Title: Snap, Crackle and Pop

Speakers: Roger Blandford

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 26, 2025 - 9:15 AM

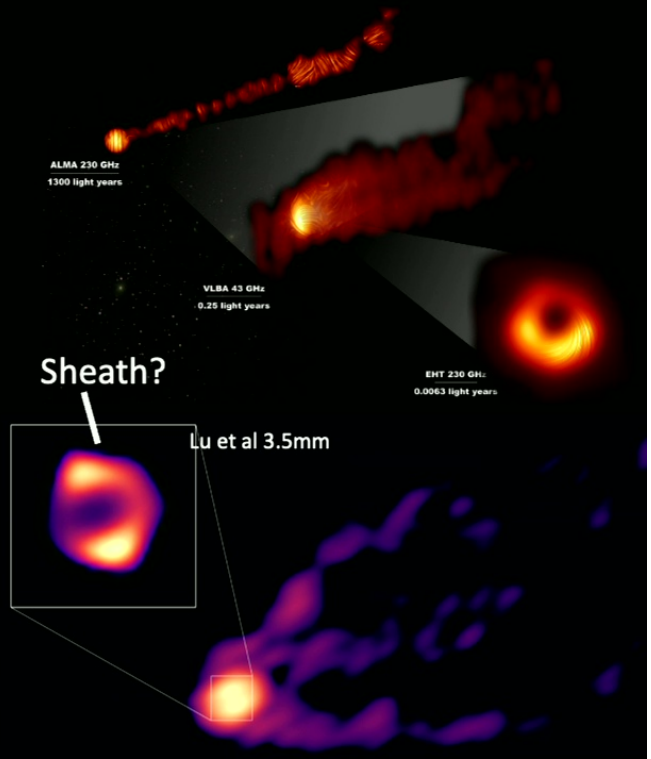
URL: https://pirsa.org/25030073

Abstract:

An alternative interpretation of the EHT observations of M87, involving a strongly magnetized ergomagnetosphere, that expels essentially of the gas supplied at large radius as a jet-collimating MHD wind is described. In this case, the emitting regions are approximated as rapidly evolving flares or sparks. Six generic consequences, that can be sought in existing data, are described.

M 8 7 : S O M E N U M B E R S

- Mass
  - M ~ 6.5 x 10^9 M_{sun}
    - Unit of length, Gm/c^2, time, Gm/c^3
    - ~ 10^{10} km, ~ 8 hr
    - P_{orb} ~ I month at r ~ 6
- Spin
  - Treat as 3-vector **a**
    - Fiducial model |**a**| = 0.9, θ_0=163° (Walker)
  - Rotational energy ~2 x 10^{56} J
    - Good for 10^{12} y
- L_{jets} ~ 6 x 10^{36} W
  - ~ 600 L_{ring} > 100 L_{disk} ~10^{-4} L_{edd}
- Mass supply rate ~ 10^{22} kg s^{-1}?



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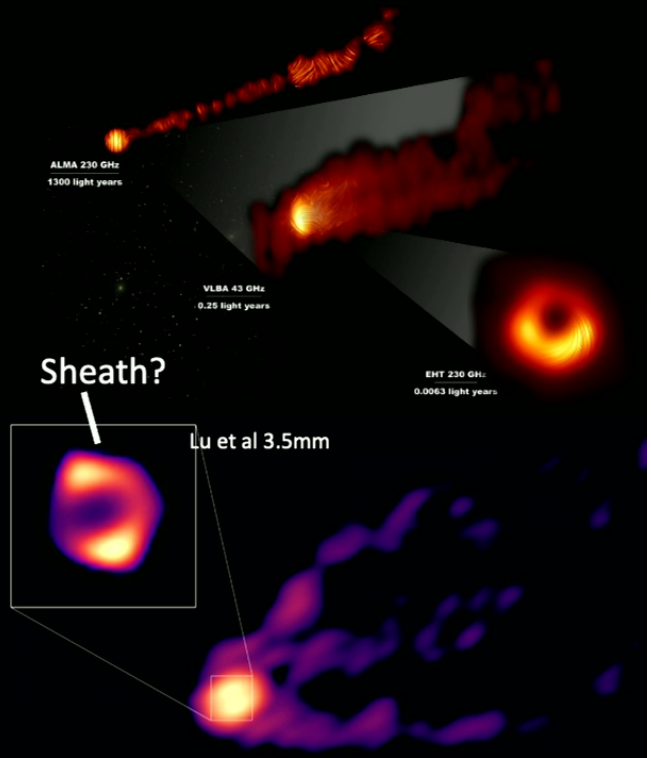

Still much uncertainty

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M87: SOME QUESTIONS

- Why are the disk, plunge so dim?
- What drives the mass supplied away with positive energy?
- How is jet collimated beyond 10,000 gravitational radii?
- Why are jets associated with elliptical galaxies?

Consider high field - B>100 G

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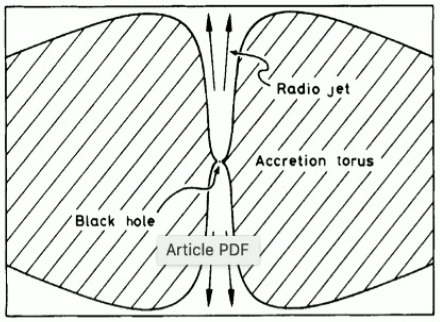
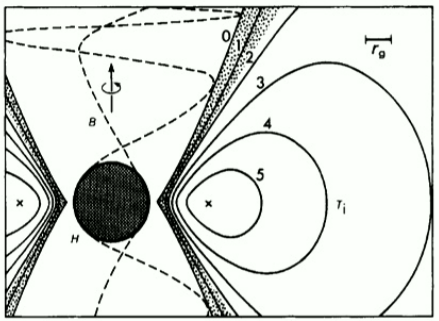
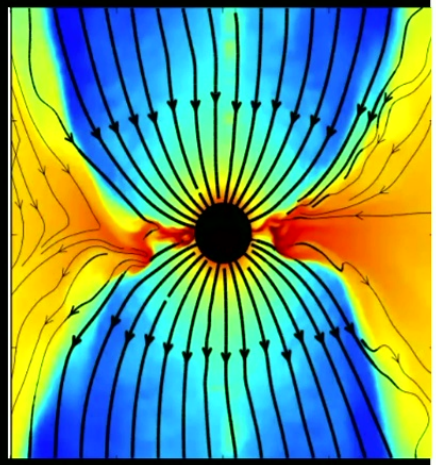
Magnetically Arrested (Accretion) Disk

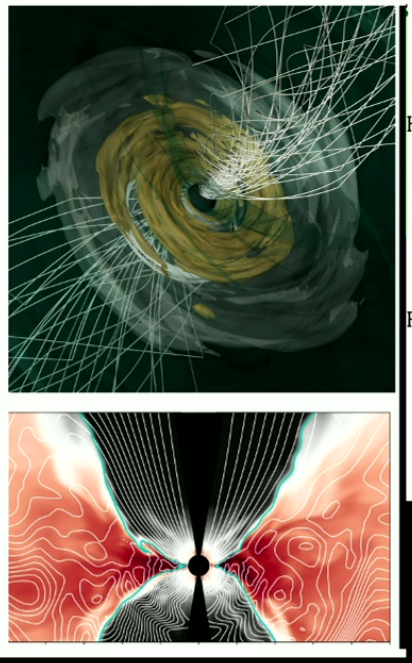




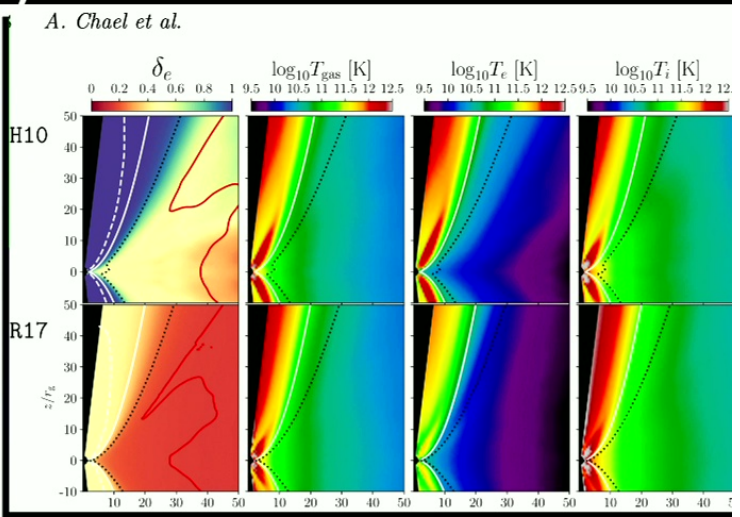
Rees, RB et al 1982



McKinney, RB 2009



Narayan & Quataert 2023



"MAD" accretion

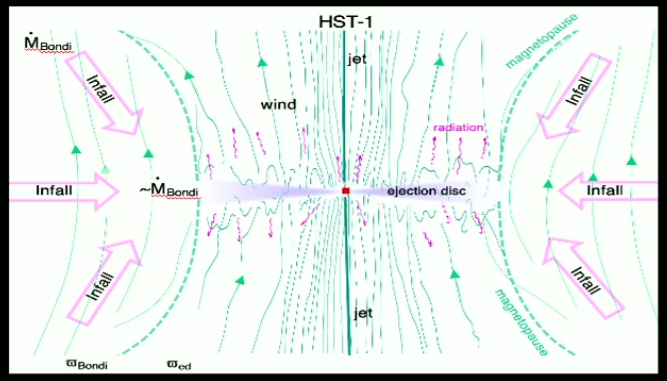
B_{jet} ~ 10G, torus weakly magnetised

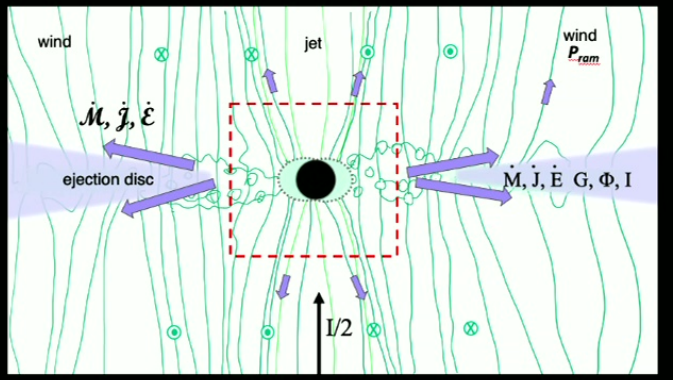
Thick, ion pressure-supported tori collimate the jets
Continuous Flow; B ~ 10G

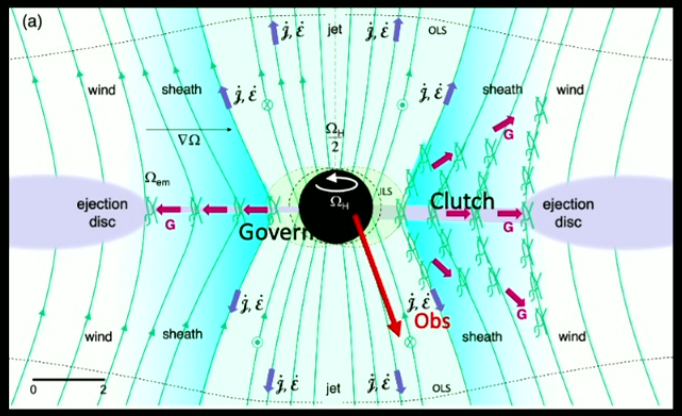
RB + Globus

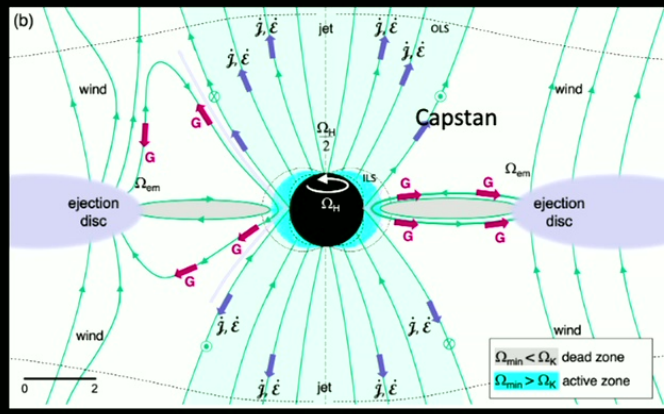
Hole-Energised, Magnetically-Mediated, Ejection-Disk

- Black hole
  - Spin
  - Magnetized
- Jets
  - Powered by hole
  - Electromagnetic
- Ergomagnetosphere
  - Hole also powers disk
  - Clutch/capstan/governor
- Ejection (not accretion) disk
  - Gas expelled
  - Large scale field
- MHD wind
  - Removes gas
  - Collimates jets at sheath
- Magnetopause at r ~ 10^5
  - High latitude infall in ellipticals









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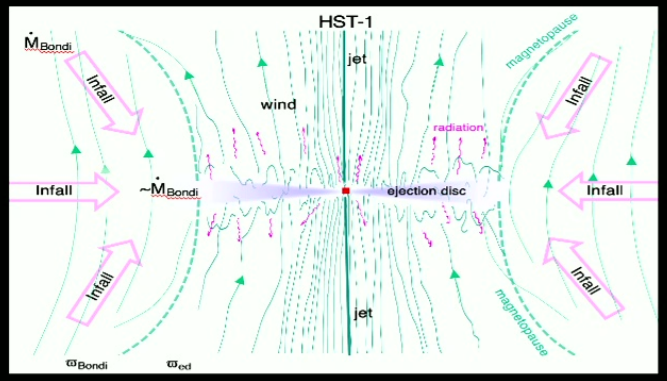

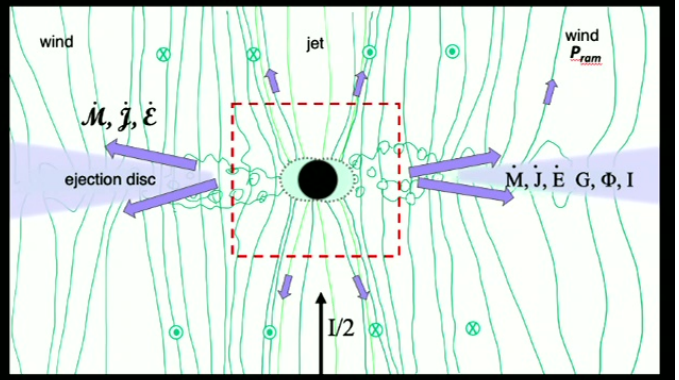

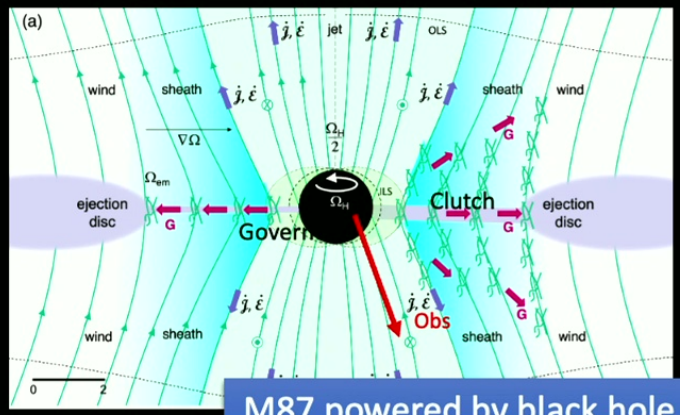

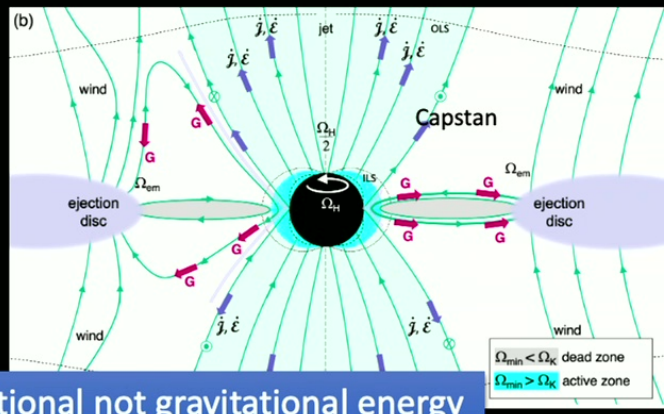

M87 powered by black hole rotational not gravitational energy
Nature not Nurture
Focus on global conservation laws not microphysical models

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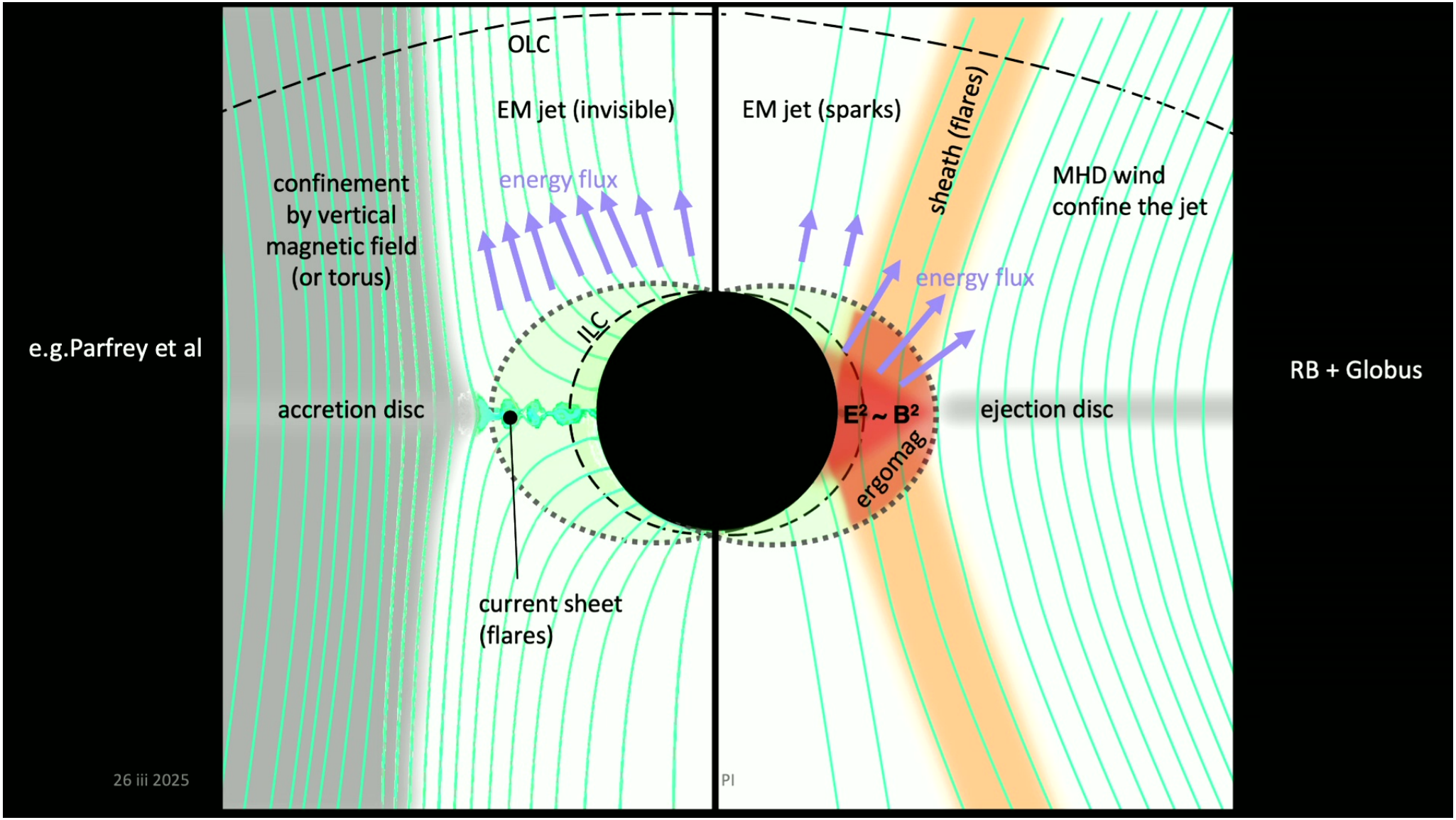
OLC
EM jet (invisible)
EM jet (sparks)
sheath (flares)
confinement
by vertical
magnetic field
(or torus)
energy flux
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e.g.Parfrey et al
RB + Globus
accretion disc
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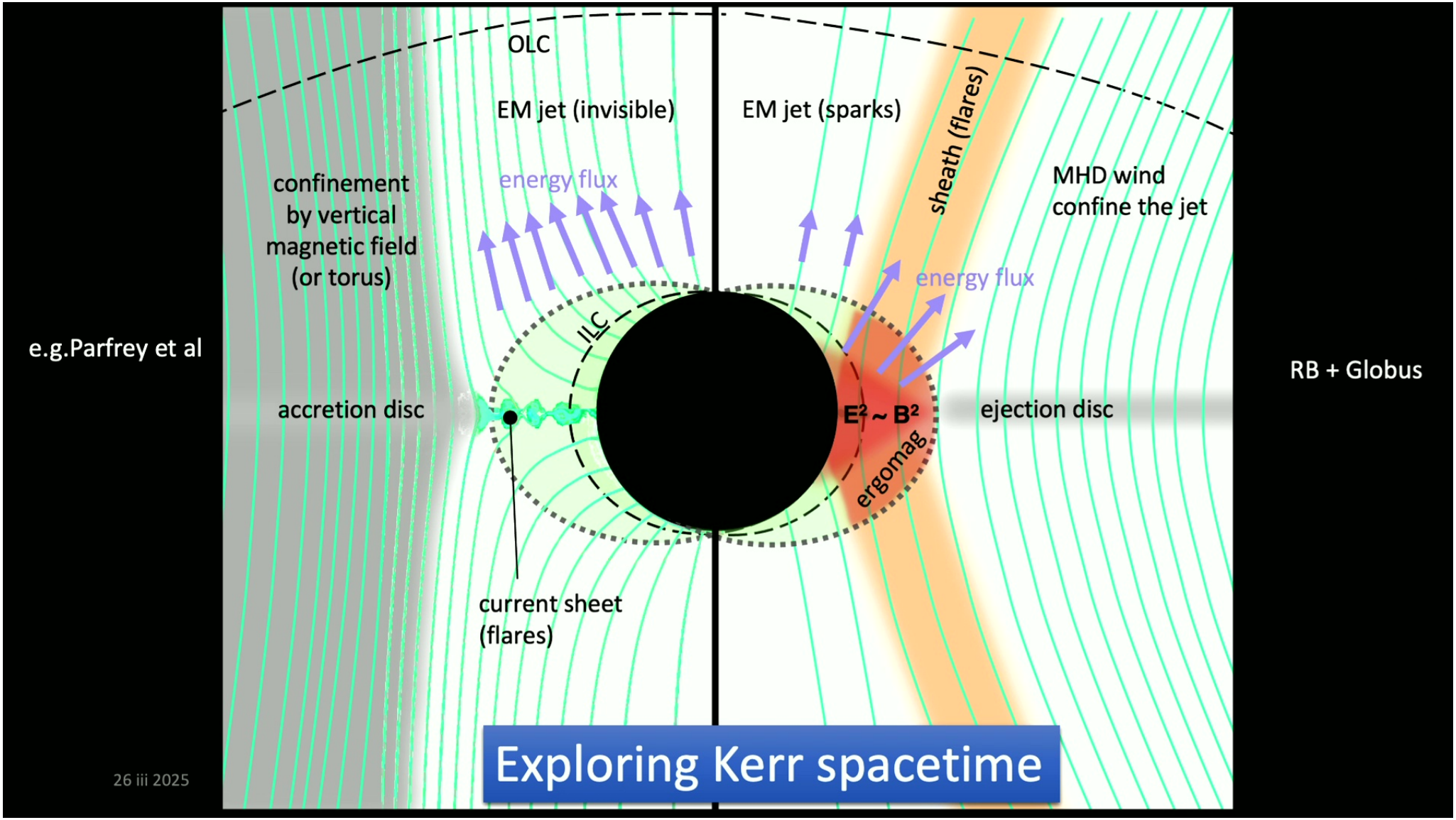
26 iii 2025
PI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Exploring Kerr spacetime
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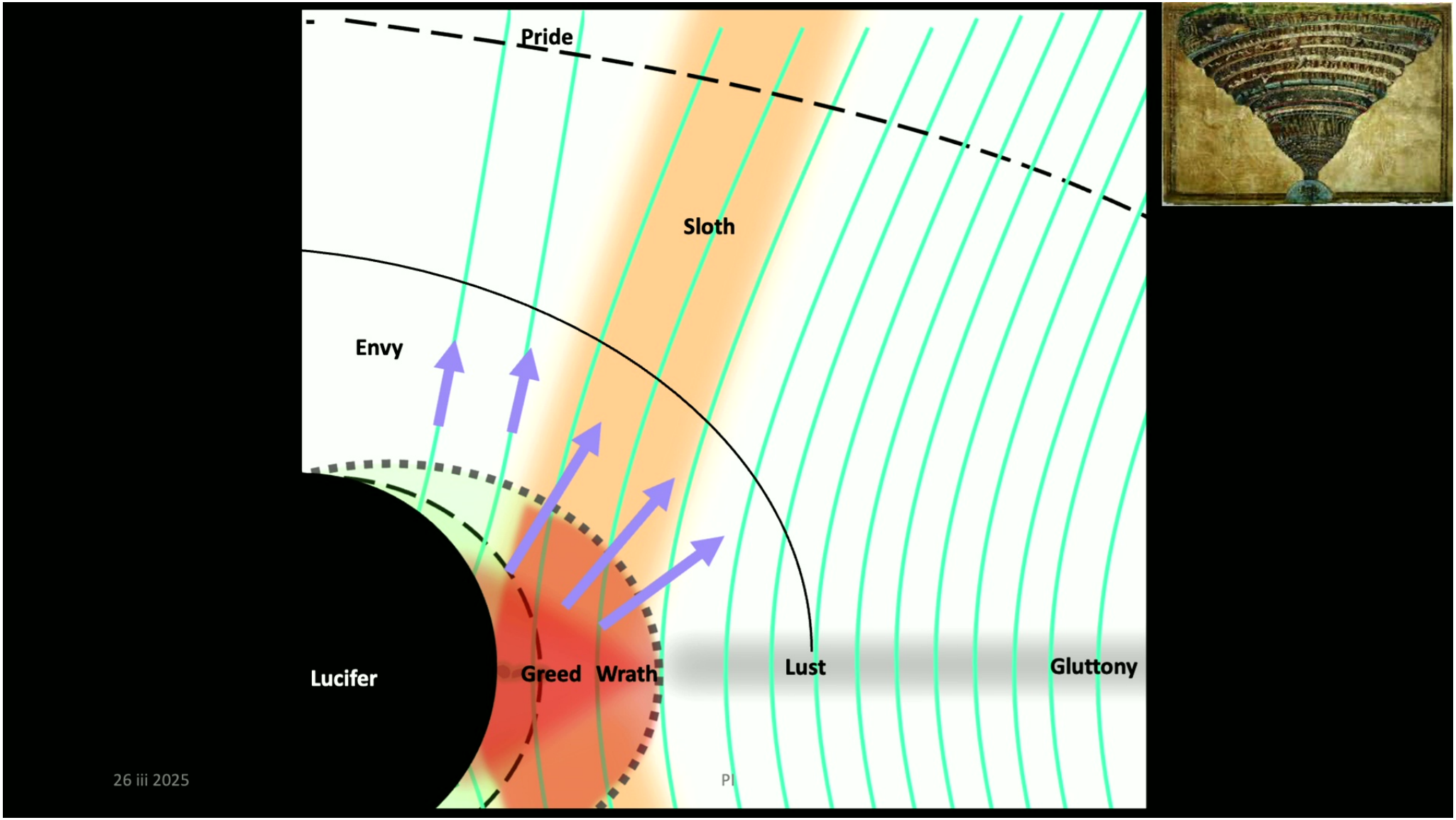
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Sloth
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Lucifer
Greed
Wrath
Lust
Gluttony
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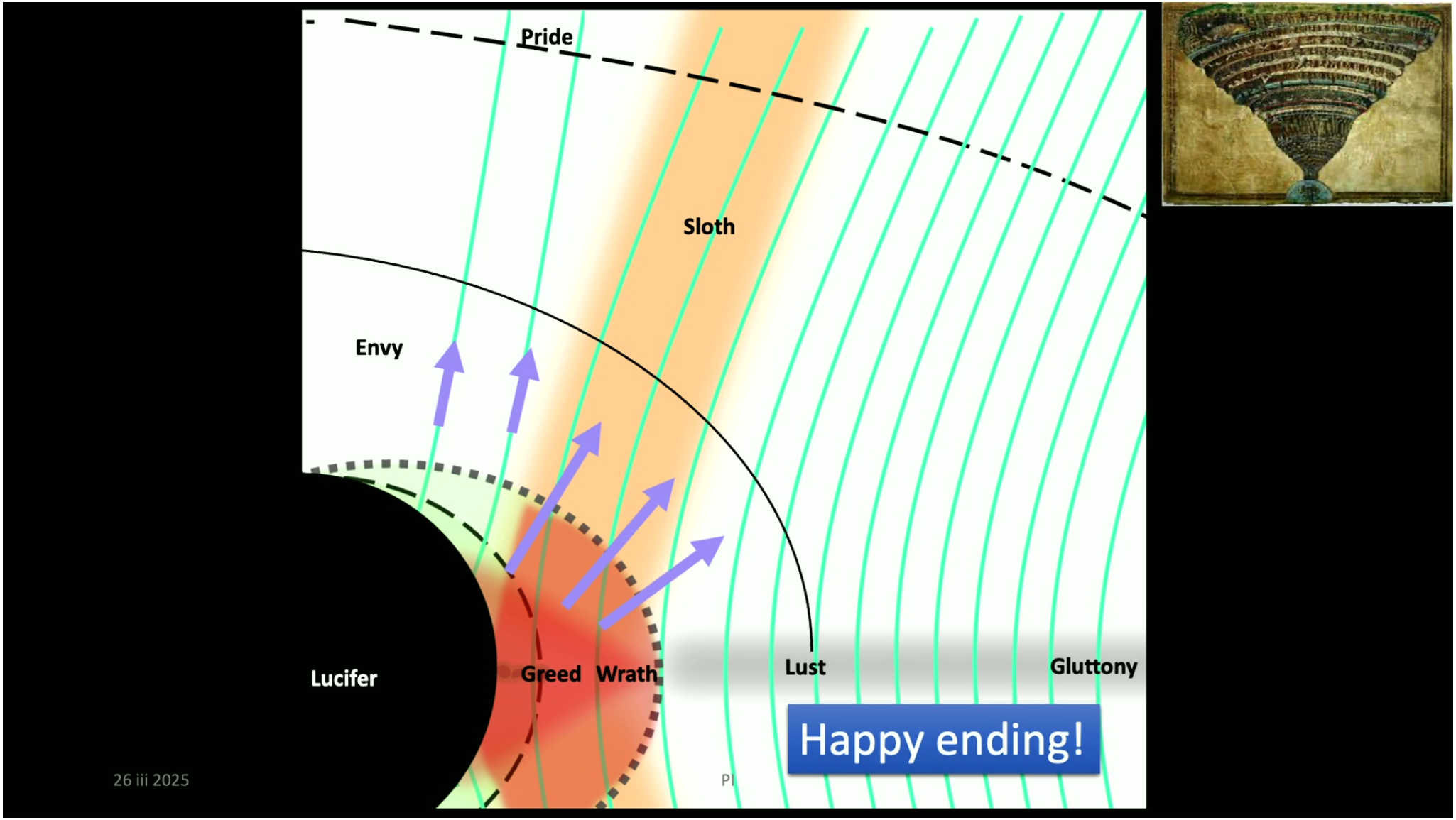
Pride
Sloth
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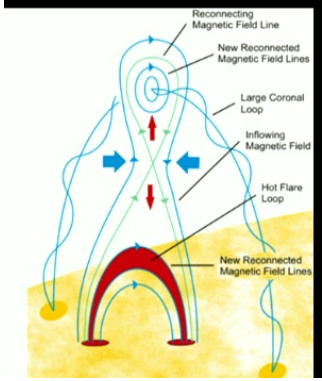
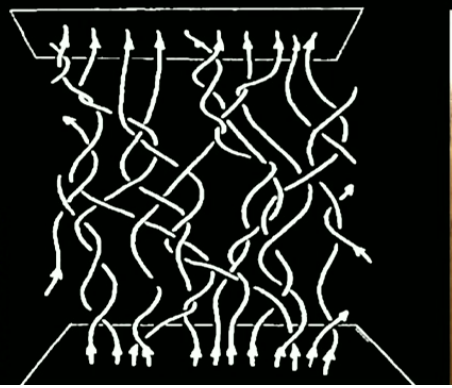
Lust
Gluttony
Happy ending!
26 iii 2025

SNAP

- Impulsive acceleration in magnetically dominated regions
  - Radiative, relativistic reconnection / magnetoluminescence?
- Emission from local, fast “flares “
  - Radiative and expansion cooling
  - Orbit with electromagnetic angular velocity
- $t_{cool} \sim 1000\ B_2^{-3/2}$ s; $l_{cool} \sim 10^{13}\ B_2^{-3/2}$ cm << r; $L_{mm} < 10^{39}\ B_2^{-1}$ erg s^{-1}; $N_{flares} > 100\ B_2$?
- Absorption – $T_B < 10^{11}\ B_2^{-1/2}$ K
- Strong variable linear/circular polarization
- Faraday rotation mainly from sheath, wind





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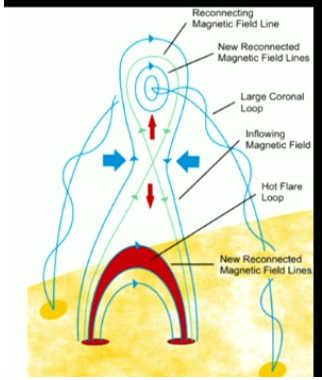
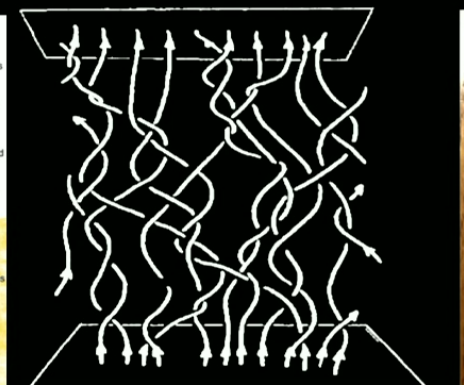
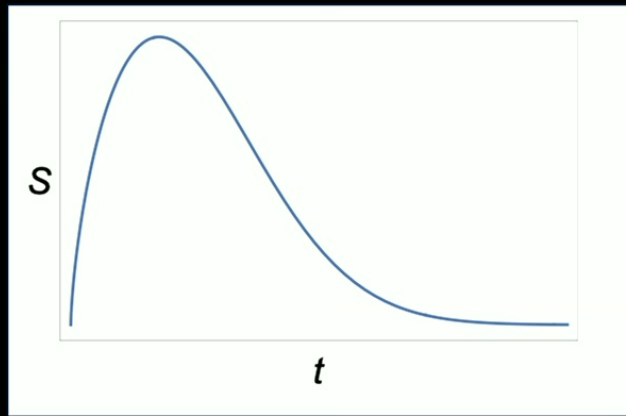




Local, fast acceleration is a feature

CRACKLE - Flares

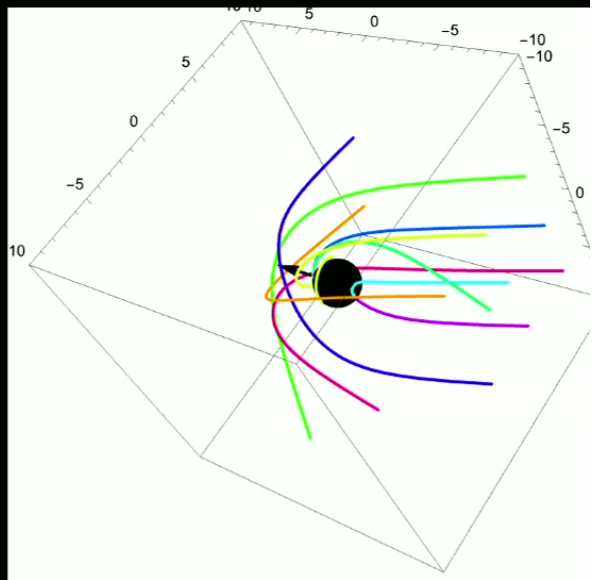
- Flux from individual flare should be time-asymmetric when a few flares dominate
- Timescale ~ hours
  - e.g. cooling flare: $S \sim t^{2/3} \exp(-t^2)$; independent of frequency
    - Arrow of time: three point correlation function. e.g. $\langle S(t+\tau)(S(t+\tau)-S(t))S(t)\rangle$
  - e.g. expanding flares peak frequency falls
    - Whistler: Two point cross-correlation e.g. $\langle S(t+\tau,\nu')S(t,\nu)\rangle$
- Use raw flux data; do not excise spikes/RFI

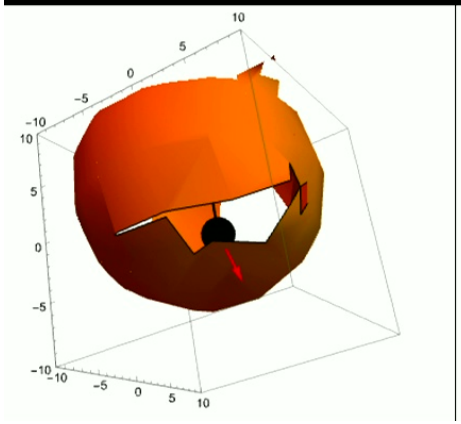


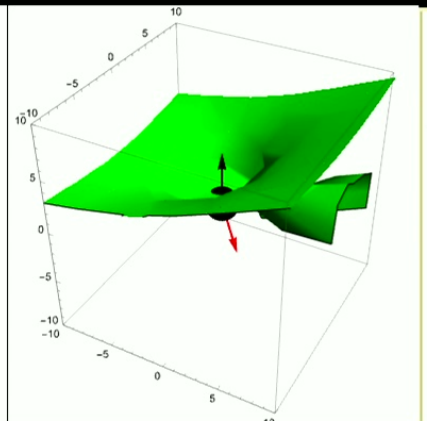
Seek in existing flux data

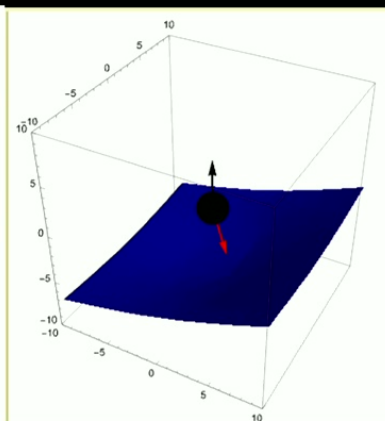
RELATIVISITIC GEOMETRICAL OPTICS IN KERR SPACETIME

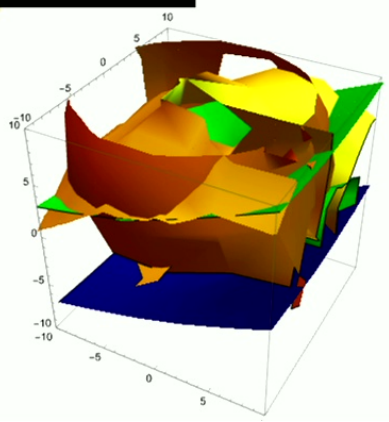
- Kerr spacetime; m=GM/c^2=1; -1 <a<1; point is $\vec{x}$ $ds^2 = -\alpha^2 dt^2 + \varpi^2(d\phi - \omega dt)^2 + \rho^2(\frac{dr^2}{\Delta} + d\theta^2)$
- Boyer-Lindquist coordinates {t,r,θ,ϕ}
- Ray from source $\mathcal{S}$ to observer $\mathcal{O}$ satisfies $\frac{d\vec{x}}{d\zeta} = \vec{k} = \vec{\nabla}\psi;\ \vec{k}\cdot\vec{k} = 0;\ \zeta$ is affine parameter
- Constants at $\mathcal{O}$: energy = 1, angular momentum = L, Carter constant = K;
- (L, K) -> sky vector **X** for fixed **a**
- Solve first order ODEs for paths : $\vec{x}(\zeta; \mathbf{X})$ => **x**(ζ ; **X**), t(ζ ; **X**)
- Escaping, ambivalent and curious photons; photon sphere: r ~ 3 => |**X**-Δ**X**| ~ 5
- Hessian (inverse magnification): H(ζ; **X**) = $\left[\frac{\partial x_\perp}{\partial X}\right]$; gravitational rotation of E-vector
- **Compute wavefronts that converge on $\mathcal{O}$ using ψ = t(x), once!**
- Source Doppler shift: $\mathcal{D}$ = -$(\vec{u}\cdot\vec{k})^{-1}$; Intensity ~ $\mathcal{D}^3$

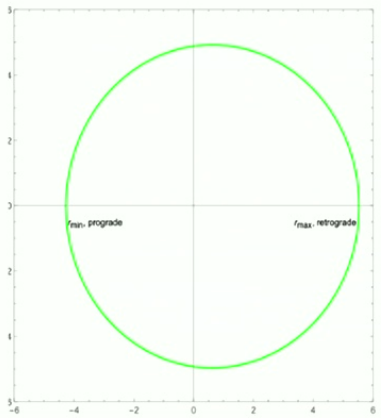












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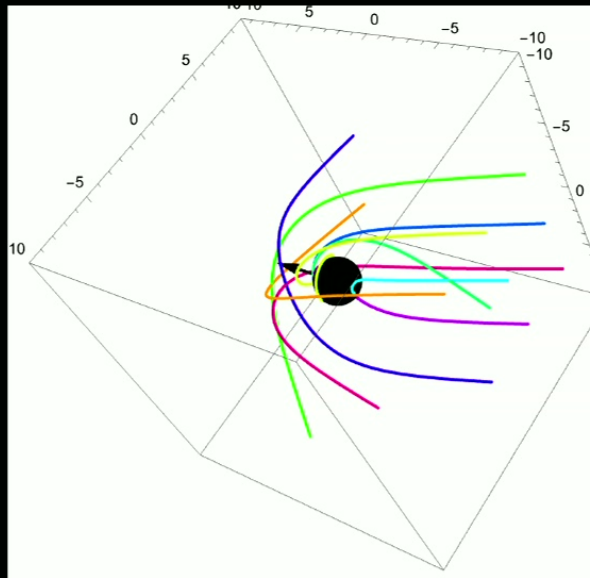
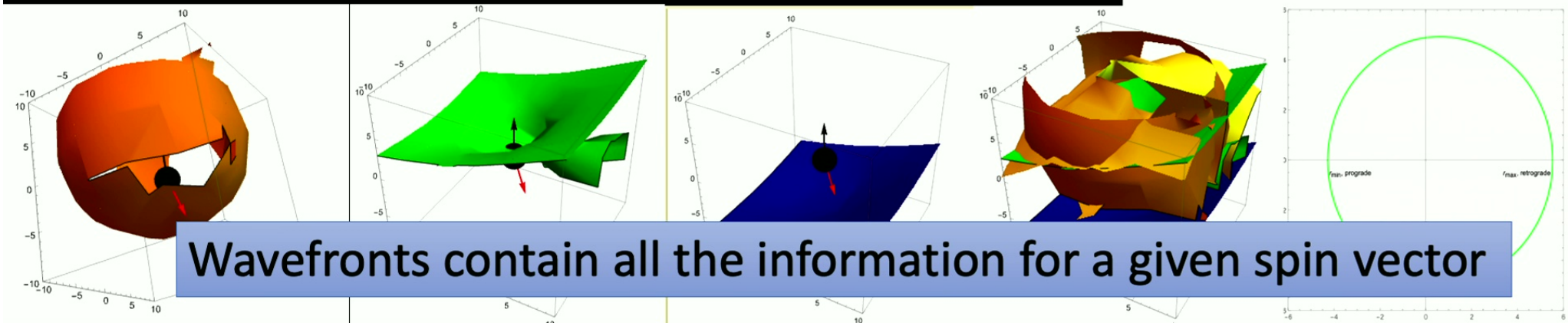
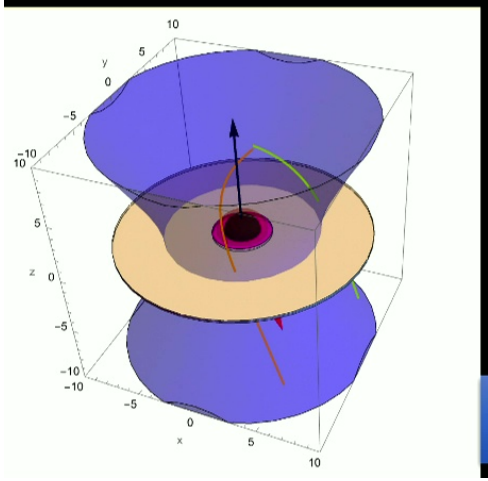


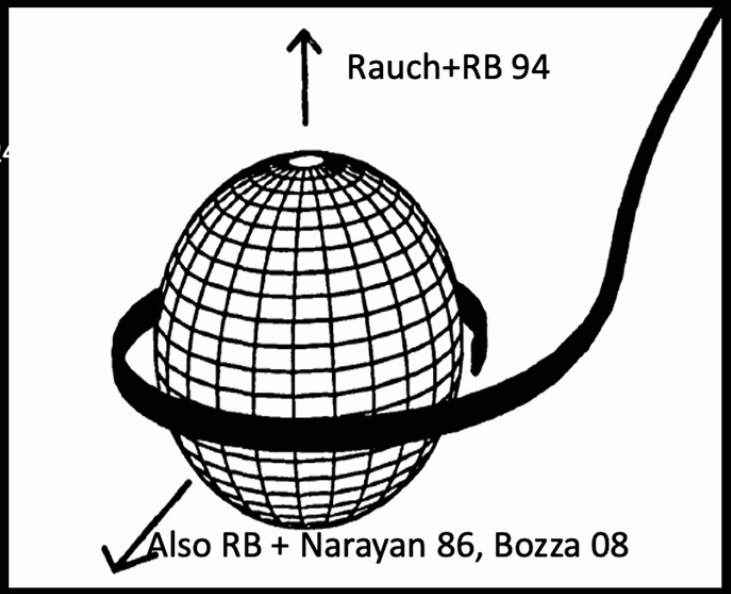


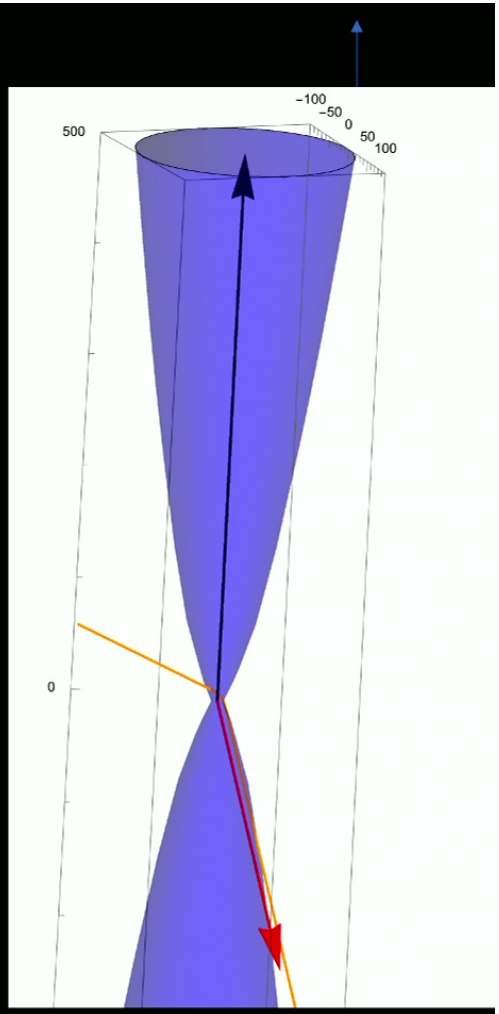
Wavefronts contain all the information for a given spin vector

CRACKLE - echoes

- Every source imaged by every black hole
  - Infinite number of times, but…
- A generic ray touches caustic where rays cross; conjugate point for congruence
  - $|H| = M^{-1} \rightarrow 0$; image inverts
- Conversely every $\mathcal{S}$ connects to $\mathcal{O}$ with
  - Primary ray, inverted secondary echo
    - Cf Rauch +RB 94 Zhou et al 24, Wong et al 24
  - $\Delta t \sim M^2$ close to caustic
  - Convolve with finite source size



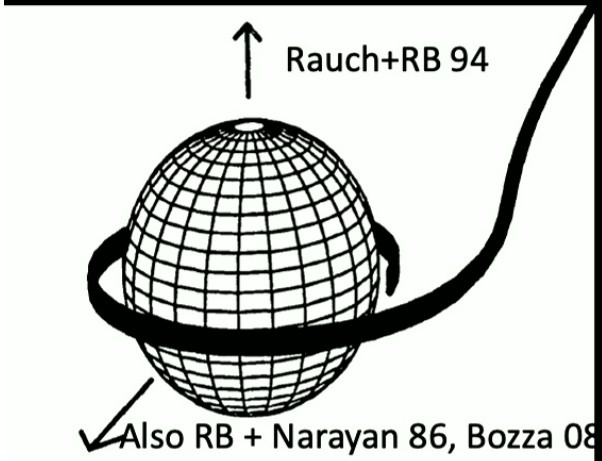


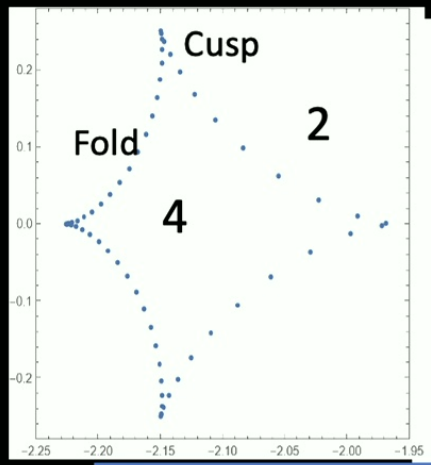


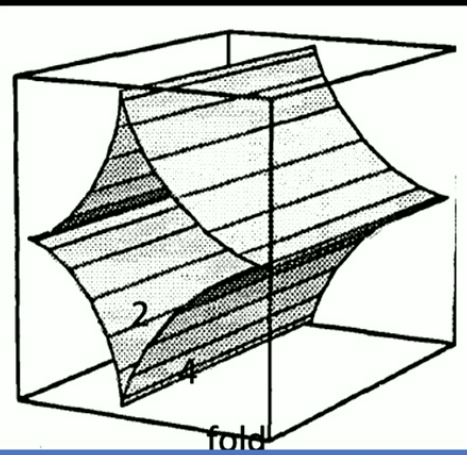
Fairly common, if there are sources

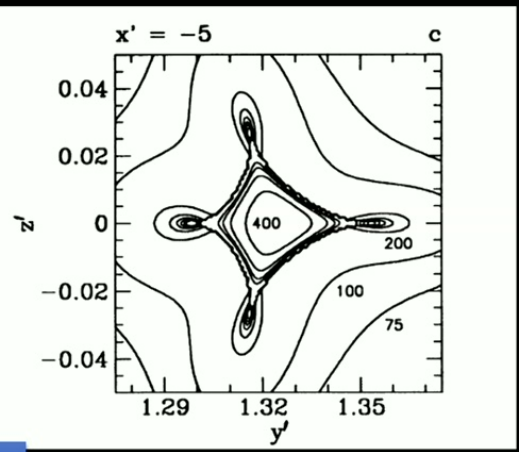
Caustics

- Spherical black hole has line focus making Einstein ring on sky
- Symmetry broken by spinning black hole making caustic ribbon
- Astroid cross section
  - Effective spin is a sin θ
  - Size: $l_{caustic} \sim 0.03 r^{-1}$
  - Central magnification: $M_{caustic} \sim 200 r^{3/2}$





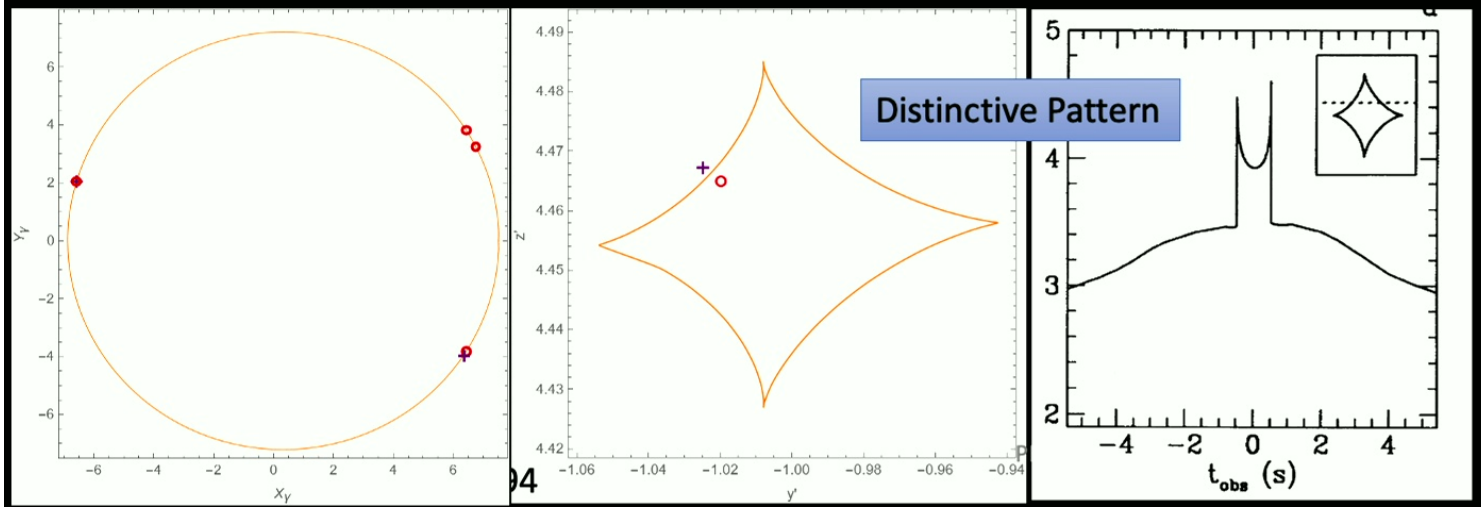




Occasional but highly distinctive events

POP – Caustic Crossing

- Occasional traversals of caustic by jet sparks or sheath flares
  - Seek in flux
    - Ingress: create 2 images which fade ~ $t^{-1/2}$
    - Egress: 2 images brighten ~$(-t)^{-1/2}$ and then vanish
  - Seek in raw visibility (Fourier transform of brightness)
    - Image locations swing around near circular Einstein ring on sky with radius X~5
    - Convolve with finite source size
  - Diffractive optics plasma effects might be relevant



Summary

- EHT observations are magnificent accomplishment
  - MAD model has thick torus supported by hot ions
    - Weak field; quasi-steady emission
  - HEMMED model has ergomagnetosphere/ejection disk/magnetopause
    - Strong field
    - SNAP: reconnection, magnetoluminescence: flares and sparks
    - CRACKLE : Varibility: arrow of time, whistlers, echoes, polarization
    - POP: caustic crossing: rapid spikes; visibilities
    - Seeking in public data