Title: Workshop Talk

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Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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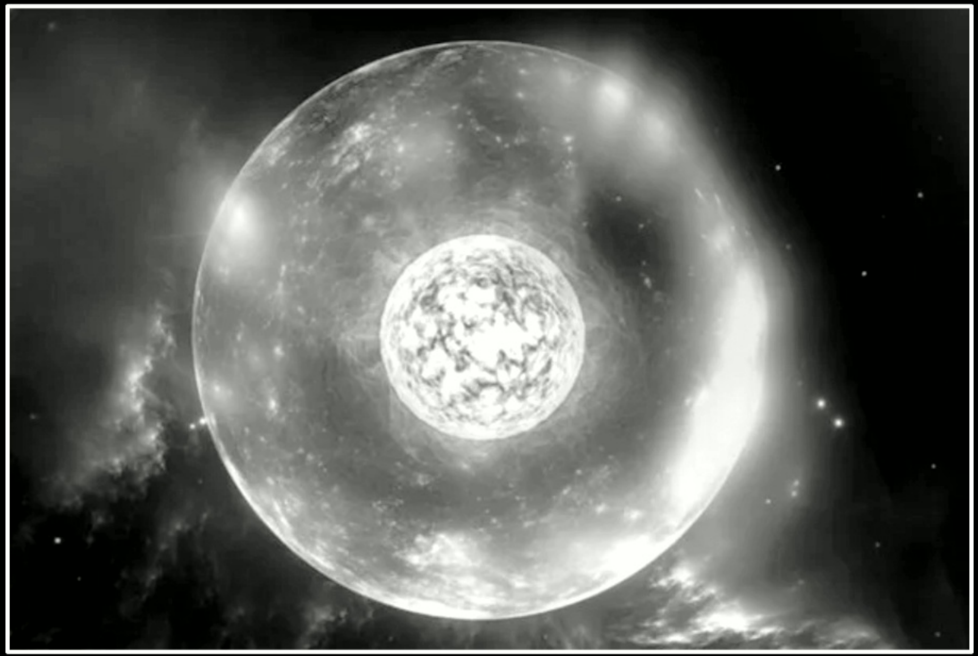
Hot accretion flows onto Neutron Stars

Ab-initio GRMHD simulations

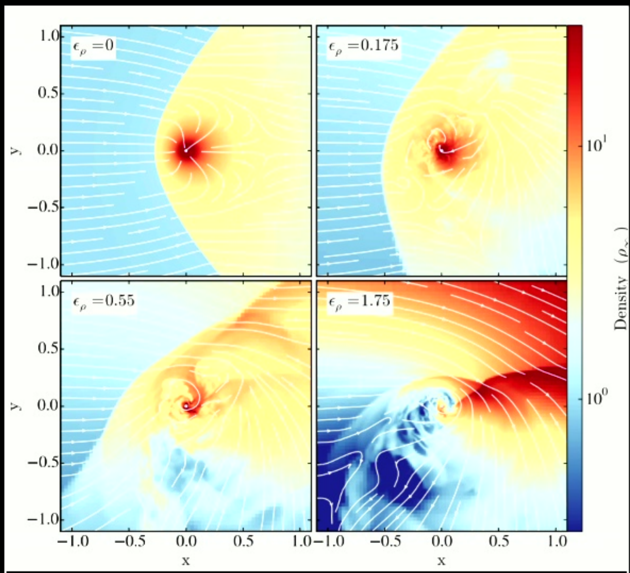


Luciano Combi (Perimeter Institute/CITA NF)
with C. Thompson (CITA), D. Siegel (Greifswald), A. Philippov (Maryland), B. Ripperda (CITA)

PERIMETER INSTITUTE

SCEECS

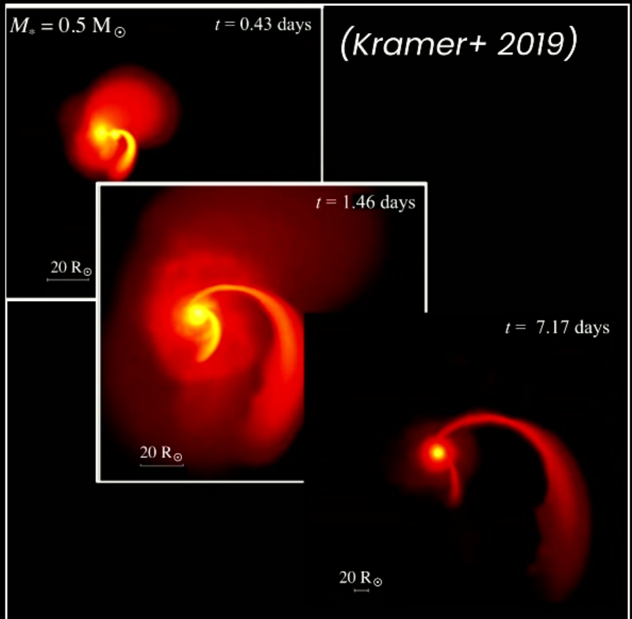
A neutron star may sometimes intercept huge amounts of gas from a non-degenerate star



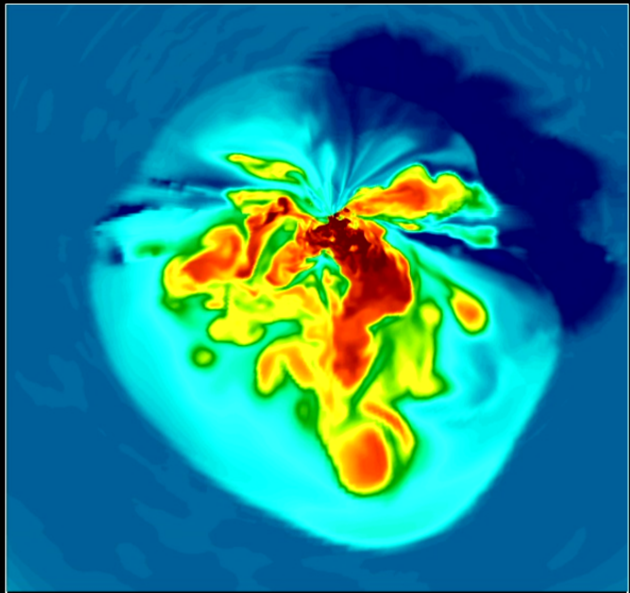
(McLoud&Ruiz 2015)

Common-envelope phase

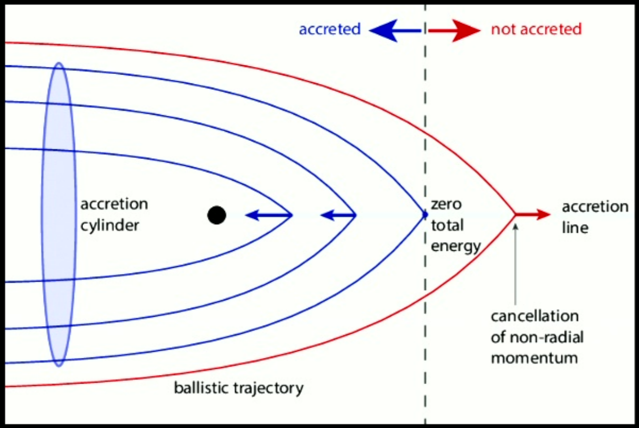
(Kramer+ 2019)



Tidal disruption event



Fallback supernova



Matter is channeled to the NS from the accretion radius.

$$r_{\rm acc} \sim \frac{2GM_{\rm NS}}{v_{\rm NS}^2} \sim 10^{11} v_{\rm NS,7.5}^{-2} {\rm cm} \sim 10^5 v_{\rm NS,7.5}^{-2} r_\star$$

Densities could be so high that photons remain trapped and advected with the flow

$$r_{\rm tr} = \frac{\dot{M}\kappa}{4\pi c} = 3.4 \times 10^{13} \left(\frac{\dot{M}}{M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{\kappa}{0.2\ {\rm cm}^2\ {\rm g}^{-1}}\right)\ {\rm cm}$$

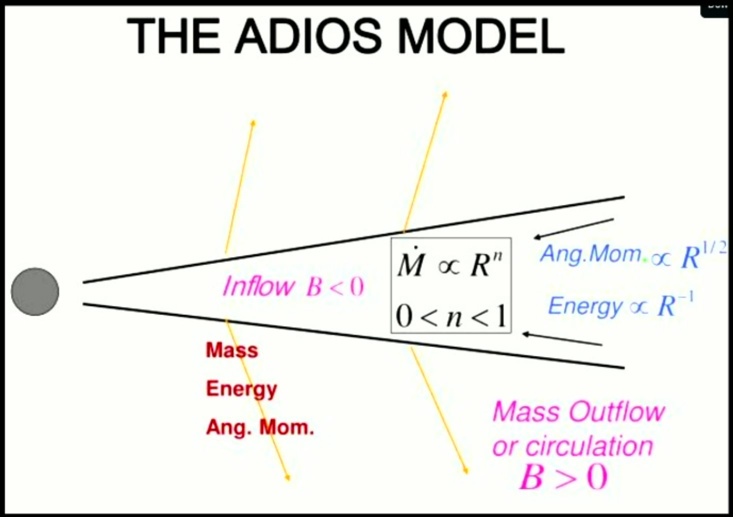
$$\dot{M}(r_{\rm acc}) \gtrsim 100\ M_\odot {\rm yr}^{-1}$$

Enormous accretion rates beyond the Eddington limit!
is it then easy to form black holes in this way? (Brown&Bethe 1998)

Not so fast: <u>hot flows with angular momentum</u> can very easily launch winds. Little mass ends up near the NS.

Energy outward transport mediated by torques unbinds gas unless radiation efficiency is high.

$$(\text{Torques}) \times \Omega = B_e \times \dot{M}$$



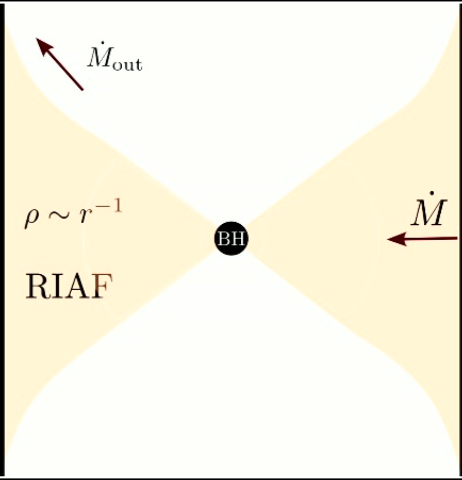
(Blandford&Begelman + 1999)

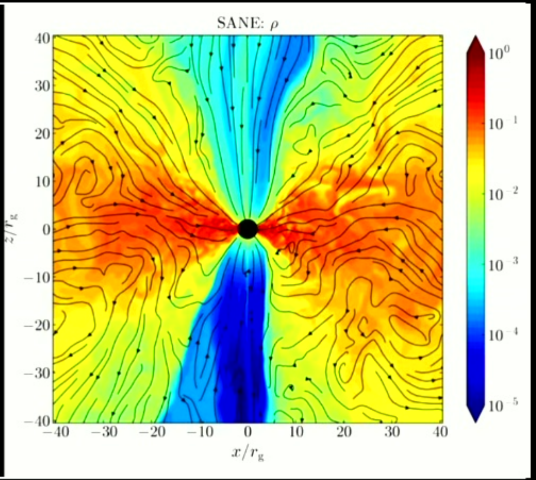
Hot accretion flow models show that mass accretion is inefficient:

$$\dot{M} \propto r^s, \quad s \sim 0.0 - 1.0$$

In a hot flow, a black hole will absorb all energy advected onto the horizon.

(Chaterjee+ 2022)





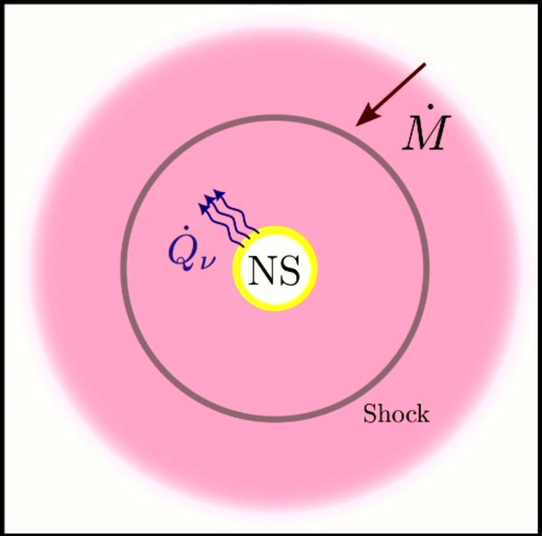
A neutron star is very different: gravitational energy must be released to allow gas to settle onto its solid surface.

Neutrinos are needed

The flow must build up large pressures to ignite weak interactions.

$$K_\nu^{\rm cap}\rho T^6 + K_\nu^{\rm ann} T^9 \ (e^\pm \text{ capture} + e^\pm \text{ annihilation})$$

Early models by Chevalier and others show that neutrinos are efficient for radial flows; a shock-front that stalls the infalling gas forms.



Hypercritical accretion onto a neutron star

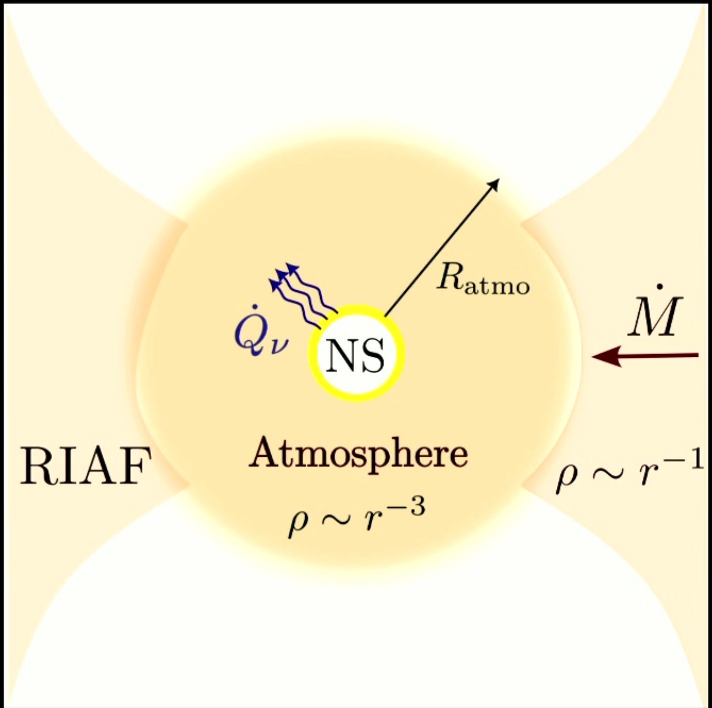
If no energy is released, a hydrostatic isentropic atmosphere must form around the NS

Such hydrostatic atmosphere has a density cusp compared to the softer RIAF profile. Neutrino cooling is thus greatly enhanced

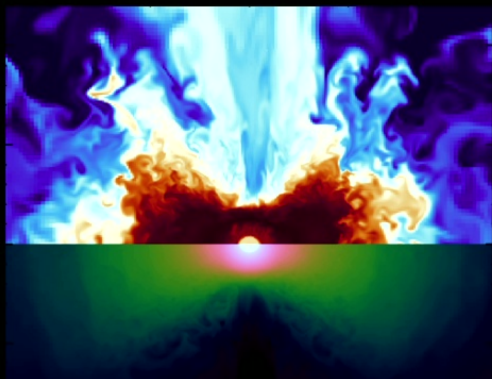
We can build a simple model matching the outer RIAF with the hydrostatic atmosphere and balancing neutrino cooling and accretion power on the surface.

$$\frac{R_{\rm atm}}{R_{\rm NS}} = 73\,\alpha_{-1} R_{0,10}^{2/3} \left(\frac{M_0}{10^{-2}\,M_\odot}\right)^{-1/3}; \qquad (3)$$

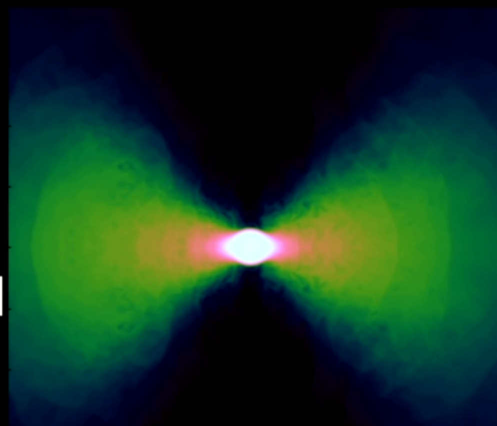
$$\dot{M}_{\rm atm} = 6\times 10^{-7}\,\alpha_{-1}^{10/9}\,R_{0,10}^{-5/3}\left(\frac{M_0}{10^{-2}\,M_\odot}\right)^{5/6} M_\odot\ {\rm s}^{-1}. \qquad (4)$$



Notice this is different when matter is assembled close to the NS.

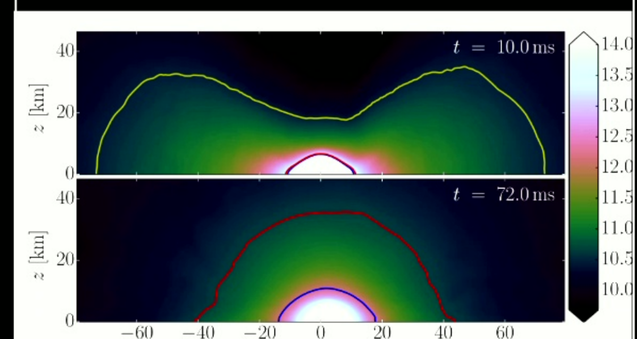


Core-collapse or accretion-induced collapse



Binary mergers

Even here, neutrinos are essential to accrete. If not included in the model, matter piles up as seen in simulations without cooling (e.g. Ciolfi+2017)



Enormous accretion rates near the star are possible in these scenarios.

$$\dot{M} \sim 1\, M_{\odot}\, s^{-1} \sim 10^{16}\, M_{\rm Edd}$$

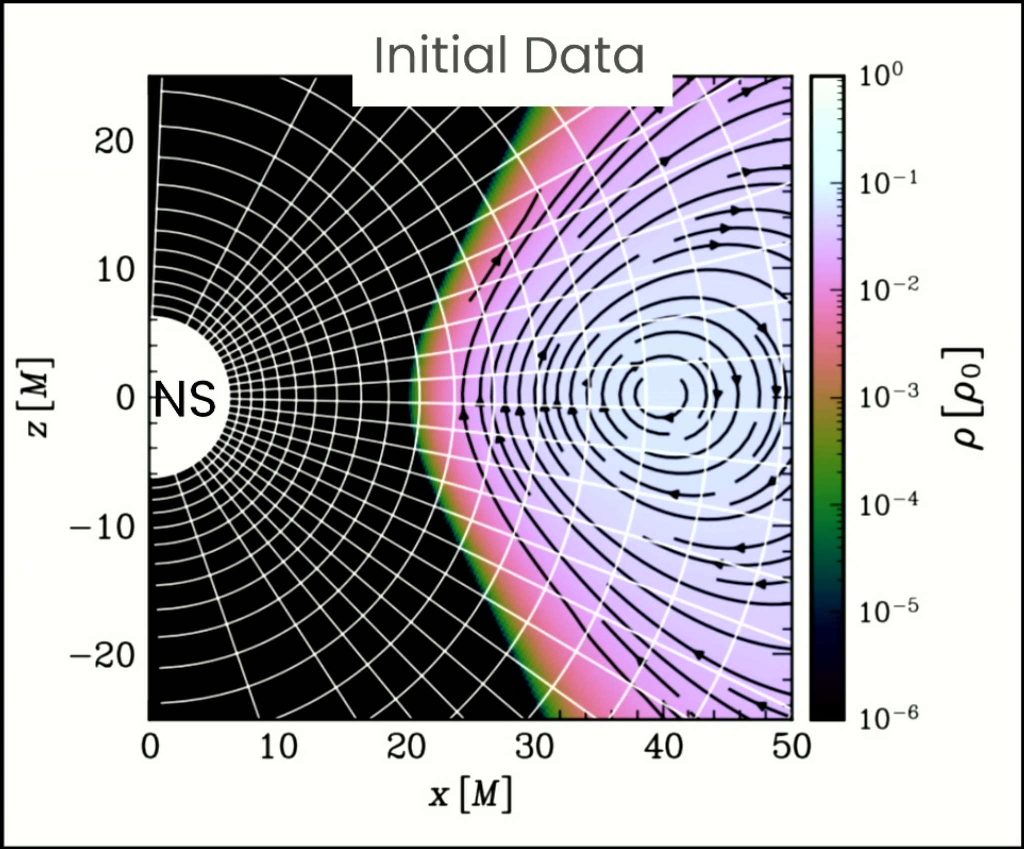
Open questions

How much gas and angular momentum manages to be accreted onto the NS in a photon-trapped flow?
What is the impact of magnetic fields? What are the outflows?

We perform new general relativistic magnetohydrodynamic simulations of RIAFS onto non-magnetized neutron stars

LC, C. Thompson, D. Siegel, A. Philippov, B. Ripperda (2025, in prep)

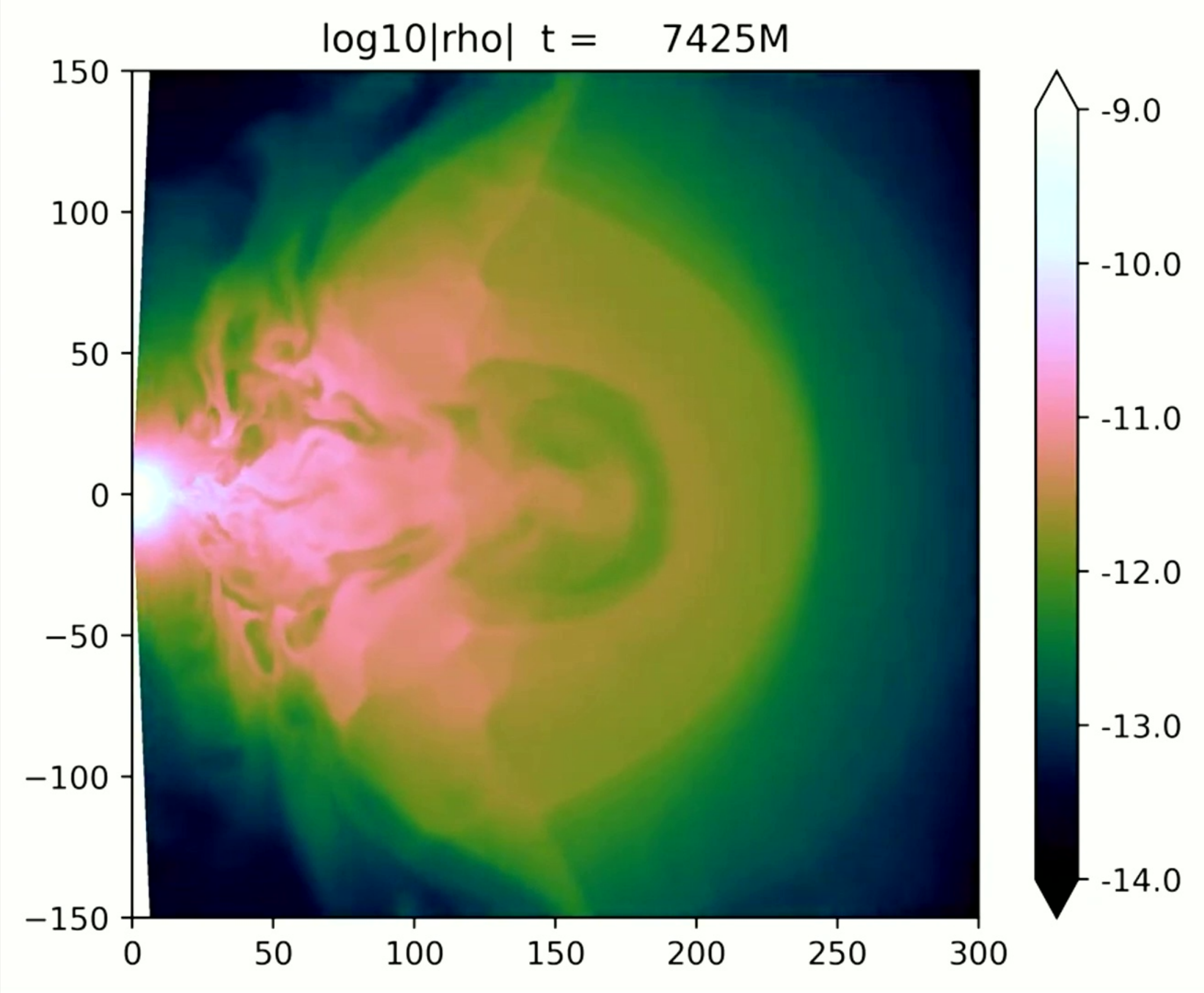
We evolve a magnetized accreting torus with a neutron star as boundary condition.



- We evolve the ideal GRMHD equations with the code Harm3D in a fixed Schwarzschild background and spherical coordinates.
- Inner boundary conditions are fixed by using a non-rotating TOV solution. Density contrast is 6 orders of magnitude with respect to disk.
- We evolve a set of simulations:
  - Adiabatic
  - With optically-thin neutrino cooling.
  - With a larger magnetic field reservoir.

$$\nabla_a T^{ab} = -Q u^b,$$

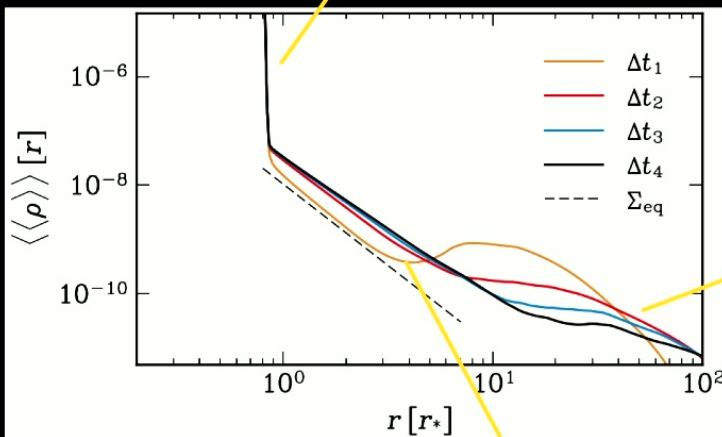
$$Q = A\rho p^{3/2},$$



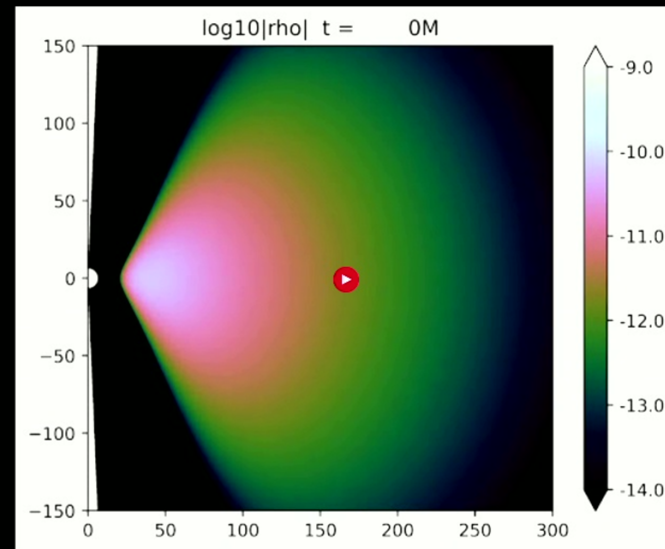
log10|rho| t = 7425M
150
100
50
0
−50
−100
−150
0
50
100
150
200
250
300
-9.0
-10.0
-11.0
-12.0
-13.0
-14.0

Adiabatic accretion flow onto a NS

NS surface.

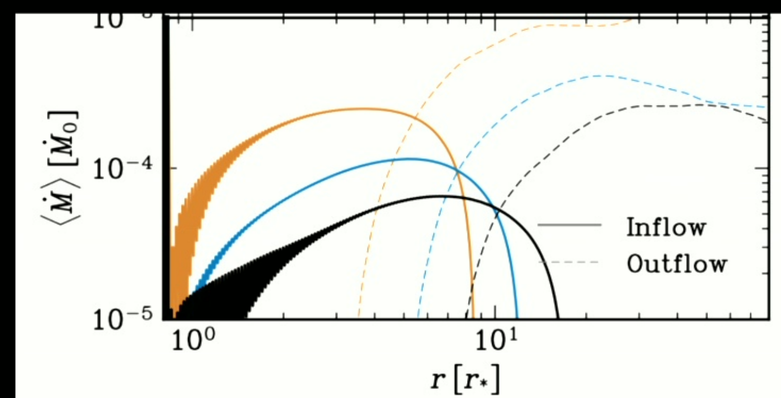


RIAF

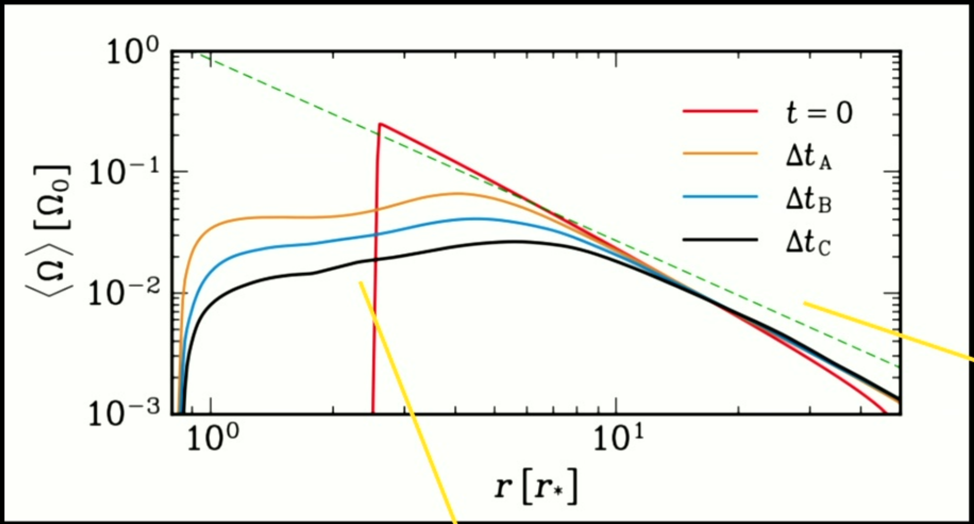


Nearly hydrostatic atmosphere

A growing, nearly-hydrostatic atmosphere forms around the NS. Pressure forces slow down the incoming gas and the accretion rate drops:
no inflow equilibrium.



Angular velocity flattens in the atmosphere



If angular velocity is reduced in this way, angular momentum transferred to the star might be quite smaller than a naive application of RIAF.

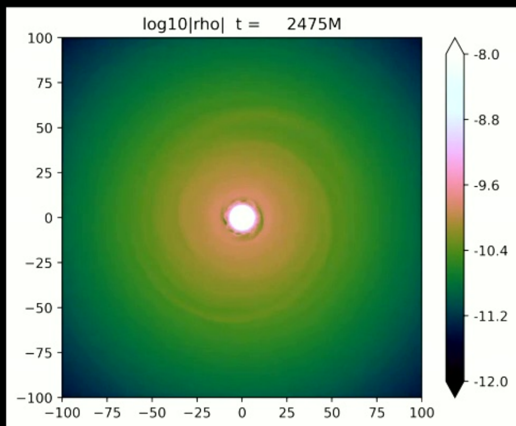
Keplerian-like profile

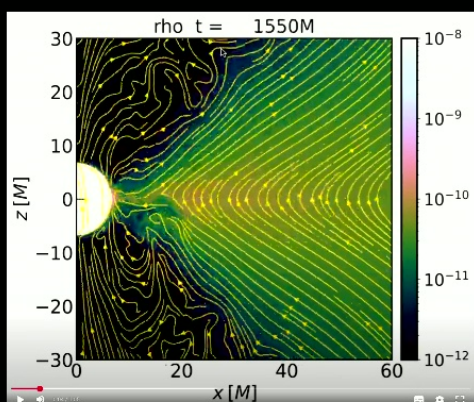
The rotation of the atmosphere is roughly constant and matches the Keplerian angular velocity of the atmosphere radius

$$T ds/dr = \Omega r^3 d\Omega/dr$$

Formation of an angular momentum "belt" has also been found in other local MHD boundary layer simulations (e.g. M. A. Belyaev and E. Quataert 2018)

Can strong magnetic fields disrupt the atmosphere?

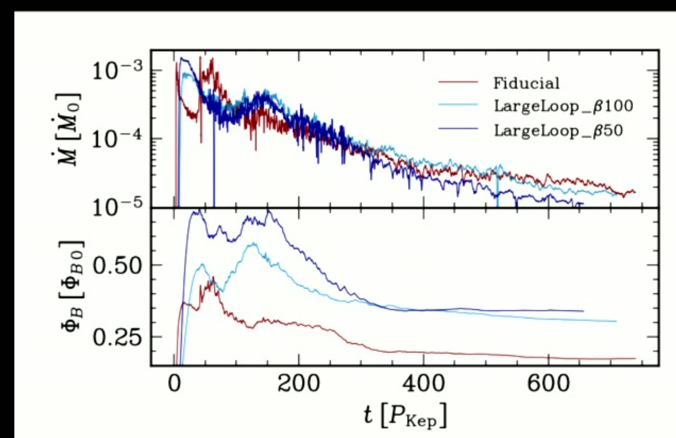




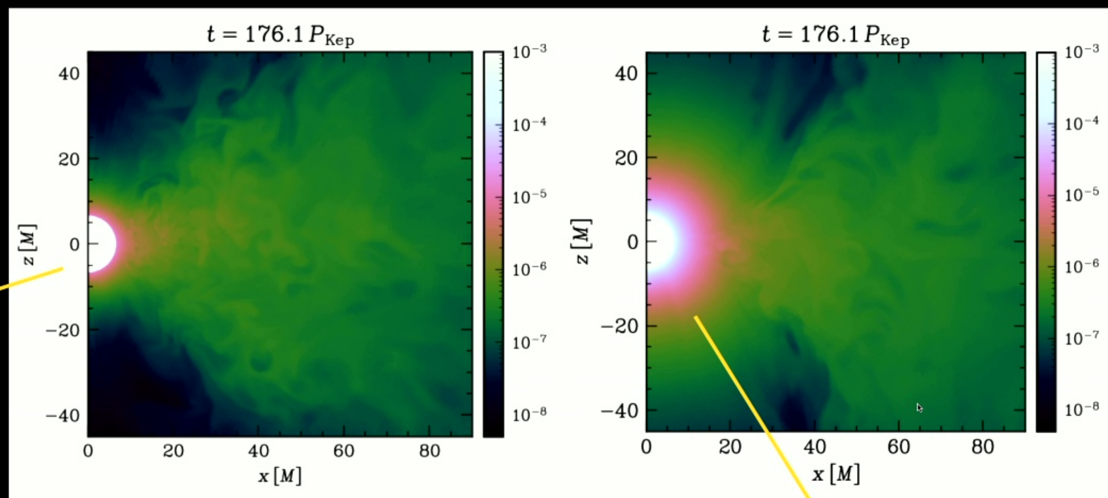
Saturation of magnetic flux near the star produces eruption of flux tubes similar to BHs.

However, the atmosphere grows and is efficient in trapping the flux.

Eruptions eventually stop and flux is stored in there



We now compare strong and weak neutrino cooling



When cooling is very strong, no envelope is formed around the NS.

For weaker cooling, an adiabatic atmosphere grows until cooling becomes efficient.

Take aways

1. Neutron stars can intercept huge amounts of mass from a less evolved star and accrete at hypercritical Eddington rates, where the photons are trapped and advected with the flow.

2. These accretion flows are very inefficient and only a portion of the mass will reach the NS surface.

3. Because energy cannot be absorbed as in a BH, a hydrostatic atmosphere will form until neutrino cooling becomes efficient.

4. We perform GRMHD simulations with neutrino cooling of non-rotating unmagnetized NSs to show how angular momentum and magnetic field are transported in the system

5. We show self-consistently that a hydrostatic, slow-rotating atmosphere forms. The atmosphere can trap magnetic flux and also produce a Poynting flux. The system is very far from a naive application of a RIAF onto NSs.