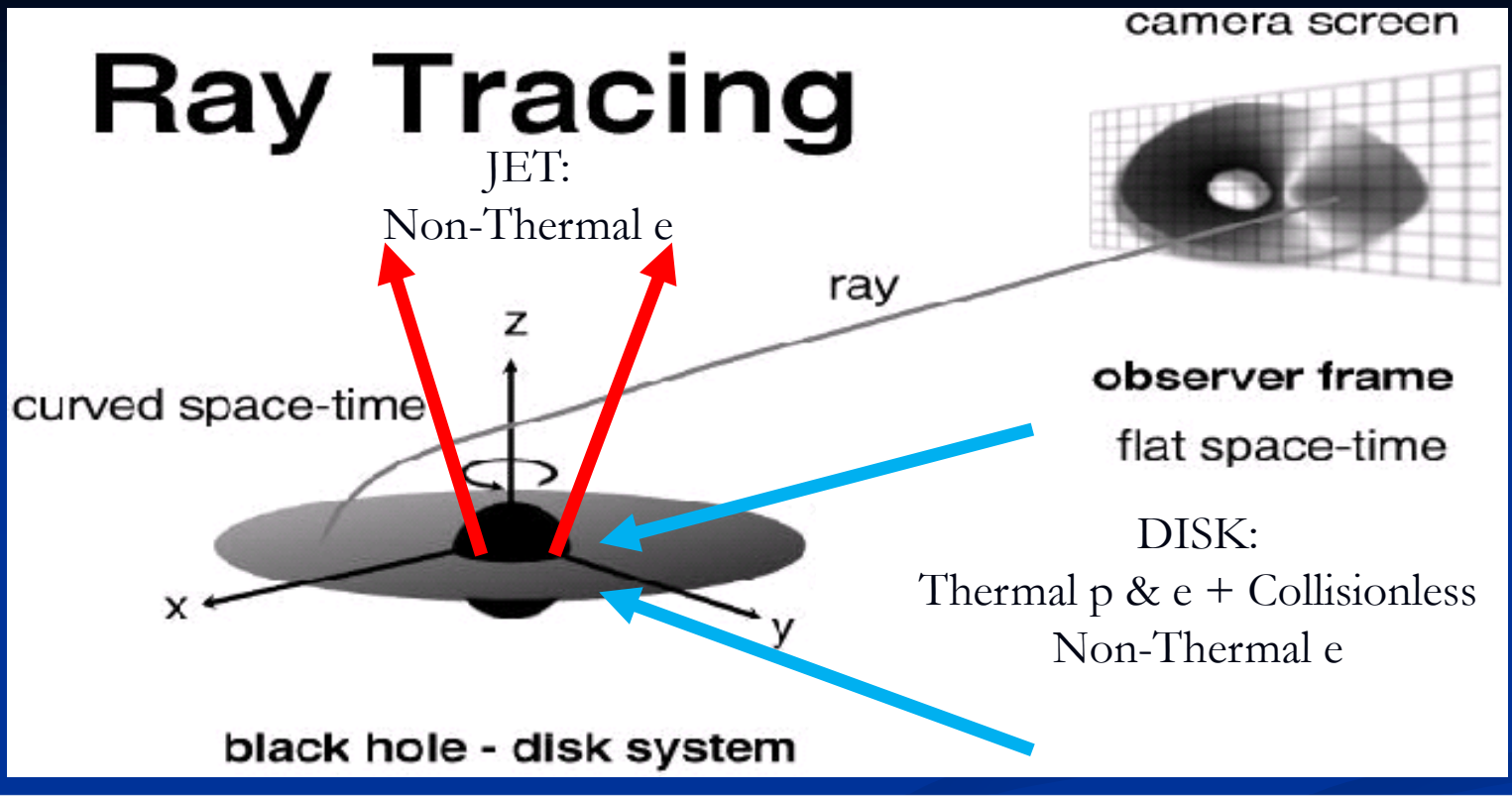
- Two ang. mom. axes near BH / Twisted jet (Polarization?)

EventHorizonTelescope

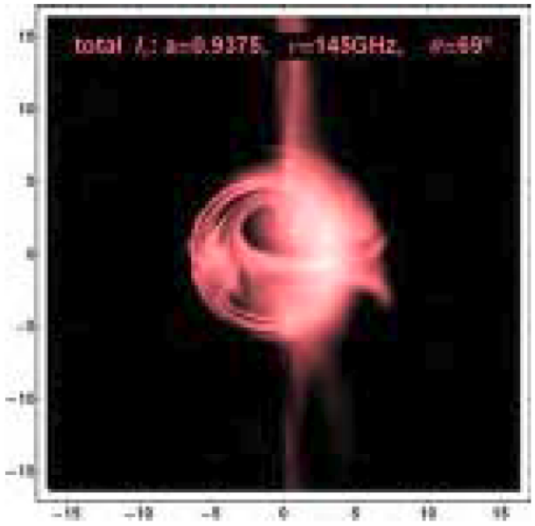
http://www.eventhorizontelescope.org/

- *Earth-sized mm VLBI array*
- *Existing telescopes.*
- *Resolutions of* $\sim 10\ \mu as$

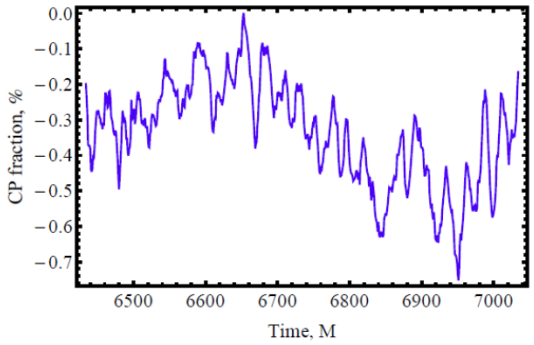
Ray Tracing



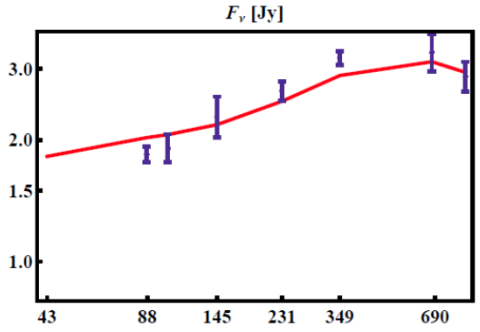
Shcherbakov & McKinney 2012,2013



(Polarized) Resolved Images

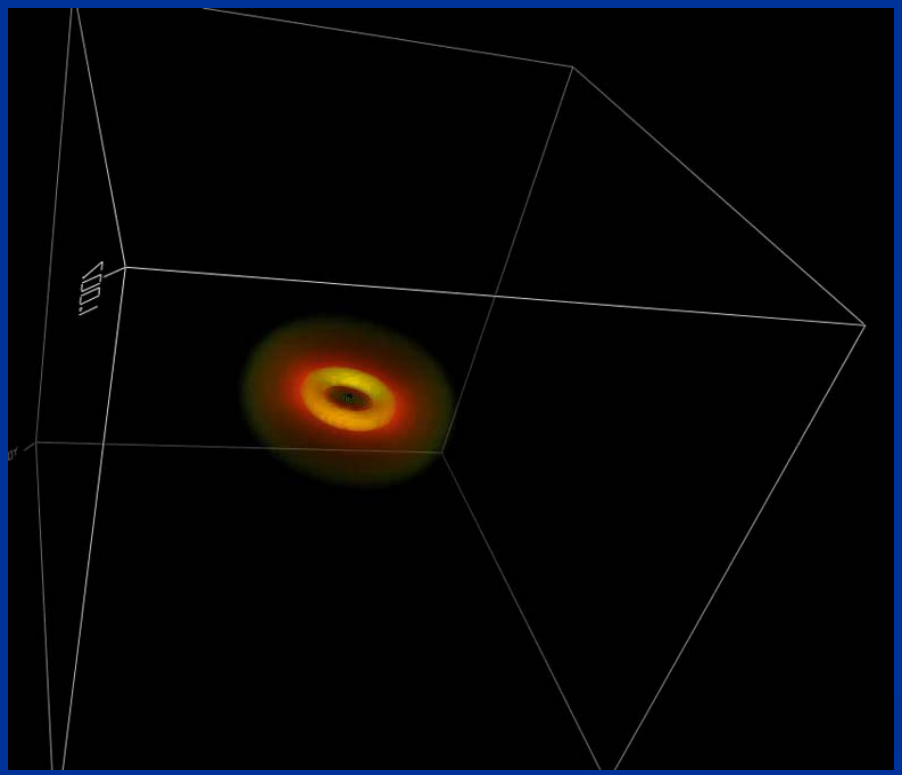


(Polarized) Timing

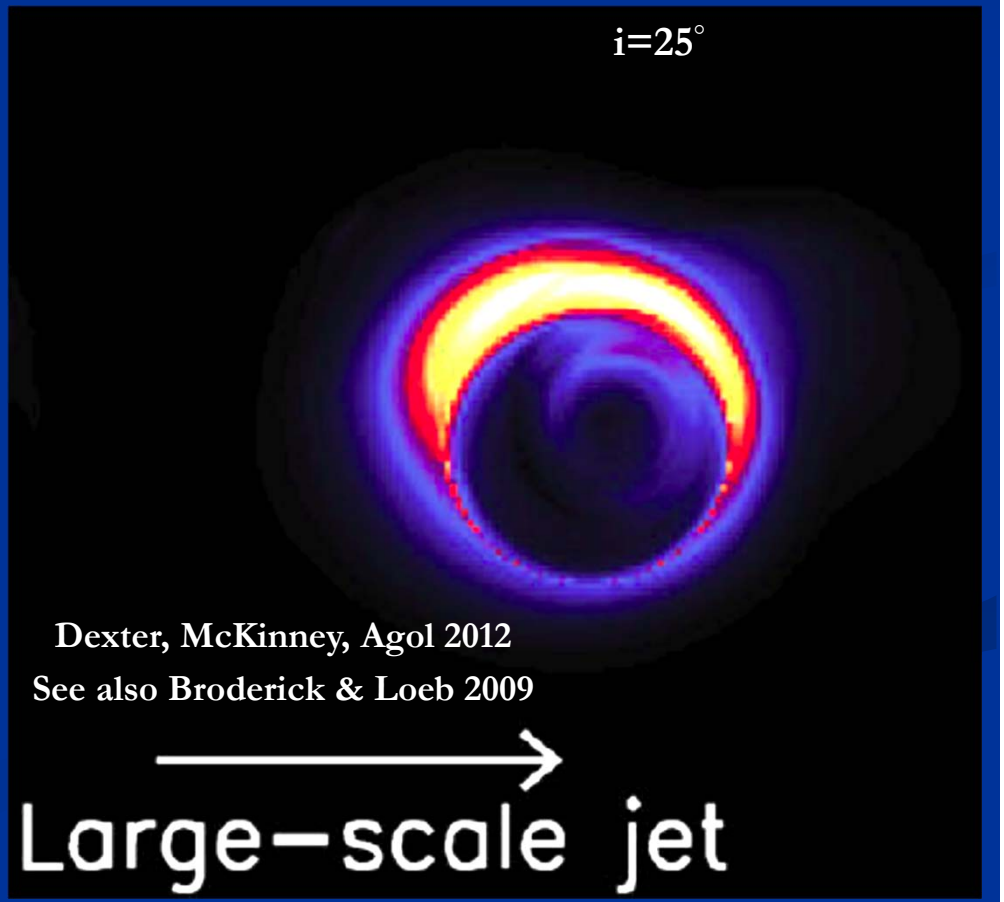


(Polarized) Spectra

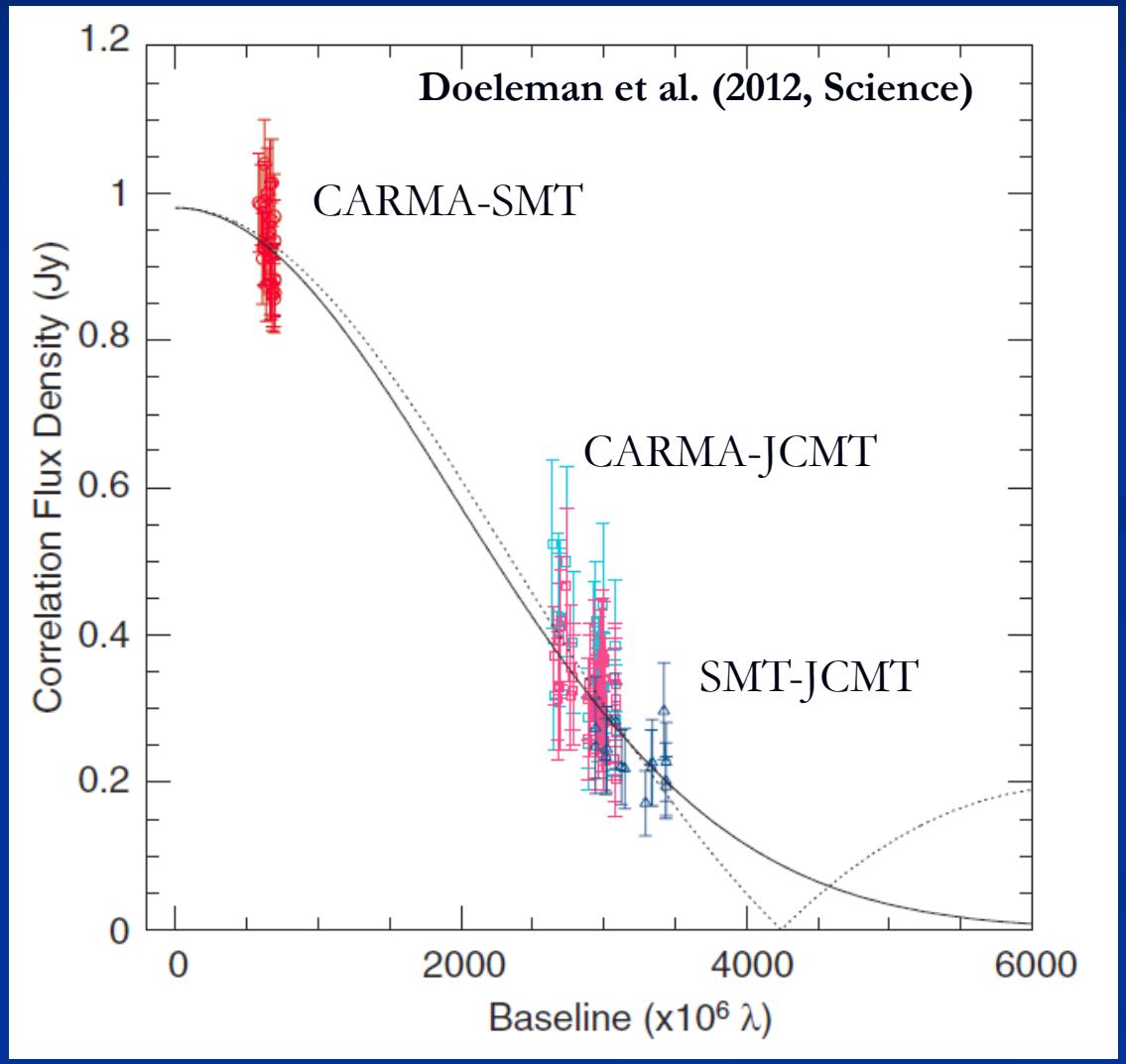
GR Radiative Transfer Sims. Predict M87 Jet Base of size ~5rs

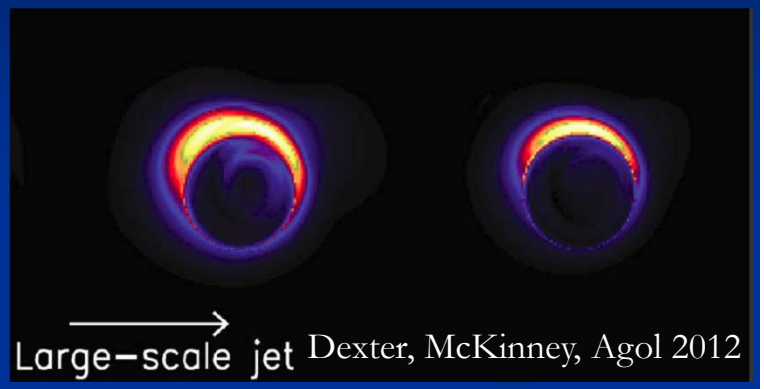


McKinney & Blandford (2009)

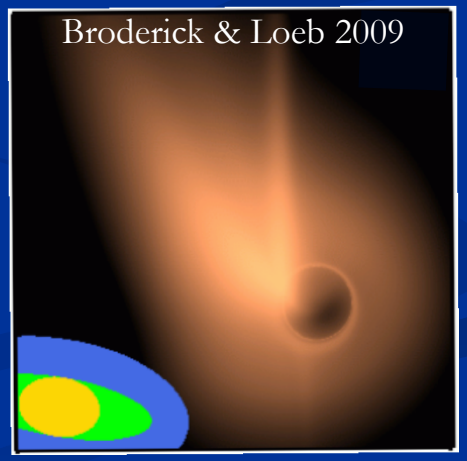


EHT: M87 correlated flux at 1.3mm Size~5rs!



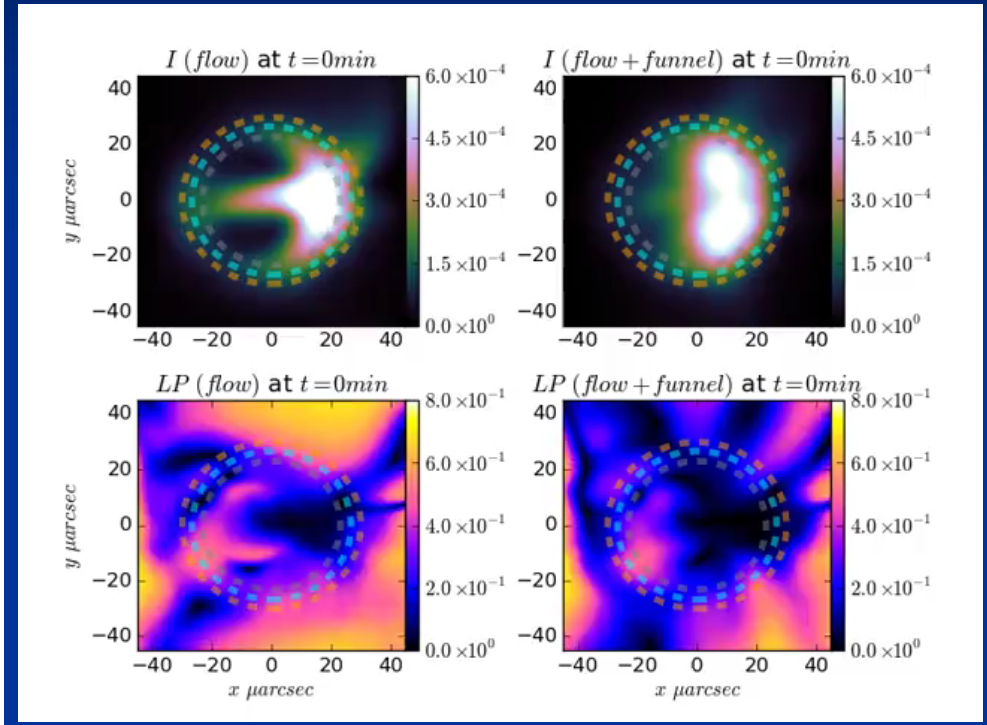


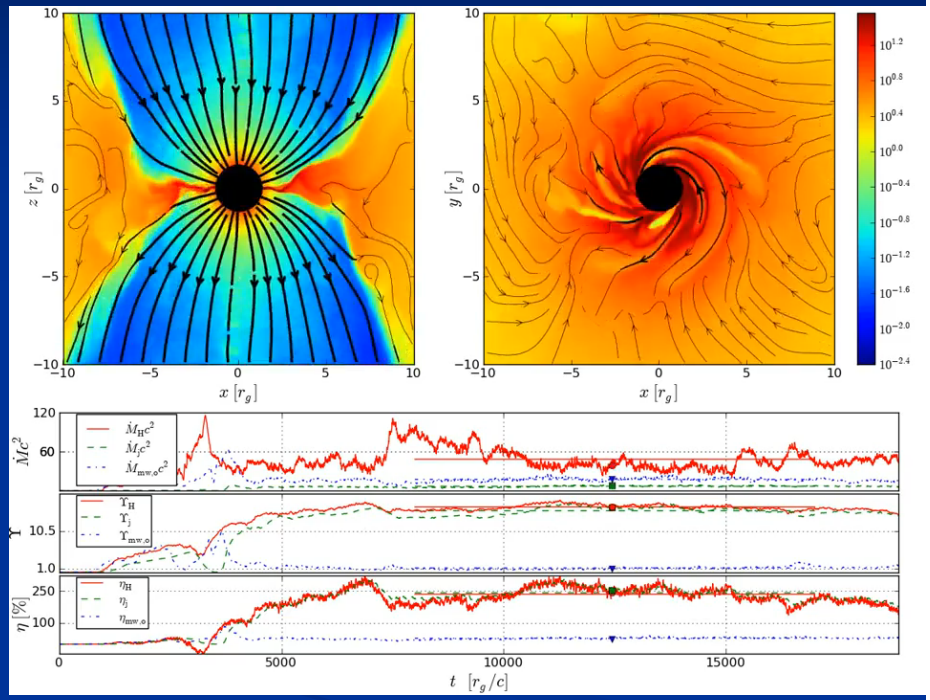
As we predicted!



Other models can work, but require very high spin

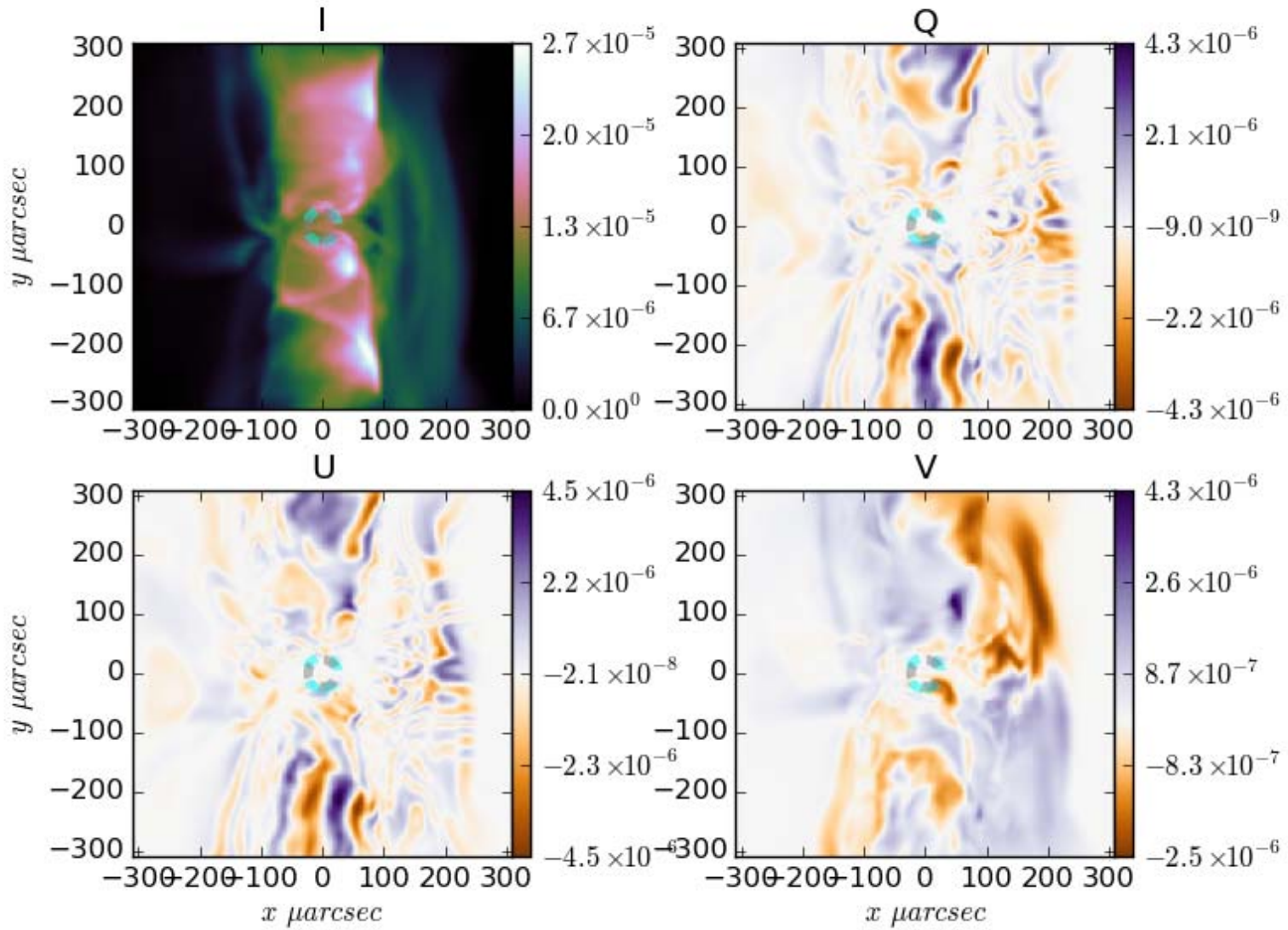
230 Ghz

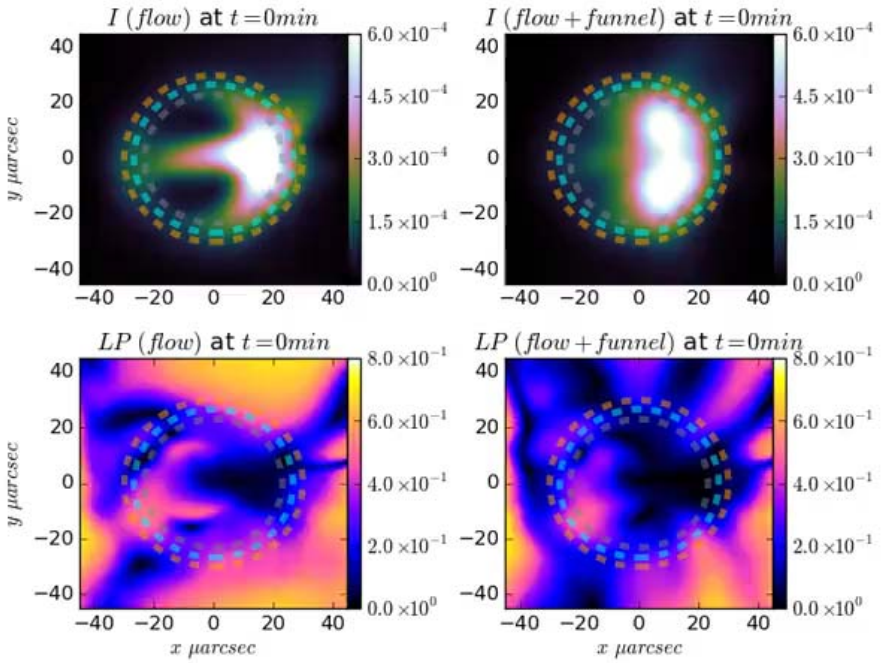


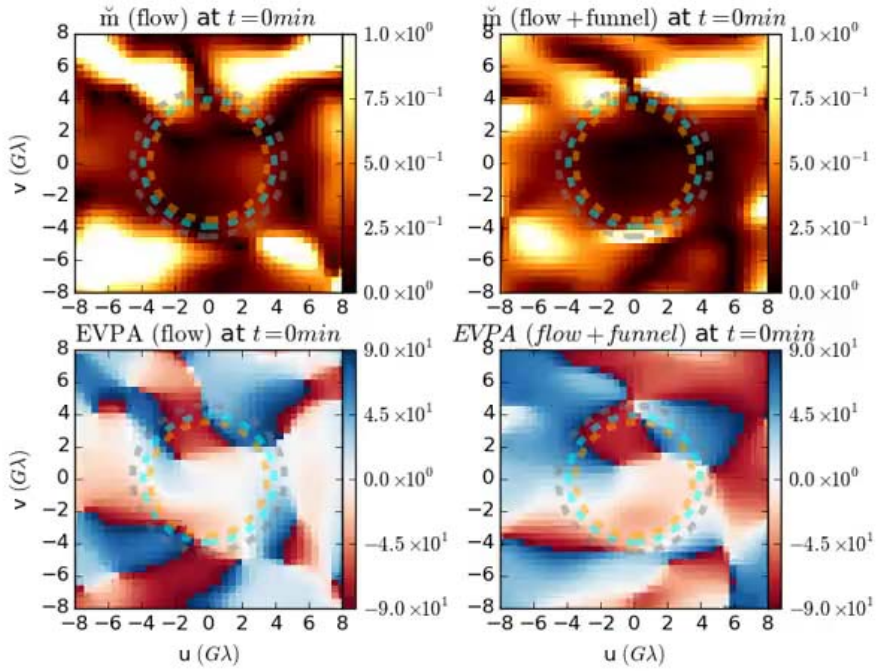


J rog#) #P fN lqqh|#+5348,#dqg#Mrkqvrq/#G rhdnp dq/#nw#dol#+5348,

43 Ghz

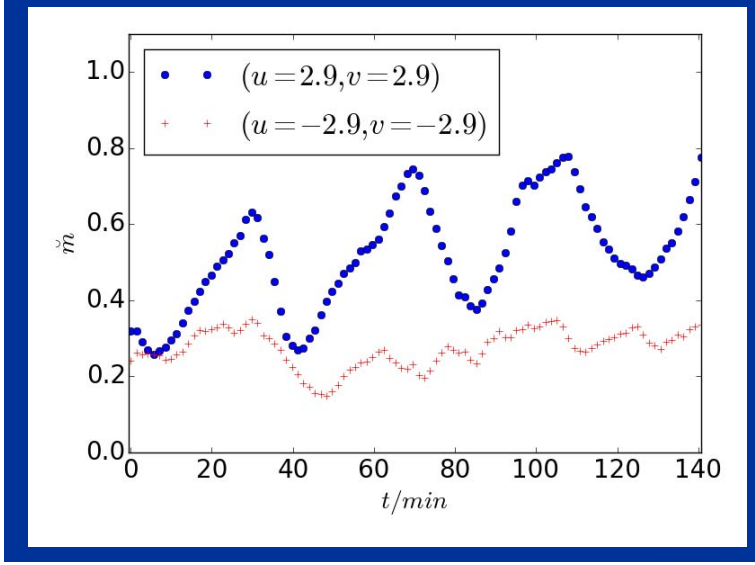

I
Q
U
V
300
200
100
0
−100
−200
−300
−300 −200 −100 0 100 200 300
y μarcsec
x μarcsec
2.7 ×10^−5
2.0 ×10^−5
1.3 ×10^−5
6.7 ×10^−6
0.0 ×10^0
4.3 ×10^−6
2.1 ×10^−6
−9.0 ×10^−9
−2.2 ×10^−6
−4.3 ×10^−6
4.5 ×10^−6
2.2 ×10^−6
−2.1 ×10^−8
−2.3 ×10^−6
−4.5 ×10^−6
4.3 ×10^−6
2.6 ×10^−6
8.7 ×10^−7
−8.3 ×10^−7
−2.5 ×10^−6

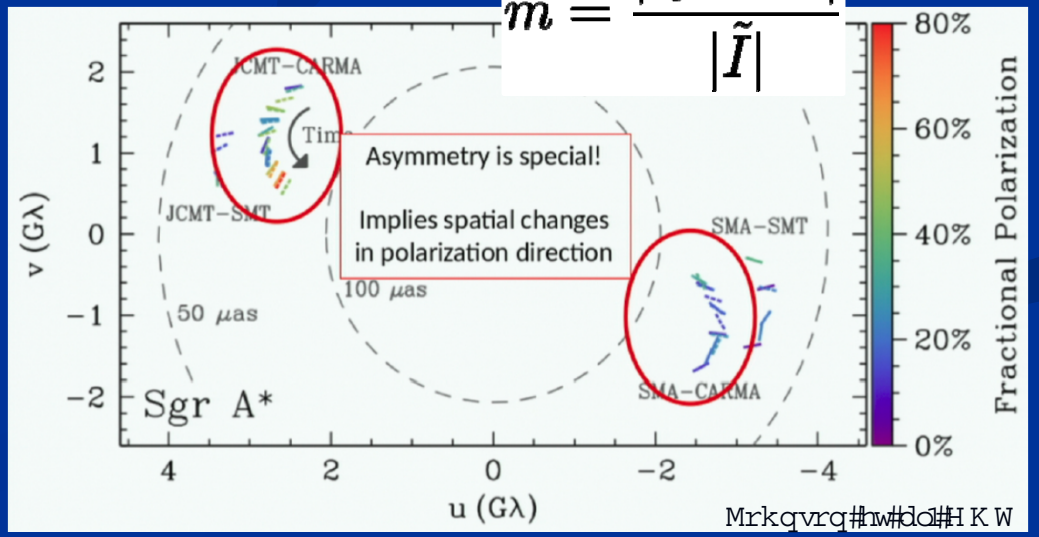




J rog#) #P fN lqqh|#+5348,#dqg#Mrkqvrq/#G rhdp dq/#hw#do#+5348,

$$\breve{m} = \frac{|\tilde{Q} + i\tilde{U}|}{|\tilde{I}|}$$

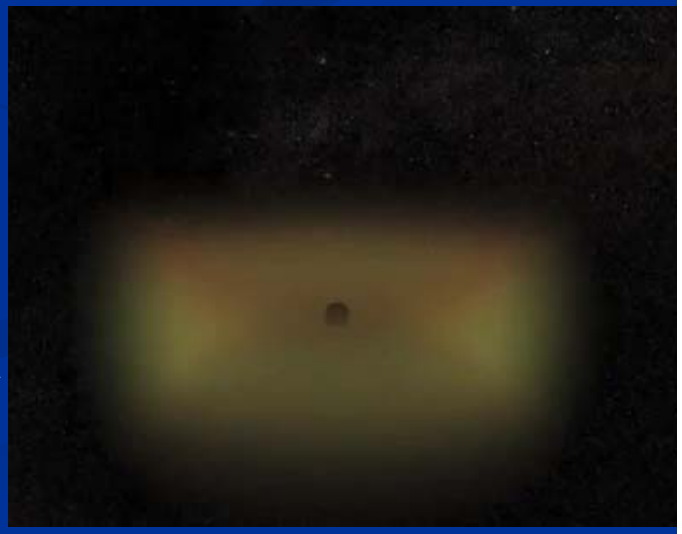




Mrkqvrq#hw#do#H K W

Summary

- Powerful combo: Harmrad + Astroray + Grmonty
  - HARMRAD: Compt + Synch + Photon chem. pot. + Opacity
  - ASTRORAY: Thermal + Non-Thermal e's in all Stokes Params.
  - GRMONTY: Comptonized Spectra (Thermal e, soon non-th-e)
- Probe strong Gravity (e.g. shadow, jet)
  - Concordance Models (spectra, temporal, resolved imaging, etc.)
- Polarization adds 3 indep. Constraints
  - SgrA* Horizon-Scale Emission Polarized
  - MAD vs. MRI disk / Toroidal vs. Poloidal
  - BZ : Twisted Jet or 2 Ang. Mom. axes?



McKinney et al. 2013 & Polko et al. 2015)