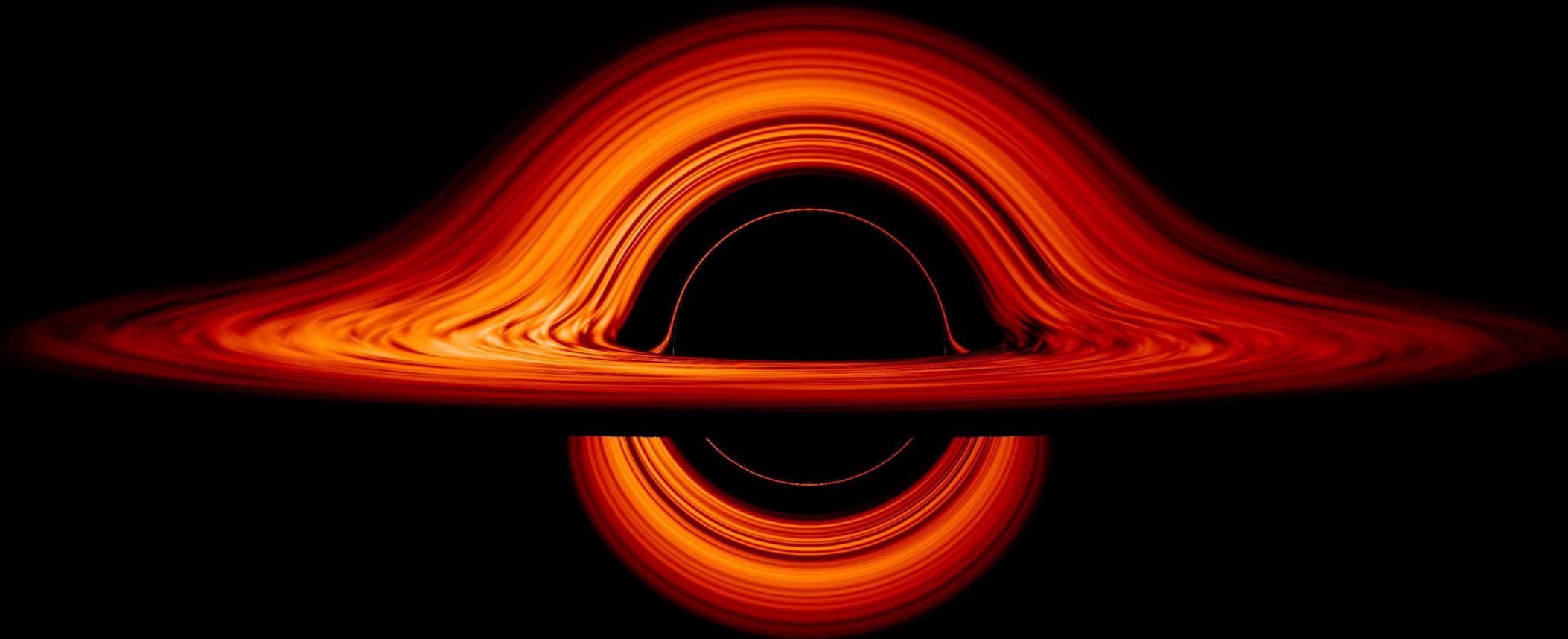


# SPIN SIGNATURES ON THE SOLUTION AND EMISSION SPECTRA OF ACCRETION FLOWS AROUND BLACK HOLES



## Collaborators :

- Indranil Chattopadhyay (ARIES, Nainital)
- Dipanjan Mukherjee (IUCAA, Pune)

<https://www.nasa.gov>

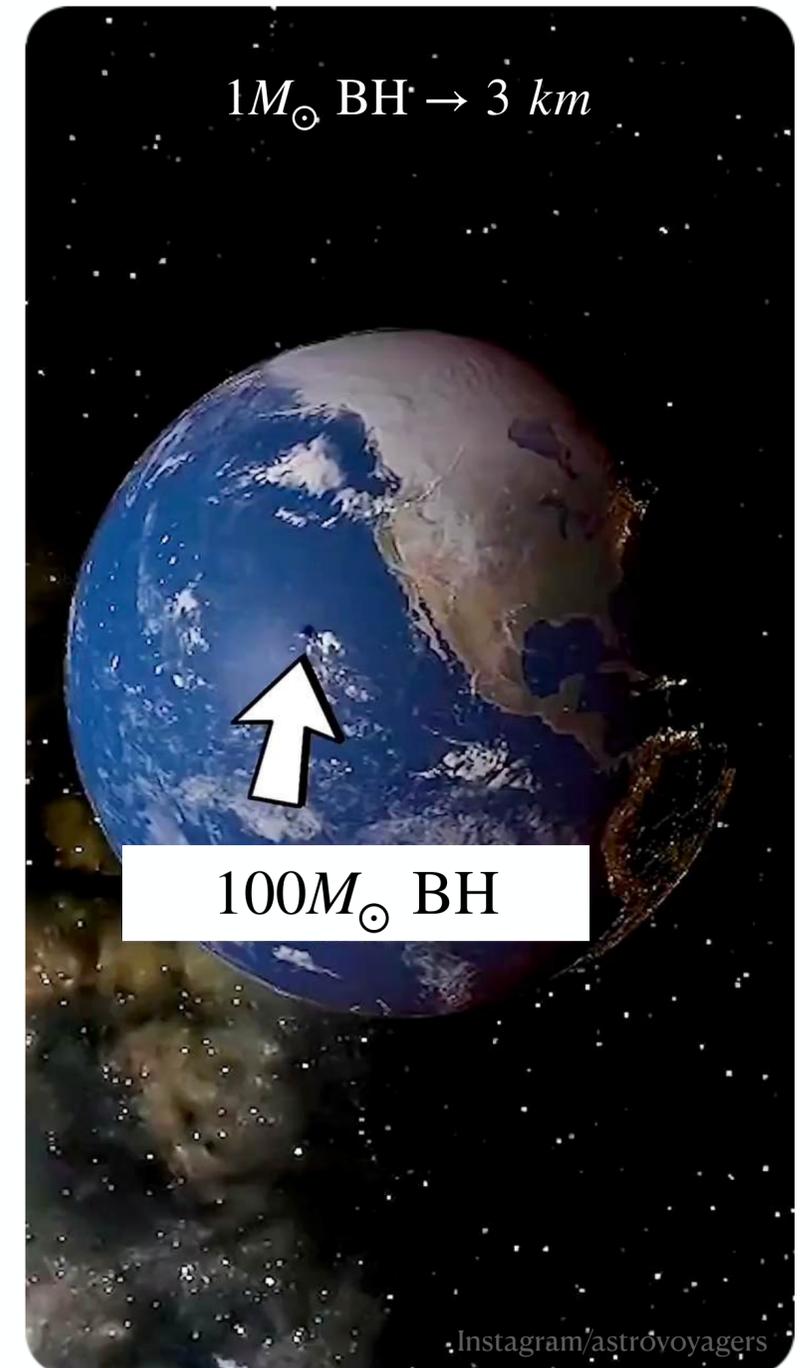
## SHILPA SARKAR



Harish-Chandra Research Institute, India

# Black Holes

- ▶ Class of astrophysical objects with extreme small size : **Compact Objects**
- ▶ Extreme small size : Compactness ratio =  $\frac{M_*}{R_*}$



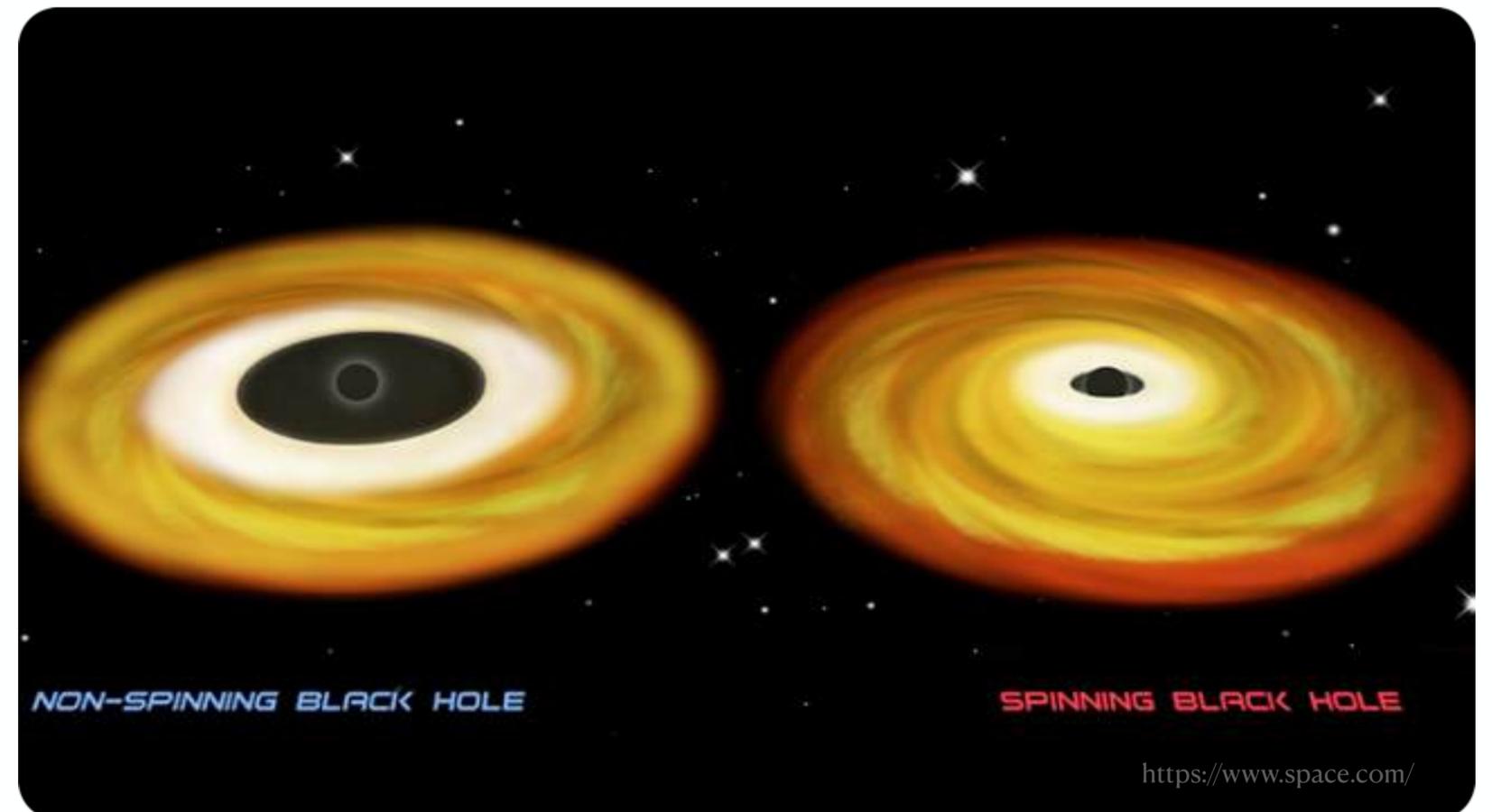
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- ▶ In case of spinning BHs, event horizon is dragged to a region  $< r_s = 2GM/c^2$

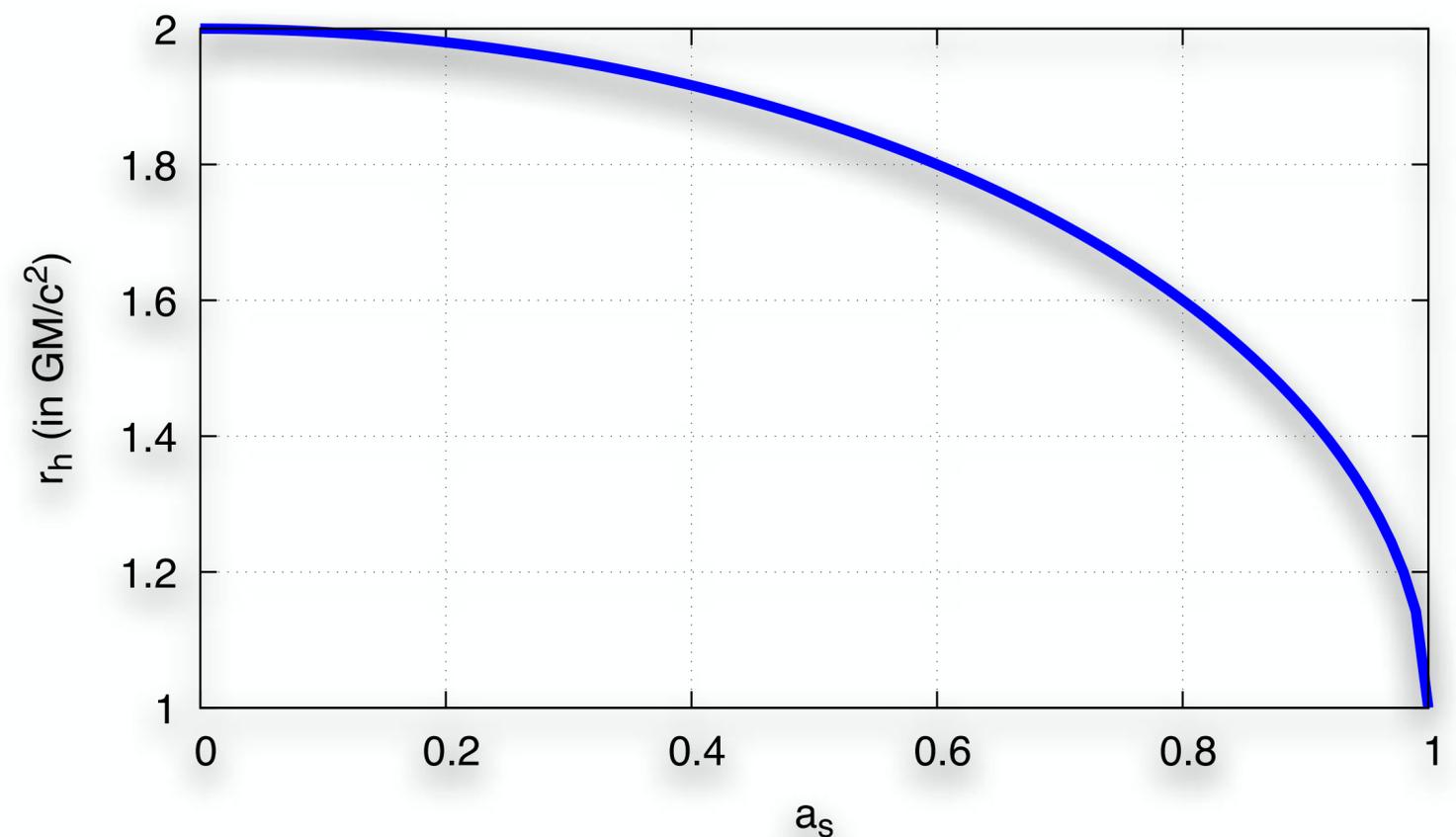


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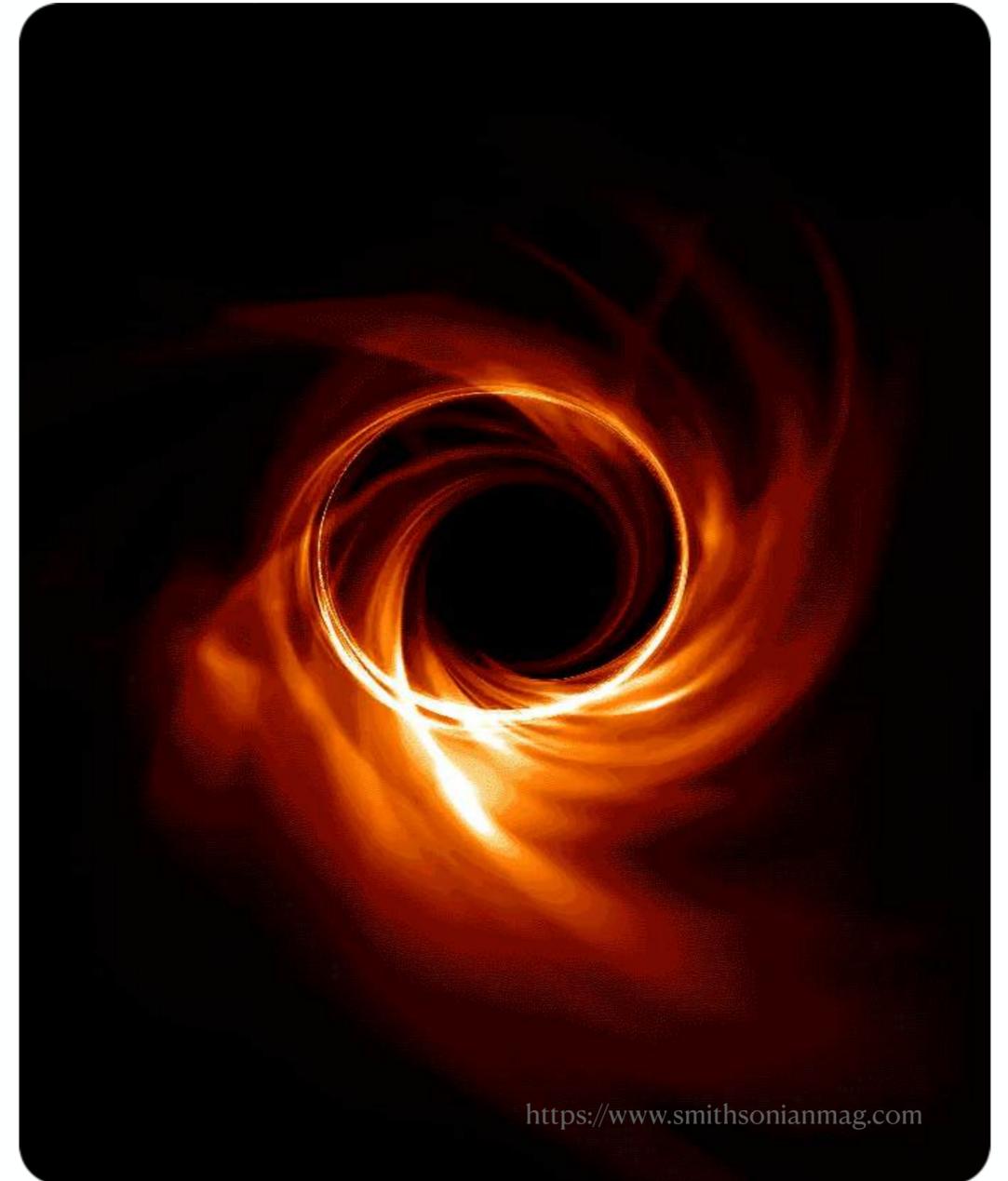
▶ For a BH with spin  $a_s$ , the horizon is at

$$r_h = \left[ 1 + \sqrt{1 - a_s^2} \right] GM/c^2$$


The effect of spin ( $a_s$ ) on the location of BH horizon ( $r_h$ )

# Motivation

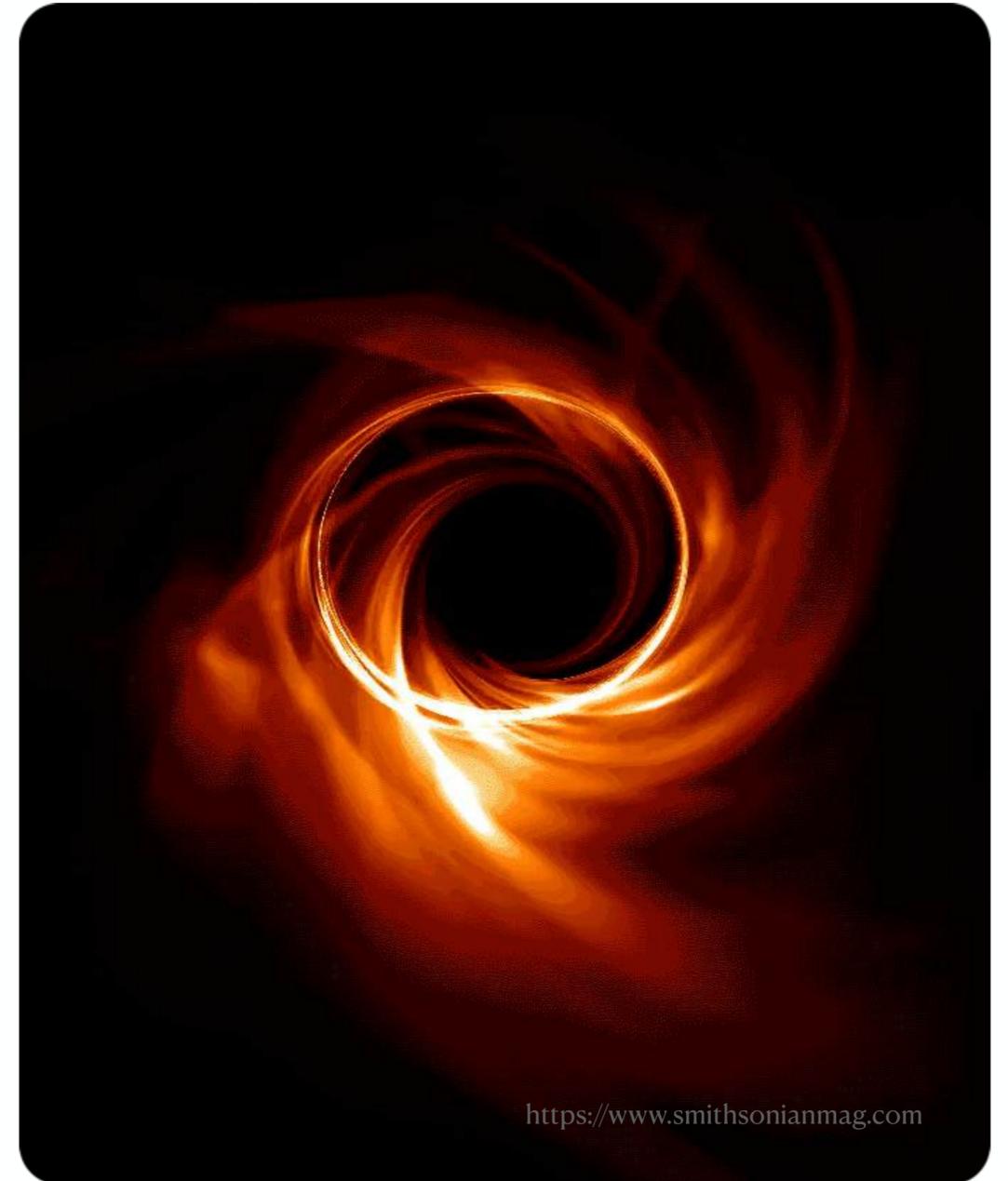
- \* Accretion flows carry imprints of the nature of the central object.
- \* The structure of accretion flows close to the horizon is of considerable astrophysical interest
  - ◉ Most of the gravitational binding energy is released close to the BH
  - ◉ Strong-field gravitational effects close to the horizon that are unique to BHs
  - ◉ Temperatures are highest close to the horizon, so exotic physical processes may occur there.



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  - ◉ Strong-field gravitational effects close to the horizon that are unique to BHs
  - ◉ Temperatures are highest close to the horizon, so exotic physical processes may occur there.

*Our goal is to describe accurately the fluid flow in the highly relativistic regime close to the horizon and study the effect and imprint of BH spin, if any, on the spectrum.*



Motivation .....▶ Literature

# Motivation ..... Literature

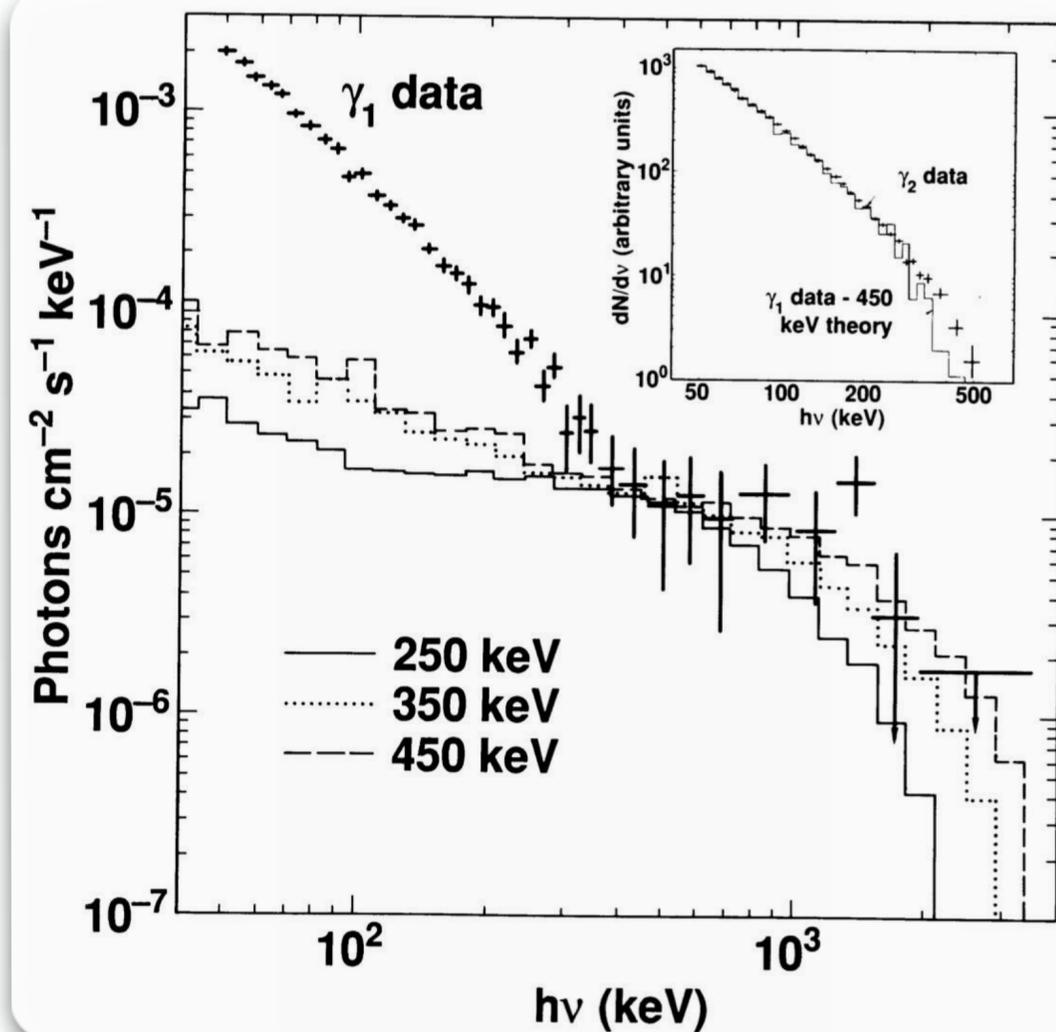
# Cygnus-X1

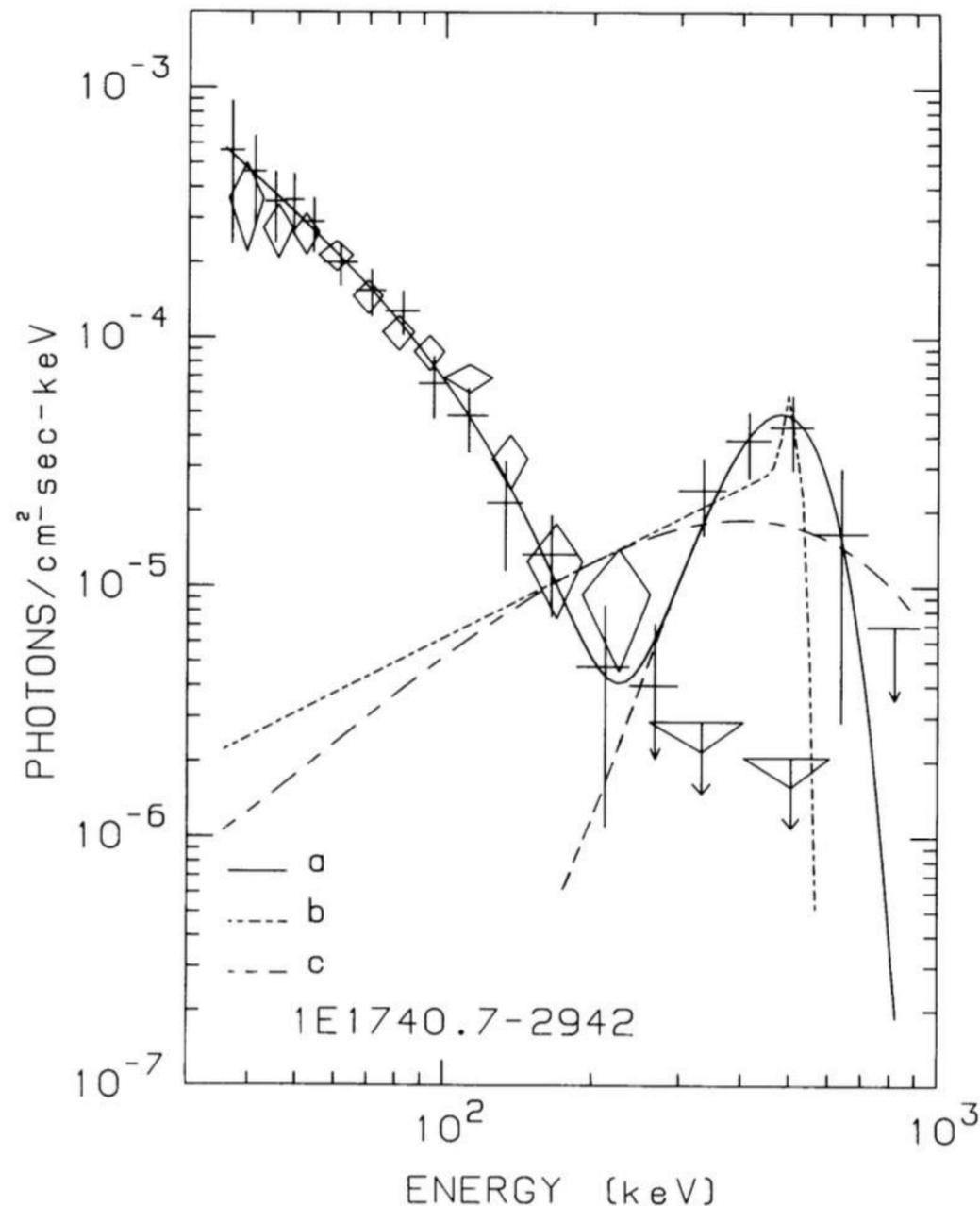
THE ASTROPHYSICAL JOURNAL, 325:L39-L42, 1988 February 15  
© 1988. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## INTERPRETATION OF THE GAMMA-RAY BUMP FROM CYGNUS X-1

EDISON P. LIANG AND CHARLES D. DERMER  
Physics Department, Lawrence Livermore National Laboratory  
Received 1987 September 21; accepted 1987 November 24

- The most dramatic feature is an unusually strong gamma-ray “bump” between 400 keV and ~ 2 MeV
- Gamma rays are produced in the inner region of the accretion flow at the expense of the normal power-law hard X-rays producing **pairs** which **annihilate** to give this feature
- $M_* \sim 21M_{\odot}$ ,  $a_s > 0.9985$  ([Zhao et.al 2021](#))
- $D \sim 2.2 \text{ kpc}$





THE ASTROPHYSICAL JOURNAL, 383:L45-L48, 1991 December 20  
 © 1991. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## SIGMA DISCOVERY OF VARIABLE $e^+e^-$ ANNIHILATION RADIATION FROM THE NEAR GALACTIC CENTER VARIABLE COMPACT SOURCE 1E 1740.7-2942

L. BOUCHET, P. MANDROU, J. P. ROQUES, AND G. VEDRENNE  
 Centre d'Etude Spatiale des Rayonnements, 9, Avenue du Colonel Roche, BP4346, 31029 Toulouse Cedex, France

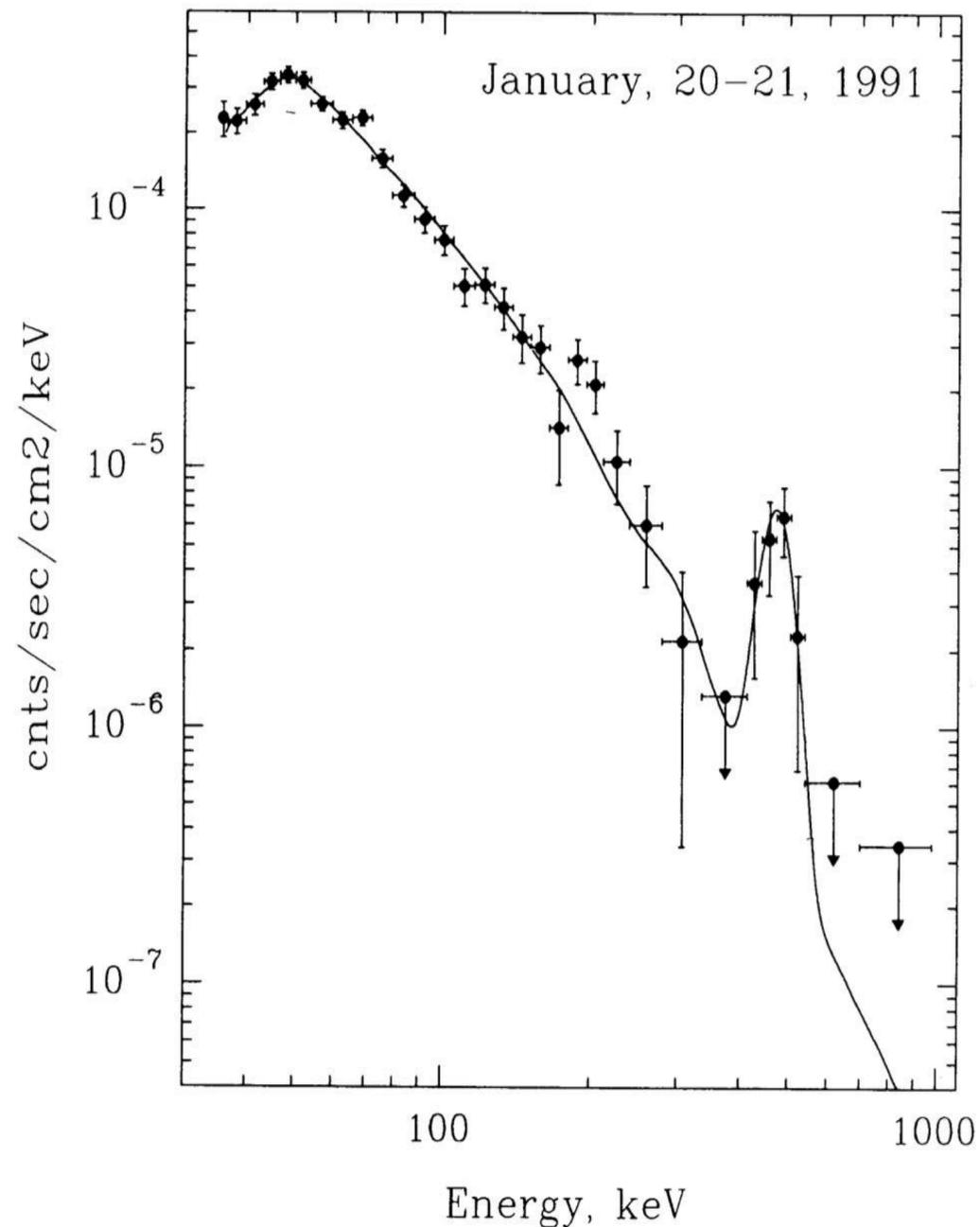
B. CORDIER, A. GOLDWURM, F. LEBRUN, AND J. PAUL  
 Service d'Astrophysique du CEA, CEN de Saclay, 91191 Gif sur Yvette, Cedex, France

AND

R. SUNYAEV, E. CHURAZOV, M. GILFANOV, M. PAVLINSKY, S. GREBENEV, G. BABALYAN,  
 I. DEKHANDOV, AND N. KHAVENSON

Institute of Cosmic Research, Profsovnaya, 84/32, Moscow, 117296, USSR  
 Received 1991 July 24; accepted 1991 September 30

- Emitter of 511 keV  $e^-e^+$  annihilation line : *"The Great Annihilator"*
- Spectacular feature centered on 500 keV region was discovered in the emission spectrum, suggesting that this object can produce hot plasma of pairs in a short time.
- $M_* \sim 5M_\odot$ ,  $a_s \sim 0.998 \pm 0.01$  (*Stecchini et.al 2020*)
- Situated near the GC



THE ASTROPHYSICAL JOURNAL, 389:L75-L78, 1992 April 20  
 © 1992. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## X-RAY NOVA IN MUSCA (GRS 1124-68): HARD X-RAY SOURCE WITH NARROW ANNIHILATION LINE

R. SUNYAEV, E. CHURAZOV, M. GILFANOV, A. DYACHKOV, N. KHAVENSON, S. GREBENEV,  
 R. KREMNEV, AND K. SUKHANOV

Space Research Institute, Russian Academy of Sciences, Profsovnaya 84/32, 117810 Moscow, Russia

A. GOLDWURM, J. BALLET, B. CORDIER, AND J. PAUL

Service d'Astrophysique, Centre d'Etude Nucleaire de Saclay, 91191 Gif-sur-Yvette Cedex, France

AND

M. DENIS, G. VEDRENNE, M. NIEL, AND E. JOURDAIN

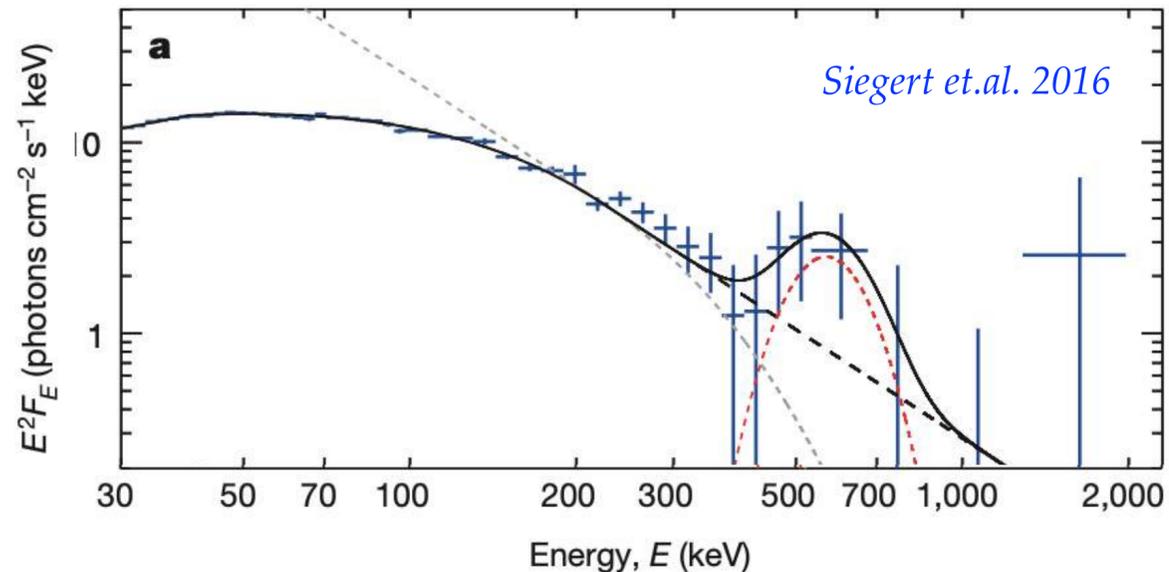
Centre d'Etude Spatiale des Rayonnements, 9, avenue du Colonel Roche, BP 4346, 31029 Toulouse Cedex, France

Received 1991 November 20; accepted 1992 February 6

- Discovery of an relatively narrow emission feature around 500 keV in the source spectrum
- Production of pairs in the hot plasma of the innermost region of a BH accretion disk
- $M_* \sim 5.6M_{\odot}$ ,  $a_s \sim 0.63 \pm 0.1$  (*Fishbach and Kalogera, 2022*)
- Distance  $\sim 5$  kpc

Motivation ..... Literature

V404 Cygni



LETTER

doi:10.1038/nature16978

## Positron annihilation signatures associated with the outburst of the microquasar V404 Cygni

Thomas Siegert<sup>1</sup>, Roland Diehl<sup>1</sup>, Jochen Greiner<sup>1</sup>, Martin G. H. Krause<sup>1,2</sup>, Andrei M. Beloborodov<sup>3</sup>, Marion Cadolle Bel<sup>4</sup>, Fabrizia Guglielmetti<sup>1</sup>, Jerome Rodriguez<sup>5</sup>, Andrew W. Strong<sup>1</sup> & Xiaoling Zhang<sup>1</sup>

- The emission spectrum around 511 keV shows clear signatures of positron annihilation, which implies a high rate of positron production.
- Microquasars may be the main sources of the electron–positron plasma responsible for bright diffuse emission of annihilation  $\gamma$ -rays.
- $M_* \sim 9M_\odot$ ,  $a_s \sim 0.92$  (Walton 2017)
- $D \sim 2.39 \text{ kpc}$

# Conclusions from literature

- ▶ All the candidates have stellar mass BHs at the center
- ▶ High spinning BH at the center
- ▶ **Distinct narrow annihilation lines centered around  $\sim 511\text{keV}$**

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- ▶ All the candidates have stellar mass BHs at the center
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Need to model these accretion flows to get an insight into the physical processes going on in these systems

## Conclusions from literature

- ▶ All the candidates have stellar mass BHs at the center
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- ▶ **Distinct narrow annihilation lines centered around  $\sim 511\text{keV}$**

Need to model these accretion flows to get an insight into the physical processes going on in these systems

## Our motivation

- ▶ Obtain self-consistent global solutions : *Missing in previous modelling*
- ▶ Taking particular care of the radiation processes present in the system: *Earlier studies considered selective photon production mechanisms which made pair production mechanism and its annihilation a debatable phenomena in accretion flows.*
- ▶ Obtaining spectrum and check if there are any distinct spectral signature of the central object

# Modelling

# Basic Equations

- ▶ Continuity equation
- ▶ Momentum conservation
- ▶ Energy conservation equation

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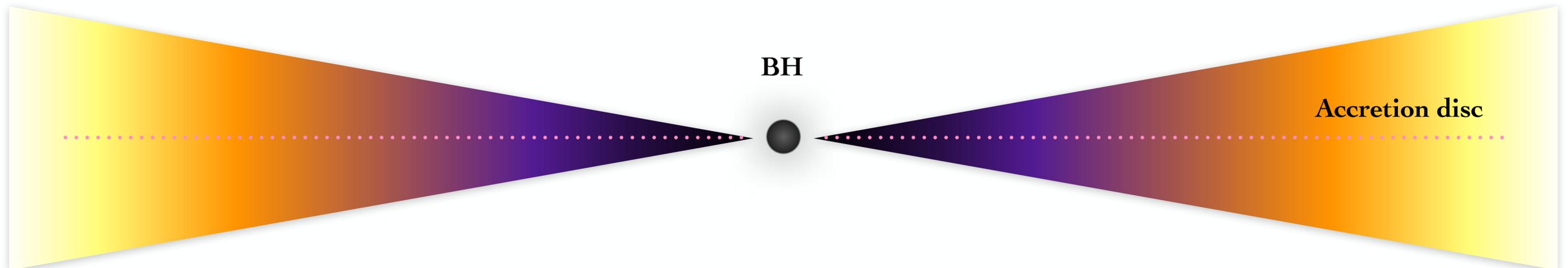
**Equation Of State**

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**Equation Of State**

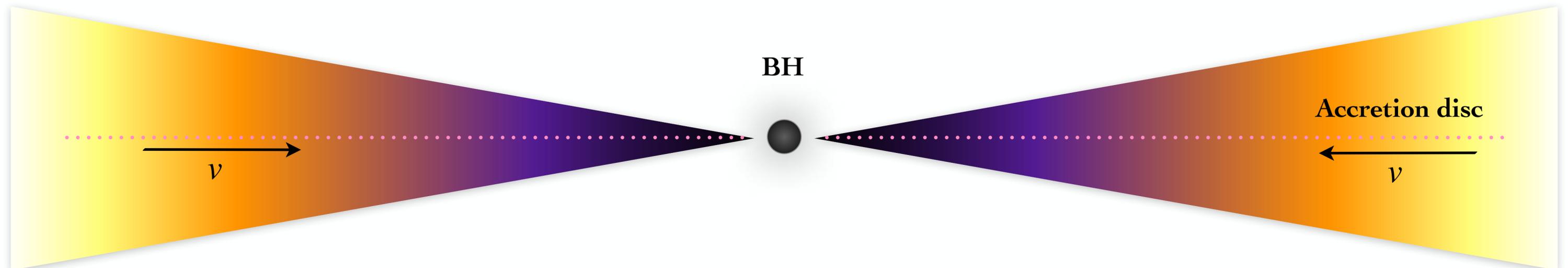


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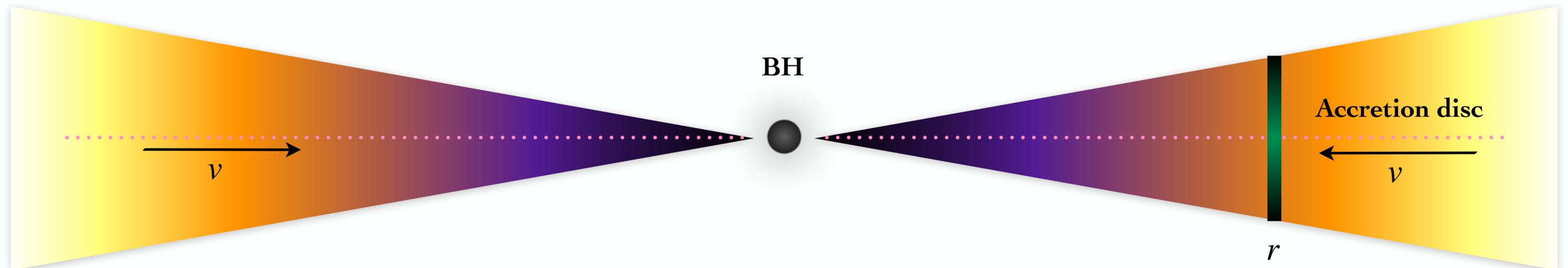


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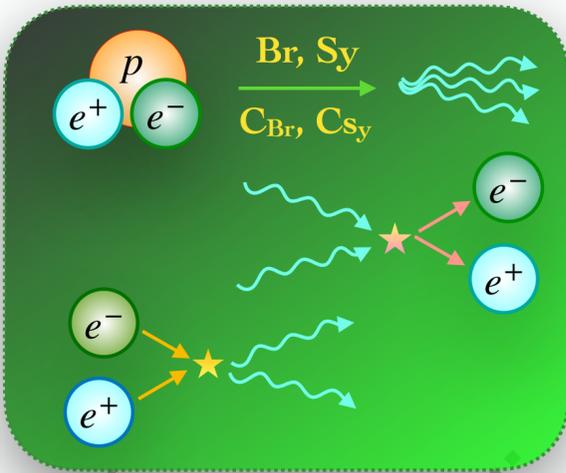


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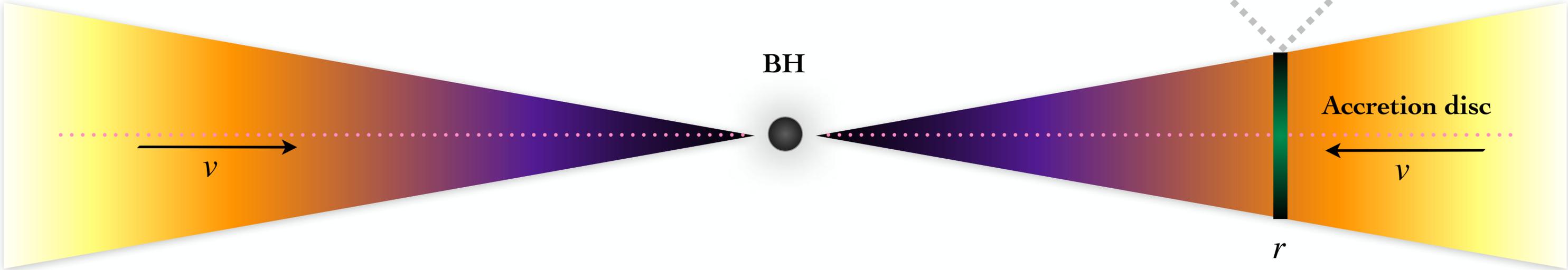
## Equation Of State



Photon production

Pair production

Annihilation

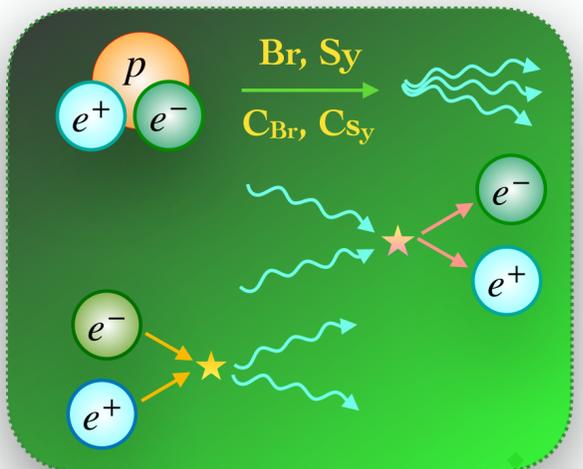


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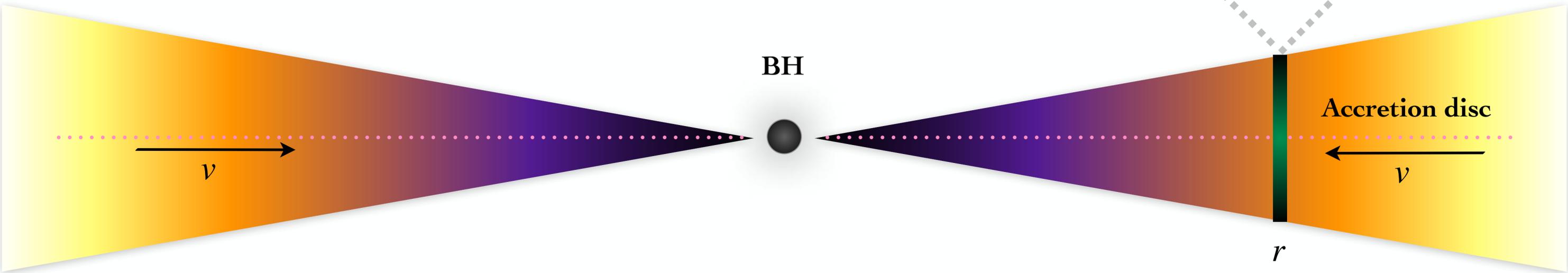
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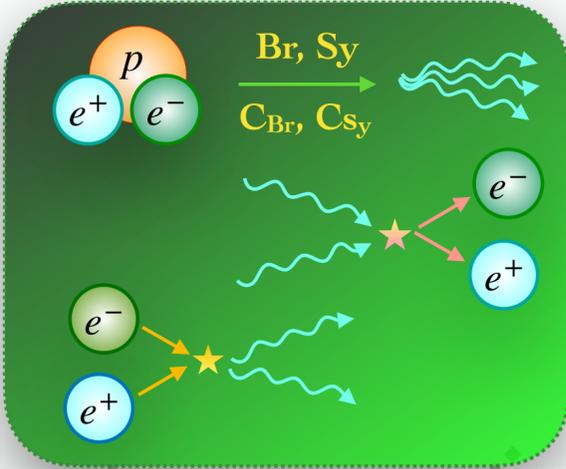
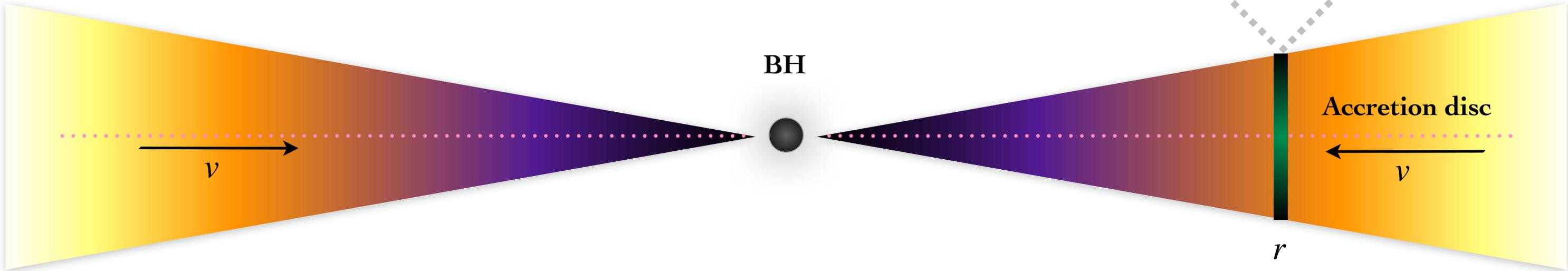


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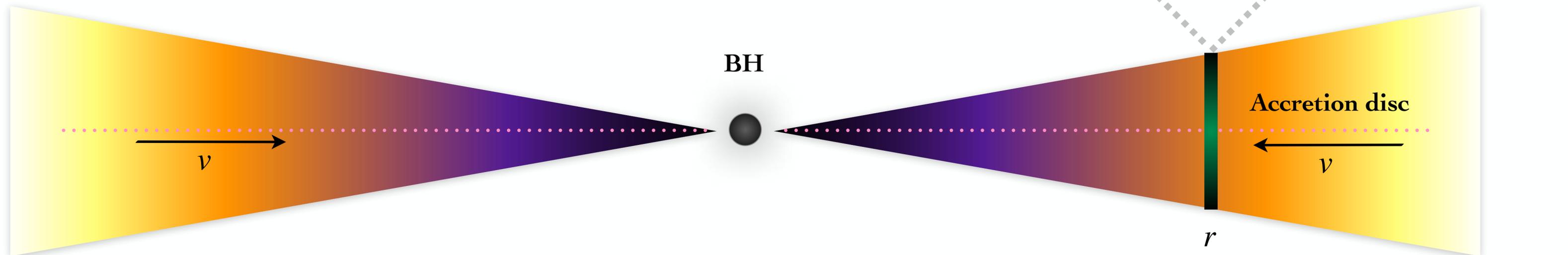
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**Equation Of State**



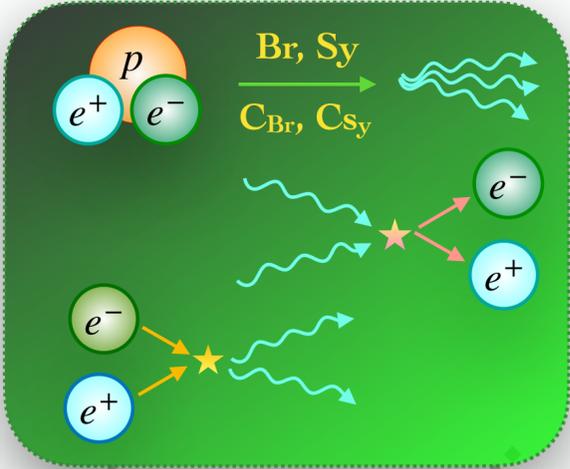
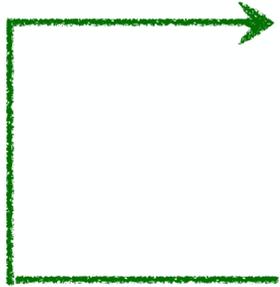
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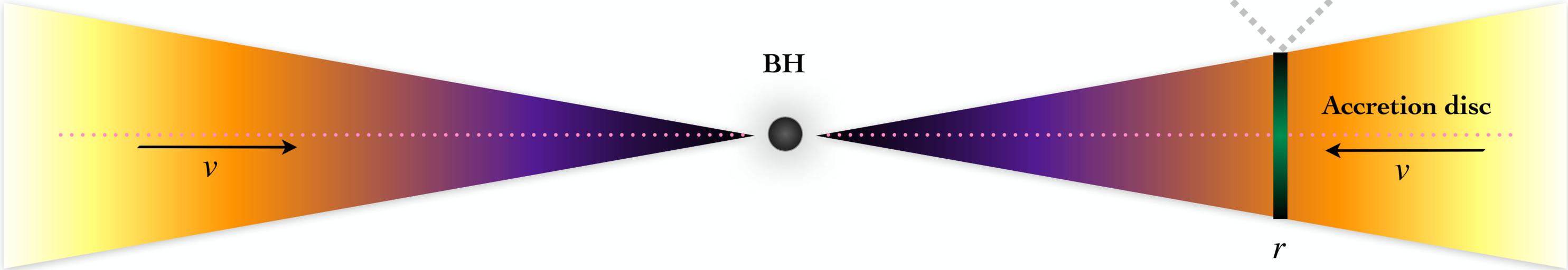
Highly non-linear: Pairs produce photons & photons produce more pairs



Photon production

Pair production

Annihilation



# METHODOLOGY

# METHODOLOGY

- \* Finding a transonic solution without pairs :

# METHODOLOGY

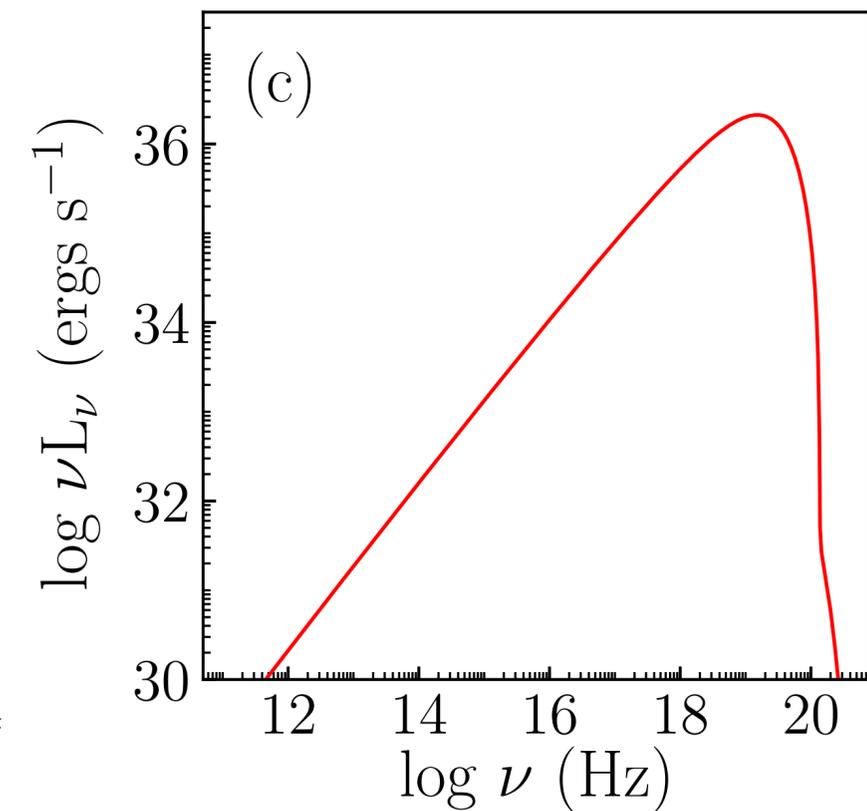
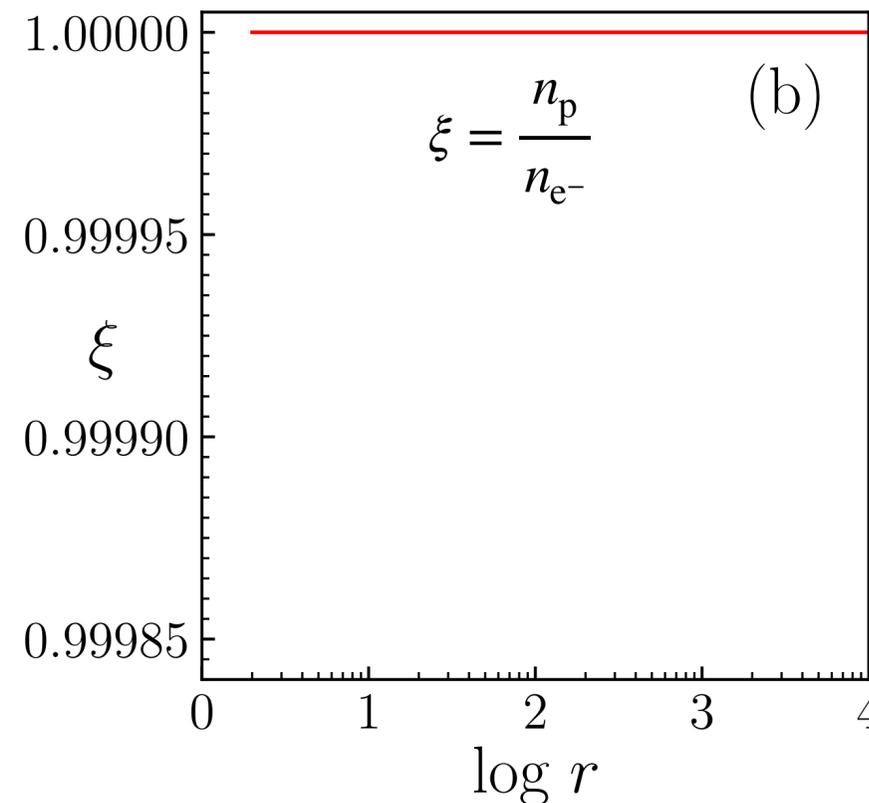
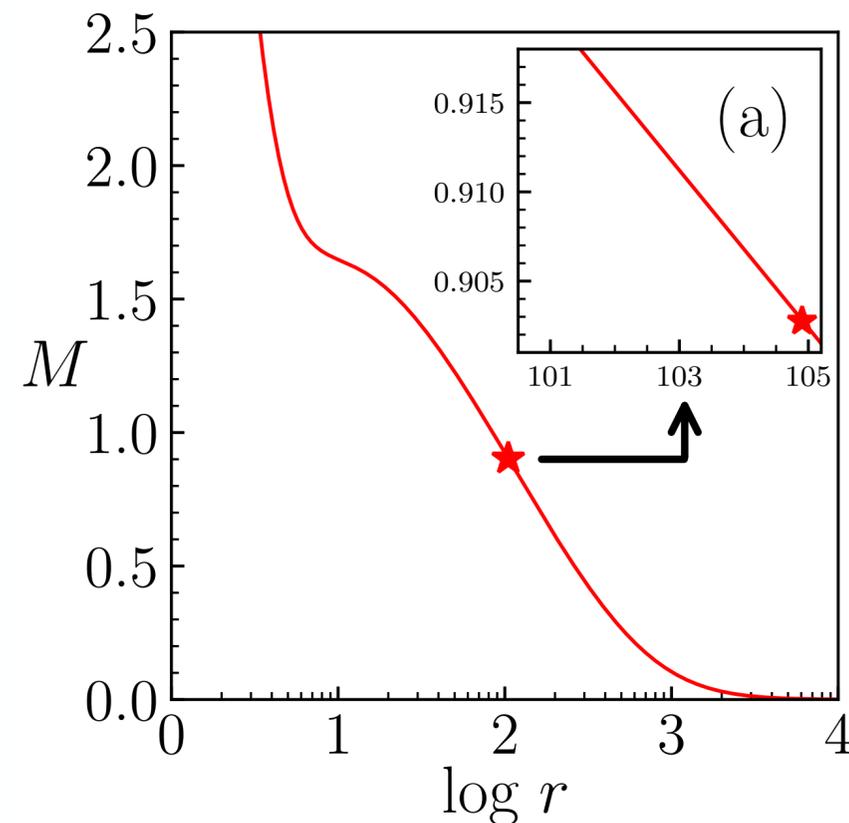
\* Finding a transonic solution without pairs :

▶ Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons

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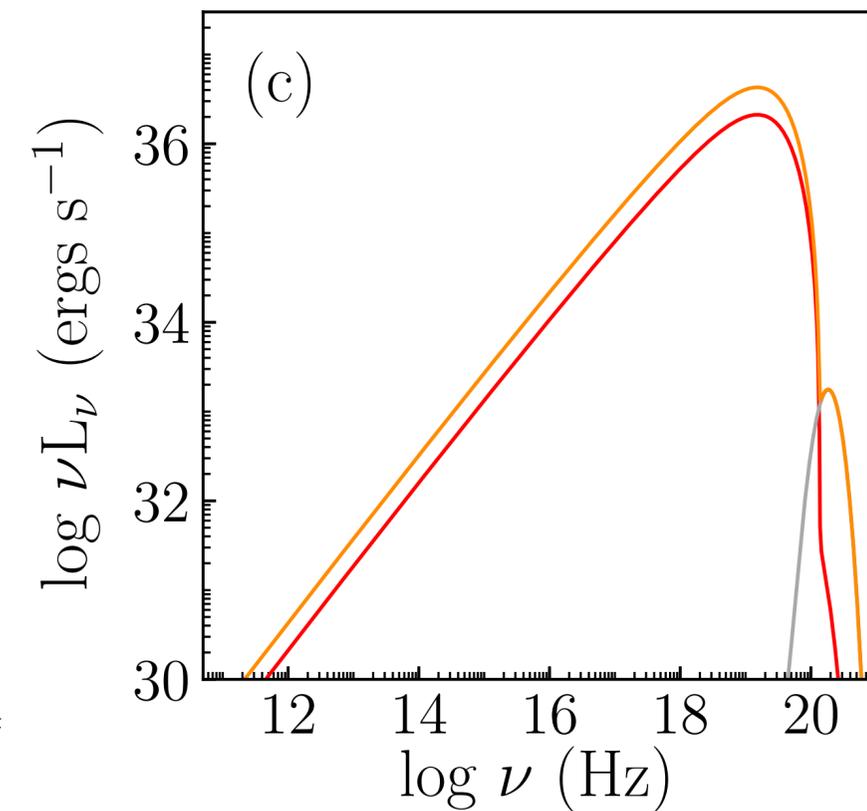
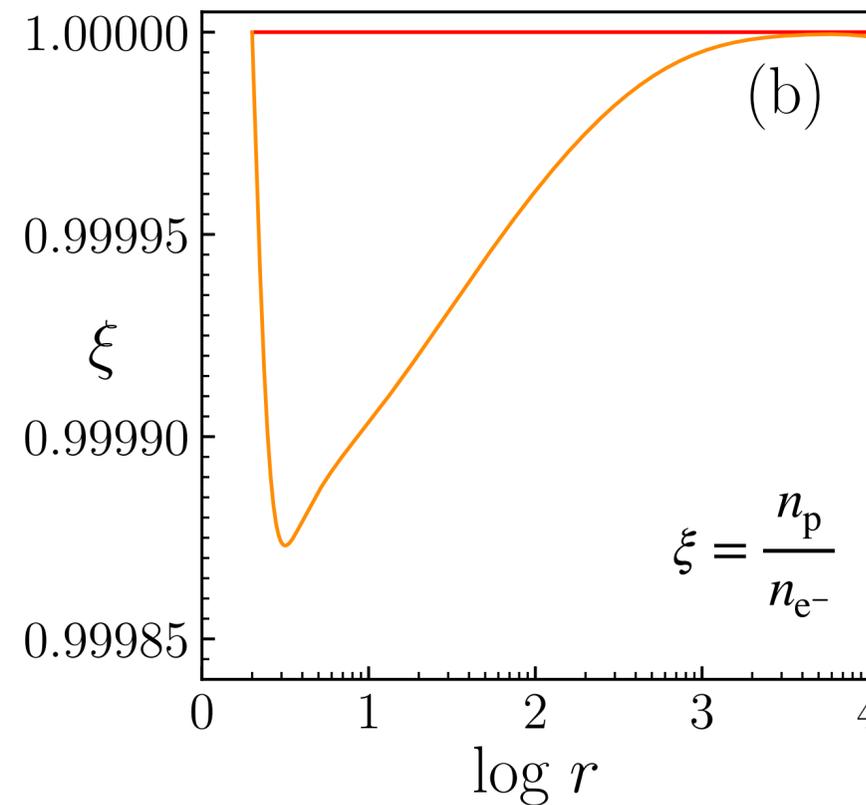
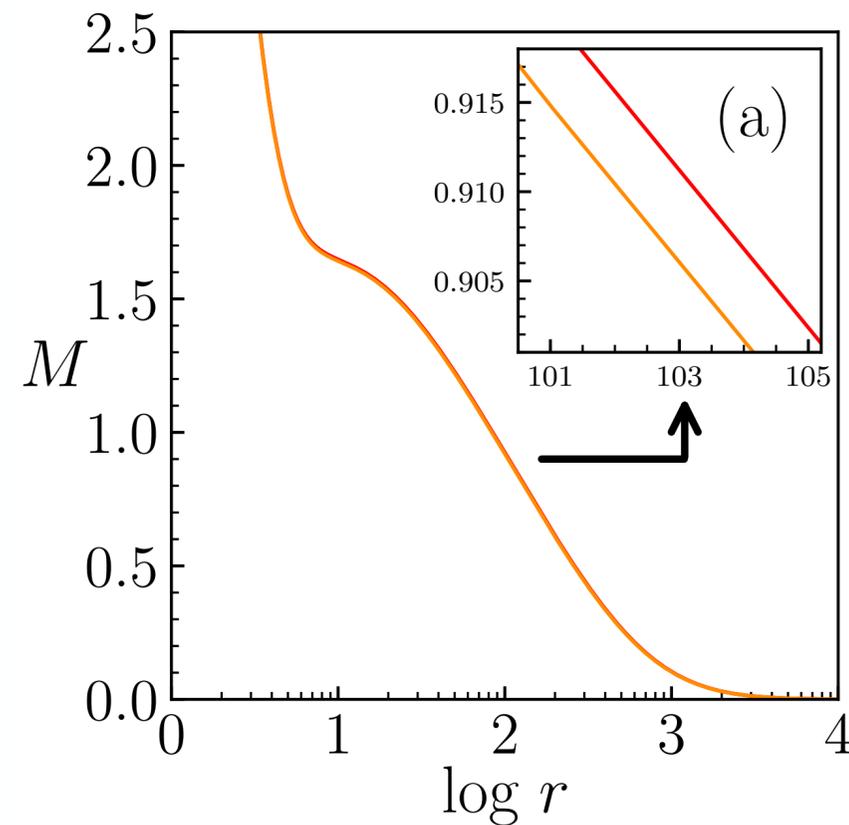


Iteration : 1

# METHODOLOGY

## \* Finding a transonic solution with pairs :

► Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons + Annihilation photons

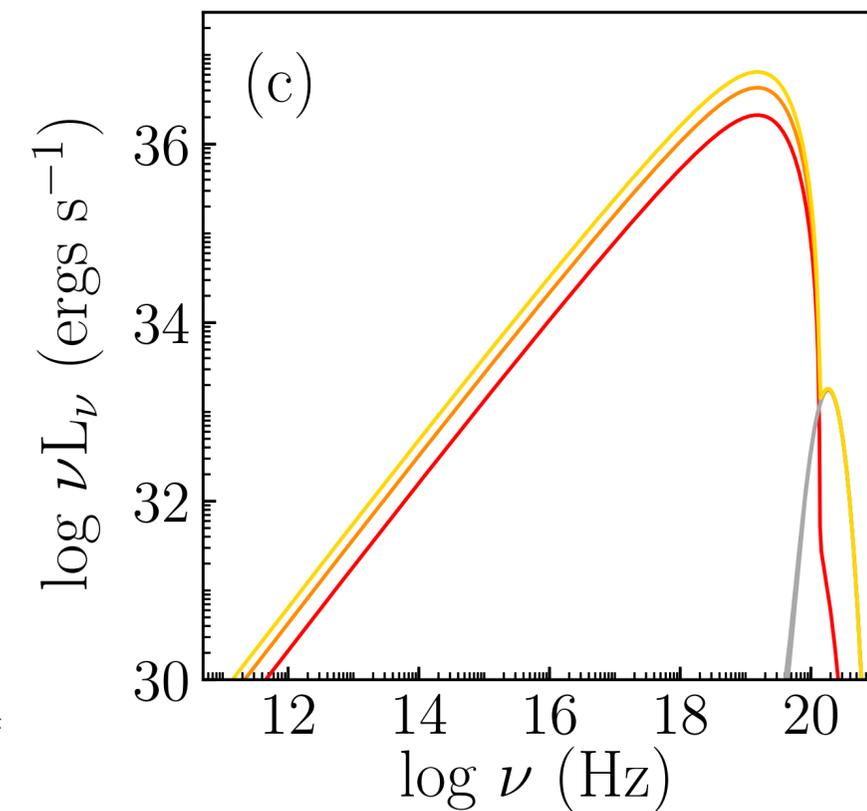
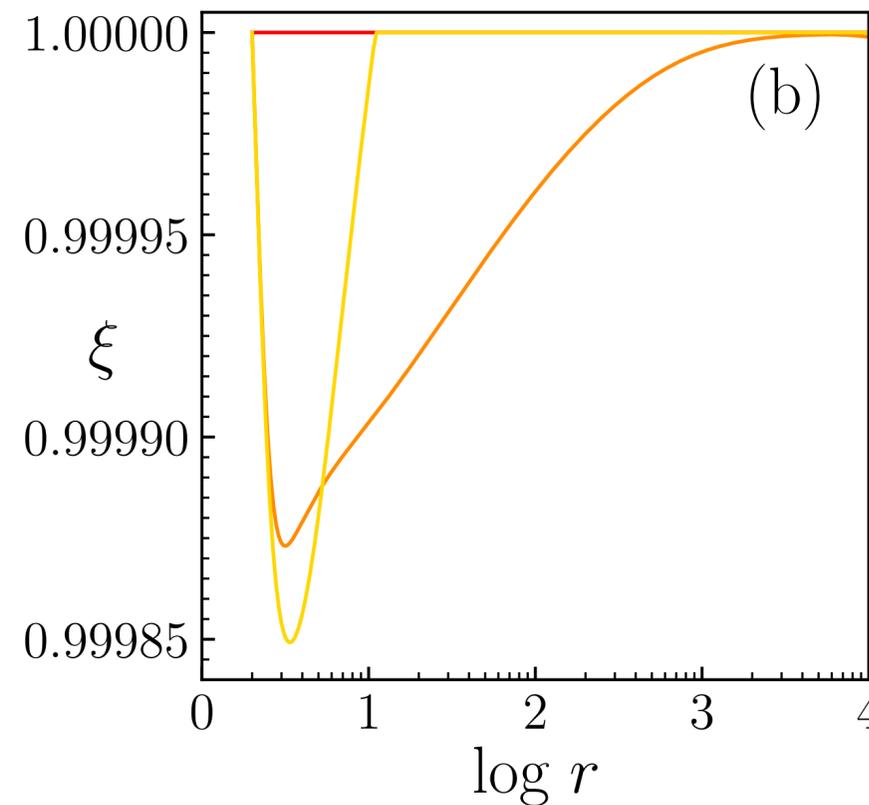
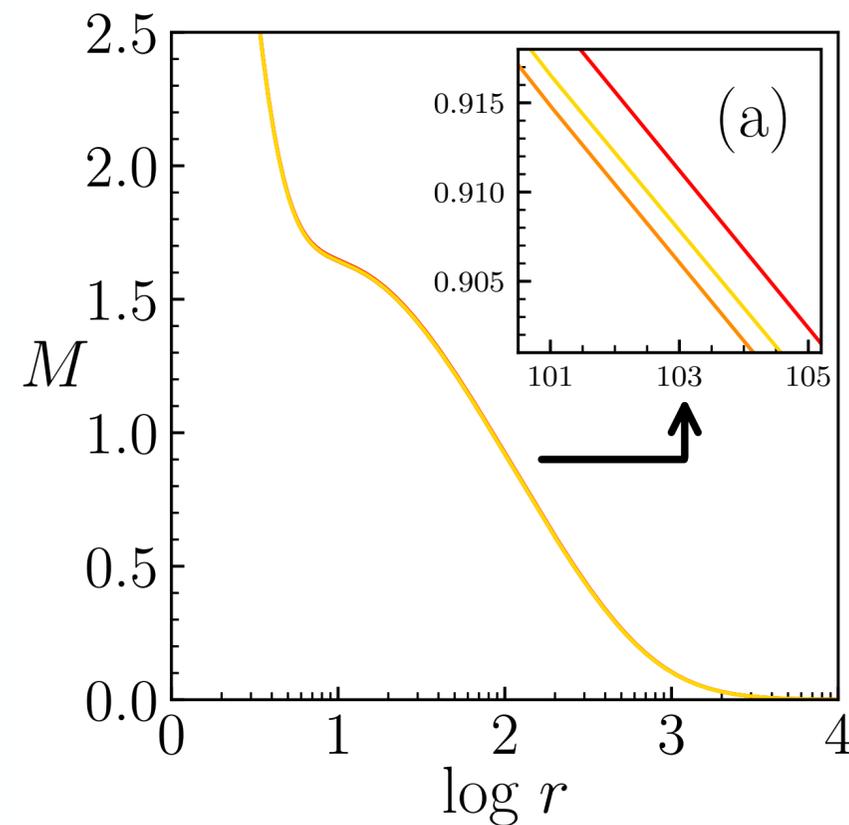


Iteration : 2

# METHODOLOGY

## \* Finding a transonic solution with pairs :

► Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons + Annihilation photons

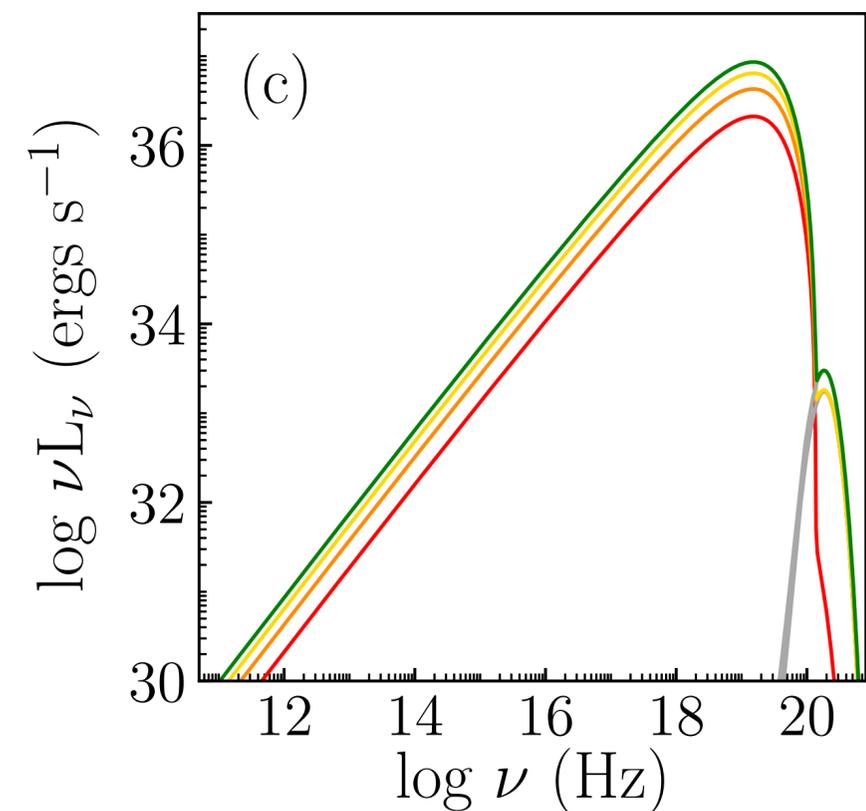
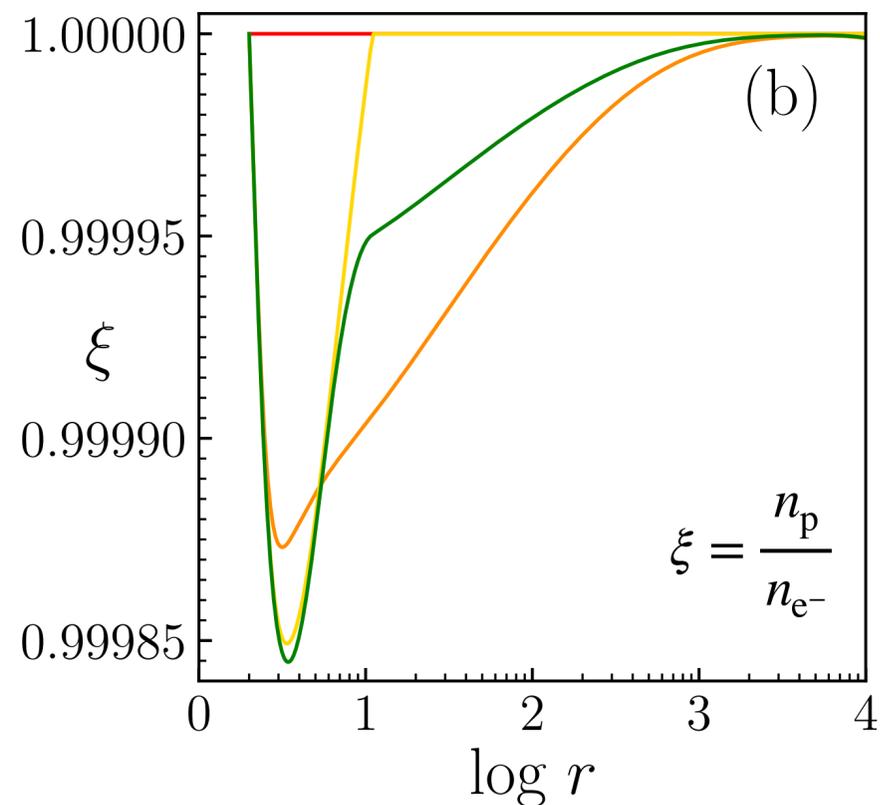
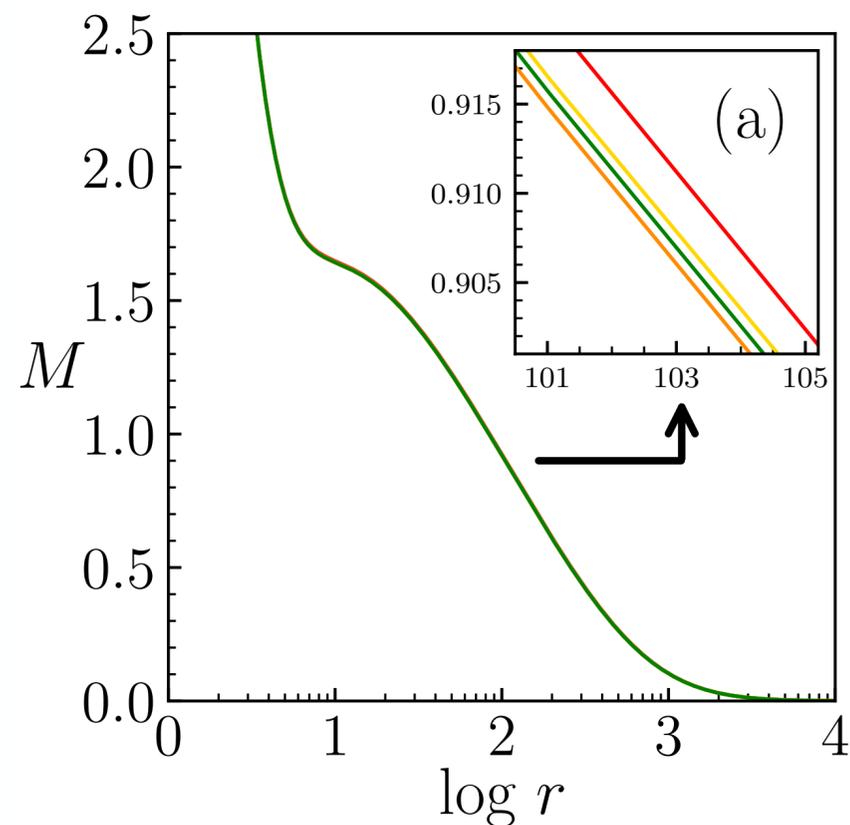


Iteration : 3

# METHODOLOGY

## \* Finding a transonic solution with pairs :

► Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons + Annihilation photons

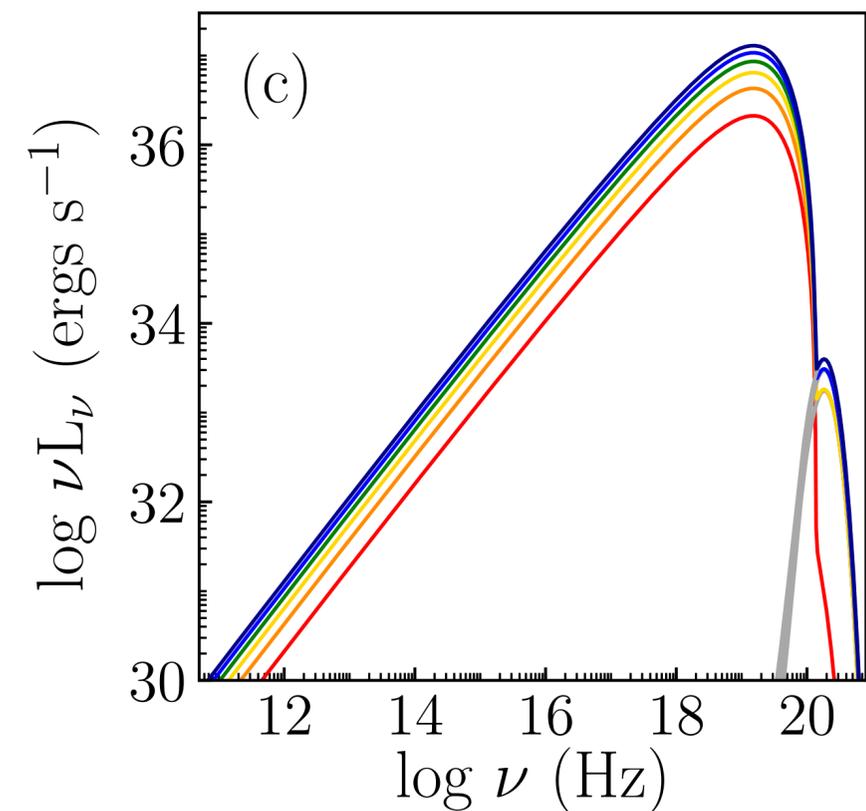
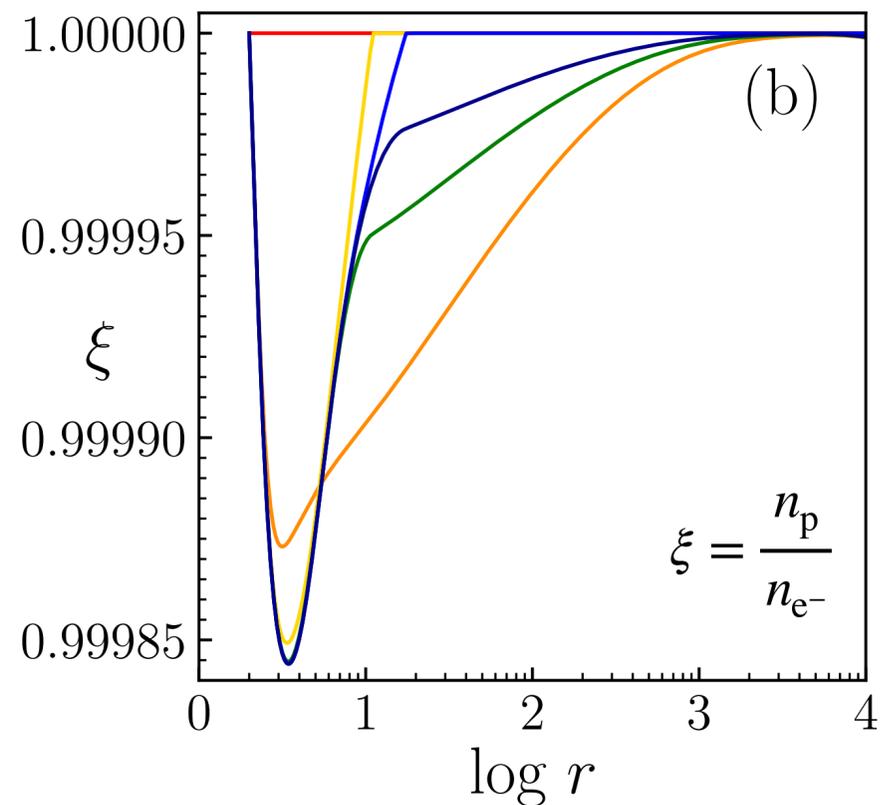
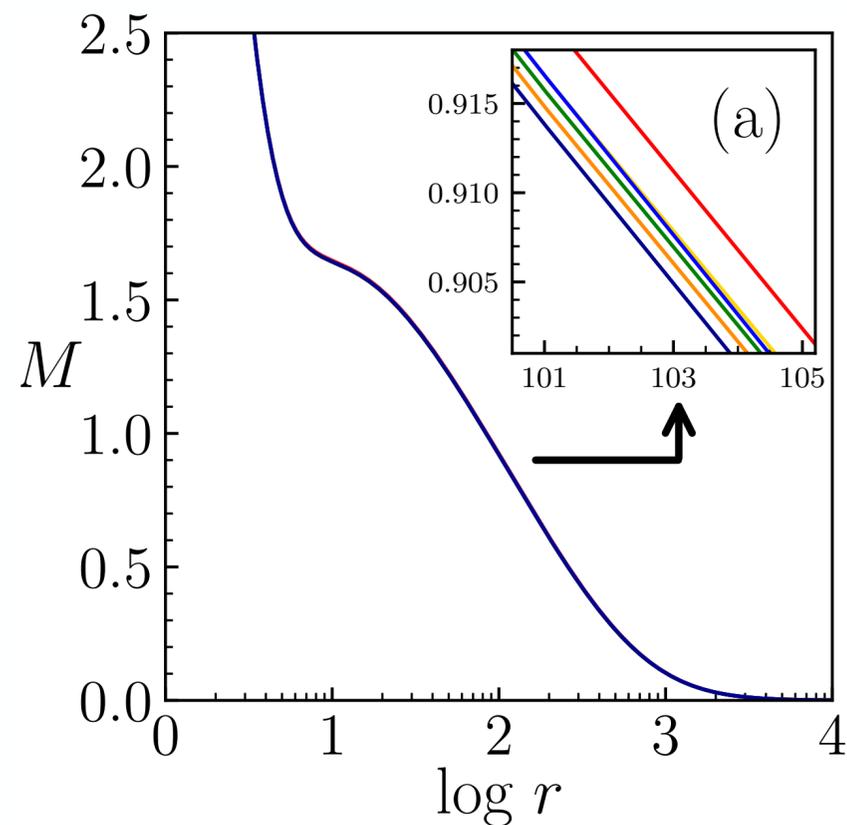


Iteration : 4

# METHODOLOGY

## \* Finding a transonic solution with pairs :

► Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons + Annihilation photons

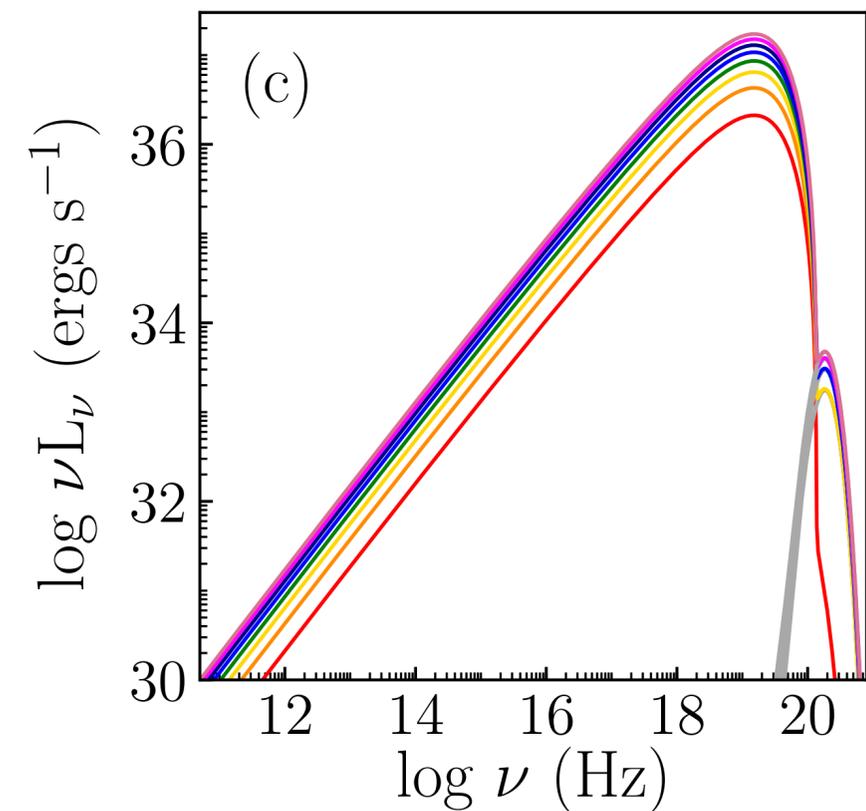
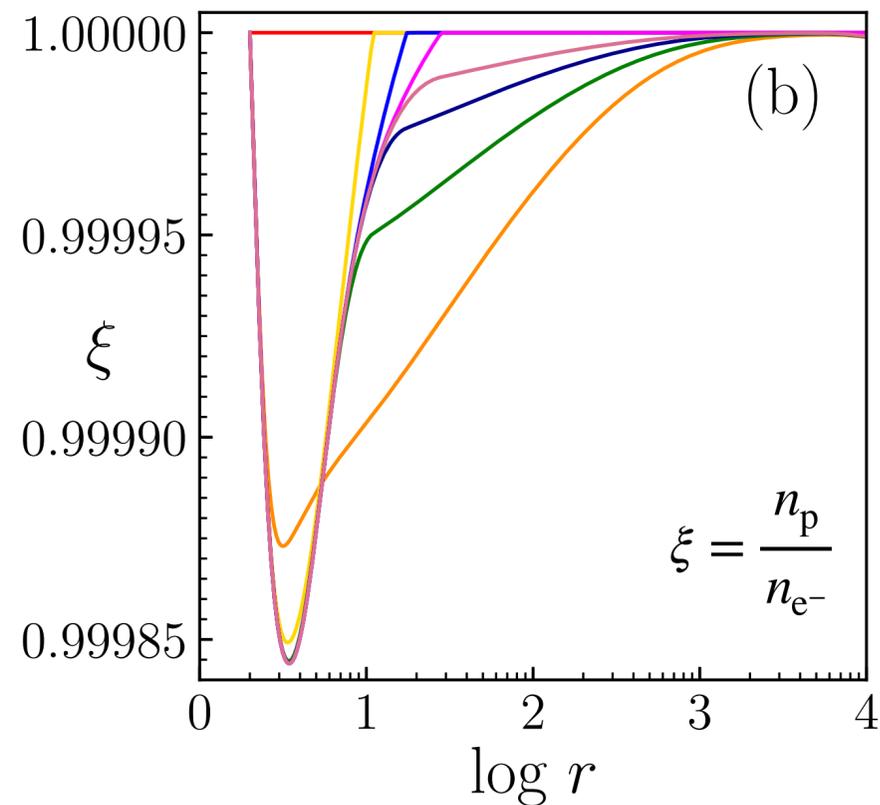
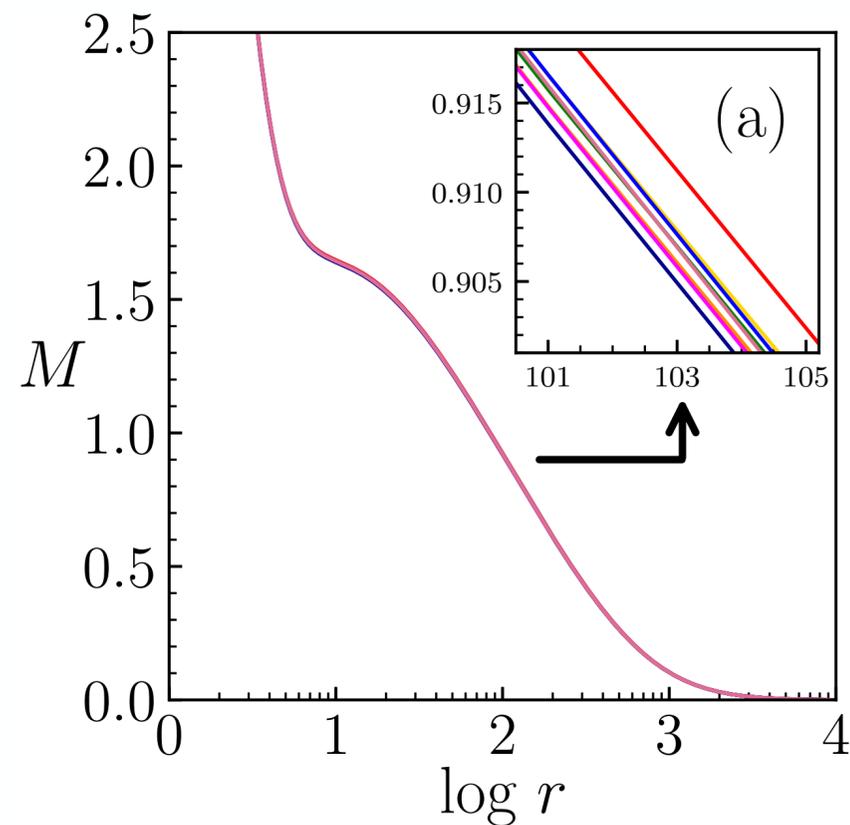


Iteration : 6

# METHODOLOGY

## \* Finding a transonic solution with pairs :

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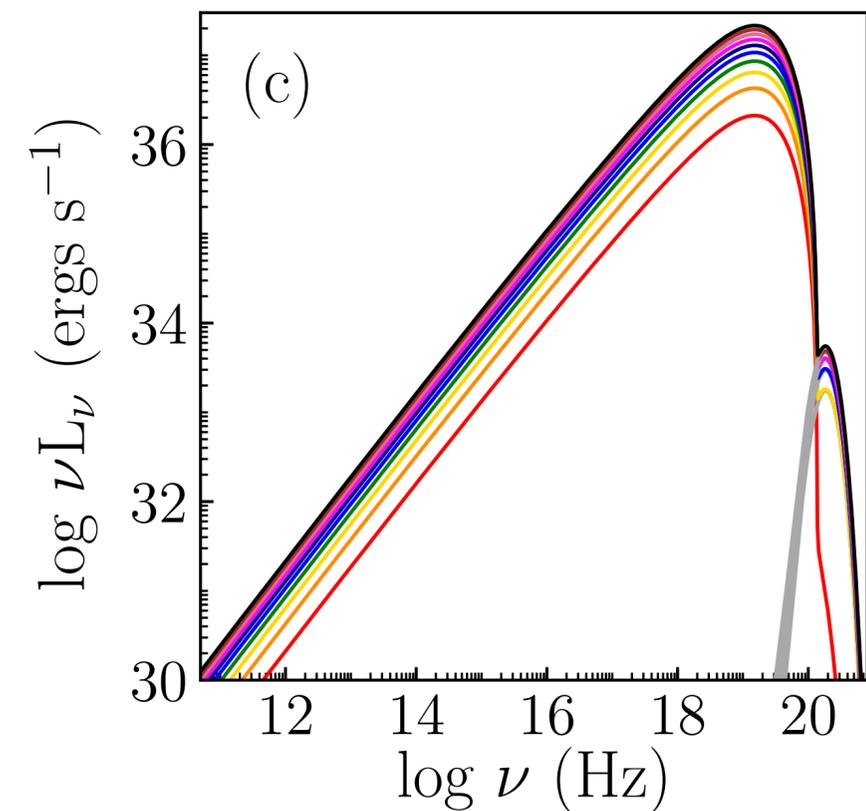
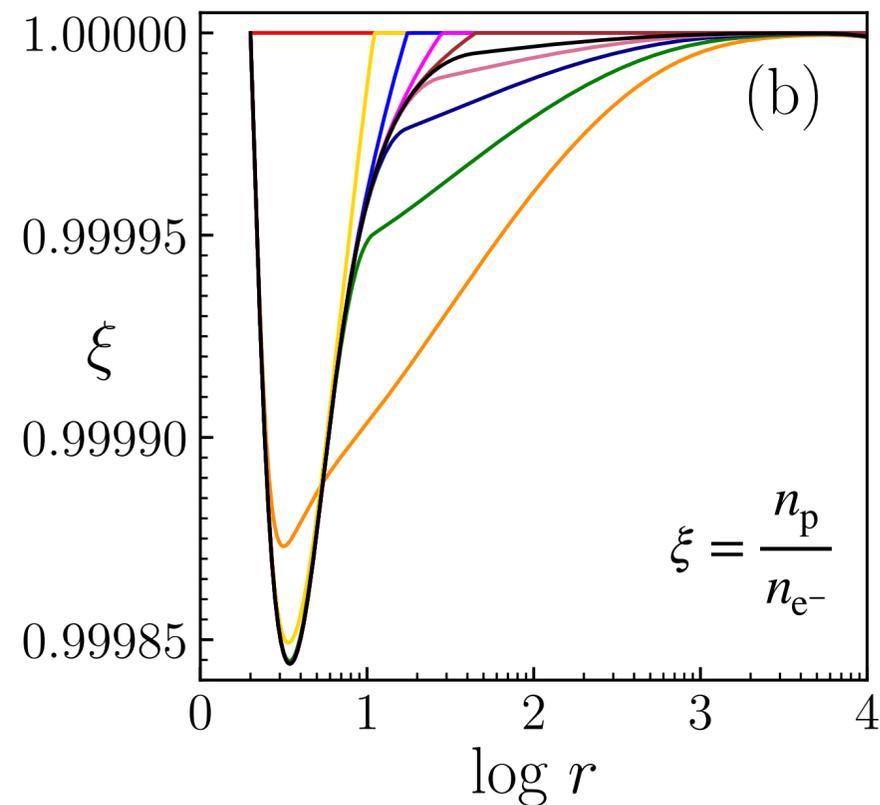
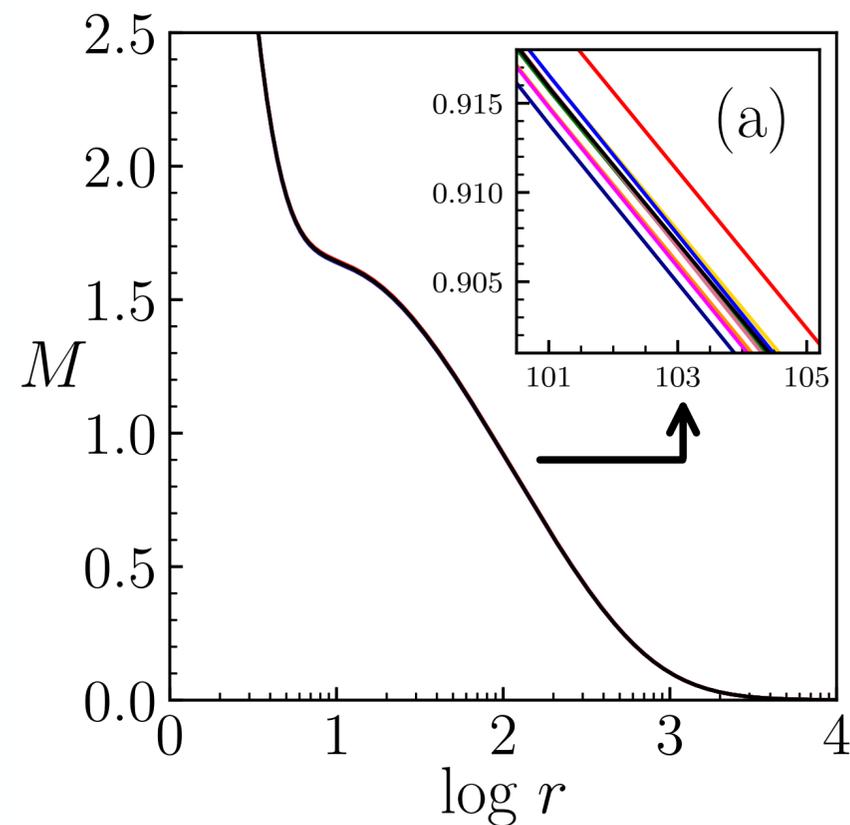


Iteration : 8

# METHODOLOGY

## \* Finding a transonic solution with pairs :

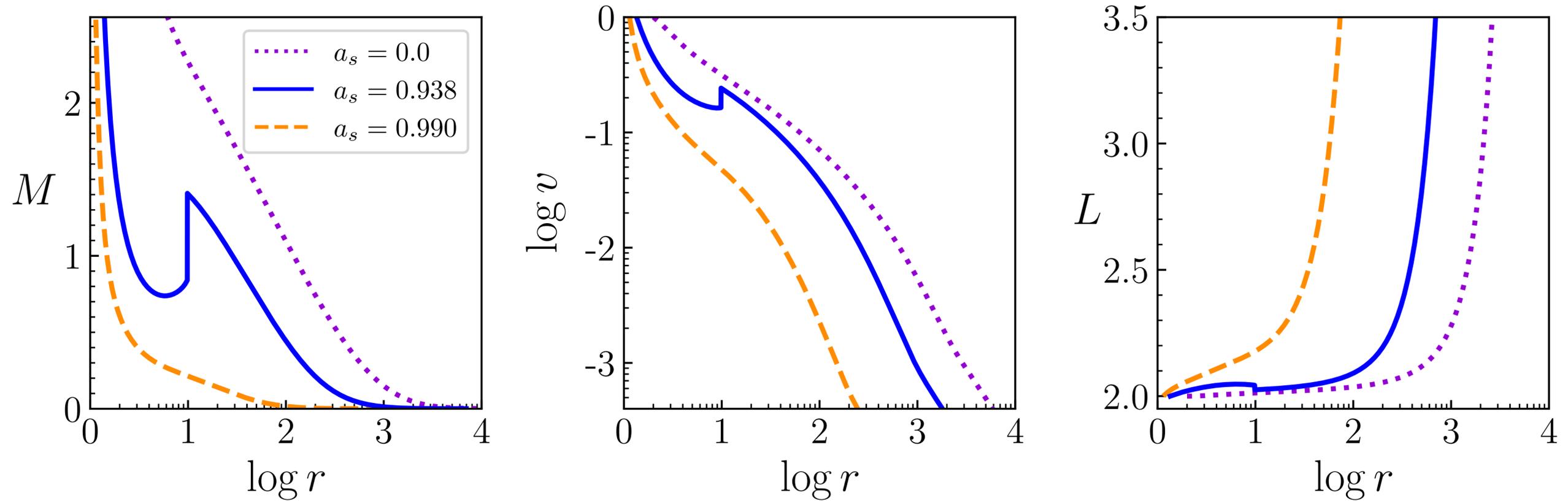
► Radiation field : Bremsstrahlung + Synchrotron + Comptonized photons + Annihilation photons



Iteration : 10

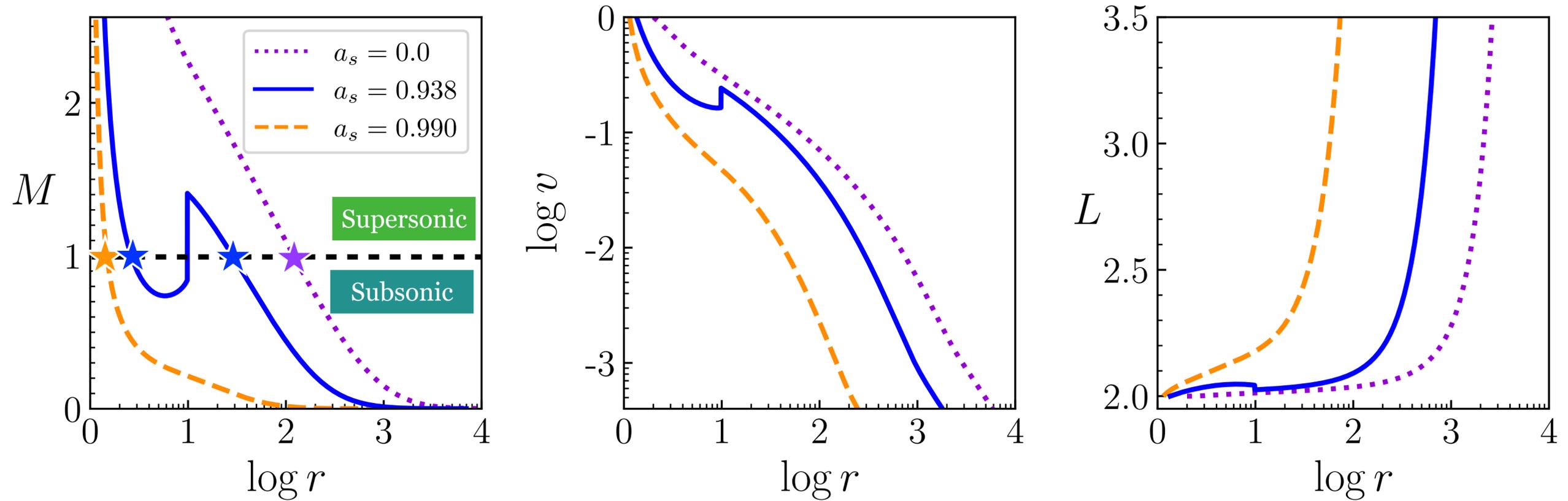
# Results

# Typical Solutions



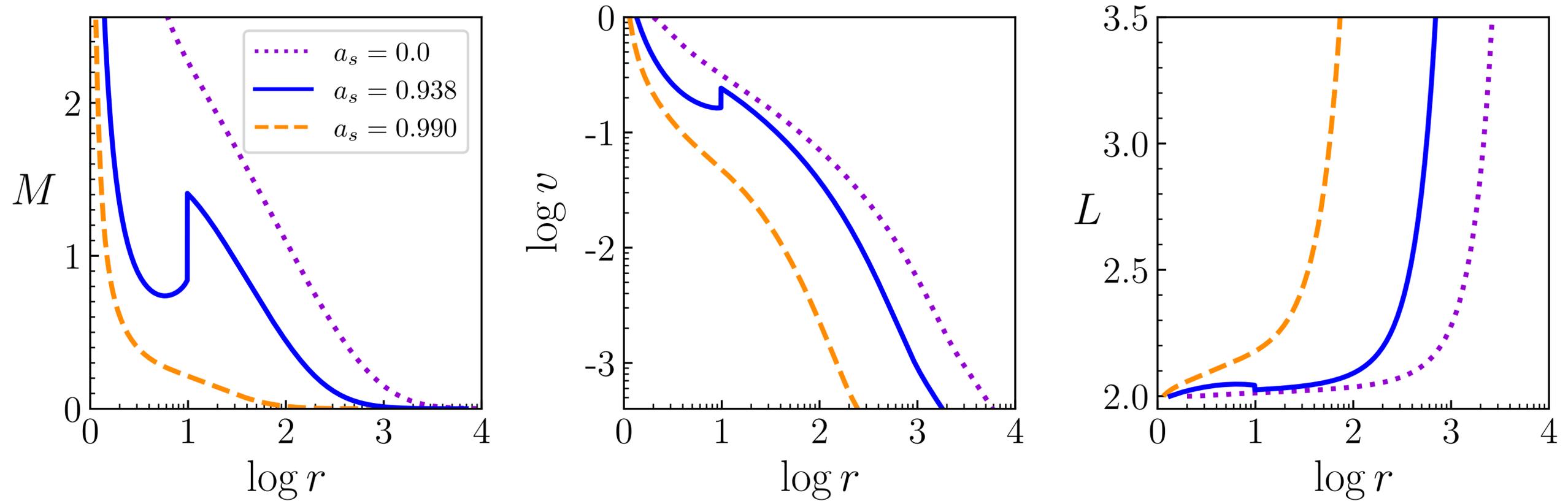
$$E = 1.001, L_0 = 2.1, \alpha_v = 0.001, \beta = 0.1, \xi = 1.0, \dot{M} = 0.1\dot{M}_{Edd}, M_{BH} = 10M_{\odot}$$

# Typical Solutions



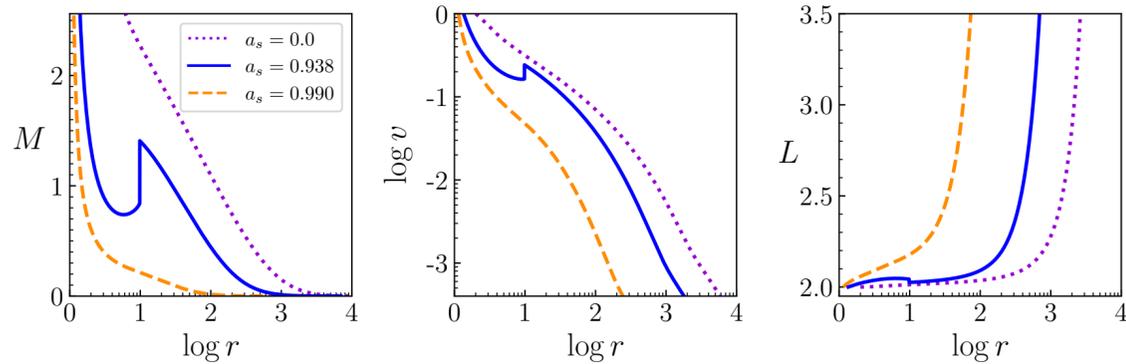
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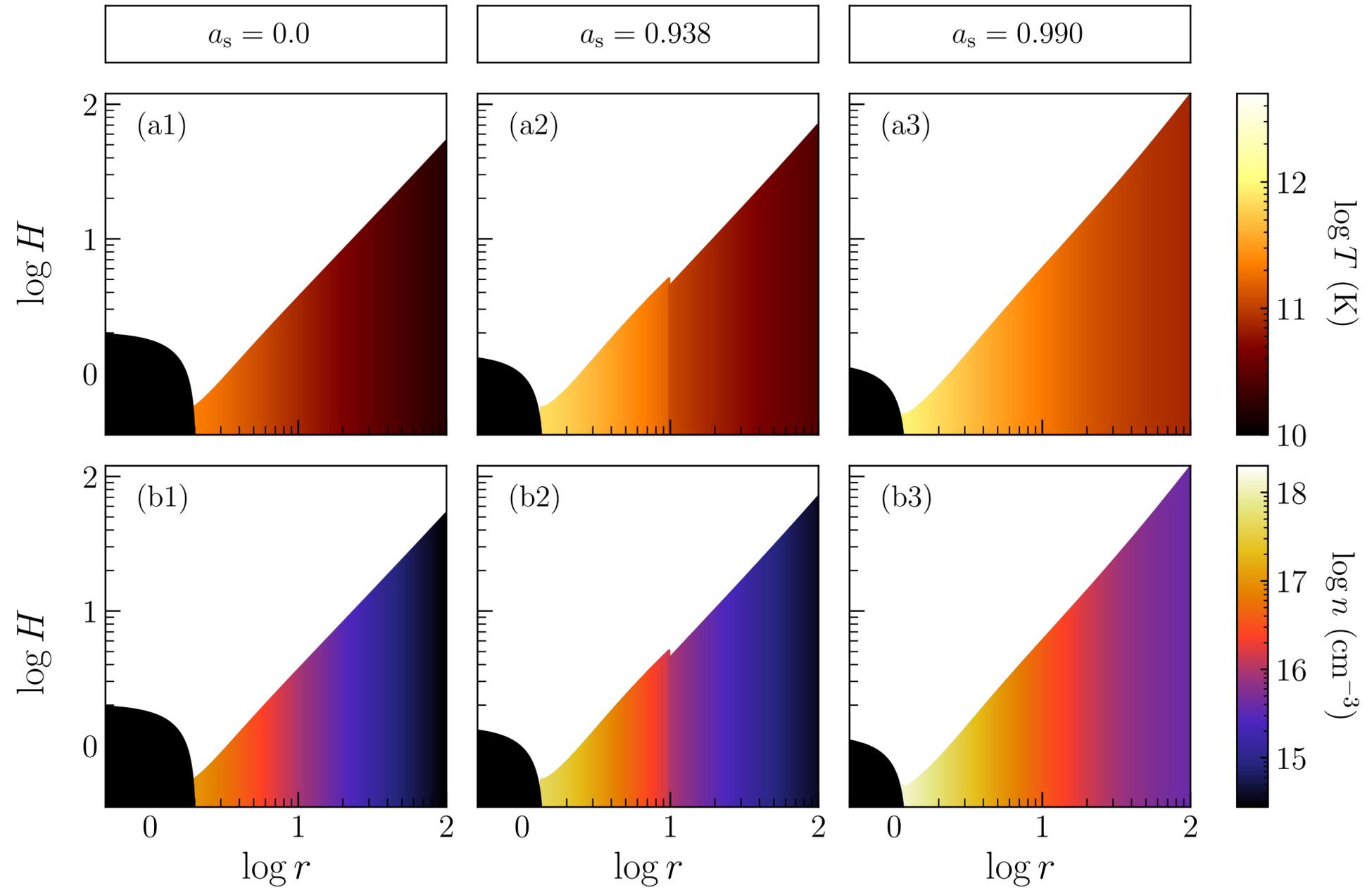


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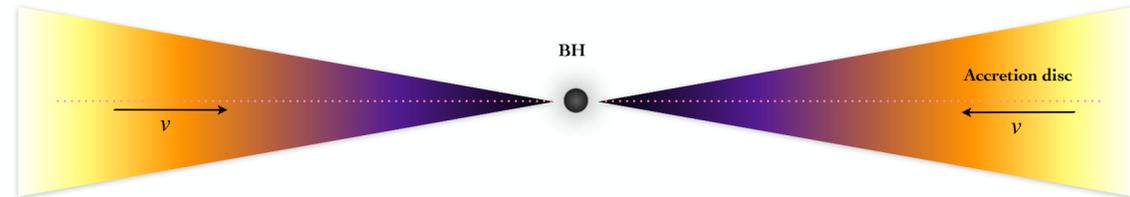
# Typical Solutions



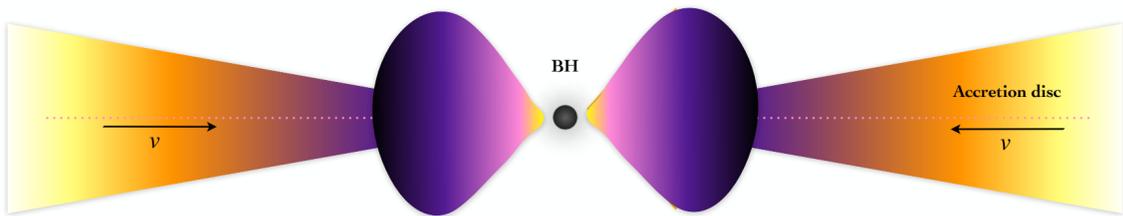
$E = 1.001, L_0 = 2.1, \alpha_v = 0.001, \beta = 0.1, \xi = 1.0, \dot{M} = 0.1\dot{M}_{Edd}, M_{BH} = 10M_\odot$



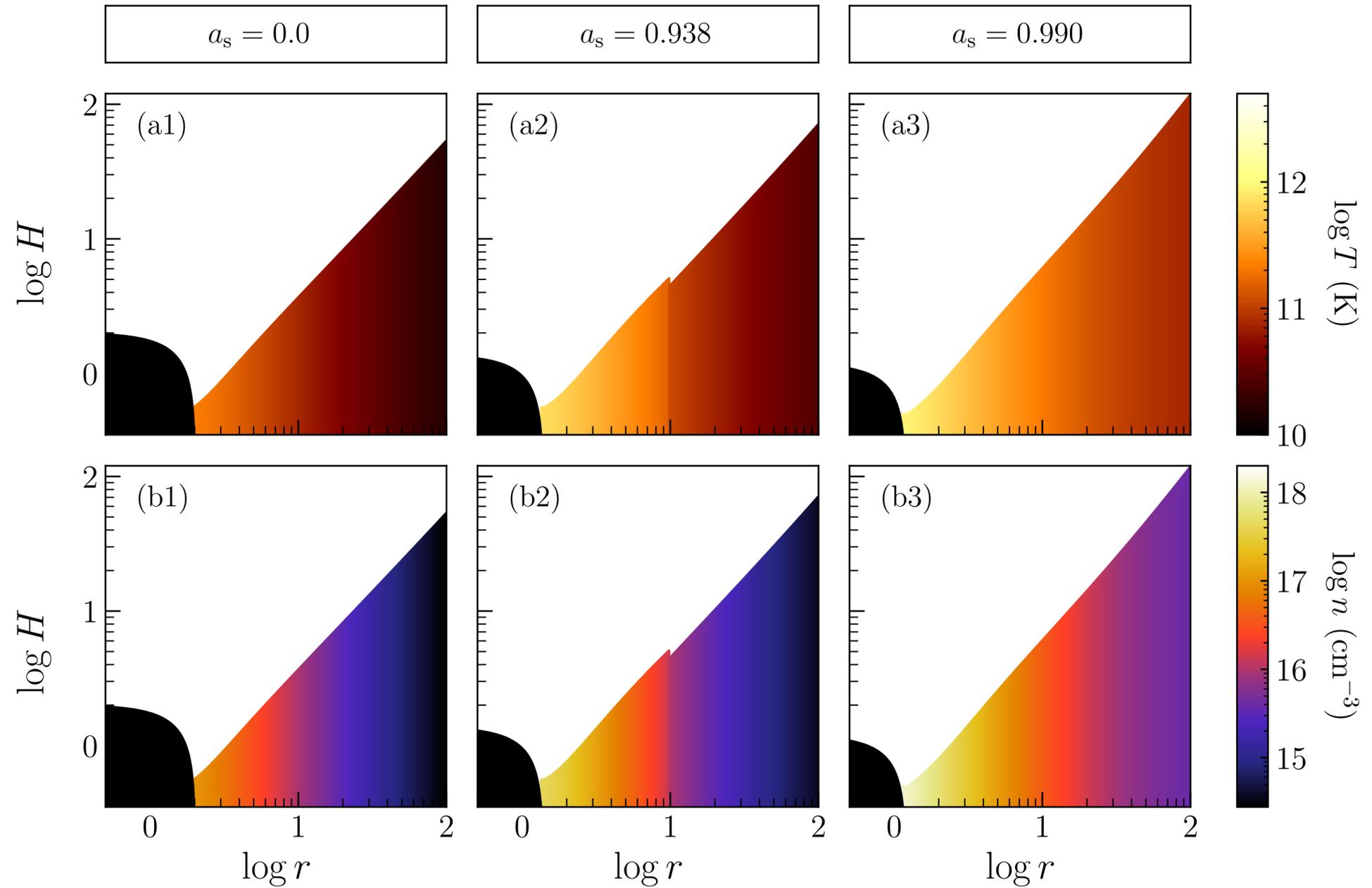
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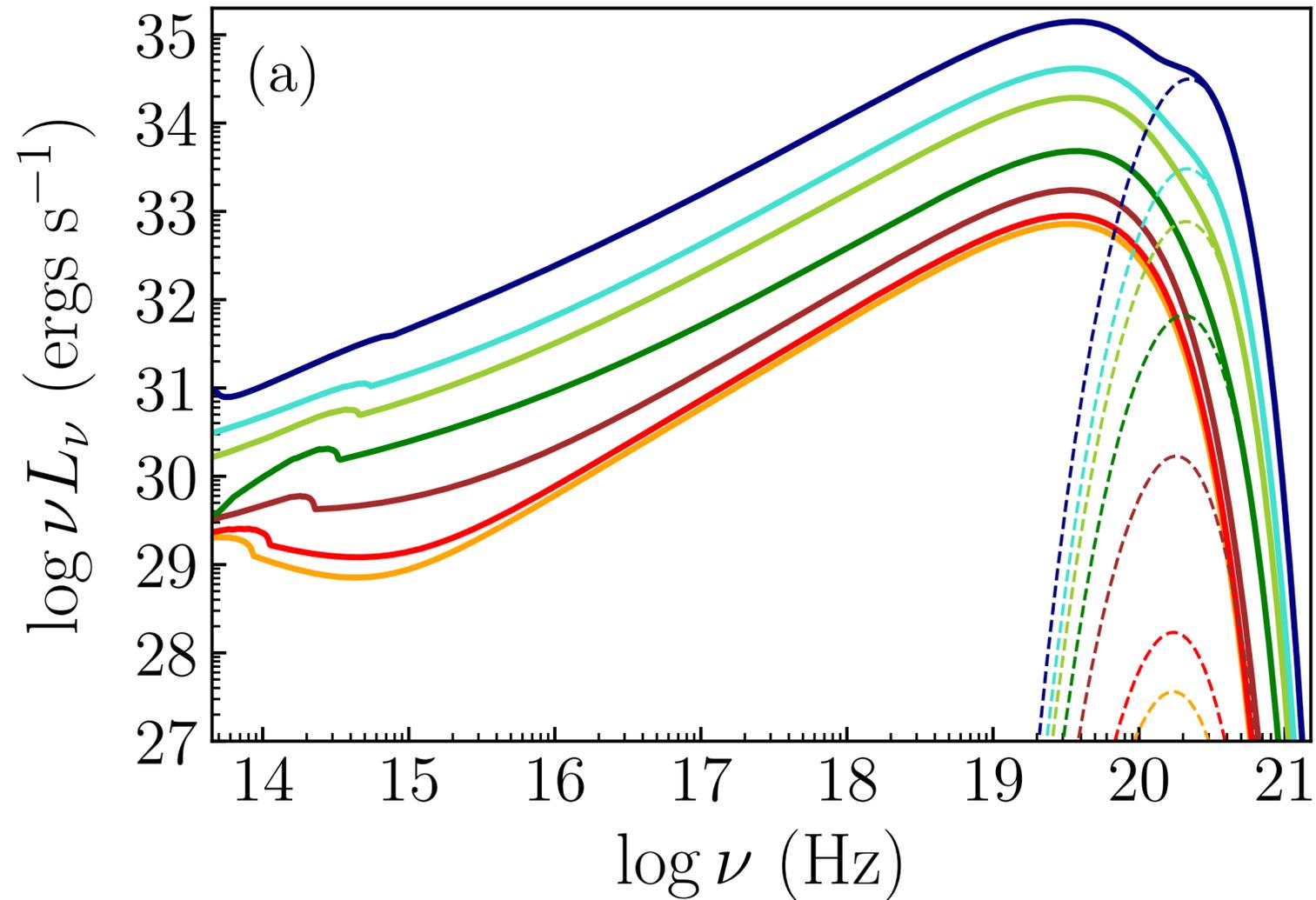
No shock



In presence of shock



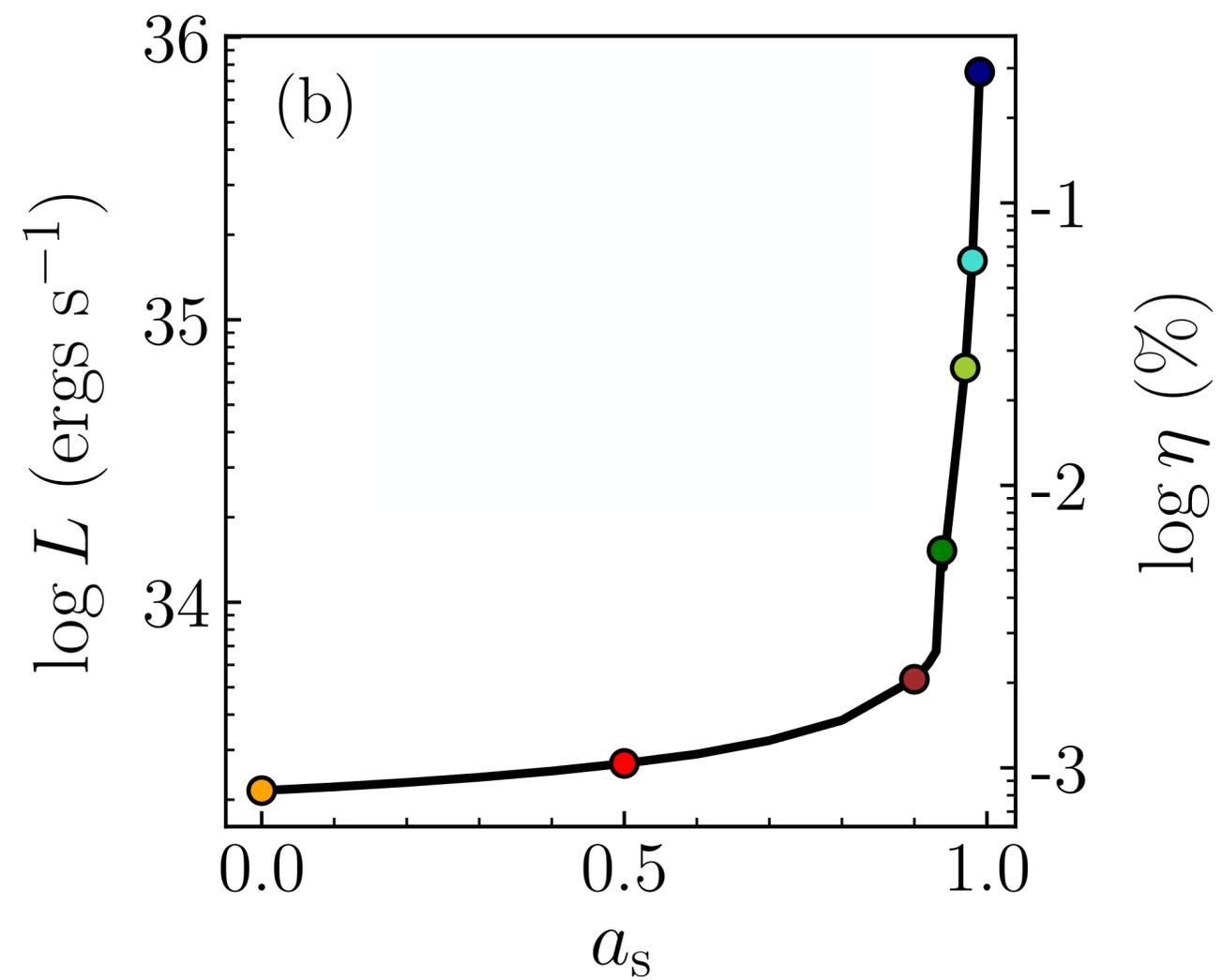
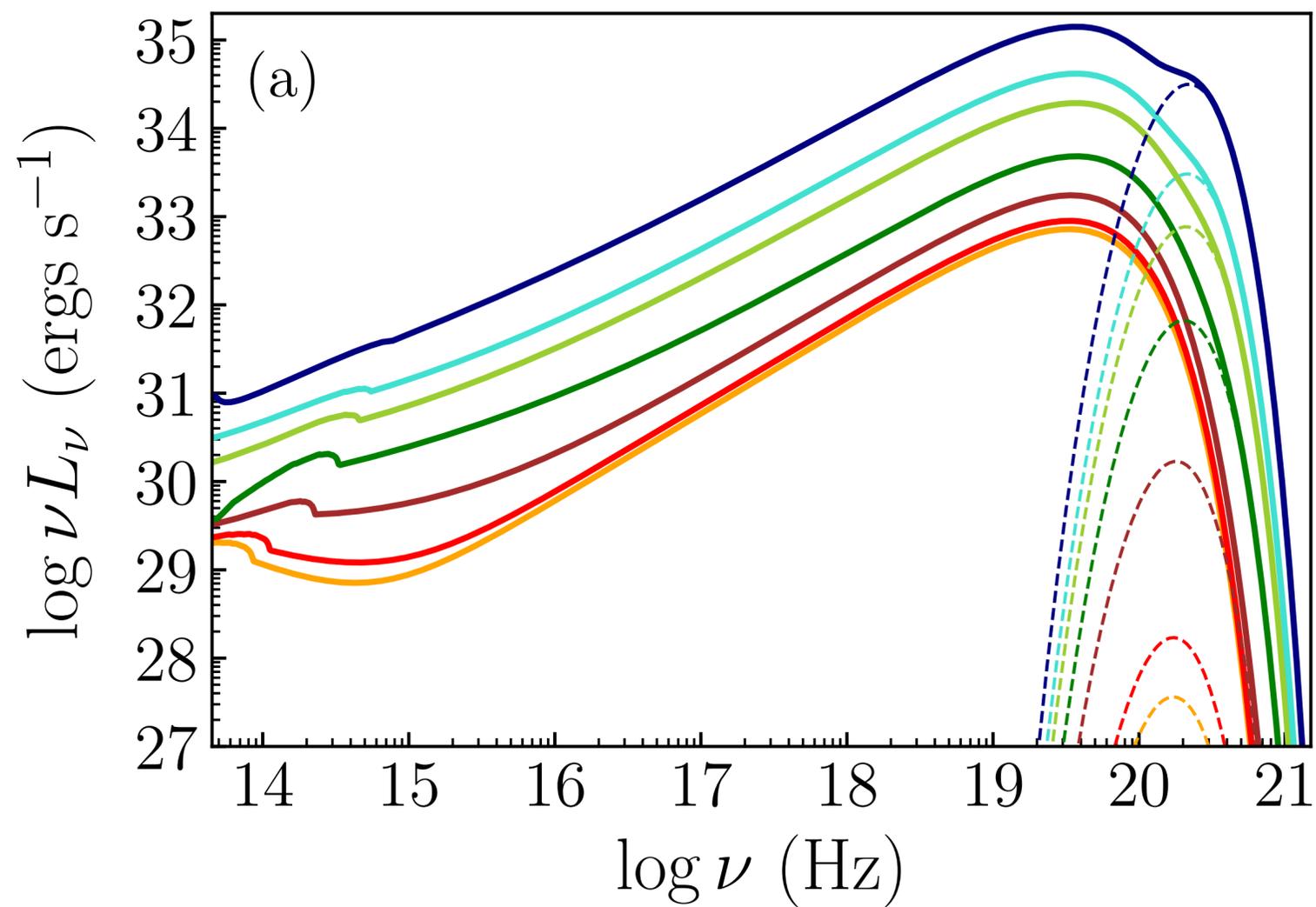
# Spectrum



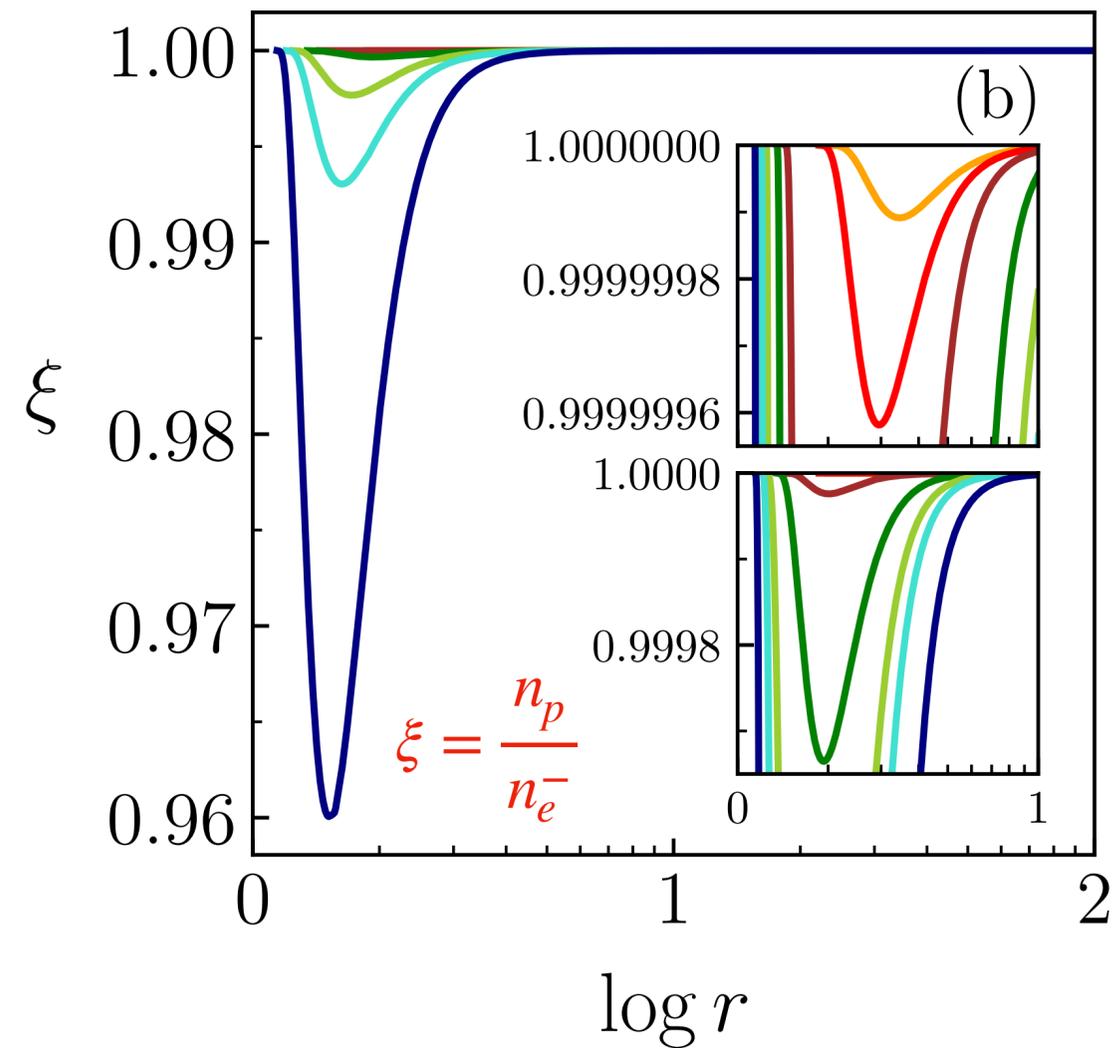
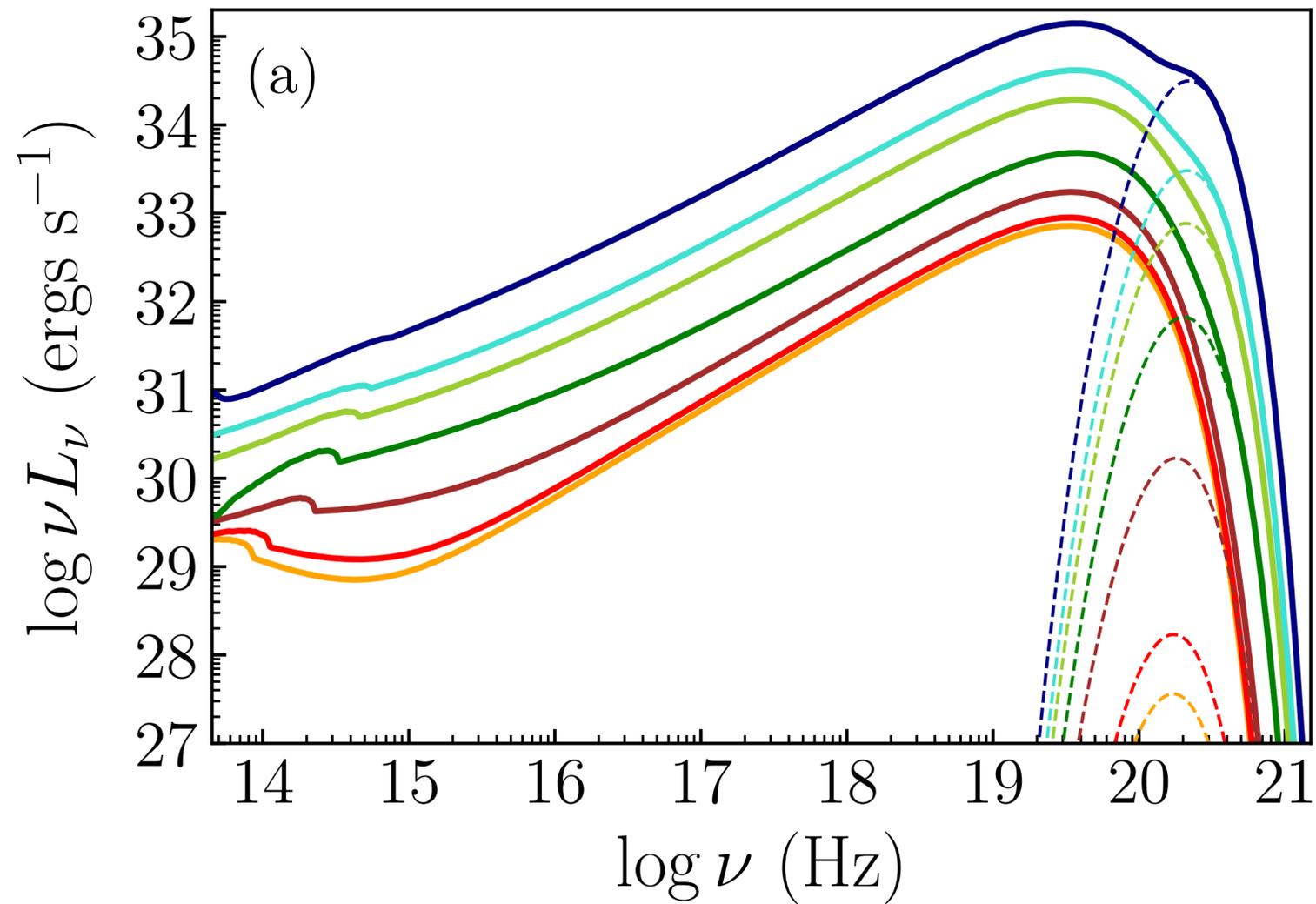
$E = 1.001$ ,  $L_0 = 1.9$ ,  $\alpha_v = 0.001$ ,  
 $\beta = 0.1$ ,  $\xi = 1.0$ ,  $\dot{M} = 0.2\dot{M}_{Edd}$ ,  
 $M_{BH} = 10M_\odot$

Spin values are: 0.0 (orange), 0.5 (red), 0.9  
(brown), 0.938 (dark-green), 0.97 (light-  
green), 0.98 (sky-blue), 0.99 (dark-blue).

# Spectrum

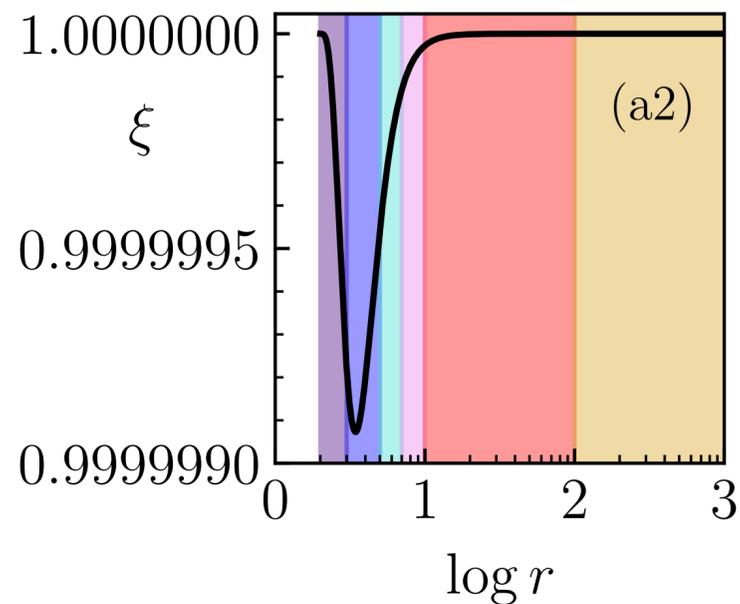
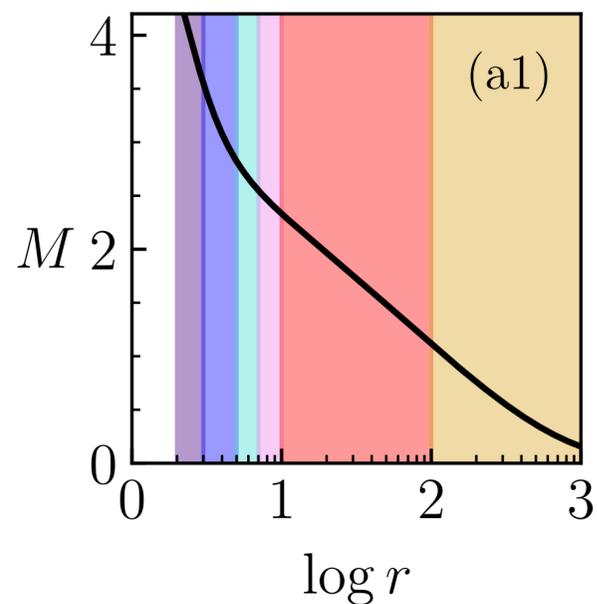


# Spectrum

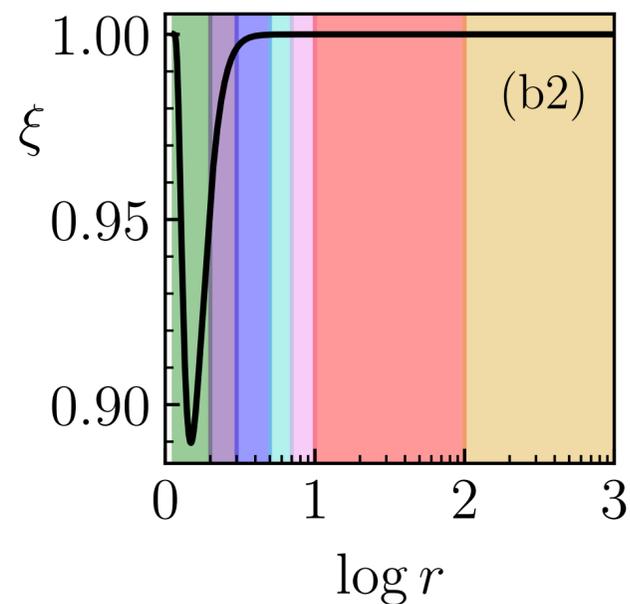
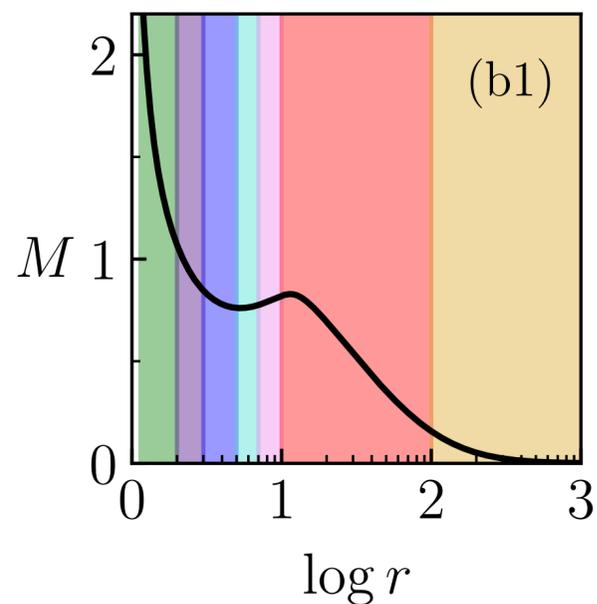


# Contribution of different regions

$a_s = 0.0$



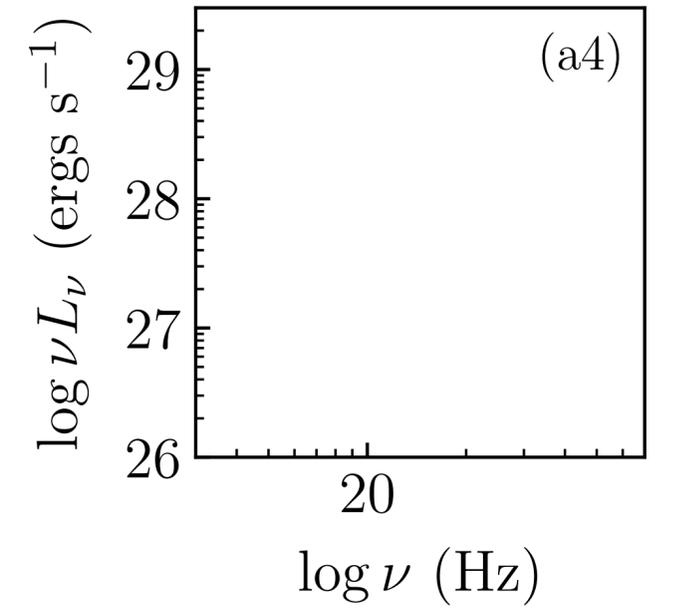
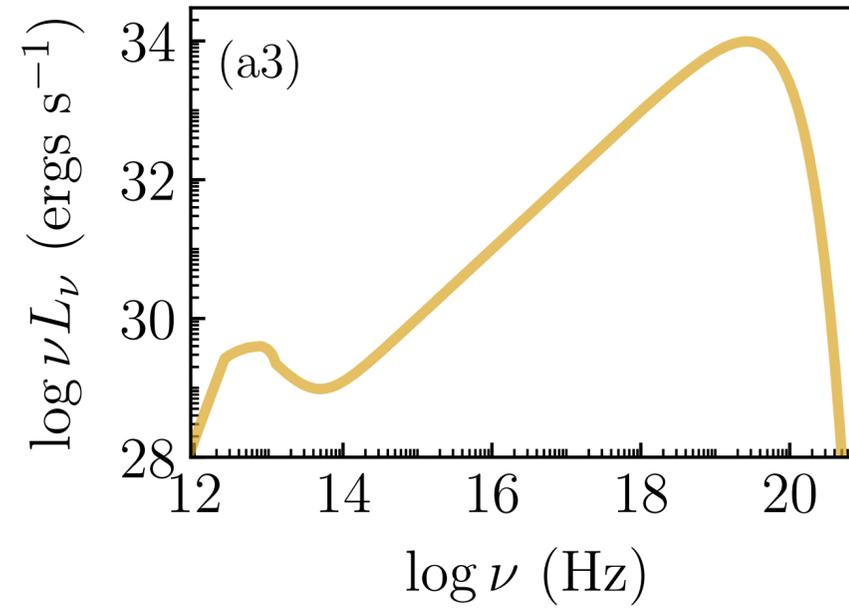
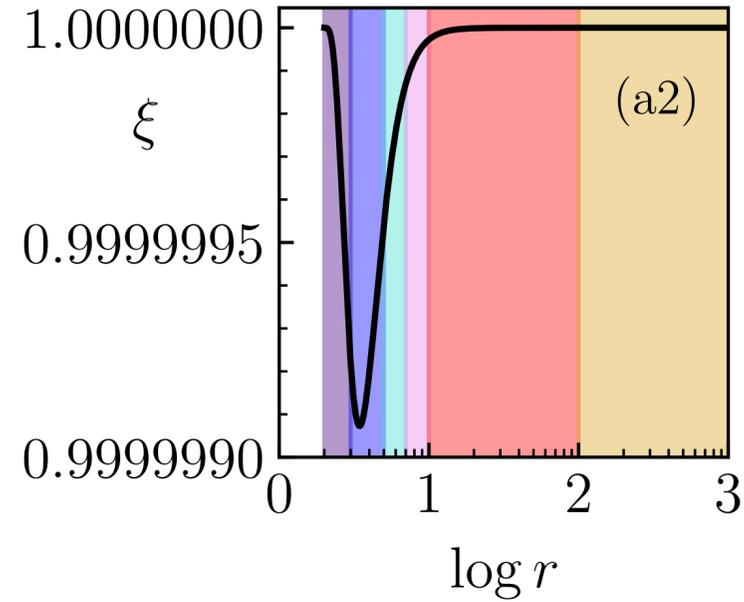
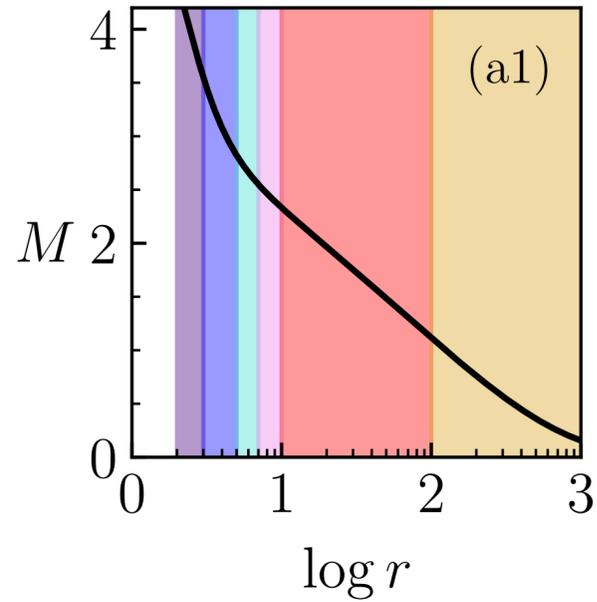
$a_s = 0.99$



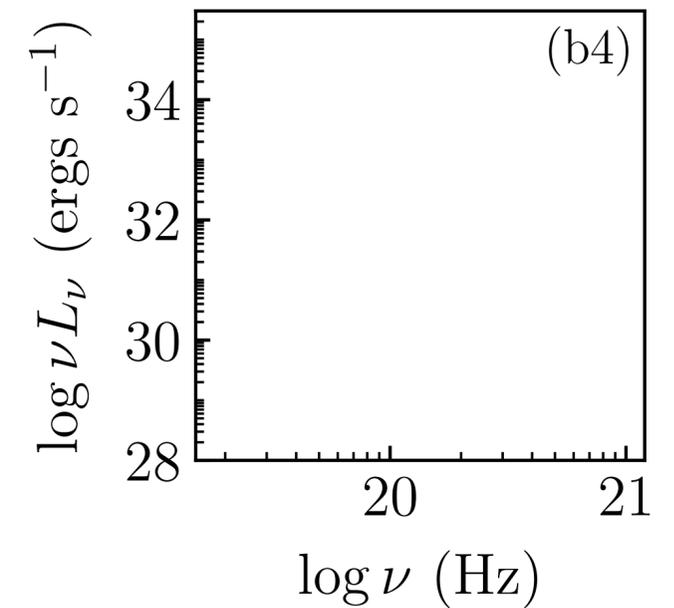
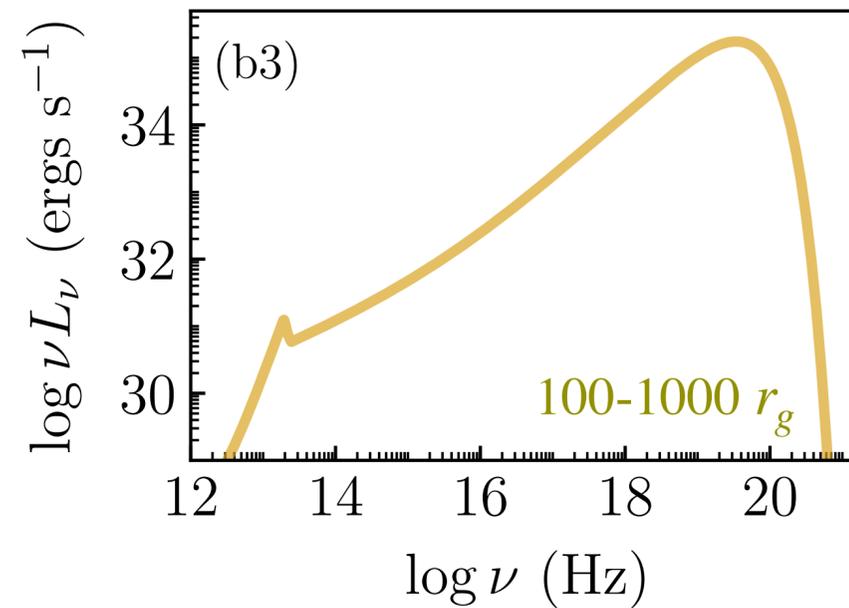
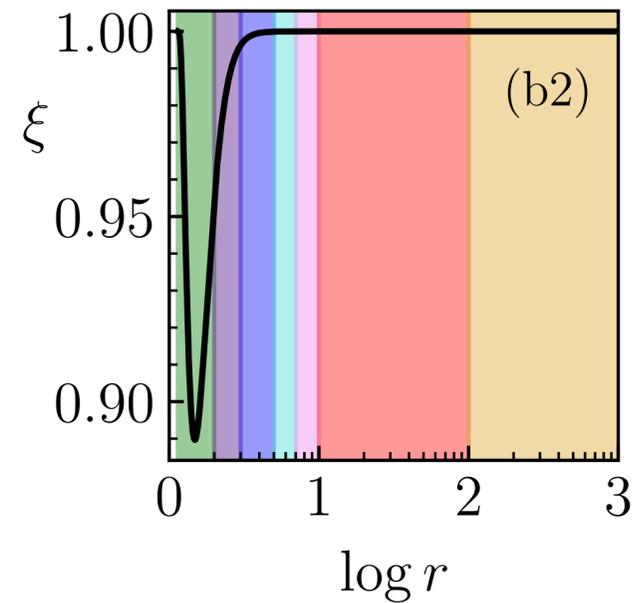
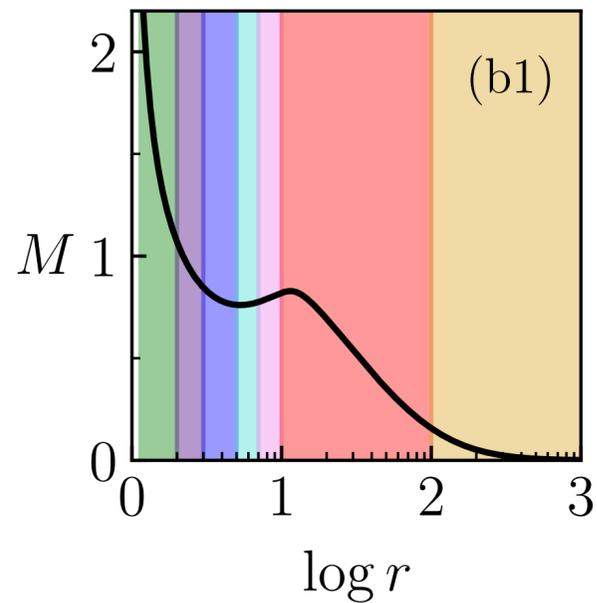
$$E = 1.001, L_0 = 2.1, \alpha_v = 0.01, \beta = 0.1, \dot{M} = 0.5\dot{M}_{Edd}, M_{BH} = 10M_{\odot}$$

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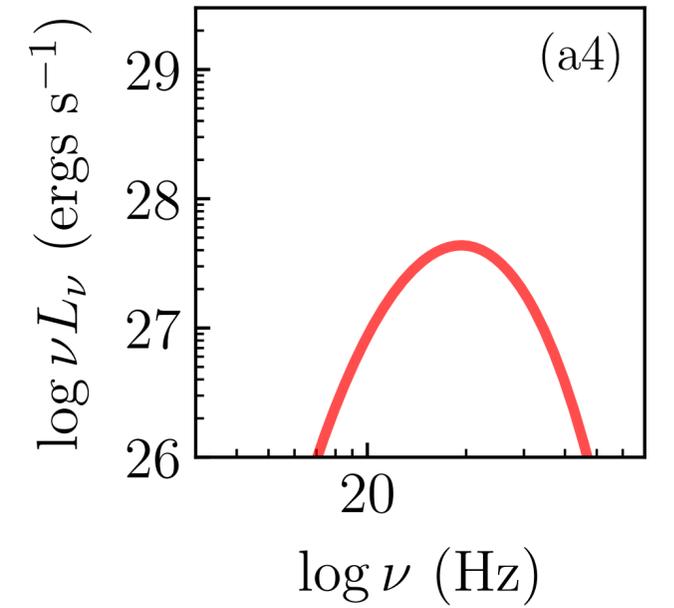
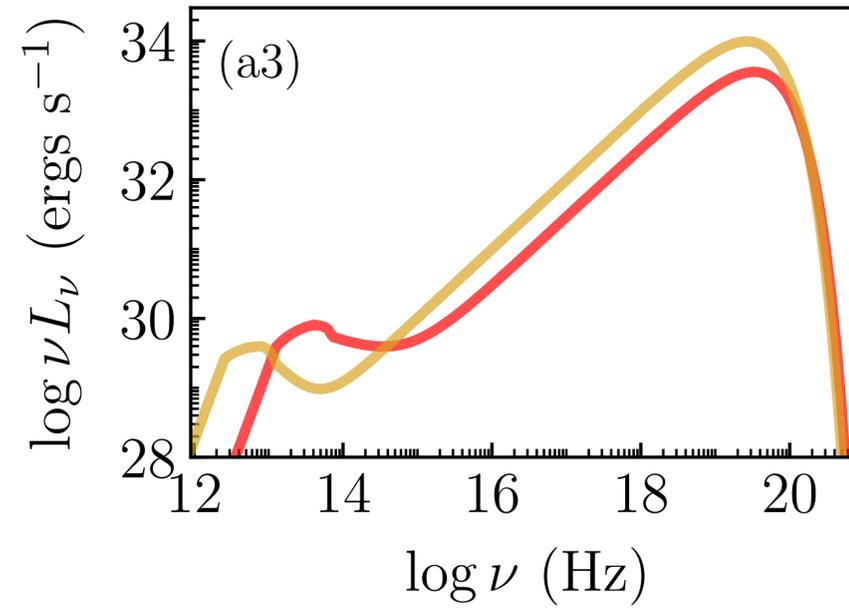
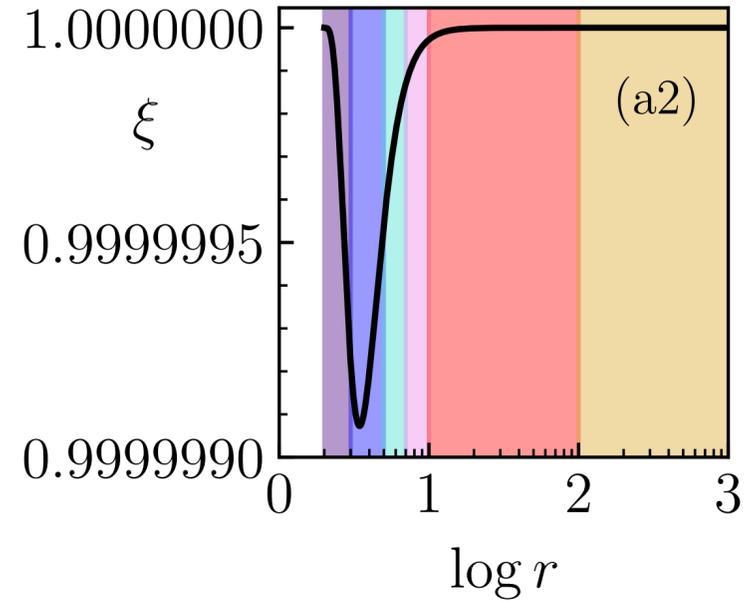
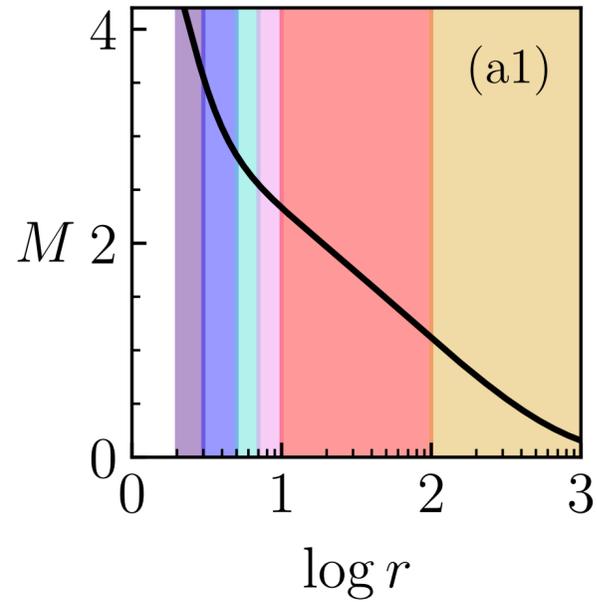
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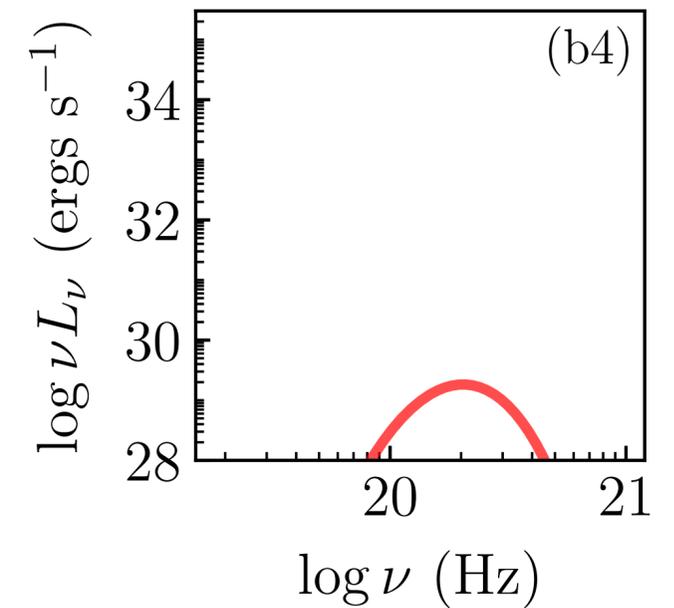
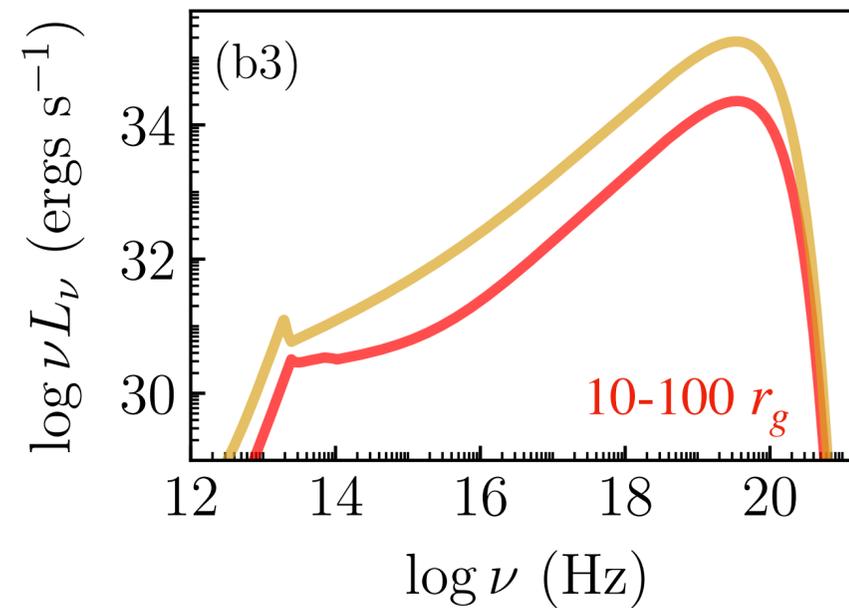
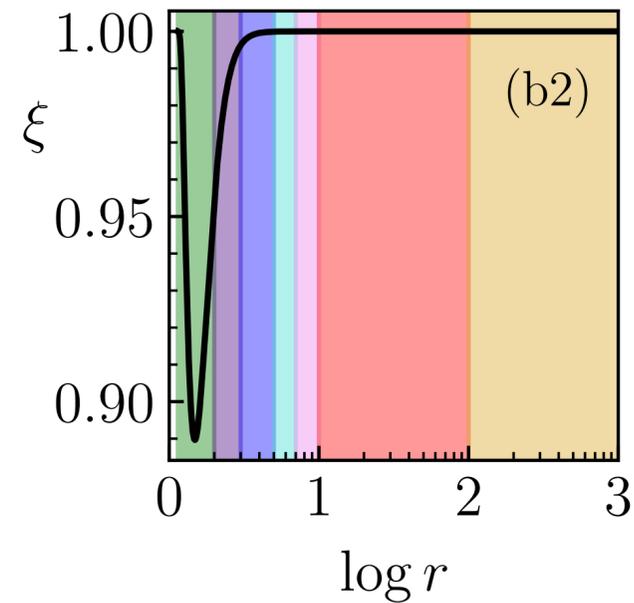
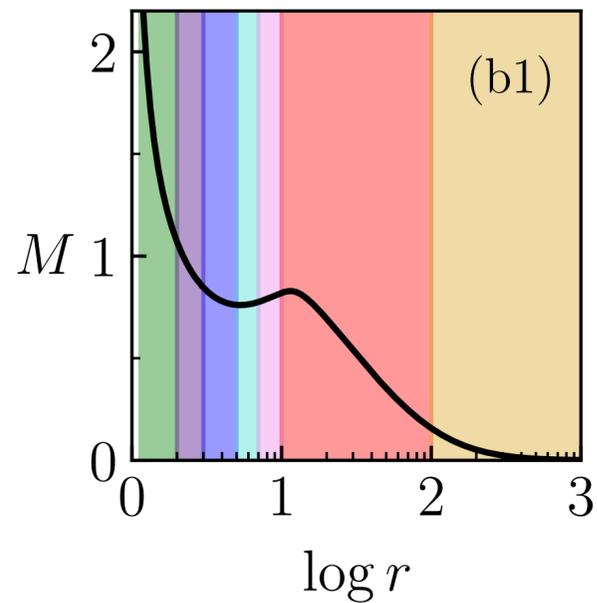
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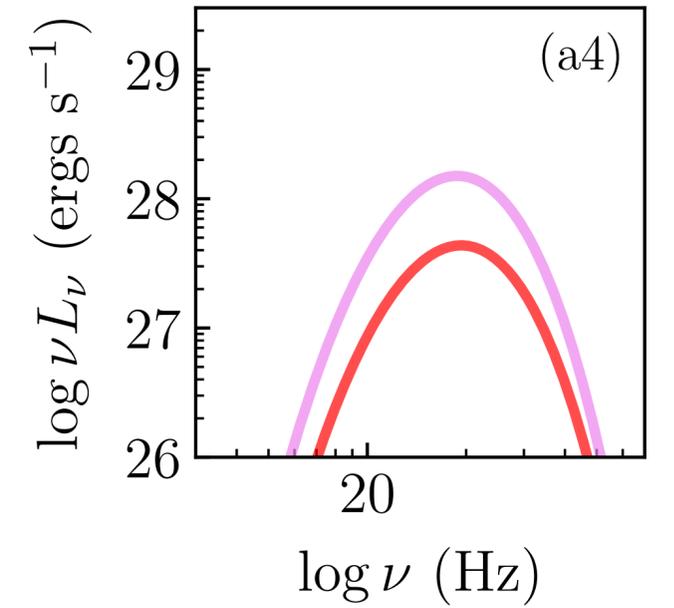
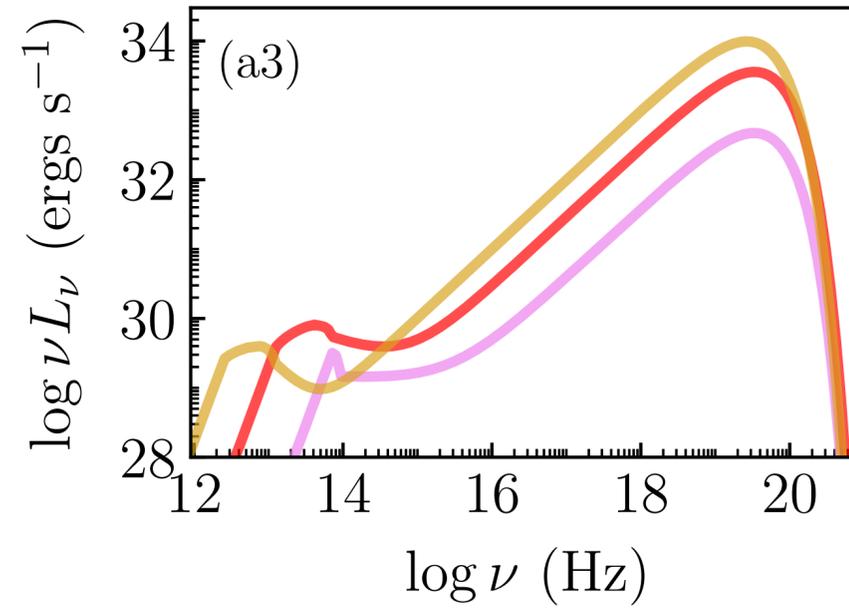
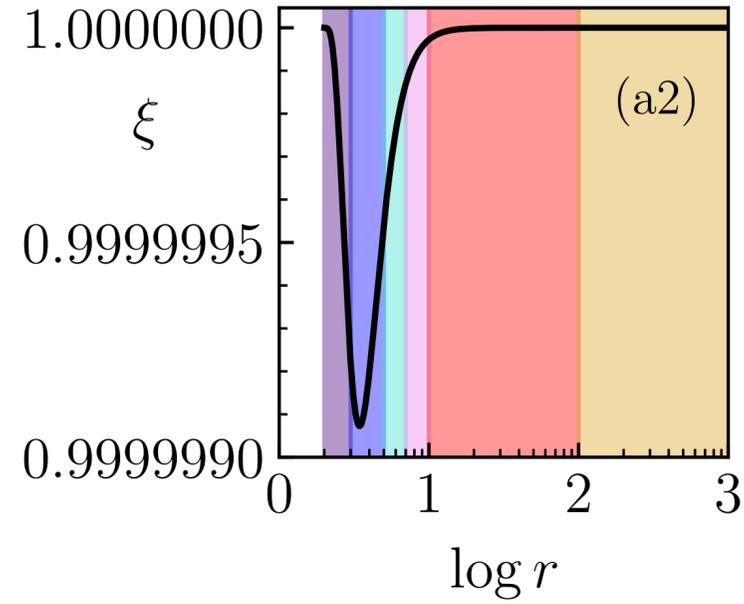
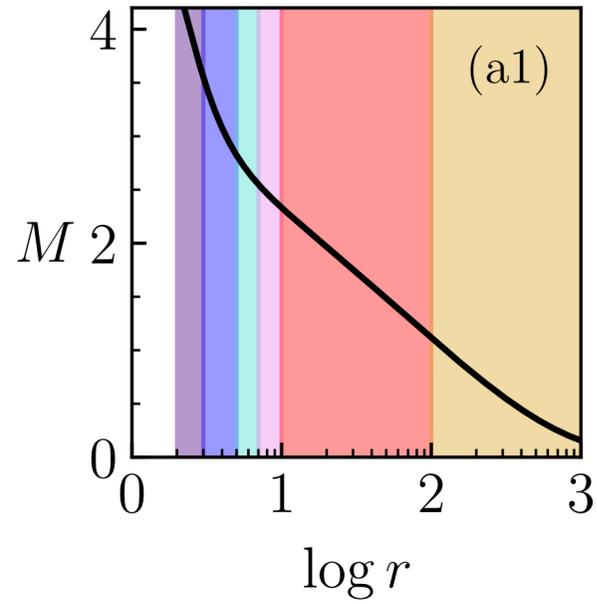
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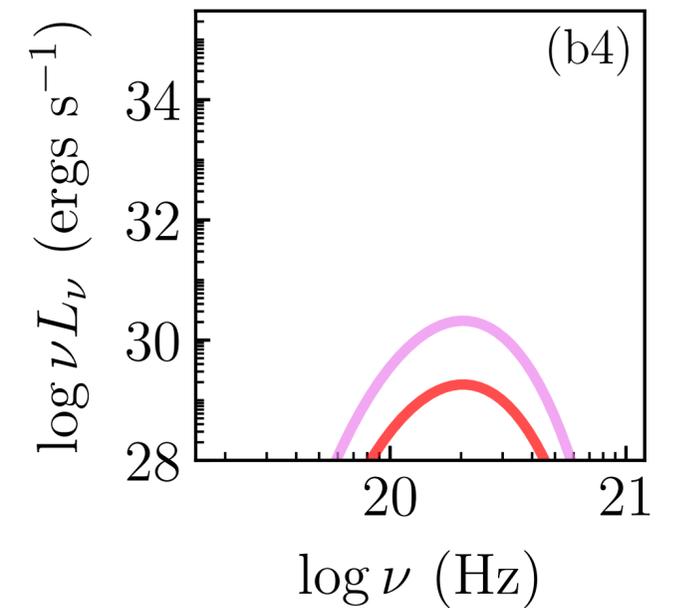
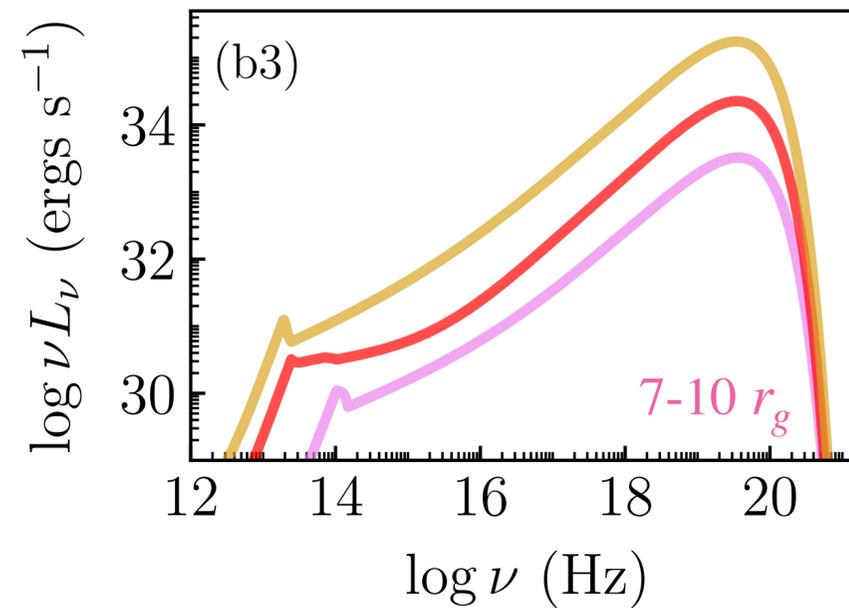
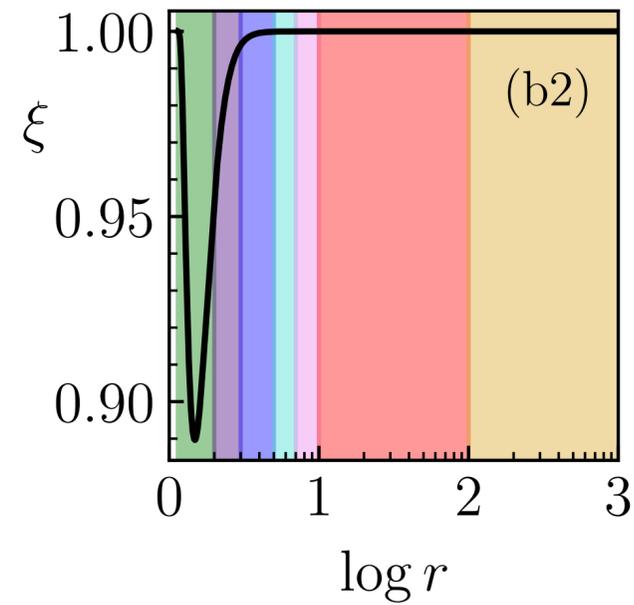
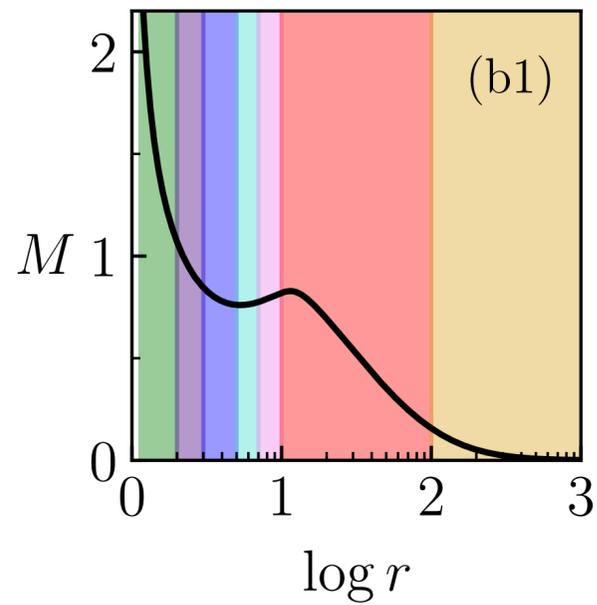
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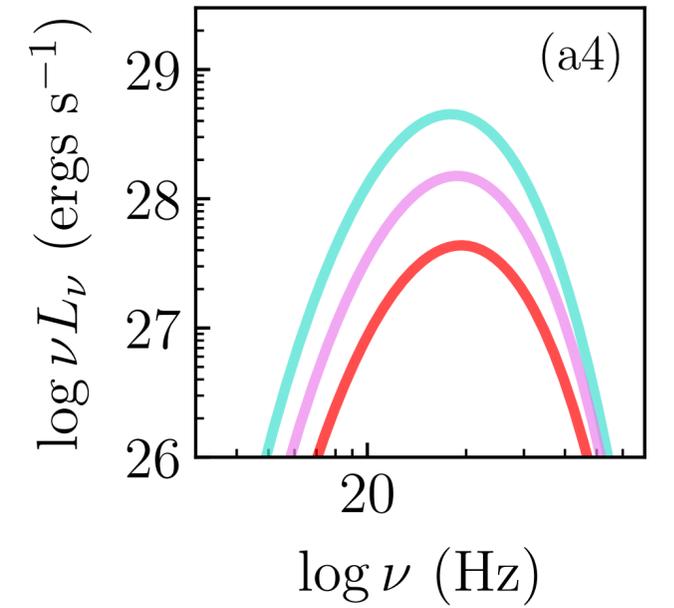
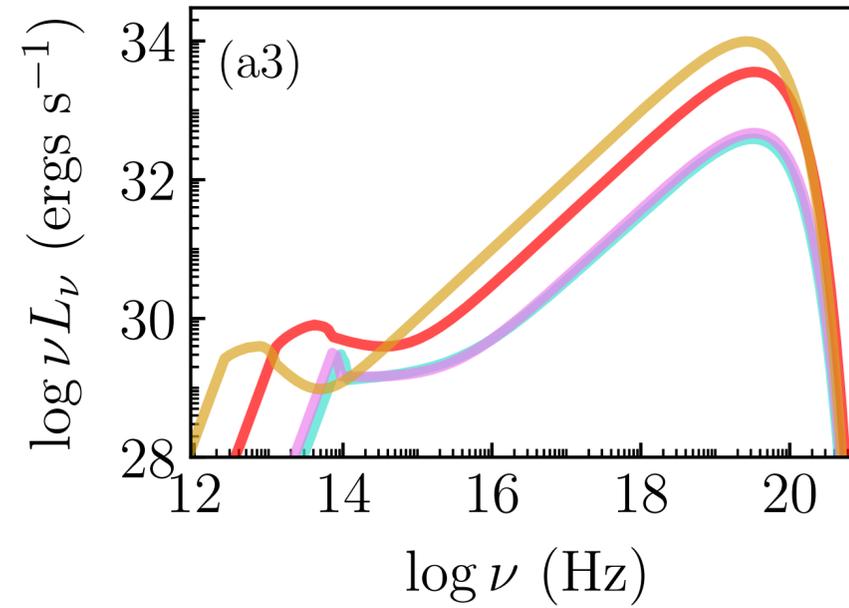
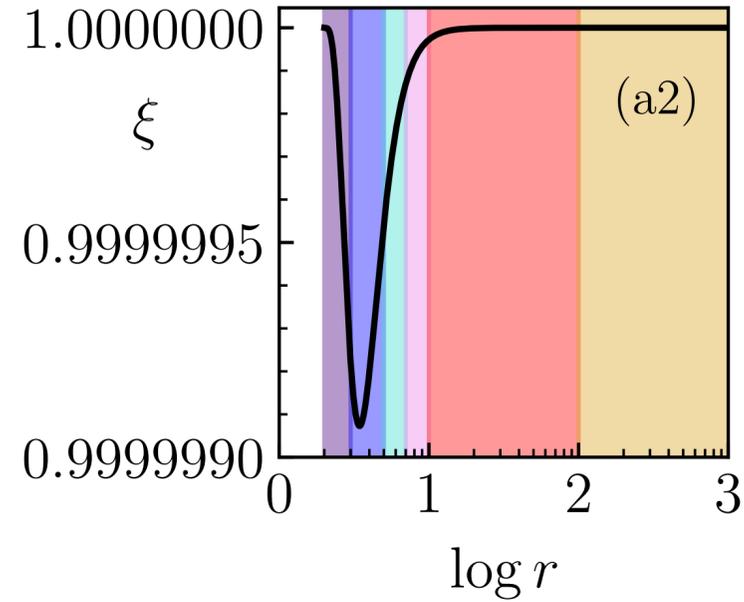
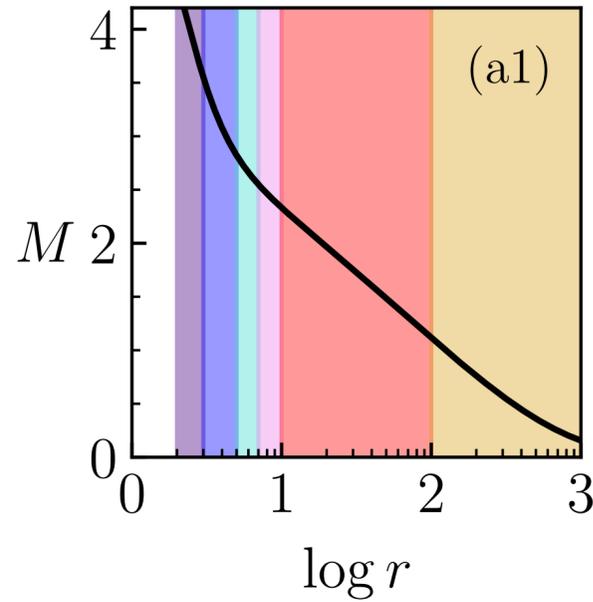
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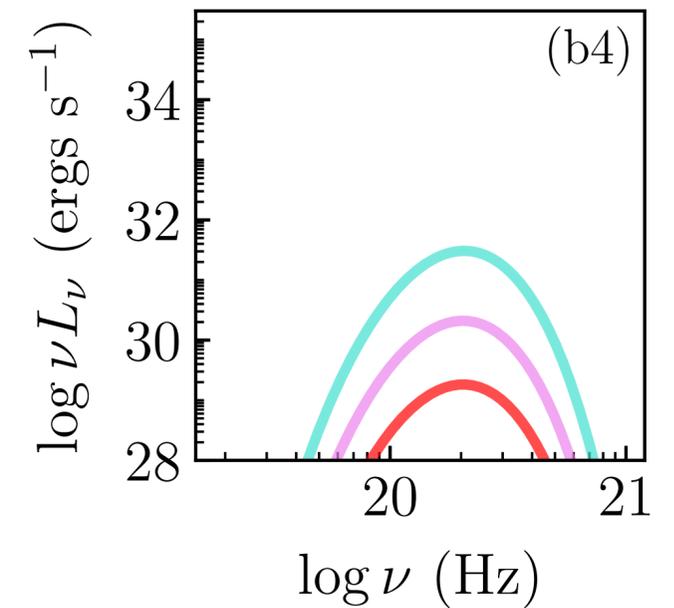
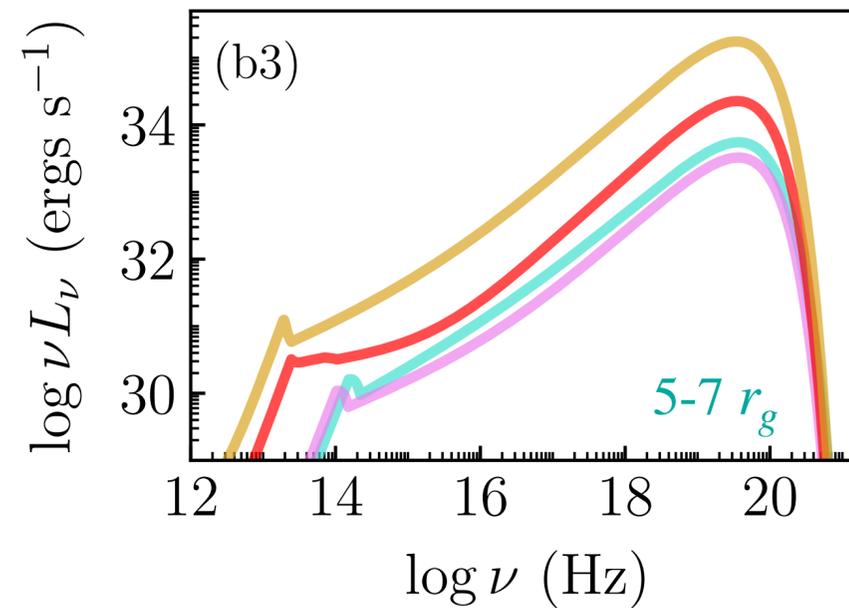
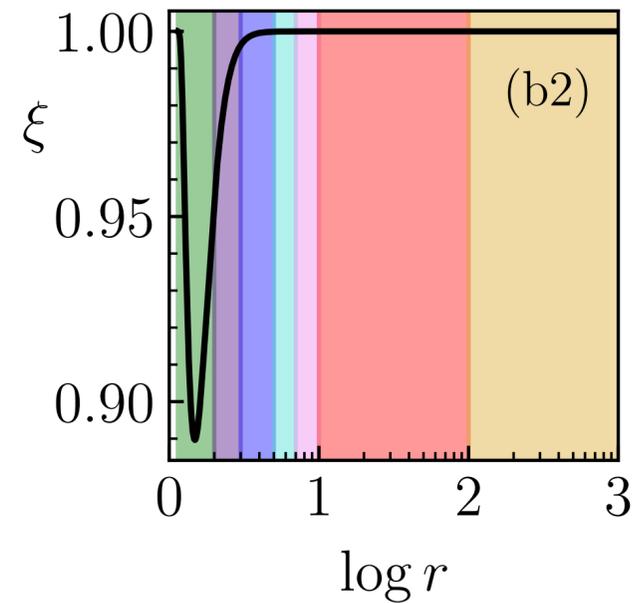
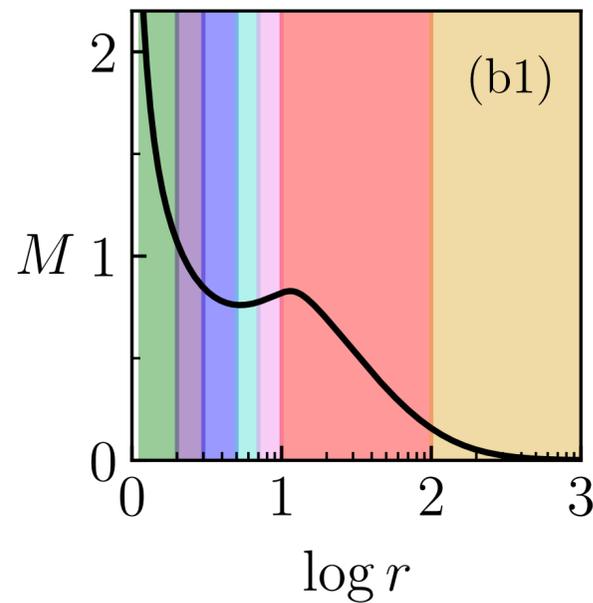
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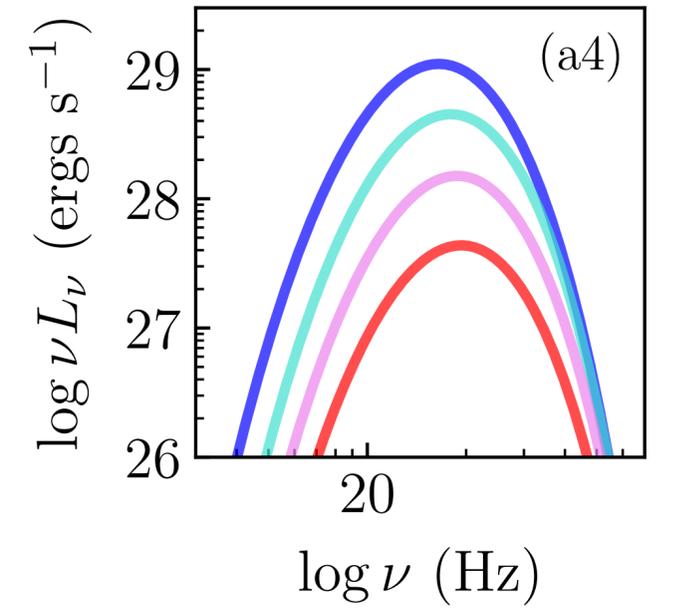
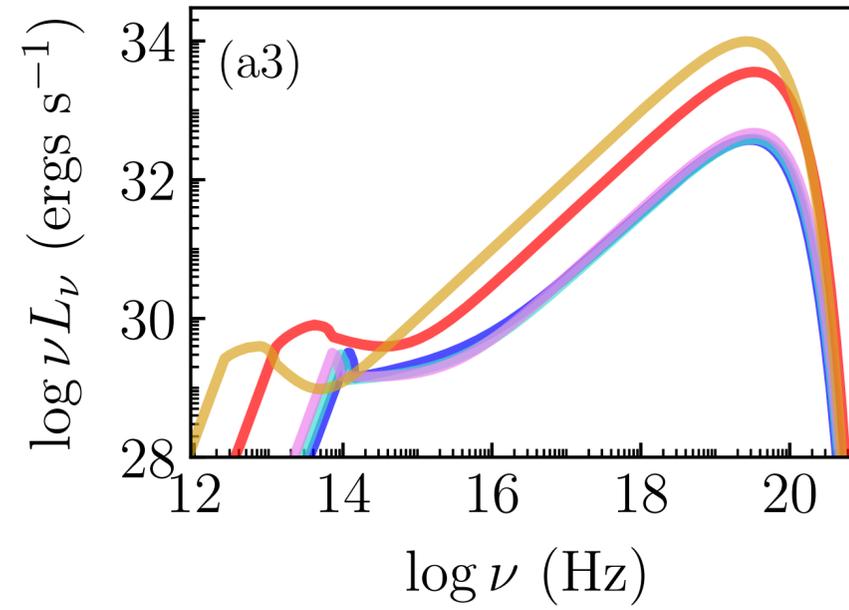
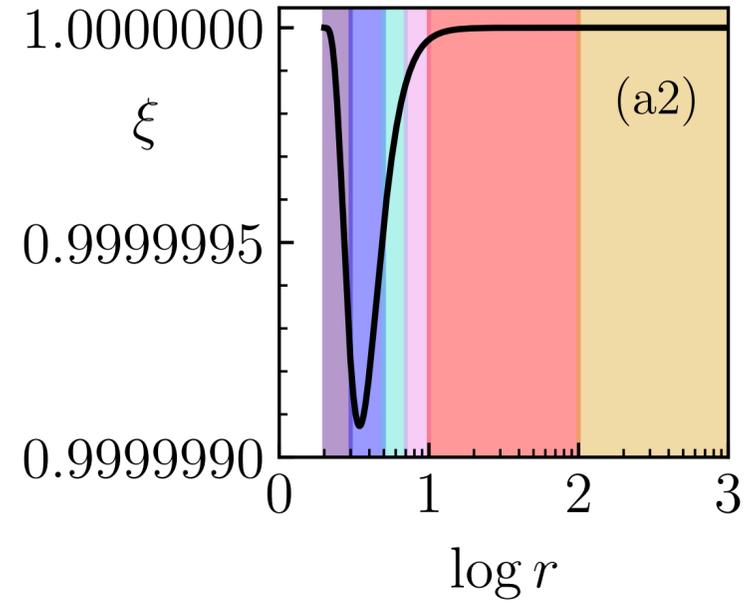
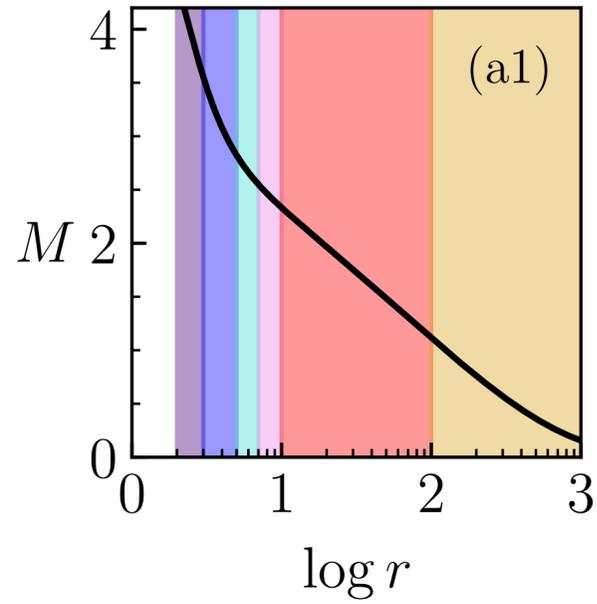
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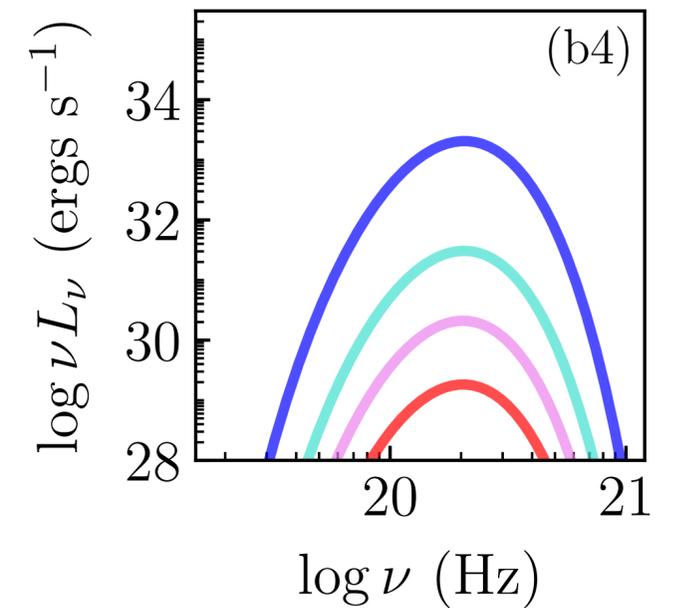
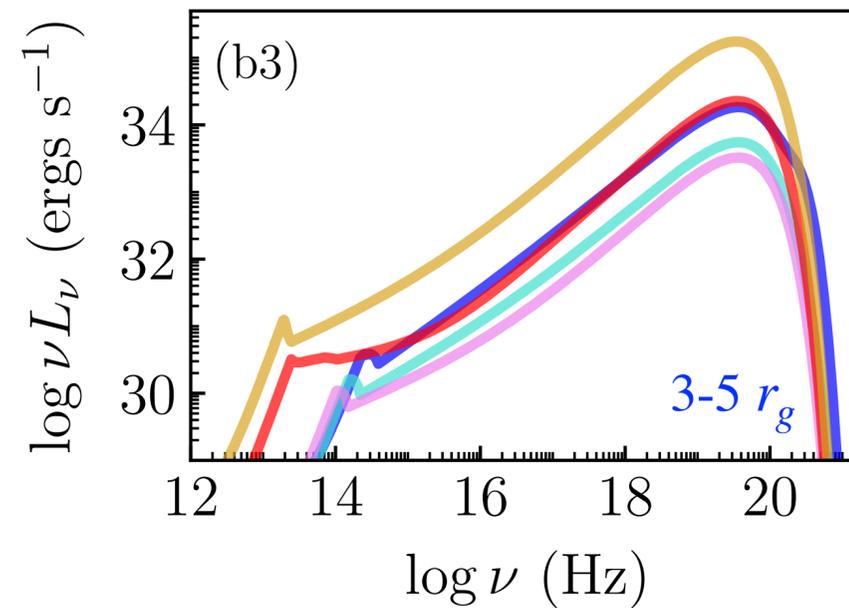
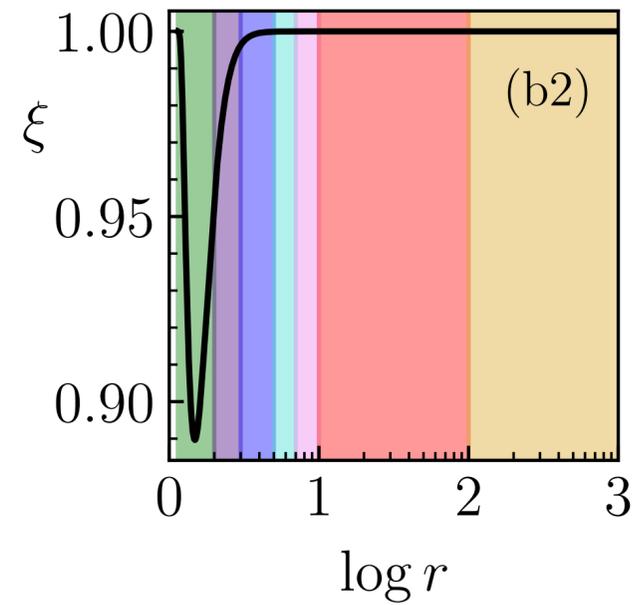
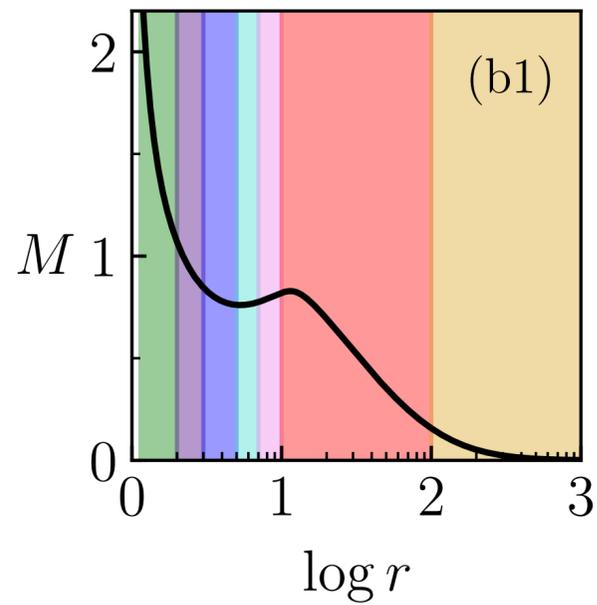
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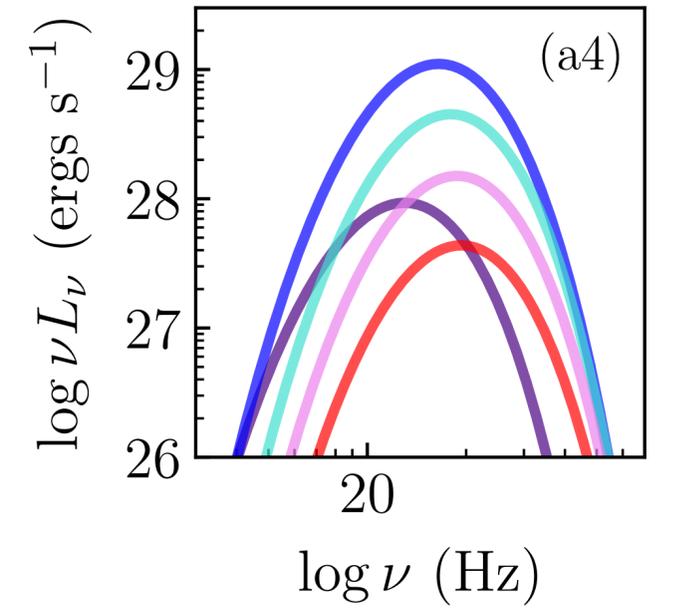
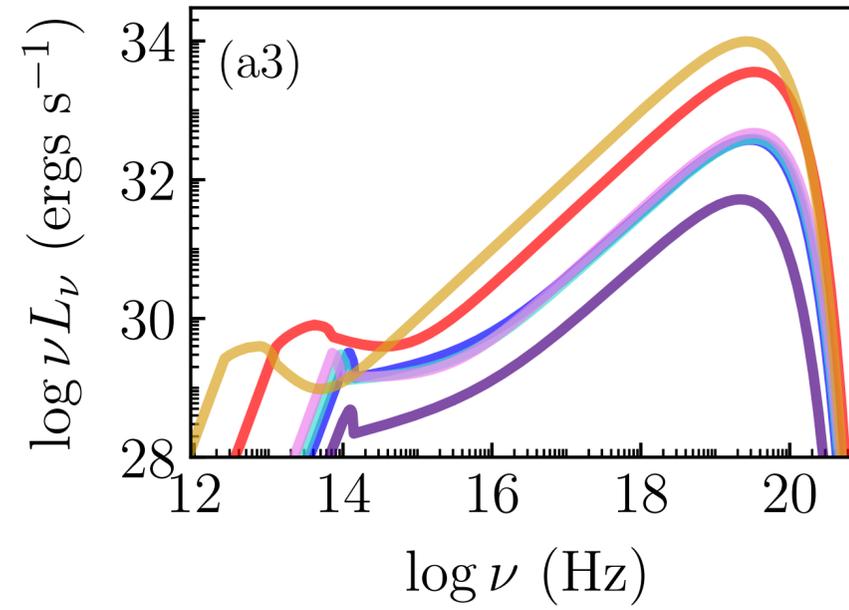
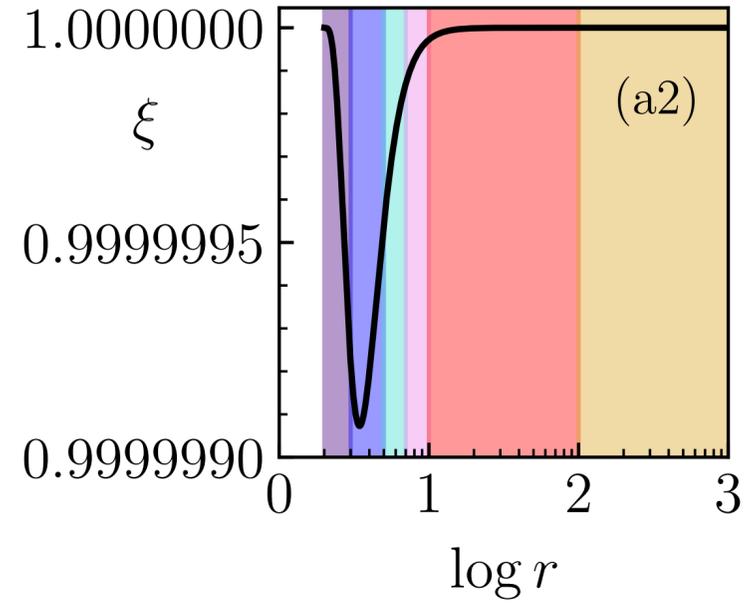
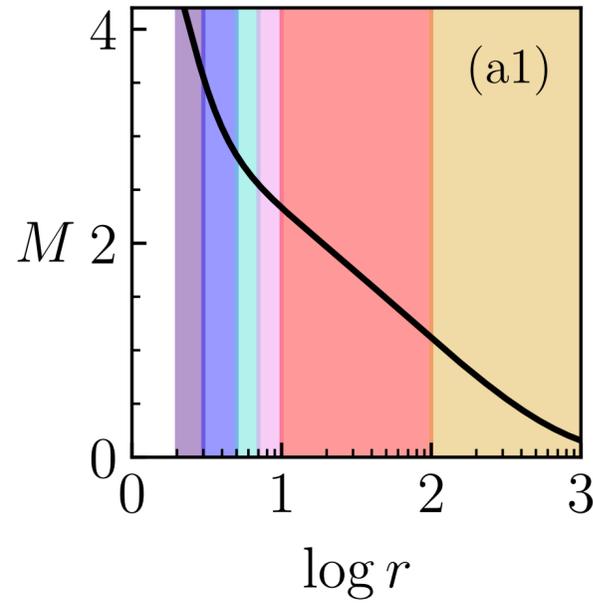
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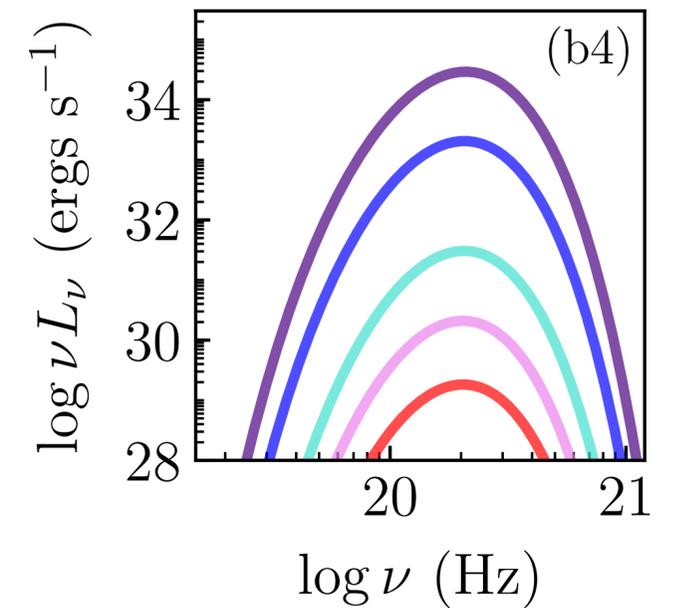
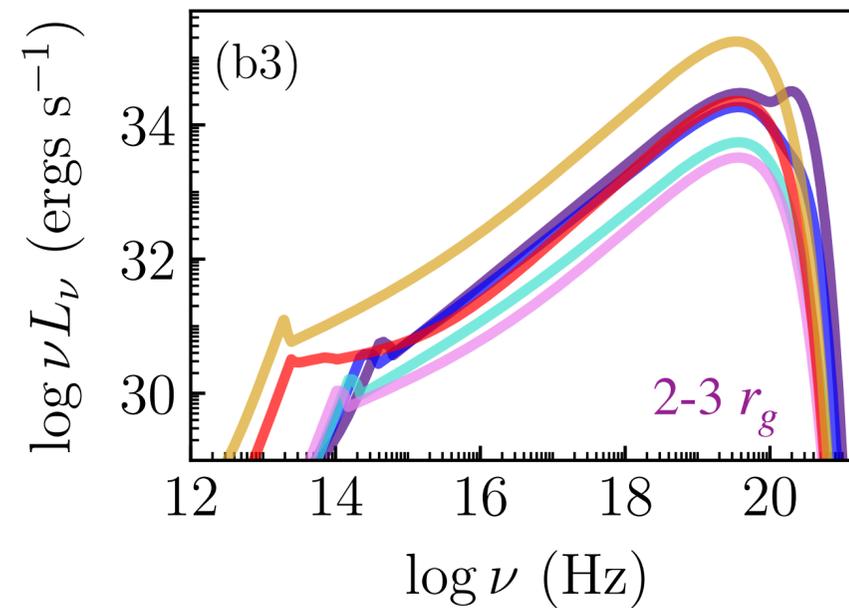
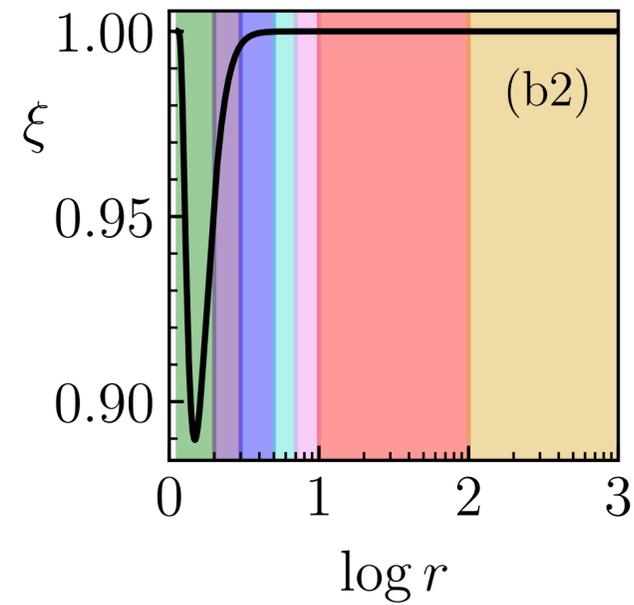
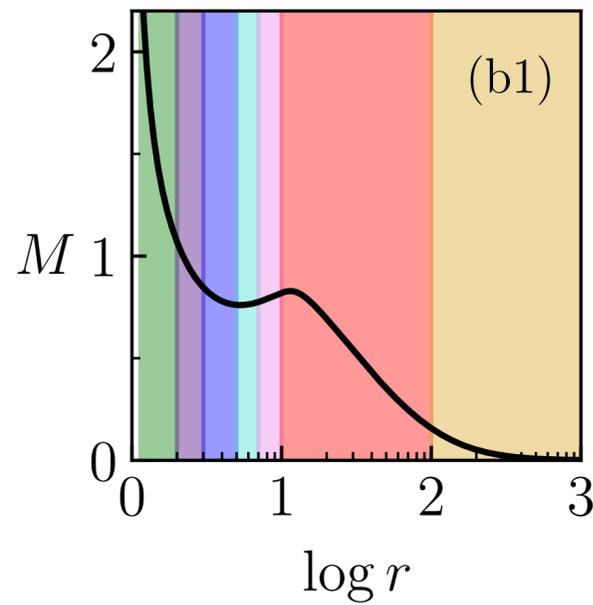
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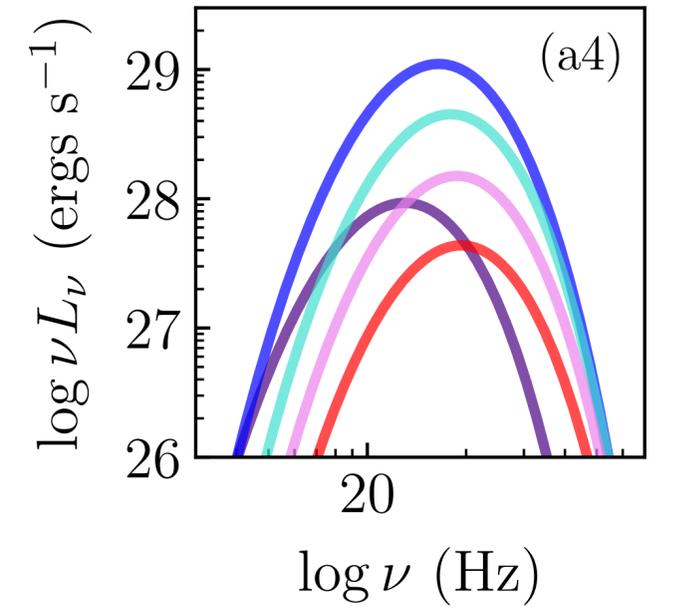
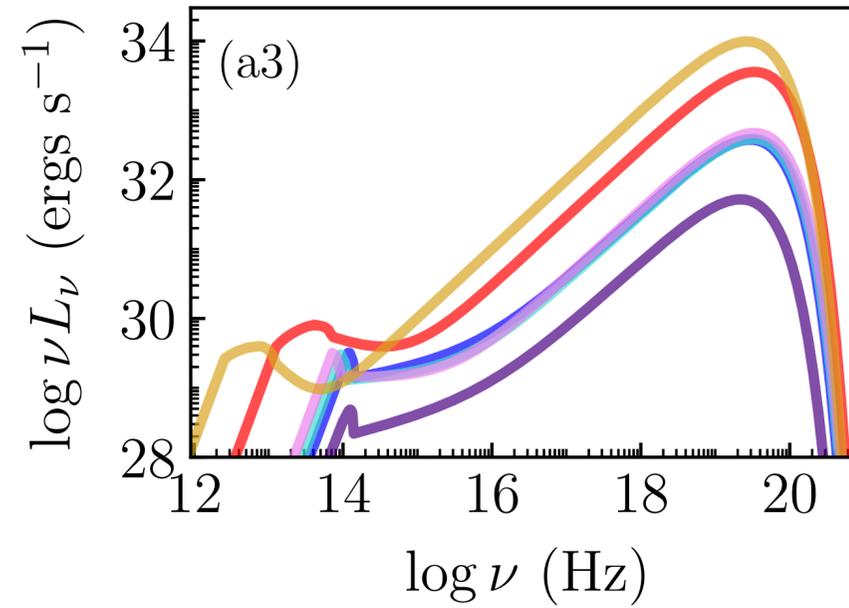
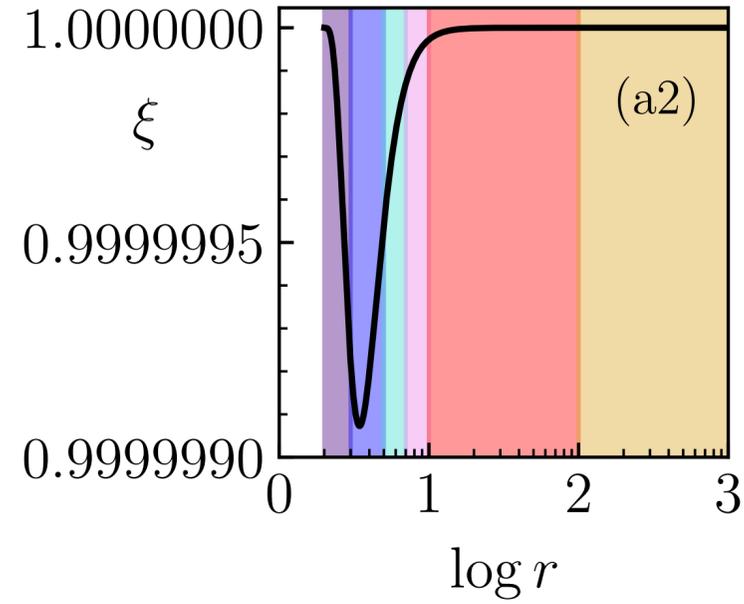
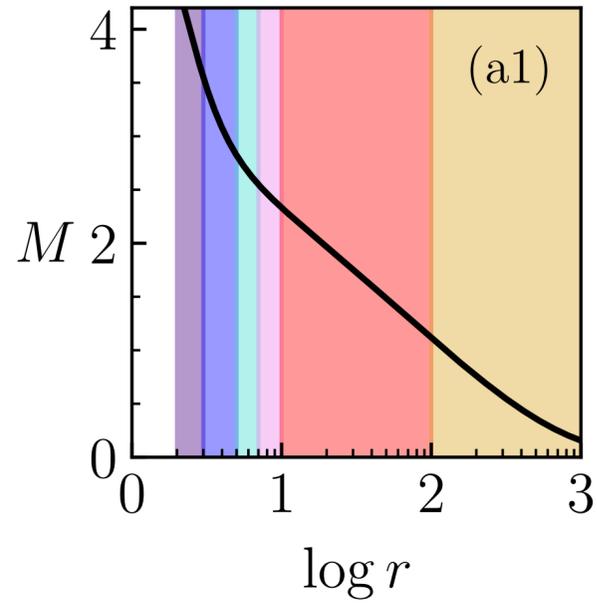
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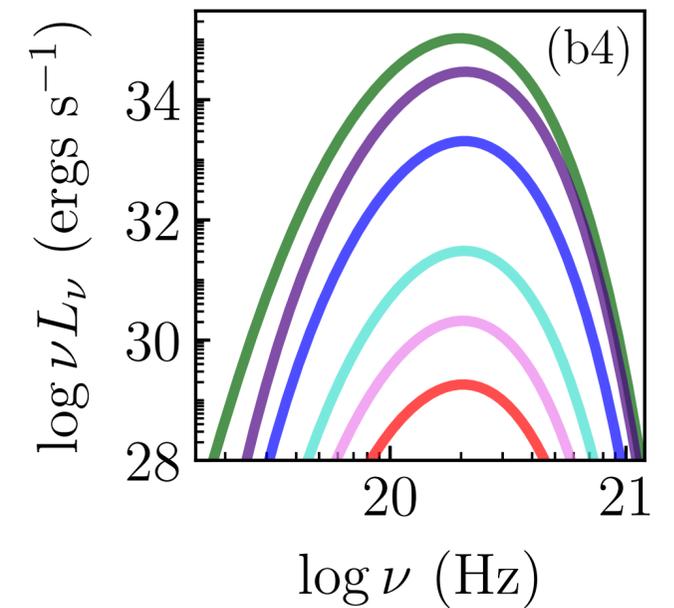
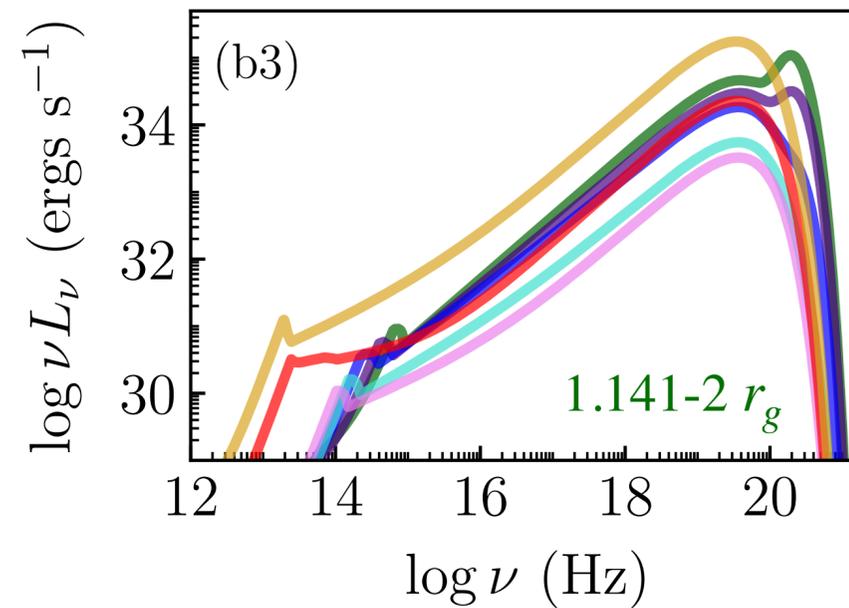
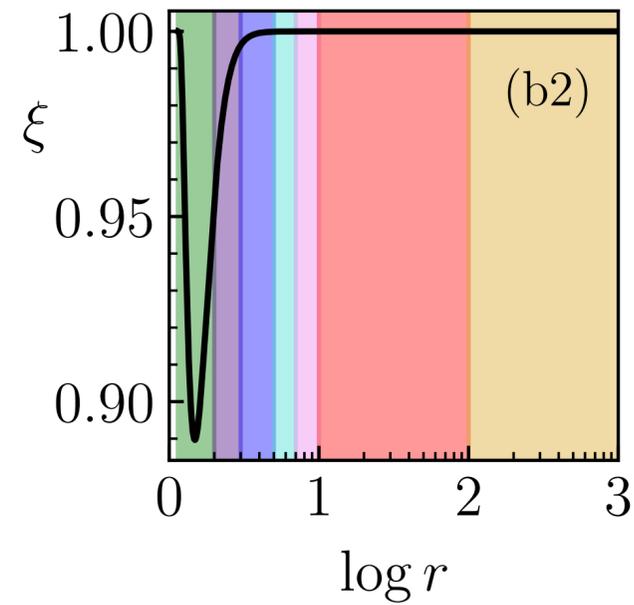
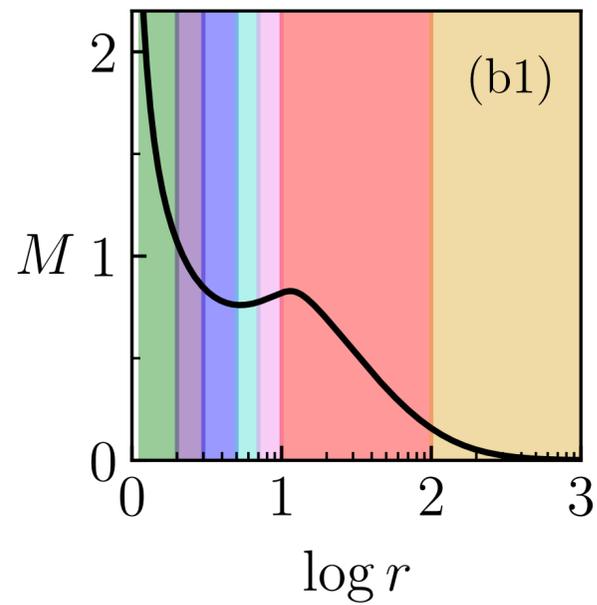
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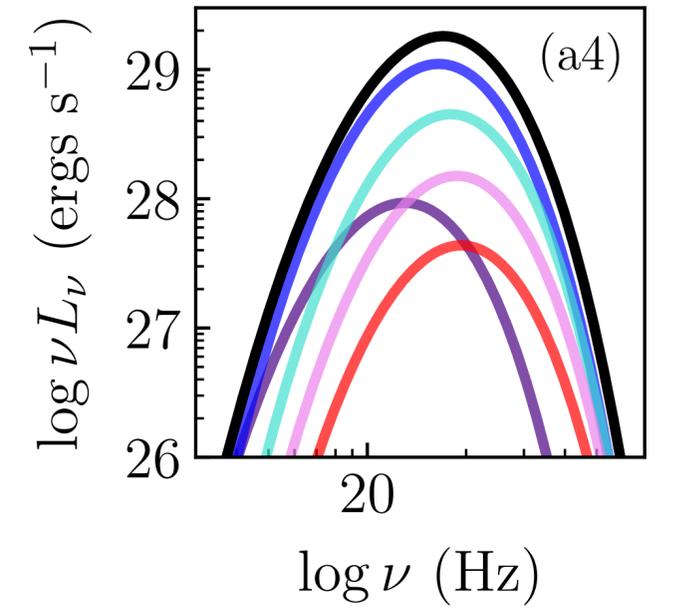
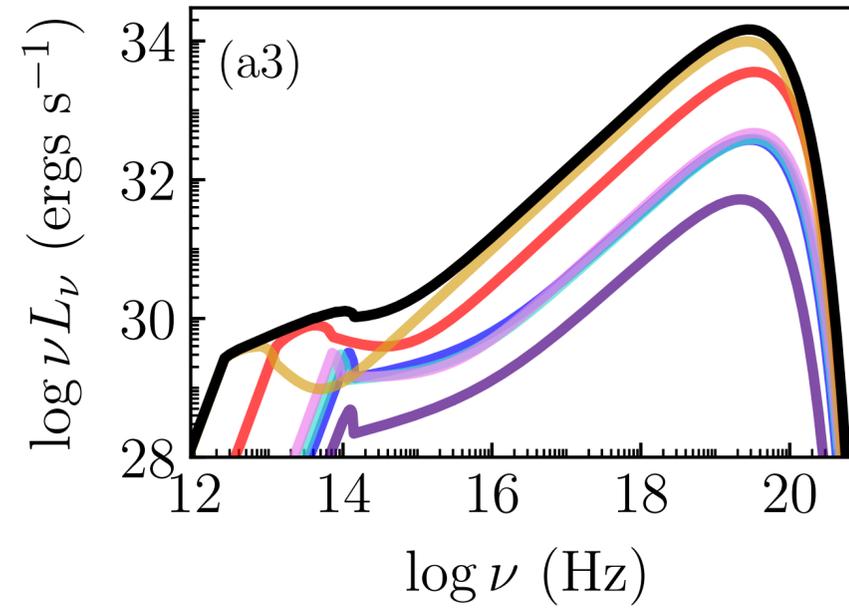
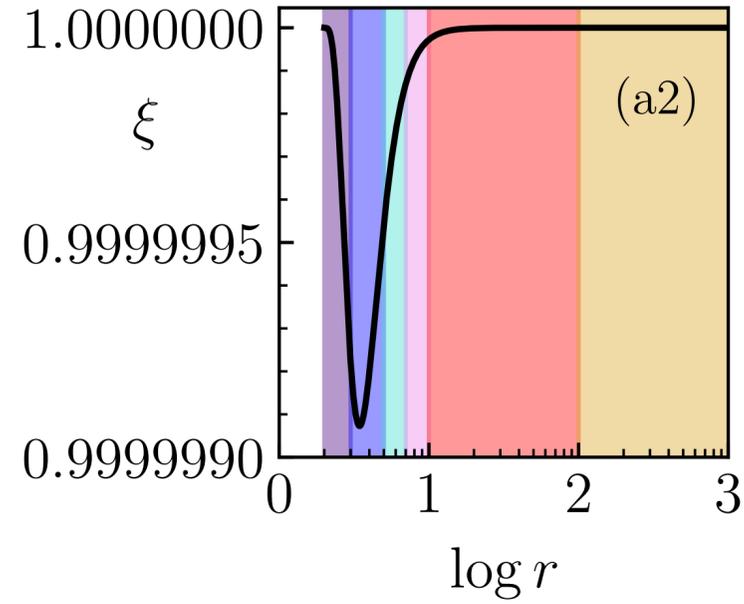
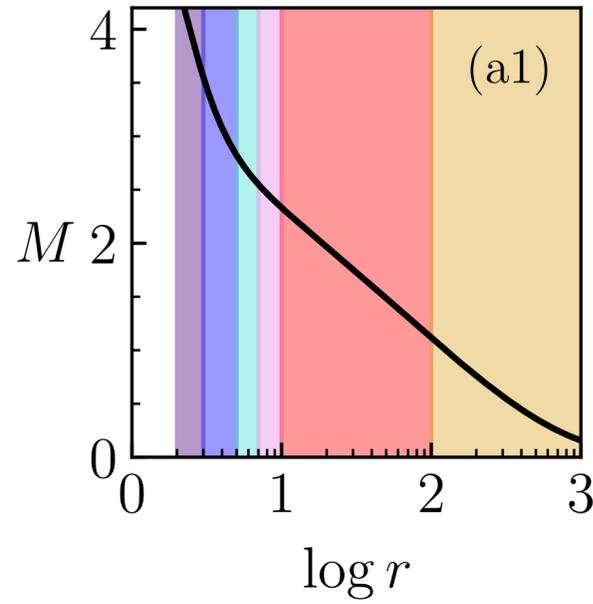
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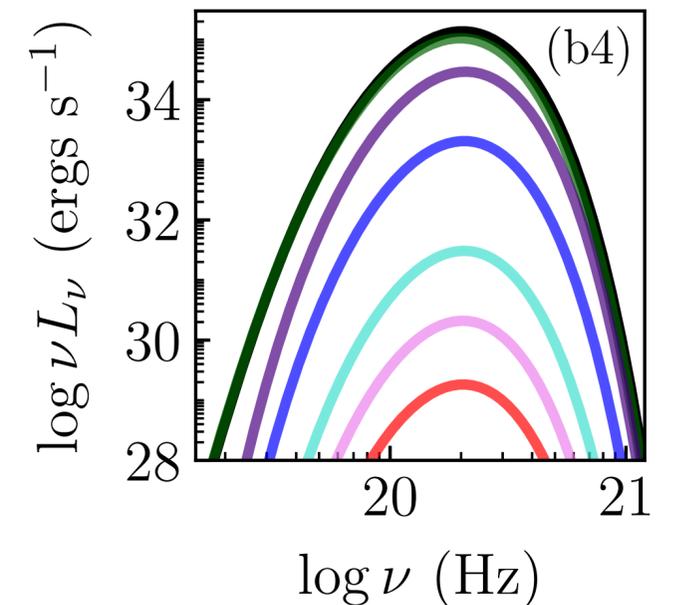
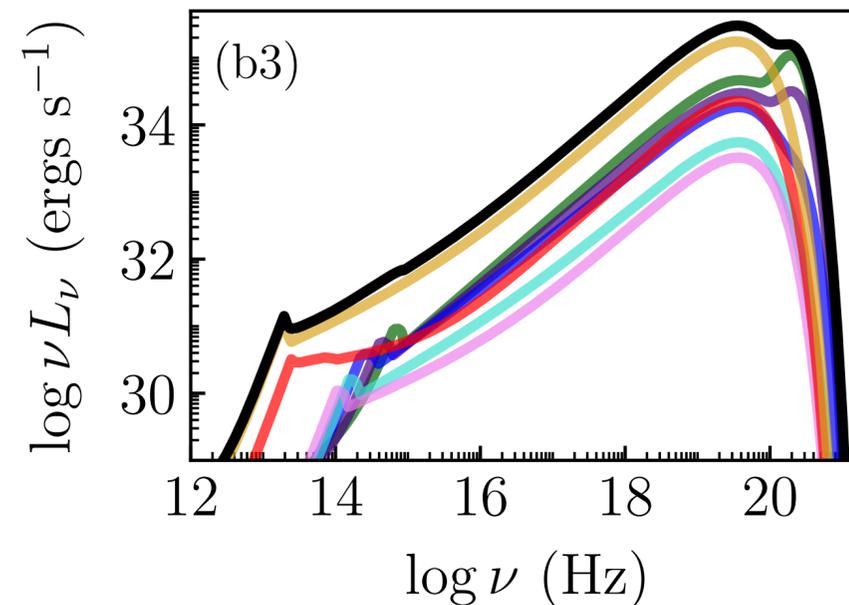
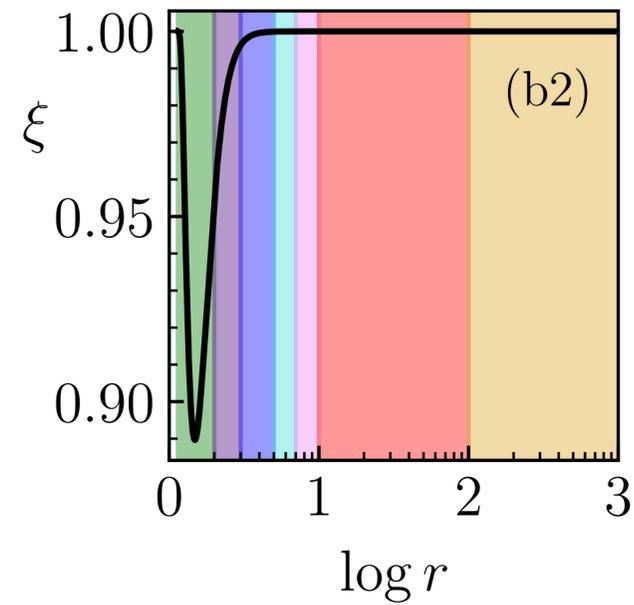
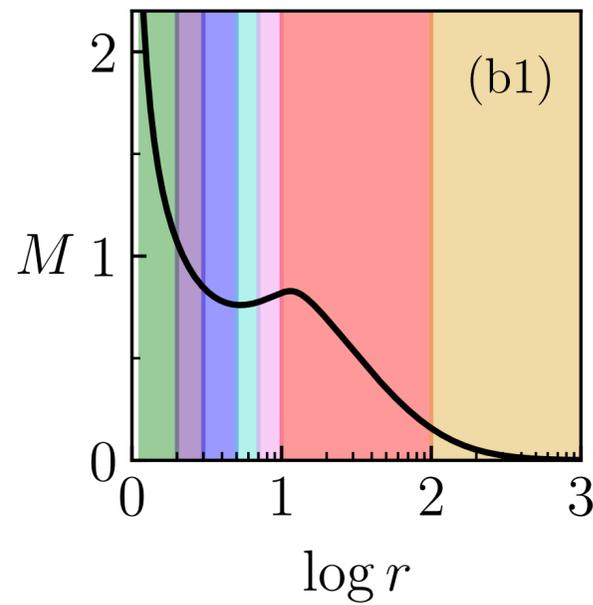
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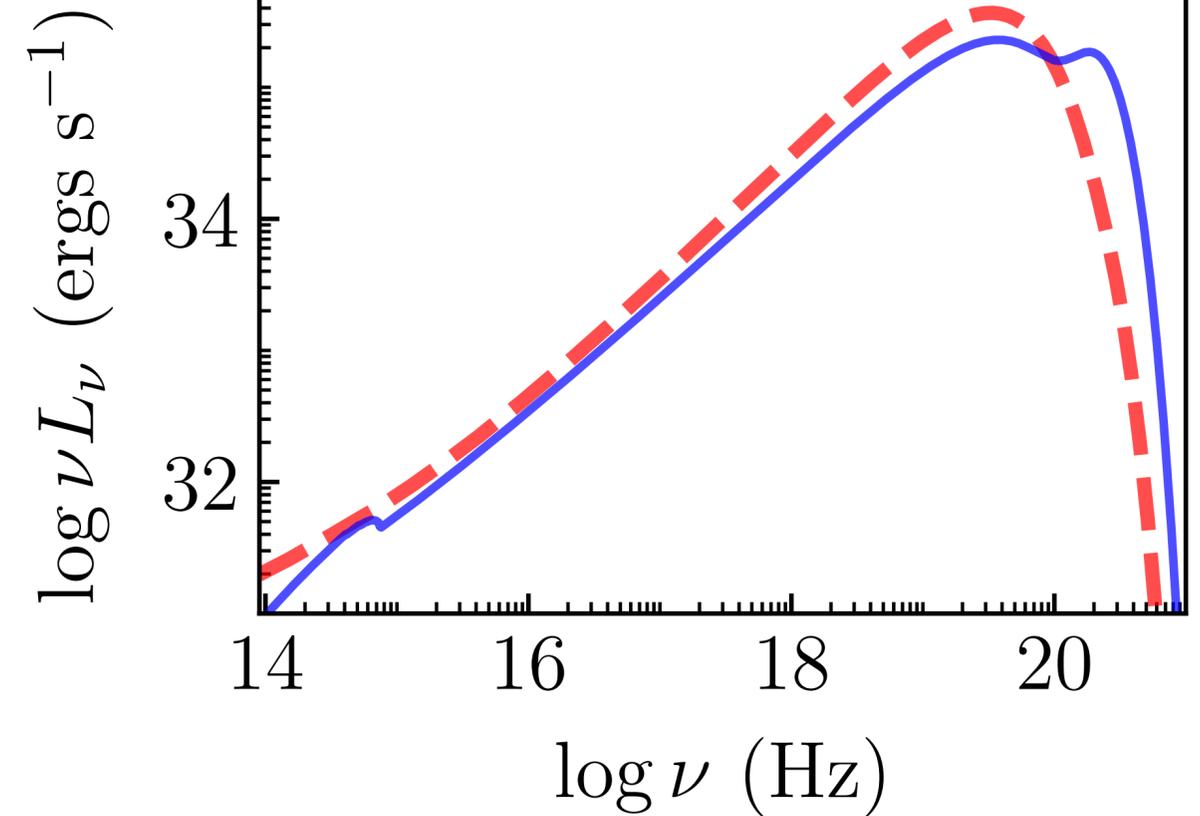
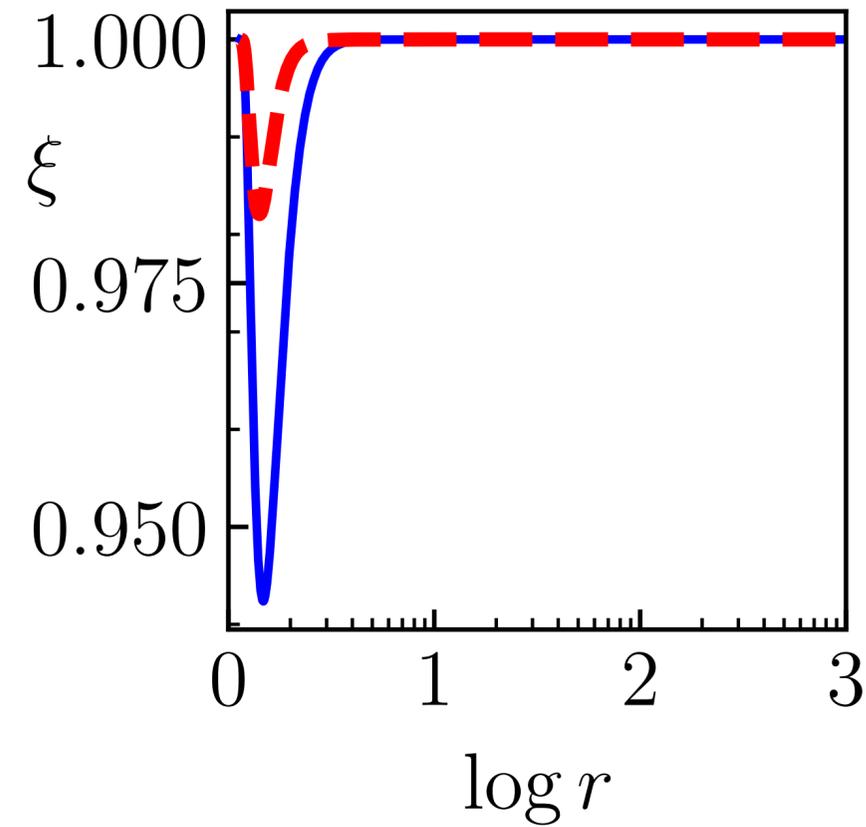
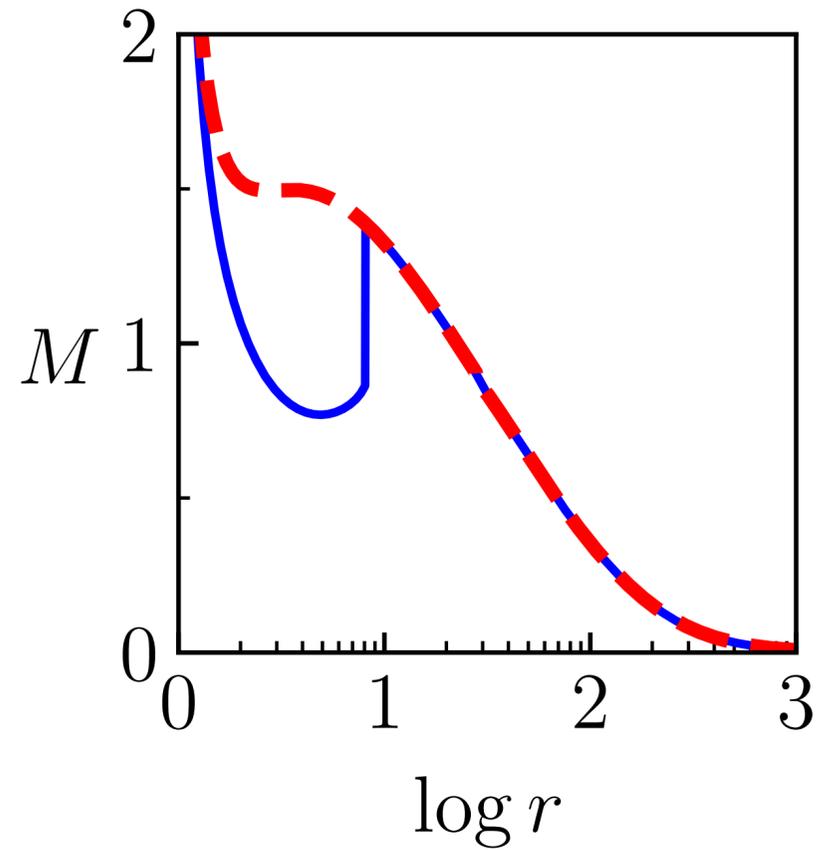


$a_s = 0.99$



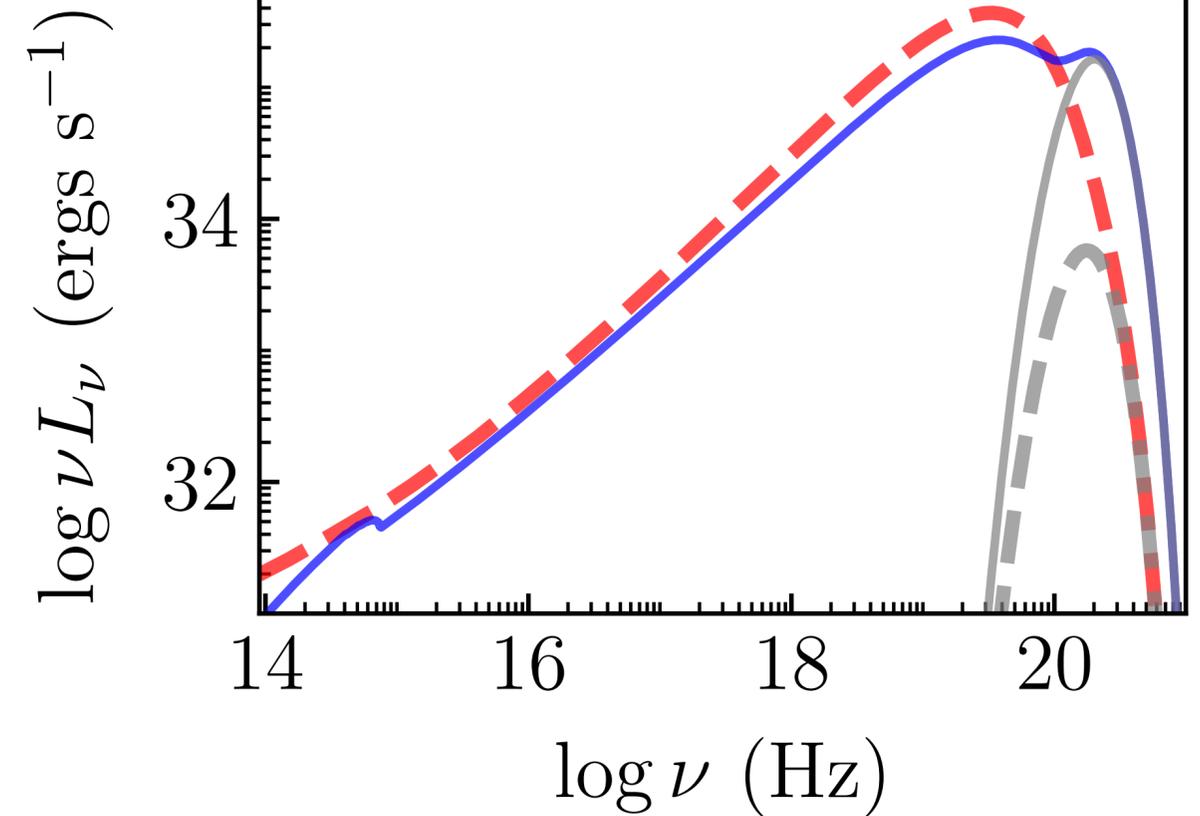
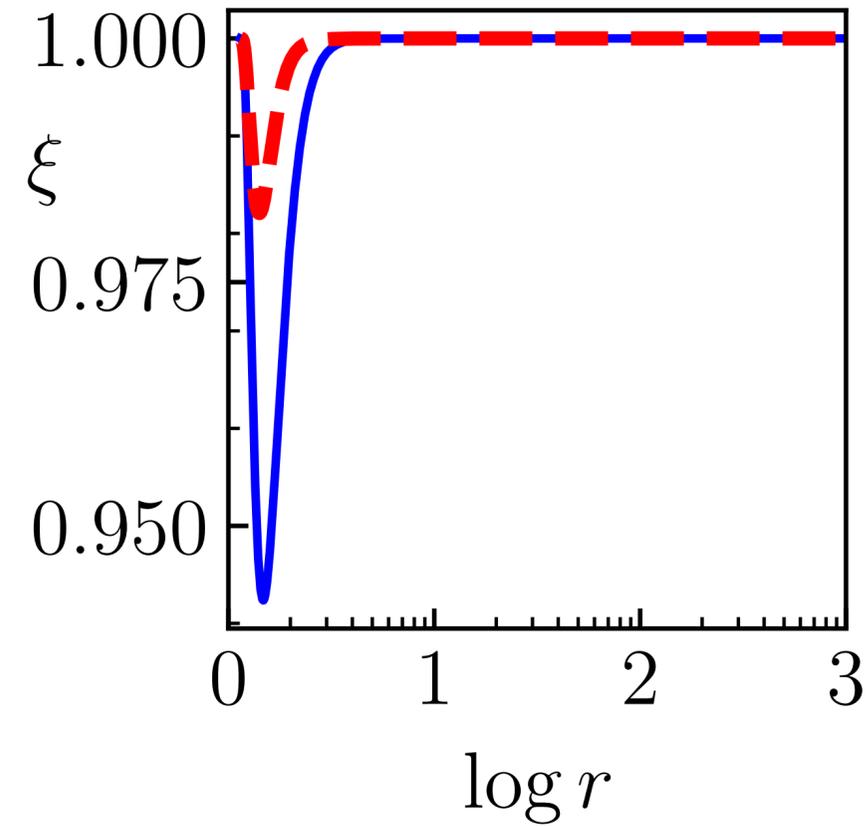
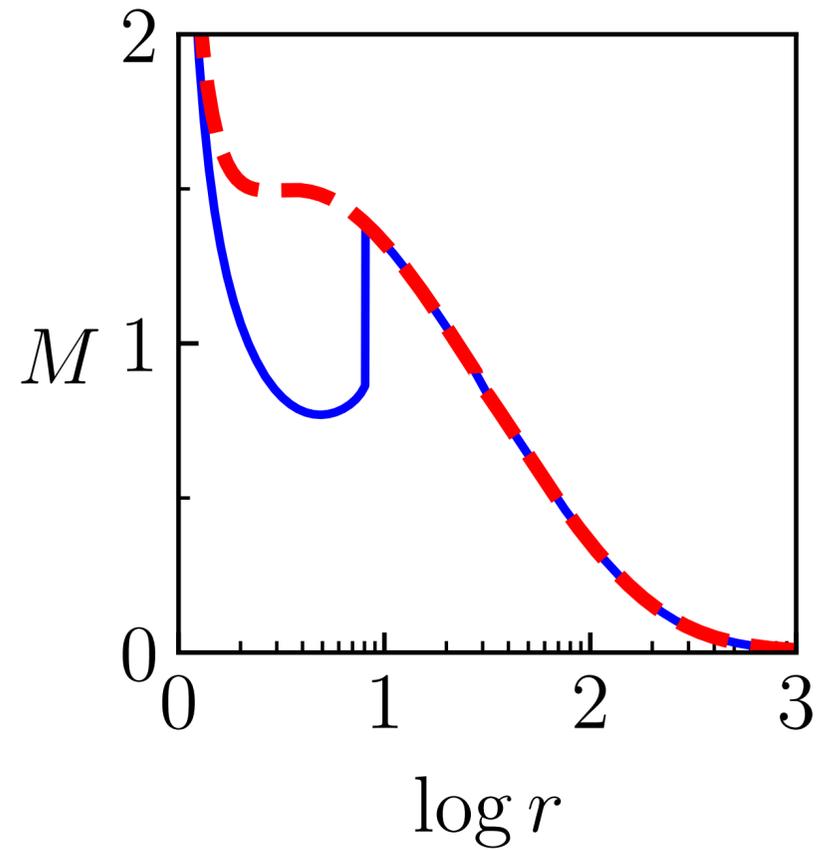
$E = 1.001, L_0 = 2.1, \alpha_v = 0.01, \beta = 0.1, \dot{M} = 0.5\dot{M}_{Edd}, M_{BH} = 10M_{\odot}$

# Shocked solutions



$$E = 1.001, L_0 = 2.1, \alpha_\nu = 0.01, \beta = 0.1, a_s = 0.99, \dot{M} = 0.4\dot{M}_{Edd}, M_{BH} = 10M_\odot$$

# Shocked solutions

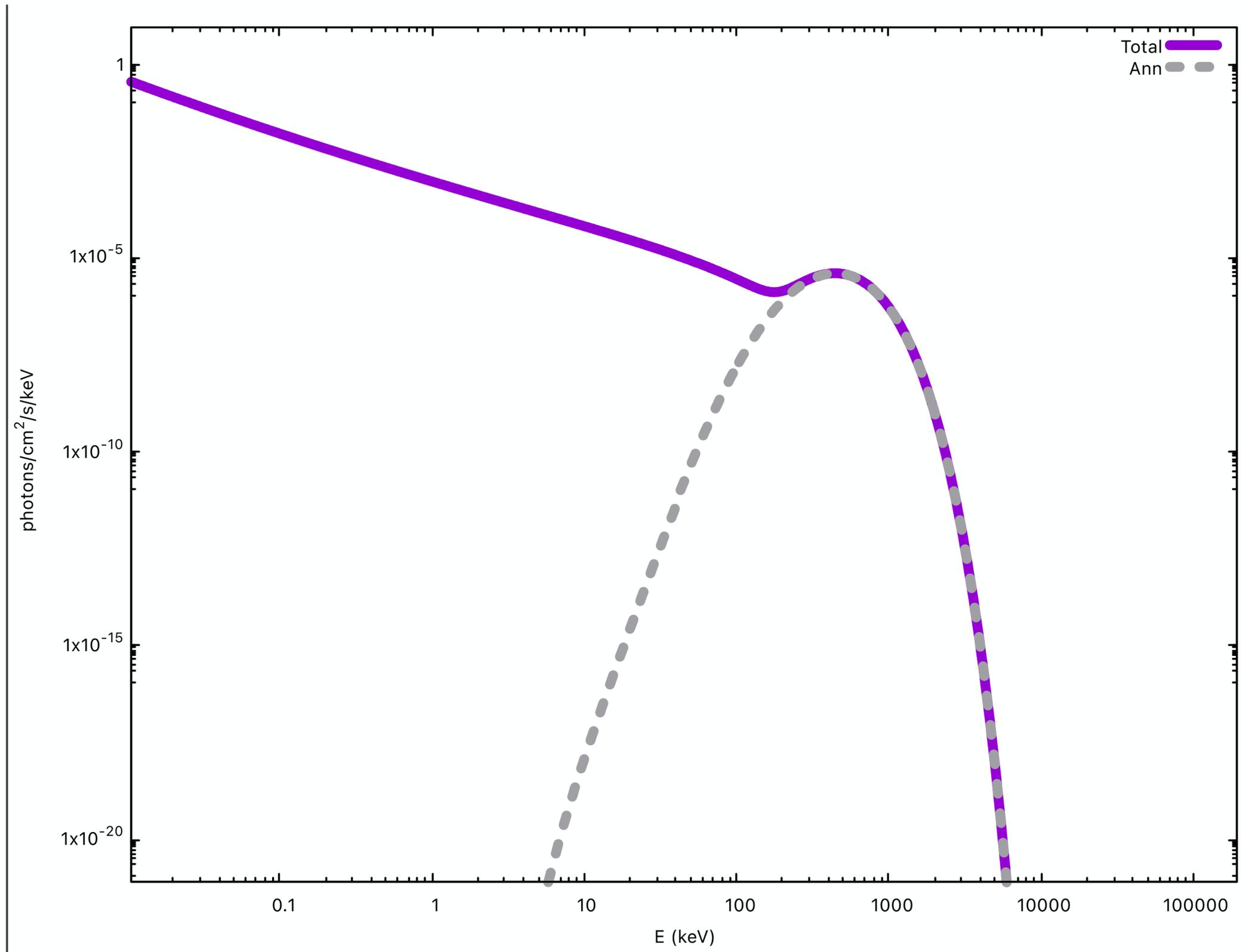


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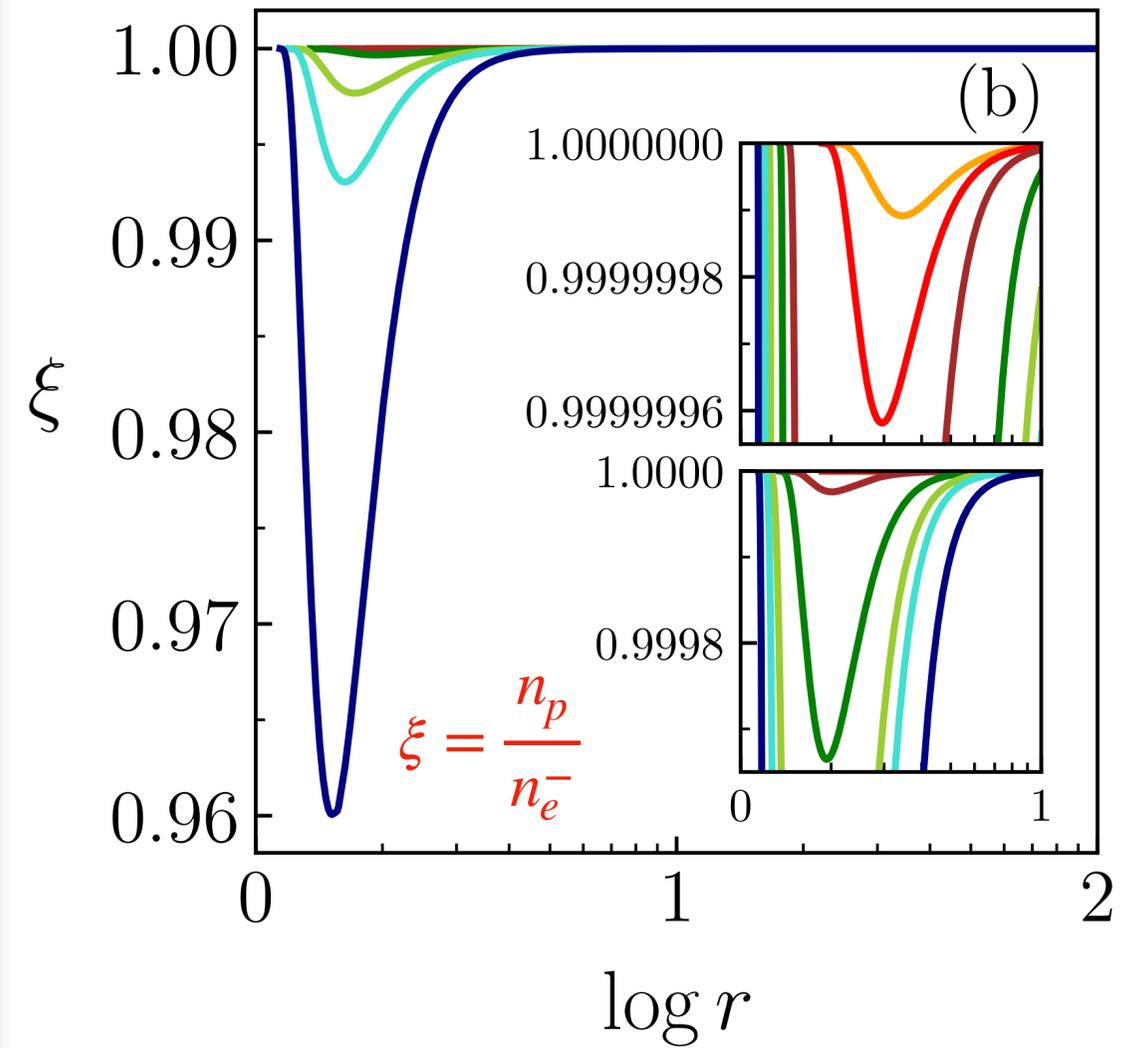
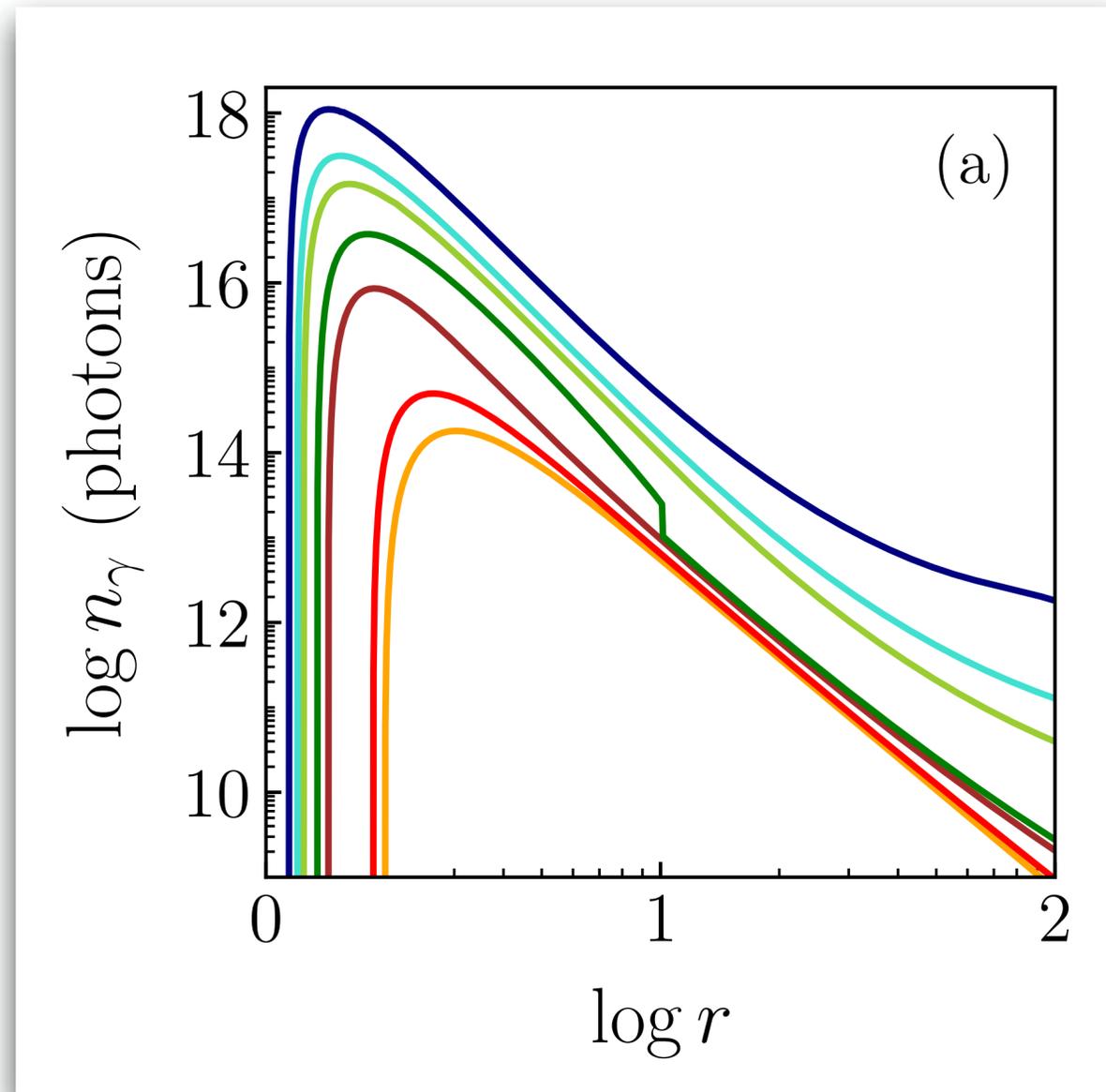
# Conclusions

- ▶ Schwarzschild BHs have no specific signature of the event horizon.
- ▶ Kerr BHs have a distinct annihilation signature!
- ▶ Shocked solutions with Kerr BHs have very strong annihilation line signature.

Thank you !

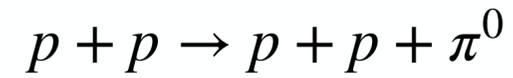


# Results: Spin signature?

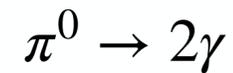


# PROPOSED FUTURE PLANS

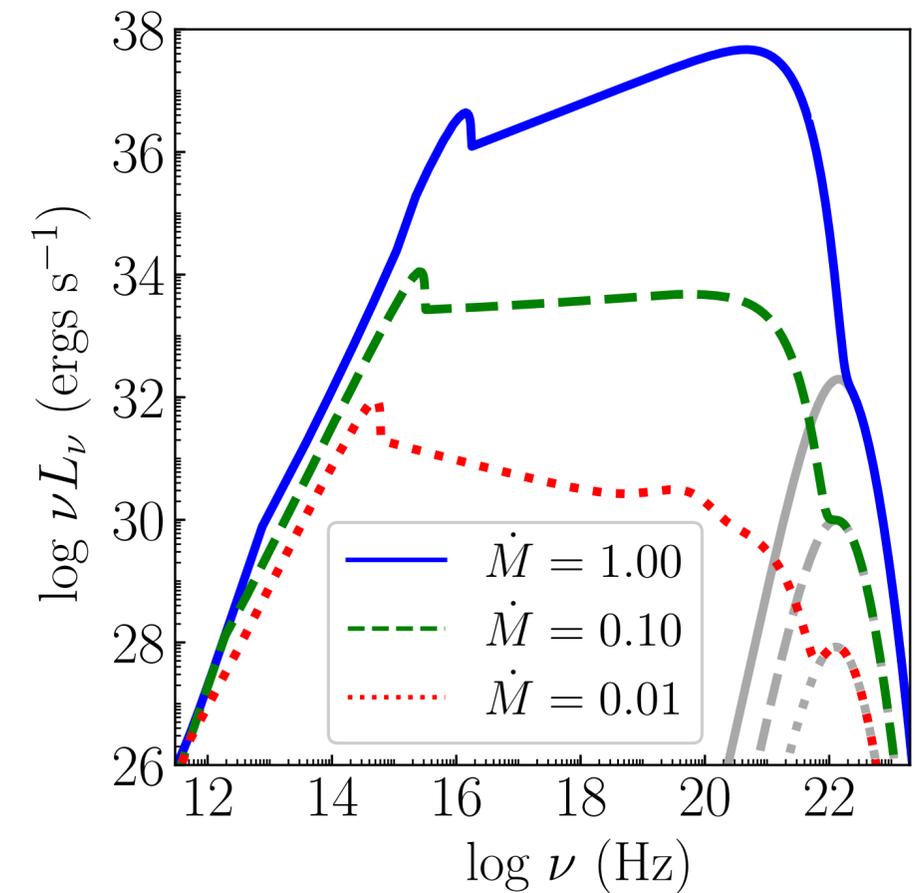
## Gamma Ray production



- ▶ Threshold for this reaction is 290 MeV

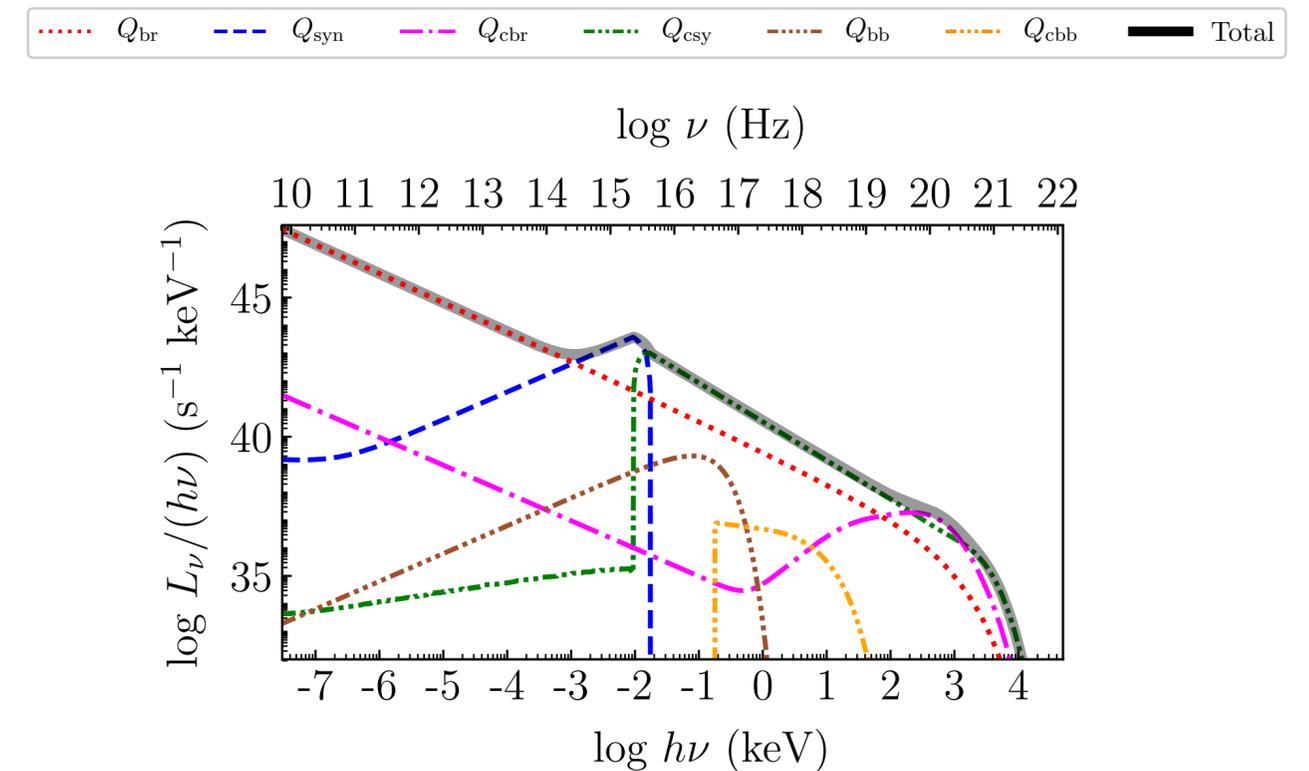
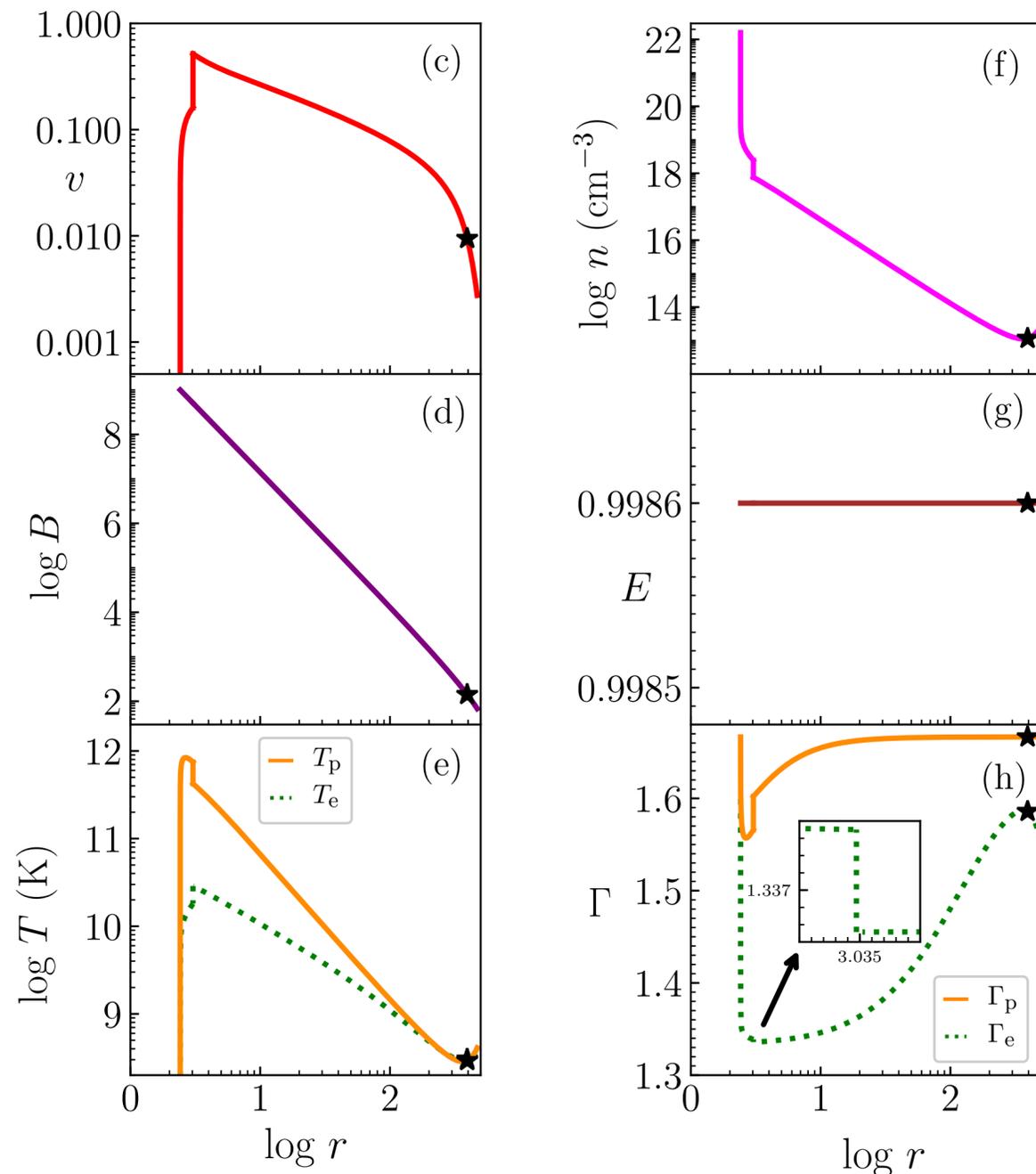


Fractional change in luminosity  
 $< 10^{-4}$



Distinct spectral signature in gamma wavelengths

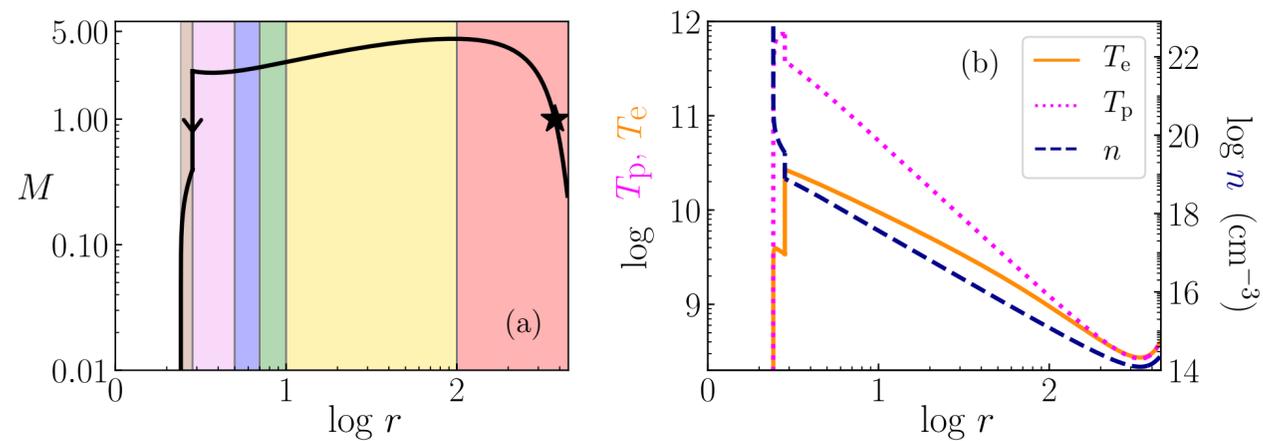
## Typical solution and spectrum



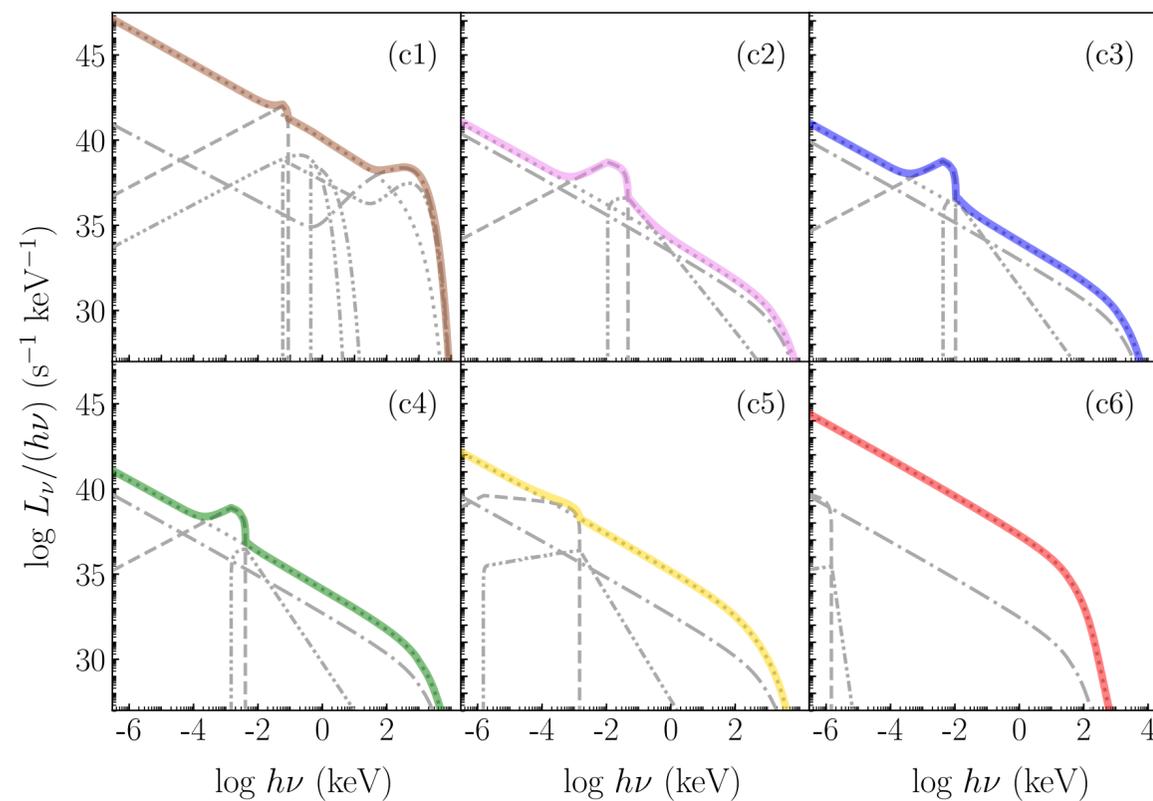
► Relativistic equation of state for thermally trans-relativistic flows (*Chattopadhyay & Ryu 2009*)

The flow parameters are,  
 $E = 0.9986$ ,  $P = 1.25s$ ,  $B_* = 10^9 G$ ,  $\dot{M} = 10^{14} \text{g/s}$

## Contribution from different regions

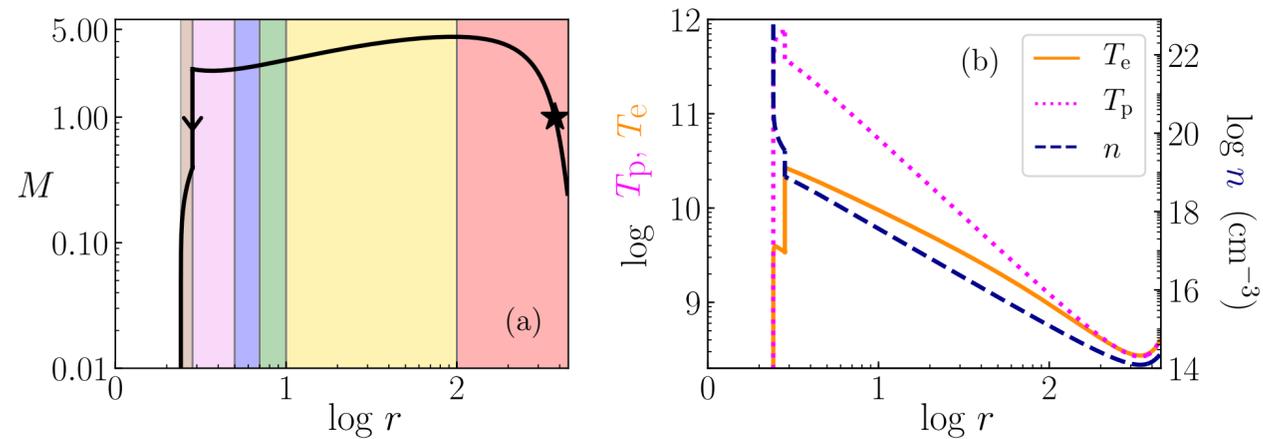


The flow parameters are,  $E = 0.9985$ ,  $P = 1.15s$ ,  $B_* = 5 \times 10^9 G$ ,  $\dot{M} = 10^{15} g/s$

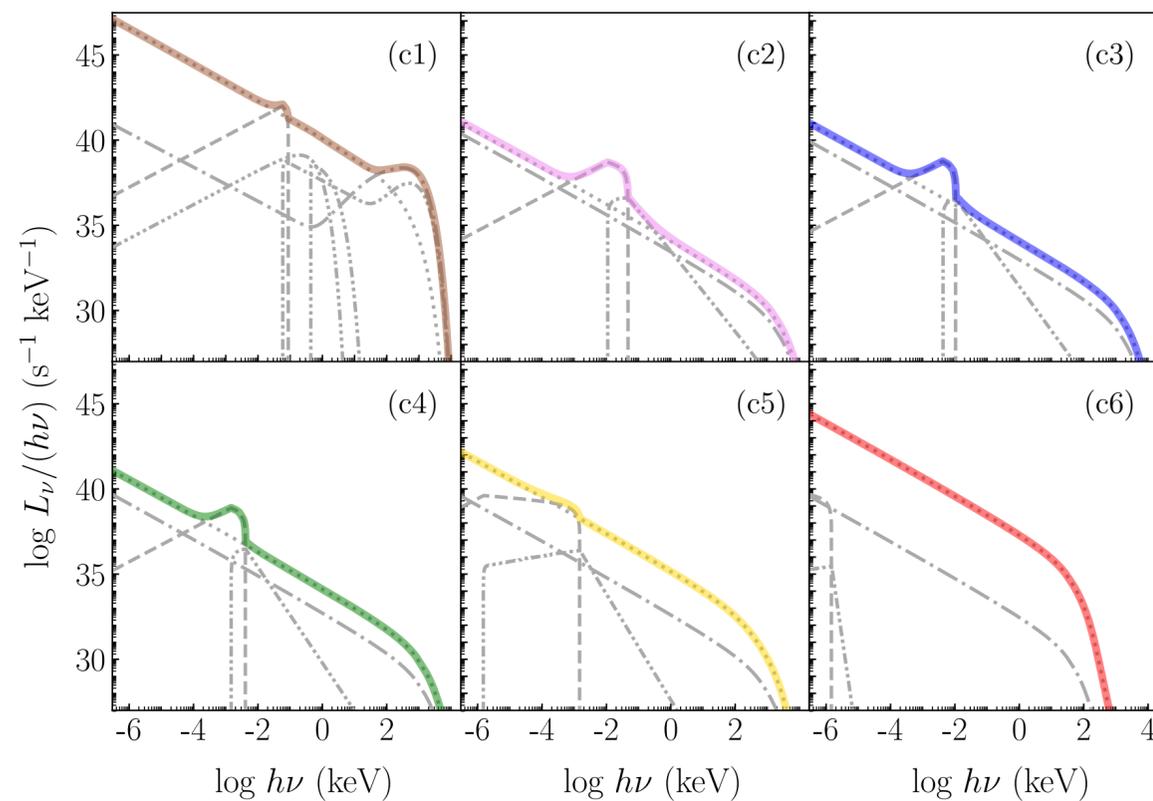


Region ( $r_g$ )	% $L_{tot}$	Colour
2.418-2.829	99.98	Brown
2.829-5.0	$4.873 \times 10^{-6}$	Violet
5.0-8.0	$3.150 \times 10^{-6}$	Blue
8.0-10.0	$1.209 \times 10^{-6}$	Green
10.0-100.0	$6.674 \times 10^{-6}$	Yellow
100.0-444.71	$1.355 \times 10^{-4}$	Red

## Contribution from different regions

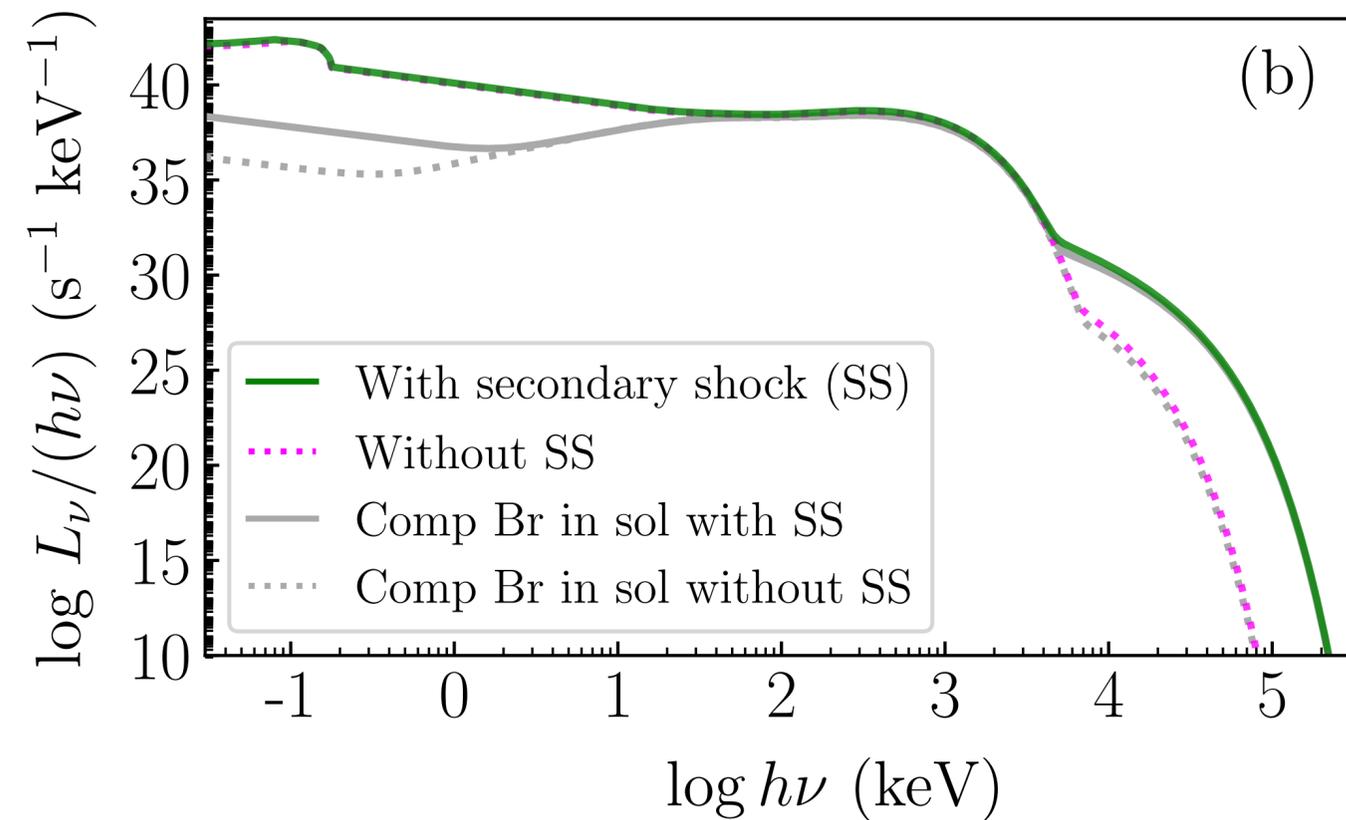
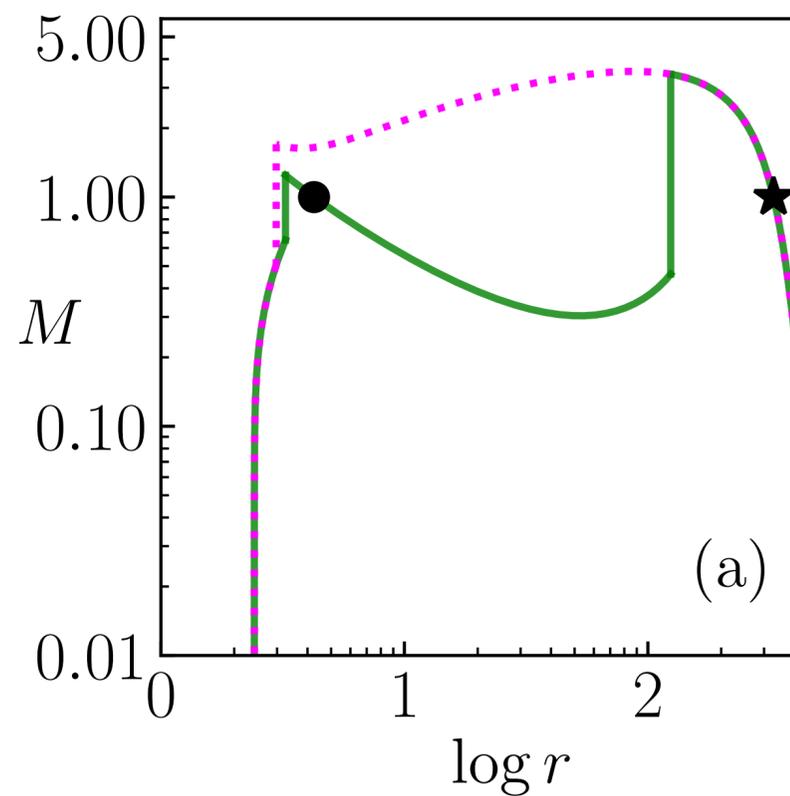


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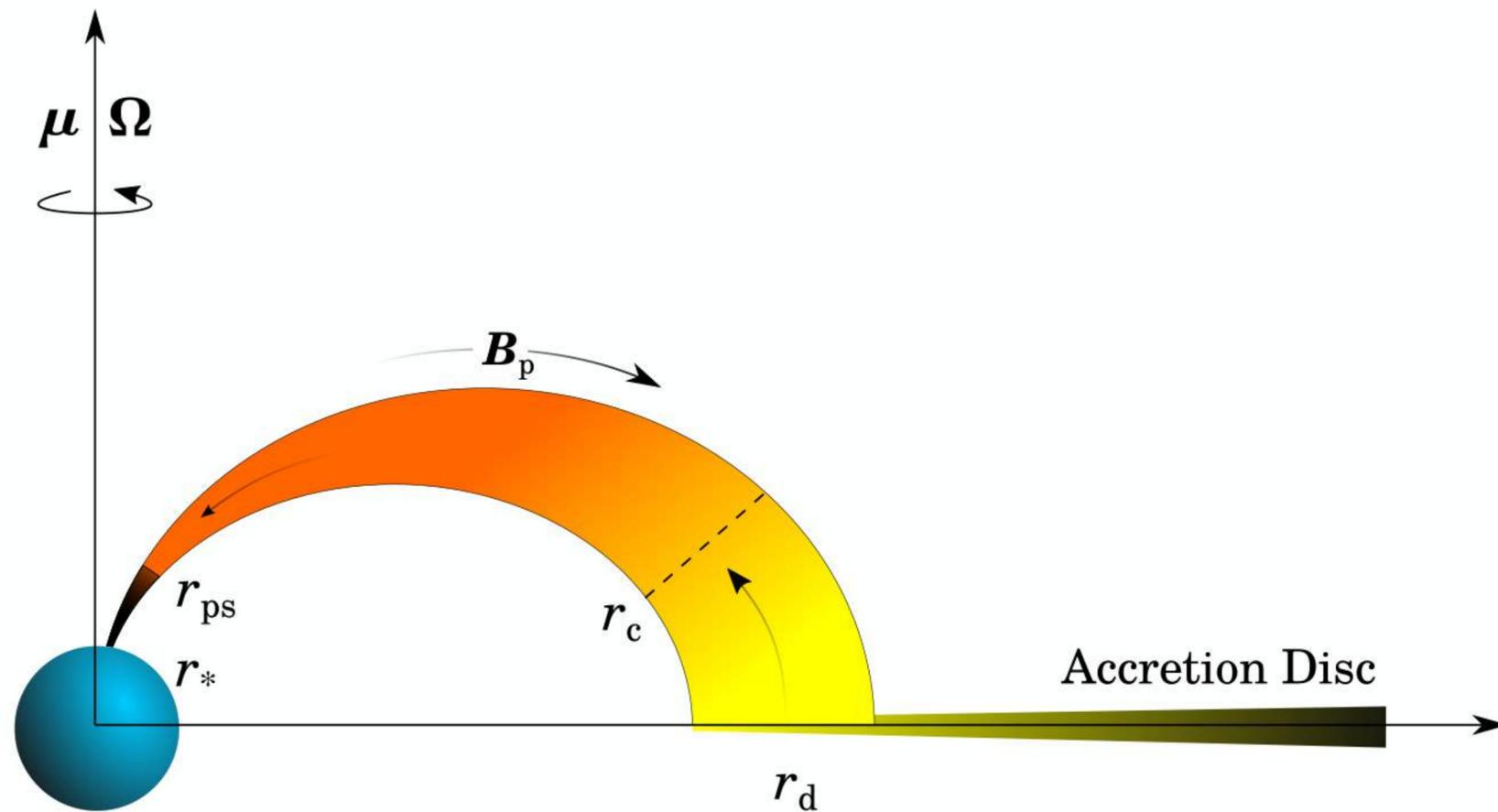


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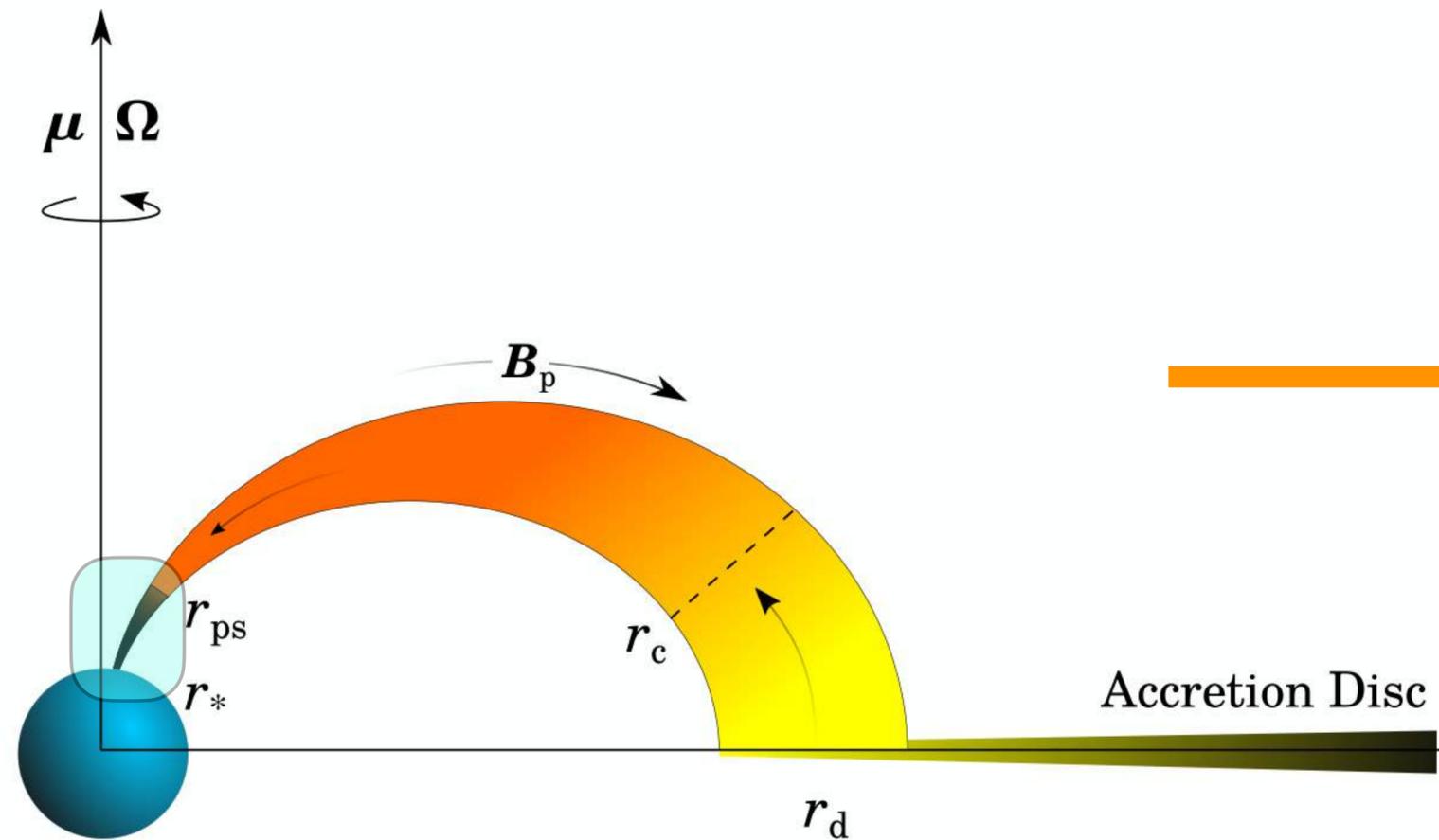
## Signature of secondary shocks



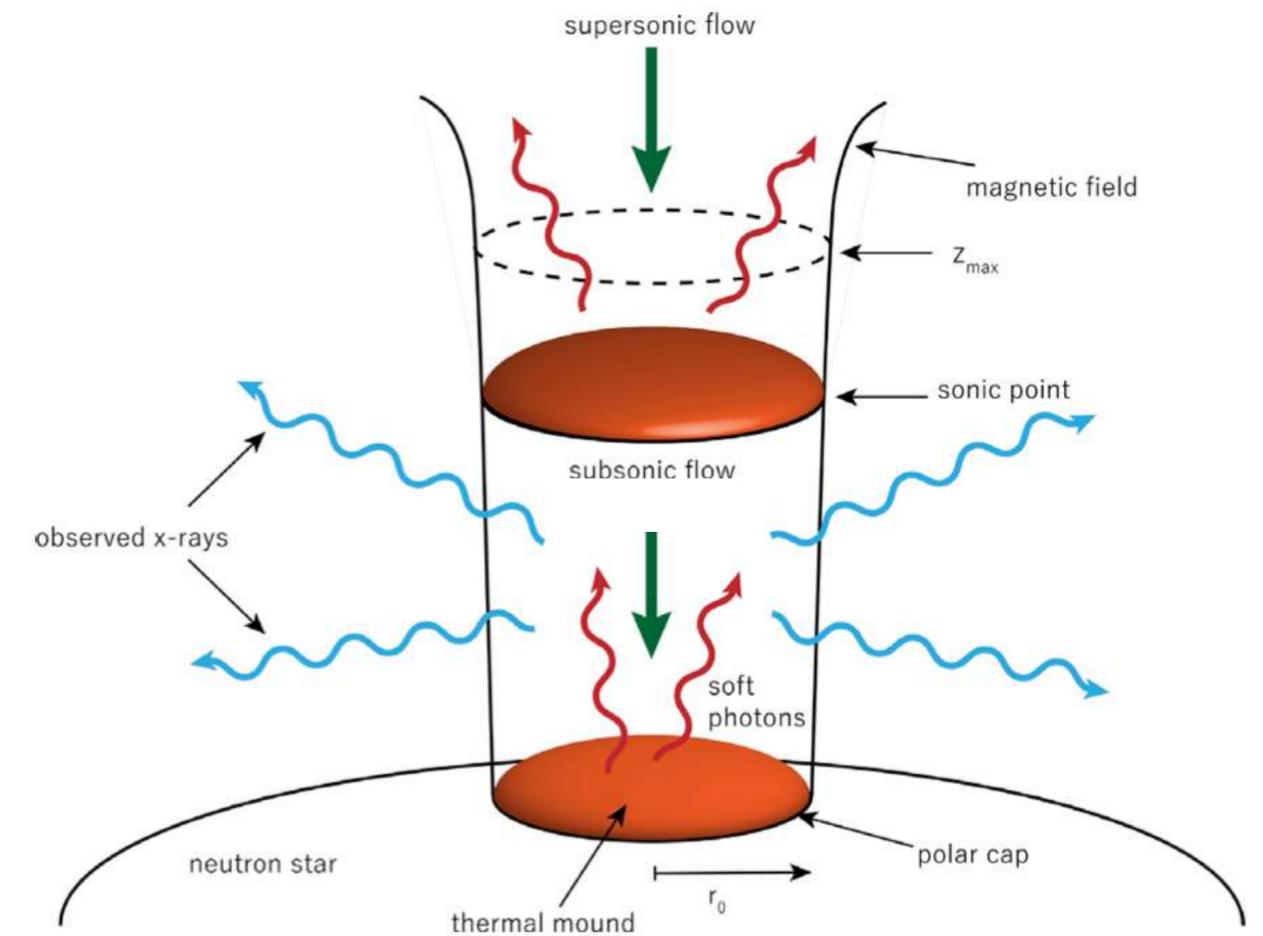
The flow parameters are,  $E = 0.9984$ ,  $P = 0.98s$ ,  $B_* = 10^{10}G$ ,  $\dot{M} = 10^{15}g/s$



Representation of accretion flows around NS.



Representation of accretion flows around NS.

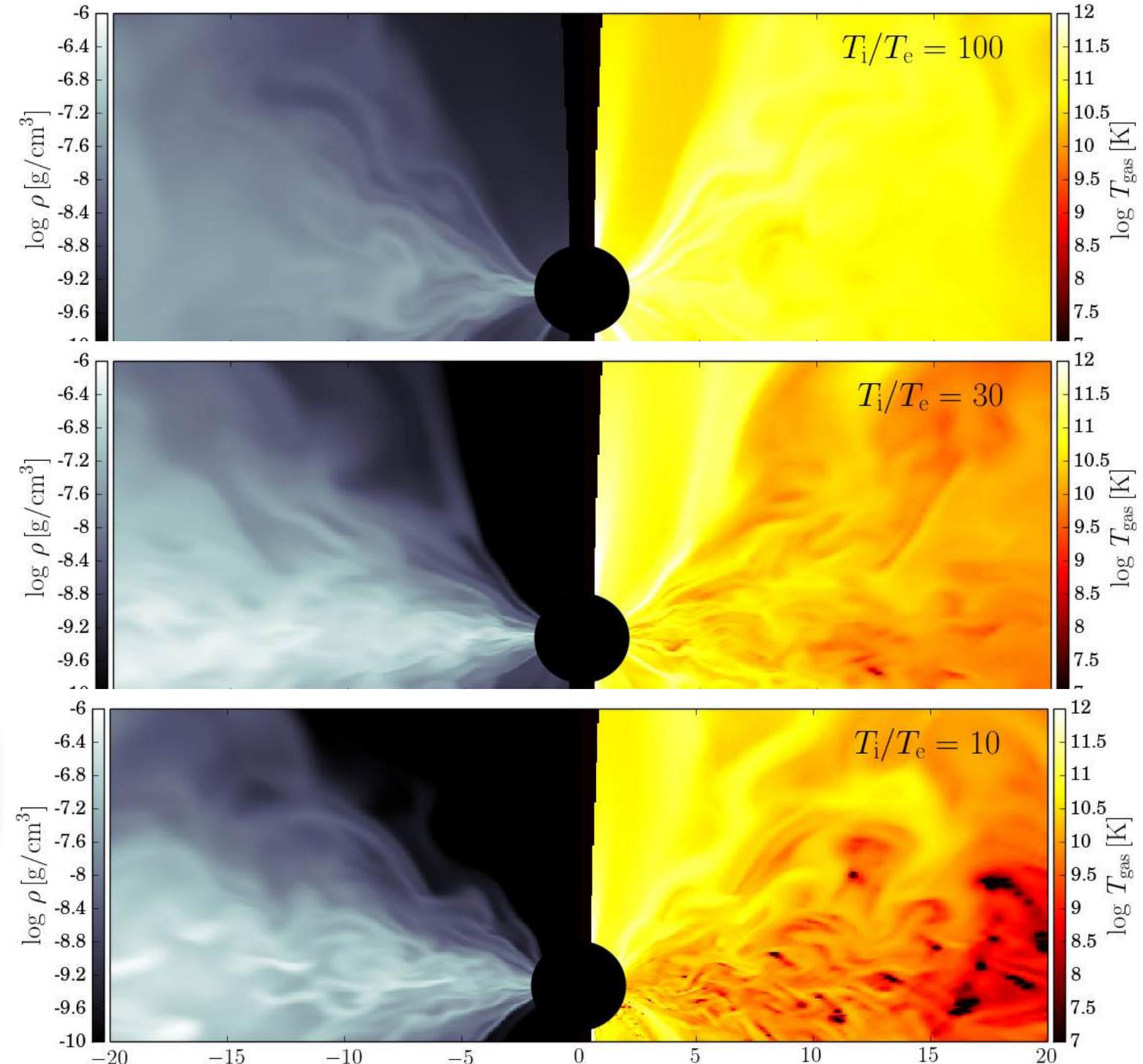
Structure of the accretion column (*Caiazzo & Heyl, 2021*)

# Its SERIOUS !

- ◉ **Liang & Thompson et. al 1980 (Compact Objects):** “because of the uncertainty in the mechanism coupling electrons and ions, we simply parameterize  $T_p/T_e$  as a constant”
- ◉ **Medvediv & Narayan 2001 (Neutron Stars):** “Compton cooling balances heat transfer from the ions. Equating the two rates, we find, approximately  $T_e \Rightarrow Q_e^+ = Q_e^-$ ”
- ◉ **Saxton et. al 2005 (White Dwarfs):** “The physics of how the electrons couple with the ions is not well understood. We therefore treat the ratio between proton and electron temperature as a free parameter”

Every work on two-temperature regime, considered to parameterize  $T_p/T_e$  to certain constant values or have forced some relation between them

- ▶ This degeneracy is irrespective of the type of central object
- ▶ Intrinsic of two-temperature regime

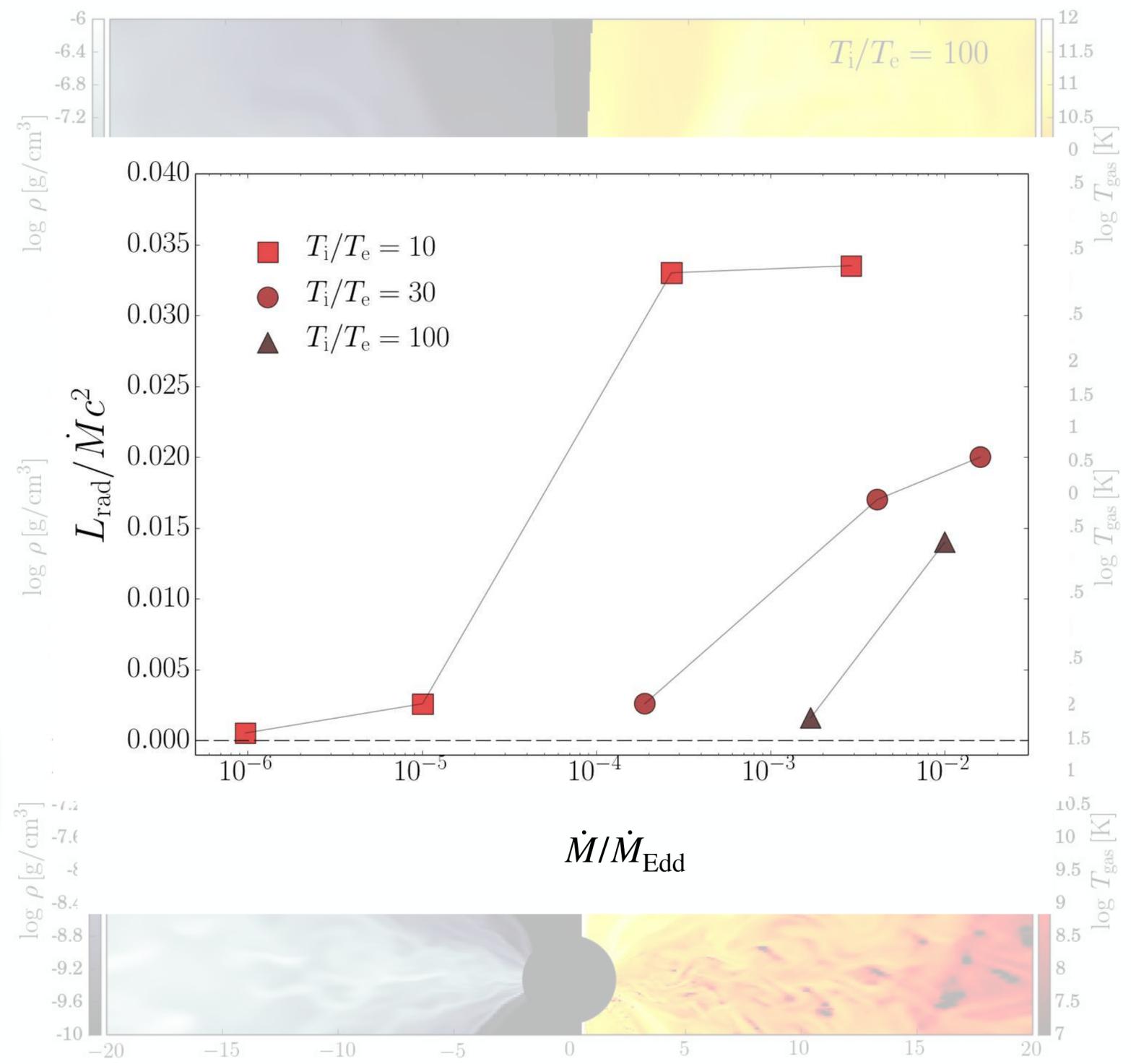


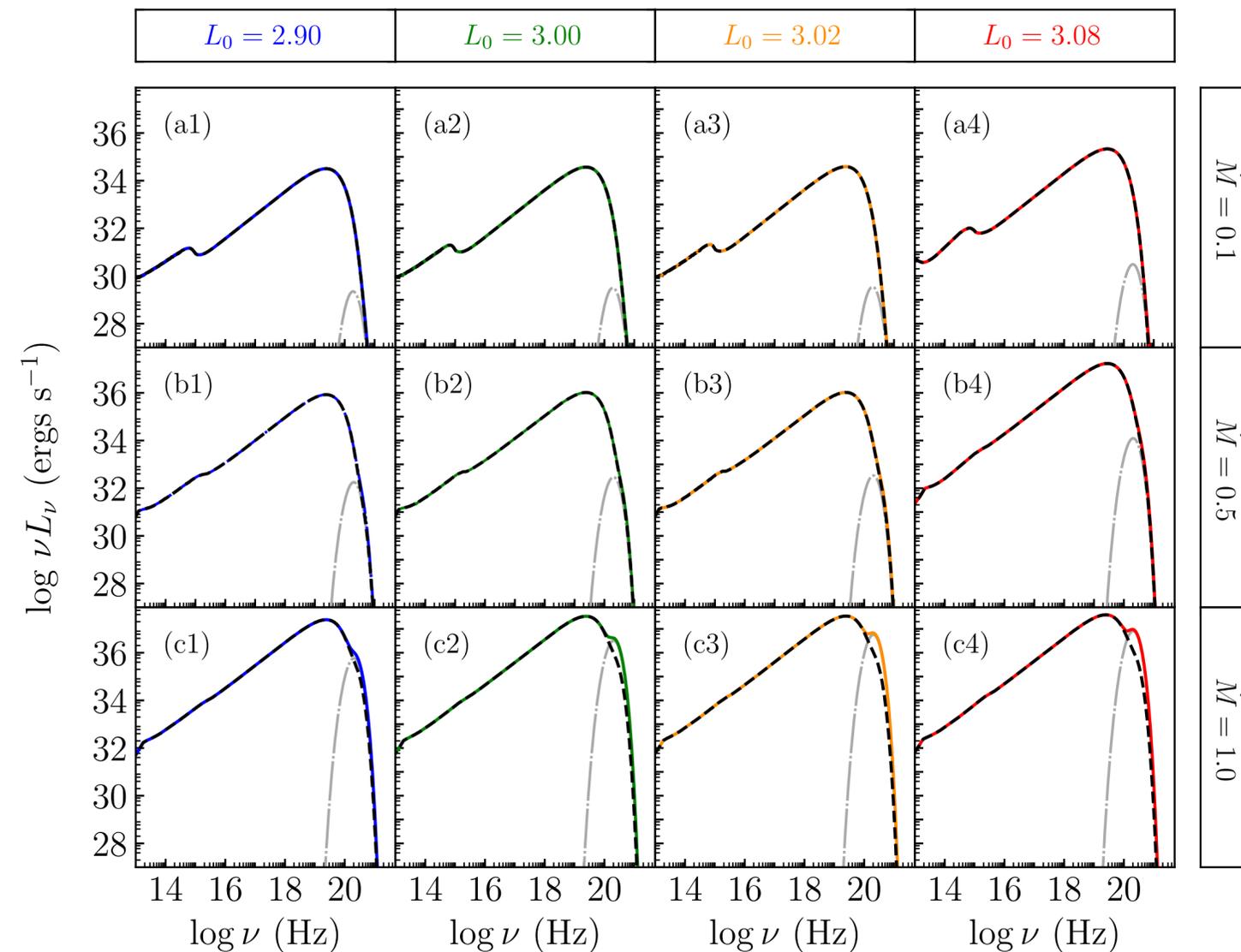
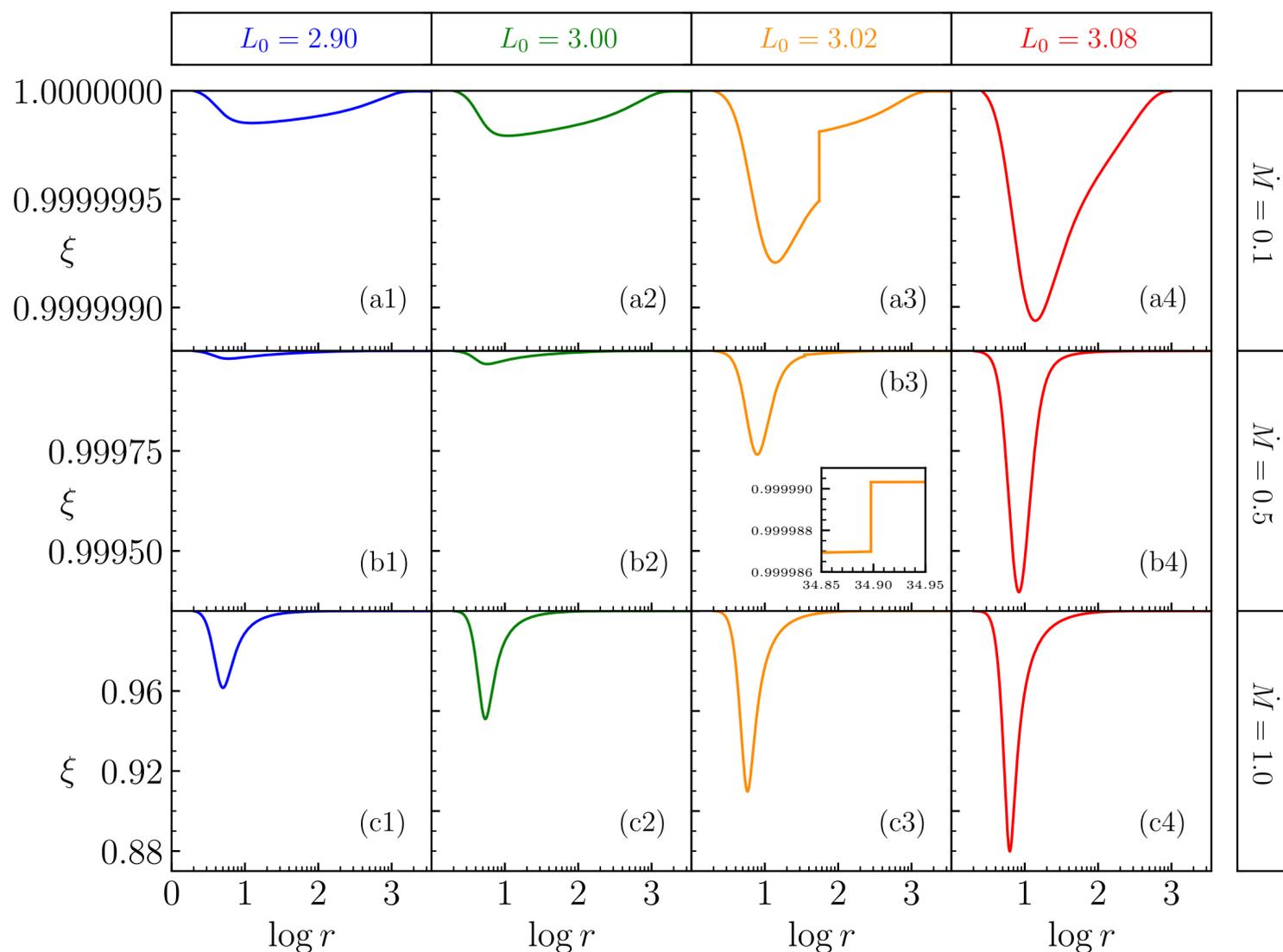
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Every work on two-temperature regime, considered to parameterize  $T_p/T_e$  to certain constant values or have forced some relation between them

- ▶ This degeneracy is irrespective of the type of central object
- ▶ Intrinsic of two-temperature regime



RESULTS:  $L_0 - \dot{M}$  PARAMETER SPACE

\* Higher  $\dot{M}$ s :  $n_e^+$  produced are higher, the fractional increase in  $L$  is large and the maximum found— 7% for  $\dot{M} = 1\dot{M}_{\text{Edd}}$

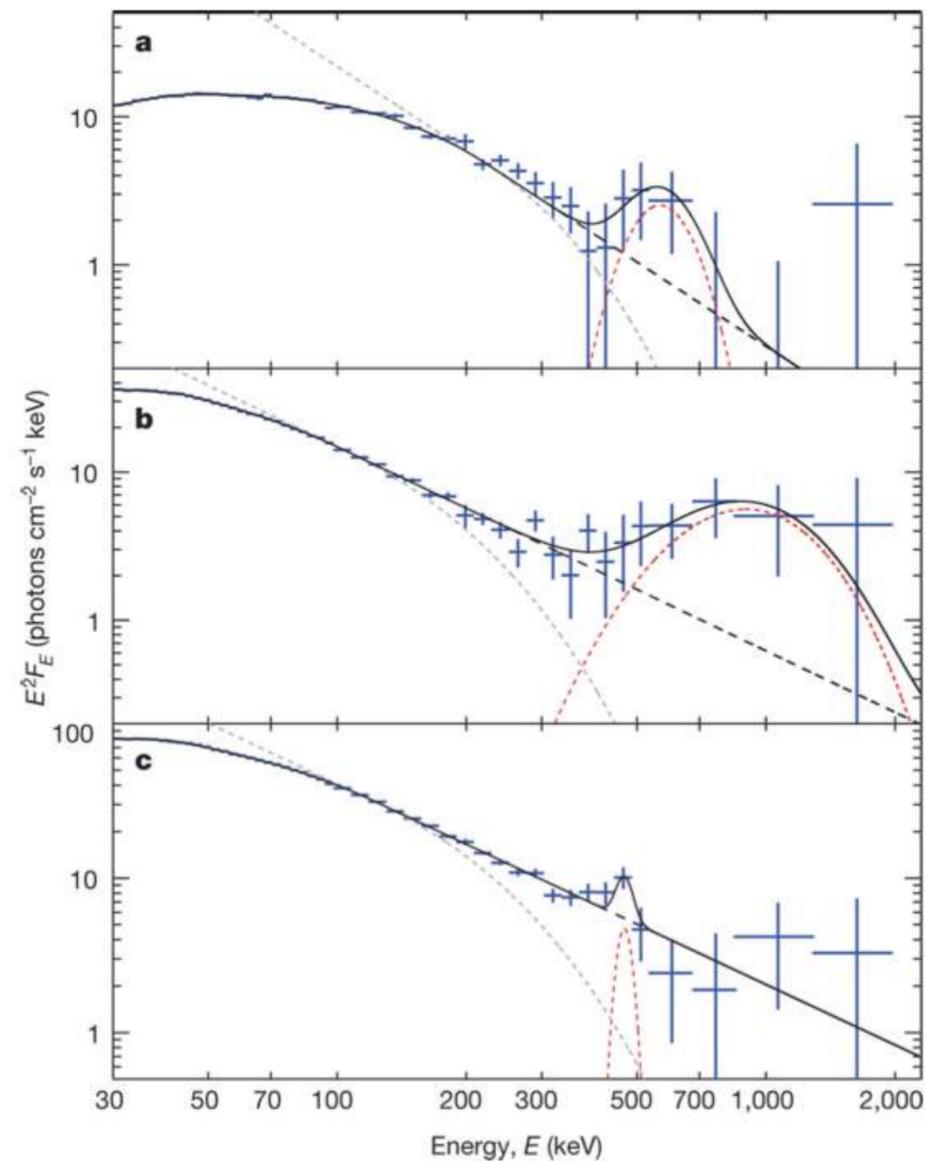


Figure 1: Spectral evolution of V404 Cygni. a-c, Spectra in the soft  $\gamma$ -ray band in three different flaring epochs (a-c show the spectra measured in INTEGRAL orbits 1554, 1555 and 1557, corresponding to epochs 1, 2 and 3, respectively). Data (blue; error bars, 1 s.d.) are fitted as the sum of the Comptonization continuum (black dashed curve) and annihilation radiation from a relativistic hot plasma (red dashed curve). The standard thermal Comptonization model (grey dashed curve) fits the data up to  $\sim 200$  keV; it declines exponentially at higher energies and falls short of the observed flux. Our conservative, modified continuum model follows a power law instead.  $E$ , energy;  $F_E$ , flux at energy  $E$ .

The black hole spin of V404 Cygni has been estimated to be  $a^* > 0.92$  from NuStar X-ray data (Walton et al. 2017)

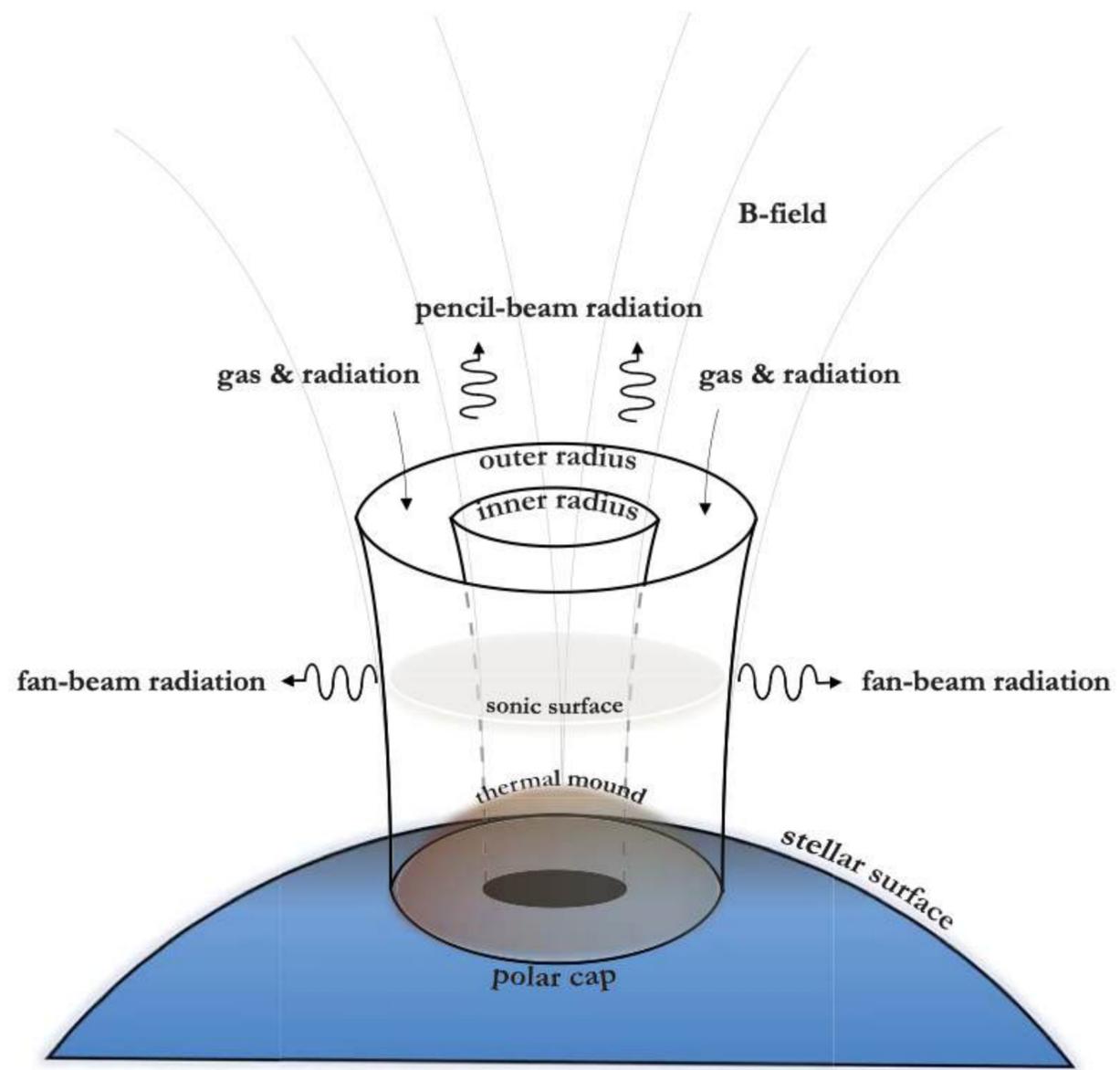
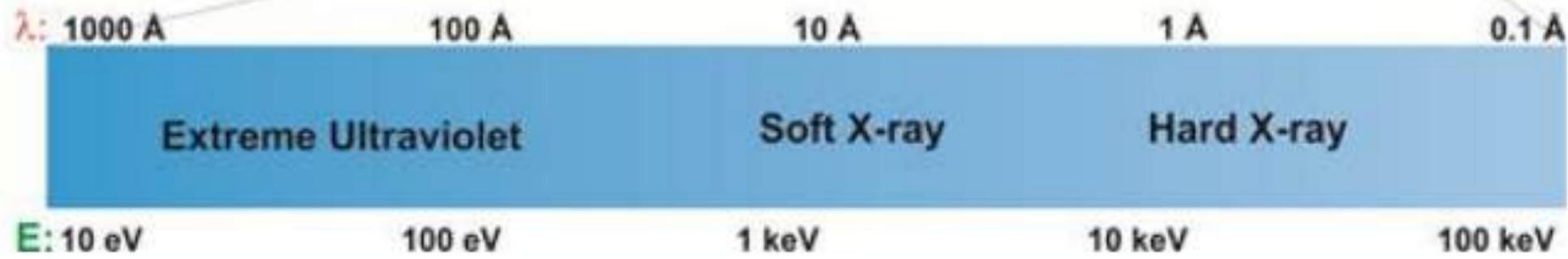
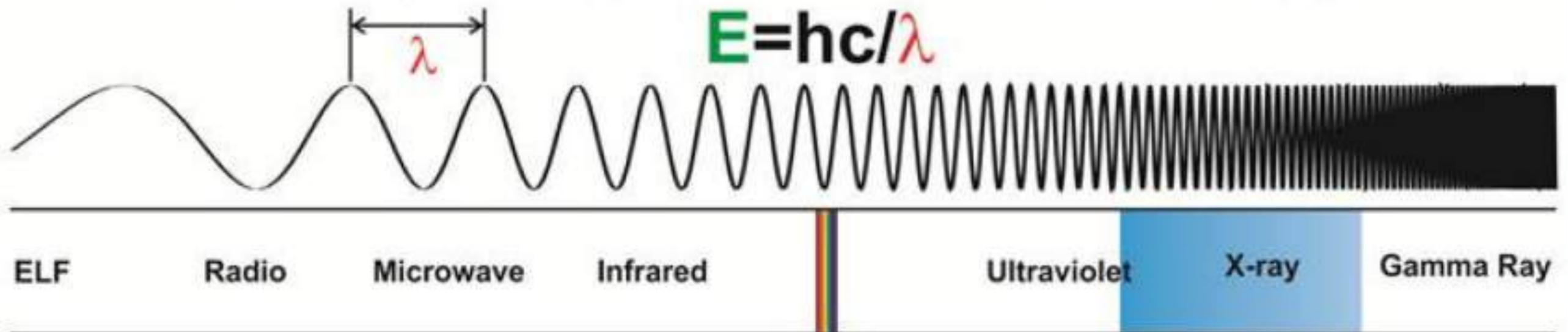


Fig. 1.— Accretion column formation in the two-fluid model. Ions and electrons enter at the top of the column as coupled and interacting fluids. X-ray photons are produced in the column and escape through the top and the sides as pencil and fan beam components, respectively. Also indicated are the thermal mound surface (where the absorption optical depth in the parallel direction equals unity,  $\tau_{\parallel}^{\text{abs}} = 1$ ), and the radiation sonic surface, where the radiation Mach number  $\mathcal{M}_r = 1$ .

# The Electromagnetic Spectrum

← increasing wavelength,  $\lambda$                       increasing energy,  $E$  →

$$E = hc/\lambda$$



Reflective X-ray Optics

<b>T</b>	$\sim 10^5$	$\sim 10^6$	$\sim 10^7$	$\sim 10^8$	$\sim 10^9$
<b>K</b>	K	K	K	K	K
	$\sim 10^{15}$ Hz	$\sim 10^{16}$ Hz	$\sim 10^{17}$ Hz	$\sim 10^{18}$ Hz	$\sim 10^{19}$ Hz

# (1) General expression for the internal energy :

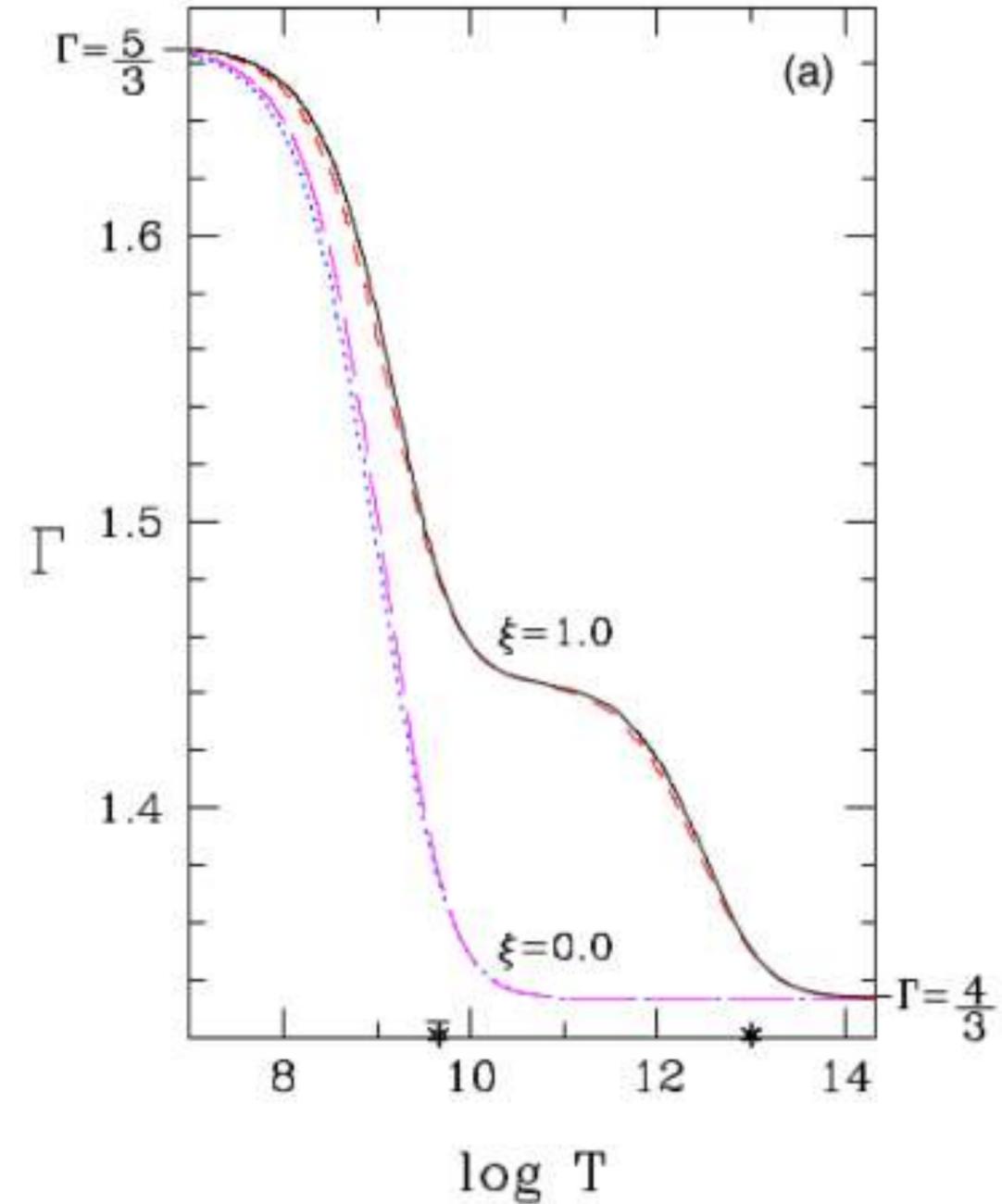
$$\epsilon \equiv \epsilon(T) \longrightarrow \epsilon = c_v T$$

- where  $c_v$  = specific heat at constant volume per unit mass

$$c_v = \frac{R}{\Gamma - 1}$$

$$\Gamma = \frac{c_p}{c_v}$$

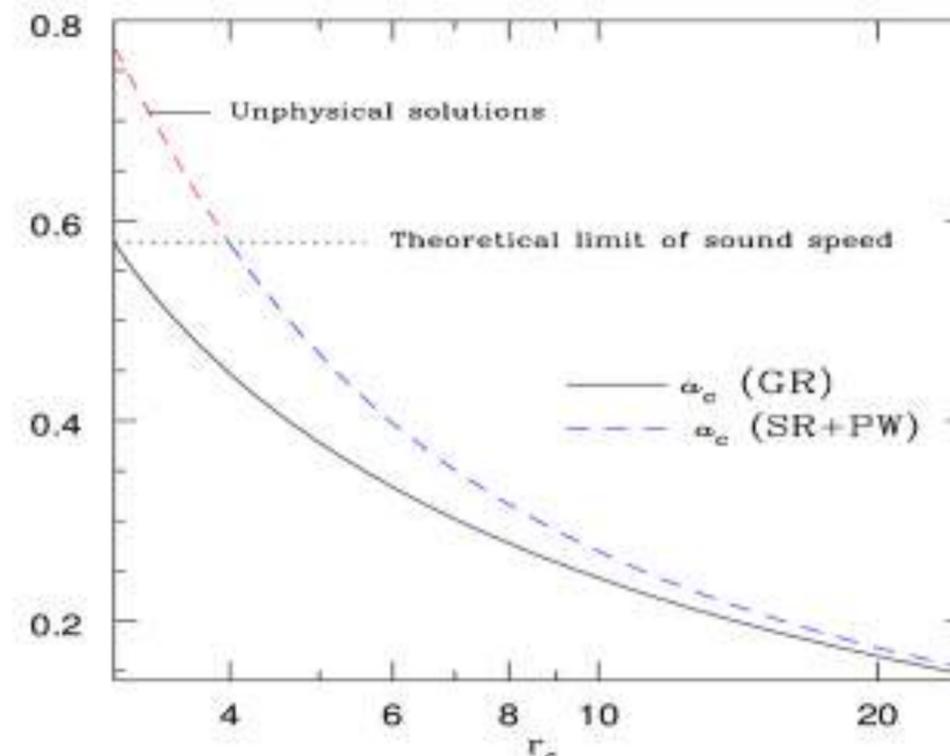
- where,



\*  $\log(m_e c^2/k)$   
\*  $\log(m_p c^2/k)$

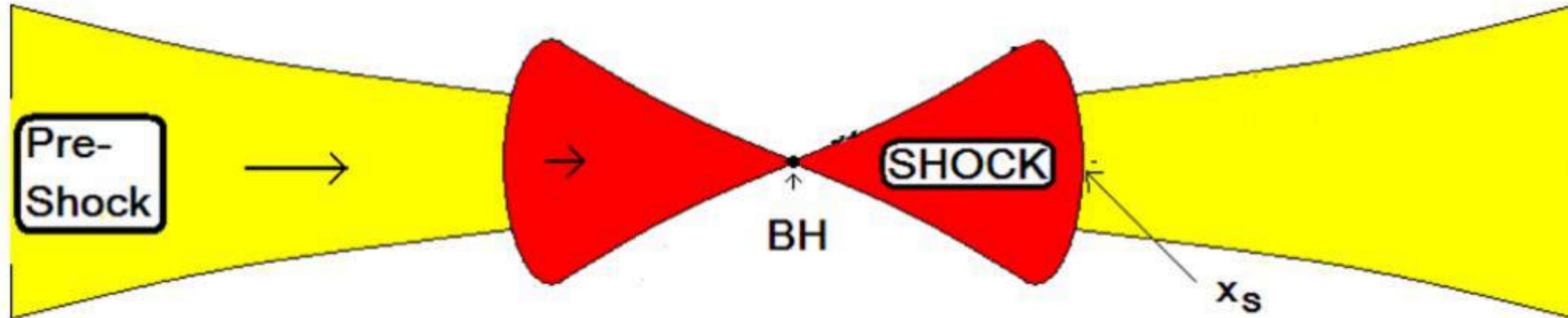
# PW vs GR :

- Matter achieves  $c$  outside horizon
- Effective potential : 0 (GR), -Infinity (PW)
- The curvature term ( $g_{\mu\nu} s$ ) should couple with the thermal and the kinetic terms i. e., the curvature term is coupled with the thermal term in the form of sound speed  $a$  and also the Lorentz factor  $\gamma$ . Consequently, if there is a discontinuity like shock in the flow, then the gravity term in SR+PW will not change across the shock, but in GR it will change, since both  $a$  and  $v$  jump across a shock
- Causality imposes an upper limit of sound speed which is  $a < \sqrt{1/3}$ . In GR this translates to a lower bound in the location of sonic points ( $r_c > 3$ ). Since pseudo potentials makes the flow unphysically hot, so the lower limit of sonic point in pNp+SR regime extends to a larger distance ( $r_c > 4$ ).



B.1:  $a_c$  as a function of  $r_c$  for  $\ell = 0$ . Solid curve is for GR solutions while dotted shows solutions with PW potential

# Shocks :



- Shocks are centrifugal pressure mediated
- Characterized by an abrupt, nearly discontinuous change in **pressure, temperature and density** of the medium
- The Rankine-Hugoniot shock conditions :

$$[nu^r]=0, \quad [(e+p)u^r u^r + pg^{rr}]=0, \quad [E]=0 \text{ but } \epsilon_+ = \epsilon_- - \Delta\epsilon$$

# Accretion models developed so far :

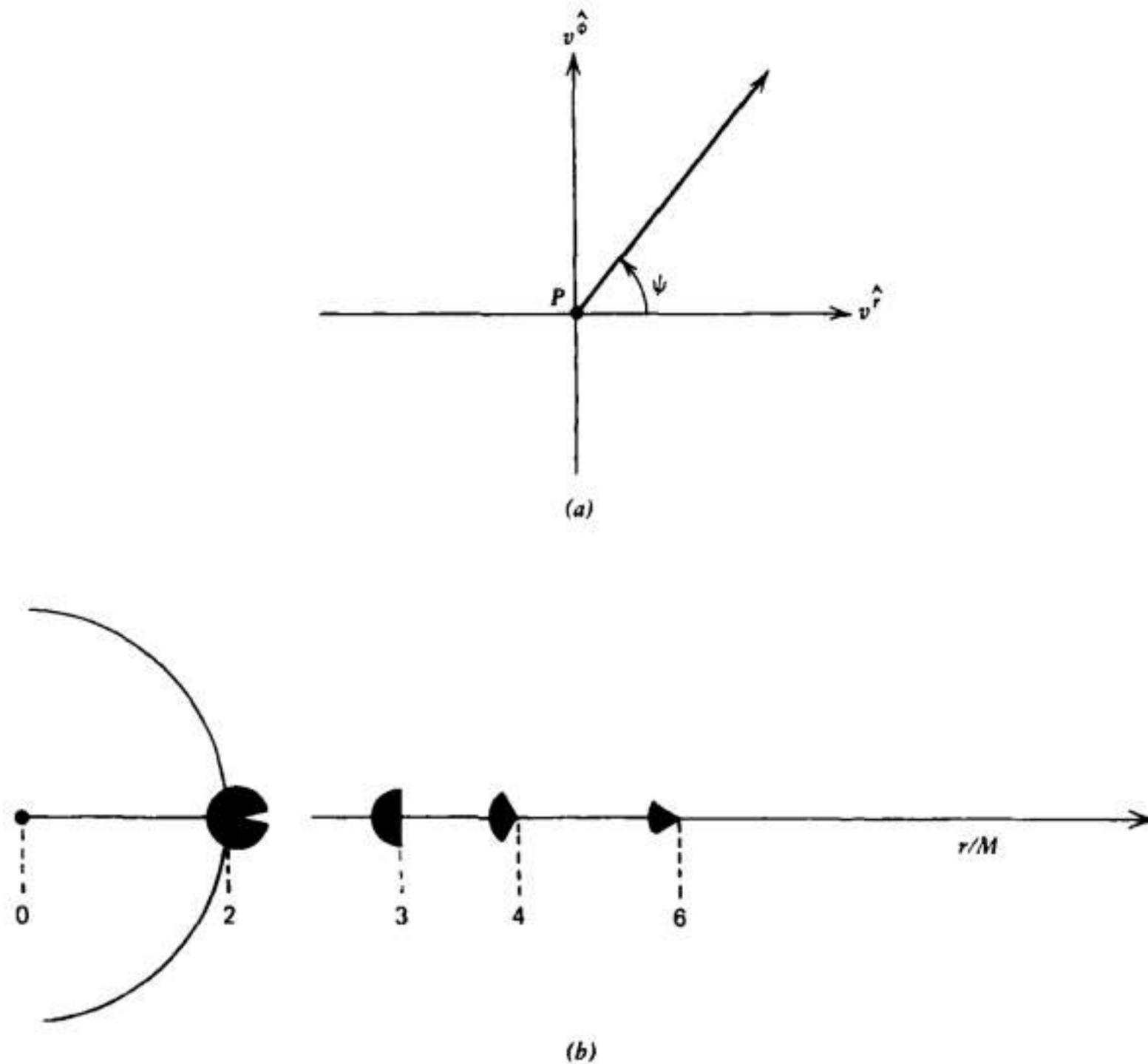
Radial component of the momentum balance equation :

$$v \frac{dv}{dr} + \frac{1}{\rho} \frac{dp}{dr} - \frac{\lambda^2}{r^3} + \Phi = 0$$

Model	Assumptions
Bondi (Bondi, 1952)	Adiabatic $\lambda = 0$
SS disk (Shakura and Sunyaev, 1973)	$V_r = 0$ $\lambda = \lambda_K$ Thin, Cooling efficient
Thick disk (Abramowicz, 1993)	$V_r = 0$ $\lambda < \lambda_K$ Thick, Cooling inefficient
Advective disk Narayan & Popham (1993)	$V_r \neq 0$ Contains all terms Sonic points can be anywhere
ADAF (Advection dominated accretion flow) (Narayan et al., 1995)	Subset of advective disks Valid for low accretion rate Sonic points are near the horizon
Slim disks (Abramowicz et al 1988)	Advective disk Valid for high accretion rate



**One  
temperature  
solutions  
&  
No self  
consistent  
solutions**



**Figure 12.6** (a) The angle  $\psi$  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.

We can understand photon orbits by means of an effective **potential**

$$V_{\text{phot}} = \frac{1}{r^2} \left( 1 - \frac{2M}{r} \right), \quad (12.5.9)$$

so that Eq. (12.5.8) becomes

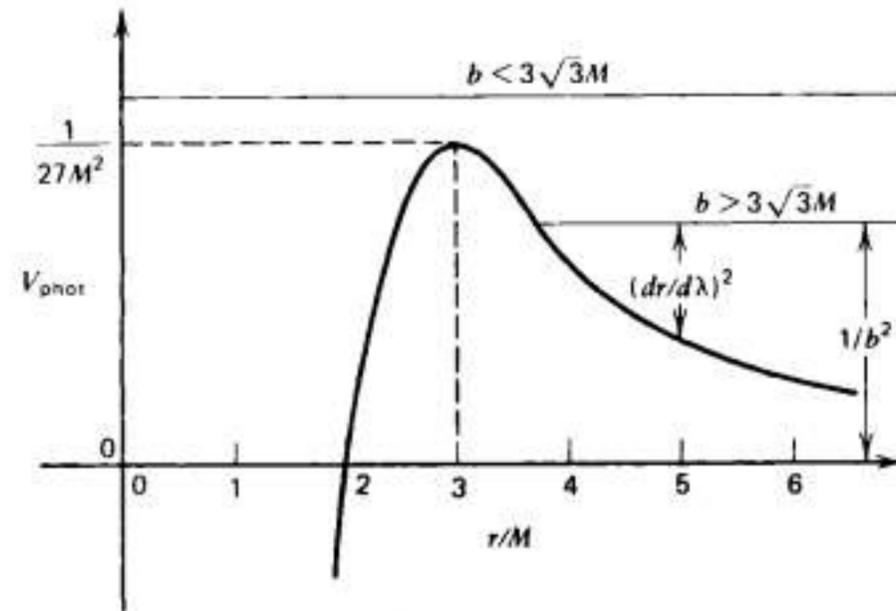
$$\left( \frac{dr}{d\lambda} \right)^2 = \frac{1}{b^2} - V_{\text{phot}}(r). \quad (12.5.10)$$

Clearly the distance from a horizontal line of height  $1/b^2$  to  $V_{\text{phot}}$  gives  $(dr/d\lambda)^2$ . The quantity  $V_{\text{phot}}$  has a maximum of  $1/(27M^2)$  at  $r = 3M$ ; it is displayed in Figure 12.5. We see that the critical impact parameter separating capture from scattering orbits is given by  $1/b^2 = 1/(27M^2)$ , or

$$b_c = 3\sqrt{3}M. \quad (12.5.11)$$

The capture cross section for photons from infinity is thus

$$\sigma_{\text{phot}} = \pi b_c^2 = 27\pi M^2. \quad (12.5.12)$$



**Figure 12.5** Sketch of the effective **potential** profile for a particle with *zero* rest mass orbiting a Schwarzschild black hole of mass  $M$ . If the particle falls from  $r = \infty$  with impact parameter  $b > 3\sqrt{3}M$  it is scattered back out to  $r = \infty$ . If, however,  $b < 3\sqrt{3}M$  the particle is captured by the black hole.

Thus an inward-moving photon escapes the black hole if

$$\sin \psi > \frac{3\sqrt{3} M}{r} \left(1 - \frac{2M}{r}\right)^{1/2}. \quad (12.5.15)$$

At  $r = 6M$ , escape requires  $\psi < 135^\circ$ ; at  $r = 3M$ ,  $\psi < 90^\circ$  so that all inward-moving photons are captured (i.e., 50% of the radiation from a stationary, isotropic emitter at  $r = 3M$  is captured).

**Exercise 12.14** Show that an outward-directed photon emitted between  $r = 2M$  and  $r = 3M$  escapes if

$$\sin \psi < \frac{3\sqrt{3} M}{r} \left(1 - \frac{2M}{r}\right)^{1/2}.$$

Only the outward-directed radial photons escape as the source approaches  $r = 2M$ . See Figure 12.6 for a diagram of these effects.

$$t_{ee} = \frac{2}{\sqrt{\pi}} A \frac{m_e^2}{n_e} \theta_e^2. \quad (2)$$

The energy exchange time scale between electrons and ions by Coulomb interaction is

$$t_{ei} = \frac{A}{4\sqrt{2}} \frac{m_e m_i}{Z_i^2 n_e} (\theta_e + \theta_i)^{3/2} \quad (3)$$

in the nonrelativistic regime (Spitzer 1962). No simple formulae exist when electrons are arbitrarily relativistic and  $T_i$  and  $T_e$  are arbitrarily different. But when  $\theta_e \gg 1$  and  $\theta_i \ll 1$ , the time scale is given by (Gould 1981)

$$t_{ei} = \frac{A}{2\sqrt{\pi}} \frac{m_e m_i}{Z_i^2 n_e} \theta_e. \quad (4)$$

The equations (3) and (4) are well represented by the interpolation formula

$$t_{ei} = 9.0 \times 10^{15} \frac{1}{n_e} \frac{\theta^{3/2}}{1 + \theta^{1/2}} \text{ s}, \quad (5)$$

where  $\theta \equiv \theta_e + \theta_i$ . When  $m_e c^2 < kT_e$ ,  $kT_i < m_i c^2$ , the time scales usually satisfy  $t_{ee} < t_{ii} < t_{ei}$  (Gould 1981). When compared with the free-fall time scale,

$$t_{\text{ff}} = \frac{r}{u} = 10^3 \left( \frac{r}{R_s} \right)^{3/2} M_8 \text{ s}, \quad (6)$$

where  $r$  is the radius,  $u$  the flow velocity,  $R_s (\equiv 2GM/c^2)$  the Schwarzschild radius, and  $M_8$  the mass of the hole,  $M$ , in  $10^8 M_\odot$ ,  $t_{ee}$  is generally much shorter than  $t_{\text{ff}}$  for  $\dot{m} > 1$ . So we assume electrons and positrons always have the same temperature  $T_l$ . But  $t_{ei}$  and  $t_{ii}$  are not always shorter than  $t_{\text{ff}}$ . So ions can be weakly coupled with electrons, resulting in the different temperatures for ions and leptons. Also, ions may not follow the Maxwellian distribution or behave as a fluid. However, a very small magnetic field can make the Larmor radius of the ions smaller than the scales of interest so that ions behave as a fluid: for example,  $10^{-11}$  of the equipartition field is all that required at the horizon for  $\dot{m} = 1$ ,  $M = 10^8 M_\odot$  accretion. The Maxwellian description of ion distribution is

$\beta=0.01, M.=0.10, M_{\text{BH}}=0.10\text{E}+02, \lambda=2.5000, E=1.001000$

