Radiation processes and models

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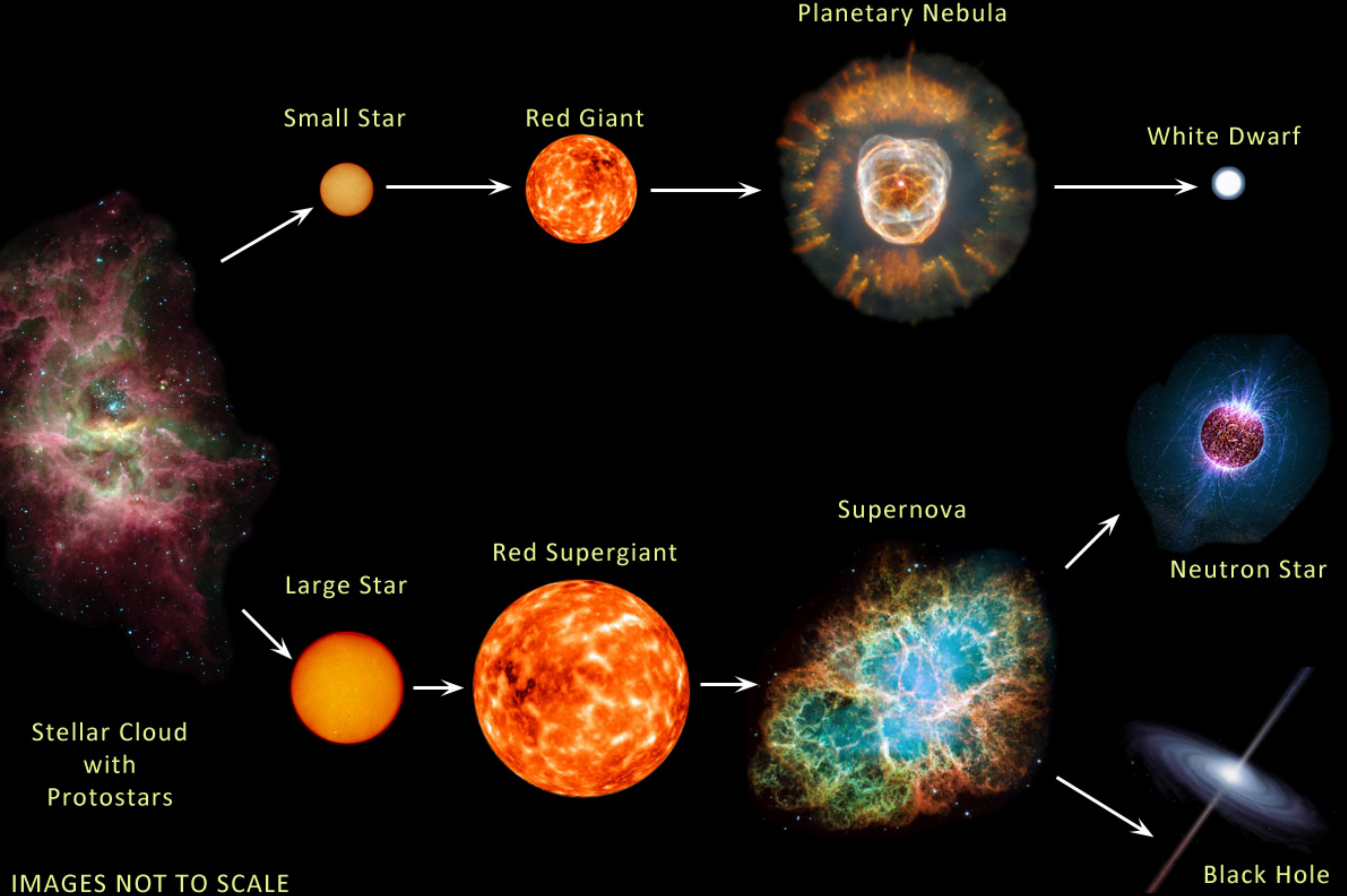
- **Lesson 1: Introduction to compact object physics**
- **Lesson 2: Radiation processes**
- **Lesson 3: Models for accreting black hole binaries: accretion flows**
- **Lesson 4: Models for accreting black hole binaries: compact jets**

Compact objects

- Extreme physics: dense matter; strong field general relativity; strong magnetic fields; particle acceleration processes…
- Accretion & ejection: fundamental astrophysical processes

EVOLUTION OF STARS



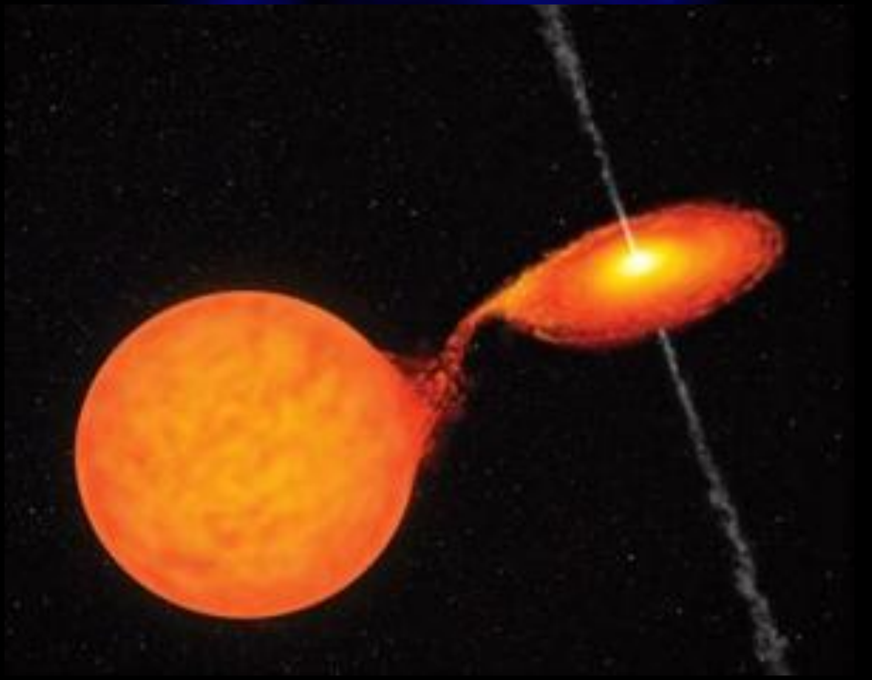
IMAGES NOT TO SCALE

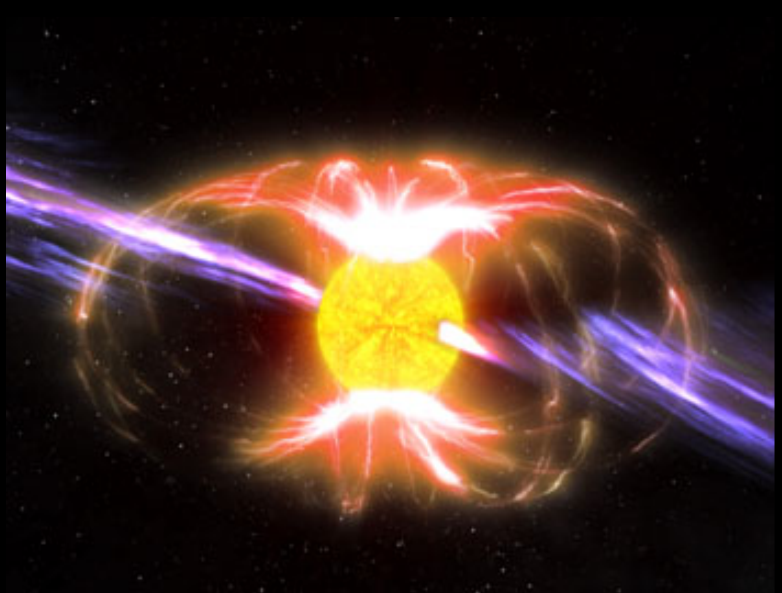
Compact objects are compact!!

	Earth	Sun	WD	NS	Stellar BH
Mass (M	3x10	1	1	1.5	10
Radius (km)	6x10	7x10	7x10	10	15
Density (g/cm	7	1.4	10	7x10	10
Surface gravity (m/s	10	300	3x10	2x10	6x10
Light crossing time (ms)	20	2 x 10	20	0.03	0.05
Keplerian period @ 6 R	1 d	2 d	200 s	8 ms	6 ms

Compact objects are powerful !!

- **Several energy sources:**
  - **Rotation (NS in pulsars, BH jets ?)**
  - **Accretion (WD, NS, BH in binary systems)**
  - **Magnetic fields (NS in Magnetars)**
  - **Nuclear fusion (NS in X-ray bursters/WD novae)**





- **Combination of short dynamical times-scales and huge power release:**

➡ **Prime targets for High Time Resolution Astronomy**

Rotation energy

- Imagine a star of radius R, mass M and rotation period P:

Its moment of inertia is: $$I_\star \simeq \frac{2}{5} M_\star R_\star^2$$ (homogeneous sphere)

Its angular momentum: $$L_\star = I_\star \Omega_\star \sim \frac{2}{5} M_\star R_\star^2 \frac{2\pi}{P_\star}$$

- Squeeze it to the size of a neutron star i.e. R~10 km, assuming conservation of angular momentum:

$$P \simeq 0.5 \left(\frac{P_\star}{P_\odot}\right) \left(\frac{R}{10\,\mathrm{km}}\right)^2 \left(\frac{R_\star}{R_\odot}\right)^{-2} \mathrm{ms}$$

- In fact angular momentum loss in SN or wind leads to somewhat larger periods, typical young neutron stars have

$$P \sim 10\,\mathrm{ms}$$

Rotation energy

- **Rotational energy:**

$$E = \frac{I\Omega^2}{2} = \frac{I}{2}\left(\frac{2\pi}{P}\right)^2 = \frac{2I\pi^2}{P^2}$$

$$I = \frac{2}{5}MR^2$$

$$\frac{E}{Mc^2} = \frac{4}{5}\left(\frac{\pi R}{cP}\right)^2 \simeq 10^{-4}\left(\frac{R}{10\,\mathrm{km}}\right)^2\left(\frac{P}{0.01\,\mathrm{s}}\right)^{-2}$$

- **Energy stored in rotation comparable to energy radiated by the sun in 10^9 years !**

Spin down

- **Extraction of rotational energy implies spin down:**

$$\dot{E}_{\rm rot} = \frac{d}{dt}\left(\frac{I\Omega^2}{2}\right) = \frac{4I\pi^2}{P^3}\frac{dP}{dt}$$

$$\dot{E}_{\rm rot} \simeq 3\times 10^{50}\,\frac{M}{M_\odot}\left(\frac{R}{10\,{\rm km}}\right)^2\left(\frac{P}{0.01\,{\rm s}}\right)^{-2}\frac{1}{P}\frac{dP}{dt}\,{\rm erg/s}$$

- **In pulsars, measurement of pulse period and its evolution allows one to estimate the rotation power** $\dot{E}_{\rm rot}$
- **Crab pulsar:** $P \simeq 0.033\,{\rm s}, \quad \frac{1}{P}\frac{dP}{dt} \simeq 10^{-11} \Rightarrow \dot{E}_{\rm rot} \simeq 3\times 10^{38}\,{\rm erg/s}$
- **Estimated rotation power comparable to observed power output**

Neutron stars magnetic field

- **During gravitational collapse the magnetic flux:** $\int B dS = \text{constant}$

Magnetic field (B) **Surface** (dS)

$$B = 5 \times 10^{11} \left(\frac{B_\star}{100\,\mathrm{G}} \right) \left(\frac{R_\star}{R_\odot} \right)^2 \left(\frac{R}{10\,\mathrm{km}} \right)^{-2} \mathrm{G}$$

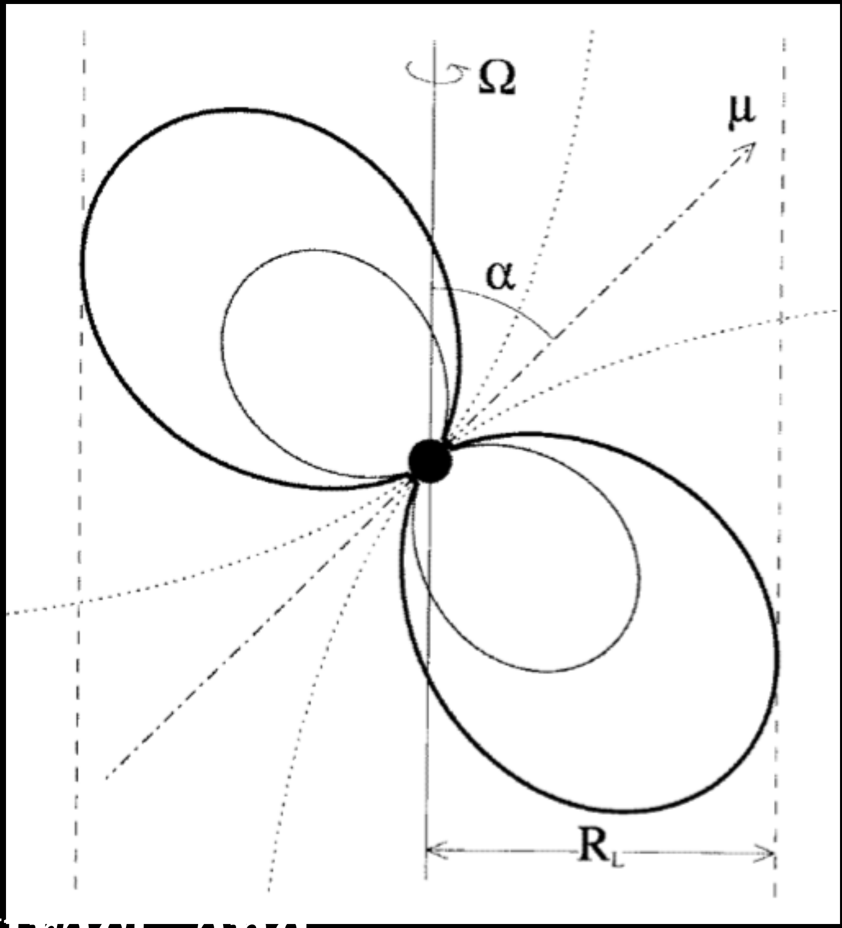
Earth magnetic field~ 0.5 G

Fridge Magnet ~ 50 G

- **Magnetic field dissipates slowly**

Magnetic dipole radiation model

- A magnetic dipole $\mu = \frac{B_p R^3}{2}$ in rotation into vacuum emits a wave



- Radiated energy: $\dot{E}_\mathrm{d} = \frac{2\mu^2\Omega^4}{3c^3}\sin^2\alpha$

$$\dot{E}_\mathrm{d} \simeq 10^{39}\left(\frac{B_p}{10^{12}\,\mathrm{G}}\right)^2\left(\frac{R}{10\,\mathrm{km}}\right)^6\left(\frac{P}{0.01\,\mathrm{s}}\right)^{-4}\sin^2\alpha \quad \mathrm{erg/s}$$

- Reality is much more complex:

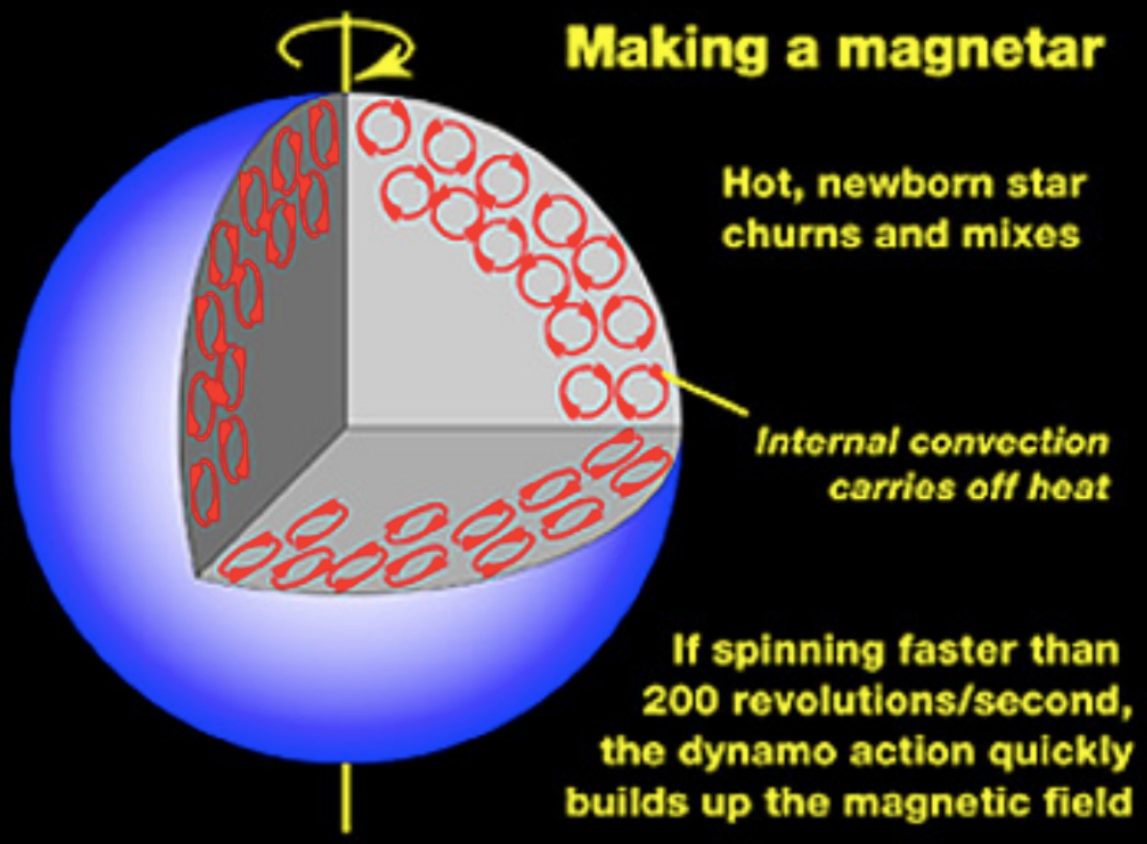
  - Huge electric fields generated close to NS surface extract and accelerate charged particles
  - Charged particles distribute themselves around the star to neutralize the electric field: an extensive magnetosphere forms (non-vacuum)
  - Streams of charged particles leave the star at high latitudes where the field lines are open: powerful wind

➡ Rotation energy dissipated through interaction of NS magnetic field with magnetosphere and wind

Magnetic field energy

- Magnetars: some NS appear to have negligible rotation energy but huge magnetic field 10^{14}-10^{16} G.

- Magnetic field amplified by dynamo processes during the first 10-30 s



- B field strong enough to push material around in star's interior and crust.

➡ leads to dissipation of large amounts magnetic energy during first 10^4 years.

➡ star remains hot and bright (X-ray thermal emission)

➡ magnetic dissipation in magnetosphere: non-thermal X-rays and gamma-rays (bursts)

Accretion

- Accretion is the growth of a massive object by gravitationally attracting more matter
- A fundamental astrophysical process. Structures the universe at different scales (galaxy formation, feedback, active galactic nuclei, stars, planets…)
- Accretion in binary systems with a compact object:
  - Black hole: no hard surface, pure accretion
  - Neutron Star or White Dwarf, accretion flow can interact with:
    - Compact star surface (boundary layer, thermo-nuclear bursts)
    - Magnetic field from compacts star (accreting pulsars, polars)

Accretion power

- Accreting matter falls into potential wells of compact object and lose gravitational energy. For accretion to occur gravitational energy (and angular momentum) must be dissipated away (mostly through radiation)

- Accretion onto the surface of an object of size R: available power at mass accretion rate $\dot{M}$:

$$P = \dot{M}\frac{GM}{R} = \eta \dot{M} c^2$$

- Accretion efficiency : $\eta = \frac{GM}{Rc^2} \sim$

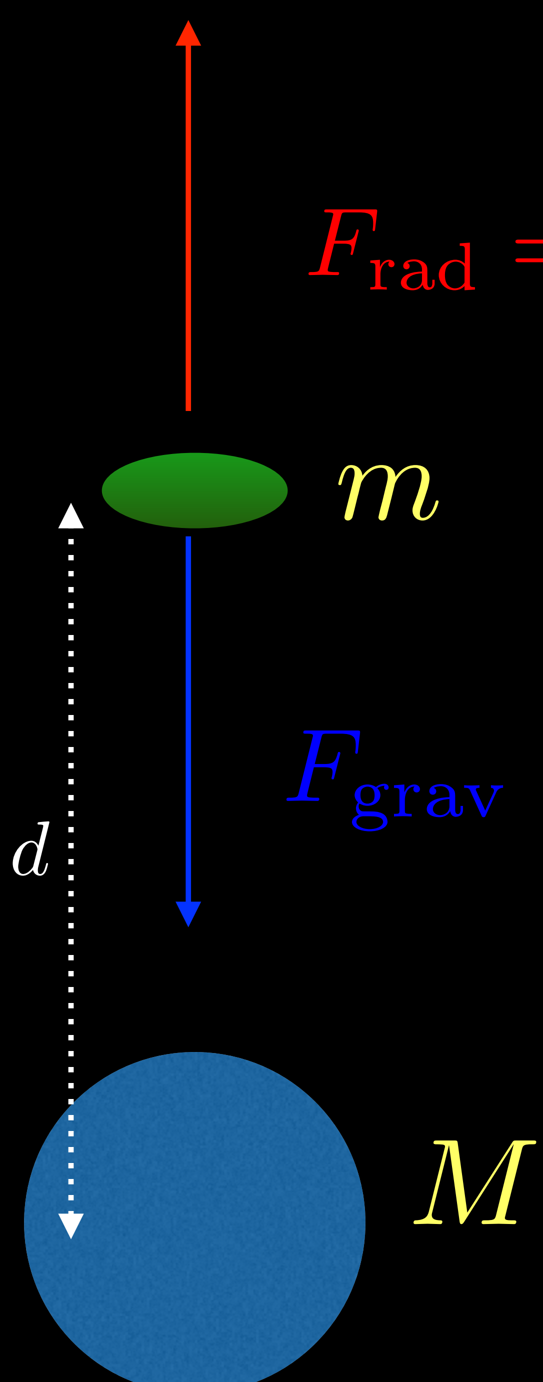
	Earth	Sun	White Dwarf	Neutron star
η	10^{-9}	10^{-6}	10^{-4}	10^{-1}

- Accretion efficiency onto black hole (no hard surface) depends on the structure of accretion flow and BH spin: 0.057< η <0.42 for thin disk

- Efficiency of Nuclear (H) fusion: η ~0.007

Eddington accretion limit

- **Eddington luminosity: maximum luminosity for which gravitational force on a fluid element exceeds the radiation pressure (i.e. the maximum luminosity at which matter can be accreted)**



$$F_{\rm rad} = \frac{L}{4\pi d^2 c}\kappa m$$

$$F_{\rm grav} = \frac{GM}{d^2} m$$

$$F_{\rm rad} < F_{\rm grav} \Rightarrow L < L_E = \frac{4\pi G M c}{\kappa}$$

- **For Compton scattering:**

$$L_E \simeq 3.8 \times 10^4 L_\odot \frac{M}{M_\odot}$$

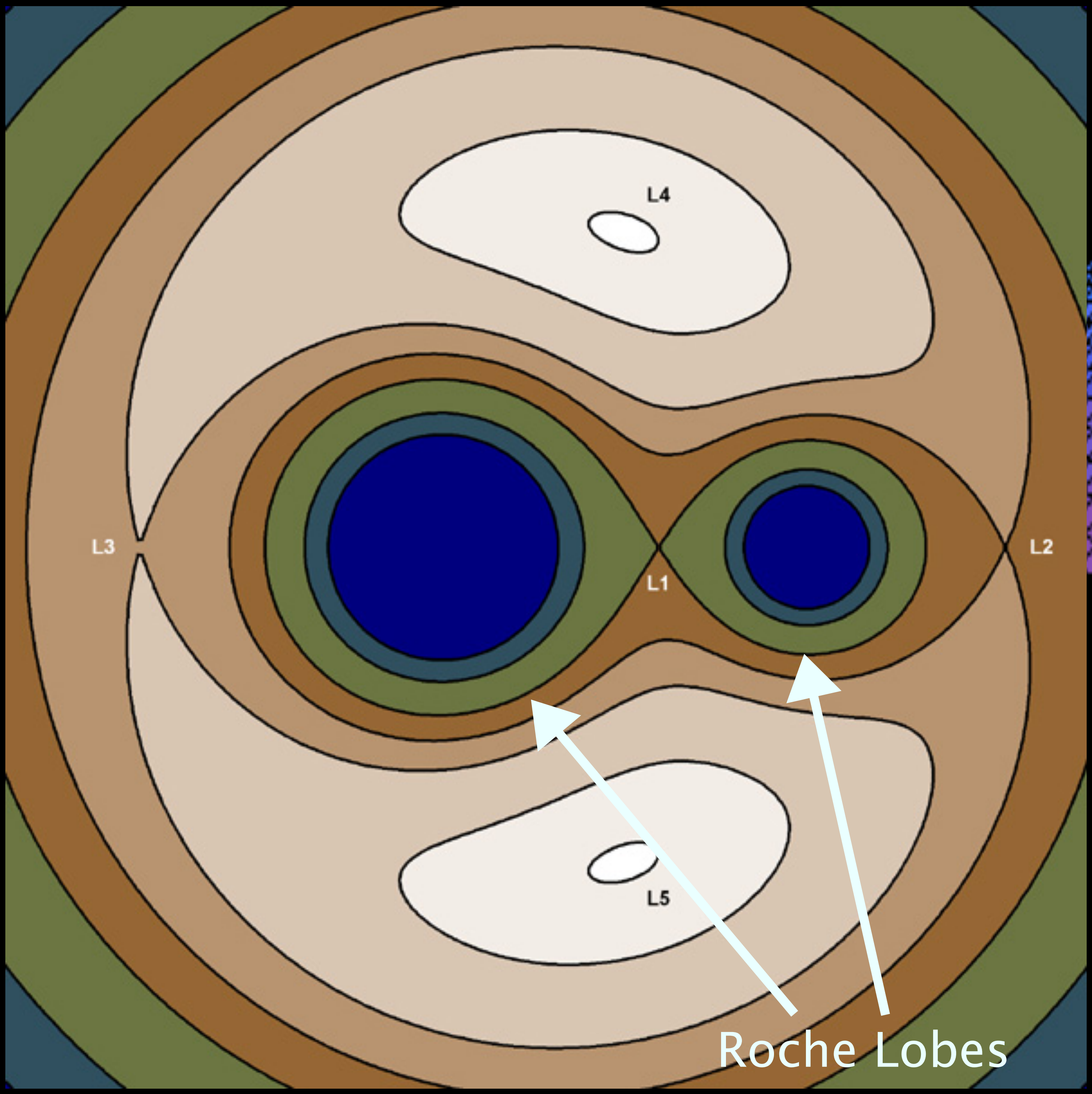
- **Eddington accretion rate**

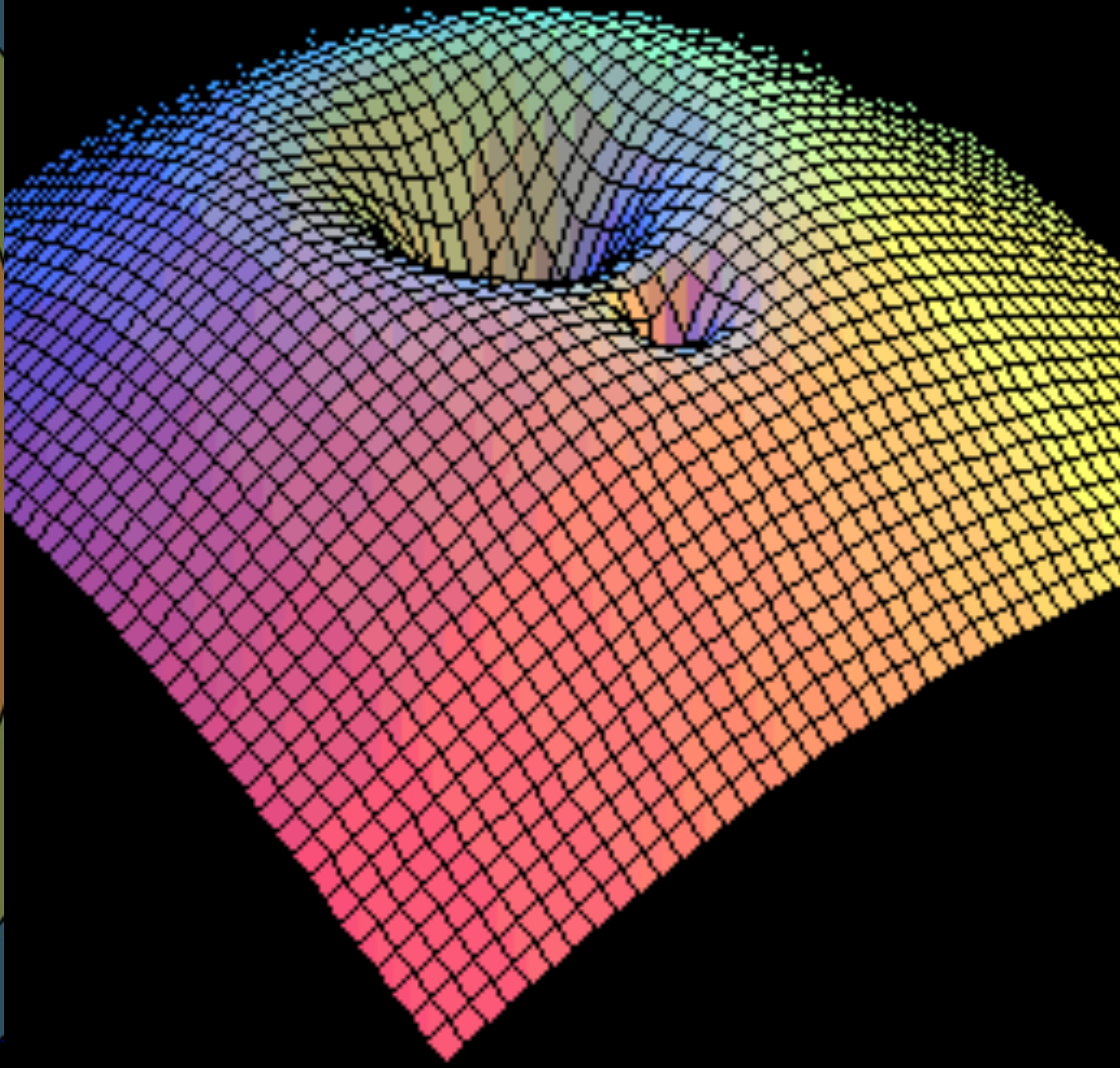
$$\dot{M}_E = \frac{L_E}{\eta c^2}$$

- **For neutron stars:**

$$\dot{M}_E = 1.8 \times 10^{-8} M_\odot {\rm yr}^{-1}$$

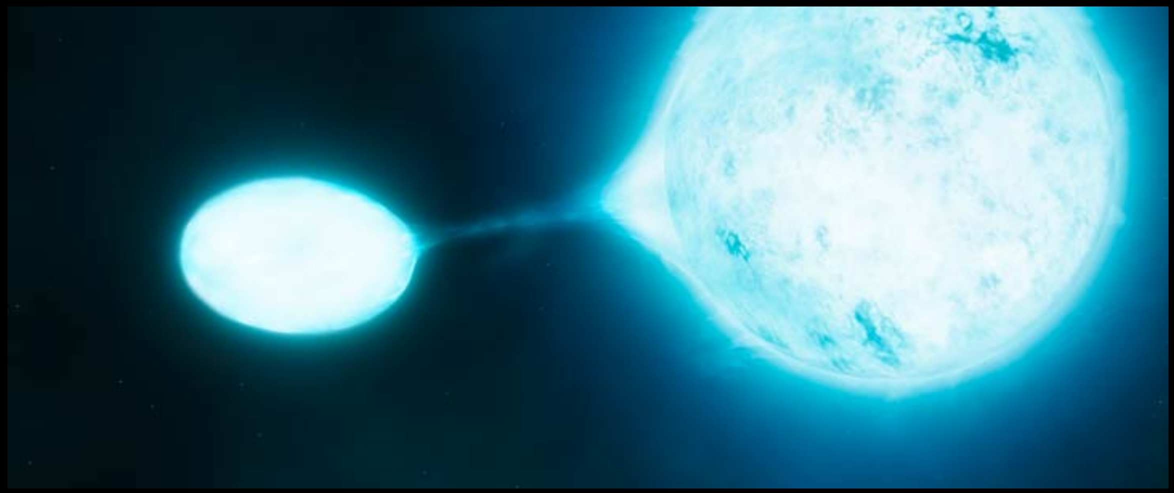
Mass transfert: Roche lobe potential

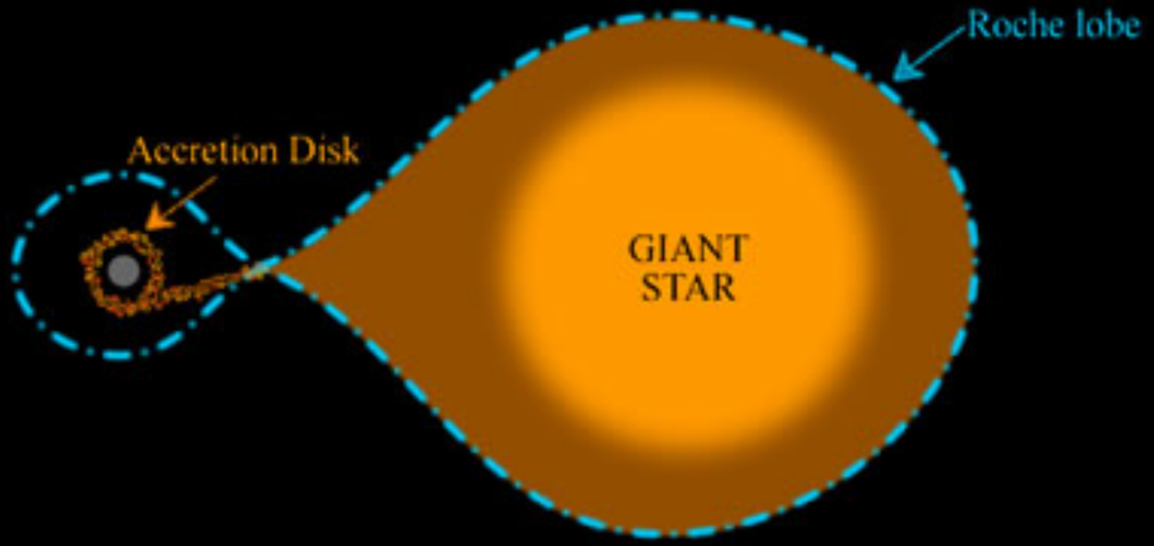




$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\Omega^2 r_3^2}{2}$$

Mass transfert: Roche lobe overflow

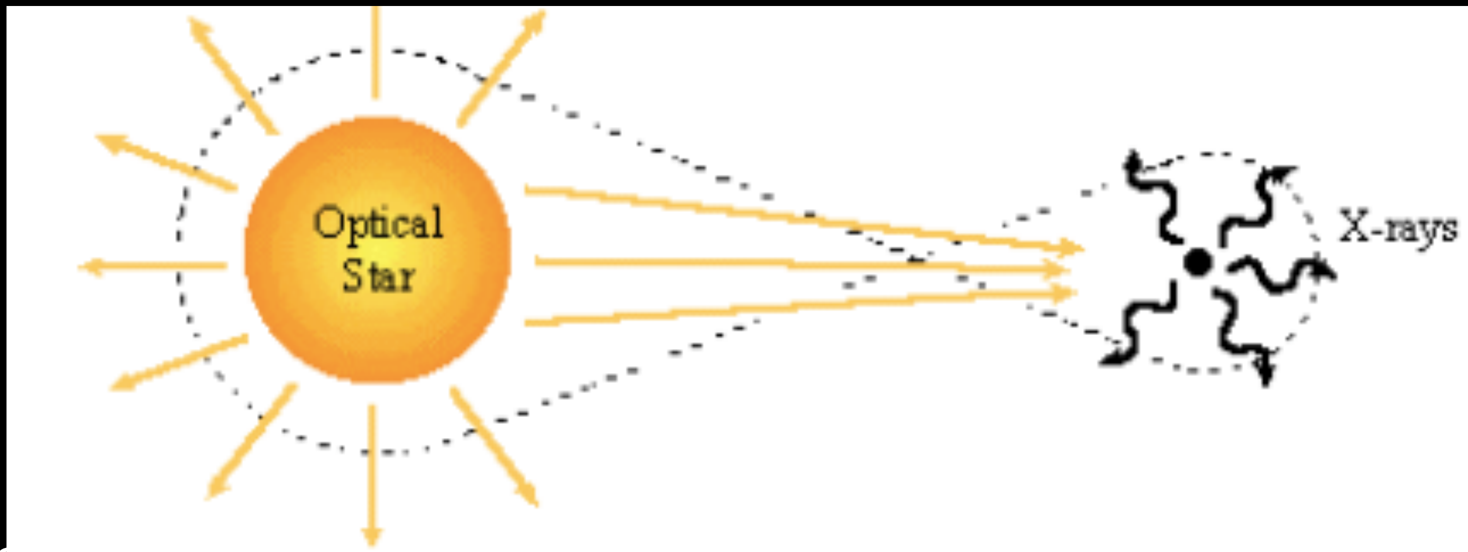




- Mass transfer if donor star fills its Roche Lobe ($R_* = R_L$)
- Lobe Roche overflow driven by:
  - Change in stellar radius (Stellar evolution)
  - Change in orbital period/separation/R_L:
    - Loss of angular momentum (GR waves, magnetic breaking, tidal torques, mass loss in stellar wind)
    - Mass transfer
- Stable Roche lobe overflow can exist if donor fills its Roche lobe AND mass of donor < mass of accretor → LMXB
- Then steady mass accretion rates

$$\dot{M} \sim 10^{-10} - 10^{-9} M_\odot yr^{-1}$$

Mass transfert: Stellar wind accretion



- Massive early type companion (O or B) can loose mass in wind at a rate 10^{-6} 10^{-5} $M_{\odot}$/yr and supersonic velocity

$$v_w \sim v_{esc} = \sqrt{\frac{2GM_\star}{R_\star}} \simeq 10^3 \quad \mathrm{kms}^{-1}$$

- Compact star captures wind material within a radius:

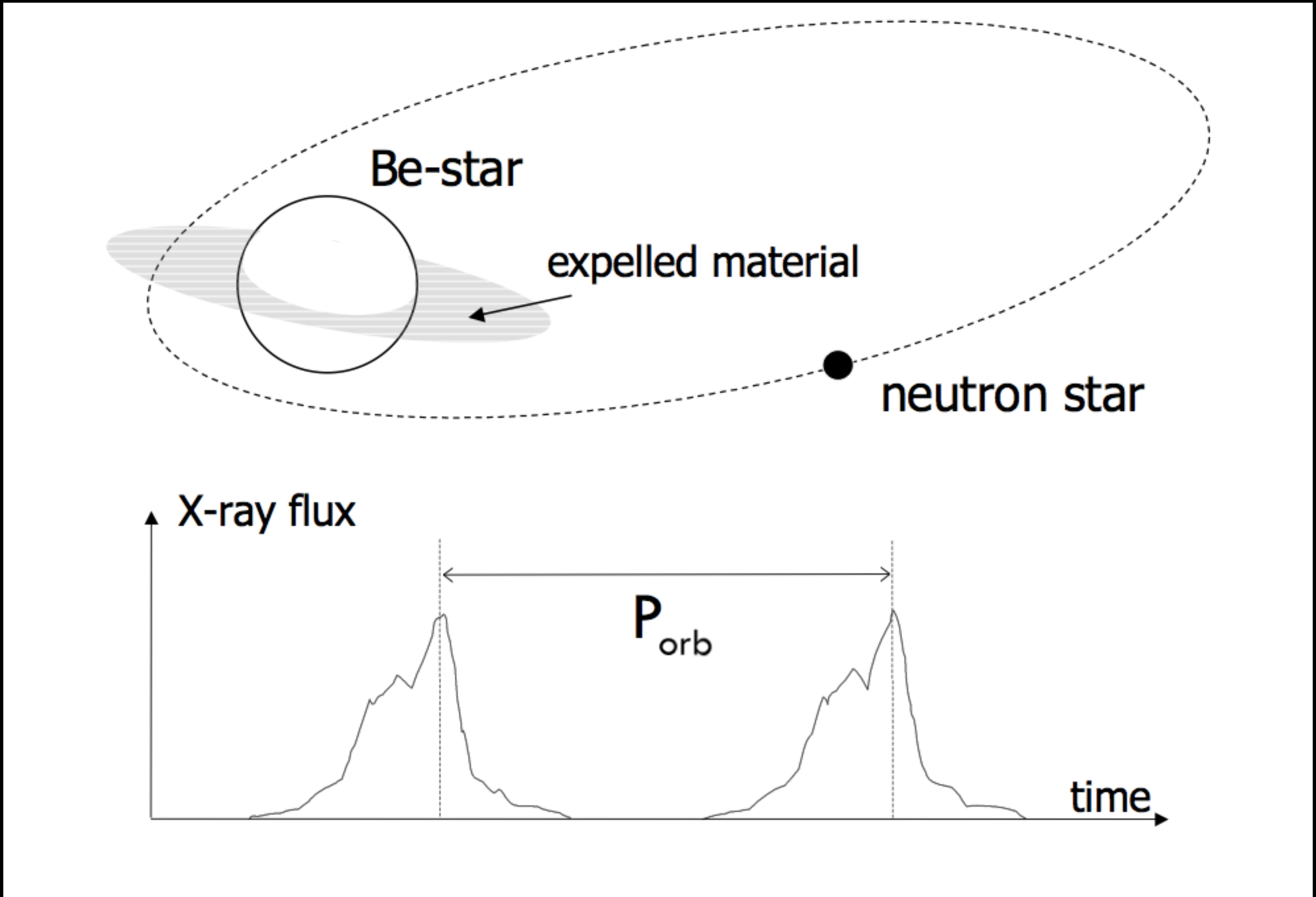
$$r_{acc} = \frac{2GM}{v_{rel}^2 + c_s^2} \quad \text{where} \quad v_{rel}^2 = v_{orb}^2 + v_w^2$$

- Accretion rate onto compact star:

$$\dot{M} = \pi r_{acc}^2 \rho v_{rel} \sim (10^{-5} - 10^{-4}) \dot{M}_w \sim 10^{-11} - 10^{-9} M_\odot/\mathrm{yr}$$

but can be a significant fraction of the Eddington limit of a NS ...
... if High Mass companion ➔ HMXB

Mass transfer: Be accretion

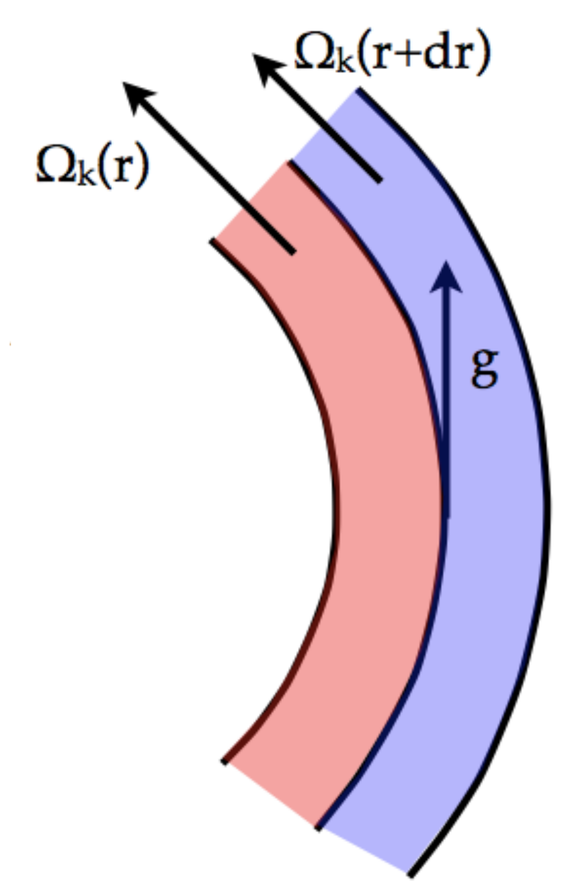


→ HMXB

Keplerian accretion discs

- Viscous torques allow angular momentum to be transferred outward and mass to spiral inwards.
- Usual microscopic viscosity not efficient enough to explain high observed accretion rates.
- Best candidate: Magneto-Rotational Instability, in differential rotating flows, generate fully developed MHD turbulence that provides efficient angular momentum transport.

Balbus & Hawley 1991, 1998

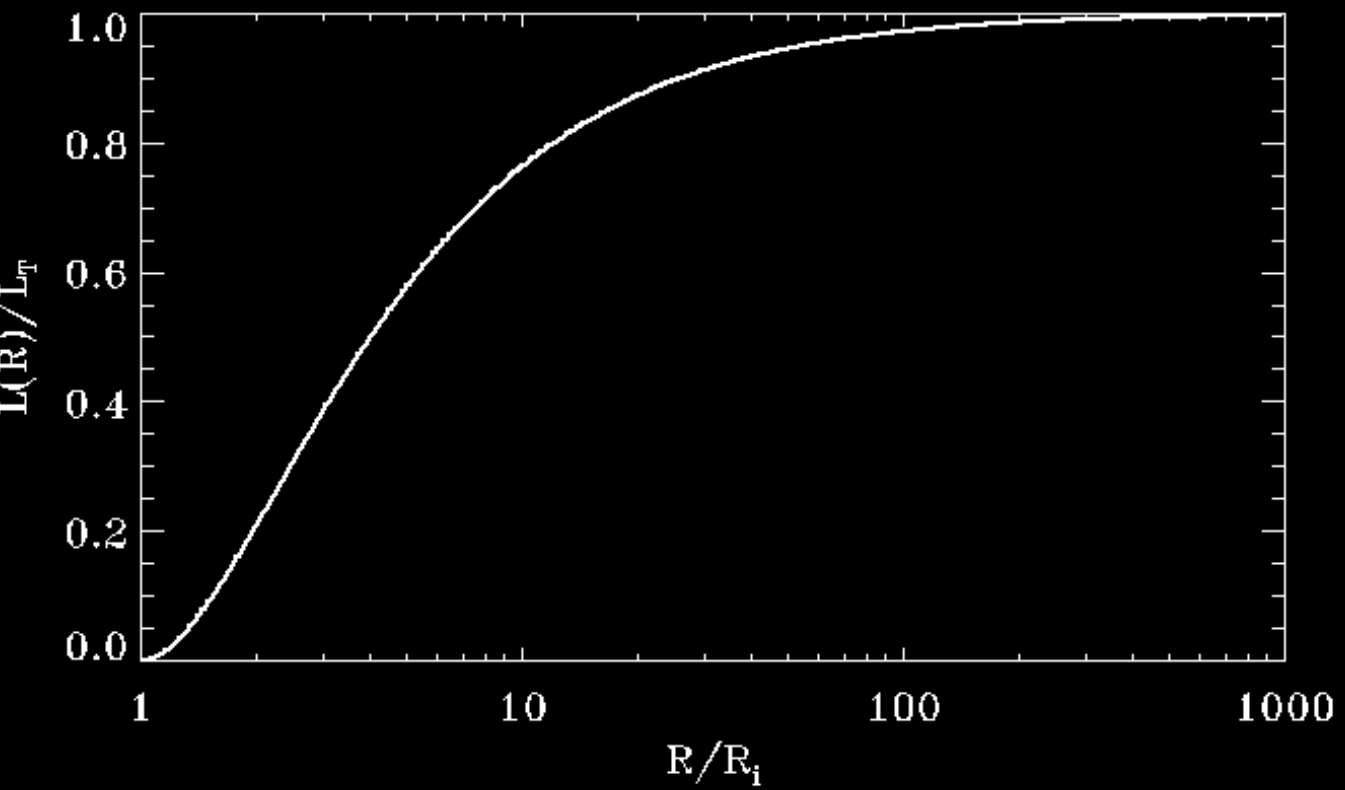


- Standard disc model assumes:
  - unspecified turbulent viscosity, $\nu = \alpha c_s H$, where α parameter $\alpha \leq 1$ (alpha discs)
  - radiation cooling is very efficient (black body) and local: disc is 'cold' and geometrically thin

Shakura & Sunyaev 1973

$$L = \frac{GM\dot{M}}{2R_i}$$

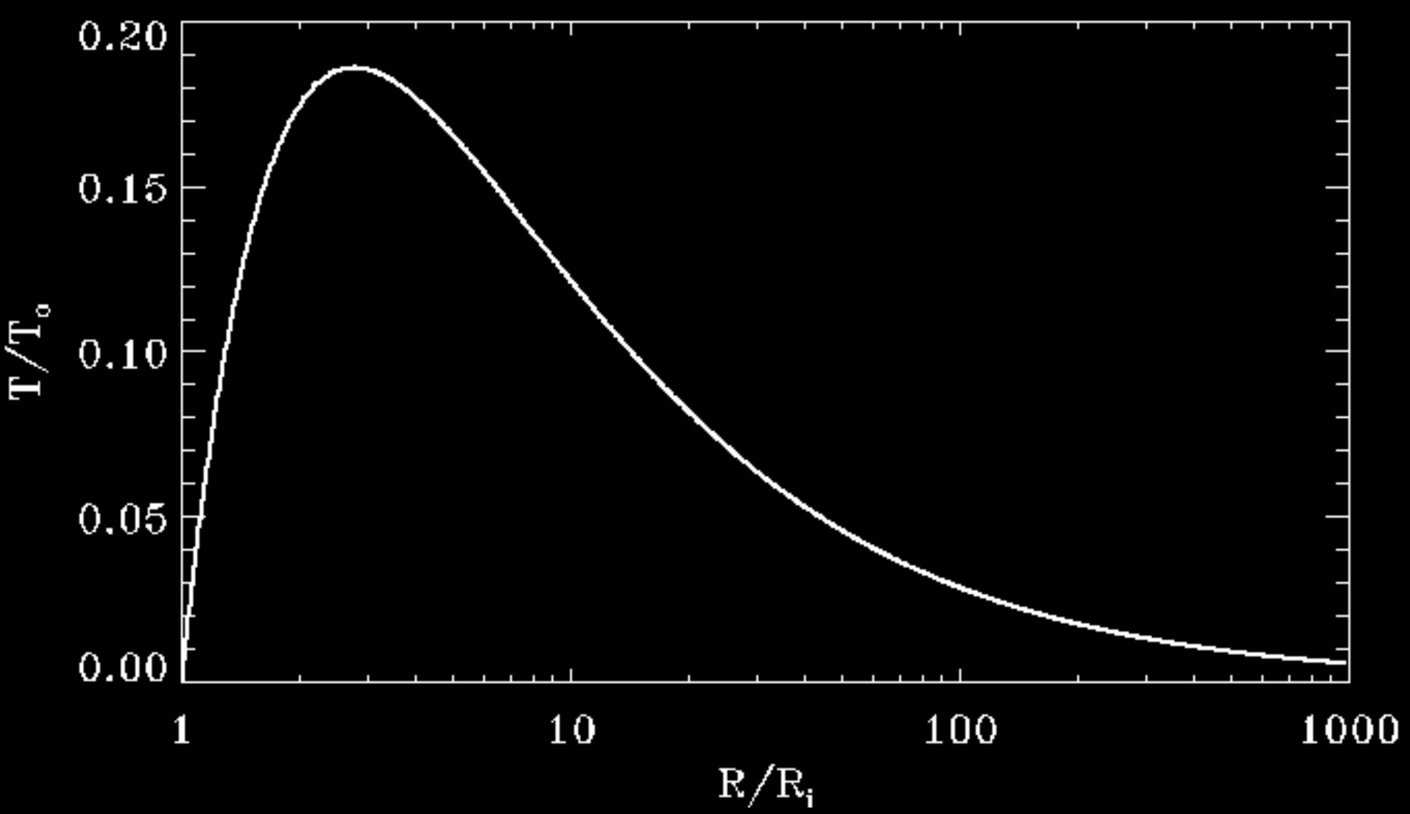
$$\frac{dL}{dR} = \frac{3}{2}\frac{GM\dot{M}}{R^2}\left(1 - \sqrt{\frac{R_i}{R}}\right)$$

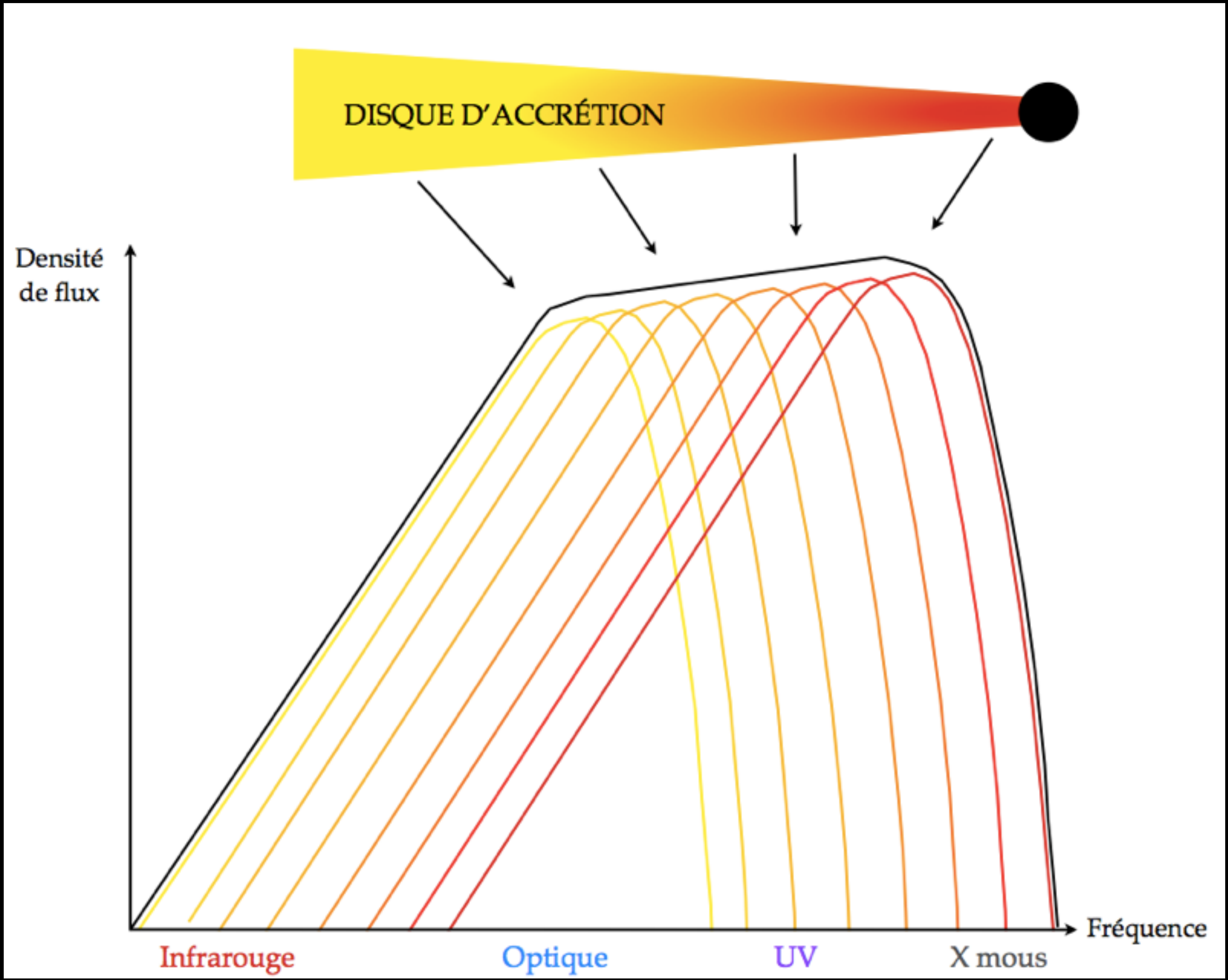


$$T(R) = T_o\left(\frac{R_i}{R}\right)^{3/4}\left(1 - \sqrt{\frac{R_i}{R}}\right)^{1/4}$$

$$T_o = \left(\frac{3GM\dot{M}}{8\pi\sigma R_i^3}\right)^{1/4}$$

$$\simeq \left(\frac{R_i}{R_G}\right)^{-3/4}\left(\frac{\dot{M}c^2}{L_E}\right)^{1/4}\left(\frac{M}{M_\odot}\right)^{-1/4} 6\times 10^7\,\mathrm{K} \quad (\simeq 5\,\mathrm{keV})$$





from M. Coriat PhD thesis

Hot accretion flows

- Thin accretion disc models assume energy thermalisation ➔ high density, small H/R, low temperature.

- If accretion flow is hot instead, scale height is large and density is low, then radiation cooling is inefficient, and high temperature can be maintained.

- Low density ➔ e-p collision time-scale can be long compared to accretion time-scale

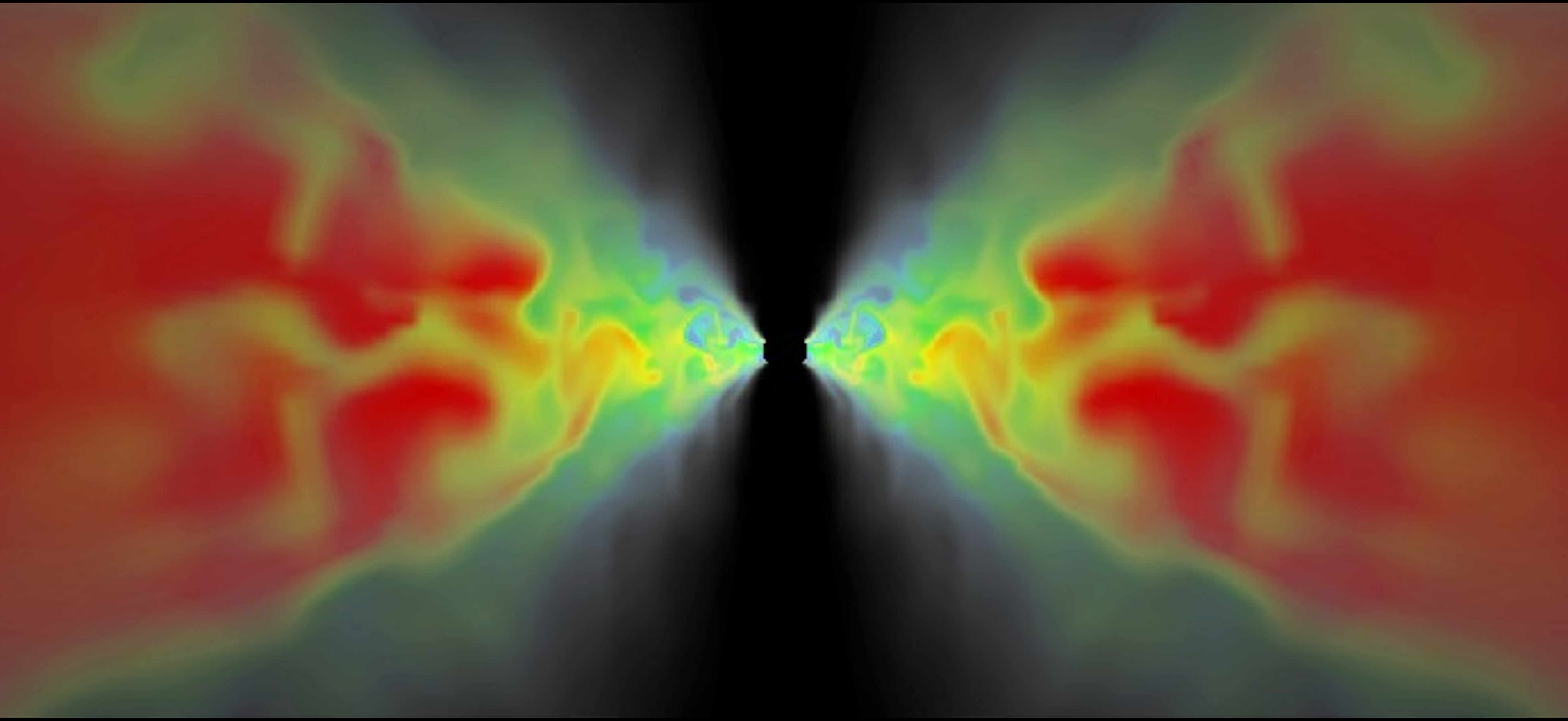
  - Protons acquire most of the gravitational energy and electrons radiate efficiently.
  - but protons and electrons are decoupled
    ➔ two temperature plasmas $T_p \sim 10^{12}$ K, $T_e \sim 10^9$ K (close to compact star)

- Advection: accretion flow energy not radiated locally. Can be carried onto compact star surface or BH.

- Non-thermal radiation processes: Bremstrahlung, Comptonization

Narayan & Yi 1994

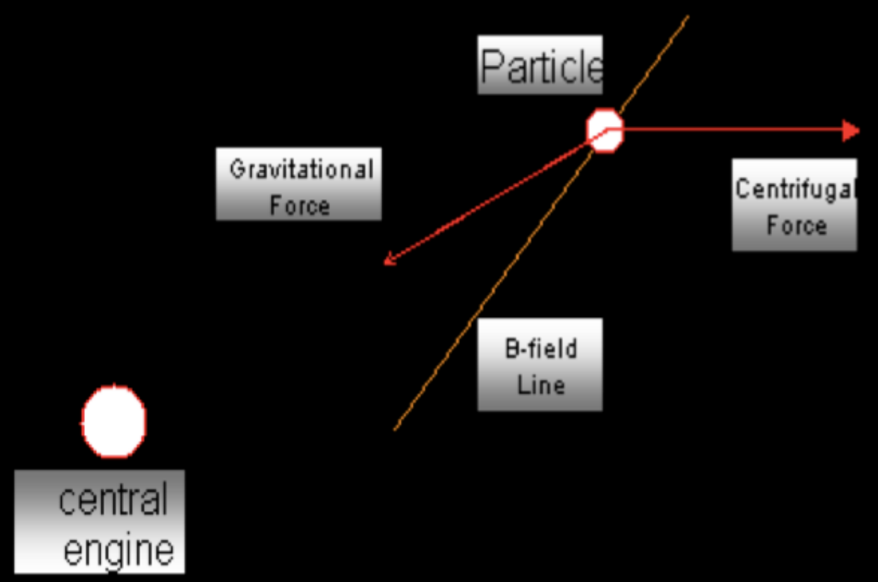
- Family of hot flow solutions: ADAF (advection), ADIOS (outflows), CDAF (convection)…
- Numerical simulations



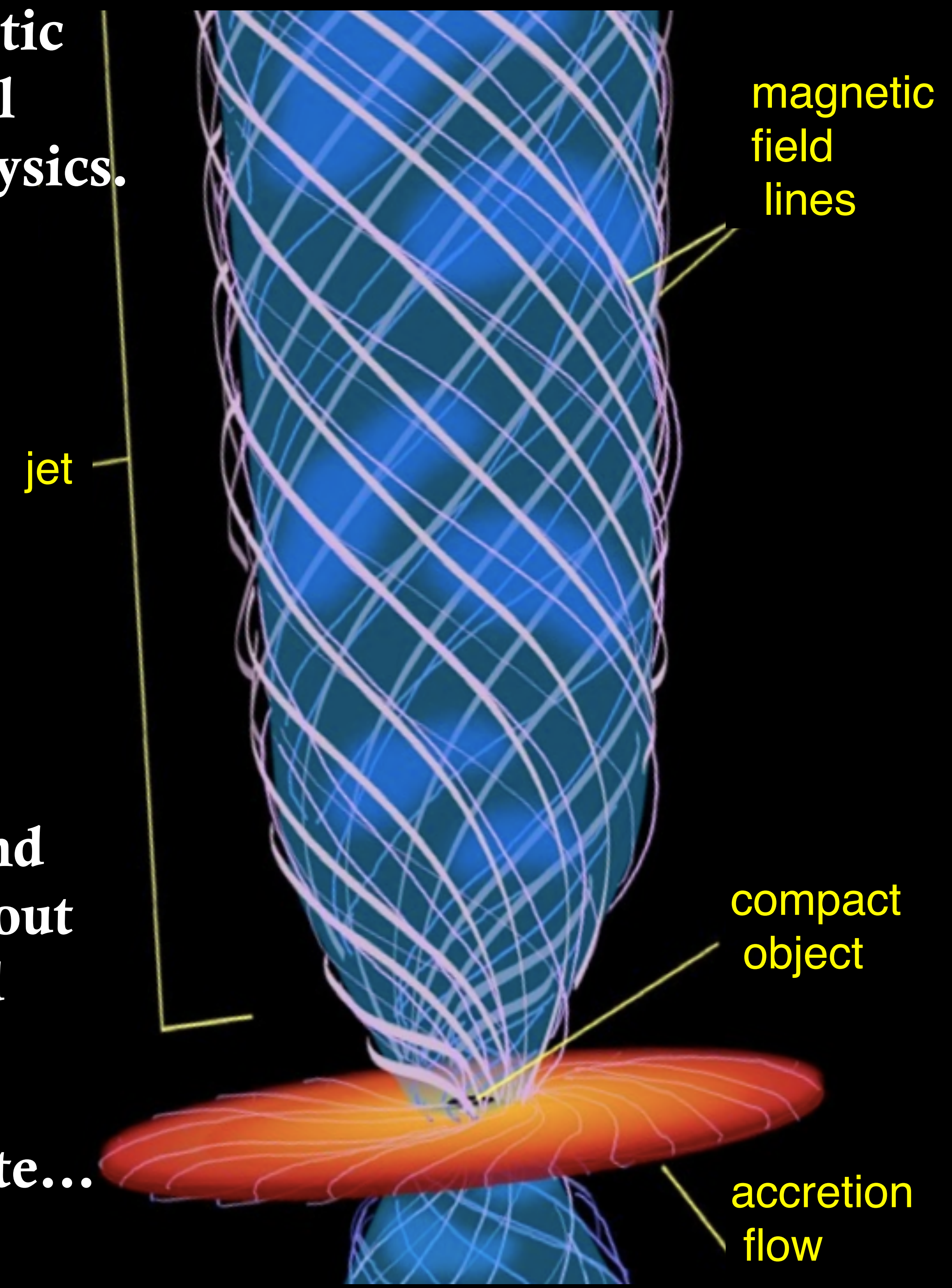
Stone et al. 1999, Igumenshchev et al. 2000, Narayan 2000…

Jet launching from accretion discs

- Accretion flows can launch powerful outflows
- All relativistic jet models require magnetic fields. None of the models and numerical simulations takes into account all the physics.

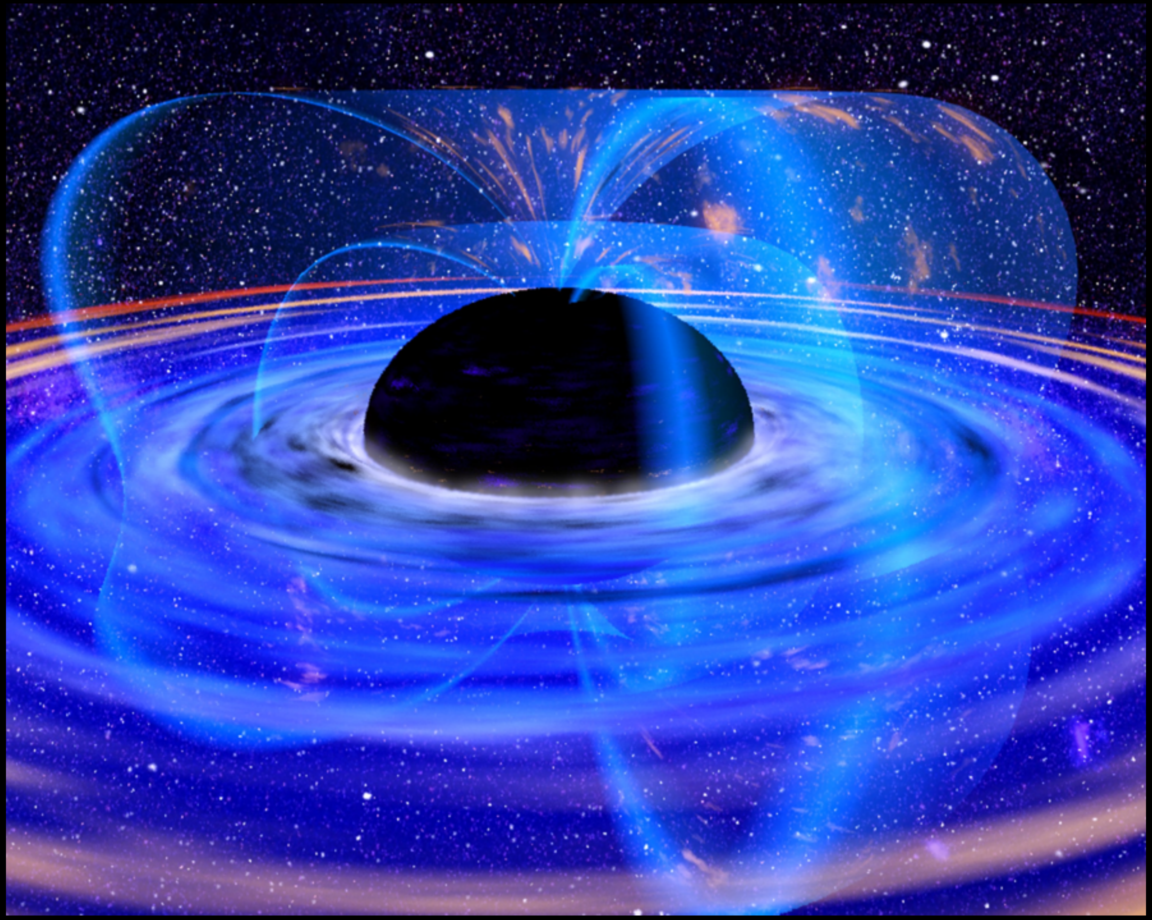


- In "bead on wire" models (Blandford and Payne 1982) centrifugal force can throw out particles which are tied to magnetic field lines.
- Then the jet needs to somewhat collimate…



Electromagnetic extraction of energy from Kerr black holes

- Penrose (69), Christodoulou (70), showed that you can extract up to 30 % of the mass energy of a maximally rotating black hole.
- An accretion disc can allow this energy to be extracted and drive a powerful relativistic jet Blandford & Znajek (1977)



- Accretion disc magnetic field lines remain threaded through horizon
- The frame of the field lines is dragged along with the rotation of the black hole. These rotating field lines induce an electromagnetic force that accelerates charged plasma at relativistic speeds along the axis of rotation. Due to the field, the particle spirals as it leaves.

Effects of NS magnetic field on accretion flow

- **Magnetic field becomes dynamically important close to the neutron star surface at a distance called Alfven radius, R_a.**
- **At R_a : kinetic energy ~ magnetic energy i.e.** $\dfrac{\rho v^2}{2} \simeq \dfrac{B^2}{8\pi}$
  - **Free fall accretion in spherical geometry**

$$v \simeq v_{\rm ff} = \sqrt{\frac{2GM_{NS}}{R_a}} \qquad \rho \simeq \frac{\dot{M}}{4\pi R_a^2 v_{ff}}$$

  - **Dipole magnetic field** $B(R_a) \sim \dfrac{B_0 R_{NS}^3}{R_a^3}$

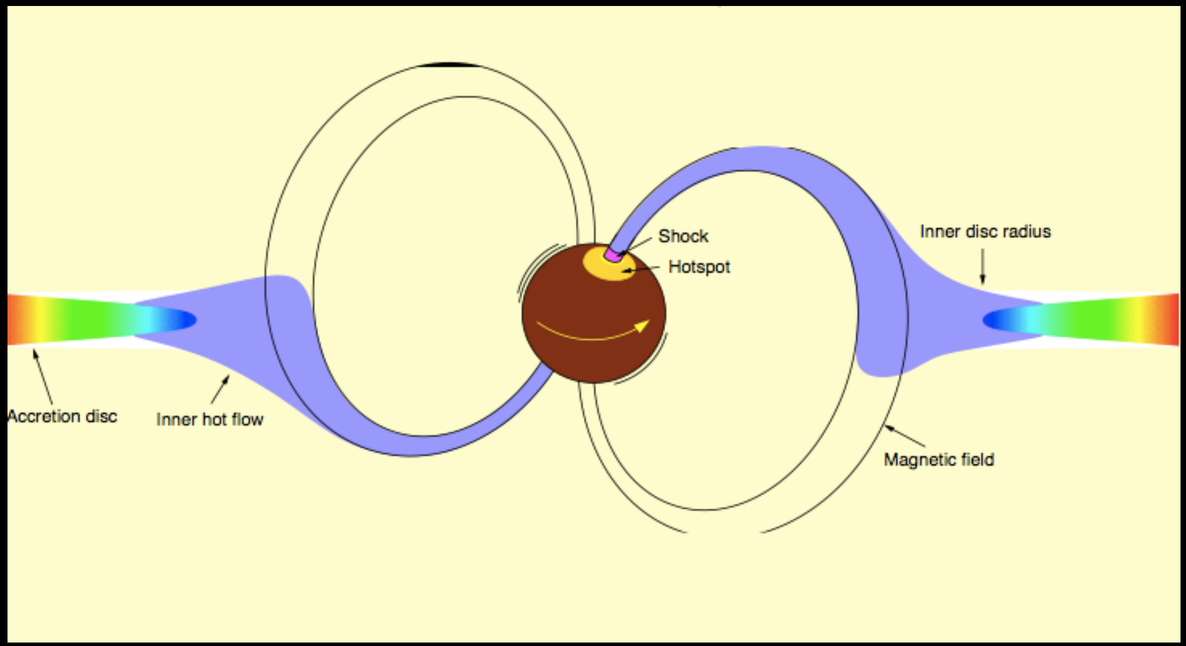
$$R_a \simeq 30\,\mathrm{km} \left(\frac{B_0}{10^9\mathrm{G}}\right)^{4/7} \left(\frac{\dot{M}}{2\times 10^{-8} M_\odot yr^{-1}}\right)^{-2/7}$$

- **Effects of magnetic field are important only if** $R_a > R_{NS}$ **:**

$$B_0 > 10^8\mathrm{G}$$

Effects of strong magnetic fields in accreting NS

- If NS spin frequency < orbital frequency of accreting matter at R_a :
  - accreting material forced into co-rotation with NS
  - channeled along field lines onto the magnetic poles ➔ X-ray pulsar
  - spin up torque on NS



- If NS spin frequency > orbital frequency
  - accretion is stopped, propeller regime
  - spin-down torque on NS

- Equilibrium spin period: P_{spin}~orbital period at $R_a \simeq 2\pi\sqrt{\frac{R_a^3}{GM_{NS}}}$

➔ $$P_{\rm eq} \simeq 2.3\,{\rm ms}\left(\frac{B_0}{10^9\,{\rm G}}\right)^{6/7}\left(\frac{\dot{M}}{2\times10^{-8}M_\odot\,{\rm yr}^{-1}}\right)^{-3/7}$$

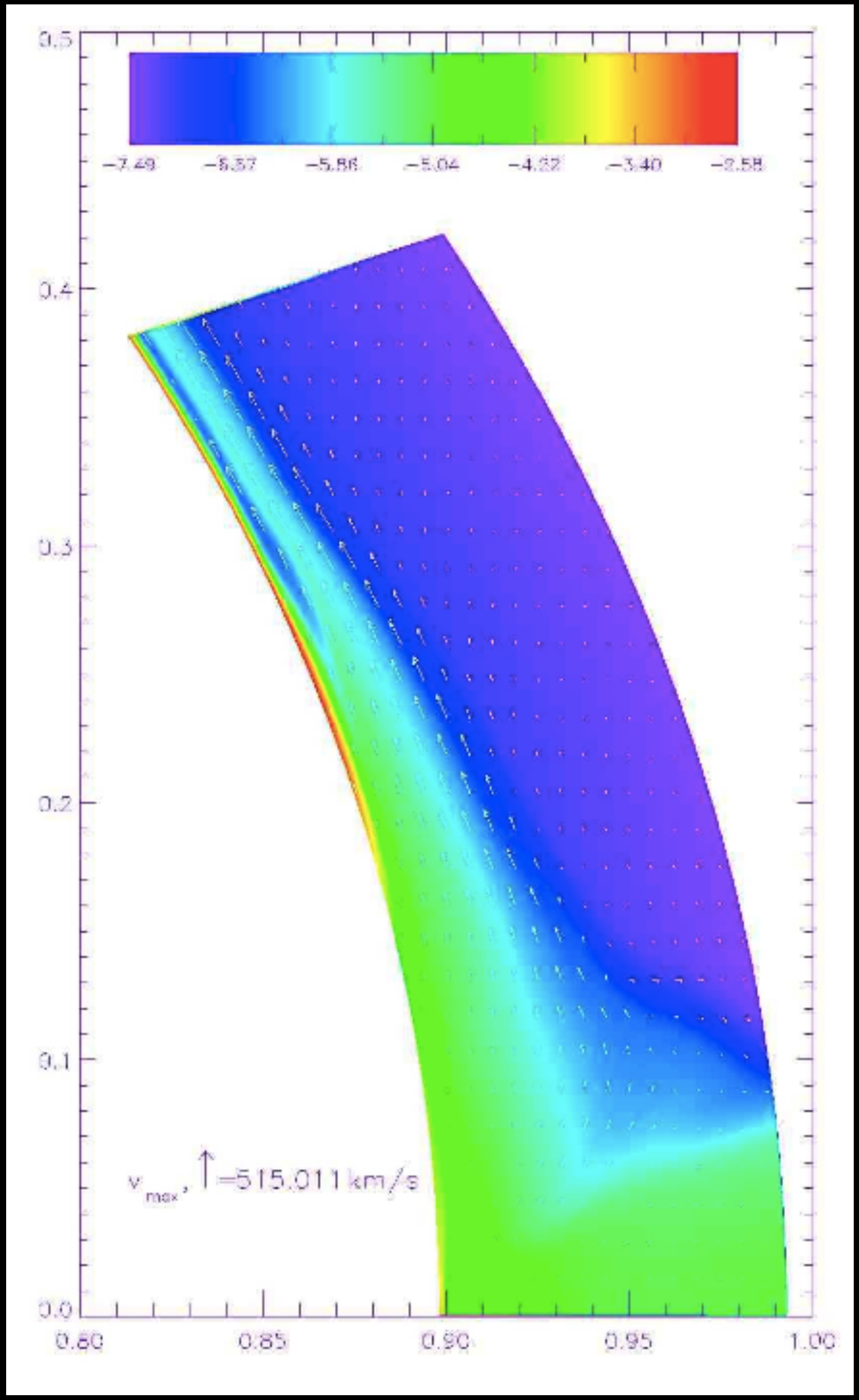
Compact stars with weak magnetic field boundary layer spreading layer

- BL: region between an accretion flow and neutron star.
- In BL fast rotating (Keplerian) accretion disk matter is decelerated to the neutron star rotation velocity.
- Spin up of compact star
- Luminosity of BL comparable to the accretion disk luminosity

$$L_{BL} \sim \dot{M}\frac{V_K^2}{2} = \frac{1}{2}\dot{M}\frac{GM_{NS}}{R_{NS}} \sim L_{AD}$$

- Size of BL is smaller than the accretion disc size. Therefore the temperature of the BL is larger than the effective temperature of the accretion disc
- Hard black body component in the soft state of LMXB a boundary layer spectrum ?

Geometry of boundary layer: spreading layer



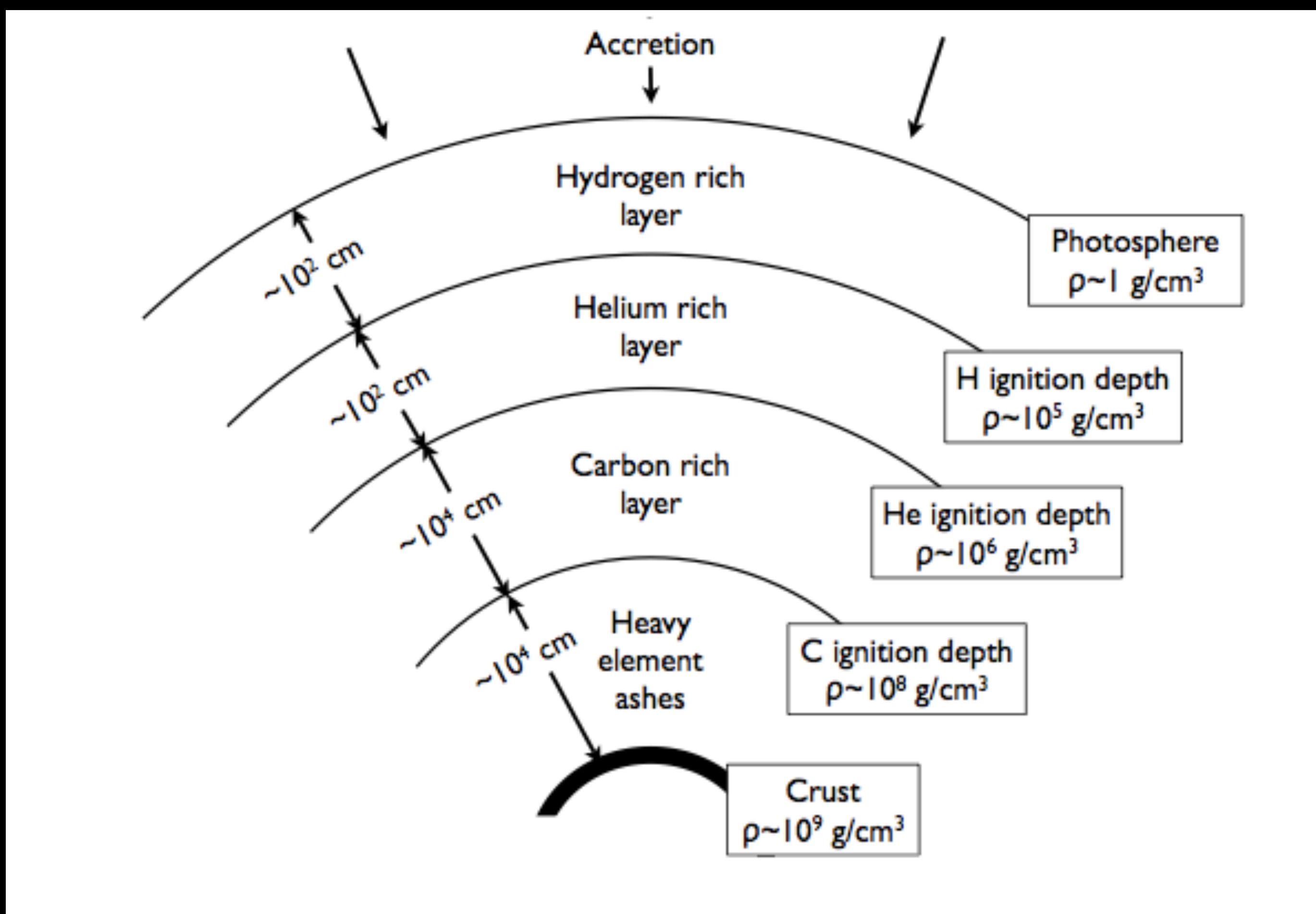
Ficker 2006

- Matter as a significant latitude velocity component , spreading above the compact star surface and decelerating due to friction at the neutron star surface (wind above the sea),

Inoganov & Sunyaev 1999

- For sources with L>0.05 Led, local radiation flux is Eddington
    - SL temperature independent of luminosity, emission models predicts Tc~2.5 keV (confirmed by observations)
    - The size of the belt must increase with accretion rate/luminosity. For L~Led, SL covers the whole CS surface.

Neutron stars weak magnetic field thermo-nuclear X-ray bursts

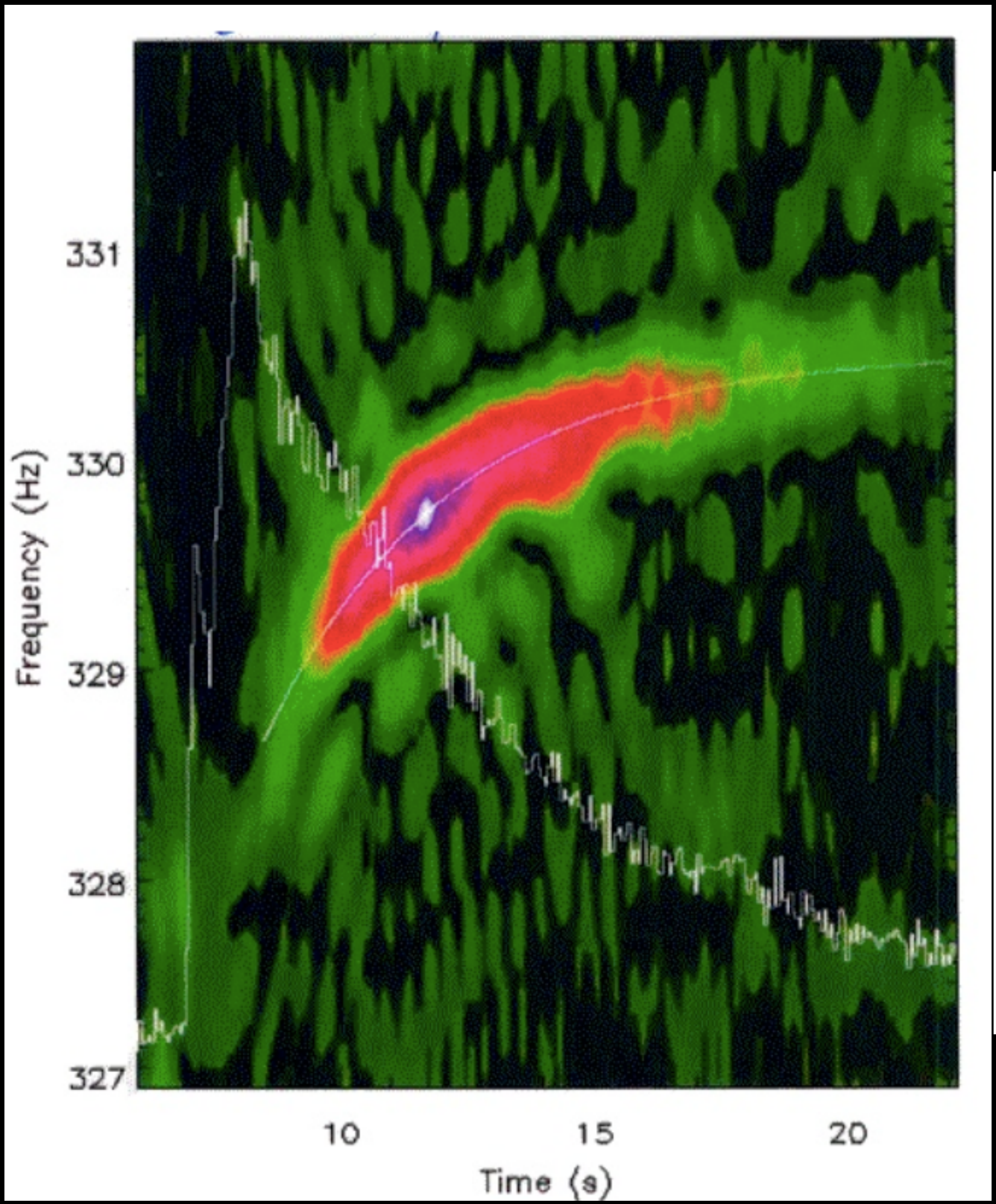


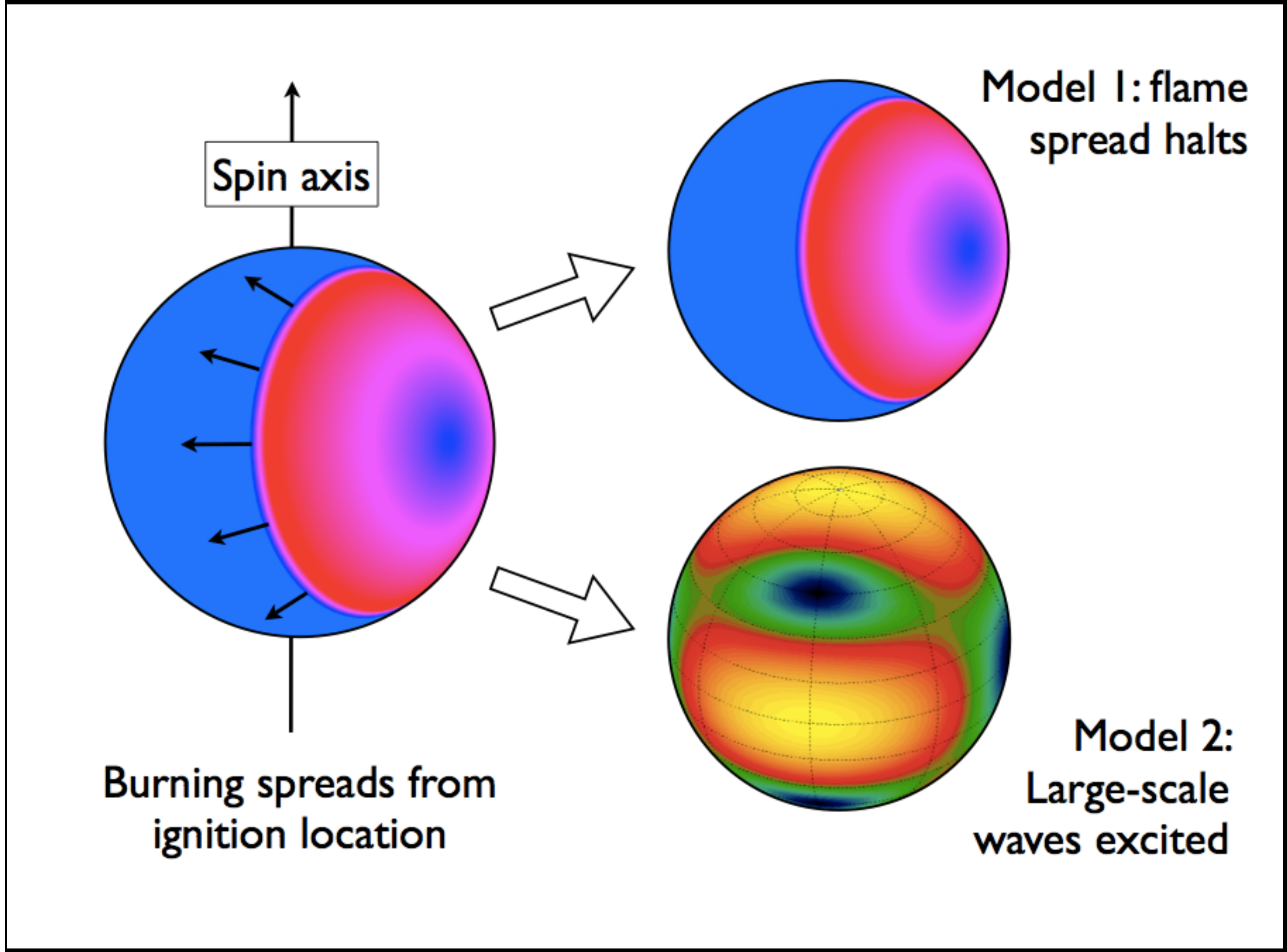
Classes of X-ray bursts:

- Type I: Normal
  - t_b~10-100 s, $E_b \sim 10^{39}$ erg
  - pure He or mixed H/He
- Type II: Intermediately long
  - t_b~up to hr, $E_b \sim 10^{40}$-10^{41}erg
  - thick layer of pure helium
- Type III: superbursts
  - several hours 10^{42}erg
  - C ignition ?

N. Degenaar

Thermo-nuclear bursts oscillations

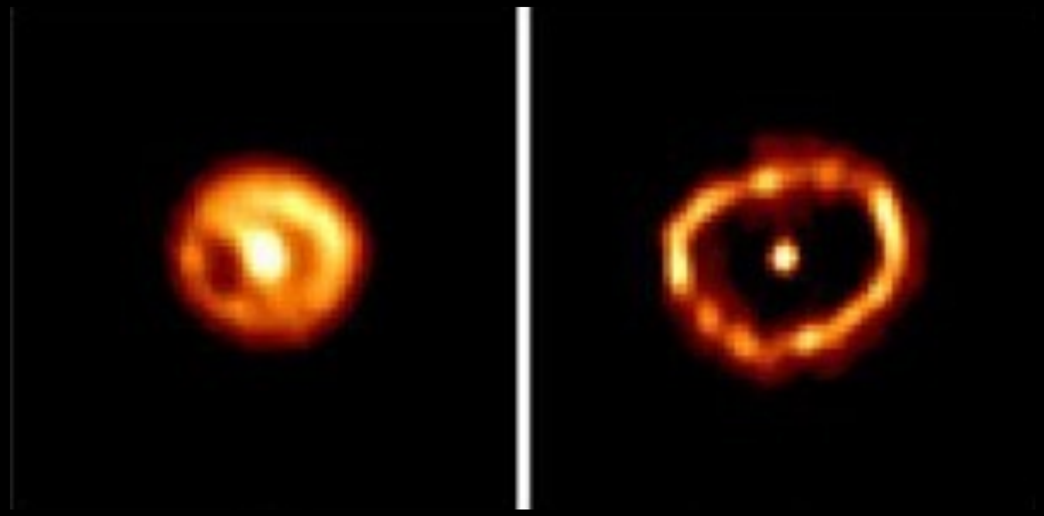




see Watts 2012

burst osicllation in 4U 1702-429

Thermonuclear explosions in accreting white dwarfs: Novae



- Accreted gas (Hydrogen) accumulates on the surface of WD, becomes degenerate, and explosive ignition of H.

- Brightness increase by 6 to 19 magnitudes. Power ~10^{44} erg over a few days to a few month (T1 SN~ 10^{51} ergs)

- Entire H layer is ejected in nova shell ~1500 km/s , leaving nova free of H

- Whole process expected to starts again after 10000 to 100000 yrs (Classical Novae), 8 sources observed with shorter (10 -100 yrs) recurrence time.

Smith 2007

References

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