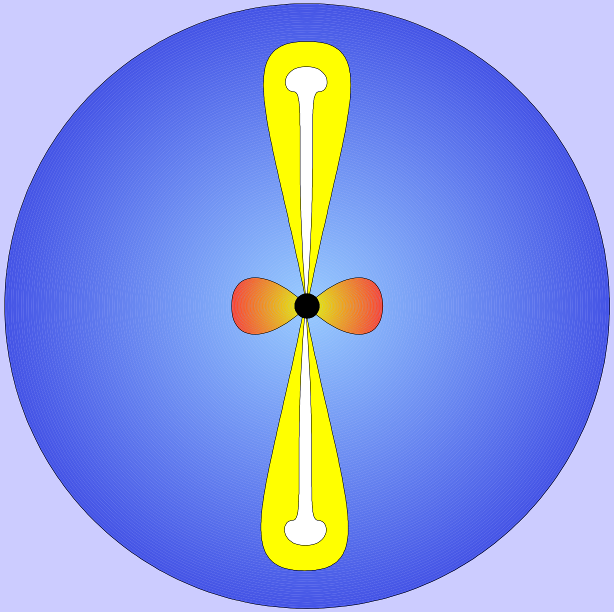
# The Collapsar model

Karsten Kretschmer

How to get two highly collimated relativistic jets from the collapse of a massive star

# Very rough overview

- The core of a rotating massive star collapses to a black hole.
- Material far from the axis does not fall straight in, but forms an accretion disk first.
- Dissipative effects in the disk convert kinetic energy into heat.
- Energy deposited over the poles of the disk powers jets.

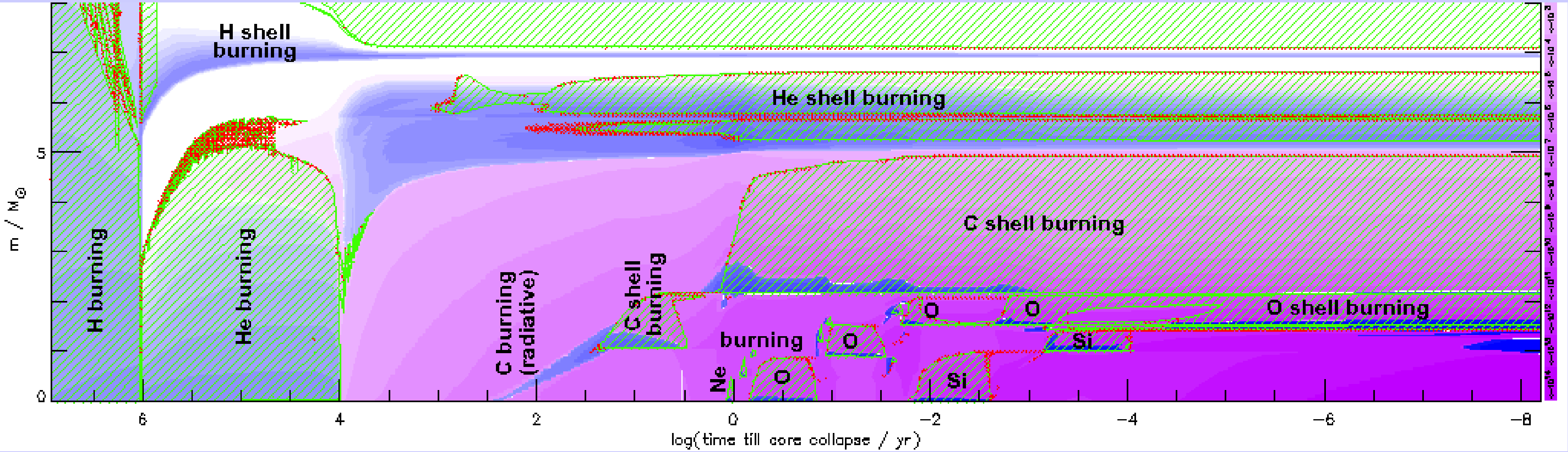


# The progenitor star

- Mass: $> 30\ M_\odot$
  - Lifetime: 4 – 7 million years
  - It will lose its hydrogen envelope through stellar winds, forming a Wolf-Rayet star, ≈ 300000 km in radius
  - Helium core $> 12\ M_\odot$
  - Iron core $> 2\ M_\odot$
- Rapidly rotating, ≈ 200 km/s at the surface

# Initial collapse

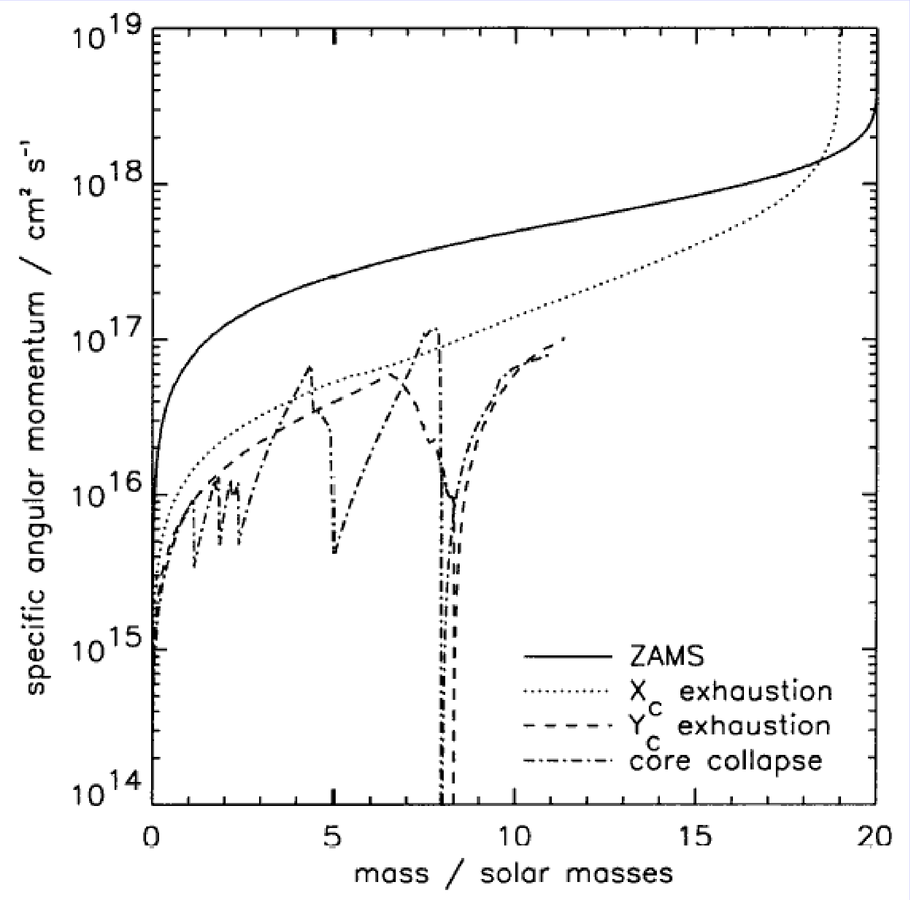
- After burning Si → Fe, the core has no nuclear energy source.
- Energy loss (by neutrino emission) leads to contraction and heating (Virial theorem).
- When T is high enough to photodissociate nuclei (endothermically), or the density is so high that the Fermi energy allows electron capture, the core becomes unstable and collapses.
- If the mass of the collapsed core is too high to form a stable neutron star (~3 $M_\odot$), a black hole will form.



A. Heger

# Accretion disk formation

- Matter further outside rotates too fast to fall directly into the hole.
- A 3 $M_\odot$ black hole has a last stable orbit with a radius between about 8 and 27 km (depending on rotation)
- If the angular momentum is larger than the orbital angular momentum at this radius, the material will orbit.
- Typical values:
  $2.5 – 4.5 \cdot 10^{16}$ $\mathrm{cm^2\ s^{-1}\ g^{-1}}$
- Problem: Current calculations still predict ×10 higher angular momentum of the core than what is observed for young pulsars. Transport of angular momentum is not yet fully understood.



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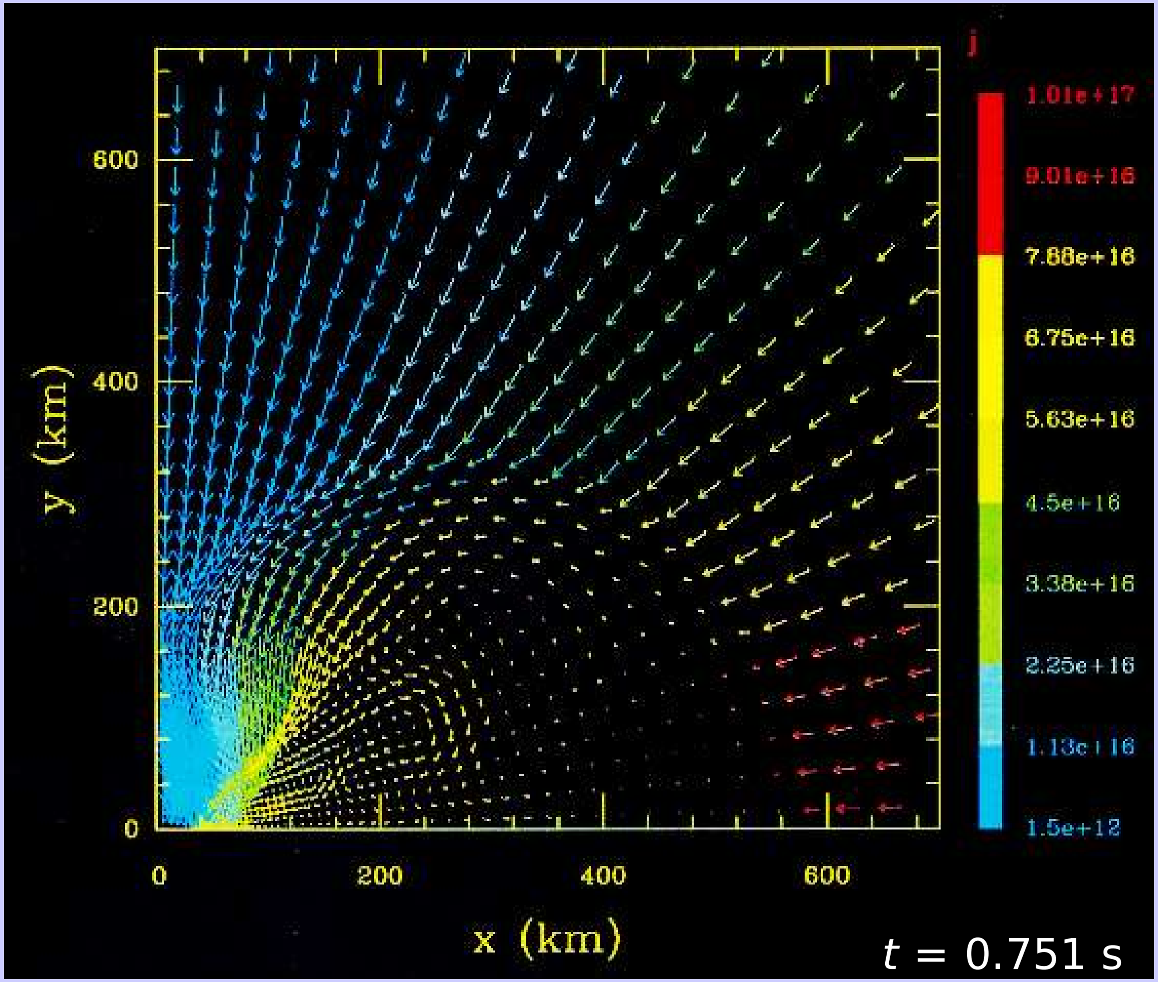
# Accretion through a disk

- Matter in an accretion disk is in orbit. To fall into the black hole, it must lose angular momentum.
- An accretion disk has *differential rotation.* Viscosity transfers angular momentum from the faster-rotating inner parts of the disk to the slower-rotating outer parts.
- Viscosity converts kinetic energy to heat or momentum (via MHD).
- The amount of viscosity determines the speed of angular momentum transfer.



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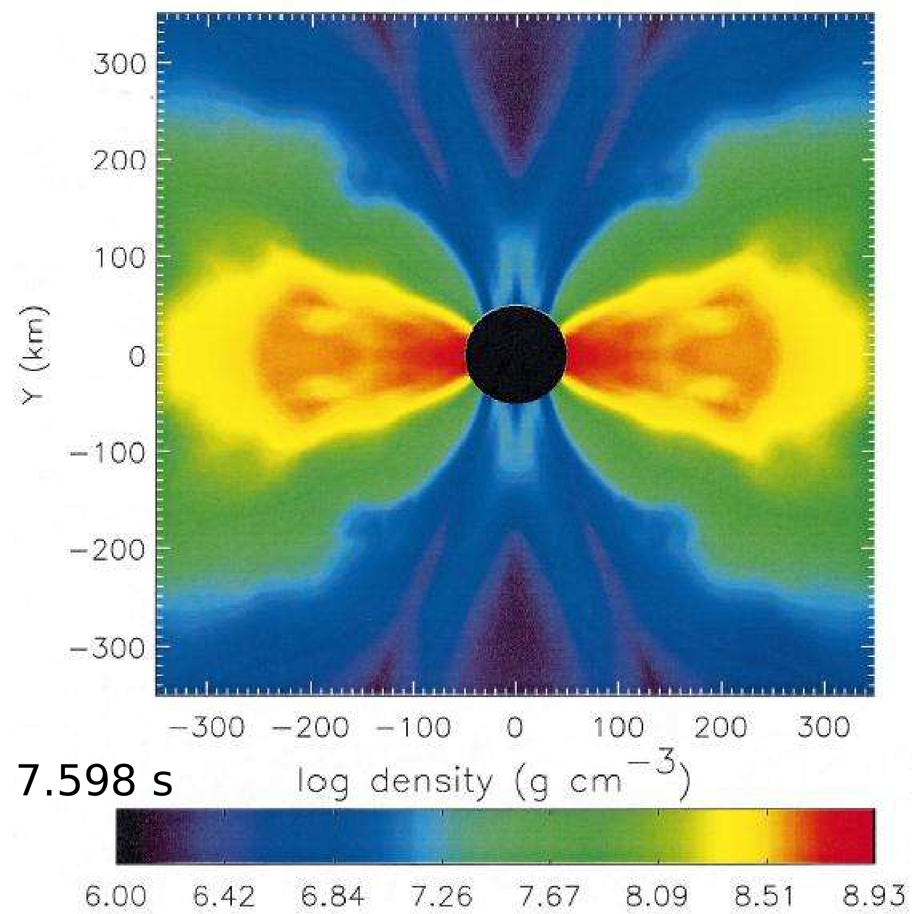
# Disk structure

- Matter collects in an equatorial disk. The space over the poles is evacuated by infall.



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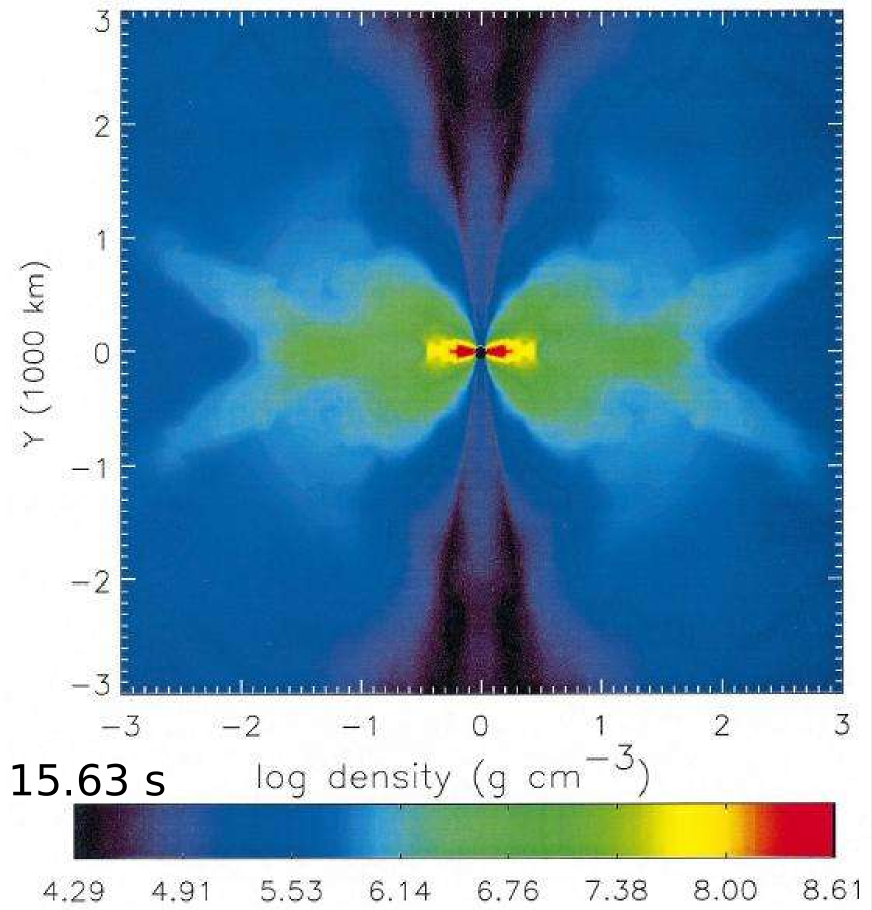

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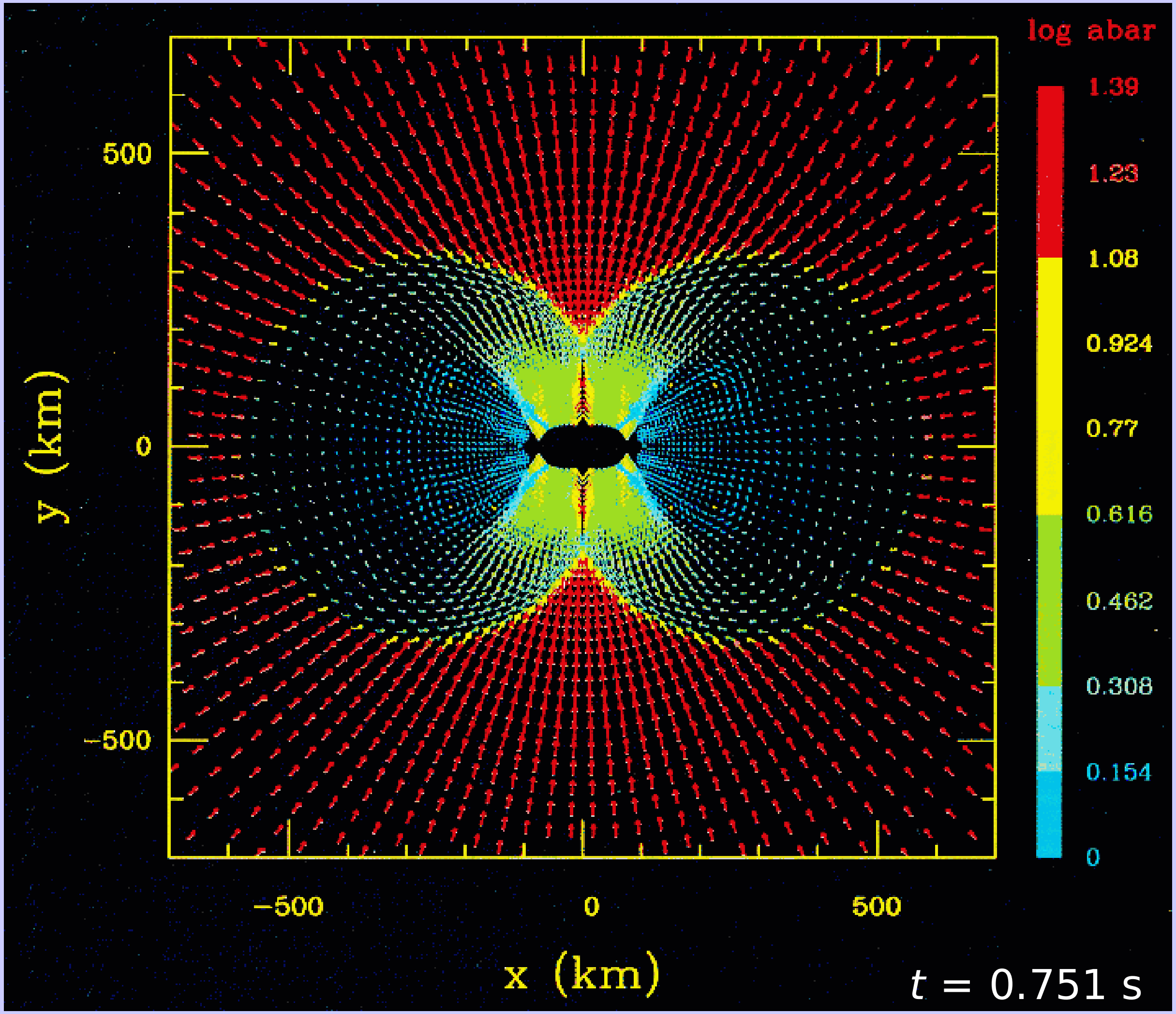
# Composition of the disk

- Matter in the inner accretion disk reaches temperatures on the order of $10^{10}$ K.
- In these conditions, nuclei are dissociated into free nucleons.

Si core

nucleons



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# Neutrino emission

- The dense matter in the stellar interior is opaque to photons.
- Energy can either be:
  - advected (transported with the gas flow) into the black hole, or
  - radiated by neutrino emission.
- Neutrino emission is sensitive to temperature and density. It occurs mainly inside of $\approx 100$ km.
- pair-annihiliation:
  $\mathrm{e}^- + \mathrm{e}^+ \rightarrow \mathrm{Z}^0 \rightarrow \nu_\mathrm{e} + \bar{\nu}_\mathrm{e}$

$$\dot{q}_{\nu,\bar{\nu}} \approx 5 \cdot 10^{33}\, T_{11}^{9}\, \mathrm{erg\,cm}^{-3}\,\mathrm{s}^{-1}$$

- pair capture on nucleons:
  $\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}, \quad \mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{n} + \nu_\mathrm{e}$

$$\dot{q}_{eN} \approx 9 \cdot 10^{33}\, \rho_{10}\, T_{11}^{6}\, X_\mathrm{nuc}\, \mathrm{erg\,cm}^{-3}\,\mathrm{s}^{-1}$$

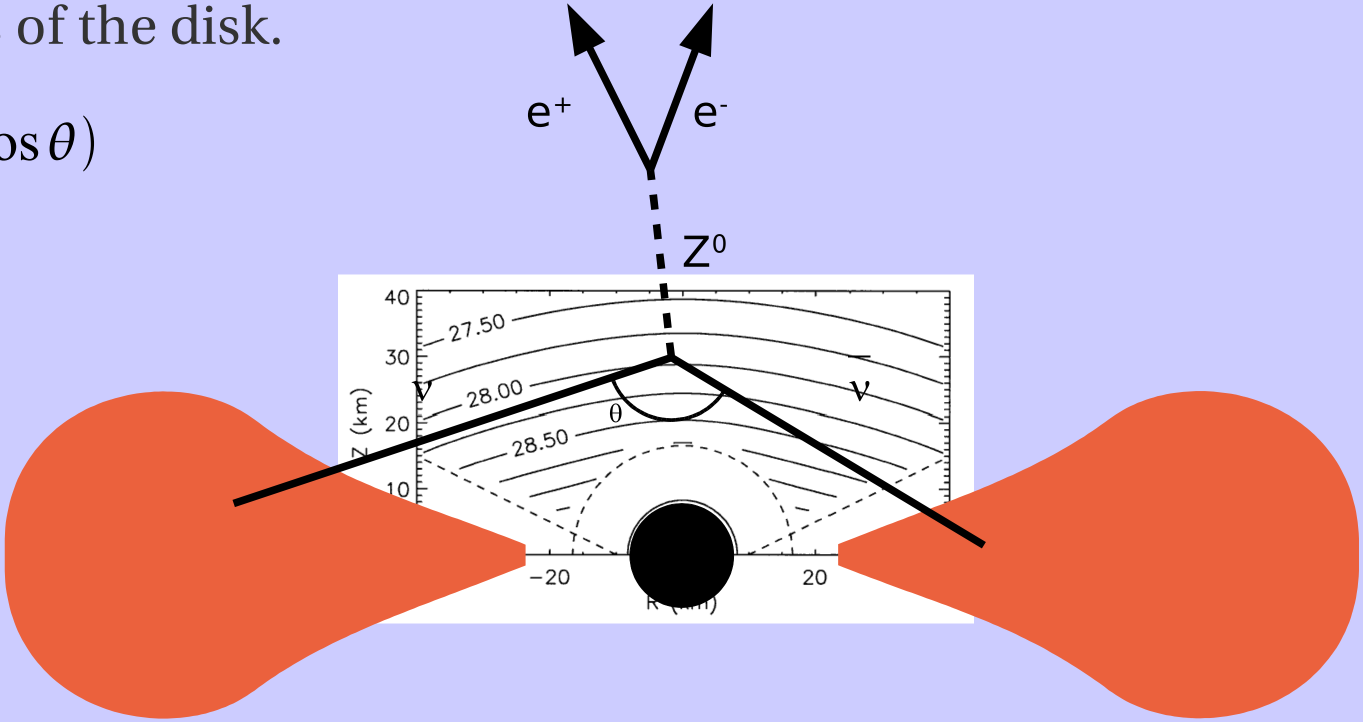
$$T_{11} = \frac{T}{10^{11}\,\mathrm{K}}, \quad \rho_{10} = \frac{\rho}{10^{10}\,\mathrm{g\,cm}^{-3}}$$

$X_\mathrm{nuc}$ = mass fraction of free nucleons

# Neutrino annihilation

- For center-of-mass energies below the mass of the exchange bosons of the weak interaction, $\mathcal{O}(100\ \text{GeV})$, neutrino cross sections rise with energy.
- For a ν pair with given energy, the cms energy is maximal for a head-on collision, so neutrino-antineutrino pairs annihilate preferentially over the poles of the disk.

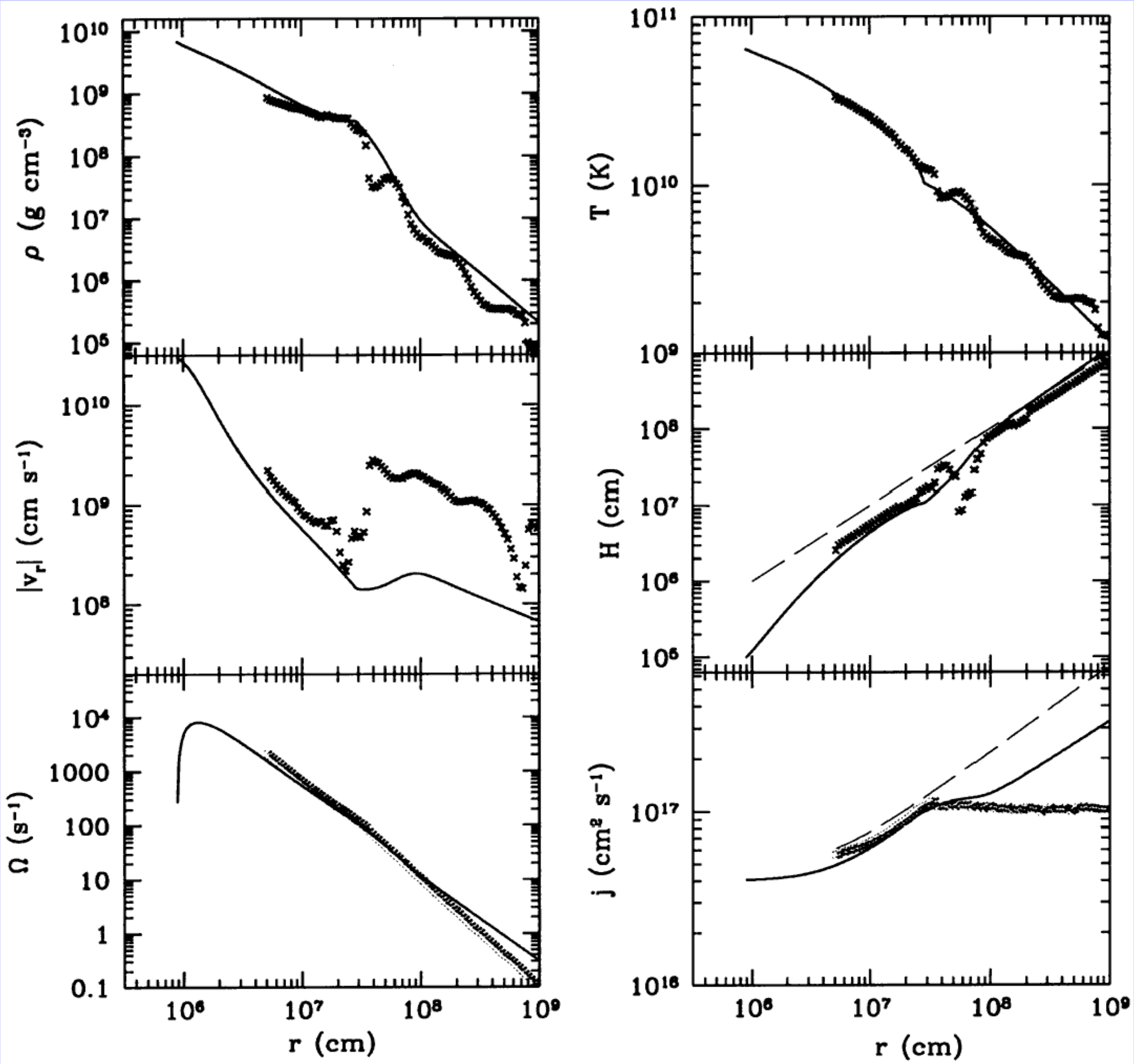
$$Q_{\nu\bar{\nu}} \propto (1-\cos\theta)$$



# Numerical / semianalytic

- For technical reasons, the numerical simulation could only be done for  50 km from the black hole.
- A semianalytic solution was used for the inner part if the accretion disk (PWF99)

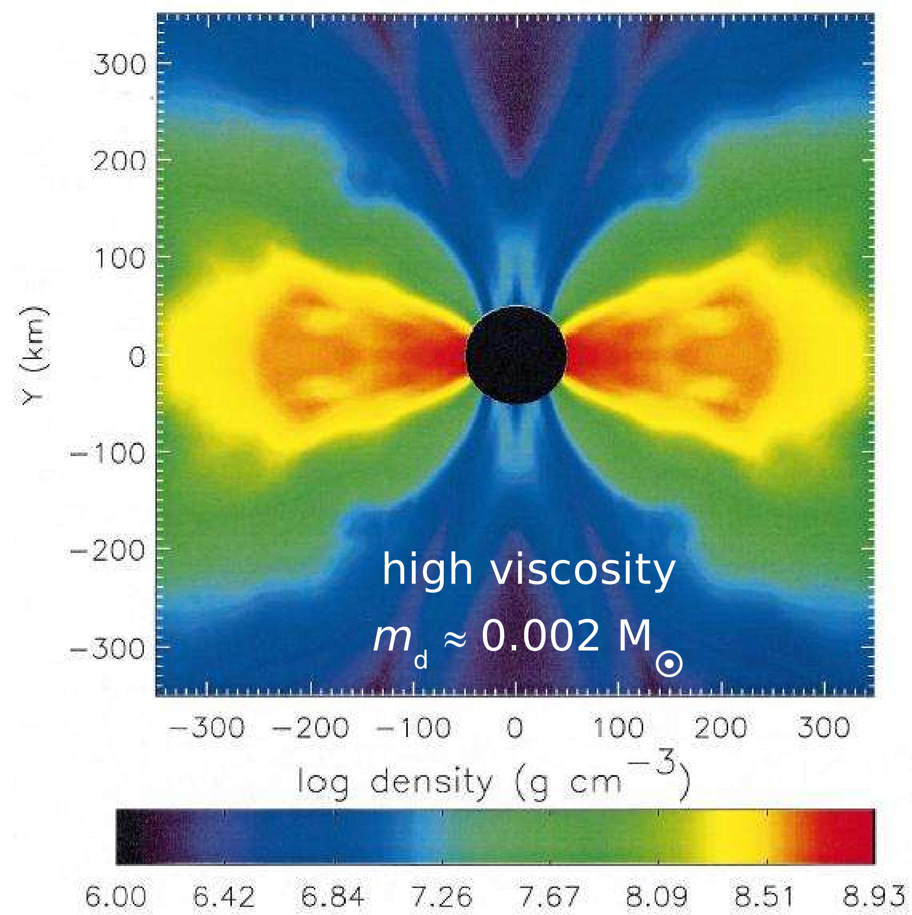
(diagrams show values in the equatorial plane)



PWF99

# Viscosity

- The mechanism providing disk viscosity and its strength is unknown and has to be parameterized.
- Varying viscosity influences disk mass, thickness, density, variability, …



high viscosity

$m_d \approx 0.002\ M_\odot$

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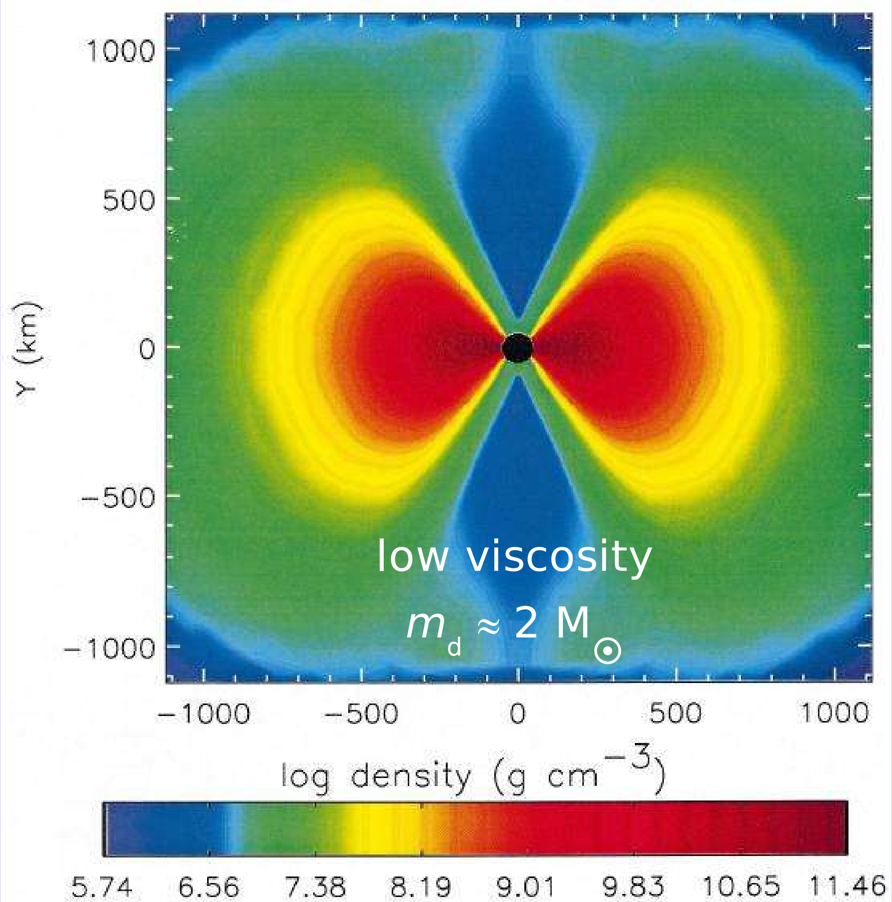

low viscosity

$m_d \approx 2\ M_\odot$

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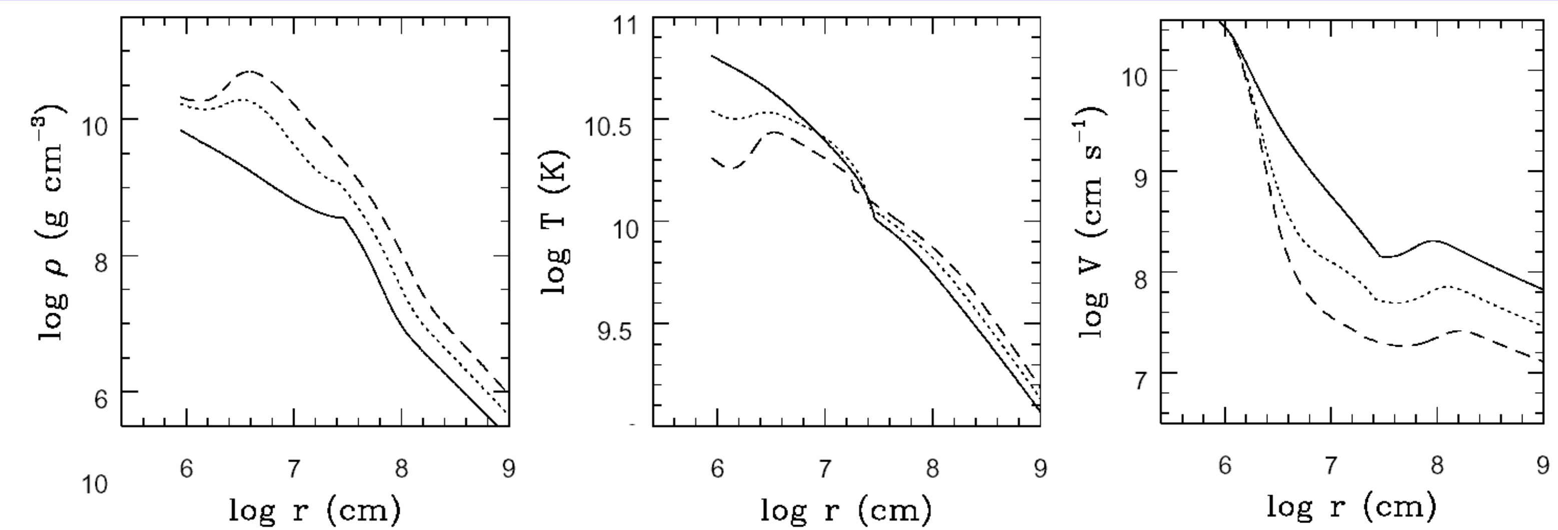
# Varying viscosity

- Density, temperature and radial velocity of the semianalytic disk approximation (PWF99) for three different values of the viscosity parameter: $\alpha = 0.1$ (solid), 0.03 (dotted), 0.01 (dashed)
- The lower the viscosity, the more orbits are required for a given energy loss, giving lower radial velocities.
- The higher the density gives the same accretion rate despite the lower radial velovity.
- The higher density favours neutrino cooling, lowering the temperature

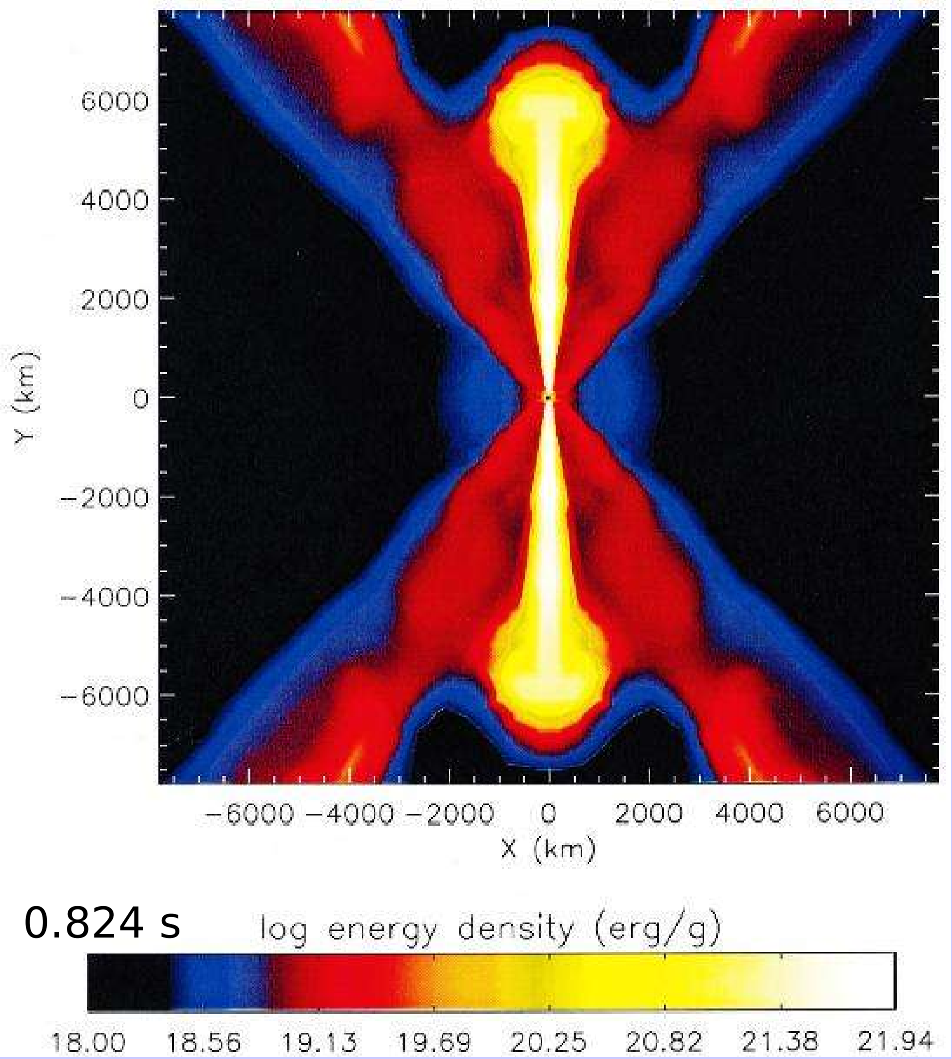


PWF99

# Jet formation

- Neutrino annihilation or other mechanisms can deposit energy over the disk poles.
- Because matter falls inward above the poles, there is a delay before energy deposition can overcome the declining ram pressure of infalling matter (≈ 7 s).
- The heated matter expands im the region of lowest resistance: along the axis.
- The energy density in the jet is larger than the mass density $(3 \cdot 10^{10}\ \mathrm{cm/s})^2 = 9 \cdot 10^{20}\ \mathrm{erg/g}$

$\Rightarrow$ The jet is relativistic.



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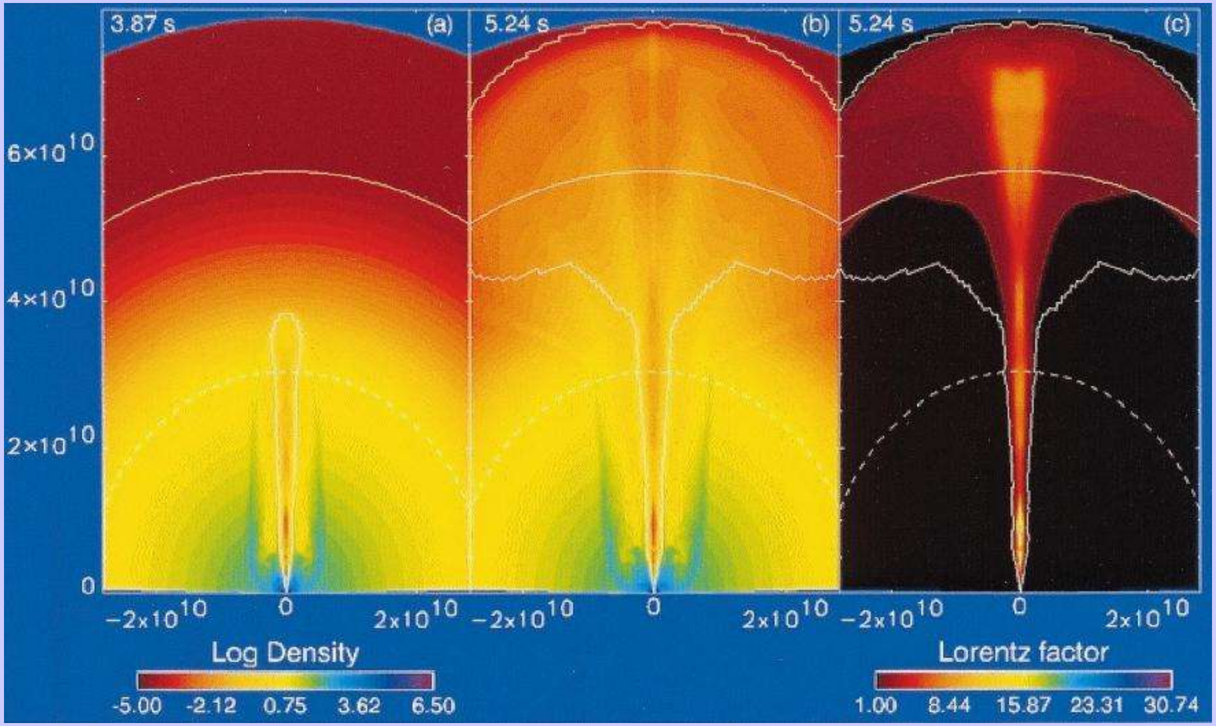
# Jet propagation

- The jet propagates along the star's axis.
- Within the star, the jet is at first confined by the density gradient left by the initial collapse, then by a self-created gradient (< 5° half-angle).
- Expansion converts internal energy (heat) into kinetic energy.
- Shocks from interaction with the stellar mantle convert kinetic energy into internal energy.
- ⇒ It probably makes little difference if the initial energy input is in the form of heat or momentum (neutrino heating vs. MHD effects).

Jet prop. movie
(Weiqun Zhang)

Jet breakout movie
(Weiqun Zhang)

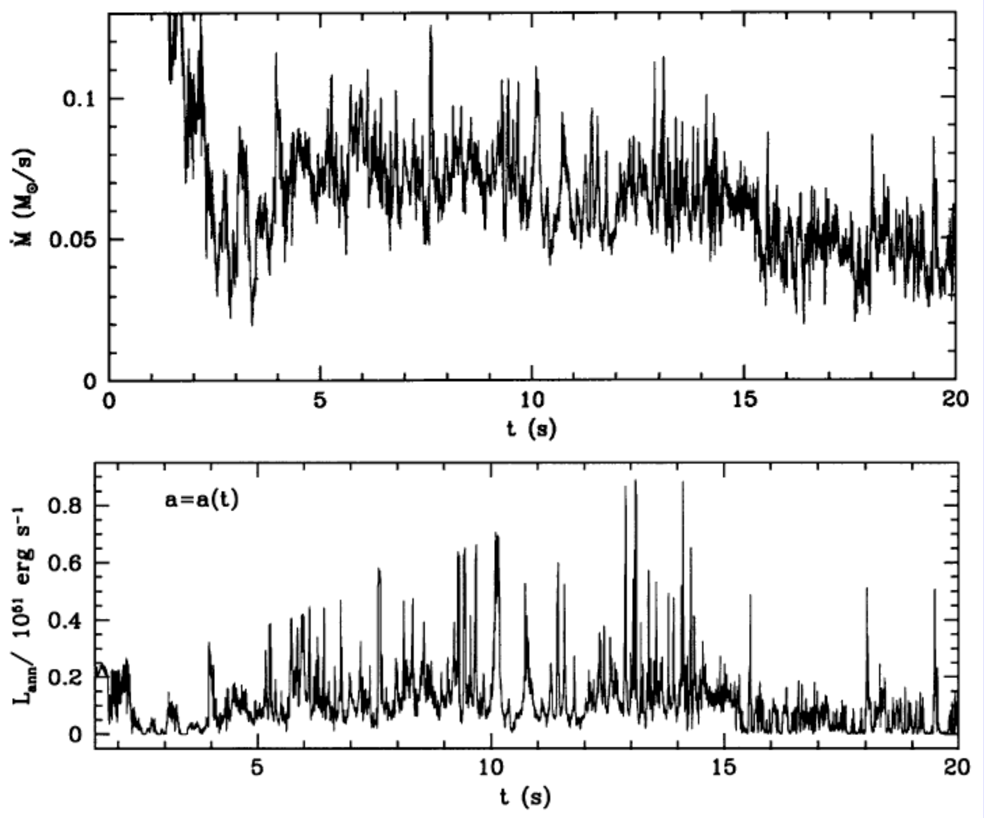


Aloy et al. 2000

# Unsteady accretion

- The accretion rate is not constant. Instabilities at the outer edge of the disk modulate the mass flow.
- The timescale of the inner disk and the jet is shorter than the timescale of the fluctuations ⇒ The jet reacts quickly, varying its Lorentz factor.

- Neutrino emission is strongly temperature dependent.
- The rate of neutrino annihilation is proportional to the square of the neutrino flux
- ⇒ The energy deposition rate varies strongly.
- The varying Lorentz factor in the jet may create the internal shocks required for the GRB.



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