Black Hole Accretion Disks

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Clermont-Ferrand, 17 May 2019

Black Holes

Black Holes in Newtonian Gravity

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- 1784 — John Michel. Escape velocity of a «dark star» equals speed of light:

  $$0 = E_{\text{tot}} = E_{\text{grav}} + E_{kin} = -\frac{GMm}{R_\star} + \frac{mv_{\text{esc}}^2}{2}, \;\; \text{for } v_{\text{esc}} = c: \;\; R_\star = \frac{2GM}{c^2}$$

  For Earth mass R ~ 1 cm, for Solar mass (2×10^{33} g) R ~ 3 km.

- 1795 — Pierre-Simon de Laplace discusses it in «Exposition du Systeme du Monde»

Black Holes in General Relativity

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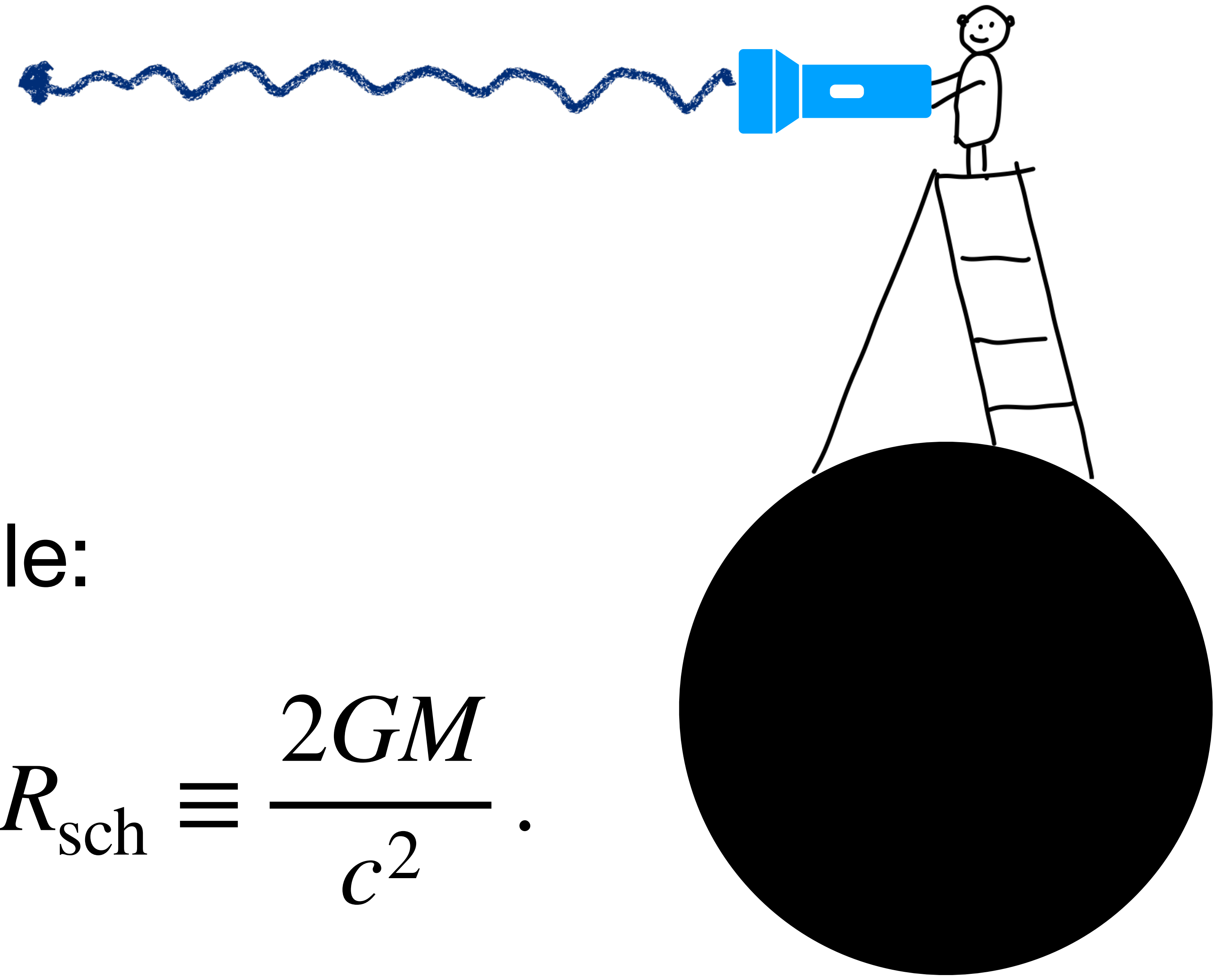
Schwarzschild radius is the event horizon radius of non-rotating black hole,
three Schwarzschild radii is its innermost stable circular orbit (ISCO).

Black Holes in General Relativity



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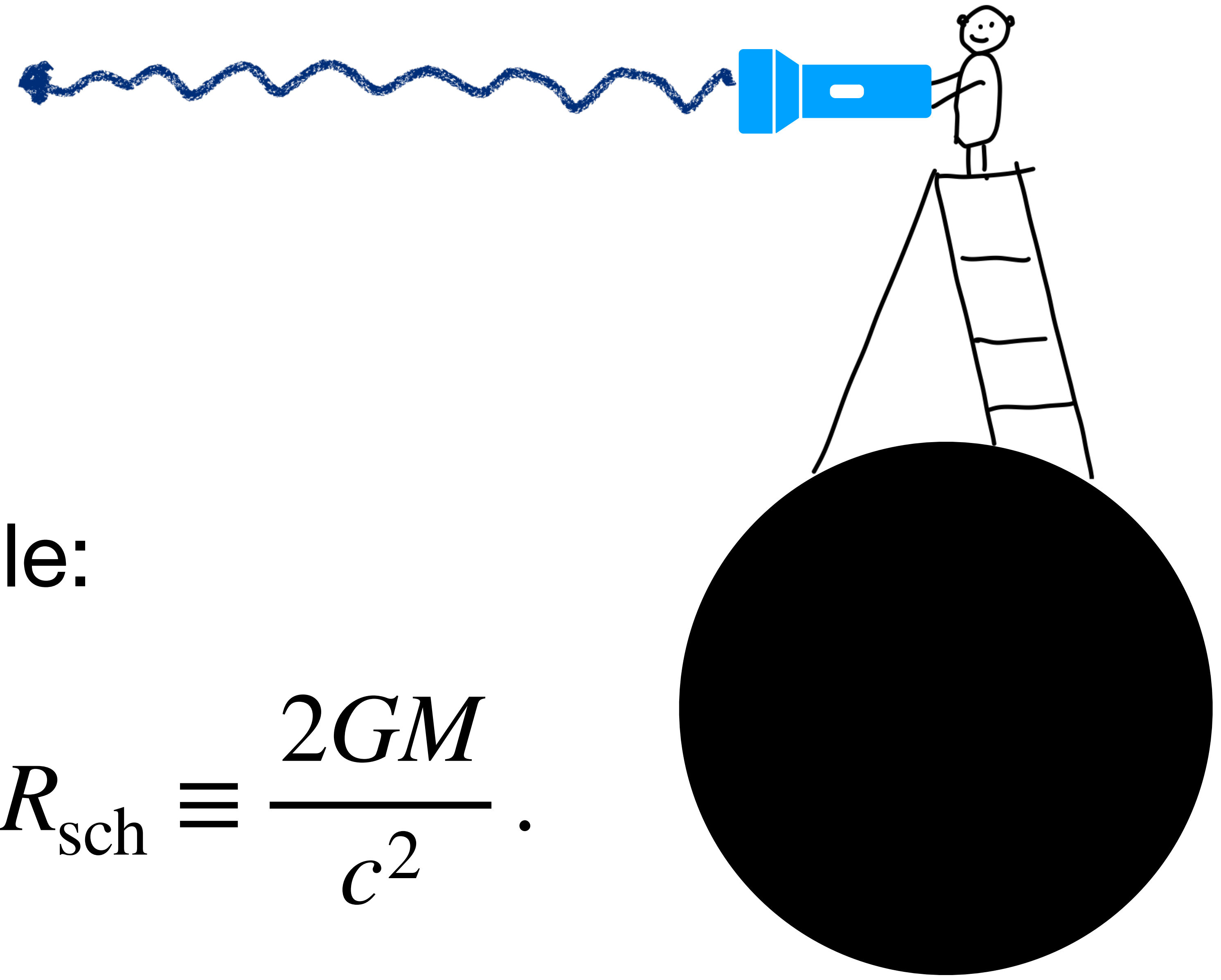

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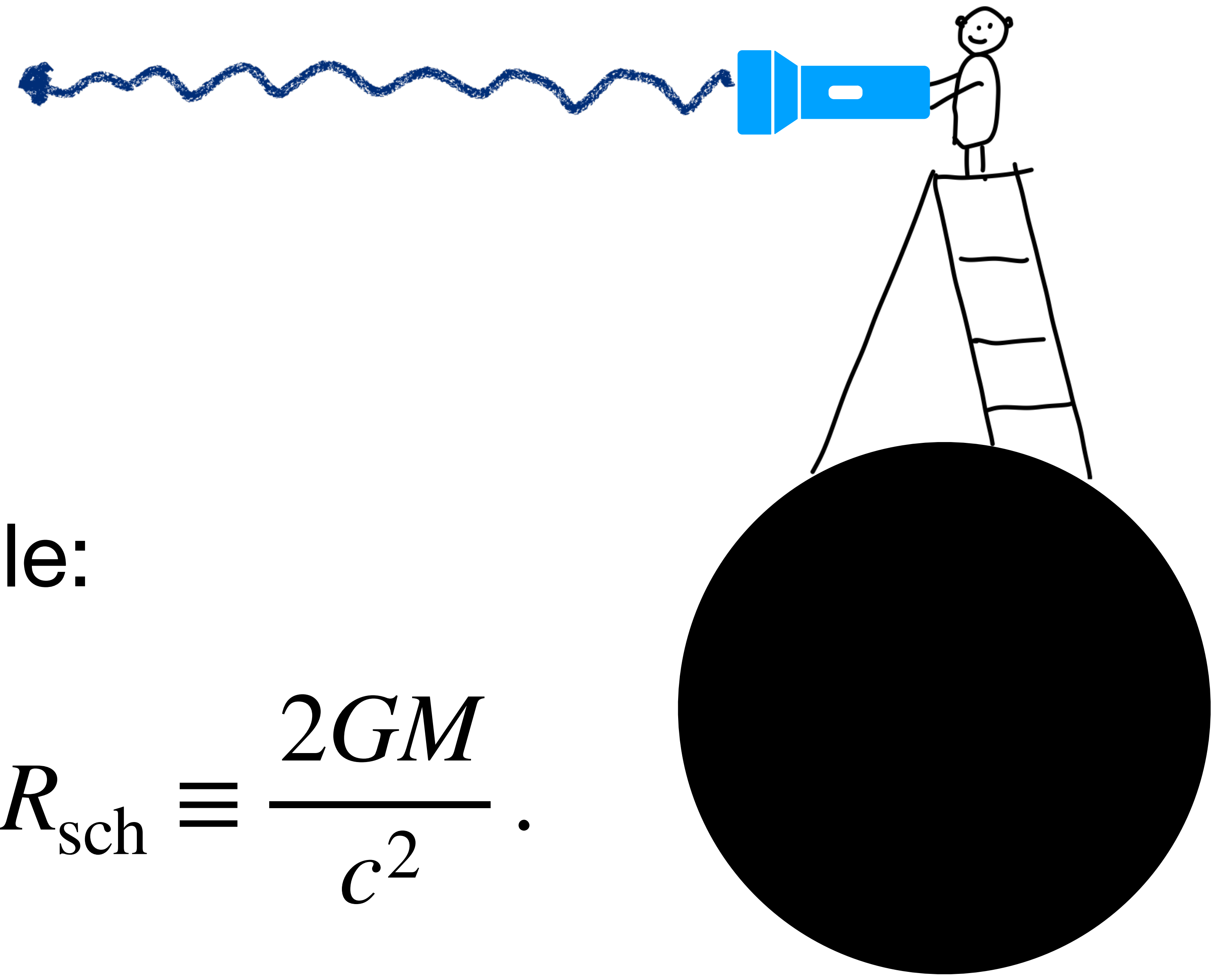

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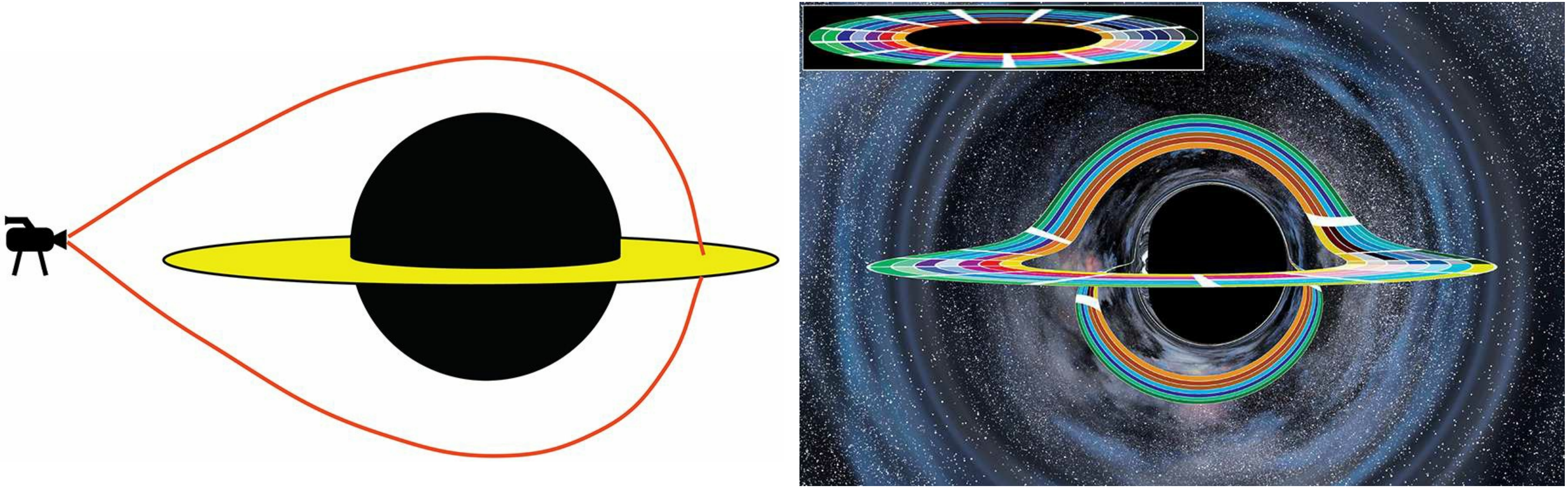
- 1967 — John Wheeler. The first known mention of «black hole».

Note: Raytracing



Kip Thorn, «The Science of Interstellar», 2014

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garfton @ Reddit

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- 1976 — Don Page found evaporation rate of the black hole due to Hawking radiation:

$$L \simeq \sigma_{SB} R_{\rm sch}^2 T^4, \quad \frac{dM}{dt} = \frac{L}{c^2} \simeq \frac{hc^4}{G^2}\frac{1}{M^2}\,. \quad \tau \simeq 2\times 10^{66}\left(\frac{M}{M_\odot}\right)^3 \textbf{years}\,.$$

Problems and Alternative Models

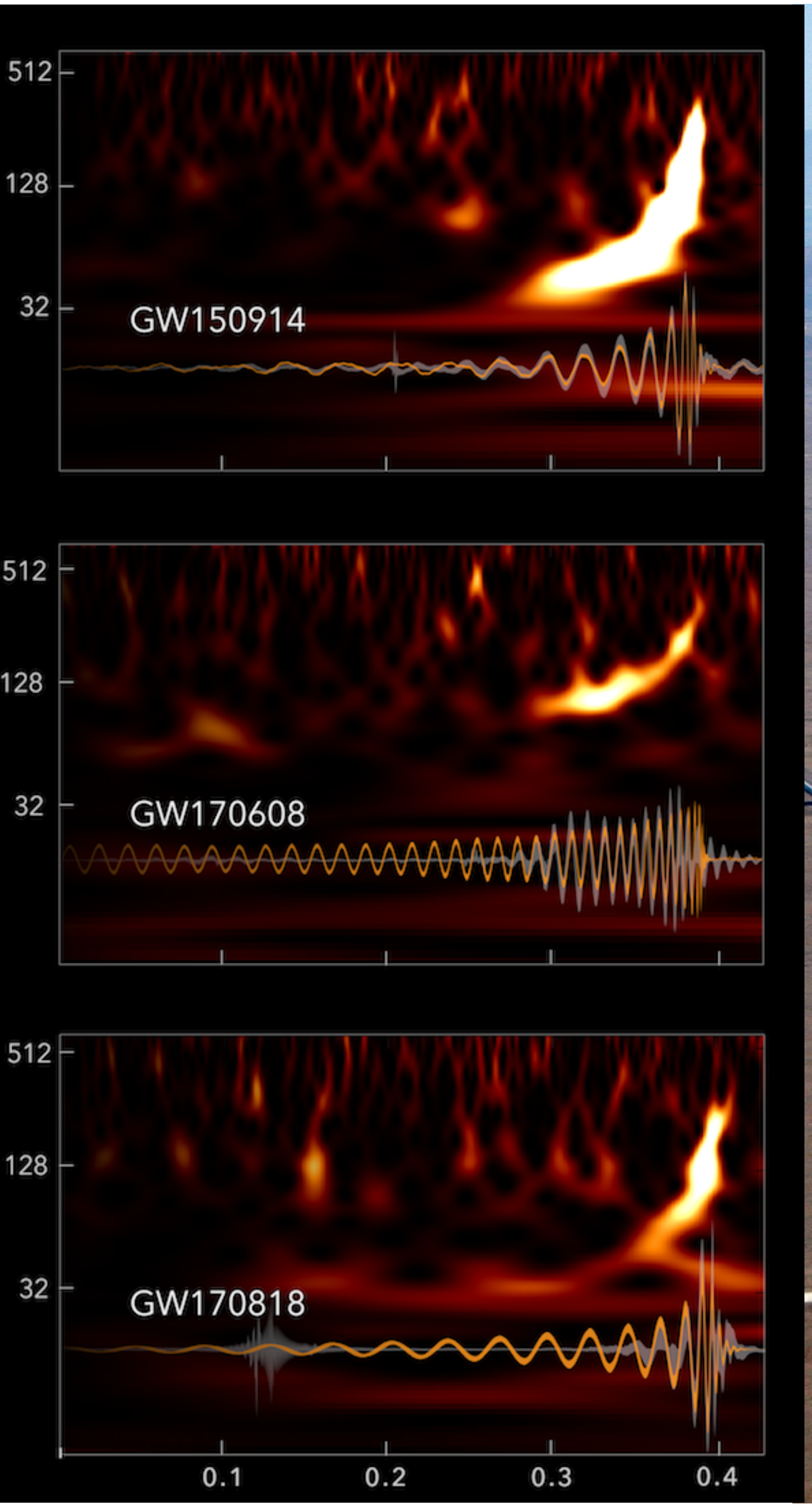
Problems:

- Information paradox — particle falling to the black hole loses information, it is denied by information theory.
- Firewall paradox — emitted by black hole particle entangles with previous radiation and with its companion particle kept inside black hole, such multiple entanglements is denied by quantum mechanics.

Alternative and exotic theories:

- **Naked singularity** — no event horizon, requires alternative gravitation theory
- **Exotic star** — made by bosons (or other exotic) matter, requires specific equation of state of quantum matter, hard to create astrophysically.
- **Gravastar** — thin shell of matter near event horizon, hard to create astrophysically.
- **Wormholes** — another prediction of general relativity, requires exotic field to keep alive, not clear how to create astrophysically.

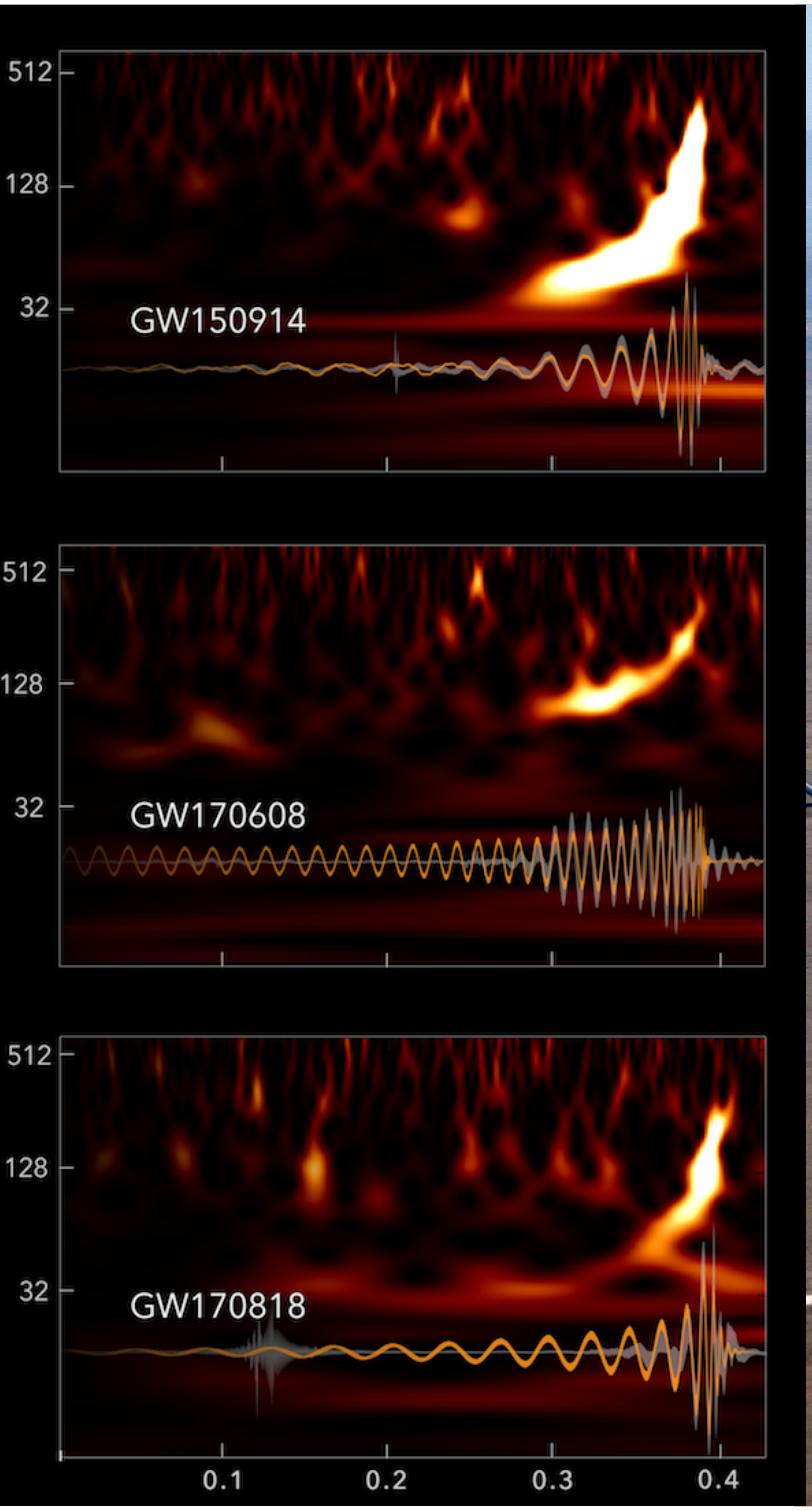
Observations of Black Holes



LIGO/VIrgo/Georgia Tech,
S. Ghonge & K. Jani

LIGO Laboratory

Observations of Black Holes



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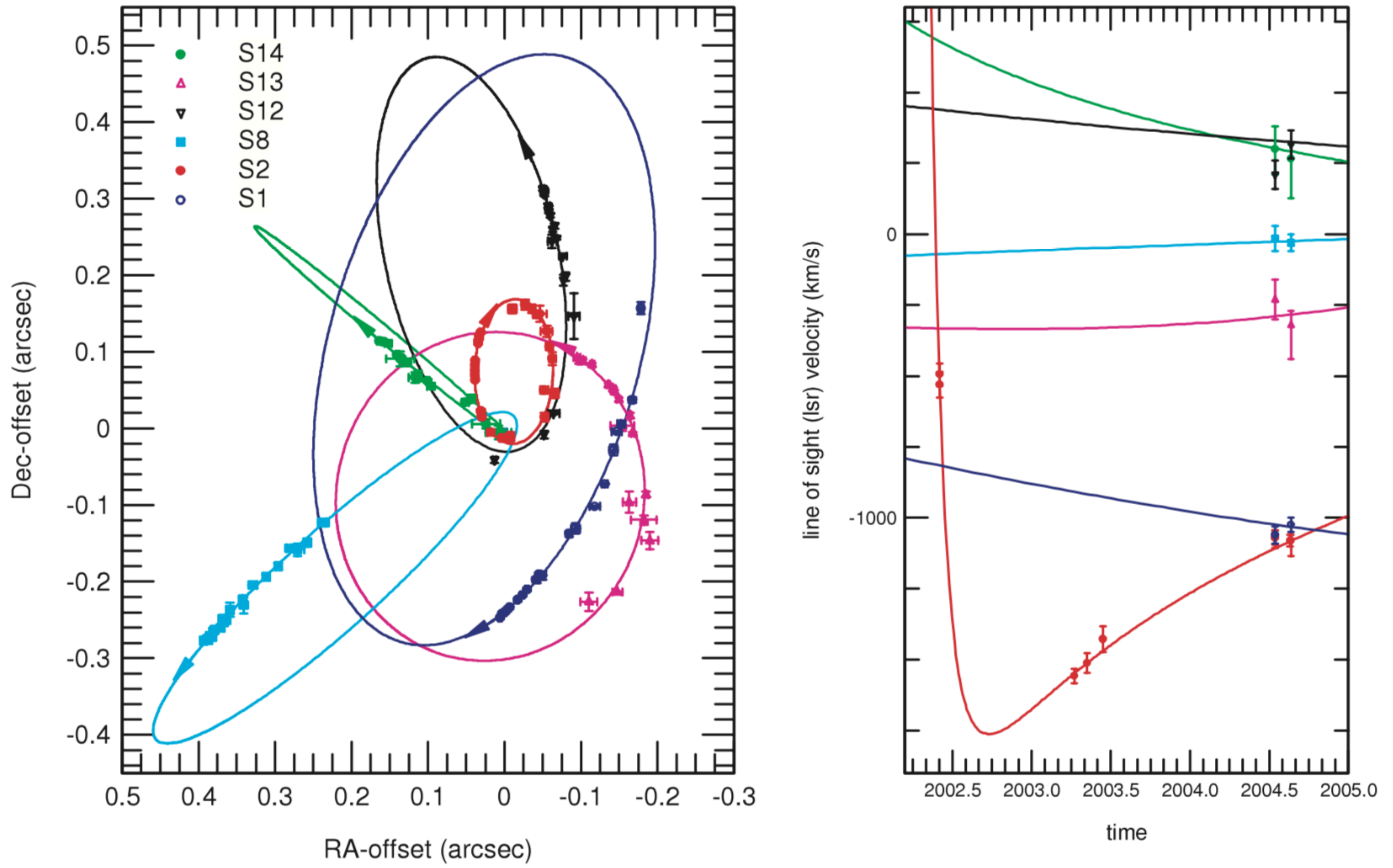
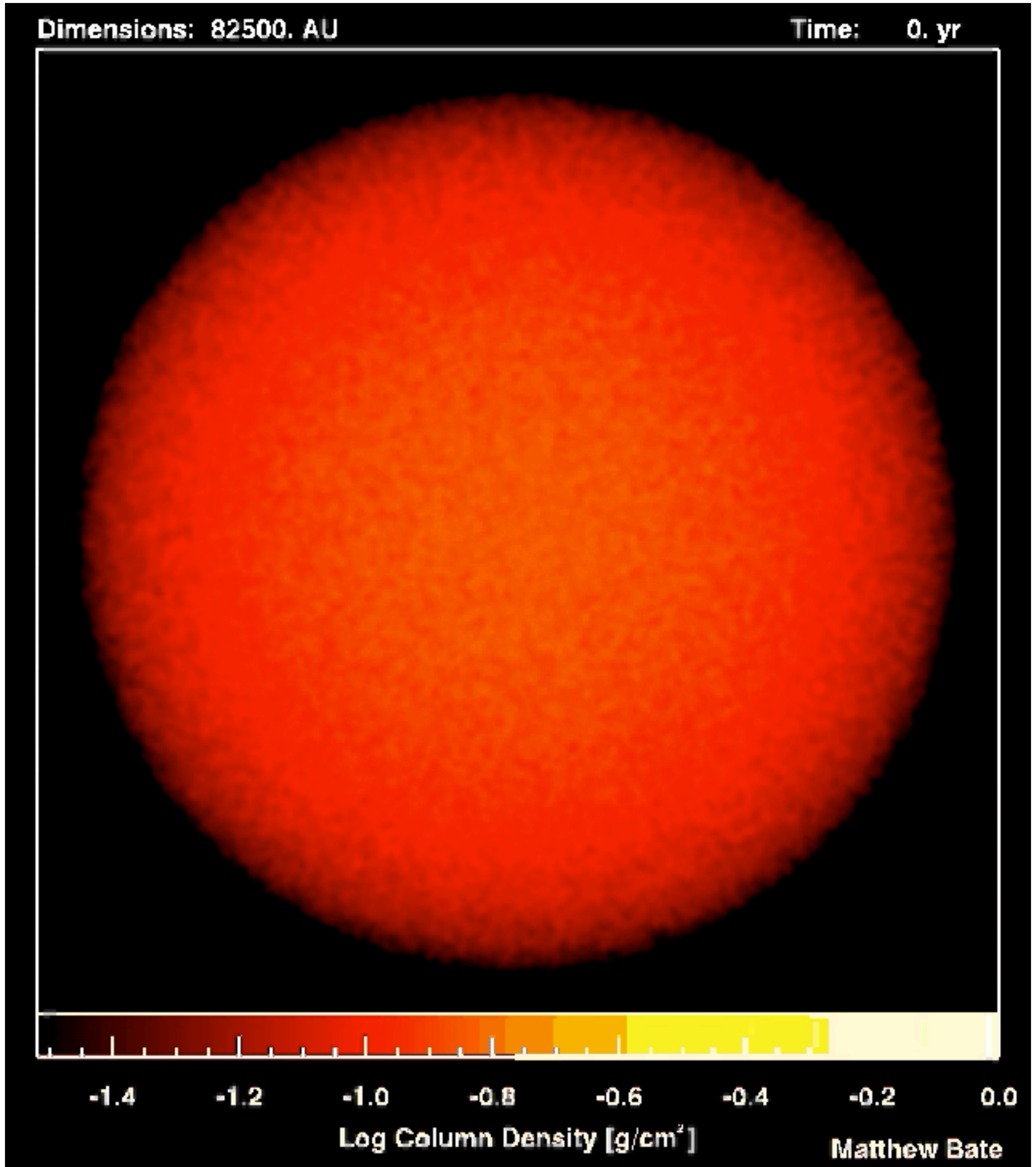


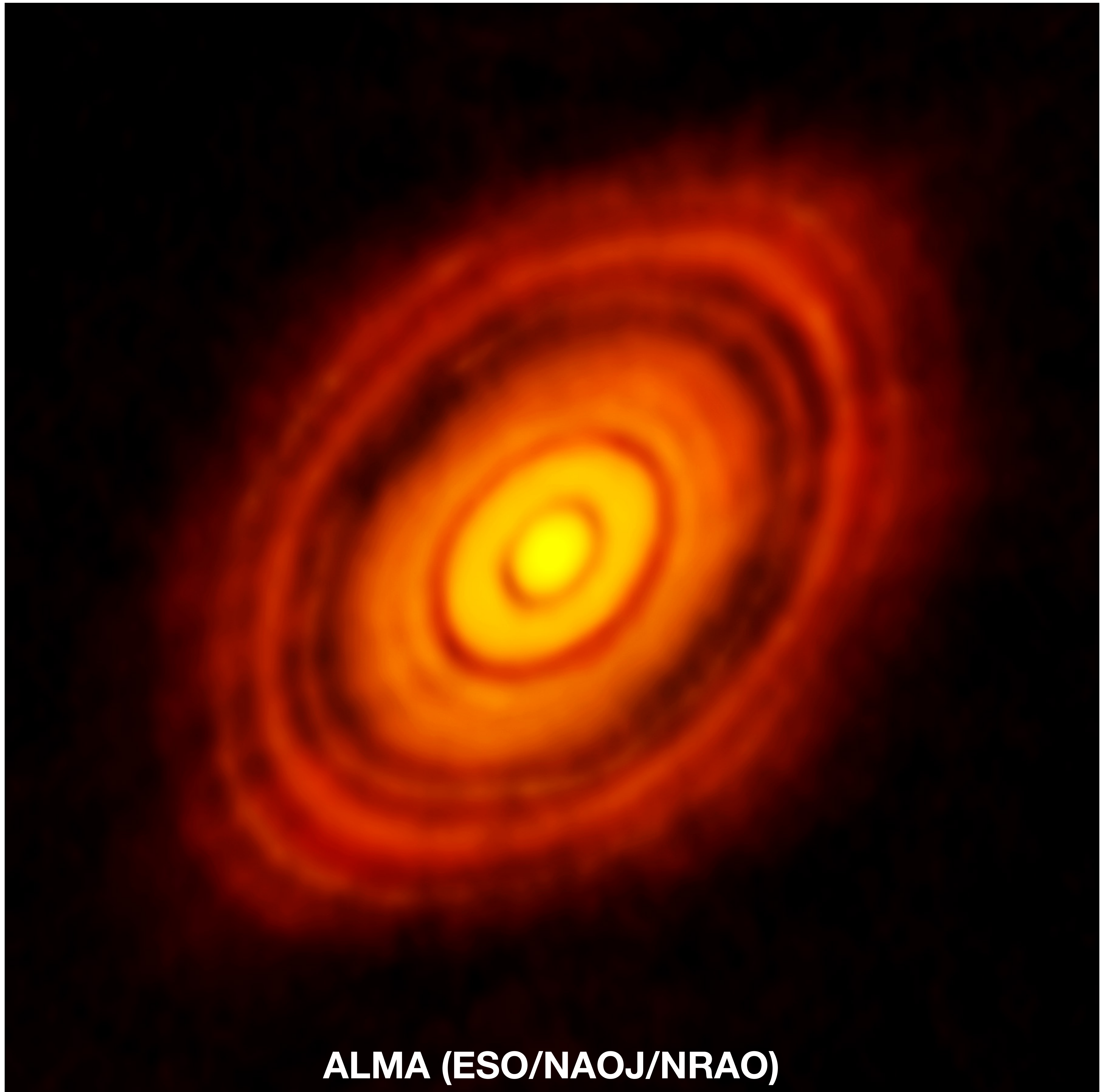
Fig. 7.—Projection on the sky (*left*) and in time/radial velocity (*right*) of the six S stars included in the fitting (see also Schödel et al. 2003). The measured radial velocity of S2 for epoch 2002 is taken from Ghez et al. (2003). The various color curves are the result of the best global fit to the spatial and radial velocity data of S1, S2, S8, S12, S13, and S14. The orbital parameters are listed in Table 2.

Eisenhauer et al., arXiv:astro-ph/0502129

Accretion Disks

Accretion Disk around Alone Star




ALMA (ESO/NAOJ/NRAO)

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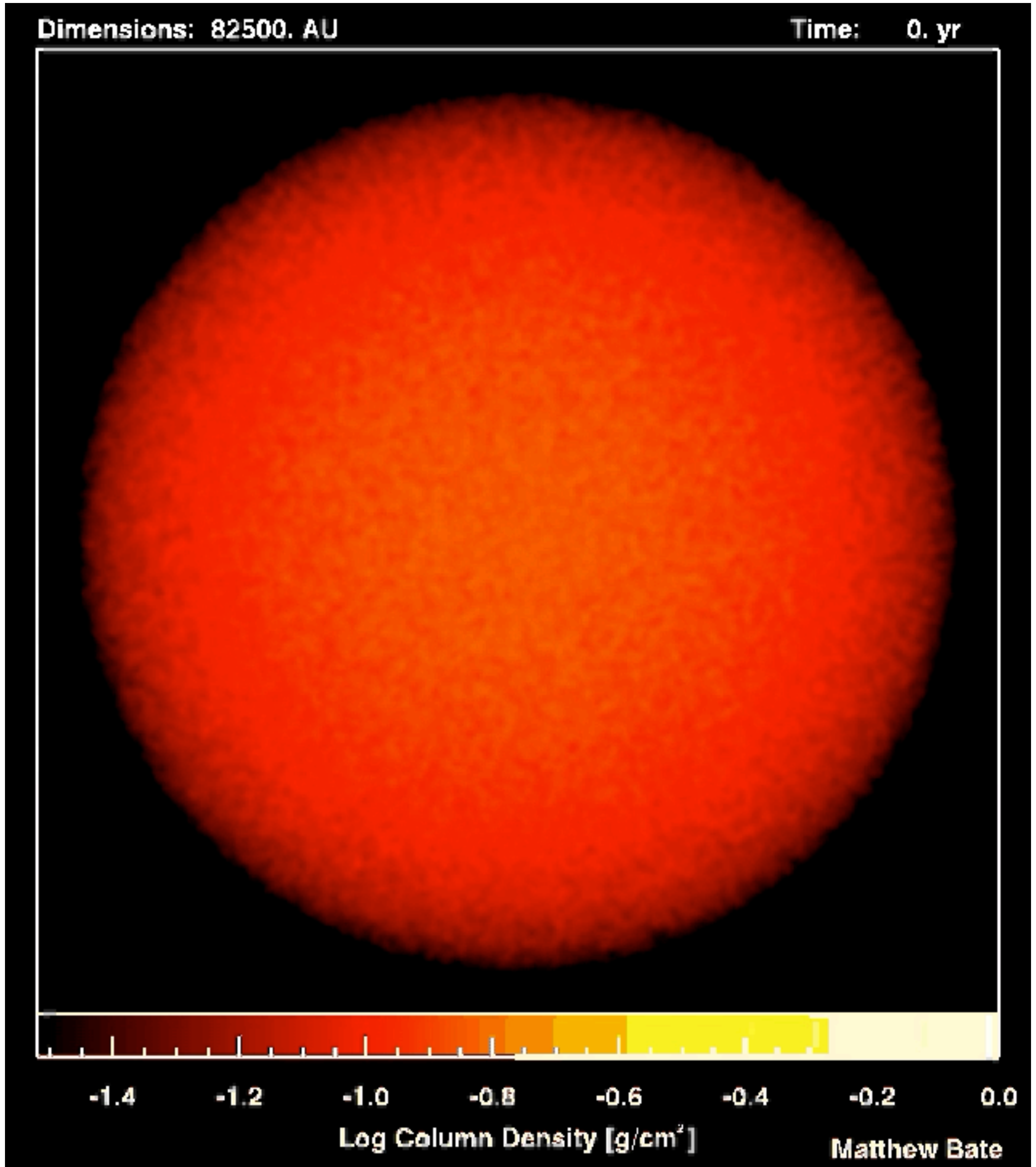
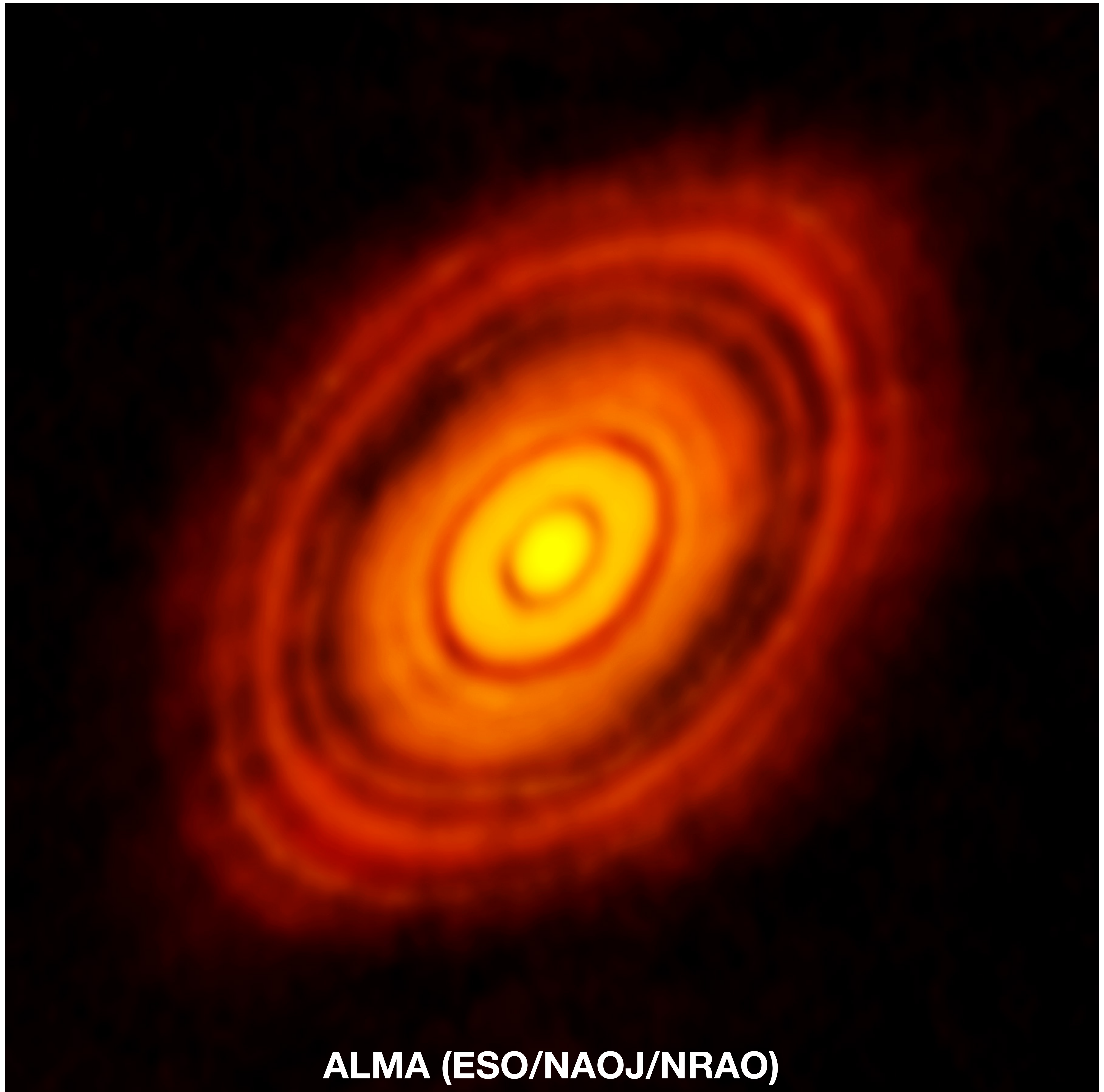
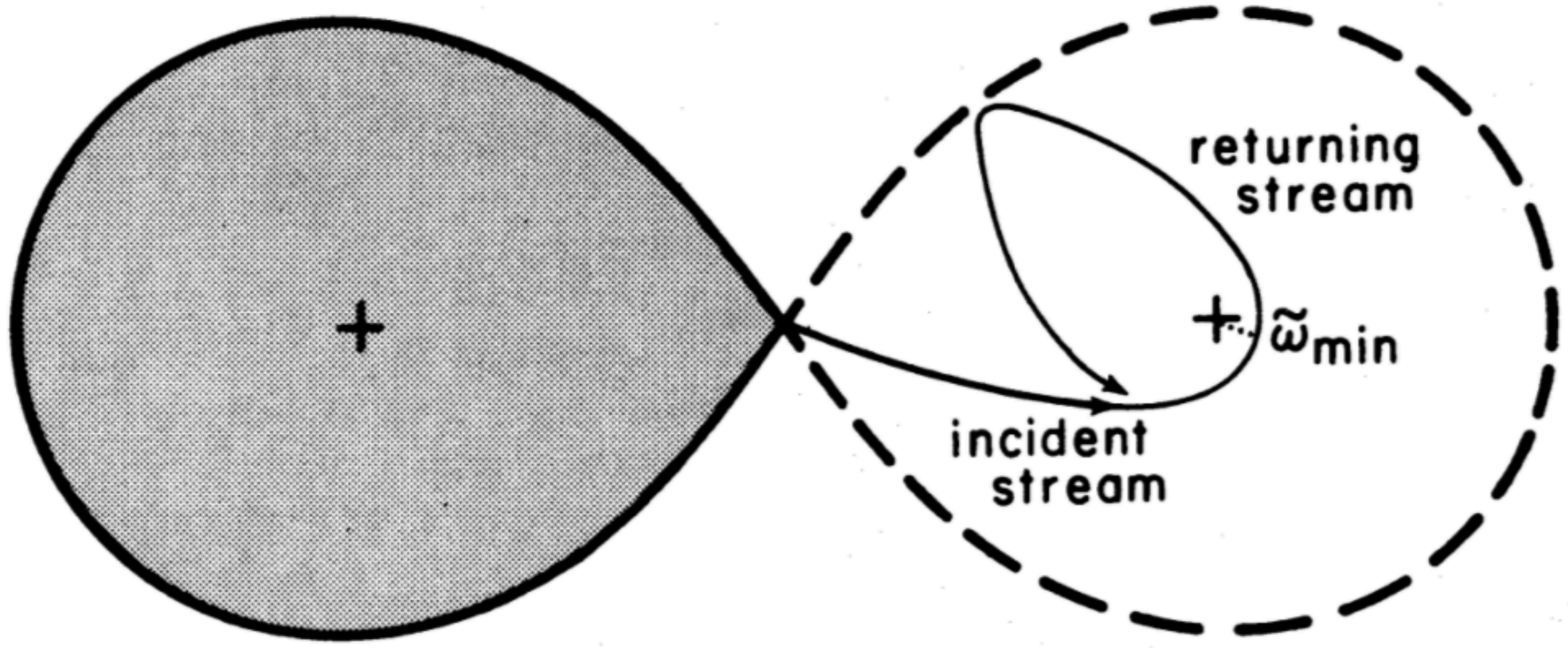


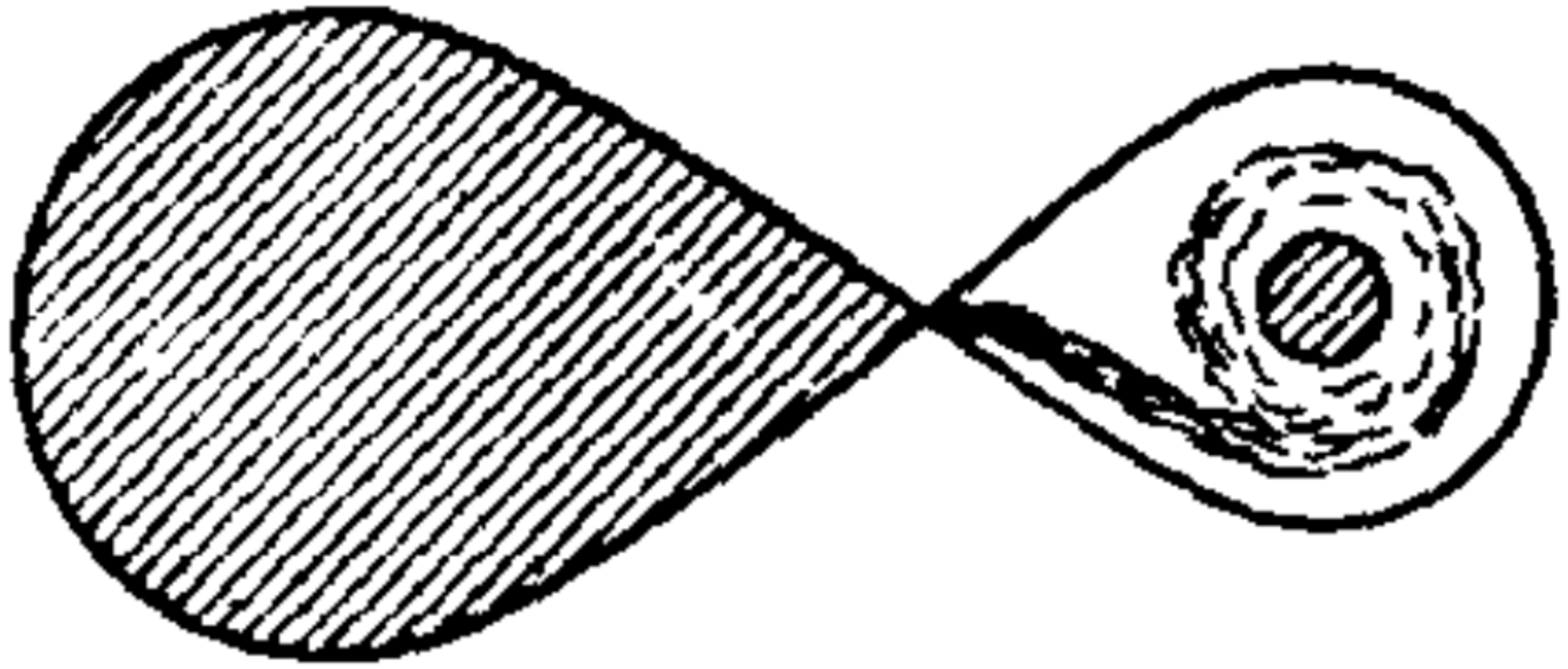


Accretion Disk in Binary System

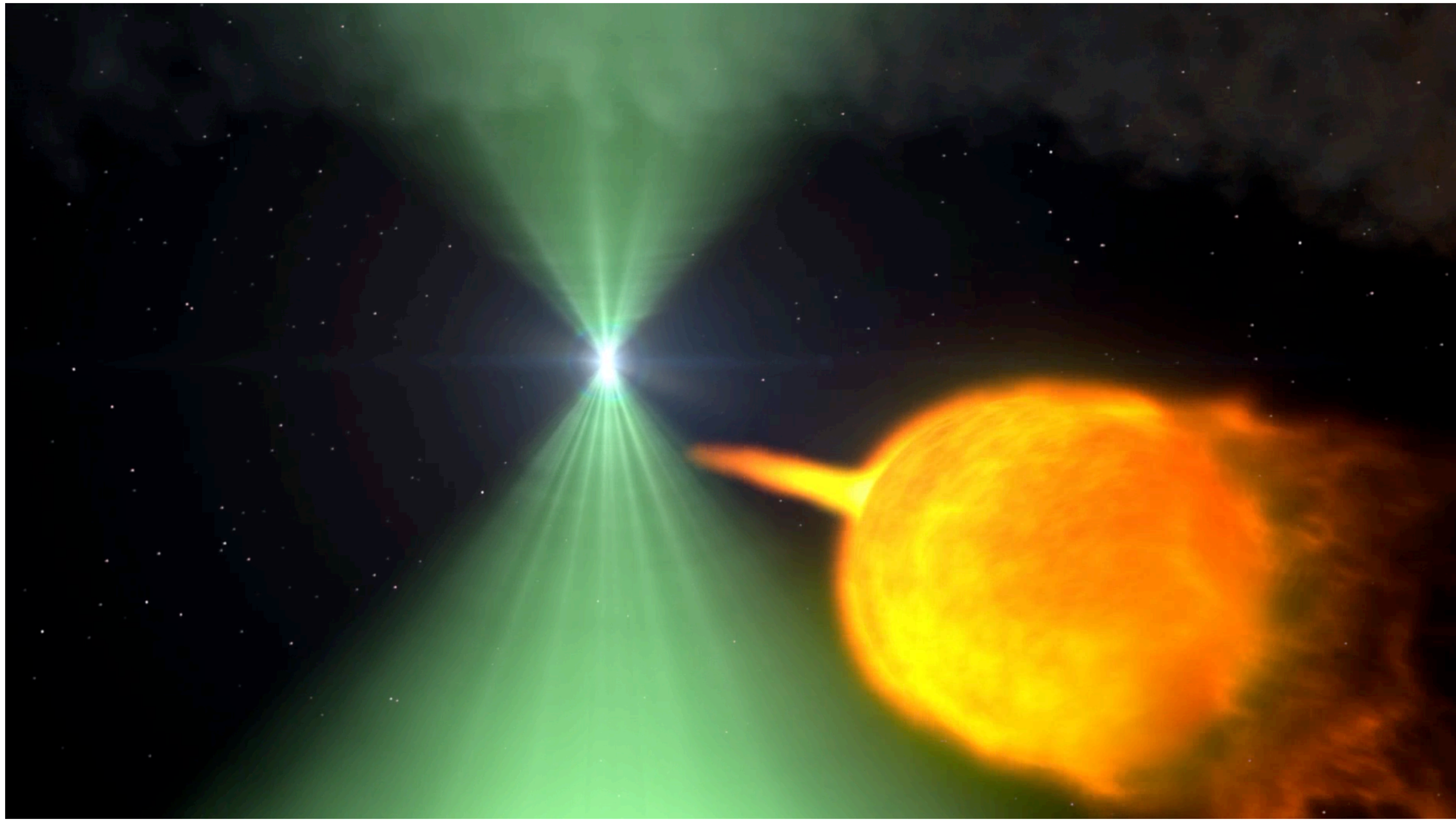
Close binary star system: accretion from star to compact star.



Lubow & Shu, 1975



Lipunov, 1986



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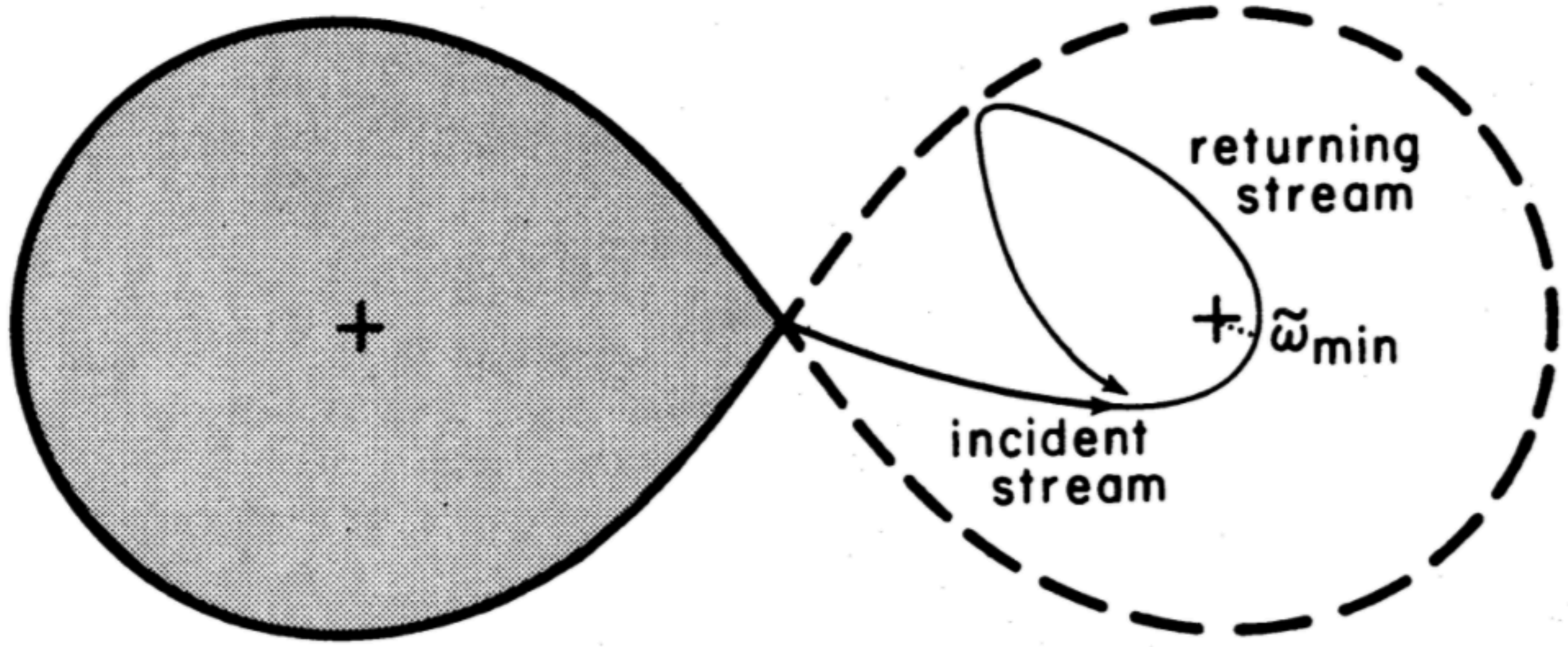

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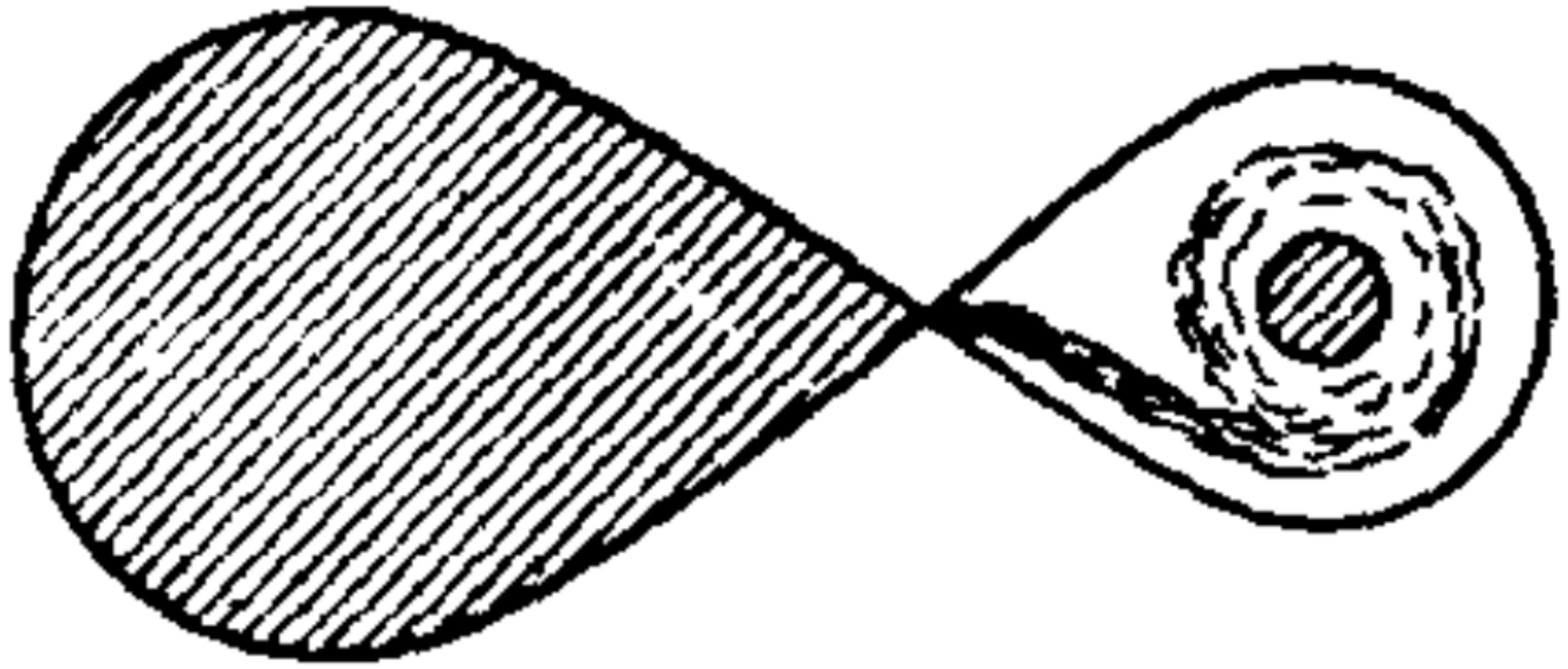

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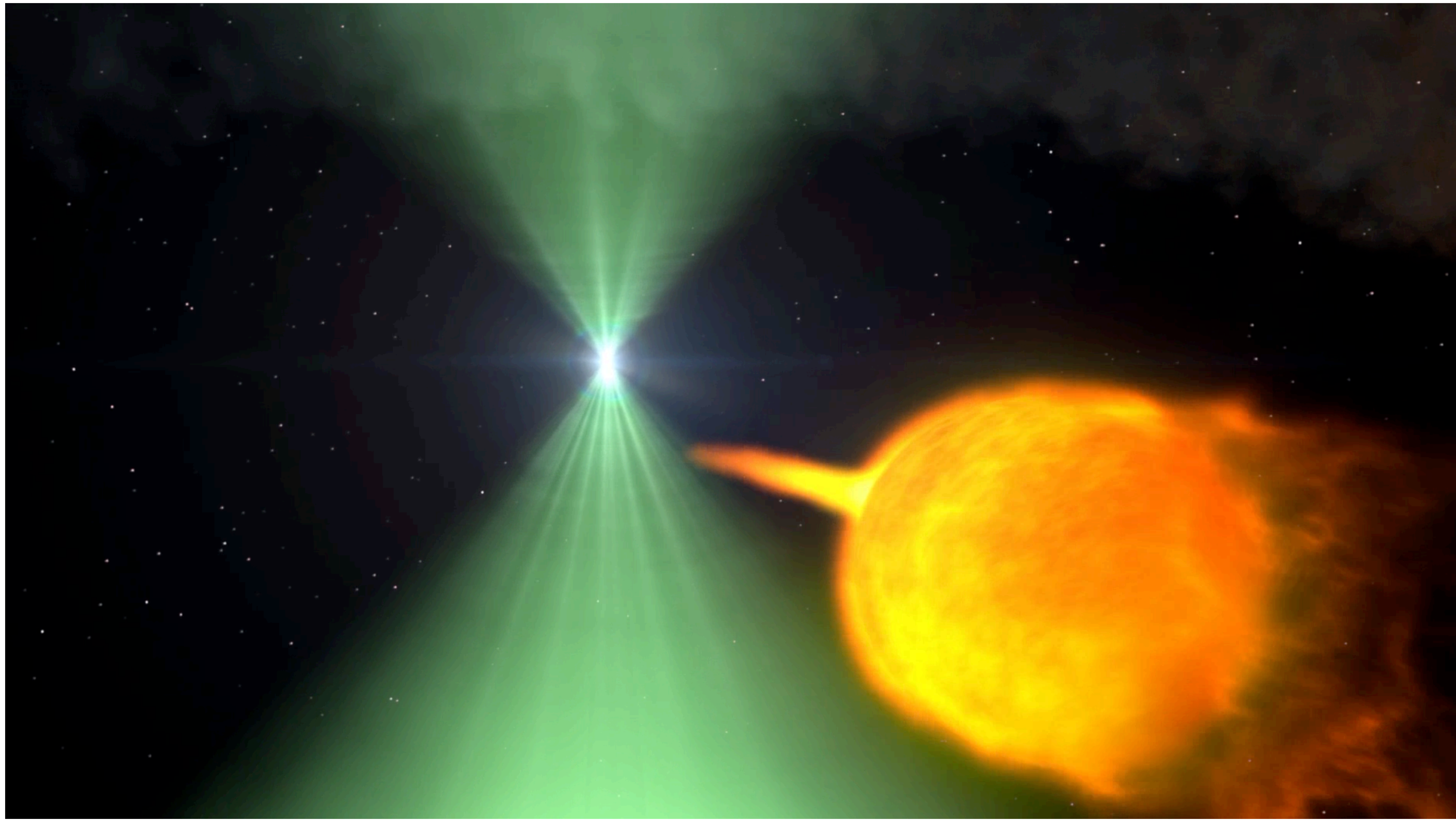

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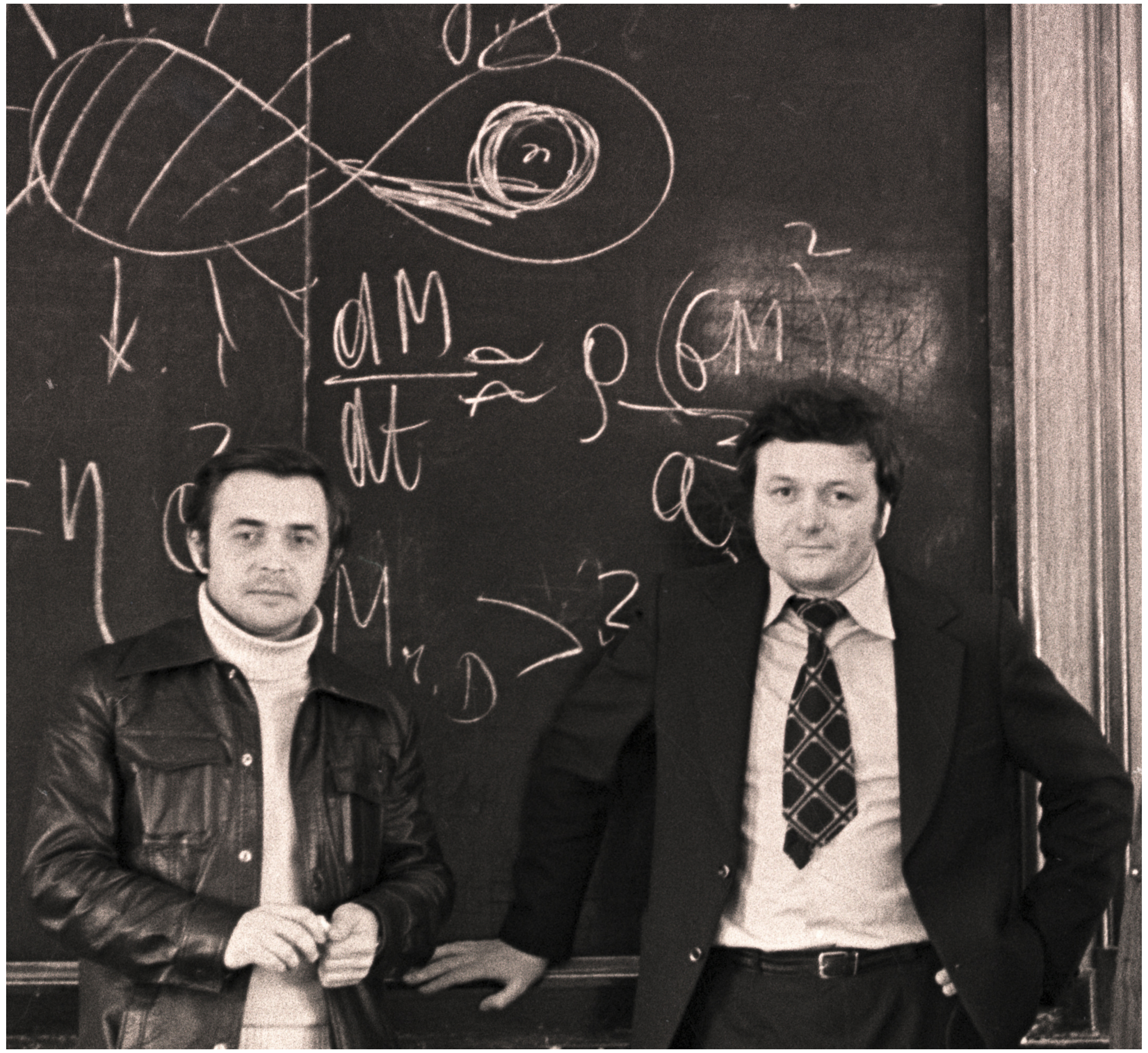
«Black Holes in Binary Systems. Observational Appearance»

In 1973 two PhD students of Yakov Zeldovich, Nikolay Shakura and Rashid Sunyaev, published a paper in A&A that describes turbulent viscosity model of disk accretion. Nowadays this model is used widely to explain observations of all types of astrophysical disks that makes the paper to be the most cited work on theoretical astrophysics ever.



Standard Theory of Disk Accretion

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- The dynamics of some flow can be described by Navier—Stokes equation:

$$\rho \frac{dv_i}{dt} = \rho g - \frac{\partial P \delta_{ik}}{\partial x_k} + \frac{\partial w_{ik}}{\partial x_k}, \quad P \text{ is a pressure}, w_{ik} \text{ is a viscous stress tensor}.$$

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  - Shakura—Sunyaev α parameter sets viscous timescale of the disk:

$$\tau_{\rm vis} = \frac{1}{\alpha}\left(\frac{R}{z_0}\right)^2 P_{\rm orb}$$

Binary: 1 year, SMBH: 10^7 yr, protoplanetary disk: 10^7 yr.

Observations of Black Hole Accretion Disks

Doppler Effect and Gravity Redshift

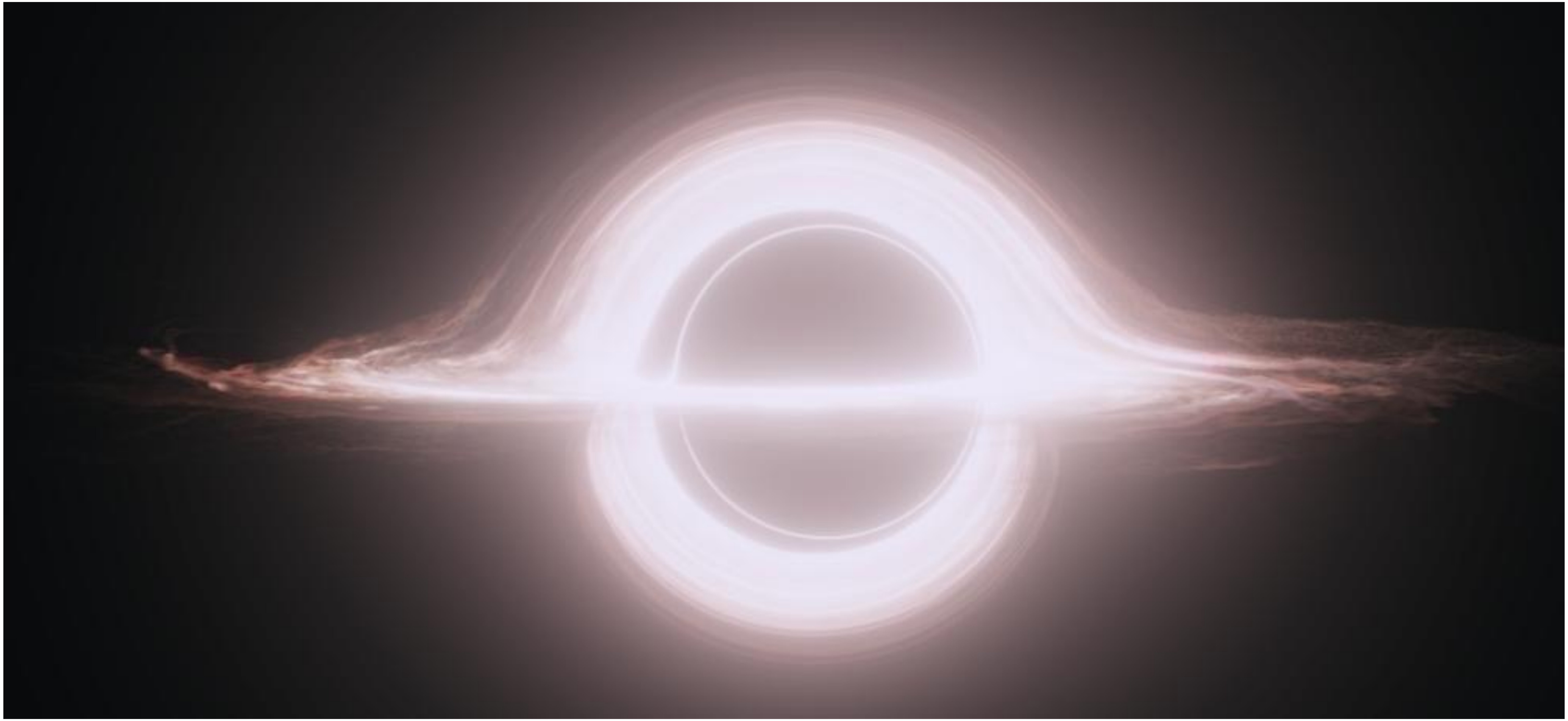

Image by Double Negative, Warner Bros, 2014

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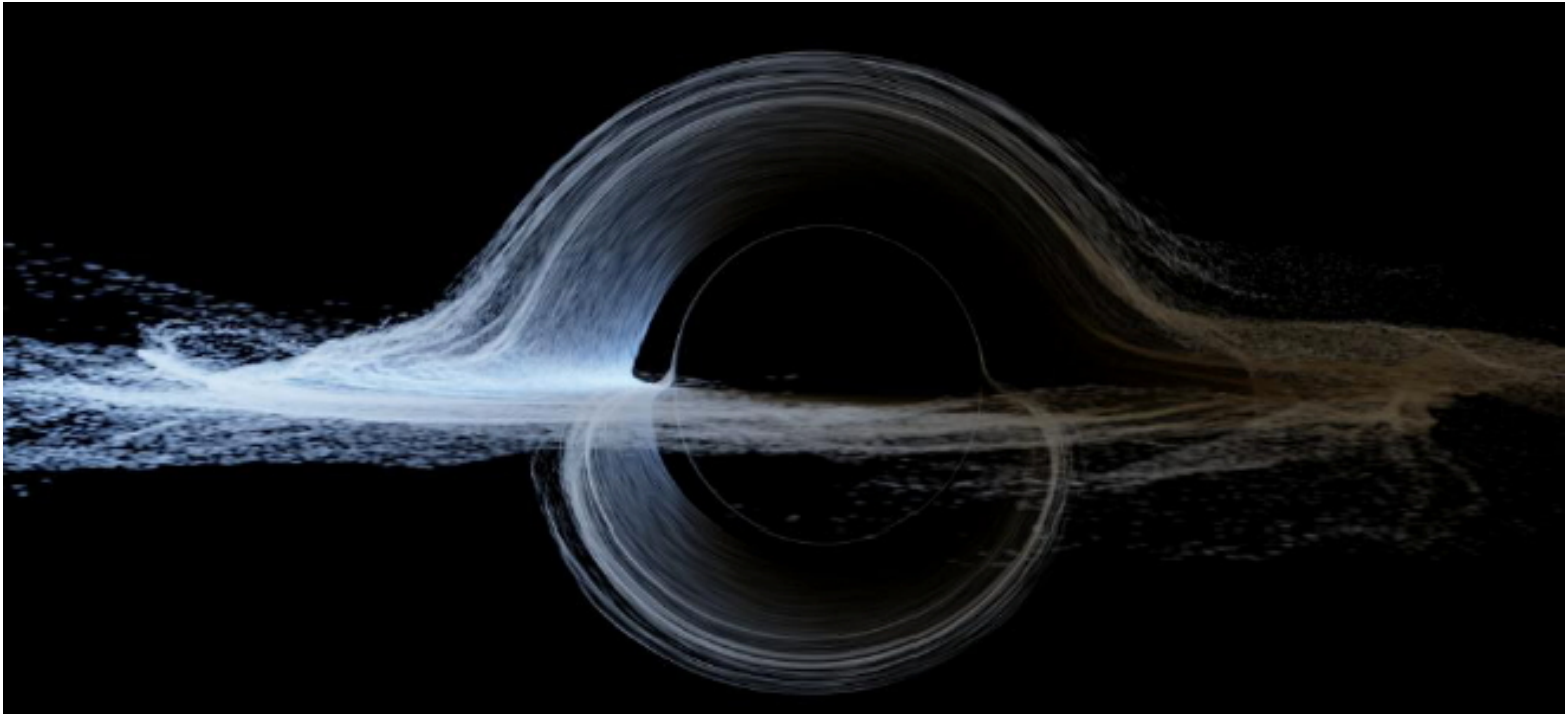


J.-A.Marck & J.-P. Luminet, «Les trous noirs», 1997

X-ray Spectrum of Black Hole Accretion Disk

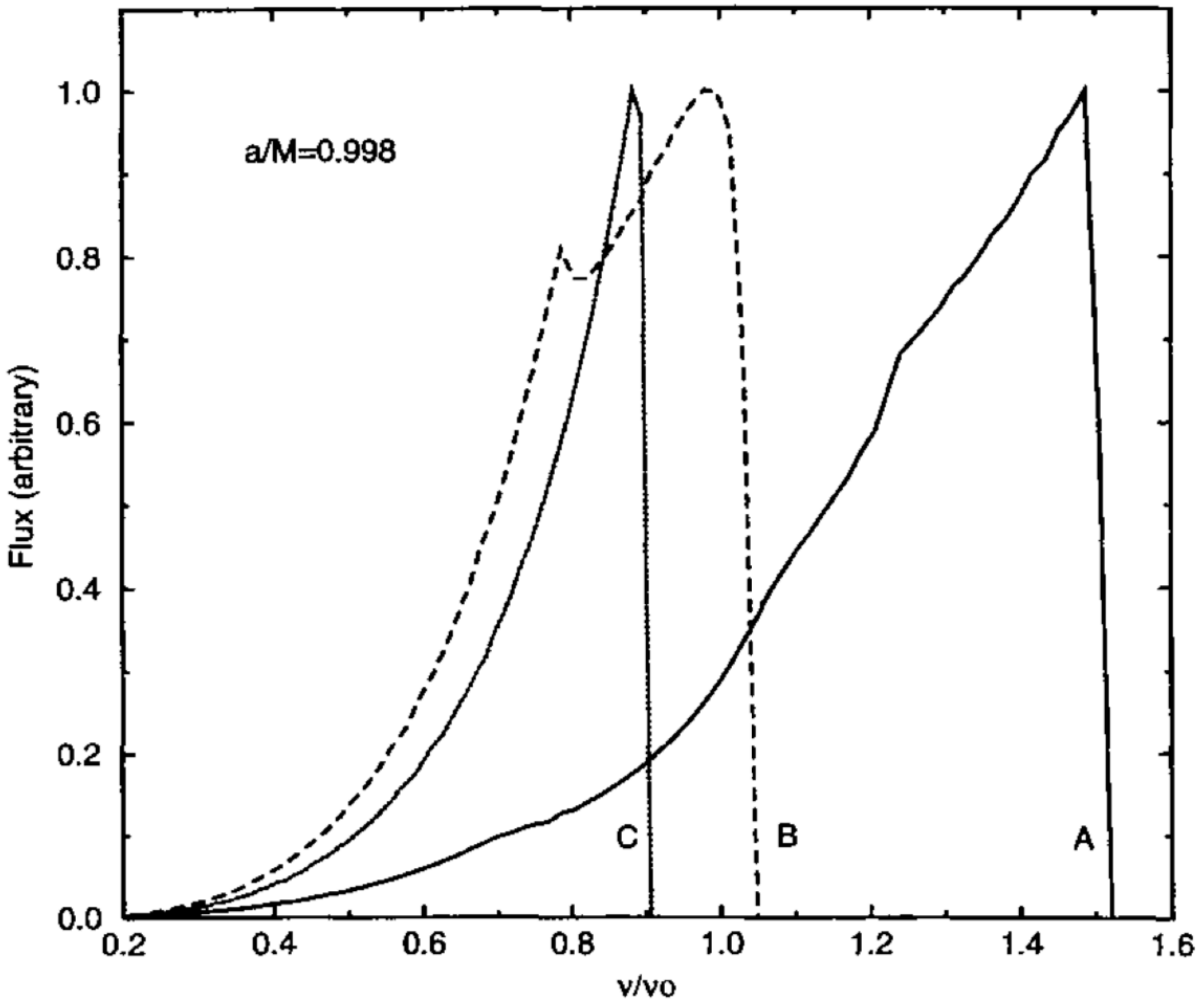


Figure 3. As Fig. 1 but for $a_* = 0.998$, corresponding to an extreme Kerr black hole (Thorne 1974).

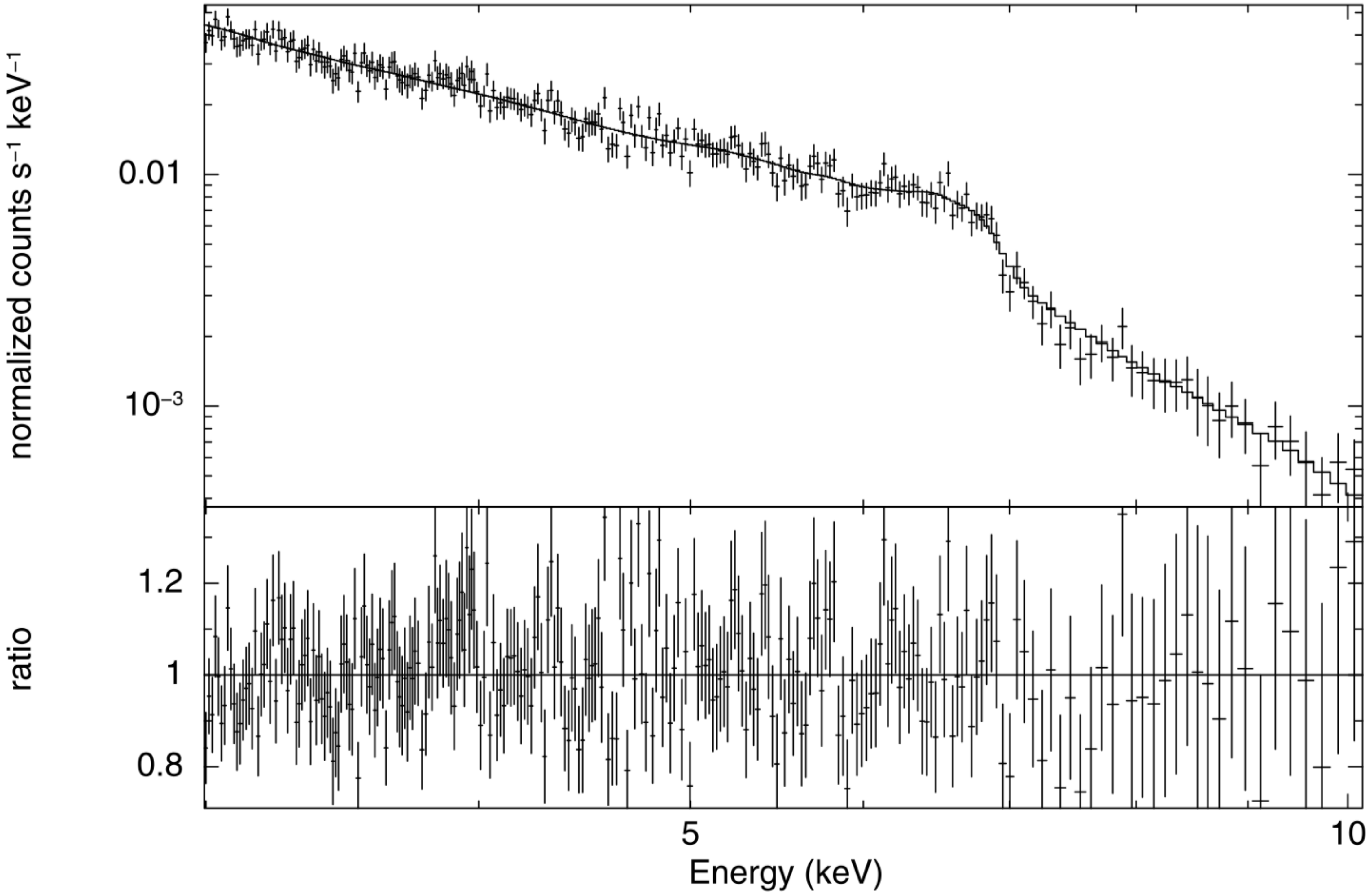
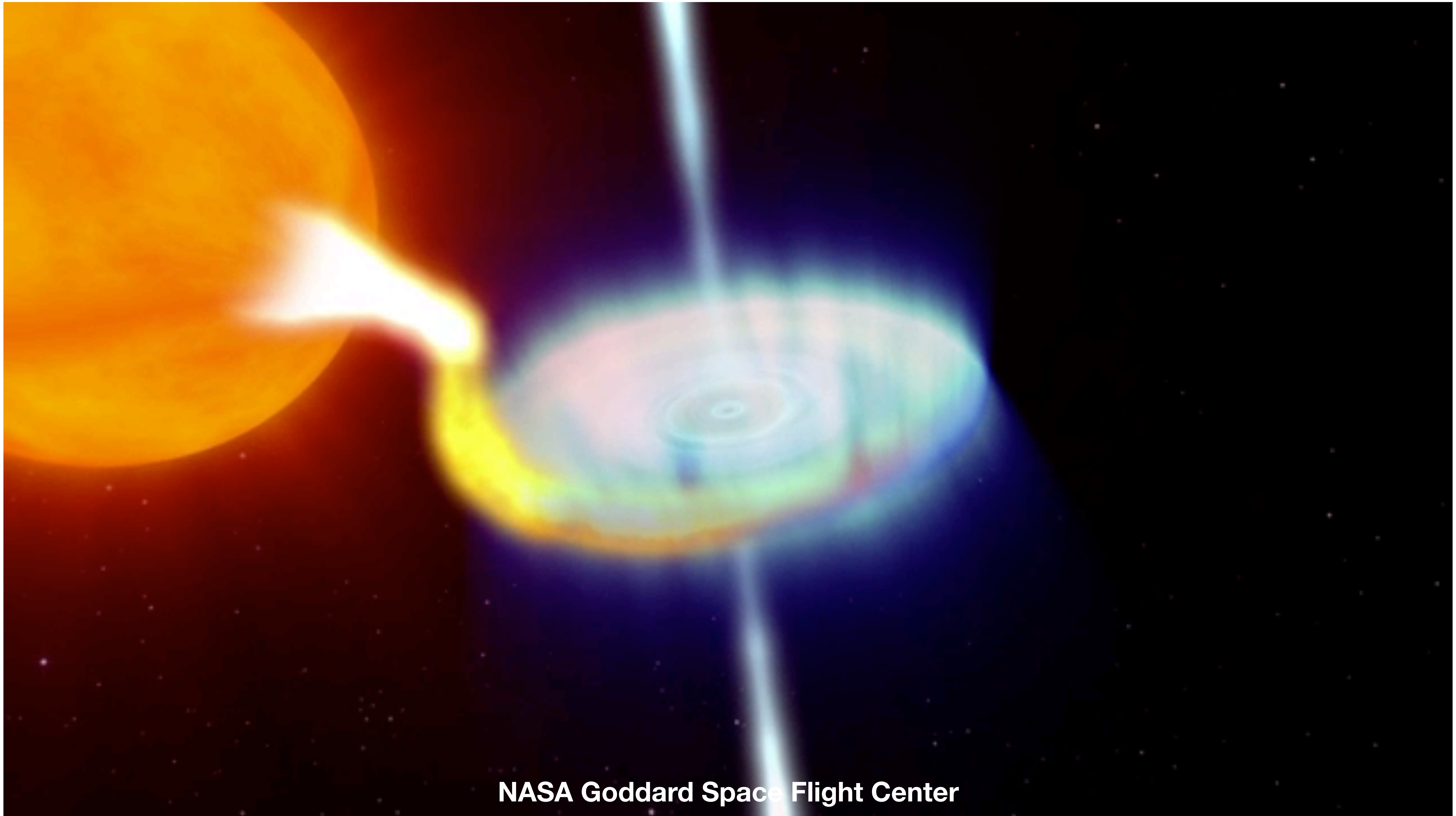


Figure 3. Fit to the iron Kα edge (3–10 keV) of 1H 0707-495 with the disc reflection considered as the sum of components from successive radii. $\chi^2/\mathrm{DoF} = 255.48/227 = 1.1255$.

Dabrowski et al., 1997, arXiv:astro-ph/9704177

Wilkins & Fabian, arXiv:1102.0433

Black Hole Binary



NASA Goddard Space Flight Center

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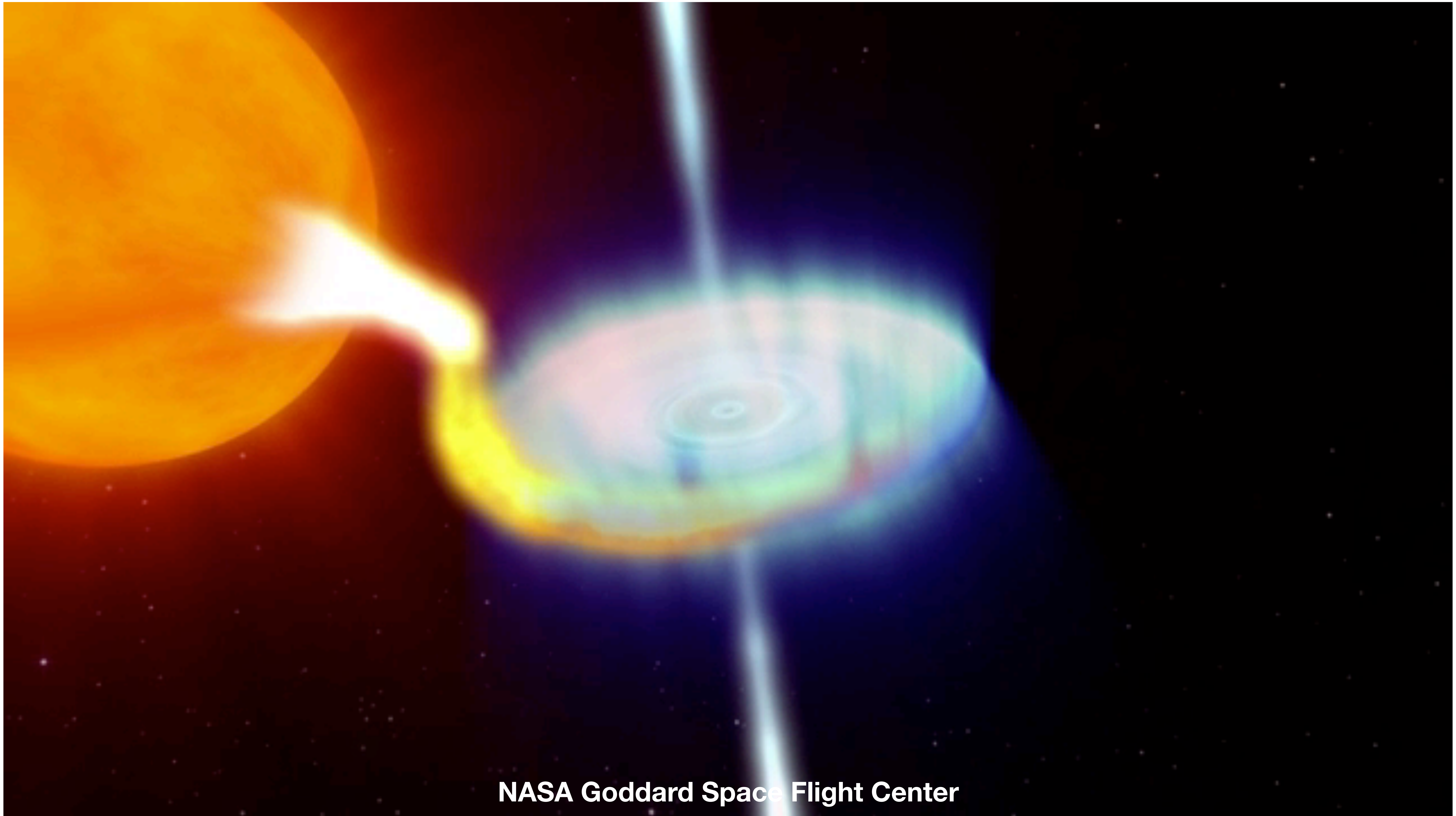


NASA Goddard Space Flight Center

Light Curves of Low-Mass X-ray Binary

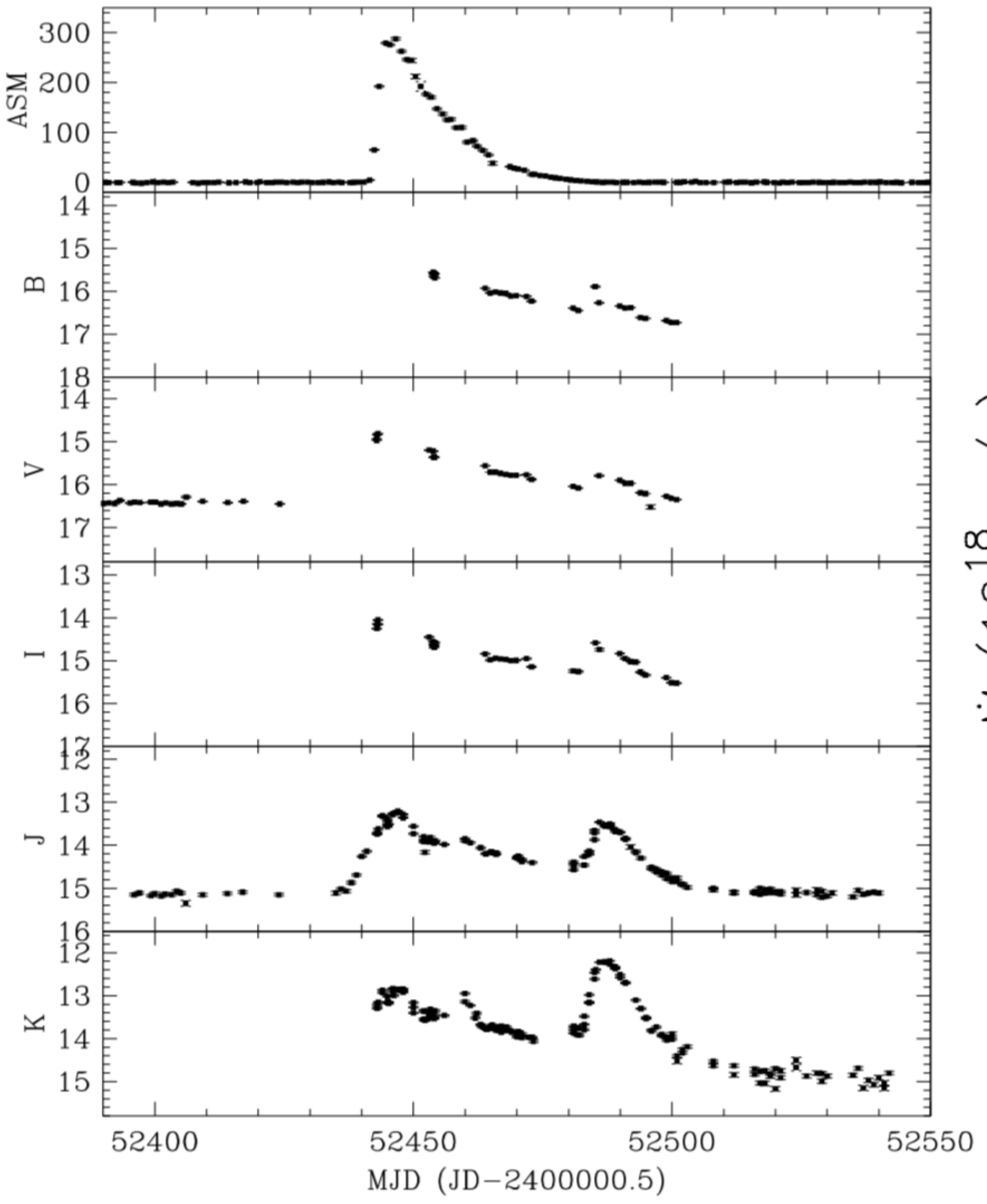
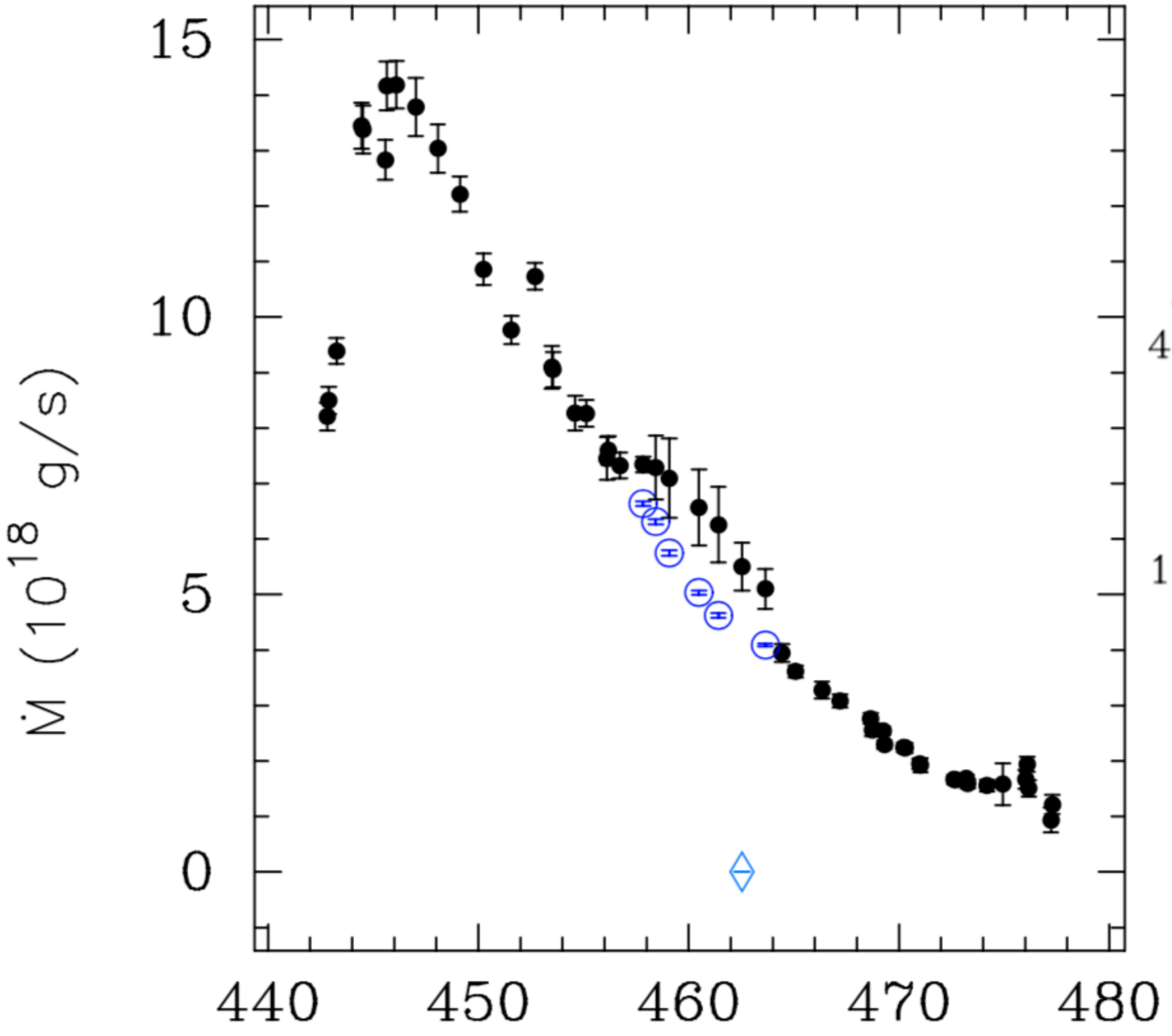
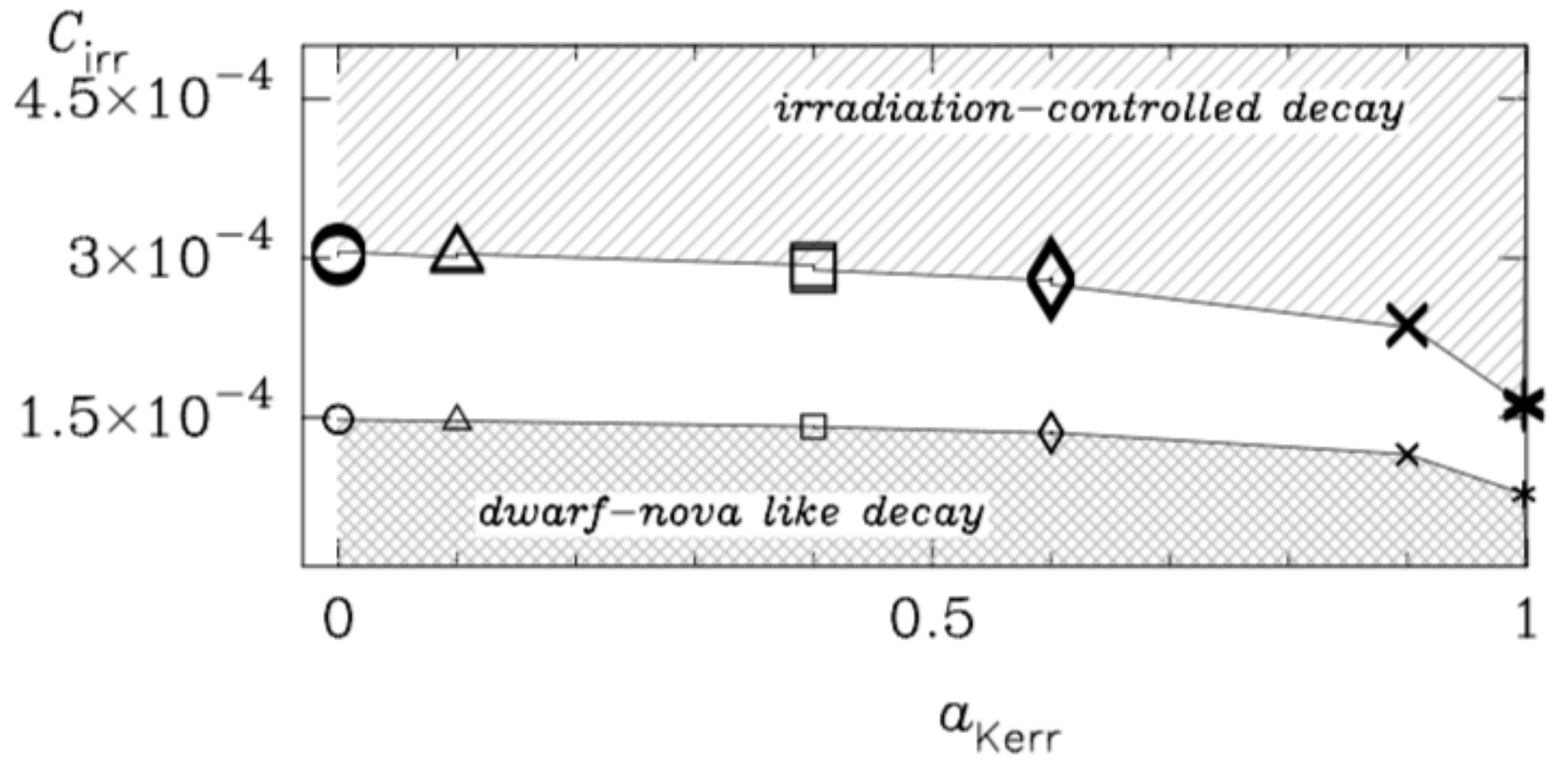


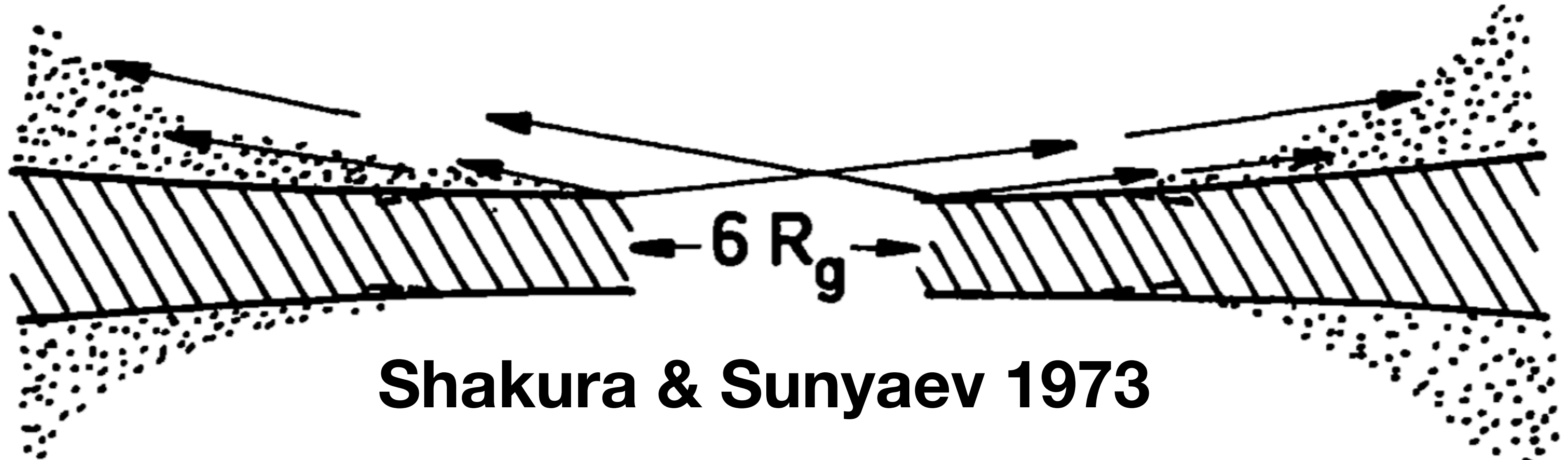
Fig. 1.—Optical and infrared data of 4U 1543−47 in 2002. The top panel is the 1 day averaged *RXTE*/ASM data provided by the ASM/*RXTE* team.

Buxton & Bailyn, 2004, arXiv:astro-ph/0408156





Lipunova & Malanchev, 2017, arXiv:1610.01399



Shakura & Sunyaev 1973

Tidal Disruption by Black Hole

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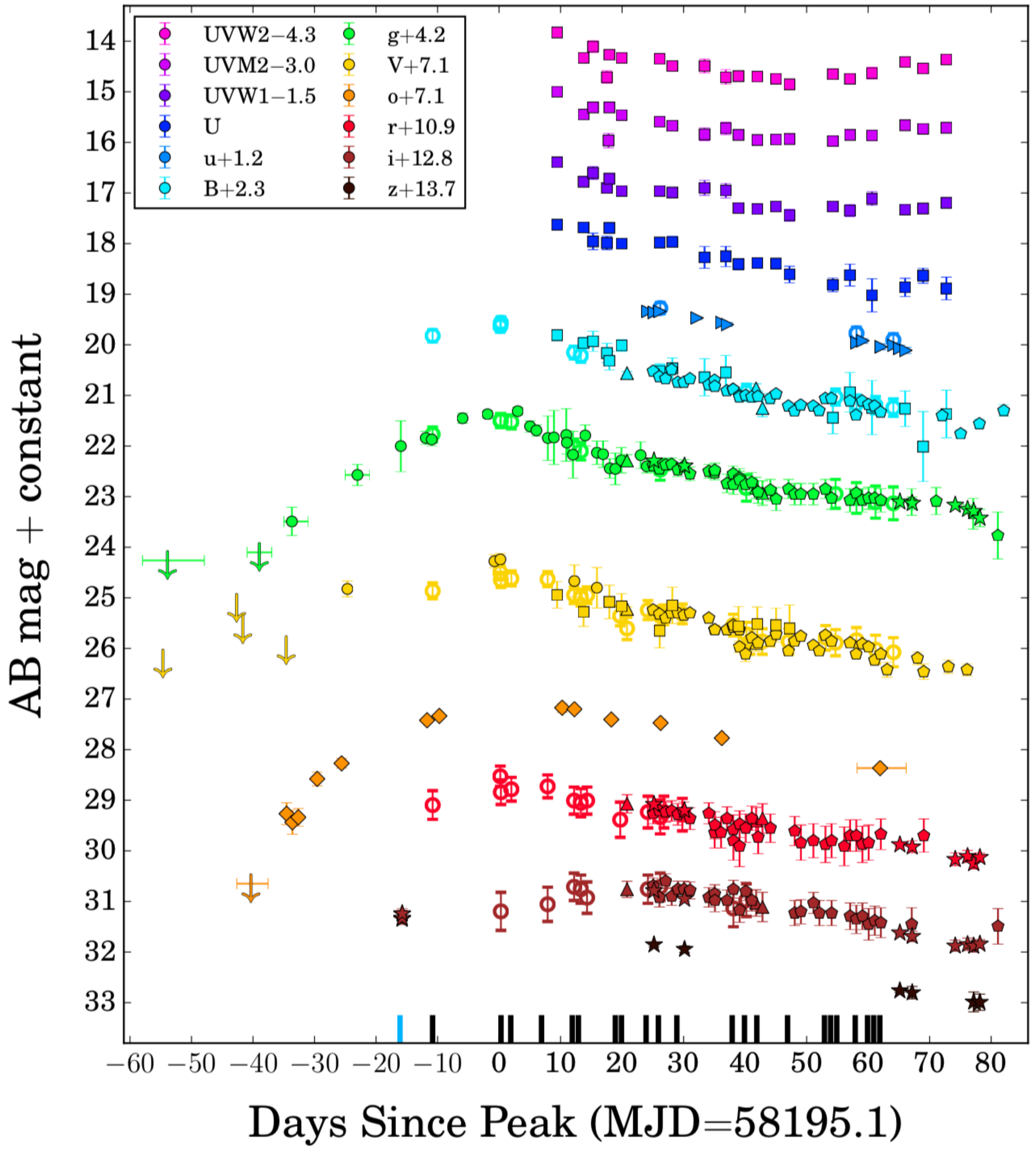
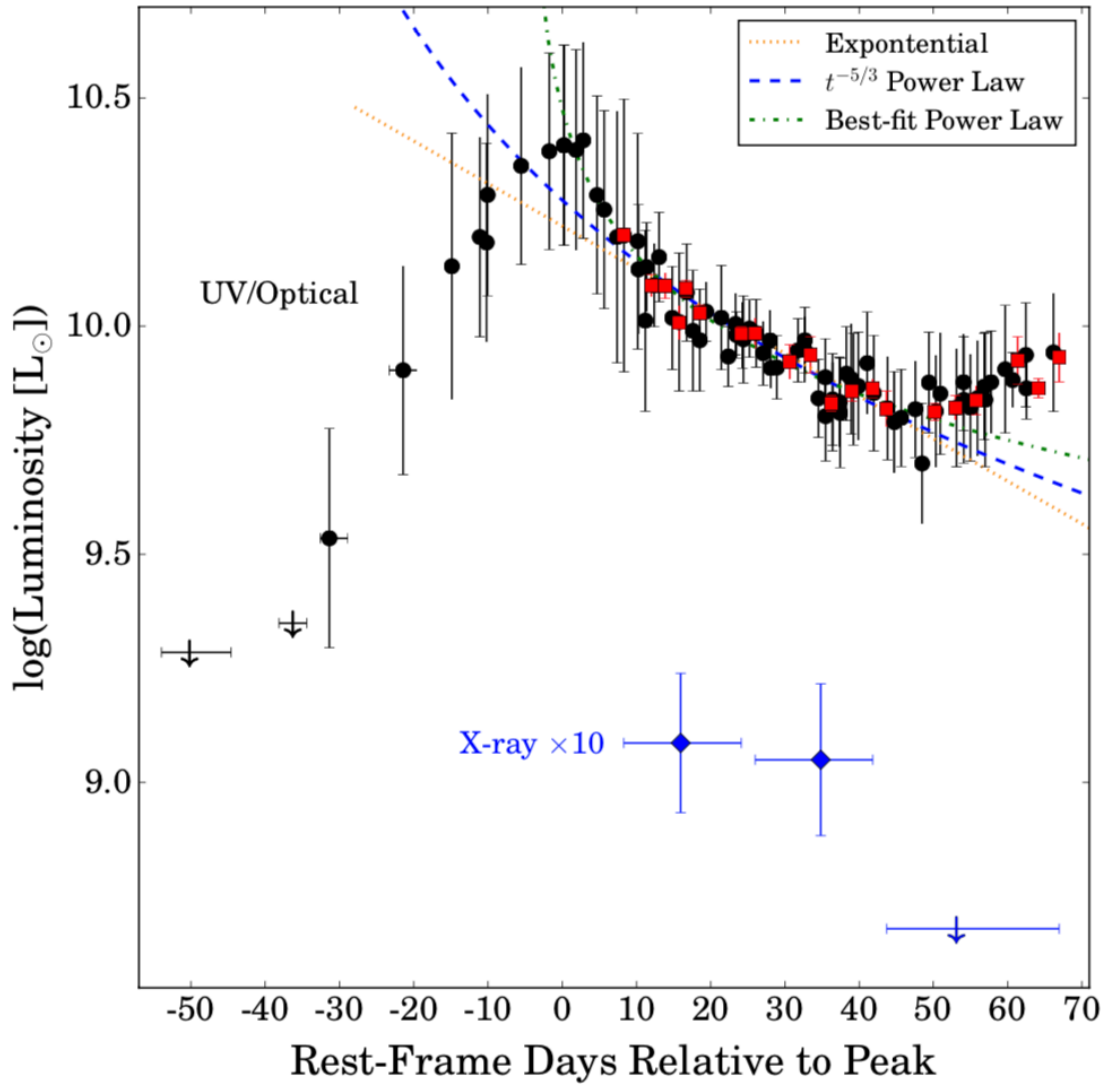
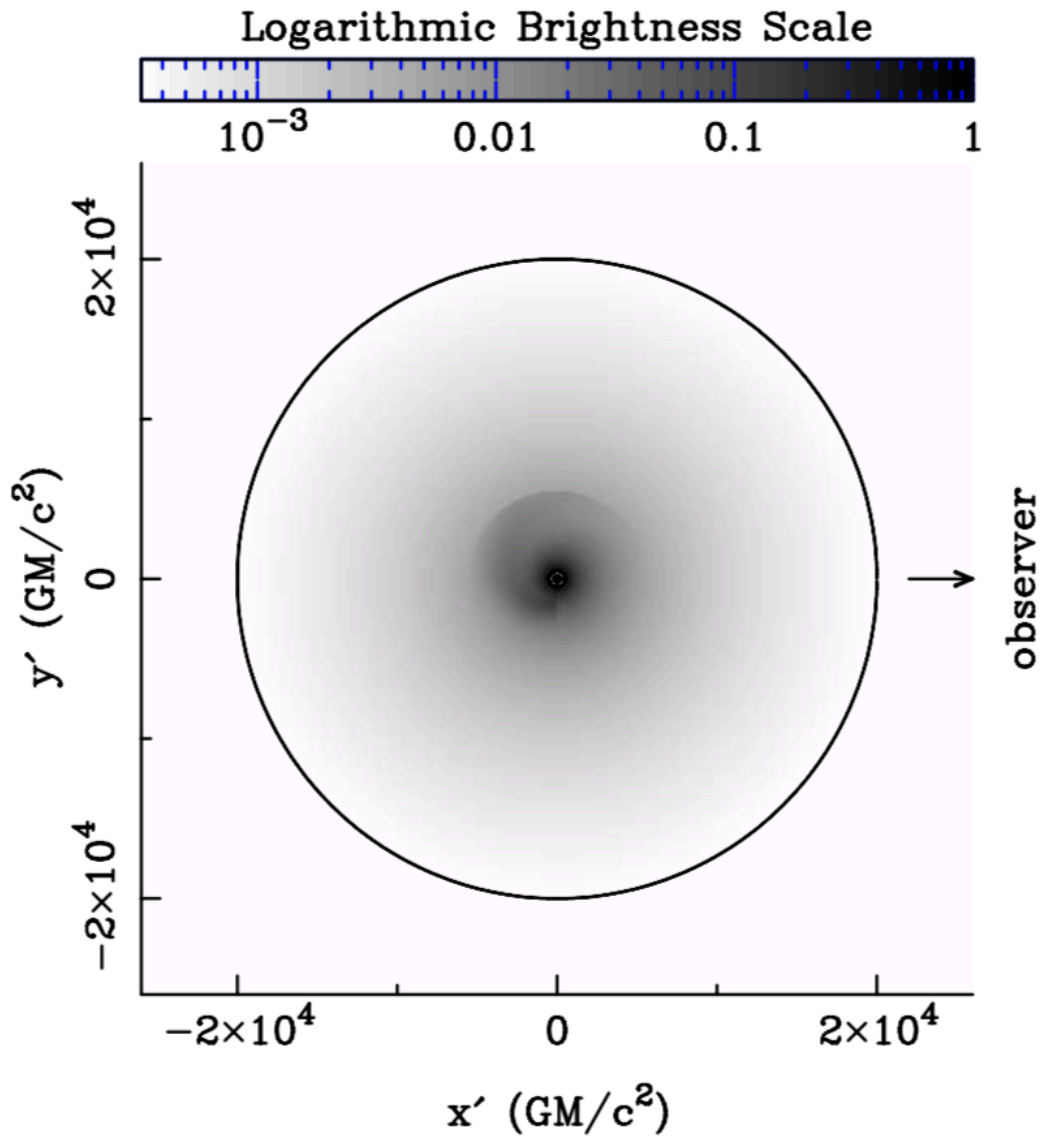
Tidal Disruption Event

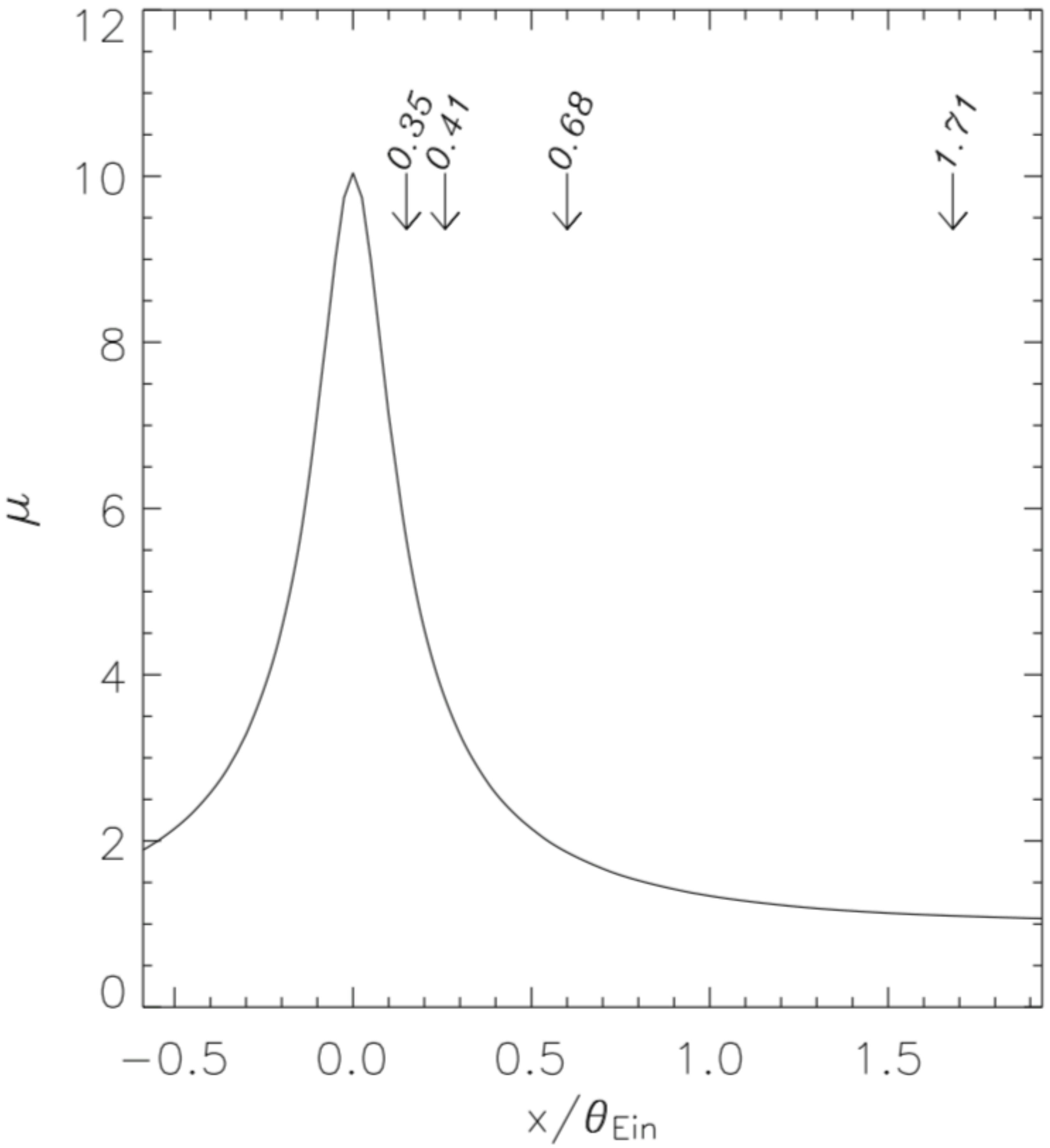


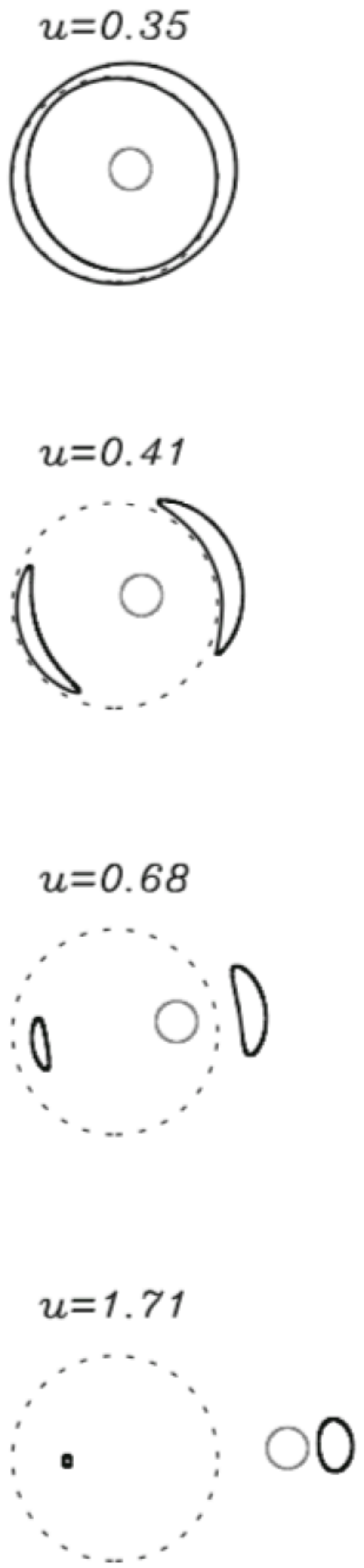


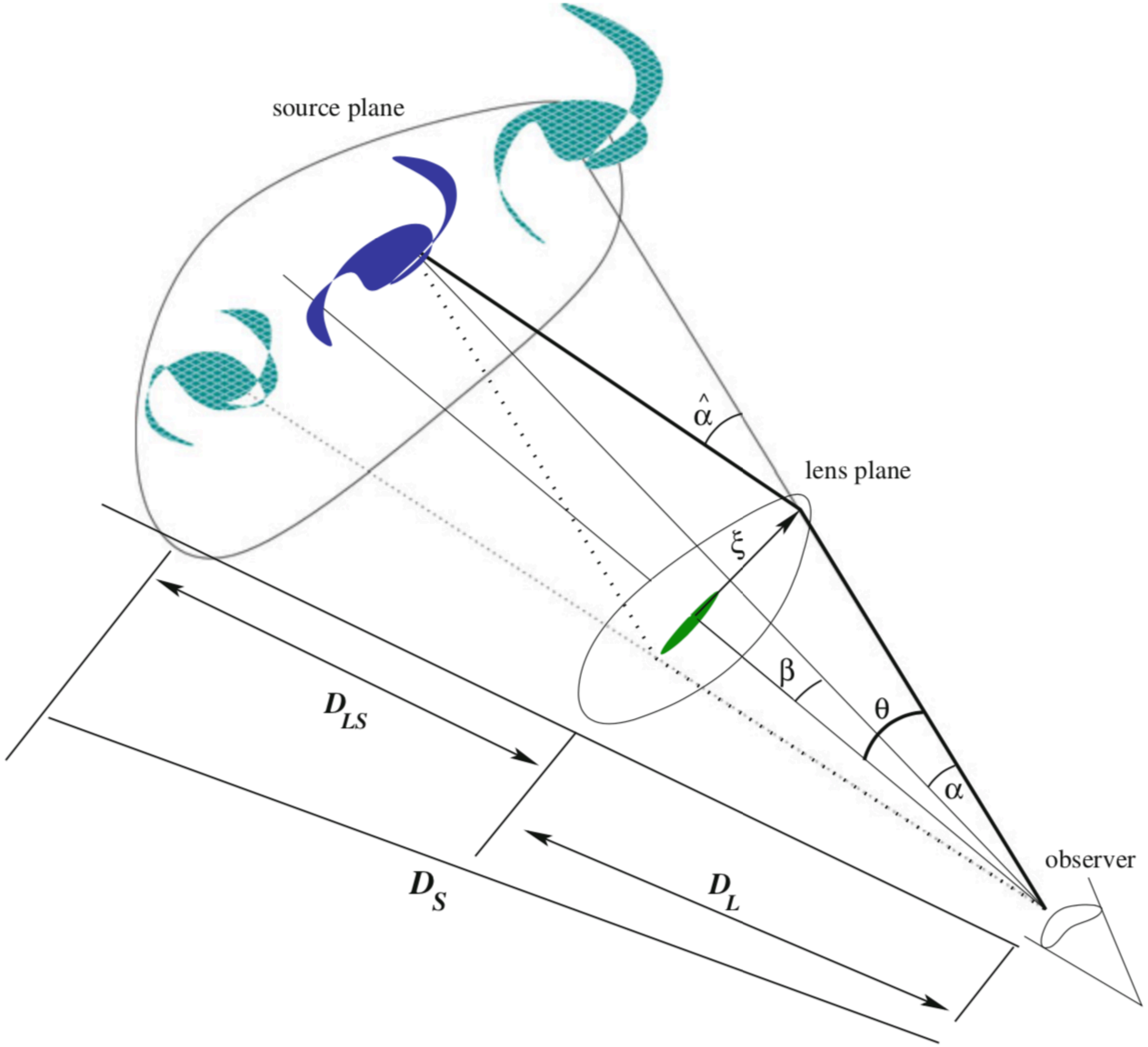


Haloein et al., 2018, arXiv:1808.02890

Microlensing







Abolmasov et al., «Accretion Flows in Astrophysics» (ed. Shakura), 2018

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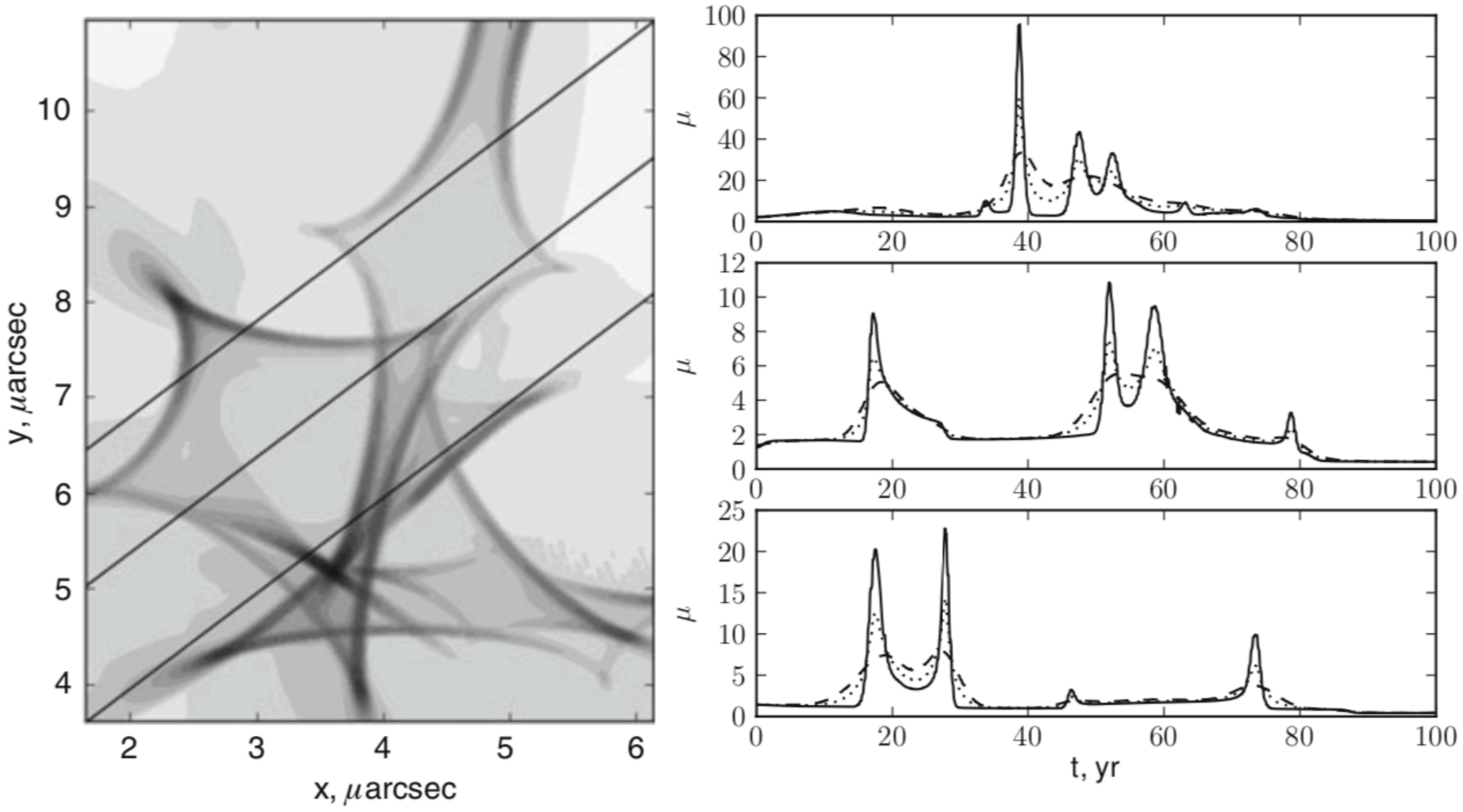
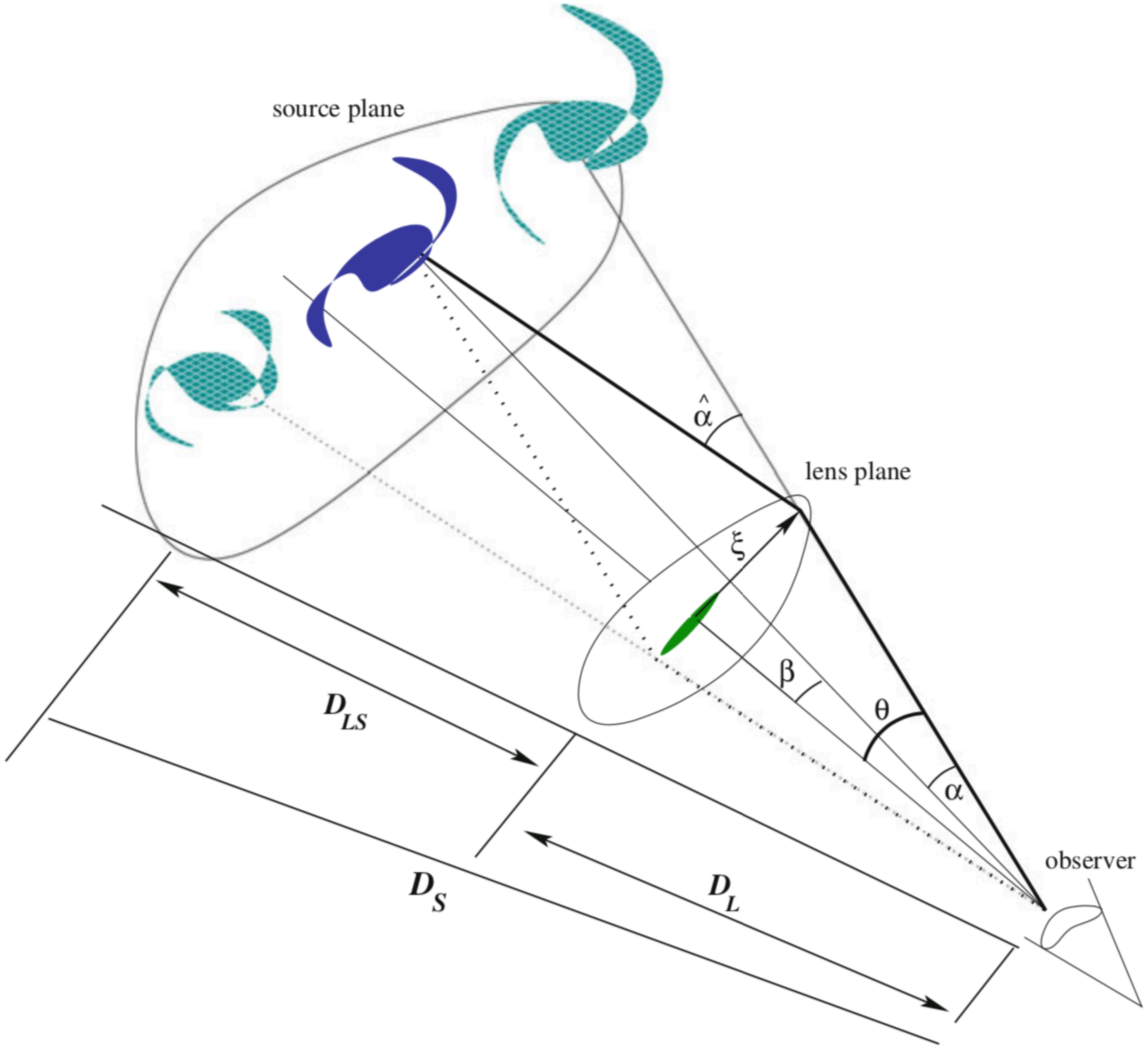
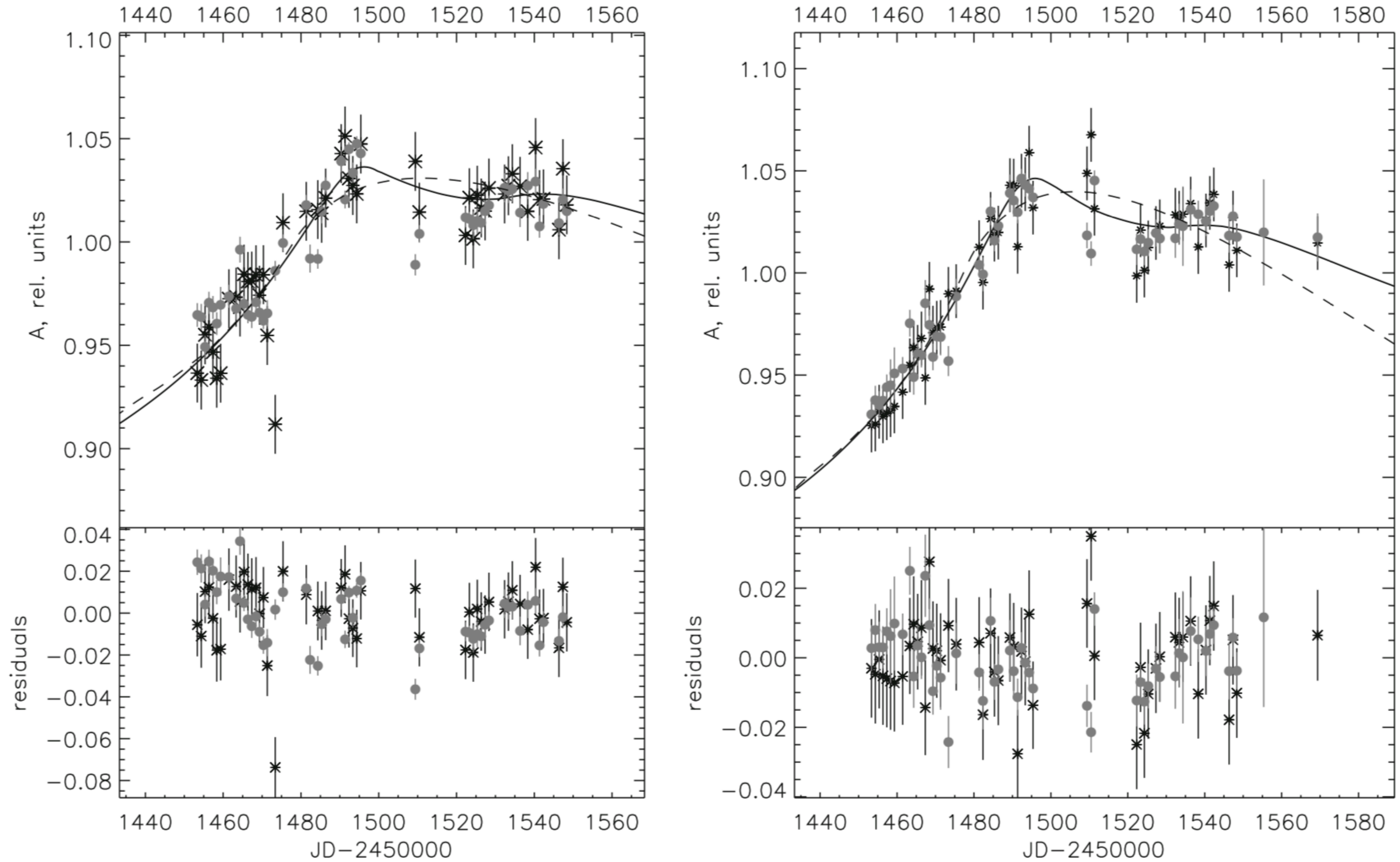




Abolmasov et al., «Accretion Flows in Astrophysics» (ed. Shakura), 2018

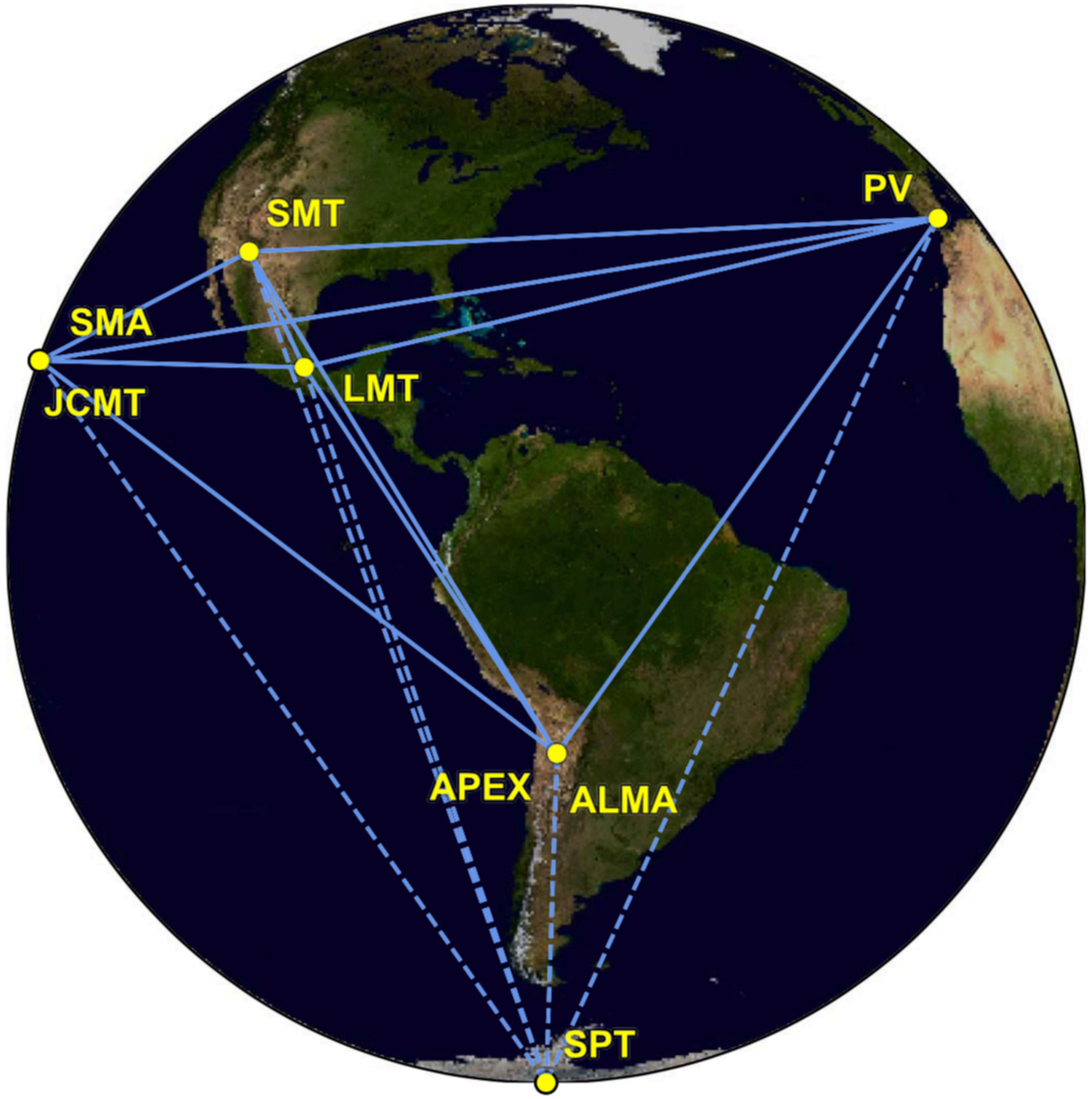
Microlensing of Quasar

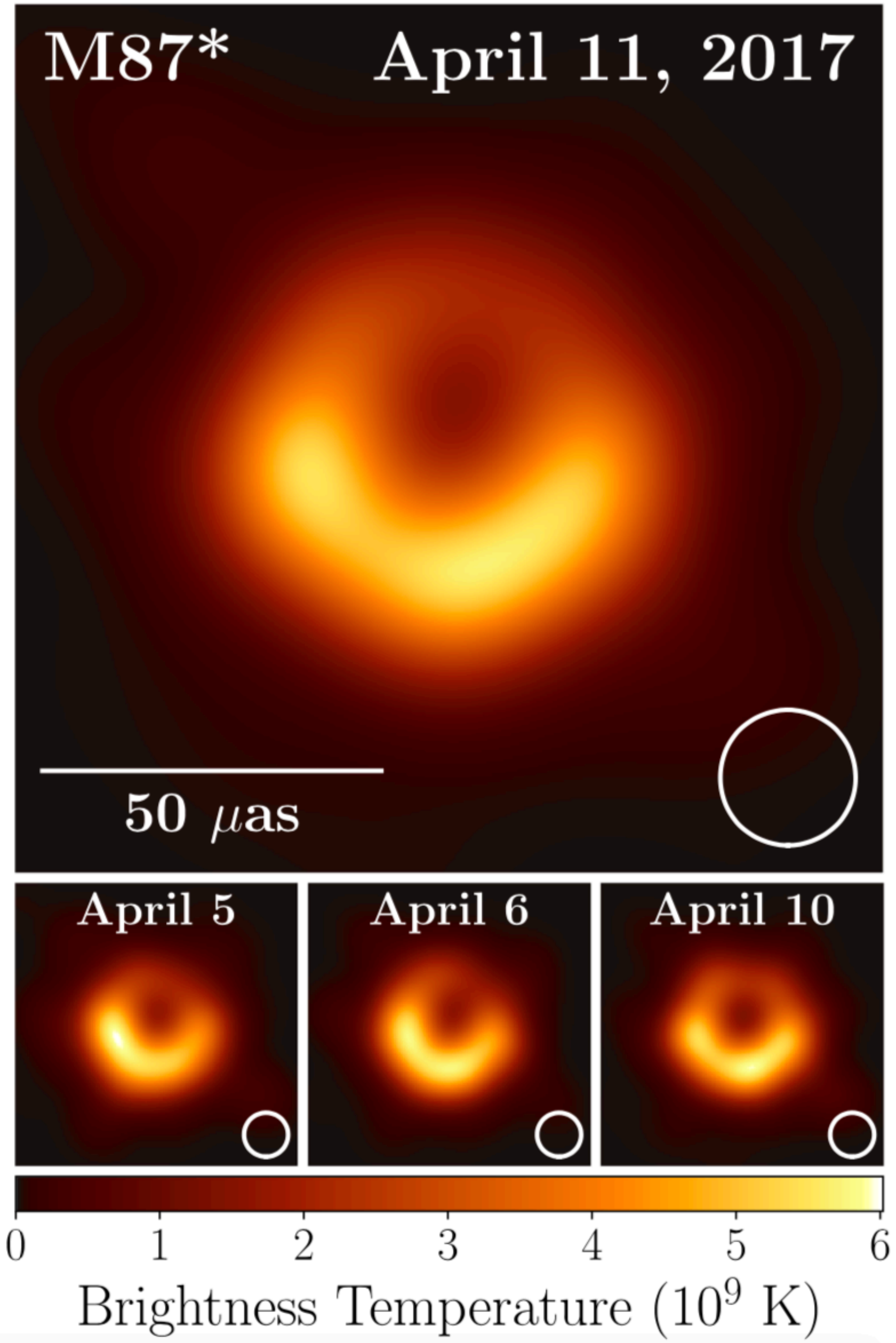
Amplification factor in R and B bands for QSO J2237+0305



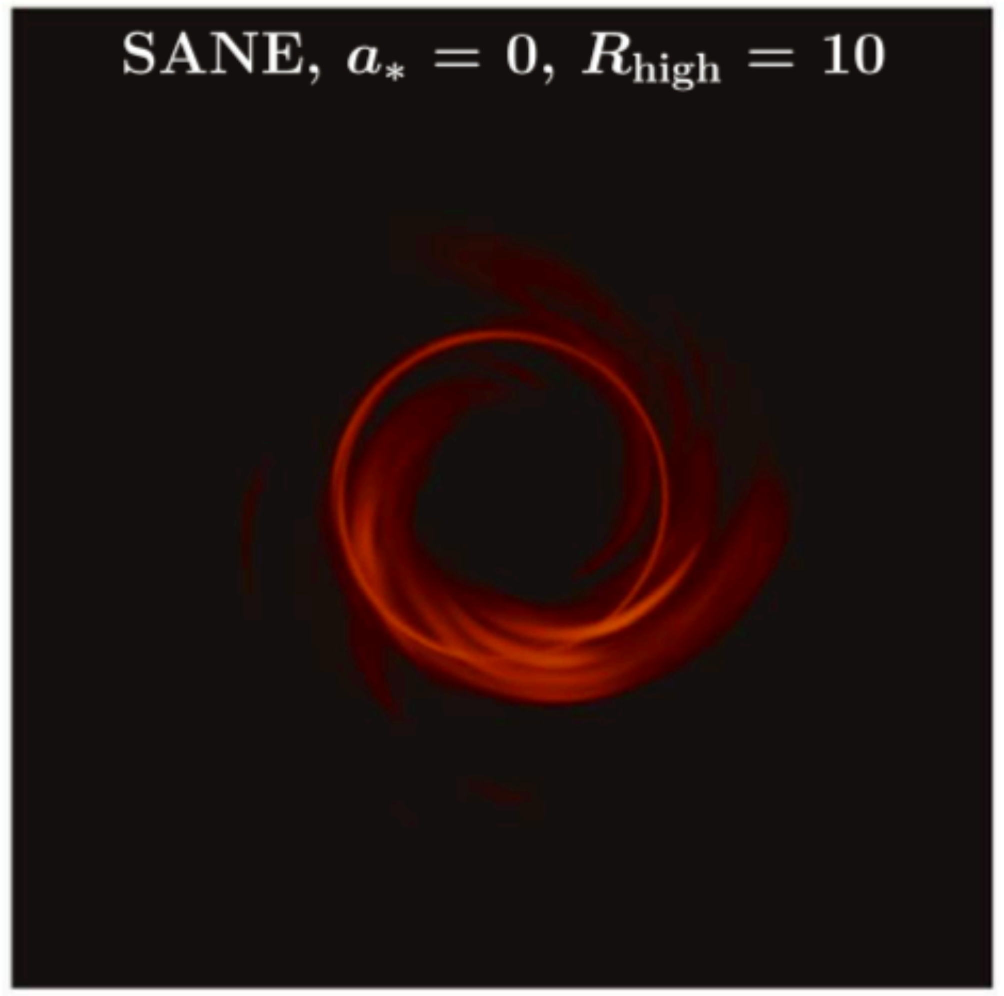
Abolmasov & Shakura, 2012, arXiv:1203.2656

Direct Image of M87 Black Hole

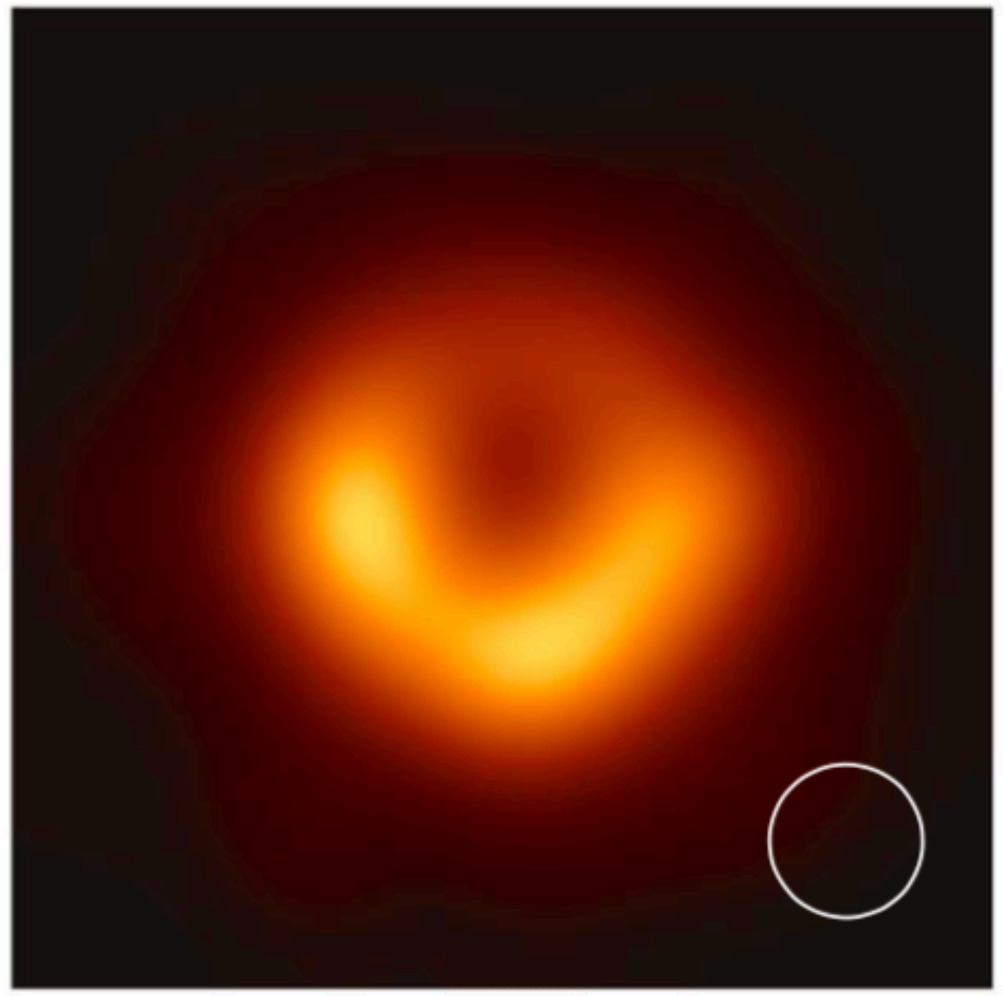




GRMHD models



Simulated EHT observations



The Event Horizon Collaboration, ApJL, V. 875, L1

NASA, JPL-Caltech, Event Horizon Telescope Collaboration

Thank you

1	☐ 1998AJ....116.1009R	11550.000	09/1998	A Z E F X D R C S N U H
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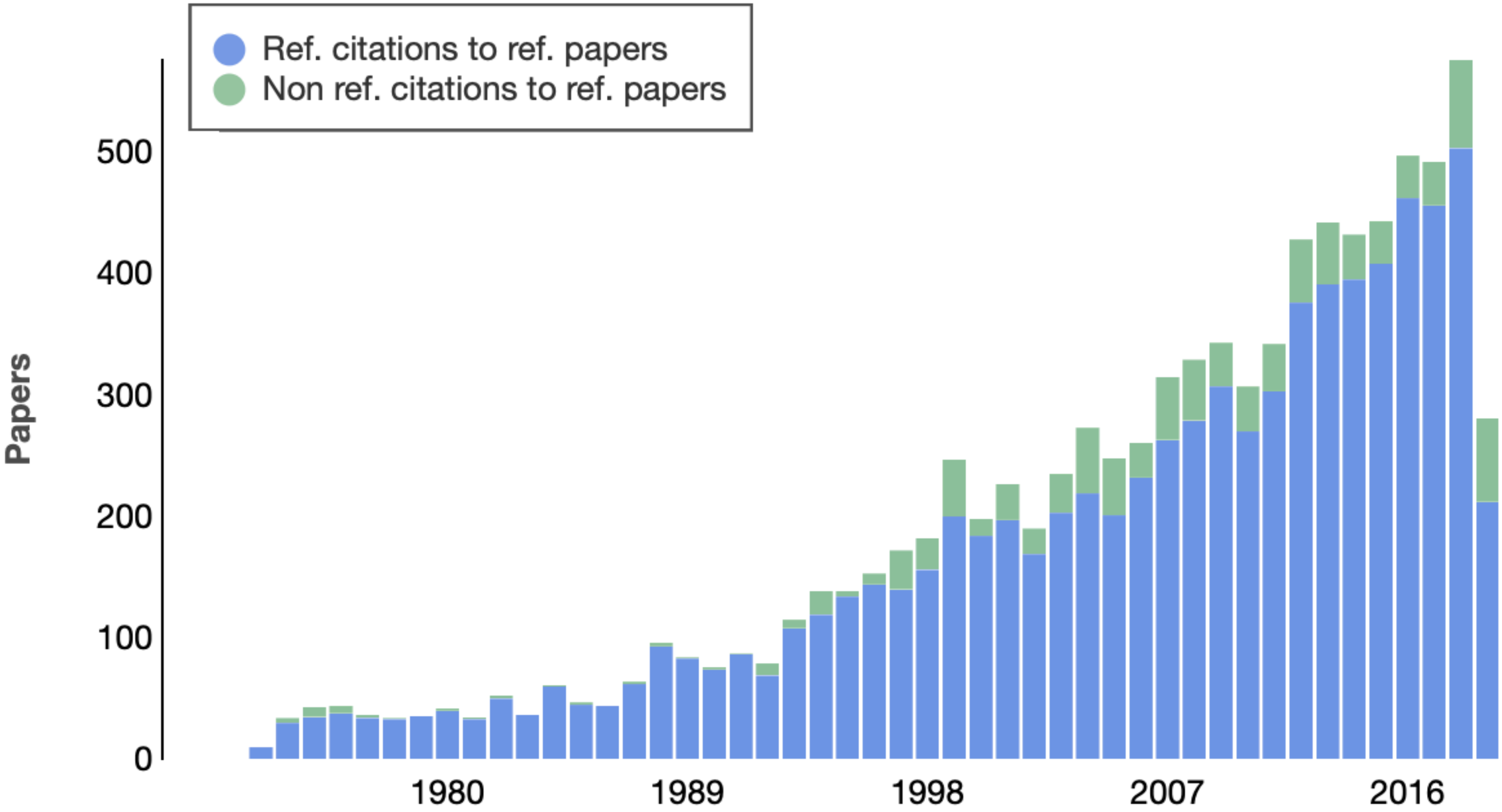
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