THEORY AND SIMULATIONS OF SUPER-EDDINGTON BH ACCRETION FLOWS

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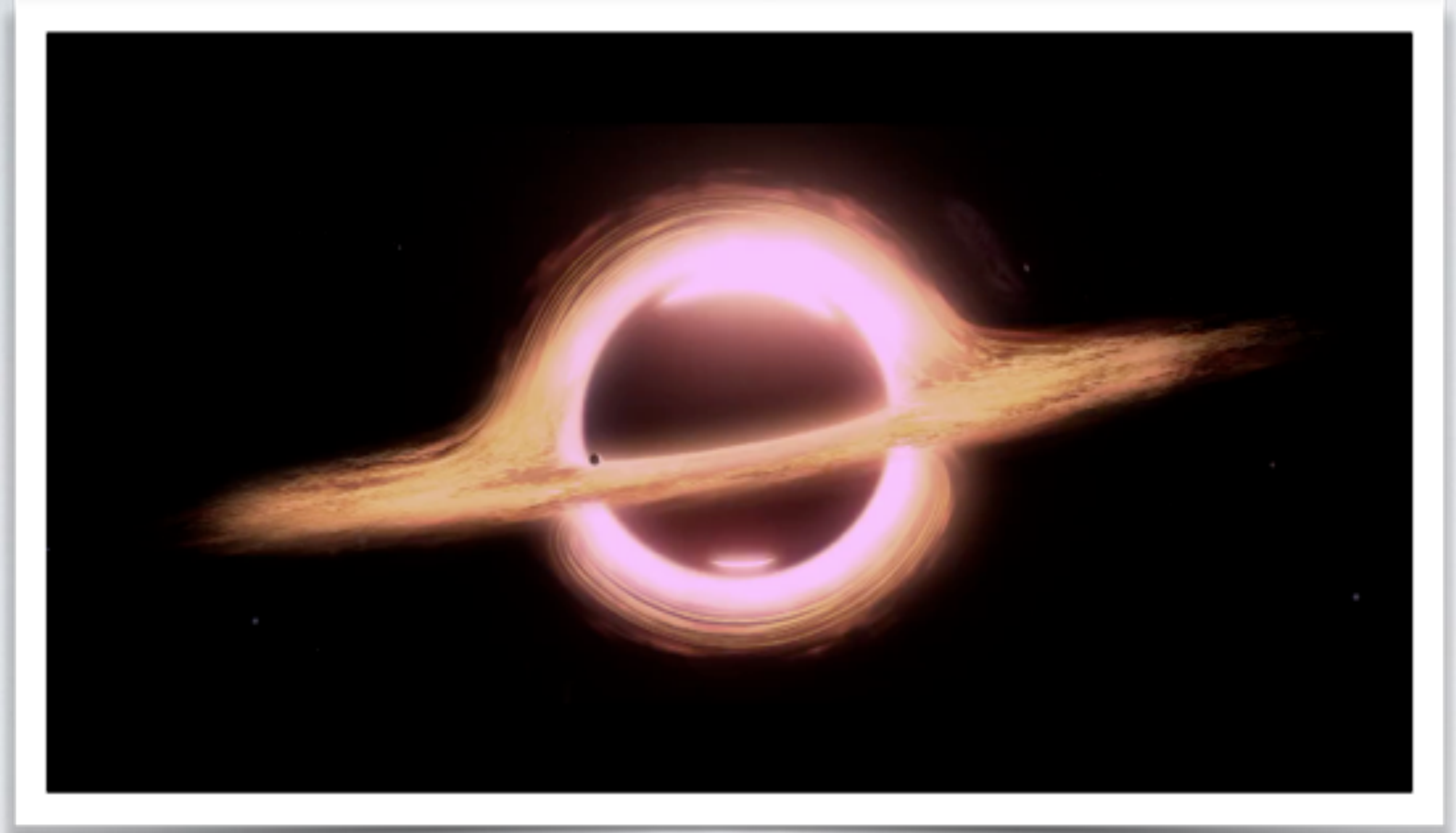
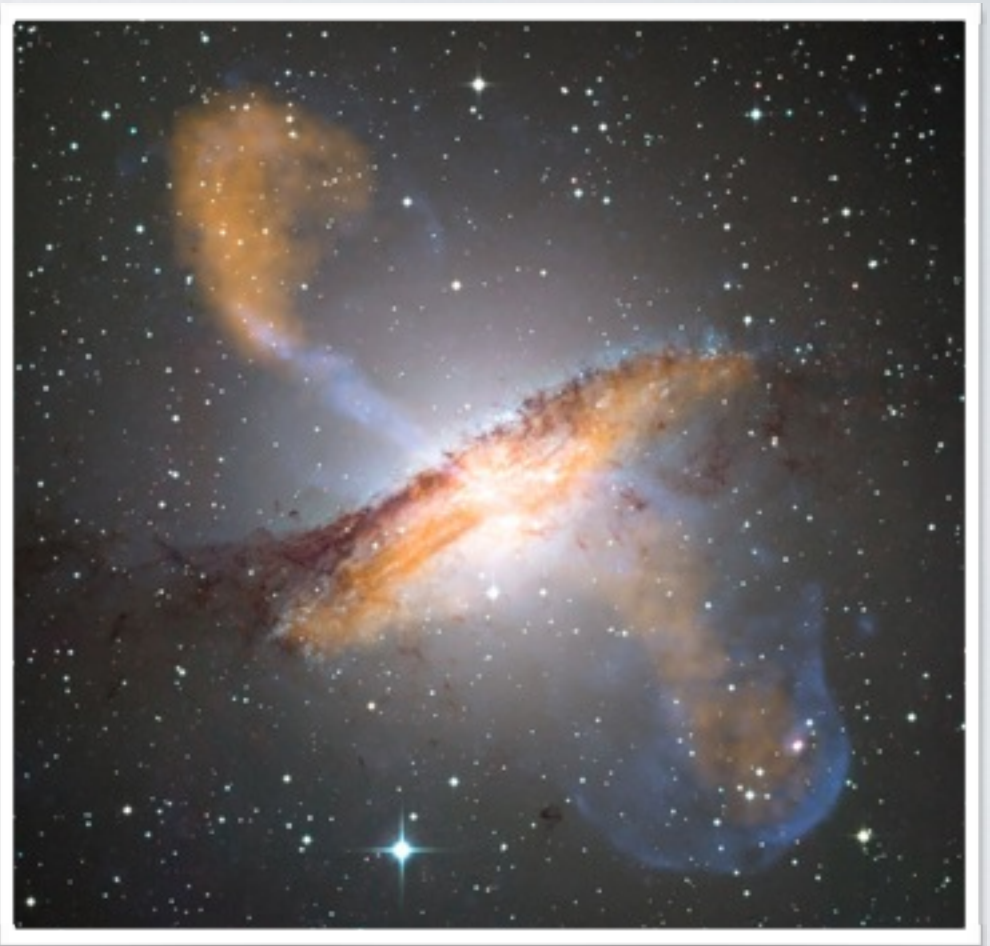
ACCRETION ON COMPACT OBJECTS



(c) Jake Lutz, https://youtu.be/Dg_ukl_QWOw



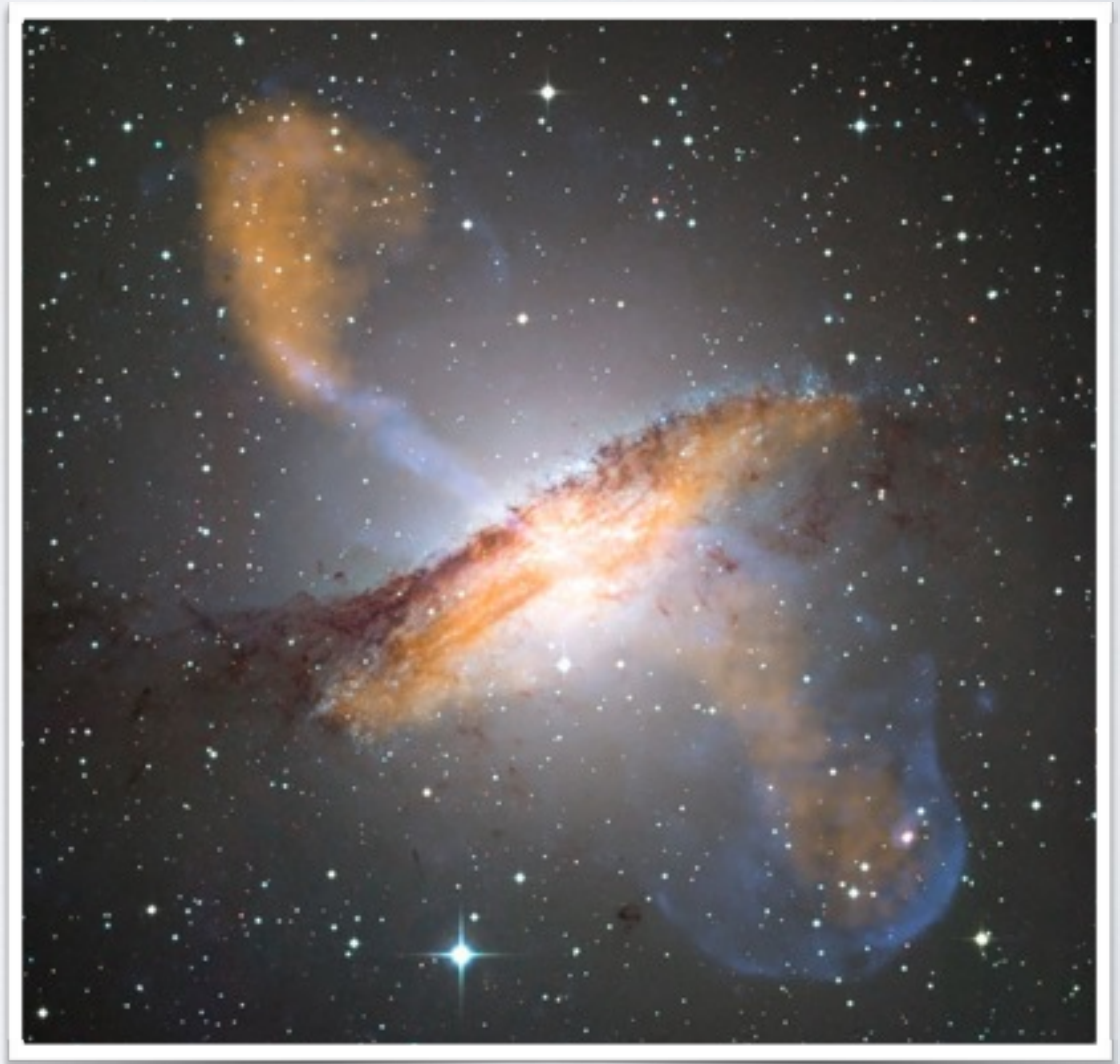
- Compactness allows for extraction of significant fraction of the gravitational energy (up to 40% of $\dot{M}c^2$ for a BH!)

ACCRETION ON BLACK HOLES

BH accretion is involved in some of most energetic phenomena:

- X-ray binaries
- Active galactic nuclei
- Tidal disruptions of stars
- Gamma ray-bursts
- NS+BH mergers
- **Ultraluminous X-ray Sources**

(NASA)



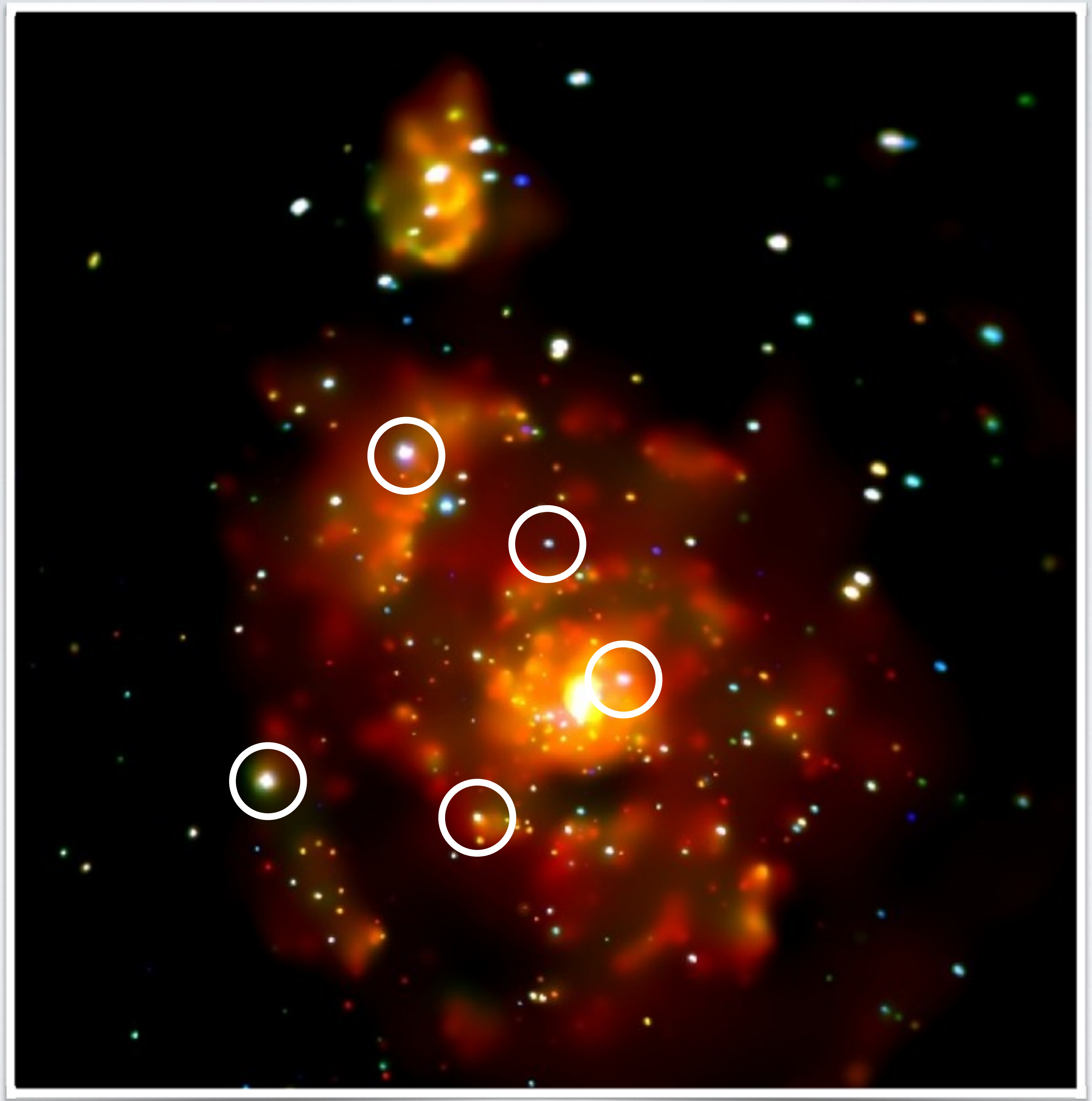
OPTICAL IMAGE OF M51 (+NGC 5195)

(c) KPNO

M51 IN X-RAYS

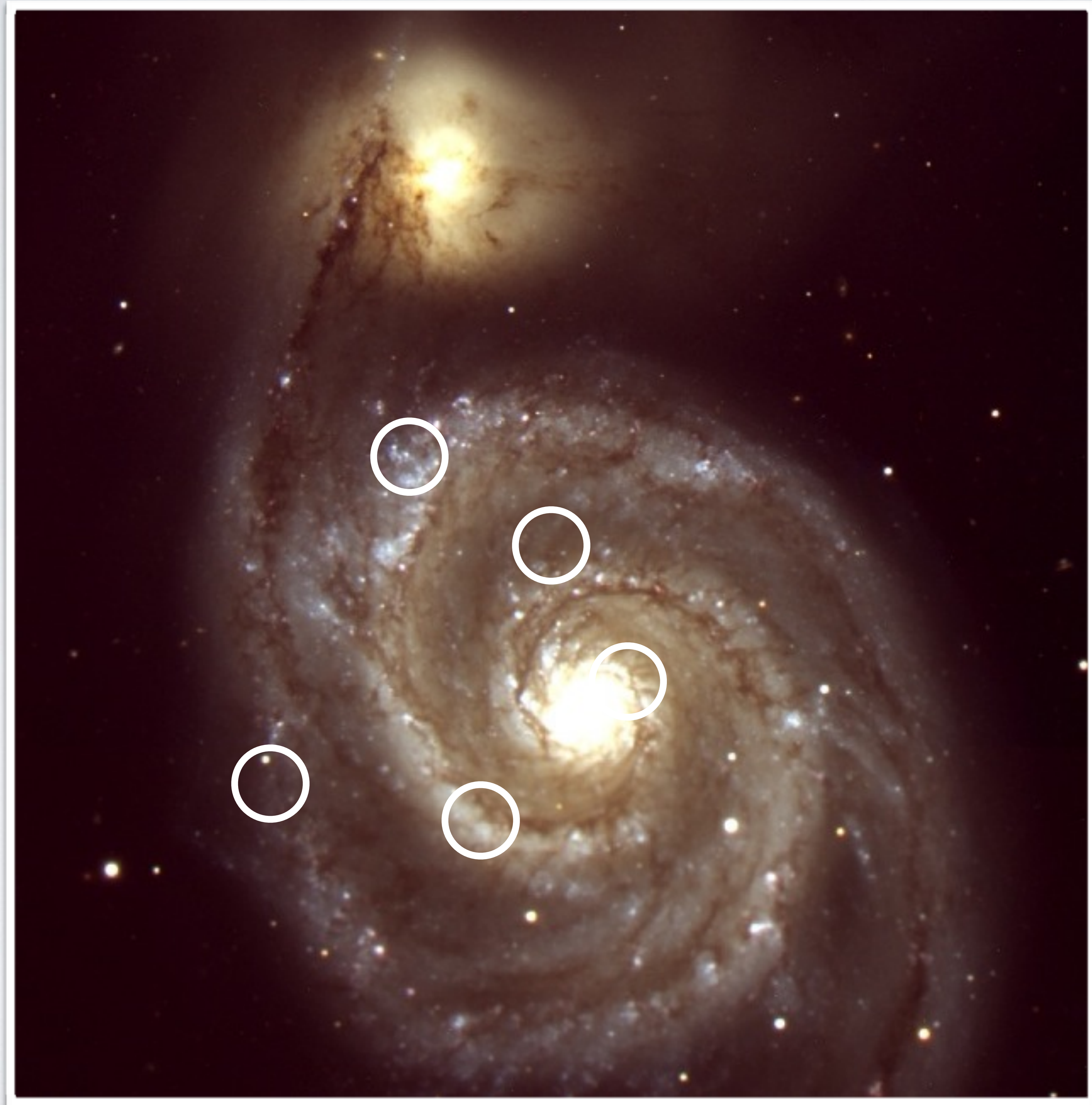
(c) Chandra

M51 IN X-RAYS



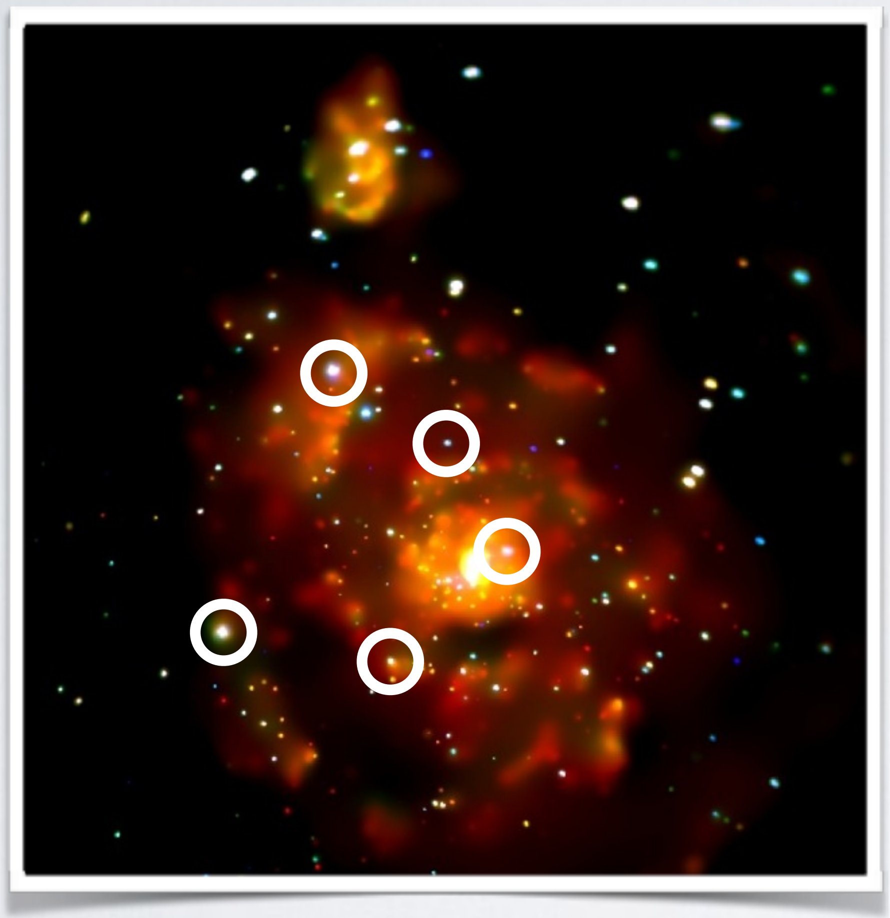
(c) Chandra

OPTICAL IMAGE OF M51 (+NGC 5195)



(c) KPNO

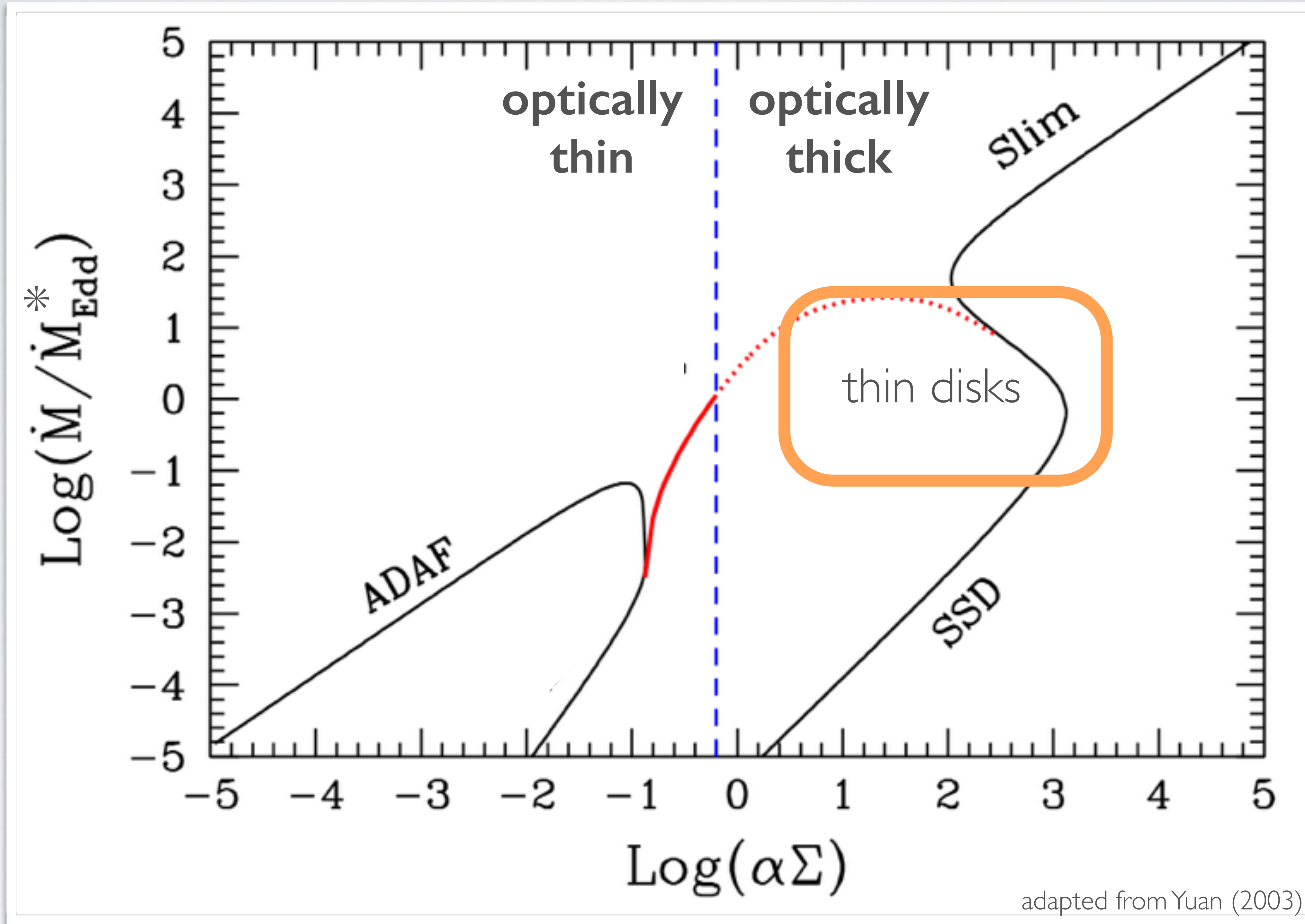
ULTRALUMINOUS X-RAY SOURCES



- Brighter than the Eddington luminosity for 10 Msun BH:
  $L > L_{\rm Edd}(10 M_\odot) \approx 10^{39} {\rm erg/s}$
- Non-nuclear
- Either sub-Eddington hosting intermediate mass BH or super-critical hosting BH or NS

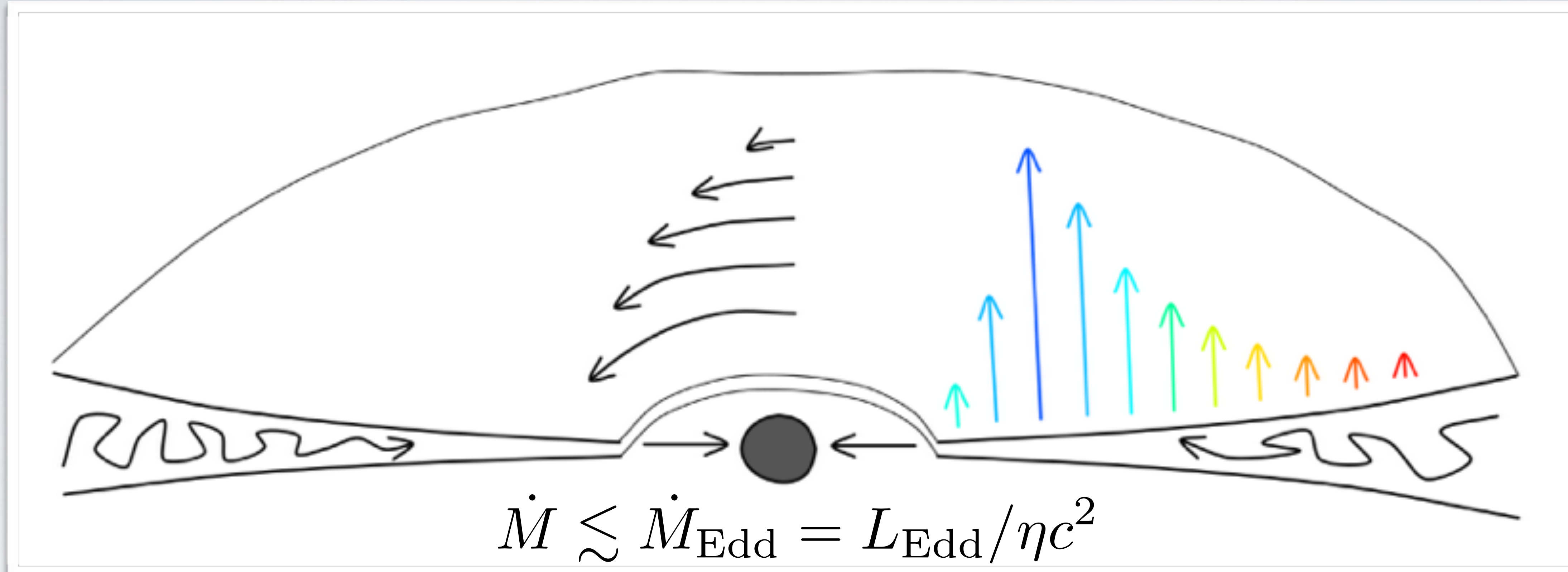
MODES OF ACCRETION

accretion rate



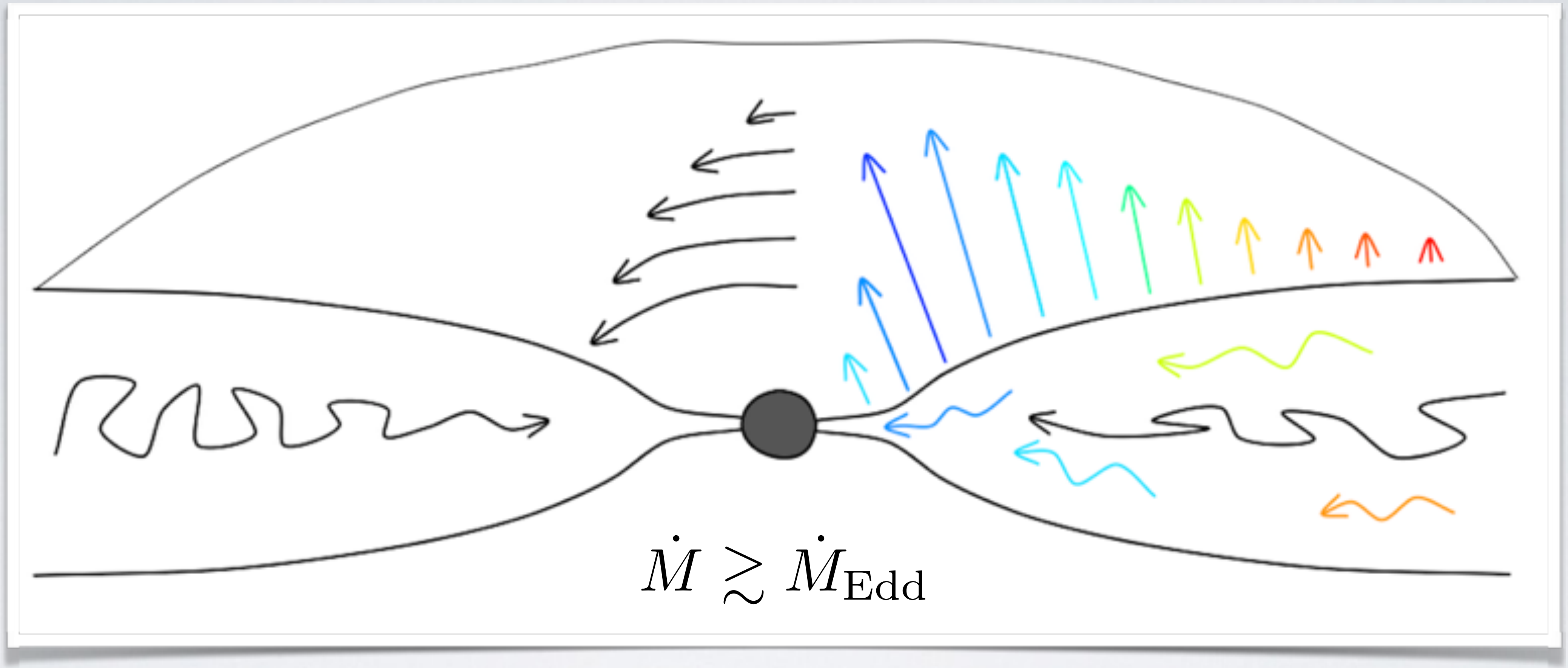
surface density (~optical depth)

THIN ACCRETION DISKS



- The standard model of a thin disk (Shakura & Sunyaev 73, Novikov & Thorne 73) provides an analytic solution of a **geometrically thin**, **optically thick**, **radiatively efficient disk**
- (Thermally unstable in the radiation pressure dominated regime)
- Radiative efficiency and emission profile uniquely determined
  - independent of viscosity

SUPER-EDDINGTON DISKS

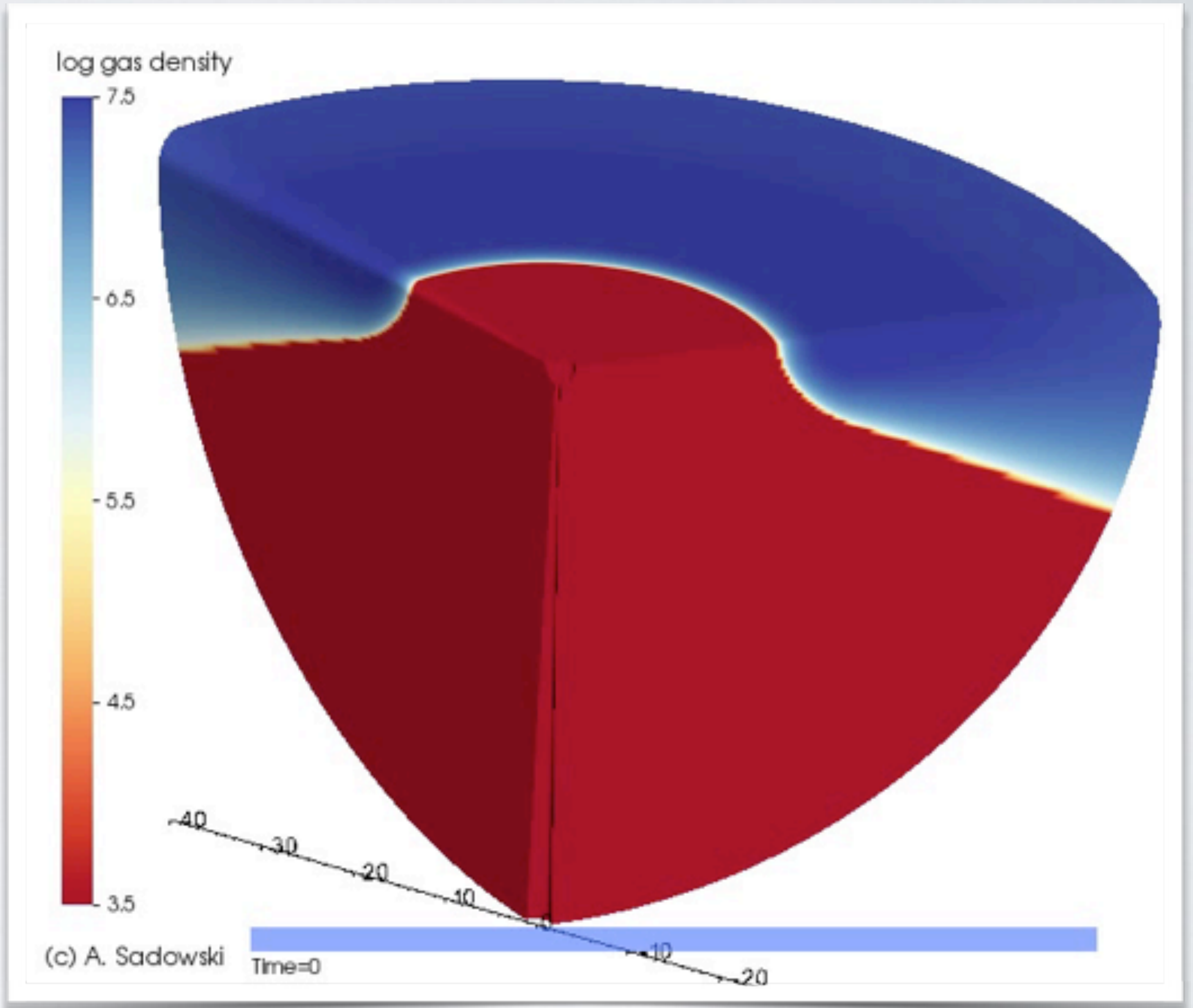


- Geometrically thick
- Non-trivial, two-dimensional (turbulent) radiative transport
- Large optical depths - photon trapping
- Radiatively driven outflows
- Sub-Keplerian
- → Require numerical solutions!

SIMULATING BH ACCRETION

Essential components:

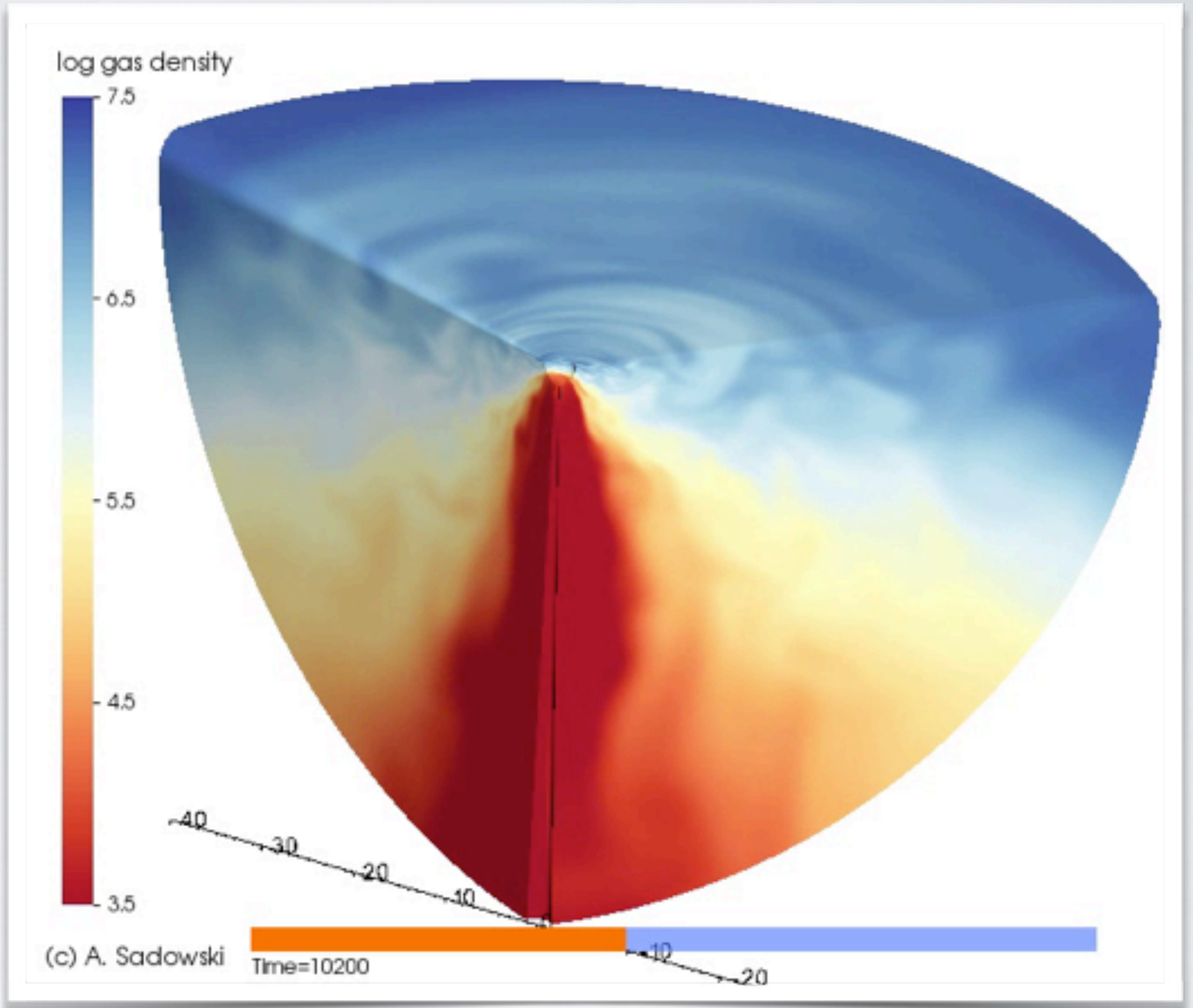
- stationary space-time: (GR, Kerr-Schild metric)
- magnetized gas: MHD (ideal)
- photons: radiation transfer (simplified)
- electrons: thermal & non-thermal
- radiative postprocessing: spectra, images
- multidimensional fluid dynamics solver



SIMULATING ACCRETION

KORAL
radiative MHD code
(Sadowski+13, …)

HEROIC
GR RTE solver
(Zhu+15, Narayan+15)



other groups performing
(GR) **radiative** MHD:

Ohsuga+
Jiang+, Fragile+, McKinney+, Gammie+, …

KORAL

- GR ideal MHD + div B=0
- Radiation evolved simultaneously providing cooling and pressure
- Radiative transfer under M1 approximation
- Conservation of number of photons (allows for tracking the radiation temperature)
- Comptonization
- Independent evolution of thermal electrons and ions providing self-consistent temperatures
- Synchrotron and bremmstrahlung Planck and Rosseland opacities dependent on both gas and radiation temperature
- Coulomb coupling
- Self-consistent (depending on electron and ion temperatures) adiabatic index

$$\begin{aligned}(\rho u^\mu)_{;\mu} &= 0\\ (T^\mu_\nu)_{;\mu} &= G_\nu,\\ (R^\mu_\nu)_{;\mu} &= -G_\nu.\\ (nu^\mu)_{;\mu} &= \dot{n}.\end{aligned}$$

$$F^{*\mu\nu}_{;\nu} = 0$$

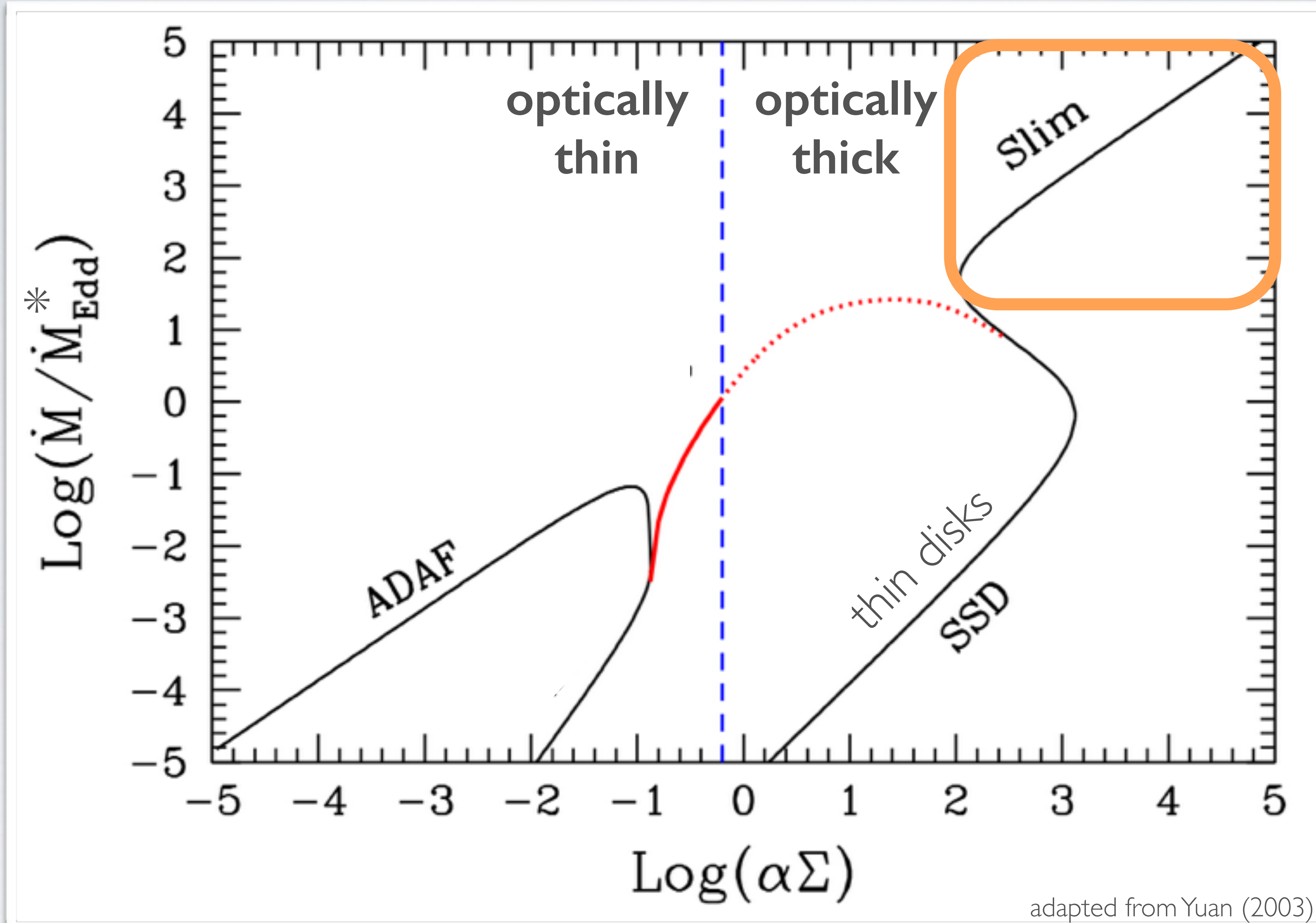
$$\begin{aligned}T_\mathrm{e}(n_\mathrm{e} s_\mathrm{e} u^\mu)_{;\mu} &= \delta_\mathrm{e} q^\mathrm{v} + q^\mathrm{C} + G_t\\ T_\mathrm{i}(n_\mathrm{i} s_\mathrm{i} u^\mu)_{;\mu} &= (1-\delta_\mathrm{e}) q^\mathrm{v} - q^\mathrm{C},\end{aligned}$$

$$\delta_\mathrm{e} = \frac{1}{1 + f(T_e, T_i, \beta)}$$

Sufficient set to study accretion flows at any accretion rate, including the intermediate regime

MODES OF ACCRETION

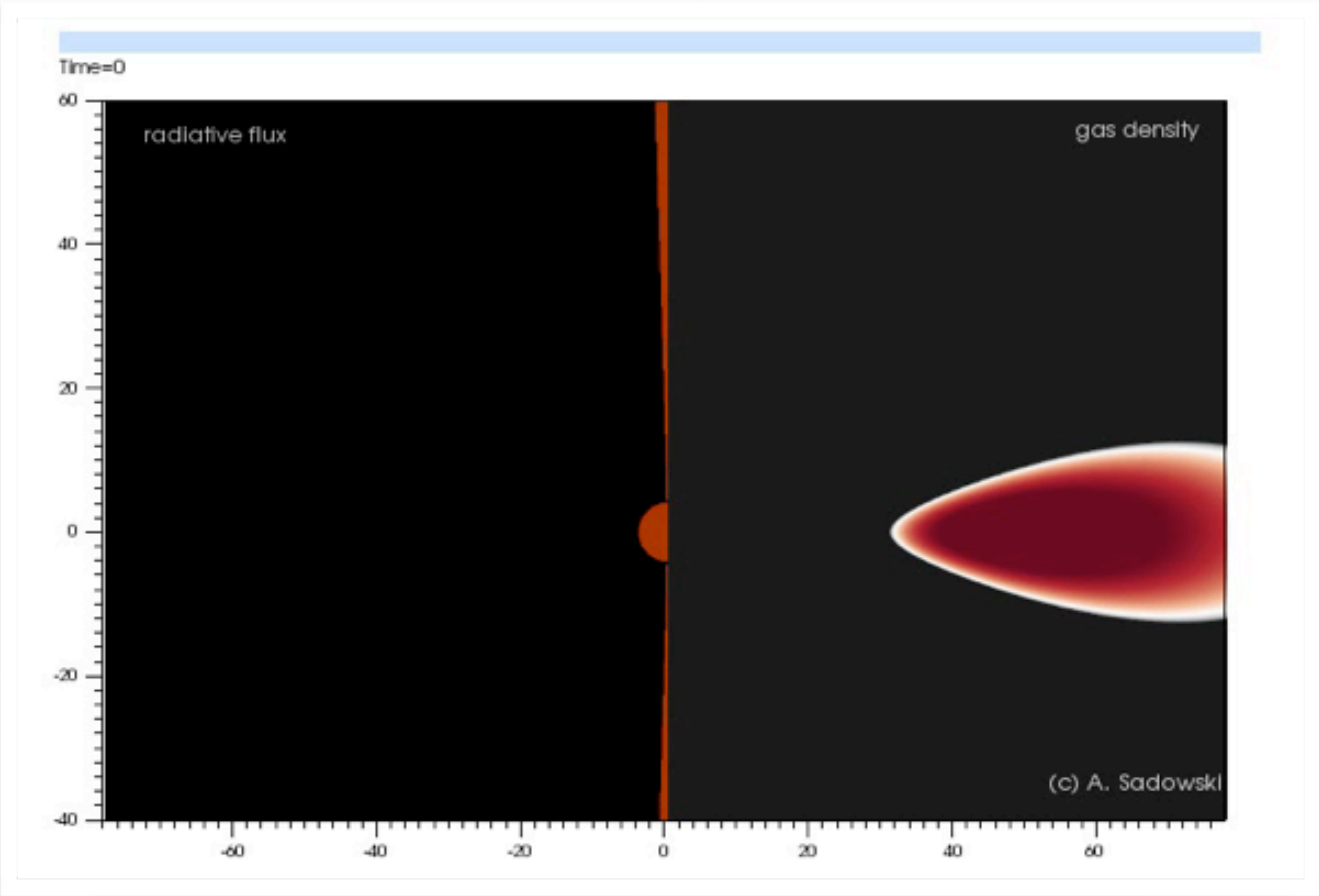
accretion rate



surface density
(~optical depth)

HIGHLIGHTS OF SUPER-CRITICAL ACCRETION

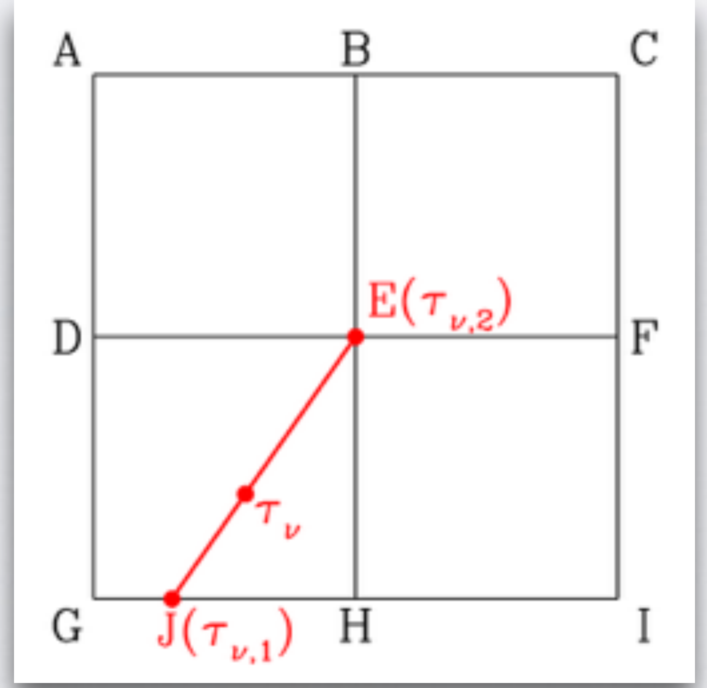
- super-Eddington accretion feasible
- geometrically and optically thick
- photosphere far from the equatorial plane
- radiatively driven outflows
- significant photon trapping (affecting both radial and vertical radiation transport)
- moderate beaming
- observables strongly inclination dependent!

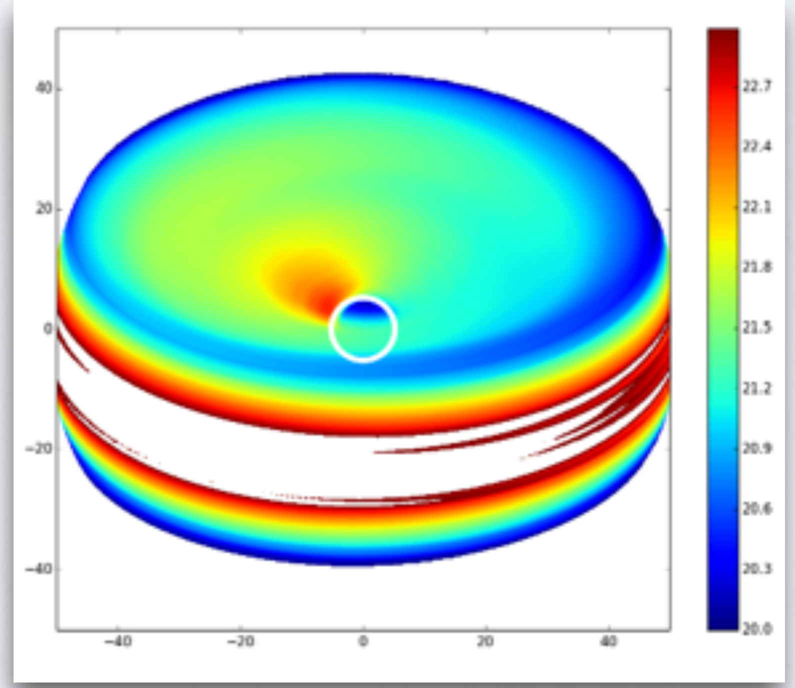


HEROIC

3D GR RADIATIVE POSTPROCESSOR WITH COMPTONIZATION

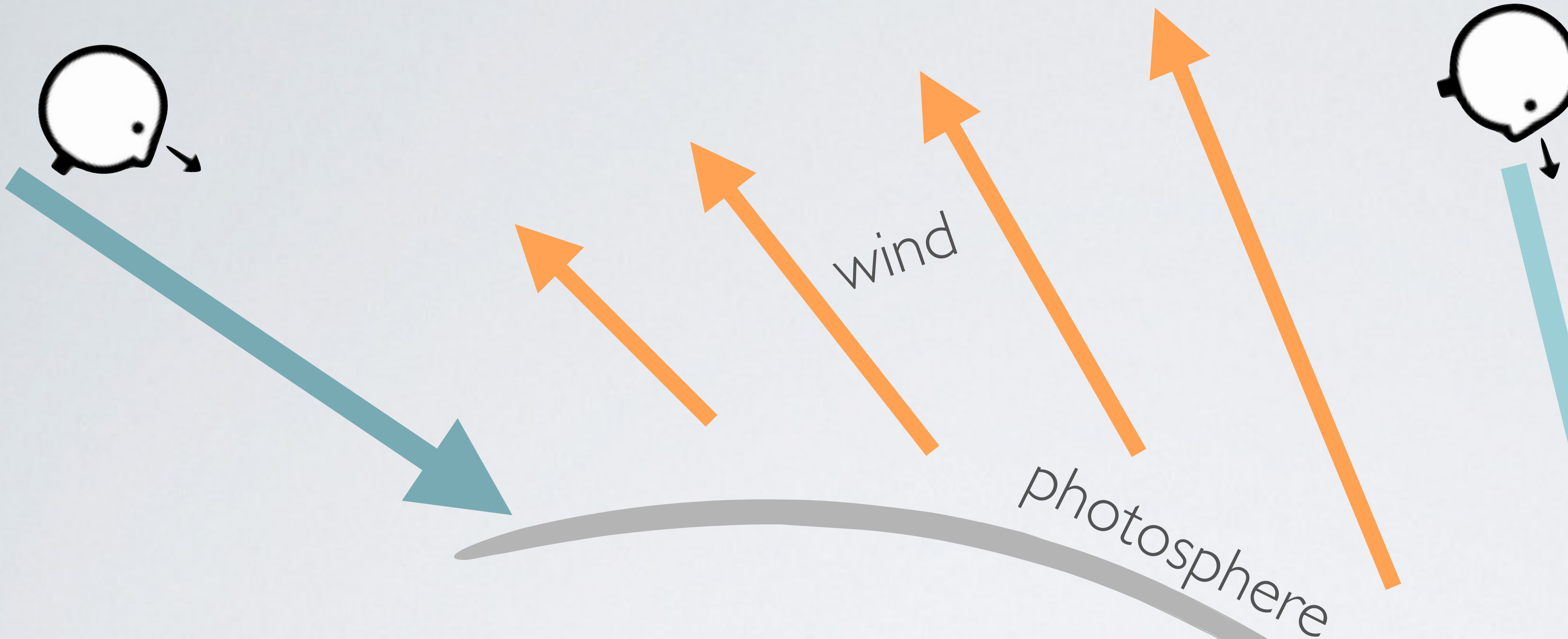
- **General relativistic, grid base** radiation transfer equation solver
- **Frequency resolved** radiation
- Short- and long-characteristics
- **Comptonization** via Kompaneets equation
- Takes density, velocities and **heating rate** as input
- Works efficiently for **any optical depth**





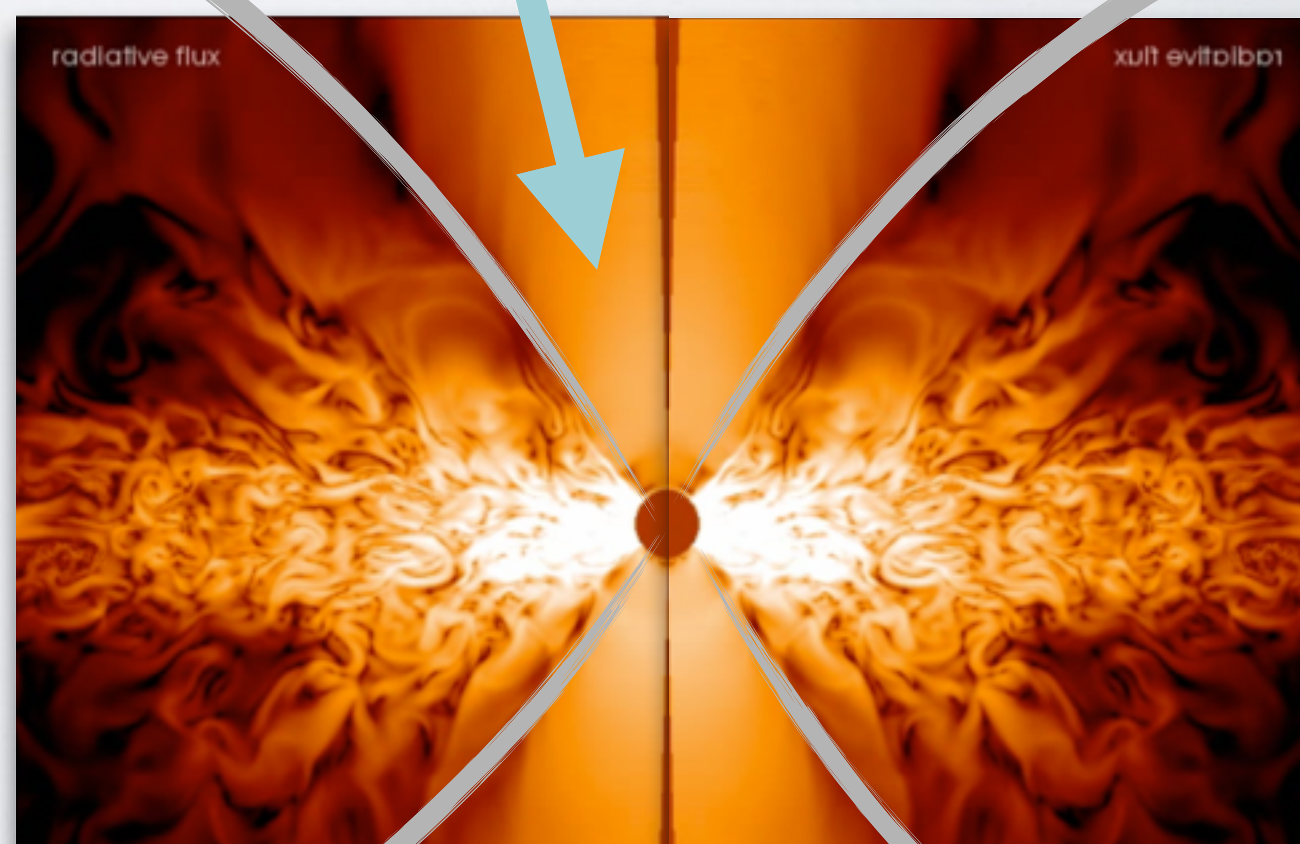
(Narayan+15)

SUPER-CRITICAL ACCRETION



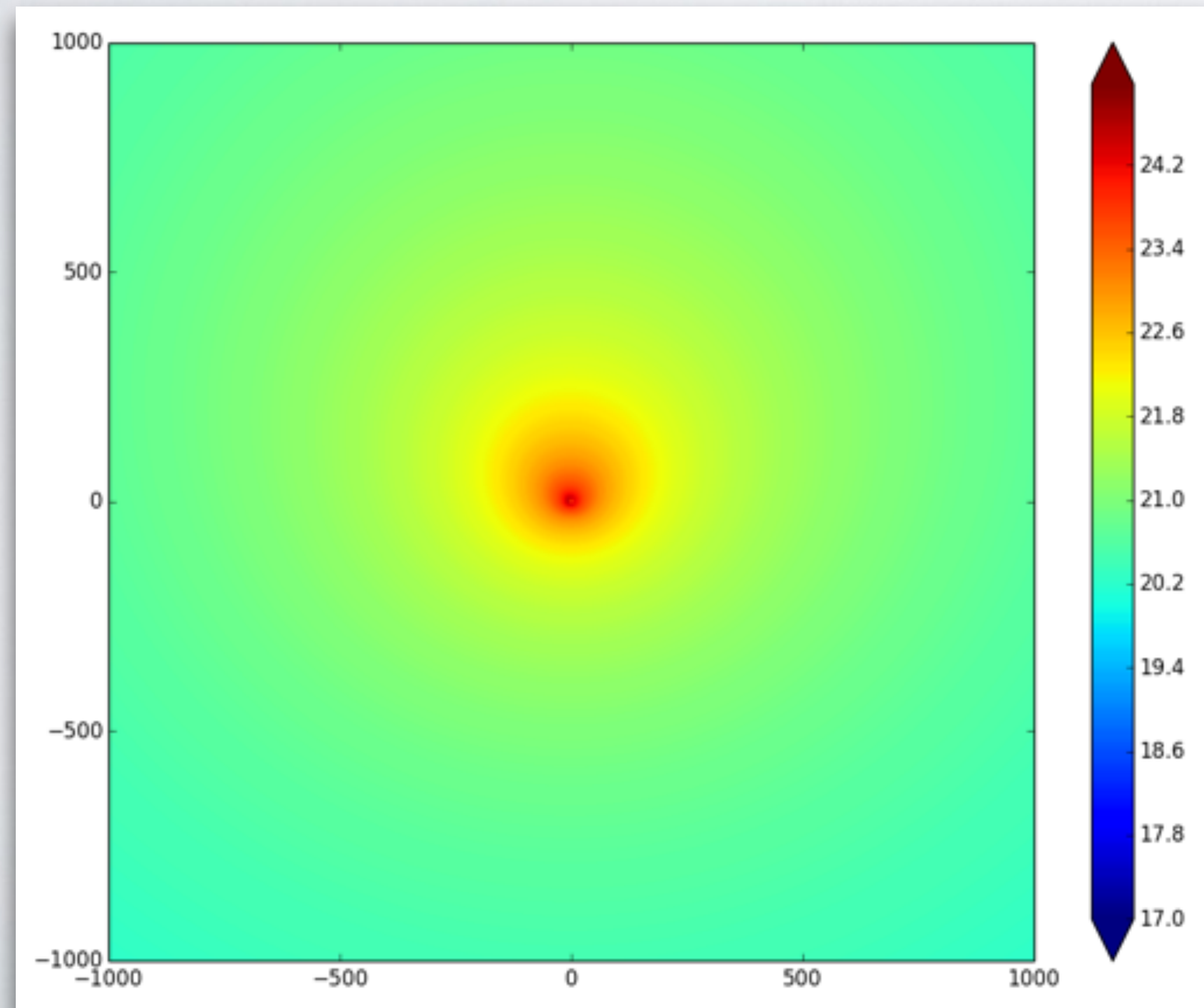
- high-inclination
- moderate beaming
  - super-Eddington
- hard spectrum
- **ULXs?**

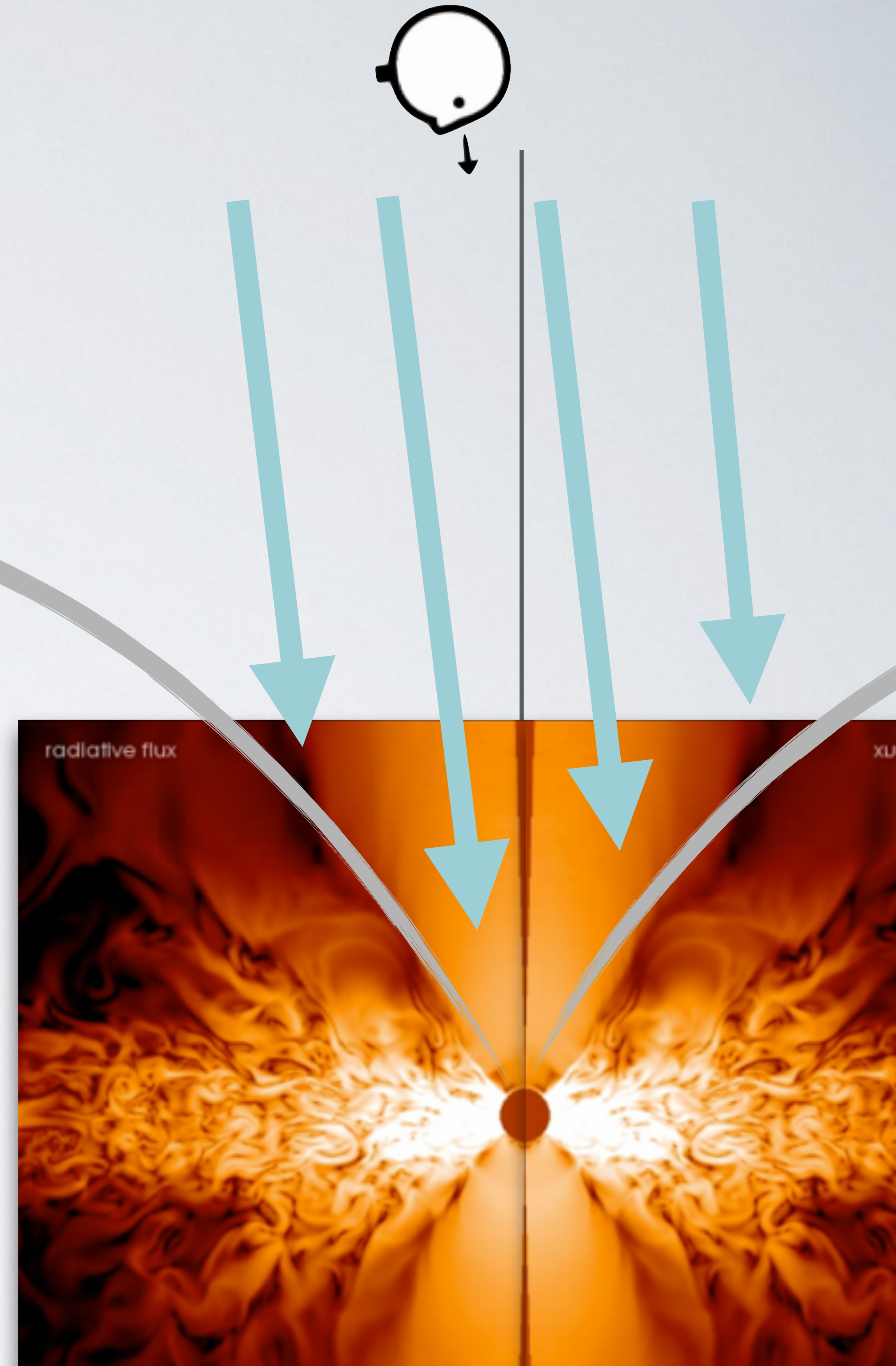
- low-inclination
- ~Eddington
- soft spectrum
- **ULSs?**
  (ultraluminous supersoft)



10 DEG

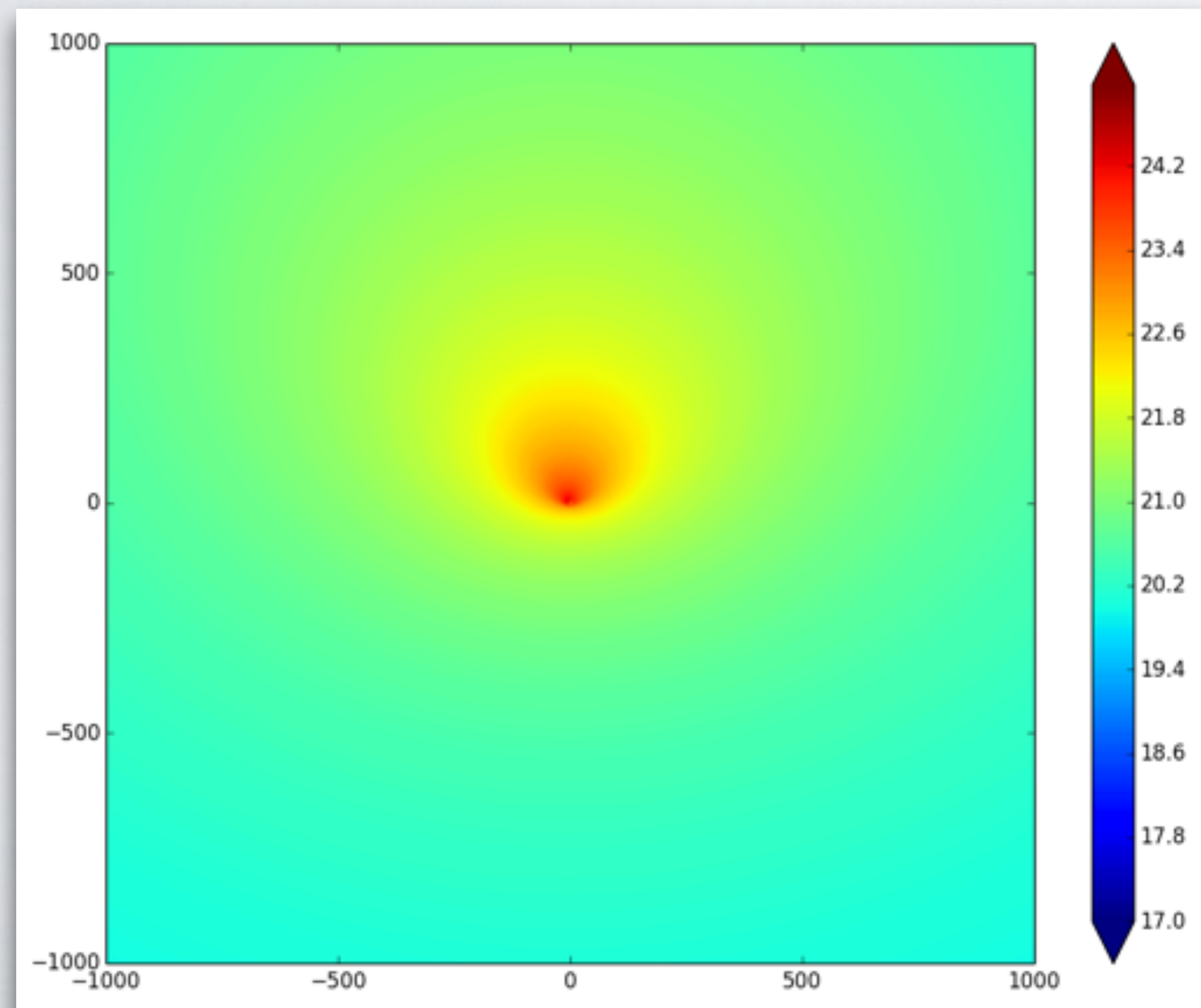
(bolometric flux)

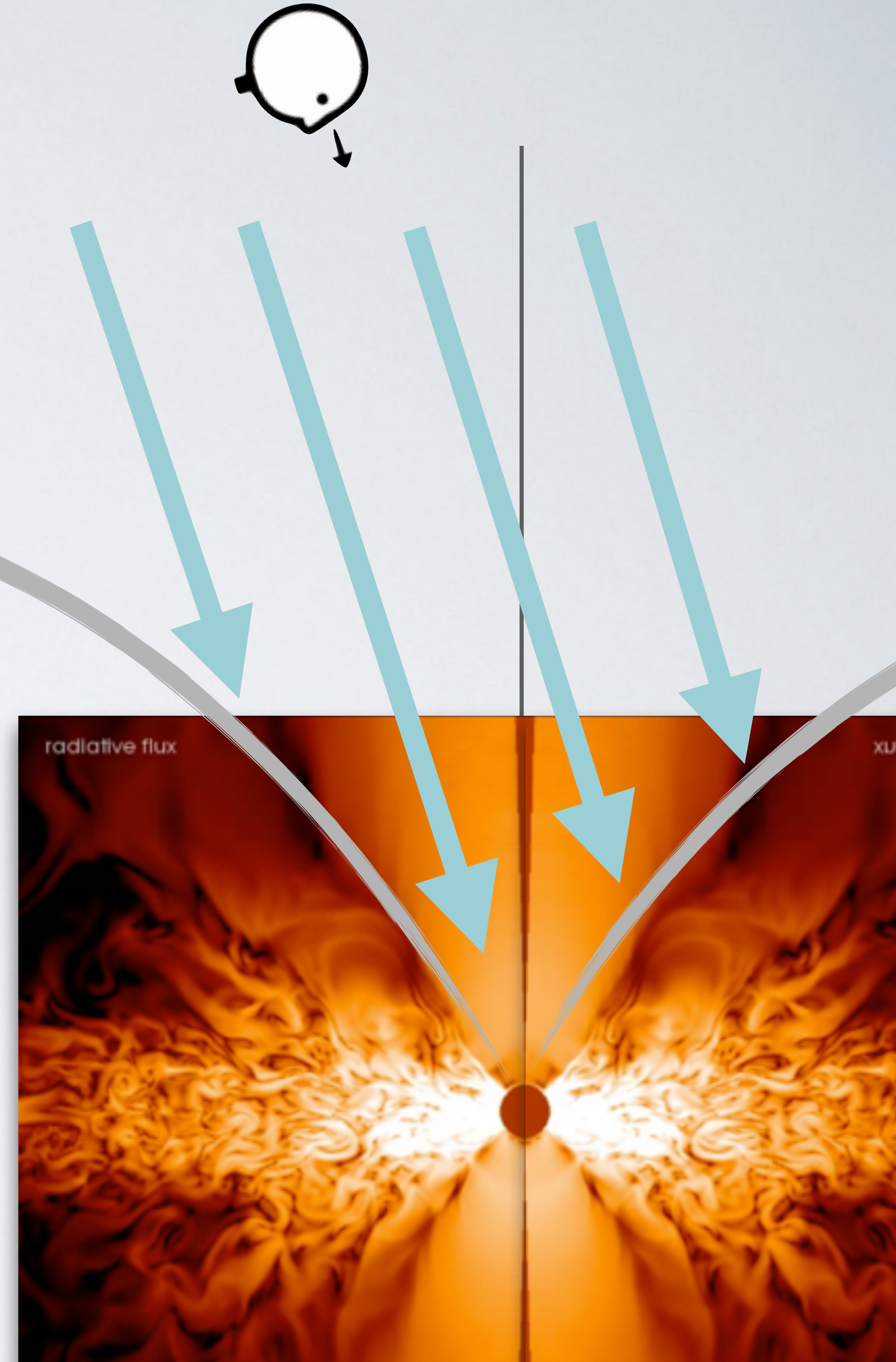




20 DEG

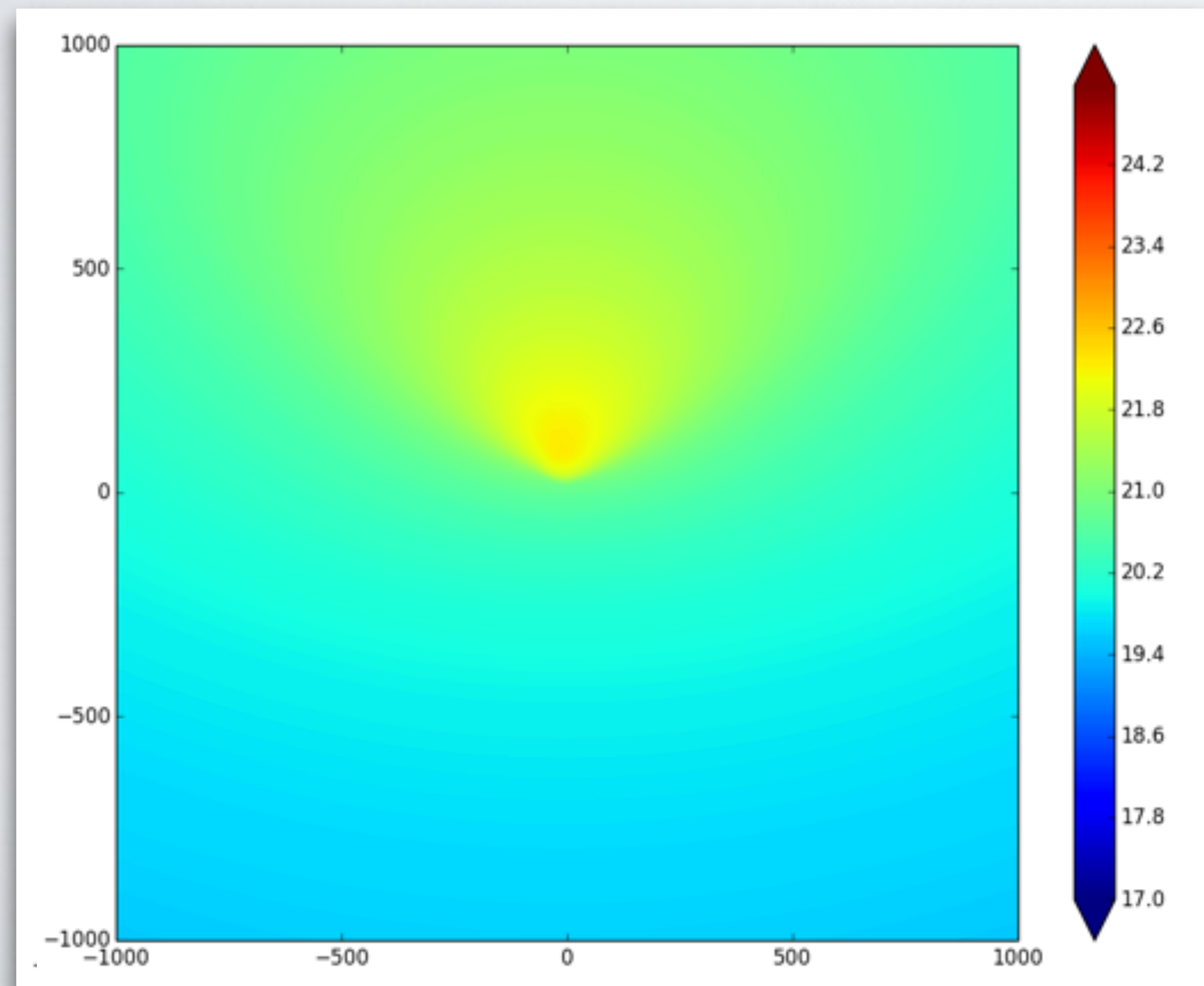
(bolometric flux)

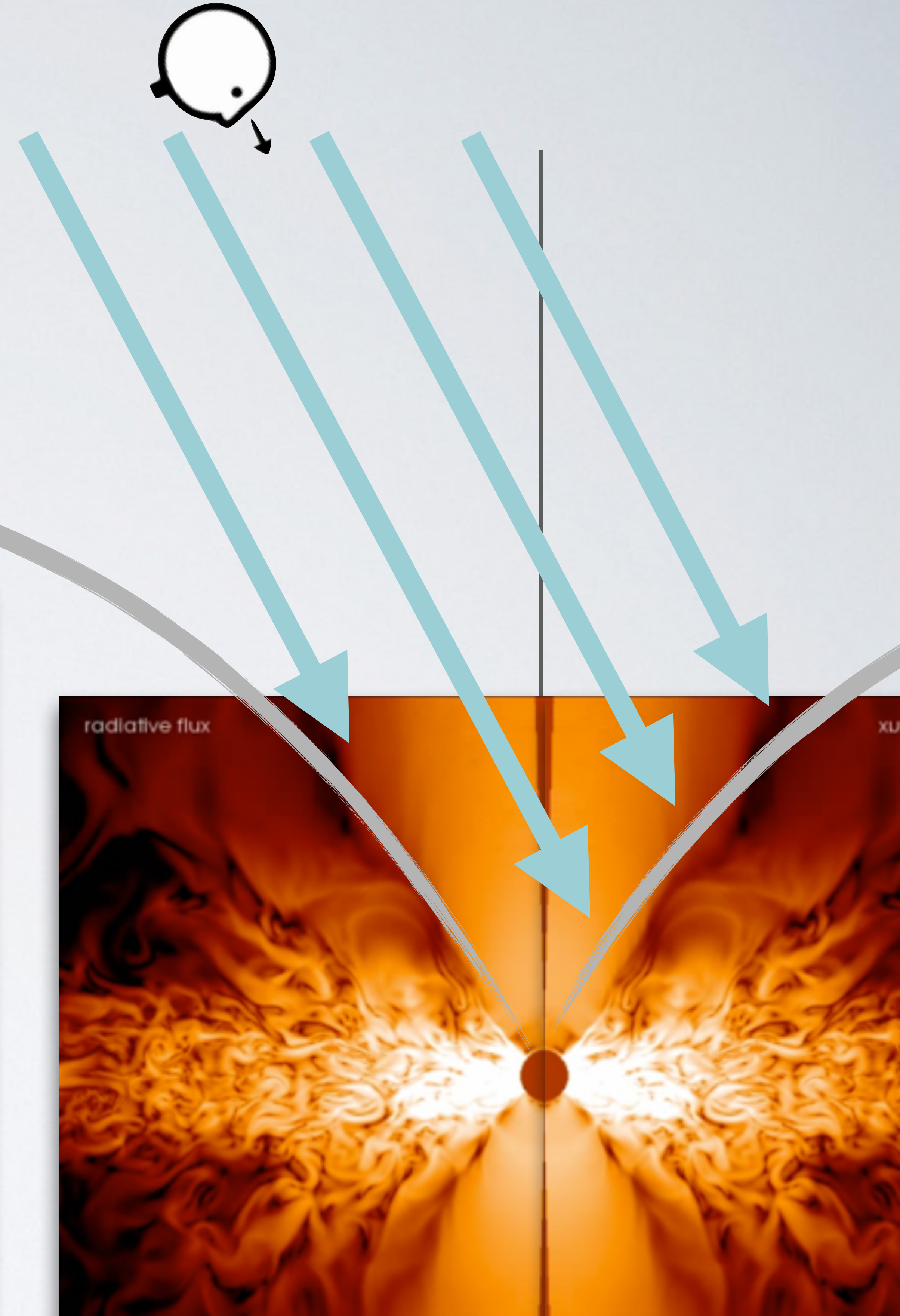




30 DEG

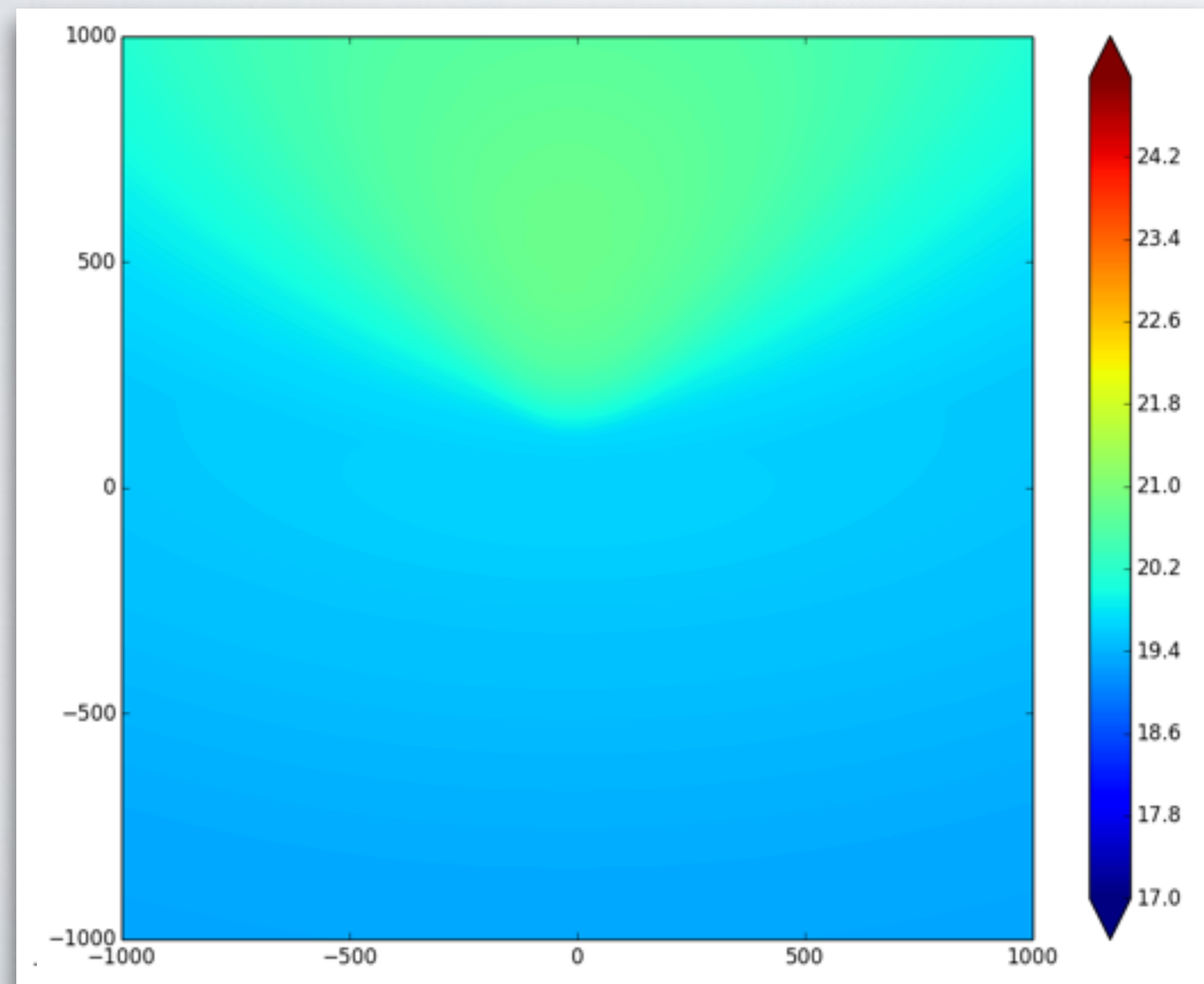
(bolometric flux)

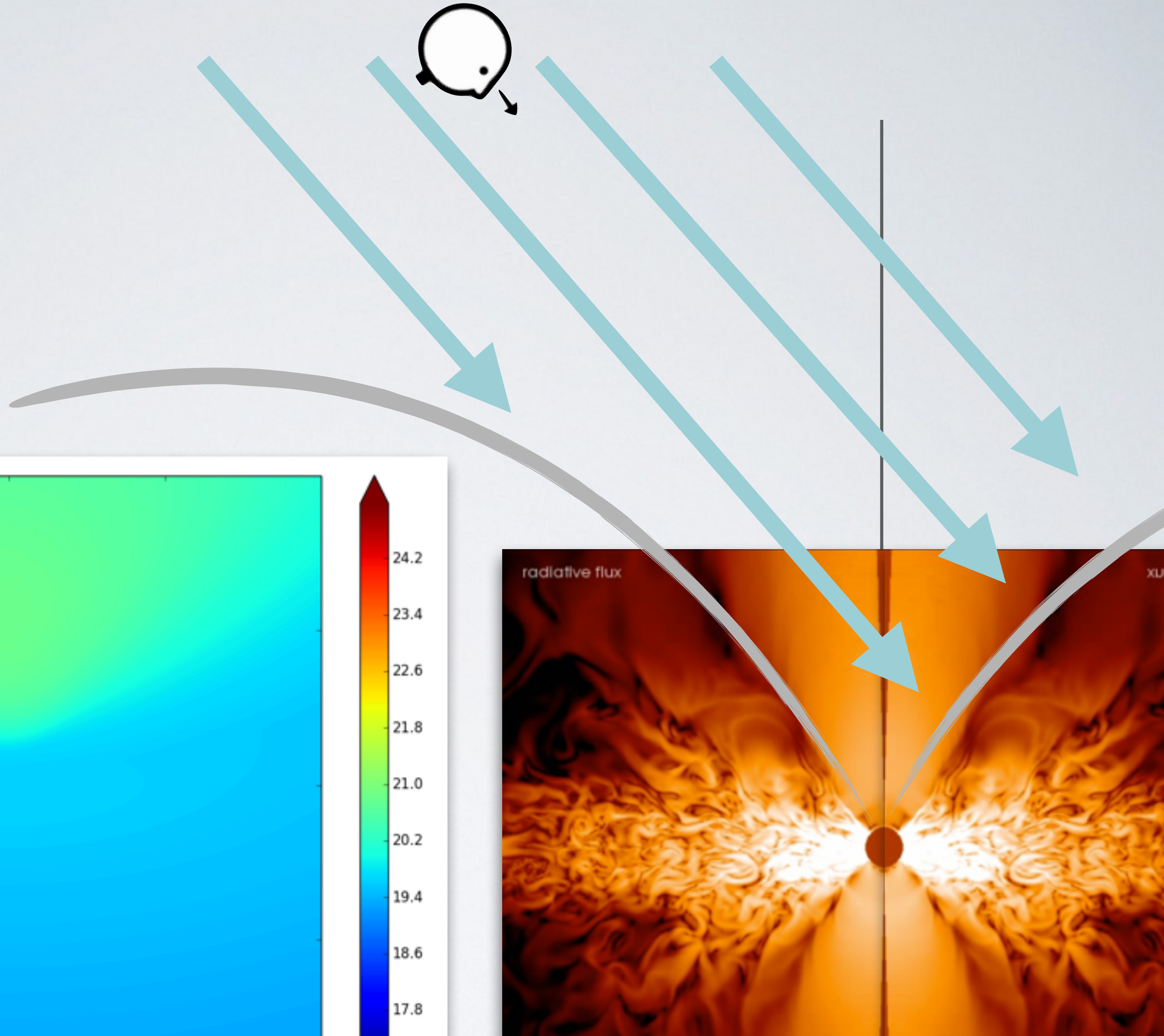




40 DEG

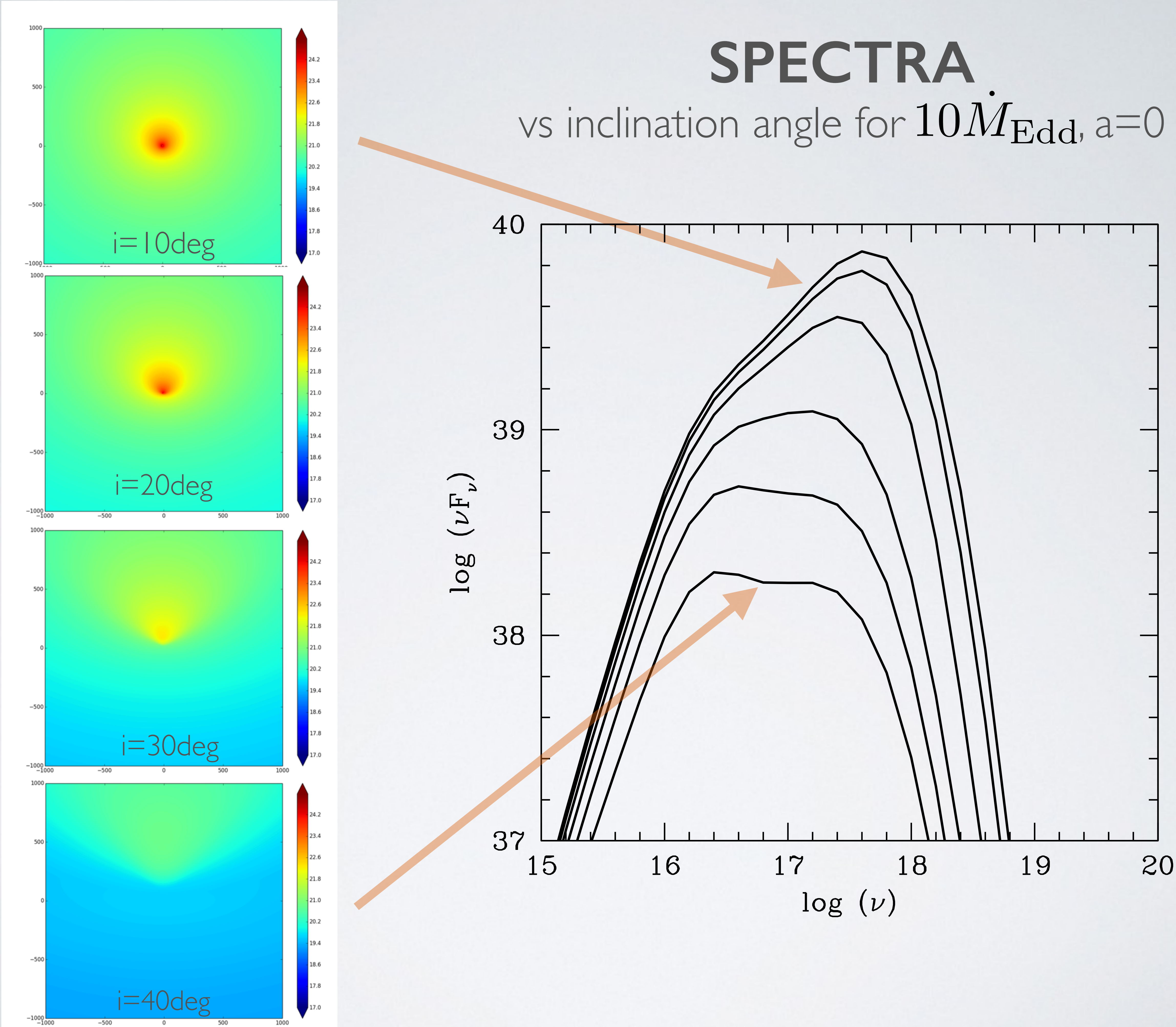
(bolometric flux)



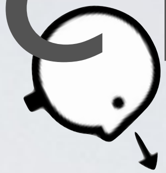


SPECTRA

vs inclination angle for $10\dot{M}_{\rm Edd}$, a=0



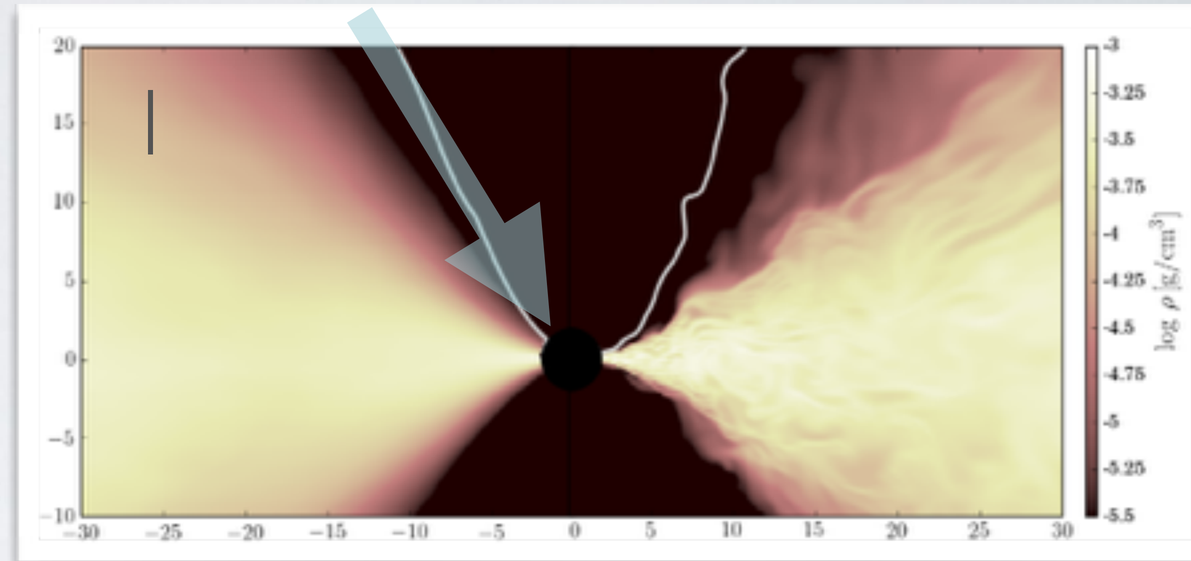
RADIATIVE & KINETIC EFFICIENCY

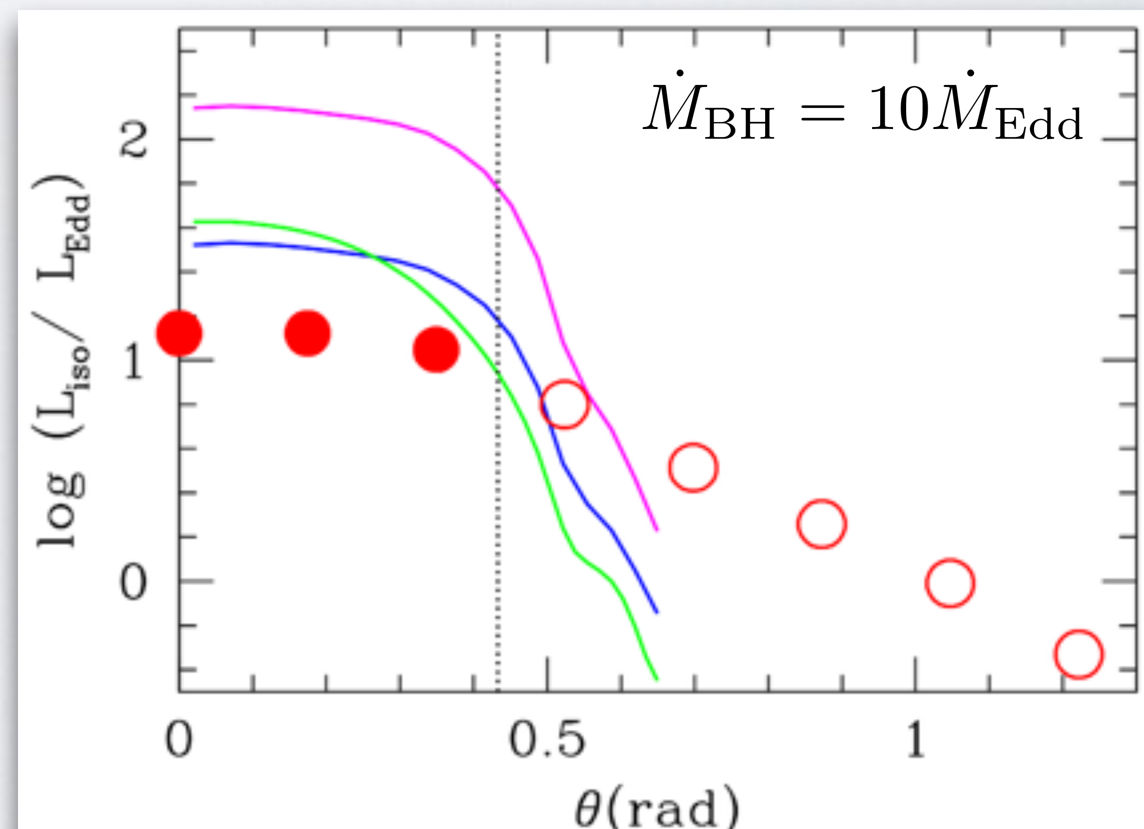


- Anisotropic radiation field

- Up to ~10 times Eddington apparent flux for near-axis observers and 10 times Eddington accretion rate
- But only ~Eddington apparent luminosity at larger inclinations
- Low total radiative efficiency!

- But the total energy extracted efficiently (total efficiency $\sim 3\% \dot{M} c^2$)
- The excess must go into the kinetic component (outflows)
- The higher the accretion rate, the higher the fraction of energy output going into kinetic energy of the outflow!

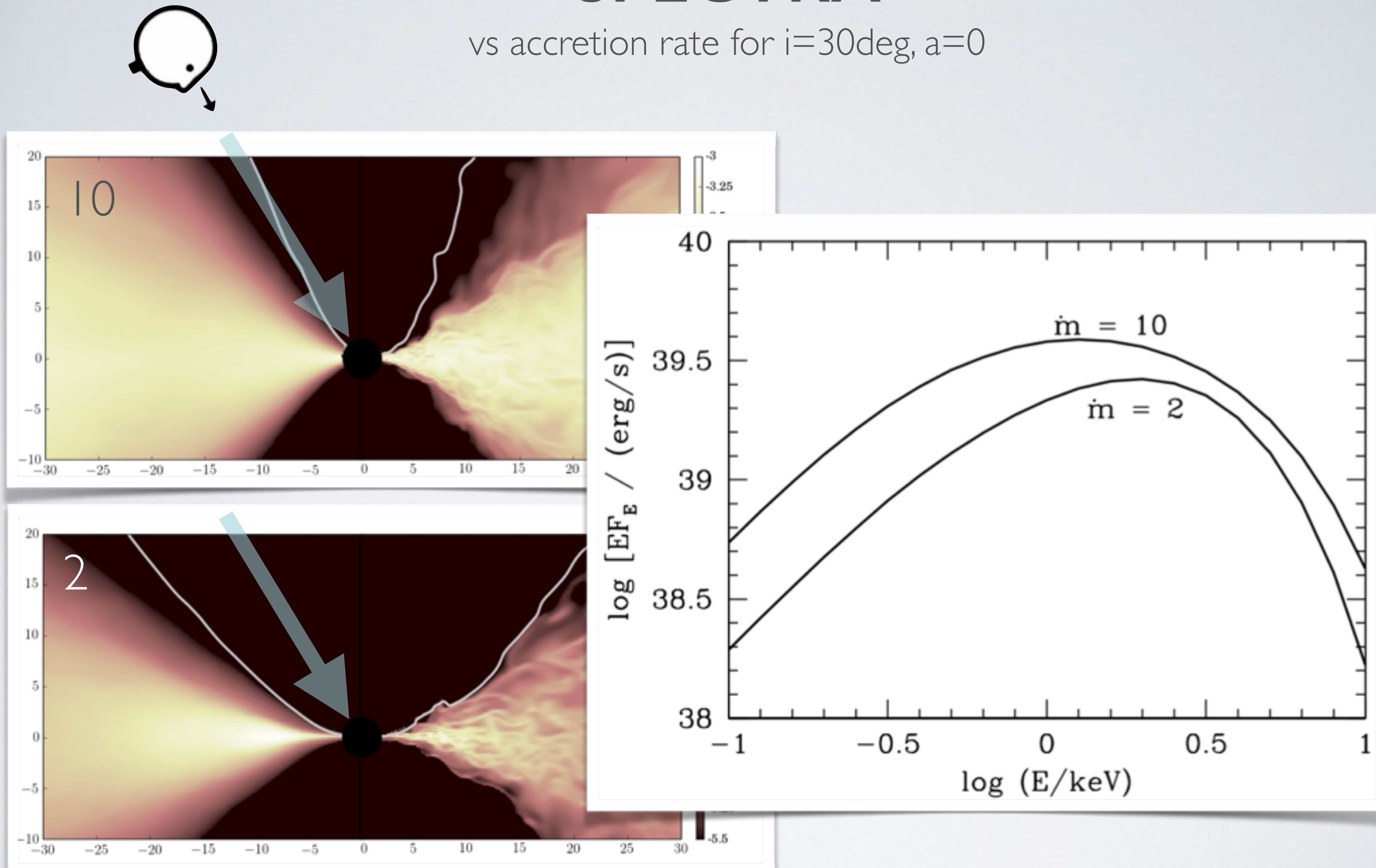




(Narayan+15)

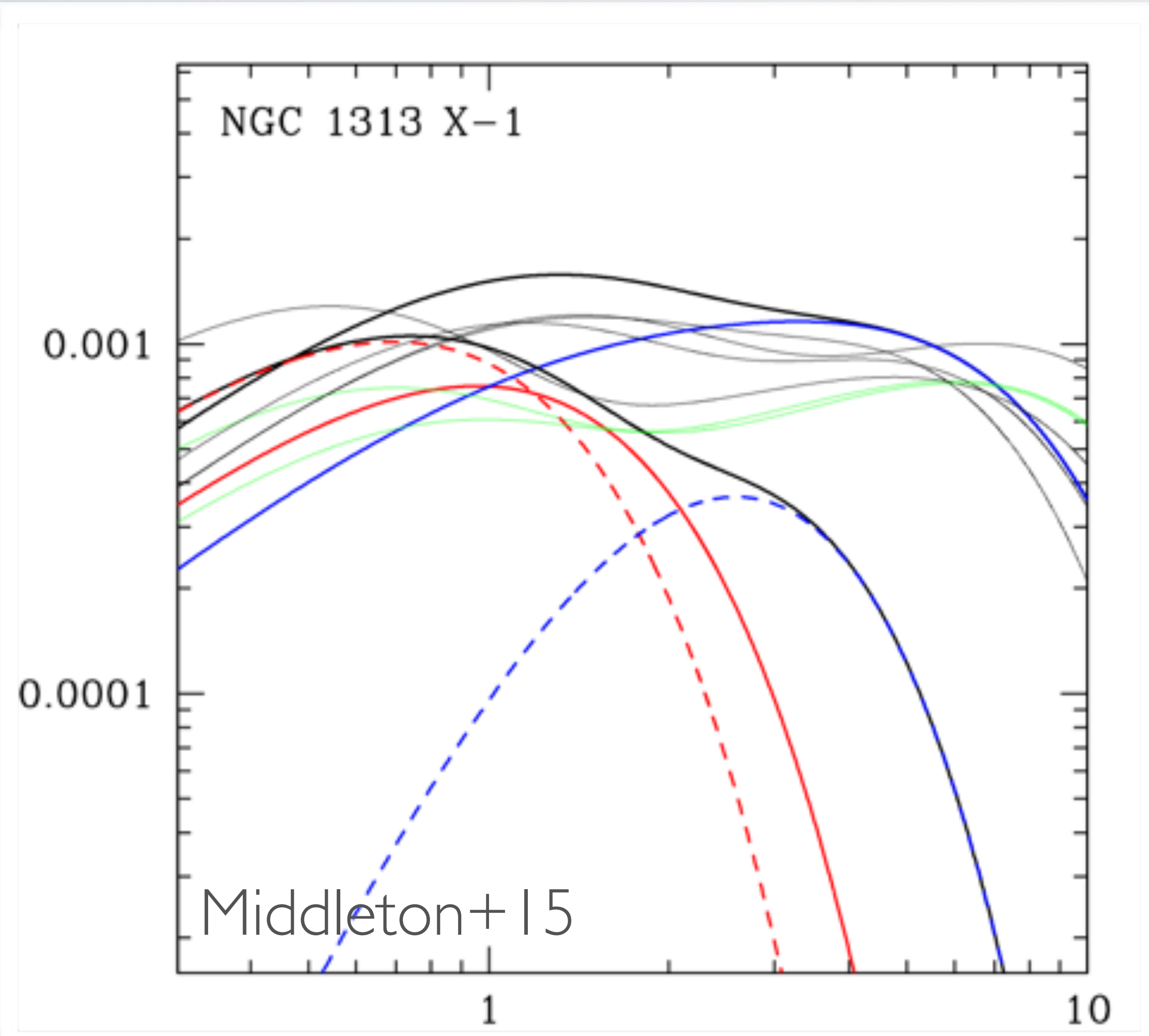
SPECTRA

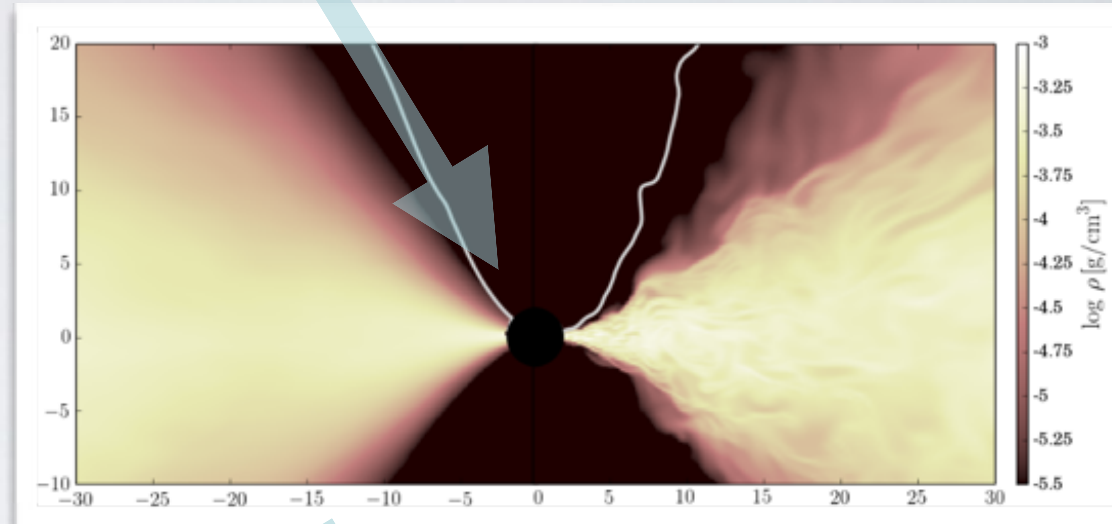
vs accretion rate for i=30deg, a=0

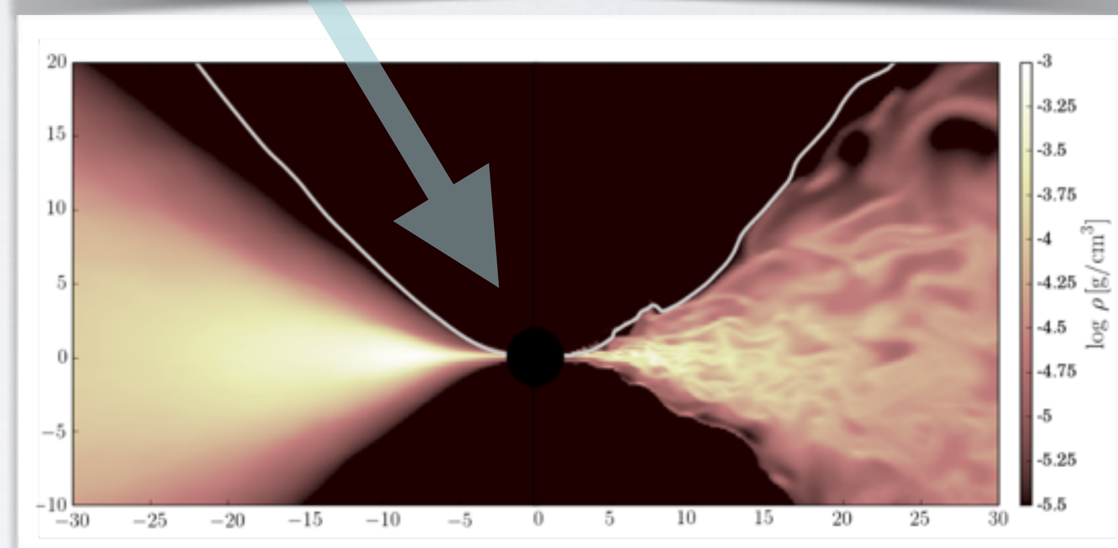


Spectrum is getting **softer** with Mdot because of increasing photosphere height

NGC 1313 X-1

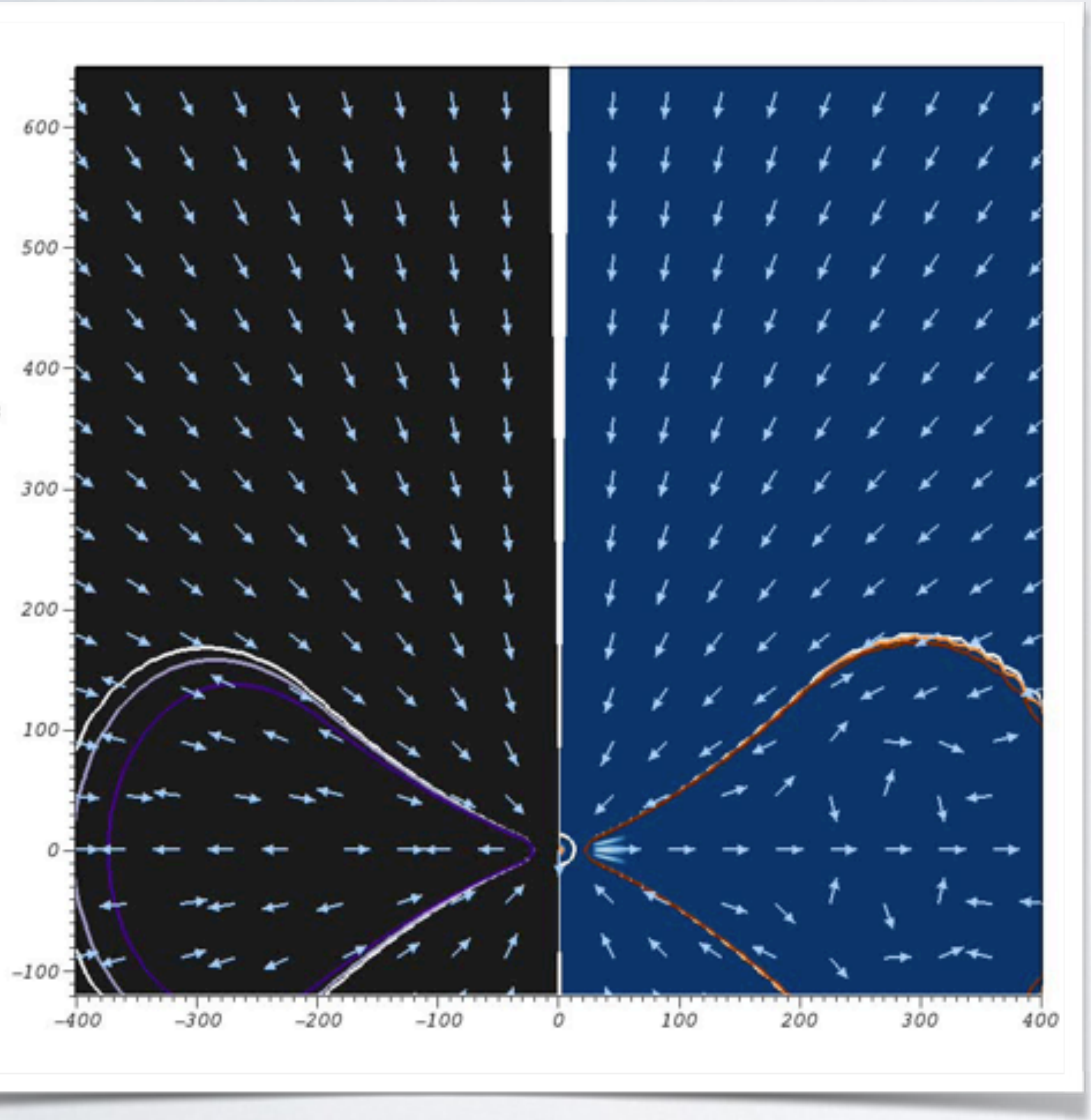






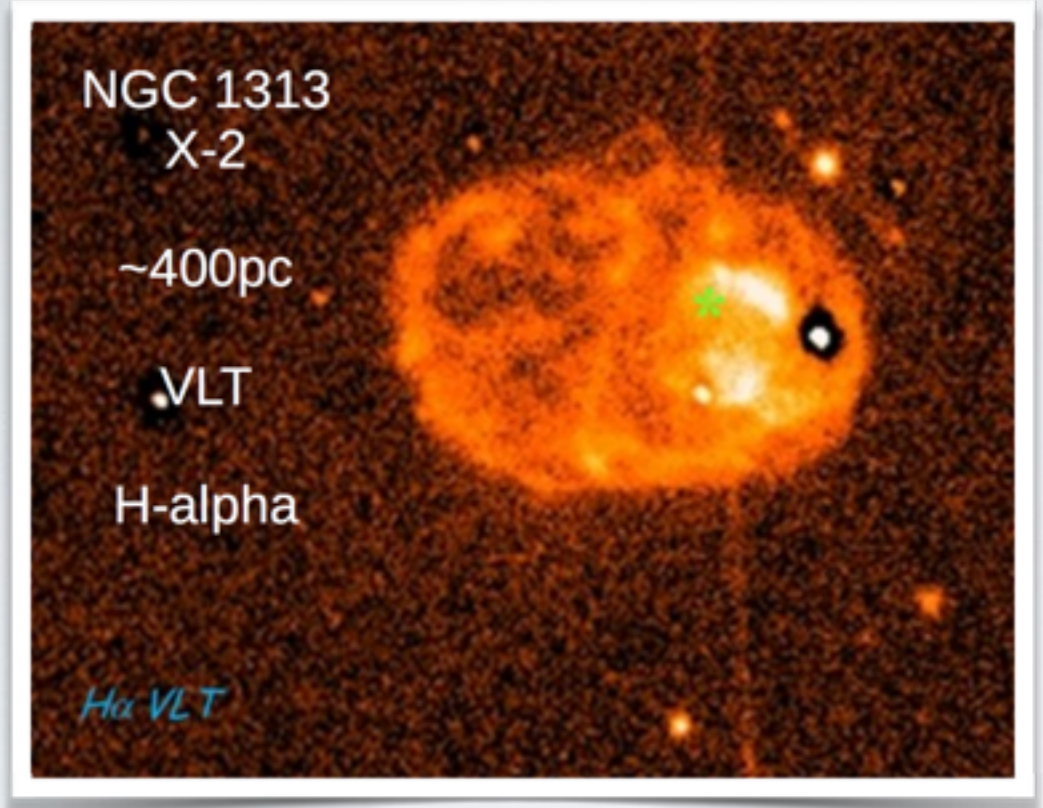
- Two distinct spectral states : softer/harder
- Funnel opening angle (photosphere height) varies with accretion rate - strongly modifies obscuration for a given observer

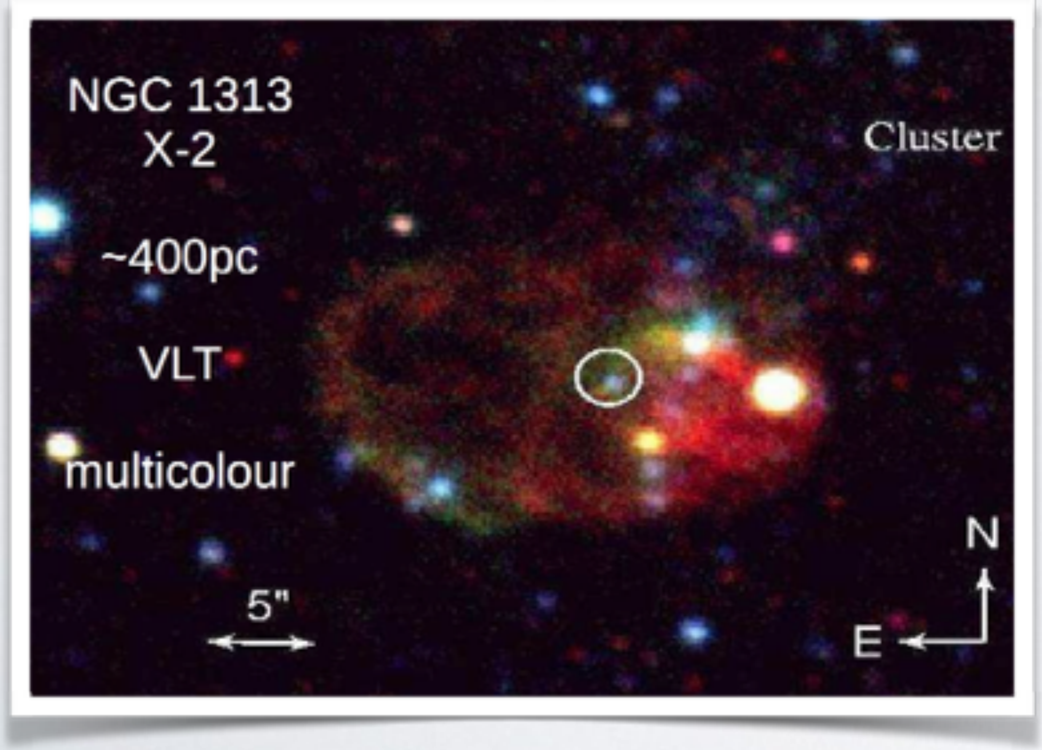
SUPER-EDDINGTON ACCRETION



- Super-critical accretion disks are geometrically and optically thick
- Total radiative efficiency drops down with increasing transfer rate
- Kinetic output balances the missing radiation
- Radiation field anisotropic - along axis observers see super-Eddington fluxes when observers at large inclinations - just Eddington
- Increasing transfer rate and the photosphere height may lead to obscuration and softer emission
- However, simulations limited to the innermost region (R<100Rg)

MOVING TO LARGER SCALES - ULX BUBBLES





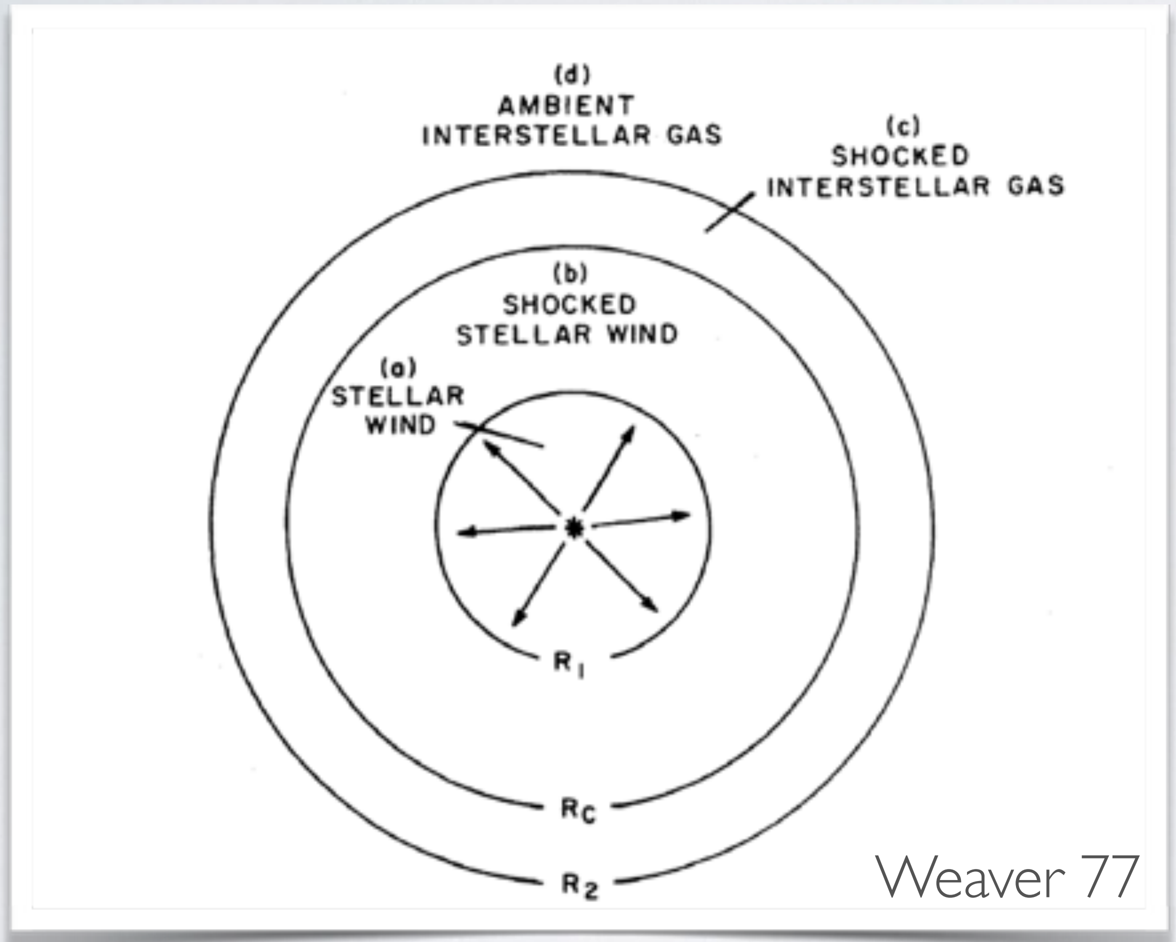
- Up to 25% ULX show ISM bubbles
- Shock-ionized nebulae
- Expansion velocity ~100 km/s
- Radius ~ 100-200pc
- Lifetime ~ 1Myrs
- Often together with jet-related hot spots

- Most likely inflated by long-lasting kinetic outflow from ULX with luminosity ~1e39 - 1e40 erg/s

EVOLUTION OF ULX BUBBLES

Project led by Magdalena Menz, Univ. of Glasgow

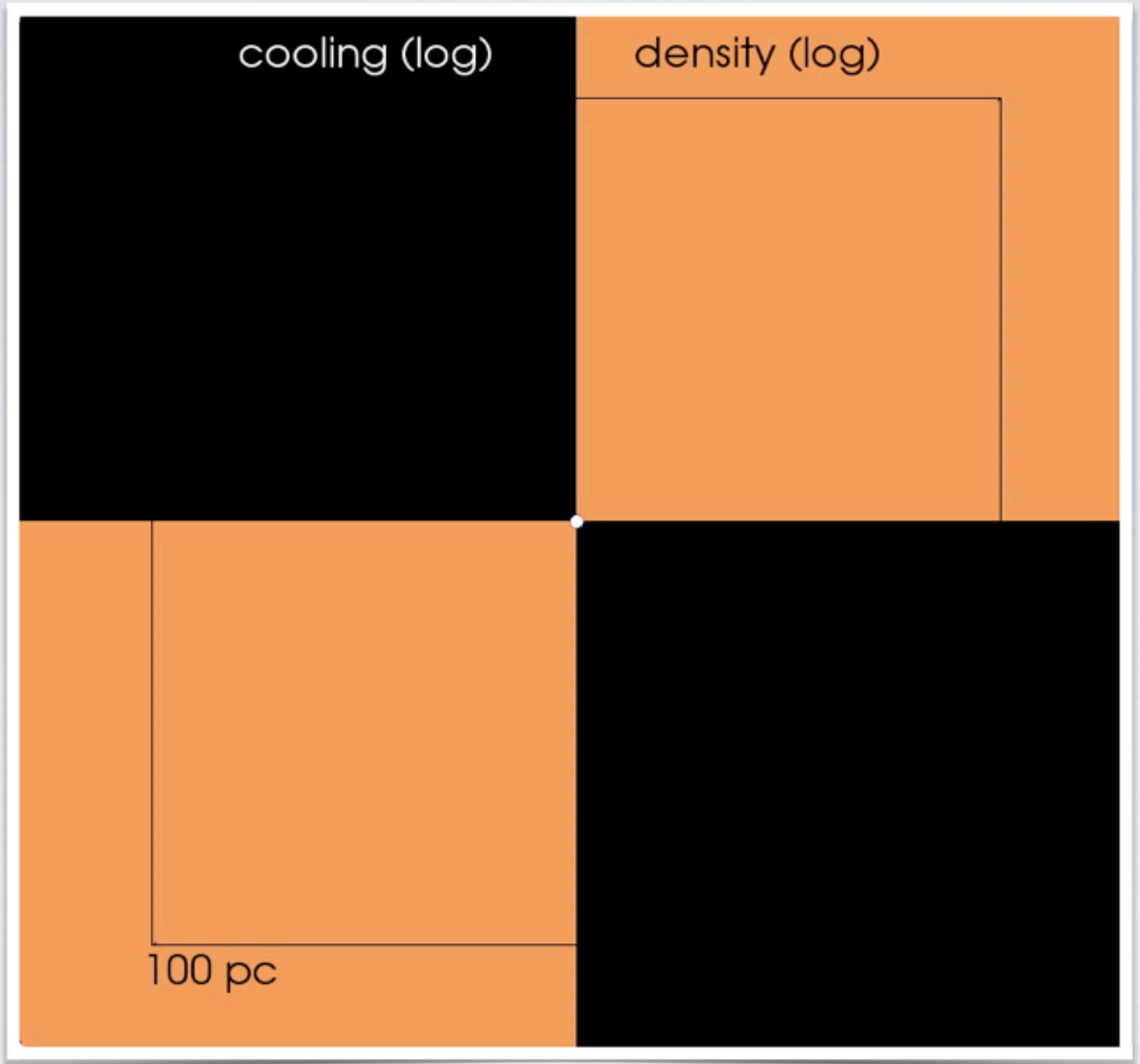
EVOLUTION OF ULX BUBBLES



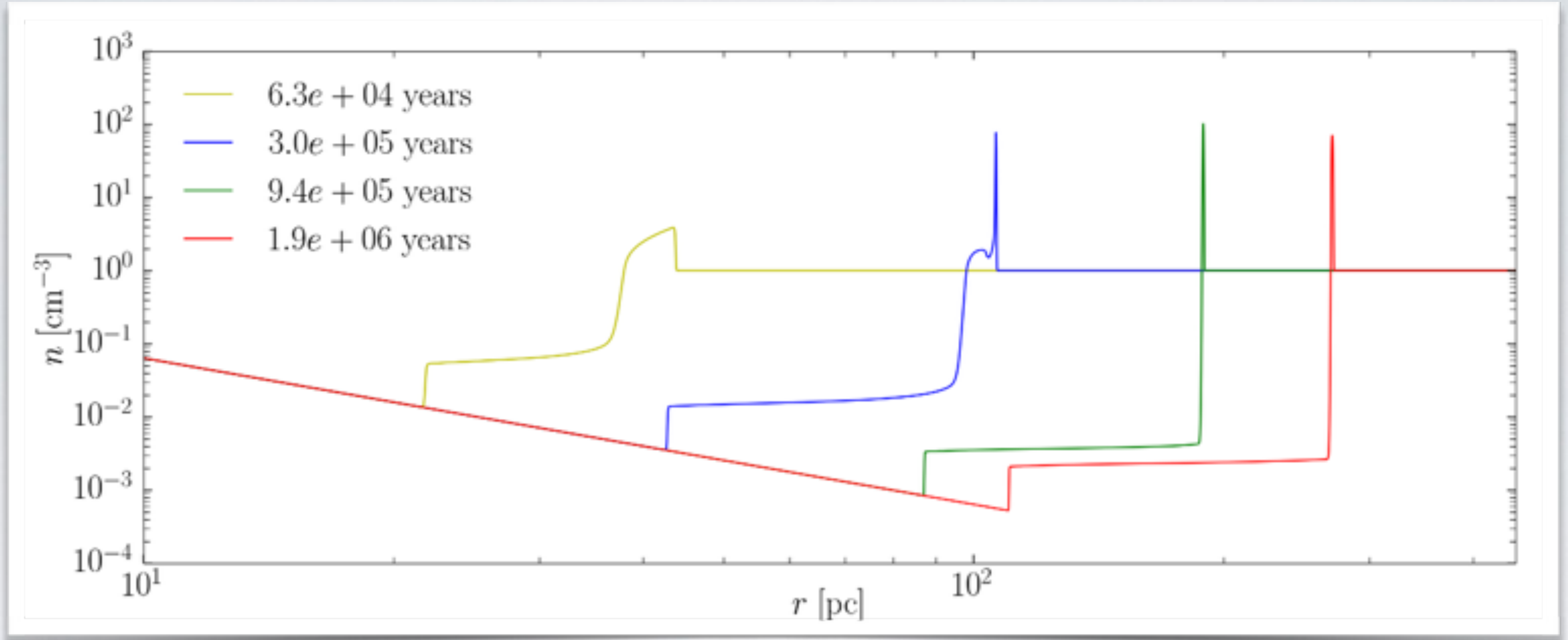
- Outflows from the accretion flow push out and shock ISM
- Front / rear shocks form
- Shocked wind hot but low density
- ISM swept into a shell which collapses once cooling starts to be efficient
- Expected opt/UV emission from the shocked ISM and X-rays from the shocked wind

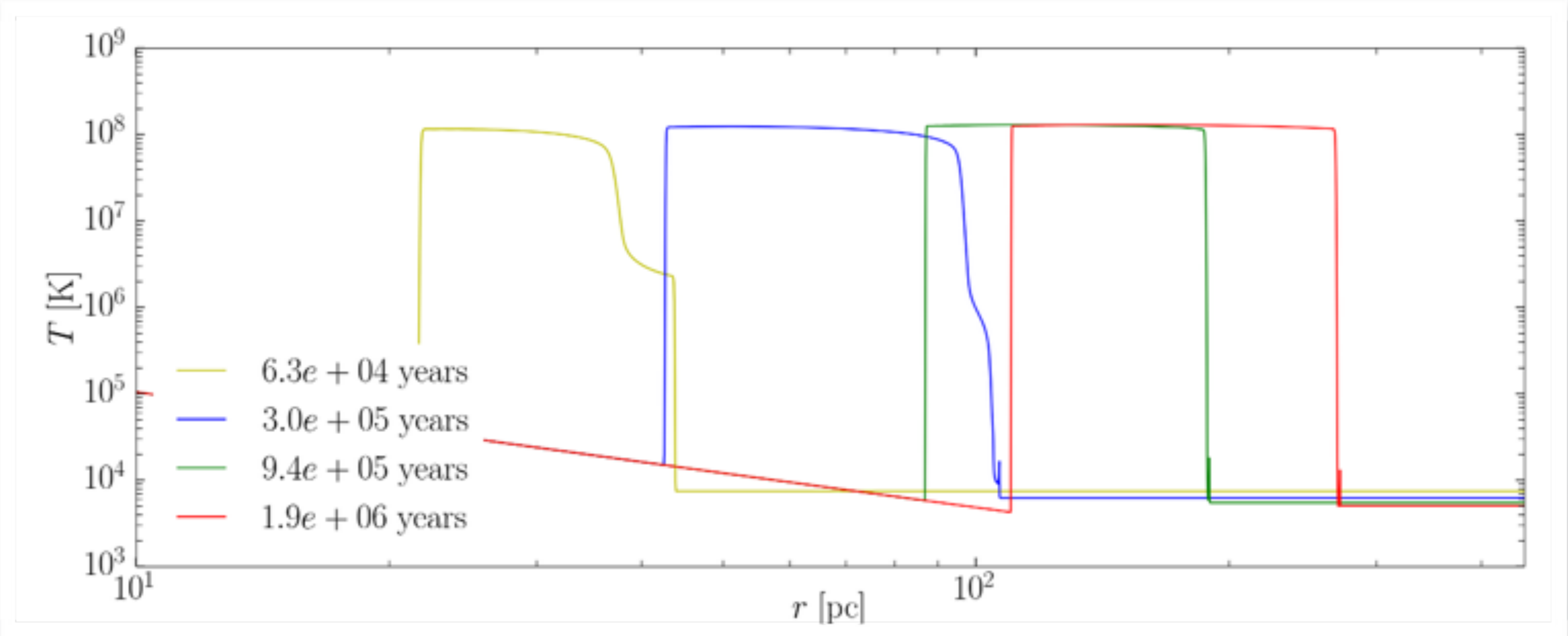
- Simulations performed with KORAL adopting free-free and bound-free opacities

EVOLUTION OF ULX BUBBLES

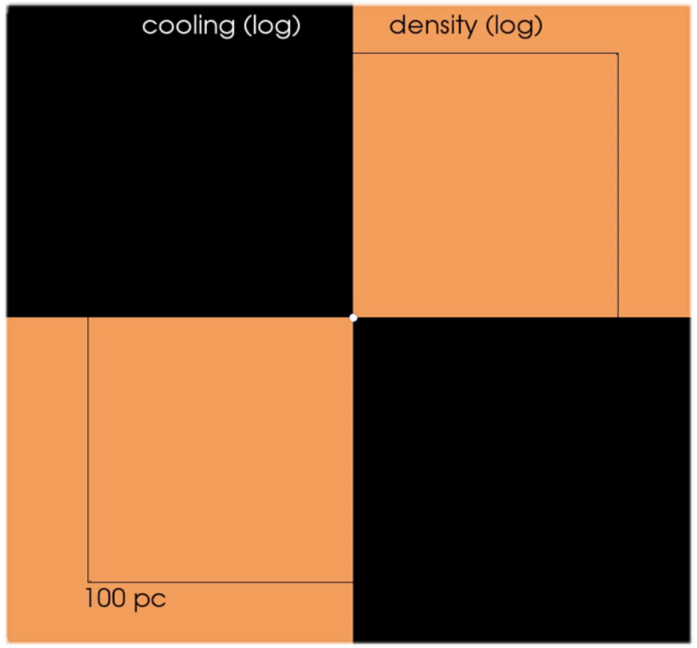


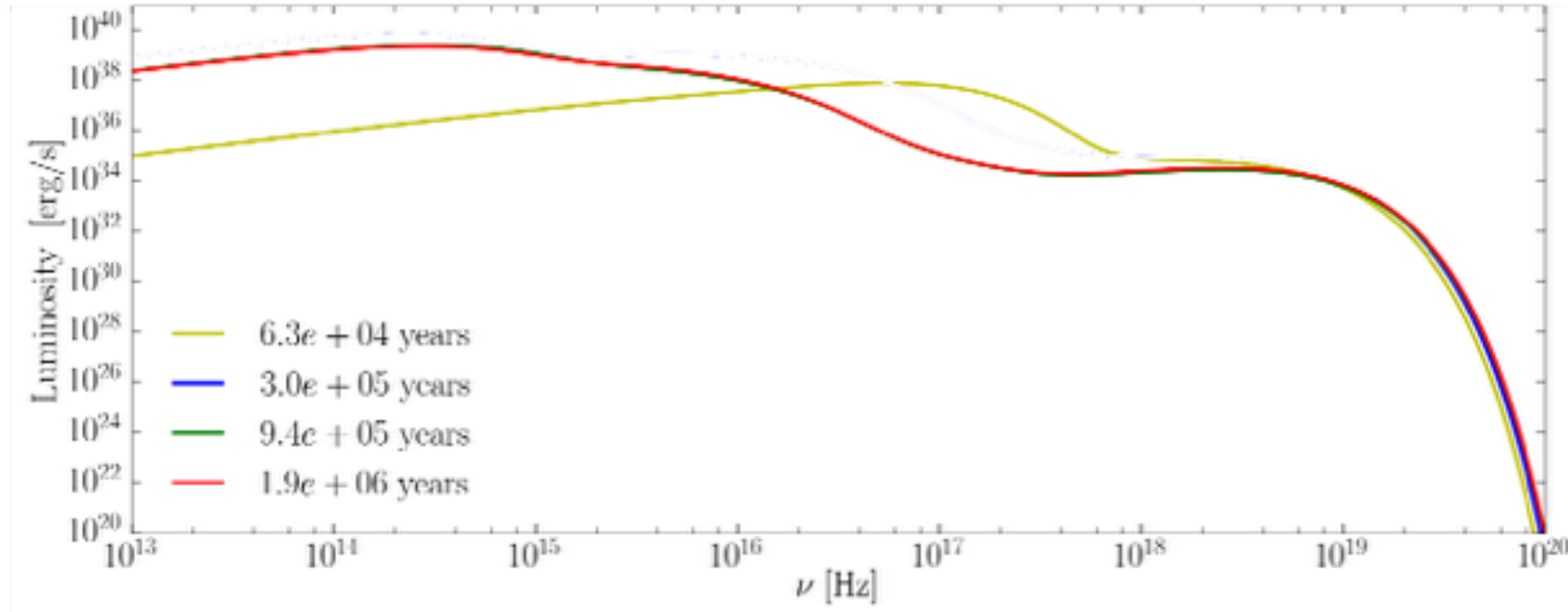
EVOLUTION OF ULX BUBBLES





EVOLUTION OF ULX BUBBLES

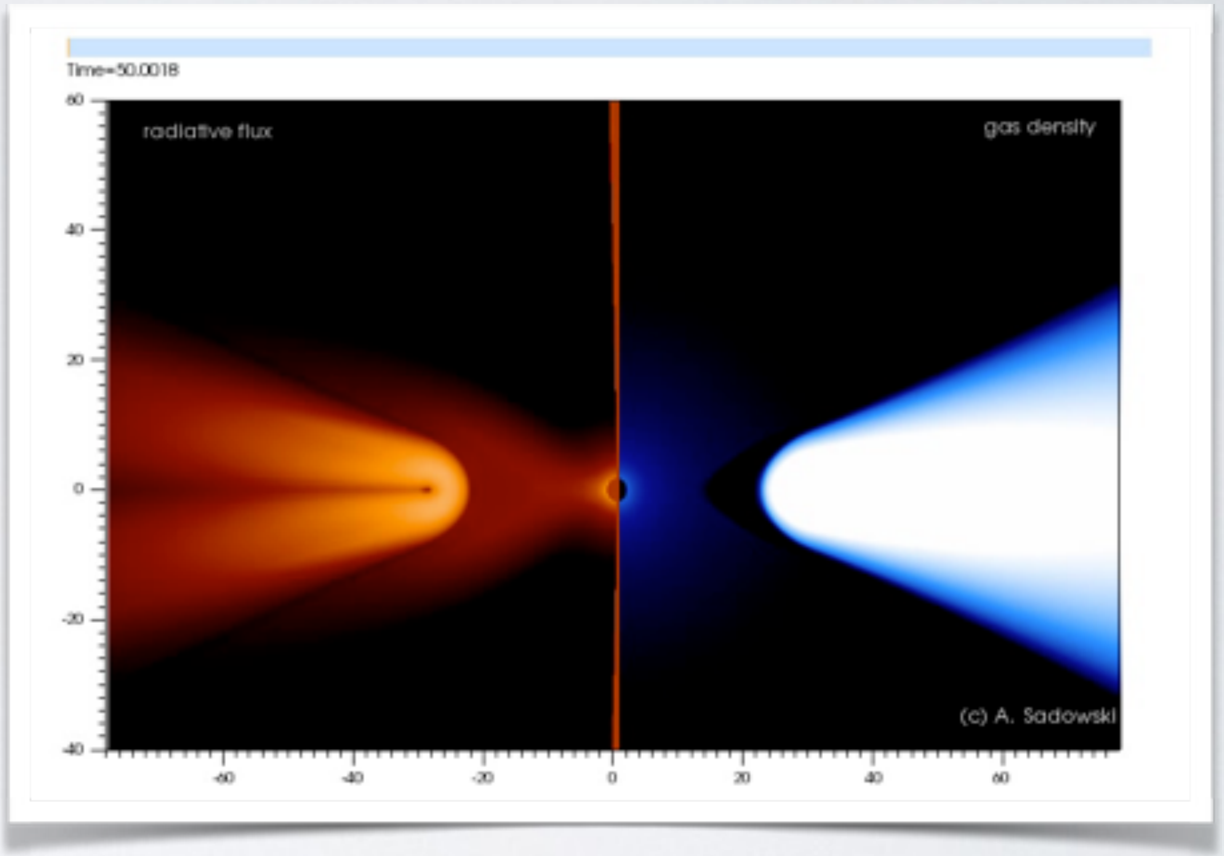




- Luminosity dominated by optical/UV from shocked ISM
- X-rays produced by the shocked wind
- But the properties of the shocked wind depend on the properties of the outflow, e.g., the mass outflow rate, not only on the kinetic power!
- **We may learn a lot about the outflow if we look how they interact with ISM!**

SUPER-EDD ACCRETION - SUMMARY

- Numerical **simulations are** a **powerful** and often required tool to understand supercritical accretion flows
- More work is required to implement **better physics** (double Compton, frequency dependent radiative transfer…)
- **Properties** of the flow **not unique** and depend strongly on a number of parameters: accretion rate, BH spin, magnetic field properties, history of accretion?
- Simulations limited to the **inner region** and short



- Constraints from the other (**large scale**) end may be very **helpful**
- Need for innovative numerical methods