Panorama des simulations GRMHD de l'environnement des trous noirs

Panorama des simulations GRMHD de l'environnement des trous noirs

not so simple prompt that raises several questions

what defines a black-hole environment or more precisely where does it stop

what is studied with simulations of a black-hole environment ?

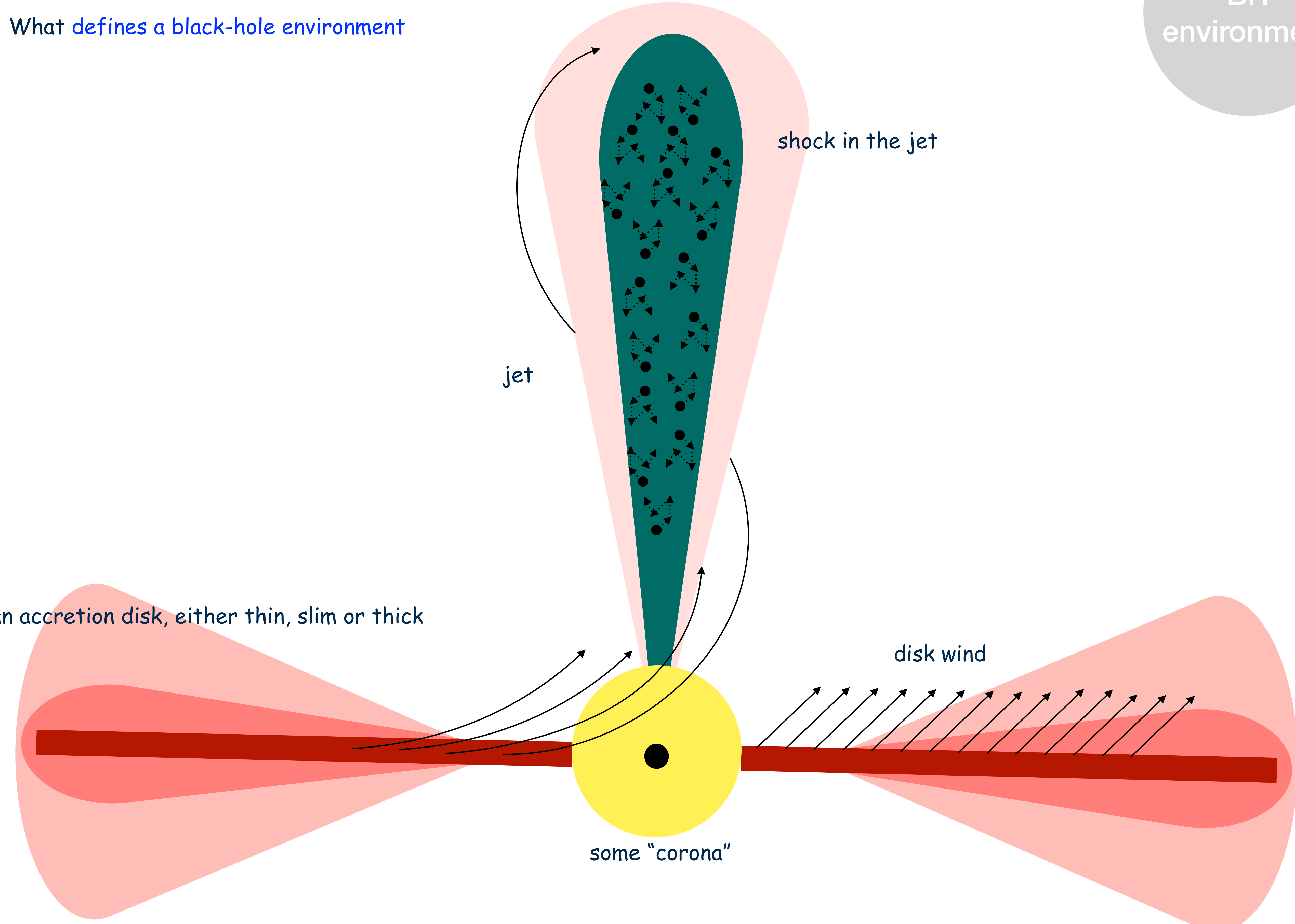
and are GR and MHD always necessary for it?

then I will highlight some recent results that show the diversity of GRMHD simulations of a BH environment

BH environment

BH
environment

What defines a black-hole environment



BH environment

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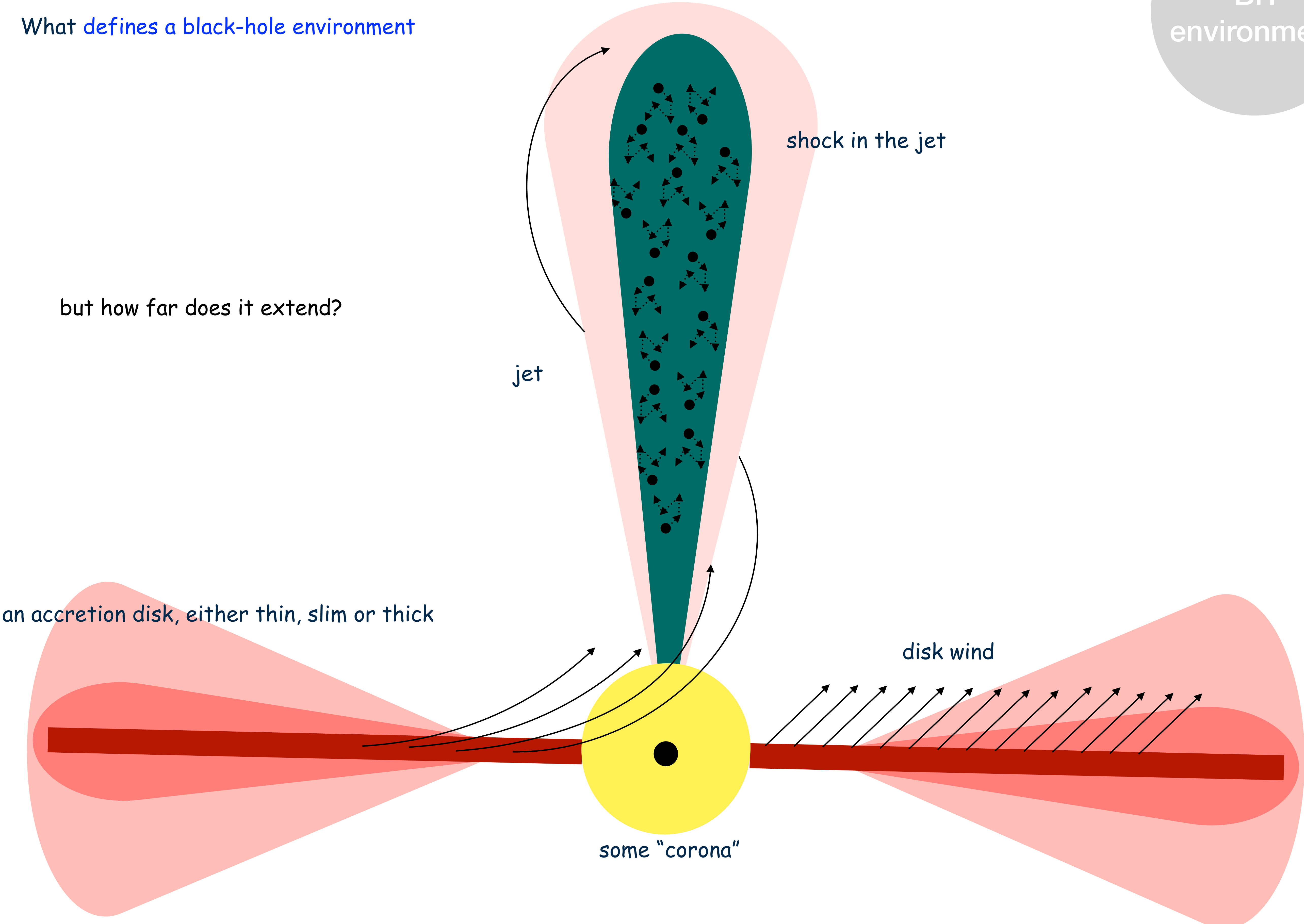
What defines a black-hole environment

but how far does it extend?



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- ➜ an accretion disk, either thin, slim or thick
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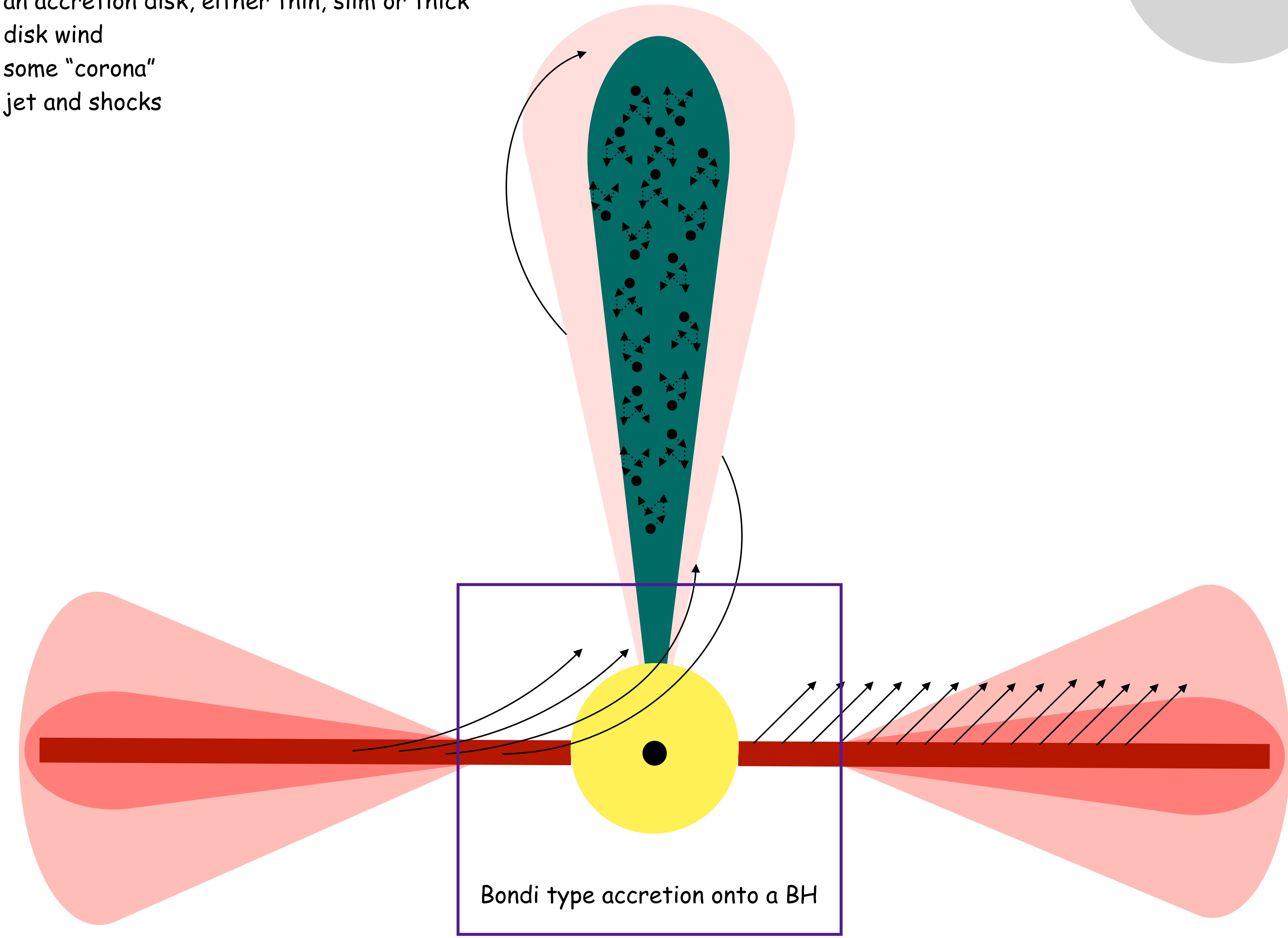

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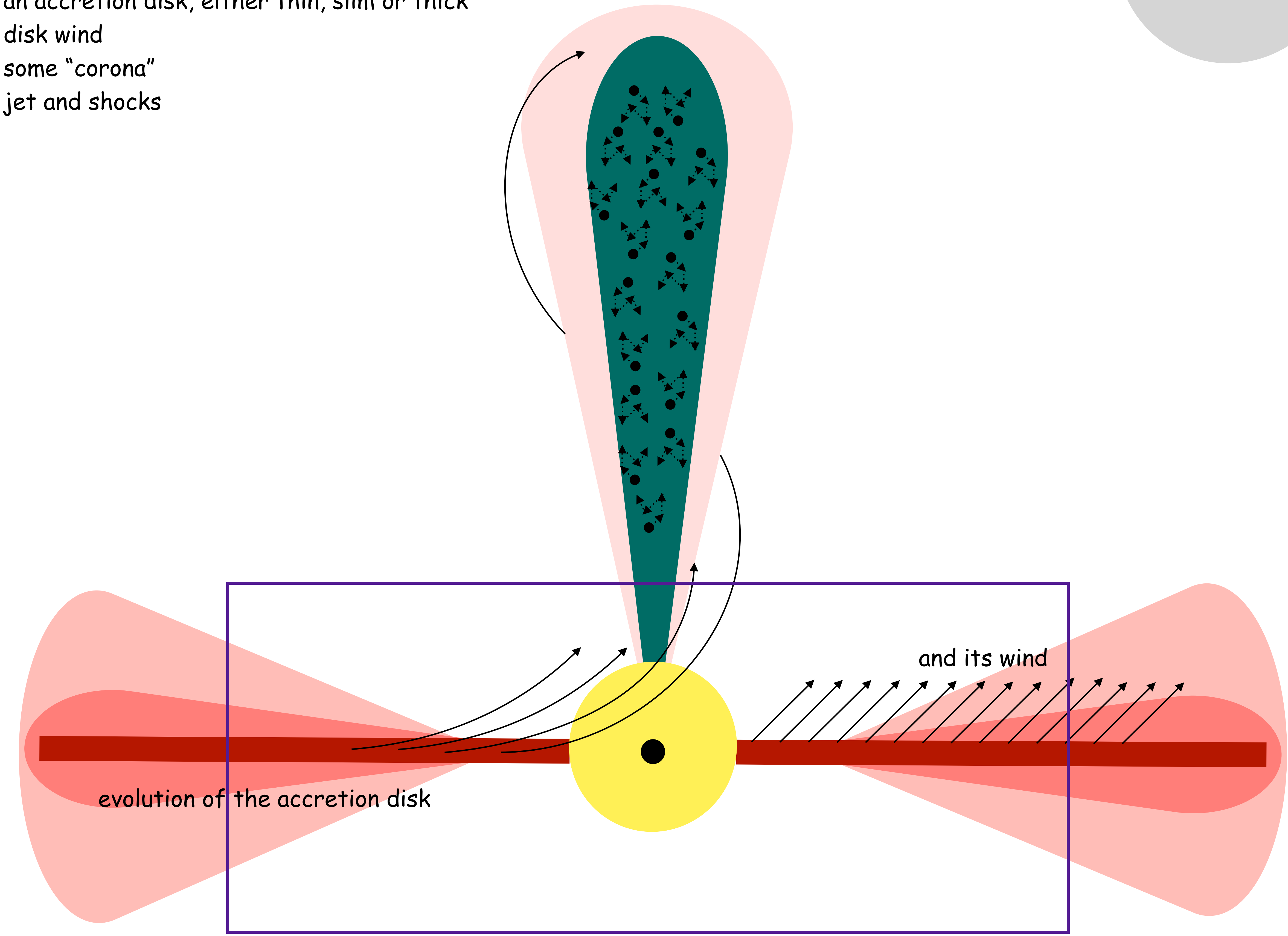

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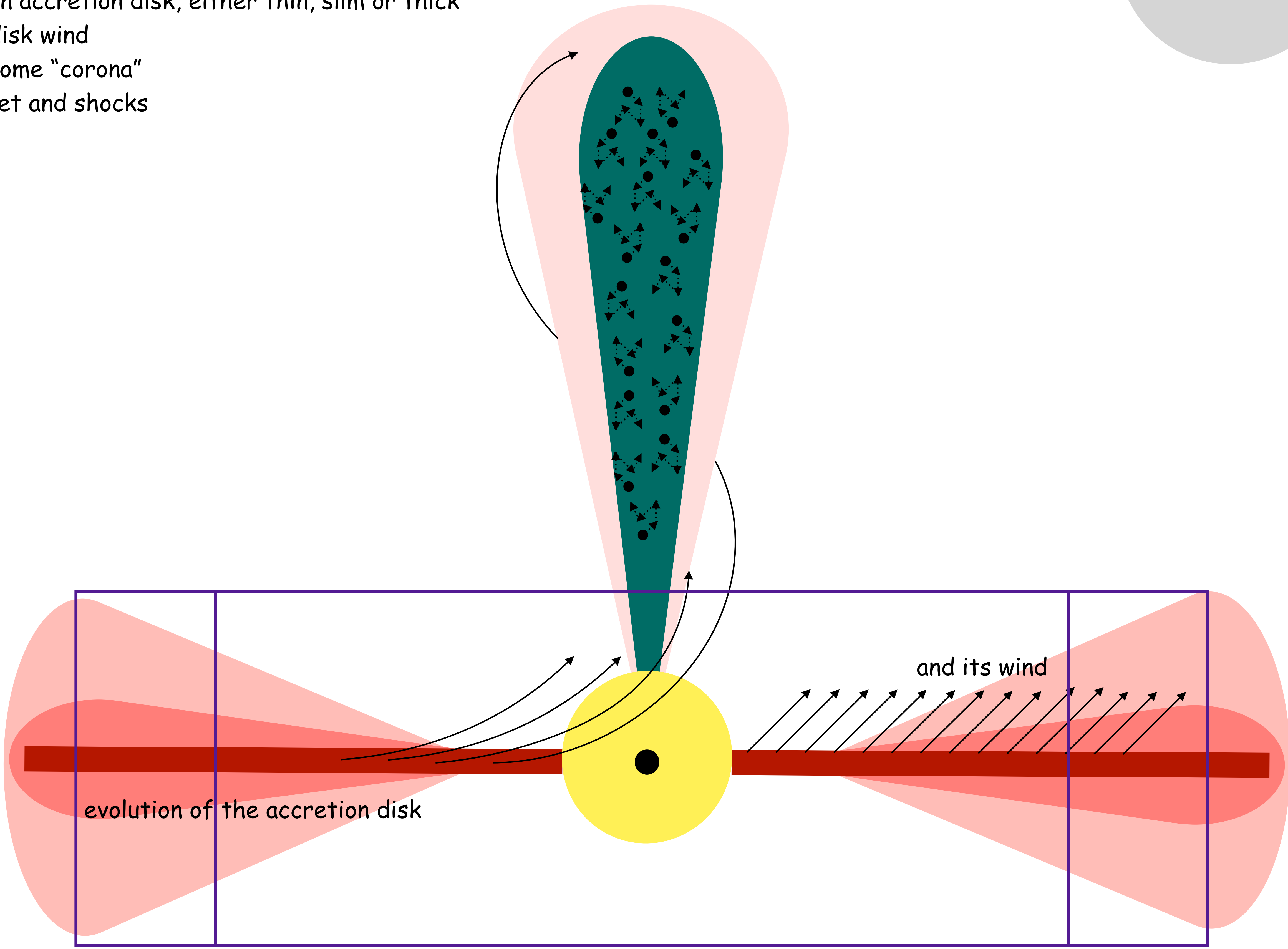

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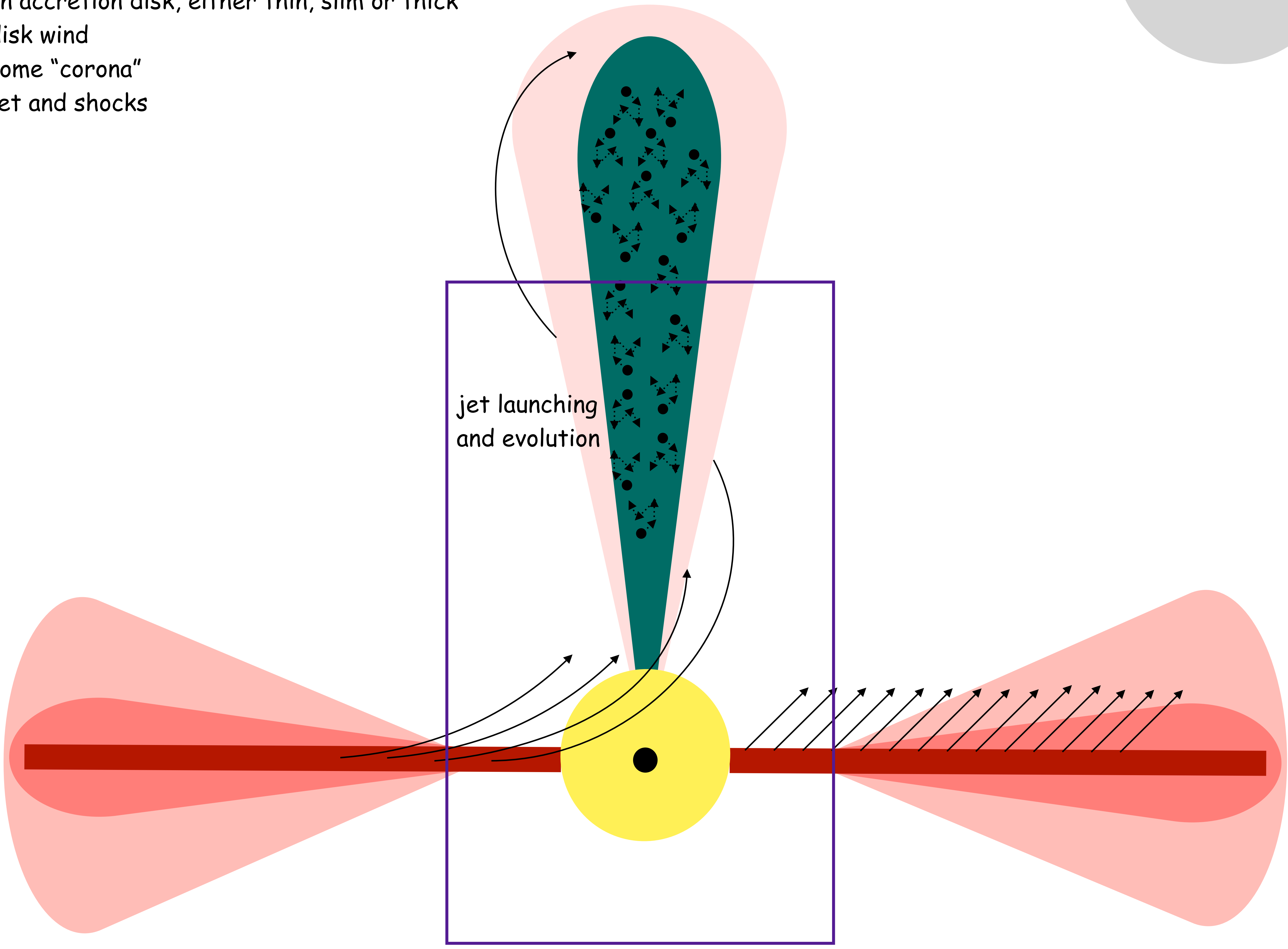

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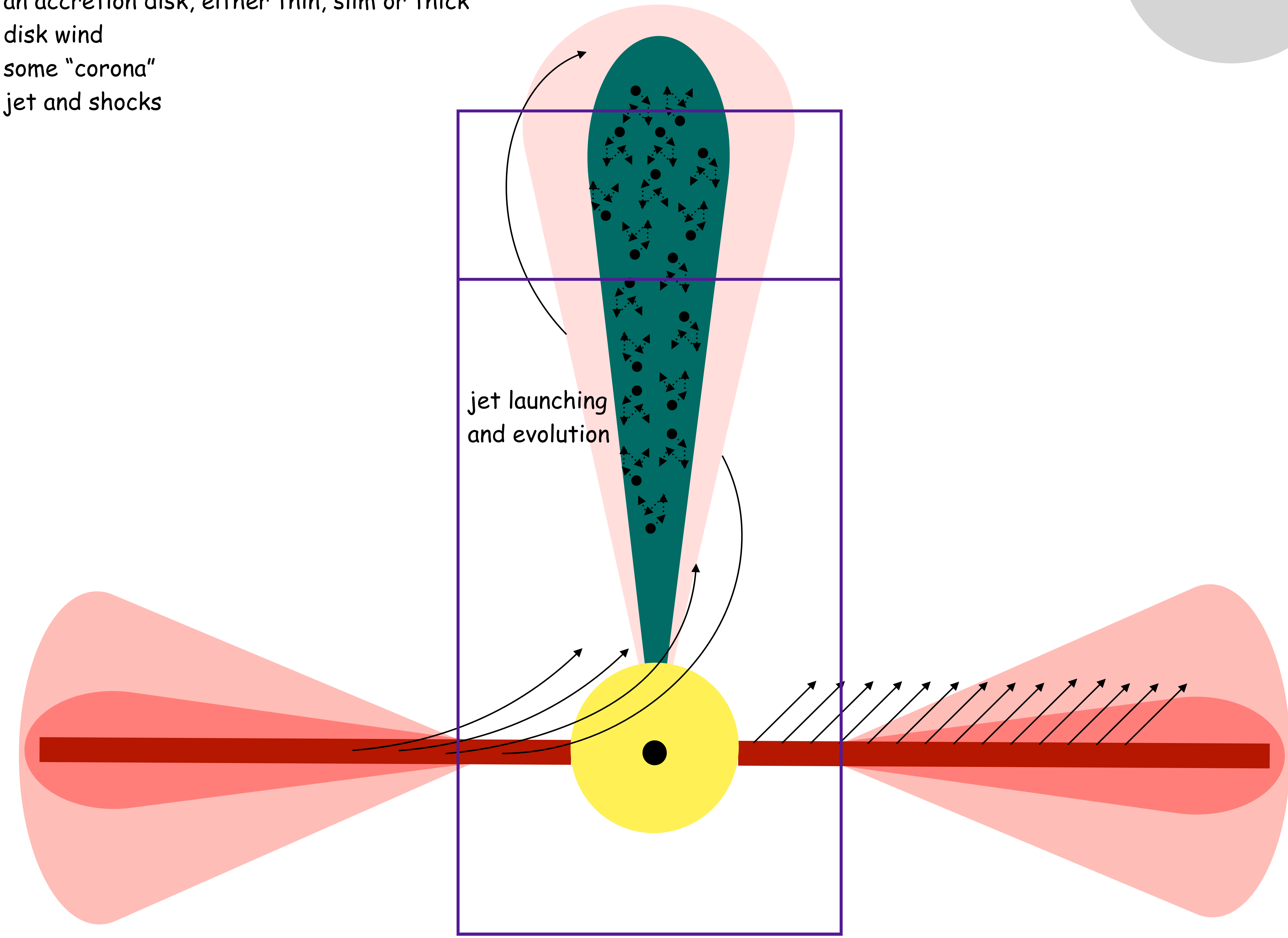

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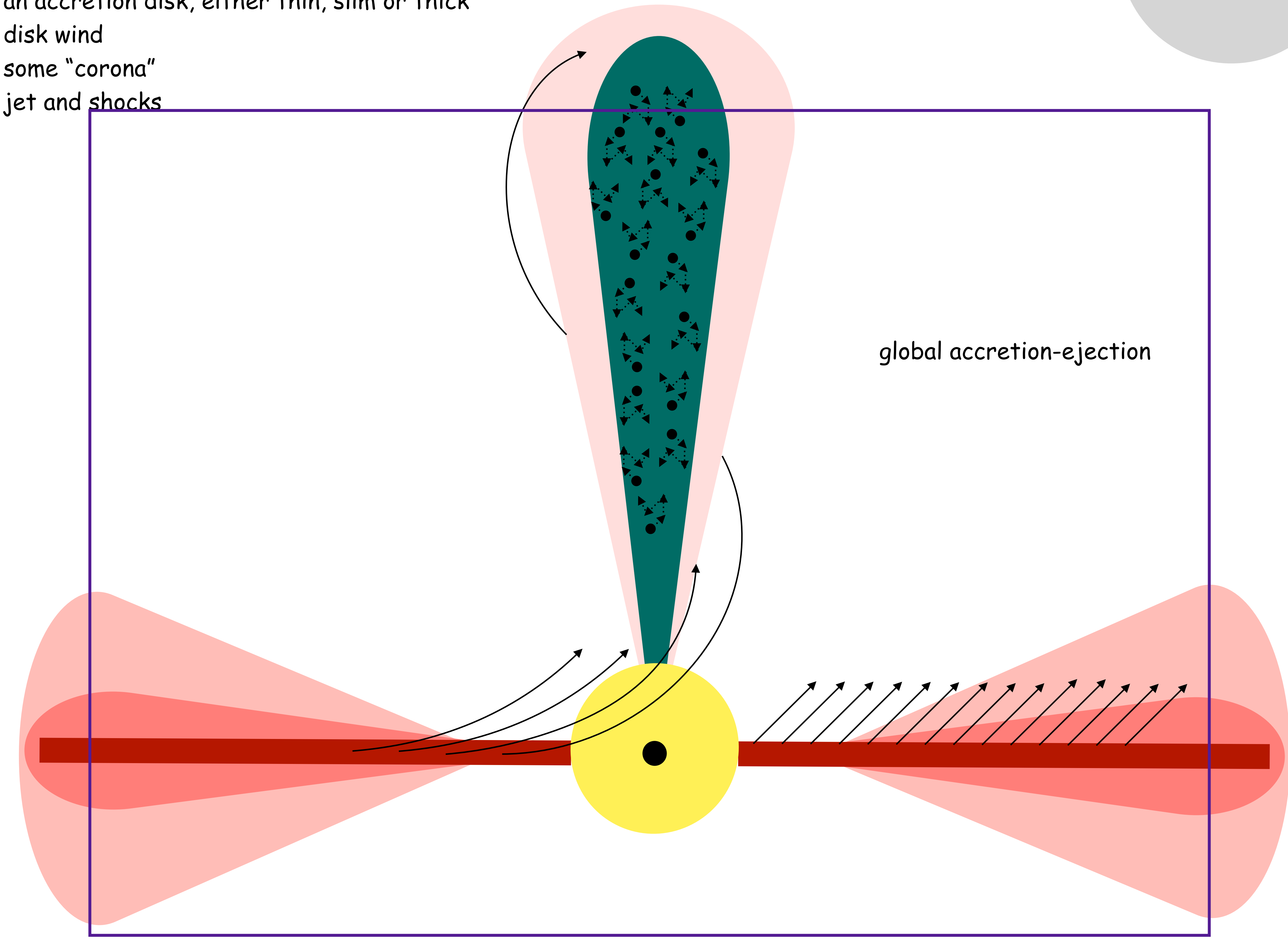

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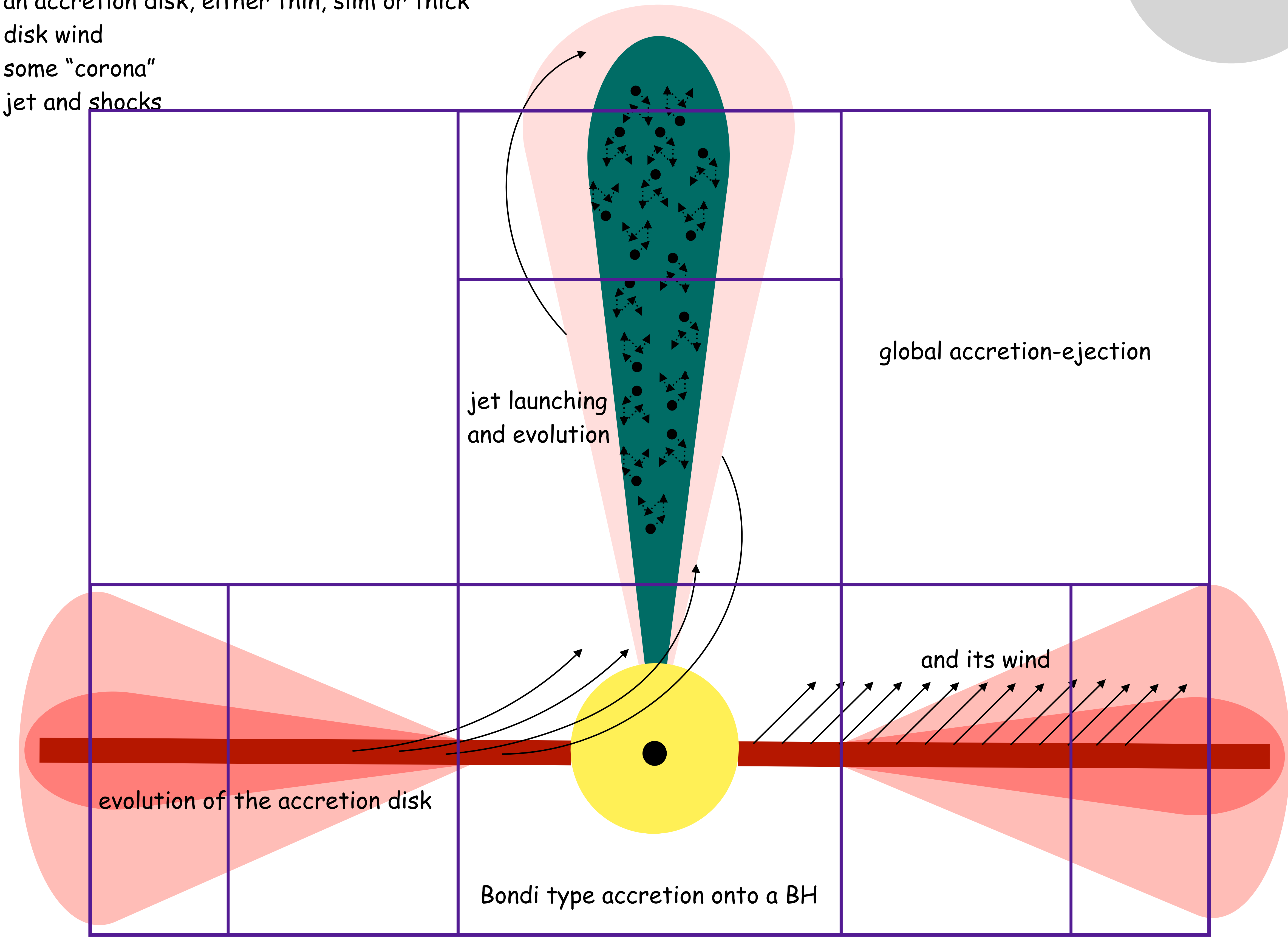

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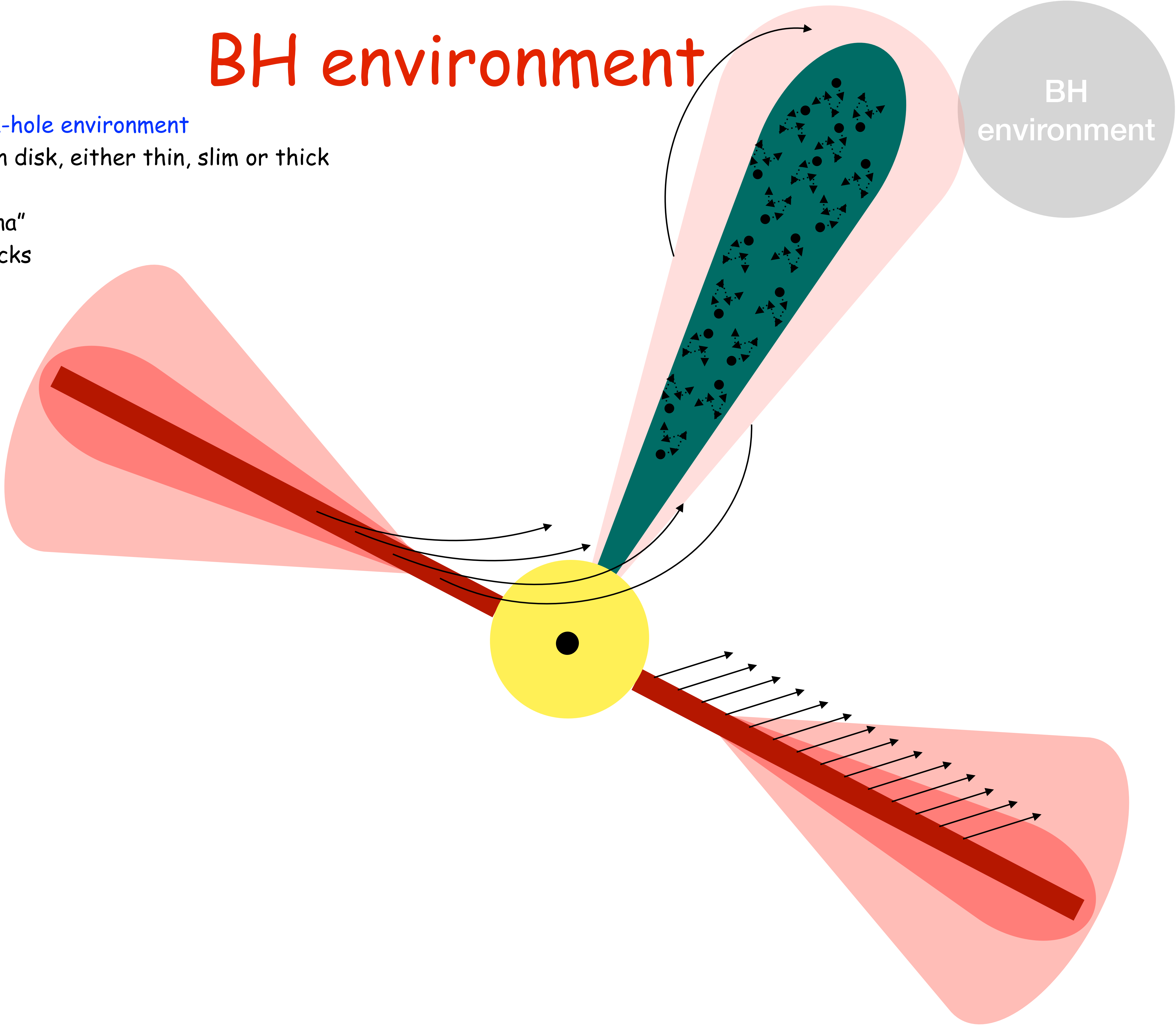

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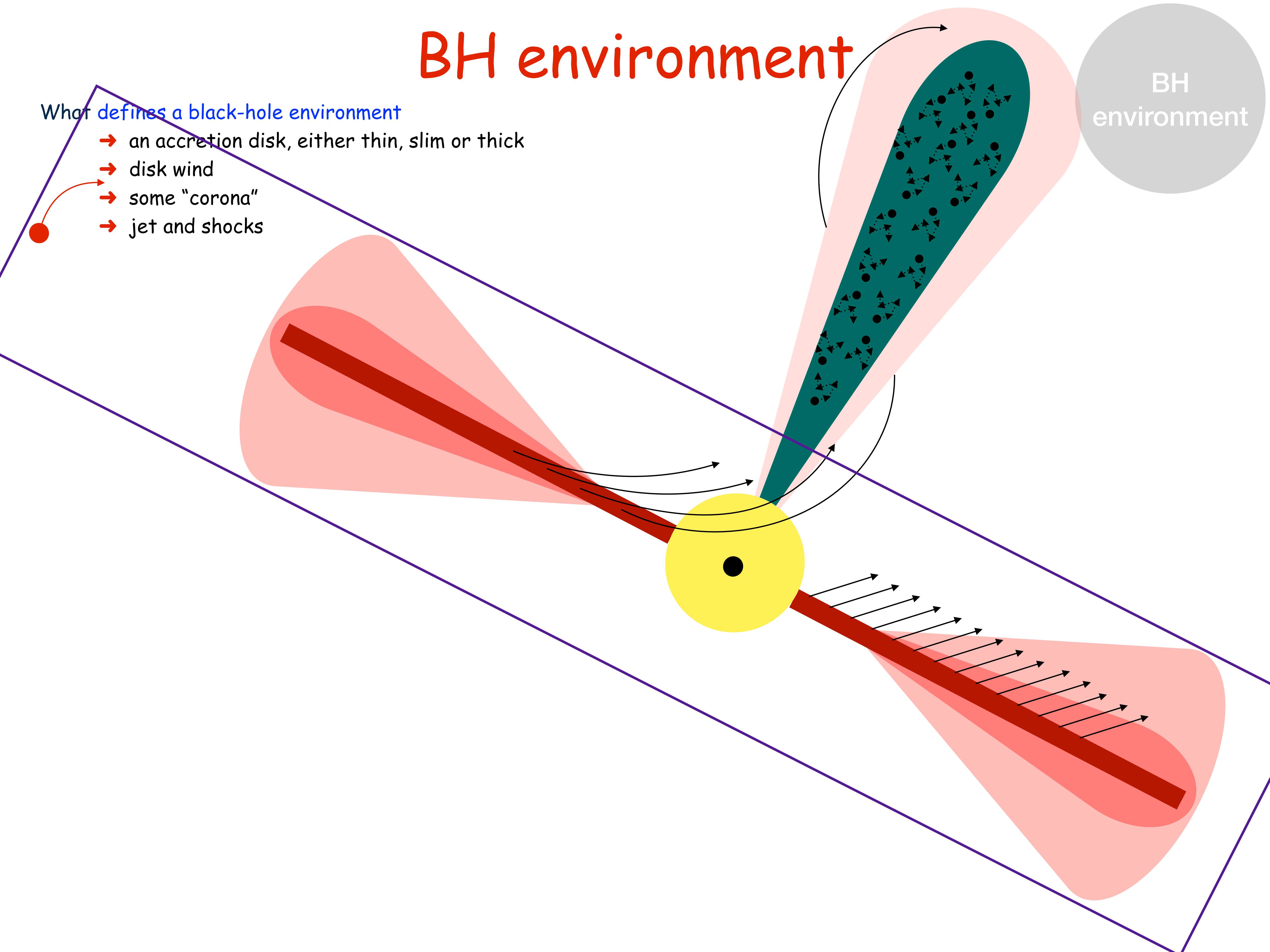

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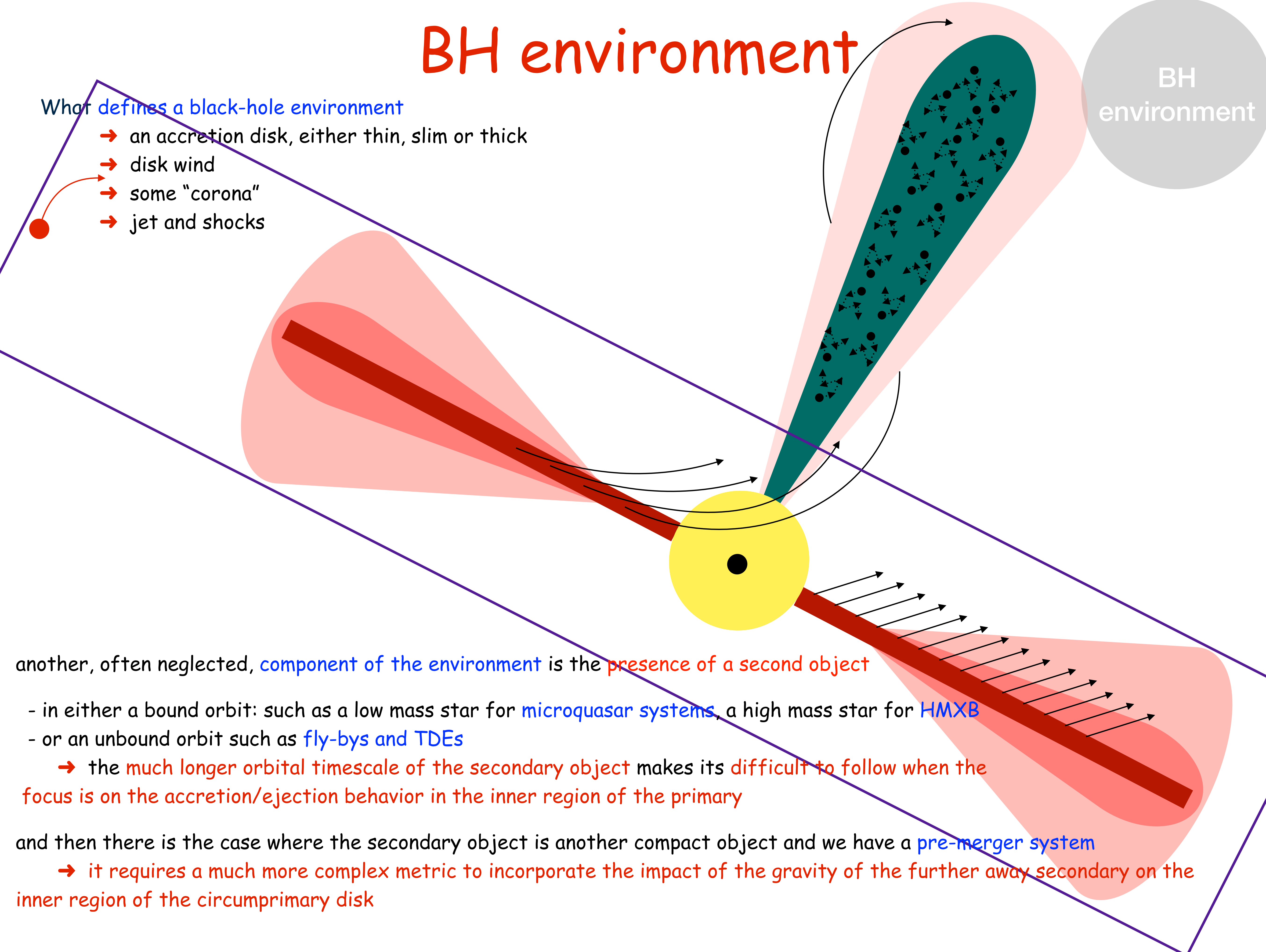

another, often neglected, component of the environment is the presence of a second object

- in either a bound orbit: such as a low mass star for microquasar systems, a high mass star for HMXB
- or an unbound orbit such as fly-bys and TDEs

➜ the much longer orbital timescale of the secondary object makes its difficult to follow when the focus is on the accretion/ejection behavior in the inner region of the primary

and then there is the case where the secondary object is another compact object and we have a pre-merger system

➜ it requires a much more complex metric to incorporate the impact of the gravity of the further away secondary on the inner region of the circumprimary disk

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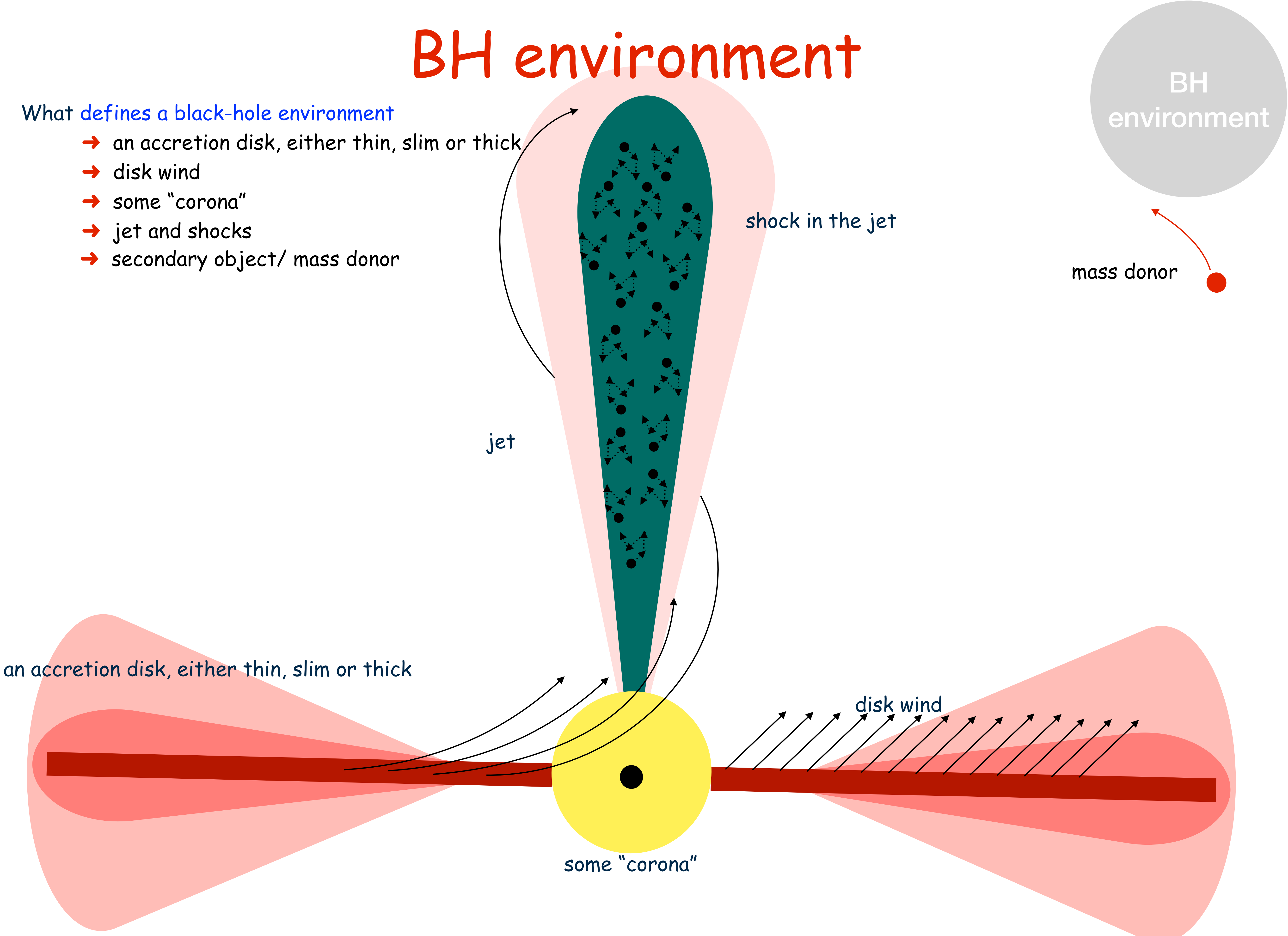

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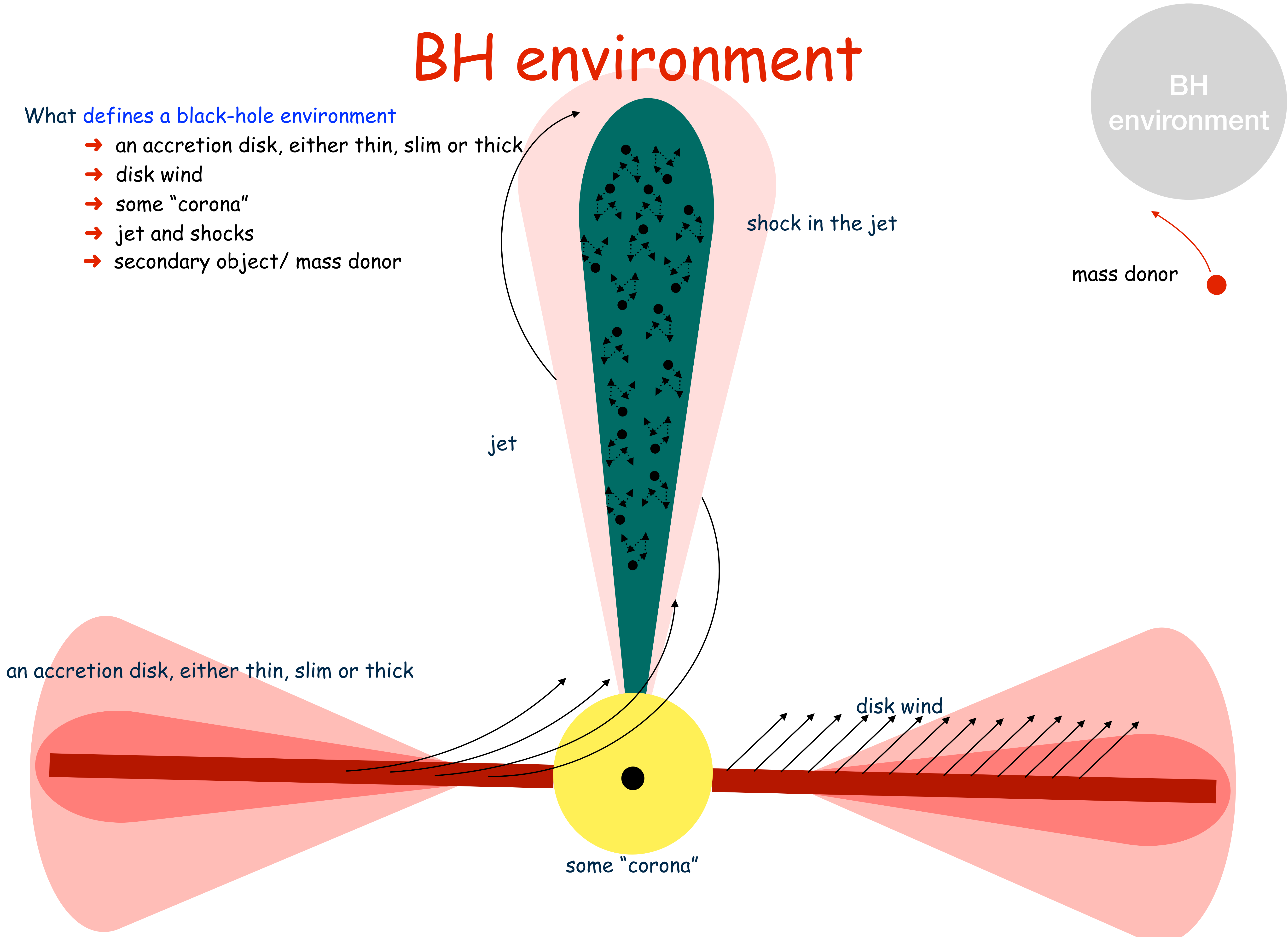
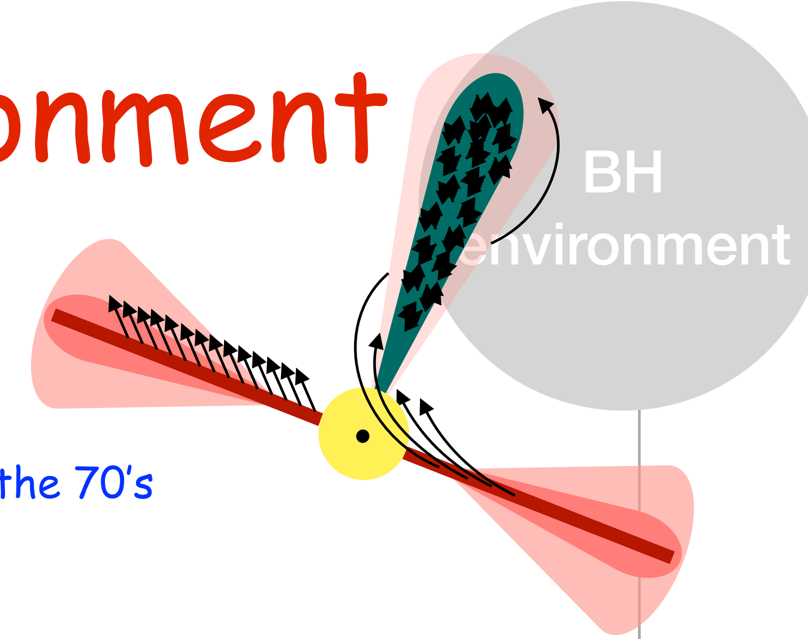


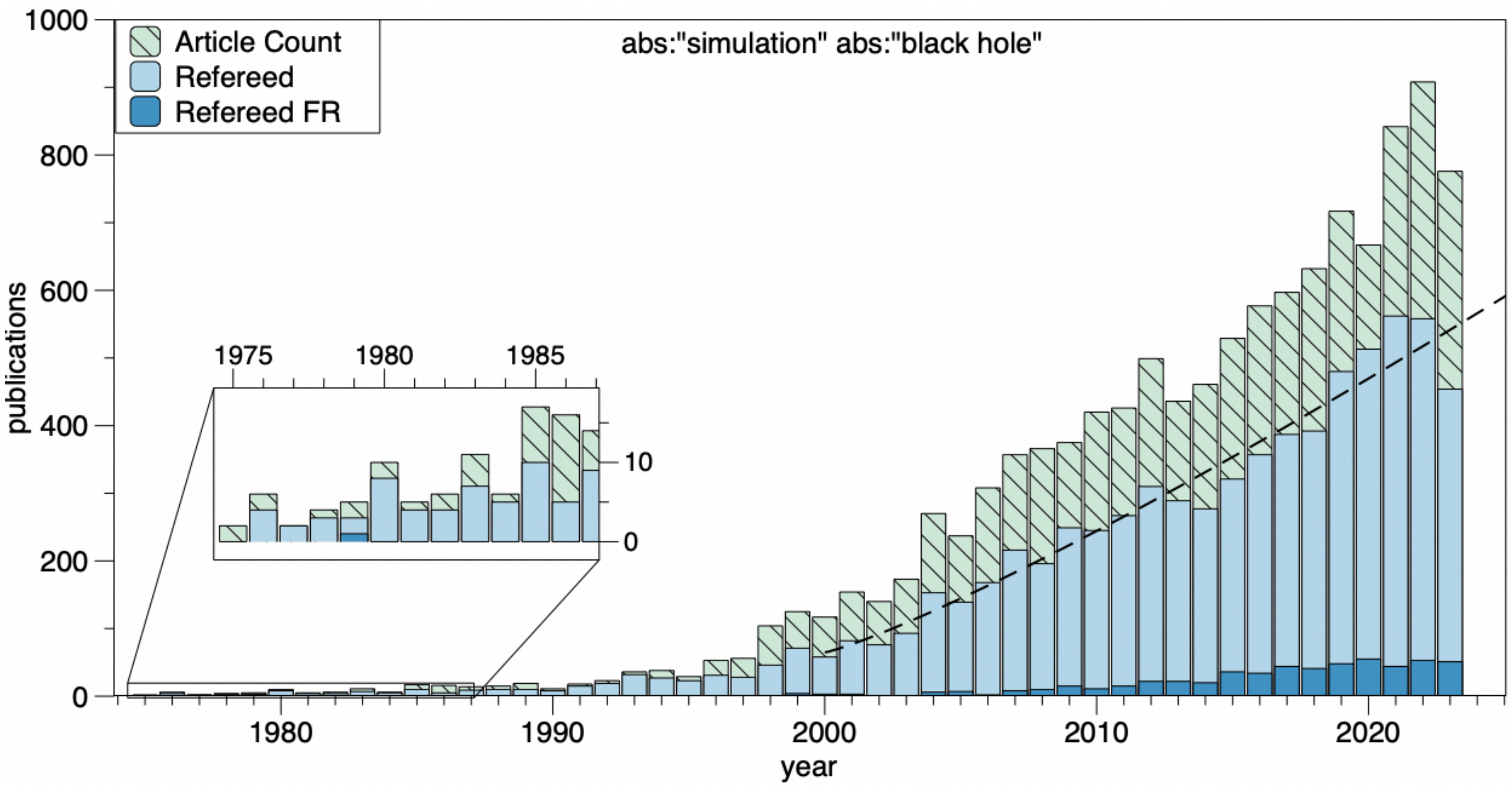
➥ a lot of components for the BH environment, hence we turn to simulations

Simulations of BH environment



looking at black-hole system with the help of simulation is not a new topic

some kind of black-hole simulations have been performed since the end of the 70's



"Black hole accretion - The quasar powerhouse", Smarr & Hawley 83

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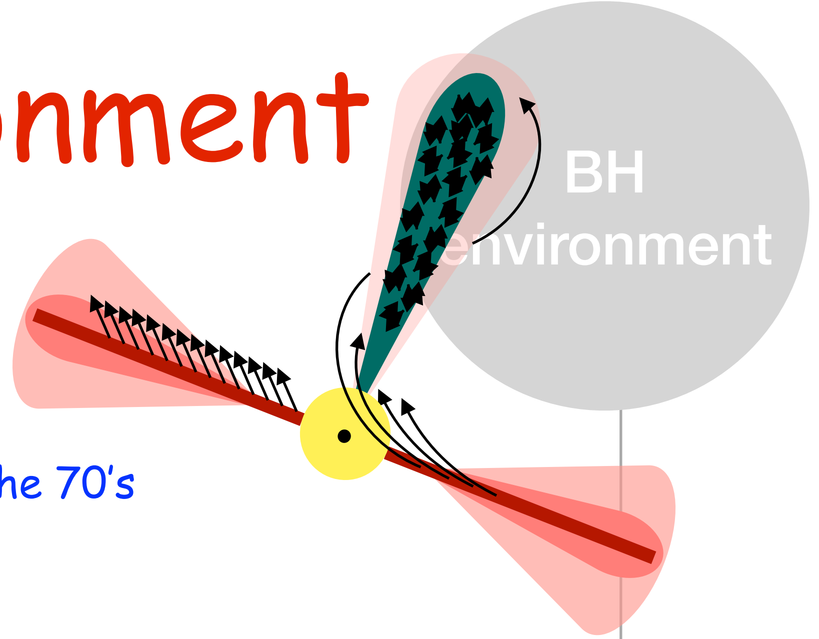

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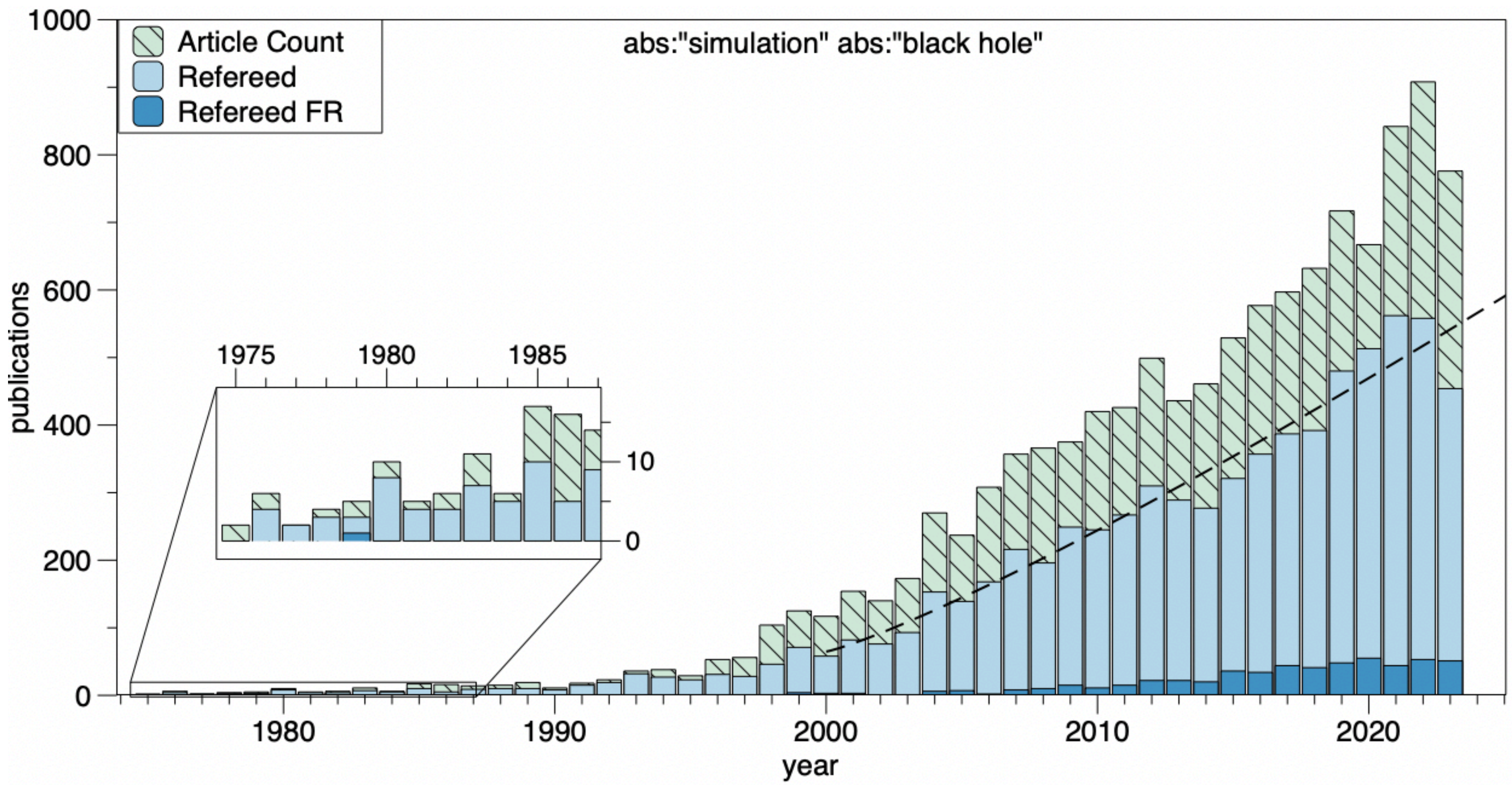

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a faster growth since the end of the 90s / early 2000s thanks to new methods, code availability and increasing computing power

➜ also a relatively stable french participation since mid 2010s

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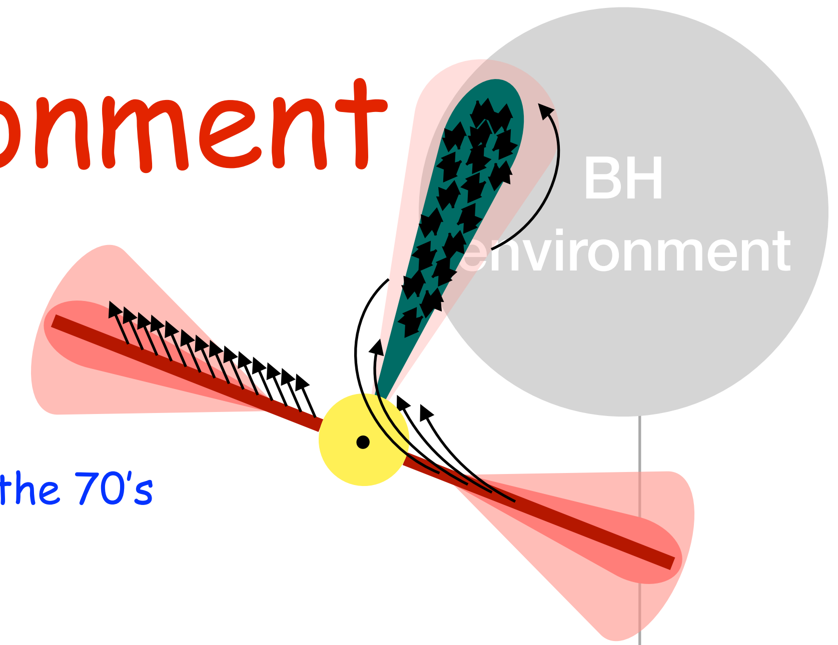
Simulations of BH environment



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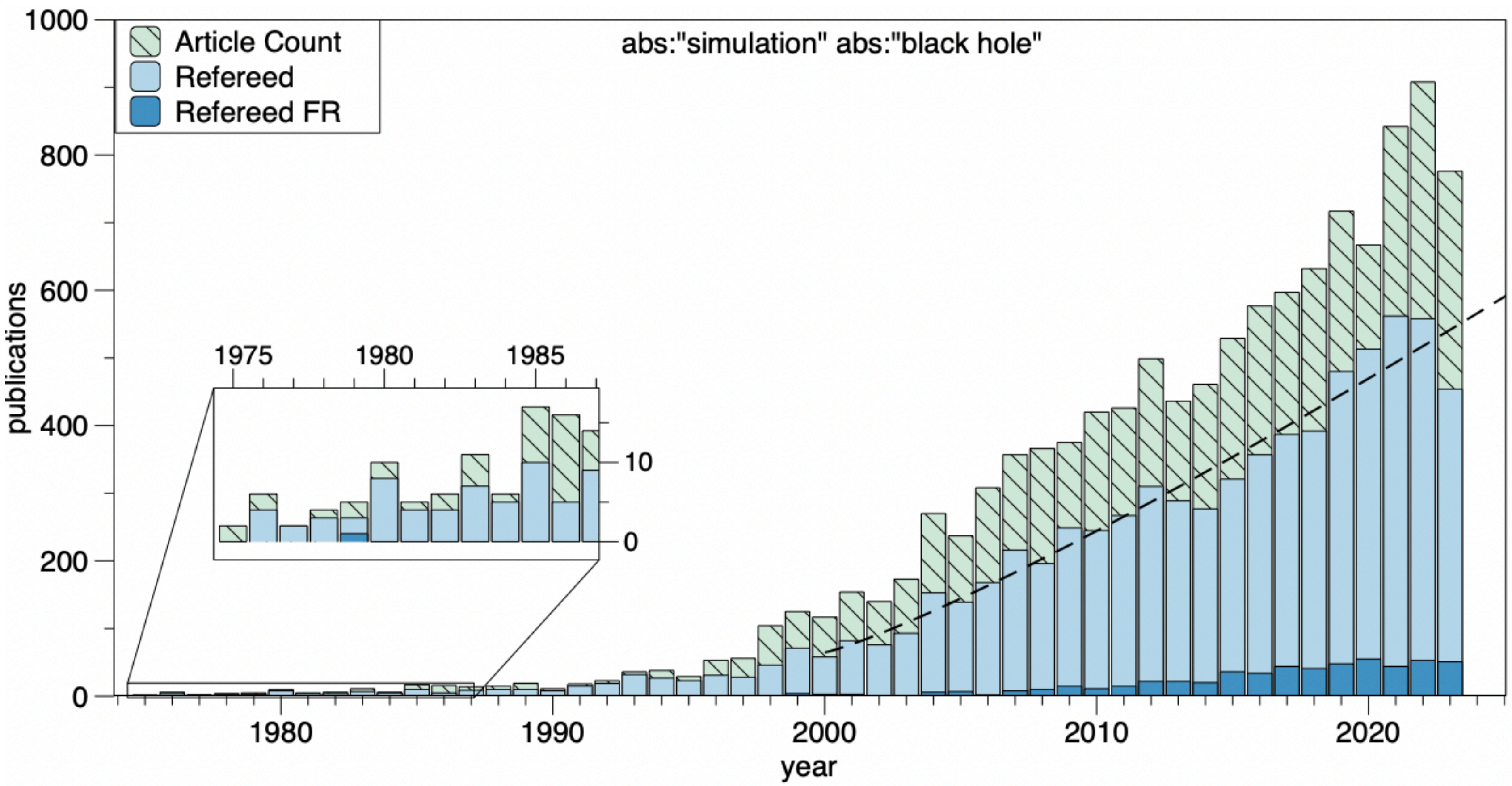

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thanks to the increasing computing capability there is also a shift from local simulation (i.e. a shearing box inside the disk or the jet…), looking at one specific aspect (MRI formation and evolution, shock propagations in jets…), not often including GR effects

to global simulation of the system exploring how multiple components of the systems interact

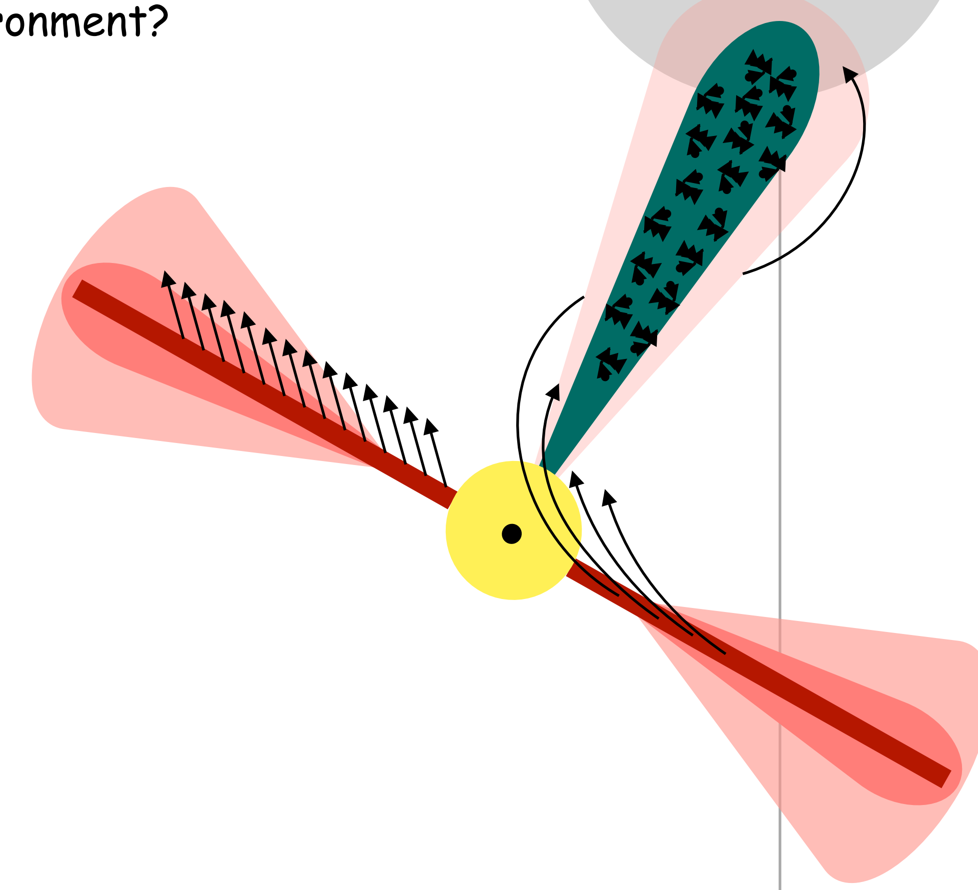
simulation

Simulations of BH environment

BH environment

why are global simulations so important for BH environment?

from BH observations we see that the different components are strongly linked



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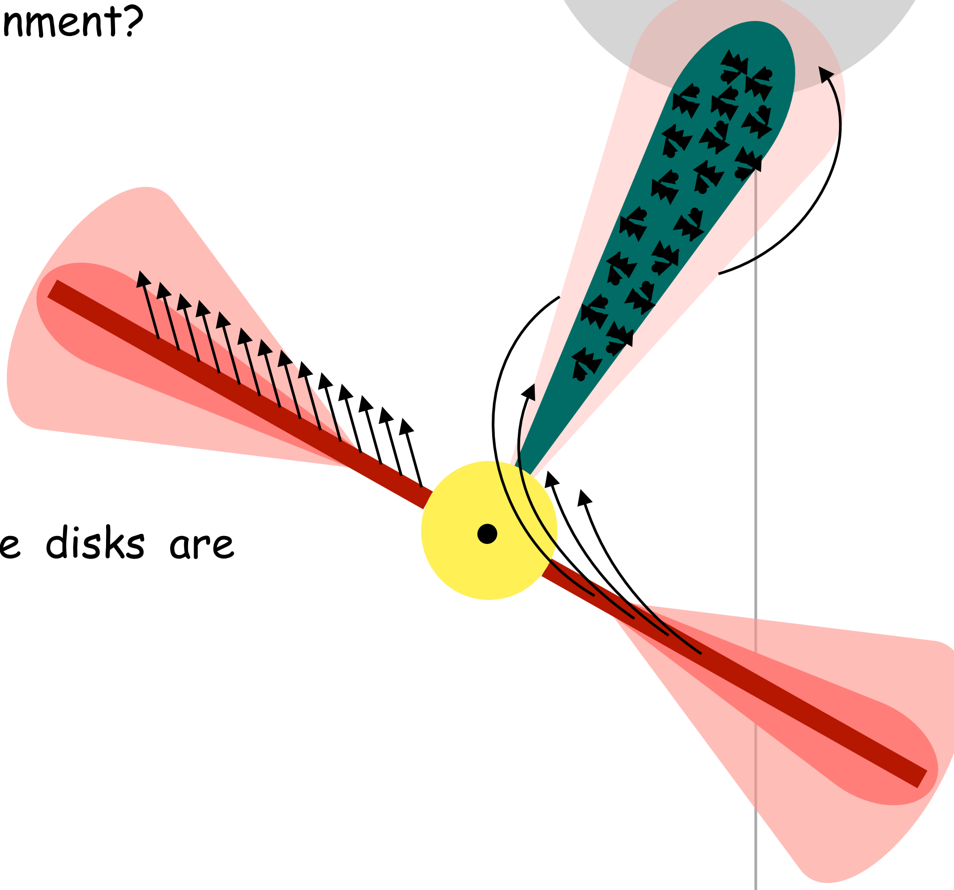

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- a source of mass is needed to form a disk
  ➜ when can you form a disk from the captured wind of a high mass companion ?

- an accretion disk always seems present when we observe ejection, but some disks are observed without jets
  ➜ what are the necessary ingredient(s) linking accretion and ejection?

- a “corona” is needed in the energy spectrum of some sources, but what is it?
  ➜ is it the base of the jet, some disk wind … ?

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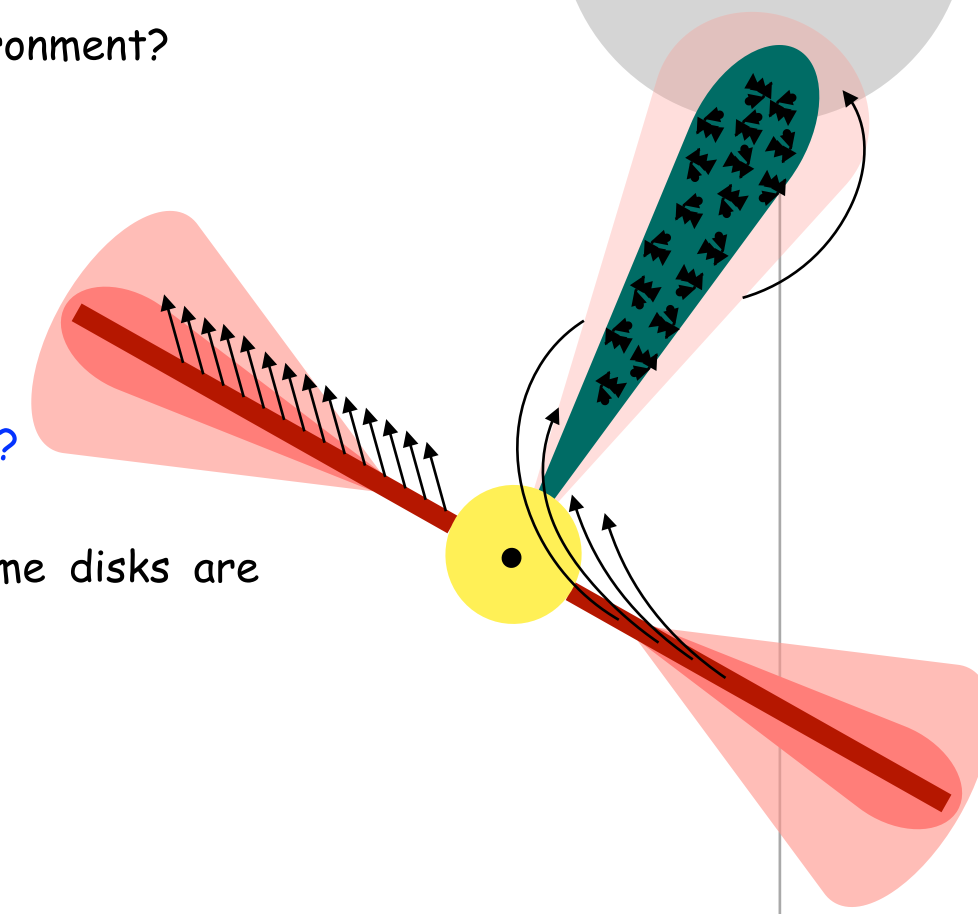

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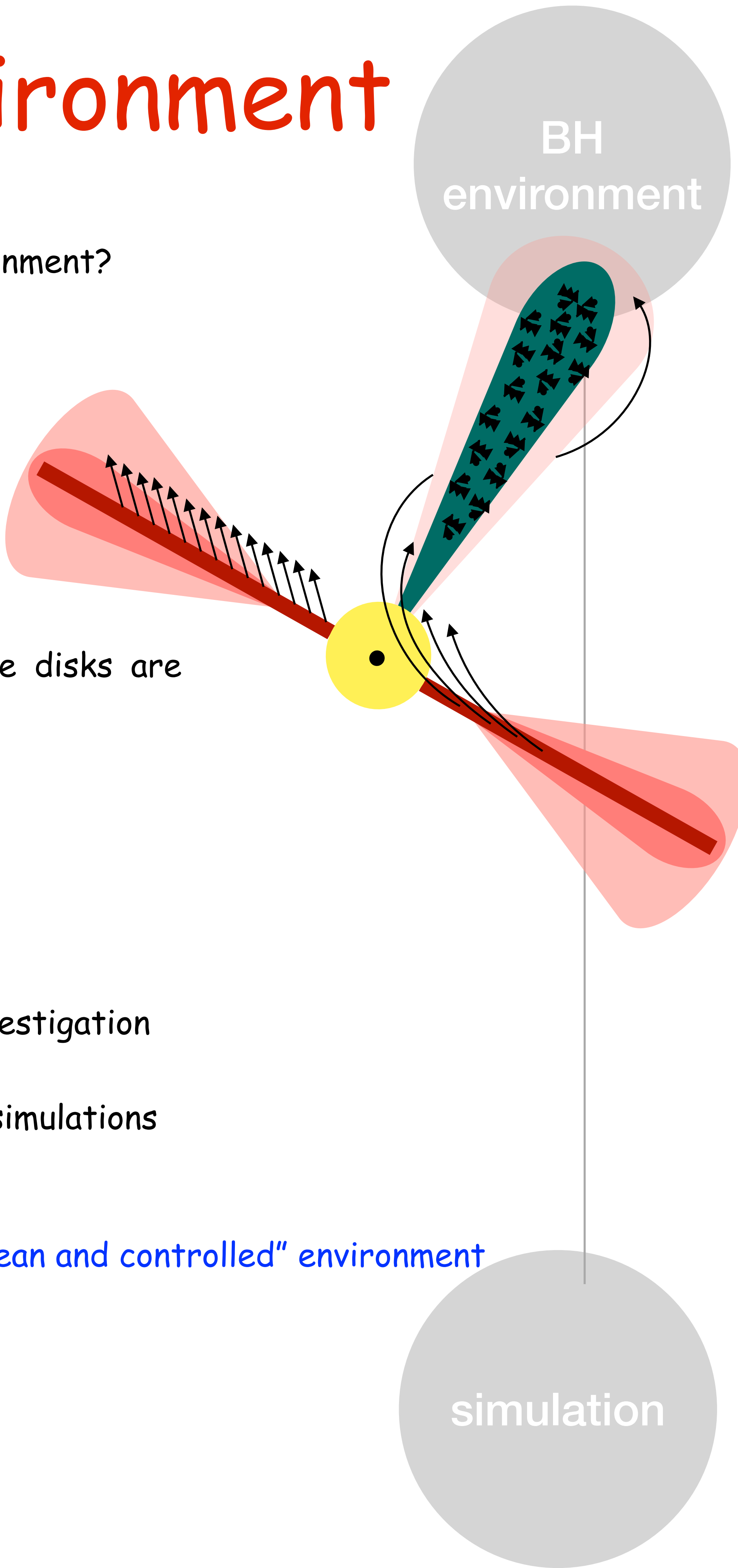

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at the same time, local simulations are useful to study individual components in a "clean and controlled" environment

➥ it depends on the aim of the simulations

Aim of Simulations of BH environment

simulation of BH environment fall into two mains types

- ➜ understanding of some aspects of the BH systems, either observed or purely theoretical
  - ➥ transport of angular momentum and magnetic flux
  - ➥ formation and evolution of disk instabilities
  - ➥ what couples the disk and the outflows
  - ➥ where do the ejections come from, how do they evolve
  - ➥ what are the particle acceleration sites and their behaviors
- ➜ more direct link with observations
  - ➥ exploring the possible origins of an observational feature such as QPOs, iron line shape, variability of the corona, origin of lag
  - ➥ direct comparison with observations by the means of synthetic lightcurves, spectra ...
  - ➥ testing new methods of data reduction, observation technics...

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another aspect linked to this, but not directly related to BH environment, is the development of new codes and methods.

In particular the recent effort toward reducing the ecological impact of the running and archiving of numerical simulations.
➥ with the new surveys and the considerable amount of archival data coming from observations this is an issue that goes beyond numerical simulations

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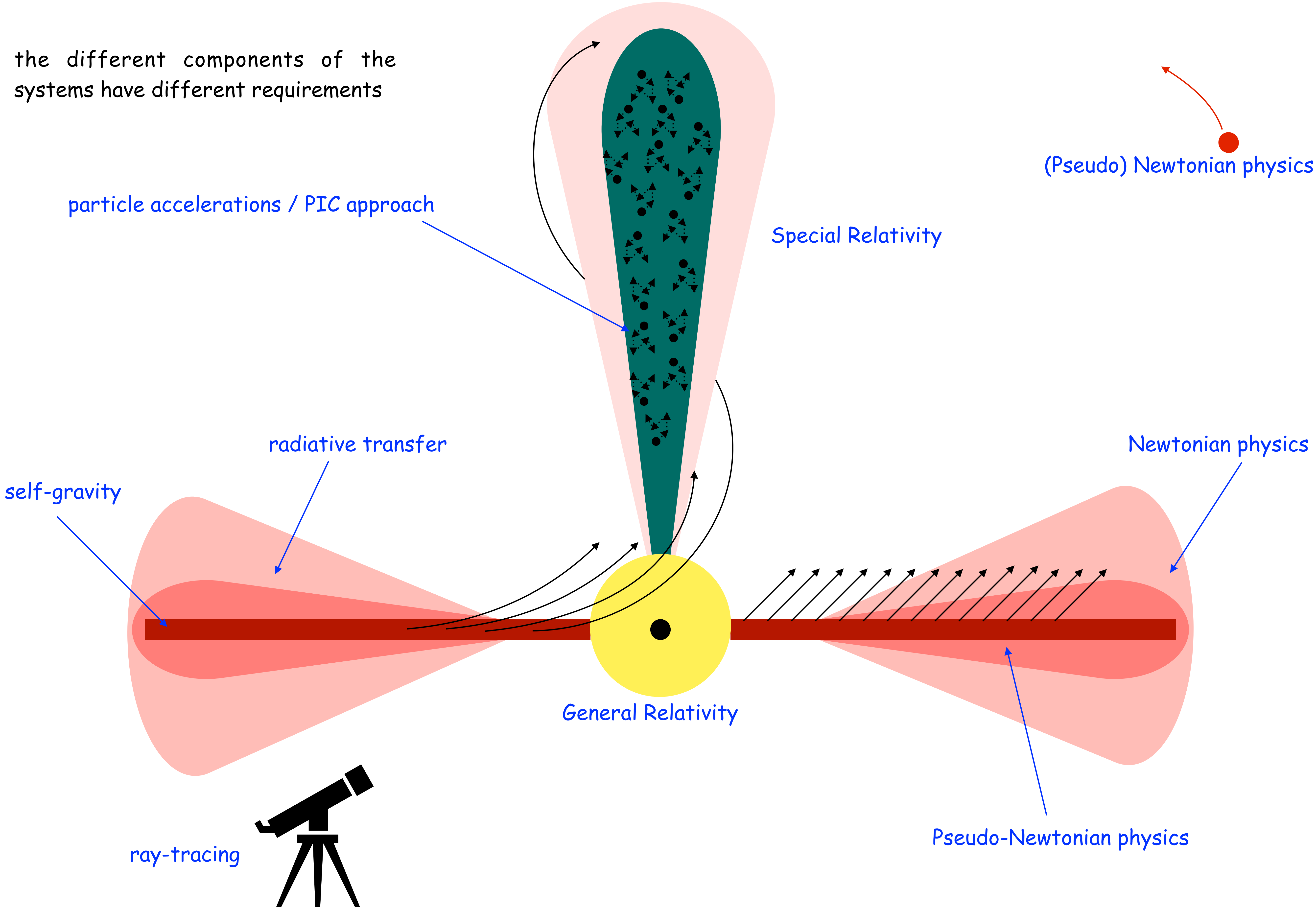
➜ but what physics and processes are involved in those simulations ?

Simulations of BH environment

the different components of the systems have different requirements



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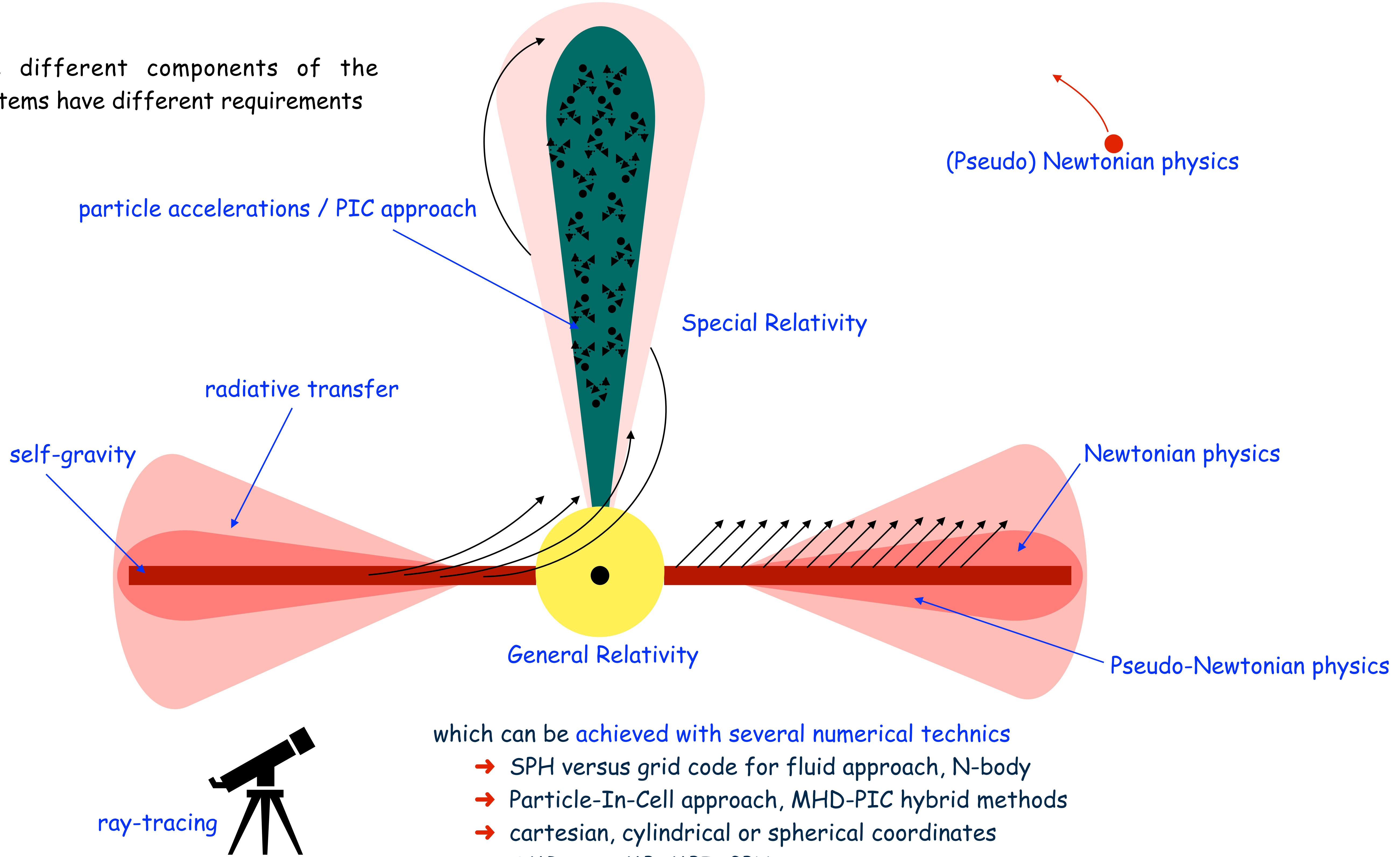

which can be achieved with several numerical technics

- SPH versus grid code for fluid approach, N-body
- Particle-In-Cell approach, MHD-PIC hybrid methods
- cartesian, cylindrical or spherical coordinates
- AMR, openMP, MPI, GPU
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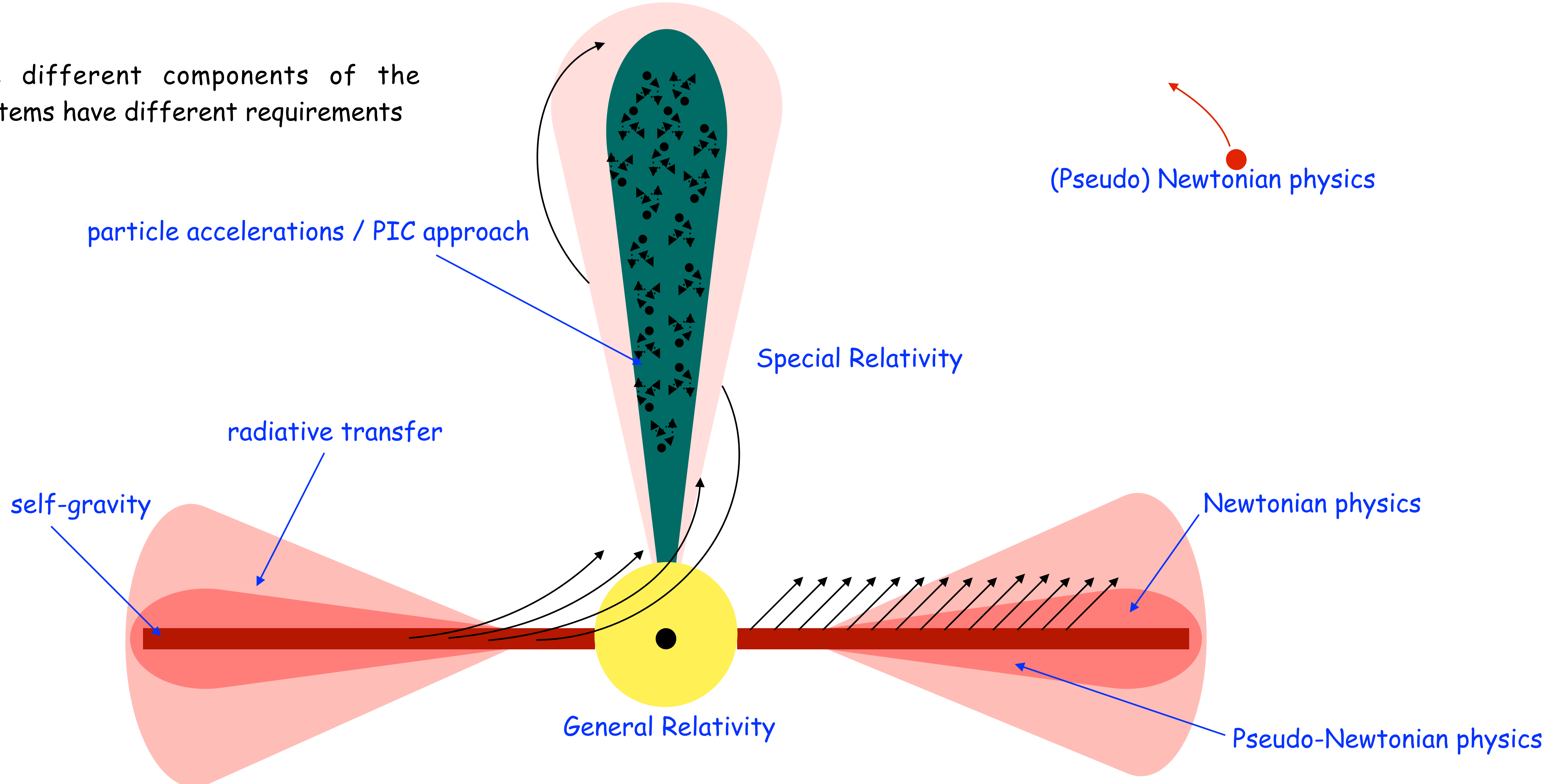

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- ➜ once in GR the metrics can be analytical, tabulated or computed on the fly

➥ wide variety of simulations possible to study the different aspects of a black-hole environment

Simulations of BH environment

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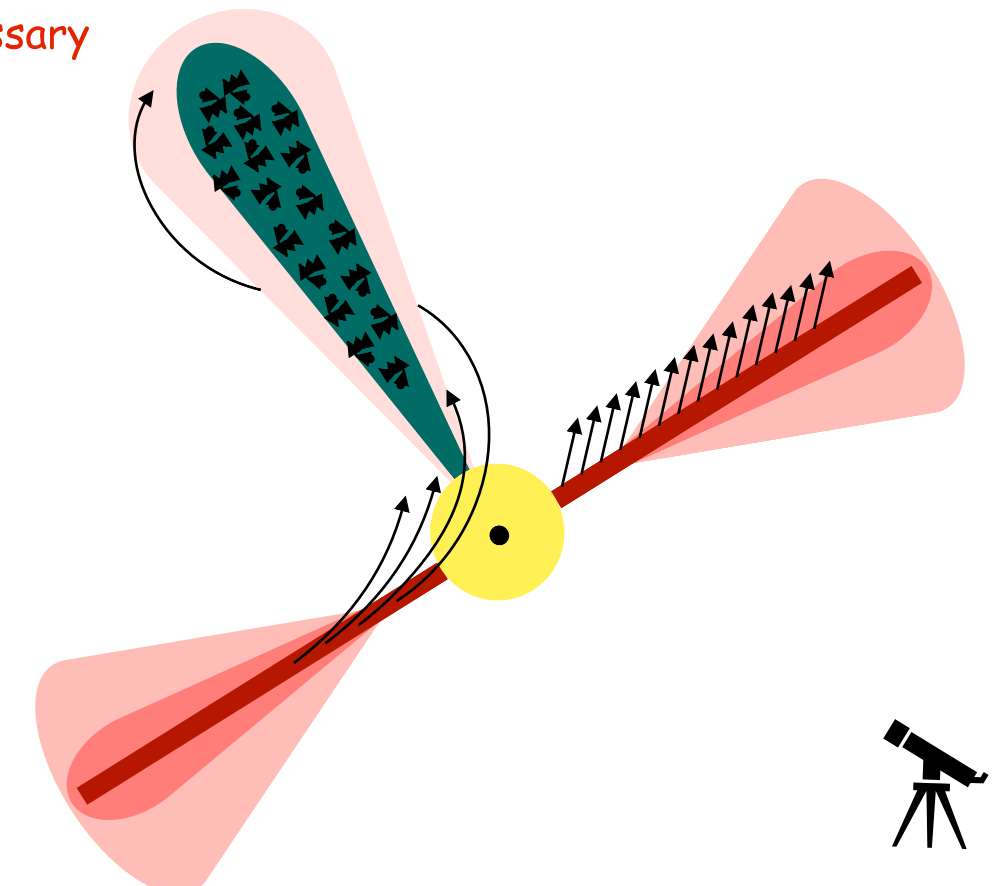
but not all aspects simultaneously necessary



if we want to look at the launching of a jet, wind or particle accelerations

➜ then MHD is necessary

similarly when looking at all the magnetic instabilities in the disk

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if we want to look at the Blandford-Znajek process, Lense-Thirring effect

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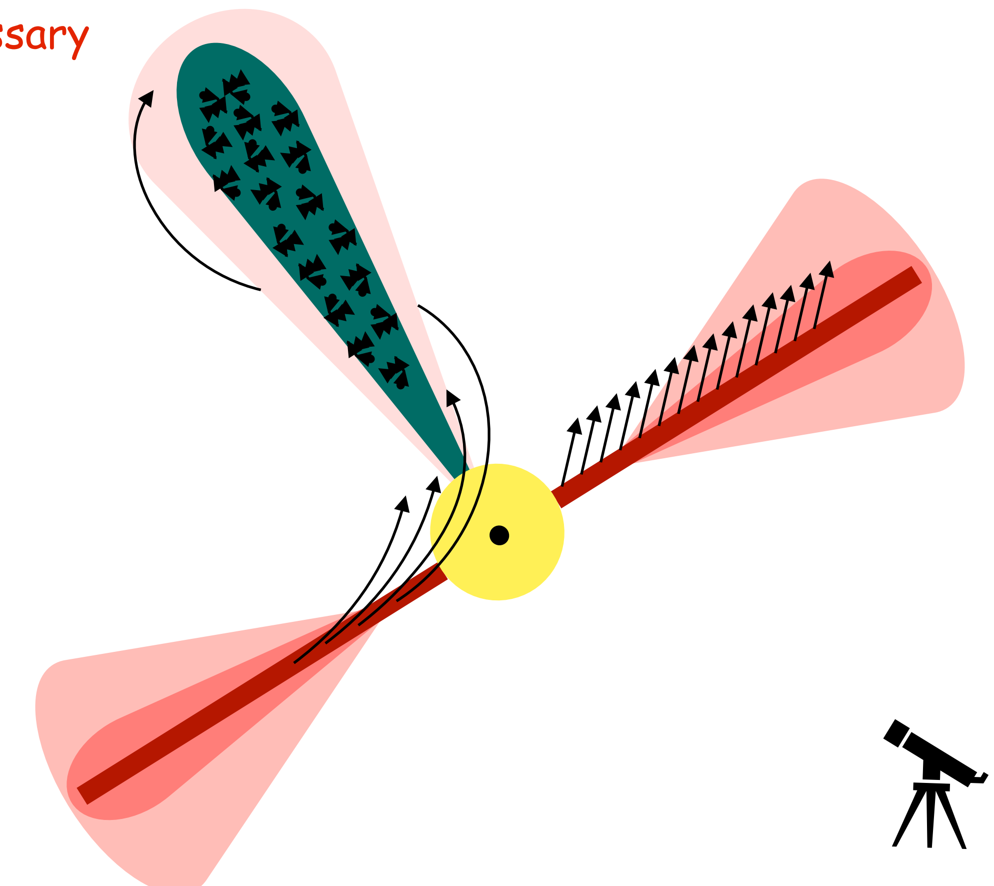

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but if we want to look at the behavior of the outer edge of the disk

➜ self gravity might have a bigger impact than the spin of the central black-hole

➥ and so the question is when is GR necessary to study a BH environment?

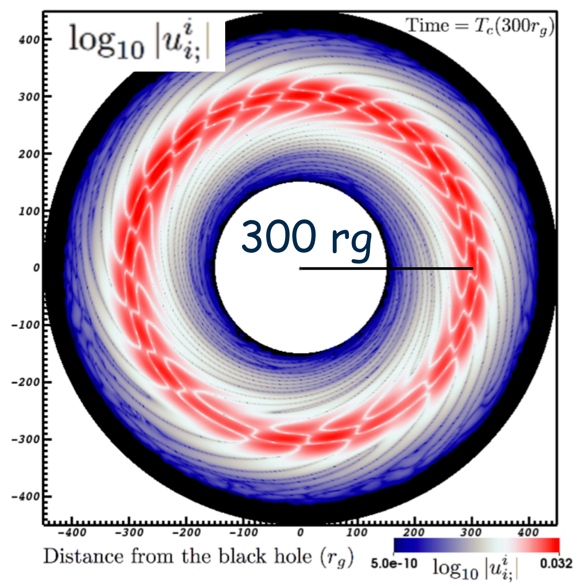
When is GR necessary for disk physics?

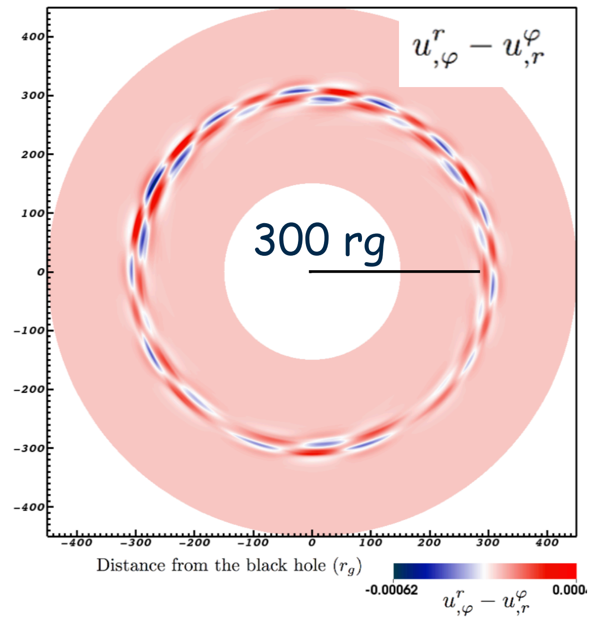
while having a black-hole system often equates the use of the Kerr metric one can ask the question of the necessity of such approach for all the possible disks

➜ when is it necessary versus when can it be ignored with limited to no-noticeable impact?

if we study something far away from the black-hole, the impact of the GR is very limited

➜ but how far is "far enough"





plots from Casse et al., 2017 and Casse & Varniere 2018

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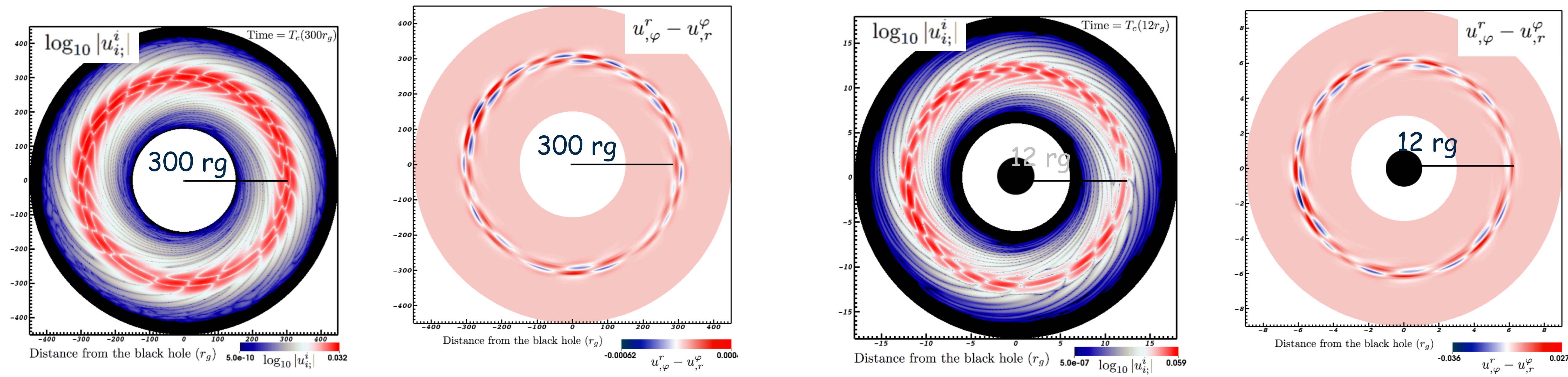

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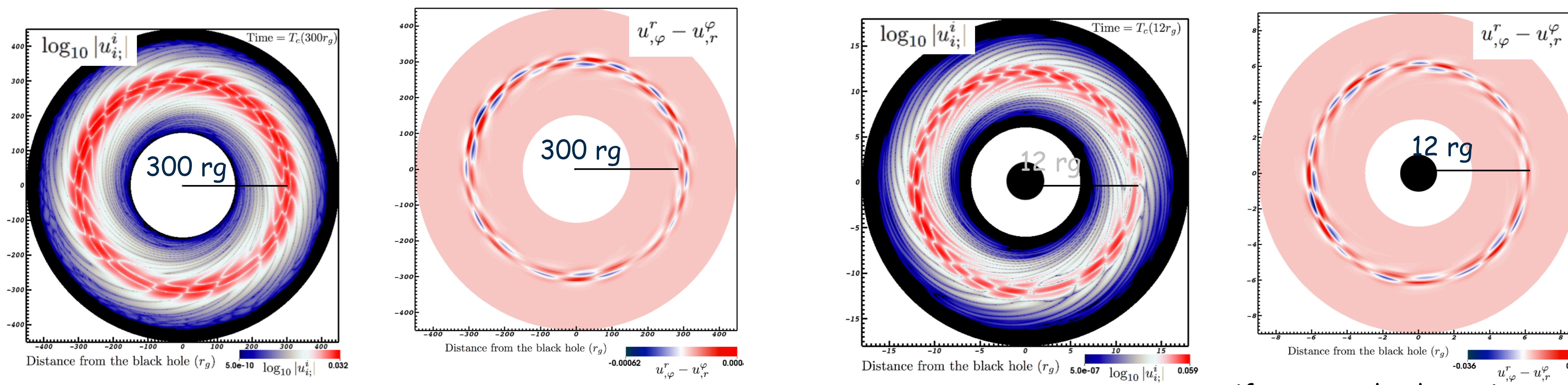

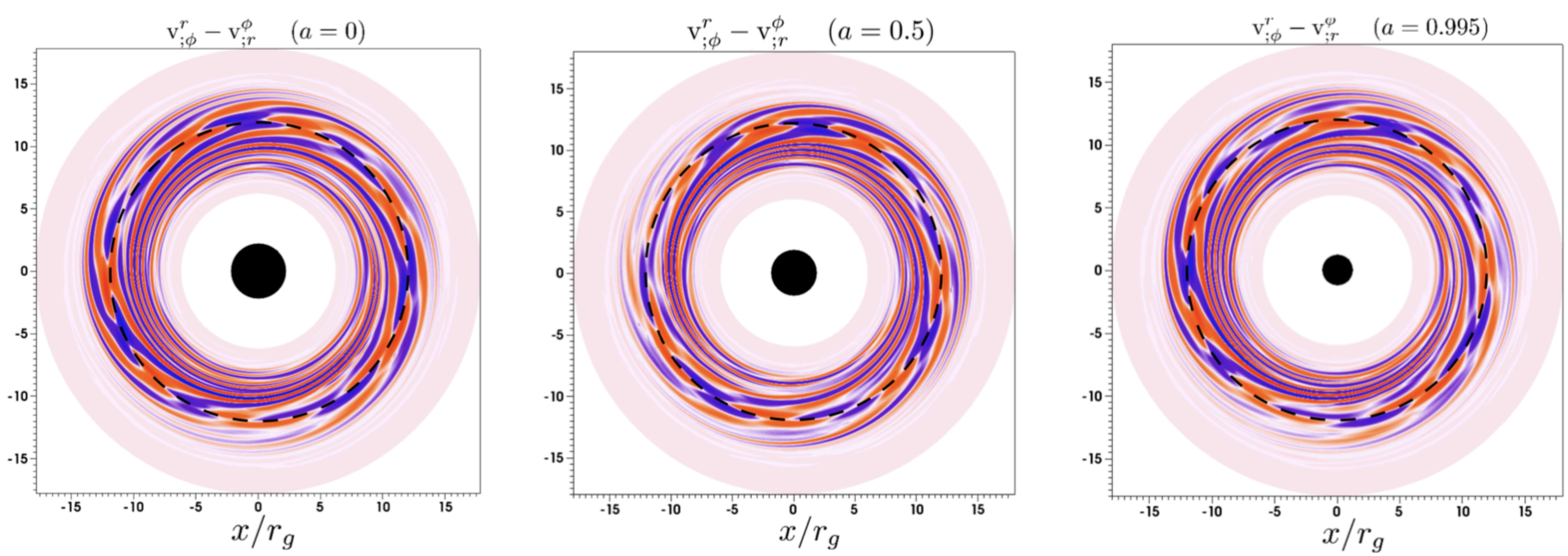

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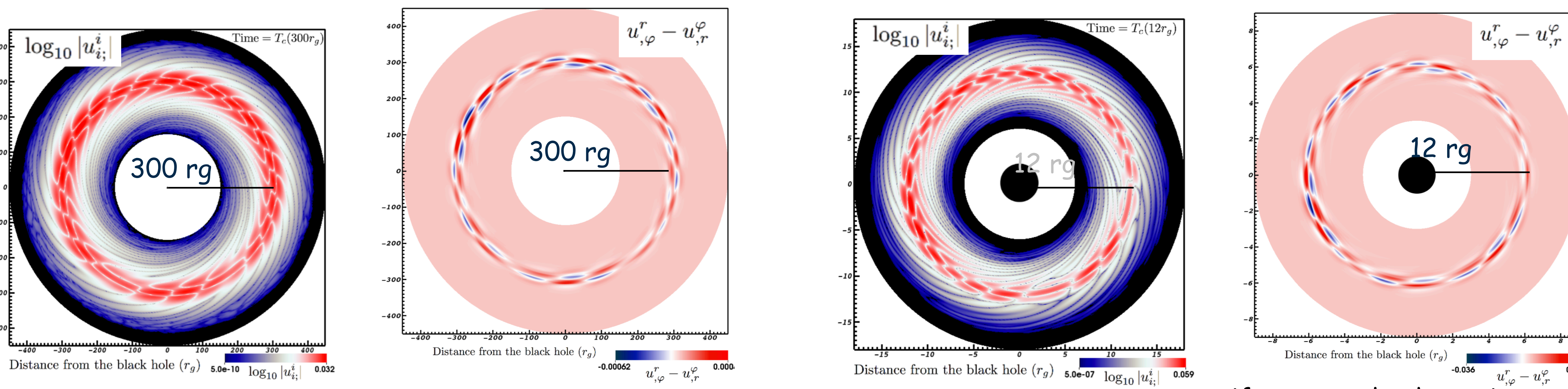

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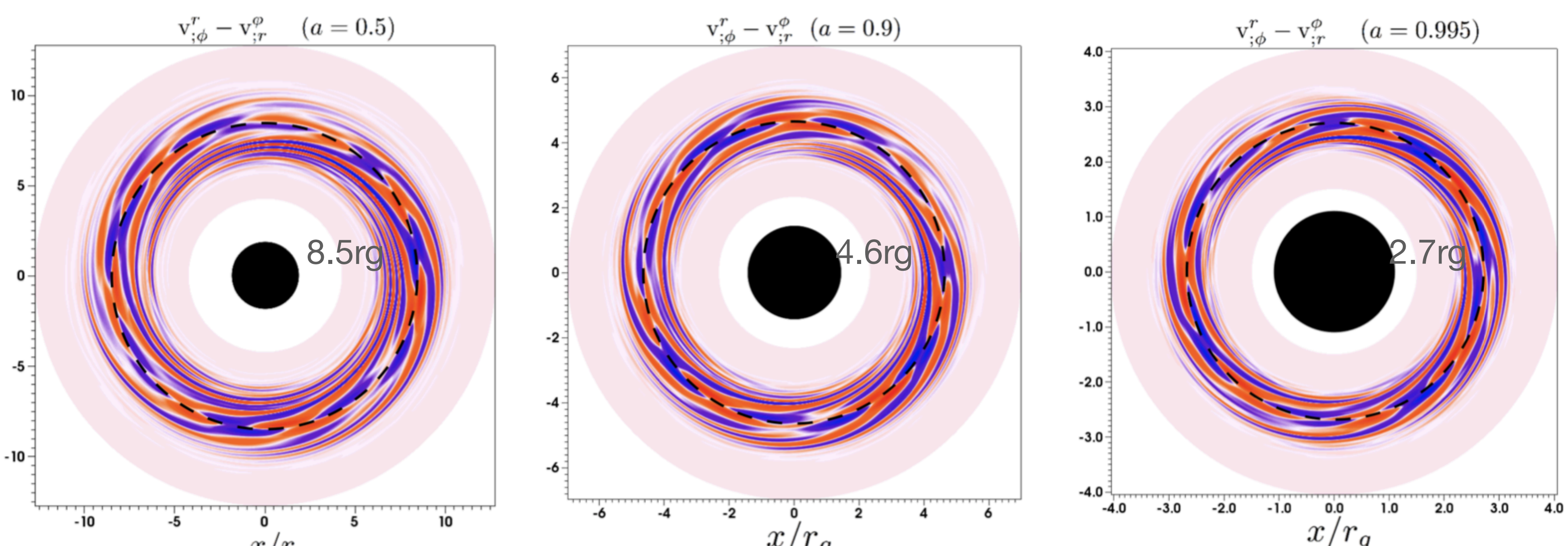


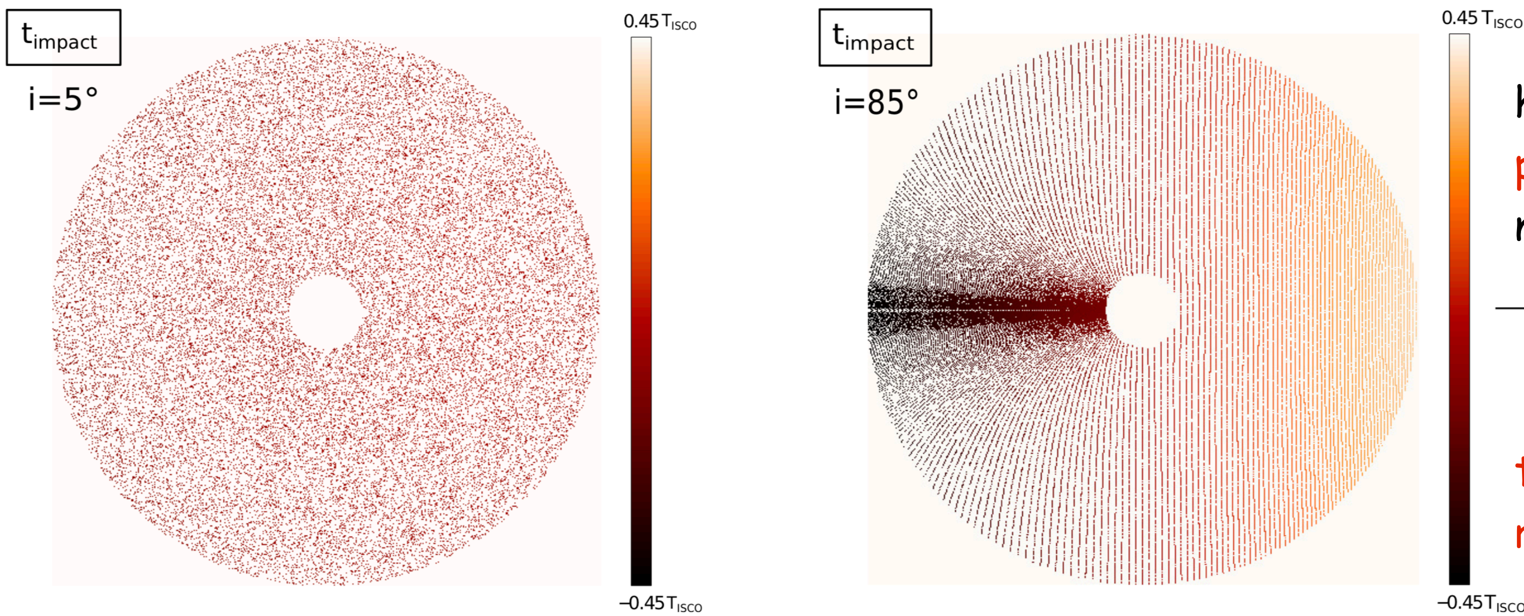
to start seeing some qualitative and quantitative change in the behavior the structure needs to be within 4.5rg of the black-hole.

➜ a spin > 0.75 is needed for the disk to reach that radius

plots from Casse et al., 2017 and Casse & Varniere 2018

When is GR necessary for BH environment?

but there is another step using GR, namely when the emission is raytraced back to the observer to produce synthetic observables



Vincent et al., 2011

➜ here we see, that even for a spin of 0, as soon as we have a high enough inclination, the raytracing needs to be performed in GR (though the fluid simulation does not need to)

➜ so if we want realistic synthetic observables from the simulation of black-hole environment we need GR raytracing

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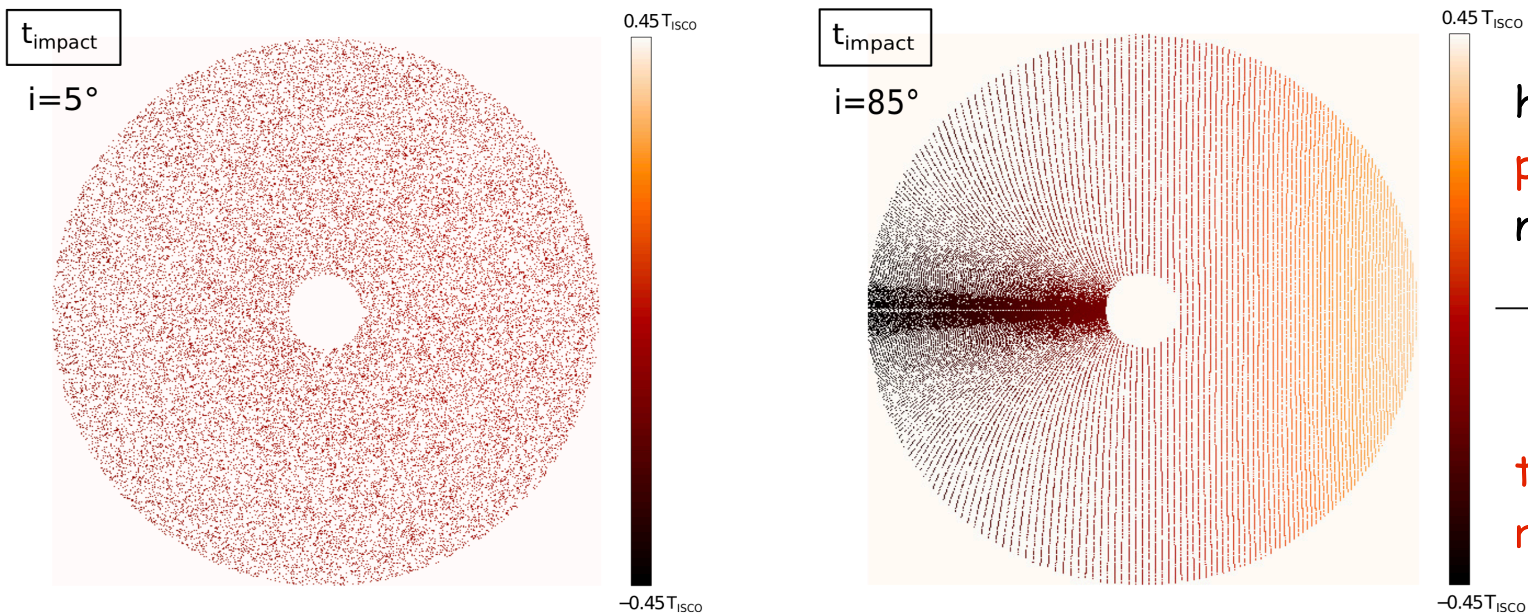

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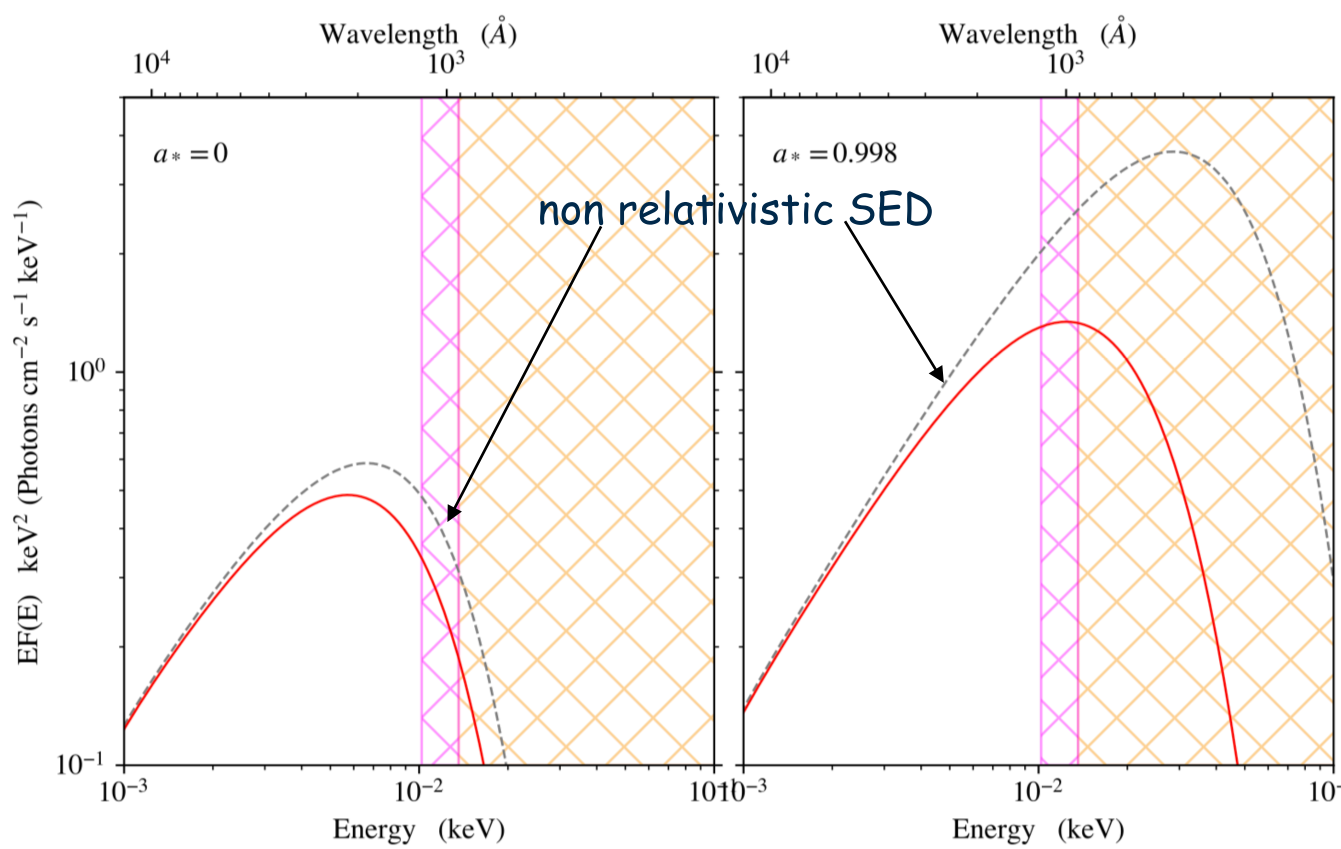
more recently Hagen & Done 2023 looked at the impact of GR ray-tracing on the energy spectrum and how it influences our estimates of black-hole spin "Estimating Black Hole Spin from AGN SED Fitting: The Impact of General-Relativistic Ray Tracing"

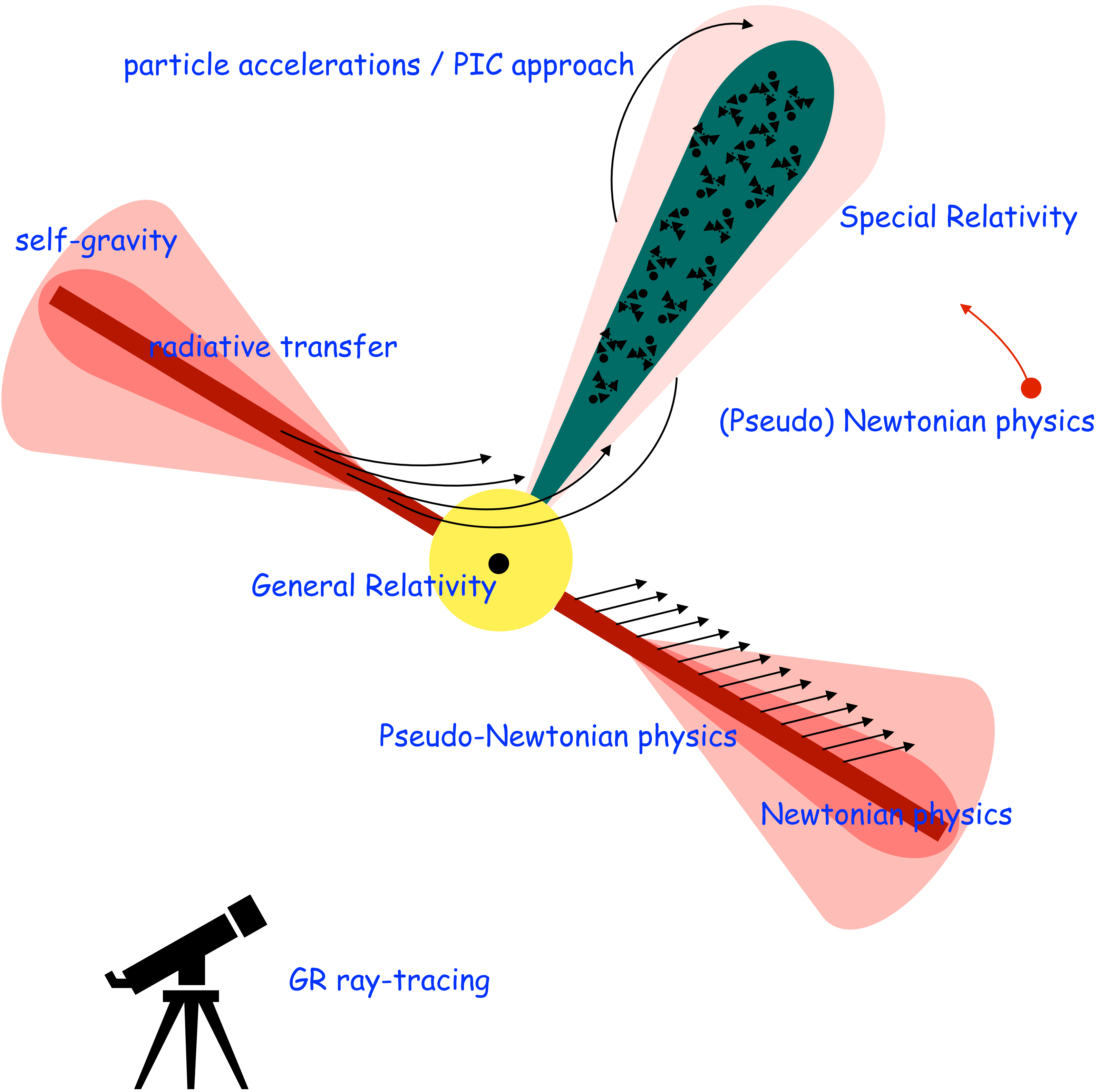
➜ ray tracing has a significant impact on the predicted SED, especially for the highest energy emission, which is assumed to originate in the innermost part of the flow.

➜ so if we want to fit the results of (GR)-(M)HD simulations to observations we need GR raytracing



log r_{out} = 3 to r_{isco}, M_{BH} = 10^9 $M_\odot$ black hole, mass accretion rate =10^{26}g/s inclination of cos(i)=0.9.

Simulations of BH environment



overview of GRMHD simulation of BH environment is not an easy task as there are so many interconnected components involved all requiring different physics, timescales and numerical technics

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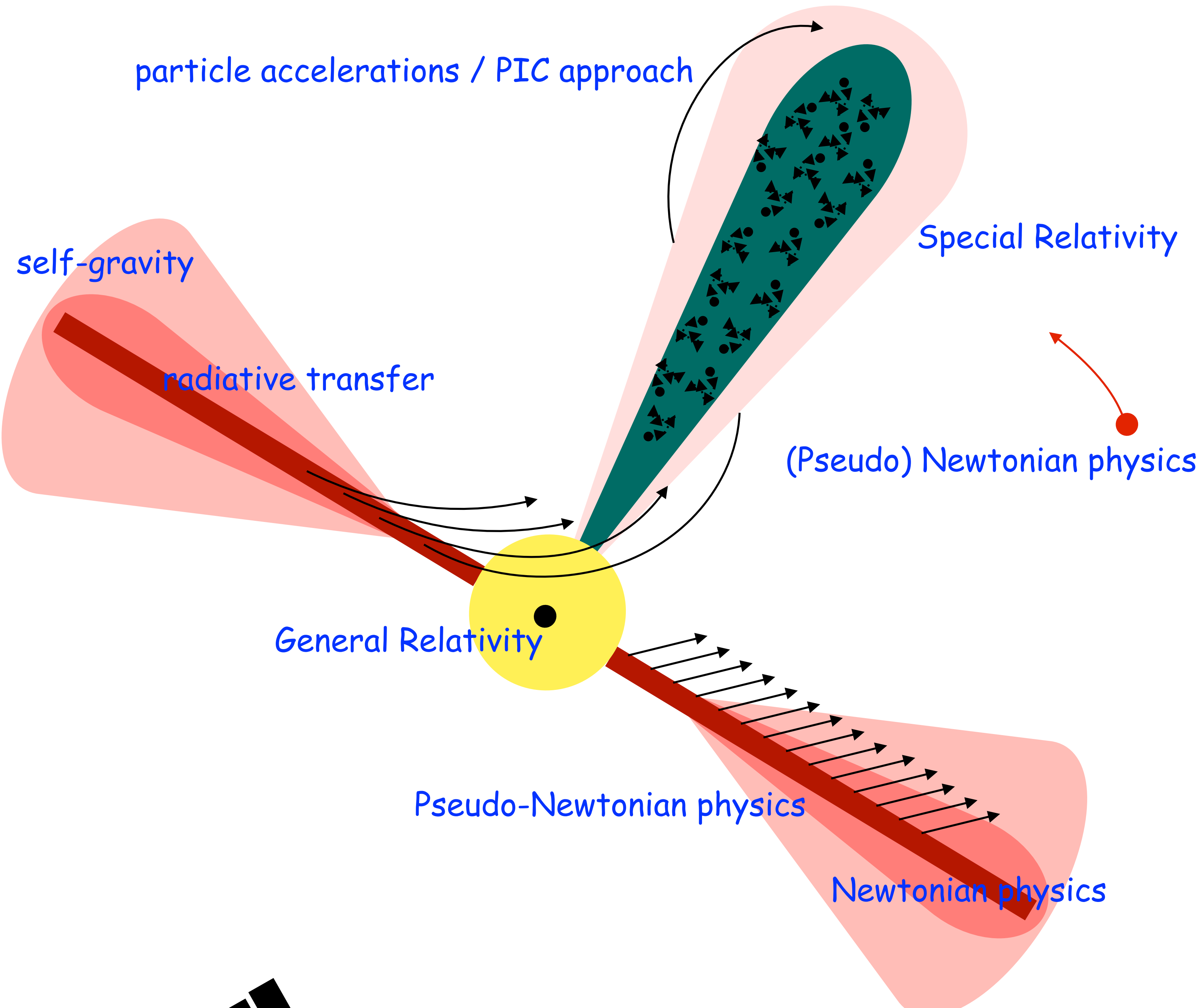

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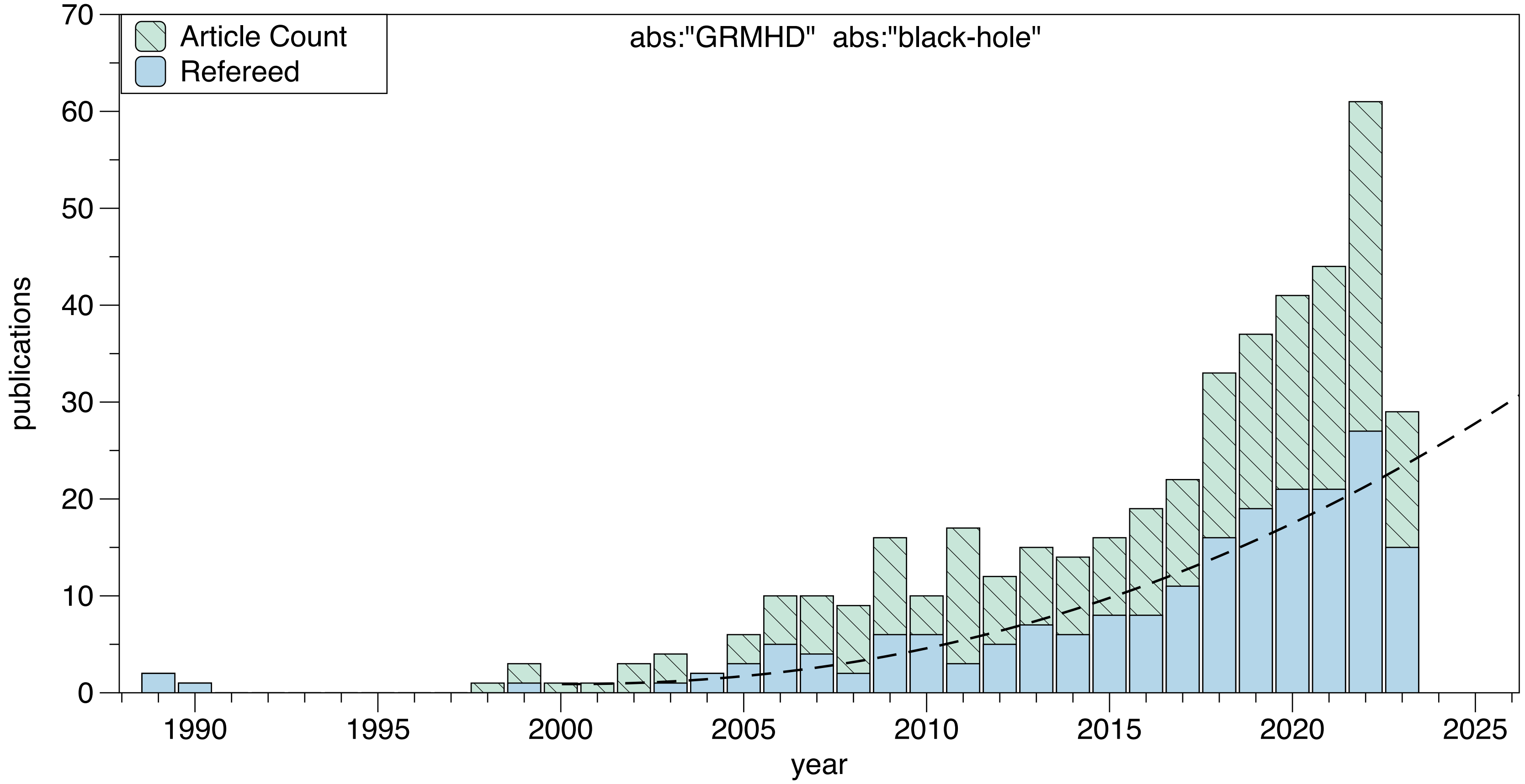

GRMHD Simulations of BH environment

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Relativistic magnetohydrodynamics in dynamical spacetimes: Numerical methods and tests

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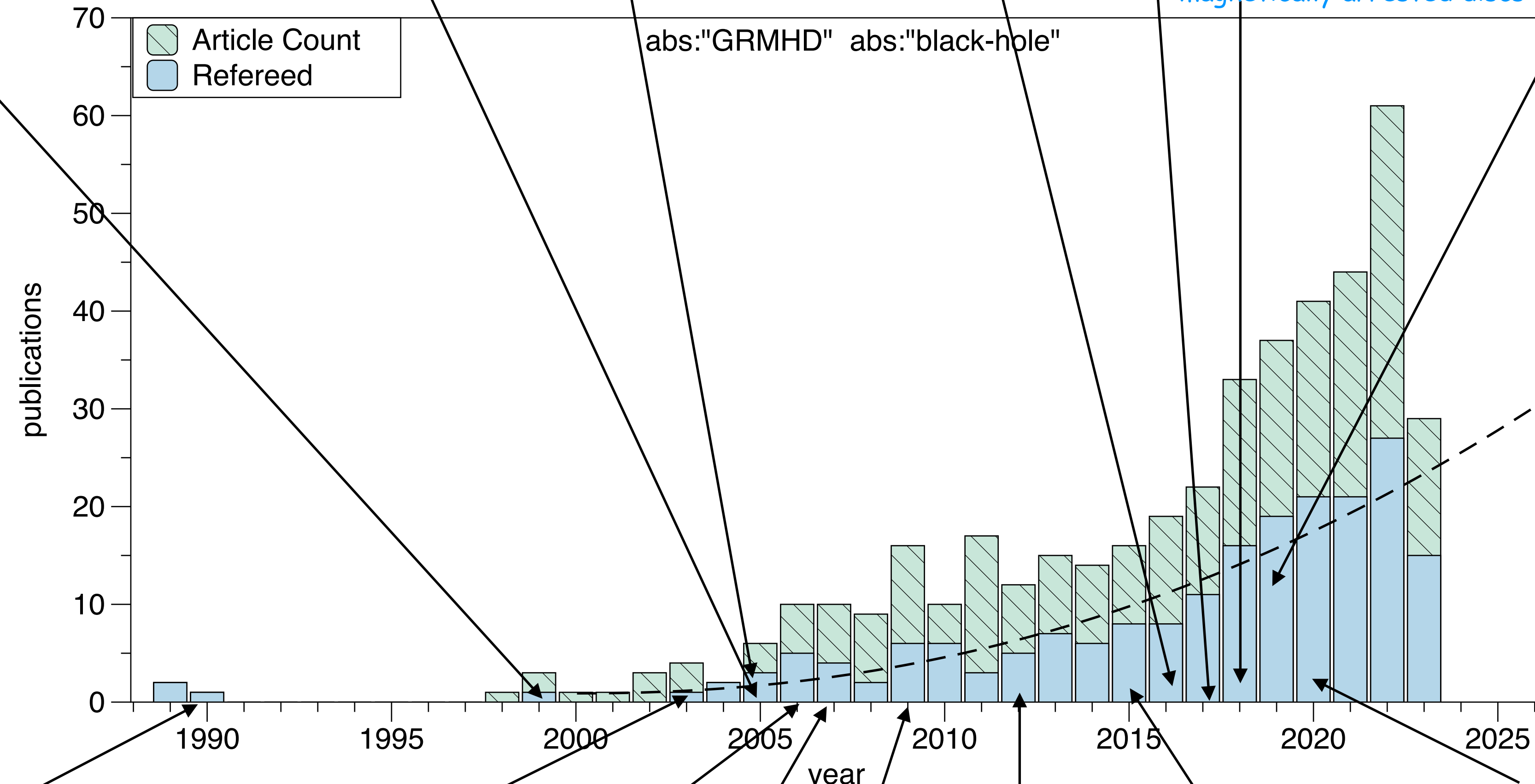
3-D General Relativistic MHD Simulations of Generating Jets



early theoretical work

A Numerical Method for General Relativistic Magnetohydrodynamics

General relativistic force-free electrodynamics: a new code and applications to black hole magnetospheres

Disc-jet coupling in black hole accretion systems - II. Force-free electrodynamical models

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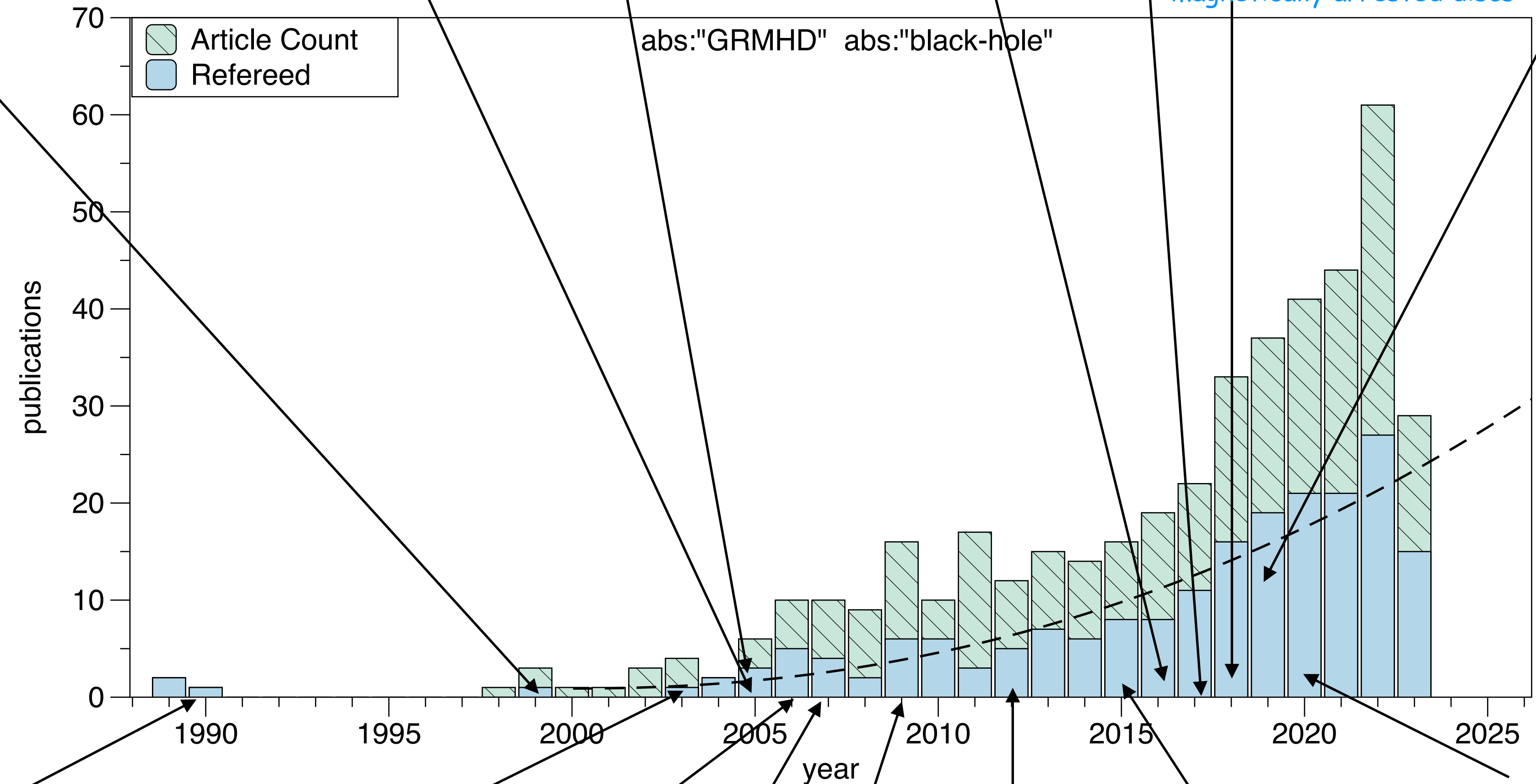

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and more recently pre-merger related papers

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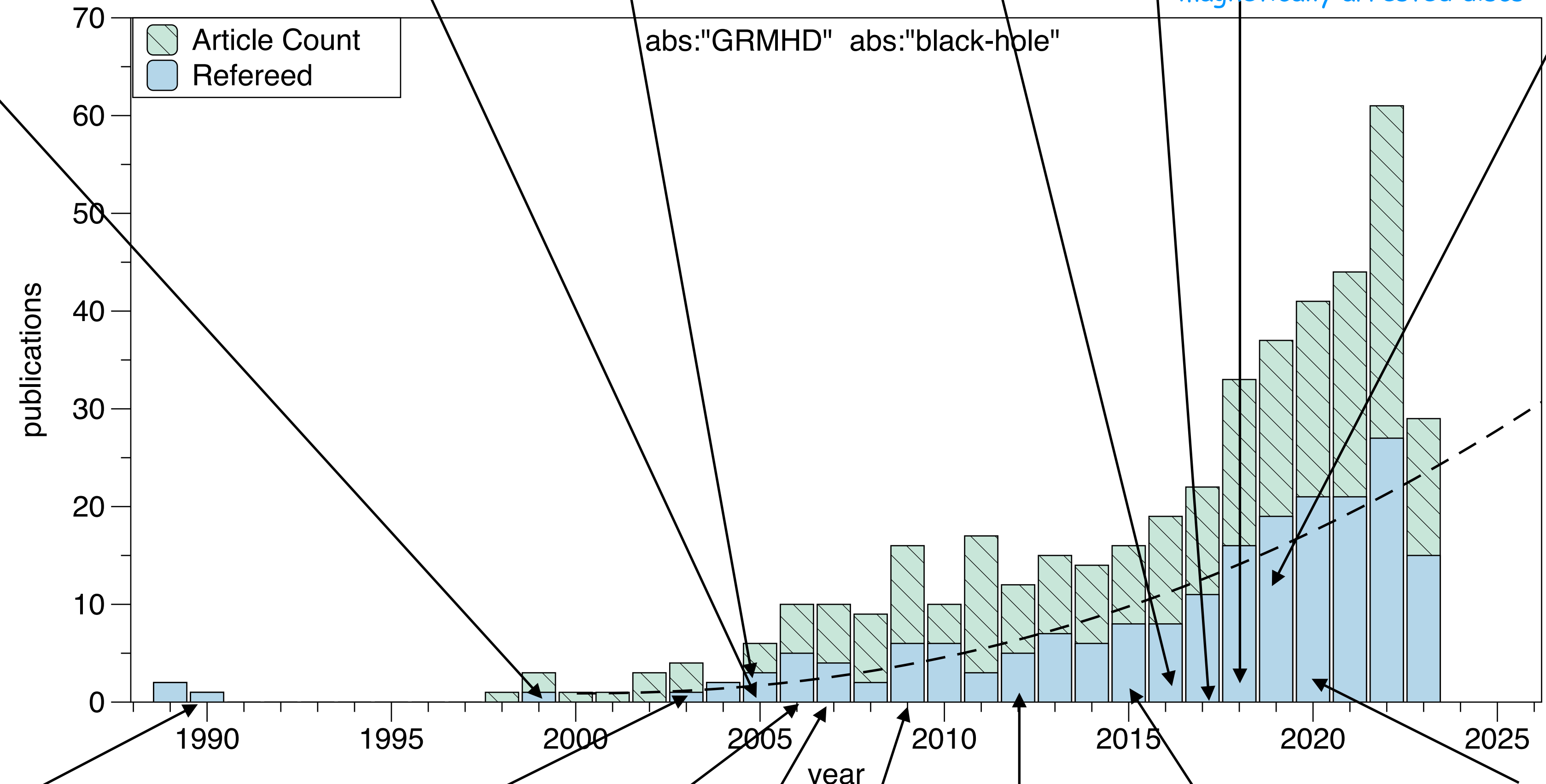

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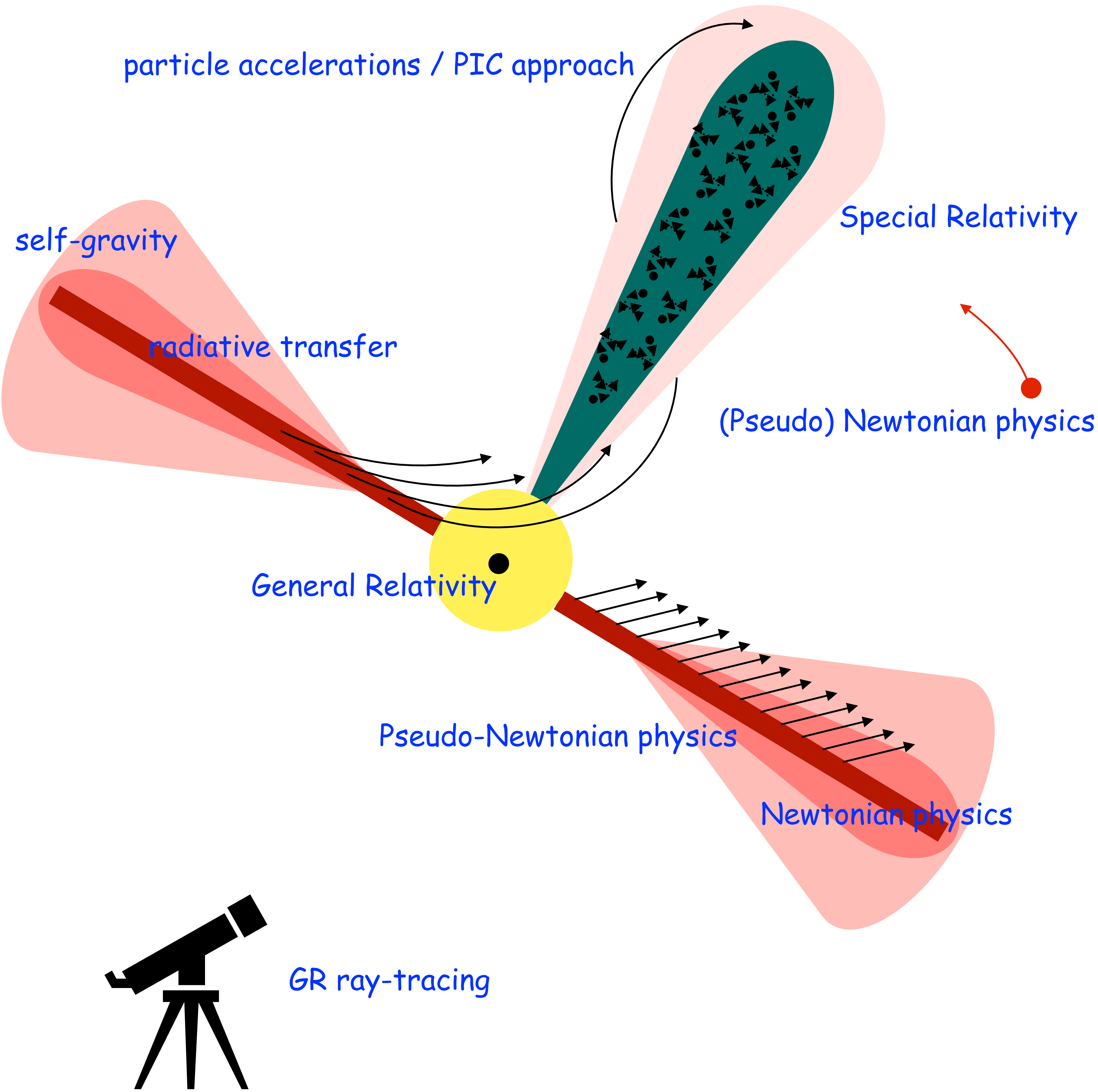
➥ very active field but with only a few groups/codes per subfield

Simulations of BH environment



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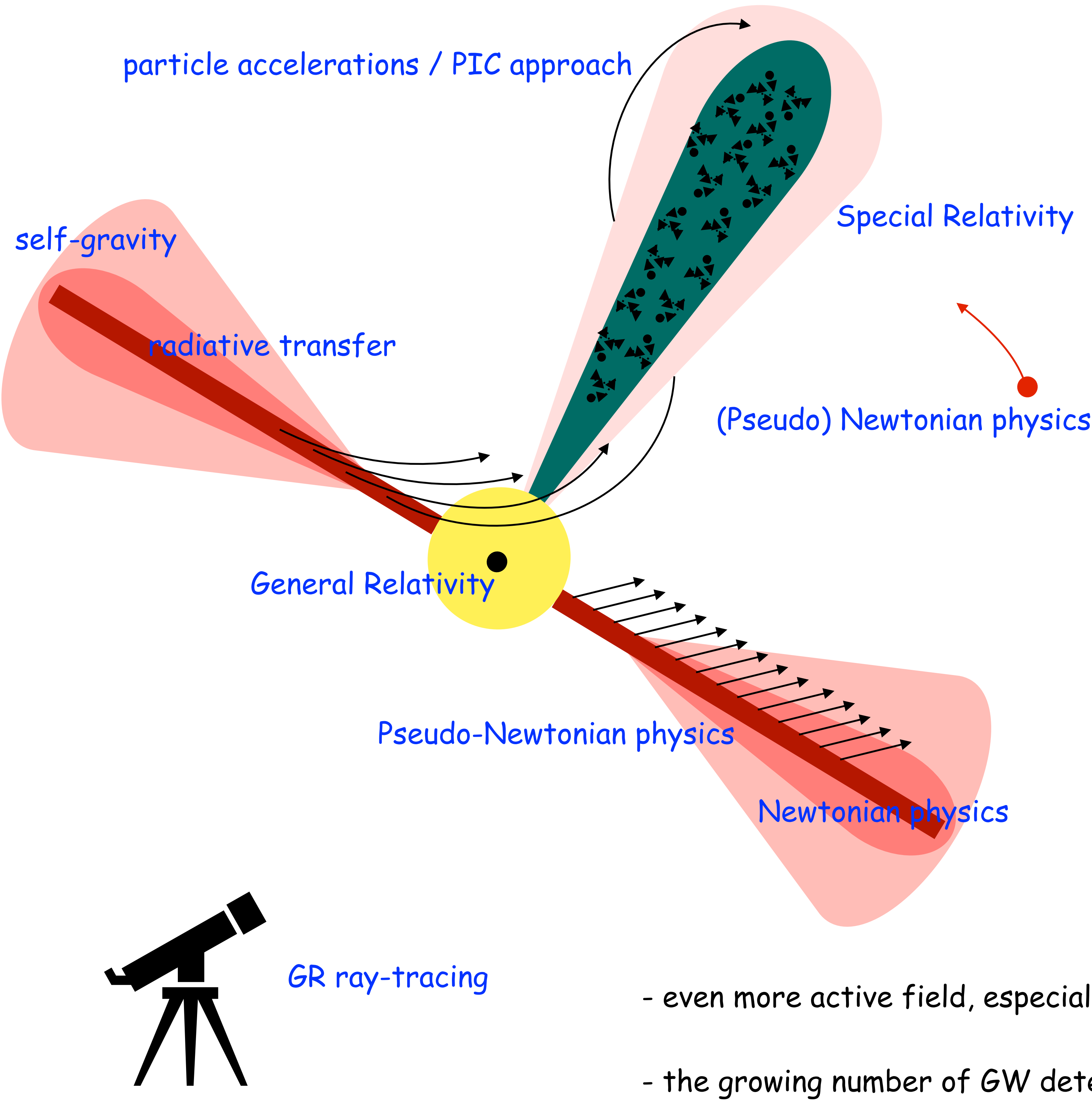

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but a few take-away points:

- numerical simulations are a **great tool** to improve our understanding of the diverse phenomena happening in the environment of BHs

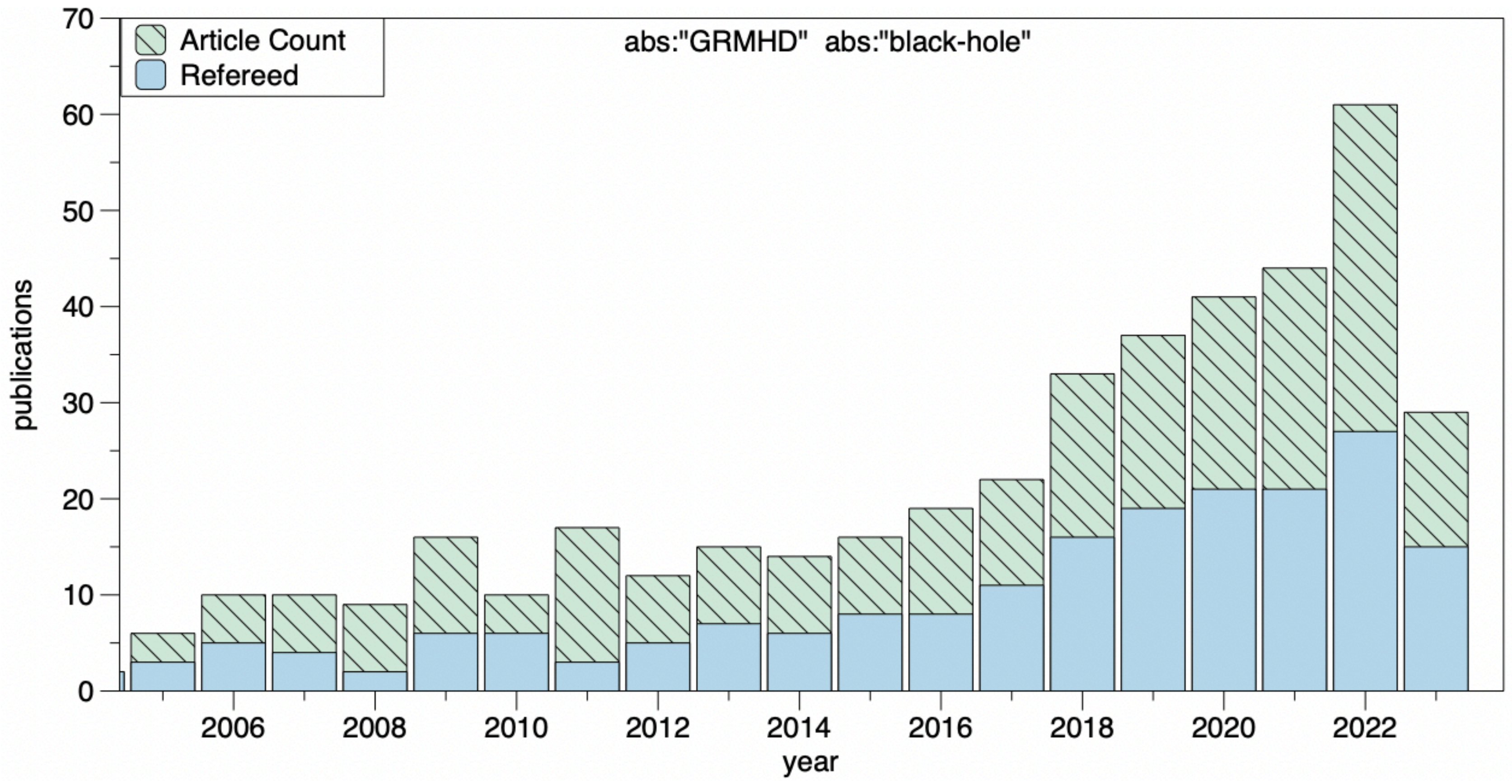
- but GR ray-tracing is **essential** to link simulations to the observables

- even more active field, especially since the EHT and gravity observations

- the growing number of GW detections from binary black-hole mergers is also pushing for a better understanding of the emission from BH in the coming years

recent GRMHD Simulations of BH environment

among the recent papers accretion disk behavior, jet launching/propagation are still the most popular study as well as a growing comparison with observations focusing primarily on EHT and gravity results



recent GRMHD Simulations of BH environment

Numerical Methods for Exascale Magnetohydrodynamics Simulations in General Relativity

Two-moment scheme for general-relativistic radiation hydrodynamics: a systematic description and new applications

Flares in the Galactic Centre - I. Orbiting flux tubes in magnetically arrested black hole accretion discs

Magnetically modified spherical accretion in GRMHD: reconnection-driven convection and jet propagation

RAPTOR. I. Time-dependent radiative transfer in arbitrary spacetimes

Observational Signatures of Mass-loading in Jets Launched by Rotating Black Holes

GR-MHD Disk Winds and Jets from Black Holes and Resistive Accretion Disks

Looking for the underlying cause of black hole X-ray variability in GRMHD simulations

Disc tearing and Bardeen-Petterson alignment in GRMHD simulations of highly tilted thin accretion discs

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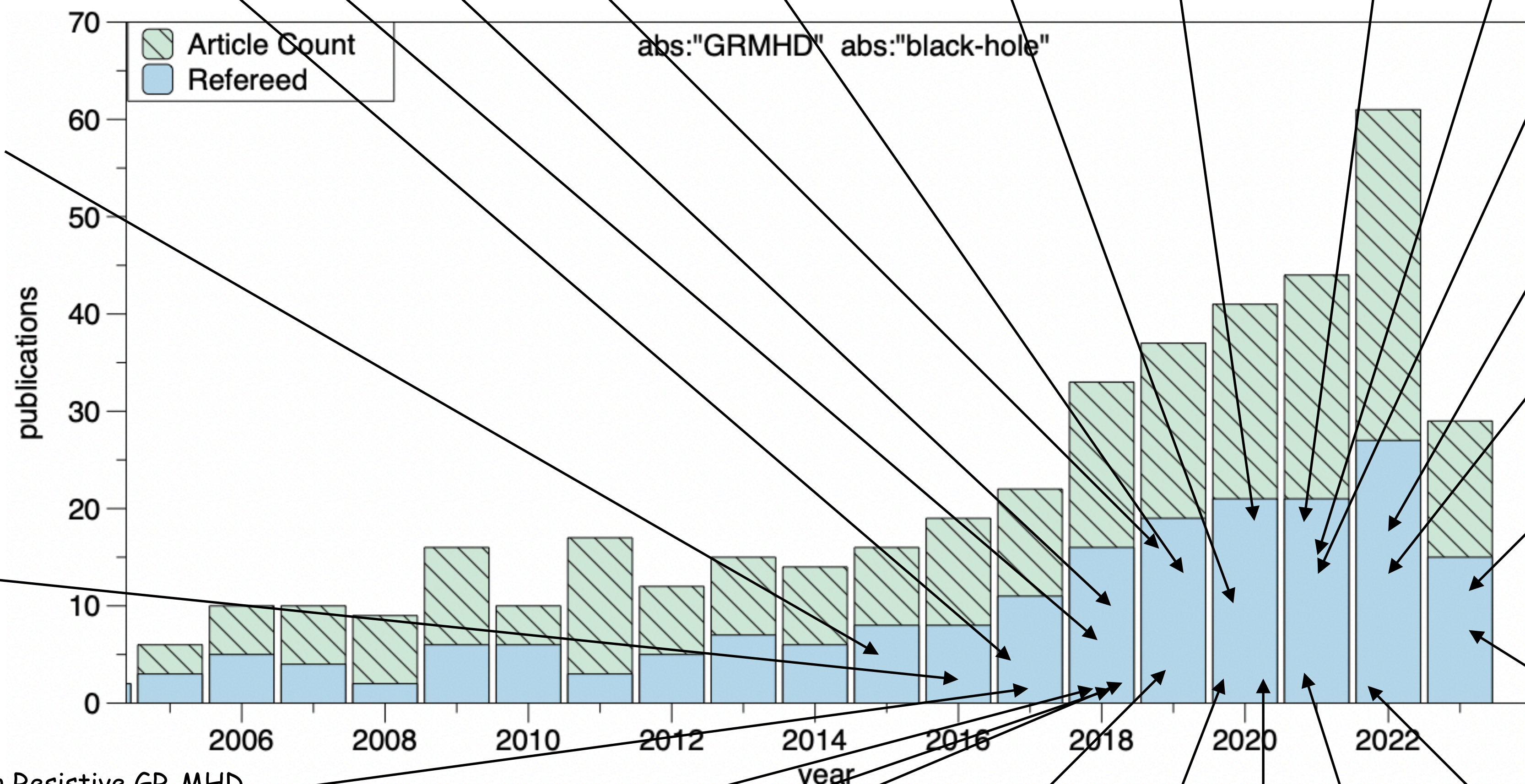
GRMHD Simulations and Modeling for Jet Formation and Acceleration Region in AGNs

IllinoisGRMHD: an open-source, user-friendly GRMHD code for dynamical spacetimes



Observational properties of puffy discs: radiative GRMHD spectra of mildly sub-Eddington accretion

Wind-fed GRMHD simulations of Sagittarius A*: tilt and alignment of jets and accretion discs, electron thermodynamics, and multiscale modelling of the rotation measure

An Extension of the Athena++ Code Framework for GRMHD Based on Advanced Riemann Solvers and Staggered-mesh Constrained Transport

Disc tearing leads to low and high frequency quasi-periodic oscillations in a GRMHD simulation of a thin accretion disc

rHARM: Accretion and Ejection in Resistive GR-MHD

Minidisk Accretion onto Spinning Black Hole Binaries: Quasi-periodicities and Outflows

The Properties of Reconnection Current Sheets in GRMHD Simulations of Radiatively Inefficient Accretion Flows

Bardeen-Petterson alignment, jets, and magnetic truncation in GRMHD simulations of tilted thin accretion discs

Radiation GRMHD Simulations of the Hard State of Black Hole X-Ray Binaries and the Collapse of a Hot Accretion Flow

Magnetic reconnection and Blandford-Znajek process around rotating black holes

General relativistic radiation magnetohydrodynamic simulations of thin magnetically arrested discs

On the comparison of AGN with GRMHD simulations: I. Sgr A*

Large-scale poloidal magnetic field dynamo leads to powerful jets in GRMHD simulations of black hole accretion with toroidal field

➥ accretion disk behavior, jet launching and propagation, comparison with observations

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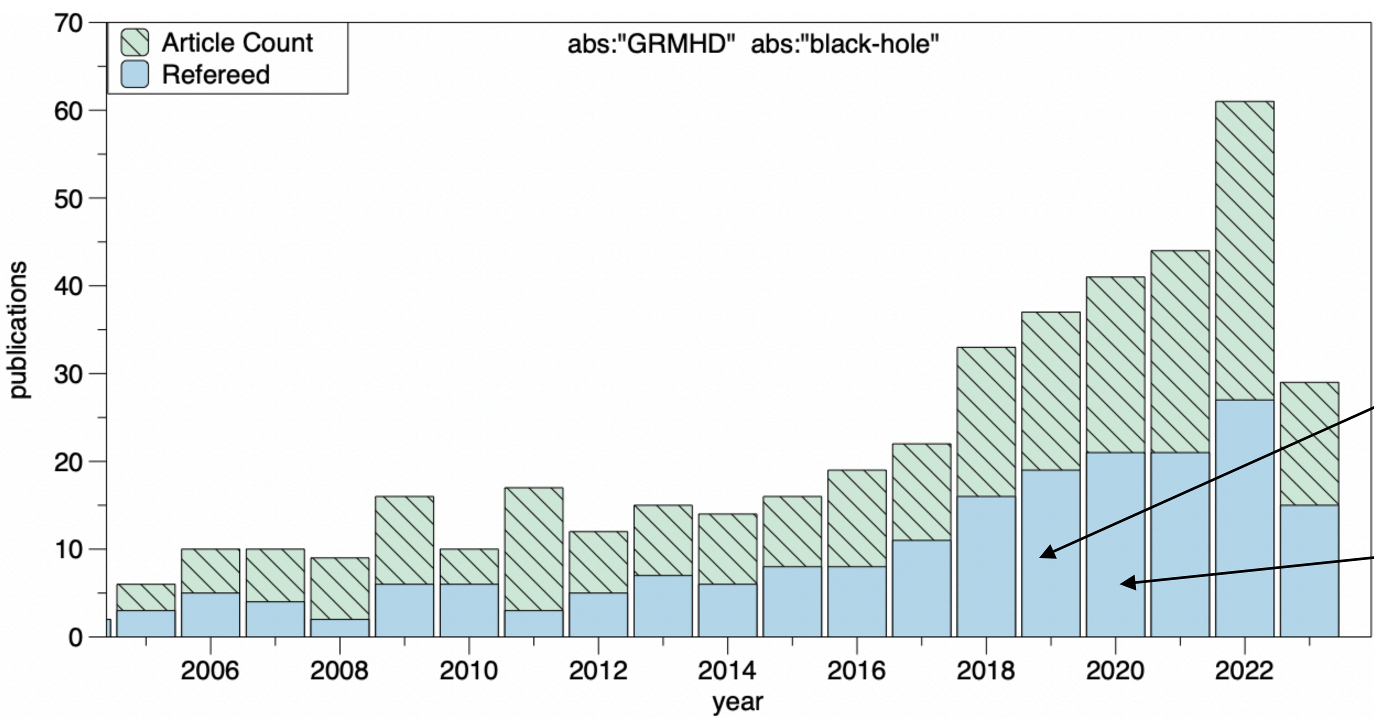


since 2016 a lot of EHT and gravity related simulations have been published

abs:"GRMHD" abs:"EHT" ➜ 42 refereed

and more importantly it lead to a vast GRMHD code comparison

"The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project" Porth et al., 2019

and a similar comparison for

"Verification of Radiative Transfer Schemes for the EHT" Gold et al., 2020

Compared GRMHD solutions for the evolution of a magnetized accretion flow where turbulence is promoted by the MRI for nine GRMHD codes: Athena++, BHAC, Cosmos++, ECHO, H-AMR, iharm3D, HARM-Noble, IllinoisGRMHD and KORAL.

➜ Agreement between the codes improves as resolution increases

➥ the paper concludes that the community of GRMHD codes is mature, capable, and consistent on these test problems.

➜ this also adds to the small number of tests and code performance metrics for new GRMHD codes

➥ several of those codes have a public version available to download

➥ the reason behind that test was that BHAC, H-AMR, iharm and KORAL are used in the model/analysis of EHT observations

recent GRMHD Simulations of BH environment

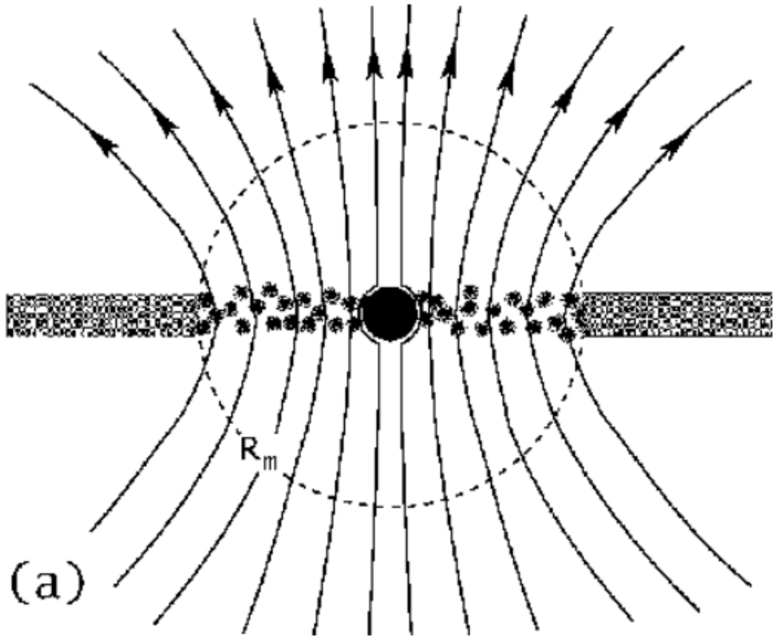
the EHT approach was to create a vast GRMHD simulation database

➜ 72,000 snapshots from numerical simulations of 120 different models of the accretion flow and jet from four GRMHD codes

➥ large database of simulation results, then processed through GR raytracing ipole, RAPTOR or BHOSS

and then compared the snapshots to the EHT observations to see which models give the best representation

➜ seems to favor magnetically arrested accretion flows compared with the Standard And Normal Evolution (SANE) and other types of accretion flows



(Narayan et al., 2003)

<u>magnetically arrested accretion disk (MAD)</u>:

piled-up poloidal magnetic fields close to the black hole are strong enough to affect how matter accretes onto the black hole. (Narayan et al., 2003)

➥ magnetic flux is accumulated onto the black hole horizon and the inner disk

➥ no more large-scale flux can be concentrated inward (magnetic forces pushing out balance gas forces pushing in)

➥ also constrains the possible mechanisms that lead to the launch of a jet

From simulation we have seen

- in general, MAD flows are compatible with a strong Blandford-Znajek (BZ) jet if the black hole spin is high enough. this is coherent with M87*, but not so clear for Sgr A*

- MAD accretion flows are also able to produce highly energetic plasmoids which may correspond to the observed flares in SgrA*.

➥ a lot of agreement but none of the models passes all the constraints from EHT and non-EHT observations

recent simulations of BH environment

Formation of Magnetically Truncated Accretion Disks in 3D Radiation-transport Two-temperature GRMHD Simulations — Liska, et al. 2022
A phase lag between disc and corona in GRMHD simulations of precessing tilted accretion discs — Liska, et al. 2023

Multiwavelength observations of hard and intermediate states of X-ray binaries

➜ suggest that the accretion disk transitions from a cold, thin disk at large distances into a hot, thick flow close to the BH.

BUT the formation, structure, and dynamics of such truncated disks are poorly constrained

➜ a lot of the simulations of accretion disk around BH are related to such disks

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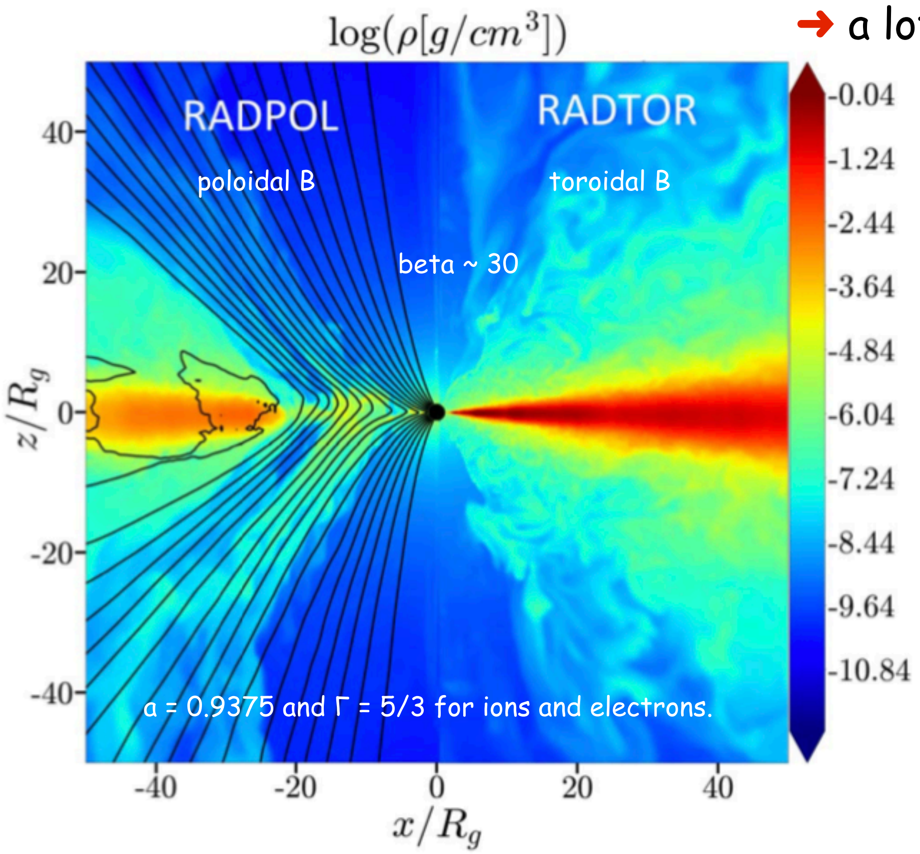

geometrically thin accretion disk threaded by large-scale net poloidal magnetic flux

➜ self-consistent transition at small radii into a two-phase medium of cold gas clumps floating through a hot, magnetically dominated corona.

This transition occurs at a well-defined truncation radius determined by the distance out to which the disk is saturated with magnetic flux.

➜ also produces radiation, powerful collimated jets, and broader winds at the total energy efficiency exceeding 90%, the highest energy extraction efficiency from a spinning BH by a radiatively efficient flow in a GRMHD simulation.

This is consistent with jetted ejections observed during XRB outbursts. The two-phase medium may naturally lead to broadened iron line emission observed in the hard state.

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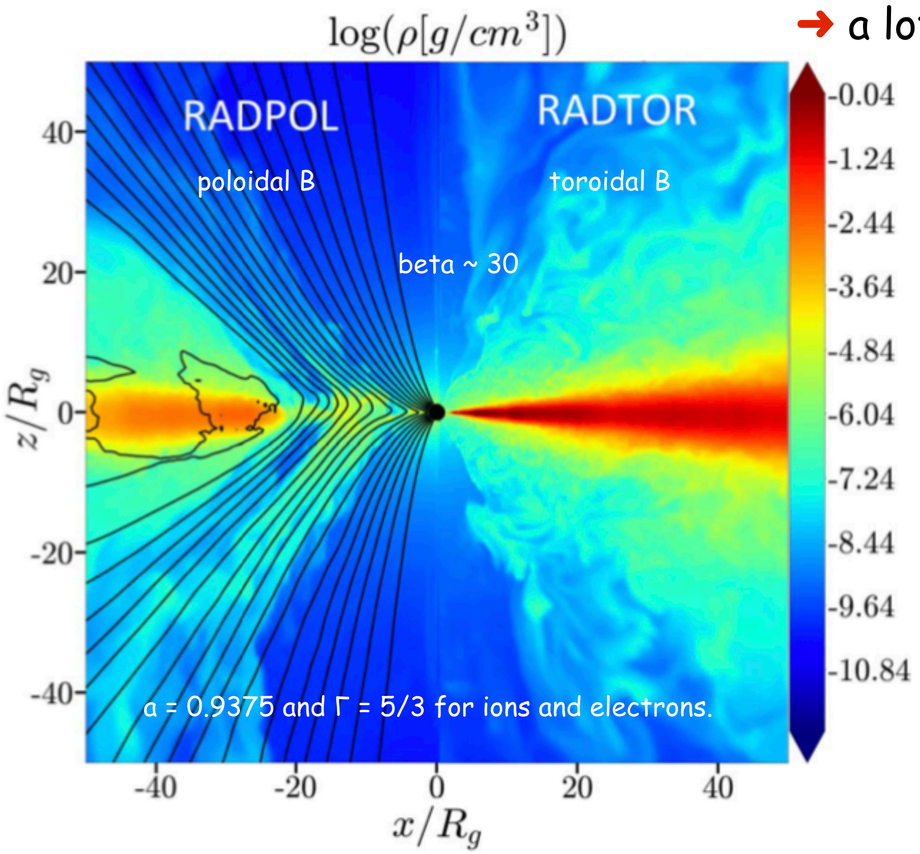

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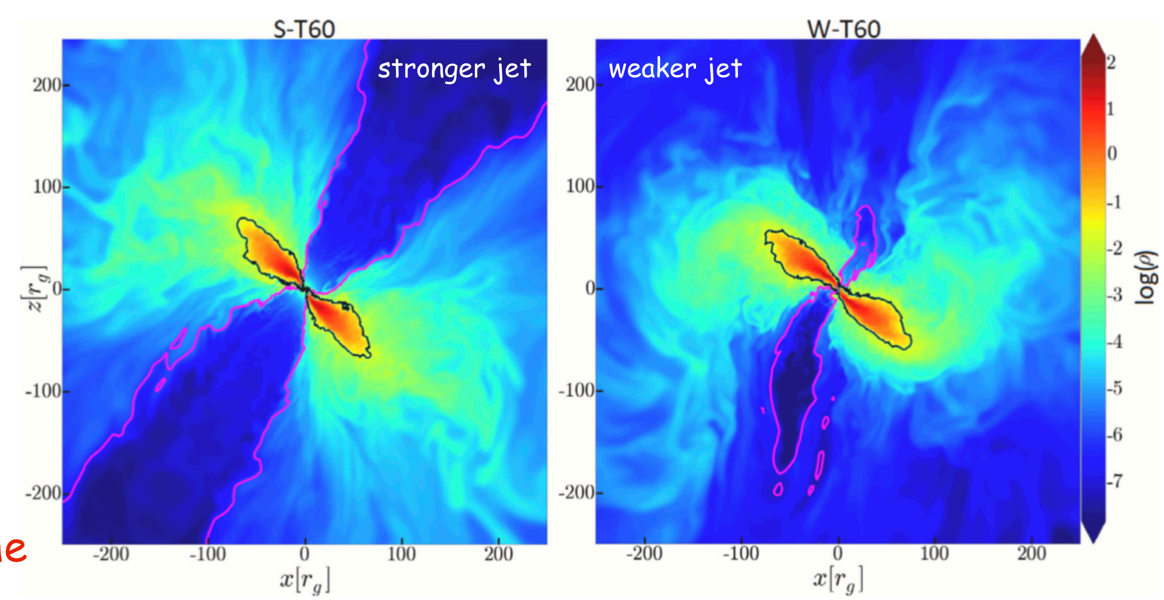
while the disc and jets precess in phase
➜ the disc wind/corona, in between, lags behind by ≳ 10°

While strong jets are unaffected by this disc-corona lag, weak jets can stall when encountering the lagging corona at distances $r \sim 100$ BH radii. This interaction may quench large-scale jet formation.

For spectral models ➜ the hard non-thermal (corona) emission lags behind the softer (disc) emission similarly to the hard energy lags seen in type-C QPO.



GRMHD simulations highly tilted (60°), moderately thin (h/r = 0.1) accretion discs around a rapidly spinning ($a \simeq 0.9$) BH. fully gas pressure dominated at the start

recent simulations of BH environment

The Luminous, Hard State Can't Be a magnetically arrested accretion disc (MAD) Fragile et al., 2023 https://arxiv.org/pdf/2307.08820.pdf

➥ uses the results of simulations (Chatterjee et al., in prep.) and observations to see if there are compatible

three core premises:

1) type-C QPO is best explained by Lense-Thirring precession of a tilted, inner, hot flow;

2) observed optical and infrared QPOs with the same or lower frequency as the type-C QPO suggest the jet precess in these systems;

3) simulations of MADs show that their strong magnetic fields promote alignment of the disc with the black hole suppressing LT precession

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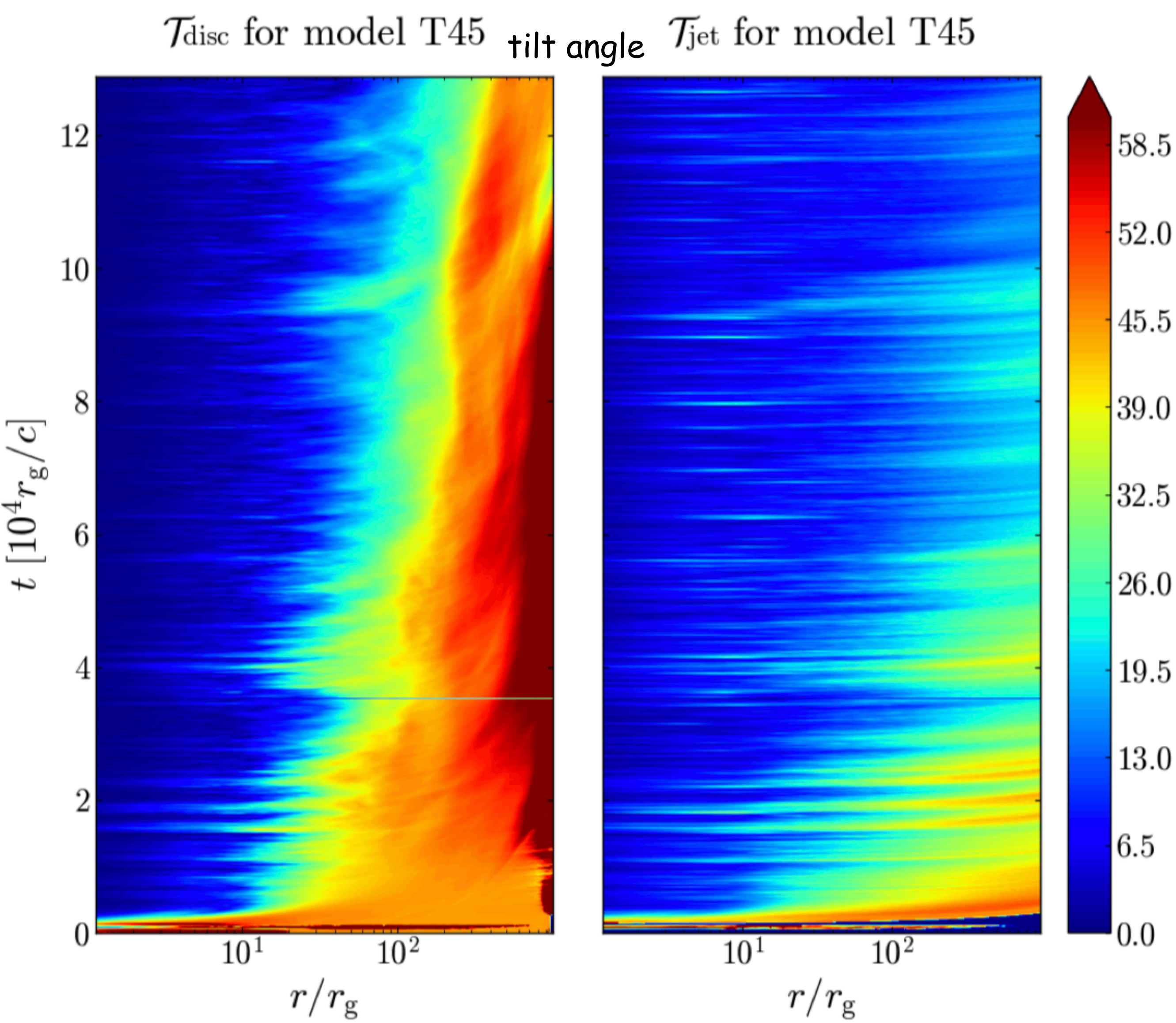

OBSERVATIONS of the hard-state (type C QPO state)

- precession seems present (LT mechanism)
- precession seems present in the jet

but no precession in arrested accretion disk simulation

(McKinney et al. 2013; Ressler et al. 2023, Chatterjee et al., in prep.)

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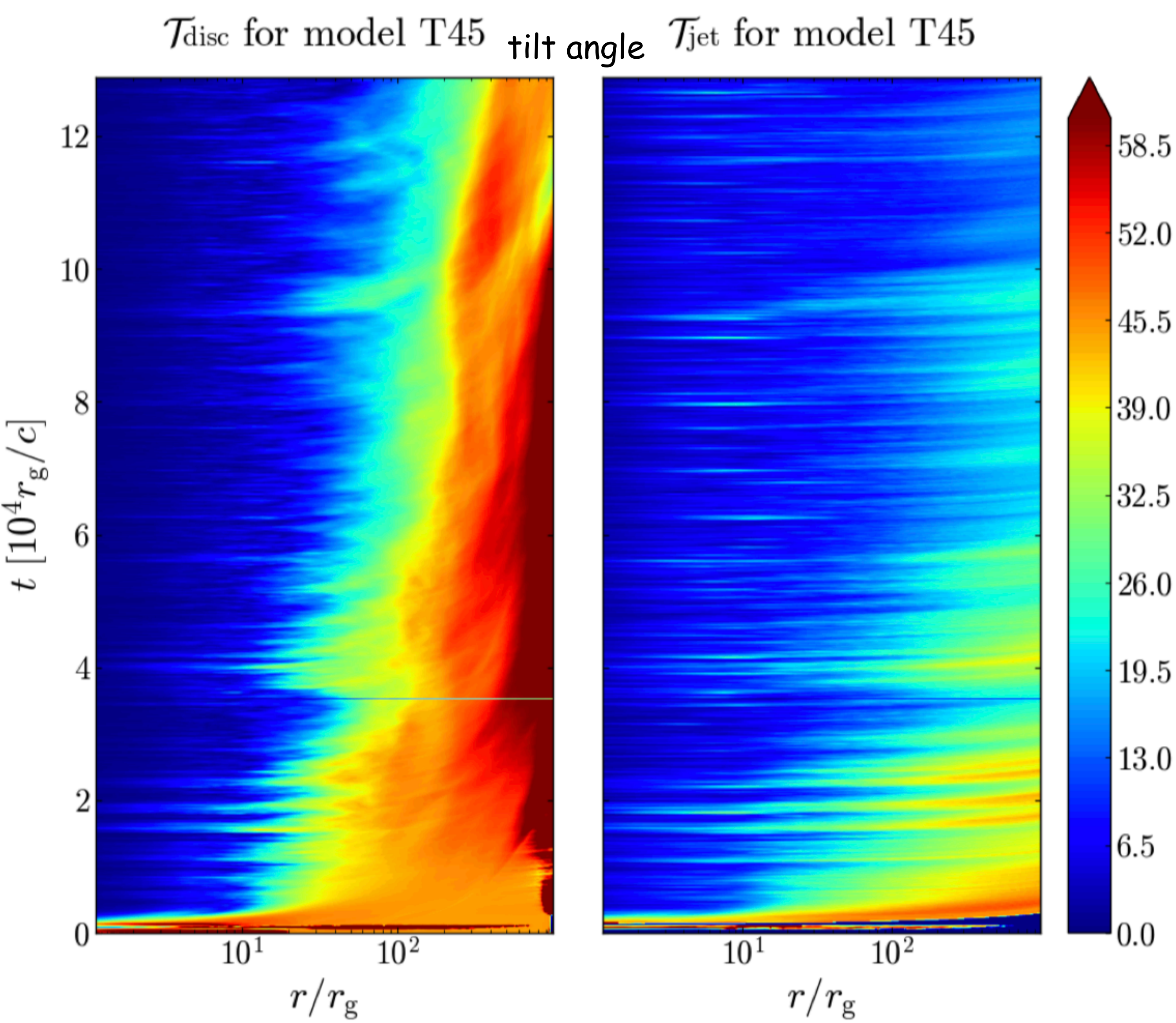

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➥ If all three premises hold true, then, at least whenever the optical and IR QPOs are observed alongside the type-C QPO, these systems cannot be in the MAD state.

➜ Extending the argument further, if the type-C QPO is always associated with LT precession, then it would rule out MADs anytime this timing feature is seen, which covers nearly all BHXRBs when they are in the luminous, hard and hard-intermediate states.

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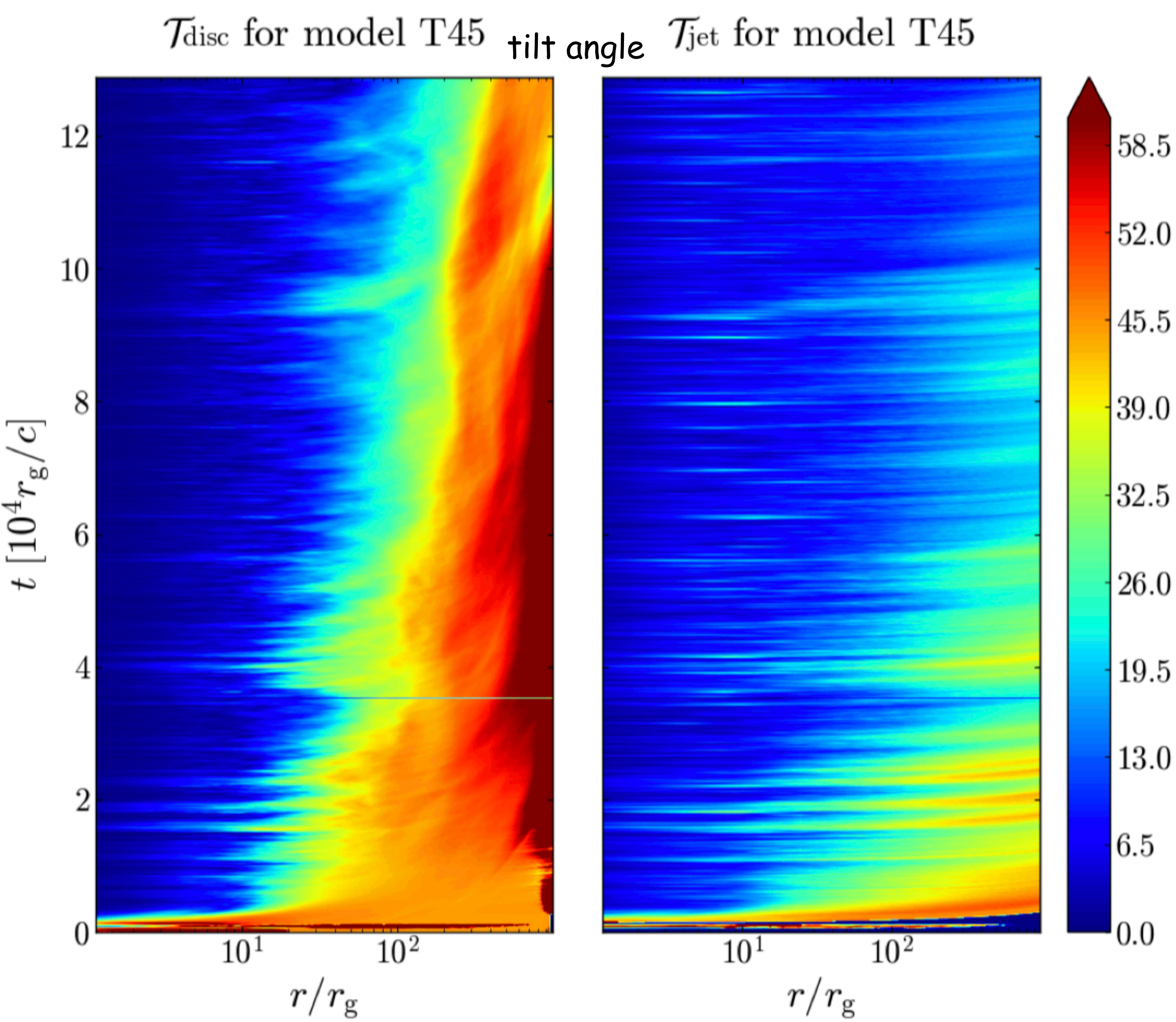

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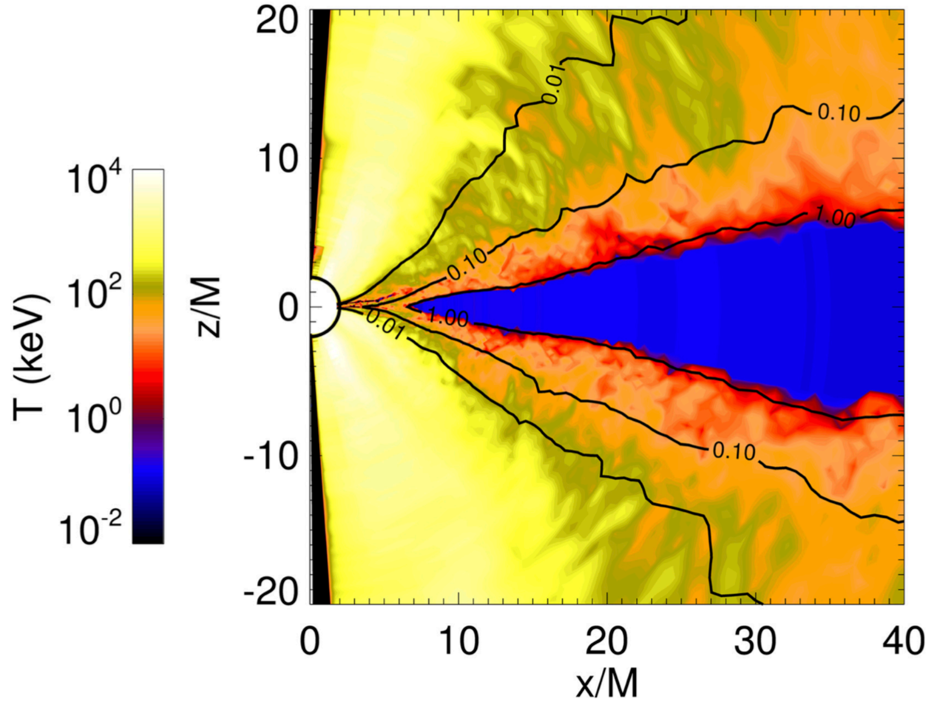
➥ it would be interesting to remove one premise at the time to see which one is essential

recent simulations of BH environment

Fe Ka Profiles from Simulations of Accreting Black Holes — Kinch et al., 2016
Predicting the X-Ray Spectra of Stellar-mass Black Holes from Simulations — Kinch et al., 2019
Inverse Compton Cooling in the Coronae of Simulated Black Hole Accretion Flows — Kinch et al., 2020

GRMHD simulation (HARM3D) are post-processed by a Monte Carlo global radiation transport code and Feautrier solver for the disk which determines the X-ray flux irradiating the disk surface and the coronal electron temperature self-consistently



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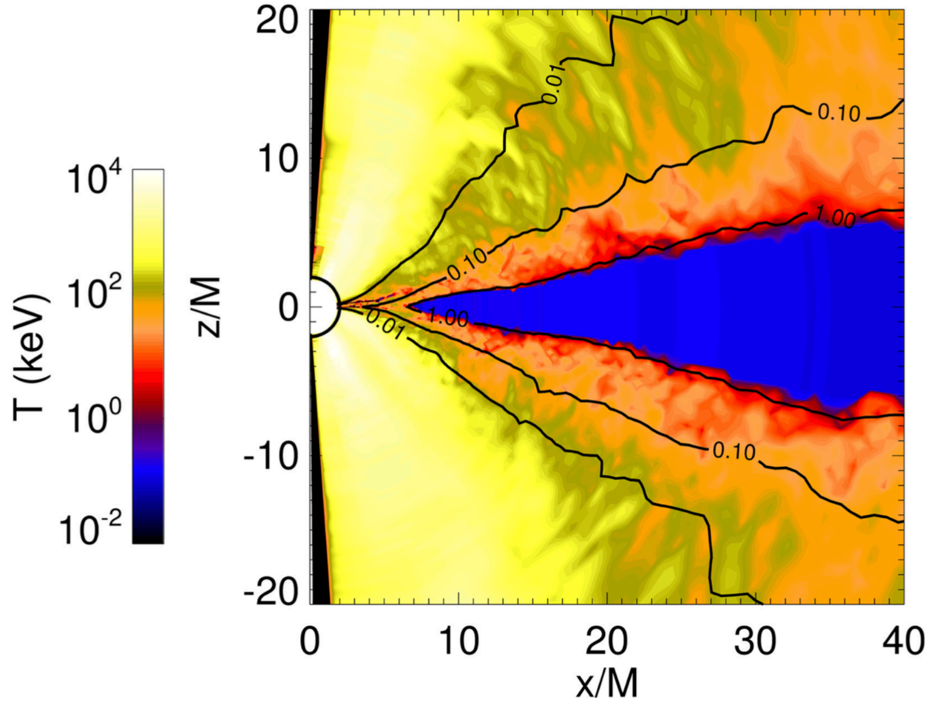

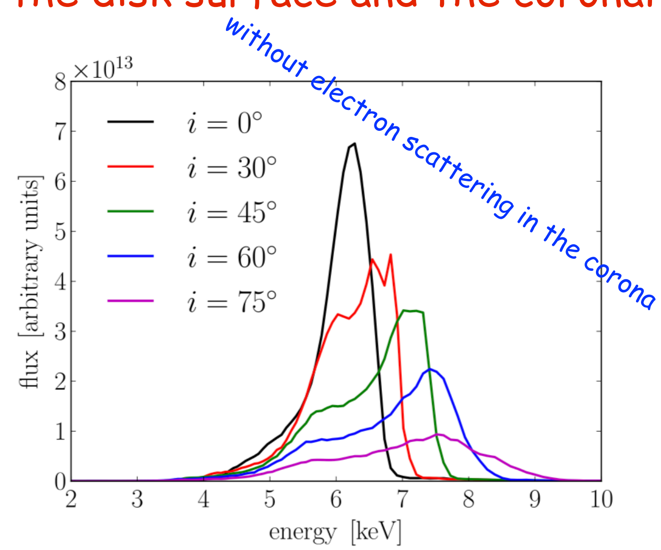

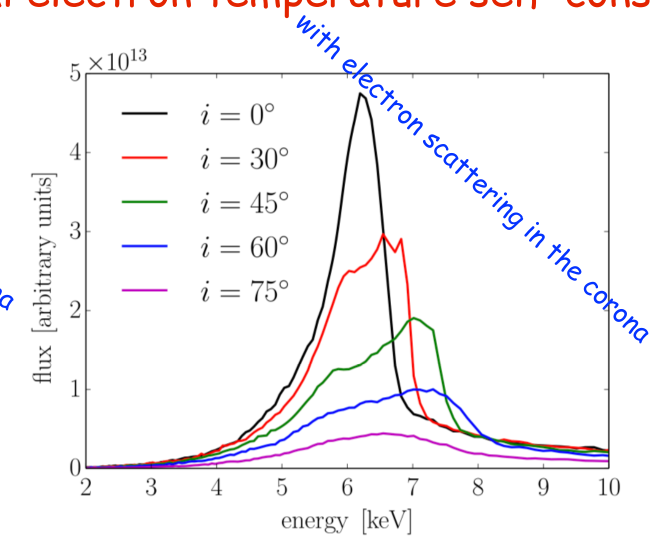

ability to quantify the impact of the separated components on observables

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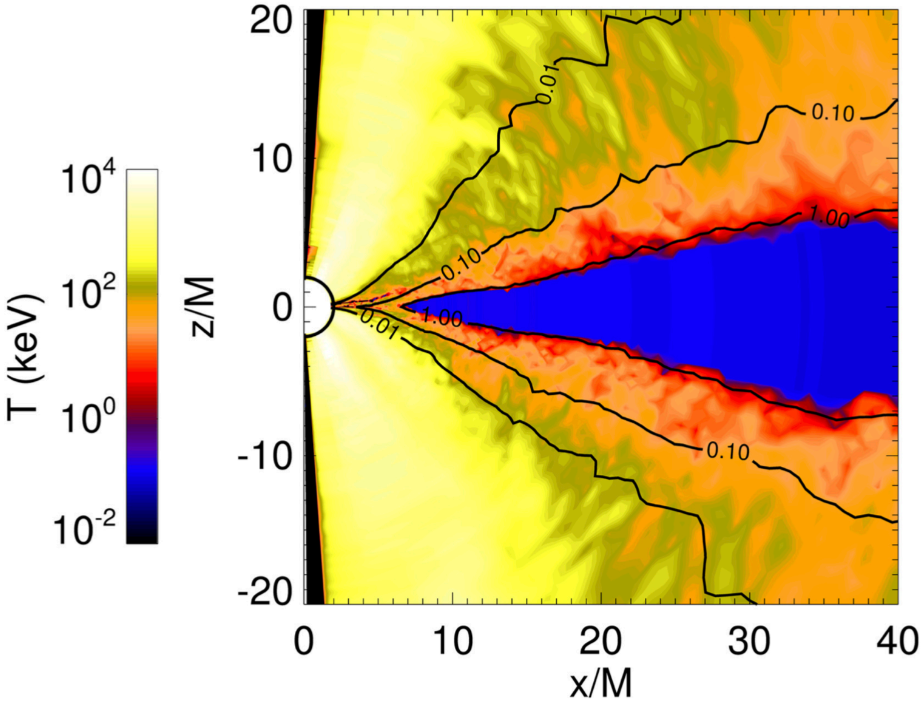

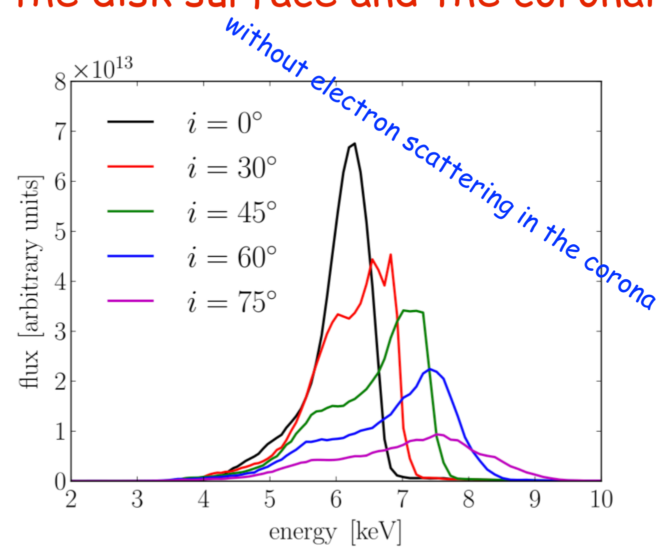

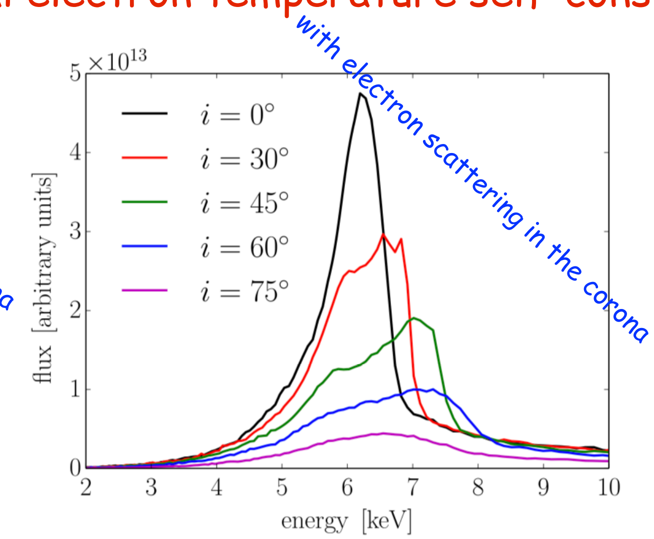

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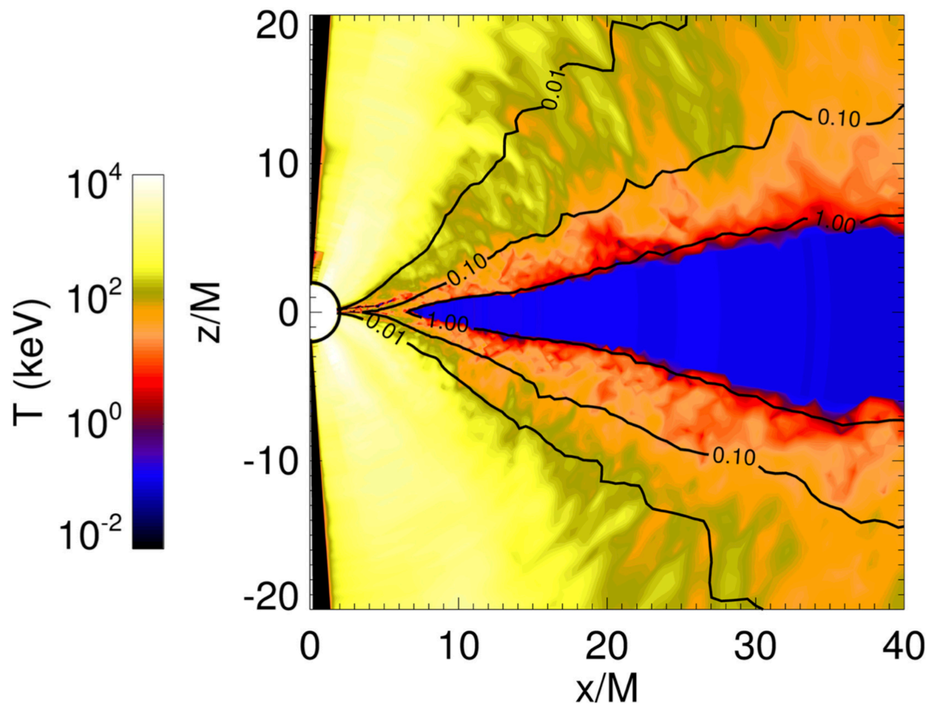

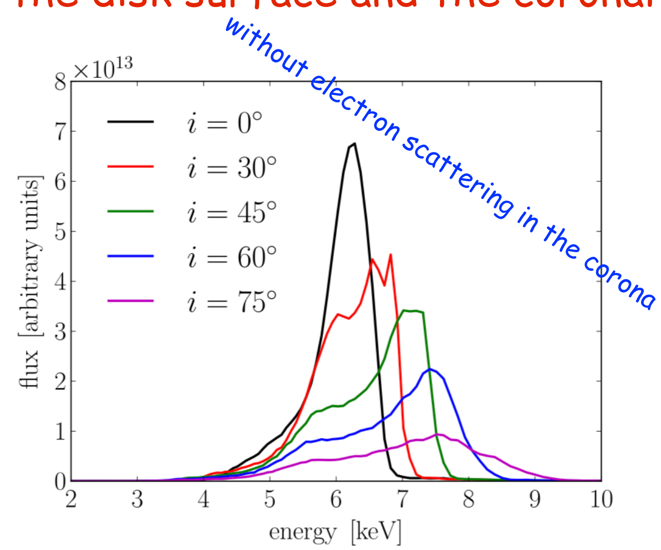

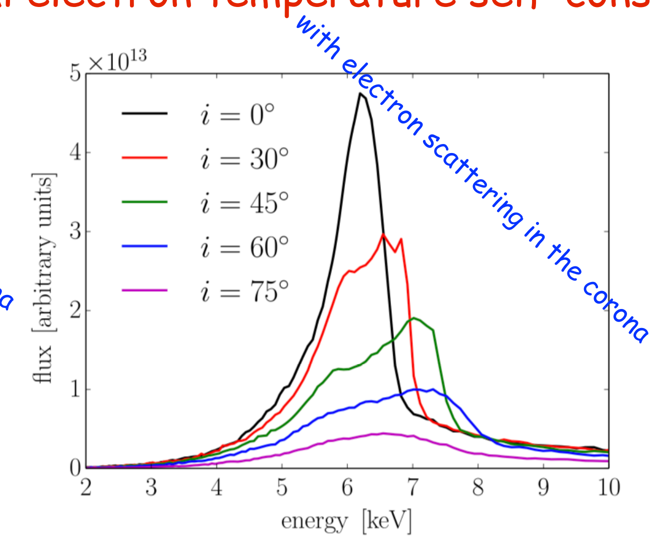

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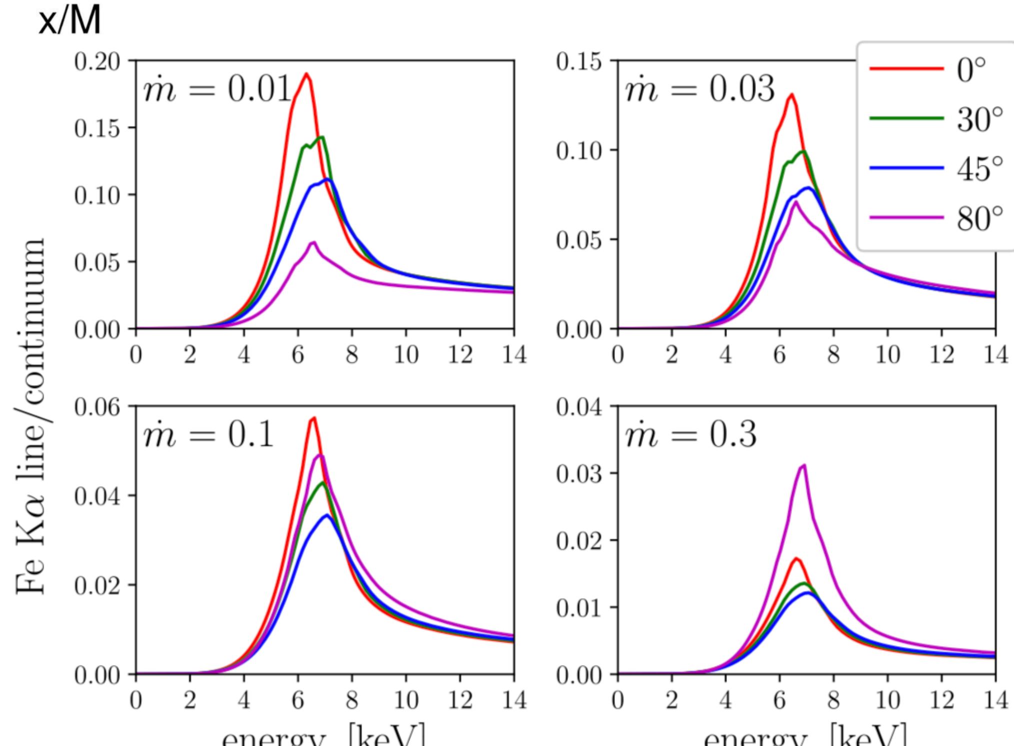

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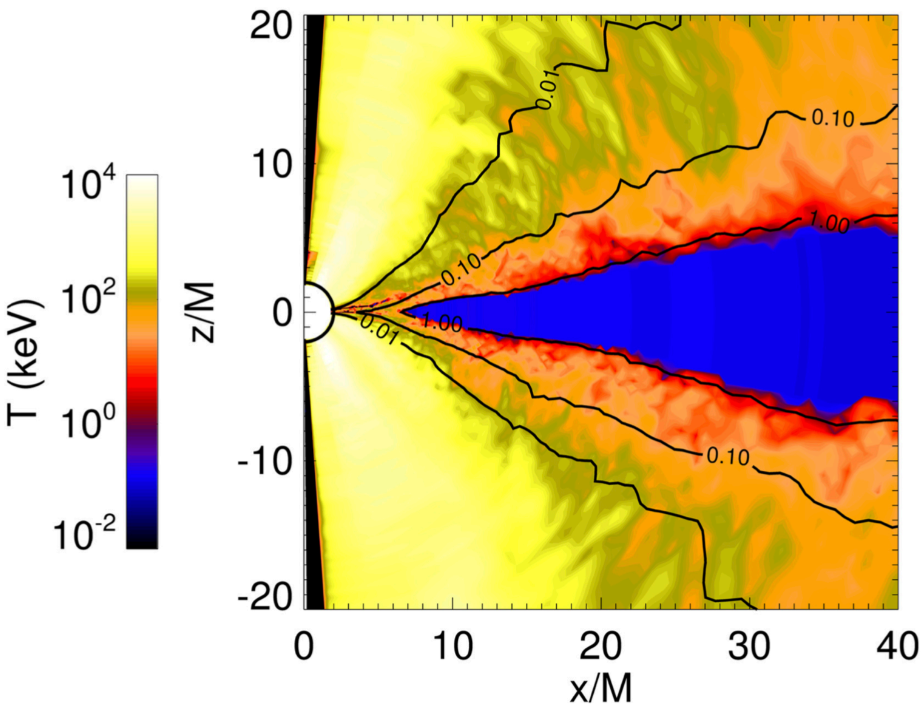

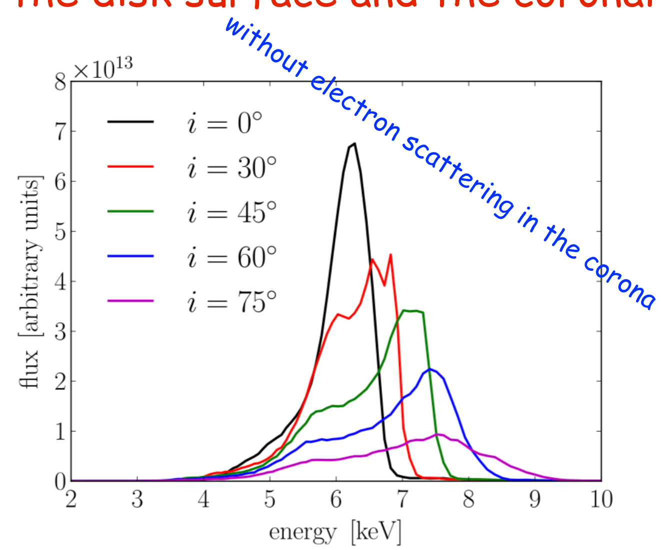

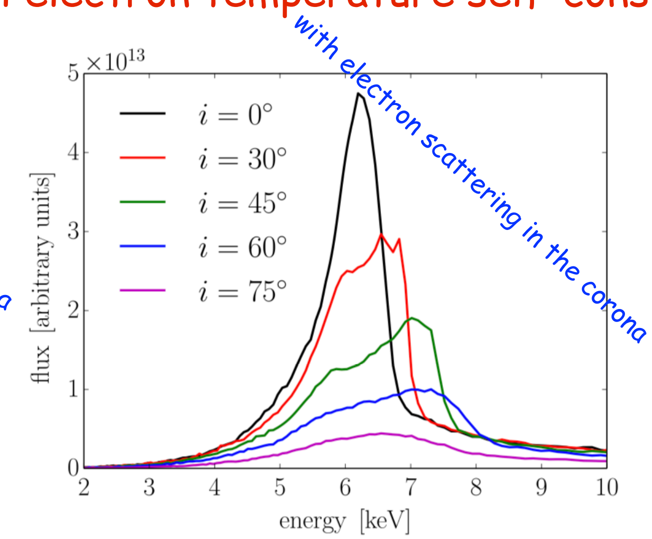

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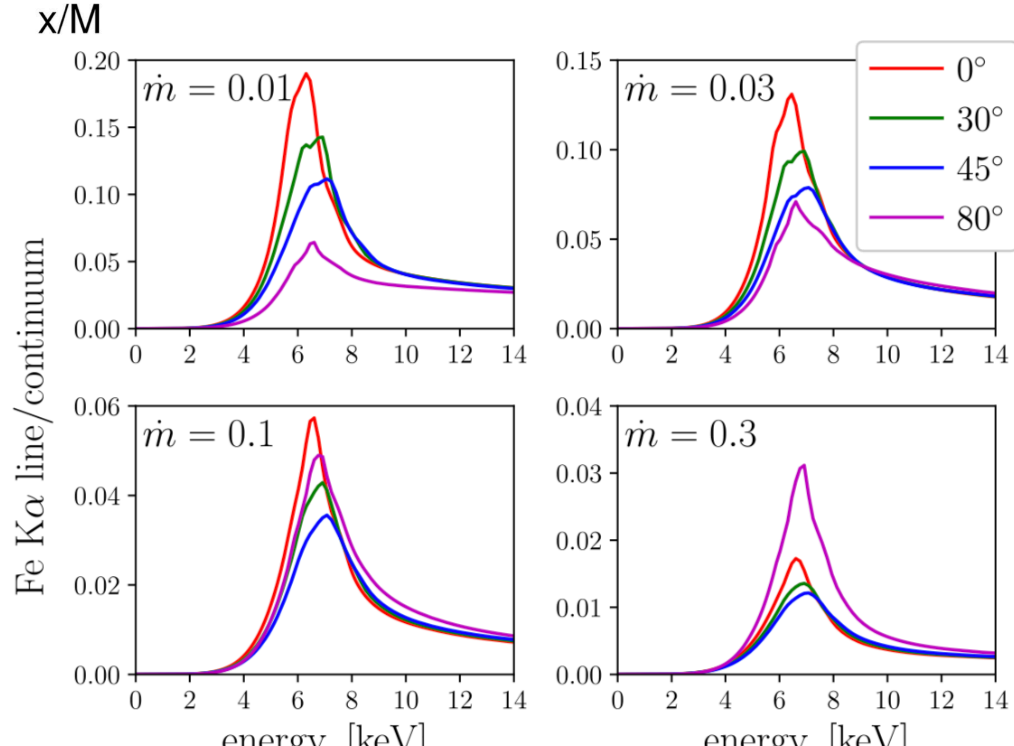

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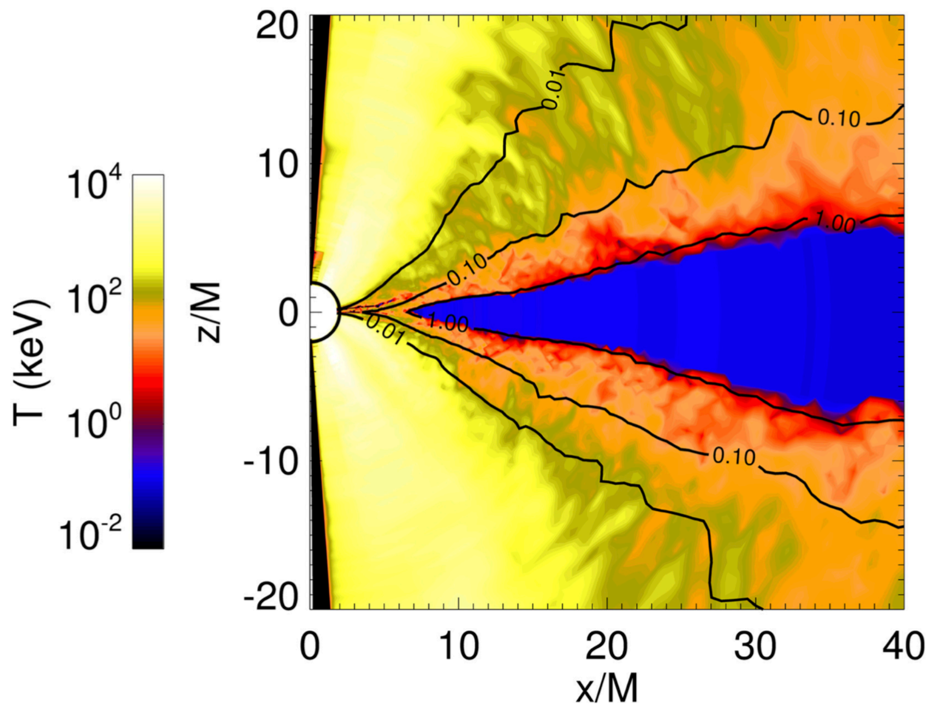

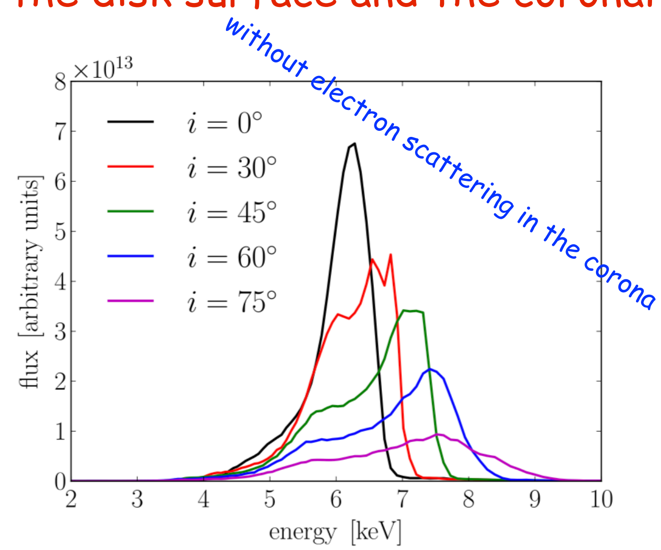

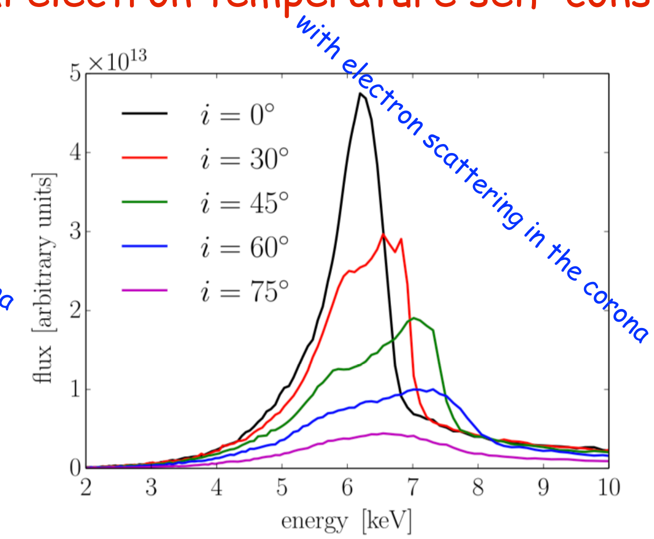

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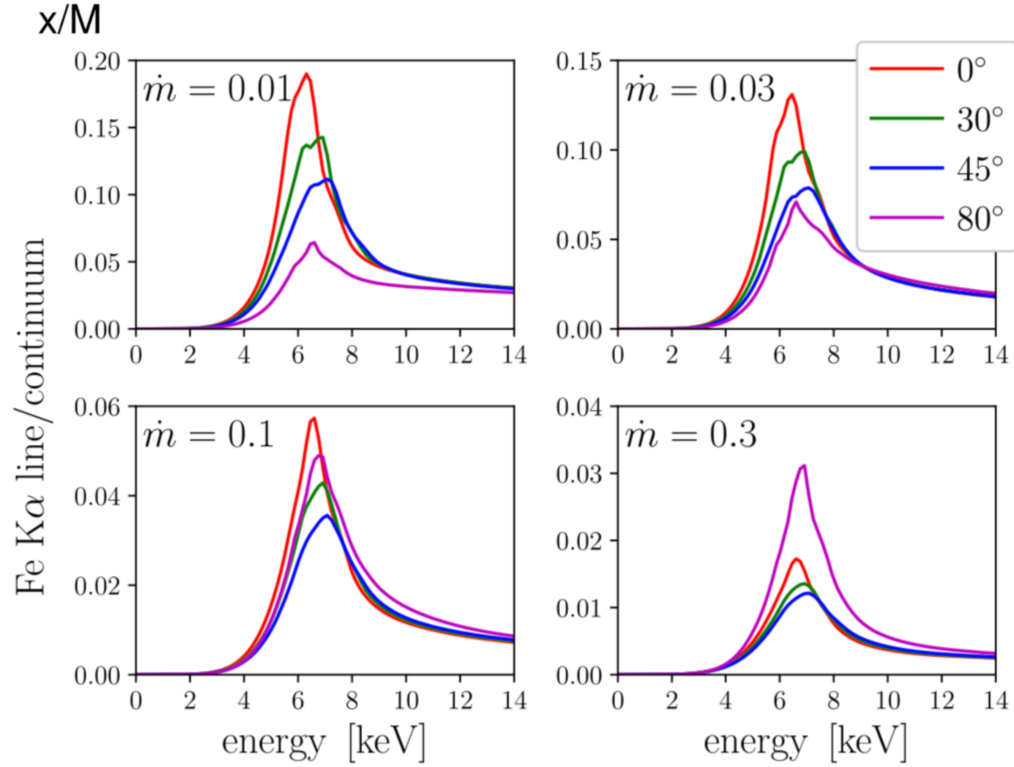

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➡ Most importantly, this work represents a direct link between theory and observation in a fully self-consistent way

➜ as it produces observable results from the theory of black hole accretion with almost no phenomenological assumptions.

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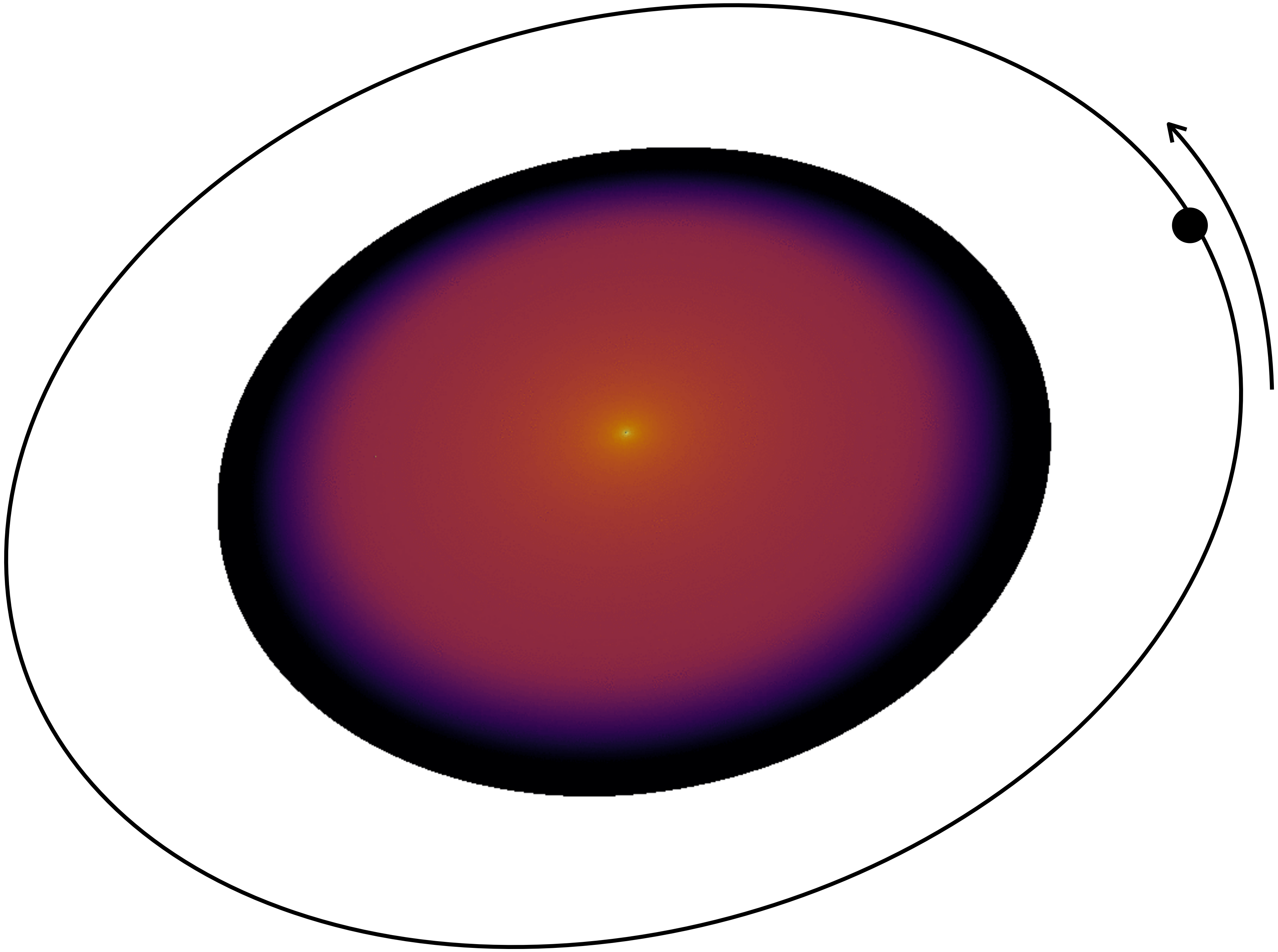
- theoretical understanding of the Black-Hole system:
    - impact of a bound object on the circum-primary disk (from 6000rg)

Casse et al., 2023 & Varniere et al., 2023



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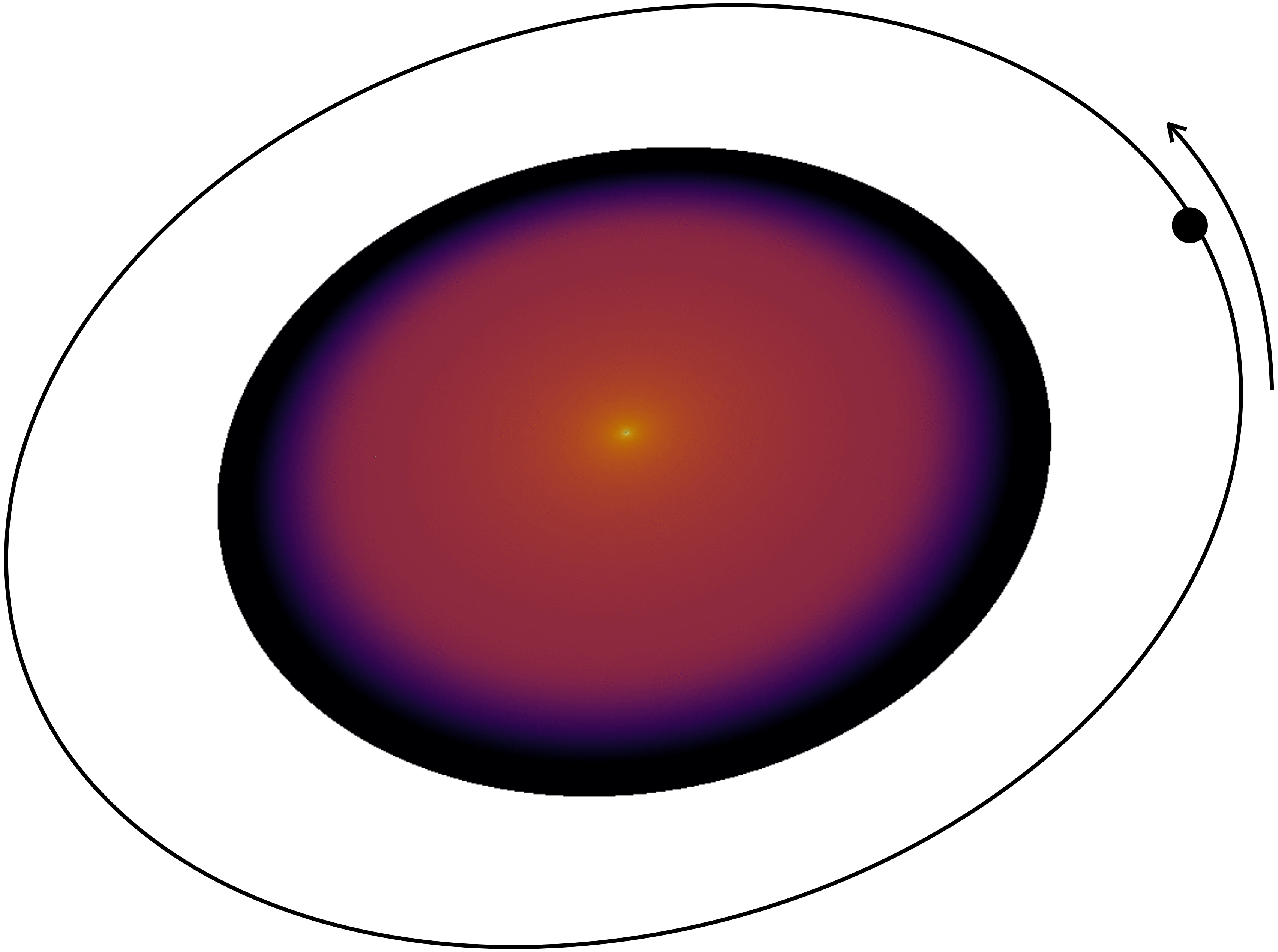

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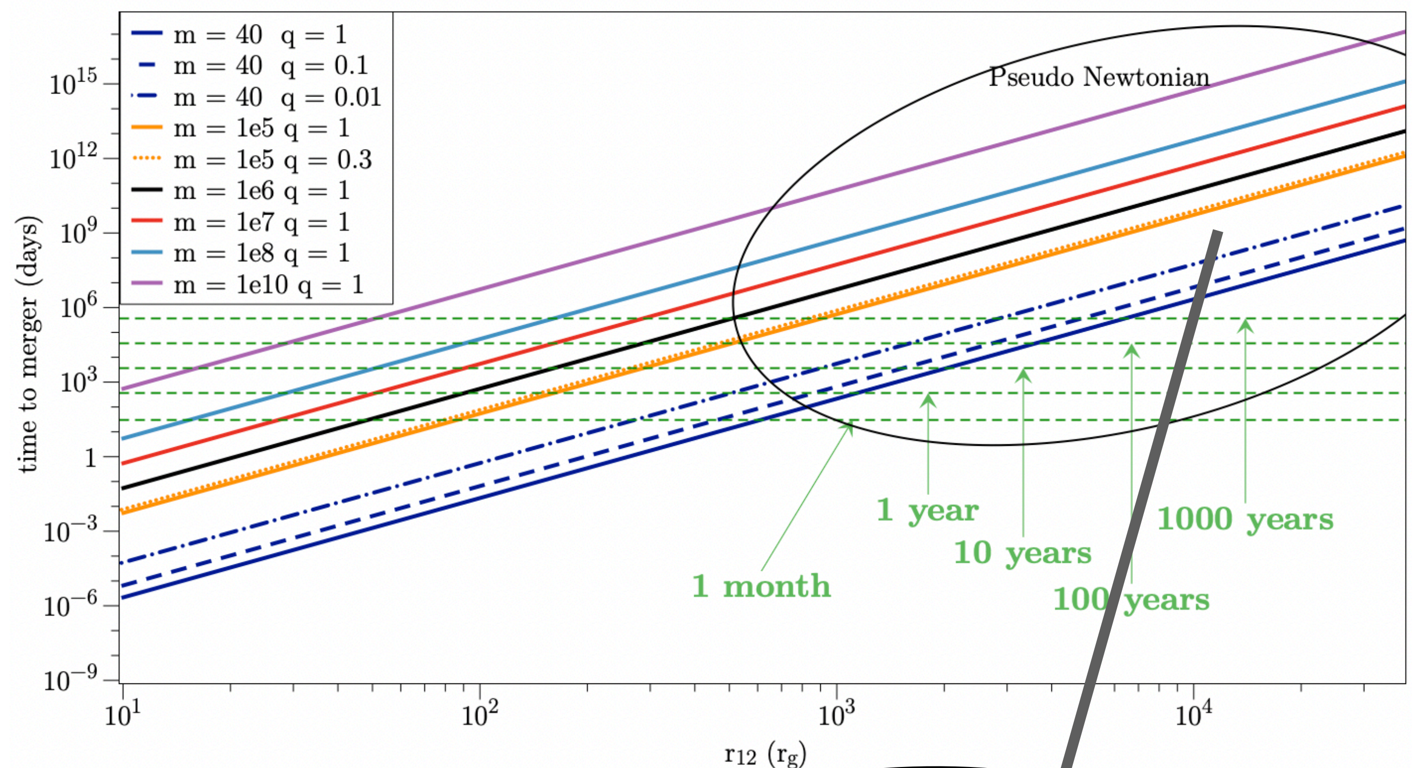
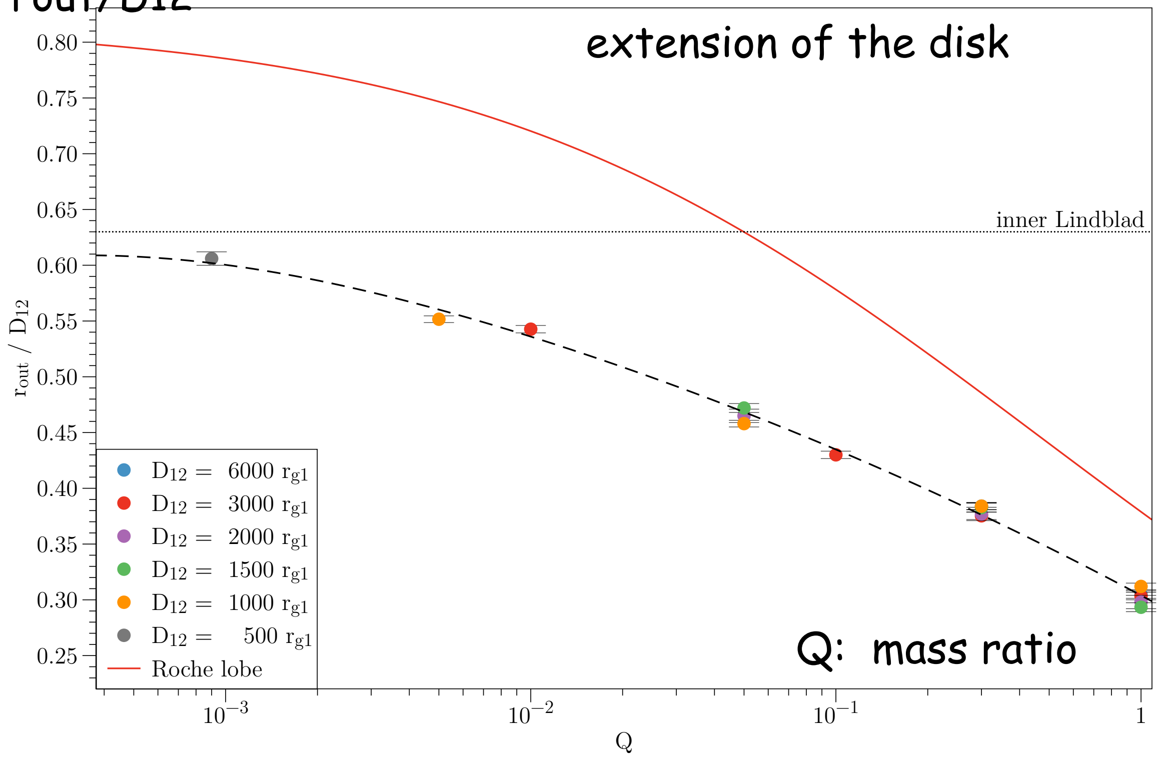
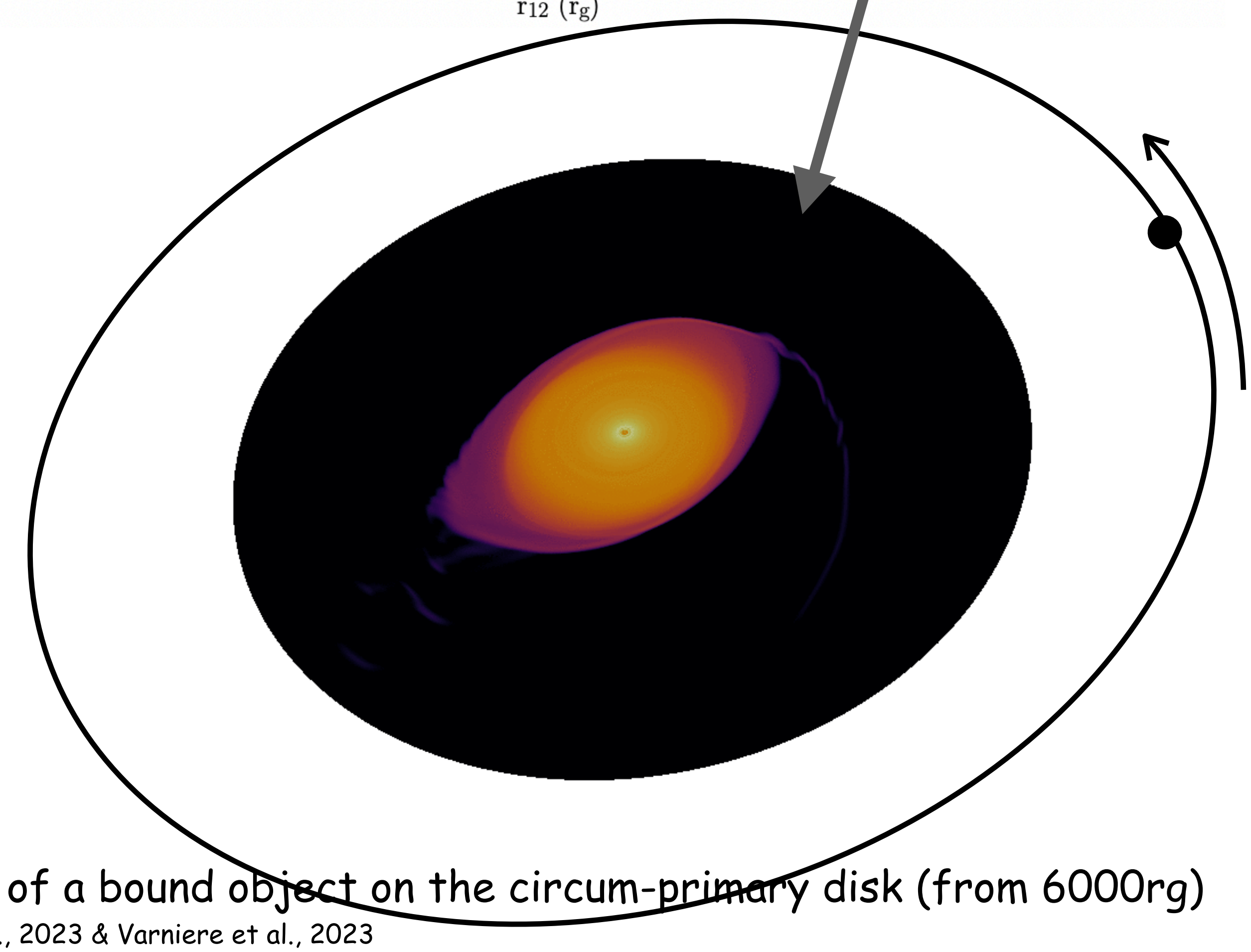


rout/D12

extension of the disk



Q: mass ratio



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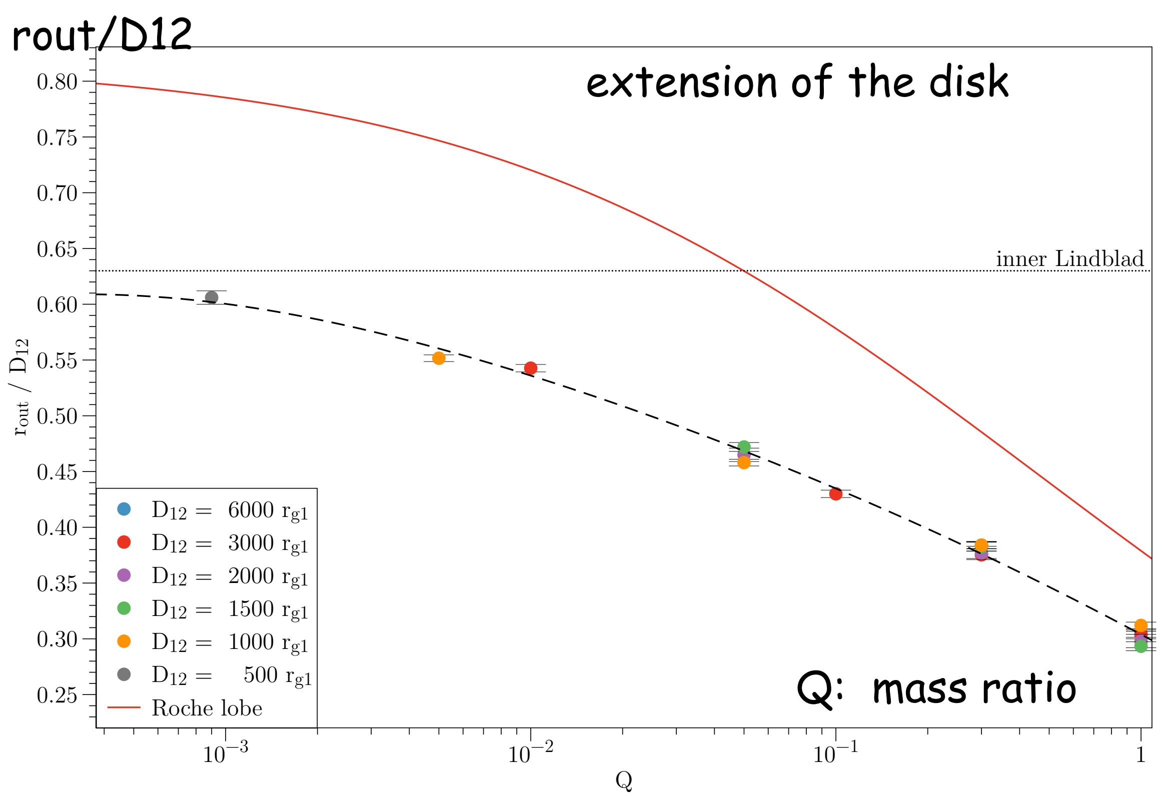

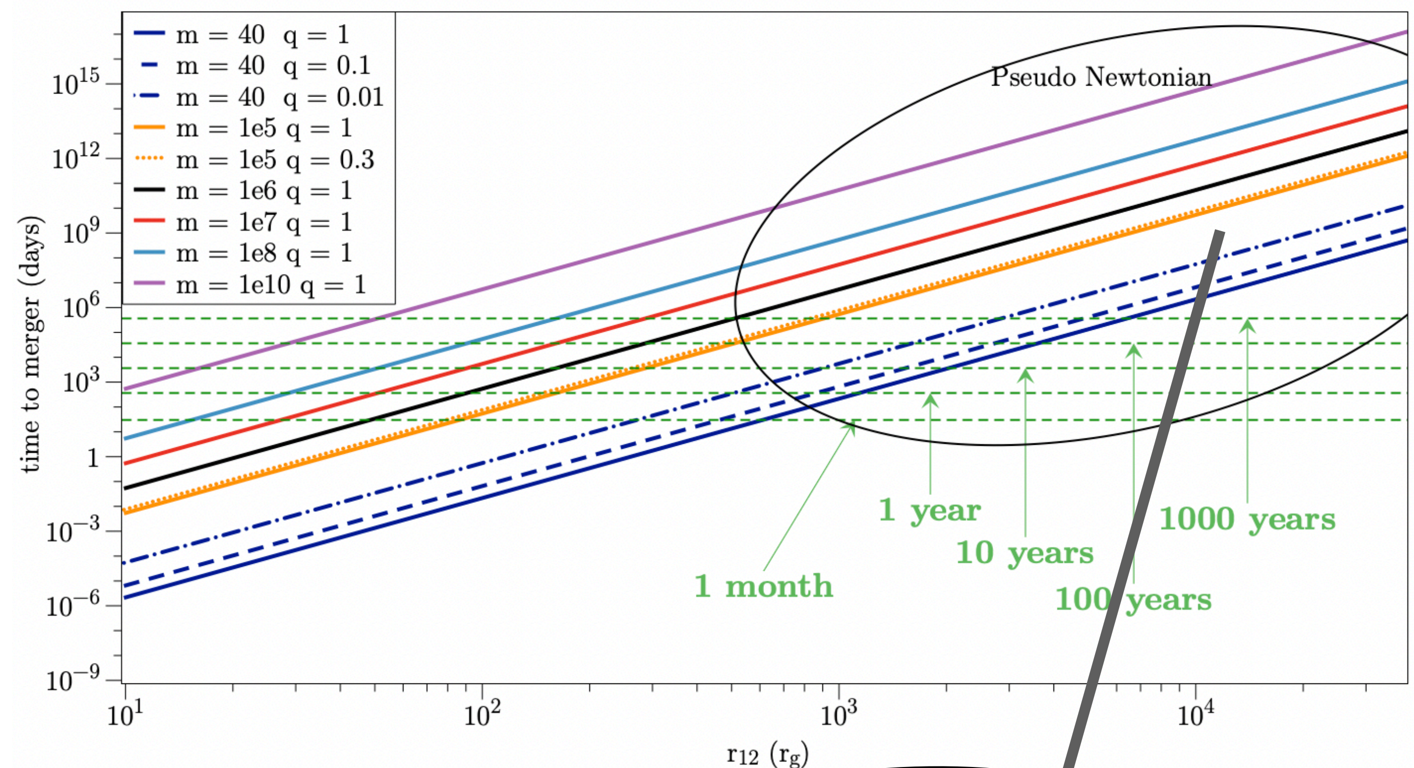

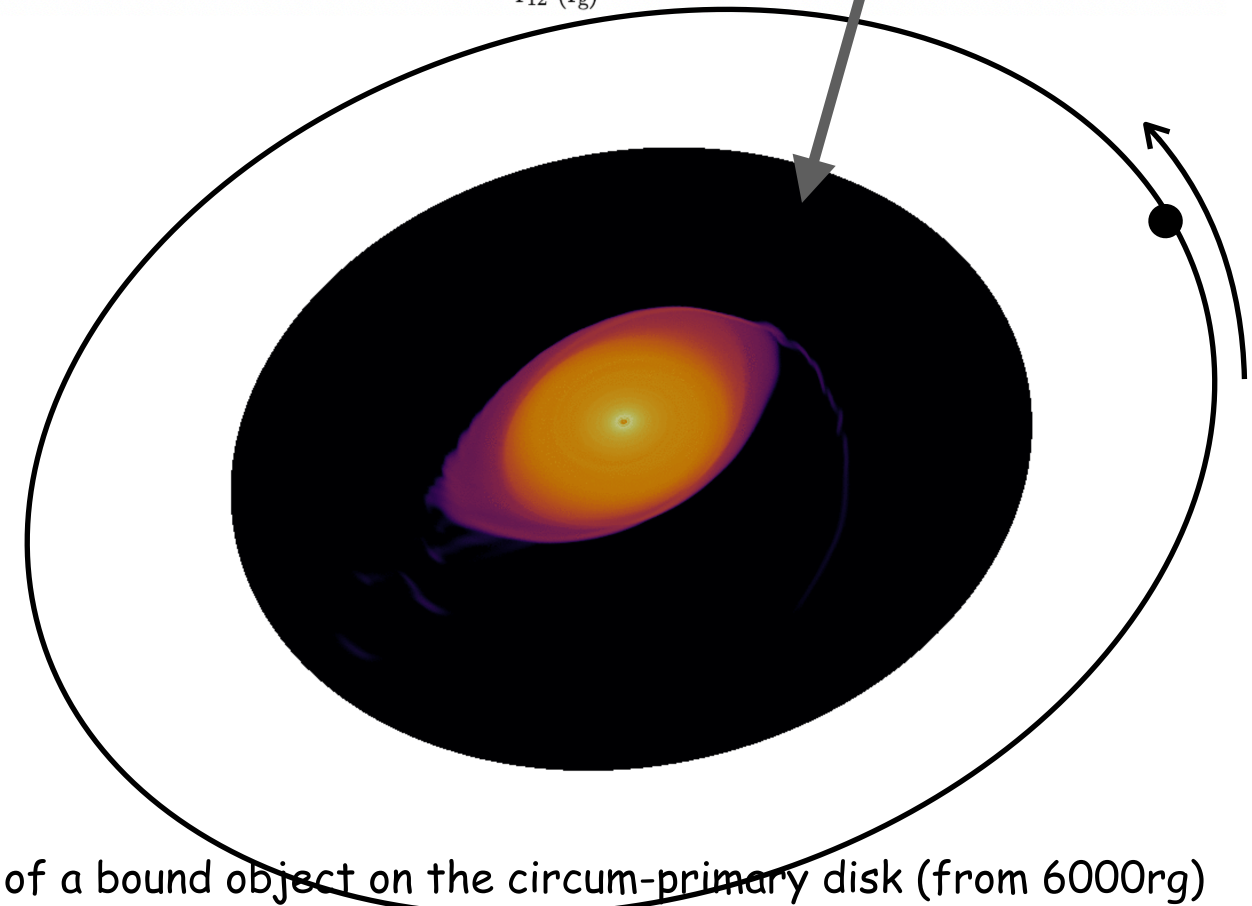

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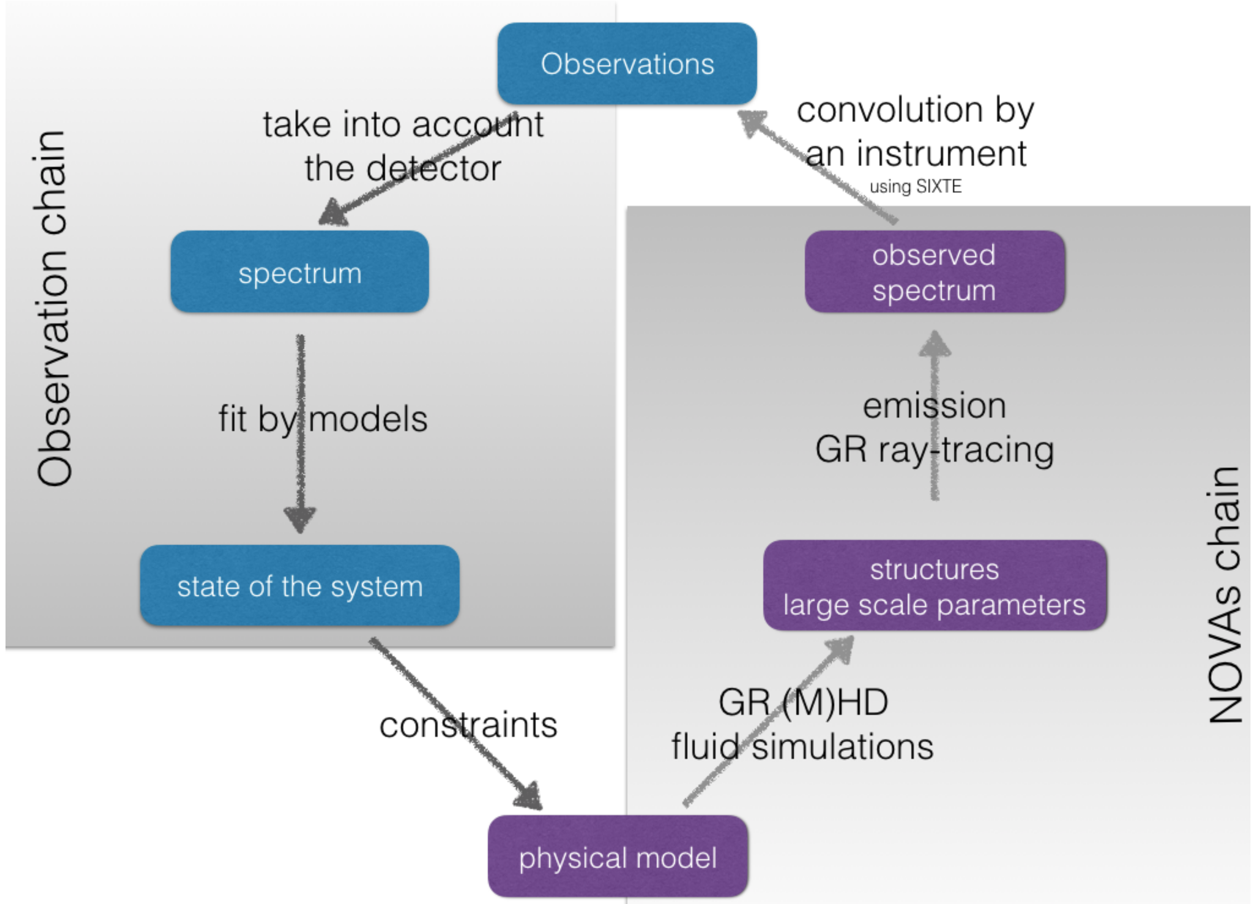

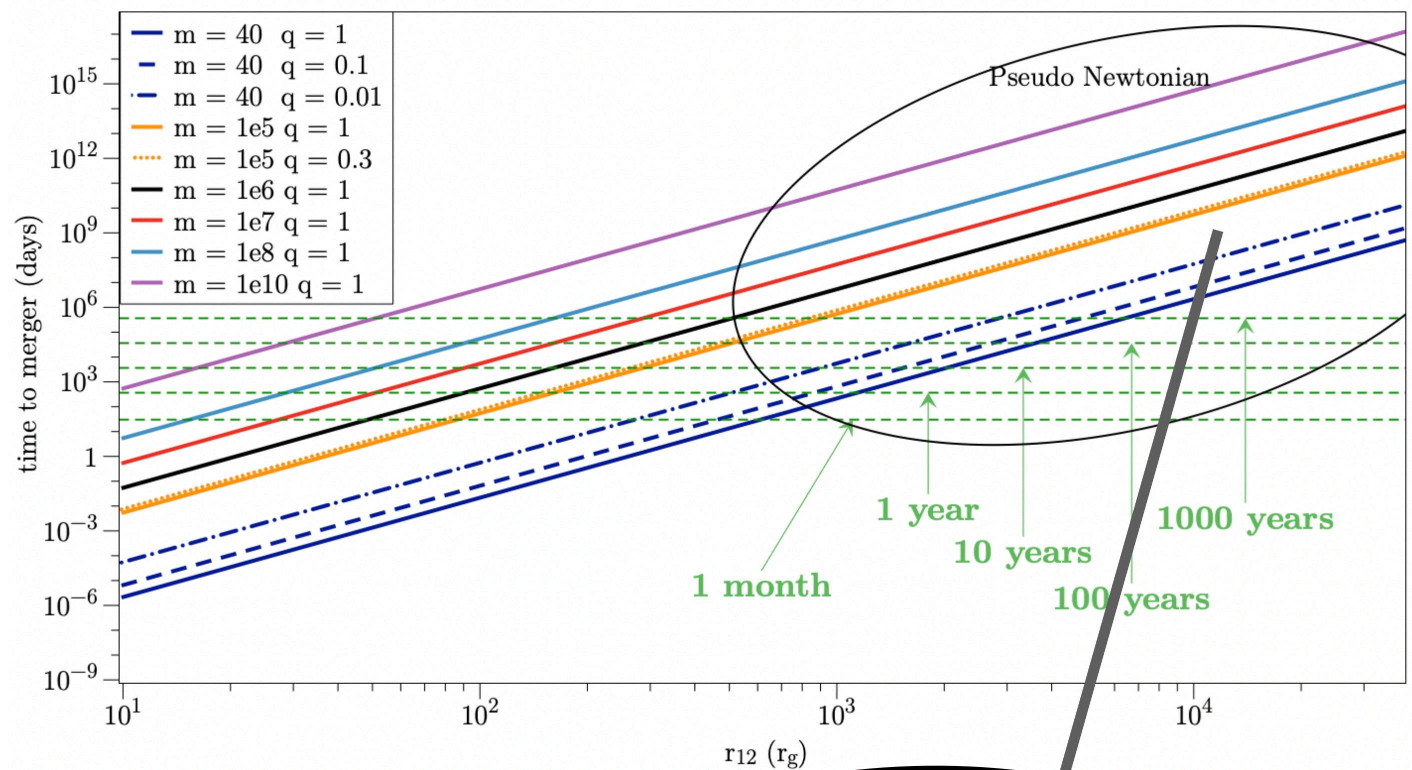

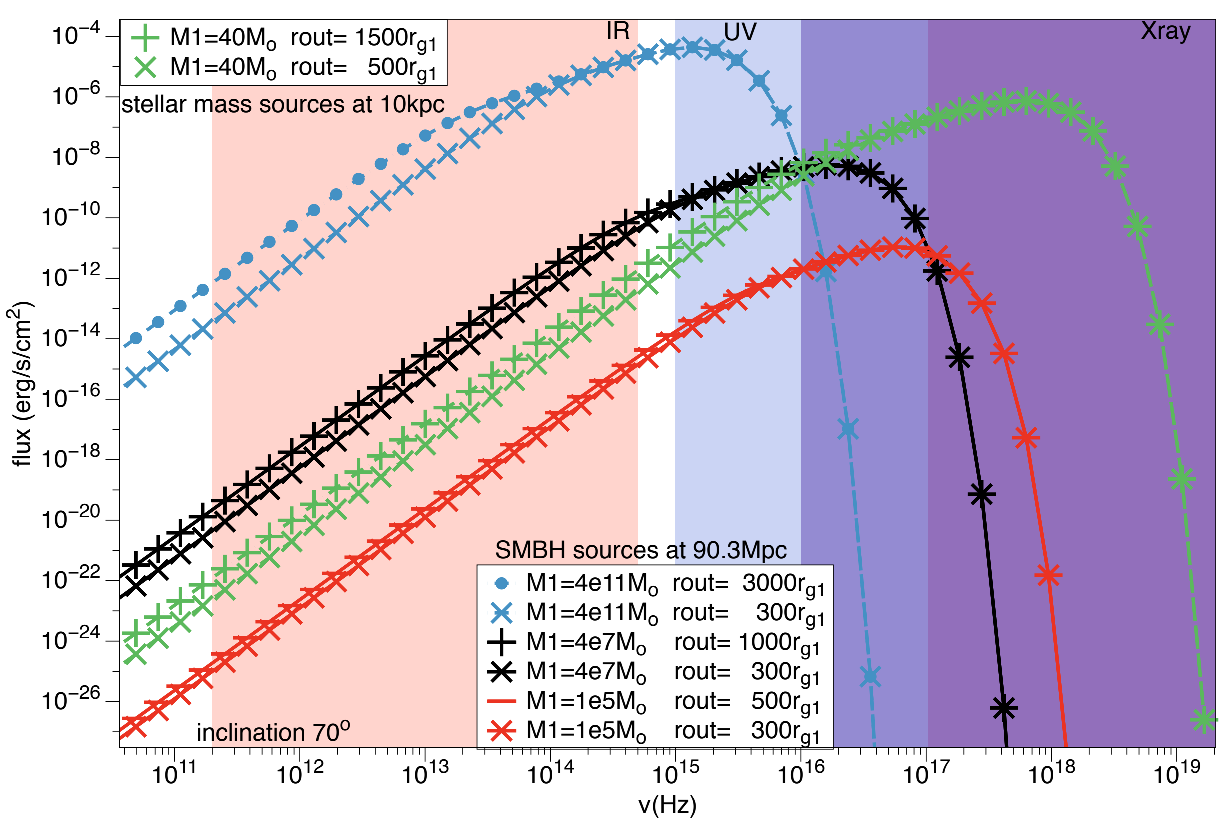

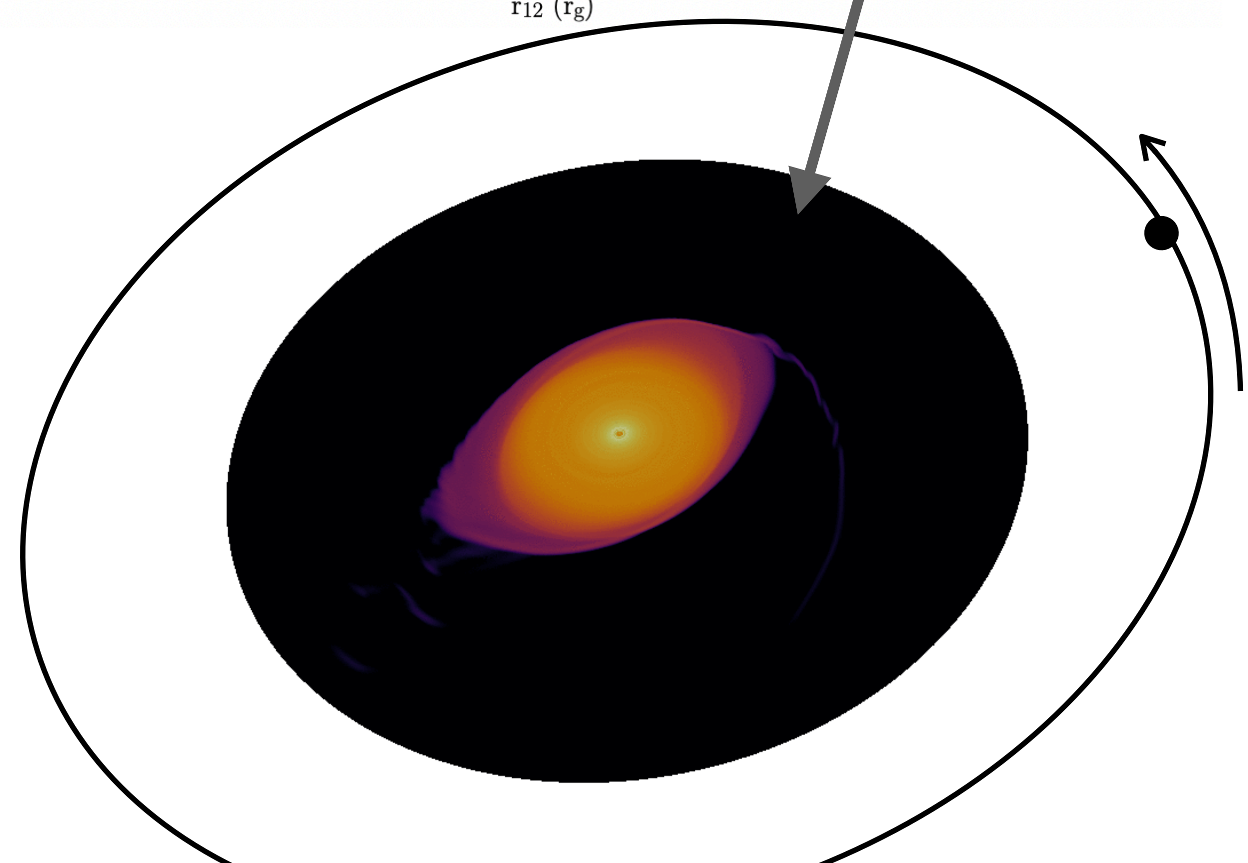

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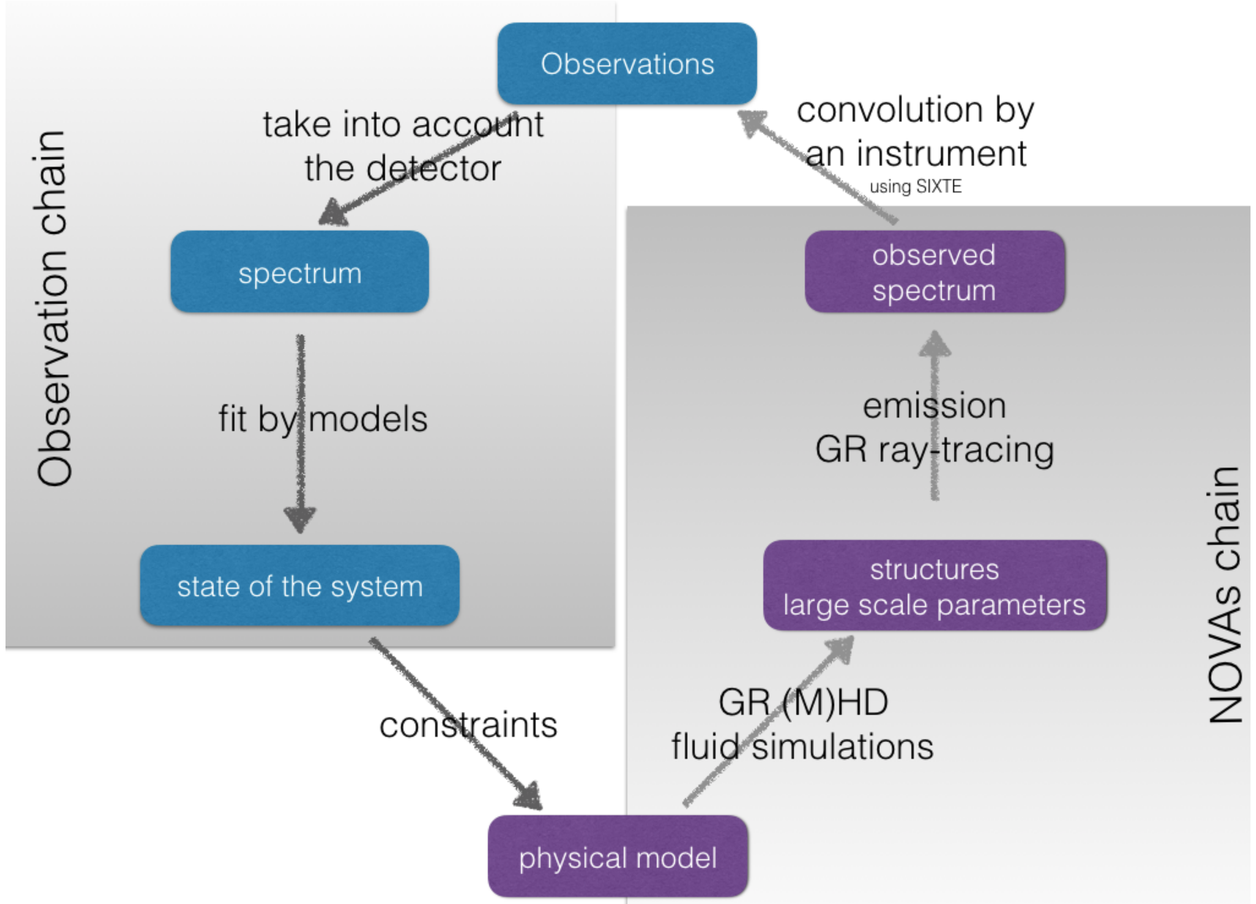

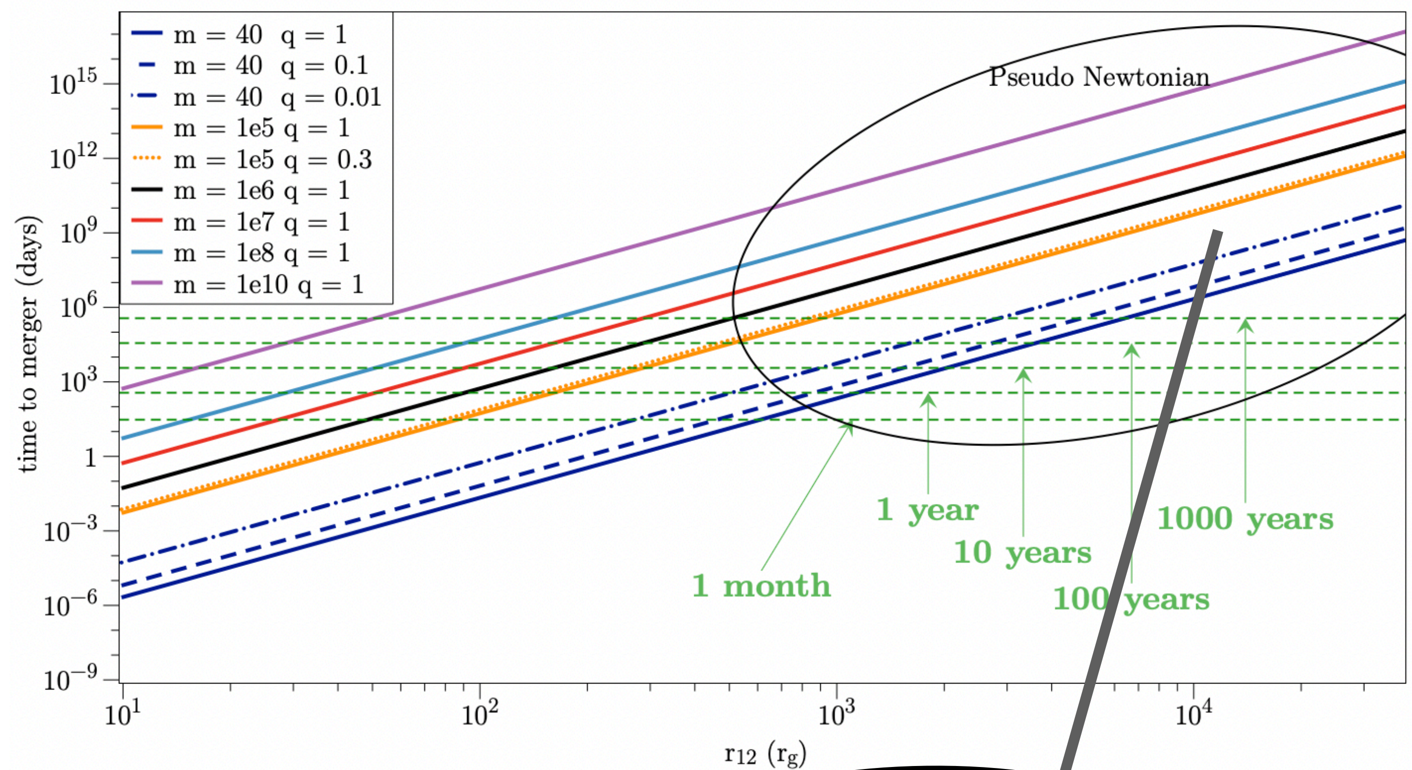

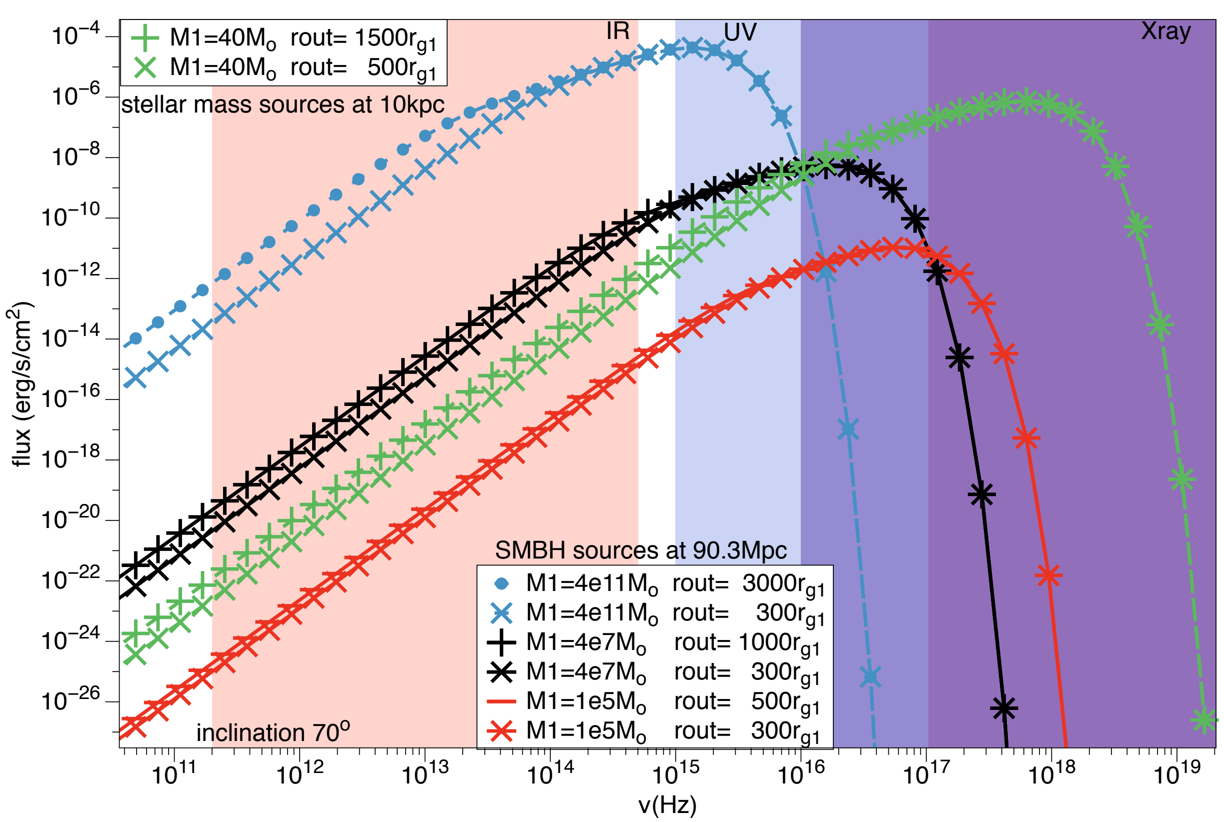

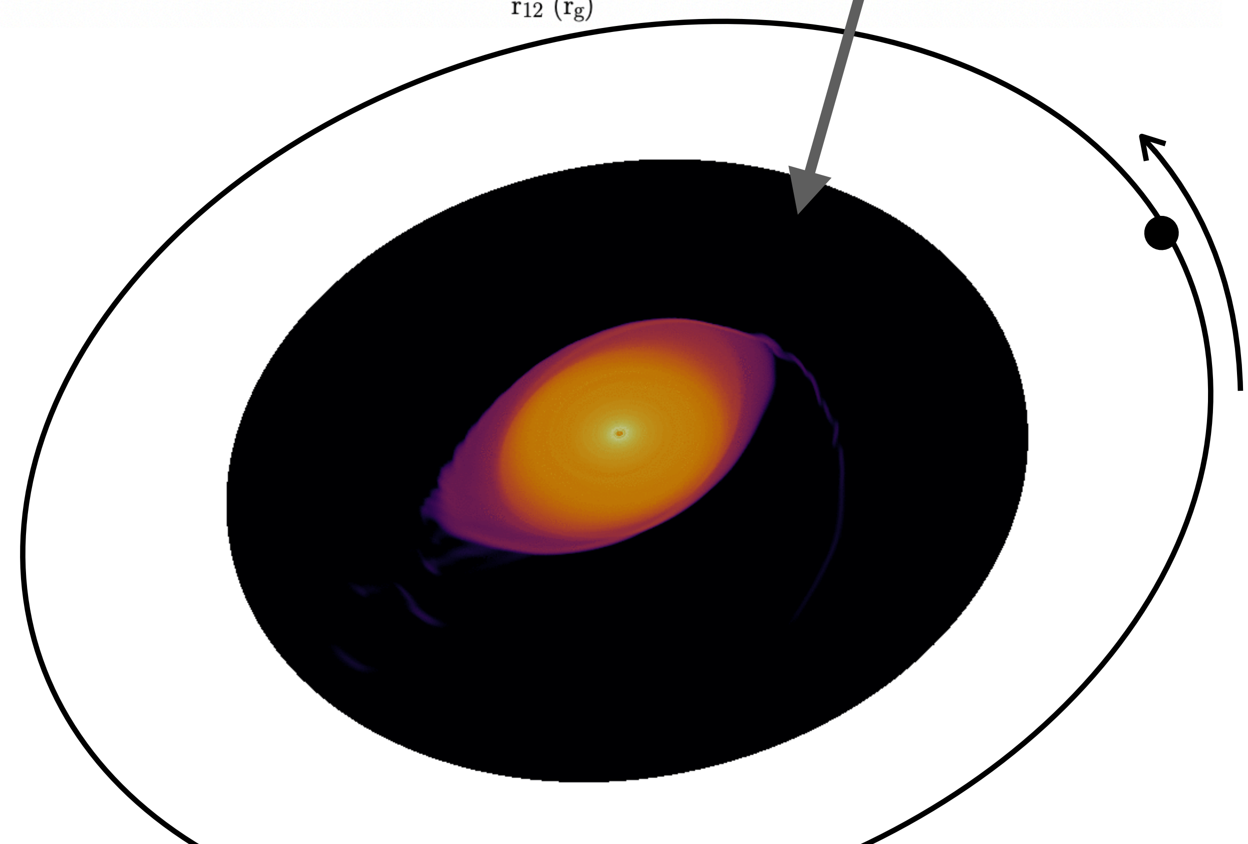

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