Title: Spinning Black Holes and the Membrane Paradigm

Date: Oct 16, 2014 01:00 PM

URL: http://pirsa.org/14100007

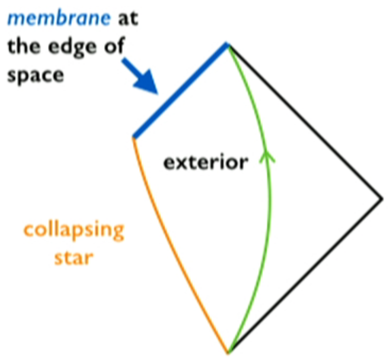
Abstract: There are about nine astrophysical black holes with measurements of the black hole's spin via the continuum fitting method. Several of these black holes drive powerful jets, which appear to extract the black hole's rotational energy. I will discuss the theory behind these observations, with a particular focus on the black hole membrane paradigm. The membrane paradigm is useful on a practical level for understanding black hole jets. However, it may also be related to fundamental physics through holography and AdS/CFT. This suggests new opportunities for interactions between fundamental physics and astrophysics.

Black hole jets and the membrane paradigm

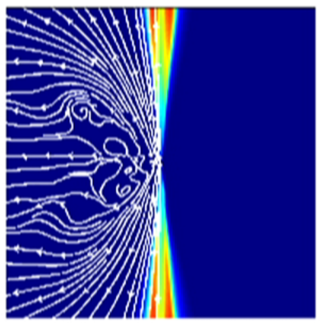
Bob Penna (MIT)

Outline

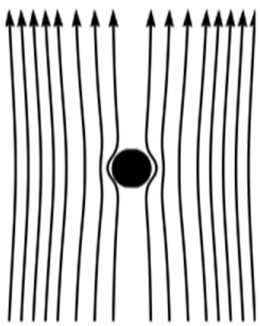
Membrane paradigm



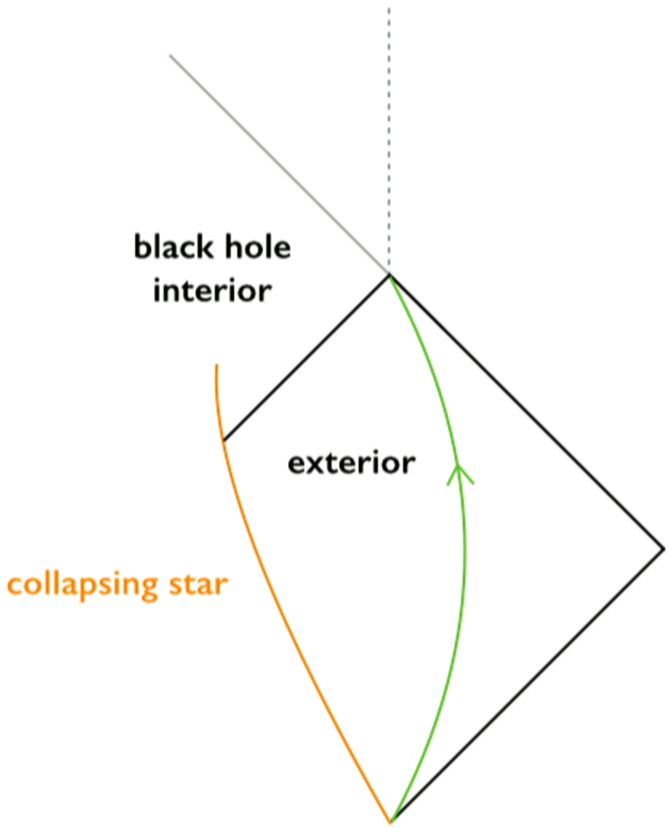
Black hole jets and the membrane paradigm



Black hole Meissner effect

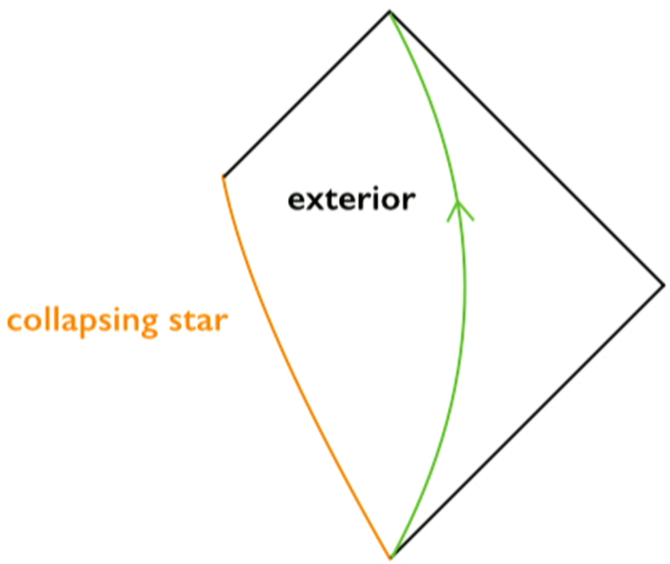


Why use membranes?



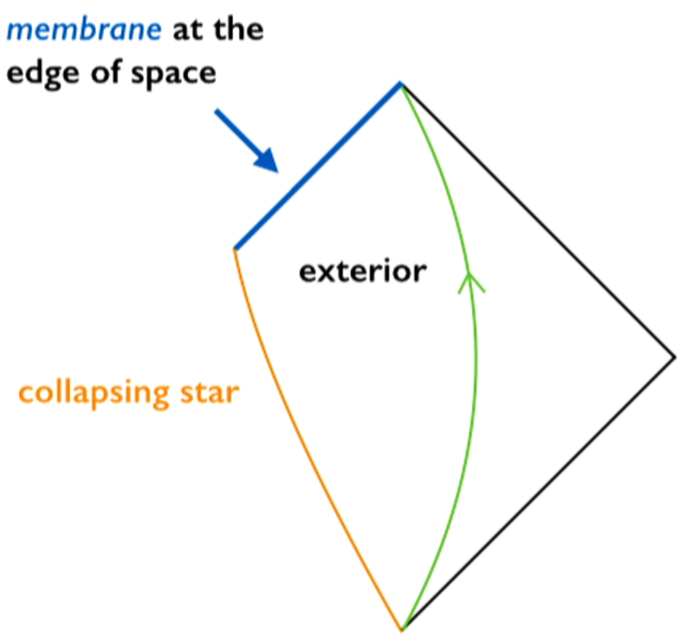
- An **observer who does not jump in the black hole** has no access to the **interior**.

The membrane paradigm



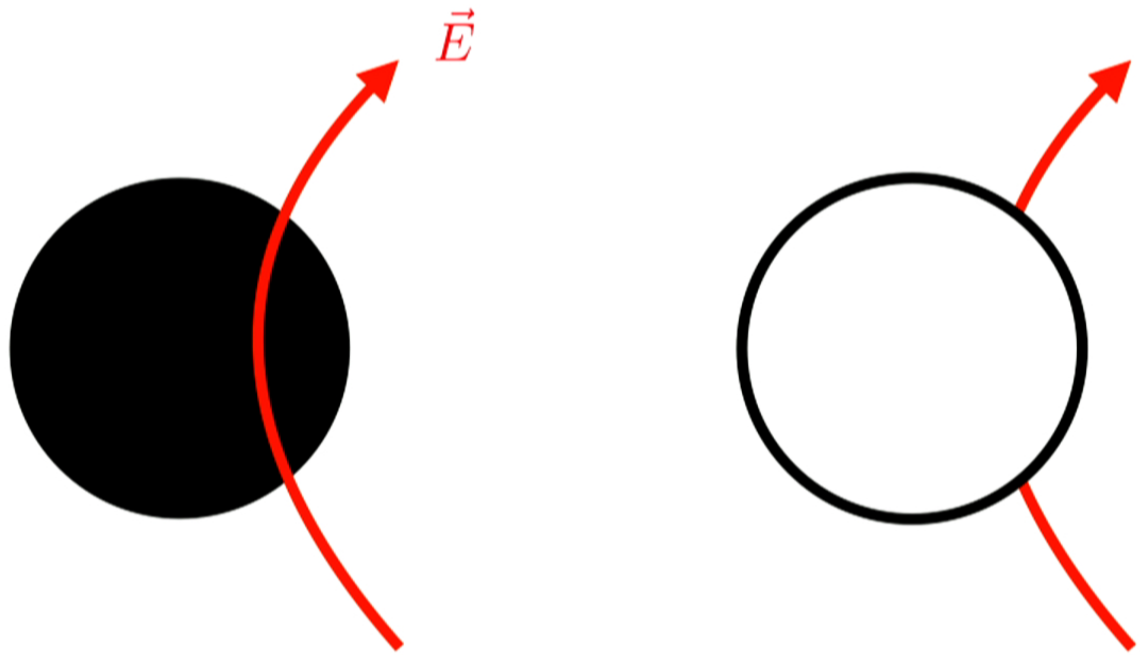
- **Idea**: throw away the black hole interior (since the exterior observer cannot measure it).

The membrane paradigm

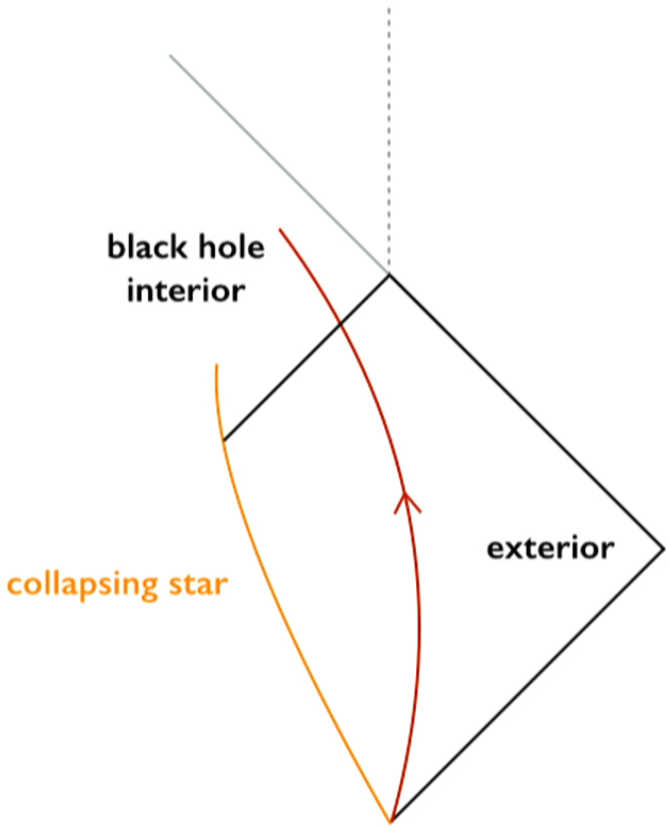


- **Idea**: throw away the black hole interior (since the exterior observer cannot measure it).
- Add a **membrane** at the edge of space.
- Define the membrane so that exterior physics is reproduced correctly.

Example: the membrane charge density

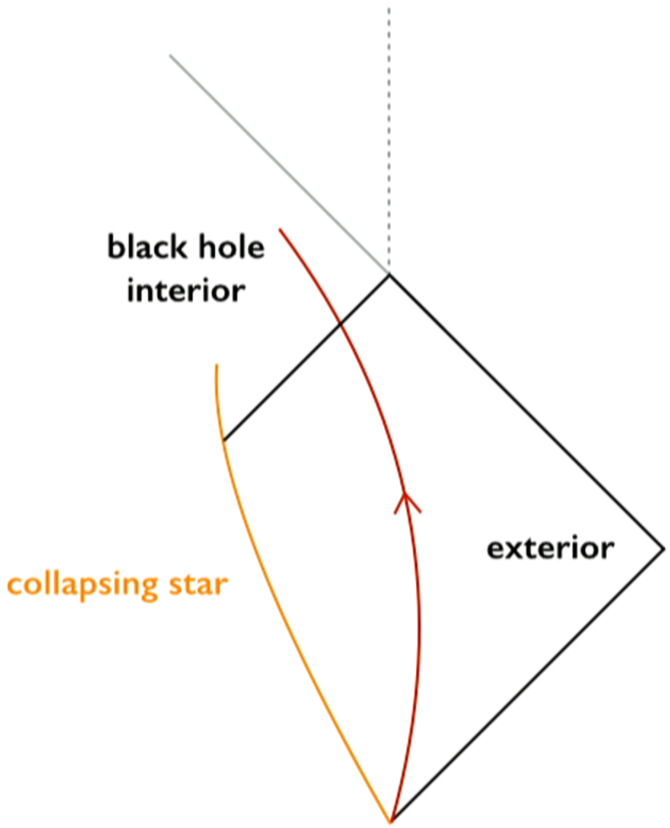


Is the membrane real or fictitious?



- An **infalling observer** thinks: **"membrane is fictitious."**

Is the membrane real or fictitious?



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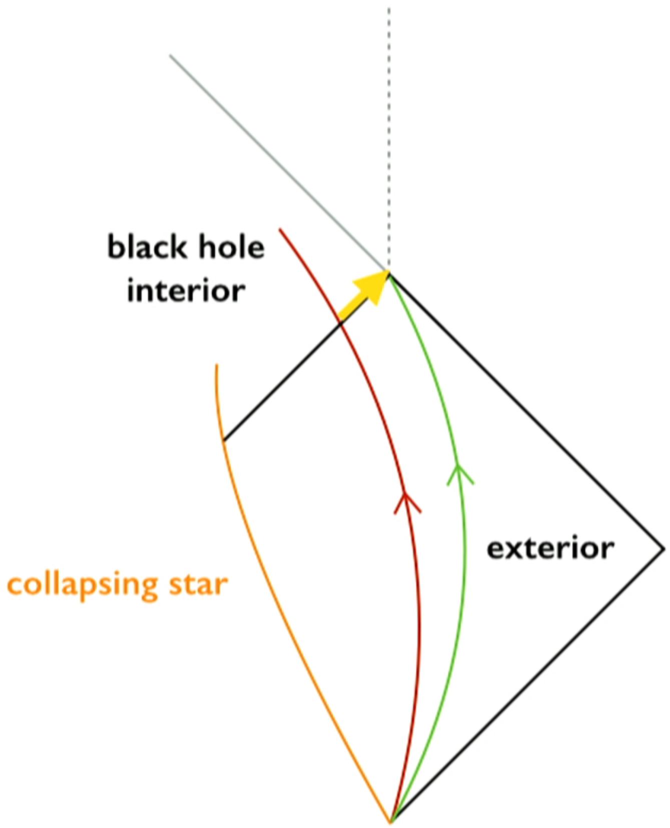

- An **infalling observer** thinks: **“membrane is fictitious.”**
- But a **message** reporting this cannot reach the exterior!
- So an **exterior observer** thinks: **“membrane is real.”**
- Black hole complementarity (*Susskind*): ***they are both correct!***

Defining the membrane

Parikh and Wilczek '98

Consider some fields with action:

$$S = \int d^4x \mathcal{L}$$

on a black hole spacetime.

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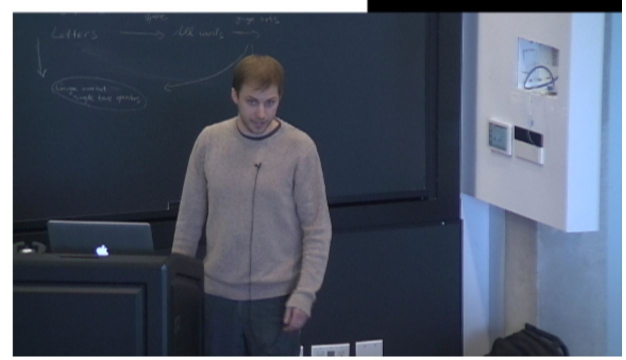
An observer outside the black hole should restrict the integral to the exterior:

$$S_{\text{exterior}} = \int_{\text{exterior}} d^4 x \mathcal{L}$$



Defining the membrane

Parikh and Wilczek '98

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$$S = \int d^4x \mathcal{L}$$

on a black hole spacetime.

An observer outside the black hole should restrict the integral to the exterior:

$$S_{\rm exterior} = \int_{\rm exterior} d^4x \mathcal{L}$$

Problem: *They differ by boundary terms supported on the event horizon!*

$$\delta S_{\rm exterior} \neq \delta S$$

Defining the membrane

Parikh and Wilczek '98

Solution: modify the action by boundary terms.

For electrodynamics:

$$S_{\text{exterior}} \to S_{\text{exterior}} + \int_{\text{horizon}} d^3x\sqrt{-h}\, j_{\text{mb}} \cdot A$$

where the ***membrane 3-current*** is:

$$j^i_{\text{mb}} = F^{ij} r_j |_{r=\text{horizon}}$$

4d field strength

spacelike normal vector to horizon

Properties of the membrane

- Applying the same argument to the Einstein-Hilbert Lagrangian implies the membrane is a viscous fluid governed by the Navier-Stokes equations.

- The stress-energy tensor of the membrane stores the mass and angular momentum of the black hole.

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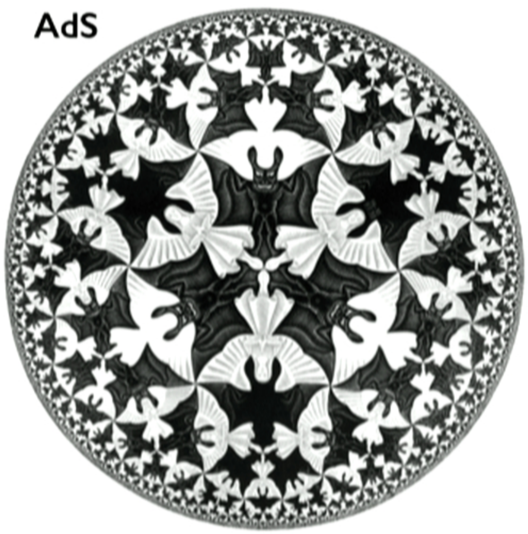
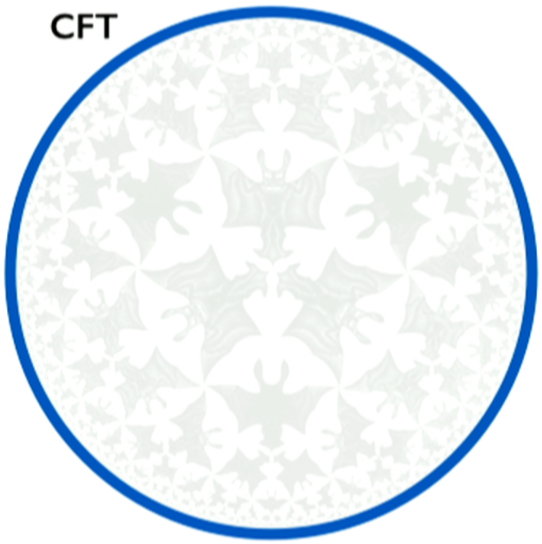
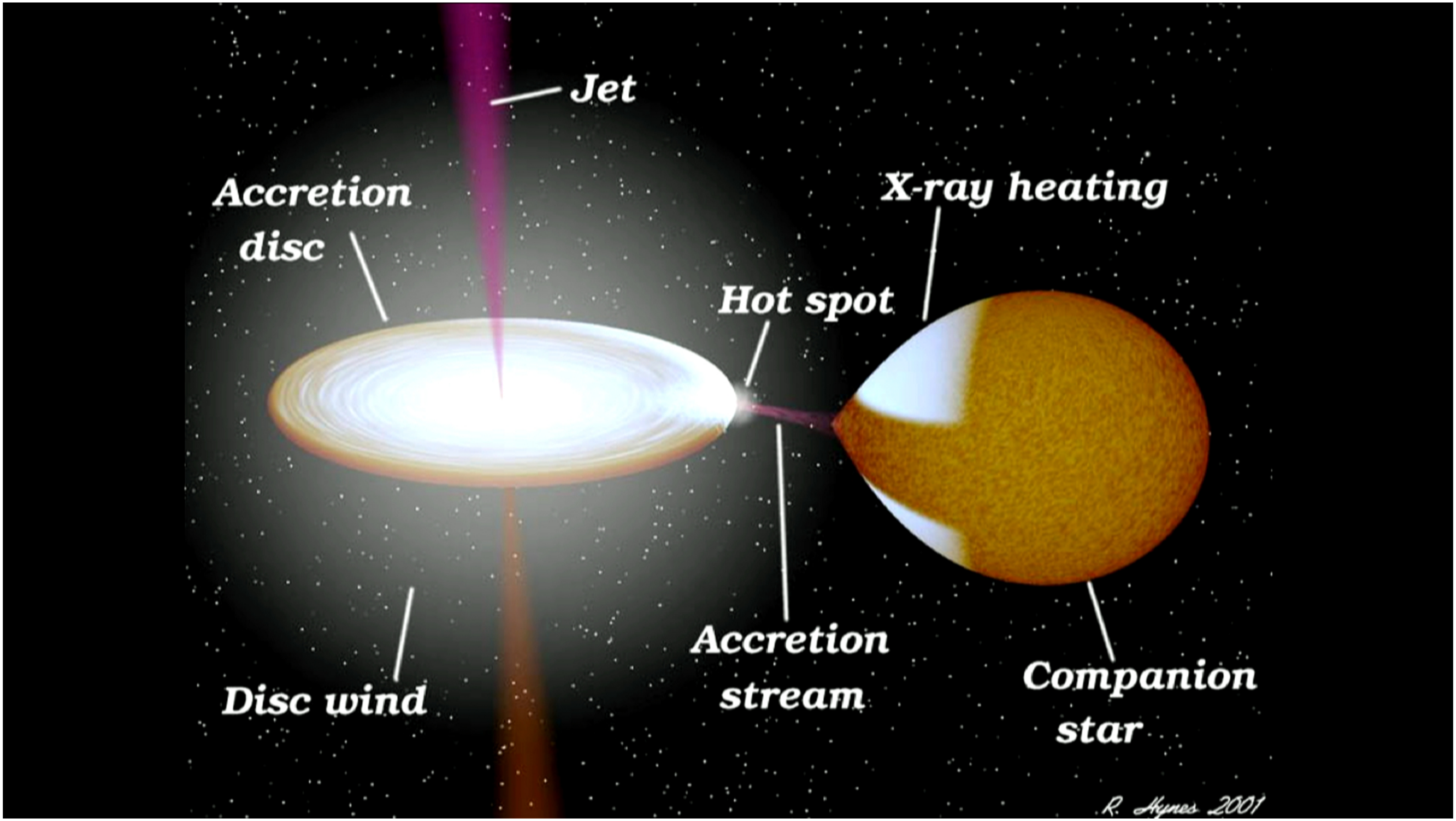
The membrane and fundamental physics

- AdS/CFT

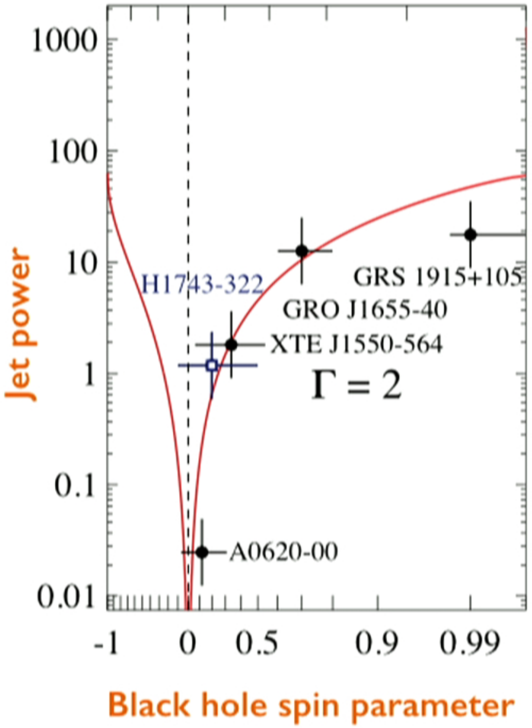


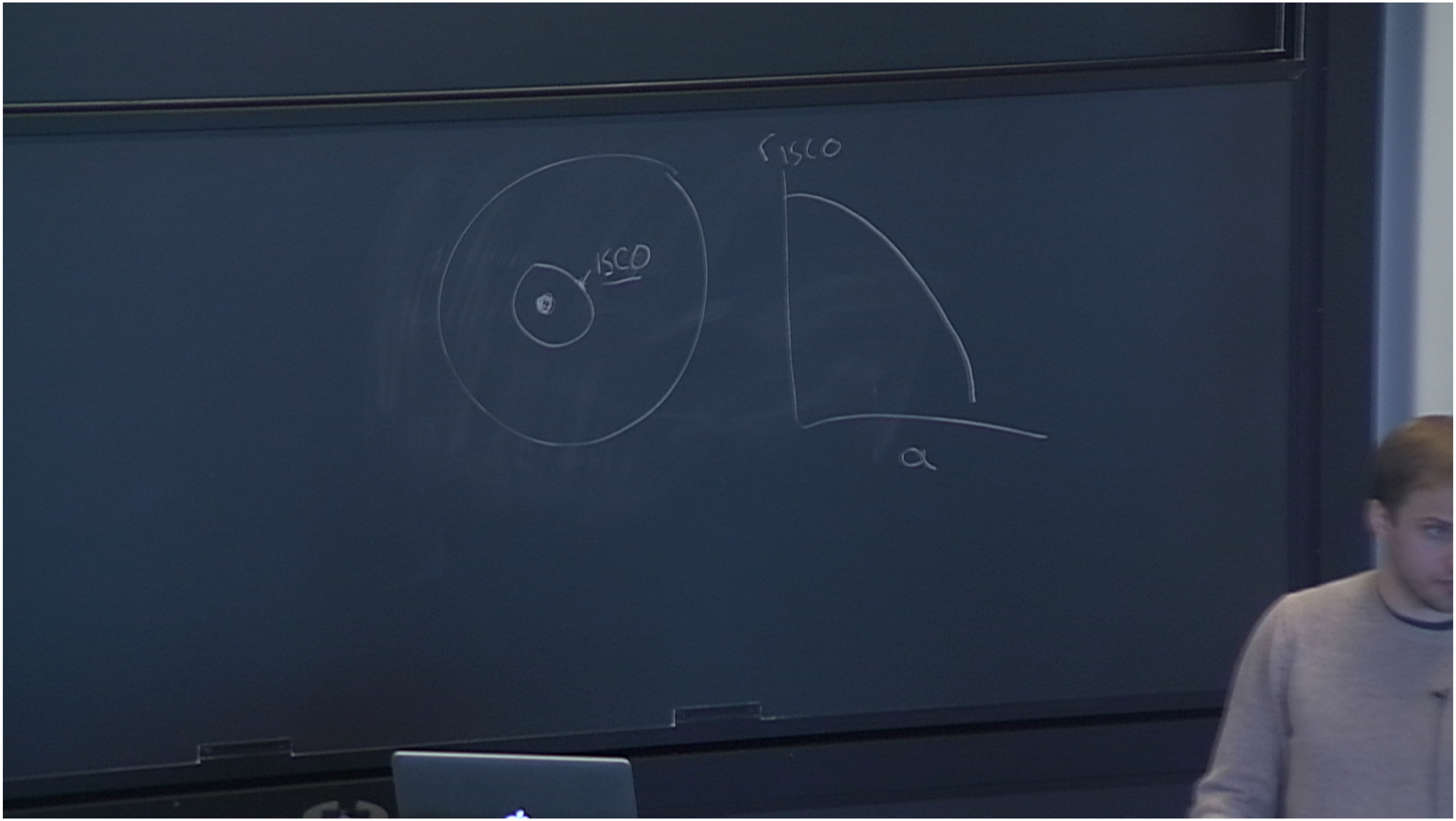



Jet
Accretion disc
X-ray heating
Hot spot
Disc wind
Accretion stream
Companion star
R. Hynes 2001

The membrane and astrophysics

Steiner et al. '12





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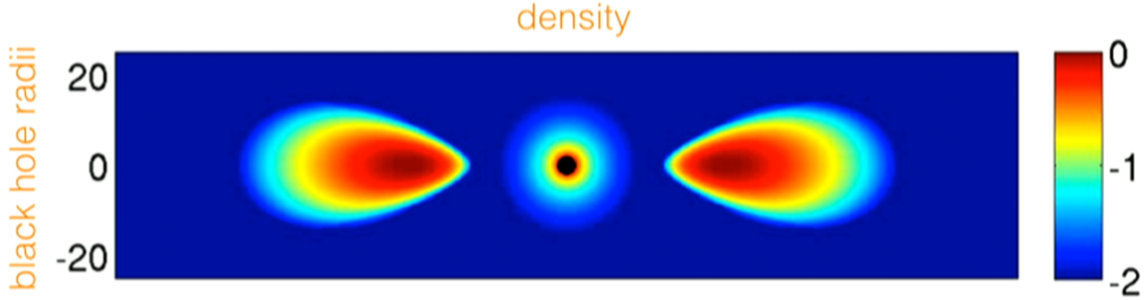
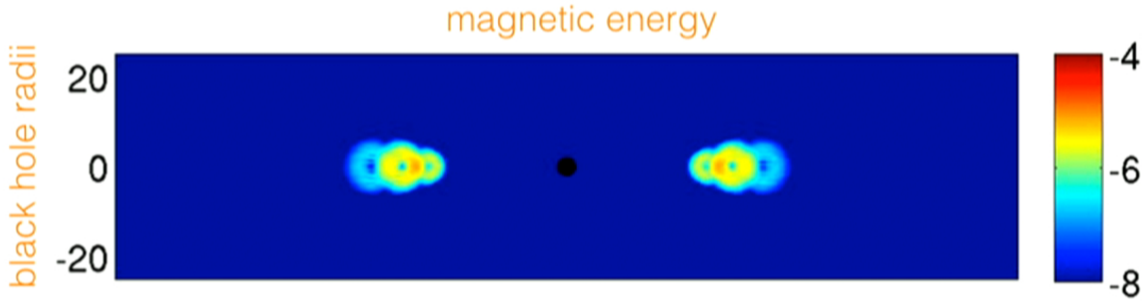
Computer simulations

- Accretion disks are messy: they are turbulent, magnetized, three dimensional…
- So I have run computer simulations.
- I use the general relativistic, magnetohydrodynamics code HARM [Gammie, McKinney, Tchekhovskoy…].
- We solve 3D MHD in a fixed Kerr background. Compute using ingoing coordinates (later switch to membrane paradigm for analysis).

Accretion disk simulation

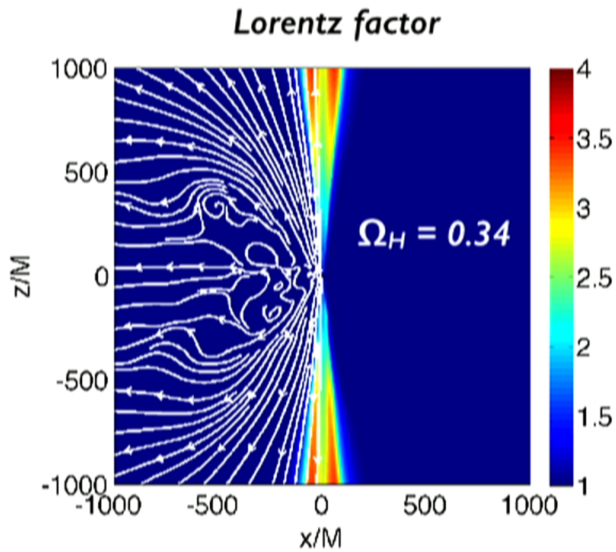
RP, Narayan, Sadowski, MNRAS (2013), 436





Simulated jets

RP, Narayan, Sadowski, MNRAS (2013), 436



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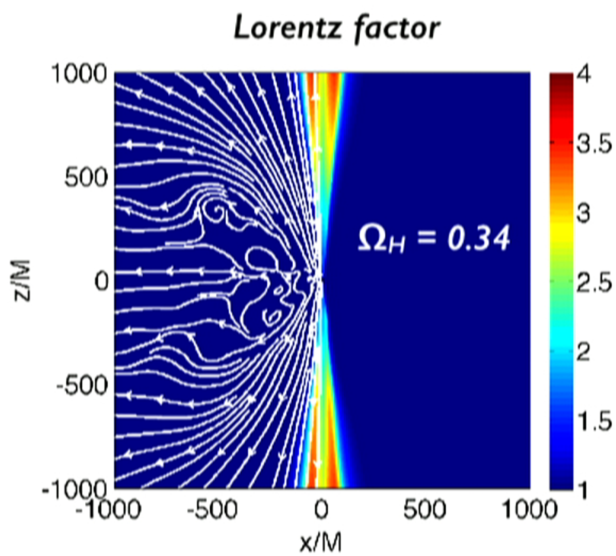

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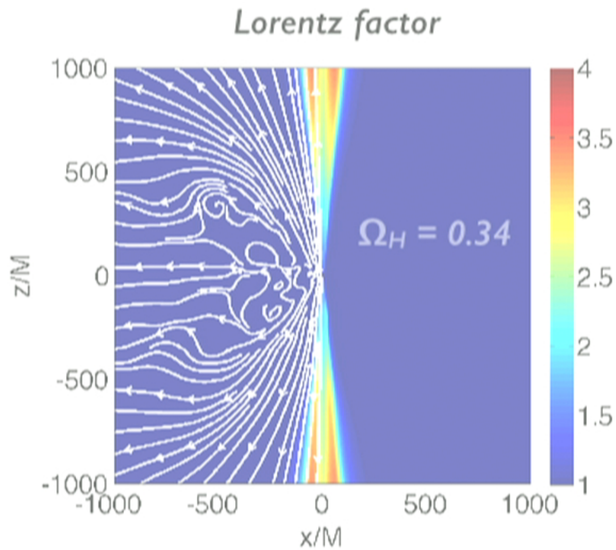
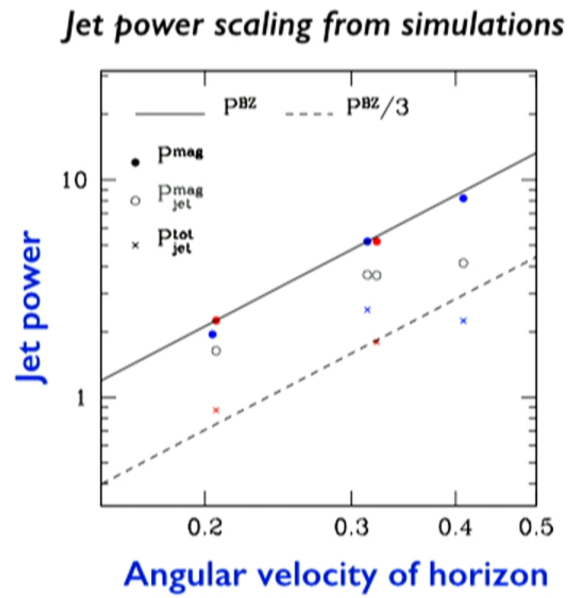
RP, Narayan, Sadowski, MNRAS (2013), 436

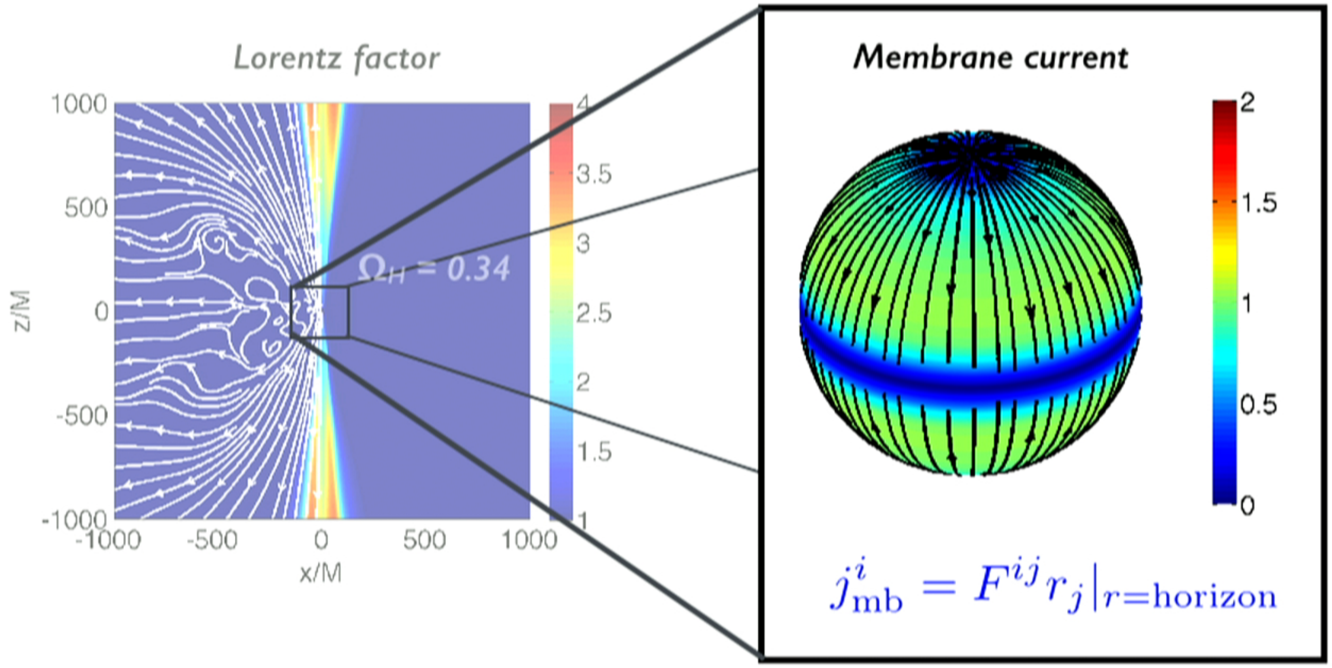




$$\text{jet power} = \frac{1}{6\pi}\Omega_H^2 \Phi^2$$

The membrane current

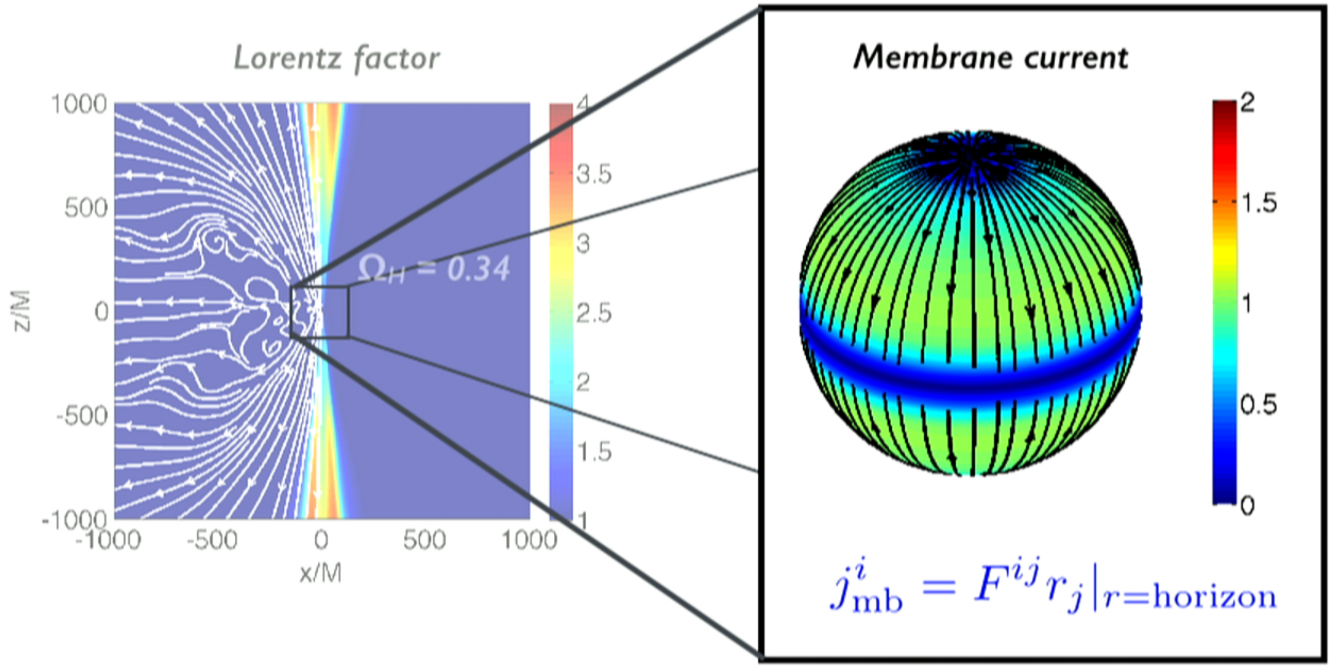
RP, Narayan, Sadowski, MNRAS (2013), 436



t- and ϕ-averaged GRMHD simulation data (Ω_H = 0.34).

The membrane current

RP, Narayan, Sadowski, MNRAS (2013), 436



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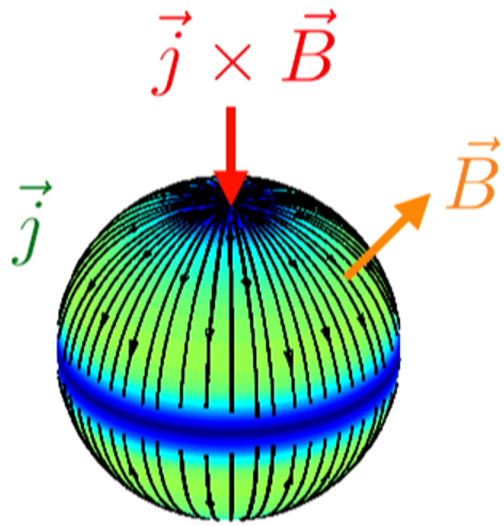
Torquing the membrane

RP, Narayan, Sadowski, MNRAS (2013), 436



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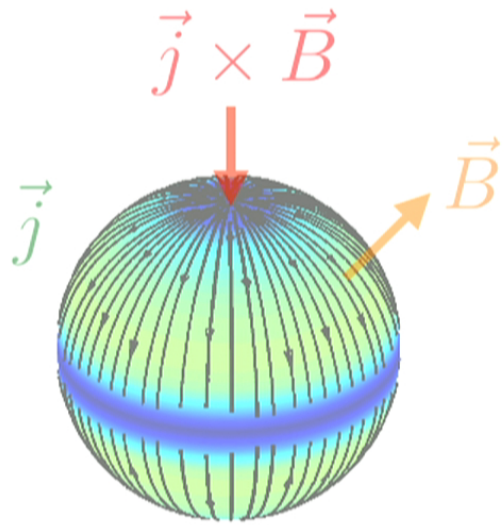
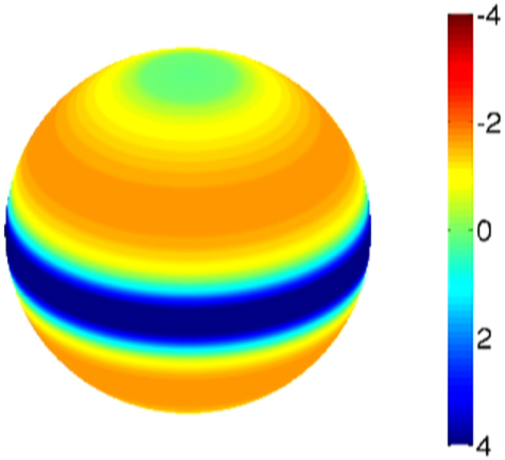


$$\Omega_H \frac{dJ}{dt} = \text{energy flux}$$



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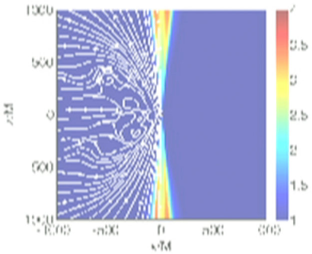
Thermodynamics

- If this was a neutron star, we would be done:

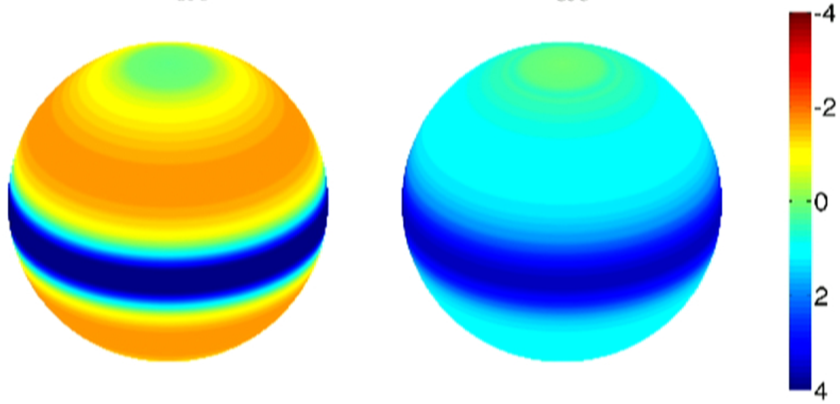
$$dE_{\rm NS} = \Omega_* dJ$$



Thermodynamics

RP, Narayan, Sadowski, MNRAS (2013), 436

$$\frac{dE}{dt} \quad = \quad \Omega_H \frac{dJ}{dt} \quad + \quad T_H \frac{dS_H}{dt}$$



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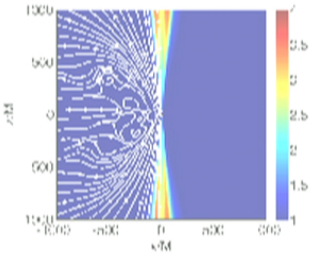
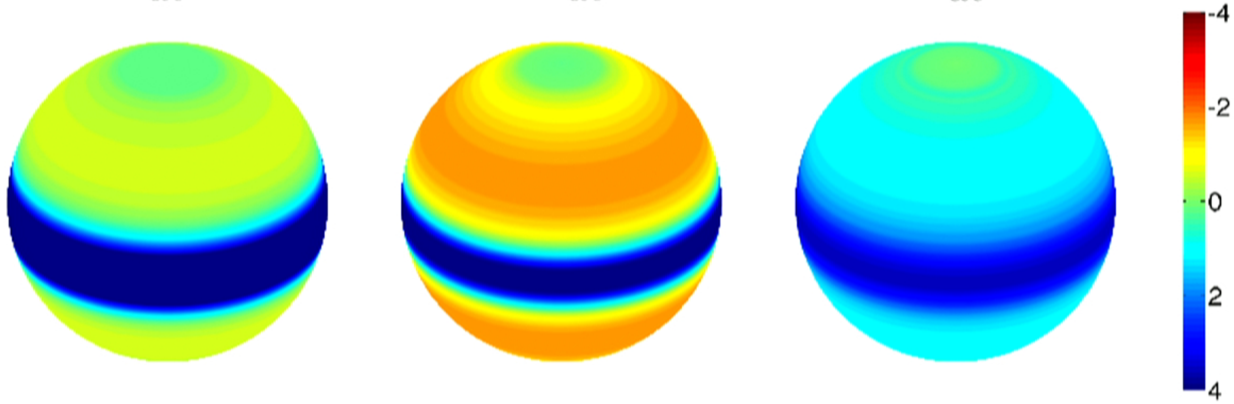


Thermodynamics

RP, Narayan, Sadowski, MNRAS (2013), 436

$$\frac{dE}{dt} = \Omega_H \frac{dJ}{dt} + T_H \frac{dS_H}{dt}$$



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Electromagnetic vs hydro

RP, Narayan, Sadowski, MNRAS (2013), 436

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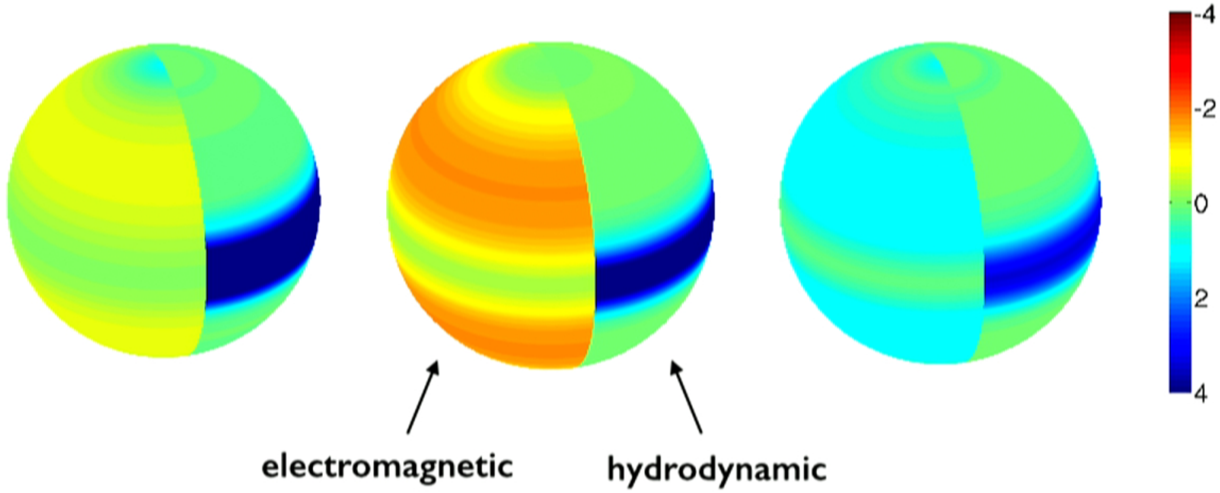

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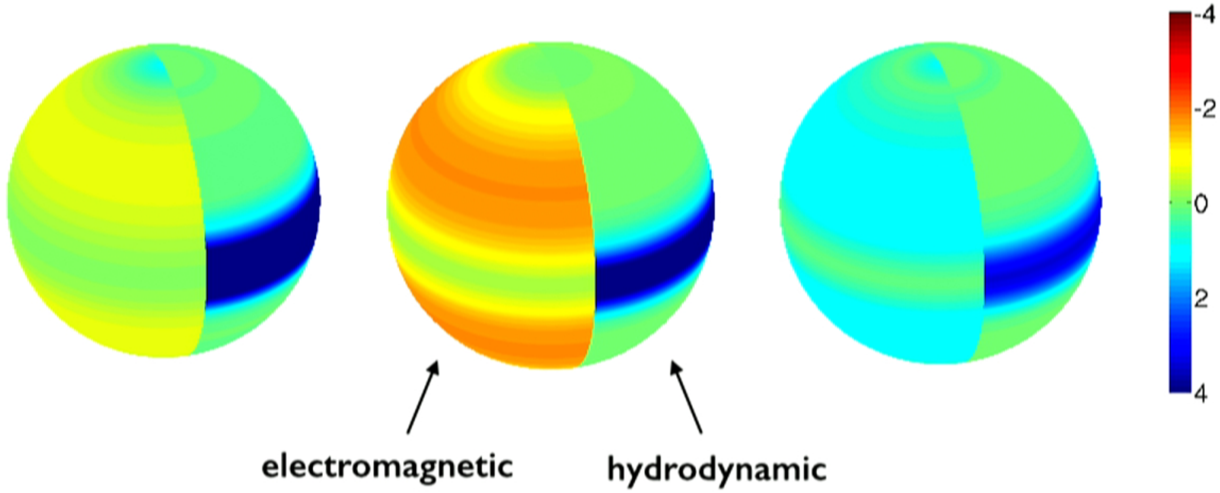
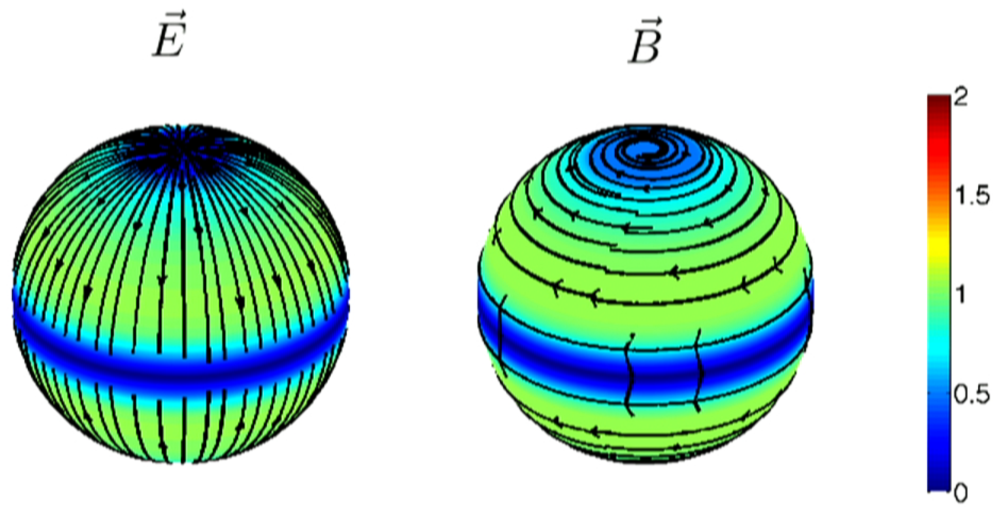


Membrane electric and magnetic fields

RP, Narayan, Sadowski, MNRAS (2013), 436



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Membrane electric and magnetic charges

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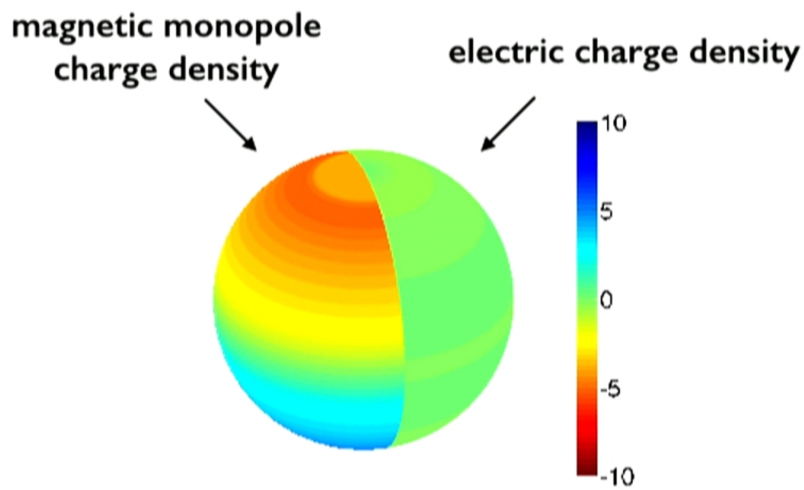
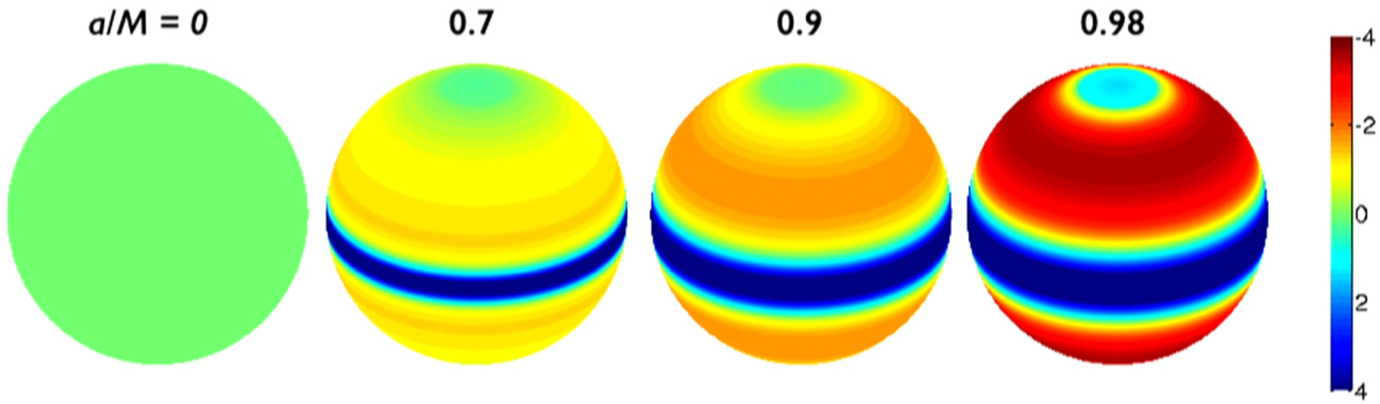


t- and ϕ-averaged GRMHD simulation data ($\Omega_H = 0.34$).

Dependence on spin

RP, Narayan, Sadowski, MNRAS (2013), 436

$$\Omega_H \frac{dJ}{dt}$$



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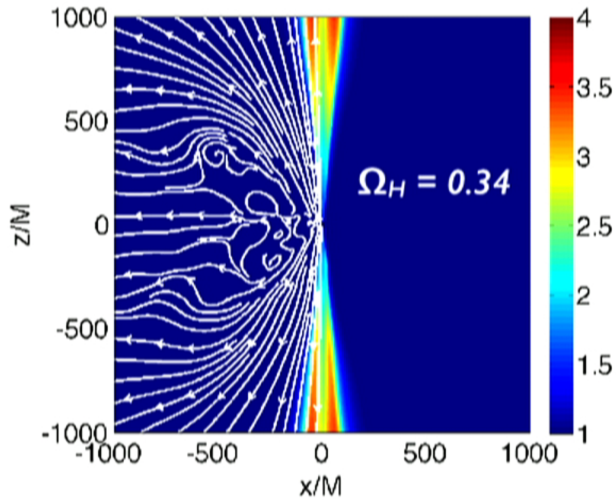
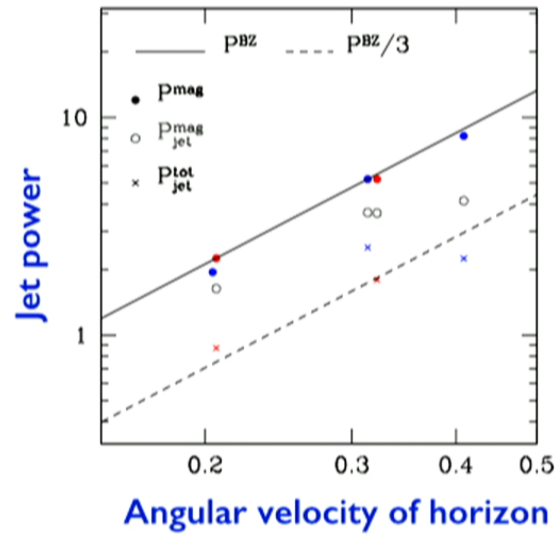
Simulated jets

RP, Narayan, Sadowski, MNRAS (2013), 436

Lorentz factor



Jet power scaling from simulations



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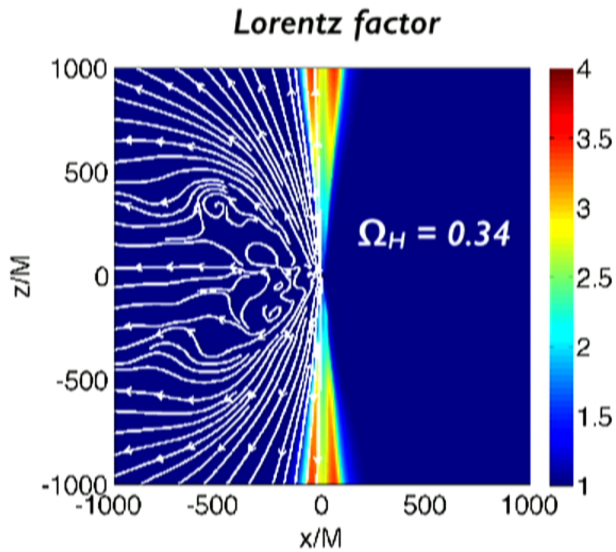
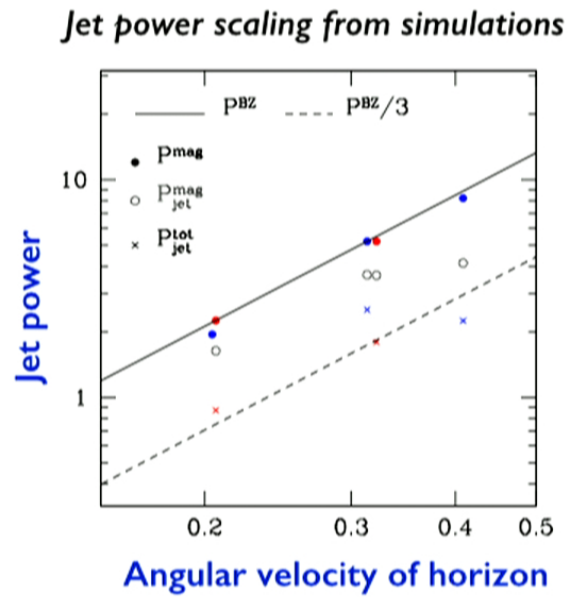
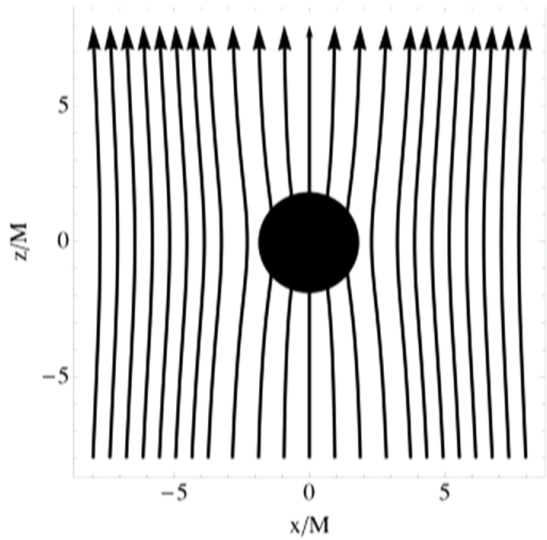




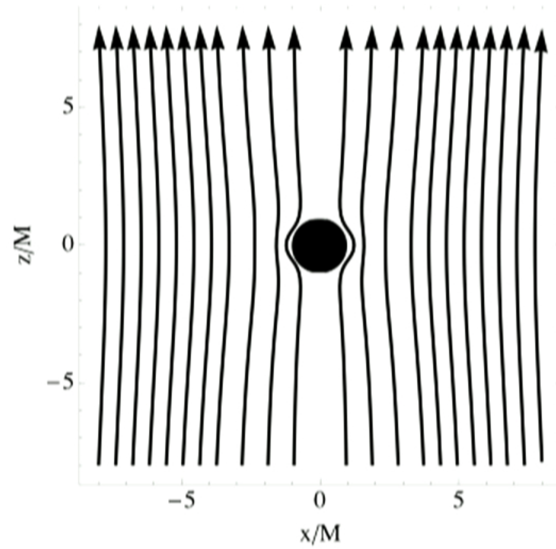
What happens at extremal spin?

King, Lasota, Kundt '75
Bicak, Dvorak '80

Black hole in uniform, vertical magnetic field.



At extremal spin, the field is expelled!

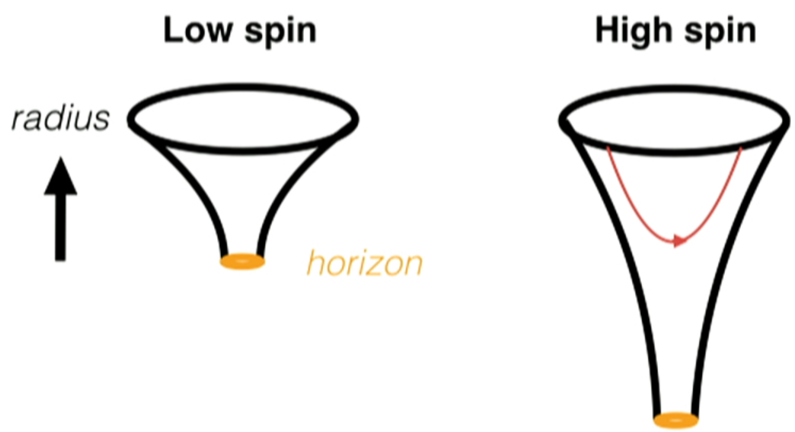


Black hole Meissner effect

RP, Phys.Rev. D90 (2014) 043003,
—, Phys.Rev. D89 (2014) 104057

- What is going on? (Many examples, unifying explanation?)
- Does it kill jets at high spins?

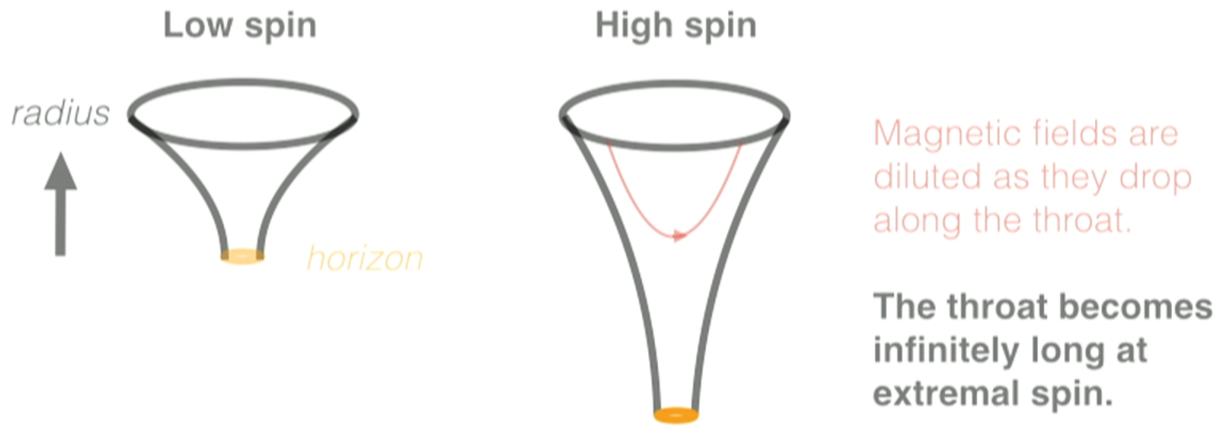
Spinning black holes have long throats



Magnetic fields are diluted as they drop along the throat.

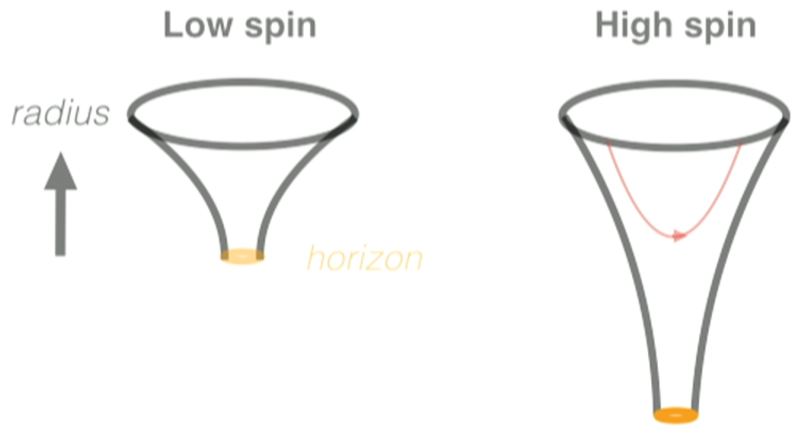
The throat becomes infinitely long at extremal spin.

Spinning black holes have long throats



- The length of the throat is related to entanglement (ER=EPR).
- Relate the black hole Meissner effect to entanglement!

Spinning black holes have long throats



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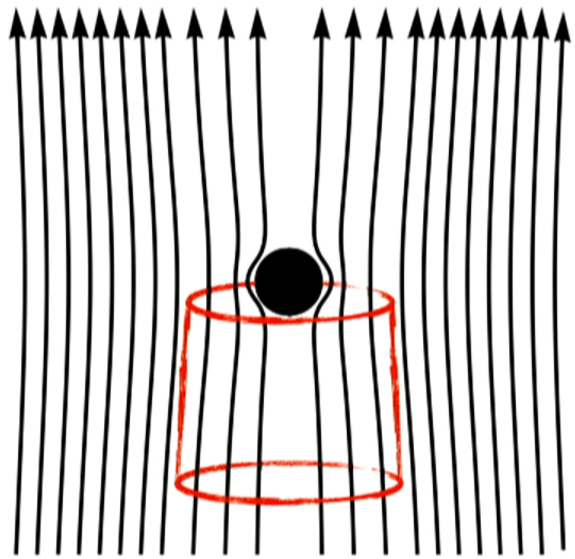
Axisymmetric fields are expelled

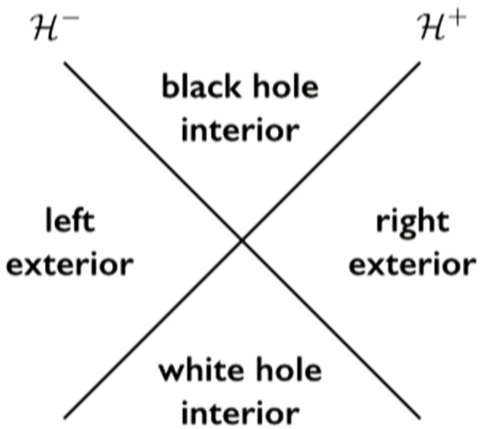


The surface area of the top of the cylinder blows up at extremal spin.

At extremal spin, the field must vanish at the horizon.

Otherwise the flux through the top of the cylinder will be infinite.

Thermofield double state



- Consider a spacetime with double sided Killing horizon in the **thermofield double state**, $|\Psi\rangle$.
- Let $\boldsymbol{\beta}$ be the **inverse temperature**.

Black hole Meissner effect

RP, Phys.Rev. D90 (2014) 043003,
—, Phys.Rev. D89 (2014) 104057

Correlations between **horizon** and **exterior** vanish as $\boldsymbol{\beta \to \infty}$:

$$\Delta_{\mu\nu}(\mathrm{horizon}; x') \equiv \langle \Psi | T A_\mu(\mathrm{horizon}) A_\nu(x') | \Psi \rangle \to 0$$

Black hole Meissner effect

RP, Phys.Rev. D90 (2014) 043003,
—, Phys.Rev. D89 (2014) 104057

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So gauge fields vanish on the the horizon (up to gauge transformations):

$$A_\mu(\text{horizon}) = \int d^3x' \Delta_{\mu\nu}(\text{horizon}; x') j^\nu(x') \to 0$$

currents in the exterior

Black hole Meissner effect

RP, Phys.Rev. D90 (2014) 043003,
—, Phys.Rev. D89 (2014) 104057

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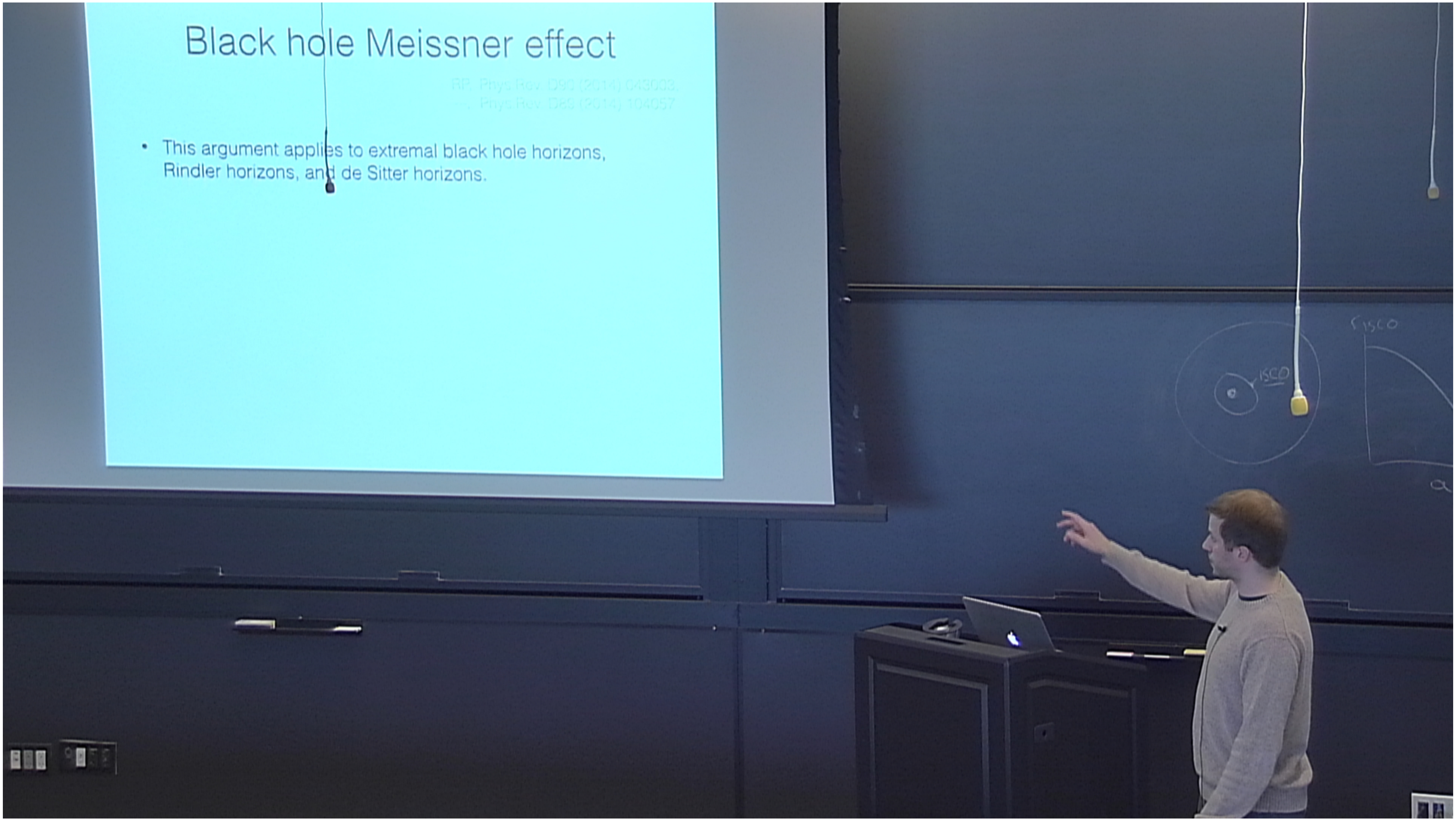
Black hole Meissner effect
RP, Phys.Rev. D90 (2014) 043003;
—, Phys.Rev. D89 (2014) 104057
• This argument applies to extremal black hole horizons, Rindler horizons, and de Sitter horizons.
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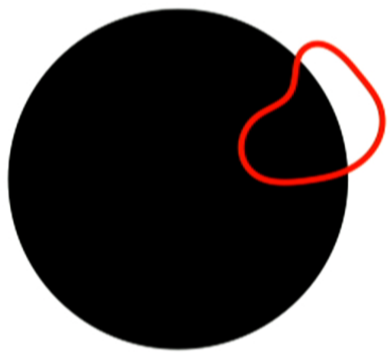
Gauge invariance and membranes

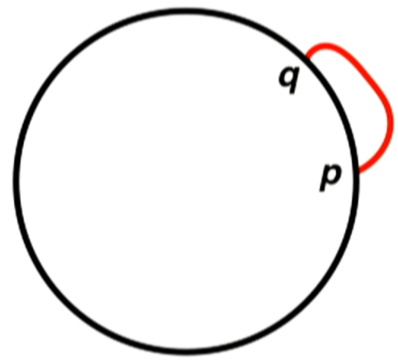
Balachandran, Momen, Chandar '96

- Horizons break gauge invariance in a certain sense:



$$\oint dx^\mu A_\mu$$

Wilson loop (gauge invariant)



$$\int_p^q dx^\mu A_\mu$$

Wilson line (not gauge invariant)

- The membrane paradigm can be defined as "edge states" that are needed to restore gauge invariance.


KdA
α


$T_H dS_H$
$K dA$
α


$T_H dS_H$
κdA
dE
α