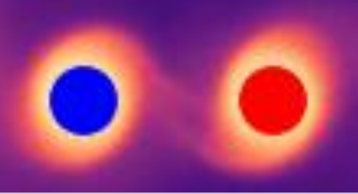
Supermassive black hole binaries on a moving mesh: the crucial role of accretion disc models for multi-messenger predictions



Sophie Koudmani

1851 Royal Commission Fellow, University of Hertfordshire

Bowring Research Fellow, St Catharine’s College, Cambridge

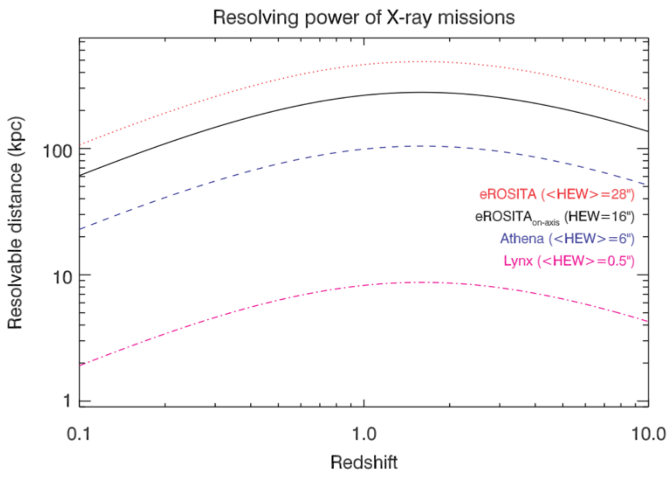
with Rachel Somerville, Debora Sijacki, Martin Bourne, Yan-Fei Jiang, Kasar Profit

LISA Astrophysics Working Group Meeting, Nov 6th, 2024

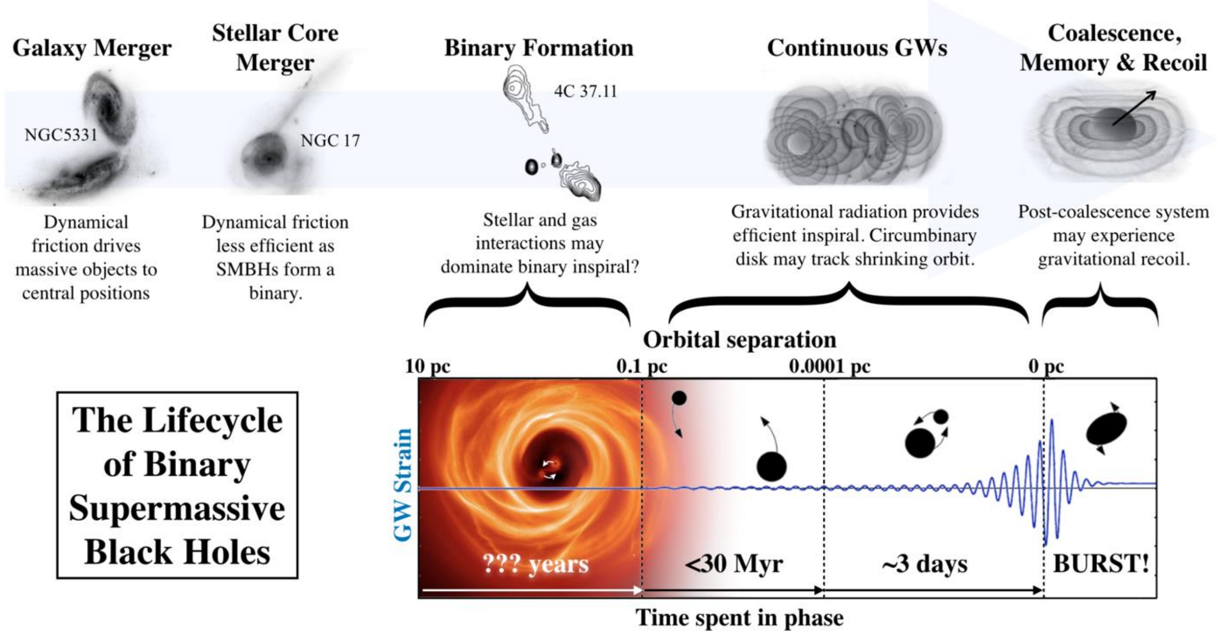
University of Hertfordshire UH

DiRAC

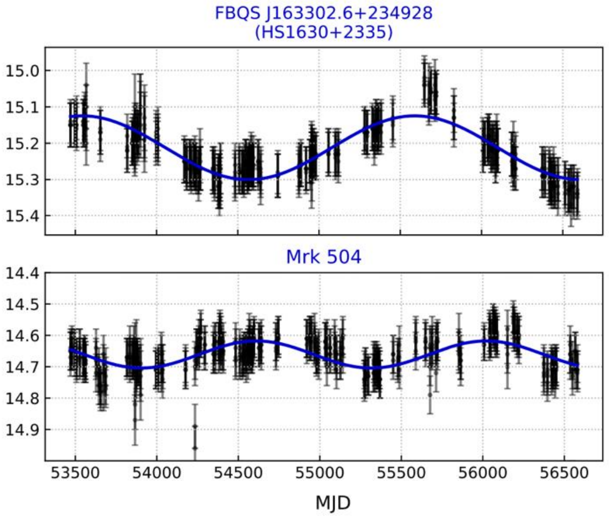
EM Signatures of Massive BH-BH Mergers



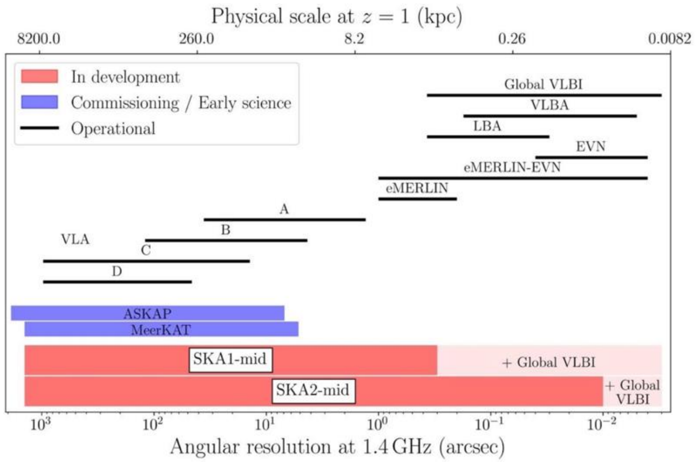
De Rosa et al., 2019



Burke-Spolaor et al., 2018

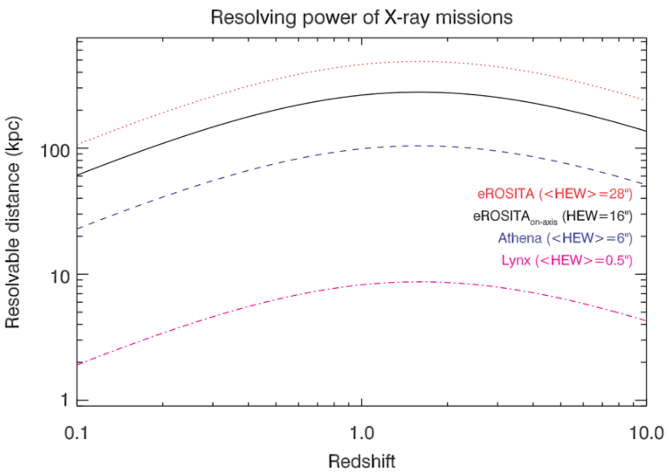


Xin et al., 2021

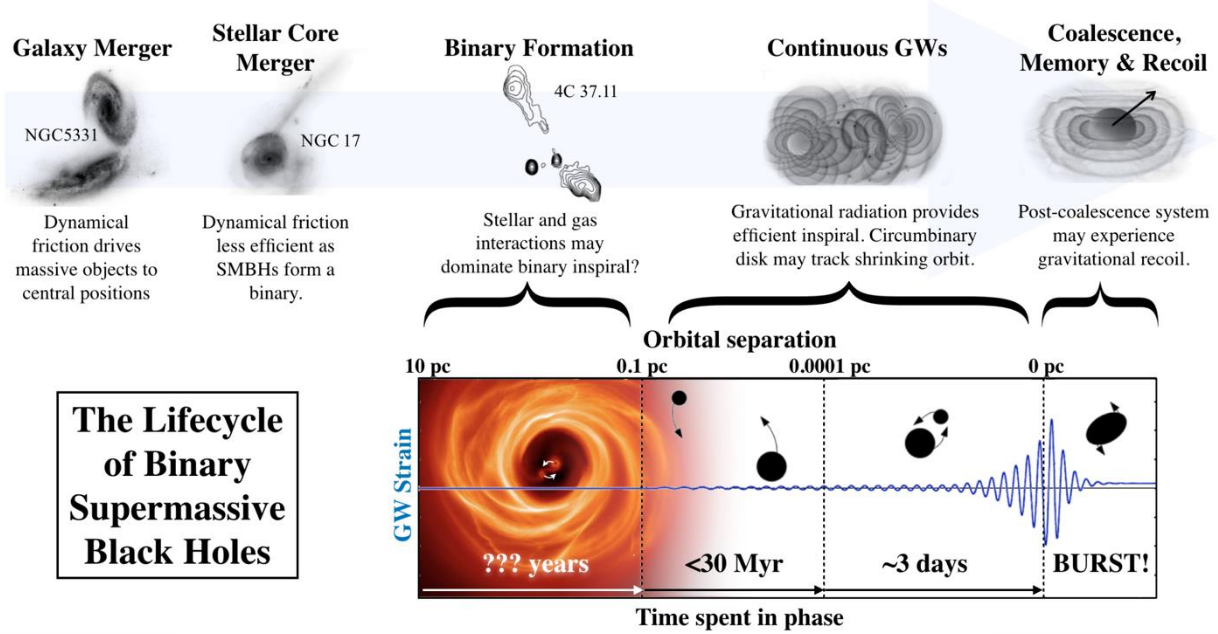


Radcliffe et al., 2018 (also see SKA-VLBI Working Group)

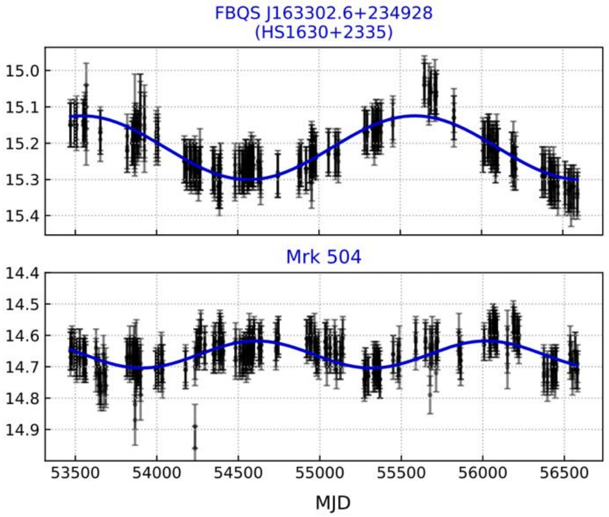
EM Signatures of Massive BH-BH Mergers



De Rosa et al., 2019

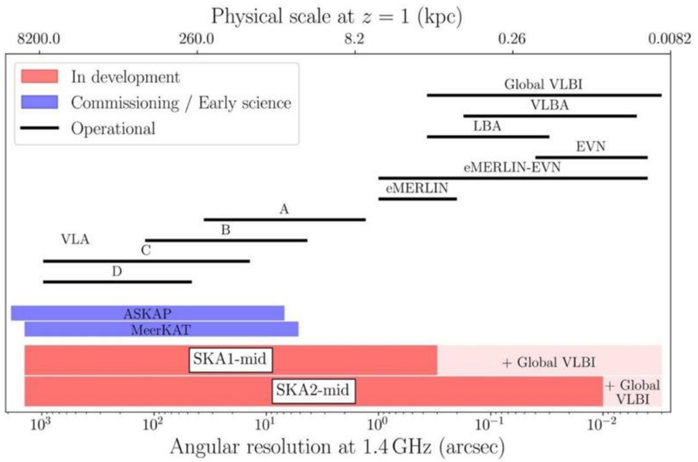


Burke-Spolaor et al., 2018



Xin et al., 2021

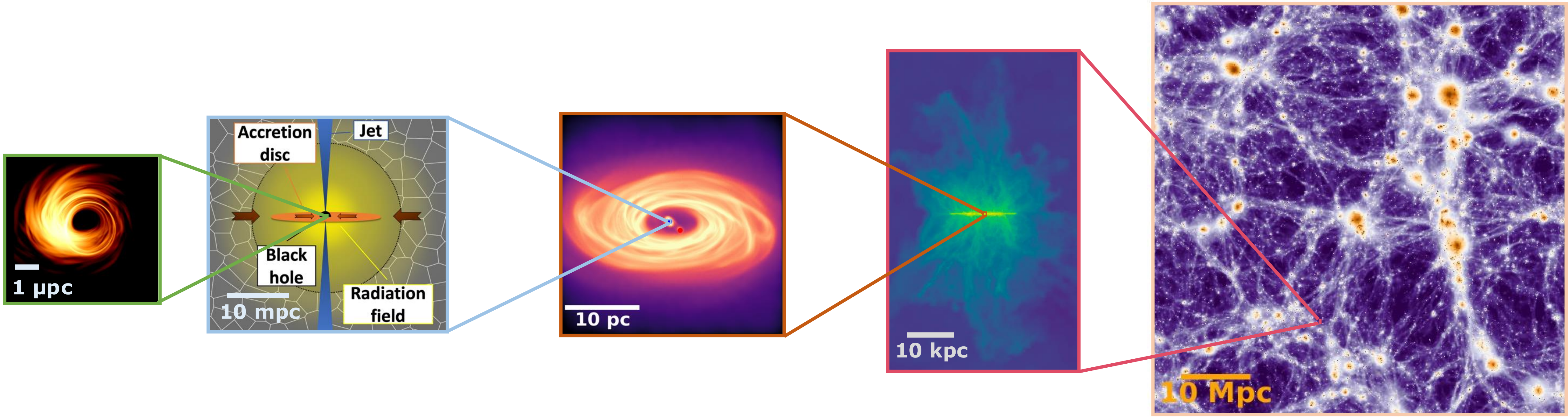
We need **theoretical predictions** for the **BH accretion discs and/or jets** of these binaries



Radcliffe et al., 2018 (also see SKA-VLBI Working Group)

SMBHs in Galaxy Formation: A Multi-Scale Problem

If we were to simulate SMBH accretion and feedback ab-initio…

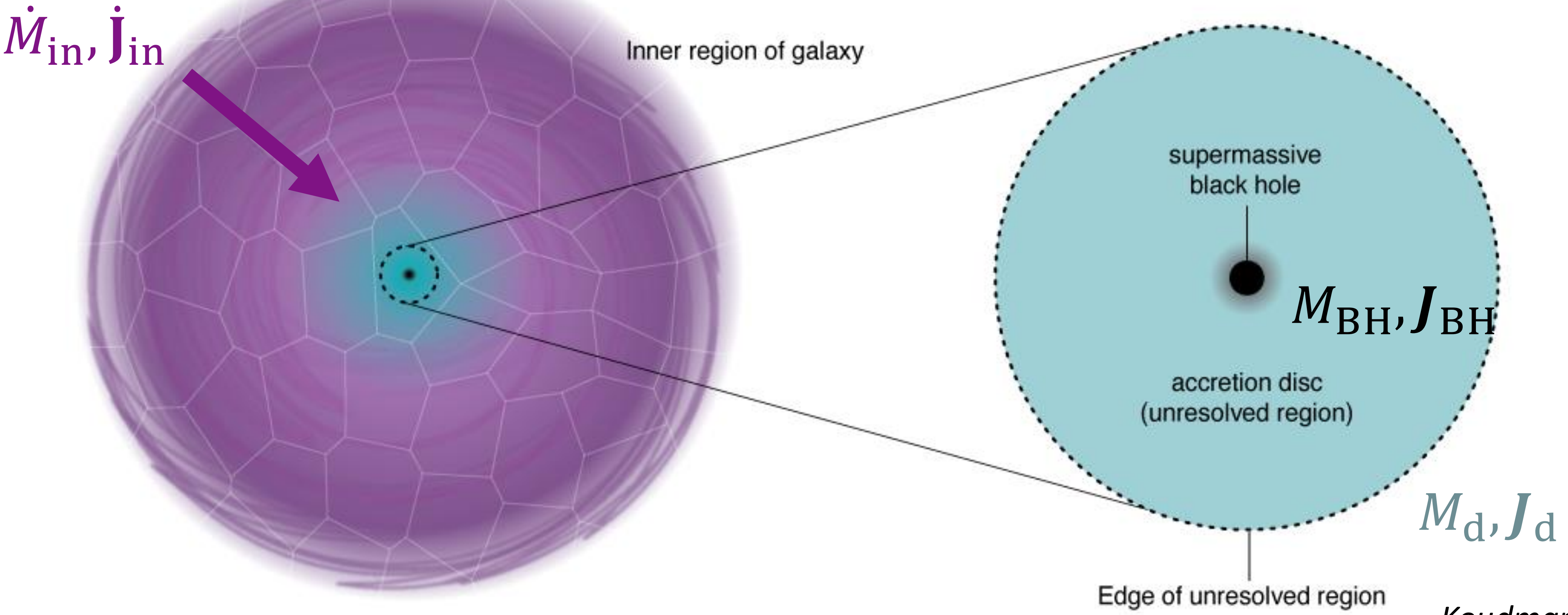


… we would need to span (at least) 14 orders of magnitude!

Image credits: Event Horizon Telescope, Koudmani+,19,21,24

Accretion disc particle method

also see Power+11, Dubois+14,21, Fiacconi+18, Bustamante+19, Cenci+21, Talbot+21,22, Husko+22,23, Massonneau+22, Tartėnas & Zubovas 22, Partmann+24 …



Koudmani+24

- **Mass and angular momentum inflows at outer accretion disc** directly from the **hydro solver**
- **BH mass/spin evolution** with the **subgrid model** → **usually Shakura Sunyaev thin α-disc**

Accretion disc particle method: mass evolution

DISC MASS M_d AND BH MASS M_BH EVOLUTION:

$$\frac{\mathrm{d}M_\mathrm{d}}{\mathrm{d}t} = -\dot{M} + \dot{M}_\mathrm{in}$$

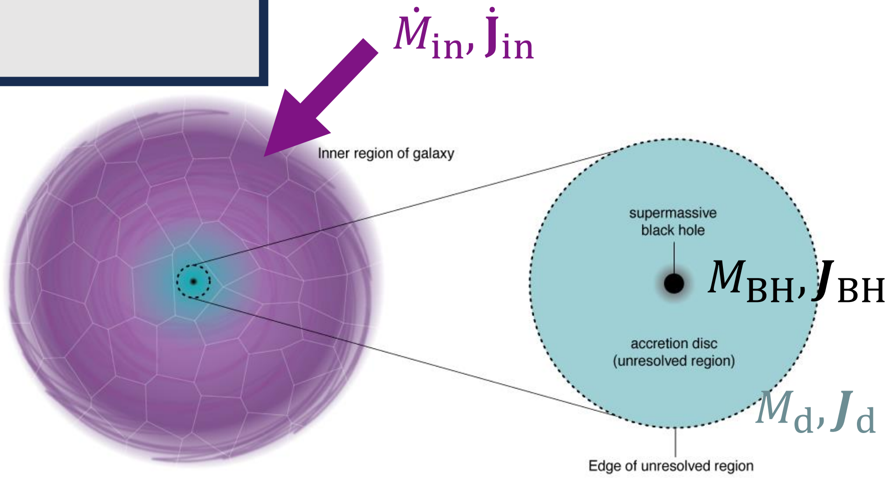
Disc mass change = – accretion + inflow from environment

$$\frac{\mathrm{d}M_\mathrm{BH}}{\mathrm{d}t} = (1-\eta)\,\dot{M}_\mathrm{BH,0}$$

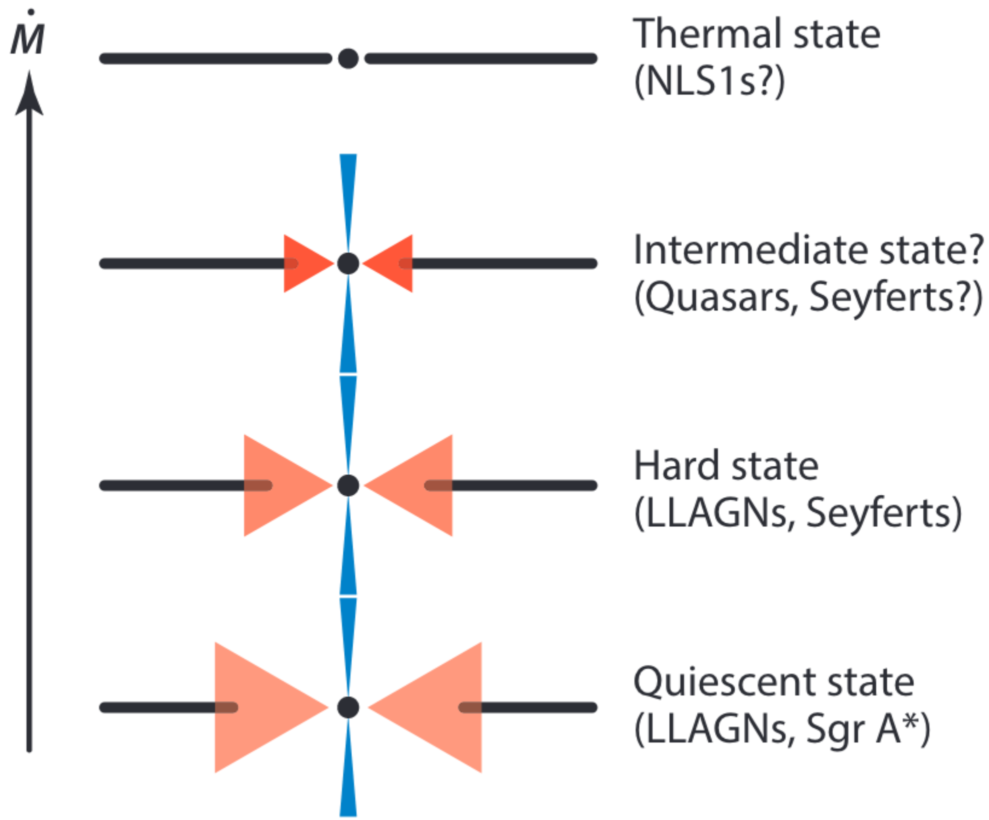
Black hole mass change = accretion corrected by radiative efficiency η

From hydro solver

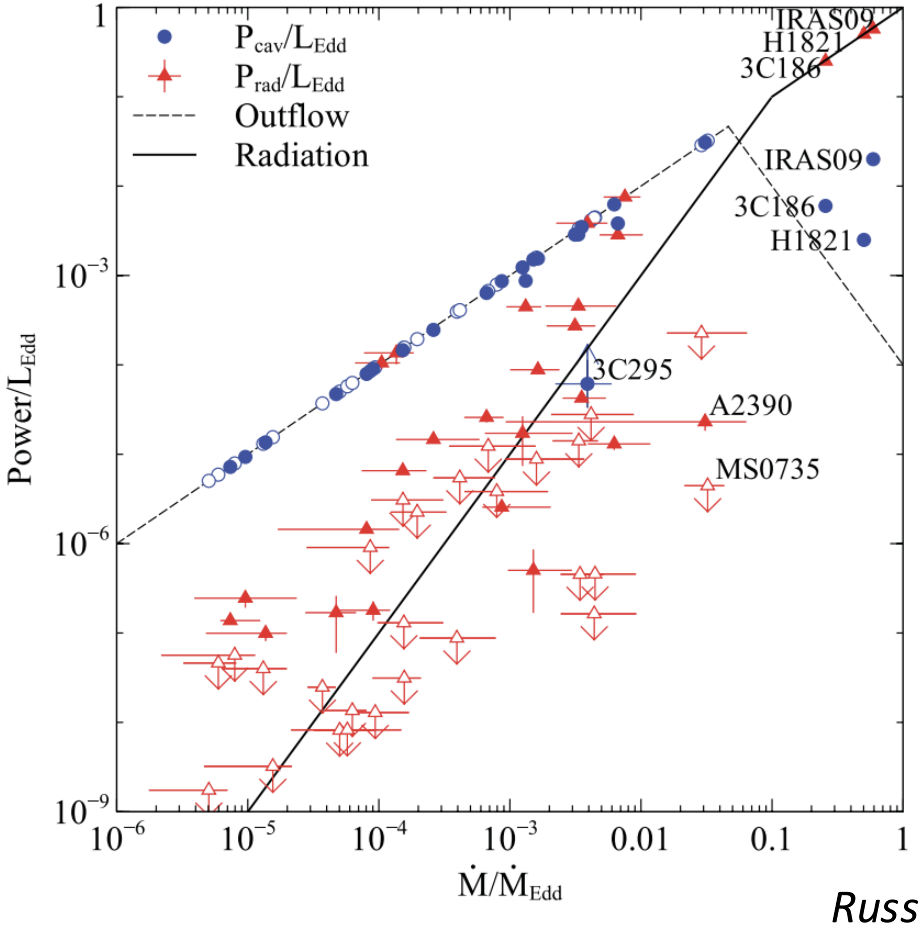
From analytical disc model:
Shakura Sunyaev thin α-disc



Radiatively-inefficient accretion



Yuan & Narayan 14

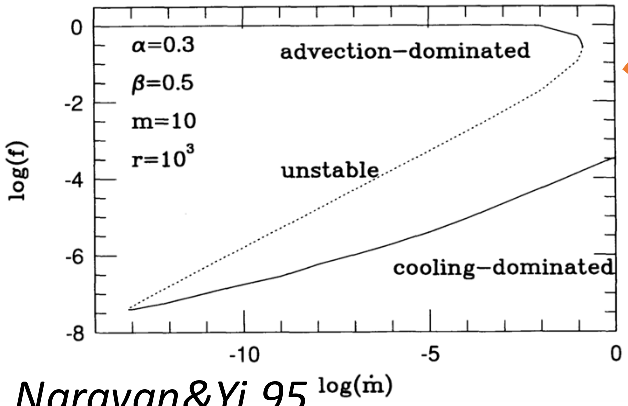


Russell+13

At low accretion rates the thin disc transitions to a **hot advection-dominated accretion flow** (ADAF, Narayan & Yi 1995)
→ viscous heating balanced by energy advection rather than cooling
→ Positive Bernoulli parameter hints at **strong outflows** in ADAF regime (**ADIOS model**, Blandford & Begelman 1999)

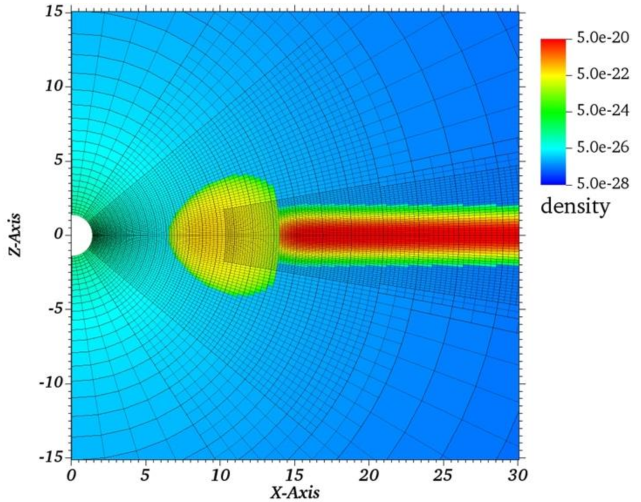
Unified accretion disc particle method

Self-similar ADAF/ADIOS theory

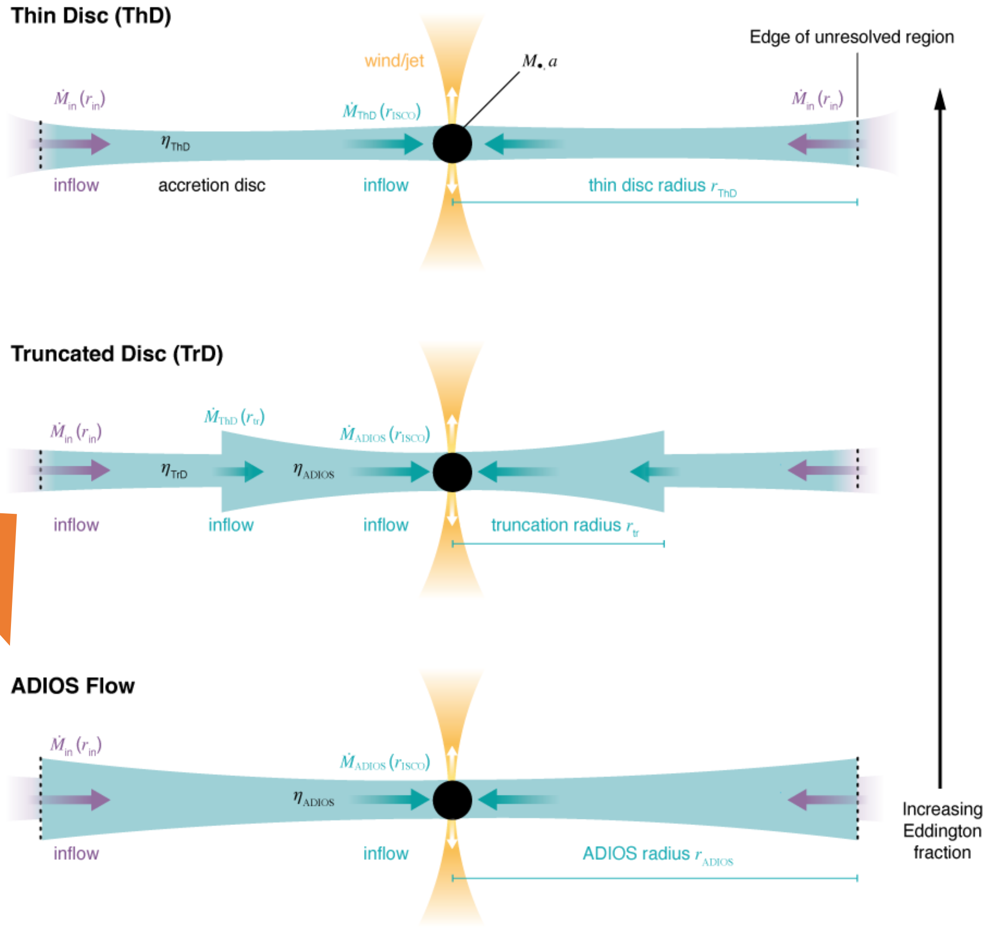


Narayan&Yi,95

GRMHD simulations: disc precession

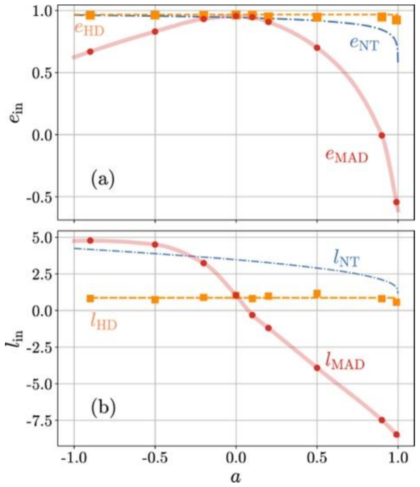


Bollimpalli+24



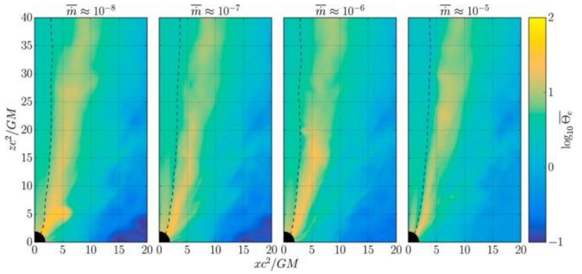
Koudmani+24

GRMHD simulations: spin-up



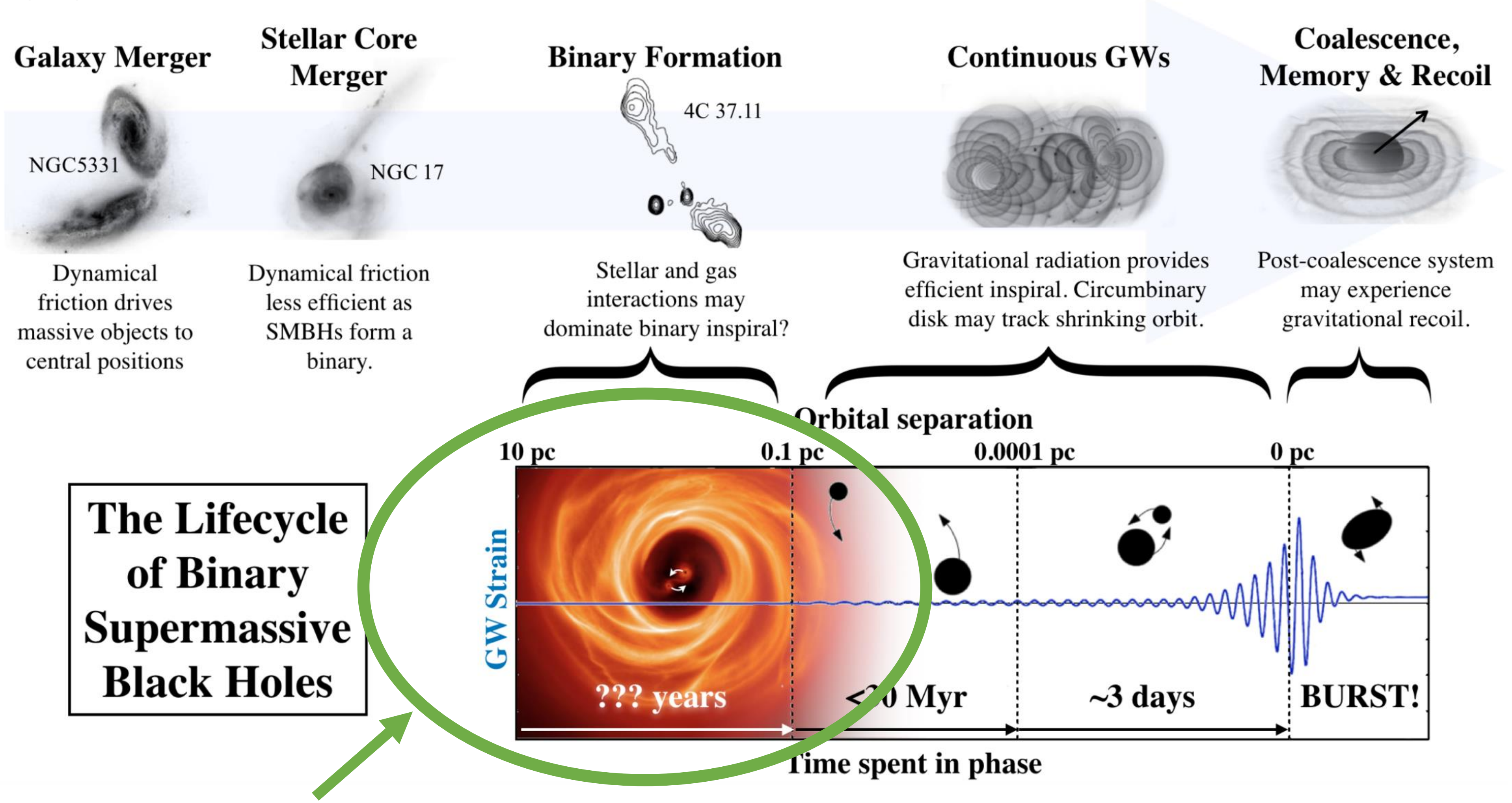
Lowell+24

GRRMHD simulations: radiative efficiency



Ryan+17

First Application: Idealised SMBH Binaries



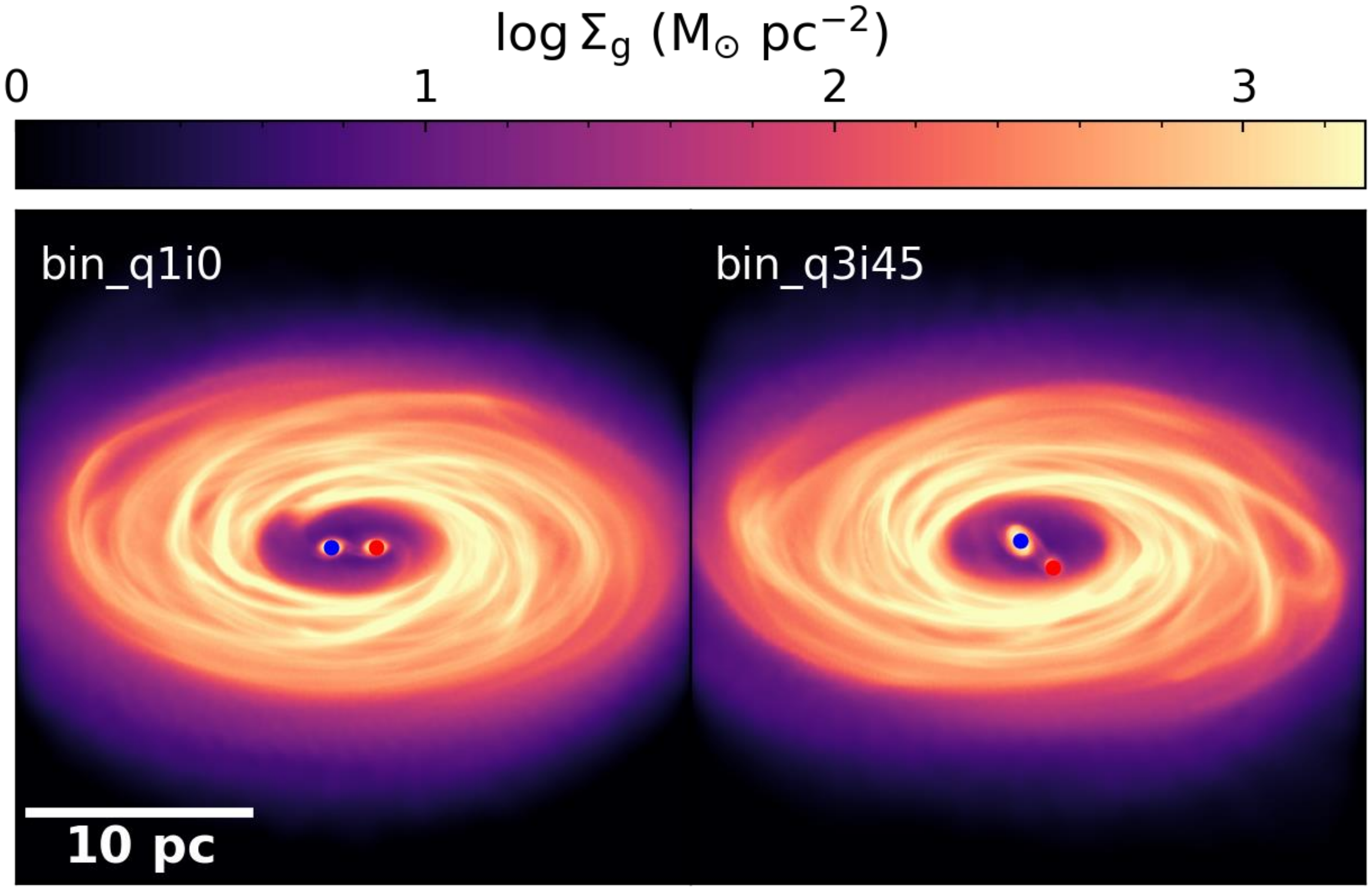
Wide binary phase in reach of next-generation radio facilities

(already some VLBI detections,

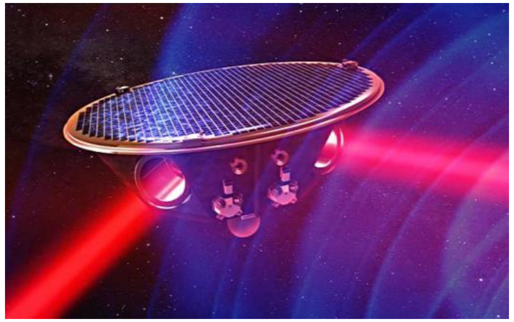
see Rodriguez et al. 2006; Bansal et al. 2017; Kharb et al. 2017)

Burke-Spolaor et al., 2018

Application to SMBH Binaries



Koudmani+24



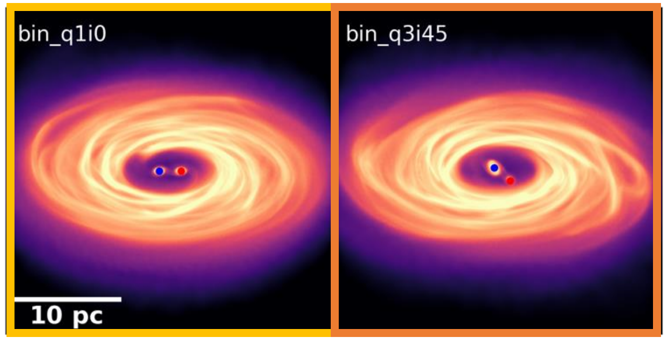
AEI/MM/exozet

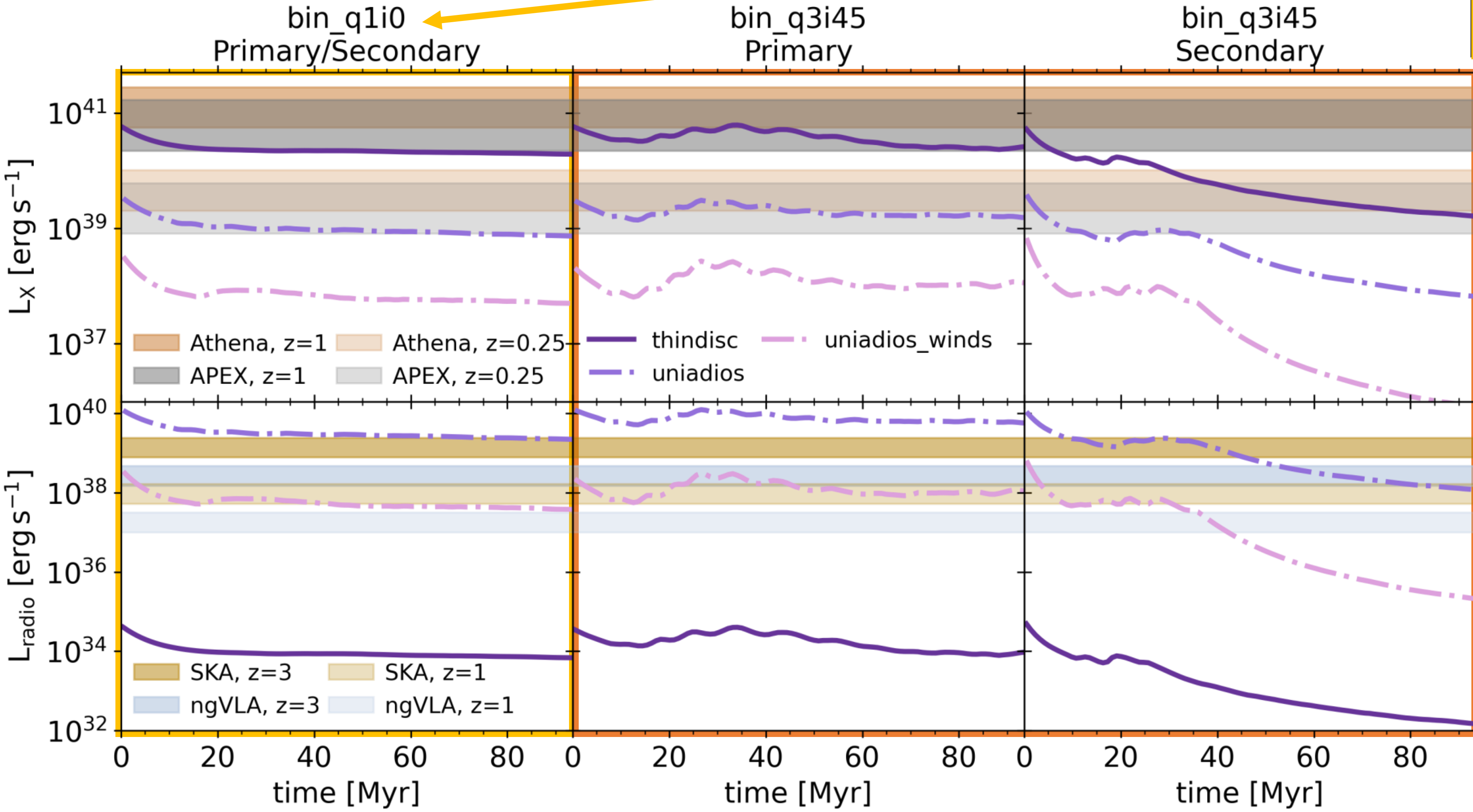
Binary set-up from Bourne et al., 2024 (inc. SK):

- Moving mesh code AREPO (Springel, 2010)
- Binary parameters:
  - M_{bin}= 2x10^6 M_{sun}
  - T_{bin} = 0.187 Myr
  - a_{bin} = 2pc, gaseous CBD from $2a_{bin}$ → $7a_{bin}$

- **bin_q1i0:** equal-mass, aligned binaries → **steady external accretion** from mini discs
- **bin_q3i45**: unequal-mass (q=3), misaligned binaries → **'chaotic' external accretion** from mini discs

Binary detectability

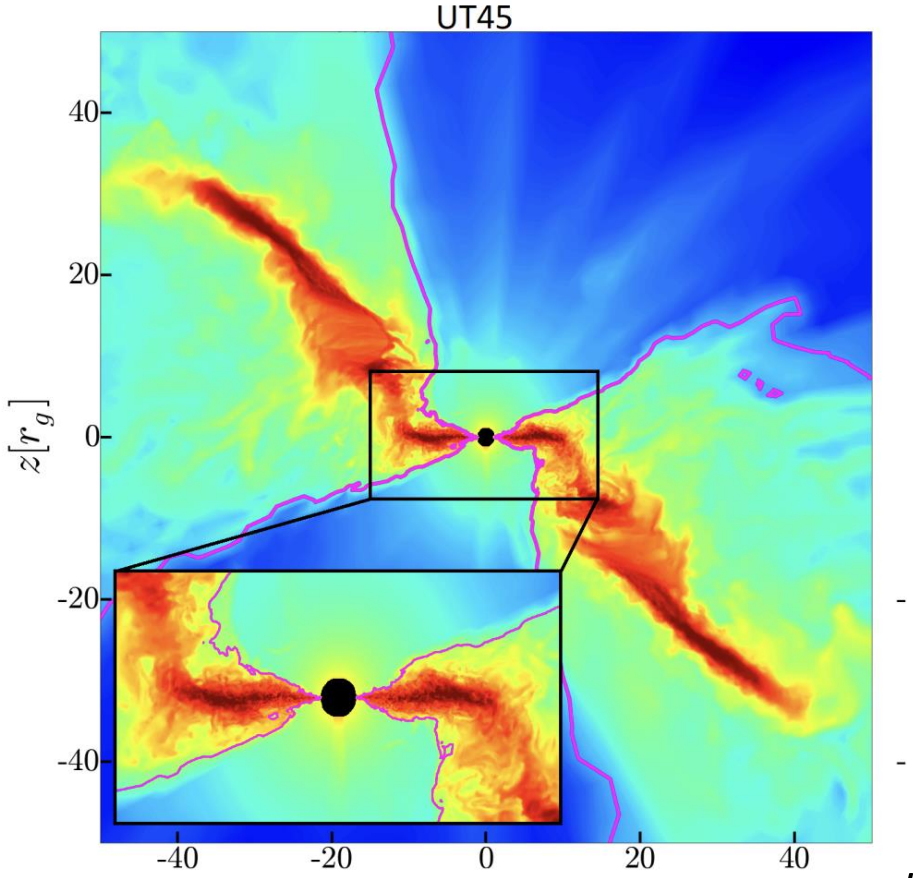




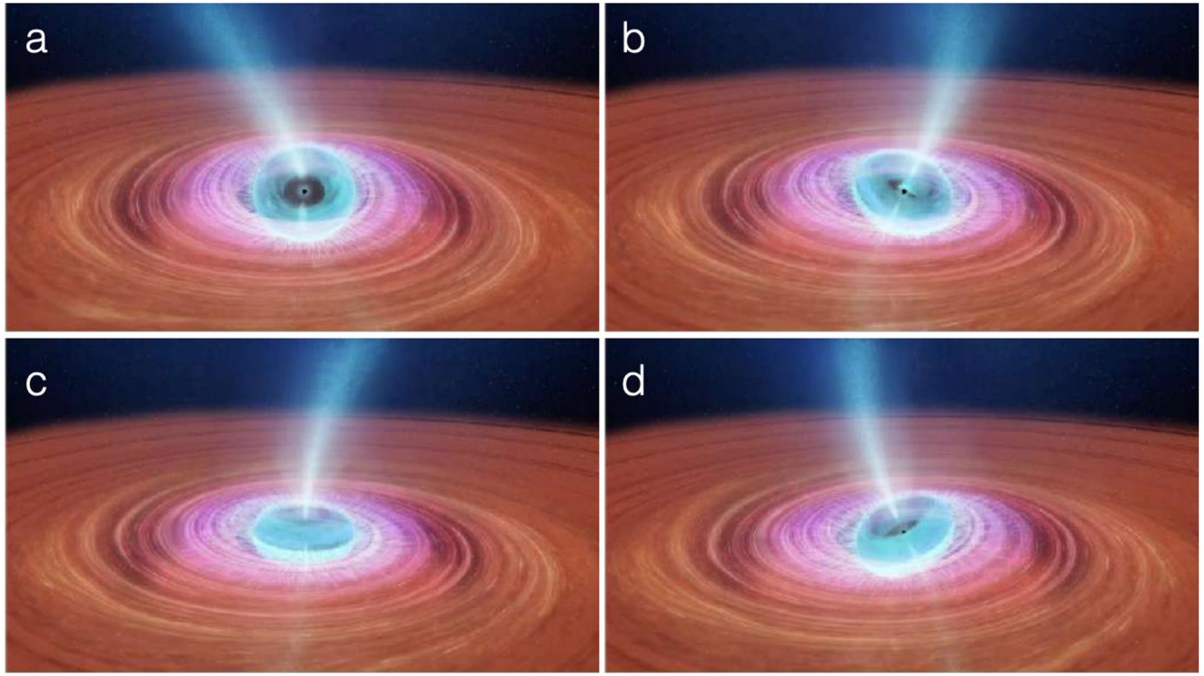
Koudmani+24

Significantly different electromagnetic counterpart predictions! (also see *Giustini & Proga, 2019)*

Disc-state-dependent Lense Thirring Precession



Liska+21

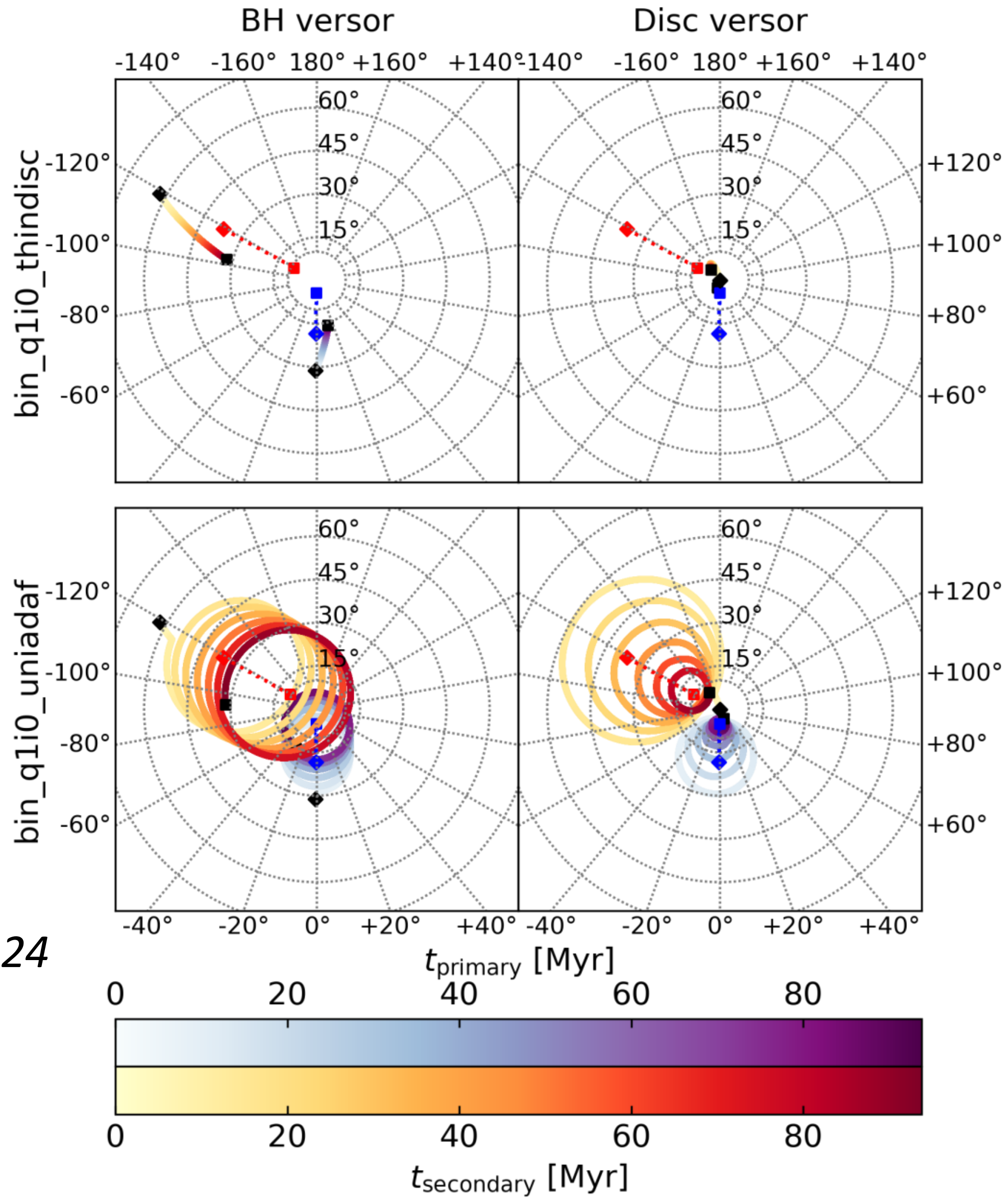


Ingram & Motta 19

Misaligned thin discs are realigned by **Bardeen Petterson effect**

Inner hot flow may **precess as solid body OR be twisted into alignment** by outer thin disc

Spin Evolution and Precession

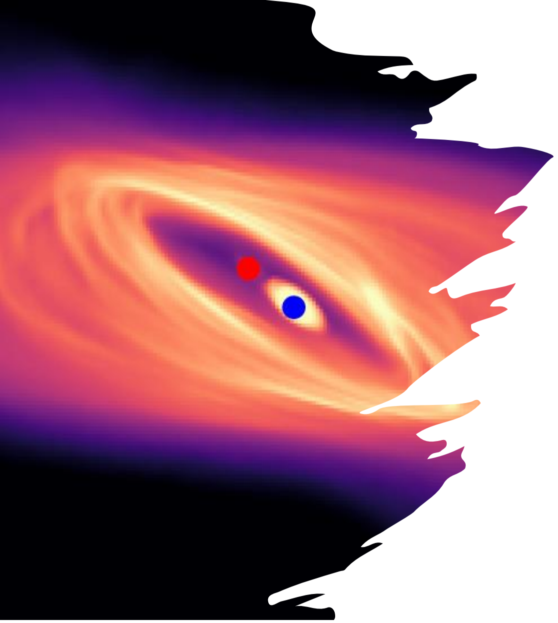


Koudmani+24

→ **Significant external angular momentum** inflows so that $\mathbf{J}_{\mathrm{tot}} = \mathbf{J}_{\mathrm{BH}} + \mathbf{J}_{\mathrm{d}}$ evolves towards mini disc angular momentum

→ **Decreasing disc precession** angle

→ Primary and secondary BH cover **large solid angle in unified model**



Conclusions & Outlook

- Developed **novel unified accretion disc model for massive BHs in galaxy formation simulations** based both on analytical descriptions of the ADIOS models and GR(-R-)MHD simulations of radiatively inefficient accretion
- **Predictions for electromagnetic signatures of massive black hole binaries are hugely sensitive to the assumed disc state**, and it is imperative to simulate this self-consistently
- With future gravitational-wave observatories, such as IPTA and LISA, also crucial to **make predictions for likely spin magnitude and orientation of merging SMBHs**
- **Outlook:** Combine with AGN feedback prescriptions, test this model in galaxy merger and cosmological zoom-in simulations, coarse-grained version for large cosmological volumes

Accretion disc particle method

DISC MASS M_{d} AND BH MASS M_{BH} EVOLUTION:

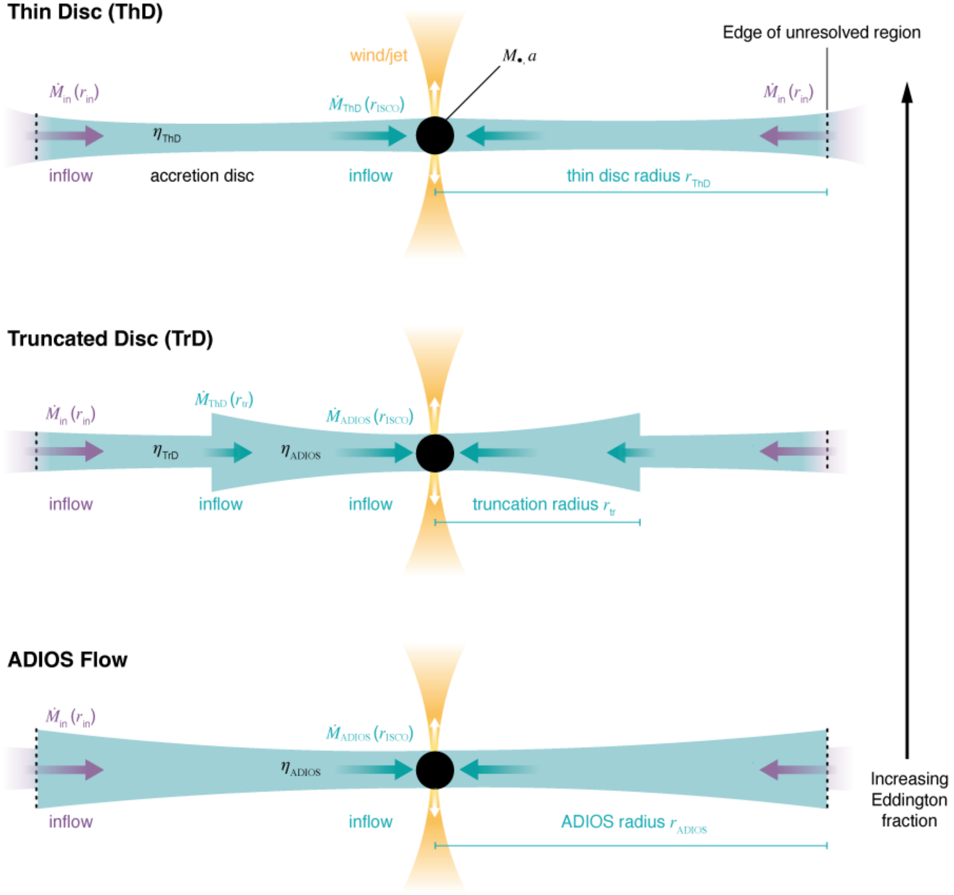
$$\frac{\mathrm{d}M_{\mathrm{d}}}{\mathrm{d}t} = -\dot{M} + \dot{M}_{\mathrm{in}}$$

$$\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}t} = (1-\eta)\,\dot{M}_{\mathrm{BH,0}}$$

DISC ANG. MOMENTUM J_{d} AND BH SPIN J_{BH} EVOLUTION:

$$\frac{\mathrm{d}\mathbf{J}_{\mathrm{d}}}{\mathrm{d}t} = -\dot{M}\,L_{\mathrm{ISCO}}\,\mathrm{sign}(\mathbf{j}_{\mathrm{BH}}\cdot\mathbf{j}_{\mathrm{d}})\,\mathbf{j}_{\mathrm{BH}} - \left.\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t}\right|_{\mathrm{LT}} + \dot{\mathbf{J}}_{\mathrm{in}}$$

$$\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t} = \dot{M}_{\mathrm{BH,0}}\,L_{\mathrm{ISCO}}\,\mathrm{sign}(\mathbf{j}_{\mathrm{BH}}\cdot\mathbf{j}_{\mathrm{d}})\,\mathbf{j}_{\mathrm{BH}} + \left.\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t}\right|_{\mathrm{LT}}$$



For truncated / pure ADIOS disc states:

- Fluxes from **hydro solver**, mass flow rates & Lense Thirring torques from **analytical theory**
- Energy and angular momentum transfer from **GR(R)MHD simulations**

Accretion disc particle method: angular momentum

DISC ANG. MOMENTUM J_{d} AND BH SPIN J_{BH} EVOLUTION:

Self consistently **track the black hole spin** and its orientation!

$$\frac{\mathrm{d}\mathbf{J}_{\mathrm{d}}}{\mathrm{d}t} = -\dot{M}\, L_{\mathrm{ISCO}}\, \mathrm{sign}(\mathbf{j}_{\mathrm{BH}} \cdot \mathbf{j}_{\mathrm{d}})\, \mathbf{j}_{\mathrm{BH}} - \left.\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t}\right|_{\mathrm{LT}} + \dot{\mathbf{j}}_{\mathrm{in}}$$

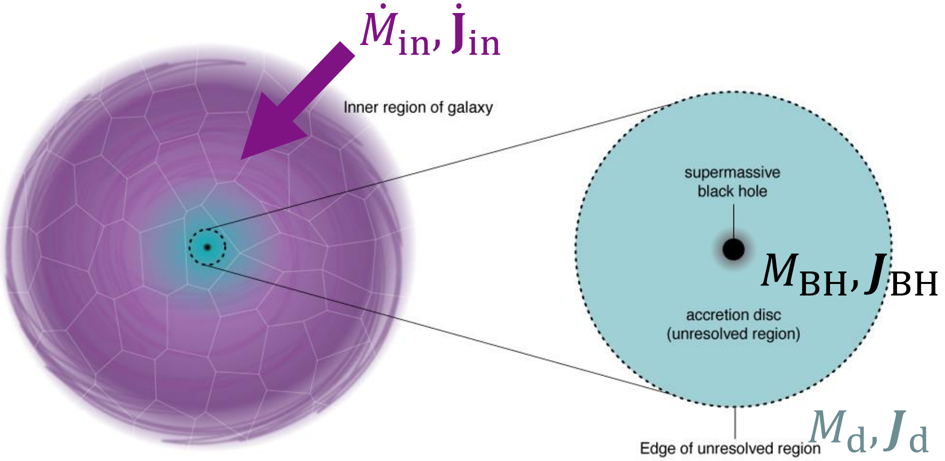
= – accretion x specific angular momentum at ISCO – mutual Lense Thirring torque + inflow from environment

$$\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t} = \dot{M}_{\mathrm{BH},0}\, L_{\mathrm{ISCO}}\, \mathrm{sign}(\mathbf{j}_{\mathrm{BH}} \cdot \mathbf{j}_{\mathrm{d}})\, \mathbf{j}_{\mathrm{BH}} + \left.\frac{\mathrm{d}\mathbf{J}_{\mathrm{BH}}}{\mathrm{d}t}\right|_{\mathrm{LT}}$$

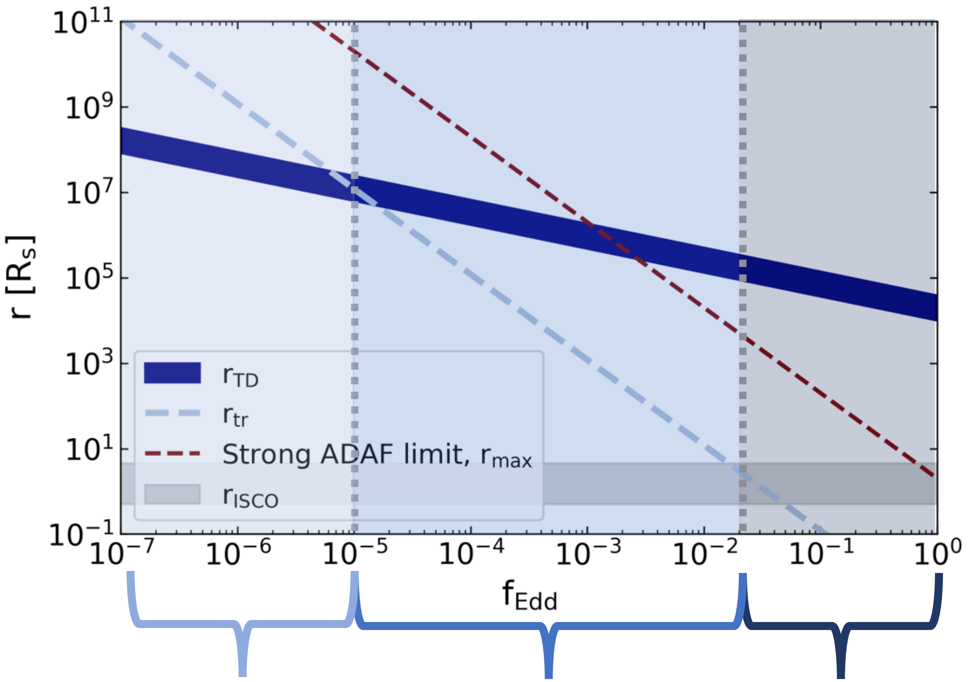
= accretion x specific angular momentum at ISCO + mutual Lense Thirring torque

The Shakura Sunyaev **thin α-disc model** offers a **global analytical solution for disc properties:**

- Take fluxes from **hydro solver**
- Infer BH/disc evolution from **thin disc analytical theory**



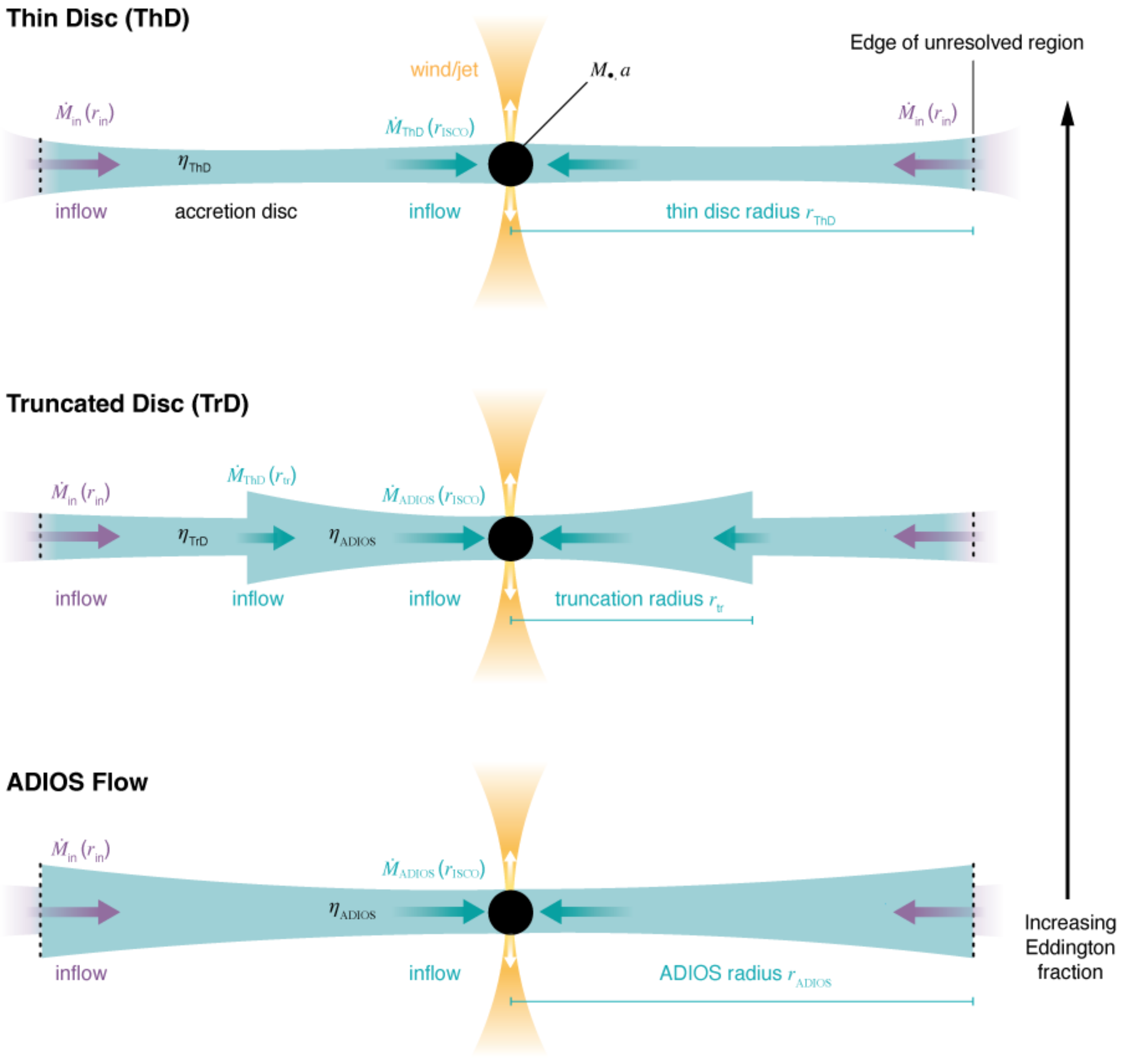
How to determine the accretion disc state?



ADAF/ADIOS **Truncated disc** **Thin disc**

“Radio mode” **“Transition mode”** **“Quasar mode”**

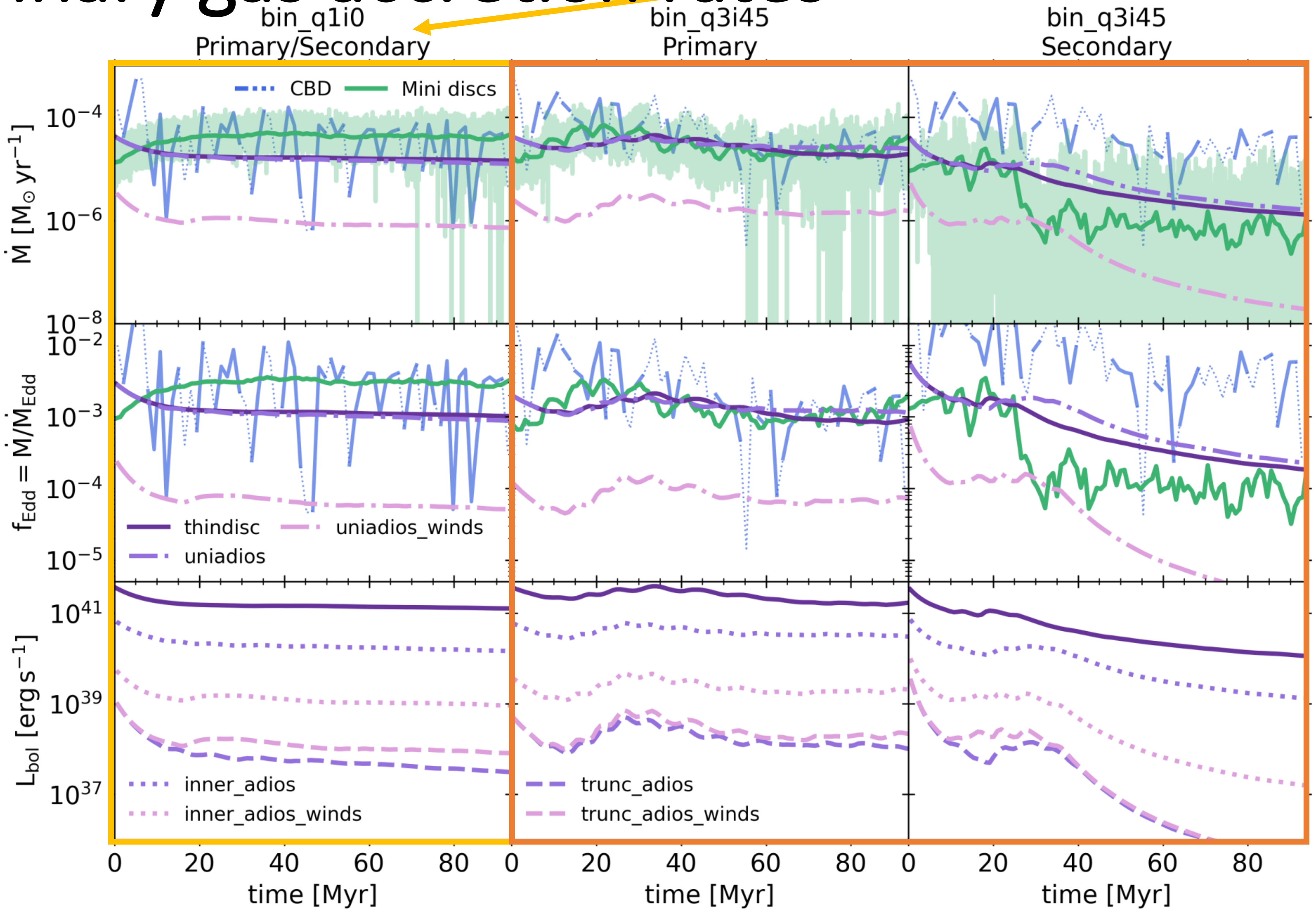
Koudmani+, 2024

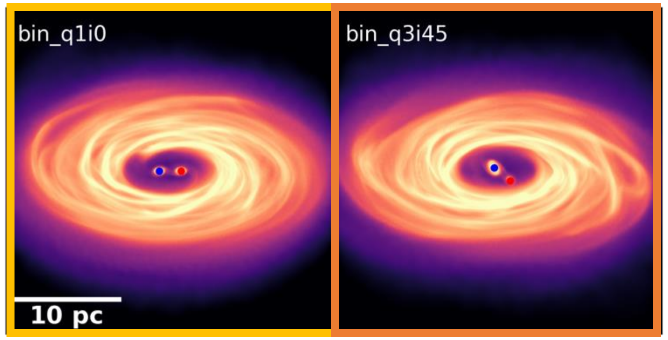


Characteristic radii set accretion disc state

--> **smooth transition** between ‘radio mode’ and ‘quasar mode’ **via truncated disc state**

Binary gas accretion rates





Relatively low gas inflows from mini discs would lead to truncated discs within our unified framework

Luminosity is **dominated by inner hot flow** in truncated regime

Koudmani+24