Quasi Stars

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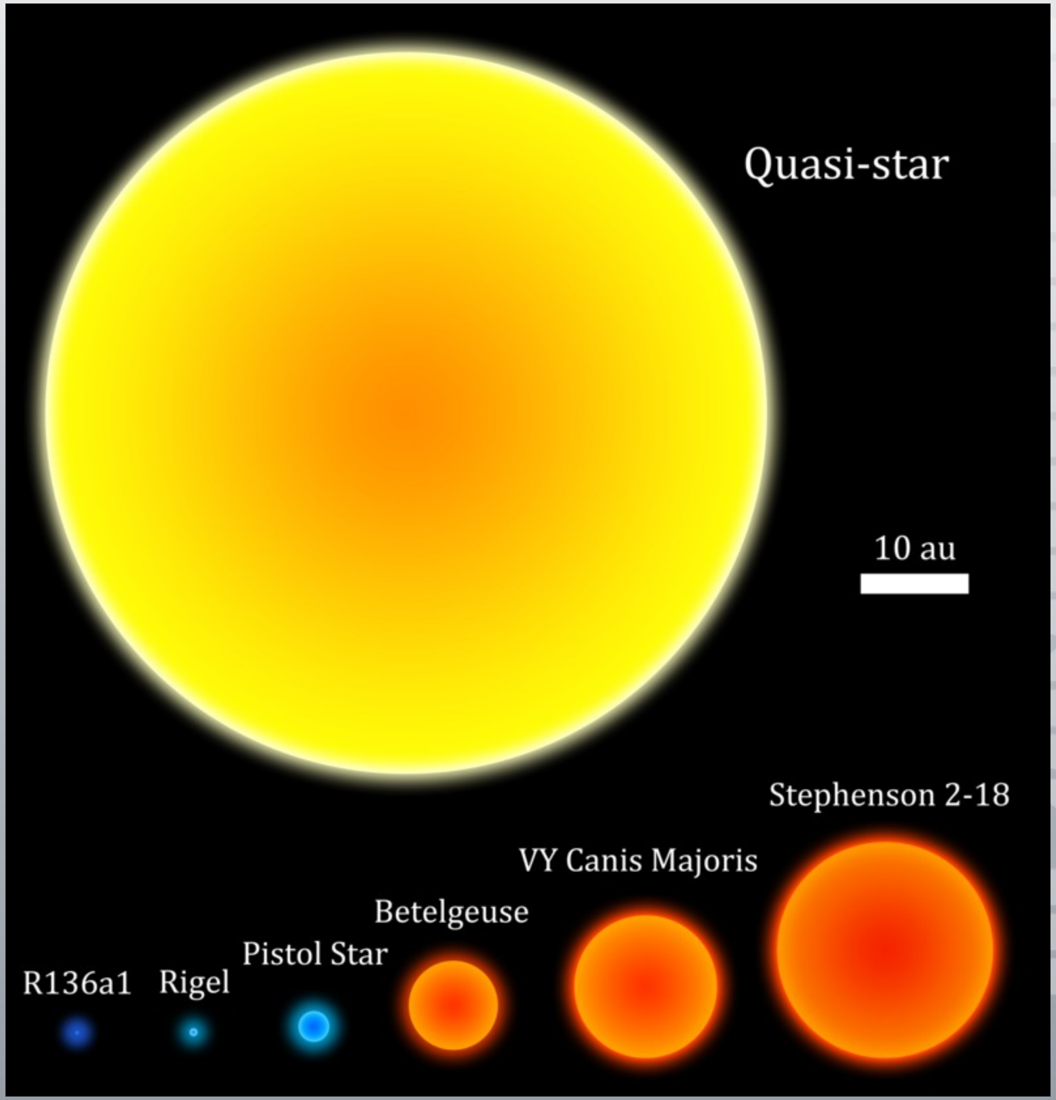
Contents

Definition of a Quasi-star

- Quasi-star (hypothetical concept)
  - Extremely bright and massive star in the early universe
  - Unlike regular stars these were powered by a central black hole

- Quasi-star could be a solution for the SMBH problem
  - Why SMBH appear much earlier than traditional theories expect

=> Lets look into in more detail

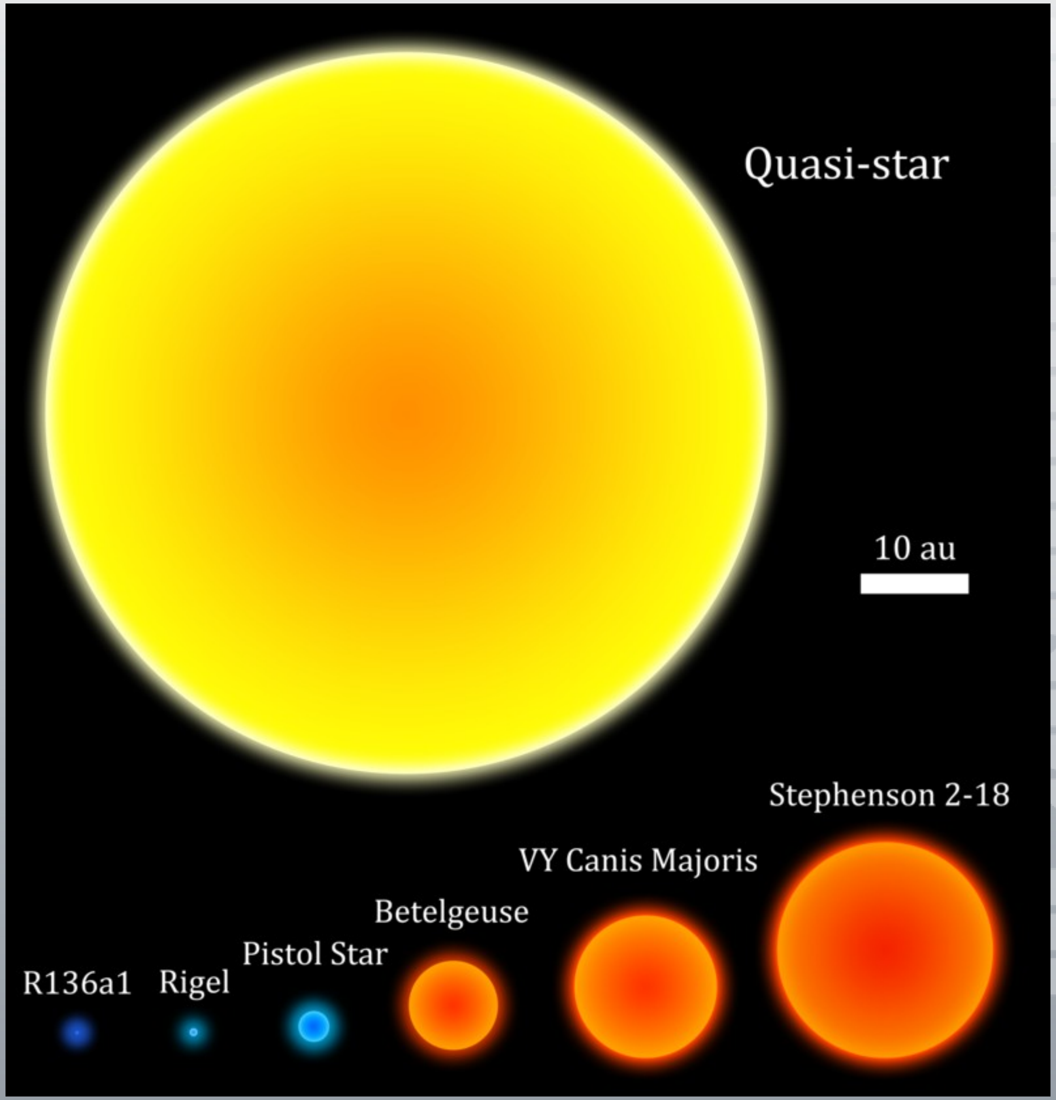


General Model

- Model of a quasi-star
  - Calculated by Begelman, Rossi and Armitage
  - To estimate
    - Maximum BH mass possible
    - Photospheric temperature
    - Photospheric luminosity

=> So that next-generation observatories could find such objects

=> Lets look at the general features of the quasi star in this model



General Model

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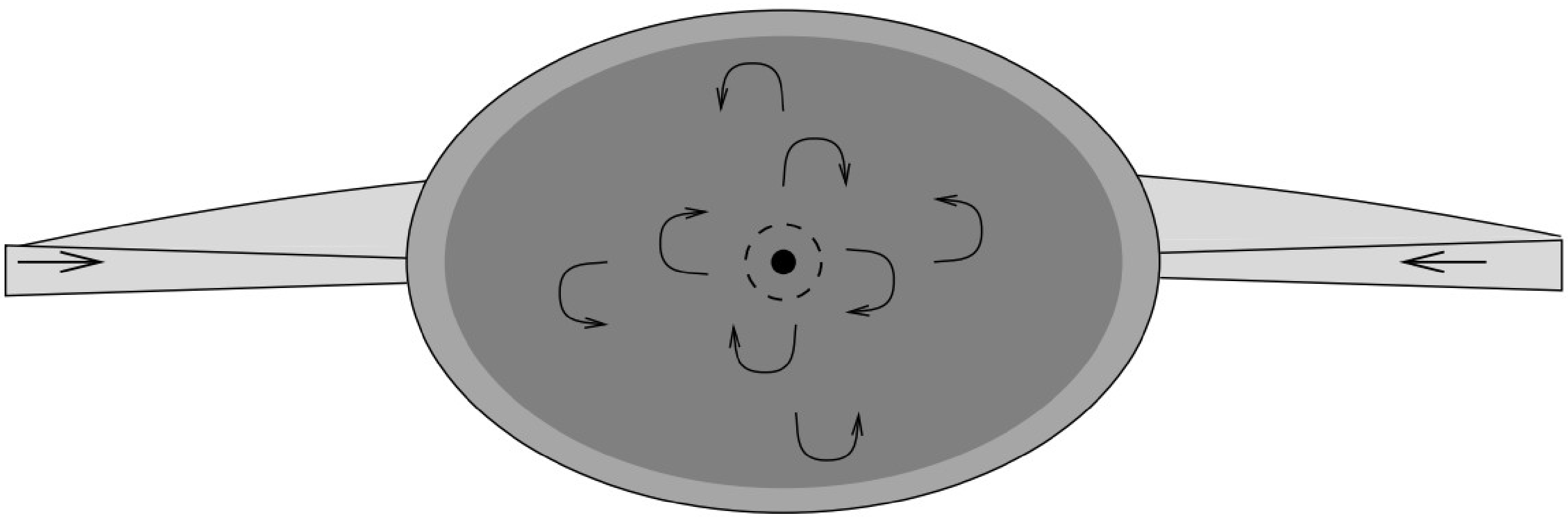


- Spherically symmetric Pop. III star
  - Created in the very early Universe
  - Made out of pristine gases
  - Unlike today's star
    - No metal pollution
    - With on-going disc accretion

- Creation of central black hole (dot)
  - Black hole grows from the envelope

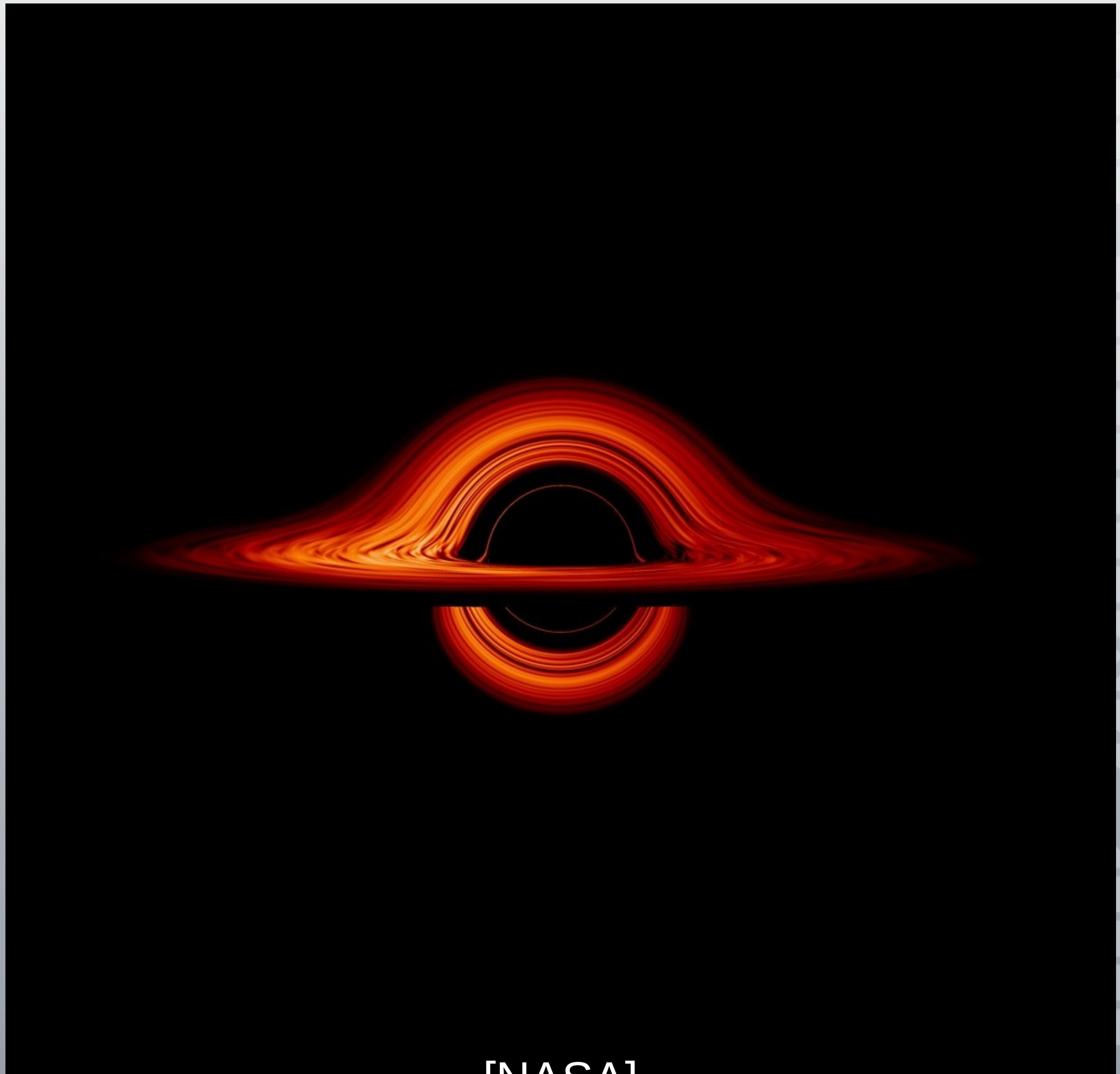
- Limited by the Eddington luminosity
  - Maximum Luminosity of a stable radiating object

General Model

- The quasi-stars accretion rate will be limited by the Eddington luminosity for the stars total mass

- Accretion rate
  - Massive object attracts mass
  - Accretion disc can form

- Super-Eddington luminosities
  - Radiation dominates Gravity
  - Blowing the envelope away



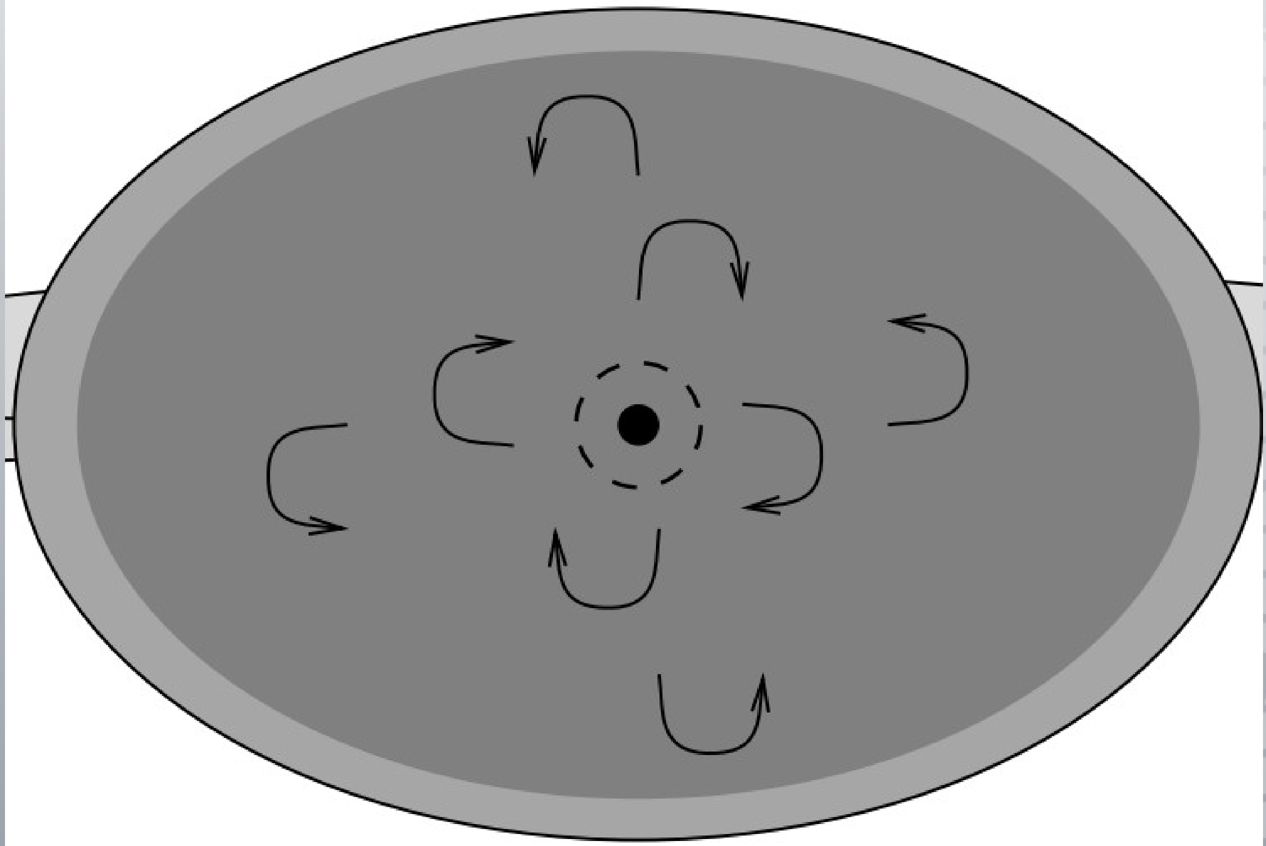
[NASA]

General Model

- Assuming hydrostatic equilibrium
  - Not exceed the Eddington Limit

- The Black holes luminosity
  - Convectively transported through the central zone of the envelope (dark grey) to the transition zone
  - Where convection becomes Inefficient and radiation takes over
    - There the radiation zone (light grey) begins

=> Go to the analytical model



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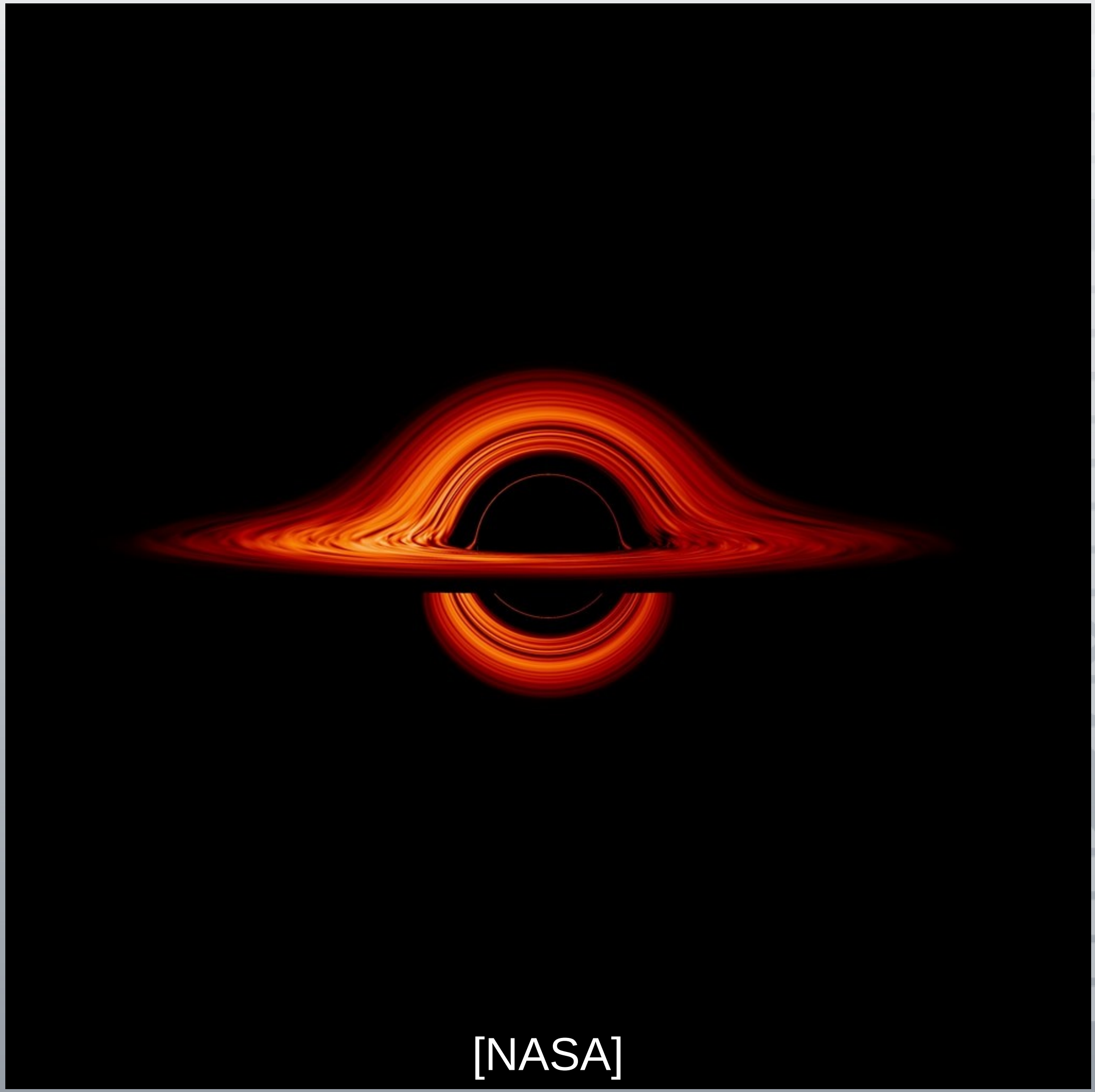
Analytic model

- The envelope mass $M_* >> M_{BH}$
  - Spherically symmetric placed

- Luminosity is exclusively generated by the BHs accretion disc
  - Fusion will be neglected
    - Black hole accretion is energetically much more efficient than fusion
    - Very small effect on the opacity

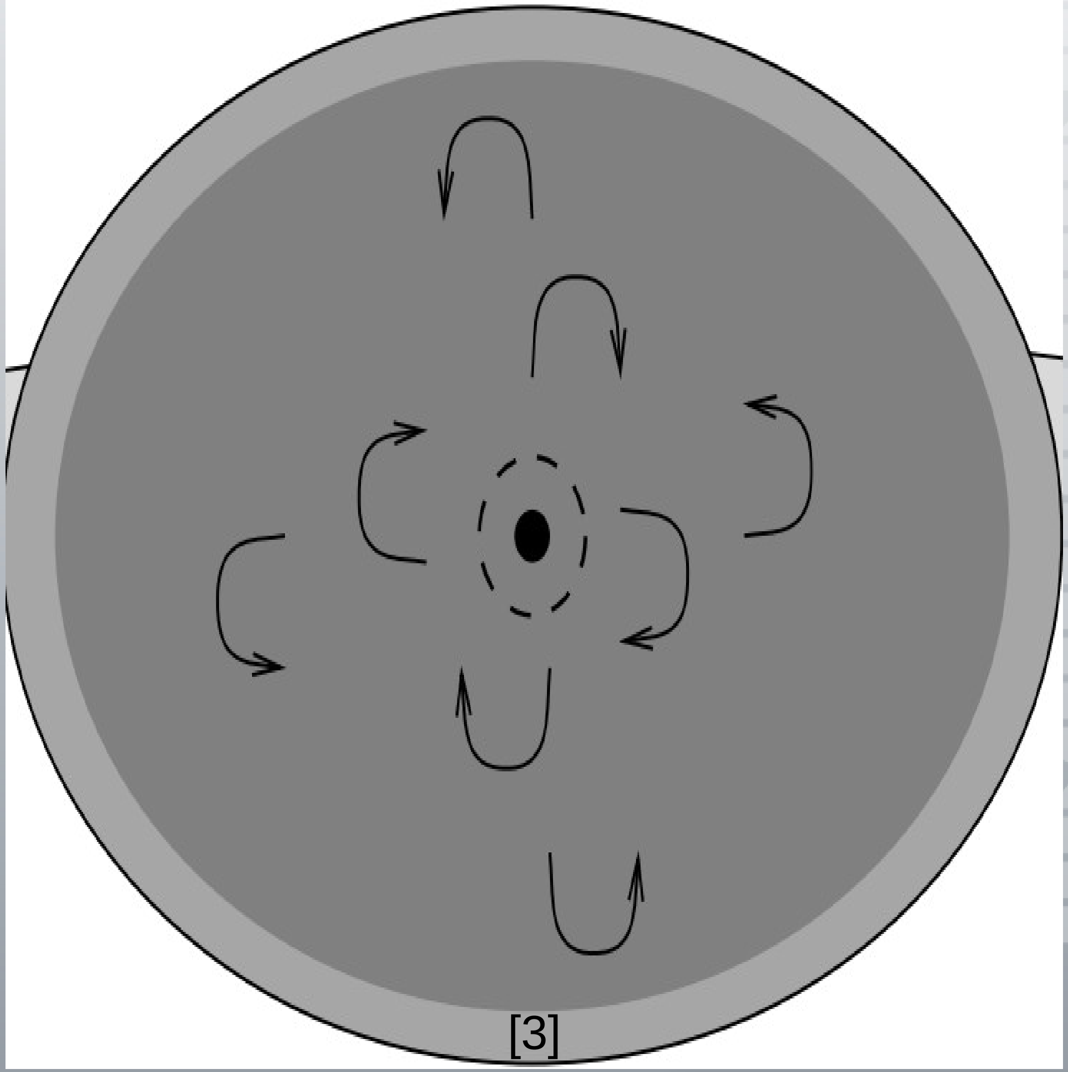
=> How does the inner region of the quasi star look like?



Analytic model

- Central regions of the envelope
  - Electron scattering opacity dominates
  - Envelops mass ≥ 10^3 $M_\odot$
    - Quasi-star envelopes are primarily supported by radiation pressure
  - Strongly convective
    - Can be described through $n = 3$ ($\gamma = 4/3$) polytropes
    - With uniform in density(ρ_c), pressure(p_c) and temperature(T_c)

=> Therefore the use of Bondi accretion is justified (similar boundary conditions)



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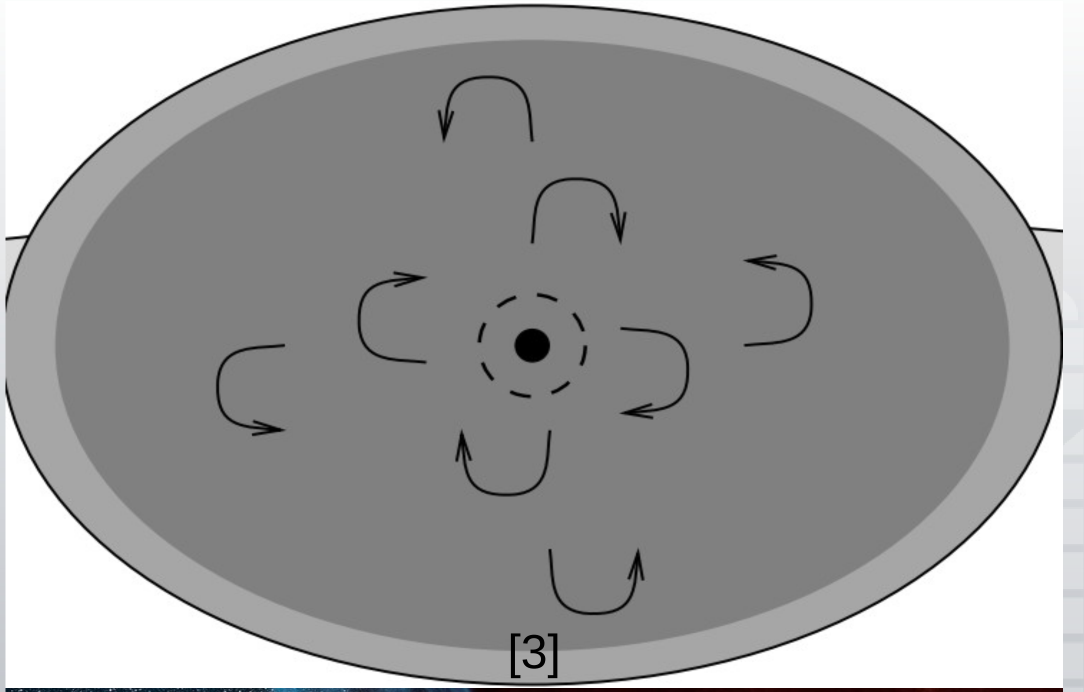
Analytic model

- Bondi accretion: Spherical accretion onto a compact object travelling through an interstellar Medium

$$\dot{M}_{Bo} = \frac{4\pi (G M_{BH})^2 \rho_c}{(c_c^3 \sqrt{2})} \qquad R_{Bo} = G \frac{M_{BH}}{c_c^2}$$

- Bondi Radius: The distance at which matter can be gravitationally captured (dotted line)
  - Absence of an efficient exhaust
    - Like jet or evacuated funnel
    - Energy must be transported beyond R_{Bo}

=>But only realistic in the complete absence of rotation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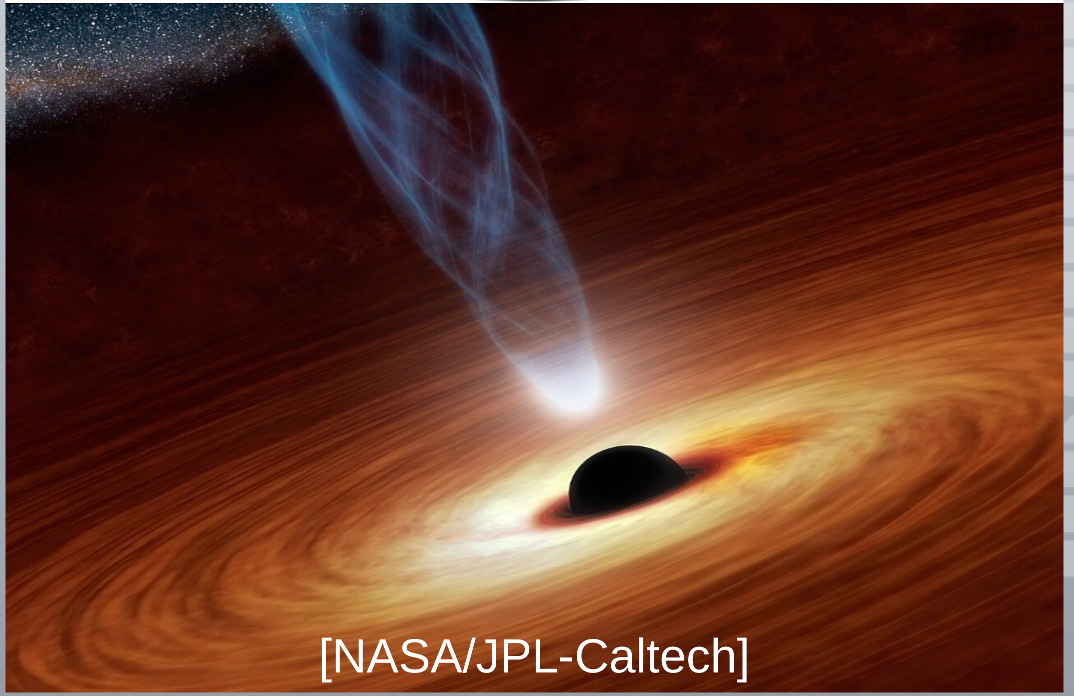

[NASA/JPL-Caltech]

Analytic model

- Thick accretion disc around the BH
  - Where angular momentum transport is needed to create accretion

=> Efficiency of the BHs accretion disc will be modified by the parameter α

- The parameter α < 1 accounts for energy sinks within the Bondi radius
  - Inefficient convection, presence of outflows, etc.
    - So any inefficiency of angular momentum transport

$$R_{Bo}=G\frac{M_{BH}}{c_c^2} \quad c_c=\left(\frac{4p_c}{3\rho_c}\right)^{1/2} \quad p_c=\frac{aT^4}{3}$$

$$\dot{M}_{Bo}=\frac{4\pi(GM_{BH})^2\rho_c}{(c_c^3\sqrt{2})}$$

$$L_{BH}=\alpha\dot{M}_{BH}c^2 \quad \alpha\approx O(0.1)$$

$$L_{Bh}=4\pi G^2\alpha M_{BH}^2\rho_c^{3/2}p_c^{-1/2}$$

$$\rightarrow L_{Bh}=6.6\cdot10^{42}\alpha m_{BH}^2 m_*^{-3/4}T_6^{5/2}\,erg\,s^{-1}$$

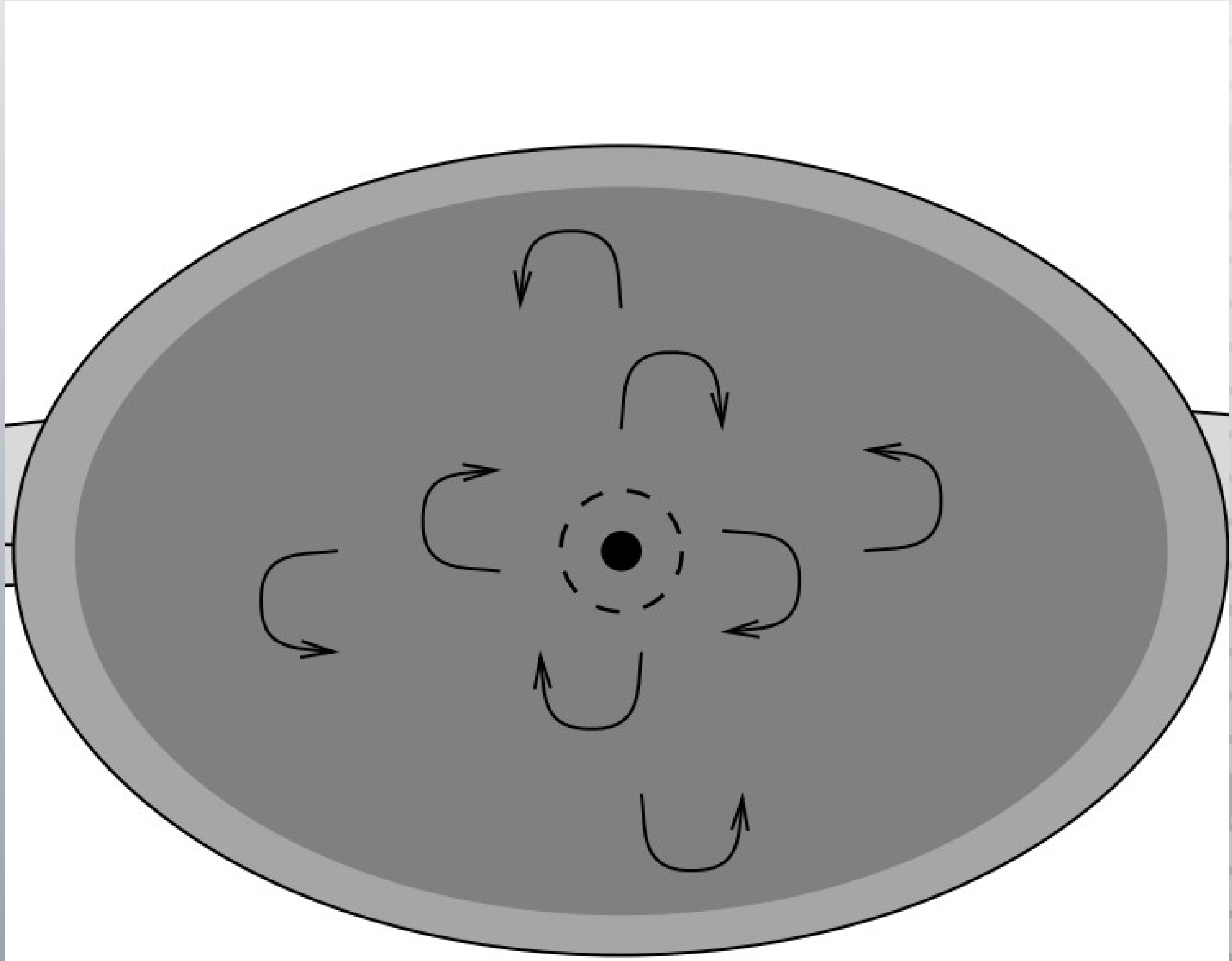
Analytic model

- Expecting L_{BH} to be very close to the Eddington limit at the transition

- Assuming the convective zone encompasses nearly the entire mass and radius of the envelope

=> Radius and mass of the radiative layer are negligible in comparision to the envelopes mass and radius

=> Estimates through polytropic relations: $R_{quasi\ star} \approx 10^2–10^3$ au, $T_{quasi\ star} \approx O(10^3 K)$ and $T_{ph} \approx 10^3$ K



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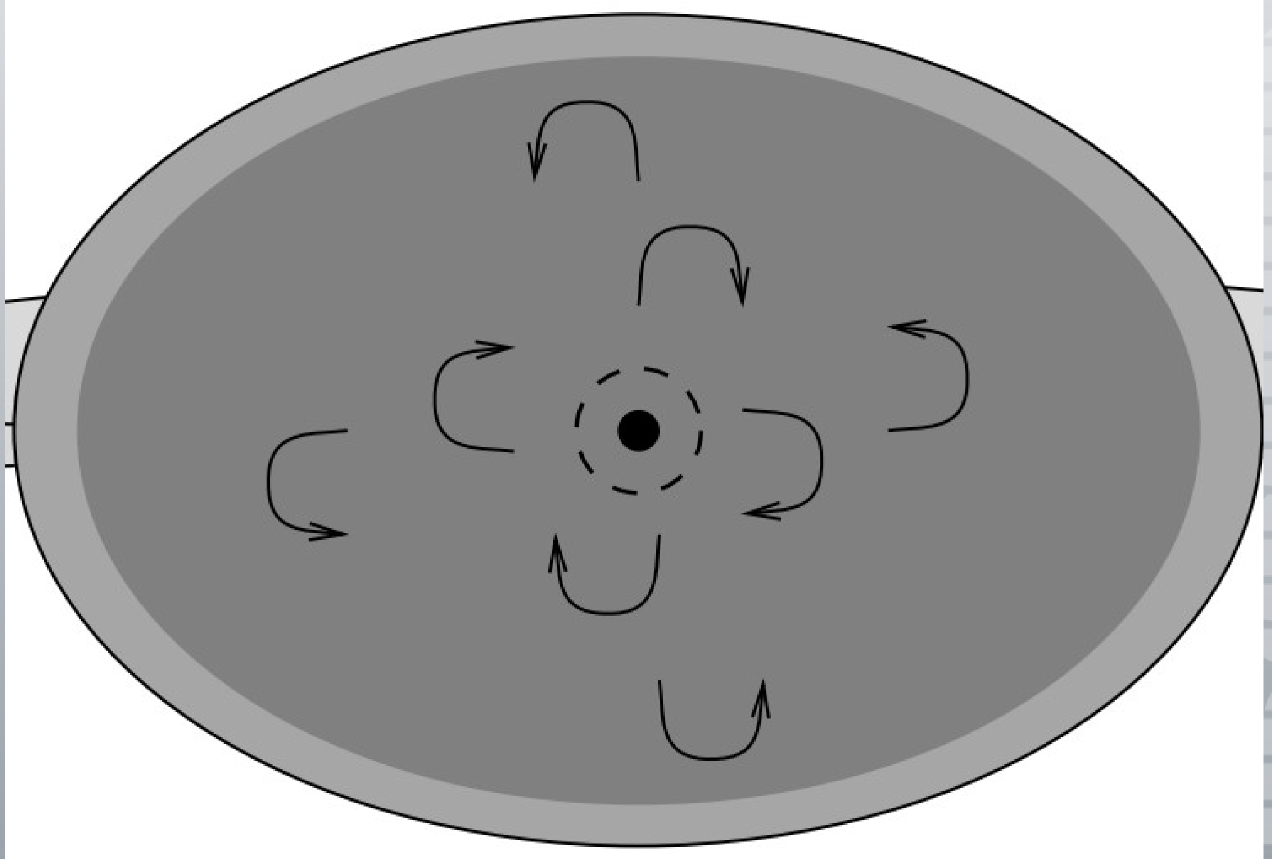
Analytic model

- Radiative layer (light grey)
  - Opacity determines the layer structure of the layer
  - Mainly electron scattering
  - Metals would increase the opacity
  - Opacity is based on Pop III opacity tables of Mayer & Duschl from 2005 (short: MD05)

$$Fitting: \kappa(T) = \frac{\kappa_0}{1+(T/T_0)^s}$$

=> The opacity is only temperature dependent in this model



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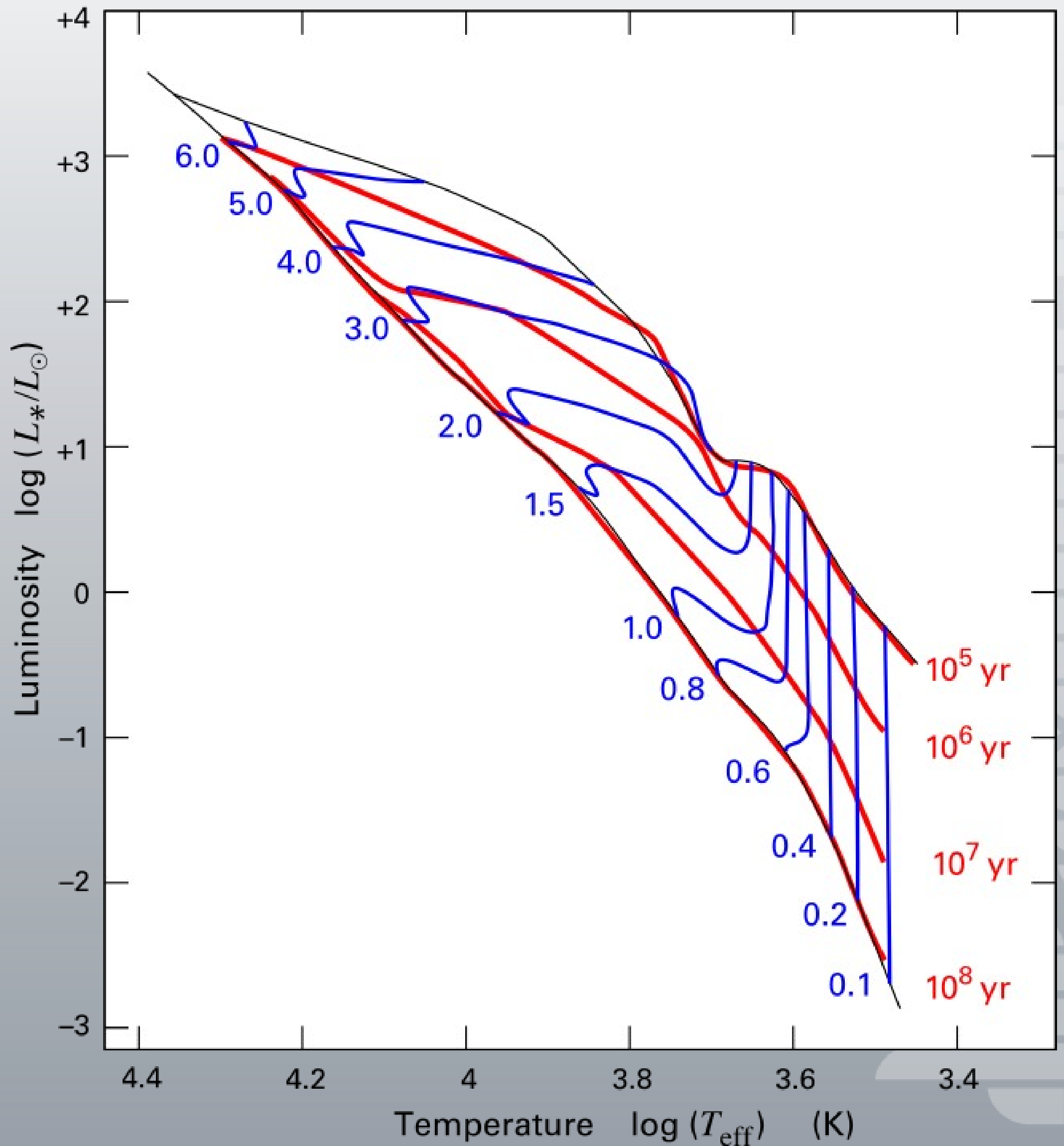
Analytic model

- Eddington factor l_{tr} at the transition radius
  - Gravity to radiation pressure ratio
  - Must be below 1 to avoid the dispersion of the quasi-star through building up pressure
  - $l_{tr} < 1$ = hydrostatic equilibrium
  - $l_{tr} > 1$ = Opacity crises

=> $T_{ph,min} \approx 4500K$, $T_{tr,min} \approx 55000K$

  - Analogous to the “Hayashi track“
  - Limits the temperatures of red giants and convective protostars



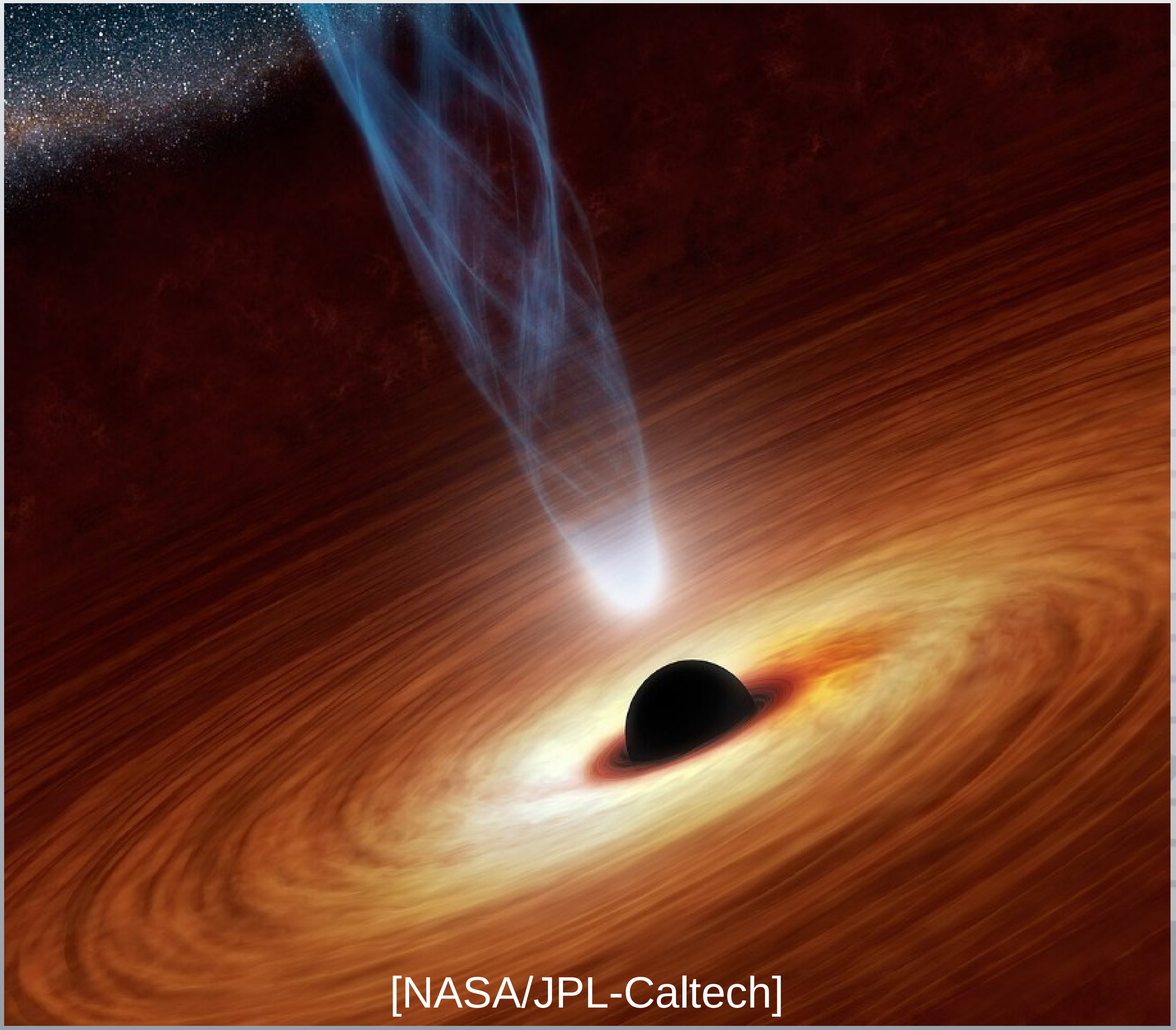
[The Formation of Stars]

Analytic model

- Analytic model
  - Decent estimate for certain features of the stars structure
  - Opacity ignores bound–free and free–free absorption at $T > 8 \cdot 10^3$ K
  - Pop III opacities are more complex than in the analytical model
  - Mass and thickness of the radiative layer can't be neglected

$$\frac{M_{Rad}}{M_*} \approx 0.2 \qquad \frac{R_{Rad}}{R_*} \approx 0.7$$

=> Upgrading to an numerical model



[NASA/JPL-Caltech]

Numerical model

- Assume the Quasi-star as a static and spherically symmetric object
  - Equation of hydrostatic equilibrium (I.)
  - Equation of enclosed mass (II.)
  - Equation of state (III.)
  - Equation of the temperature gradient (IV.)

- To solve this system by integration
  - T_{ph},α and M_{BH} are constant
  - Guess the photospheric radius R_* and the Quasi-star mass M_*

=> Still have to determine the quasi stars opacity

$$(I.)\ \frac{dp}{dr}=\frac{-G\,M(r)\,\rho}{r^2}$$

$$(II.)\ \frac{dM}{dr}=4\pi\rho r^2$$

$$(III.)\ p=p_g+p_r=\frac{\rho k T}{\mu}+\frac{1}{3}aT^4$$

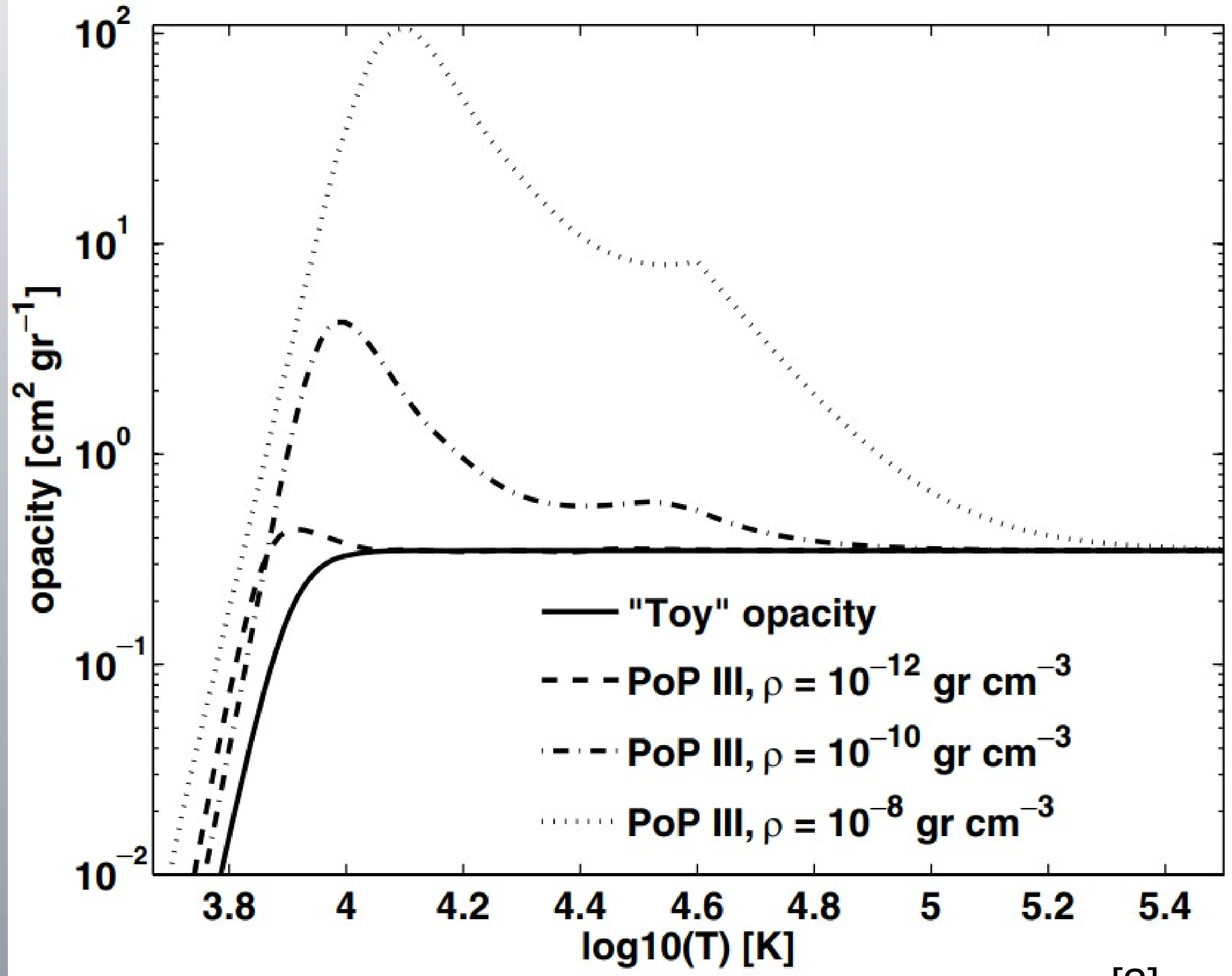
$$(IV.)\ \frac{dT}{dr}=\frac{dT_{rad}}{dr}-\frac{min\left(\frac{-dT_{rad}}{dr},\frac{-dT_{ad}}{dr}\right)+\frac{dT_{rad}}{dr}}{1+x^{10}}$$

$$F_{con_{max}}=\beta c_s p_r=0.1\sqrt{\frac{p}{\rho}}\,p_r \qquad x=\frac{F}{F_{con,max}}$$

Numerical model

- “Toy model“ or analytic model
  - Ignores density dependence
  - Reasonable approximation
    - At low density
    - Very poor at higher density and at floor value (10^4K)

- Pop III opacity (MD05)
  - Opacity increases with over the analytic fit at increasing density
  - Bound–free peak at $T = 10^4$ K
    - Due to hydrogen ionization
  - Much better option



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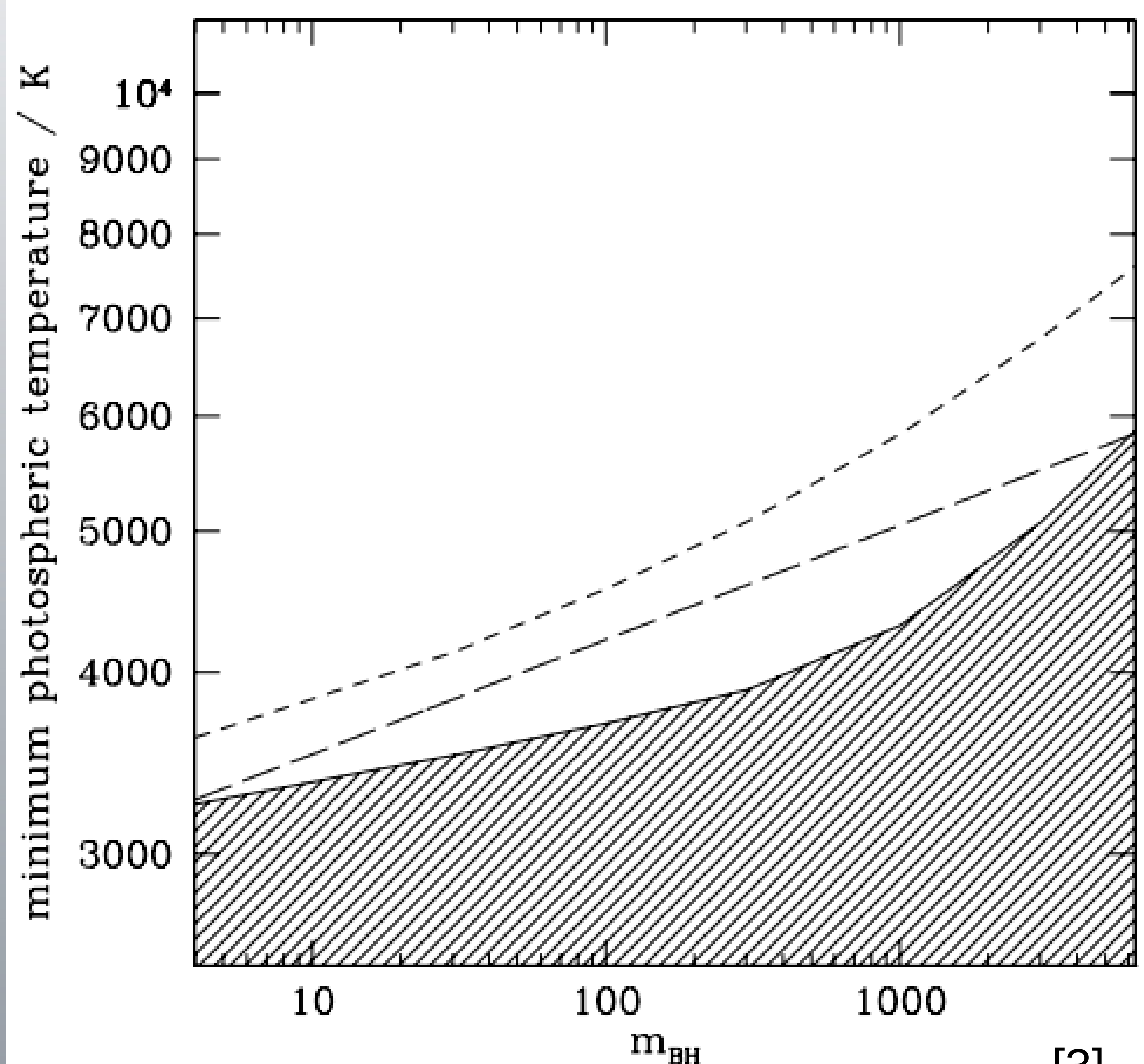
Numerical model

- Again a minimal T_{ph} can be found at a given α and M_{BH}
  - Ensuring sub-Eddington luminosity at the transition radius

- Numerical models with the “Toy” opacity (short-dashed line)

- Analytic estimate(long-dashed line)
  - Combining both analytic estimates

- Pop III opacity (solid line)
  - Static quasi-star models do not exisist under this line



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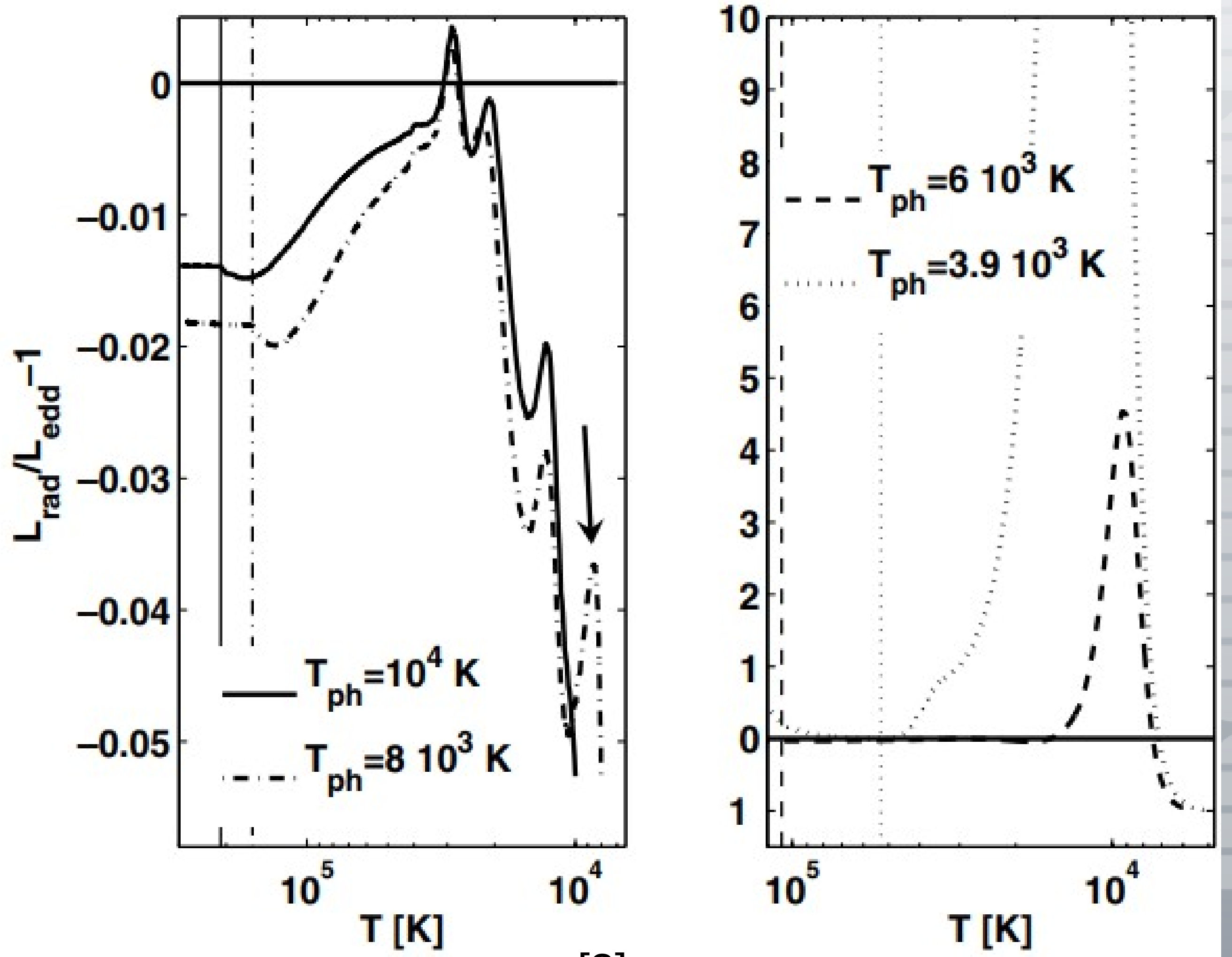
Numerical model

- Local Eddington ratio at a constant black hole mass
  - Focusing on the radiative zone
  - Some super-Eddington peaks
    - For decreasing T_{ph} at the Bound–free peak($T = 10^4$ K)
  - Narrow peak at $T = 3*10^4$ K
    - For only $T_{ph} \approx 4000$ K

=> There are still local super-Eddington fluxes for $T_{ph} > T_{min}$

=> How does this effect our star ?



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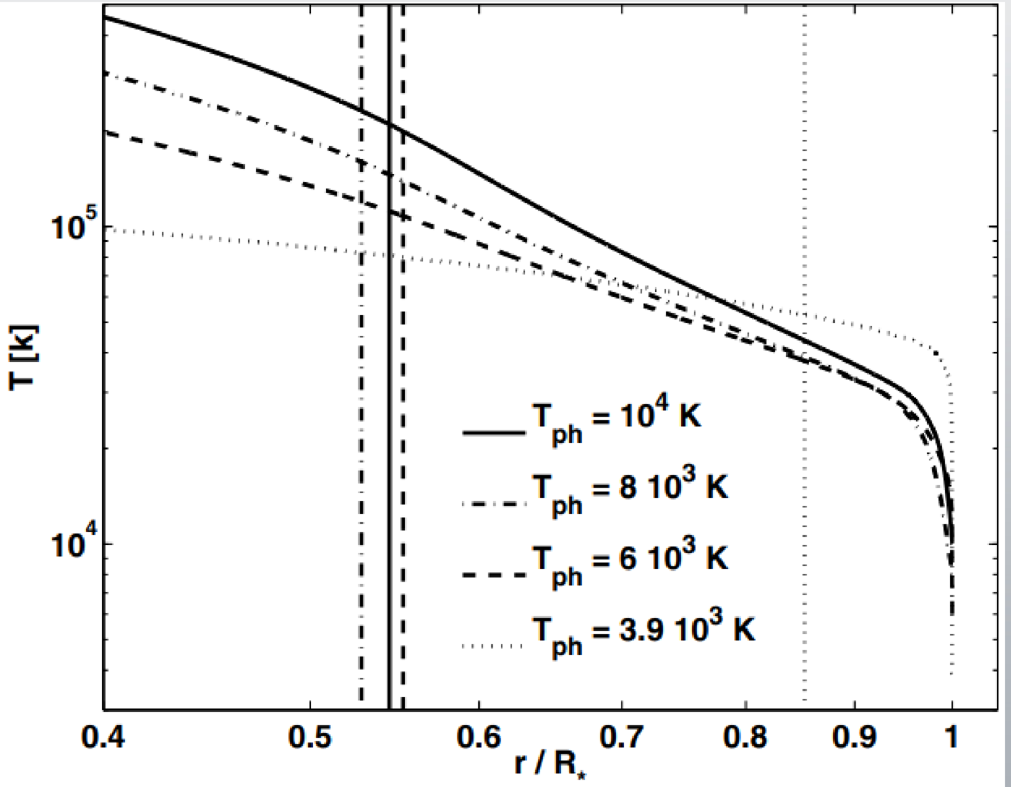
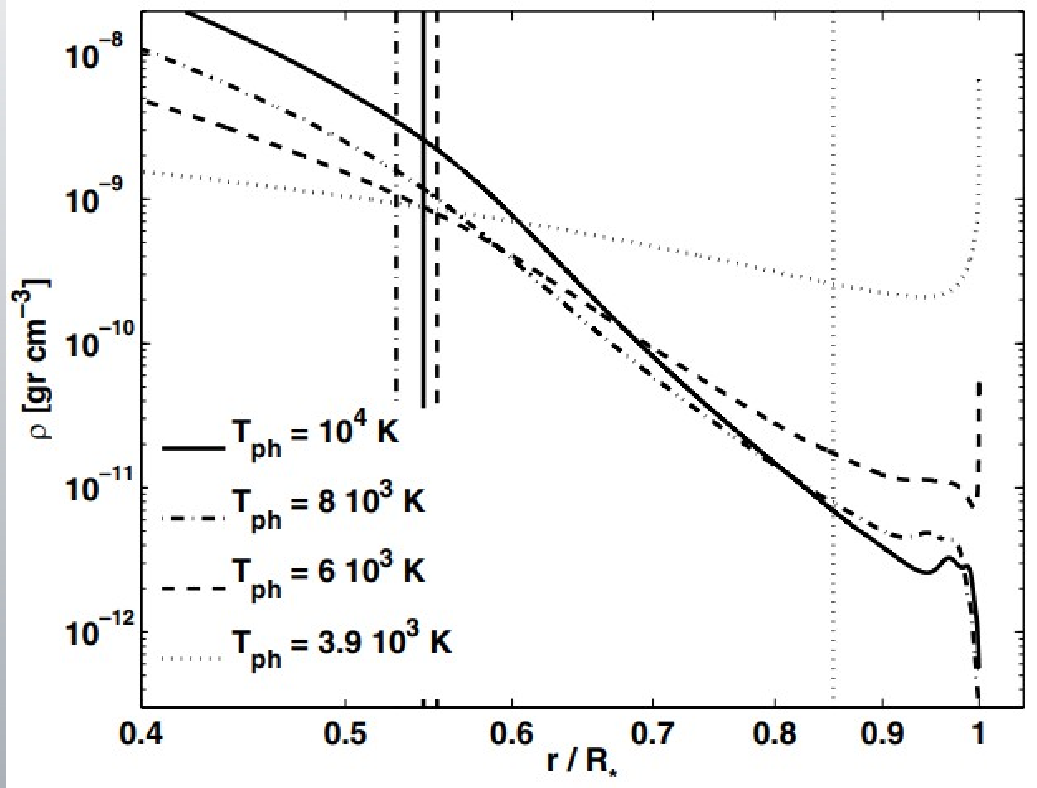
Numerical model





- Radial profiles of temperature and density of earlier models
  - Local density inversion forms
  - Meaning the density gradient becomes positive there

=> Radiative force substantially exceeds the gravitational force

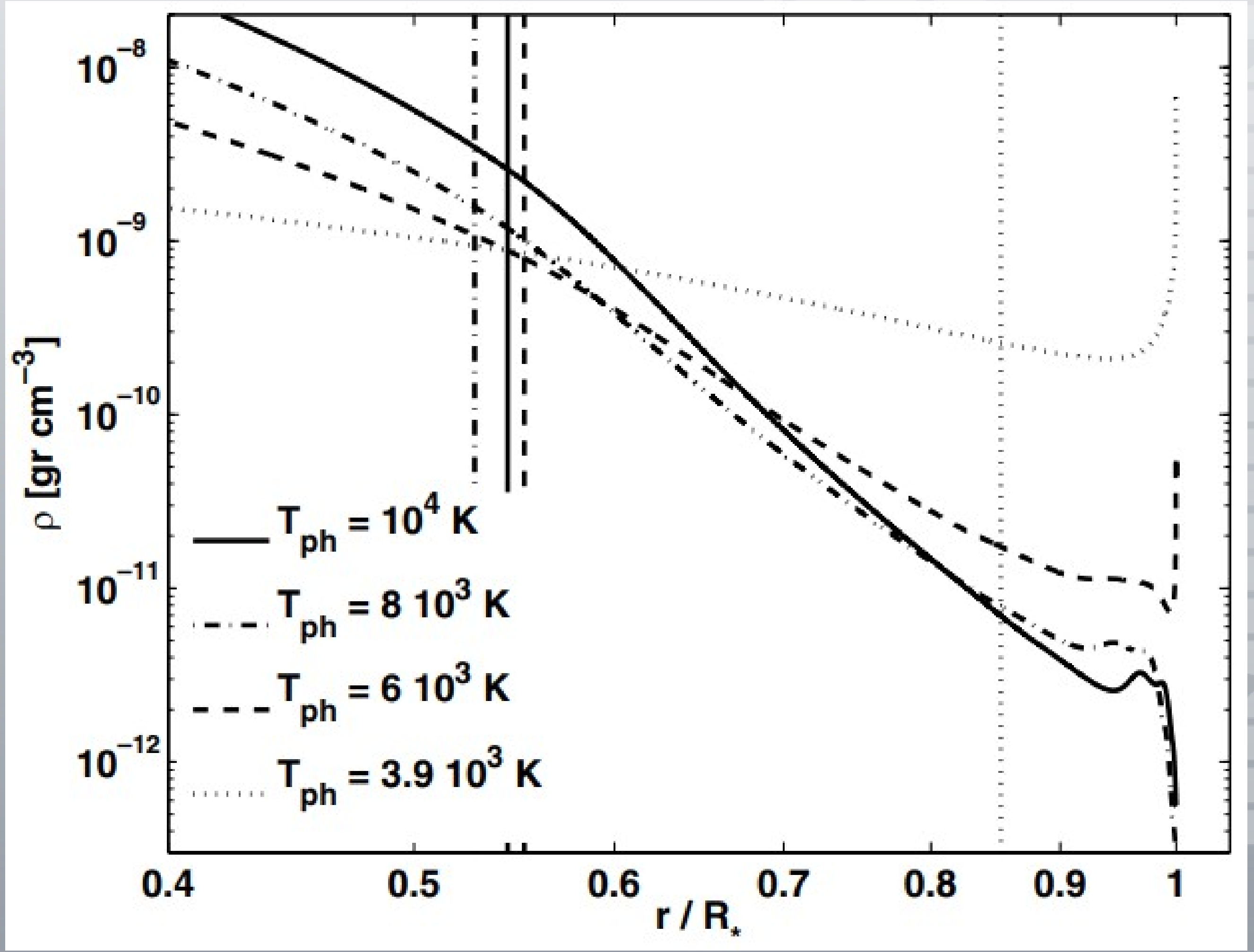
=> At the same time, the temperature gradient steepens

Numerical model

- Existence of density inversions could make the system unstable
  - It's very complicated to to estimate the mass-loss rate
  - Many possible outcomes

- Presuming for these zones
  - Creation large-scale circulation
  - Not dissimilar to convection
  - With little or no mass-loss

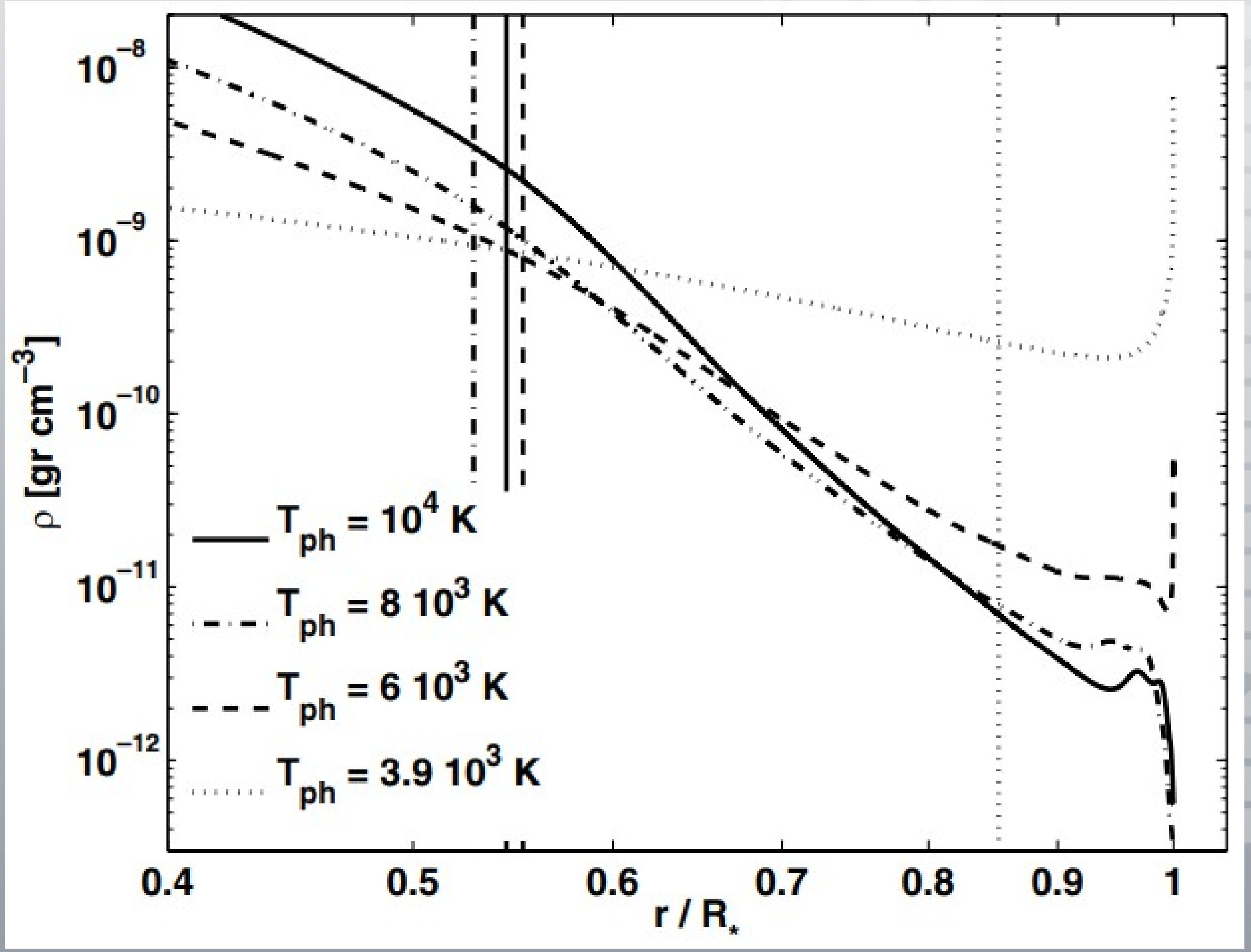
=> We adopt T_{min} as an estimate for the minimum temperature a quasi-star can sustain



Numerical model

- Numerical model
  - Confirms the existence of a minimum temperature at which the quasi star is stable
  - Numerical integration reveals the existence of narrow regions with locally super-Eddington fluxes
    - Creating local density inversions
    - With complex and unsure behaviour

=> Look at the co-evolution model to find the final mass of the BH



Co-Evolution

- Model the co-evolution of the BH and envelope as a series of equilibrium model
  - Short thermal time-scale allows quasi-statical changes
  - BH growth is confined by the Eddington limit at $T_{ph} > T_{min}$ (I.)

- Analytic Co-Evolution model
  - Constant quasi-star accretion rate at 0.1 $\dot{m}_{0.1} M_{\odot} yr^{-1}$ (I.)
  - Analytic estimates for the
    - Quasi-star mass (II.)
    - Black hole mass (III.)

$$(I.)\ \dot{m}_{BH} = 2.5 \cdot 10^{-8} \epsilon_{0.1}^{-1} m_* M_{\odot} yr^{-1}$$

$$m_{BH} = 1.2 \cdot 10^{-7} \epsilon_{0.1}^{-1} m_*^2 \dot{m}_{0.1}^{-1}$$

$$l_{tr} = \tilde{\kappa} = 1 \qquad \epsilon = accretion\ efficiency$$

$$(II.)\ m_{*0} = 1.8 \times 10^5 \epsilon_{0.1}^{8/9} \dot{m}_{0.1}^{-8/9} \alpha_{0.1}^{-4/9} T_{m,4}^{-20/9}$$

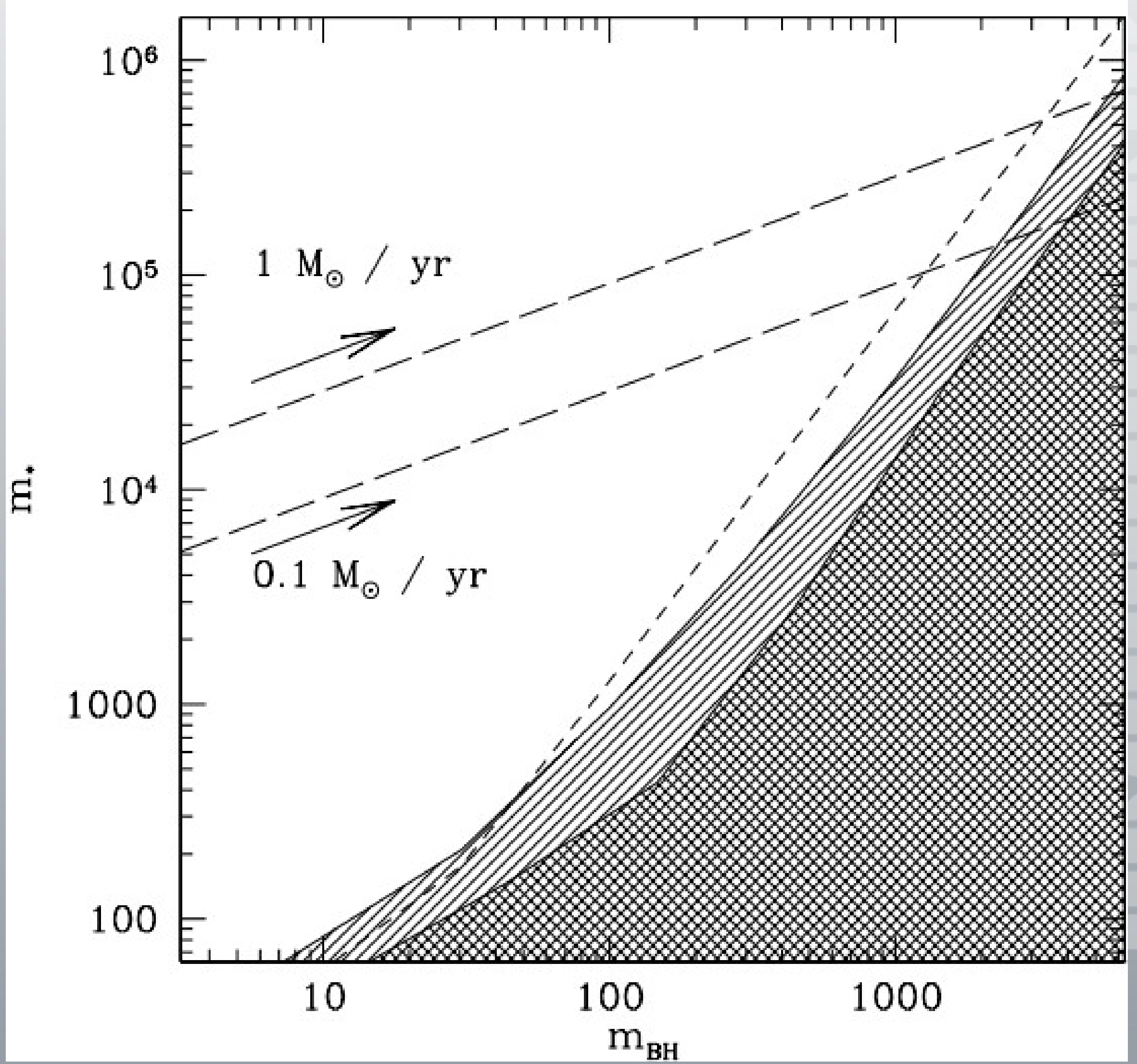
$$(III.)\ m_{BH,0} = 3.9 \cdot 10^3 \epsilon_{0.1}^{7/9} \dot{m}_{0.1}^{-7/9} \alpha_{0.1}^{-8/9} T_{m,4}^{-40/9}$$

Co-Evolution

- To check these analytic results
  - Numerically solve this set of equations while using
    - The analytic steady growth track (I.)
    - The numerically computed $T_{min,ph}$

$$\frac{dM_*}{dt} = \dot{M}_*$$

$$\frac{dM_{BH}}{dt} = \frac{L_{BH}(M_*, M_{BH}, \alpha)}{\epsilon c^2}$$

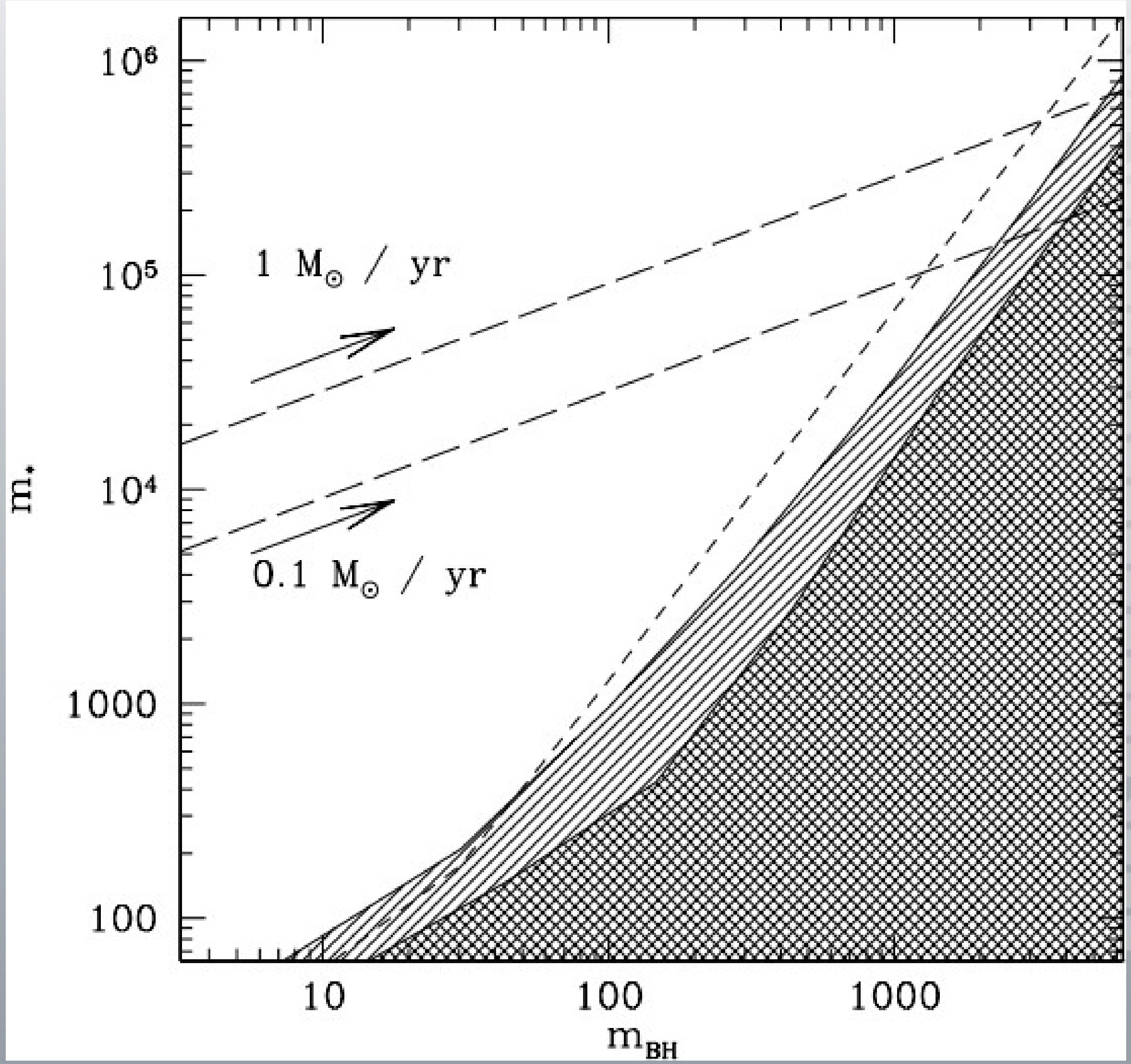


Co-Evolution

- Envelope mass versus BH mass at the minimum photospheric temperature
  - Two growth tracks
  - Short dashed line is the ‘toy’ opacity
  - Solid lines are numerical opacitys
    - Lighter shaded region is for α = 0.1
    - Darker shaded region is for α = 0.05

=> Final M_{BH} is higher for higher accretion rates on to the envelope and lower parameters α

=> Final M_{BH} is predicted to be at least a few thousand solar masses

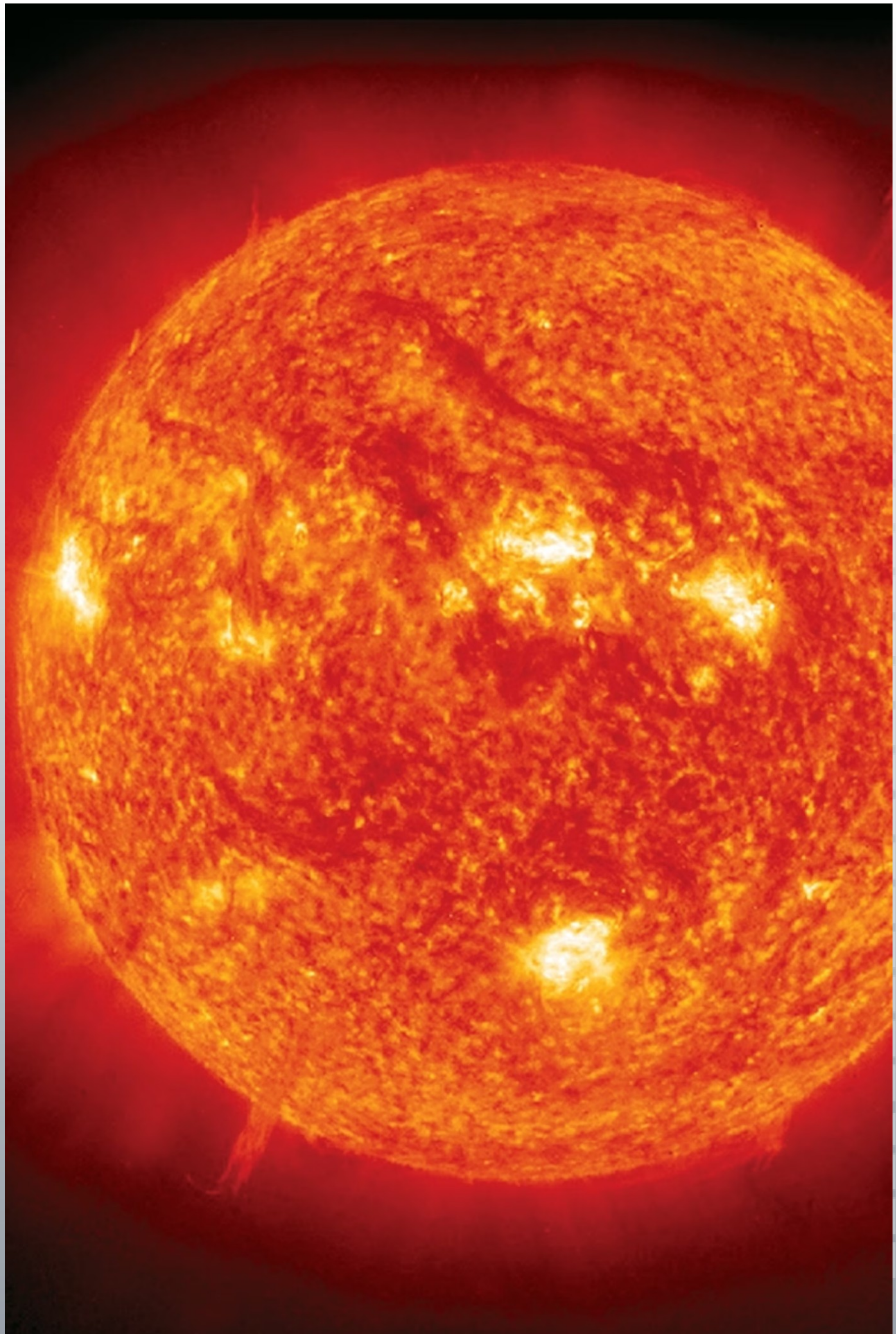


Conclusion

- Theoretical model of a quasi-star
  - Contains some uncertainties in its simplifications as well as its assumptions
  - Analytic and numerical model
    - Show the existence of a minimum photospheric temperature of around 4000 – 5000 K
    - Show that the creation of seed black holes at about a few 10^3-10^4 $M_\odot$ is possible

=> Possible solution for SMBH problem

=> Have to wait for experimental evidence (or a better theory)



[National Geographic]

Sources

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