Observational Evidence of Black Holes

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Nuclear BHs

Gabriela Canalizo

Determining *M*-σ relation in quasars from FWHM
of infrared stellar lines, instead of Balmer lines
(less contamination from QSO emission).

Margrethe Wold

Searching for relations between BH mass and
long-term AGN variability (both amplitude
and timescales). More massive BHs seem to have
higher amplitude variations (function of accretion rate?)

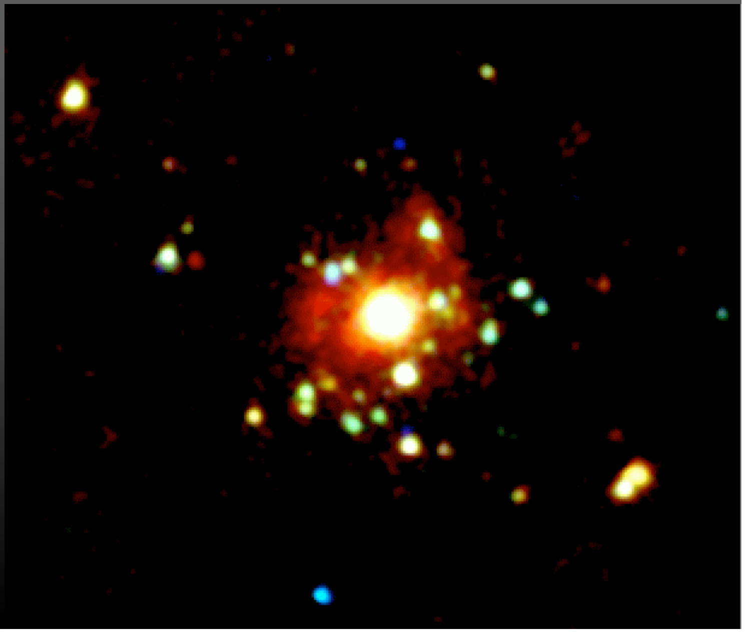
Nuclear BHs

Smitha Mathur

X-ray emission from nuclear BHs in nearby normal galaxies (Chandra data). Trying to use multiband data to distinguish between nuclear BHs and low-mass X-ray binaries. (Inconclusive so far).

Guido Risaliti

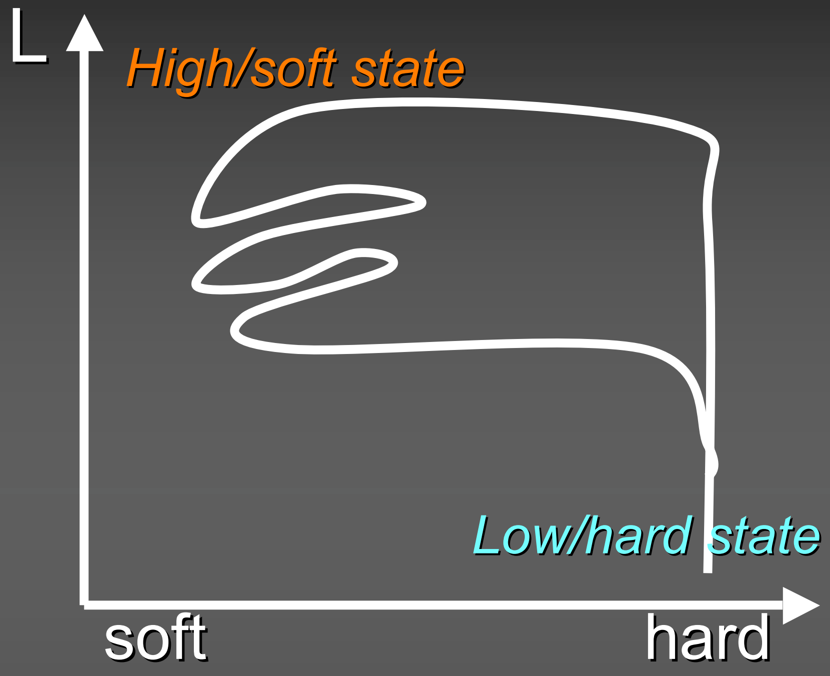
AGN in NGC1365 recurrently eclipsed by something (clouds?) over timescales of few hours. Characteristic distance of the occulting clouds ~ 10-20 R_s



Stellar BH – Nuclear BH connection

Tomaso Belloni

"Q-diagrams" (= hardness-luminosity plots) for AGN. Problem is which energy bands to choose for analogy with stellar-mass BH variability



Elmar Koerding

Fundamental planes of BH accretion:
old one ("Merloni relation"): BH mass – L_{radio} - L_x
new one?: BH mass – t_{var} – accretion rate
Also, tight relations accr rate – L_{radio} in BHs, NSs, WDs

Stellar-mass BHs

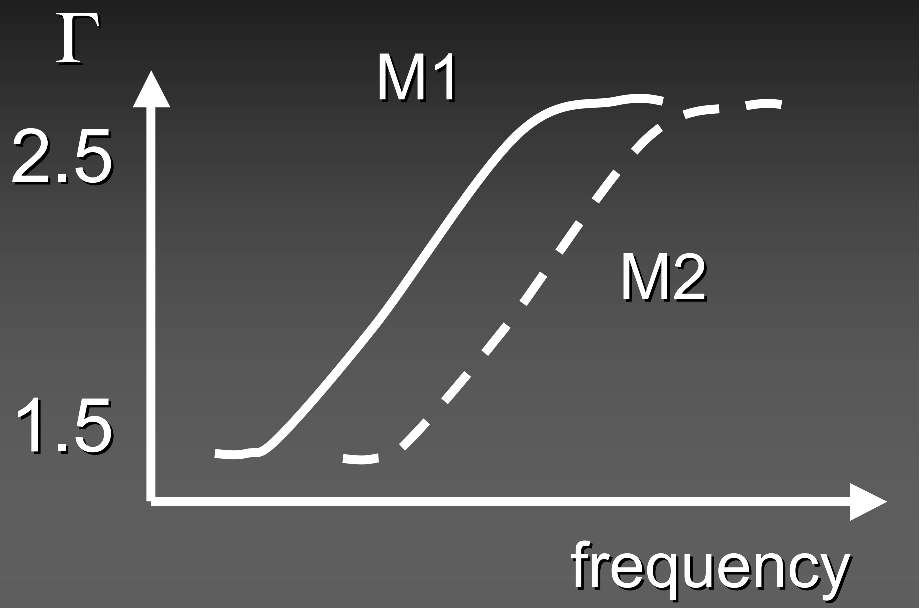
Nikolaos Kylafis

Power-density-spectrum can be modelled with Lorentian components (damped oscillators). Possible correlations between spectral photon index and frequency of Lorentian components. Jet model.

Arunav Kundu

Updates on X-ray binaries in (old) globular clusters.
BH X-ray binary in a GC of NGC4472, consistent
with stellar-mass BH.

Stellar-mass BHs



Lev Titarchuk

Correlation between photon index and QPO frequency, used to infer BH mass.

Lev Titarchuk

Hatchet job on Jon Miller’s “relativistic” Fe lines in Galactic BHs. Showed that very similar broad lines with red wings can be seen in symbiotic stars and CVs, due to downscattering in outflows.

Accretion theory & modelling

Sandip Chakrabarti

Centrifugal boundary layer theory from SK96 explains every observation of BH accretion ever done. (Shock where subsonic flow becomes supersonic).
No corona, no jet: only CENBOL is Comptonizing region

WeiMin Gu

Parameter space for slim disk solutions, standard disk solutions and “no stable solutions” in the radius vs accretion rate plane. Slim disk solutions also have a maximum accretion rate ~ 100 Eddington.

Accretion theory & modelling

Gennadi Bisnovatyi-Kogan

Steady-state solutions for magnetized accretion disks:
a large-scale poloidal field develops in the inner region;
angular velocity < Keplerian on the surface (radiative layer);
disk becomes hotter, scattering-dominated and effectively
optically thin at small radii.

Shuang-Nan Zhang

Visual appearance of shells of matter falling through
an event horizon. Do we see them crossing the horizon
or are they frozen on the surface?

Conference group photo

Content of my talk: BH masses in ULXs

- X-ray observations → constraints on BH masses

  IMBHs or super-Edd spectral state of stellar BHs?

  Basic ingredient of ULX spectra:
  most radiation in X-ray power-law component
  suggests disk transition or truncation at R >~ 10 R_{ISCO}

- How to produce BHs in the required mass range?

Why it is interesting?

- What is the mass function of BHs in the universe?

  What are the most massive BHs created
  by stellar evolution?

- How is accretion power partitioned between:
  thermal radiation
  non-thermal radiation
  mechanical power
  Poynting flux

Indirect BH mass determination

Four key constraints from X-ray data:

Stellar-mass BHs

- High luminosity $L_X \approx 10^{40}$ erg/s $[10^{38} - 10^{39}]$
- Low temperature of the disk component

$$kT_{in} <\approx 0.2\,\mathrm{keV} \qquad [1]$$

- Low frequency of X-ray QPOs

$$f_{qpo} \approx 20 - 100\,\mathrm{mHz} \qquad [1 - 5\,\mathrm{Hz}]$$

- “Power-law” X-ray spectrum at 1-10 keV

Indirect BH mass determination

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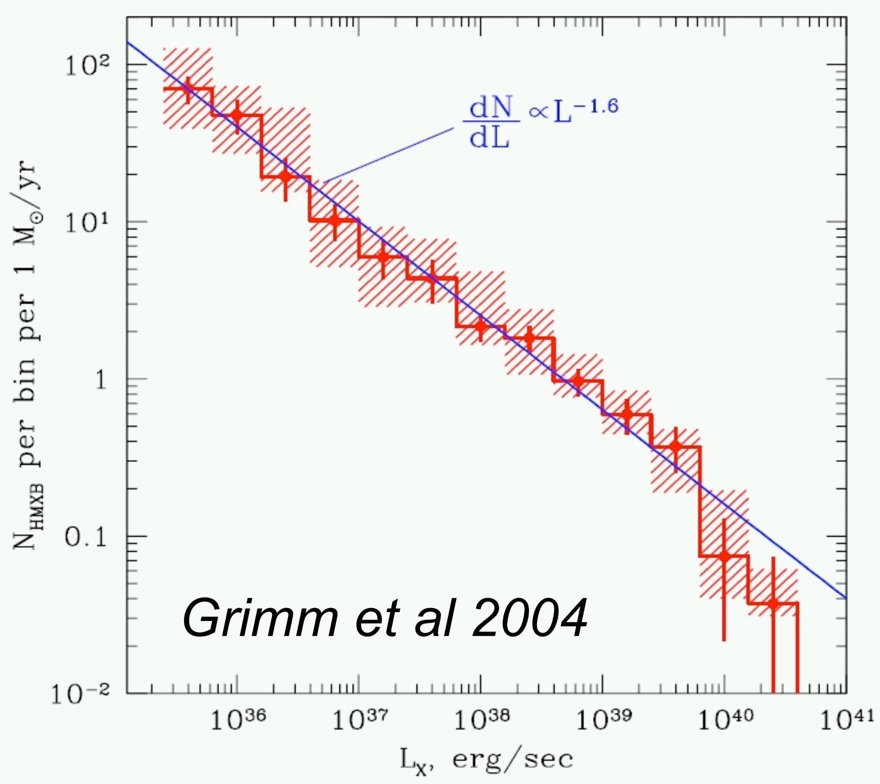


Grimm et al 2004

Cut-off at

$$L_X \approx (2-3)\times 10^{40} \text{ erg/s}$$

Suggests

$$M \approx 100\ M_{sun}$$

Low disk Temperatures etc

T_{in} ~ 1 keV
R_{in} ~ 50 km
ν_{QPO} ~ 5 Hz

? ⇒

T_{in} ~ 0.2 keV
R_{in} ~ 5000 km
ν_{QPO} ~ 0.05 Hz

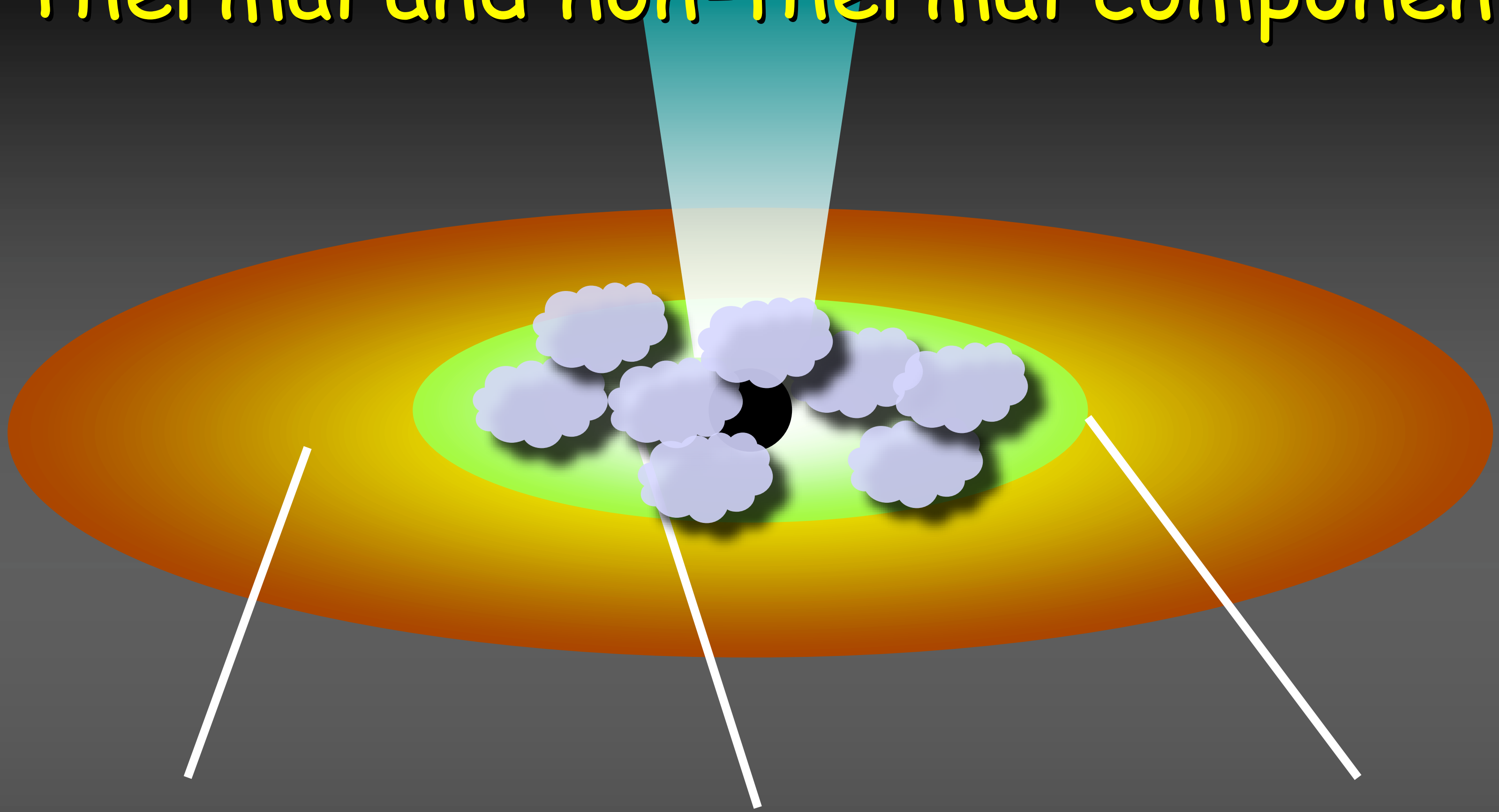
$M \sim 10\ M_{sun}$? ⇒ $M \sim 1000\ M_{sun}$?

Only if we are directly observing the disk down to $R = R_{ISCO}$ ~ a few M

Most likely NOT THE CASE

R_{in} may be >> innermost stable orbit

Thermal and non-thermal components



Standard disk

Thermal spectrum

$L_{disk} <\approx 30\% L_X$

Comptonizing region

Power-law spectrum

$L_{po} \approx 70 - 100\% L_X$

Large R_{in},
Low T_{in},
Low f_{qpo}

Structural transitions in the disk

Spherization radius R_{sph}

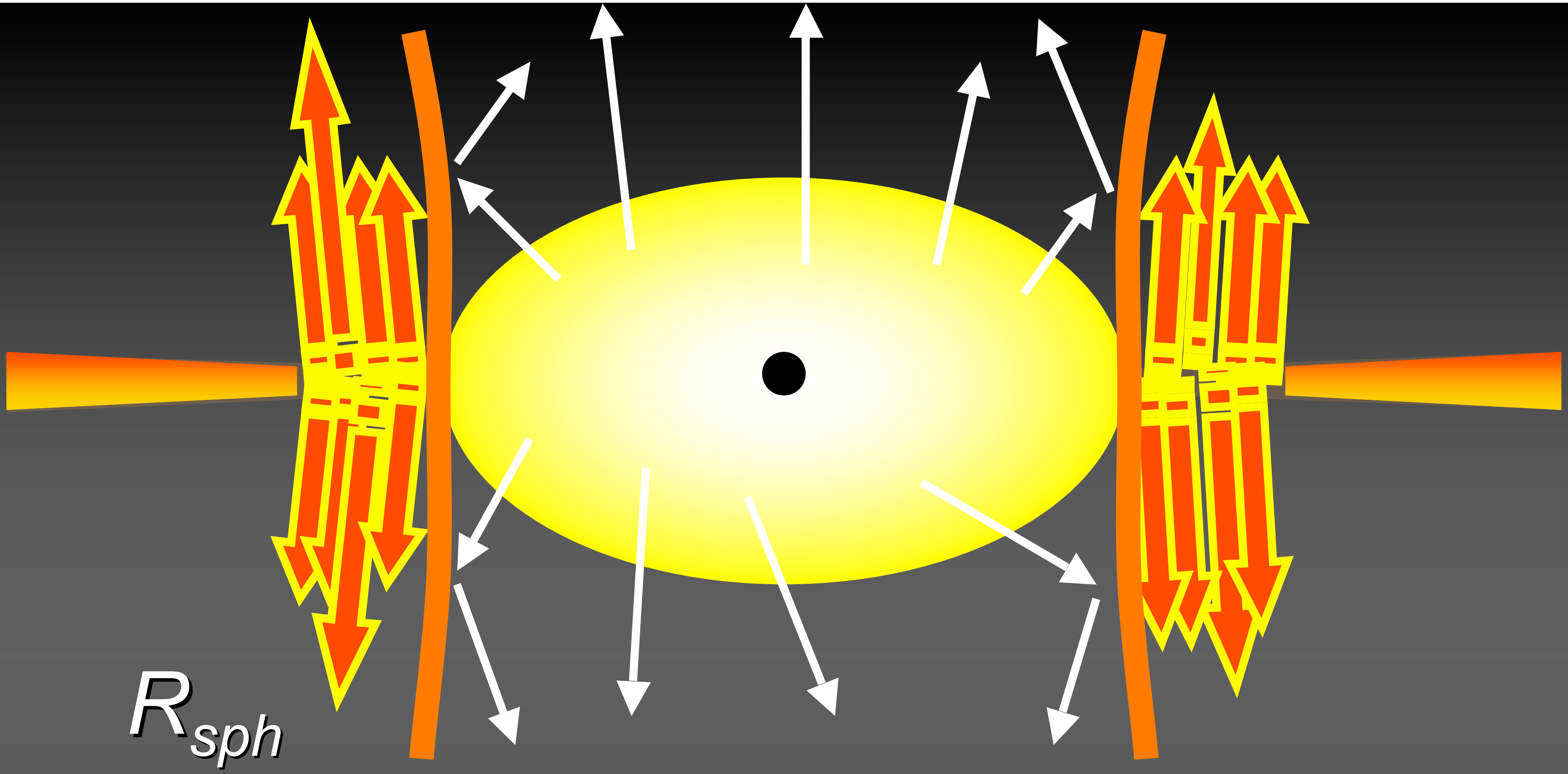
Thick disk (*H* ~ *R*), radiatively-driven outflows

Optically-thin boundary R_{thin}

Disk becomes effectively-optically-thin

(but still optically thick to scattering)

$$\tau_{\nu}^{eff}(R_{thin}) \approx n_e H \sqrt{\sigma_{ff}(\sigma_{ff}+\sigma_{es})} \approx 1$$



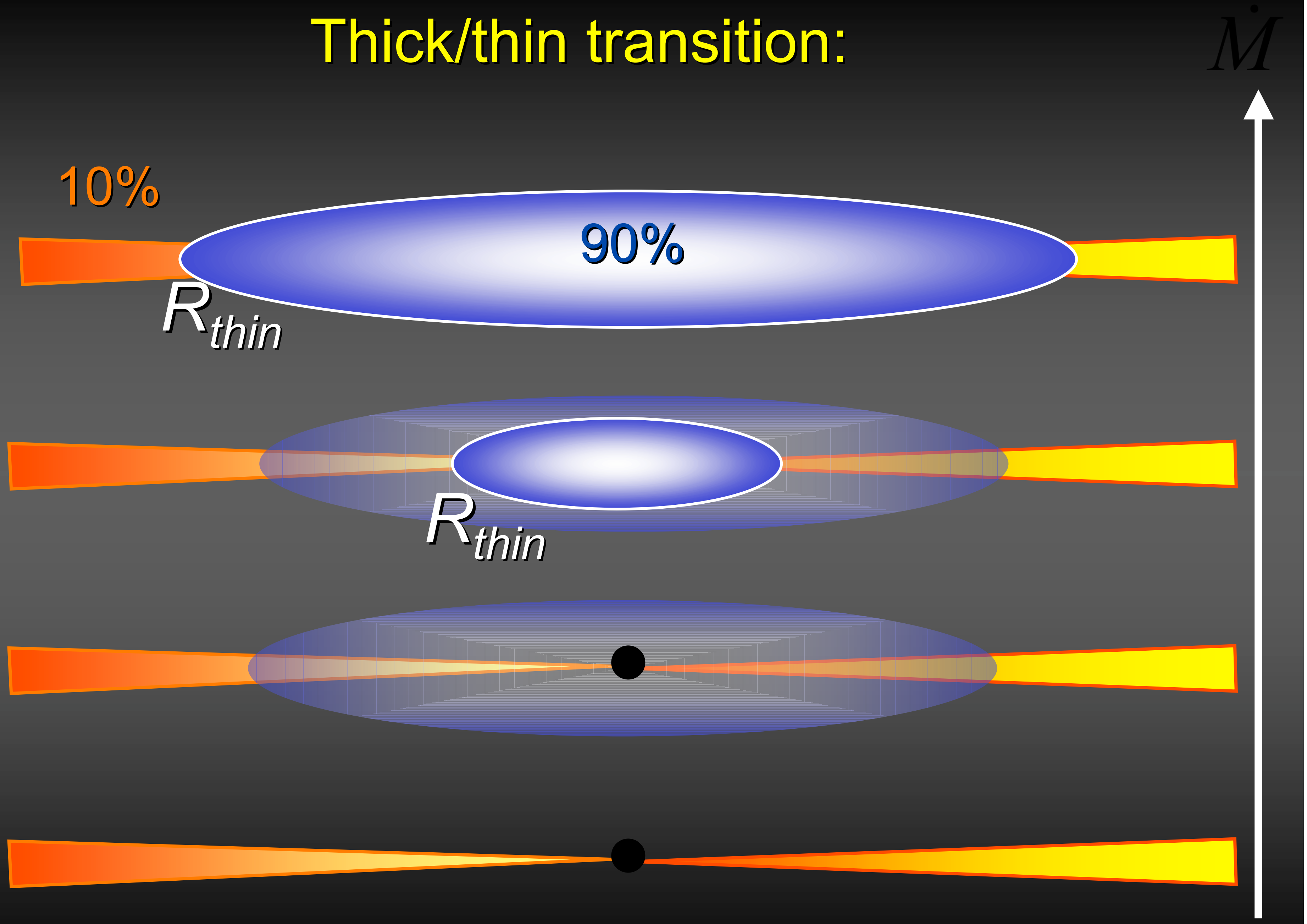
spherization radius:

outflows favour photon collimation

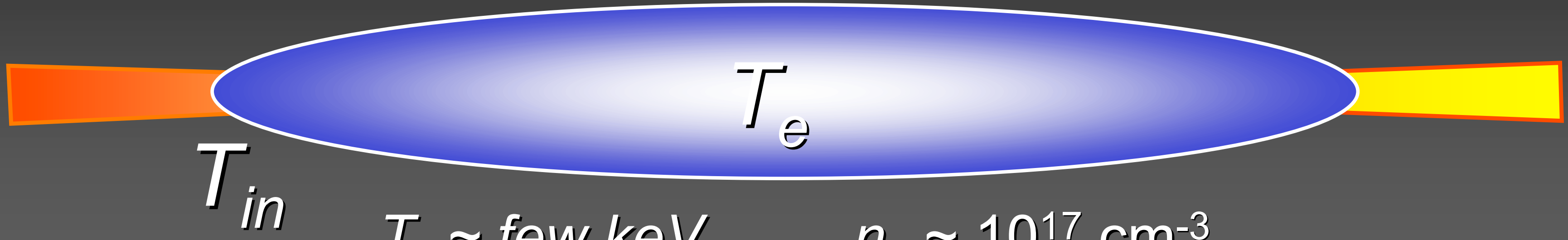
$$L(R > R_{sph}) \approx L_{Edd} \qquad L(R < R_{sph}) \approx (\ln \dot{m}) L_{Edd}$$

(Poutanen et al 06; Begelman, King & Pringle 07; King 08)

Thick/thin transition:



Thick/thin transition:



$T_e \sim$ *few keV*

$n_e \sim 10^{17}$ cm^{-3}

Radiative emission in optically-thin region
is less efficient than blackbody

→ *Higher T required to emit same flux*

$$I_\nu(R) \approx f(R, \alpha, M, \dot{m}, \nu)(1 - e^{-\tau_\nu^{eff}})B_\nu(R) < B_\nu(R)$$

$$I_\nu \approx \sqrt{\sigma_{ff}/\sigma_{es}}\, B_\nu < B_\nu$$

see Bisnovatyi-Kogan’s models

Shakura & Sunyaev 73
Callahan 77
Czerny & Elvis 87
Shimura & Takahara 95

Both transitions depend on accr rate

Spherization radius R_{sph}

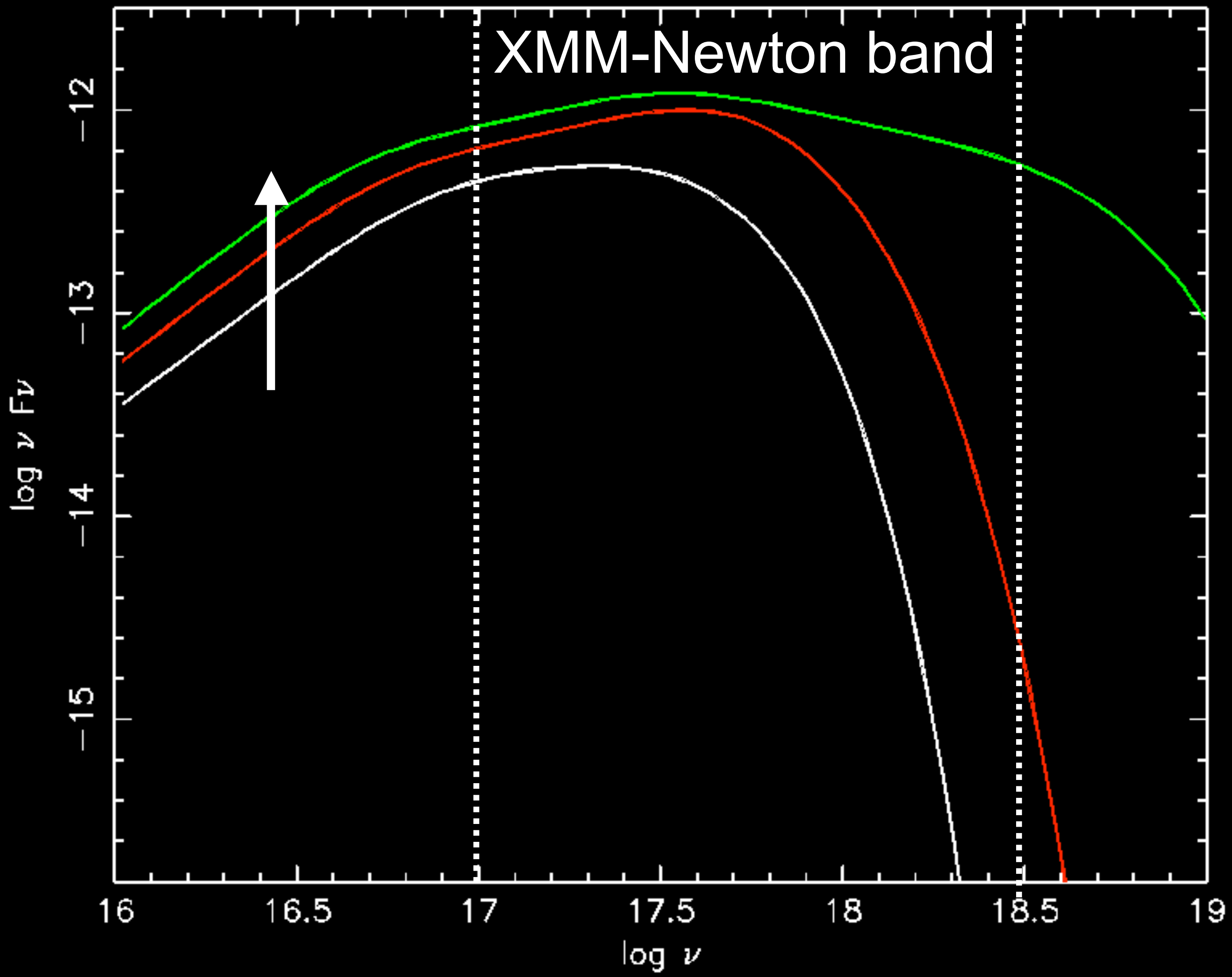
$$R_{sph} / R_g \approx (27/4)\, \dot{m}$$

Optically-thin boundary R_{thin}

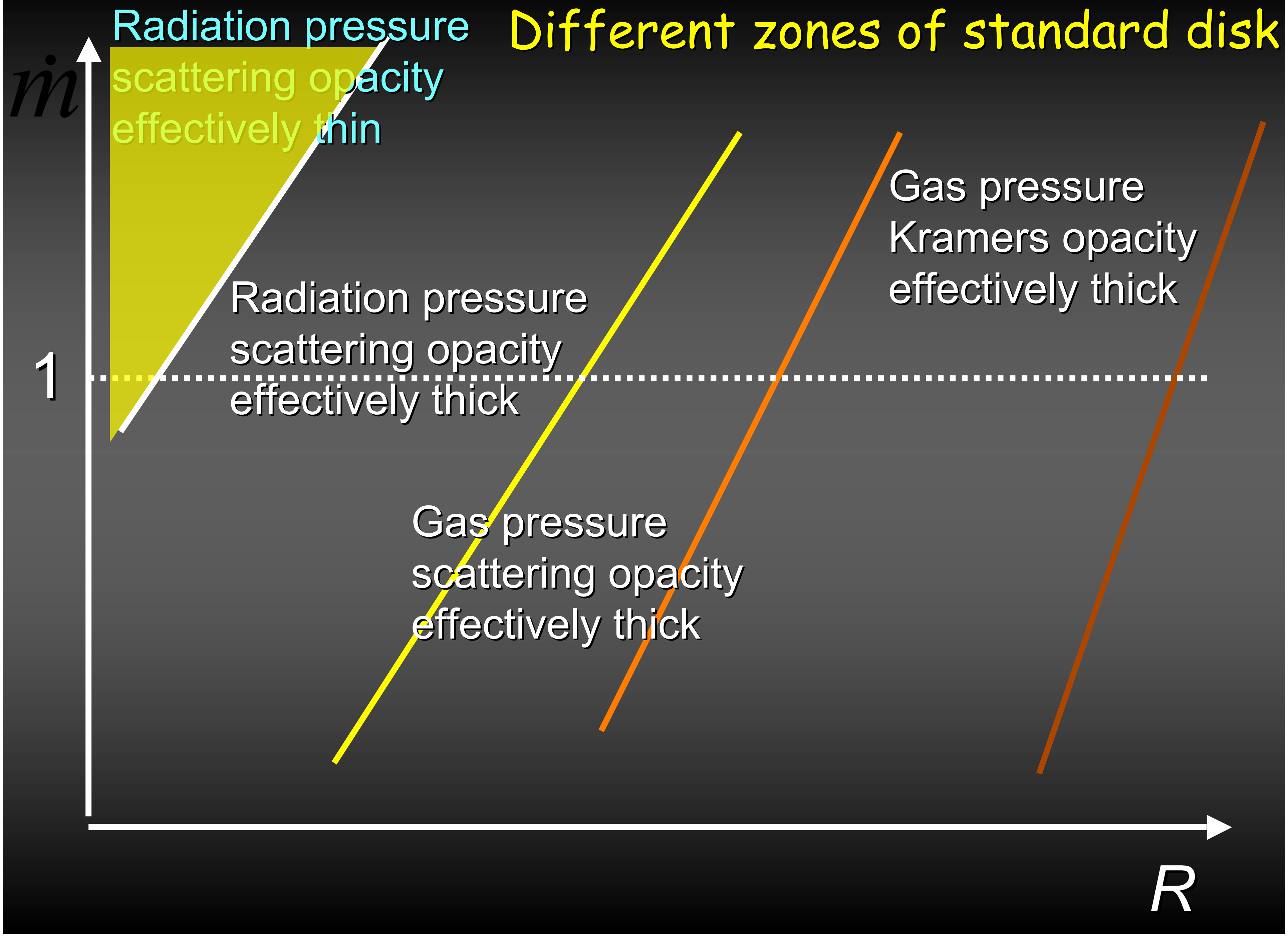
$$R_{thin} / R_g \approx 36\, \alpha^{34/93} \dot{m}^{64/93} m^{2/93}$$

(for a Shakura-Sunyaev disk) $\dot{m} \equiv \dot{M} / \dot{M}_{Edd}$

X-ray spectrum becomes power-law-like as inner disk becomes optically thinner



Different zones of standard disk



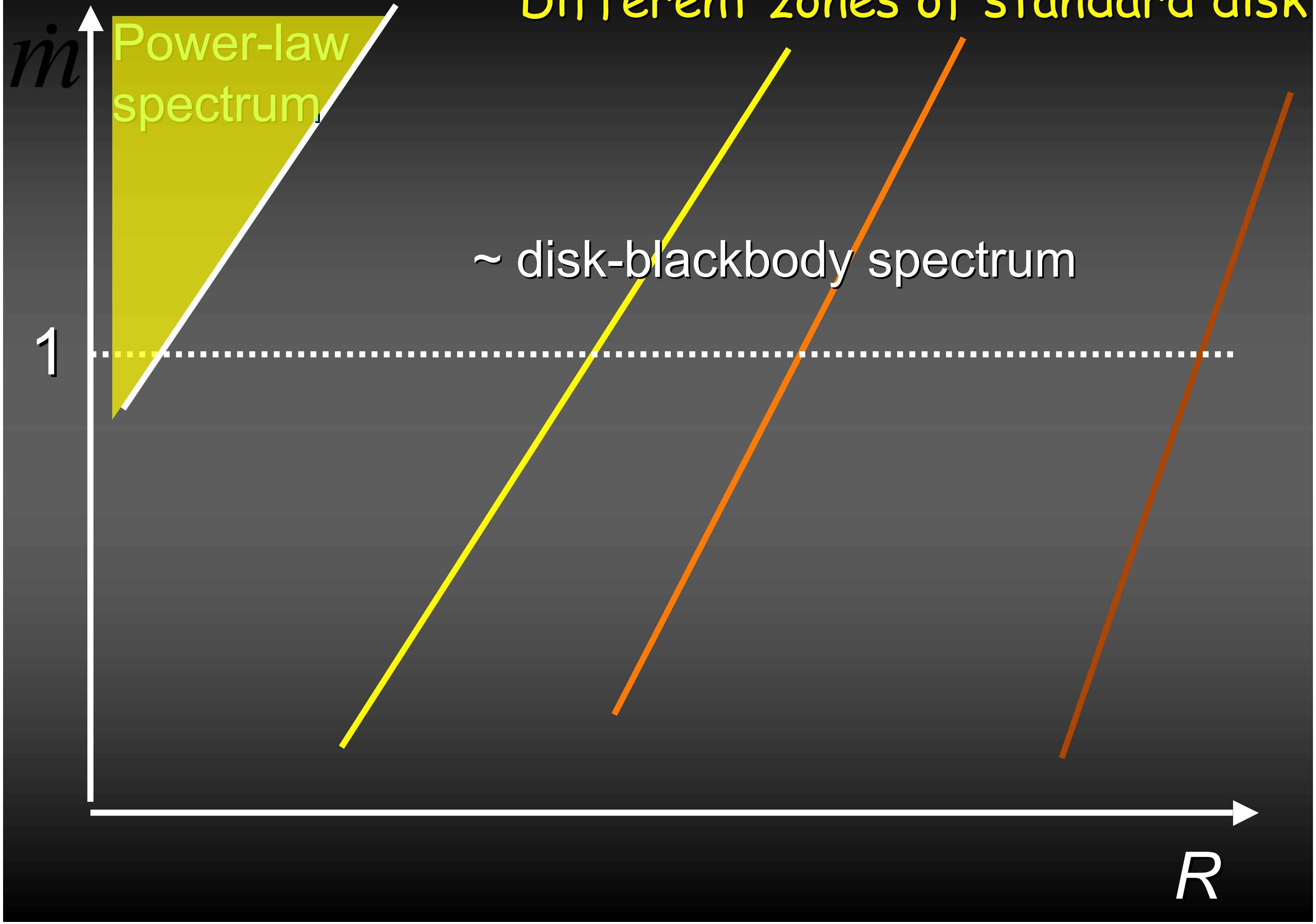
Radiation pressure
scattering opacity
effectively thin

Radiation pressure
scattering opacity
effectively thick

Gas pressure
scattering opacity
effectively thick

Gas pressure
Kramers opacity
effectively thick

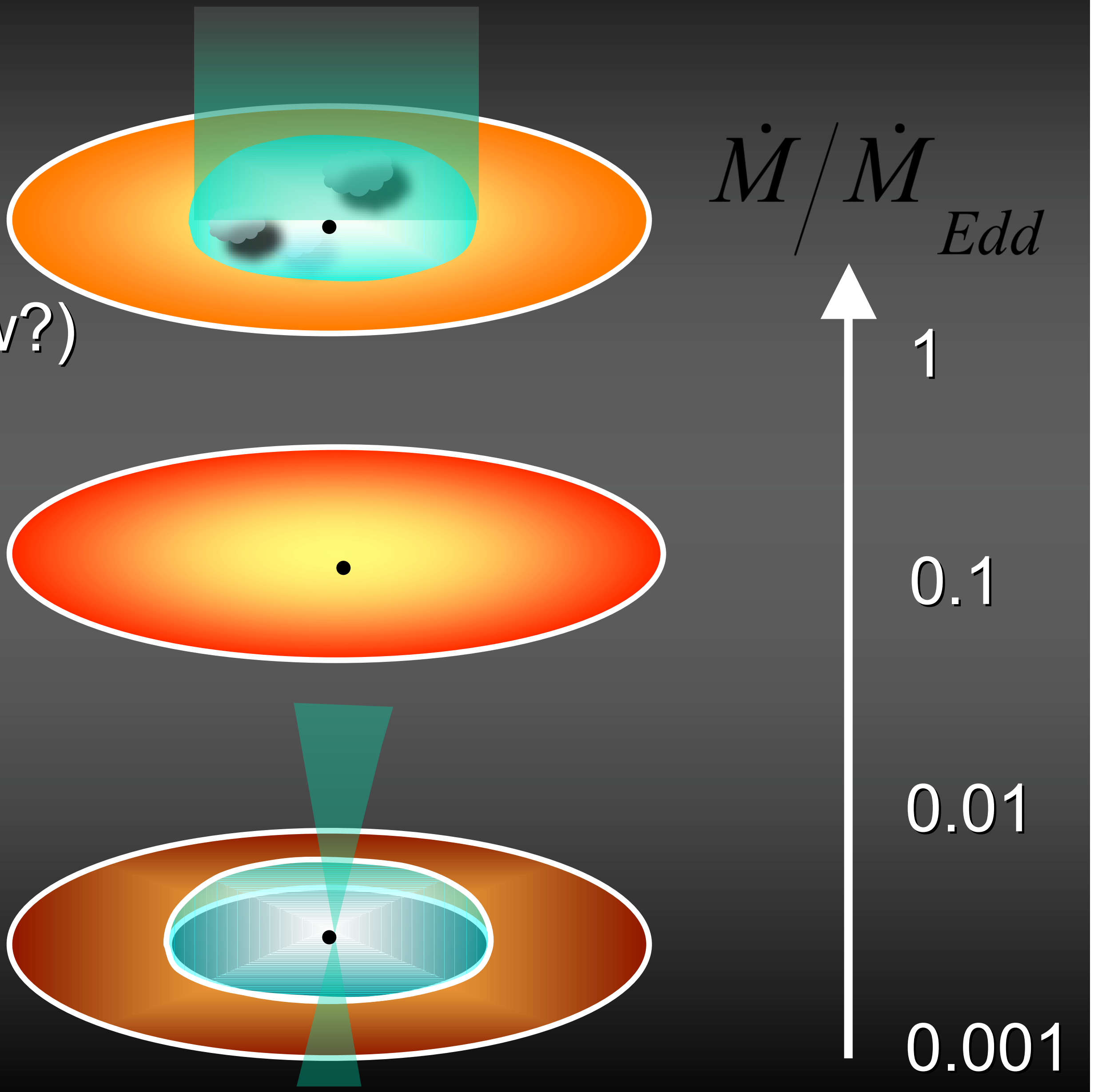
Different zones of standard disk



Power-law spectrum

~ disk-blackbody spectrum

Summary of BH accretion states



Power-law
IC in inner disk
or base of outflow
(+BMC from outflow?)

Thermal
Optically-thick
emission from disk

Power-law
IC in thin corona,
base of a jet
or CENBOL

Conclusions from X-ray observations: most ULXs consistent with:

$$M_{BH} \sim 50 - 100\ M_{sun}$$

$$(\dot{M} / \dot{M}_{Edd}) \sim 10$$

for quasi-isotropic emission

Thermal disk outside R ~ 50-100 R_g

Hot, IC-dominated at R <~ 50 R_g

How to form BHs in ULXs

(assuming they are more massive than Galactic BHs)

Pop-III remnants?

Inconsistent with observations
ULXs associated with star-forming regions

Runaway O-star mergers in super-star-clusters?

Inconsistent with observations
ULXs not found inside massive, bound clusters

but often found in smaller OB associations

IMBHs with M ~ 1000 M_{sun} highly unlikely

But stellar BHs with M ~ 50-100 M_{sun} still feasible

- Requires stars with initial M ~ 150-300 M_{sun}
- Possible in principle (η Carinae, Pistol star had initial masses up to 150-200 M_{sun})
- Need to retain ~ 100 M_{sun} at core collapse requires low metal abundance ⟶ low winds

Yungelson et al 08 for evolution of massive stars

Pair-instability SN limits initial BH mass: M <~ 65 - 70 M_{sun}

Stellar binding energy increases
faster than core-collapse energy (eg Figer 99)

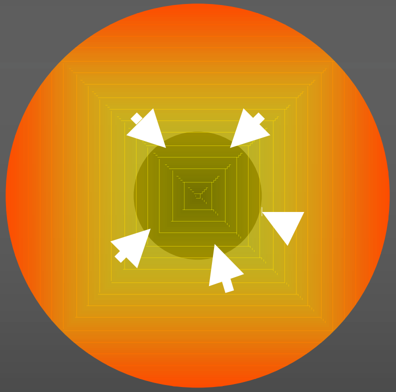
↓

Stars with initial masses >~ 50 M_{sun}
should not get disrupted by core collapse

Pair-instability SN limits initial BH mass: $M \lesssim 65 - 70\ M_{sun}$

If star is not disrupted, fallback accretion may take BH mass up to ~ 100 M_{sun}

Accretion phase after BH birth may be long and observable
(Begelman & Armitage 08)



Testable prediction:
brightest ULXs should not be associated with an SNR
ULX ionized nebulae must be due to ULX jet/winds

Conclusions

X-ray evidence suggests $M <\sim 100\ M_{sun}$
(if nearly isotropic; even less for moderate beaming)

"Plausible" stellar evolution scenarios suggest
BH masses $< 70\ M_{sun}$ (or $< 100\ M_{sun}$ with fallback)

The two constraints are still consistent with each other
(most) ULXs = upper end of high-mass X-ray binaries

Thermal / non-thermal regions in accretion flow