Title: Evidence for the Black Hole Event Horizon

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Abstract: Astronomers have discovered many candidate black holes in the universe and have studied their properties in ever-increasing detail. Over the last decade, a few groups have developed observational tests for the presence of event horizons in candidate black holes. The talk will discuss one of these tests, which indicates that the supermassive black hole at the center of our Galaxy must have a horizon.

EVIDENCE FOR THE BLACK HOLE EVENT HORIZON

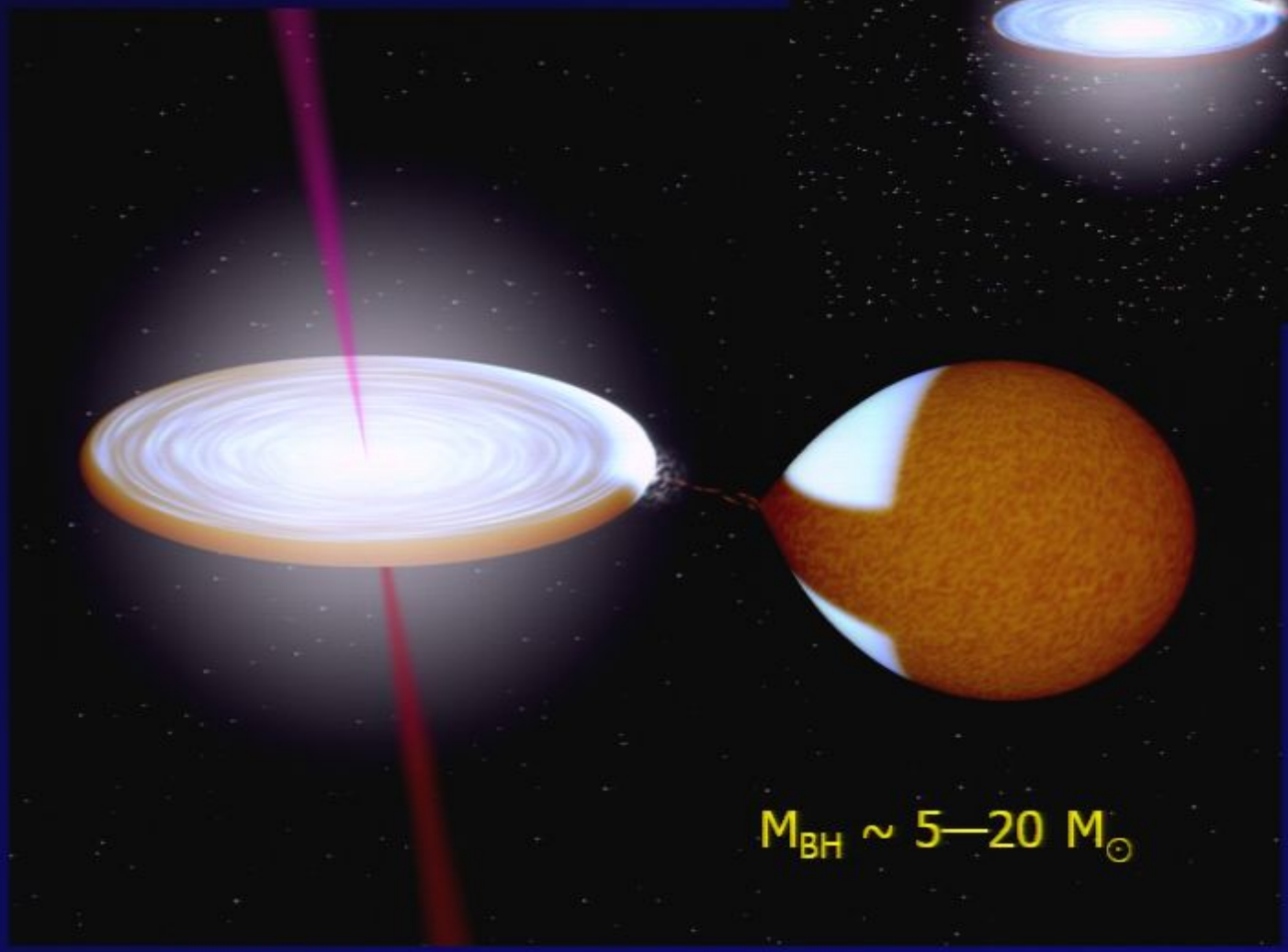
Ramesh Narayan

Black Hole

- A **Black Hole** is an object in which gravity is so strong that matter is crushed to a singularity, surrounded by an event horizon
- The **Event horizon** acts like a one-way membrane --- matter/energy can fall in, but nothing can get out, not even light
- A most remarkable prediction of General Relativity
- **Schwarzschild radius** (non-spinning **BH**):

$$R_s = \frac{2GM}{C^2} = 2.95\left(\frac{M}{M_\odot}\right)\text{km}$$

X-ray Binaries



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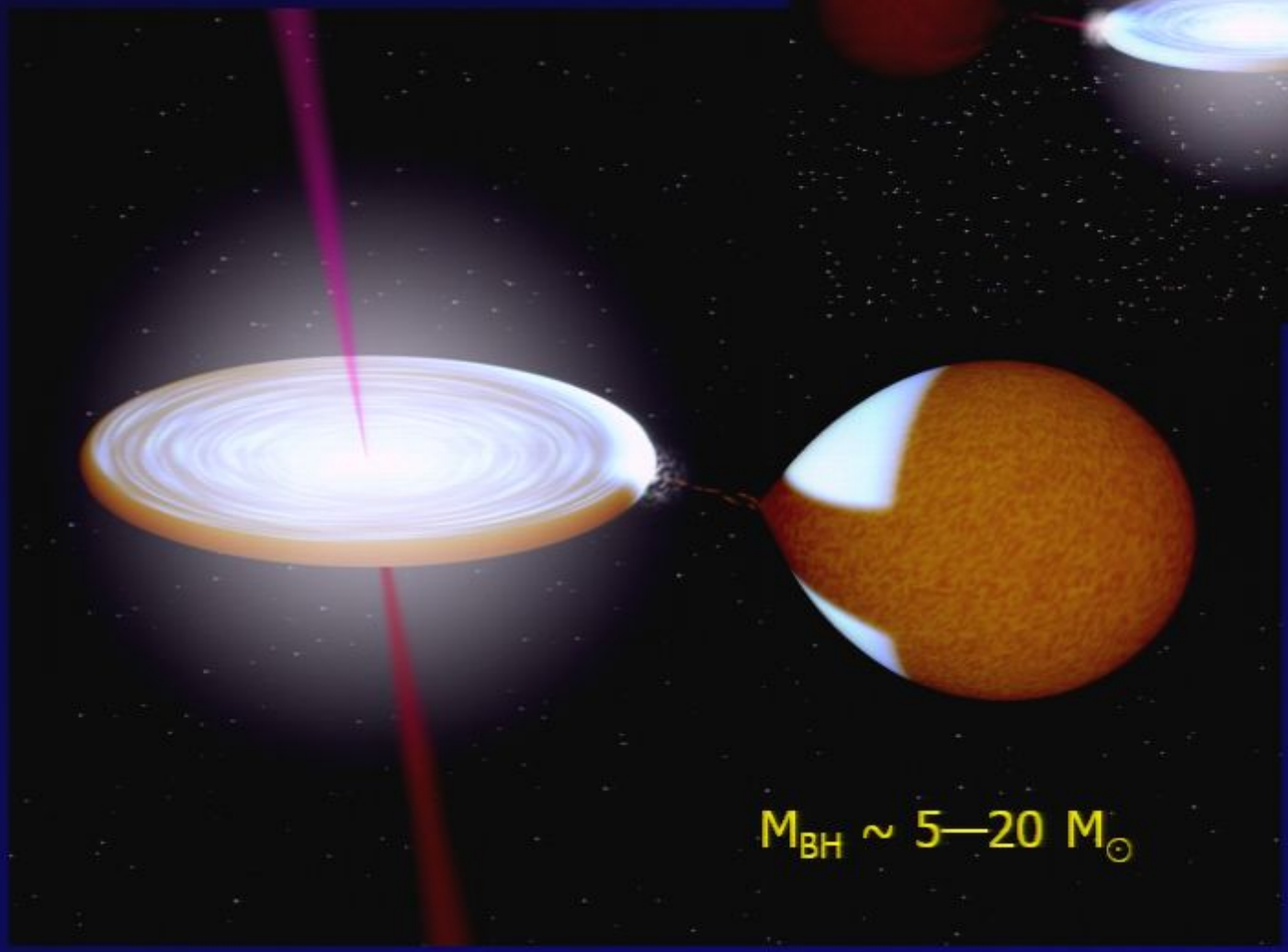

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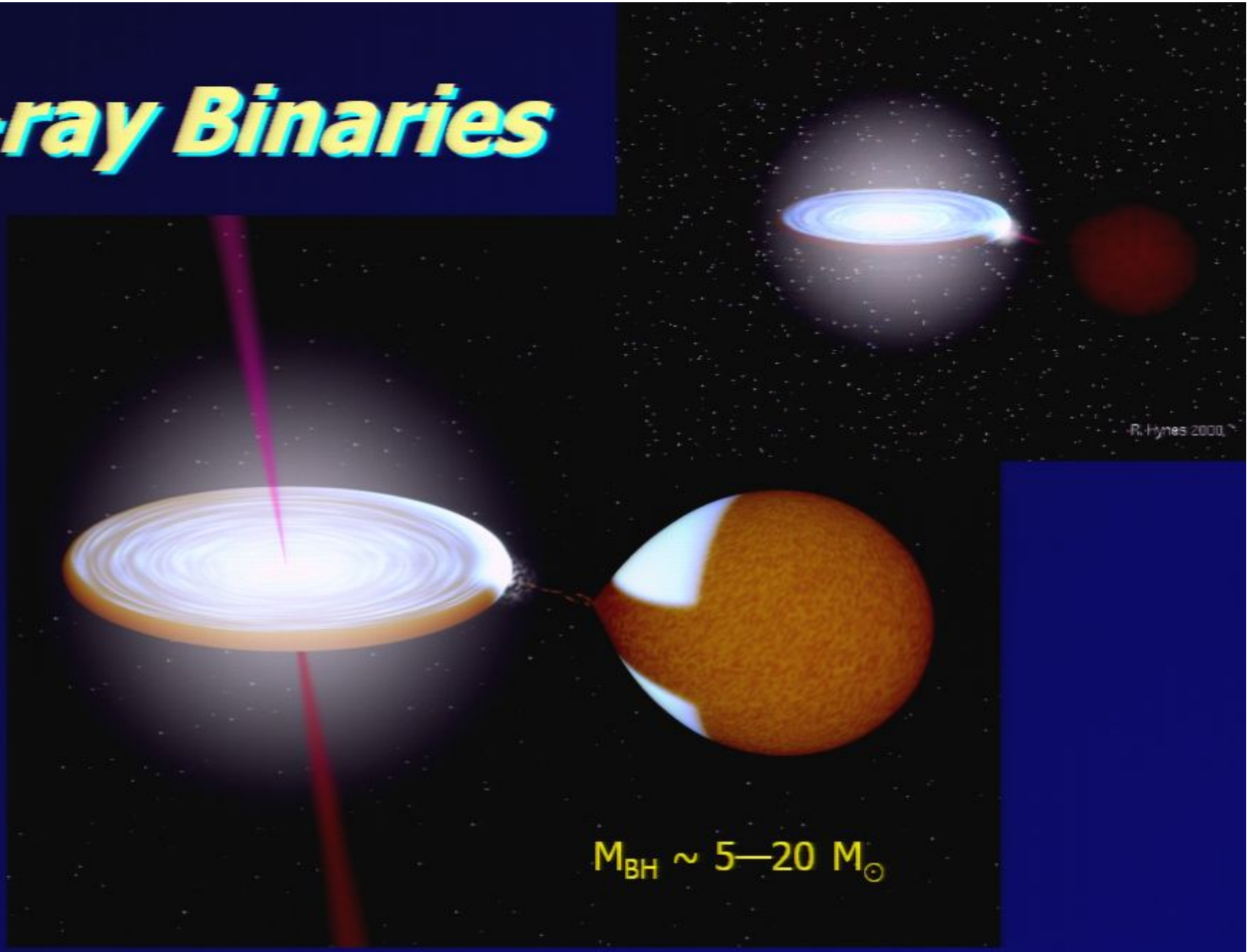

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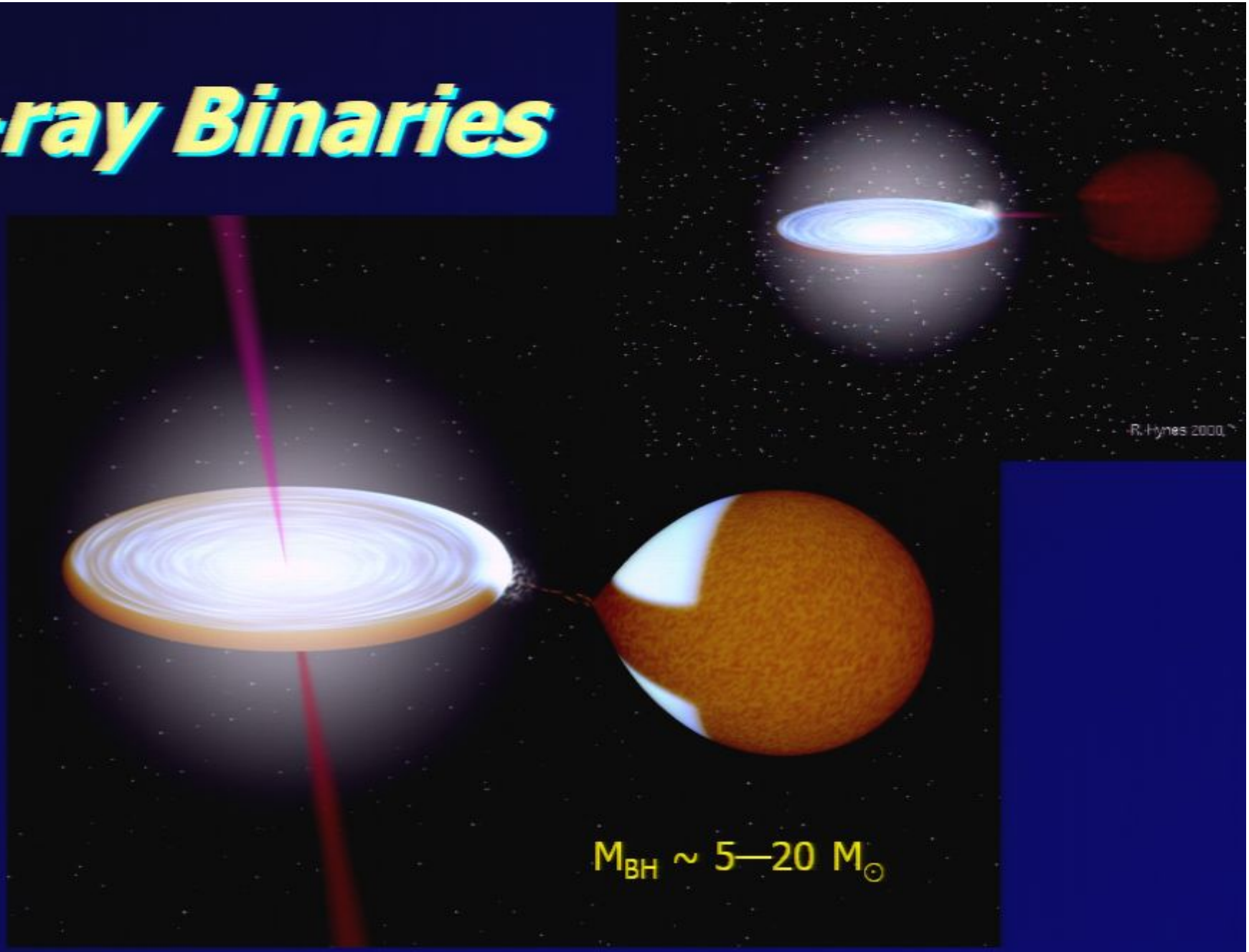

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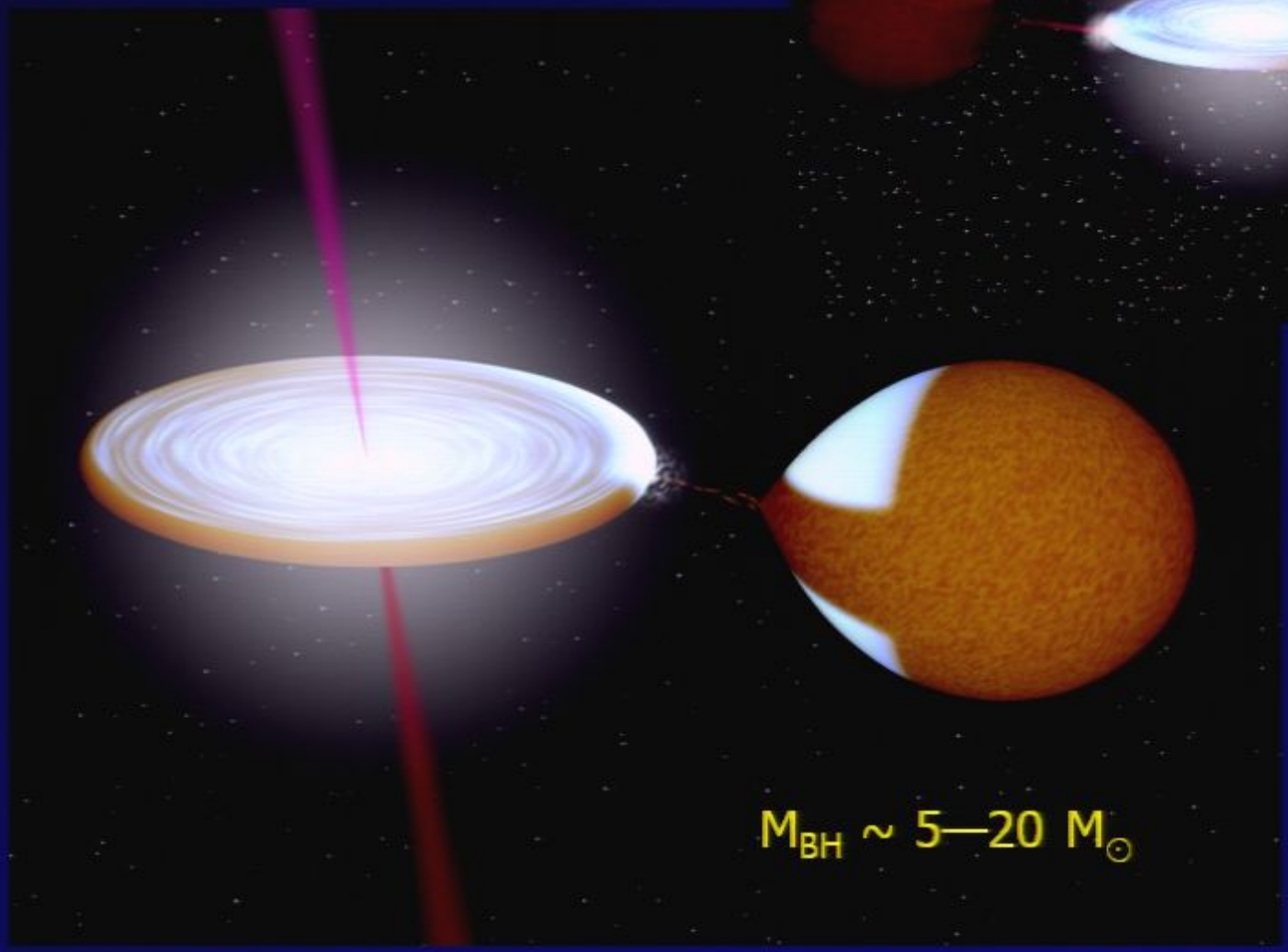

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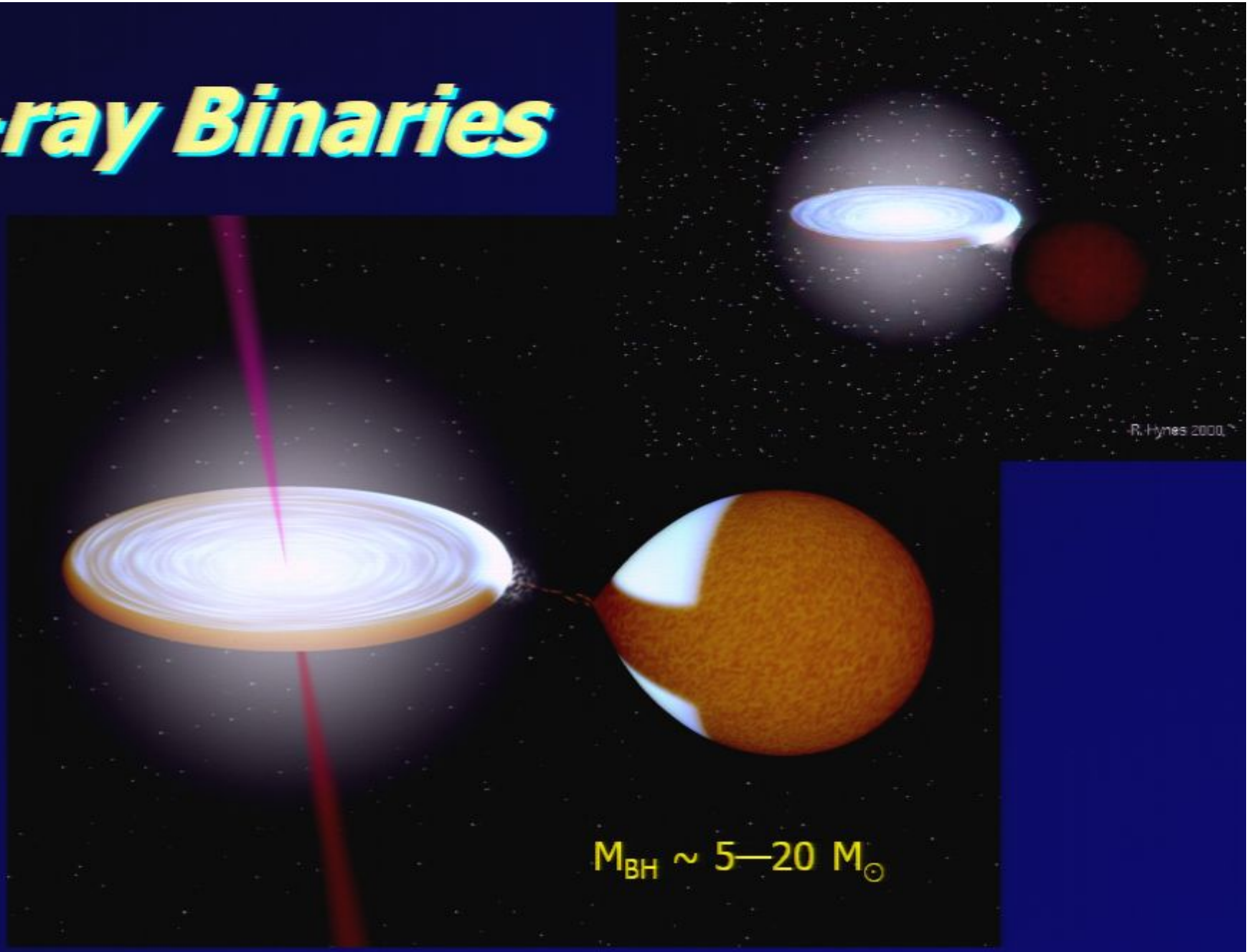

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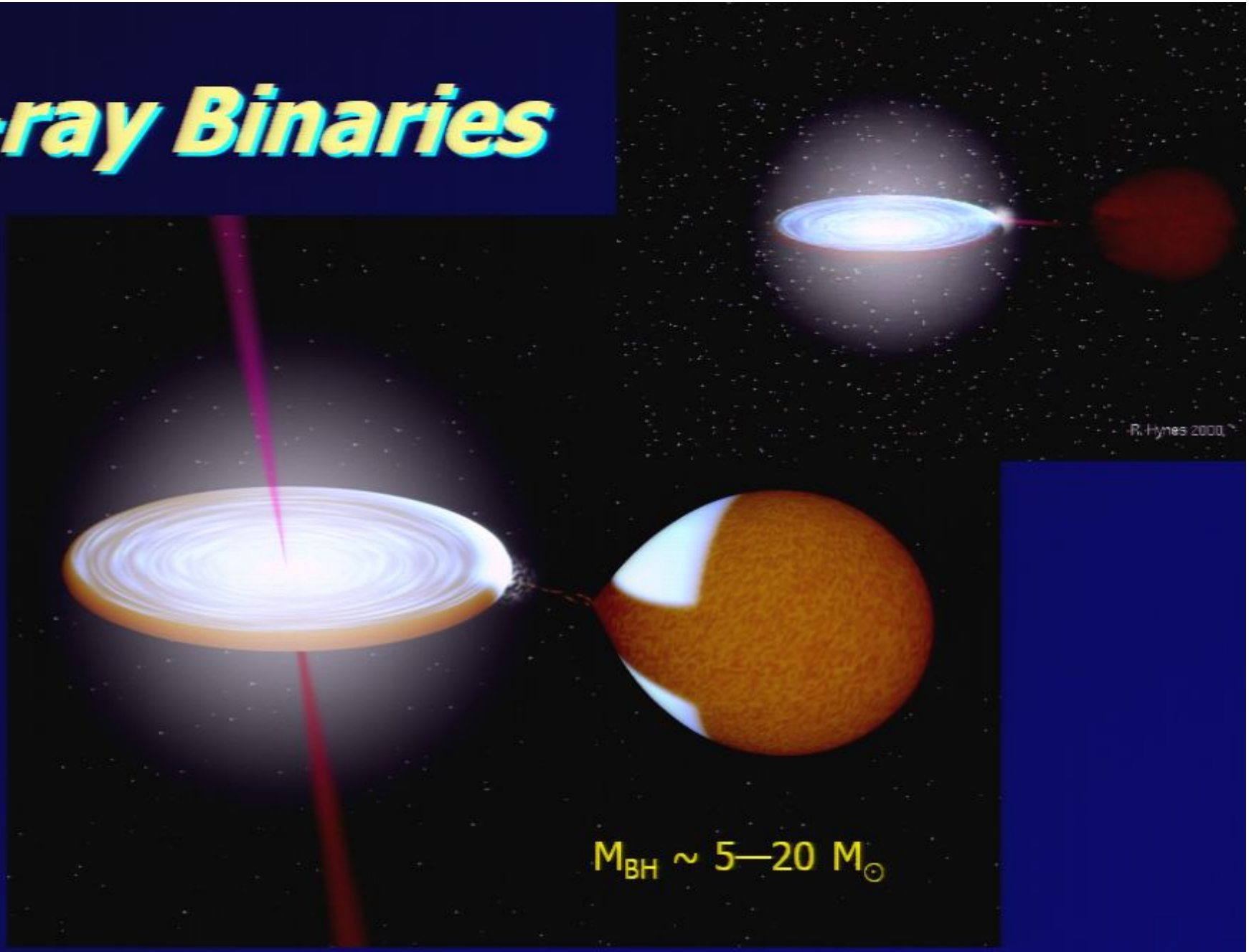

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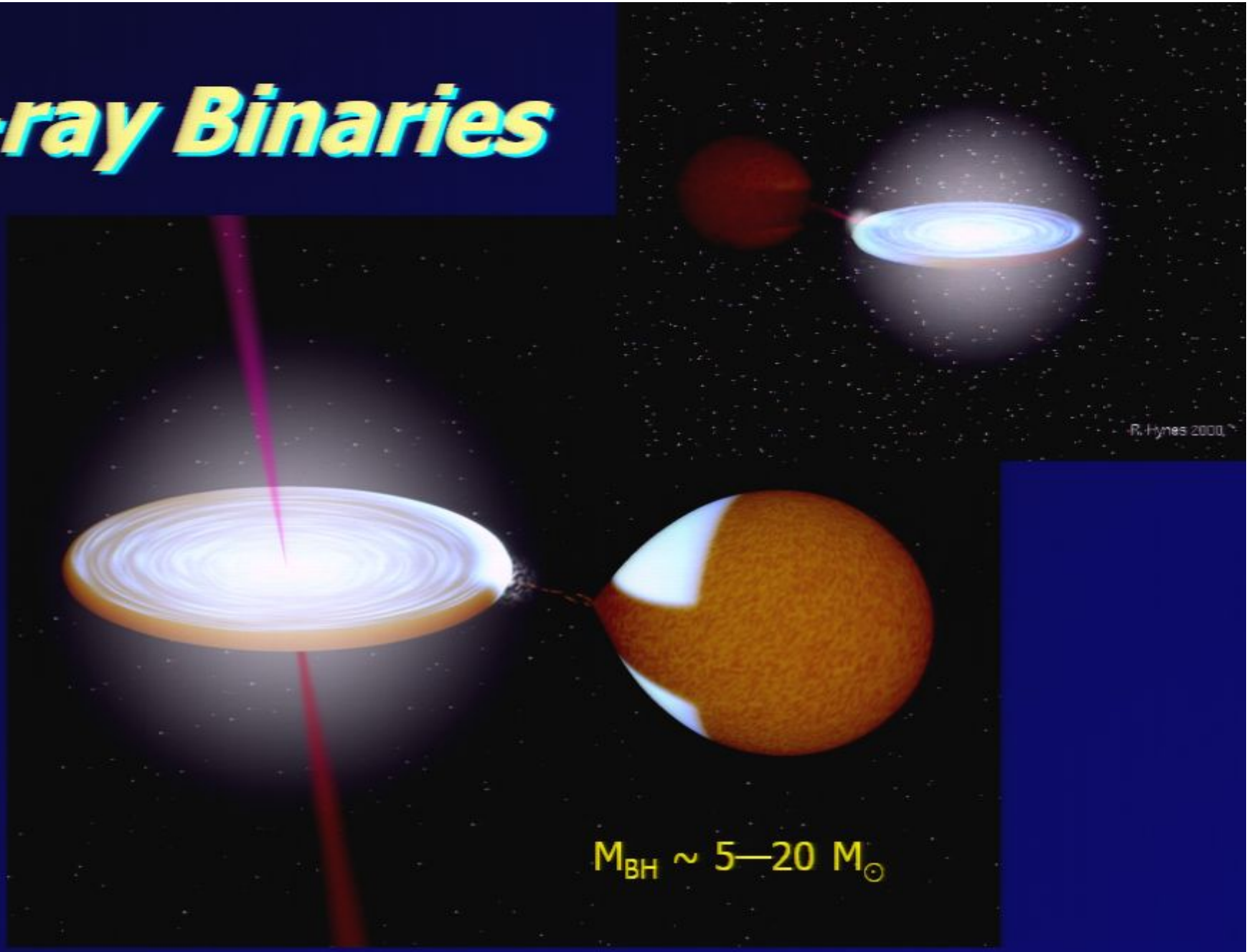

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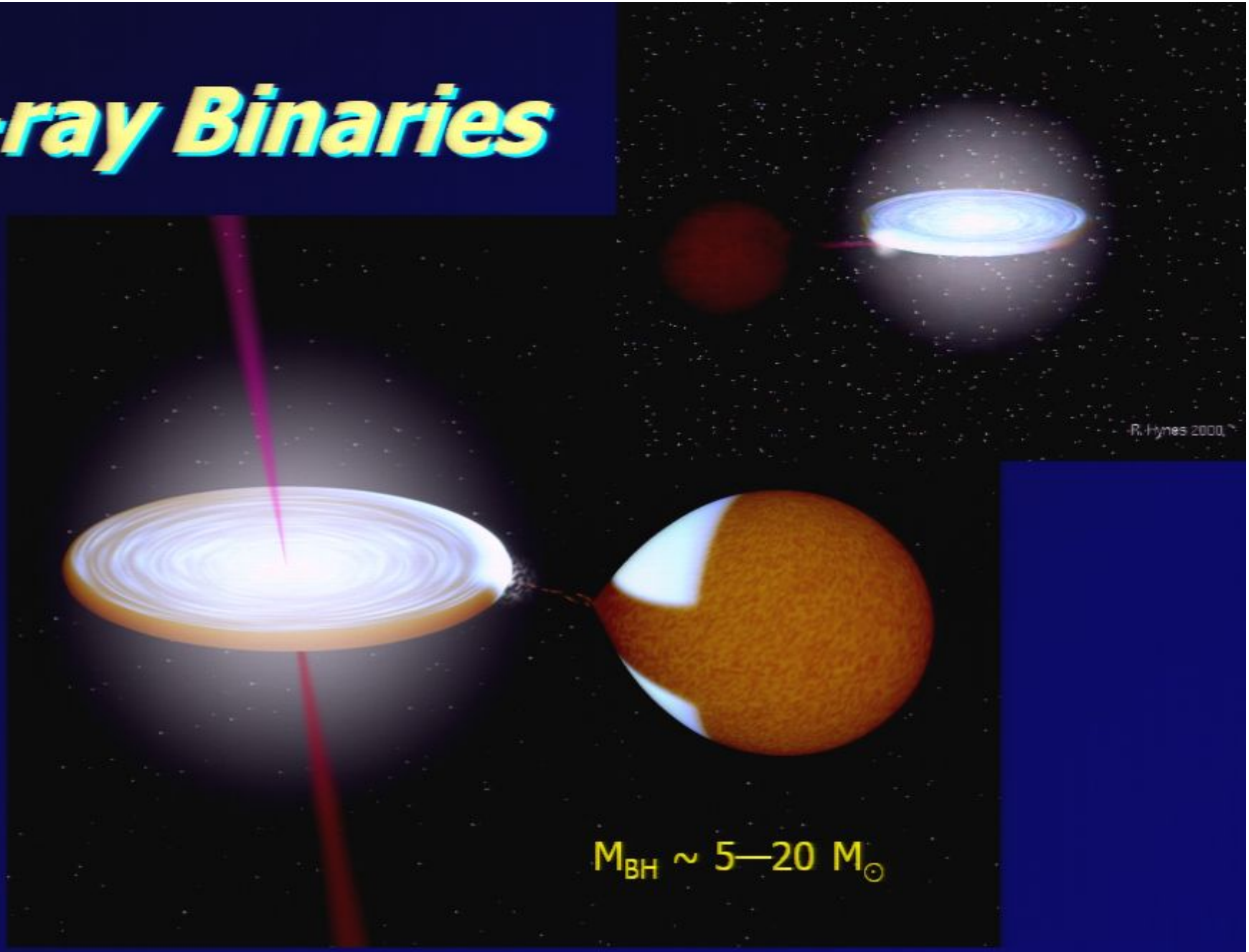

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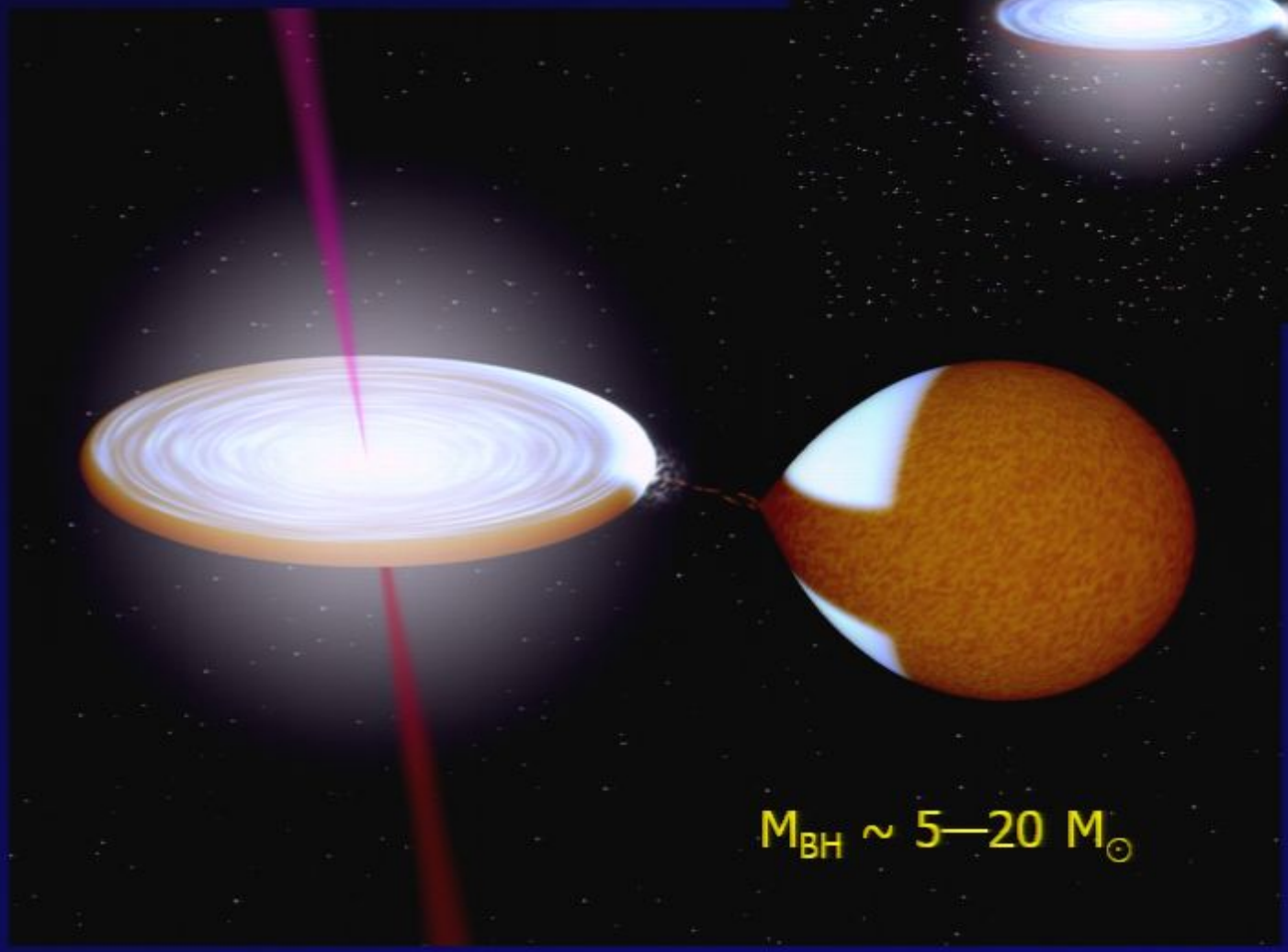

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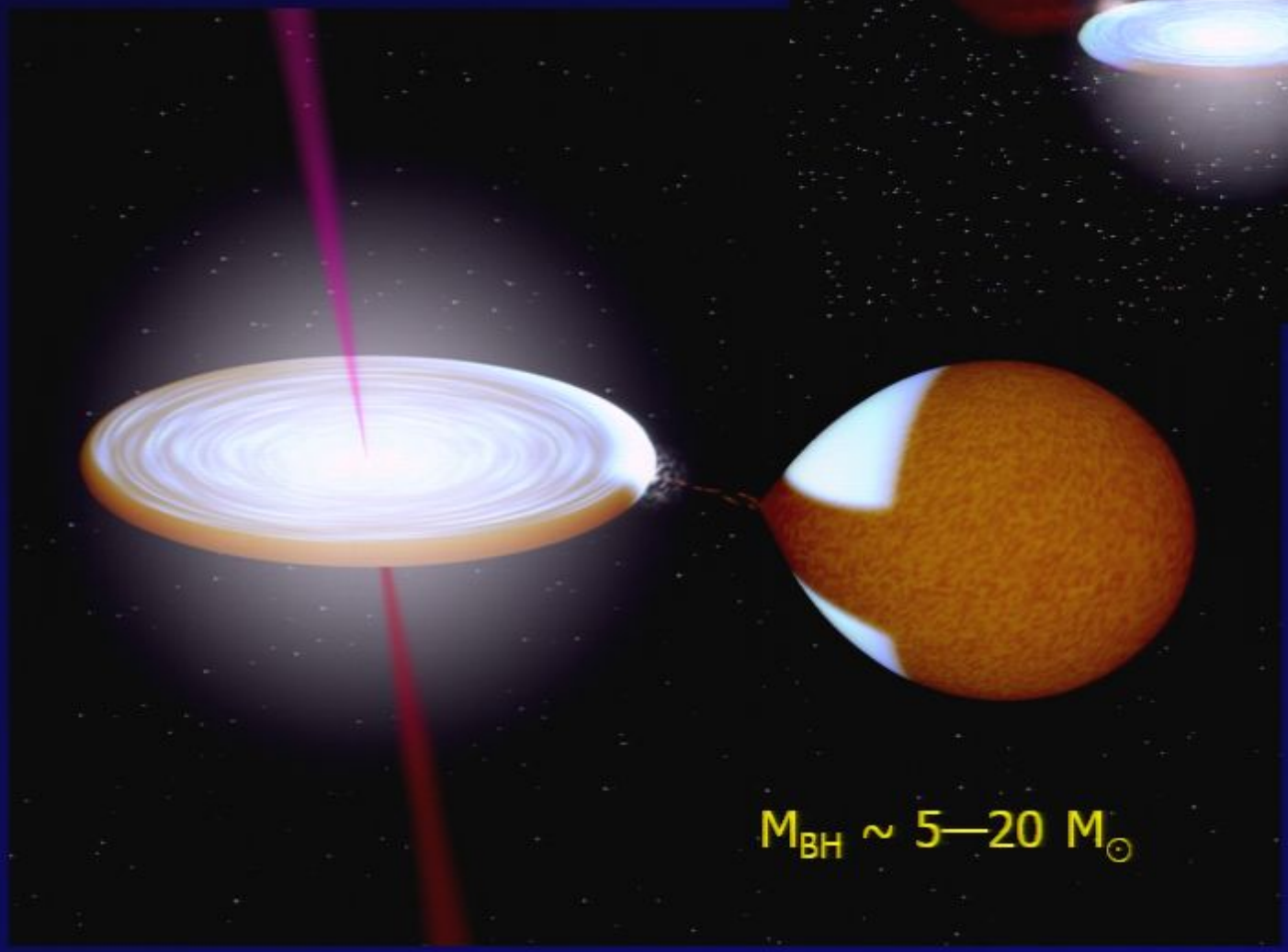

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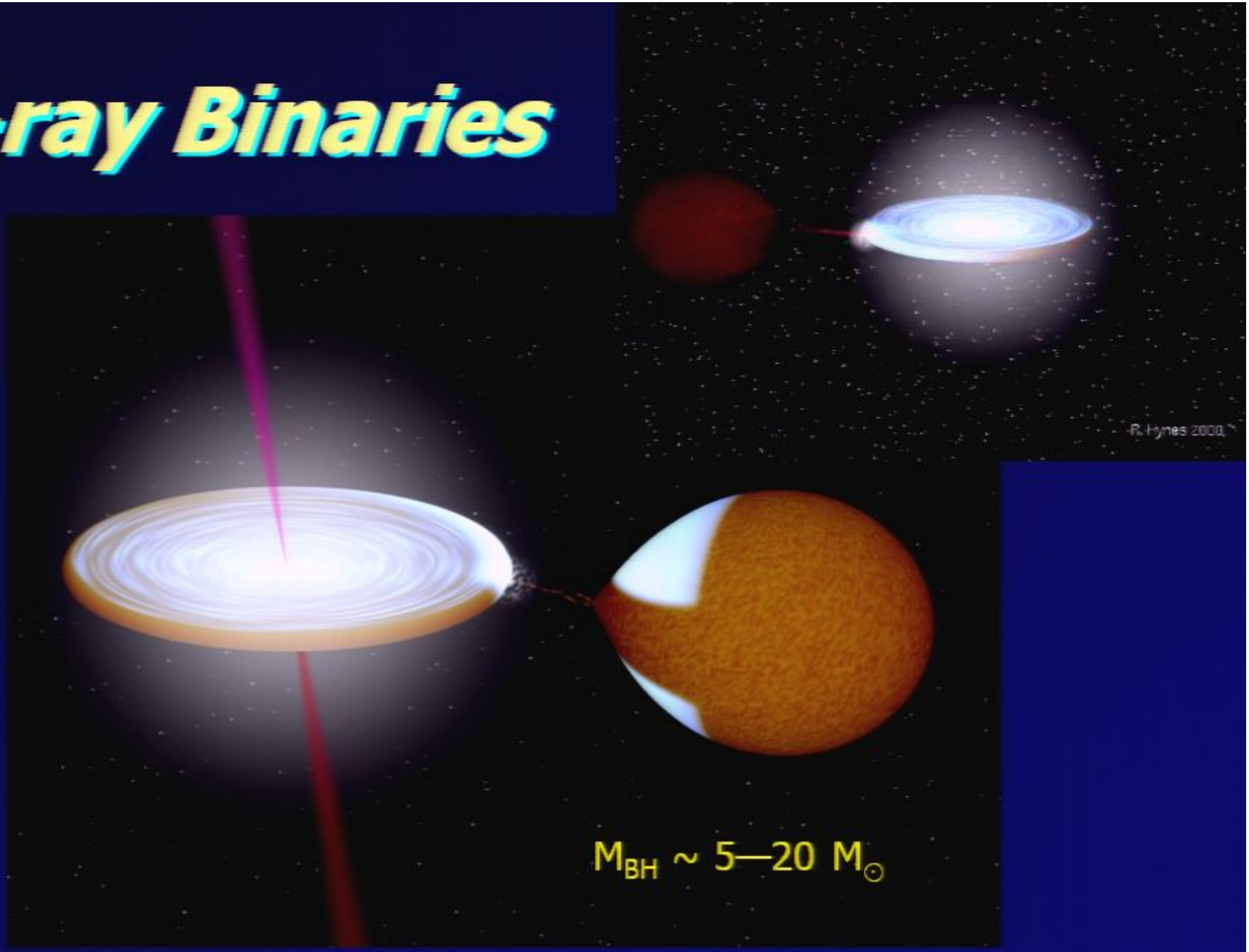

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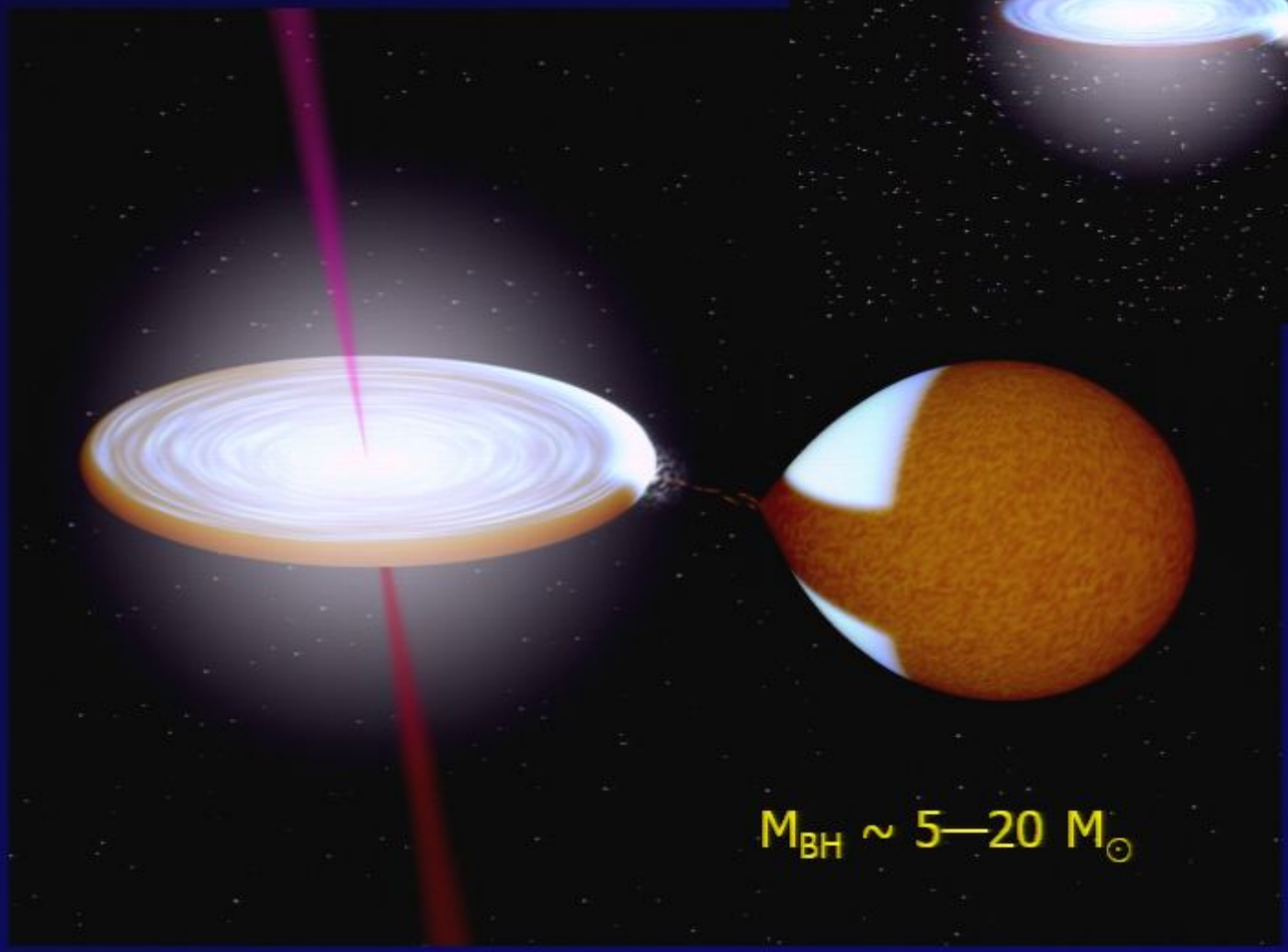

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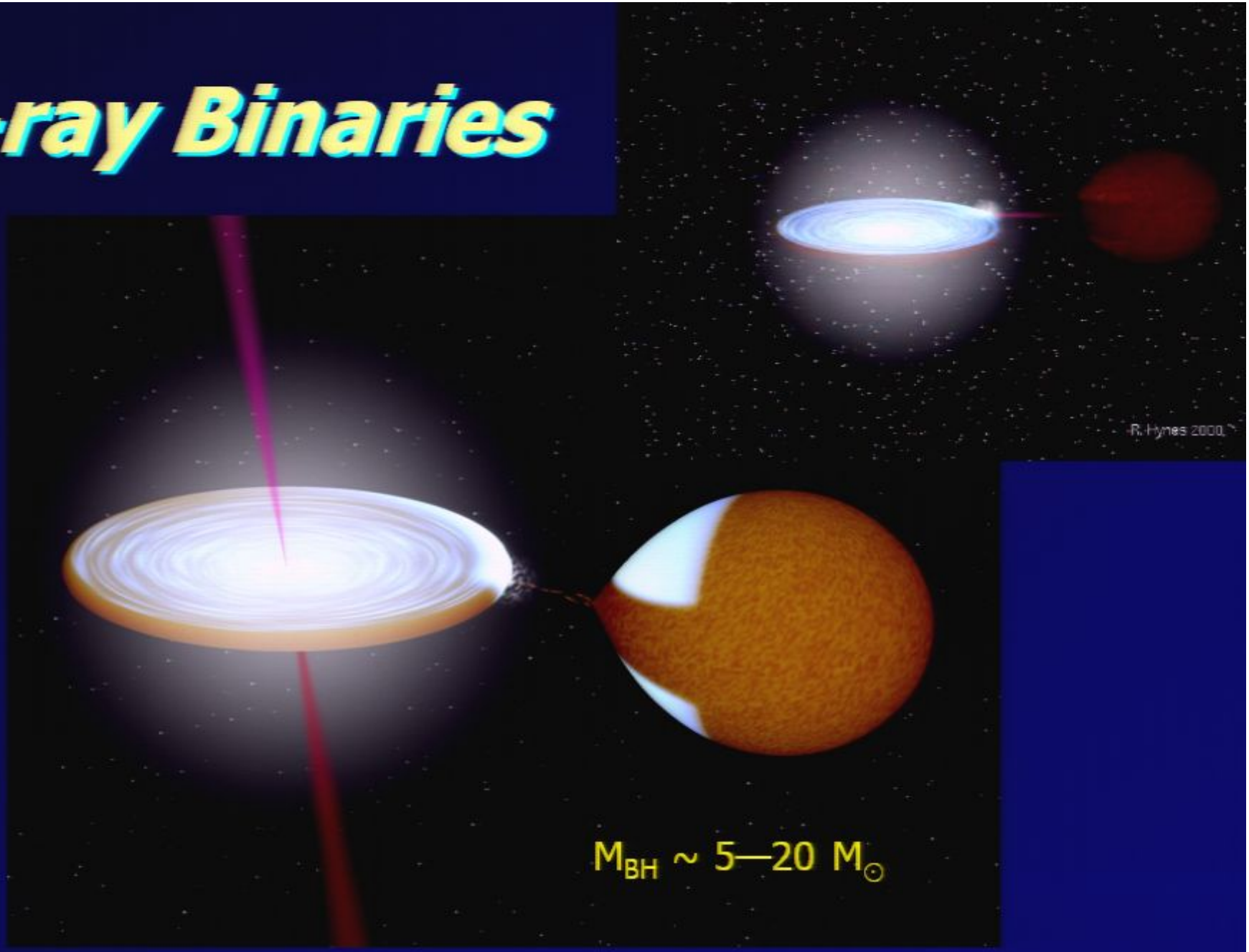

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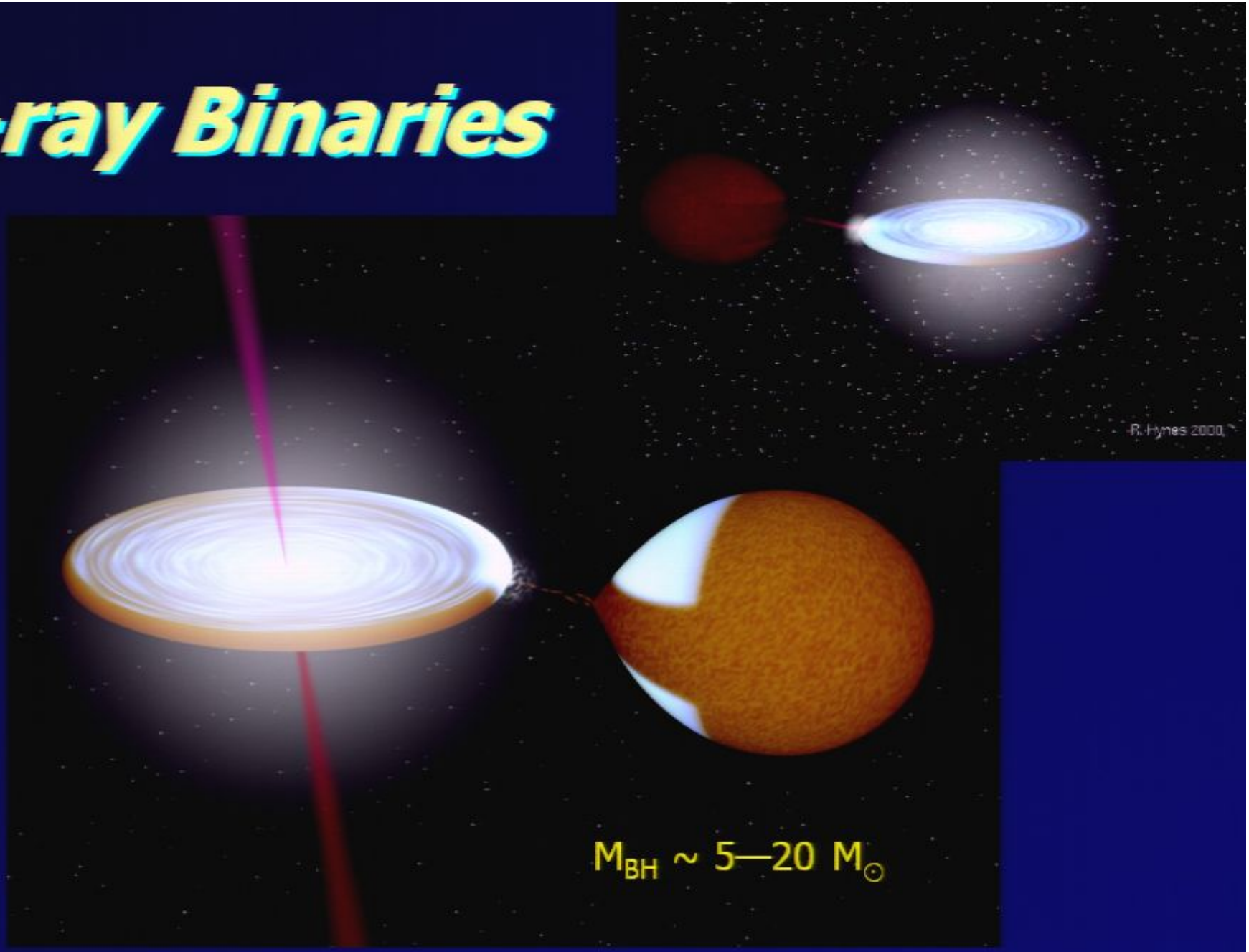

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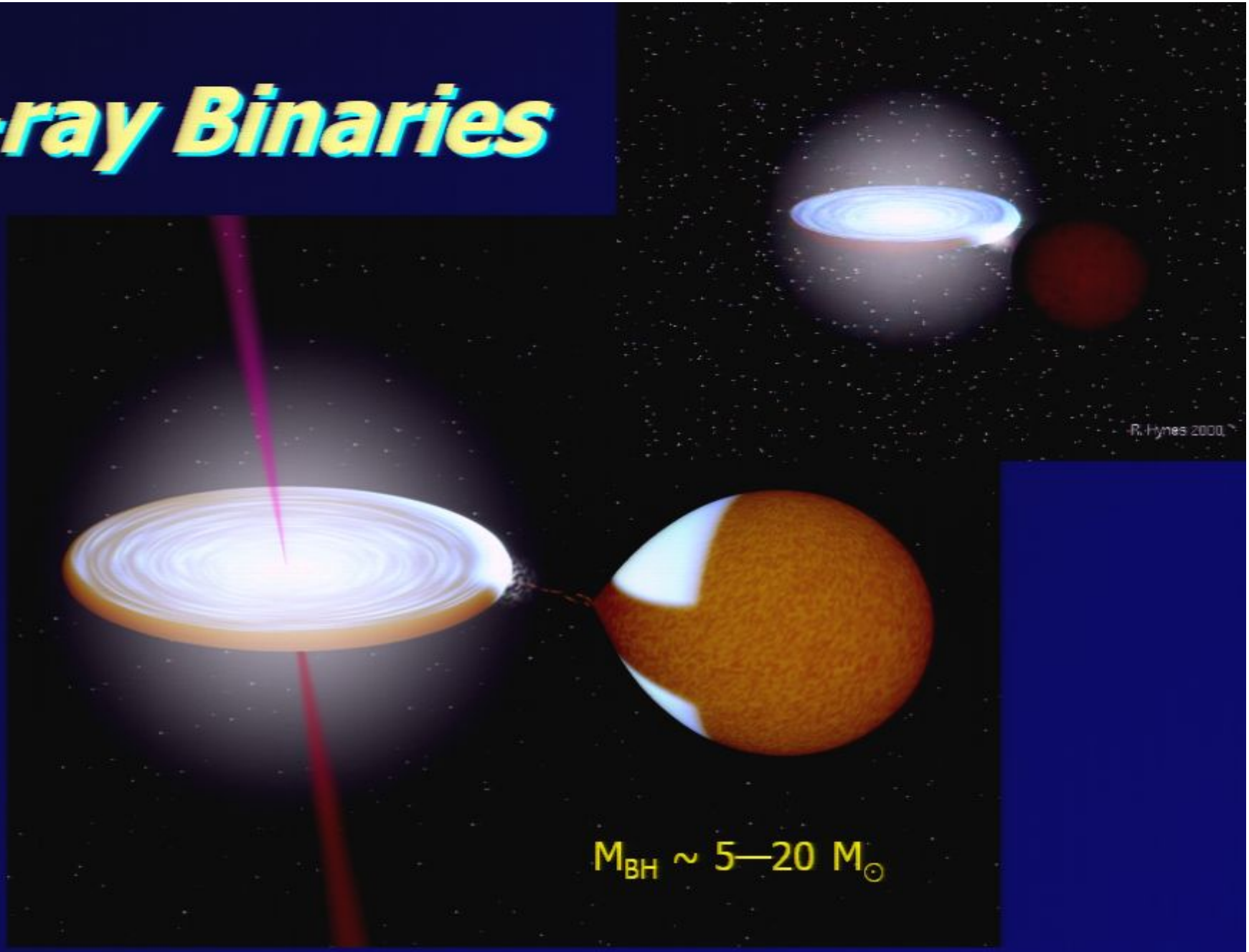

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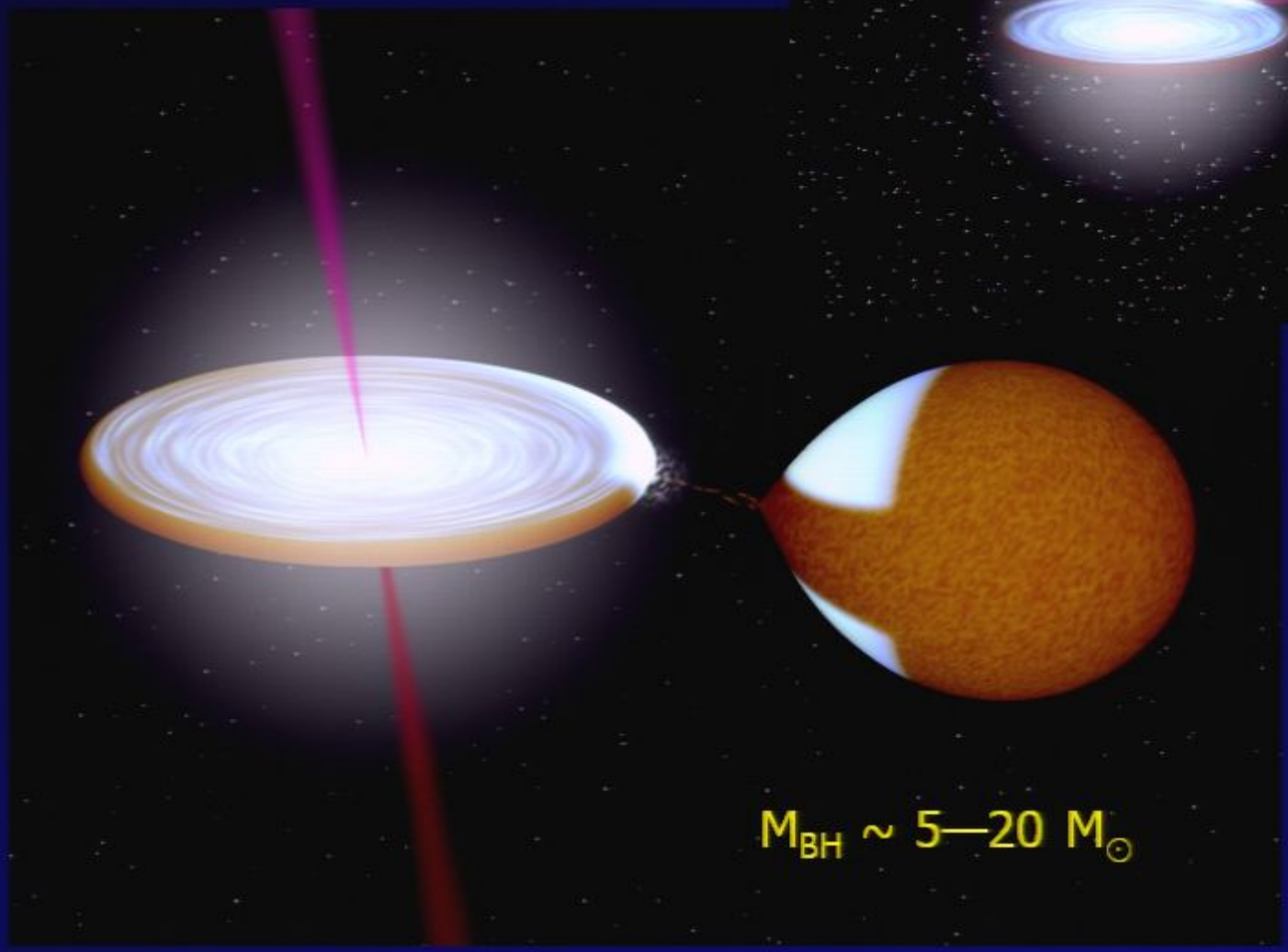

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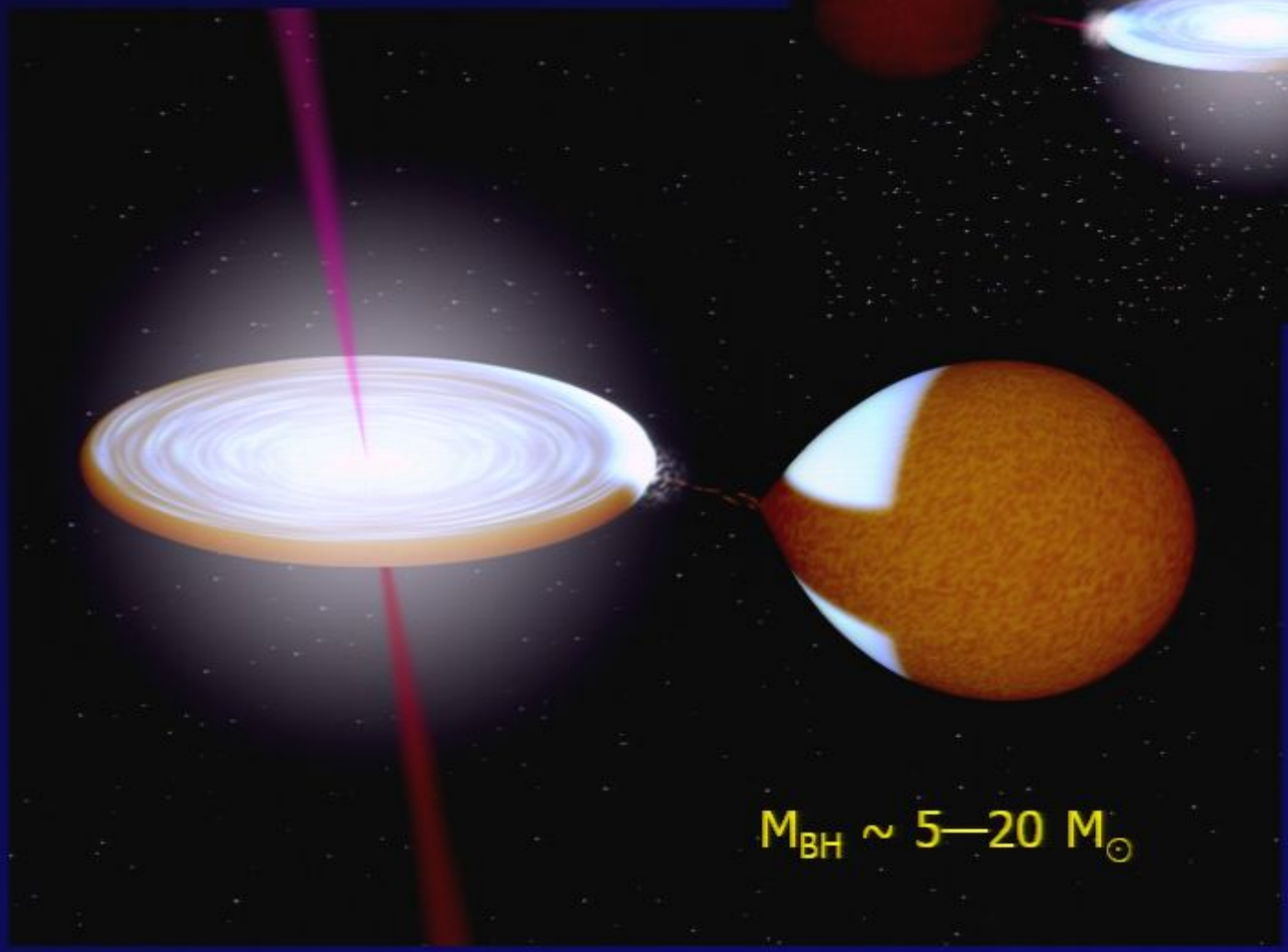

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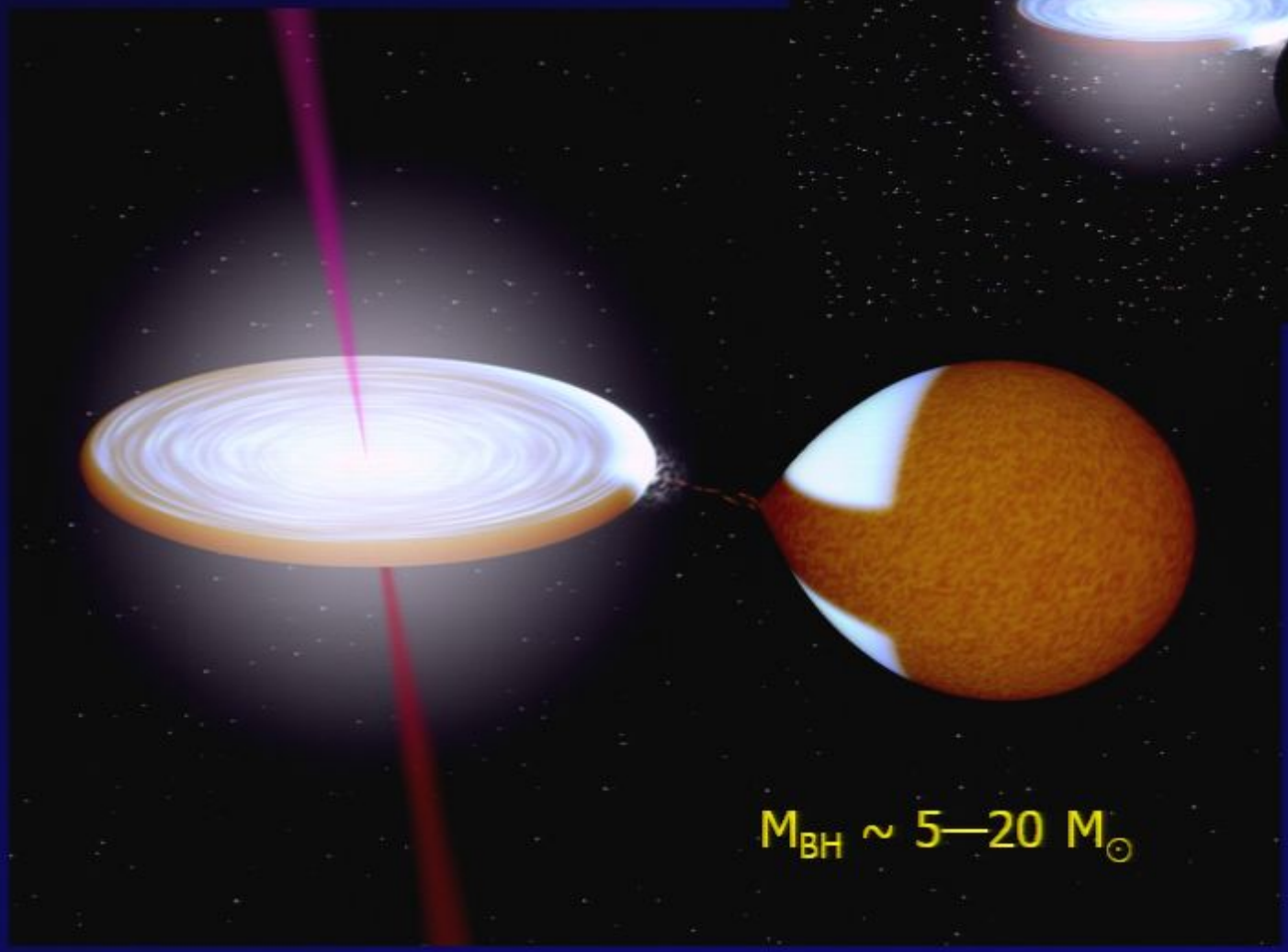

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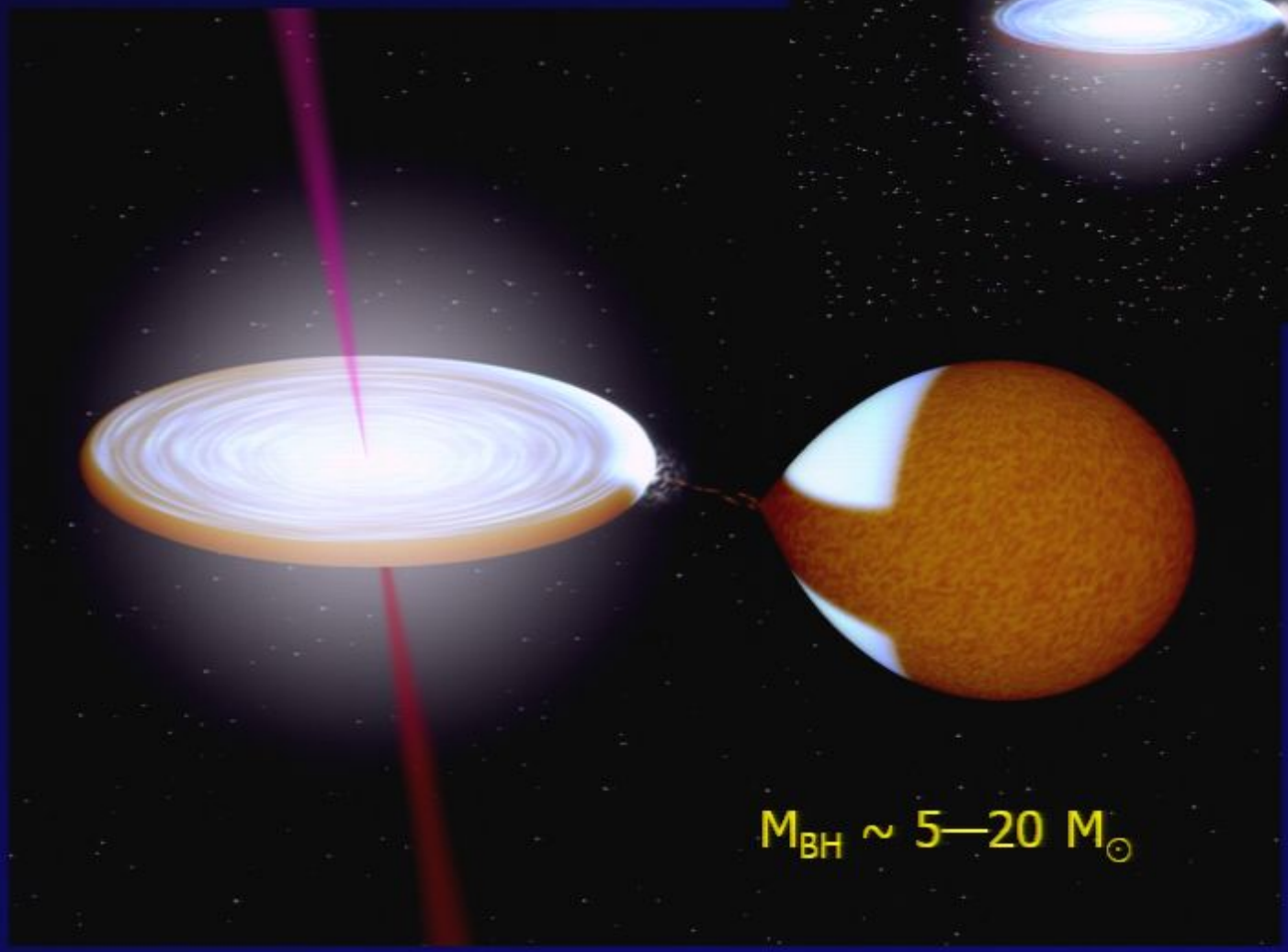

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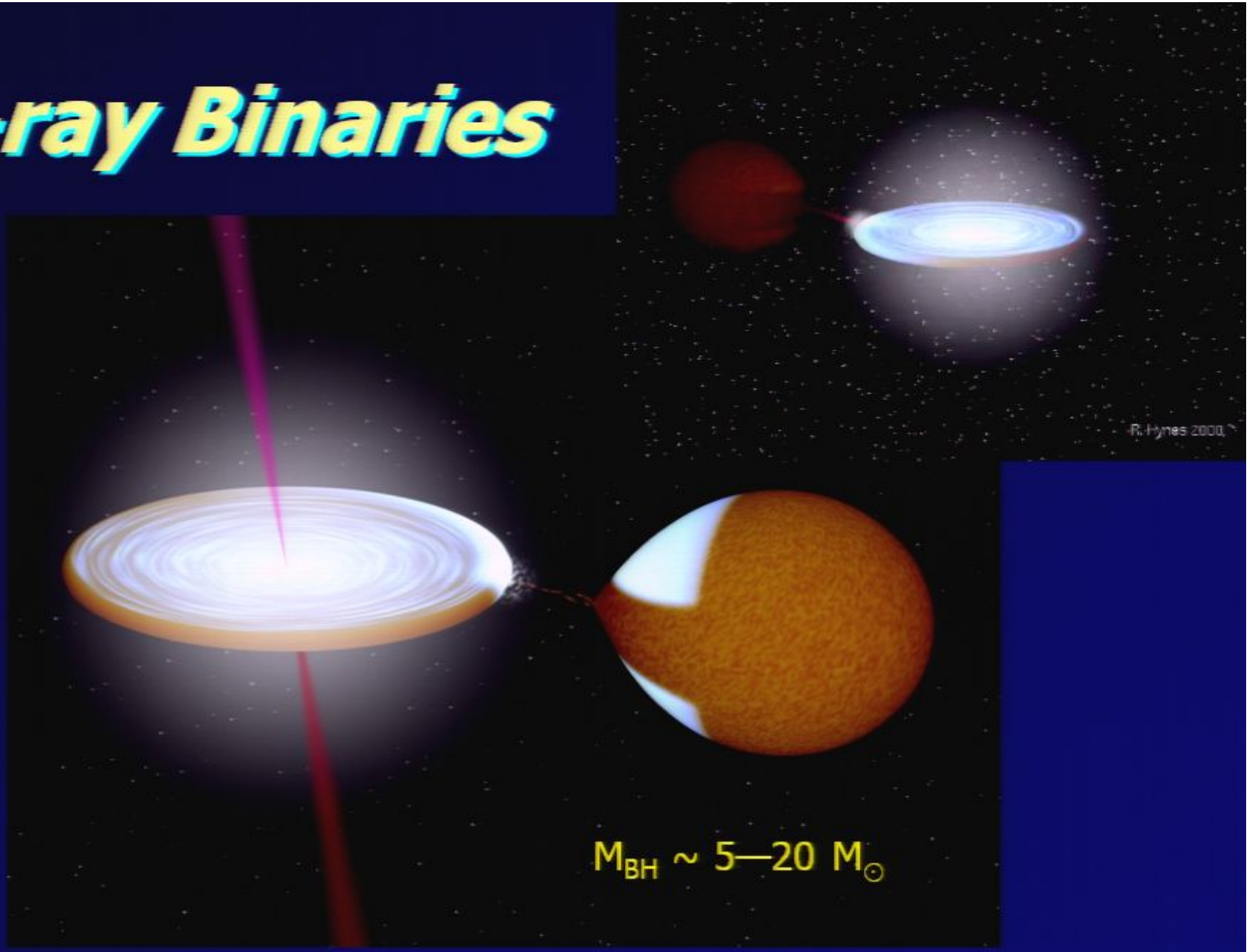

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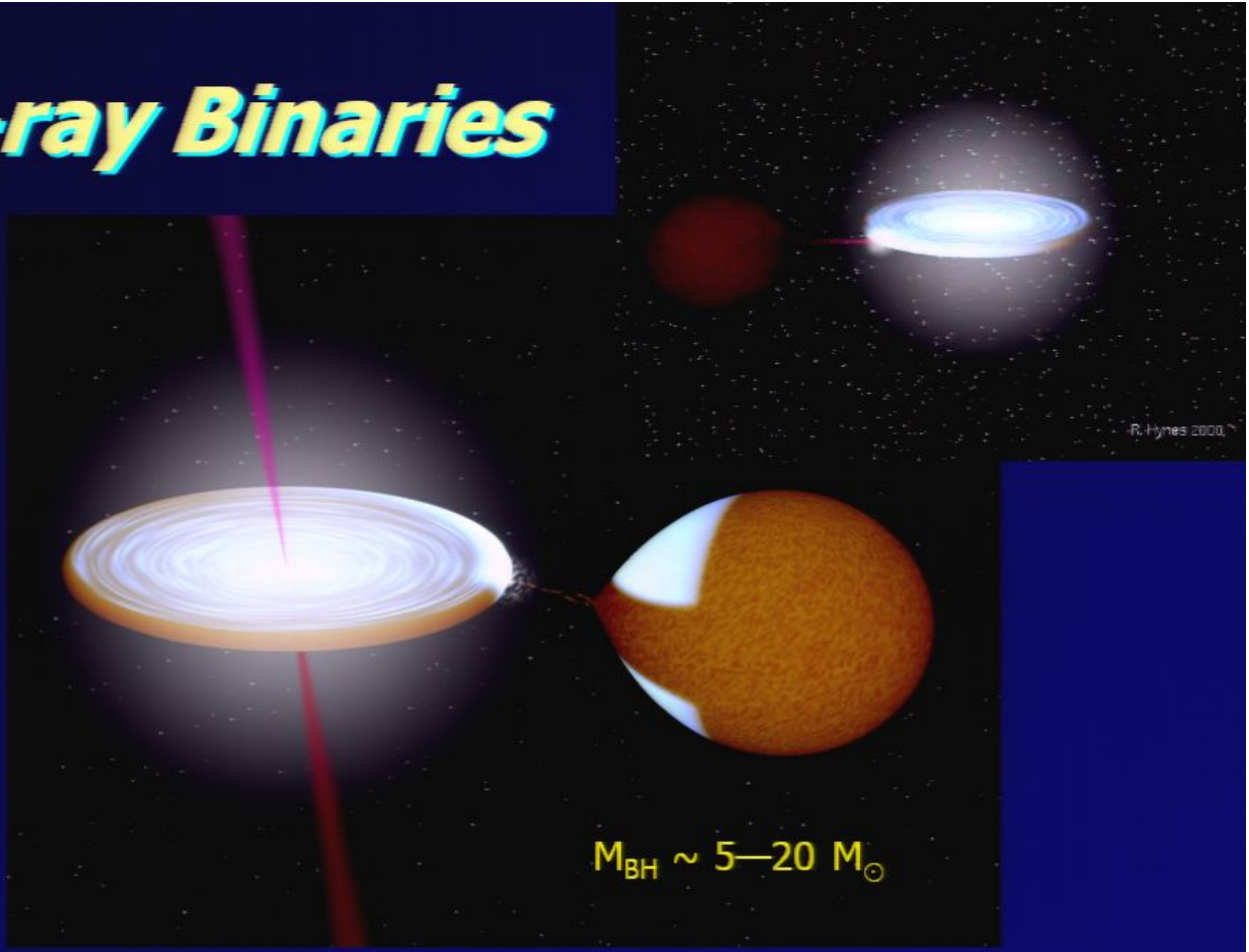

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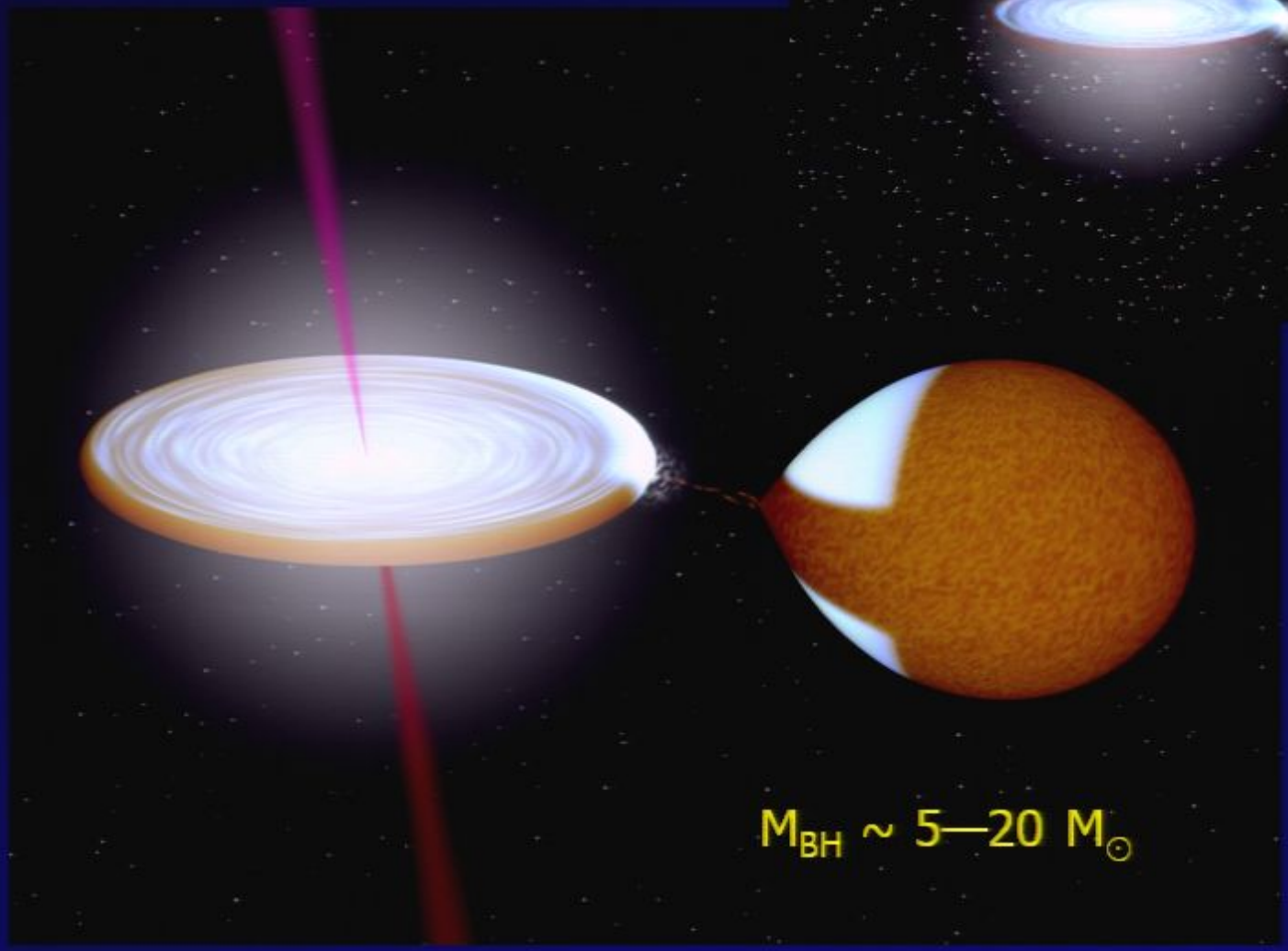

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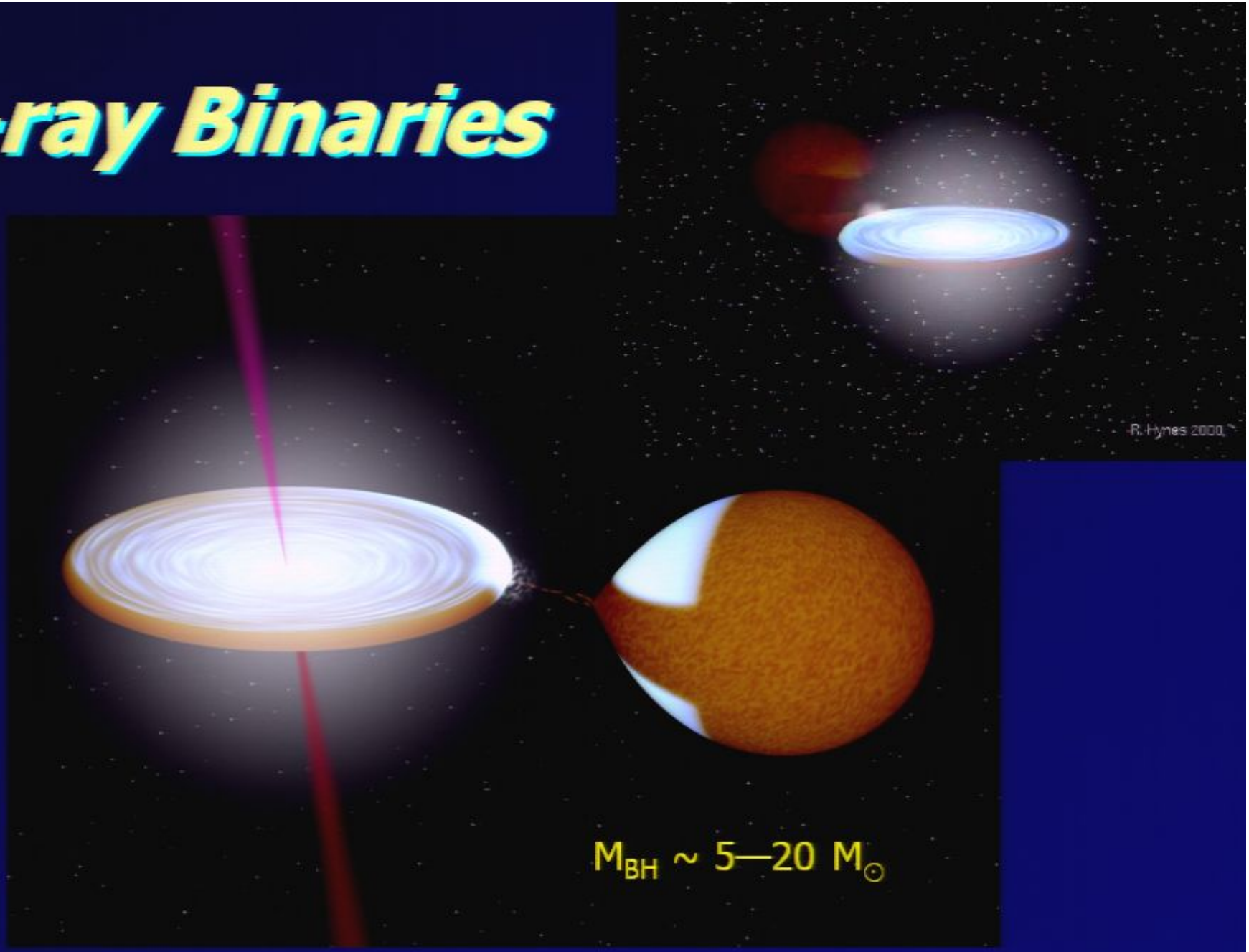

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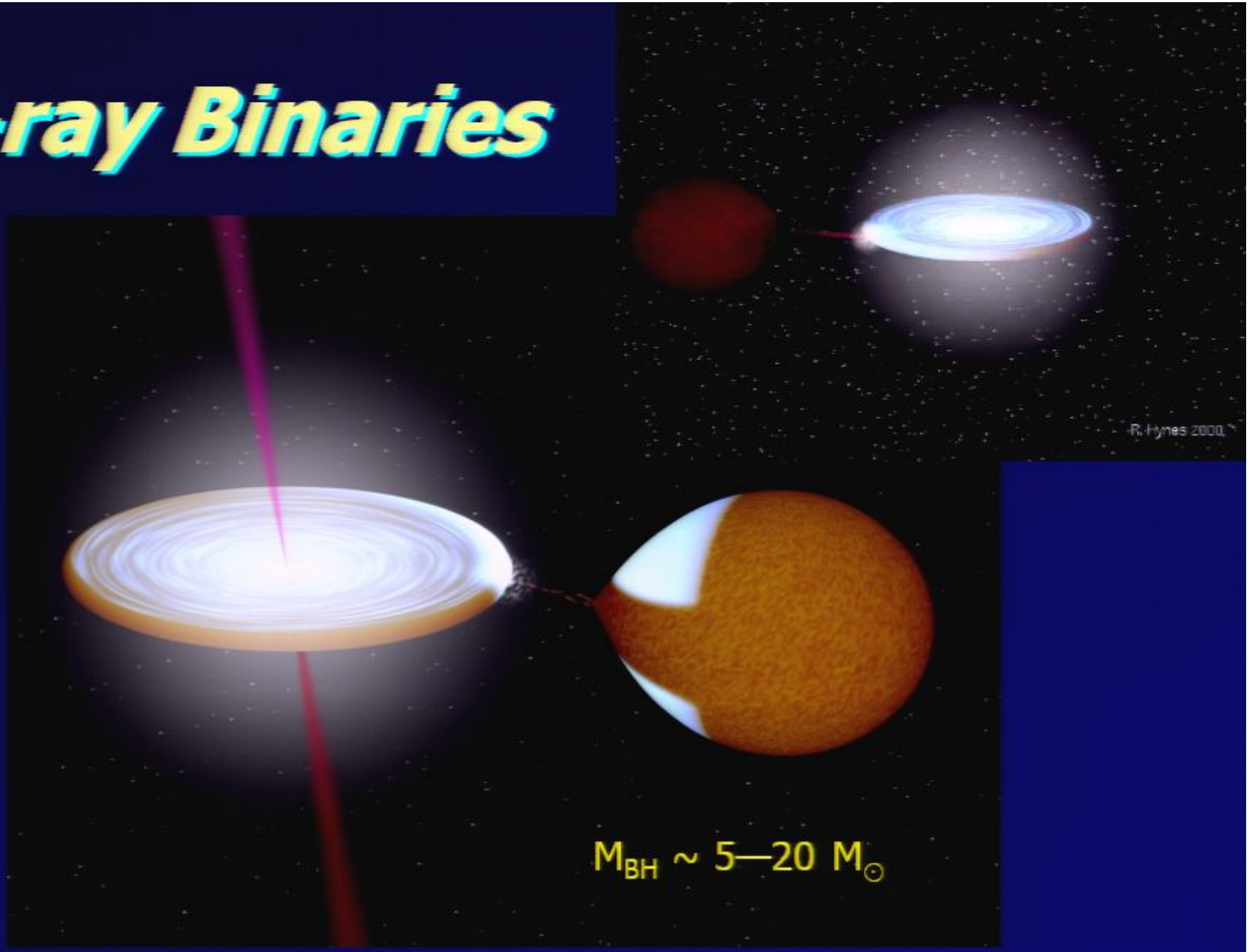

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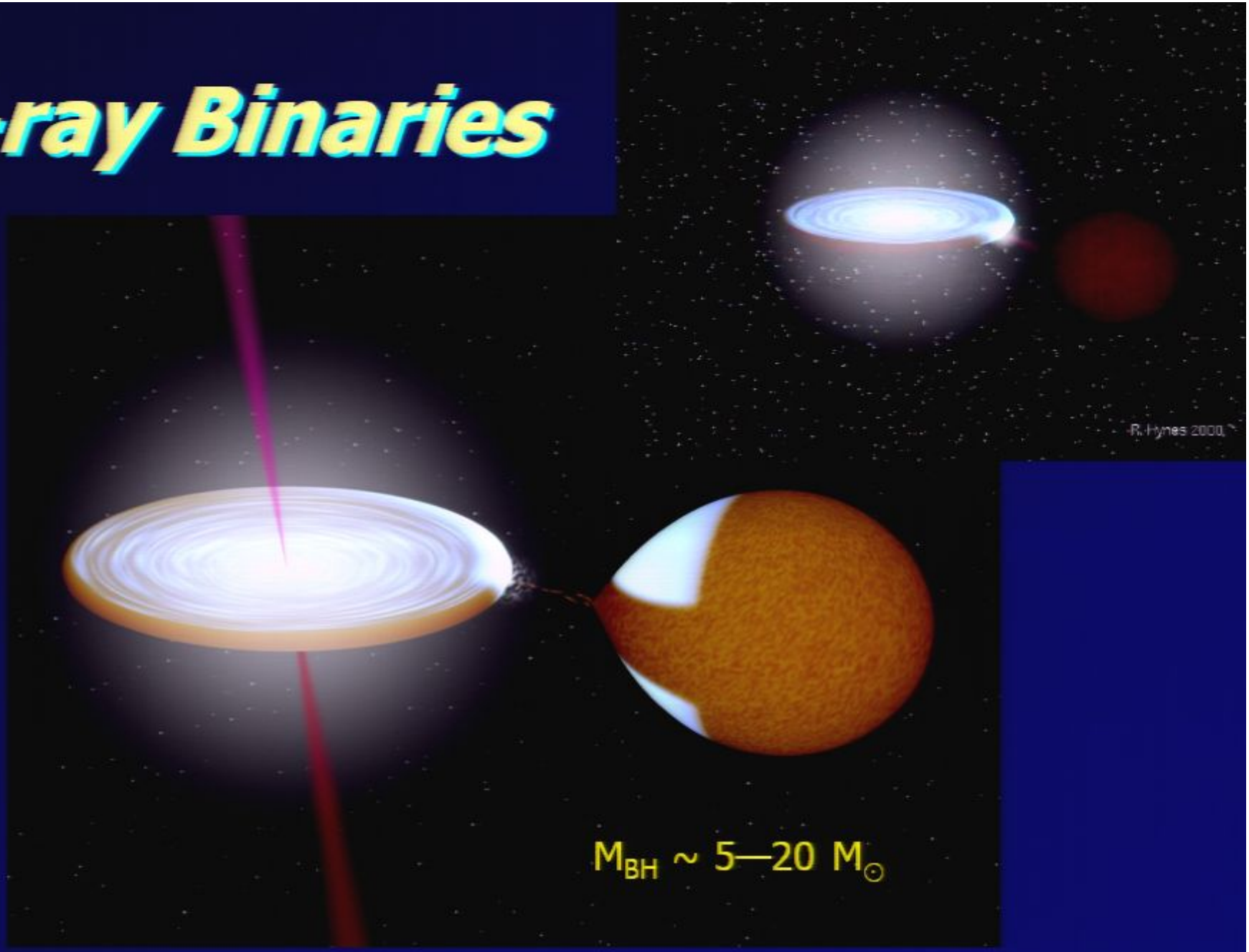

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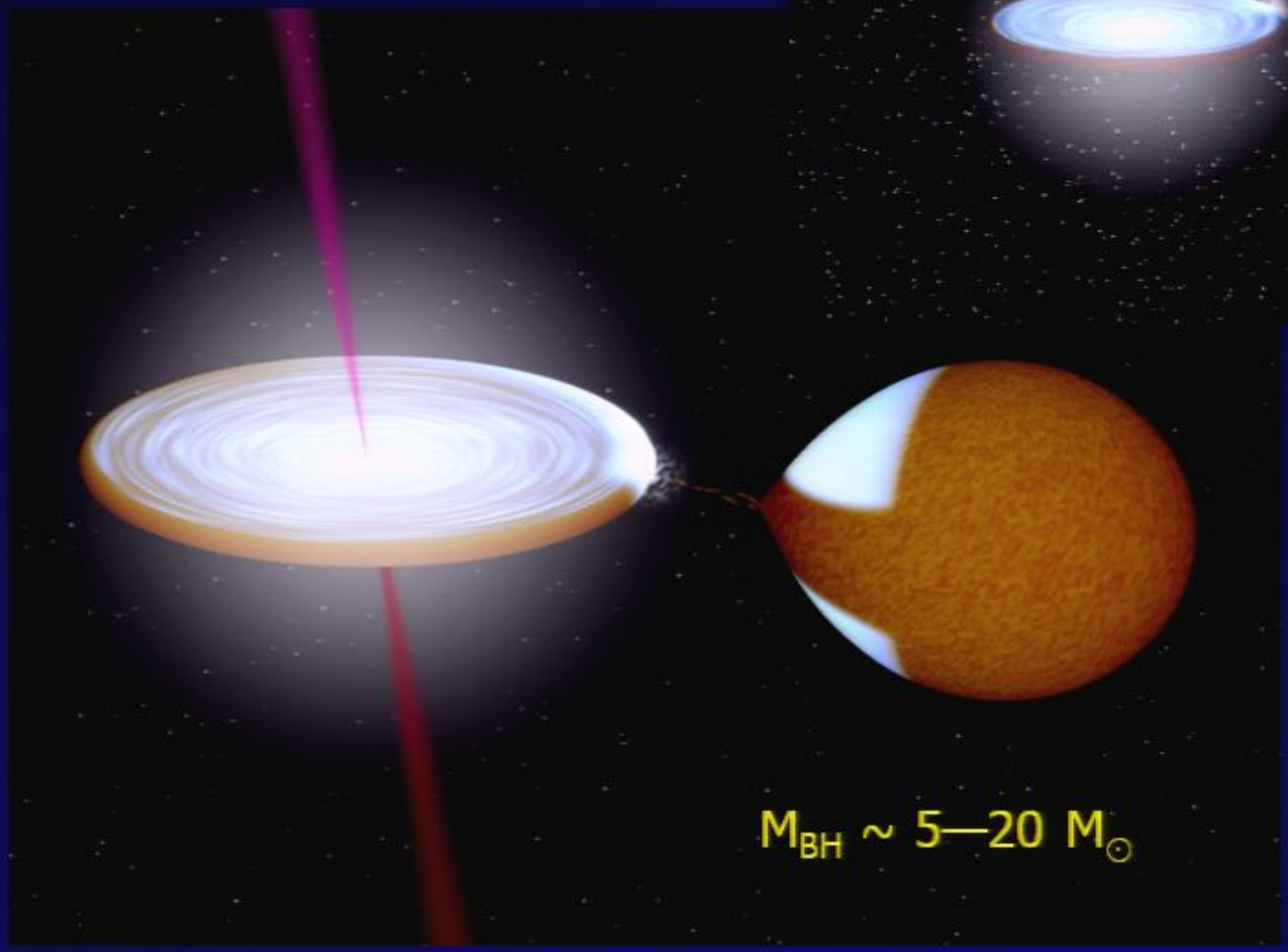

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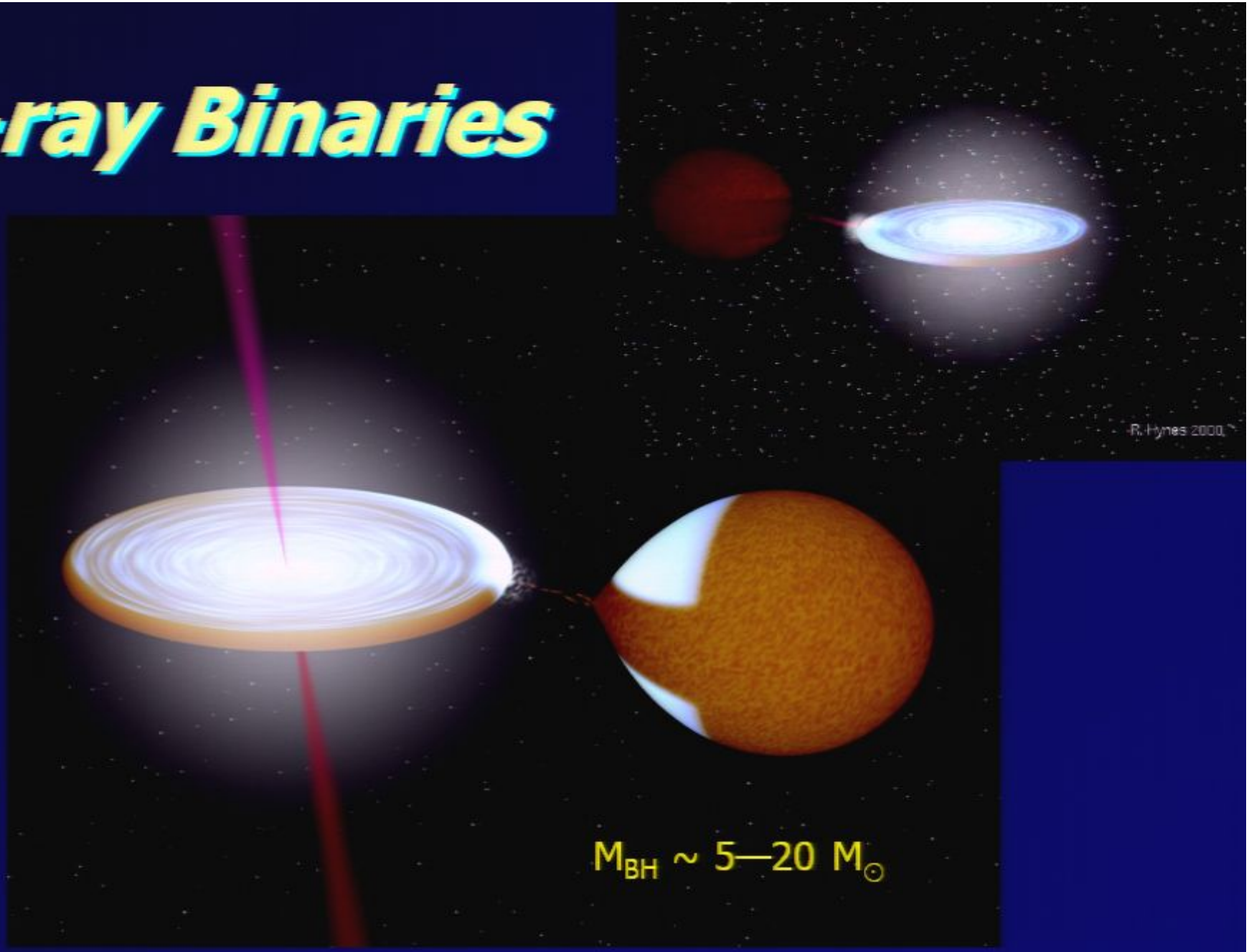

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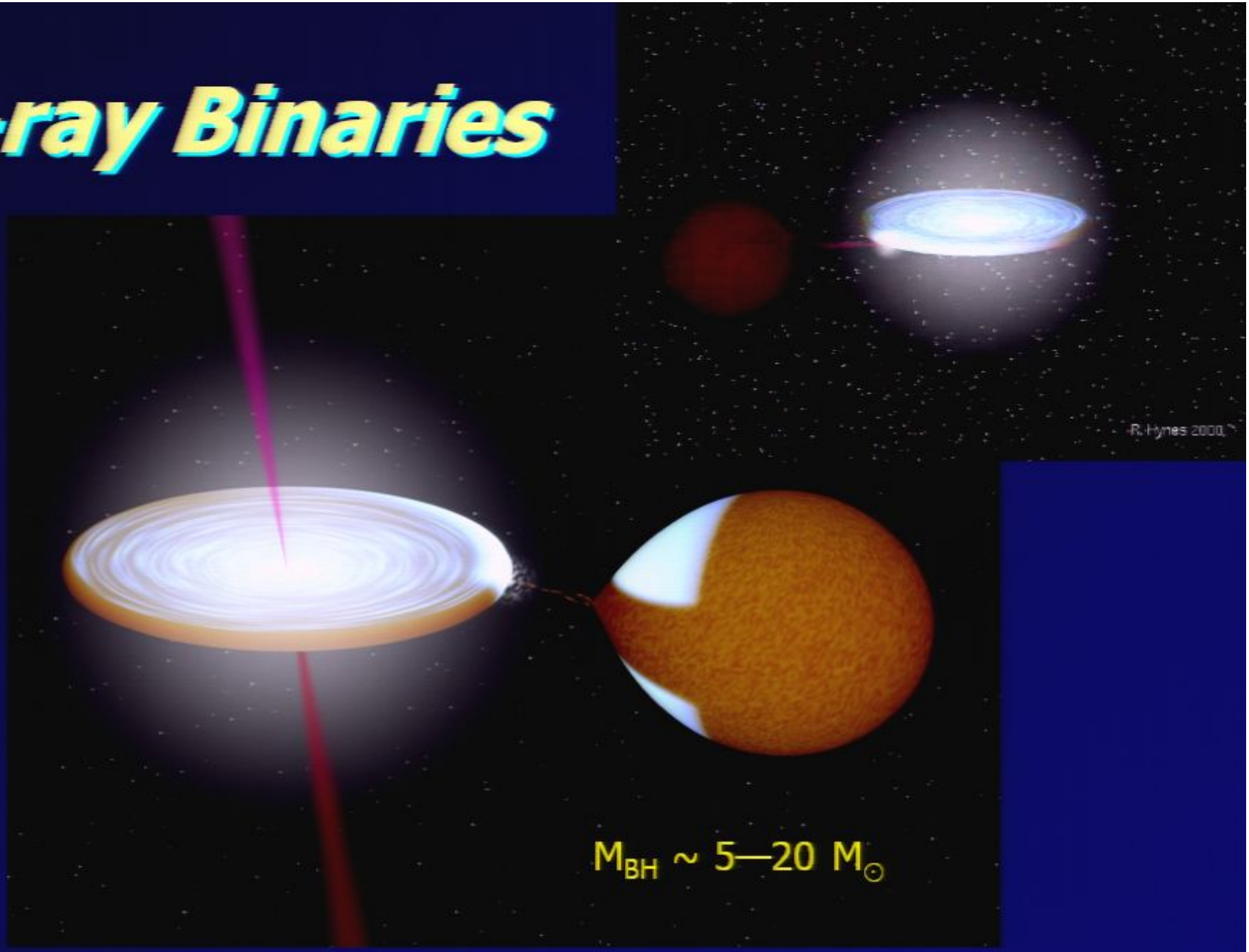

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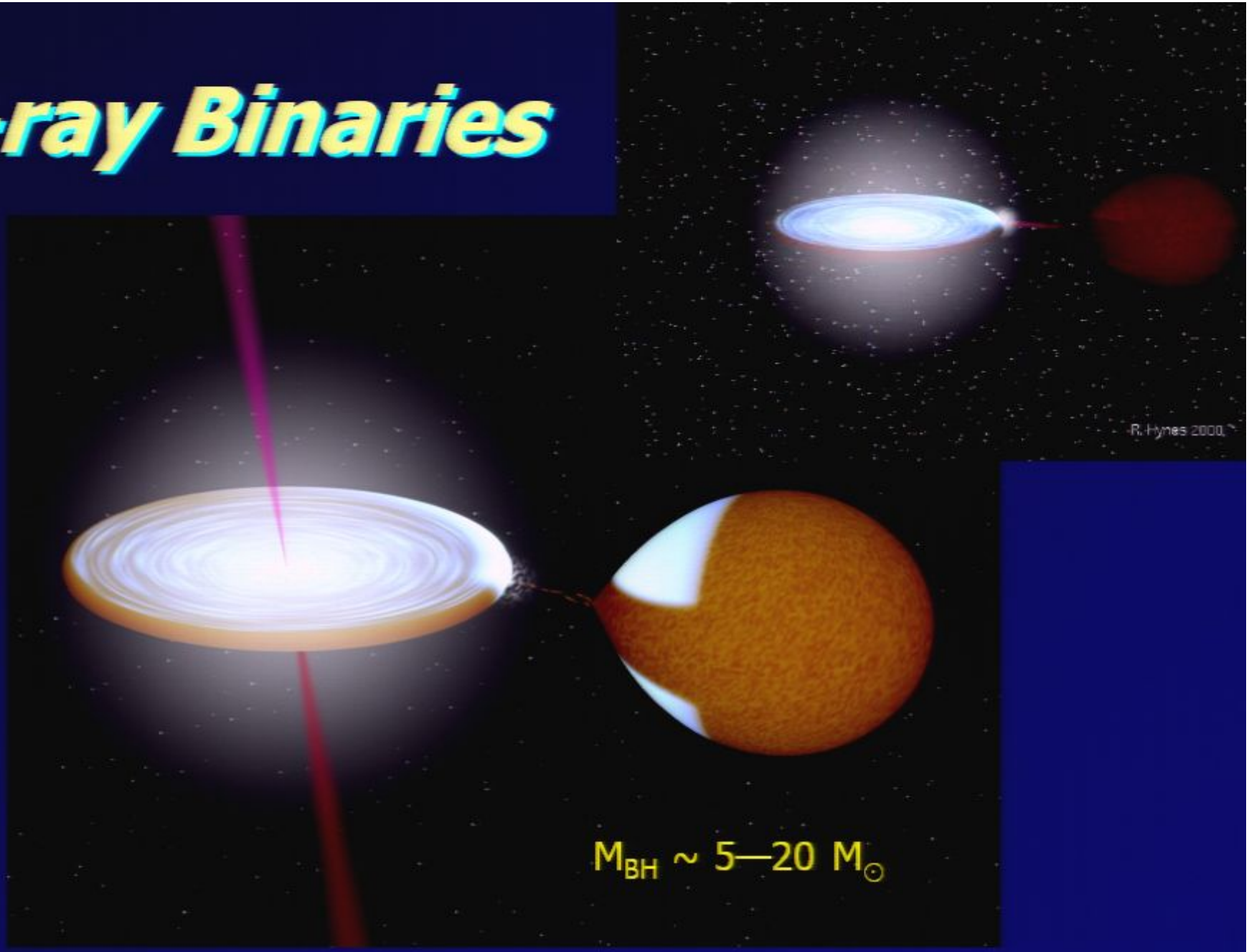

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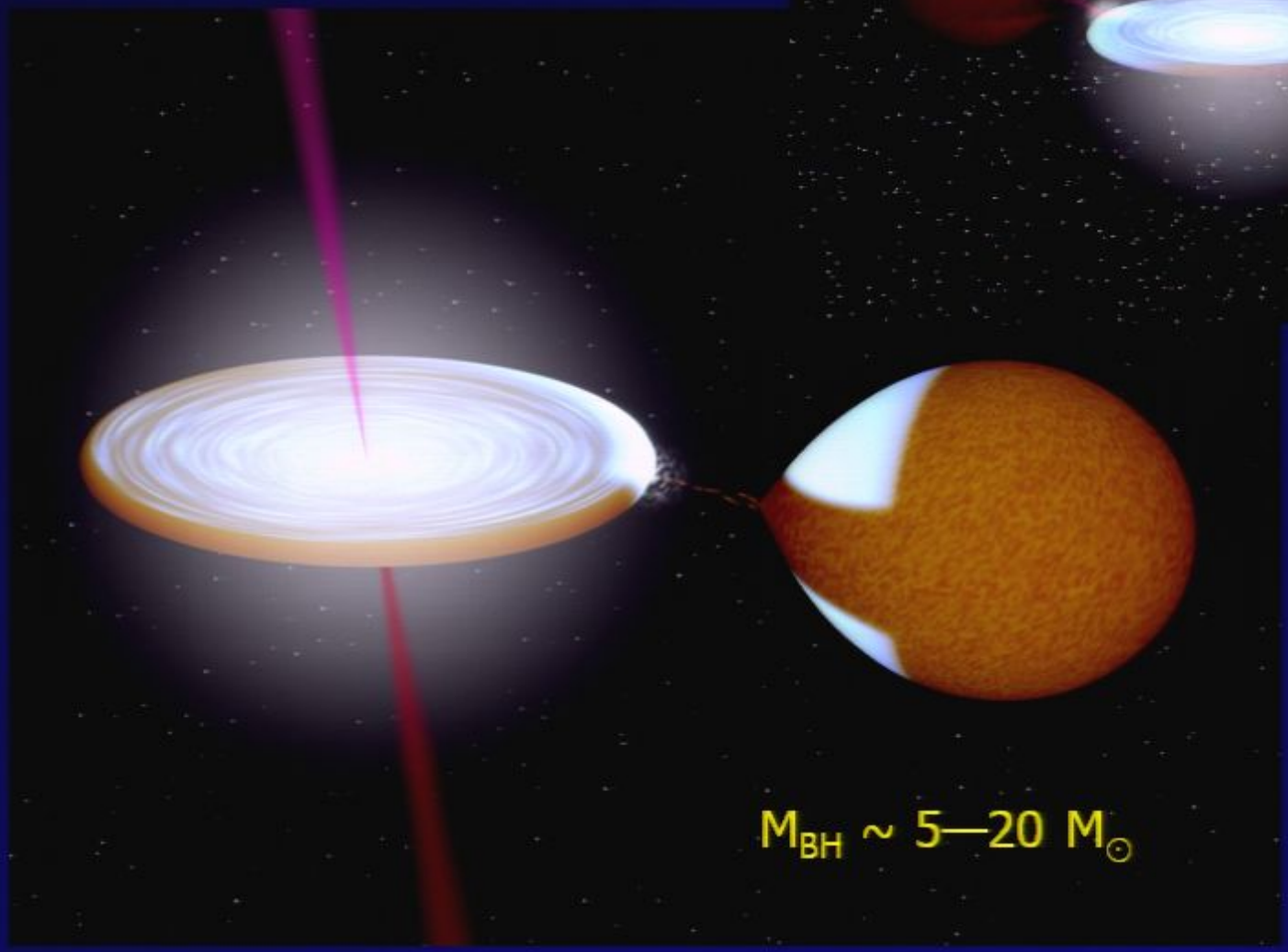

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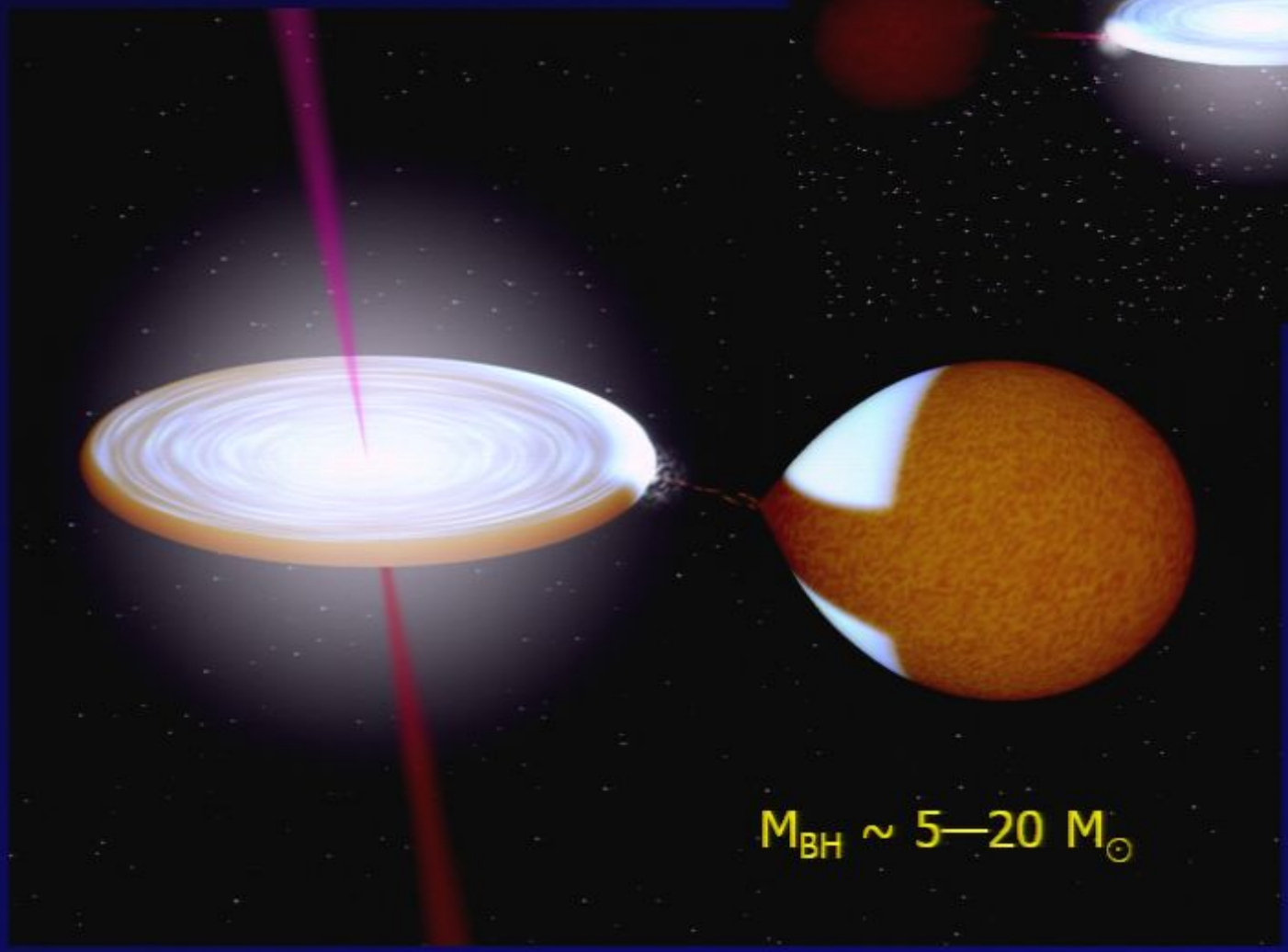

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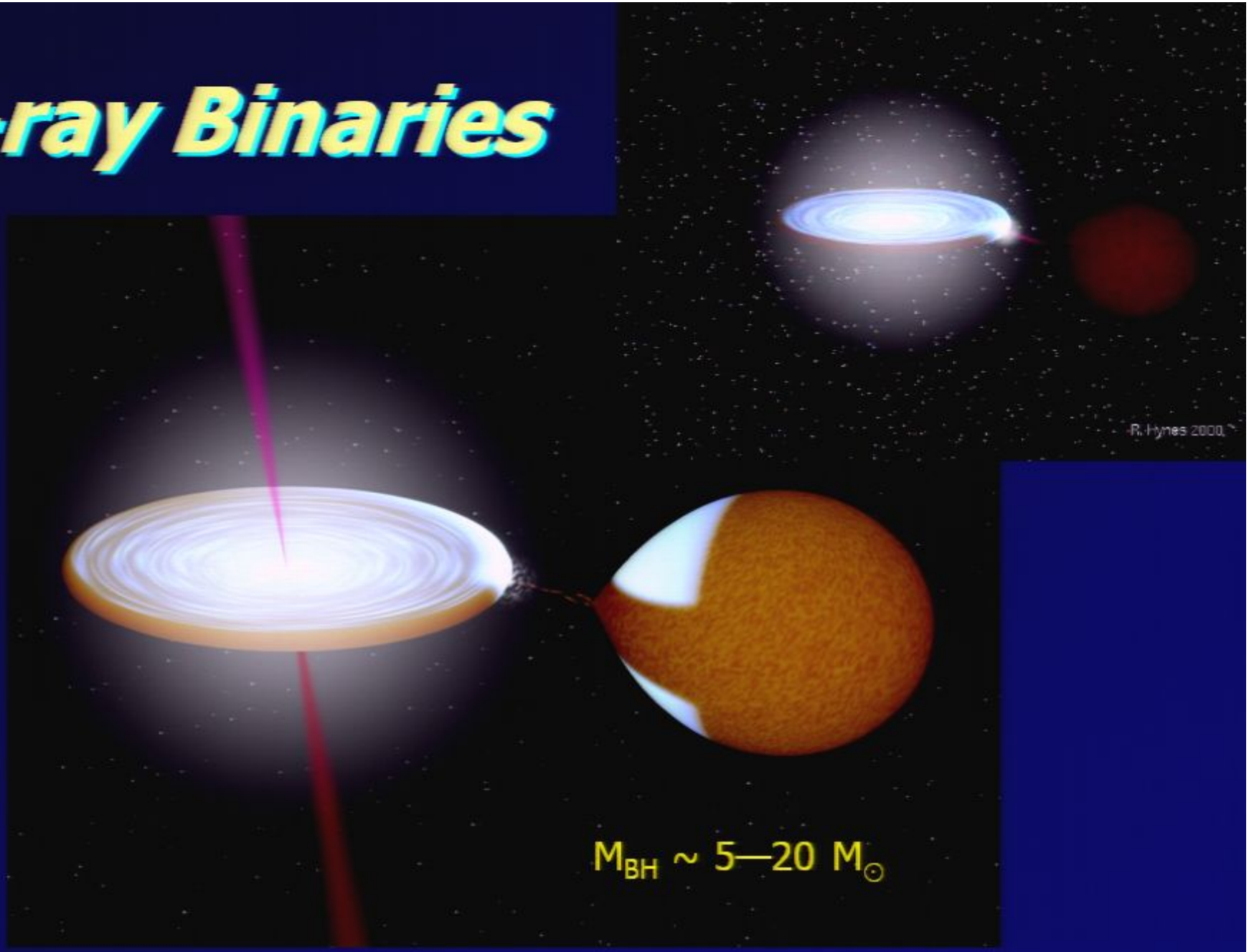

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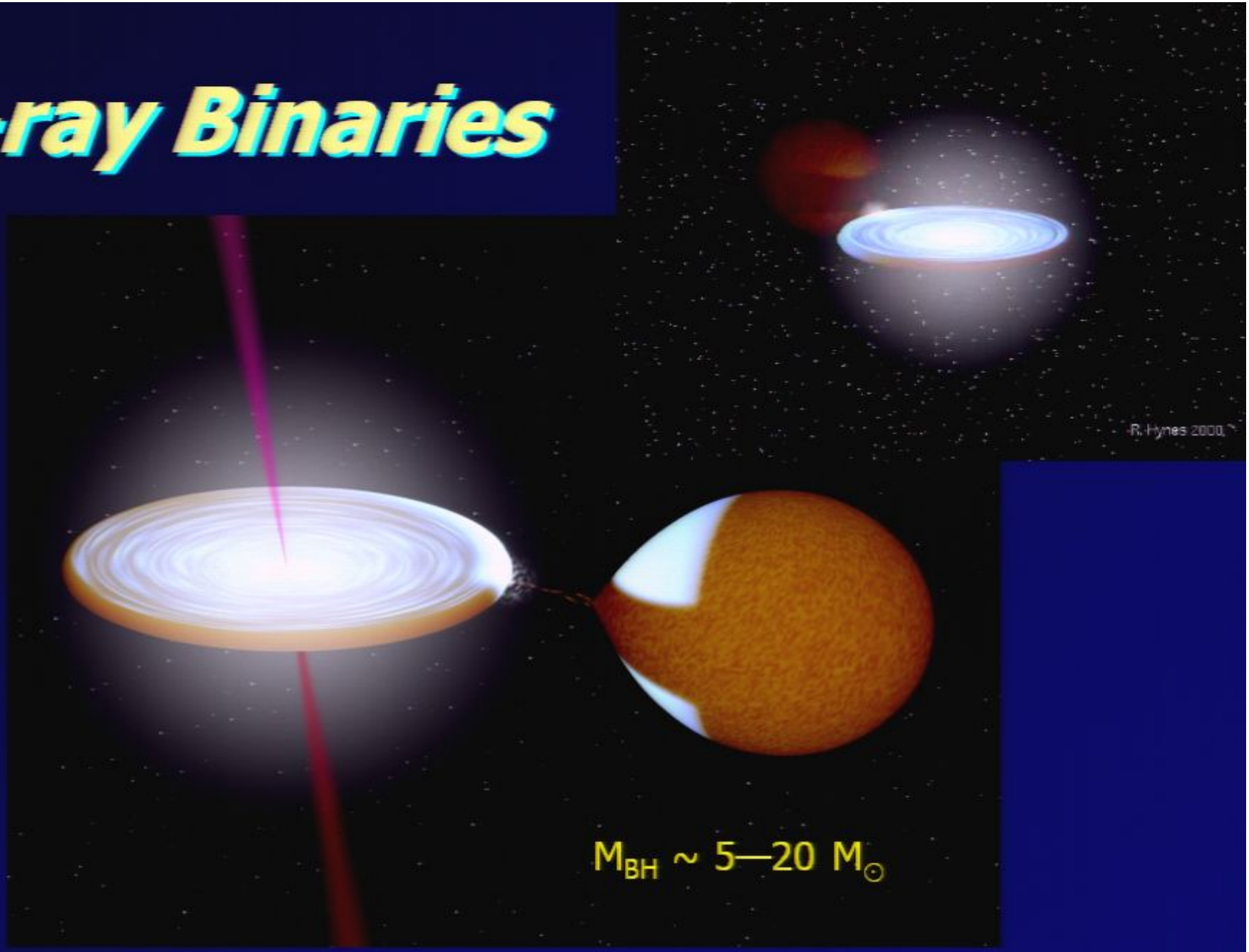

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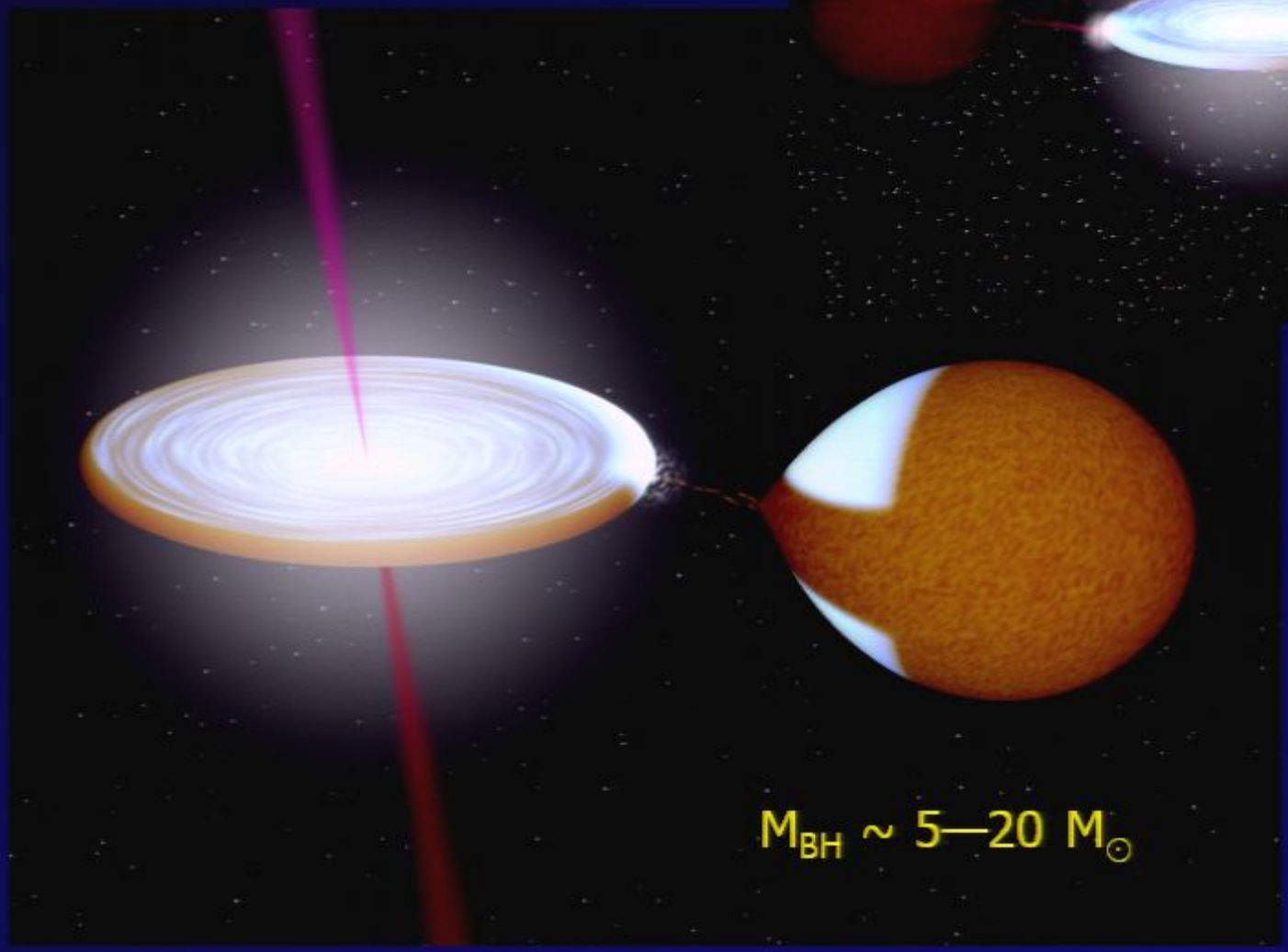

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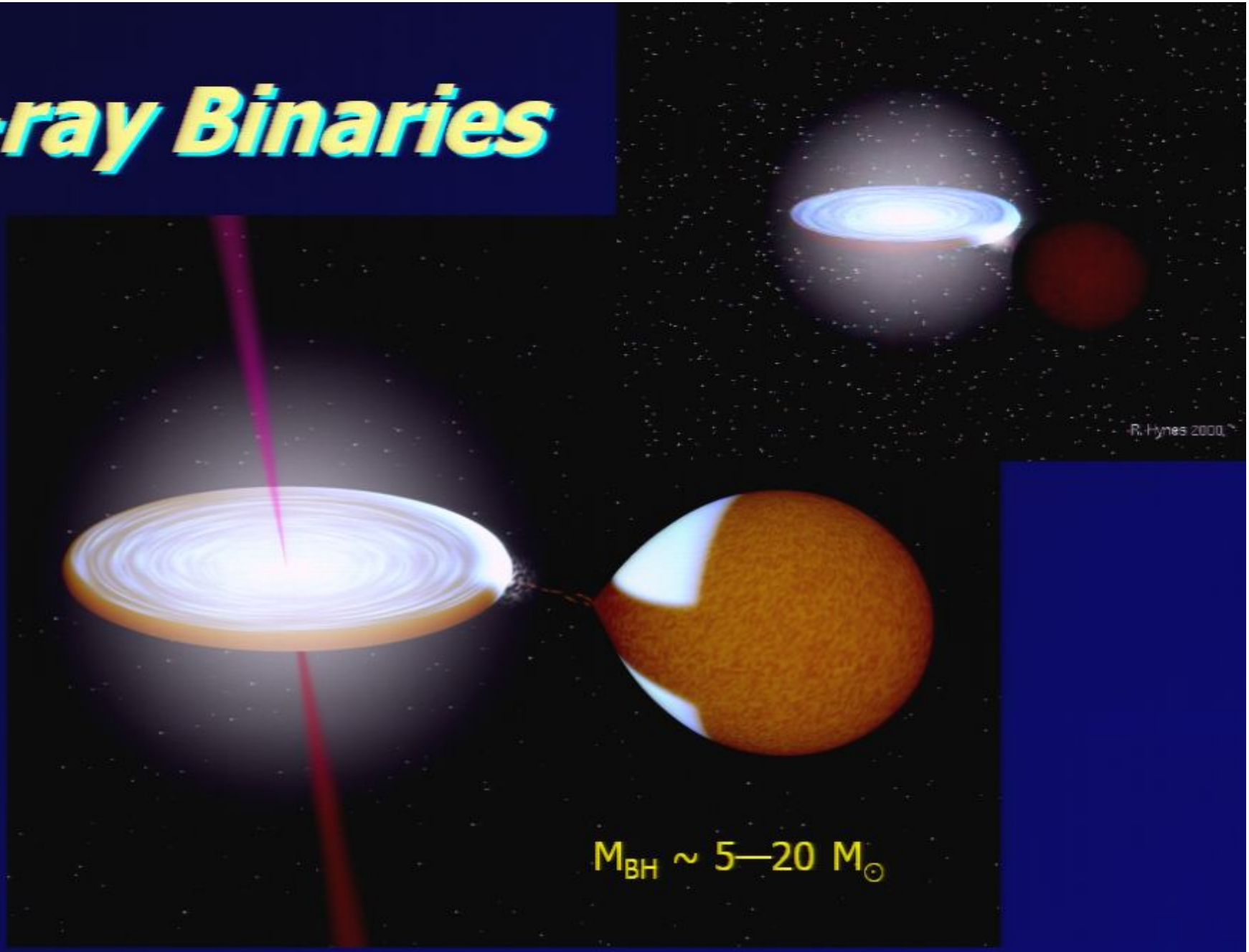

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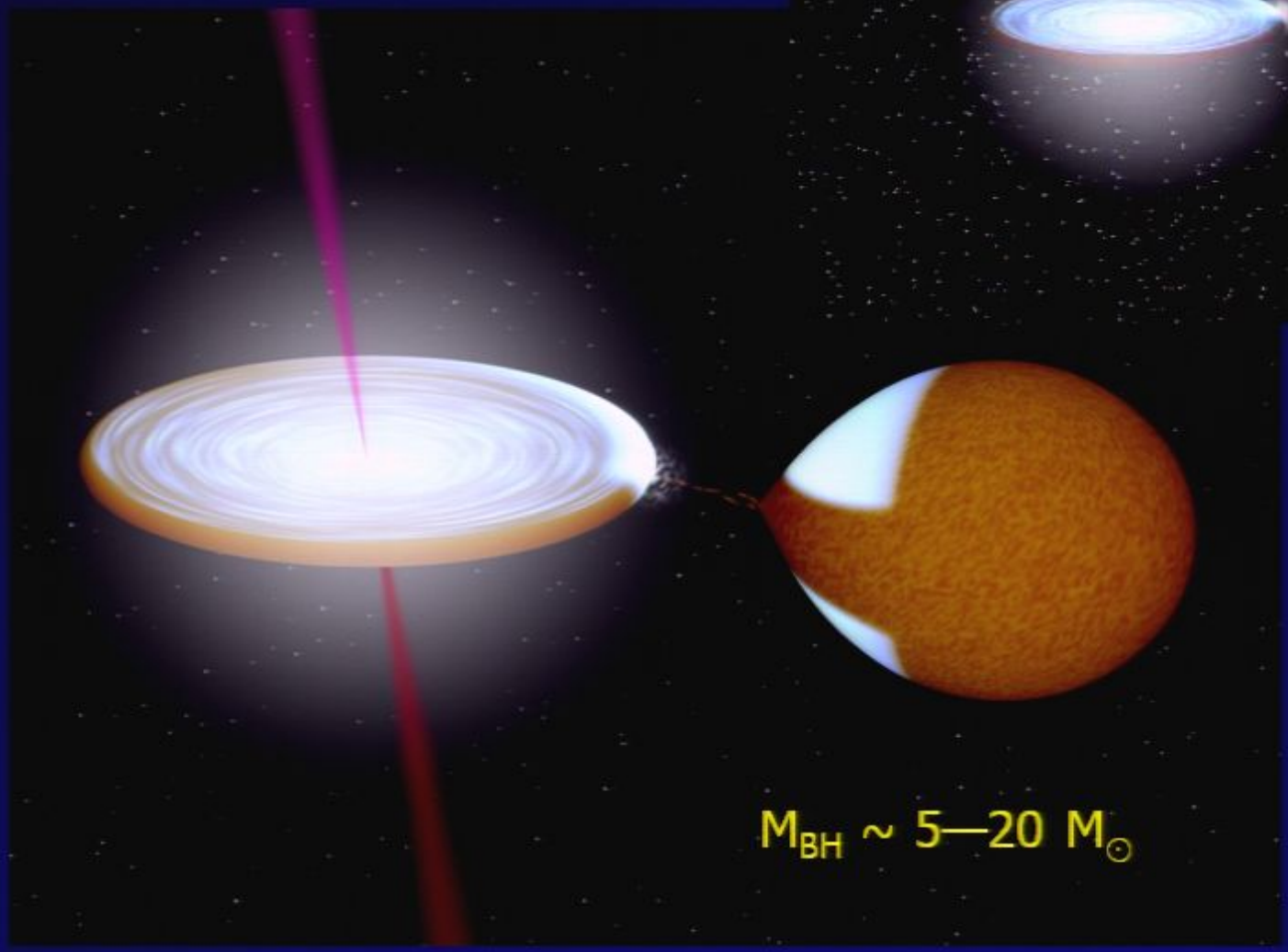

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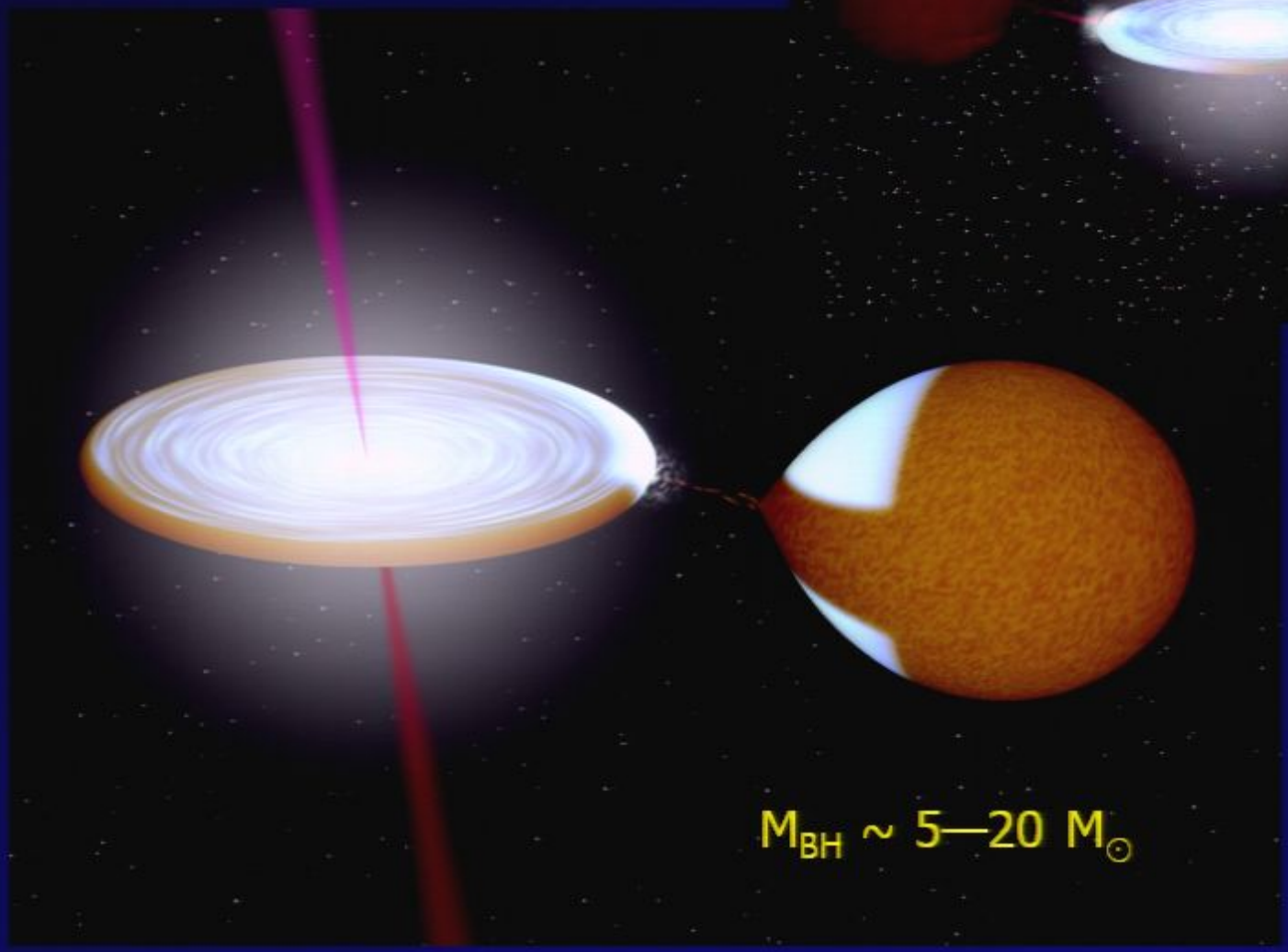

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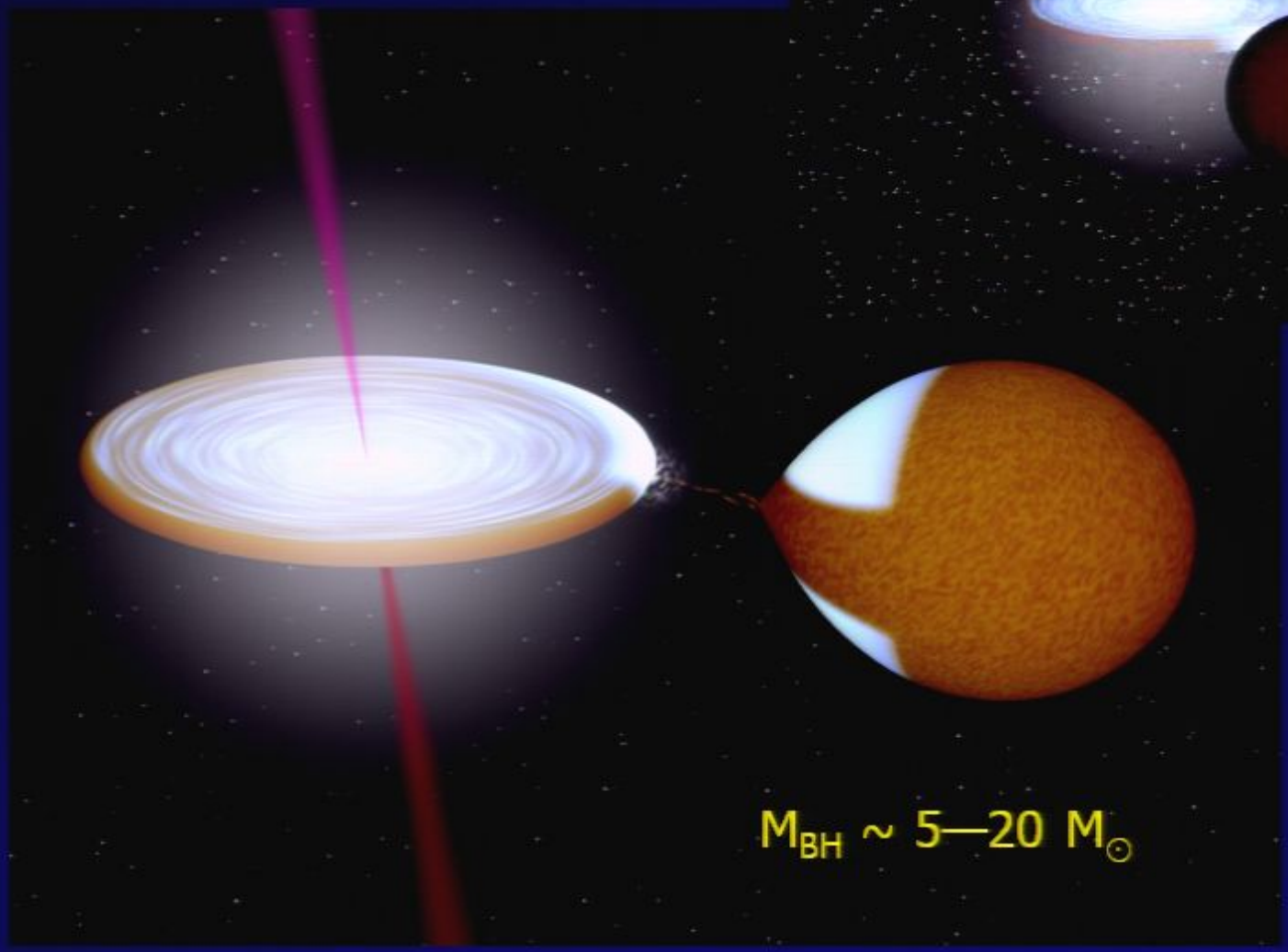

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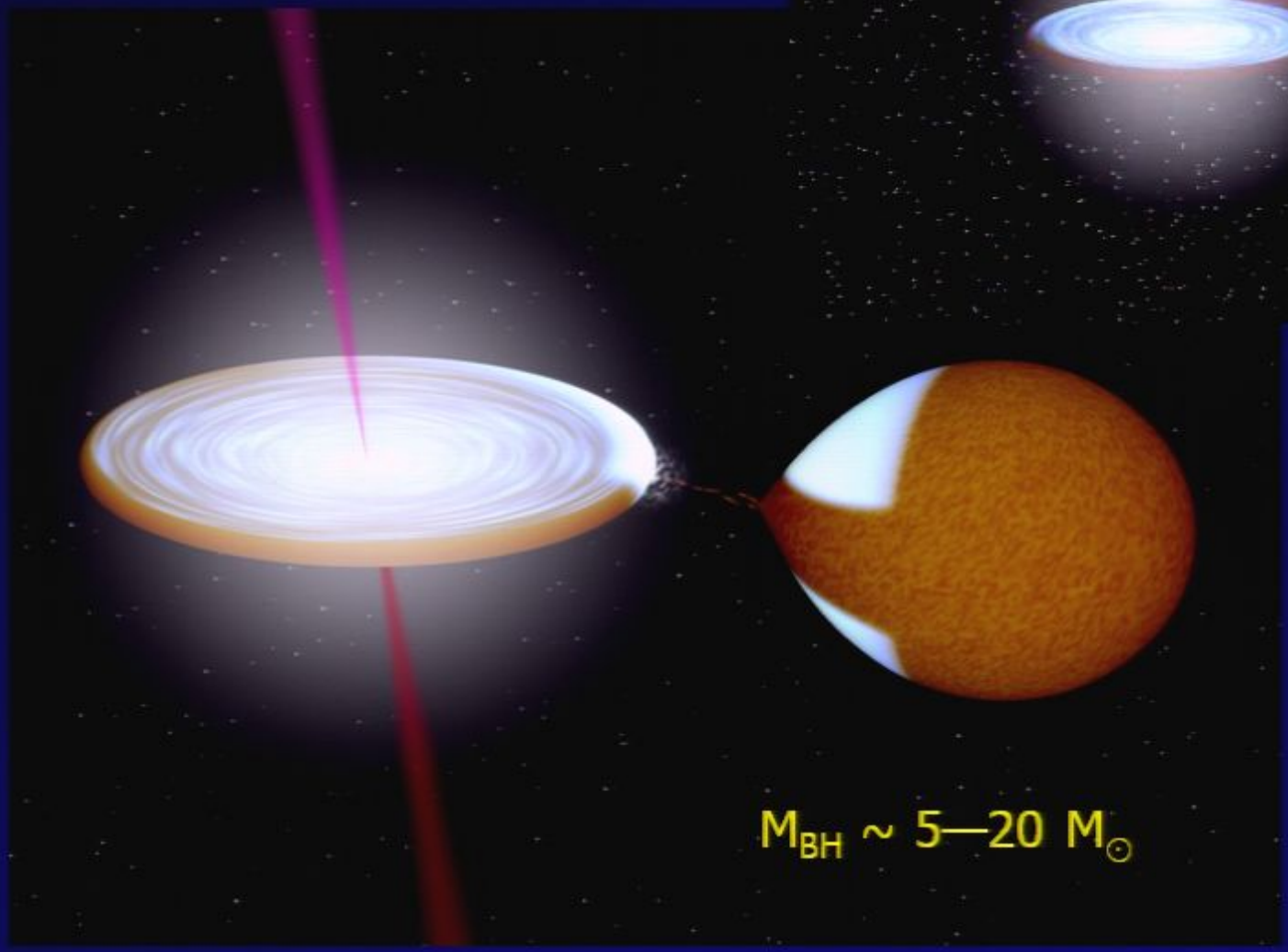

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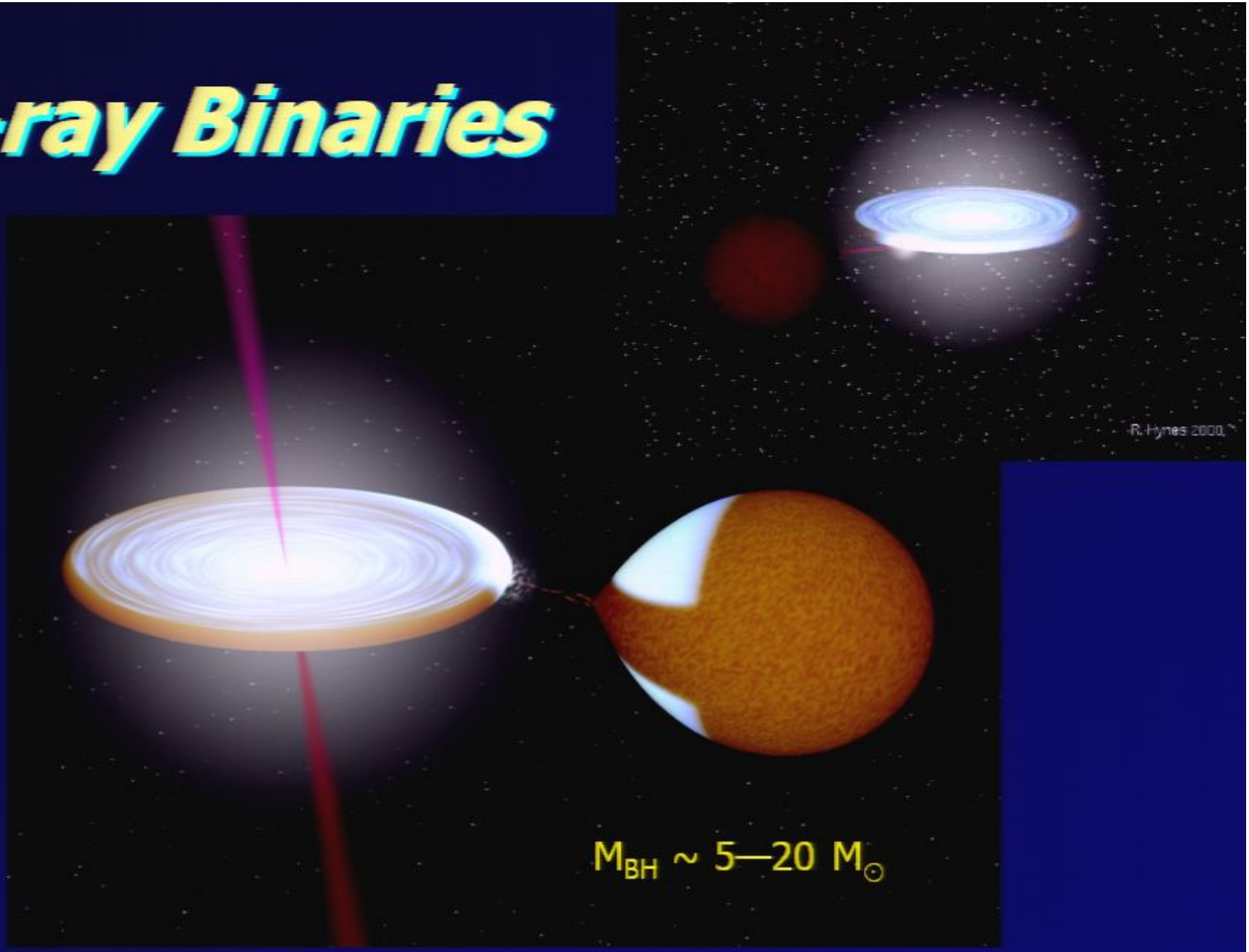

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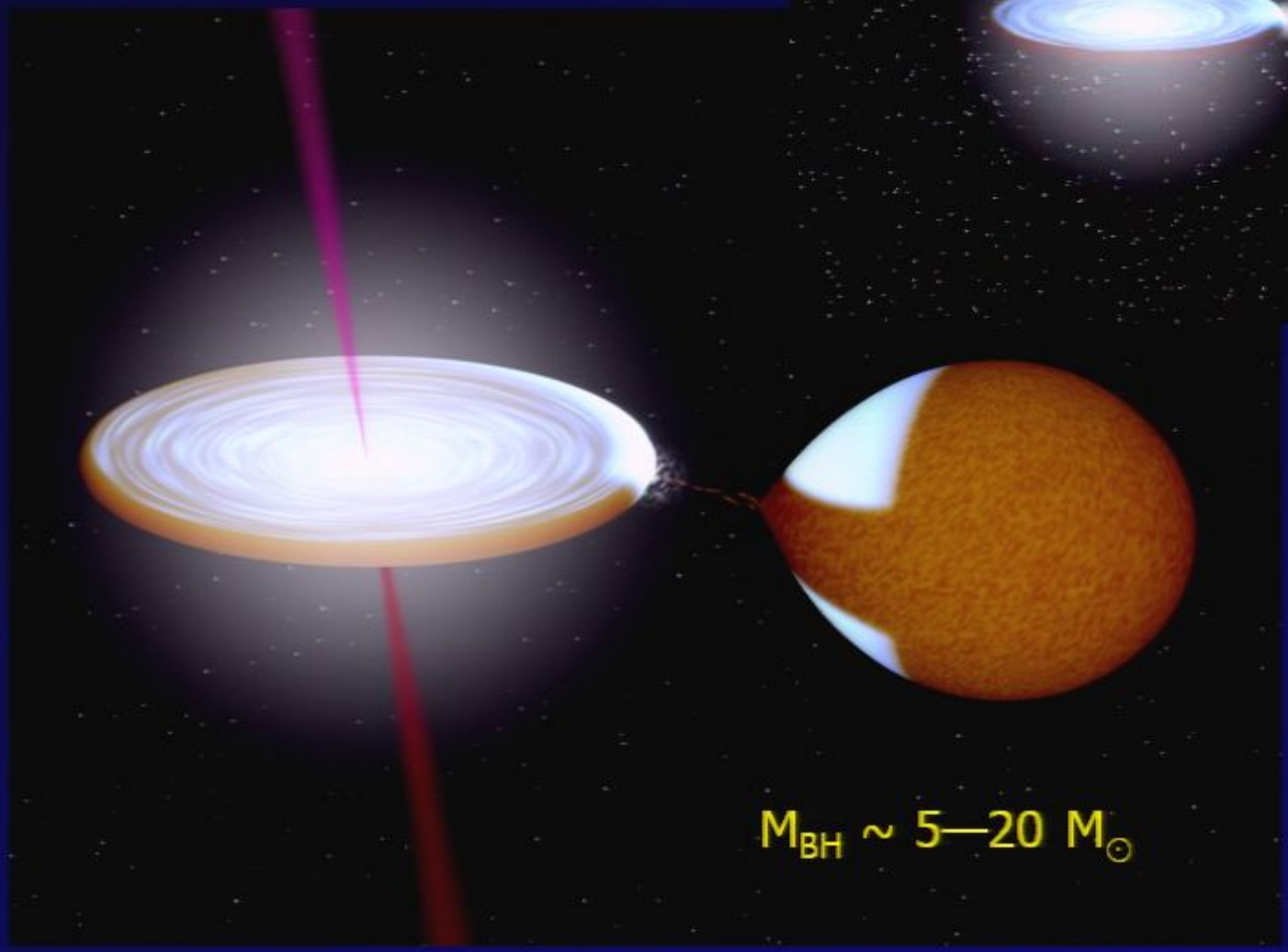

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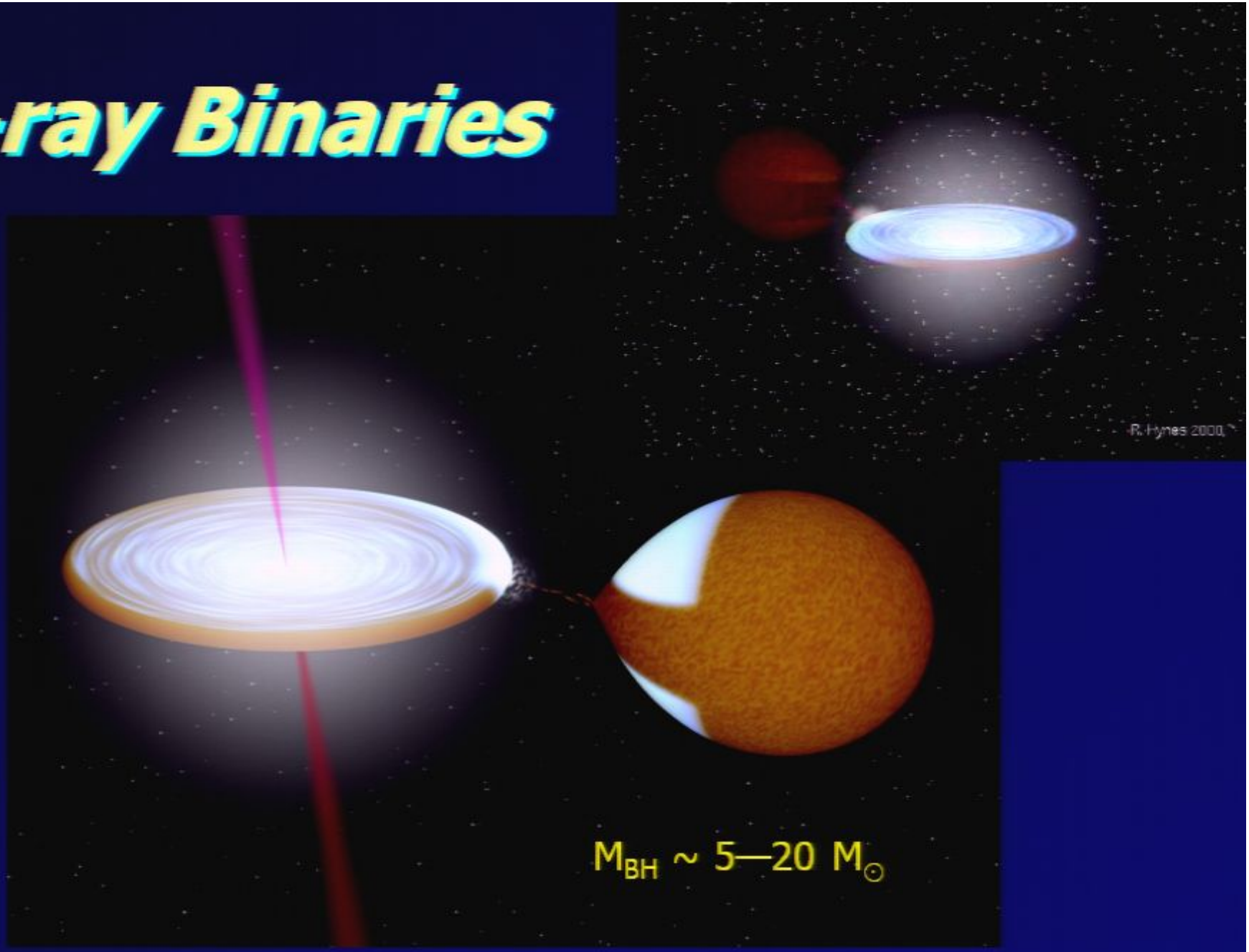

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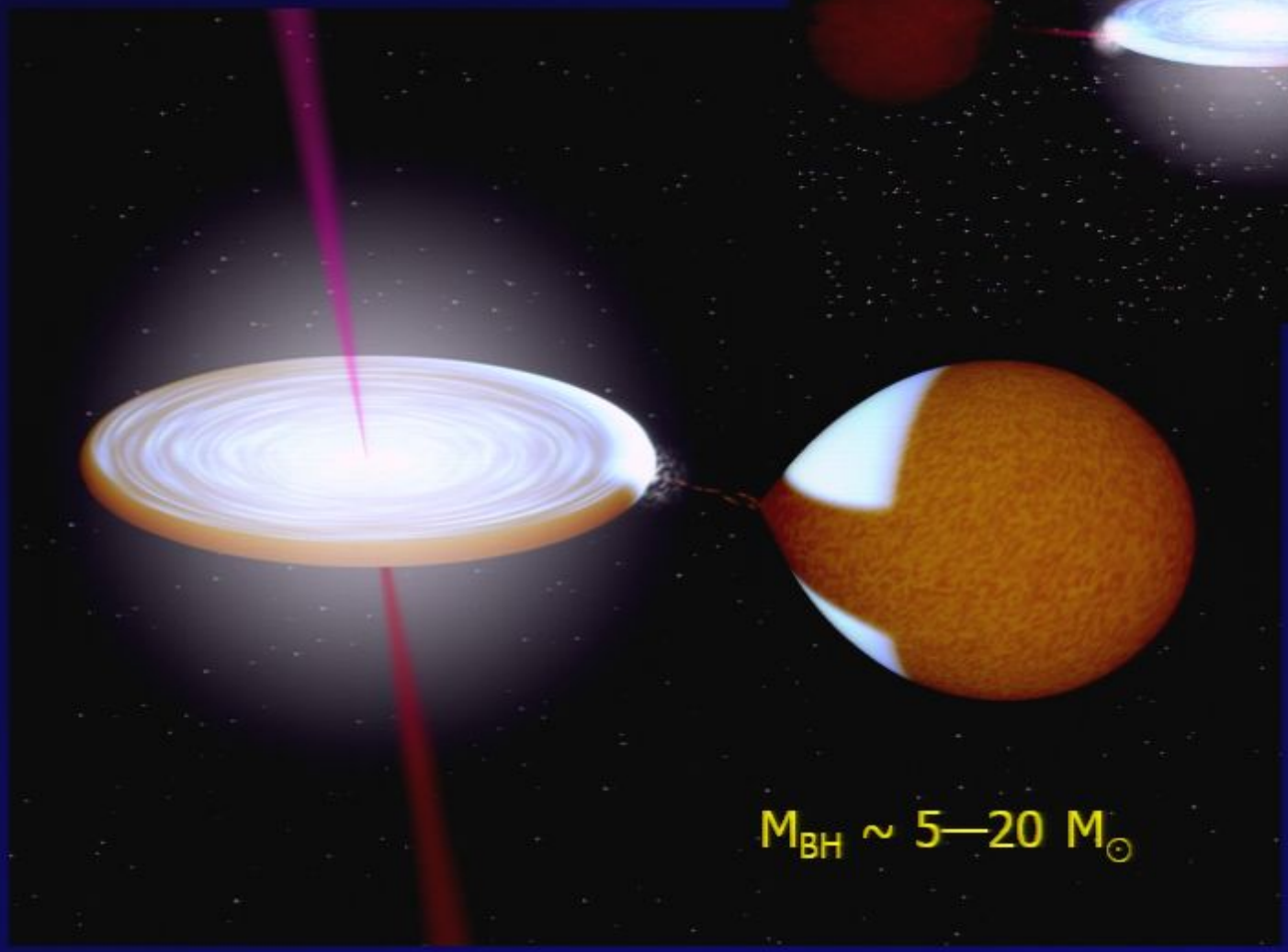

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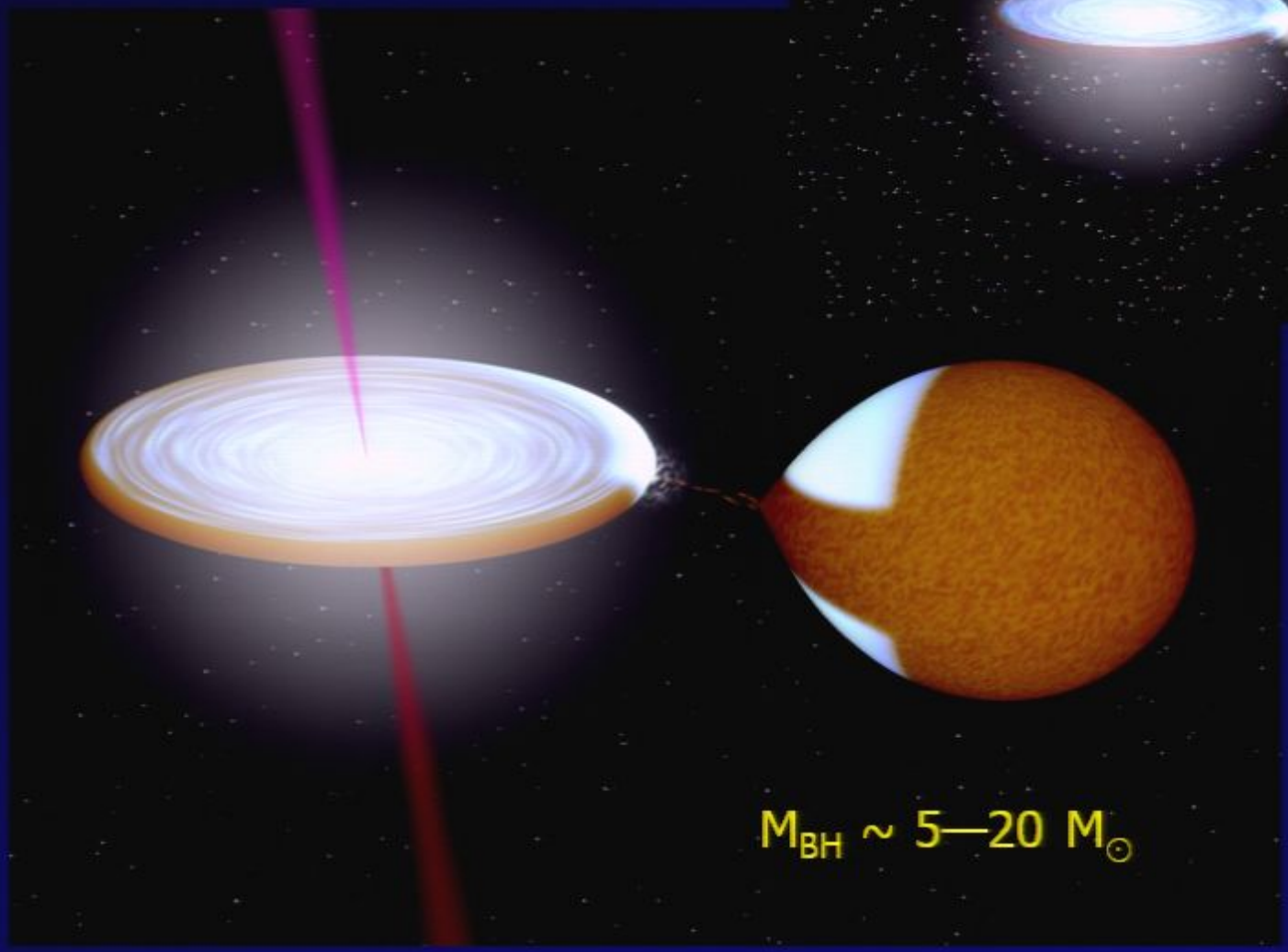

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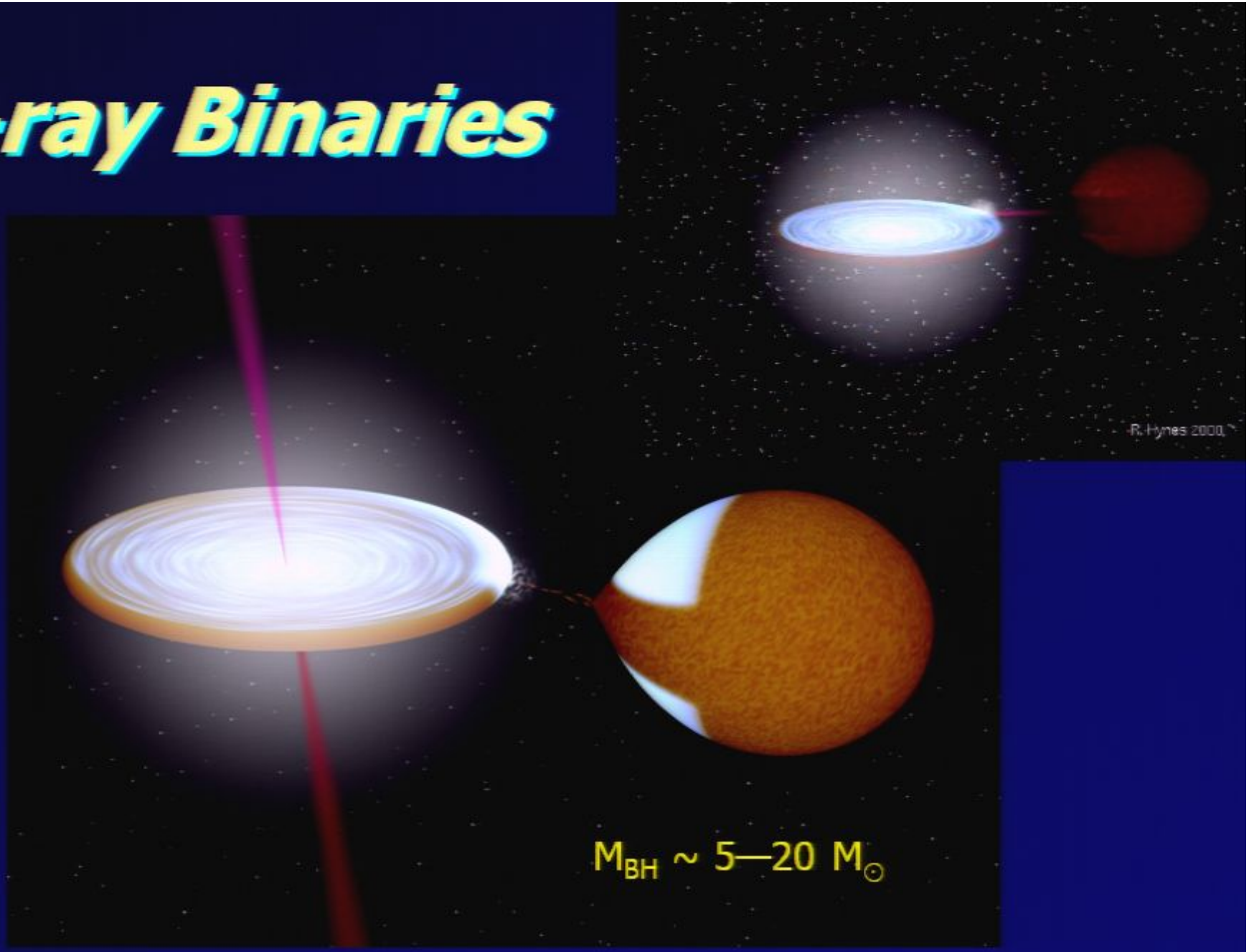

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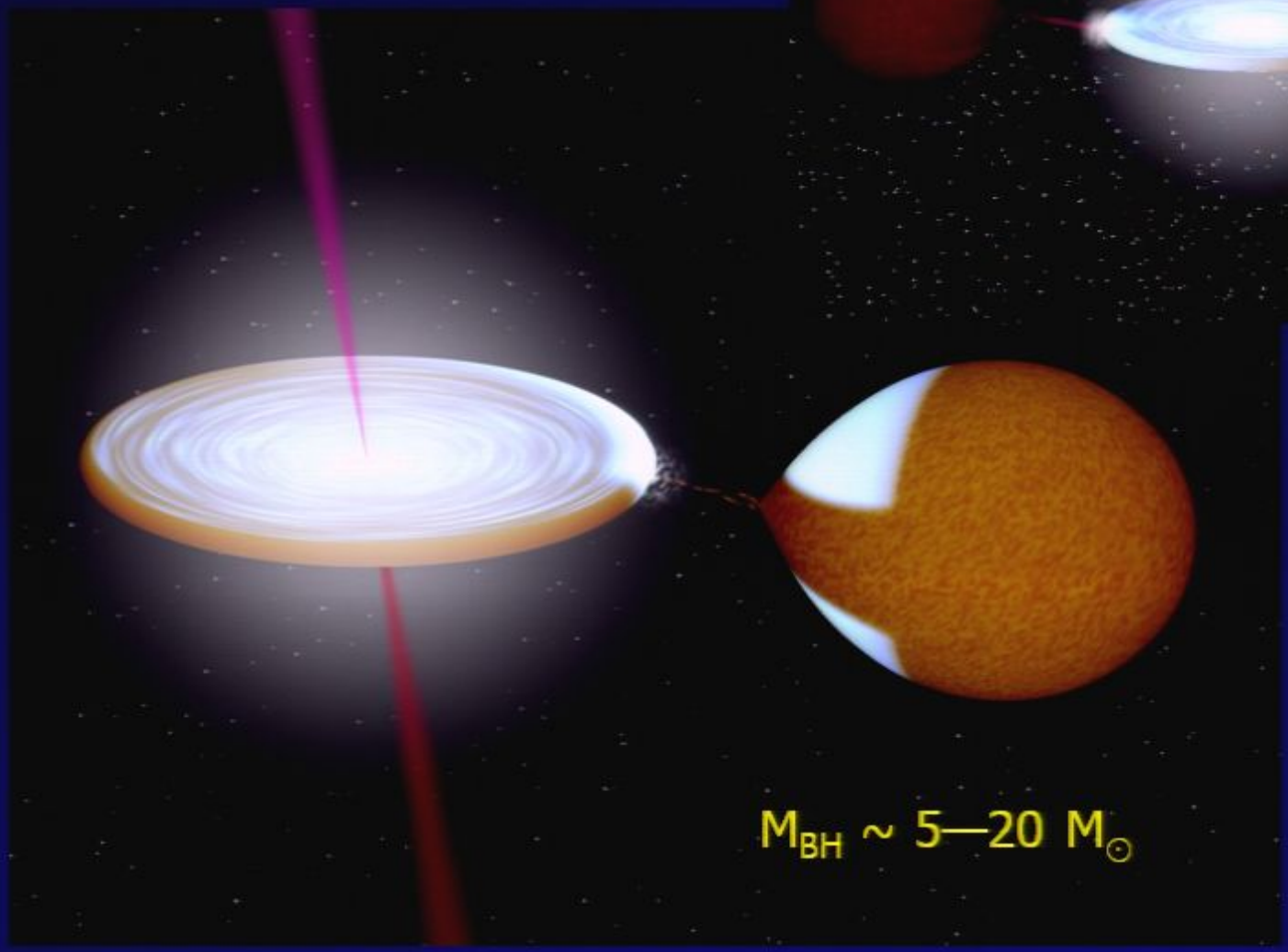

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Galactic Nuclei

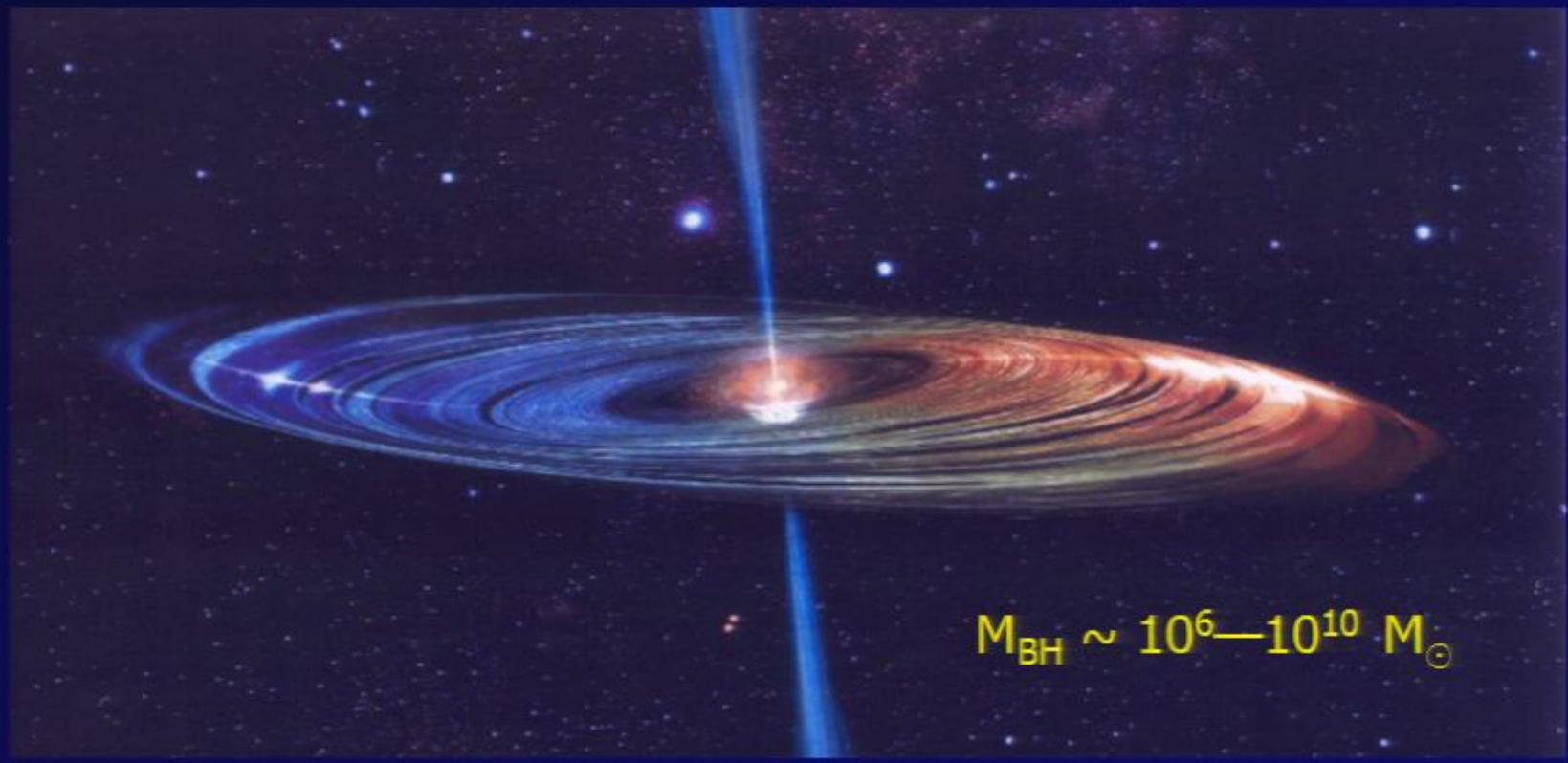
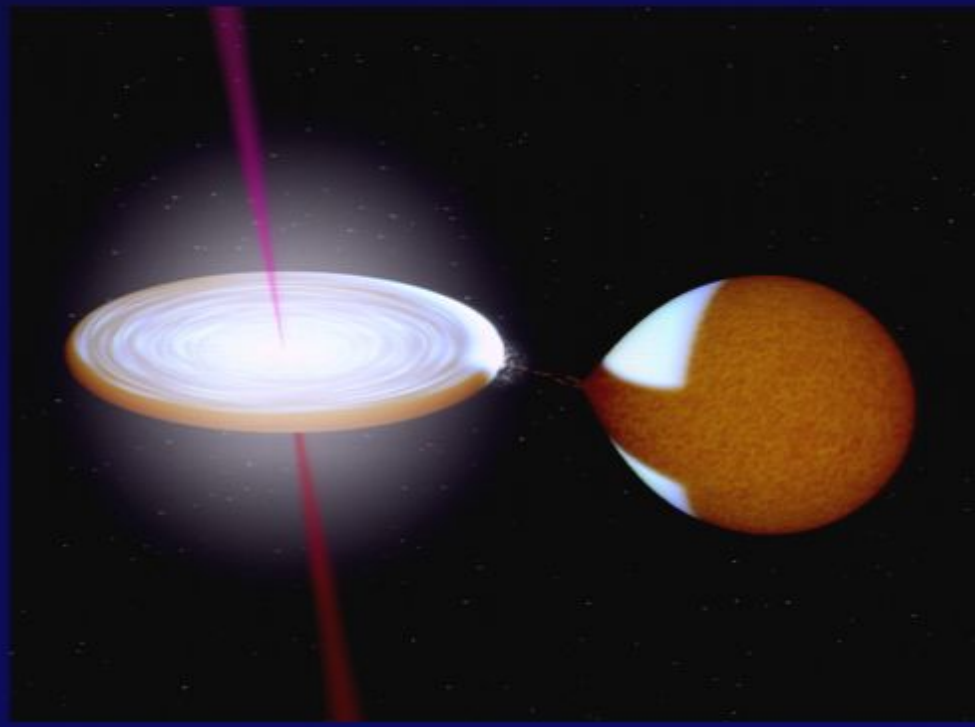


Image credit: Lincoln Greenhill, Jim Moran

Are Black Hole Candidates Really Black Holes?

- We know that BH candidates are
  - Compact: $R \lesssim$ **few** R_S
  - Massive: $M \gtrsim 3M_\odot$ (not neutron stars)
- But can we be sure that they are really BHs?
- True, there is no equilibrium solution known…
- But can we find independent evidence that **BH** candidates actually possess **Event Horizons** ?
- **This is the question addressed in this talk**

In Search of the Event Horizon



- Accretion flows are very useful, since inflowing gas reaches the center and "senses" the nature of the central object
- X-ray binaries have an additional advantage --- we can compare **NS** systems (which have surfaces) and **BH** systems (no surfaces?)

How to Check if an Object has an Event Horizon?

- If the object does not have an Event Horizon, then it must have a surface
- Accreting gas will fall on the surface and will produce extra radiation, in addition to whatever produced in the accretion disk
- We can look for this extra surface radiation
- If it is not present, then no surface → **EH**

Is this Good Enough?

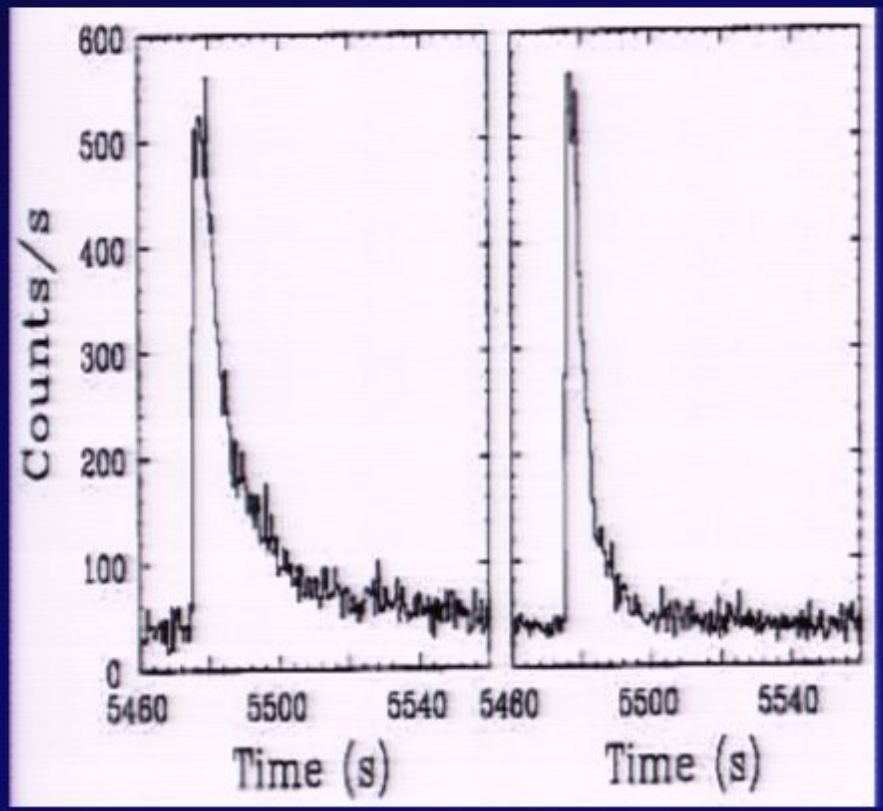
- What we hope to show is that an object does not have a surface
- We then argue that, if the object does not have a surface, it must have an event horizon
- Evidence of absence of surface… is this good enough as proof of event horizon?
- No better idea so far…

Signatures of the Event Horizon

- ✓ Differences in quiescent luminosities of XRBs (Narayan, Garcia & McClintock 1997; Garcia et al. 2001; McClintock et al. 2003;...)
- ✓ Differences in Type I X-ray bursts between NSXRBs and BHXRBs (Narayan & Heyl 2002; Tournear et al. 2003; Yuan, Narayan & Rees 2004; Remillard et al. 2006)
- Differences in X-ray colors of XRBs (Done & Gierlinsky 2003)
- Differences in thermal surface emission of NSXRBs and BHXRBs (McClintock, Narayan & Rybicki 2004)
- ✓ Infrared flux of Sgr A* (Broderick & Narayan 2006, 2007)

Type I X-ray Bursts

- Discovered by Grindlay et al. (1976)
- Very common in XRBs
- Sudden brightening, once every several hrs; lasts about 10-100 s
- Physics understood: unstable nuclear burning of accreted gas



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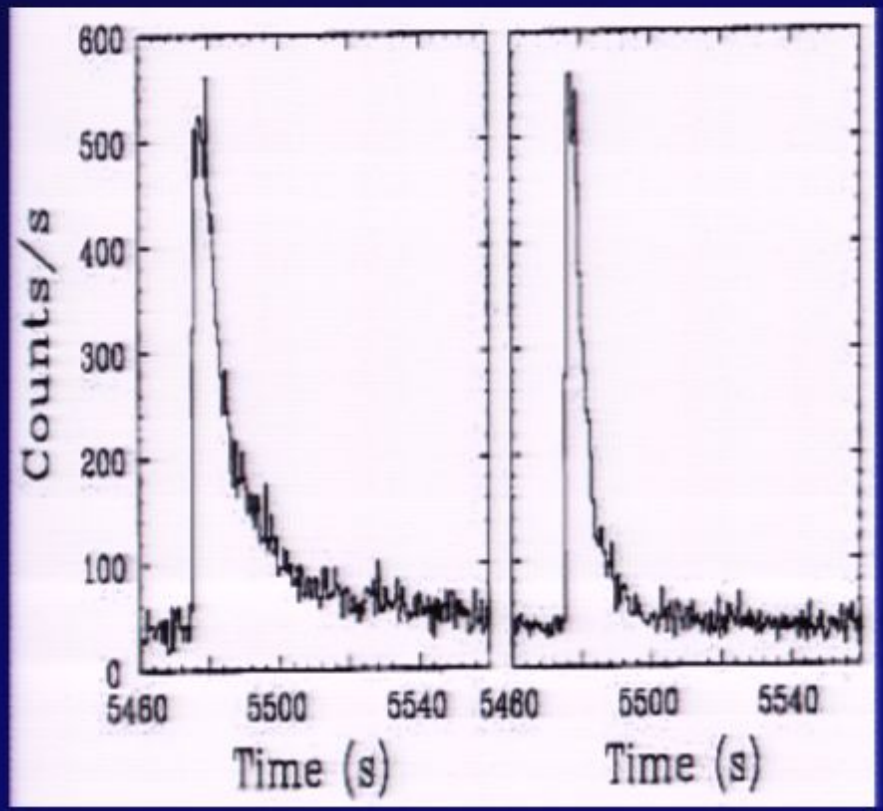

Thermal Instability

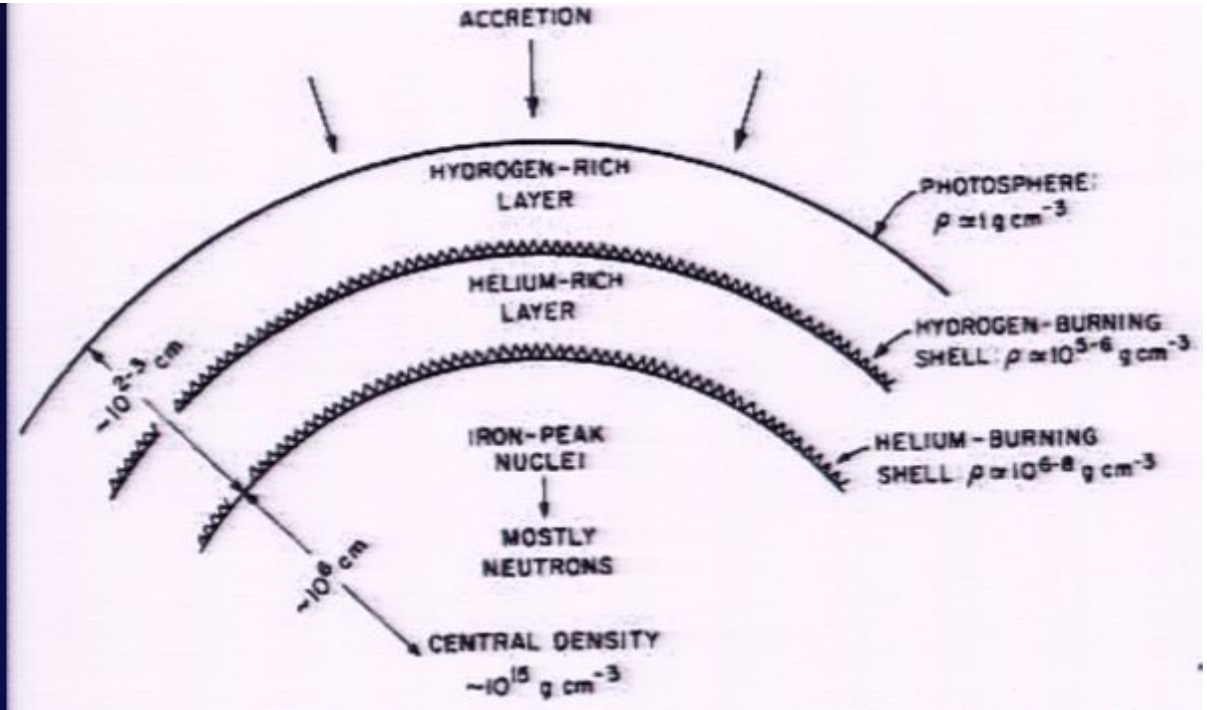

Figure 13 Schematic sketch of the surface layers of an accreting neutron star (adapted from Joss 1979a).

- Accreted gas on the surface of a compact star is heated by compression, triggering nuclear reactions: H → He, He → C/O
- Nuclear reaction rates are very steep functions of temperature.
- If $d\epsilon/dT$ is steep enough, energy production increases too rapidly with increasing T for cooling to keep up ⇒ runaway instability ⇒ **Burst**

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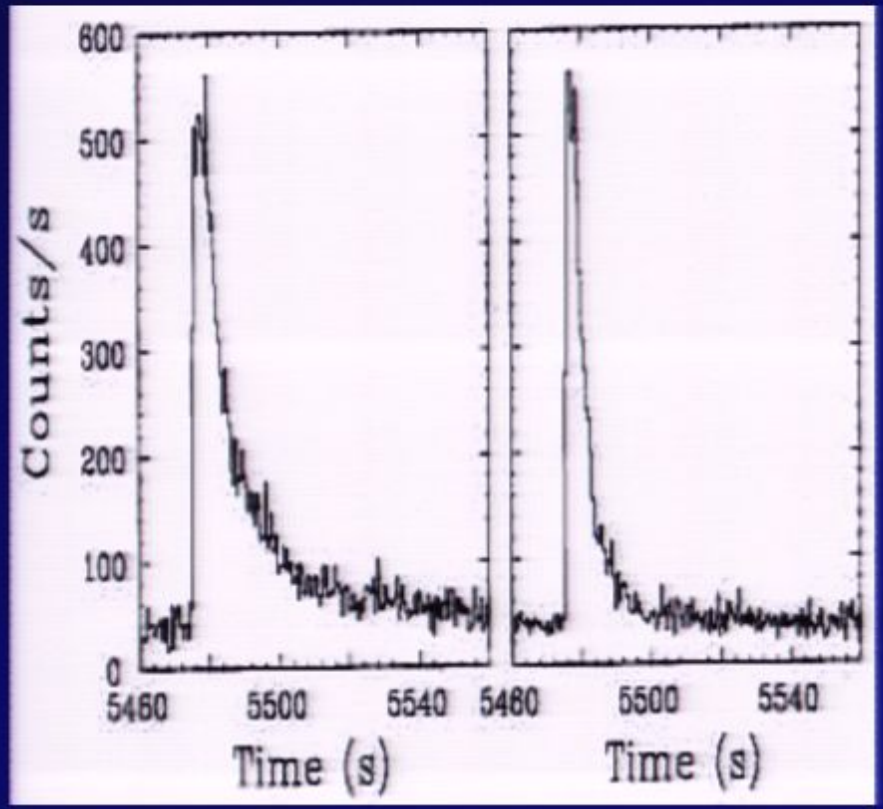

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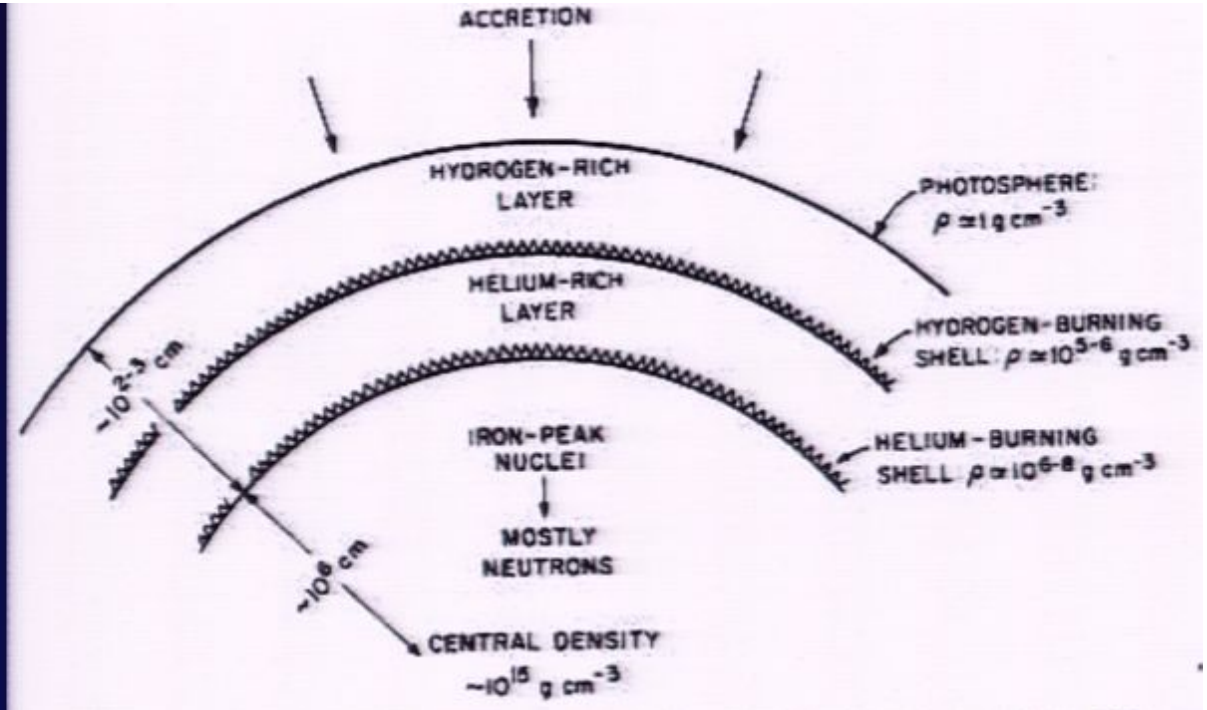

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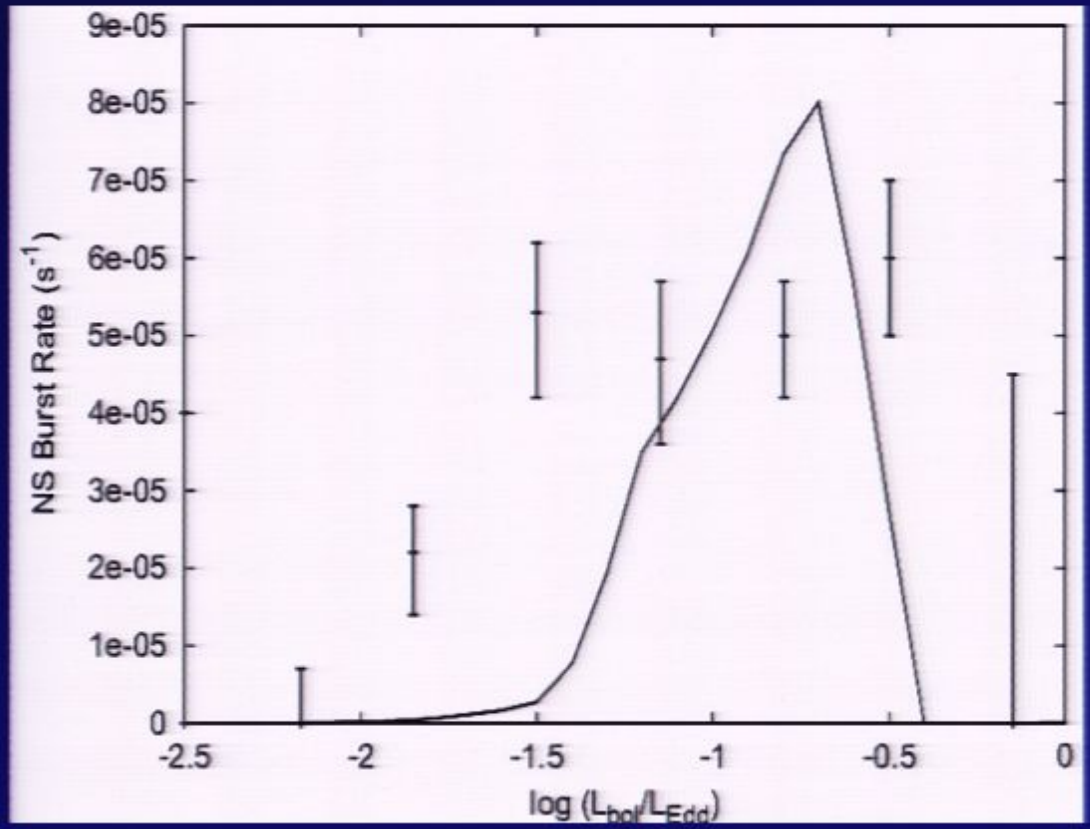
Type I Bursts in NSs

- We have a quantitative model of Type I bursts: Narayan & Heyl (2002; 2003)
- Compare model predictions against burst data (RXTE) (13 NSs, 3.7 Ms of data)
- **First principles calculation**
  - Predict **102** bursts
  - Observed **135** bursts
- Pretty good agreement
- Part of the discrepancy could be due to errors in L (due to uncertainties in D)

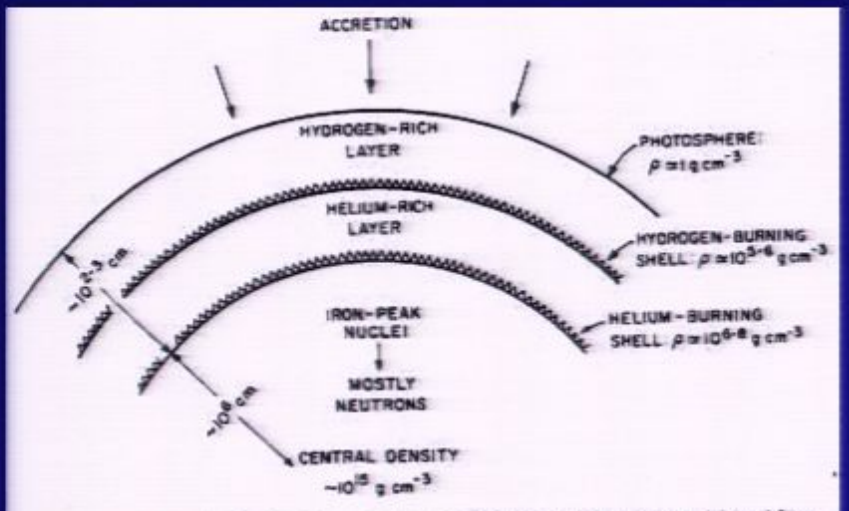


Remillard, Lin, Cooper & Narayan (2006)

$M=1.4M_{\odot}$ R=10.4 km

No Type I Bursts in BHs!!

- No BH candidate has ever exhibited a Type I burst
- Obvious explanation: They have event horizons, so material cannot pile up, and there can be no bursts
- But, would they burst if they had surfaces, and how often would they burst?
- We can use our burst formalism to calculate this



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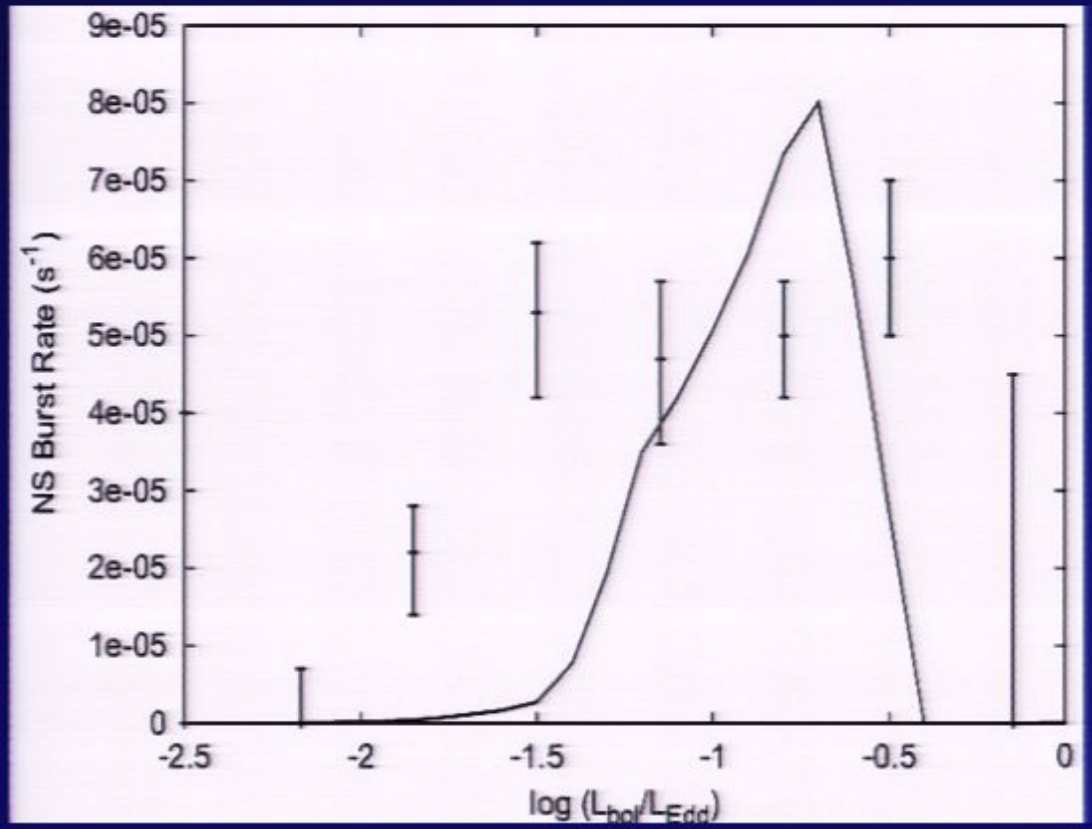

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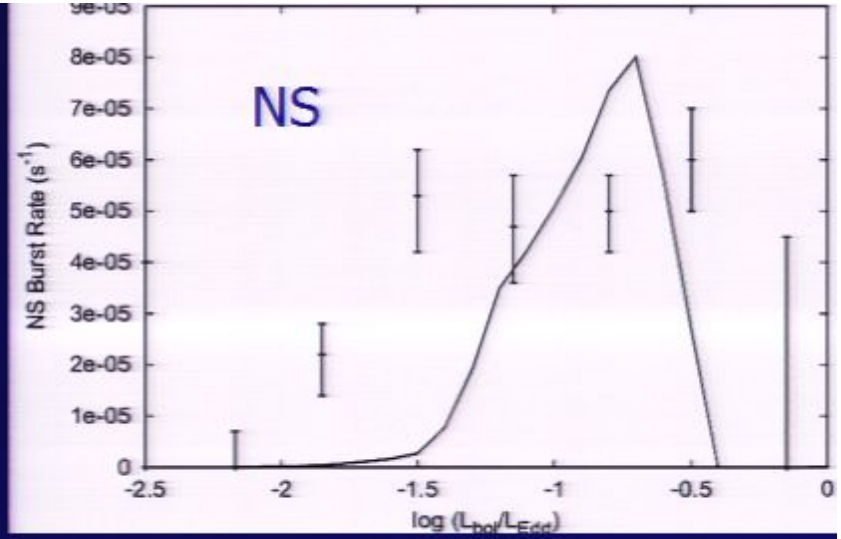
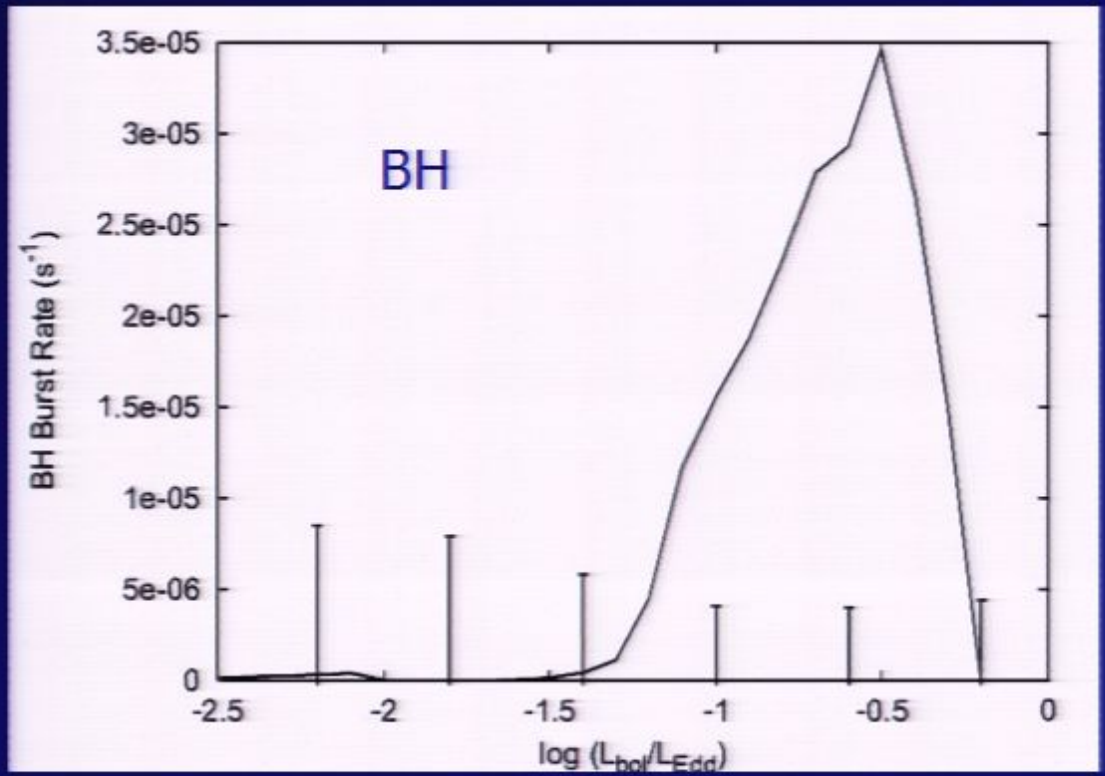
Data on BH XRBs

- Model predicts fairly high burst rate for accretion at 0.1-0.4 L_{Edd}
- No bursts seen in 6.5 Ms of RXTE data on 18 BH candidates (90% confidence limits shown)
- Impossible if objects have surfaces
- ➔ Event Horizon (Narayan & Heyl 2002)



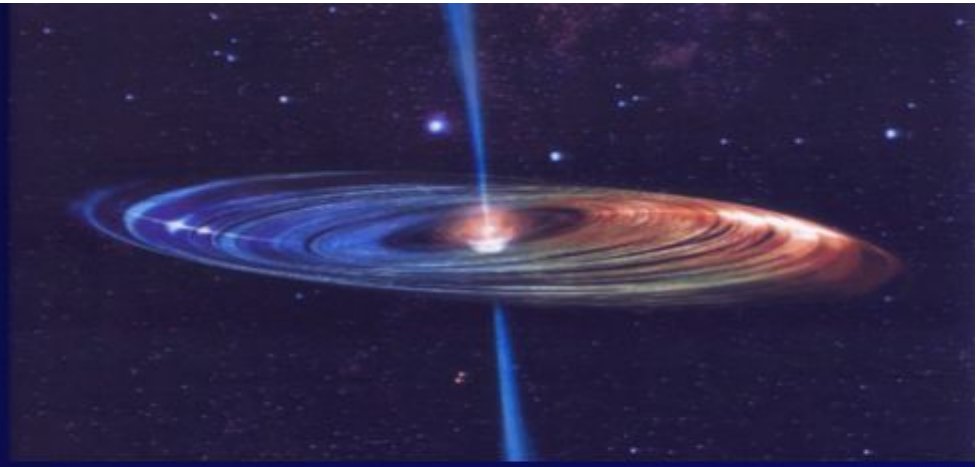


Remillard, Lin, Cooper, Narayan (2006)
Tournear et al. (2003)

Any Other Explanation?

- Very hard to explain lack of bursts in BHCs without invoking an Event Horizon
- One possibility: Our BH candidates may be made of some "exotic" matter which converts H/He nuclei on contact to exotic matter: No nuclei $\Rightarrow$ no bursts!
- Implausible ($\rho \sim 10^{6\text{-}8}$ gcm^{-3}), but logically allowed
- It would be good to find other arguments for the reality of the Event Horizon

Physics of Accretion



- Gas with angular momentum goes into orbit at a large radius around the BH
- Slowly spirals in by "viscosity" (magnetic stresses) and falls into the BH at the center
- Potential energy is converted to orbital kinetic energy and thermal energy:
- Some of the thermal energy is radiated

Accretion Energy Budget

- Gas starts with zero binding energy at large radius
- At any intermediate radius R
  - Potential Energy = – GM/R
  - Kinetic Energy = GM/2R
  - Remaining GM/2R: heat → radiation
- At the surface of the central star:
  - $KE=GM/2R_*$ → radiated from surface
  - Unless we have a BH …

How Much Luminosity from the Surface?

- If the accretion disk radiates its thermal energy efficiently (standard case), then

$$L_{\rm acc} = GM\dot{M}/2R_*$$

$$L_{\rm surface} = GM\dot{M}/2R_*$$

- inefficient (advection-dominated: ADAF)

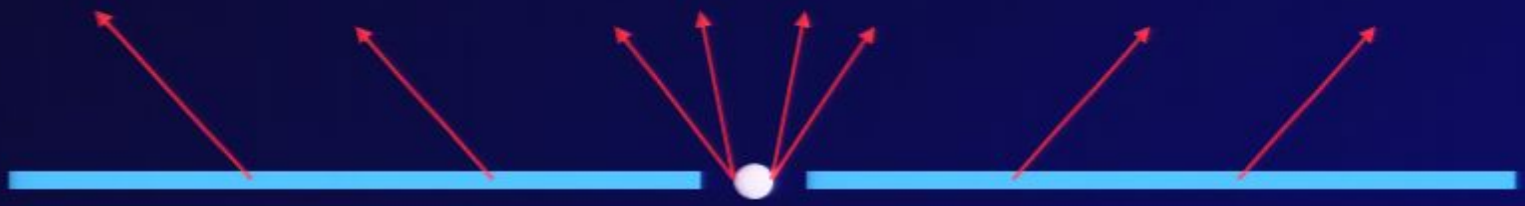
$$L_{\rm acc} \ll GM\dot{M}/2R_*$$

$$L_{\rm surface} \sim GM\dot{M}/R_*$$

Basic Idea

$$L_{surface} = \left(\frac{1}{2} - -1\right)\frac{GM\dot{M}}{R_*}$$

$$L_{acc} = \left(0 - -\frac{1}{2}\right)\frac{GM\dot{M}}{R_*}$$



- The surface luminosity is predicted to be always important: $L_{surface} \gtrsim L_{acc}$
- Unless there is no surface…
- We look for systems that have negligible surface luminosity → these must be **BHs**
- Has the potential to be a robust argument since it just uses energy conservation

Our First Approach
(Narayan, Garcia & McClintock 1997)

- We considered a complete sample of
  - BH XRBs (identified by mass)
  - NS XRBs (identified in various ways)
- Compared the luminosities of these systems in "quiescence" (astrophysics mumbo-jumbo)
- Predicted (initially by Narayan & Yi 1995) that BH XRBs would be unusually faint relative to NS XRBs --- Confirmed!

Beautifully Confirmed!!

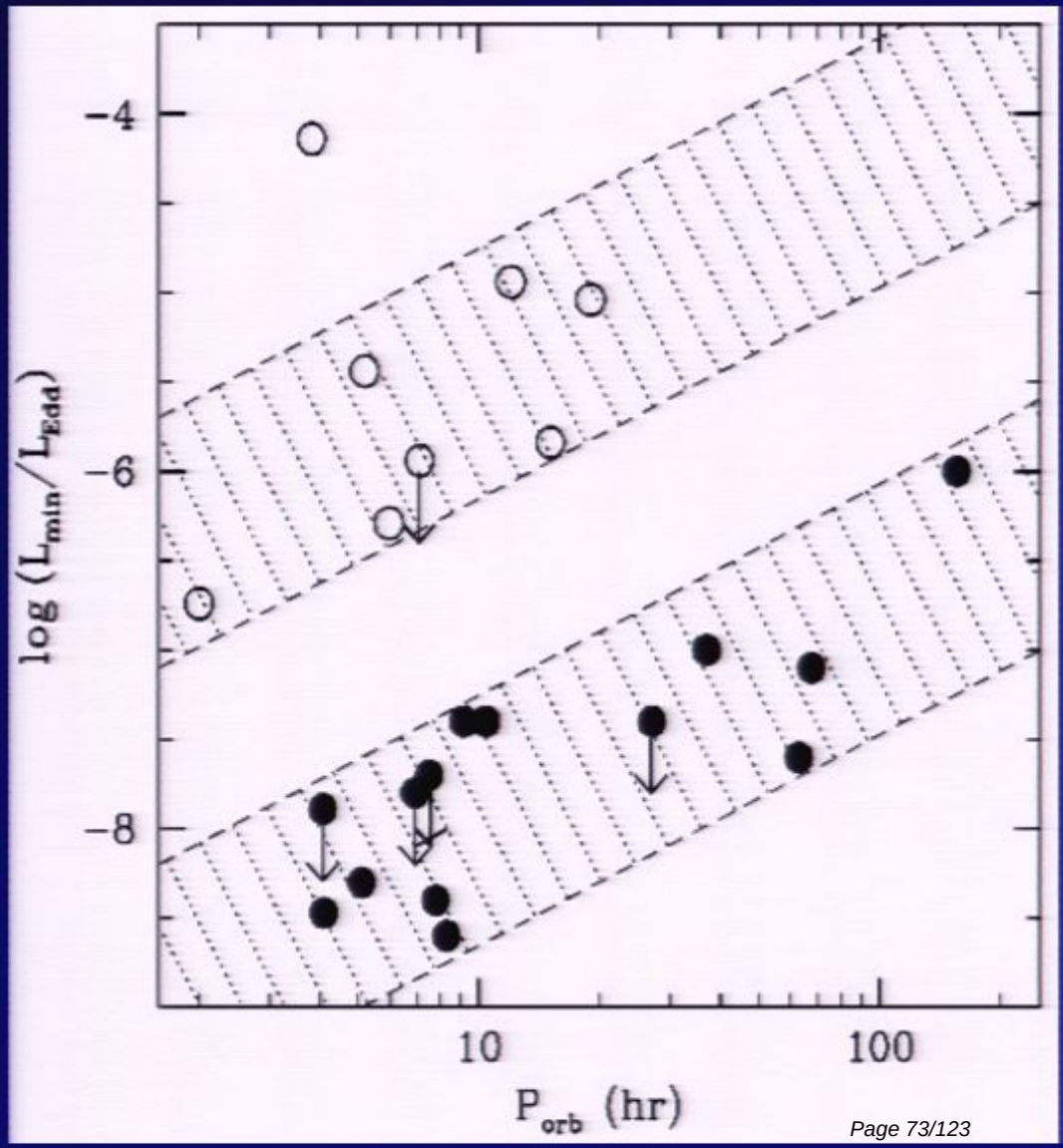
Extremely strong signal in the data

There is no question that quiescent BHs are orders of magnitude fainter than NSs

Perfectly natural if BHCs have Event Horizons

The effect was predicted!

Other explanations are very contrived



Nevertheless, One Key Assumption

- Our evidence for the EH from quiescent XRBs requires BH and NS systems to have similar accretion rates
- That is, P_{orb} has to be a good proxy for Mdot
- The argument would be stronger if we could avoid this assumption
- We can do this with the Galactic Center

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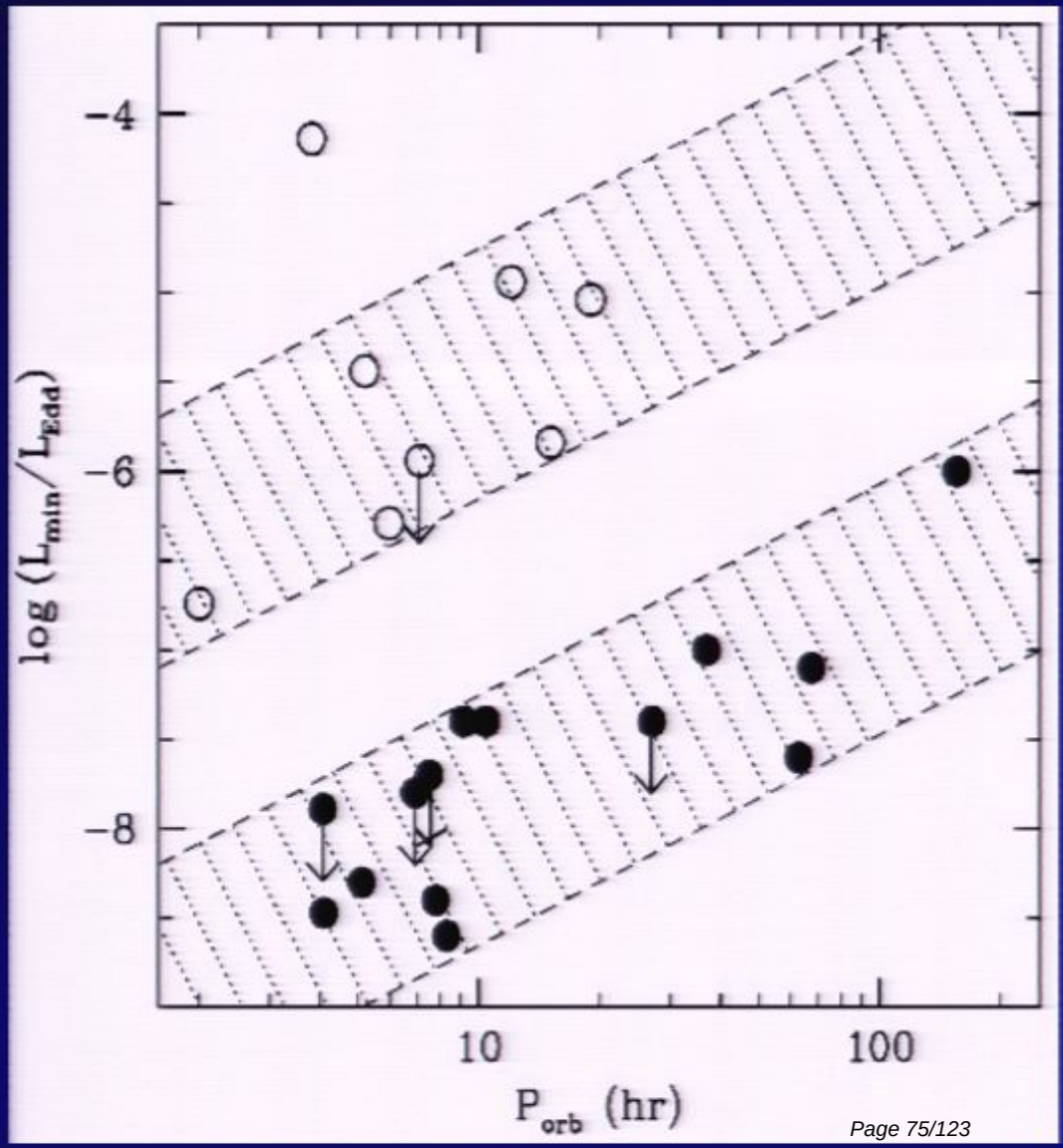

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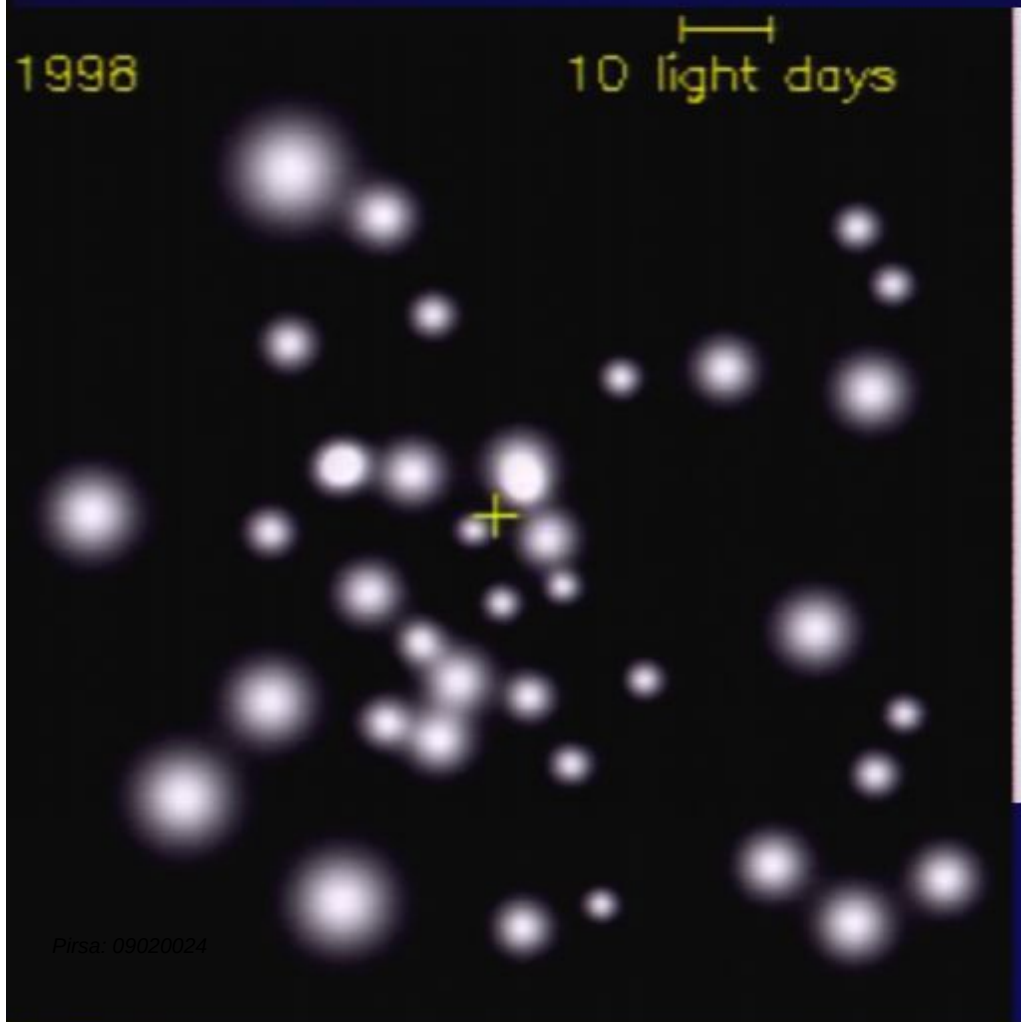
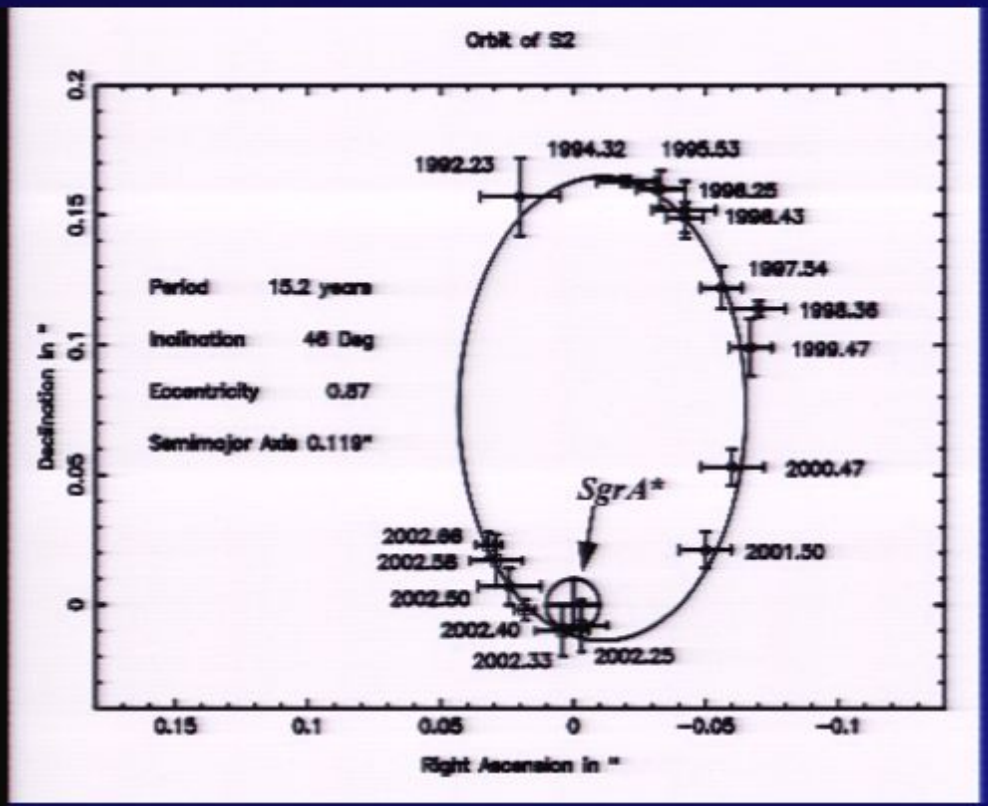
Black Hole Candidate at the Galactic Center

Dark mass ~4×10^6 $M_\odot$ at the Galactic Center (inferred from stellar motions)

Stellar Dynamics at the Galactic Center





Schodel et al. (2002)

$M_{BH}=4.0\pm0.2\times10^6\ M_\odot$

Radio Source at the GC: Sagittarius A*

- A compact radio source Sgr A* is located at the Galactic Center
- Very Long Baseline Interferometer (VLBI) observations place an exquisitely tight limit on the velocity of Sgr A* ($\perp$ to the Galactic plane): -0.4 ± 0.9 km s^{-1} (Reid & Brunthaler 2004)
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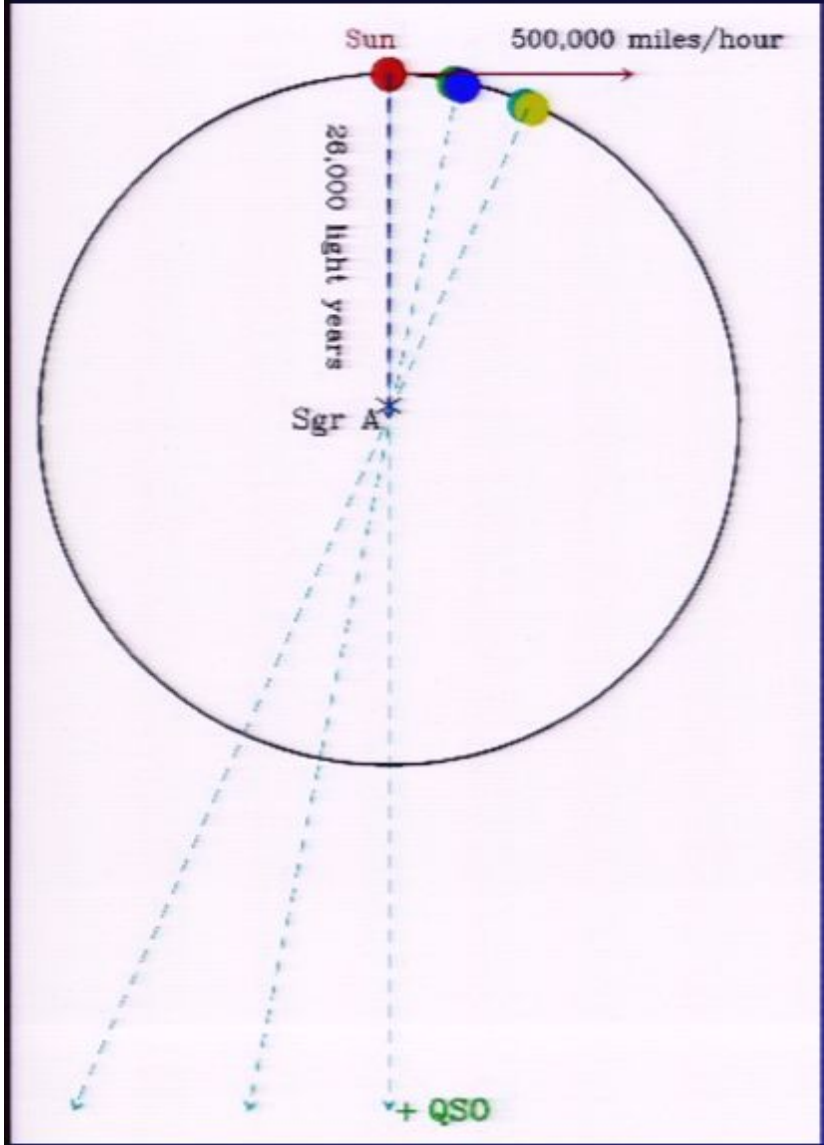

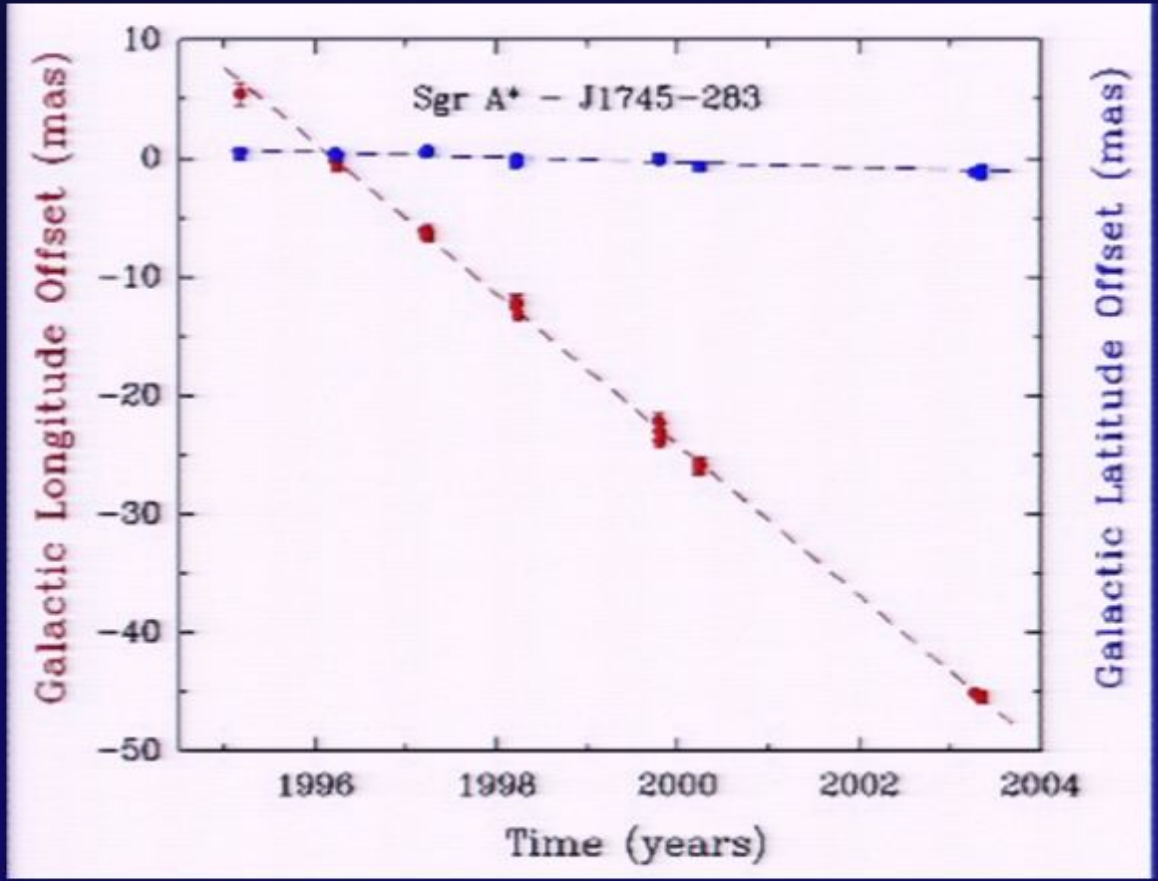

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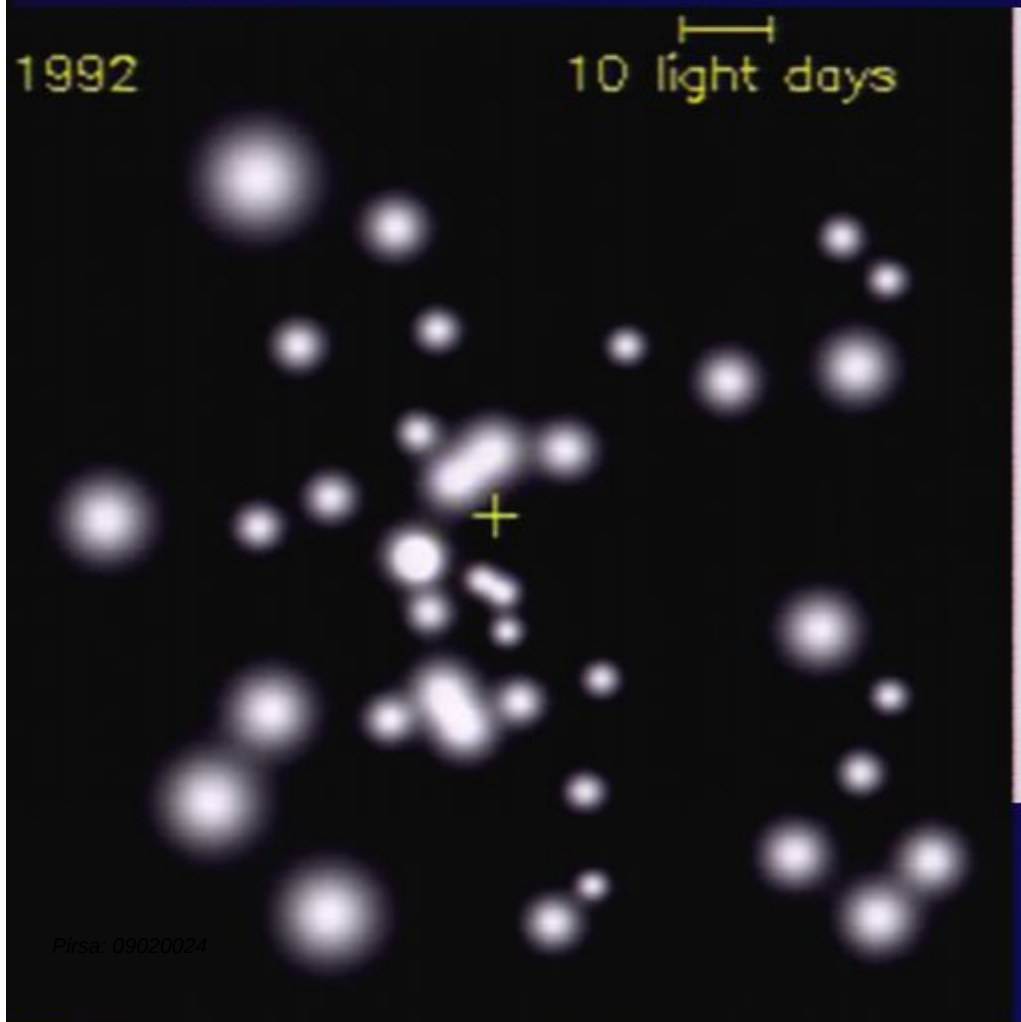

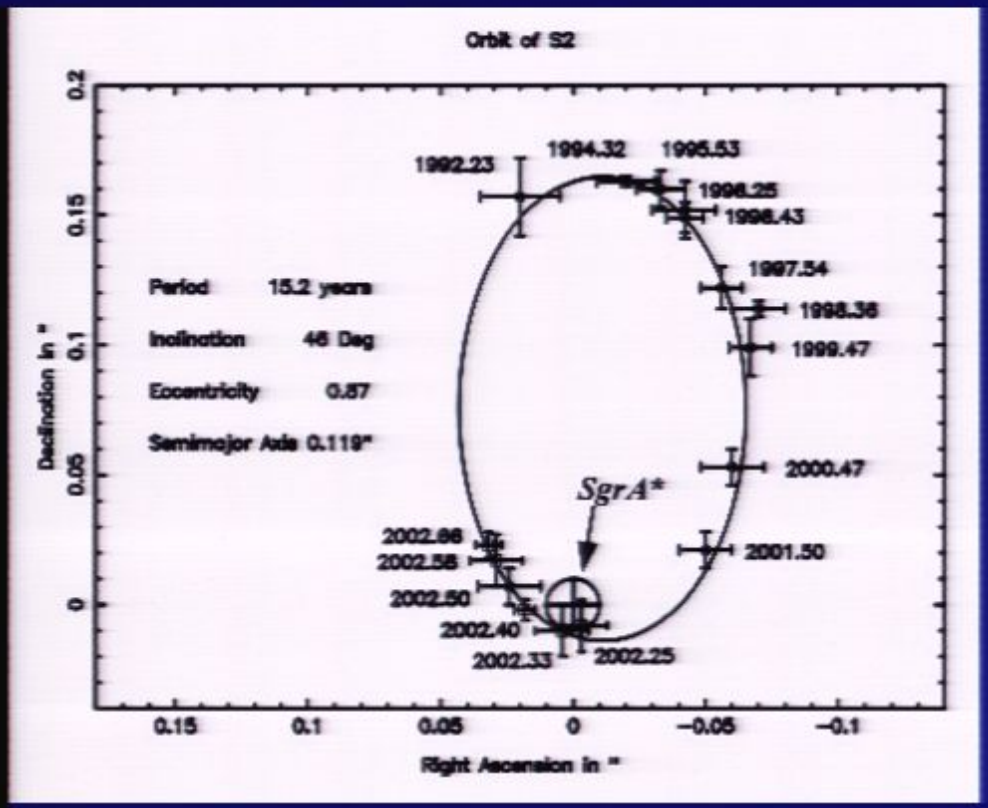

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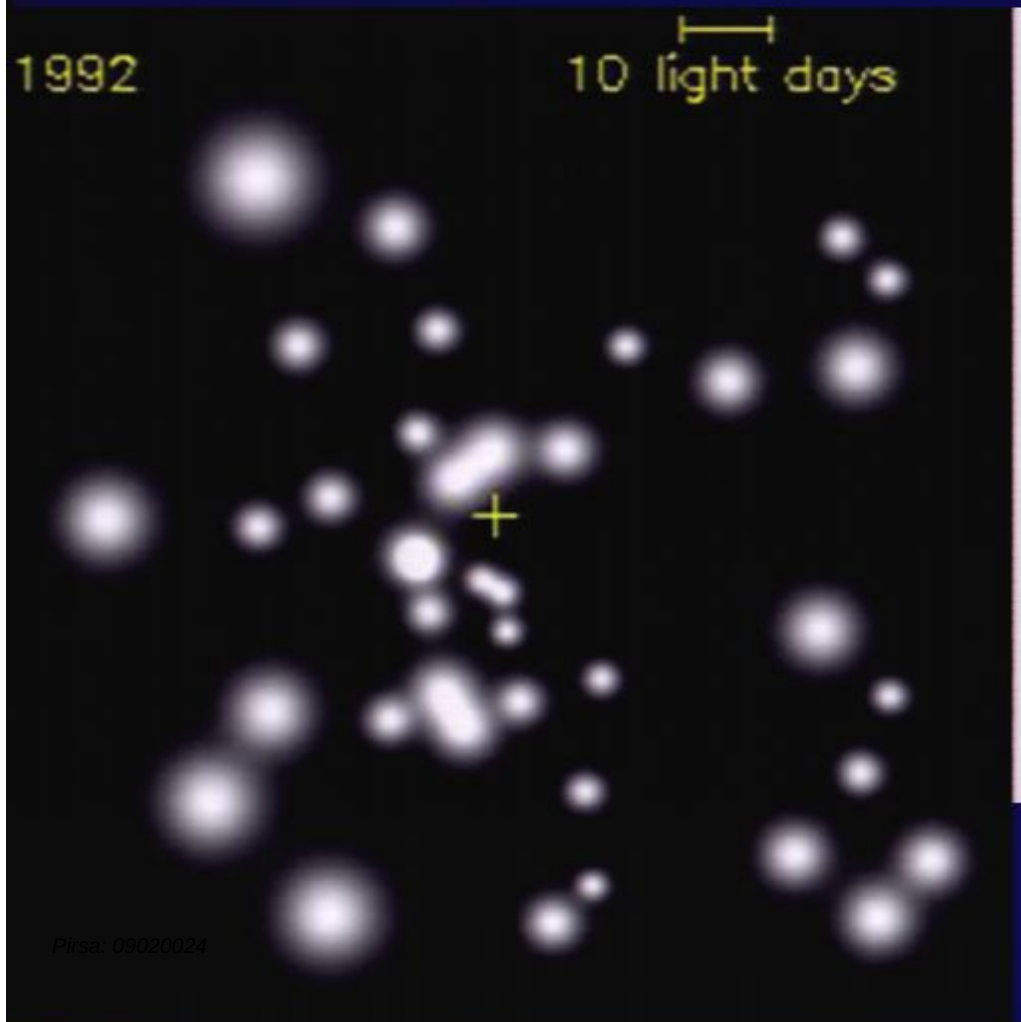

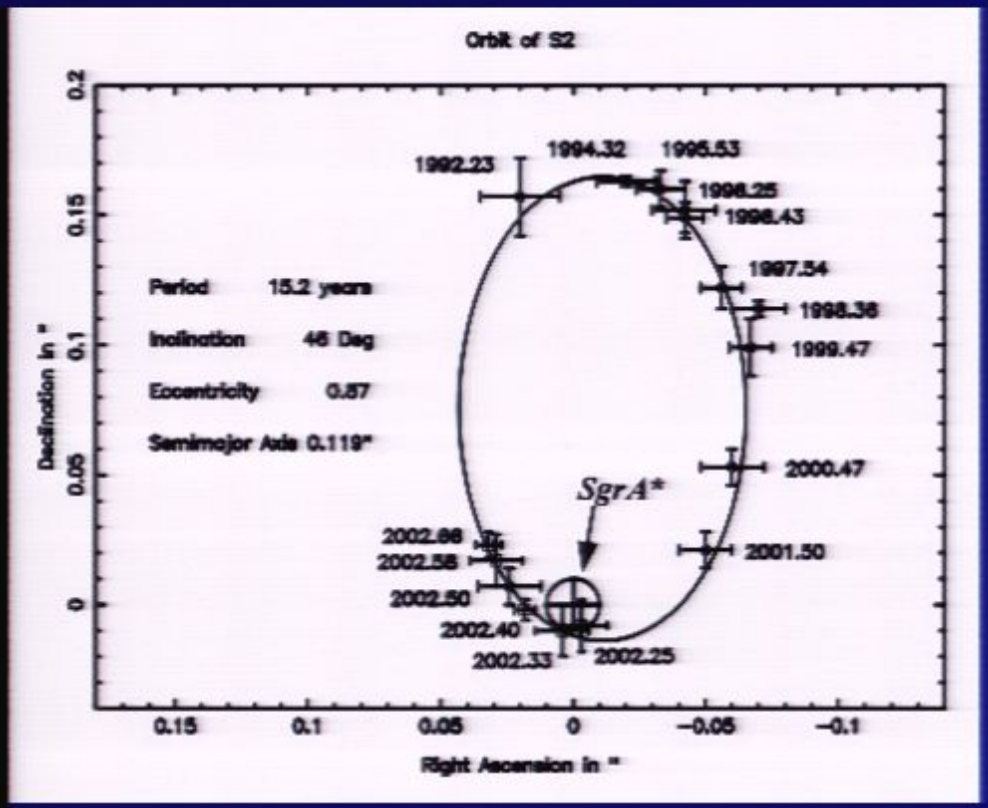

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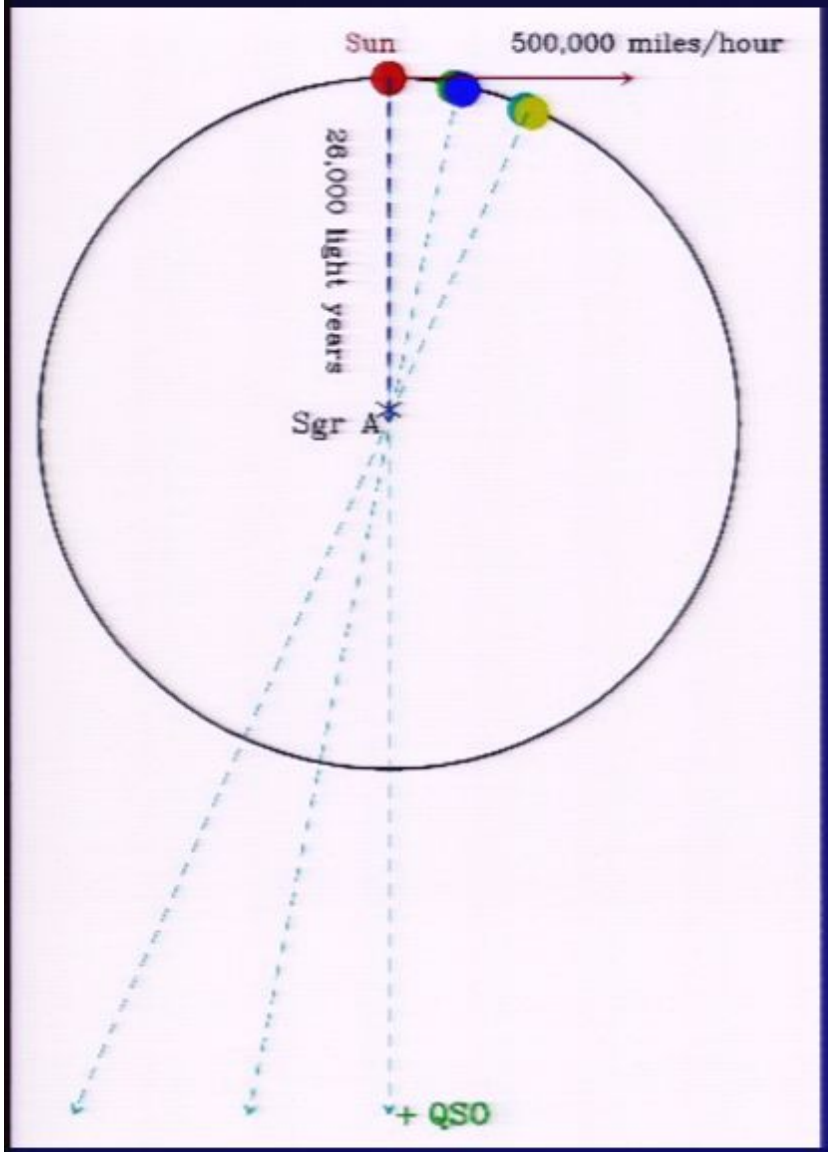

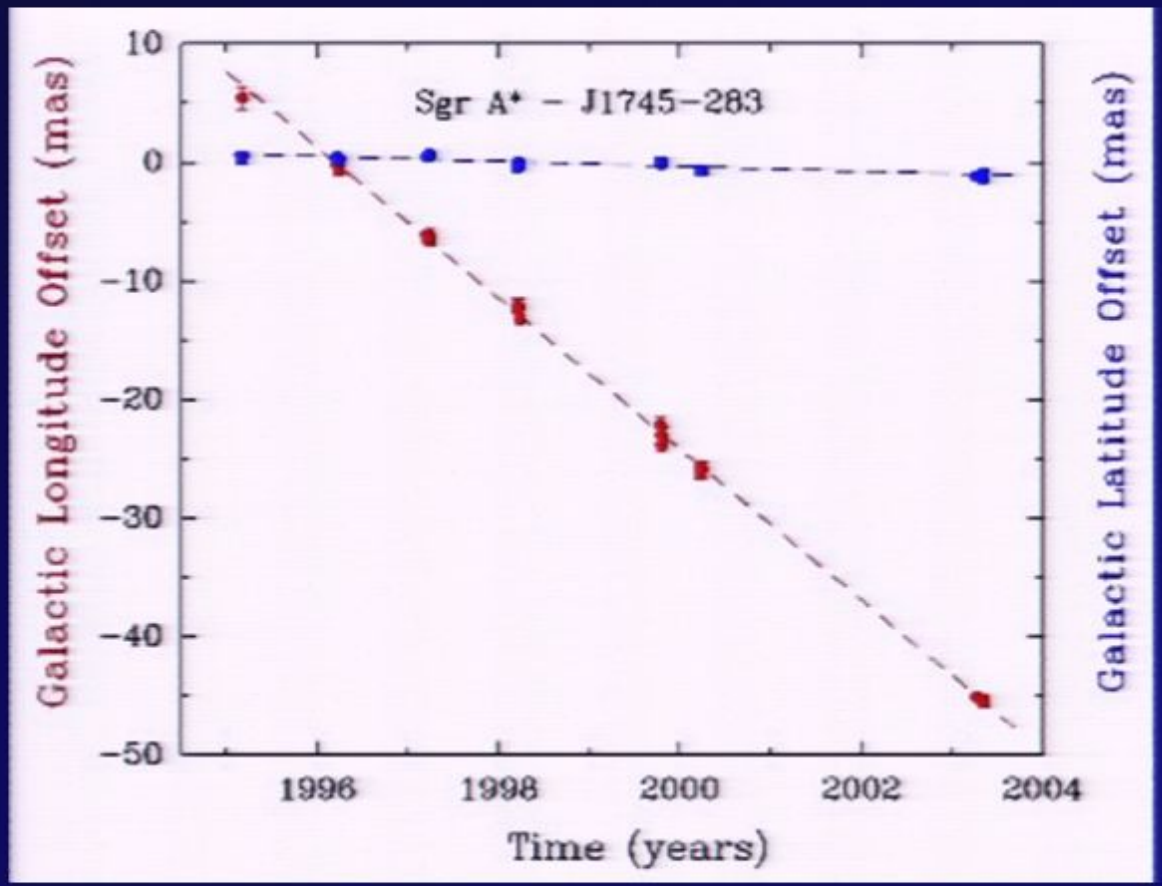

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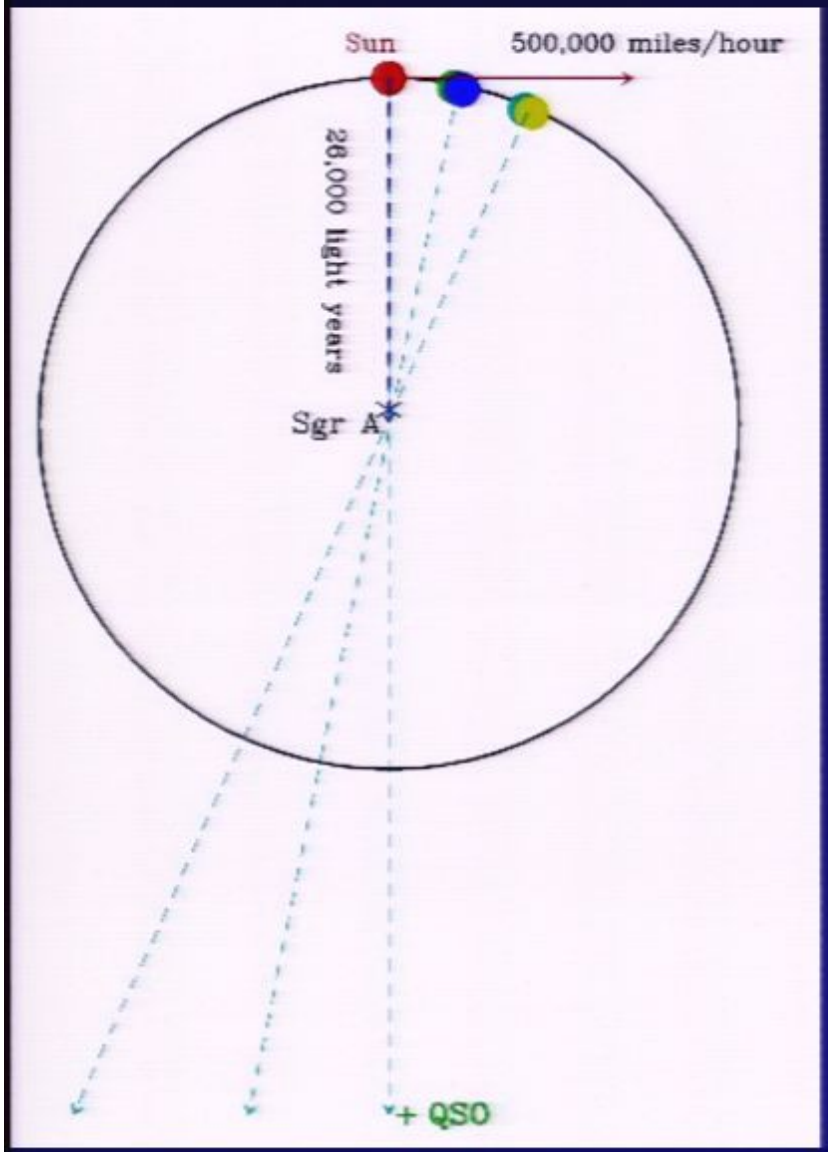

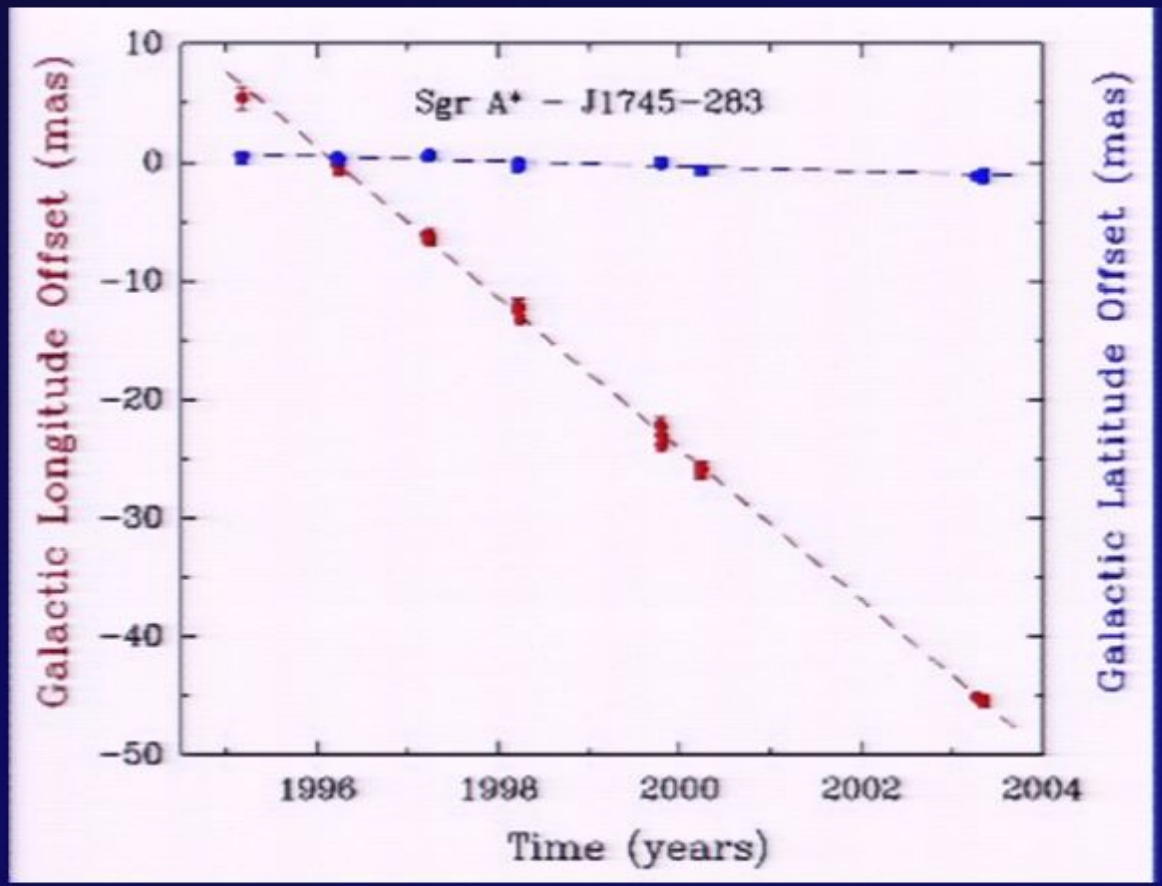

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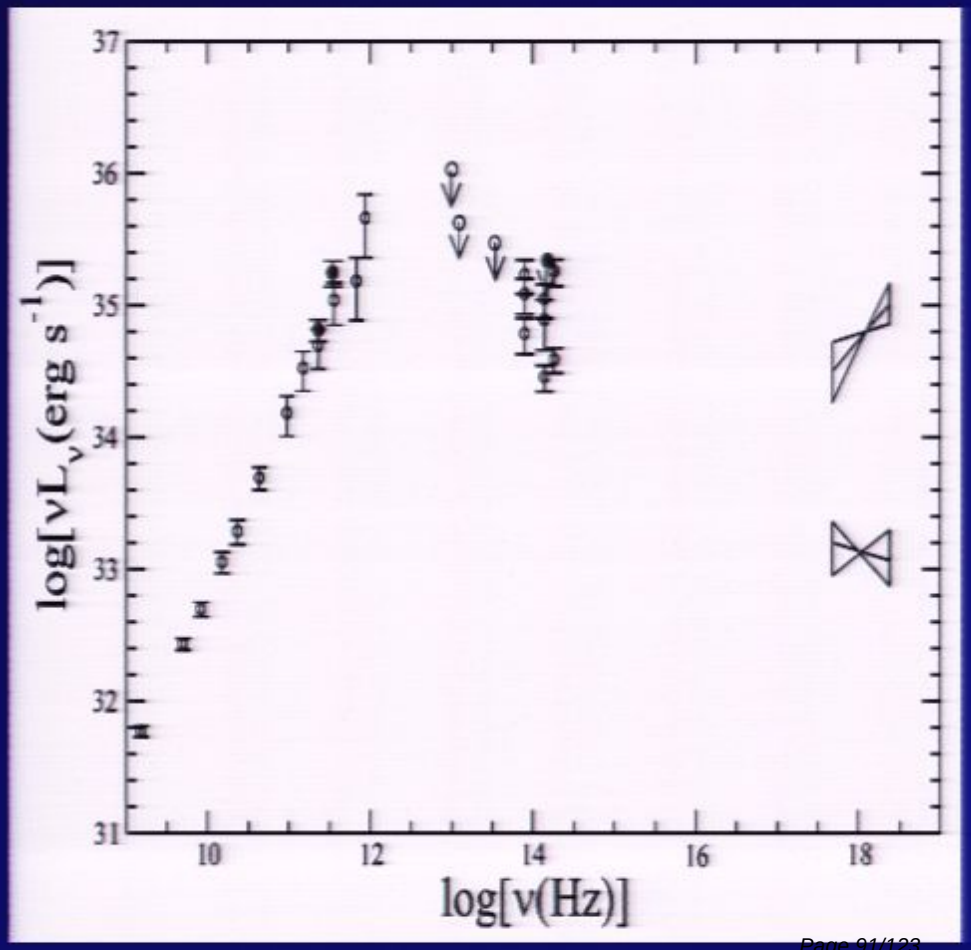
- Sgr A* has a luminosity of $\sim 10^{36}$ erg/s
- Most of the emission is in the radio/sub-mm
- **We can show that this radiation is from the accretion flow, not from the surface**



Brightness Temperature T_B

- Radio flux plus angular size gives the brightness temperature: $T_B \gtrsim 10^{10}$ K
- If the source is a blackbody, T_B gives the temperature of the object
- If not, then
  - temperature of the object is larger: $T > T_B$
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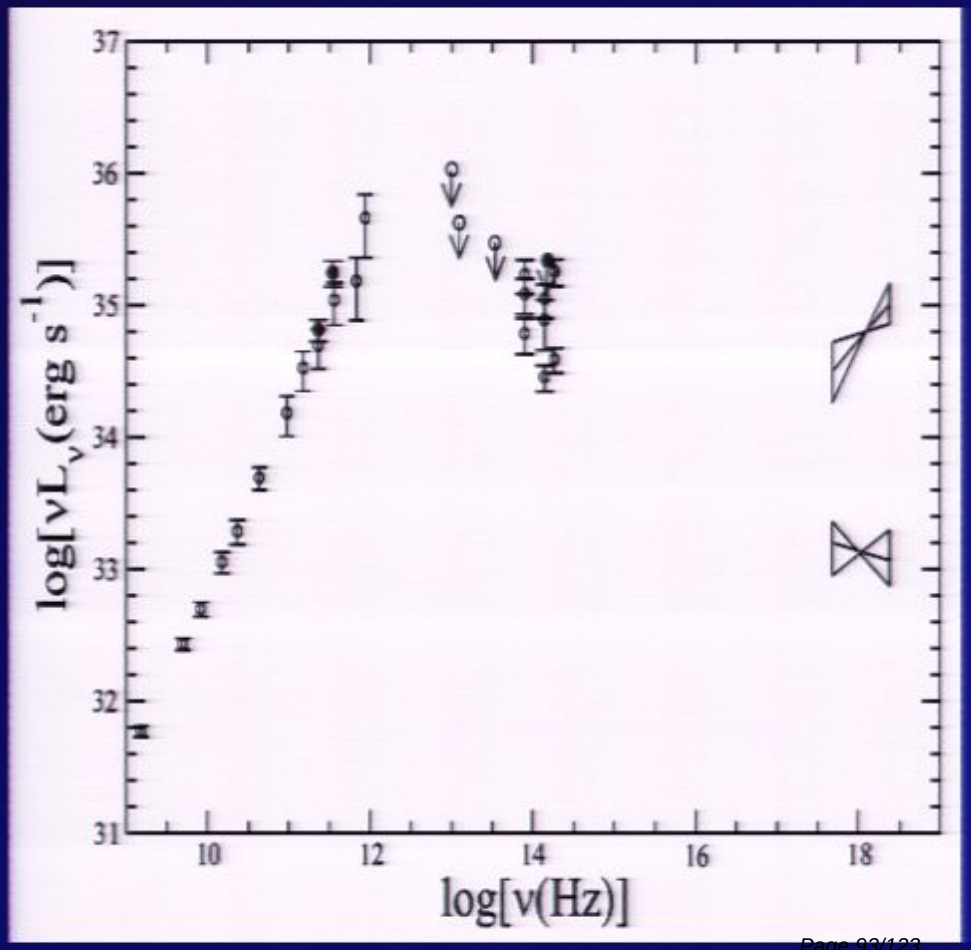

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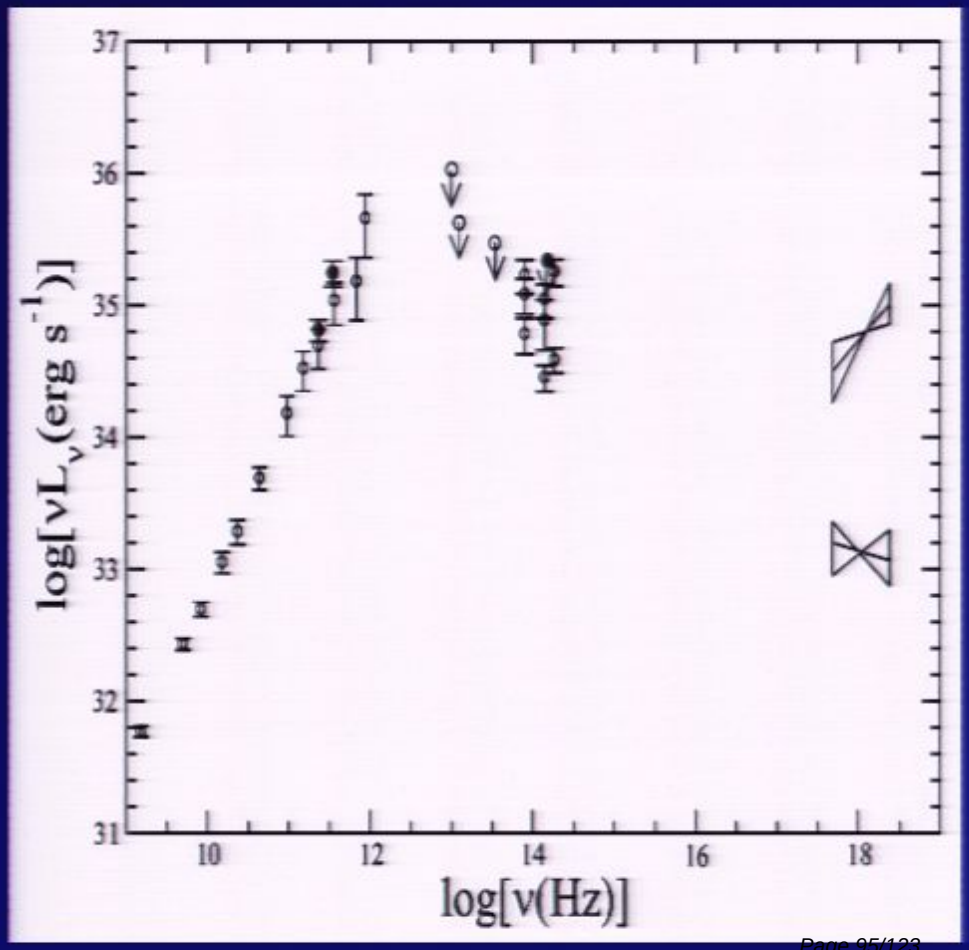

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Radio/Submm Radiation is From Optically Thin Gas

- Measured mm/sub-mm flux of Sgr A*, coupled with small angular size, implies high brightness temperature: $T_B > 10^{10}$ K
- Blackbody emission at this temperature would peak in γ -rays (and would outshine the universe!!): $L = 4\pi R^2 \sigma T^4 \sim 10^{62}$ erg/s
- Therefore, the radiation from Sgr A* must be emitted by gas that is optically thin in IR/X-rays/γ-rays

But the Surface Will Emit Blackbody Radiation

- Sgr A* has been accreting for a long time (~10^{10} years)
- Surface will radiate as a blackbody
  - Steady state → thermal equilibrium
  - Large mass → optically thick

→ observed radio/sub-mm radiation is from accretion flow, not from the "surface" of Sgr A*

So Where is the Emission from the "Surface"?

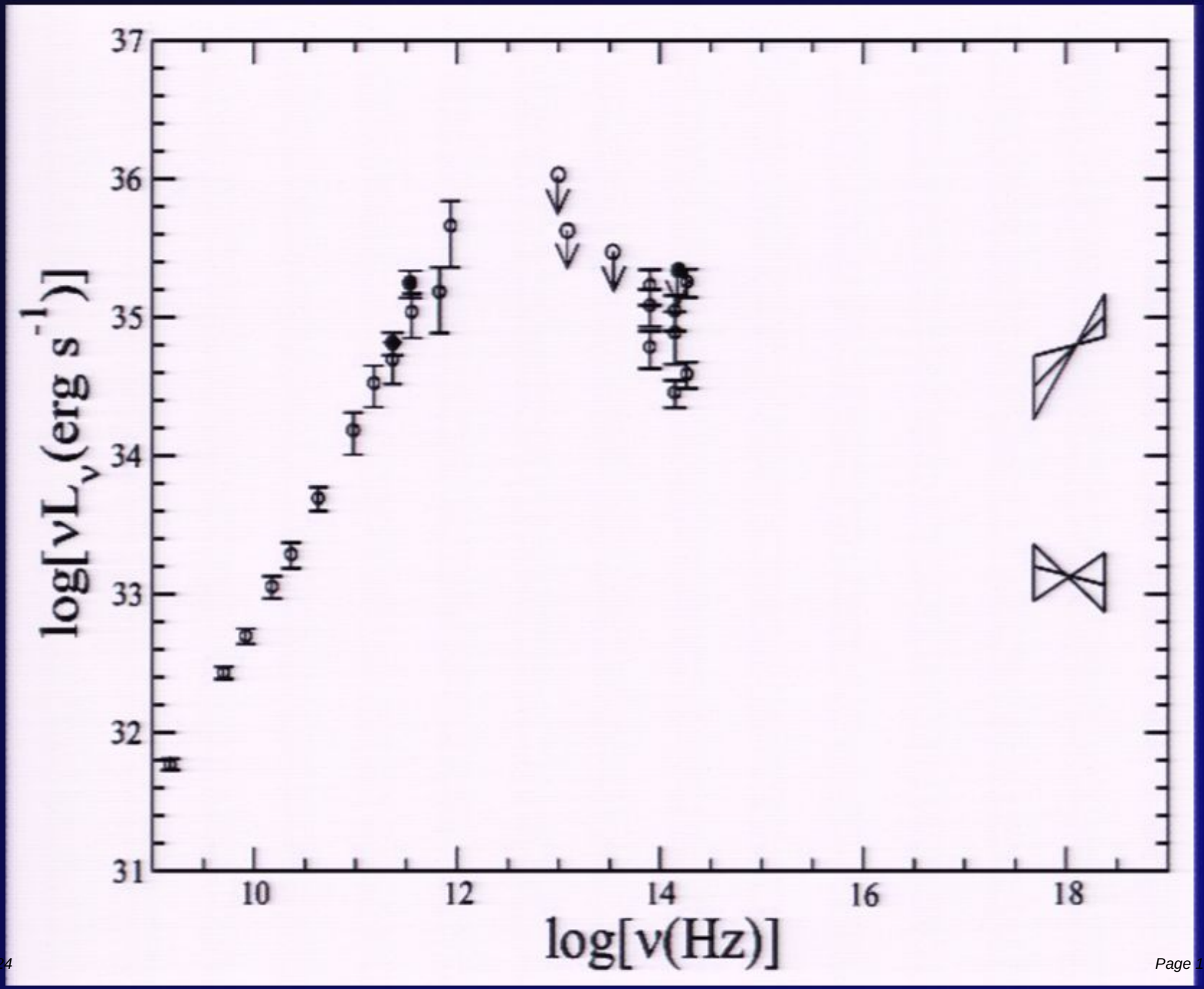
- The surface luminosity is expected to be

  $L_{surface} \gtrsim L_{acc}$

- Since we know $L_{acc} \sim 10^{36}$ erg/s, we predict:

  $L_{surface} \gtrsim 10^{36}$ erg/s

- But where is this radiation?
- There is no sign of it!
- Could it somehow be hidden?


37
36
35
34
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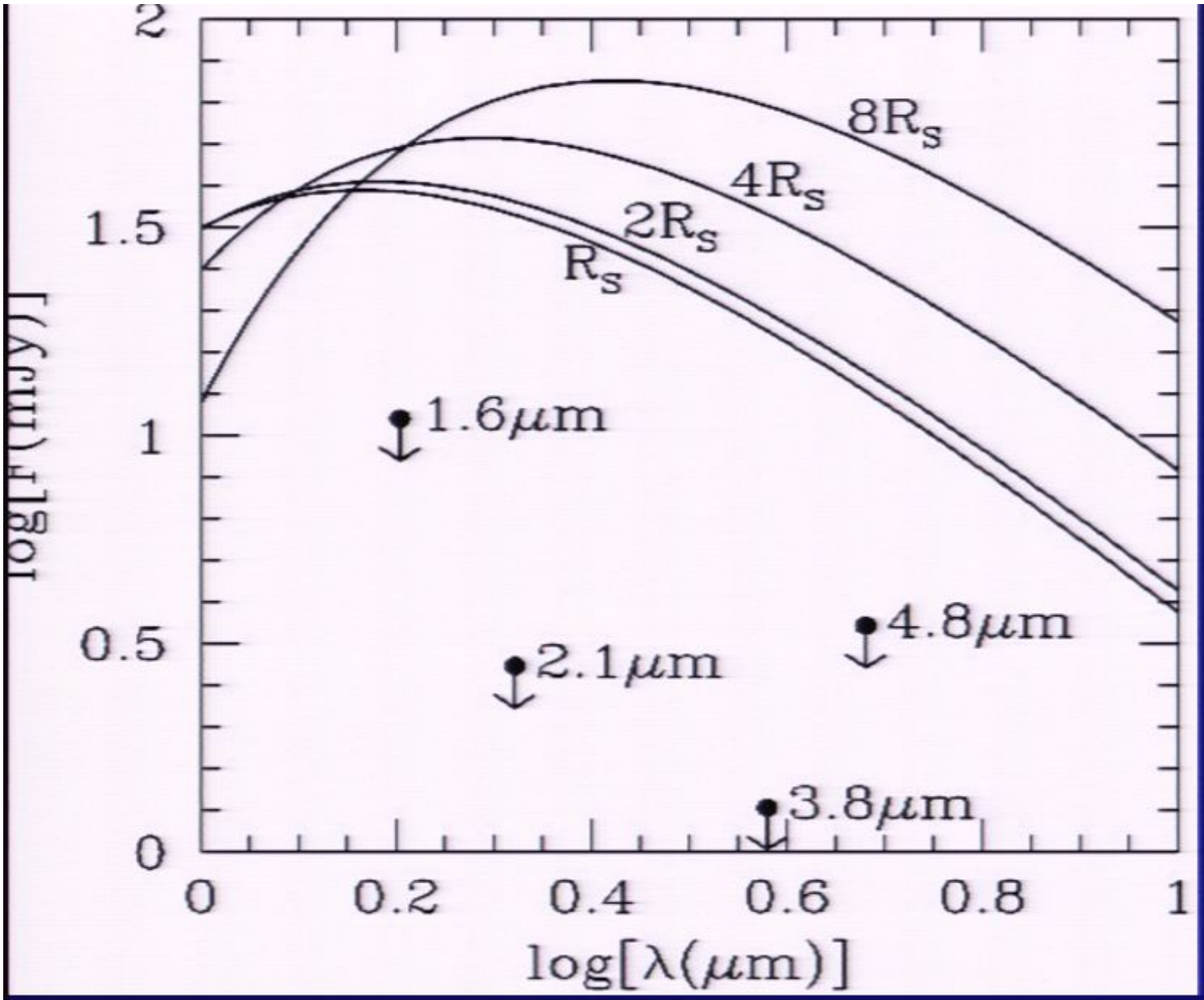
32
31
10
12
14
16
18
log[νL_ν(erg s^-1)]
log[ν(Hz)]

Expected Spectrum of the Surface Emission

- If the surface radiates as a blackbody (with modest spectral distortions), the temperature of the surface radiation is given by: $L_{surface} = (4\pi R^2)(\sigma T^4)$
- For typical radii **R** of Sgr A*'s "surface" the radiation is predicted to come out in the IR
- **There is no sign of this radiation!!**



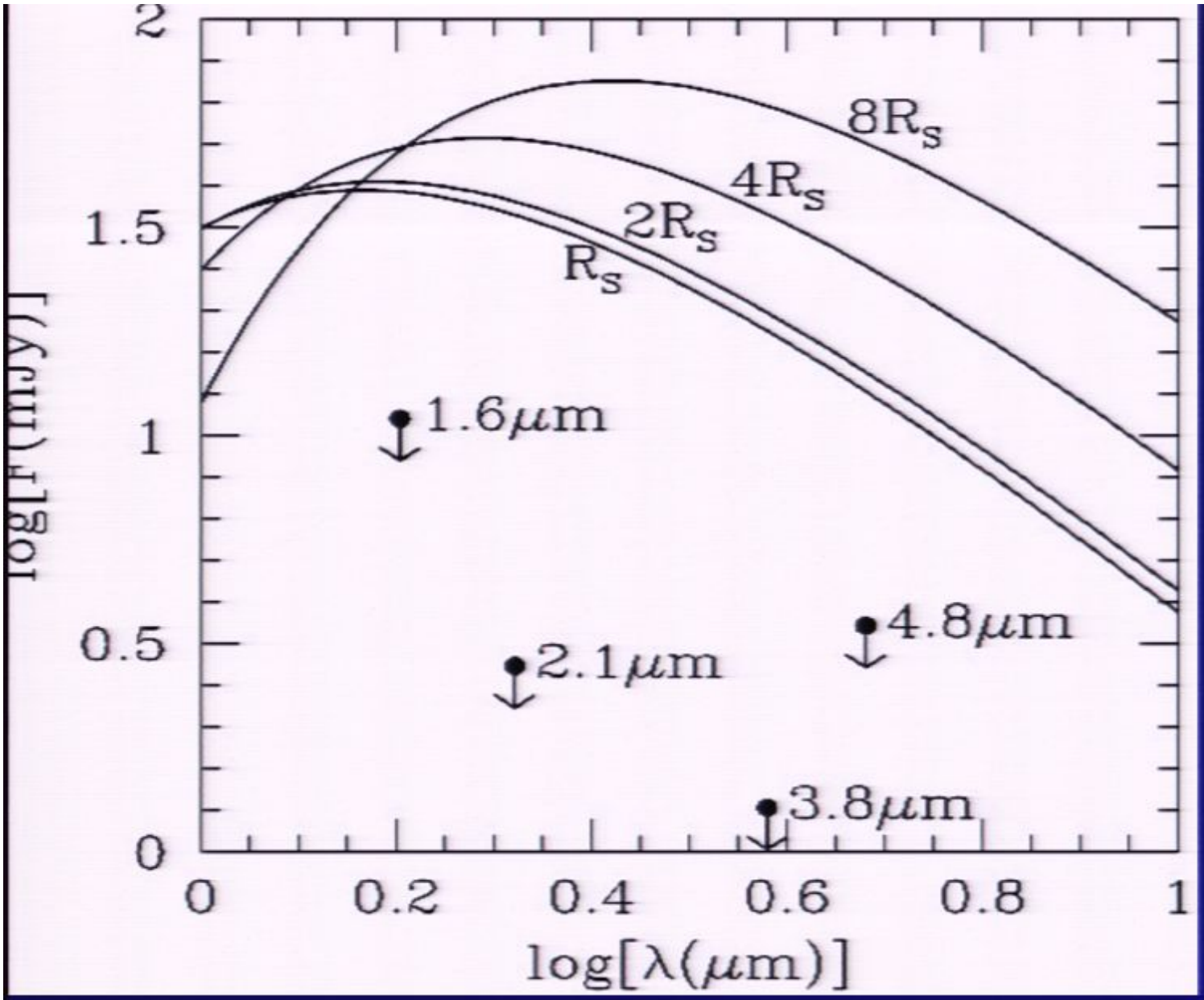
Based on Broderick & Narayan (2006)

All four IR bands have flux limits well below the predicted flux even though model predictions are very conservative (e.g., assume radiatively efficient)

→ Sgr A* cannot have a surface → Event Horizon → Black Hole

Summary of the Argument

- The observed sub-mm emission in Sgr A* is definitely from the accretion flow, not from the surface of the compact object
- If Sgr A* has a surface we expect at least $\sim 10^{36}$ erg/s from the surface
- This should come out in the IR, but measured limits are far below prediction
- Therefore, Sgr A* cannot have a surface
- It must have an Event Horizon



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Could the Mass be Ejected in a Jet or Outflow?

- Could the mass simply escape without falling on the surface?
- **NO!!** The energy source is gravity
- Therefore, in order to produce the observed L_{acc}, mass **MUST** fall on the compact star
- If the jet/outflow has a certain mechanical luminosity, then $L_{surf} \gtrsim L_{acc} + L_{mech}$
- So a jet only increases the predicted L_{surf}

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Can Strong Gravity Provide a Loophole?

- In some very unusual models of compact stars (e.g., gravastar, dark energy star), it is possible to have a surface at a very small radius:

  $R_{star} = R_S + \Delta R,\ \Delta R \ll R_S$

- Extreme relativistic effects are expected
- Can relativity cause surface emission to be hidden? (Abramowicz, Kluzniak & Lasota 2002)

Effects of Strong Gravity

- Radiation may take forever to get out
- Surface emission may be redshifted away
- Emission may not be blackbody radiation
- Emission may be in particles, not radiation
- Surface may not have reached steady state
- None of these is capable of hiding the surface emission

How Much Extra Delay?

- The extra delay relative to the Newtonian case is **TINY**

$$\Delta t_{\mathrm{GR}} \approx \frac{R_S}{c} \ln\left(\frac{R_{\mathrm{star}}}{R_{\mathrm{star}} - R_S}\right) = 10^3 \ln\left(\frac{R_{\mathrm{star}}}{\Delta R}\right) \mathrm{s}$$

- At most it is **1000 s** (for $\Delta R \sim$ Planck scale) for Sgr A* --- no big deal

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Gravitational Redshift Would Kill the Emission?

$$1+z=\left(1-\frac{R_S}{R}\right)^{-1/2}\approx\left(\frac{R_S}{\Delta R}\right)^{1/2}$$

$$L_\infty=\frac{L_{\text{loc}}}{(1+z)^2}\approx L_{\text{loc}}\left(\frac{\Delta R}{R_S}\right)$$

- Looks serious, especially if redshift is large
- But energy has to be conserved, so something is clearly wrong with this argument

ΔR	$0.1R_S$	1 mm	1 fm	l_{Pl}
1+z	3.3	3.3×10^{6}	3.3×10^{12}	2.6×10^{22}

- A little analysis shows that the accretion luminosity in the local frame is $(1+z)^2$ times greater than the Newtonian estimate of the luminosity
- As a result, what gets out is pretty much what Newton would predict
- Luminosity at infinity is largest when the redshift is greatest!
- $T_{loc}=(1+z)T_{inf}$, so the observed temperature is also the same

Accretion of particles of mass m

from $R=\infty$ at rate $\dot{N}_\infty$

$$\dot{N}_{loc} = \dot{N}_\infty (1+z)$$

$$v_{r,loc} = \left(\frac{2GM}{R}\right)^{1/2} \quad \text{(like Newtonian)}$$

$$\beta_{r,loc} \approx \left(\frac{R_s}{R}\right)^{1/2}, \quad \gamma_{r,loc} \approx 1+z$$

$$L_{loc} = \dot{N}_{loc}\,\gamma_{r,loc}\,mc^2$$

$$= (1+z)^2 \dot{N}_\infty mc^2 = (1+z)^2 \dot{M}_\infty c^2$$

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Blackbody Assumption OK?

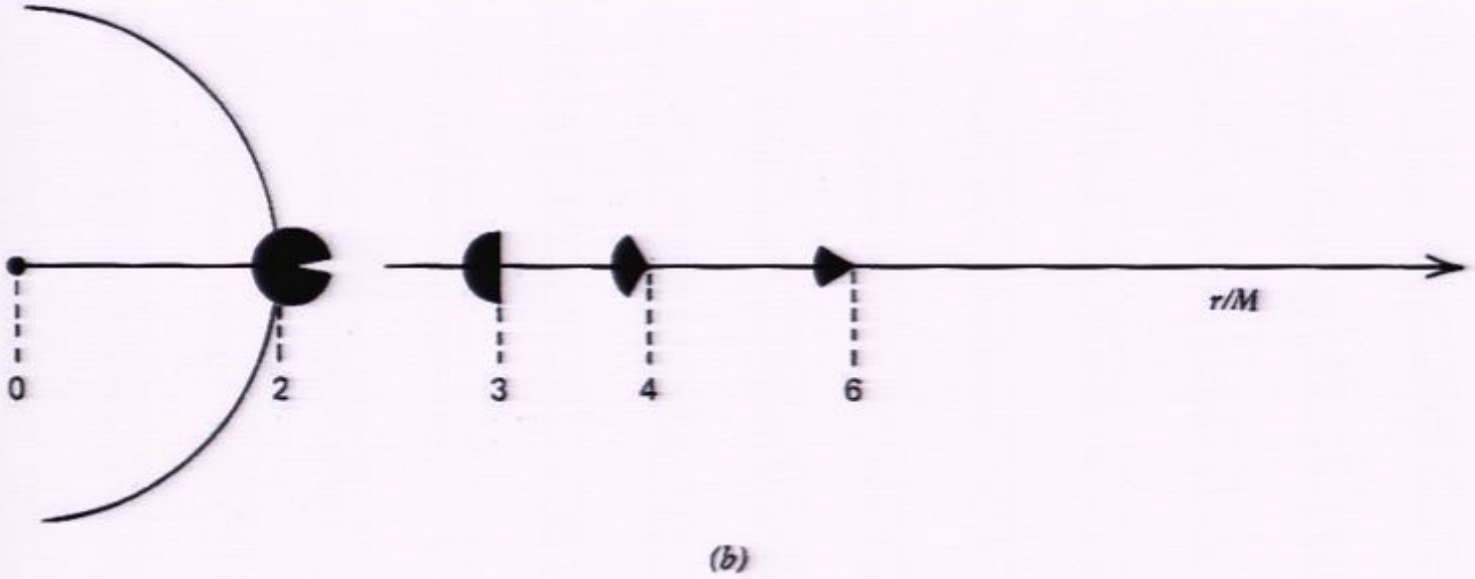


Figure 12.6 (*a*) The angle ψ between the propagation direction of a photon and the radial direction at a given point *P*. (*b*) Gravitational capture of radiation by a Schwarzschild black hole. Rays emitted from each point into the interior of the *shaded* conical cavity are captured. The indicated capture cavities are those measured in the orthonormal frame of a local static observer.

- If $R < 3GM/c^2 = (3/2)R_S$, then some rays from the surface are bent back and return to the surface

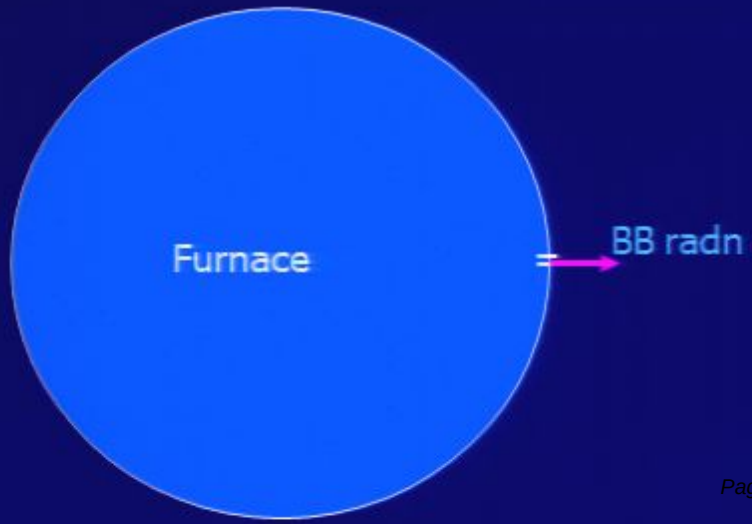
- For large redshift, there is only a tiny hole for radiation to escape
- Even though surface "looks" convex in Schwarzschild coordinates, it is actually highly concave!
- In fact, it is the **perfect textbook example of a blackbody: a furnace with a pinhole!**
- Therefore, the larger the redshift, the closer the emission will be to blackbody

$$\sin\theta_c = \frac{3^{3/2}}{2}\left(1-\frac{R_s}{R}\right)^{1/2}\frac{R_s}{R}$$

Escaping rays have

$$\theta < \theta_c \approx \frac{3^{3/2}}{2}\left(\frac{\Delta R}{R_s}\right)^{1/2}$$

$$\Omega_{esc} \approx \frac{27\pi/8}{(1+z)^2}$$



Particle Emission?

- Surface emission is thermal – expect a nearly perfect blackbody spectrum
- Only photons and particles with $mc^2 < kT_\infty$ (neutrinos) will reach infinity
- Allowing for three types of neutrinos, the observed photon luminosity is reduced by 16/29 (Broderick & Narayan 2007)
- Cosmology puts strong limits on contribution from other particles, so no escape on this front

Other Loopholes?

- Perhaps Sgr A* is a **wormhole**? (Damour & Solodukhin 2007)
- Or a **naked singularity** with perfectly absorbing boundary conditions? (Bambi & Freese 2009)
- Or…

One Key Assumption

- The argument for an Event Horizon in Sgr A* makes one key assumption
  - It assumes that the observed radio/sub-mm radiation is produced by accretion
- One way out of an Event Horizon is to say that Sgr A* is powered by something other than accretion

Summary

- A variety of astrophysical arguments for the existence of **BH Event Horizons**
  - **No Type I X-ray bursts in BH XRBs**
  - **Quiescent BH XRBs are unusually faint**
  - **No surface emission seen in Sgr A***
- Each argument by itself is pretty strong
- Combined, the evidence is **Very Strong**, even perhaps **Compelling** …
- Virtually impossible to get around…