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Active Galactic Nuclei (AGN) from an X-ray perspective

Part I

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Active Galactic Nuclei (AGN)

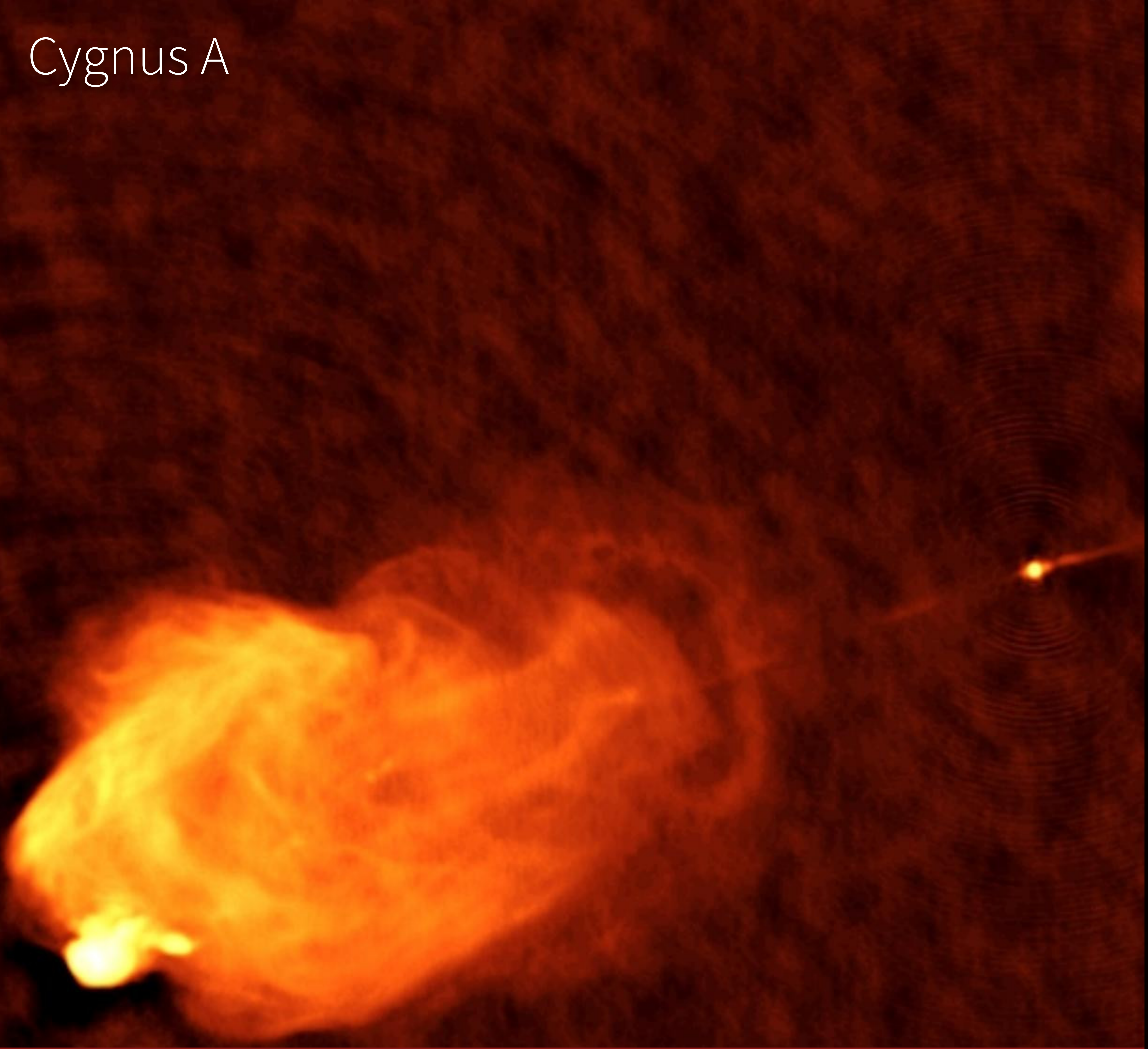
Supermassive black hole in the centre of the galaxy accreting material, producing enough luminosity to outshine all the stars in the galaxy

$M_{BH} = 10^6 \sim 10^9\, M_\odot$

$L_{bol} \sim 10^{11}\, L_\odot$

Event horizon telescope resolves the inner accretion flow and black hole shadow in M87 and Sgr A*

Cygnus A



Some supermassive black holes launch jets close to the speed of light that span many times the size of the galaxy

Likely powered by extracting energy from the spin of the black hole by magnetic fields around the event horizon

AGN are everywhere!

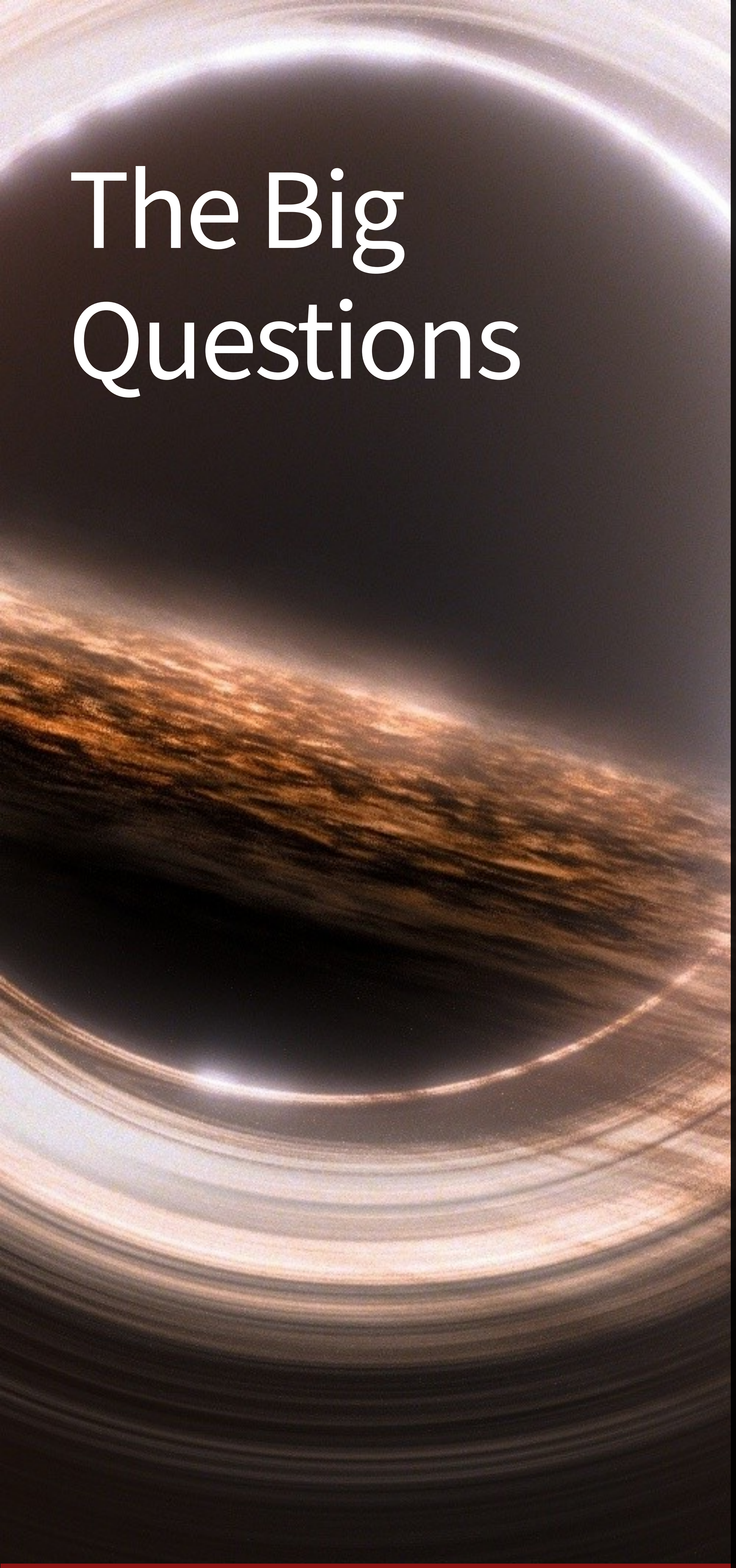
The eROSITA X-ray sky

NGC 1275 in the Perseus Cluster

Total power output from an AGN is comparable to the binding energy of the stars in the galaxy

AGN feedback pushes gas away that would fall into the galaxy

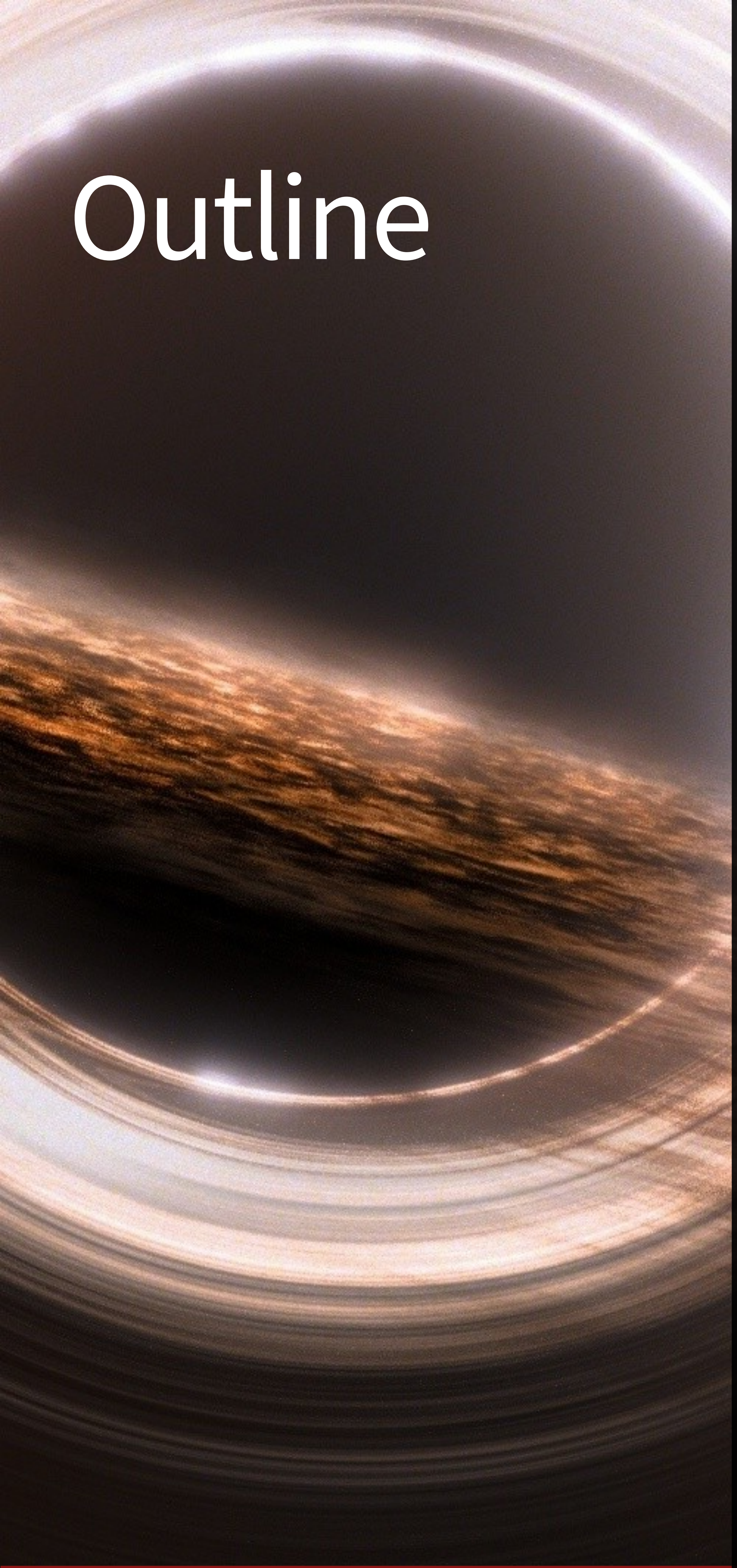
Supermassive black holes play an important role in the formation of structure in the Universe



The Big Questions

- How do black holes power some of the most luminous objects in the Universe?
- How does the in-falling plasma, the magnetic field and the spinning black hole release energy? How is the energy output moderated over time?
- How do black holes grow and how do they impact the growth of their host galaxies?
- Why do some black holes launch jets?
- Does general relativity accurately describe the extreme gravity just outside the event horizon?

Outline

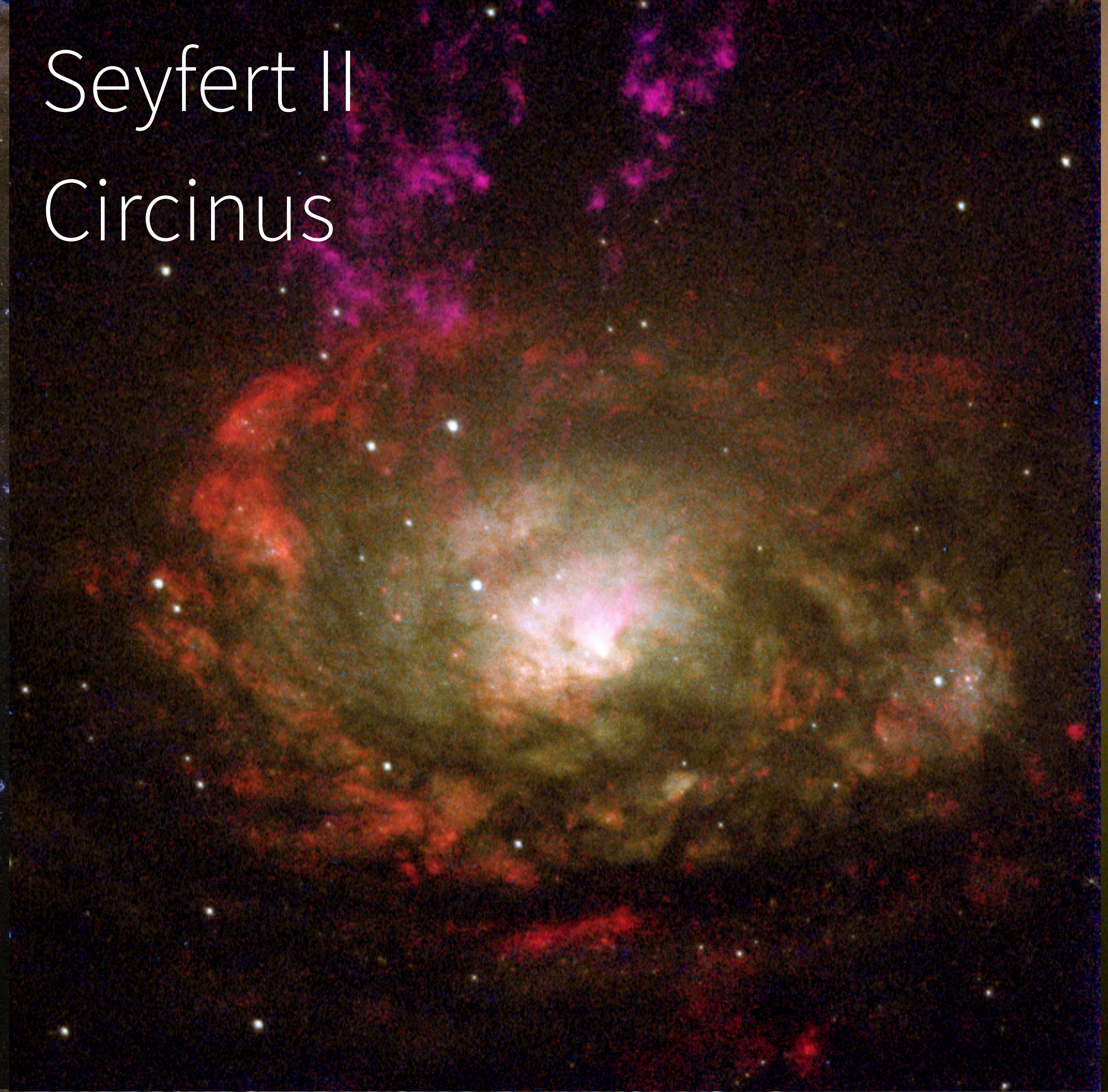


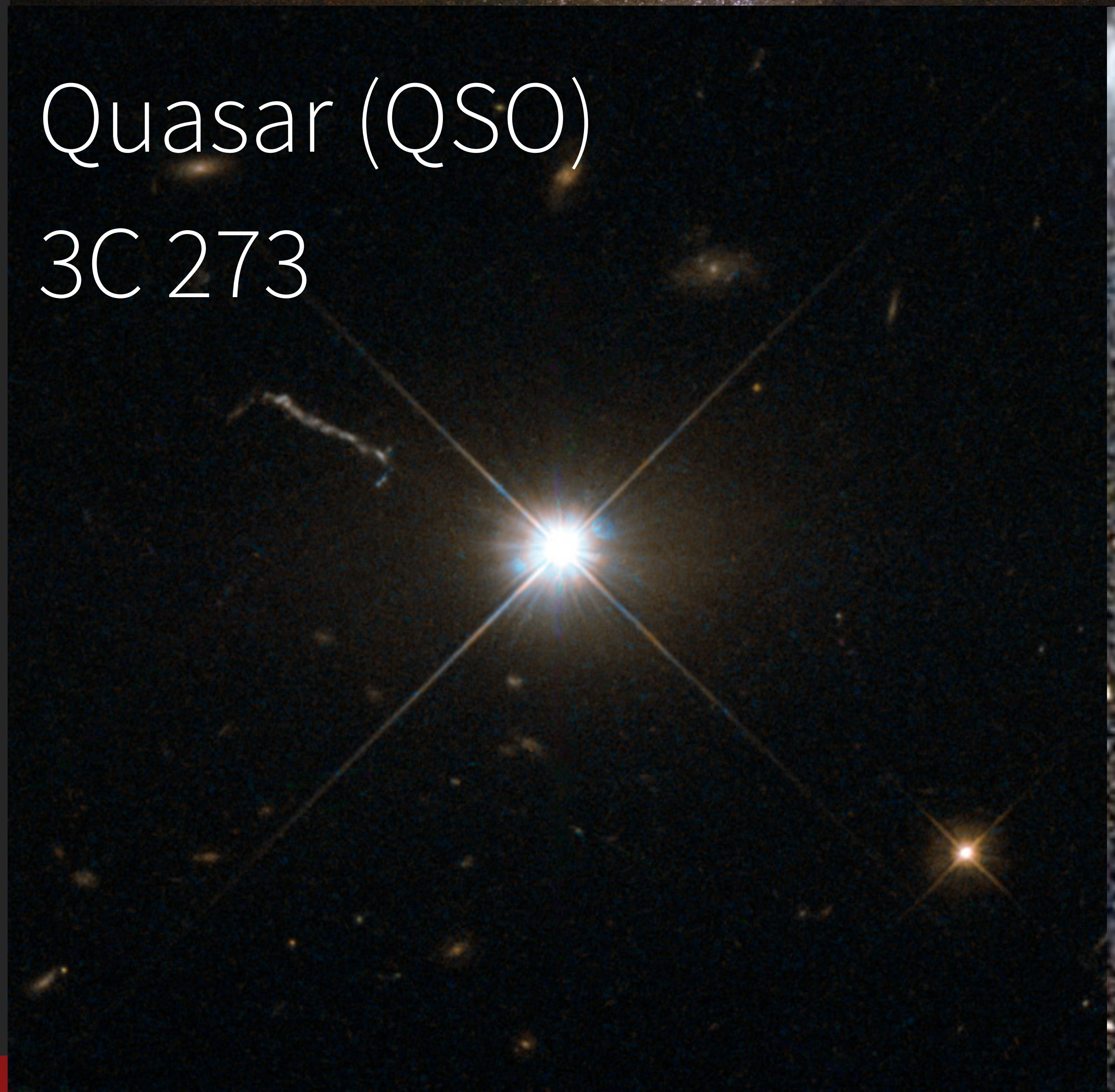
Lecture 1

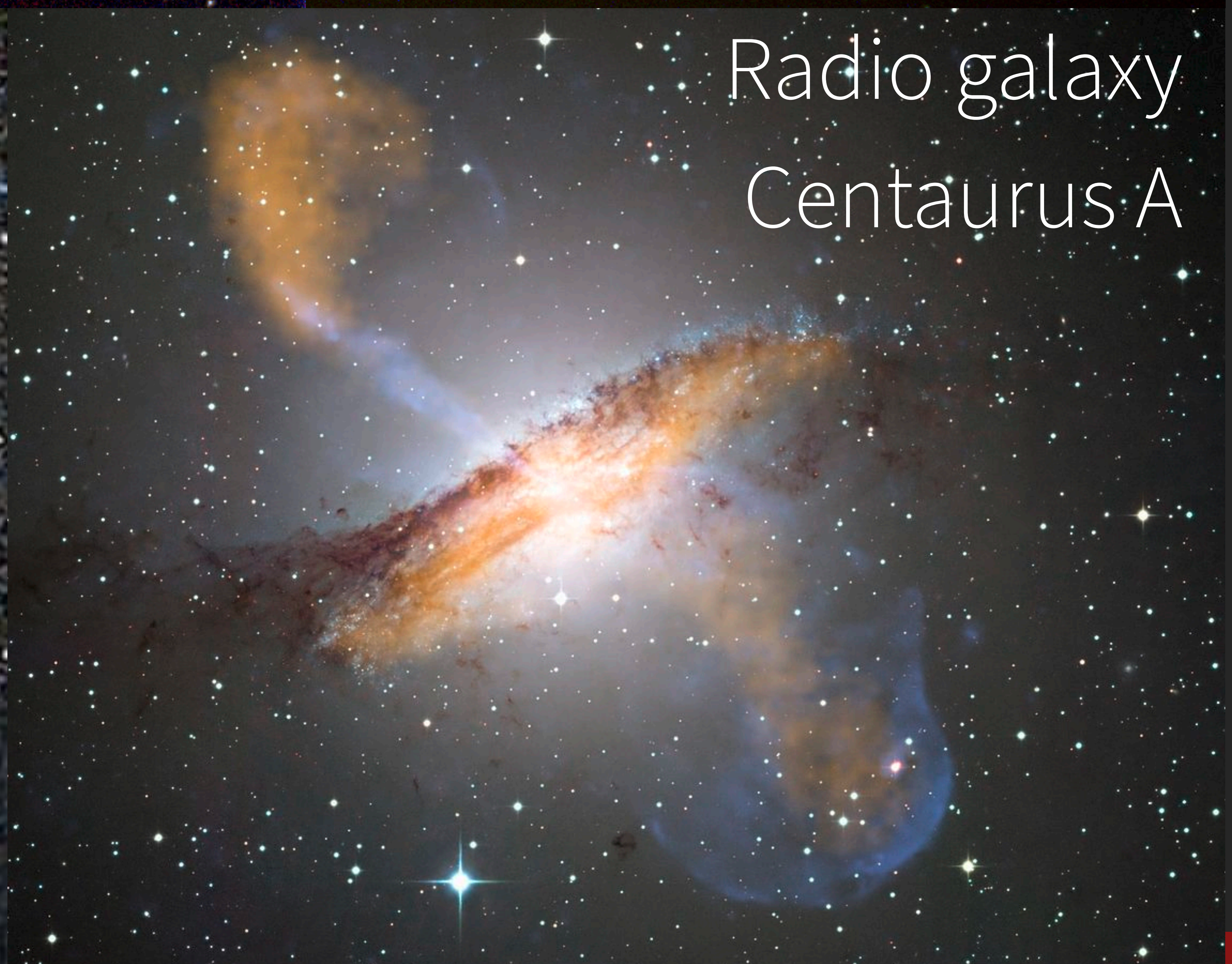
- The observable structure of AGN
  - The accretion disc
  - The corona
  - Absorbers and outflows
- AGN feedback

Lecture 2

- Seeing to the event horizon of a black hole
  - X-ray reflection
  - X-ray reverberation
- Black hole mass and spin measurements
- The formation of supermassive black holes


Seyfert I
NGC 4051

Seyfert II
Circinus

Radio galaxy
M87

Quasar (QSO)
3C 273

Blazar
Mrk 421

Radio galaxy
Centaurus A

Anatomy of an Accreting Black Hole

Anatomy of an Accreting Black Hole

Characteristic length scale: $r_{\mathrm{g}} = \frac{GM}{c^2}$

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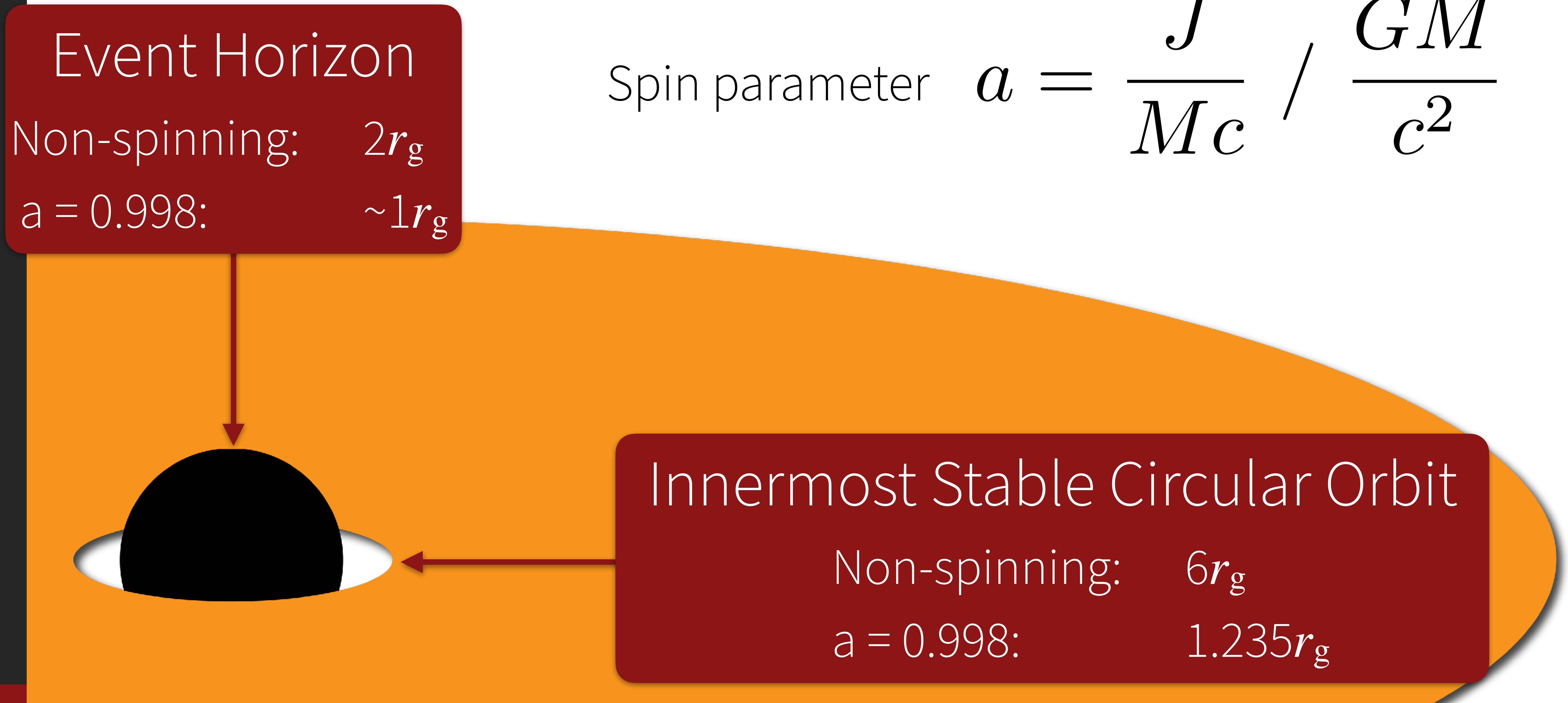

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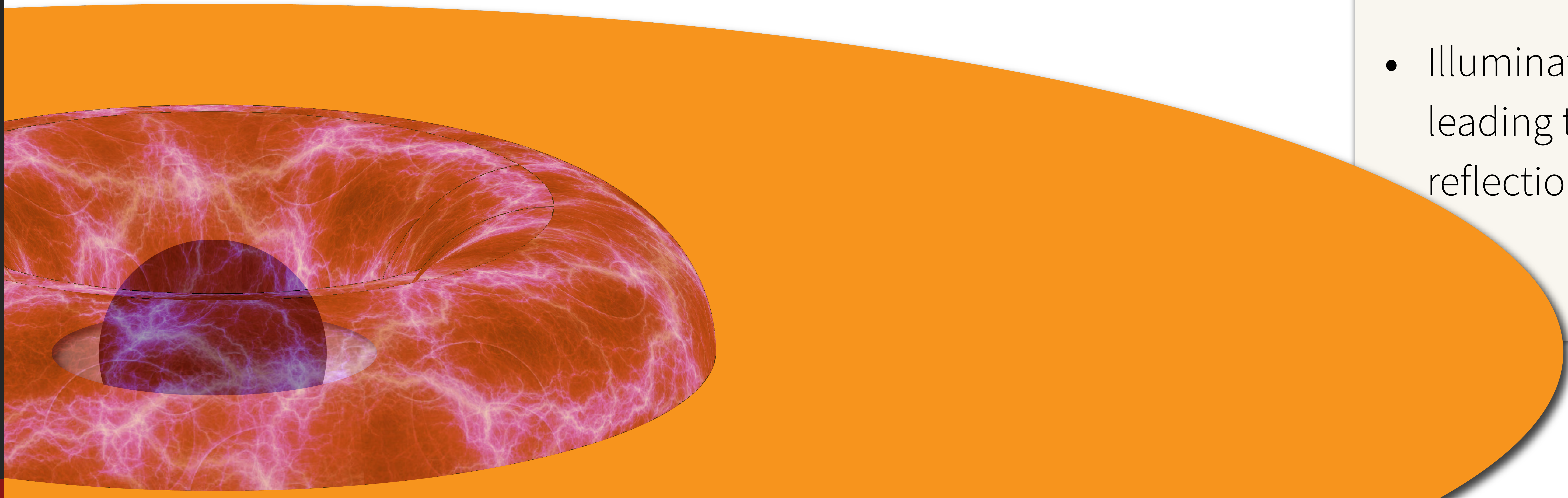

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The Corona

- Particle acceleration, likely by magnetic fields threading inner accretion disc and spinning black hole
- Source of intense X-ray continuum emission
- Illuminates the accretion disc, leading to reprocessing and reflection

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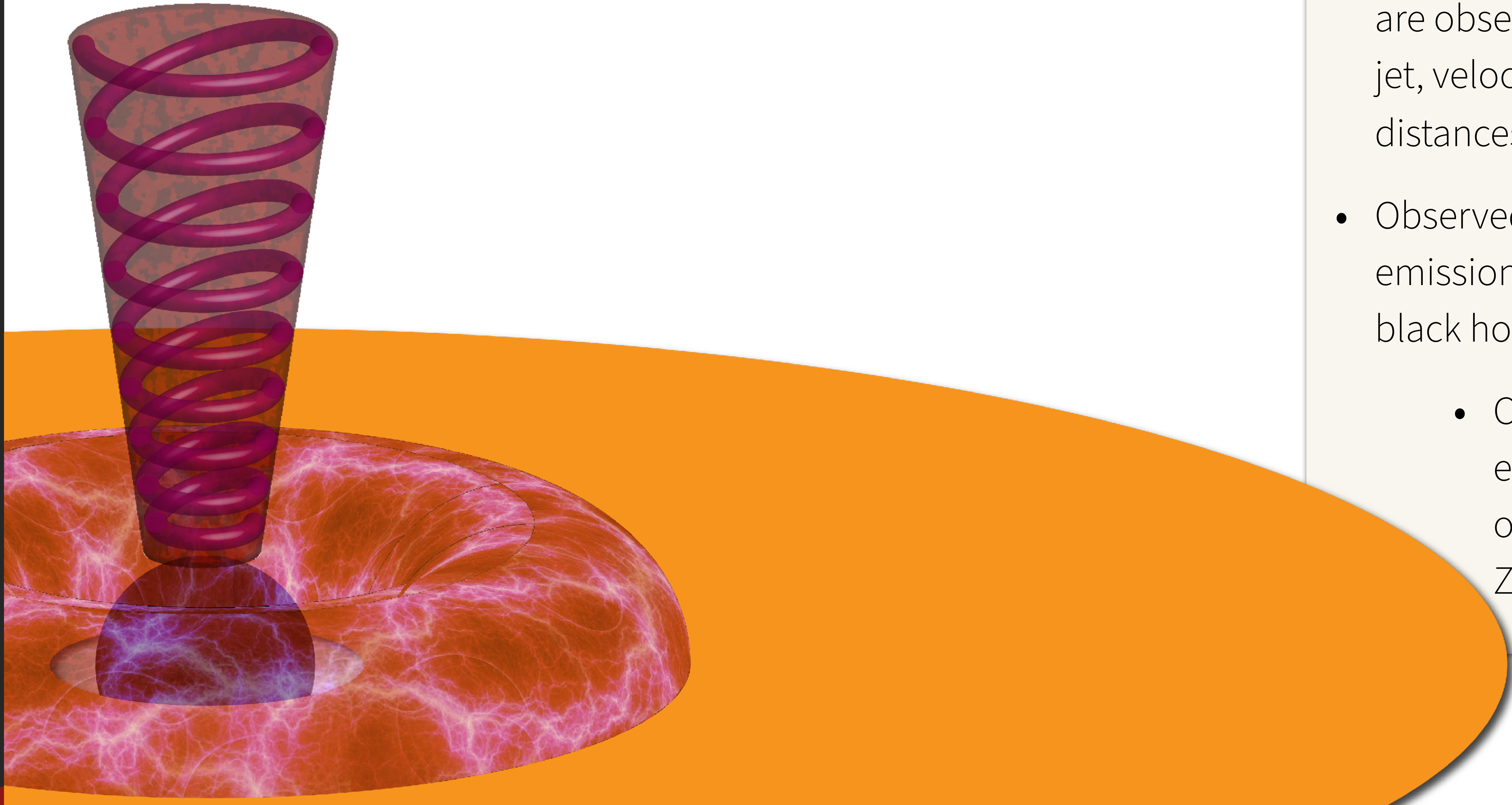
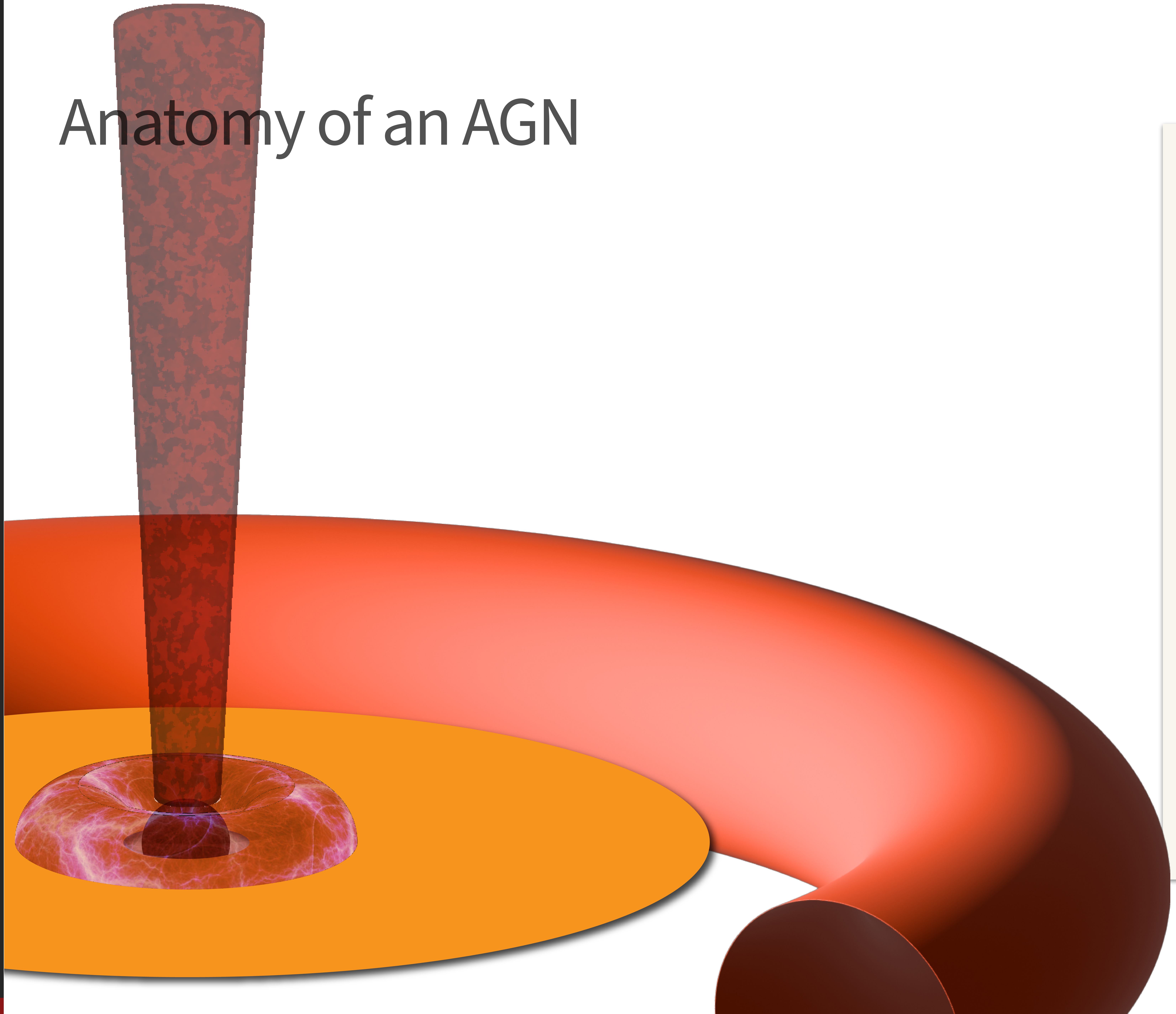
Anatomy of an AGN



The Jet

- Some supermassive black holes are observed to launch relativistic jet, velocity $\sim c$, spanning large distances out of host galaxy
- Observed predominantly via radio emission at large distance from black hole
    - Could be powered by energy extracted from spin of black hole by Blandford-Znajek process

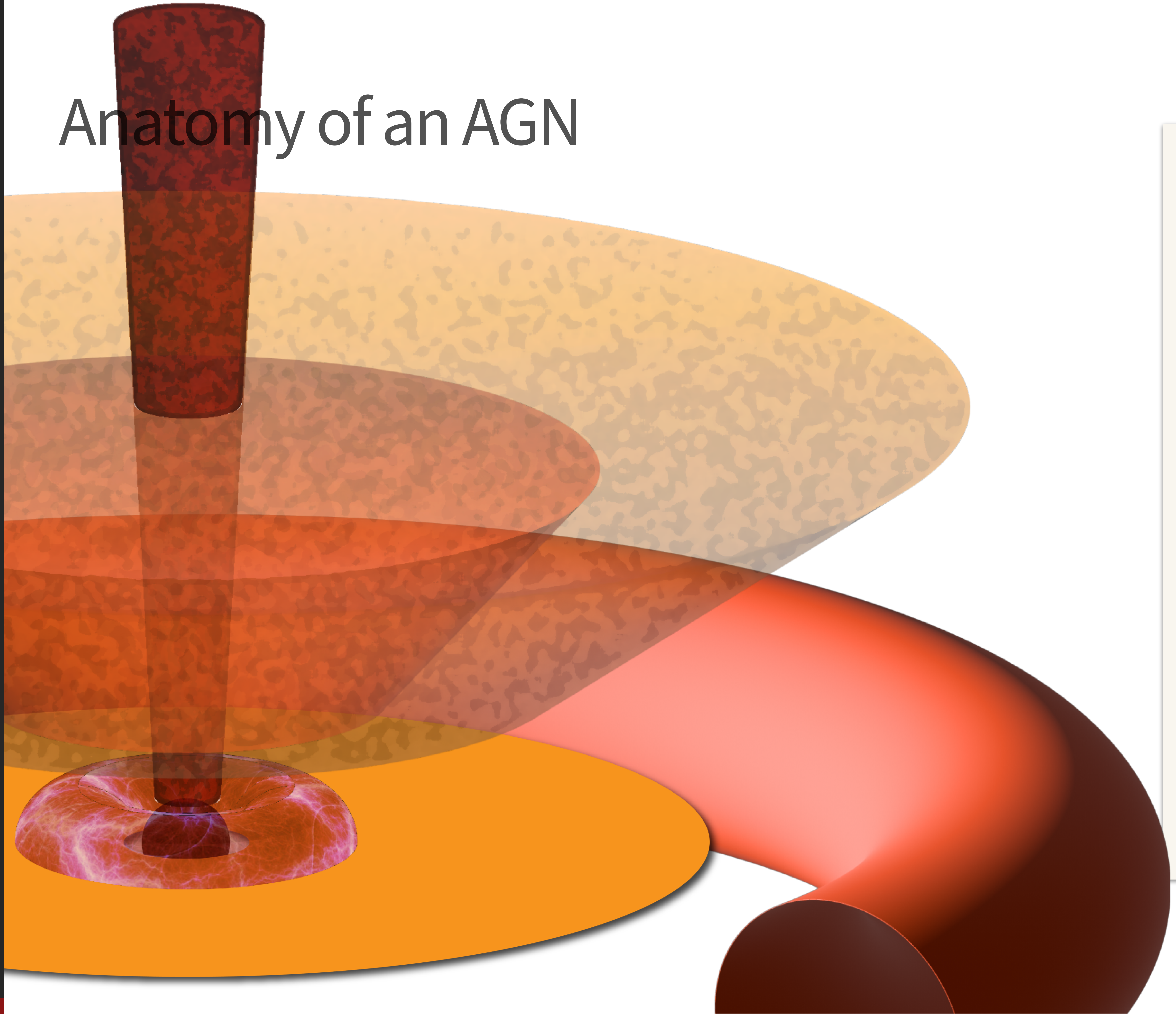
Anatomy of an AGN



The Torus

- Beyond accretion disc, large scale, optically thick, dusty torus
- Reflection from cold, neutral material (narrow emission lines in the X-ray band)
- Obscures central engine along low-latitude lines of sight
- Re-radiates infrared
- Likely clumpy

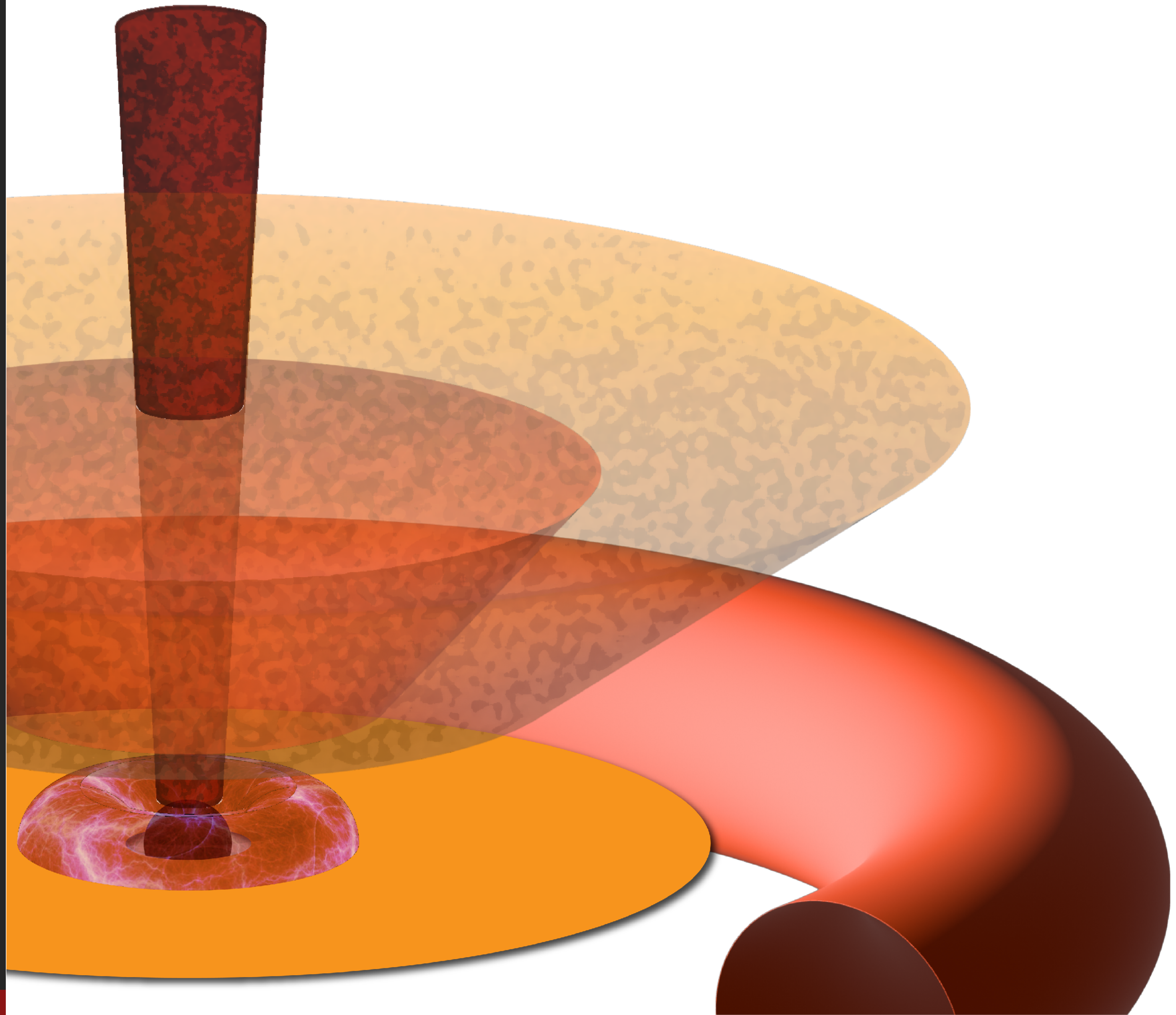
Anatomy of an AGN



BLR, NLR, Absorbers

- Gas in orbit around central black hole
- **Broad line region (BLR):** higher velocity gas, observed via broad optical line emission
- **Narrow line region (NLR):** lower density, lower velocity, at larger radius, observed via narrow optical emission lines
- **Warm absorbers:** ionised, outflowing gas, observed via absorption lines in X-ray spectrum
- Launched from outer accretion disc, or evaporation from torus?

AGN unification



- AGN are intrinsically radio loud (with large-scale jet) or radio quiet (without)
- Appearance (type I, type II, blazar) depends on the orientation of our line of sight
- But there are counter examples!
  - "Intrinsically" type II (or "bare" type II) with no NLR, but no apparent obscuration
  - Changing look AGN (type I to type II) – orientation can't be changing!

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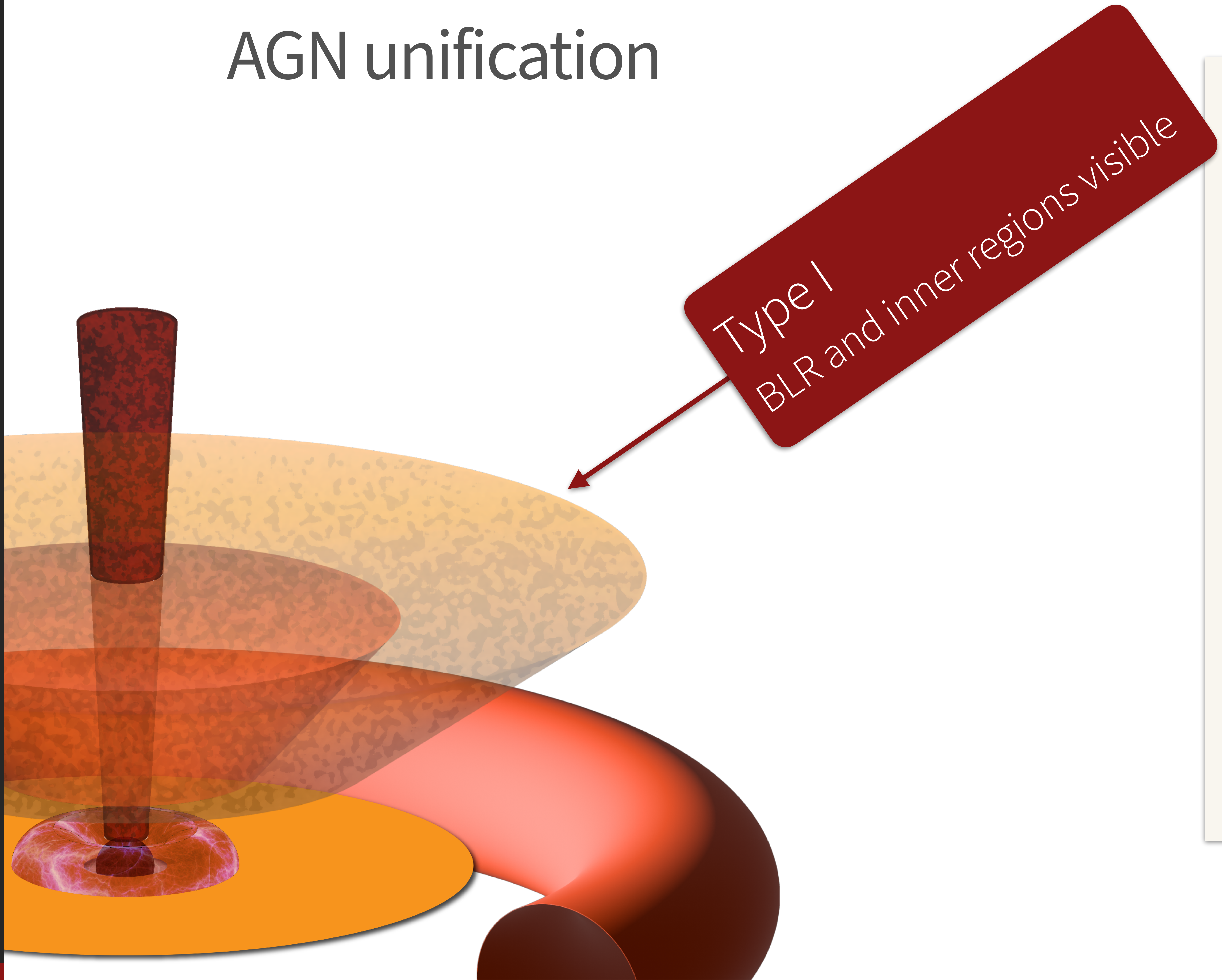

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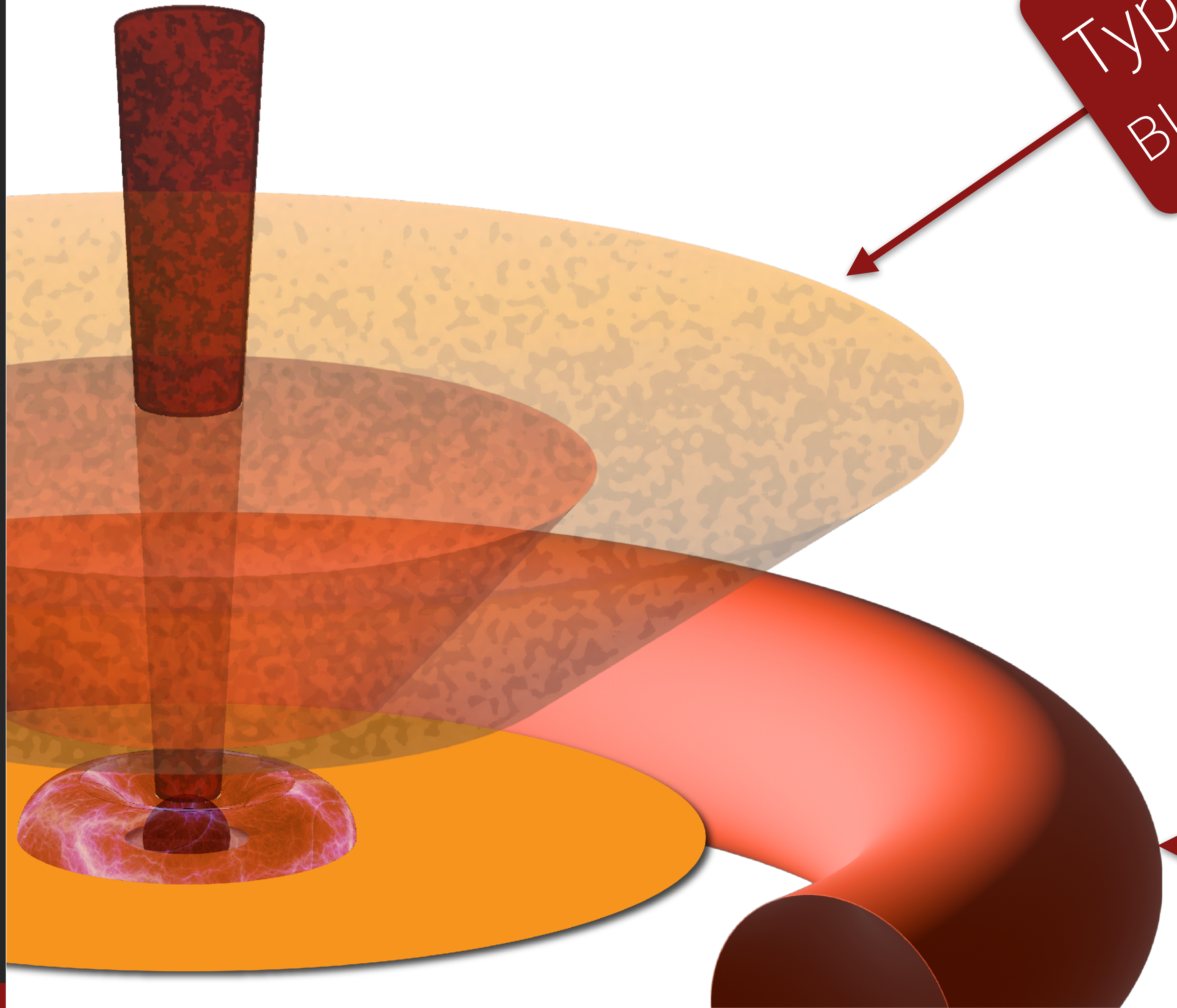

Type I
BLR and inner regions visible

Type II
BLR (and inner regions) obscured by torus

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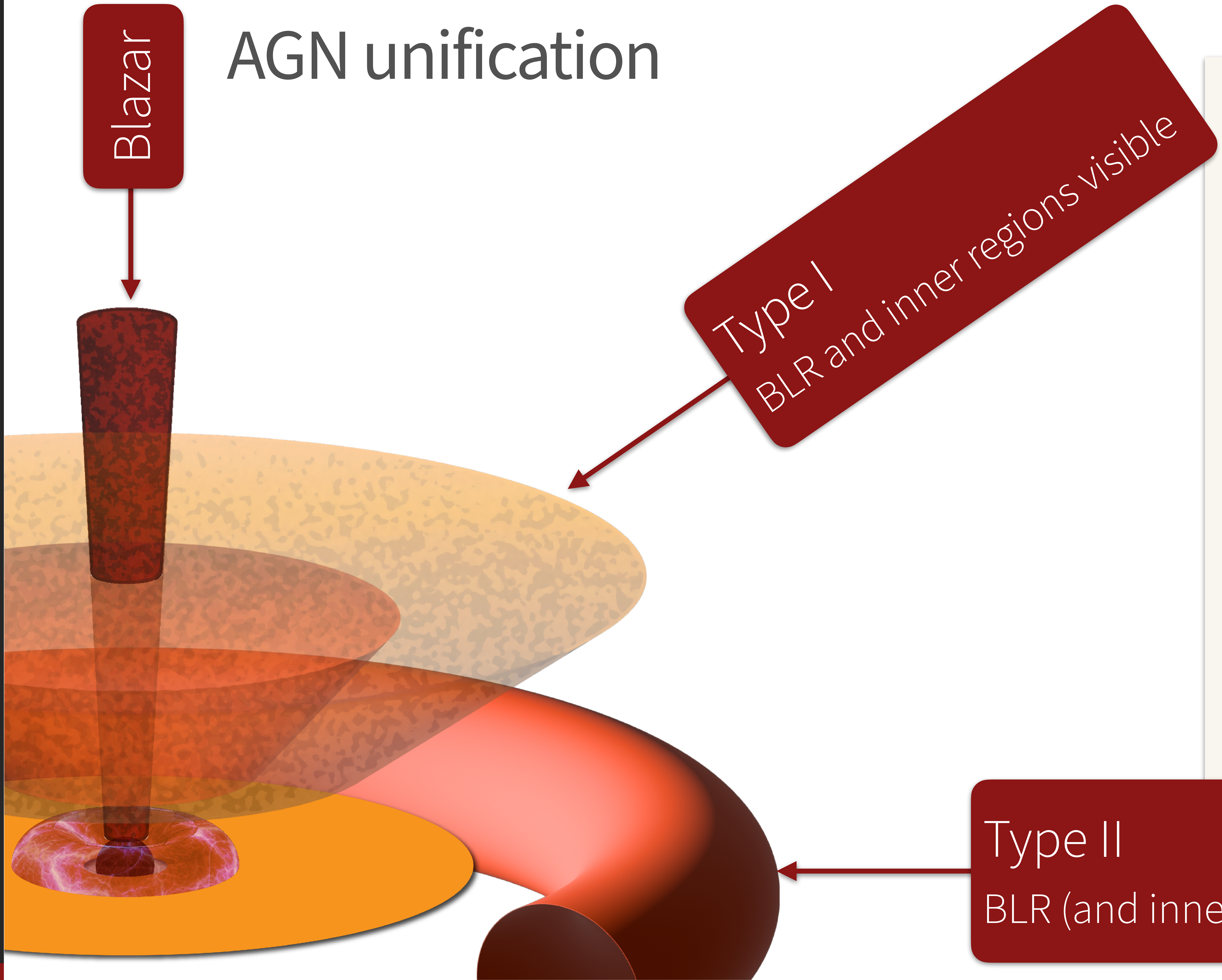

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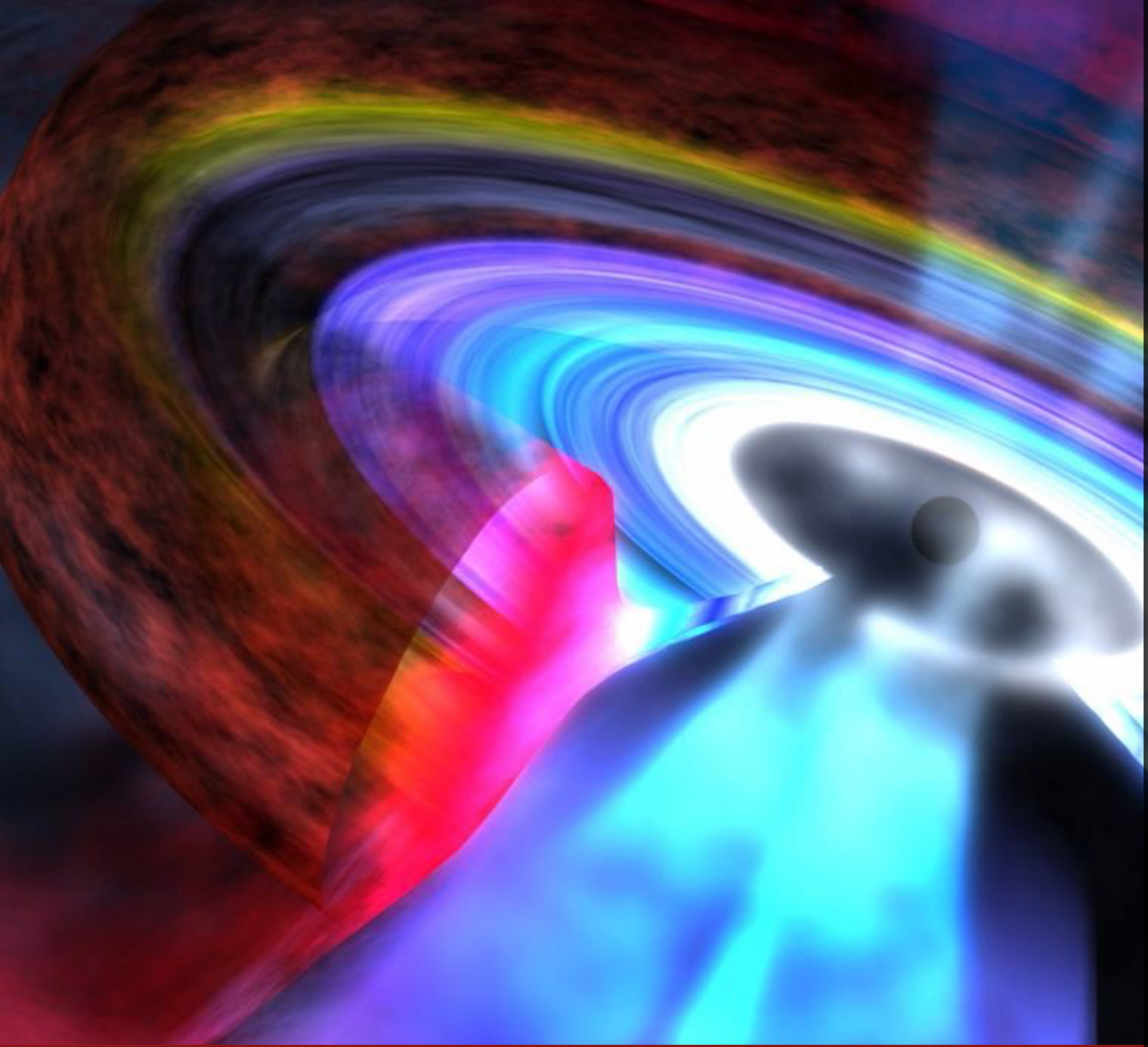
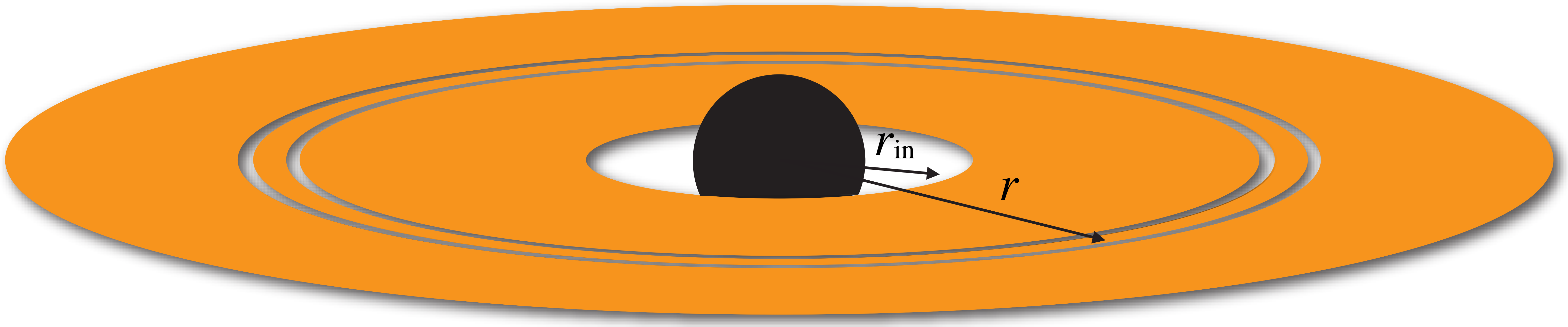


The accretion disc

The standard accretion disc



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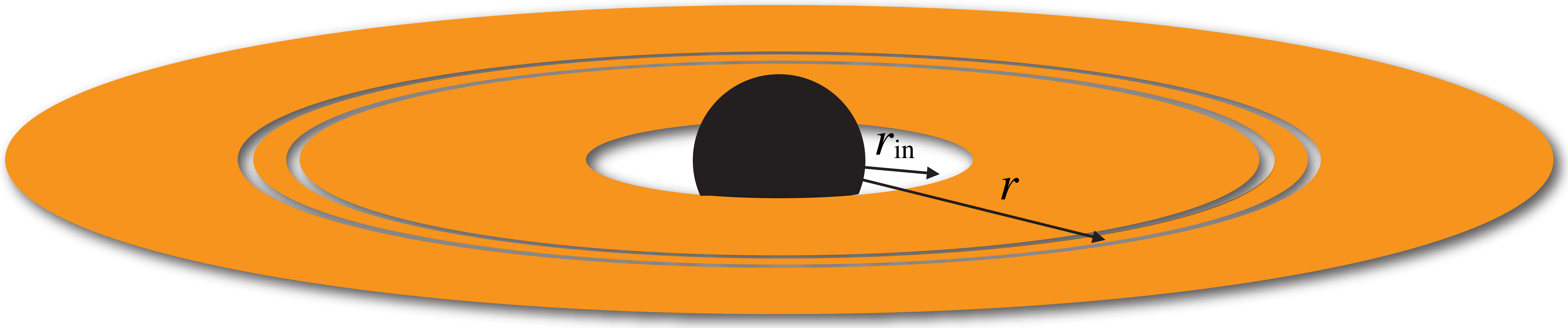

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- Material in stable circular orbit at each radius

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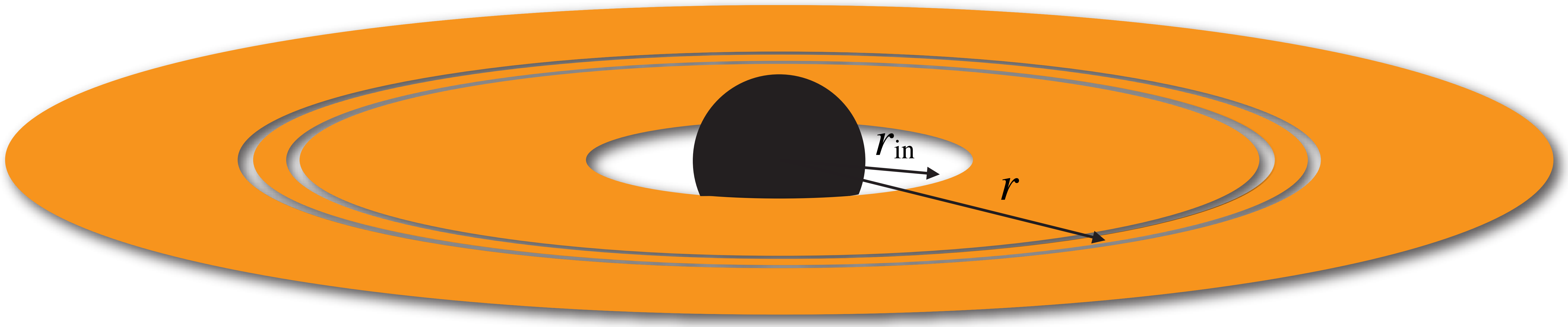

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  - Classical viscous friction insufficient to achieve mass inflow rates implied by observed luminosity. Likely magnetically-generated viscosity drives the accretion process (magneto-rotational instability)
- Material spirals inwards as it loses angular momentum

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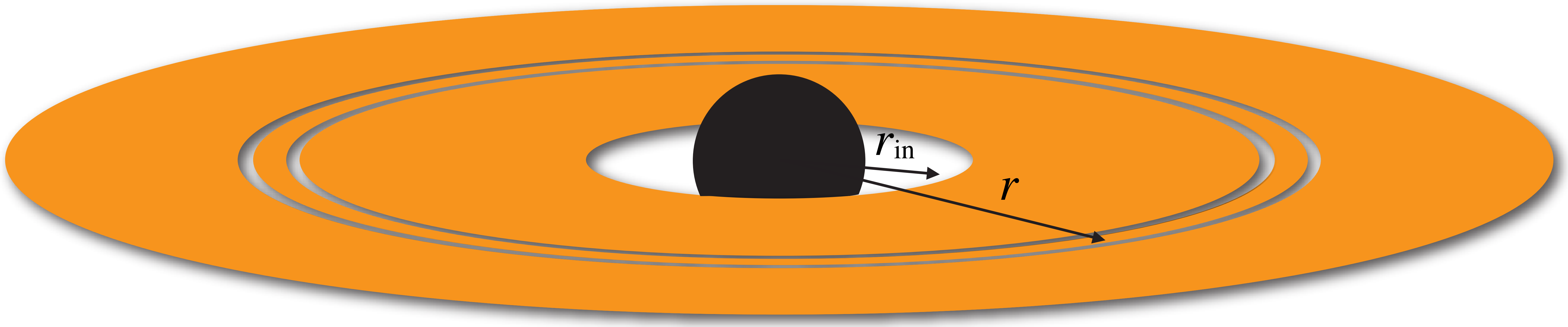

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- Material spirals inwards as it loses angular momentum
- In General Relativity, at innermost stable circular orbit, material transitions to plunging orbit. Velocity increases rapidly, so to conserve mass, density must drop in plunging region

Accretion disc emission

- Viscous forces dissipate energy locally, heating material

$$T(r) = \left[\frac{3GM\dot{M}}{8\pi\sigma_{\mathrm{SB}}r^3}\left(1-\sqrt{\frac{r_{\mathrm{in}}}{r}}\right)\right]^{\frac{1}{4}}$$

$$= (1.1\times10^6)\left(\frac{M}{10^8 M_\odot}\right)^{-\frac{1}{4}}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Ed}}}\right)^{\frac{1}{4}}\left(\frac{r}{r_{\mathrm{g}}}\right)^{-\frac{3}{4}}\left(1-\sqrt{\frac{r_{\mathrm{in}}}{r}}\right)^{\frac{1}{4}}\ \mathrm{K}$$

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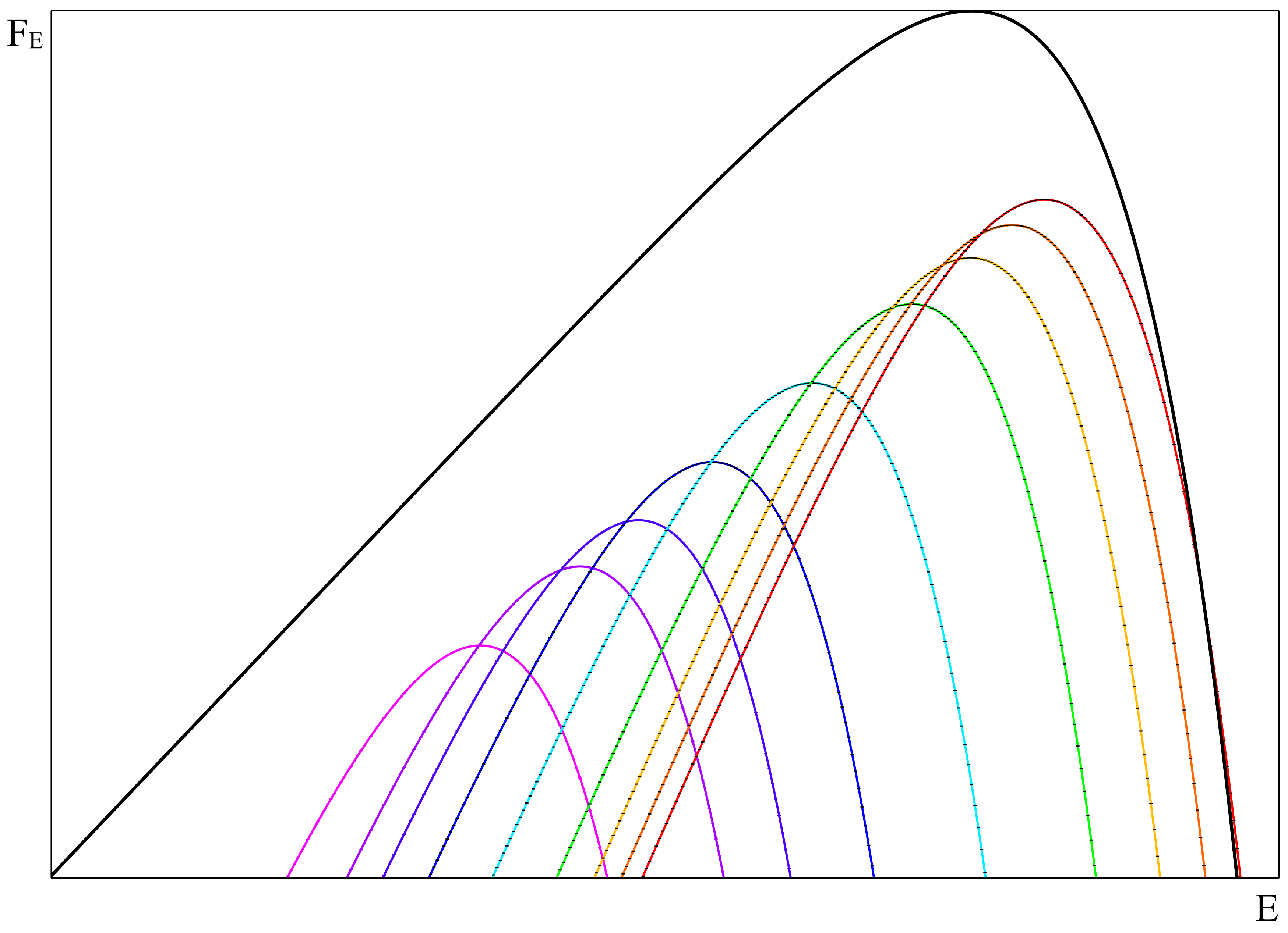

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$$h\nu_{\rm peak} \approx 2.8k_{\rm B}T$$

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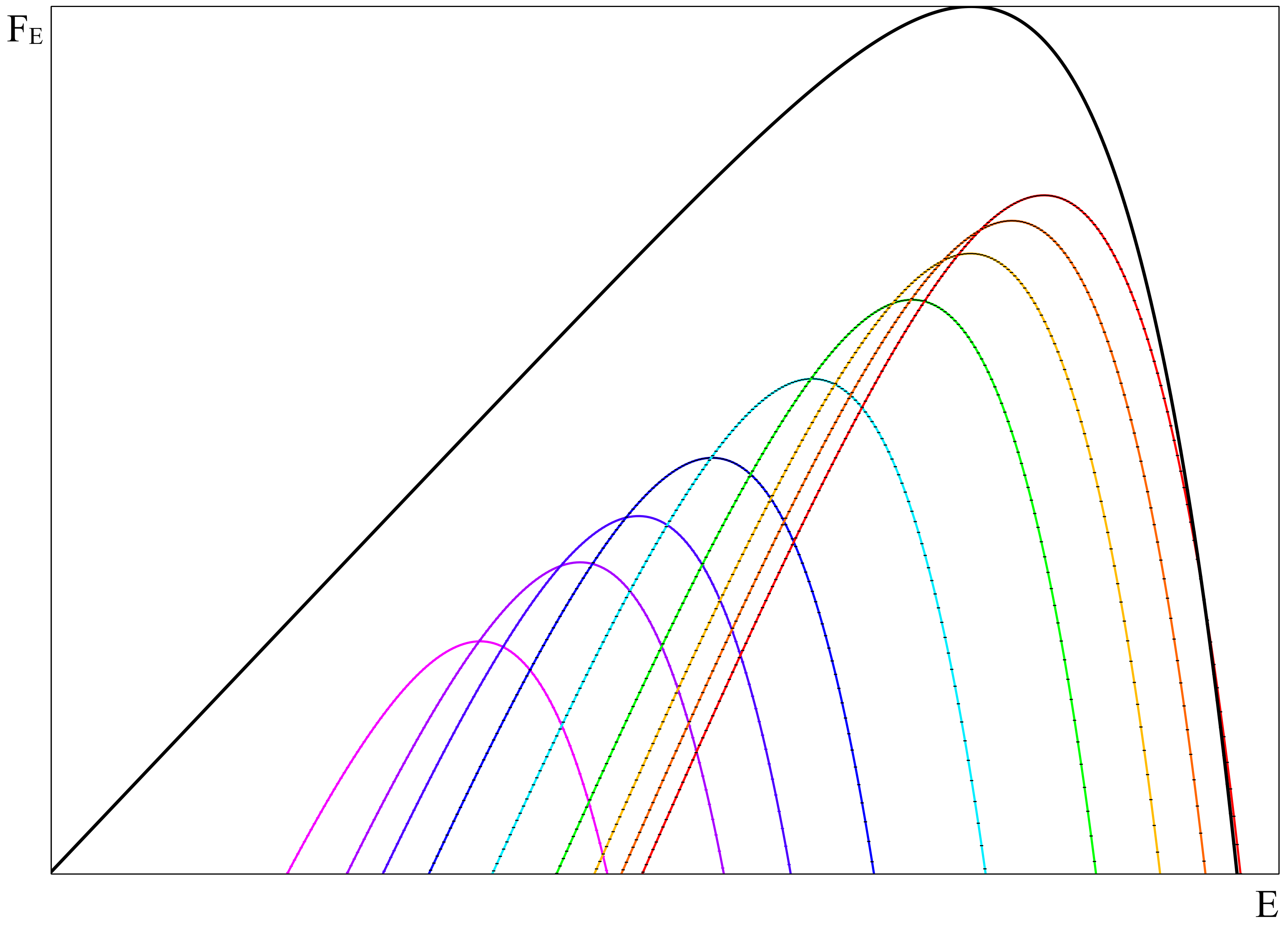

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- $T_{\rm in} \propto M^{-\frac{1}{4}}$: Accretion discs around supermassive black holes peak at UV wavelengths

Mass accretion rate

Mass accretion rate

- Measure luminosity relative to the Eddington limit (maximum luminosity for spherical accretion, where radiation pressure balances gravitational pull)

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}} \sim 10^{38} \left(\frac{M}{M_\odot}\right) \,{\rm erg\,s^{-1}}$$

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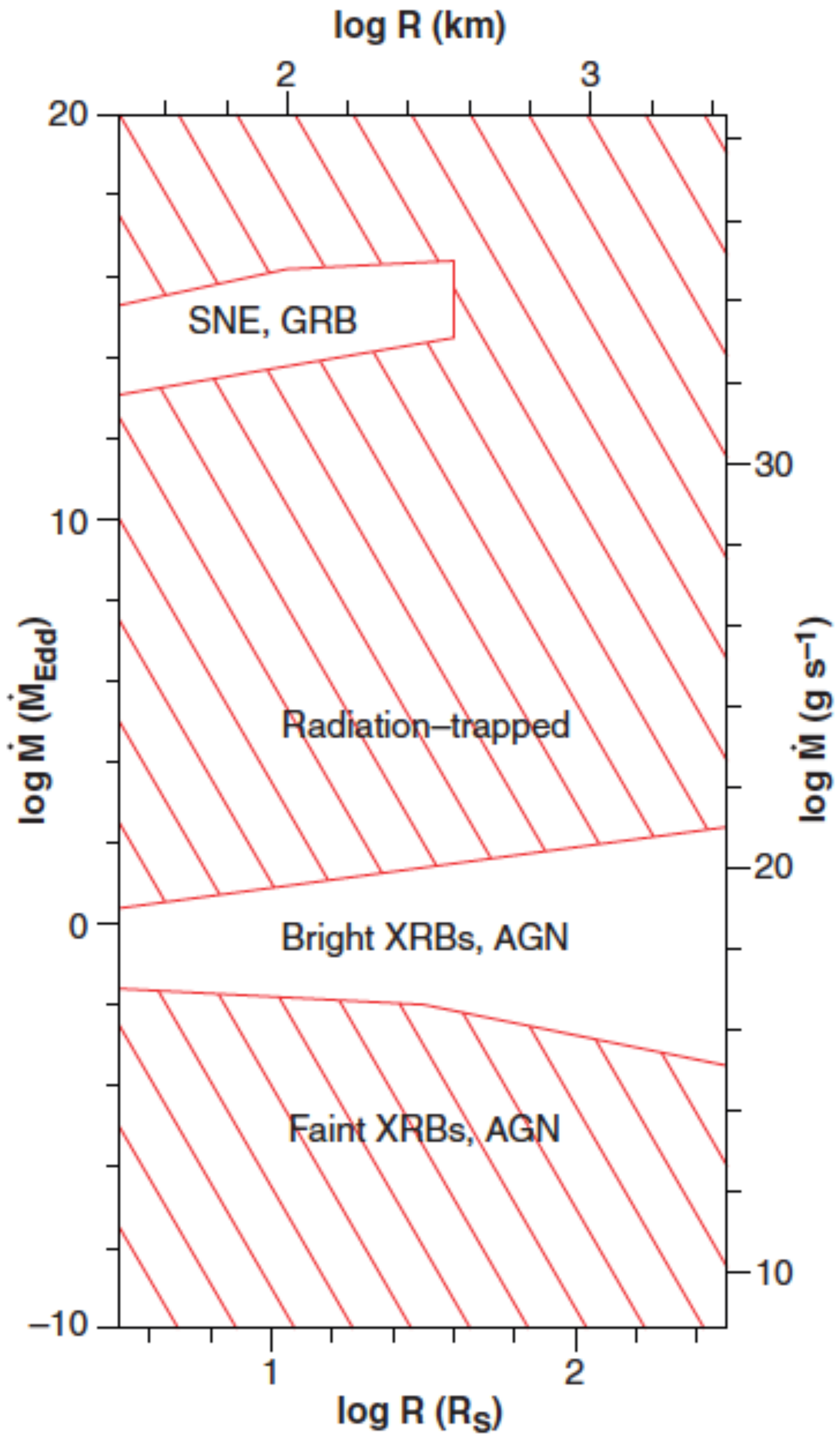
- Define the Eddington ratio $\lambda_{\rm Edd} = \frac{\dot{m}}{\dot{m}_{\rm Edd}}$

The accretion flow vs. mass accretion rate



Narayan 1998, Narayan & Quataert 2005

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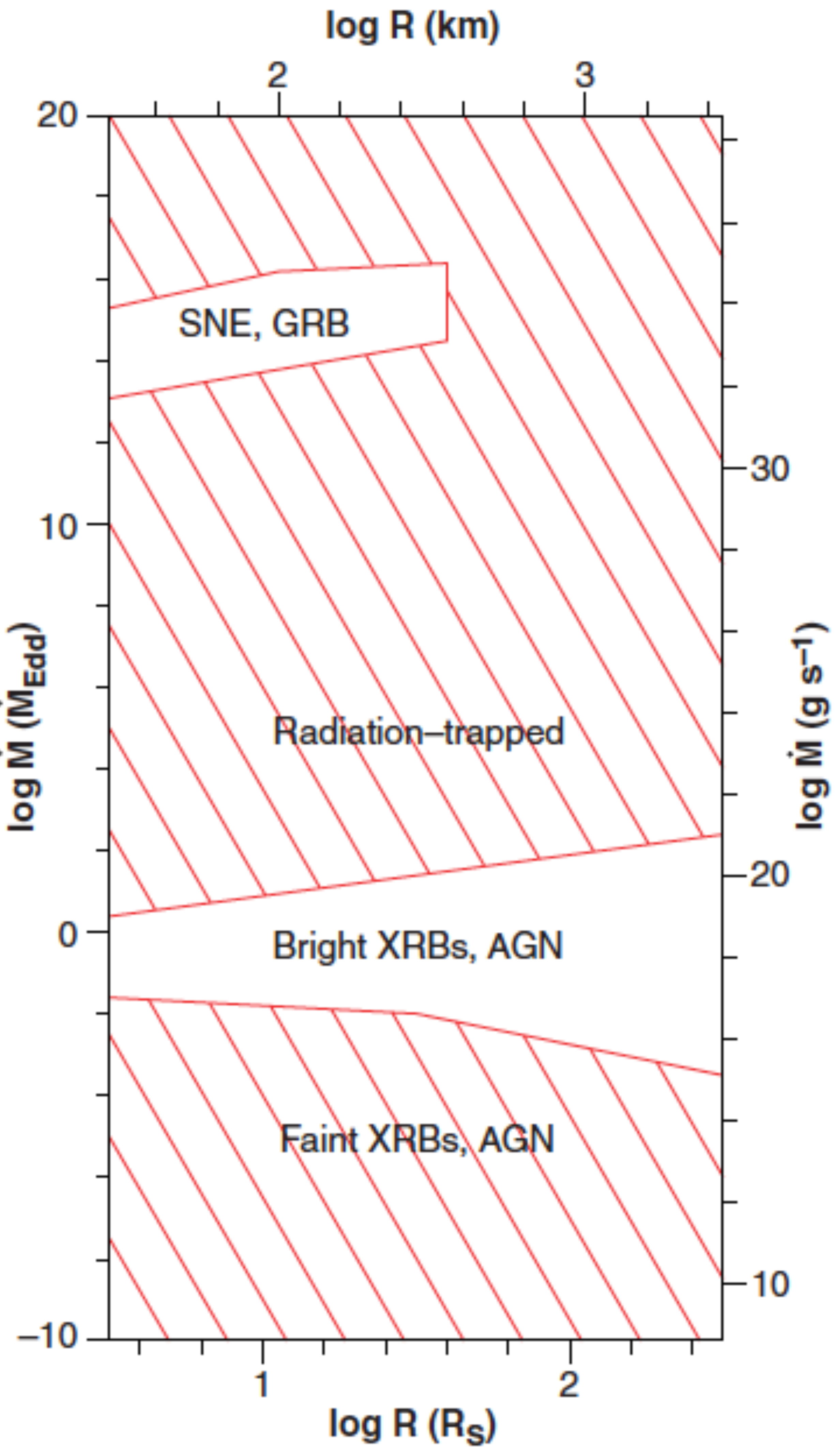
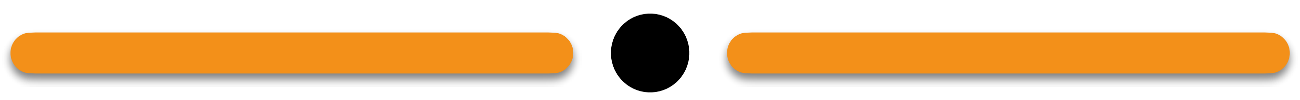


$0.1 \sim 0.3\,\dot{m}_{\rm Edd}$



Efficient cooling allows formation of geometrically thin, optically thick accretion disc ('standard' accretion disc)

Narayan 1998, Narayan & Quataert 2005

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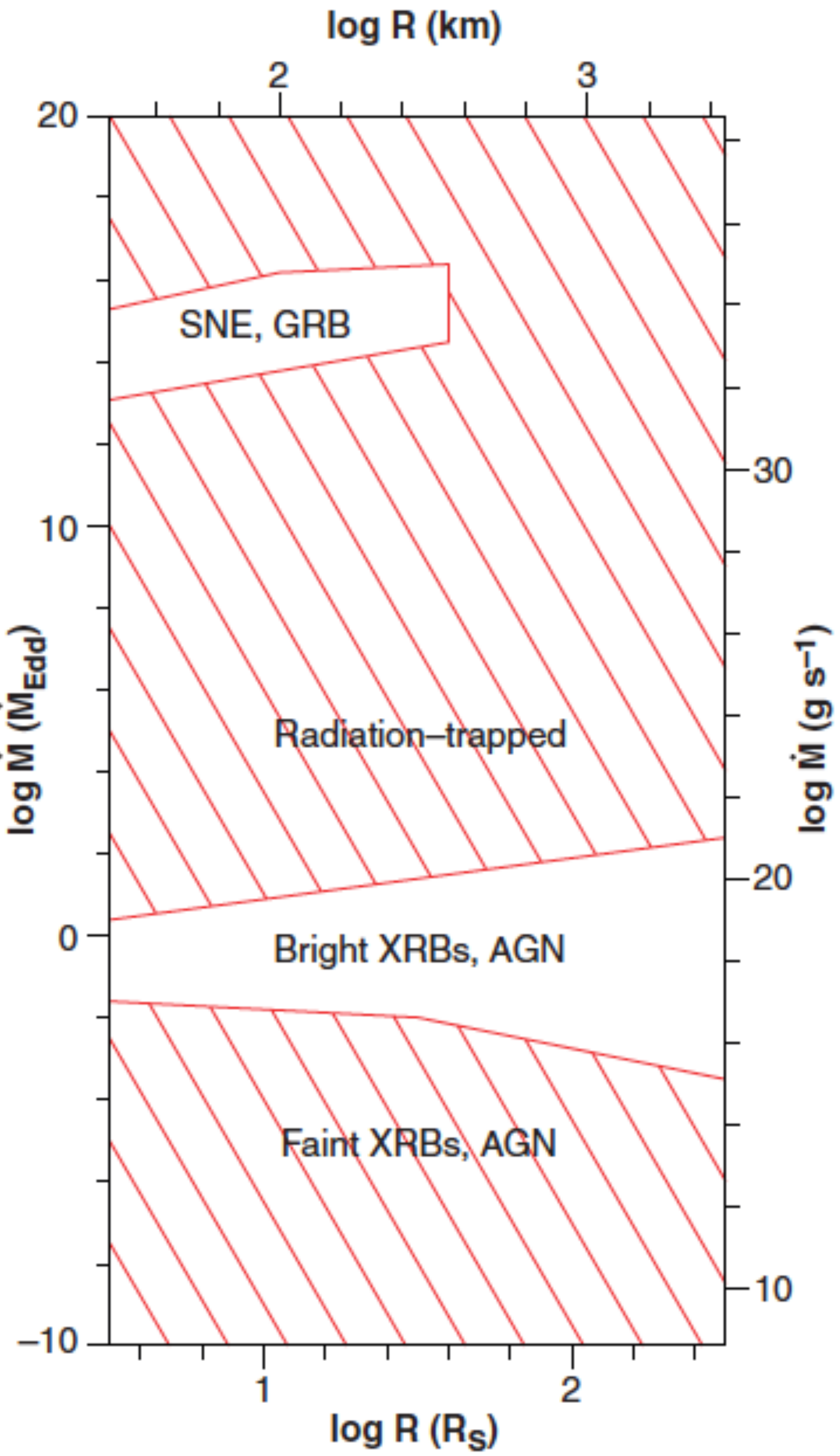
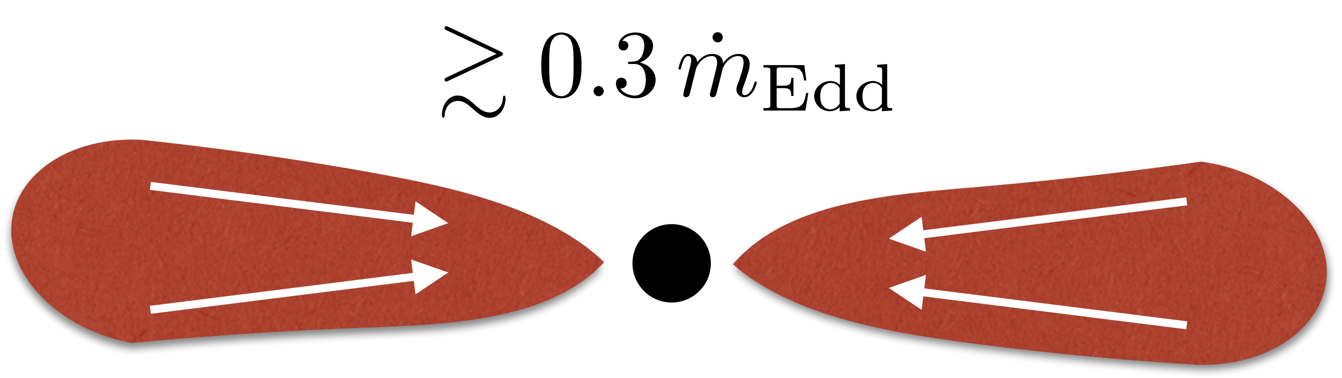
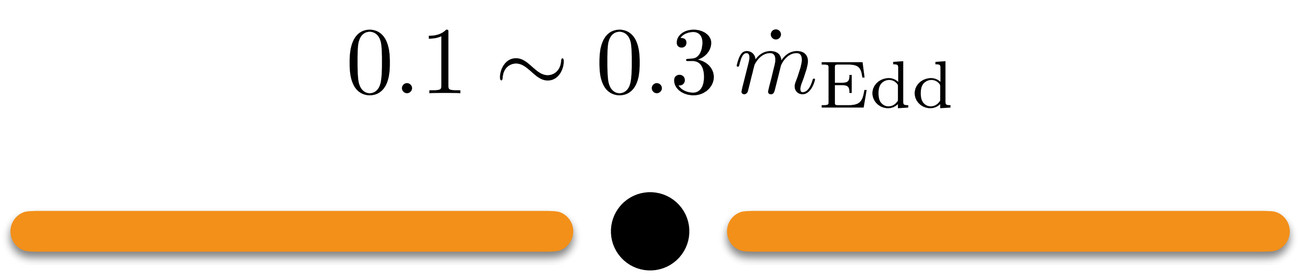




Trapping of photons causes disc to become radiation-pressure dominated and expands to slim disc (with radiation-driven outflow)



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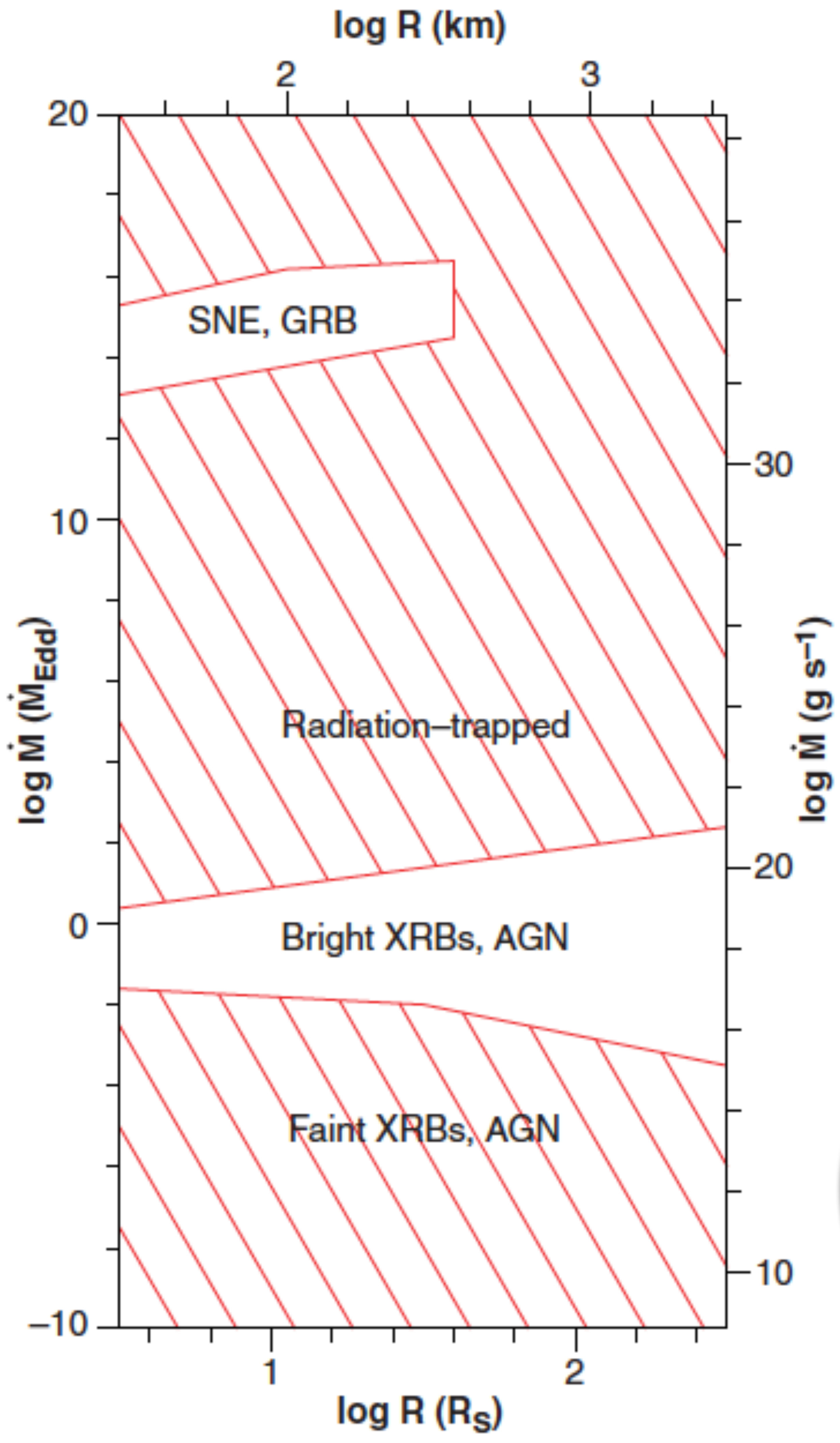
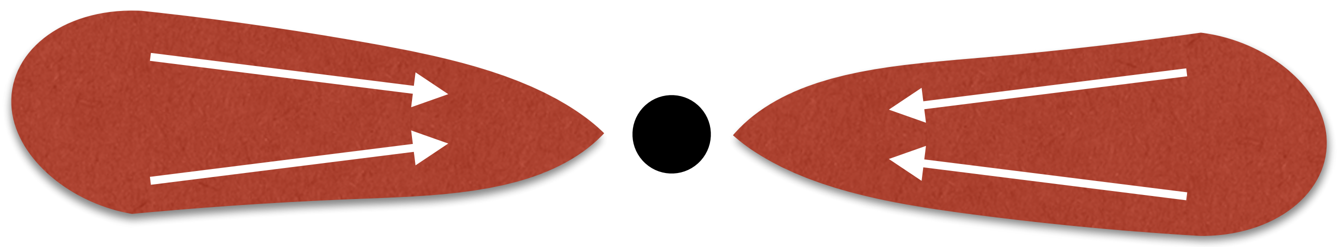


$\gtrsim 0.3\,\dot{m}_{\rm Edd}$



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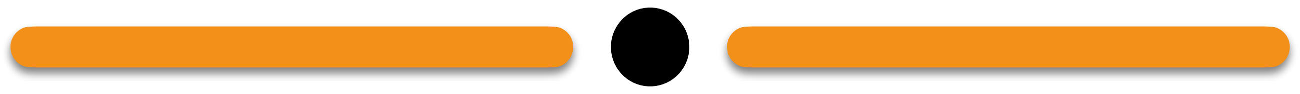

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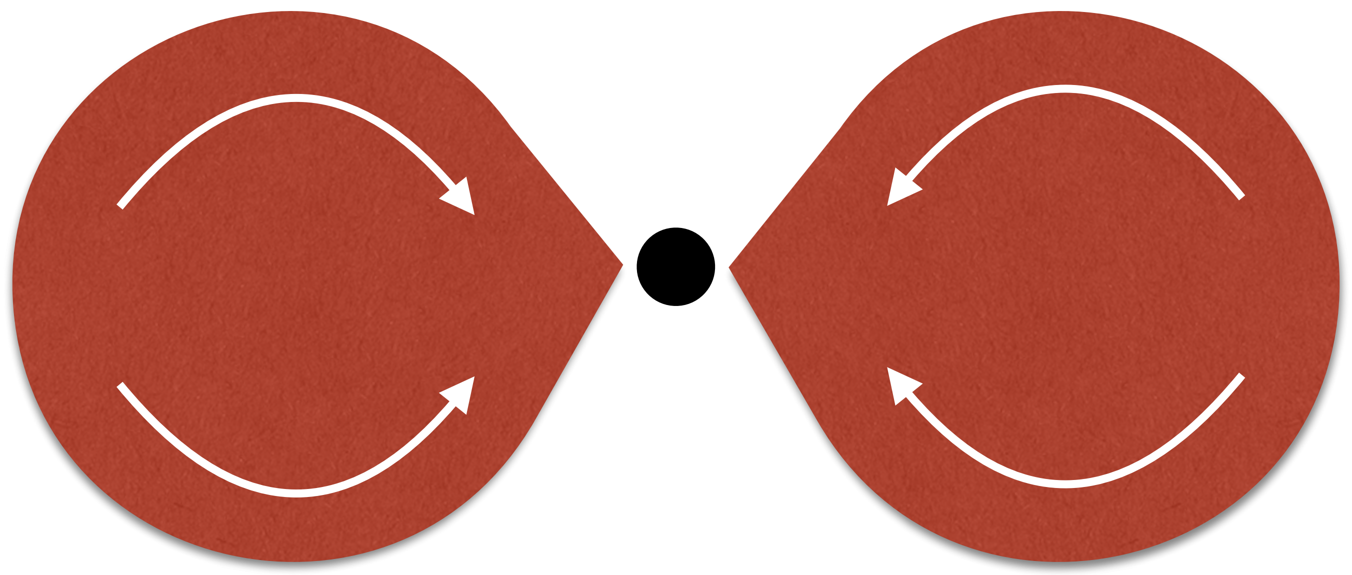
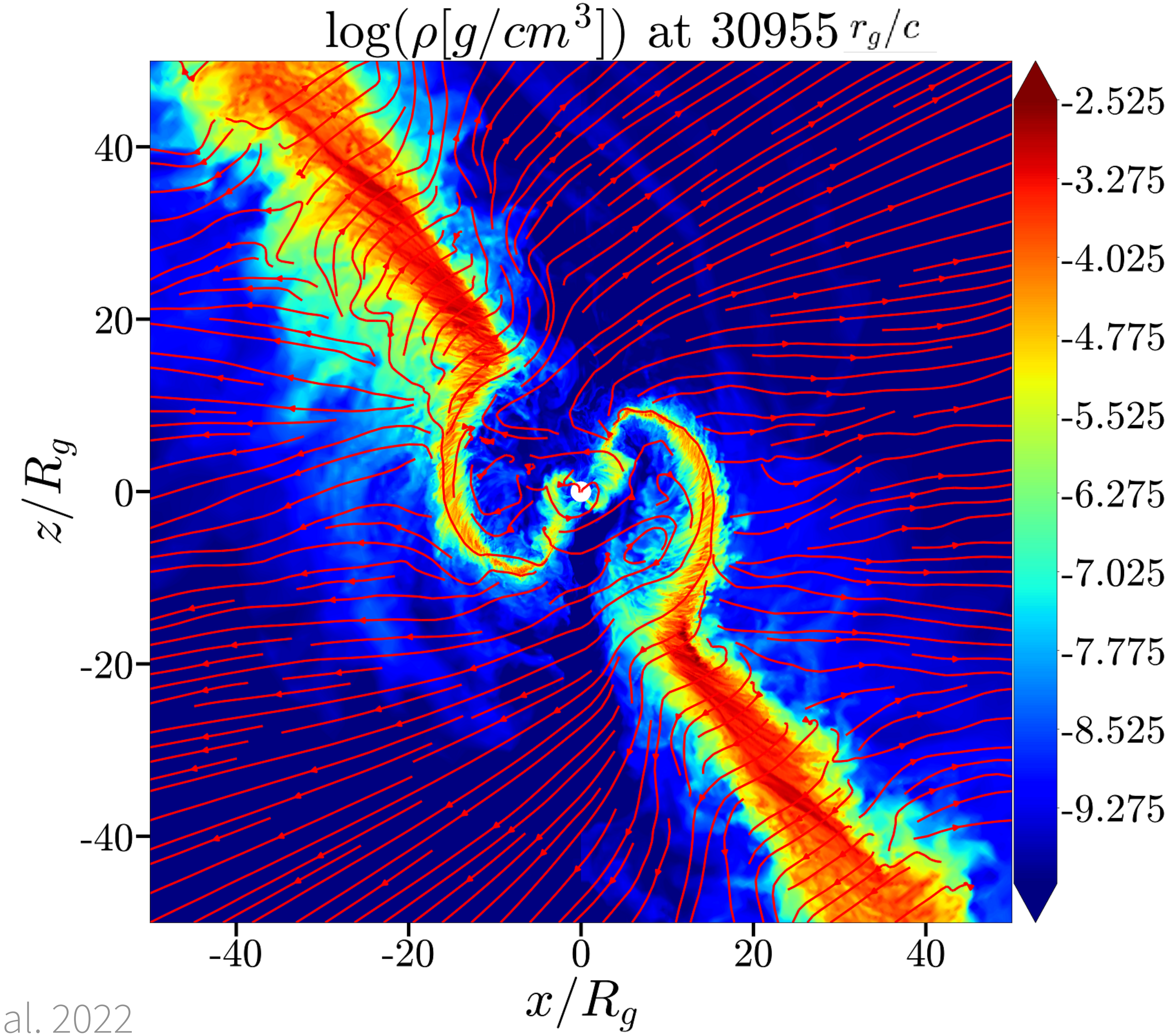


Low density leads to inefficient radiative cooling. Thermally supported, geometrically thick, optically thin flow. Advection dominated (ADAF, RIAD)

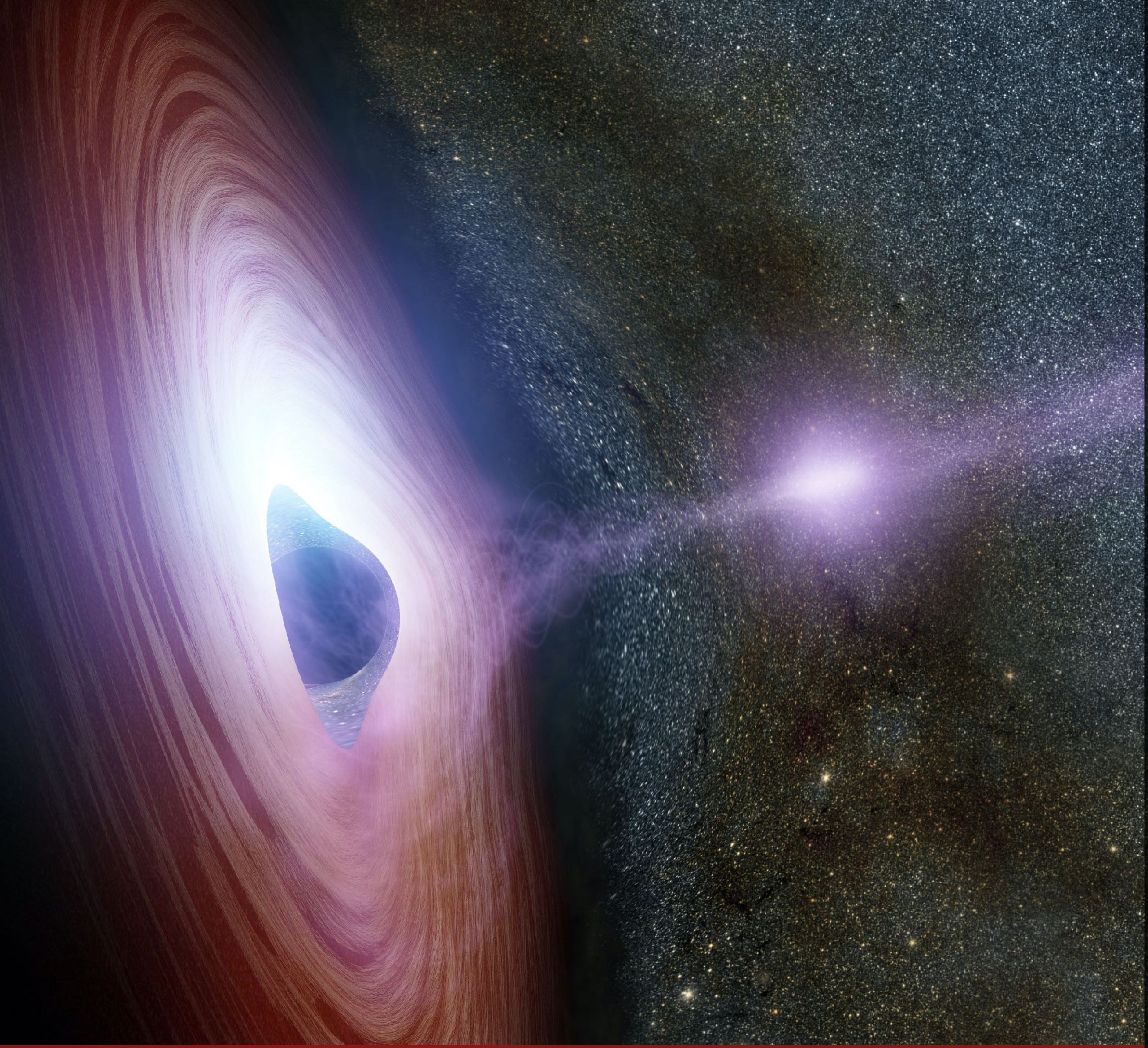
Narayan 1998, Narayan & Quataert 2005

Real accretion discs are more complicated!



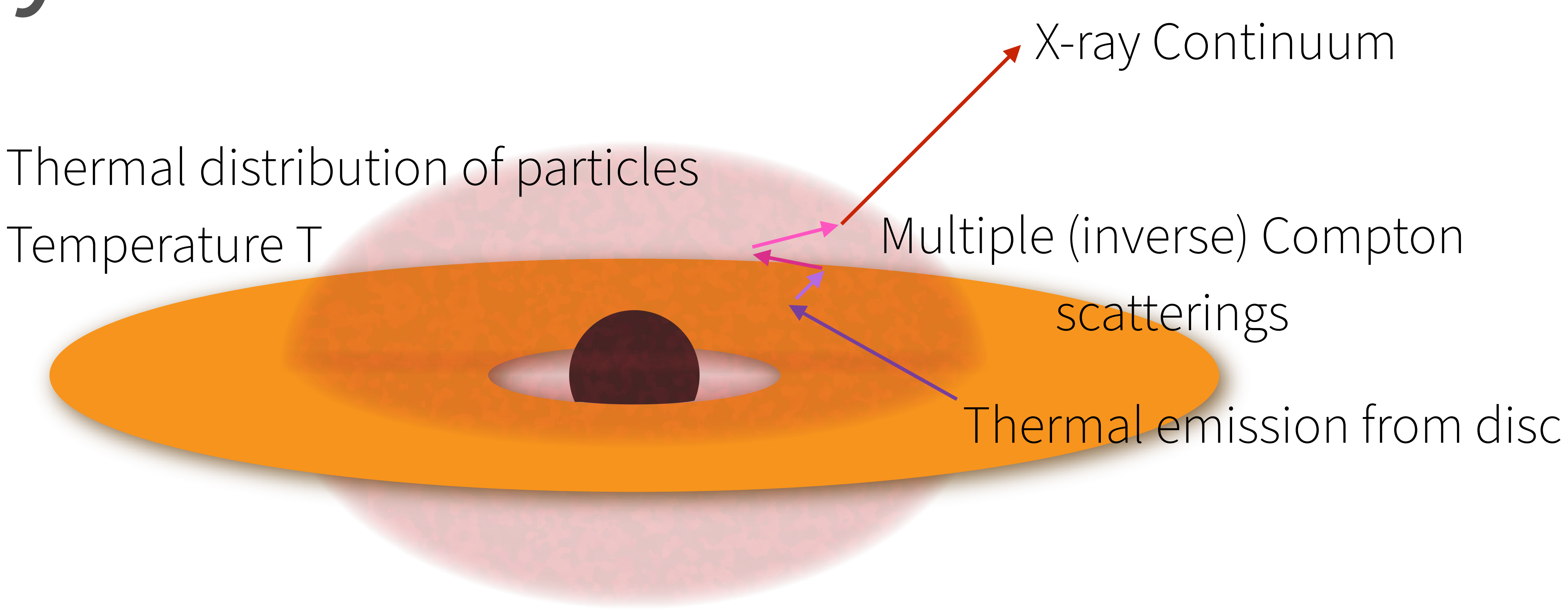
Liska et al. 2022

- State of the art simulations are RT-GRMHD (radiation transport, general relativistic magneto-hydrodynamics)
- Simulate interaction of plasma and electromagnetic fields in curved spacetime around spinning black hole
- Turbulence
- Disc dynamo generates magnetic field
- Magnetic instabilities



The corona

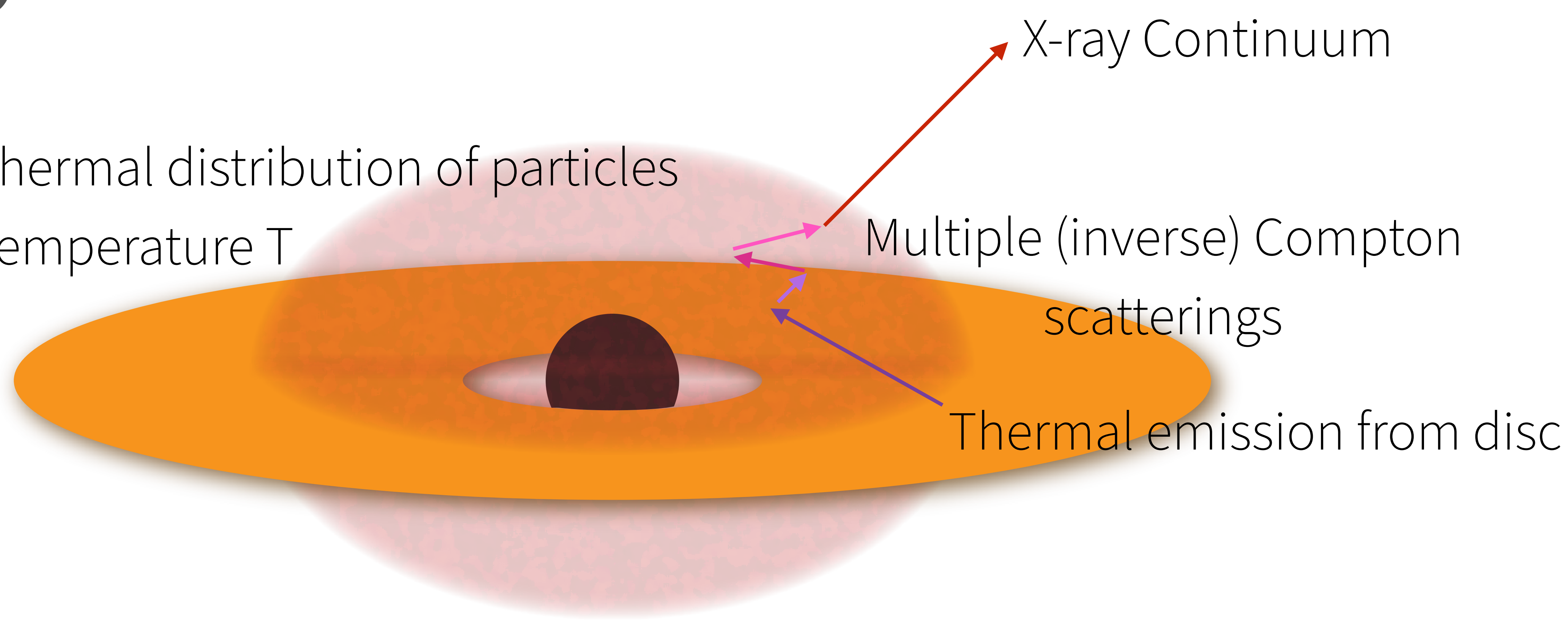
The X-ray continuum



- Compact corona of accelerated particles close to black hole
- Seed photons (inverse) Compton scatter off high-energy electrons
  - Seed photons originate from accretion disc thermal emission (UV), or can be internally generated in corona (synchrotron, SSC)
- Multiple Compton scatterings produce power law continuum spectrum (with cut-off at high energy)

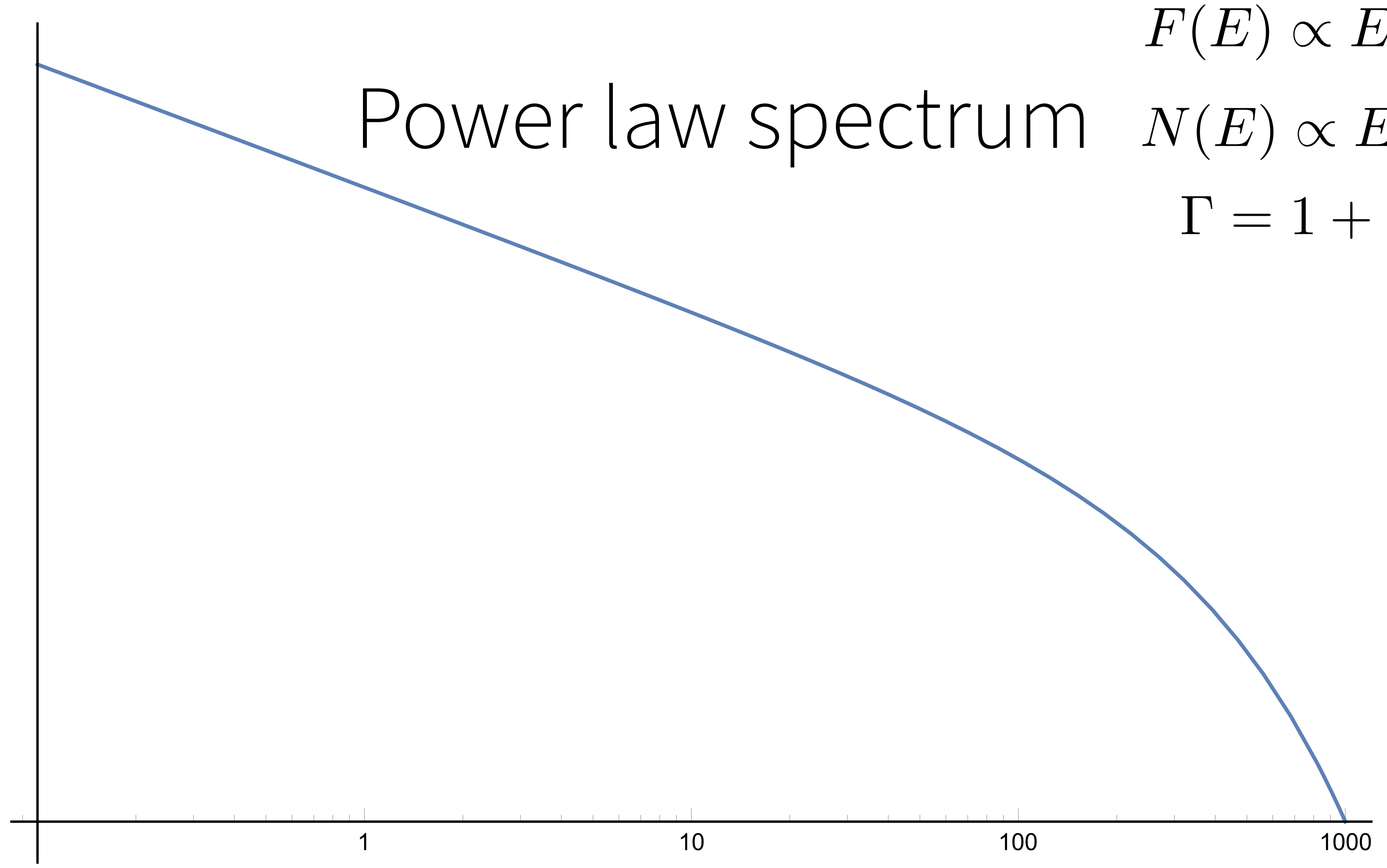
Sunyaev & Trümper 1979

The X-ray continuum



Power law spectrum

$$F(E) \propto E^{-\alpha}$$
$$N(E) \propto E^{-\Gamma}$$
$$\Gamma = 1 + \alpha$$



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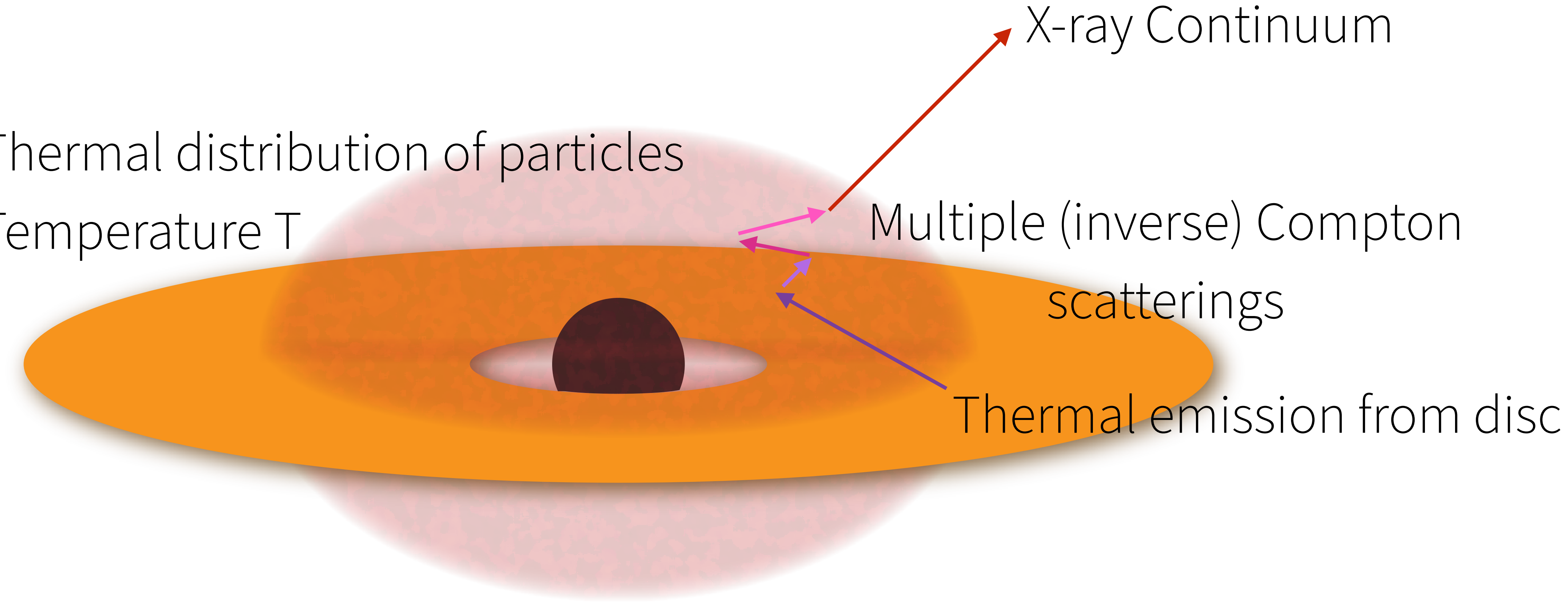
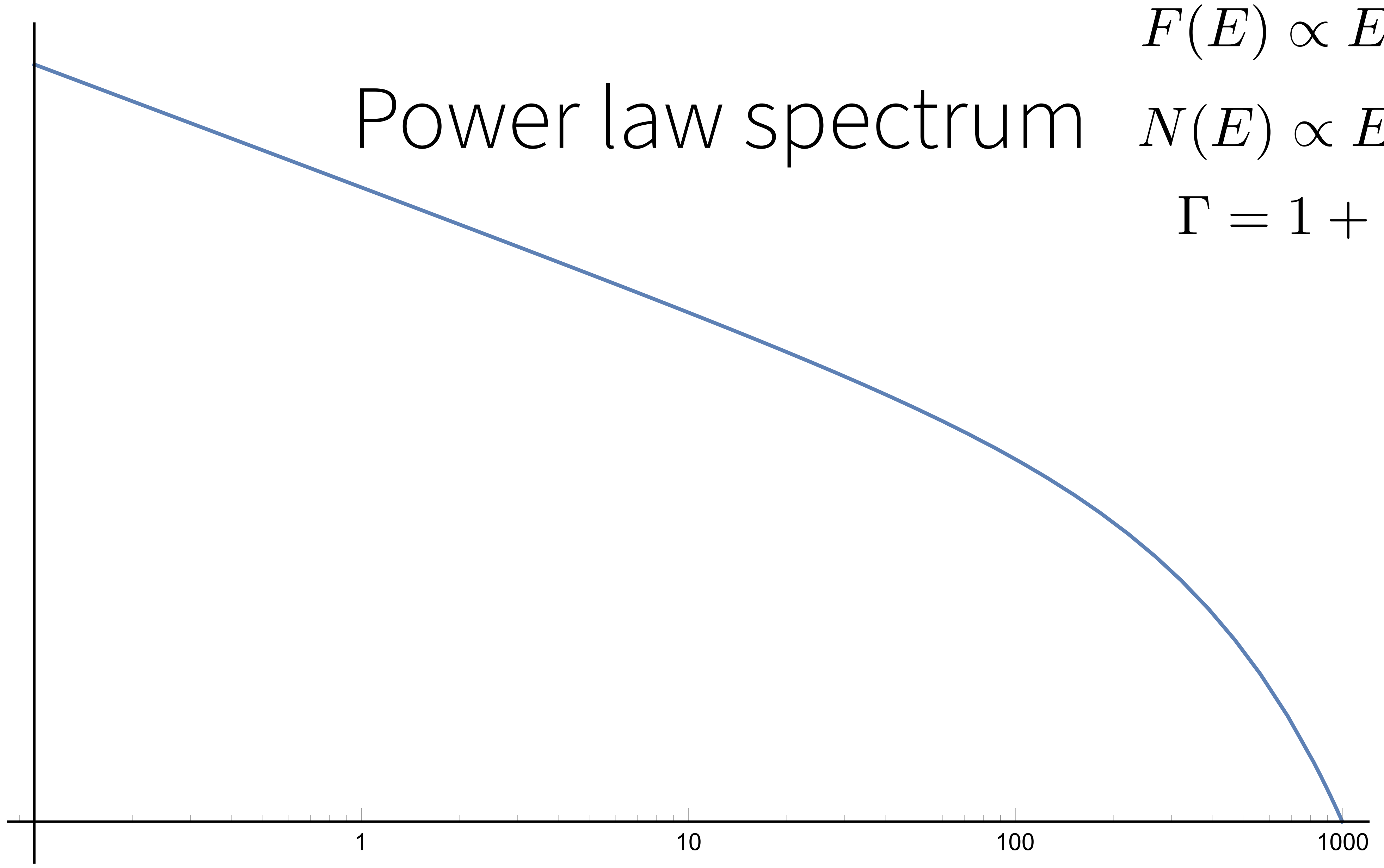


Power law spectrum



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$$\Gamma = 1 + \alpha$$

$$\alpha = -\frac{3}{2} + \left(\frac{9}{4} + \gamma\right)^{\frac{1}{2}}$$

$$\gamma = -\frac{\pi^2}{3} + \frac{m_e c^2}{kT_e \left(\tau + \frac{2}{3}\right)^2}$$

for spherical geometry

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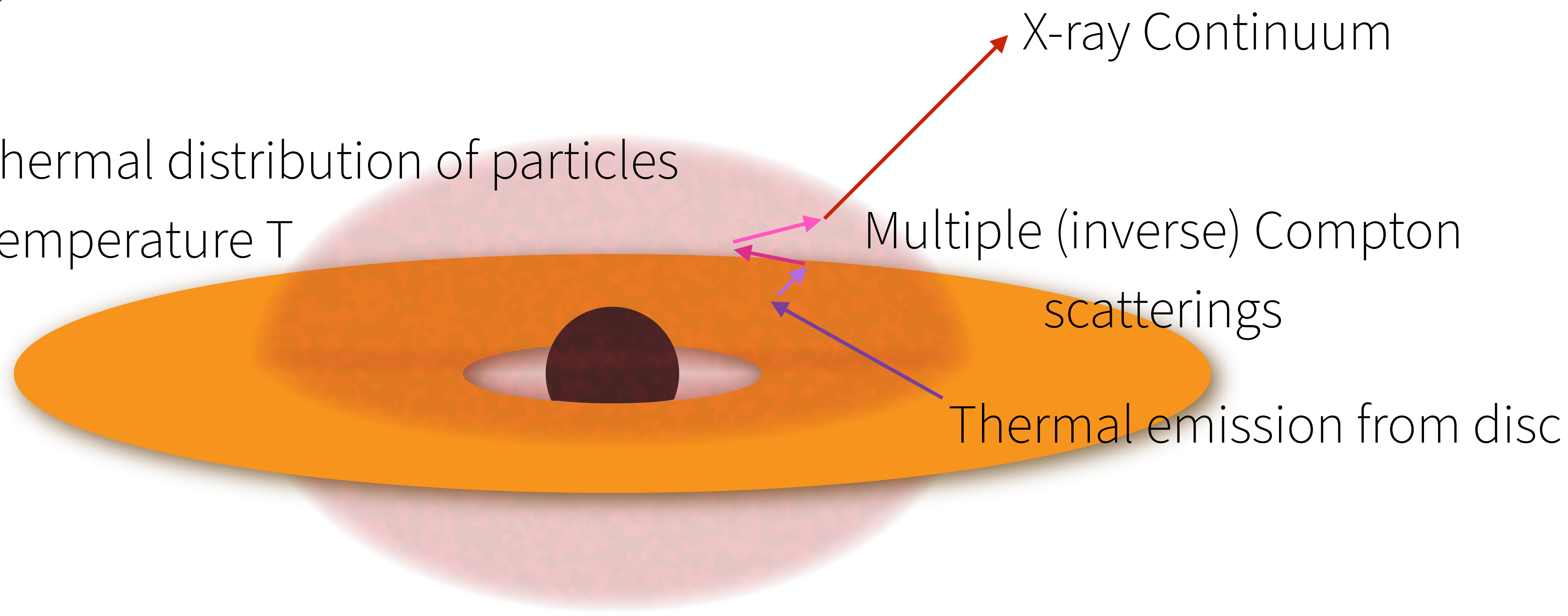
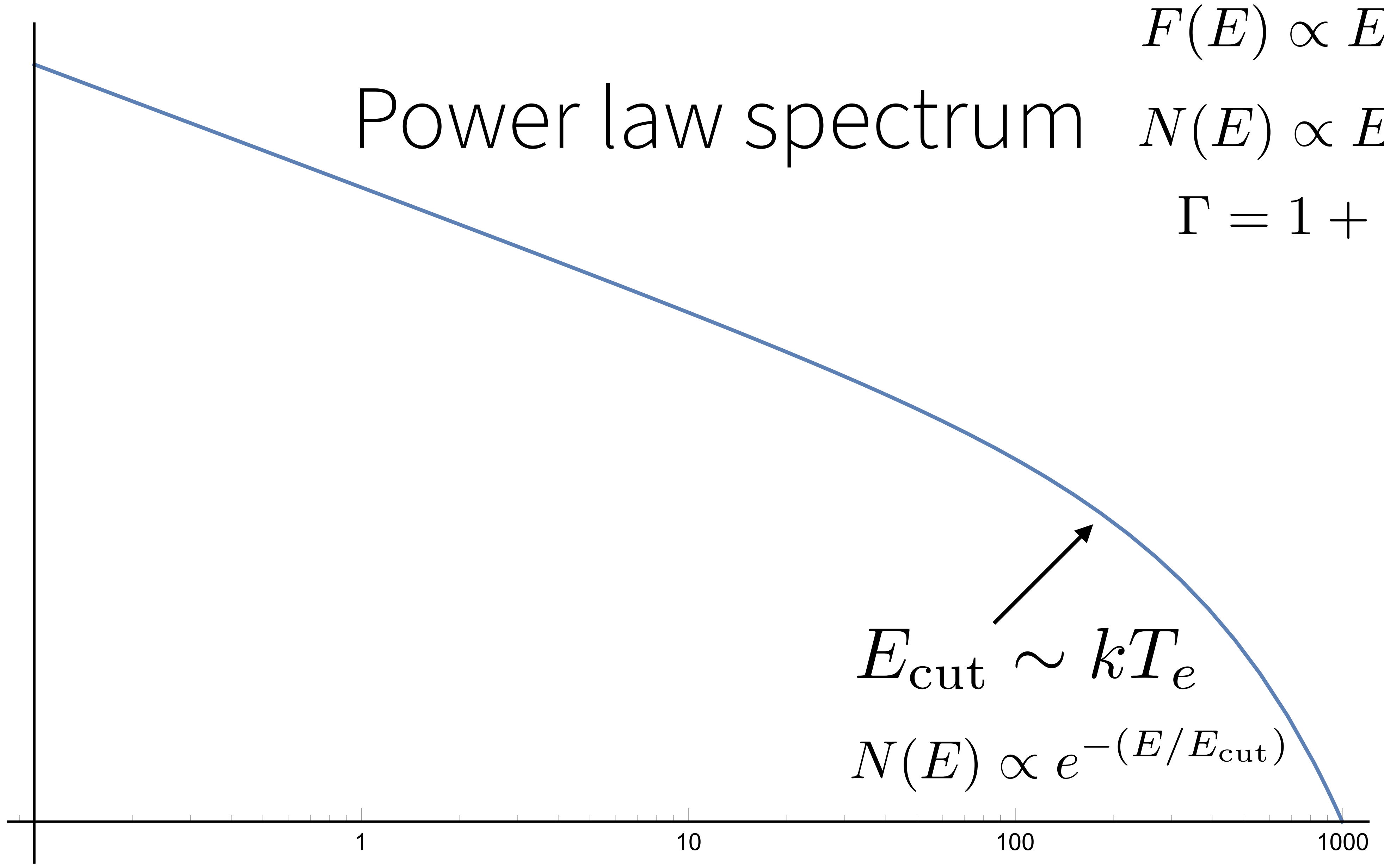
Sunyaev & Trümper 1979

The X-ray continuum





Power law spectrum

$$F(E) \propto E^{-\alpha}$$
$$N(E) \propto E^{-\Gamma}$$
$$\Gamma = 1 + \alpha$$

$$\alpha = -\frac{3}{2} + \left(\frac{9}{4} + \gamma\right)^{\frac{1}{2}}$$

$$\gamma = -\frac{\pi^2}{3} + \frac{m_e c^2}{kT_e \left(\tau + \frac{2}{3}\right)^2}$$

for spherical geometry

Cut-off at high energy, corresponding to temperature of corona

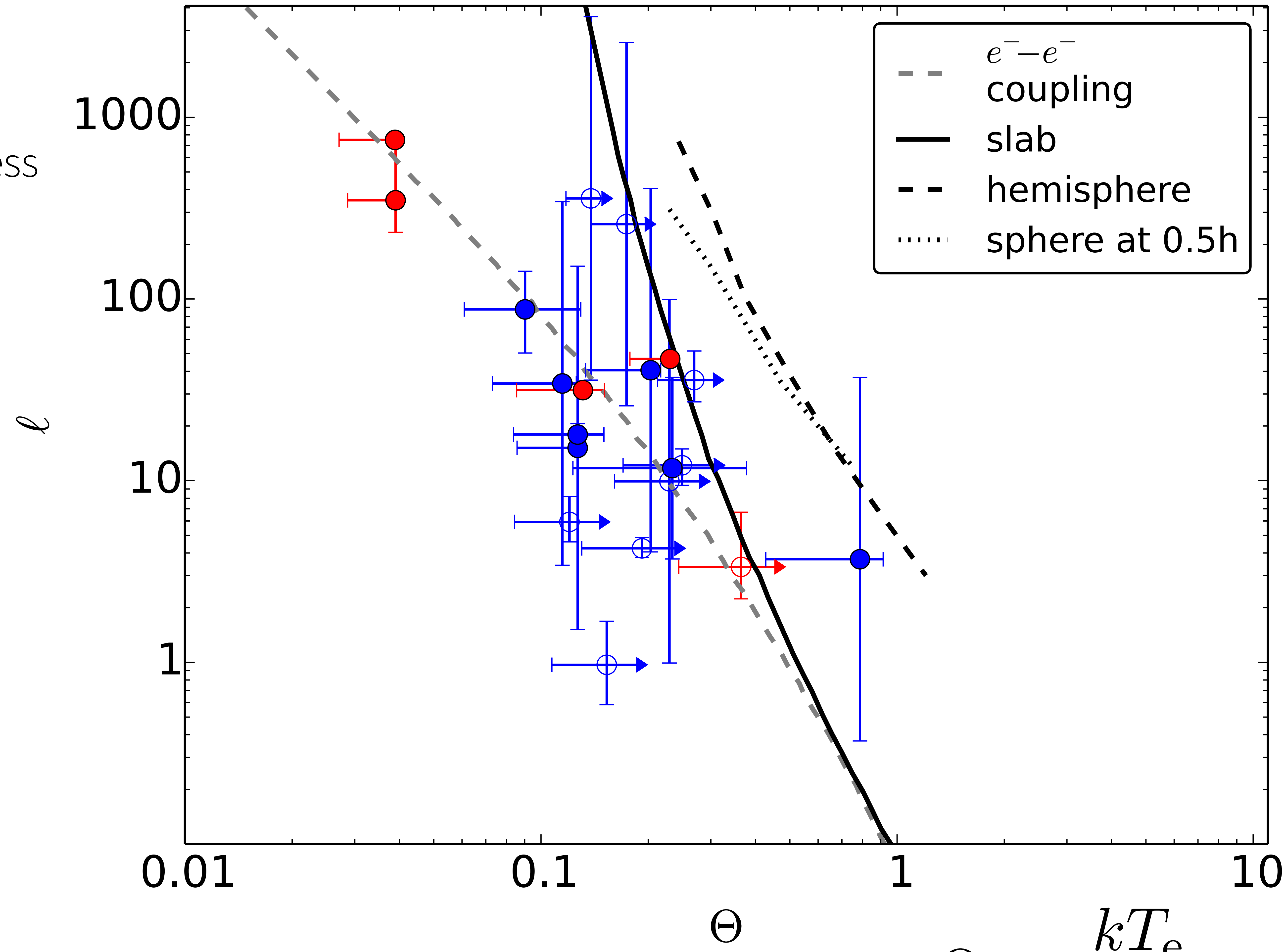
- Compact corona of accelerated particles close to black hole
- Seed photons (inverse) Compton scatter off high-energy electrons
  - Seed photons originate from accretion disc thermal emission (UV), or can be internally generated in corona (synchrotron, SSC)
- Multiple Compton scatterings produce power law continuum spectrum (with cut-off at high energy)

Sunyaev & Trümper 1979

The energetics of the corona

Compactness

$$l \sim \frac{L}{R}$$



$$\Theta = \frac{kT_e}{m_e c^2}$$

- Coronae are compact
  - Strong irradiation of inner disc observed
  - Short light travel time to disc (reverberation)
- Temperature measured from cut-off in X-ray spectrum using NuSTAR
- Cooling time is short – must be continuously heated
- Pair production in corona acts as "thermostat"
  - In compact corona, pair production causes runaway cooling

Fabian et al. 2015

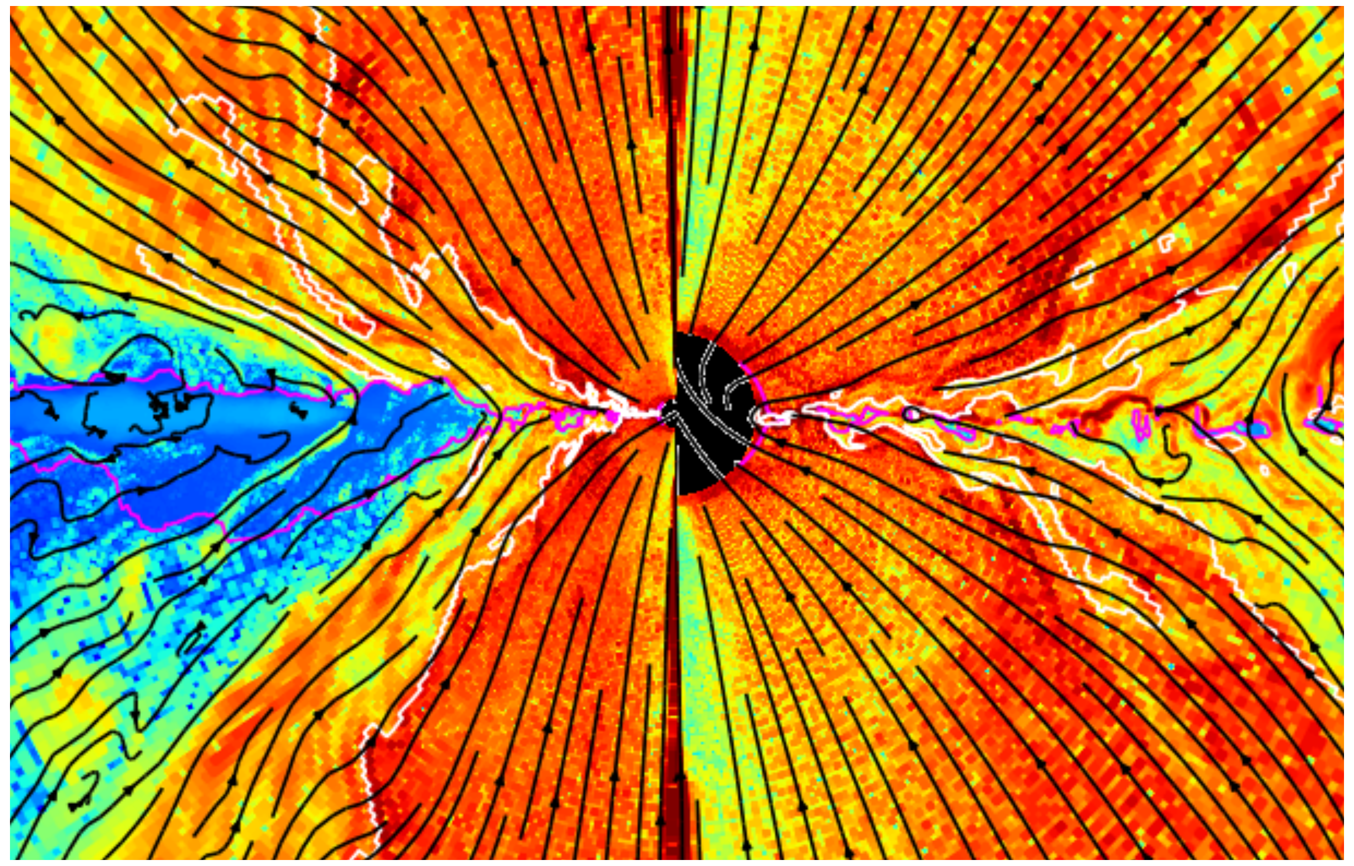
How is the corona formed?

Stanford

How is the corona formed?

Magnetically heated region

on surface of accretion disk

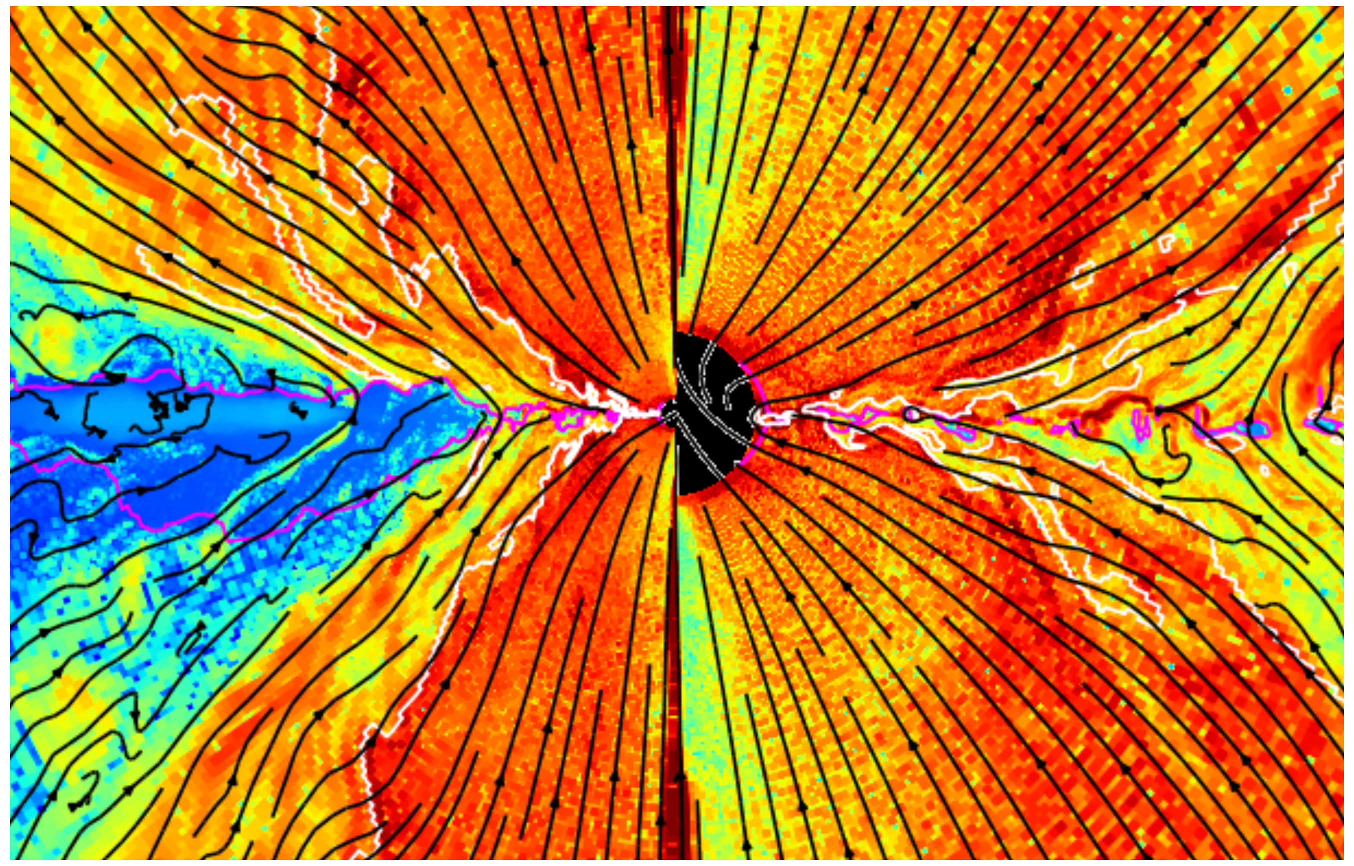


Liska et al. 2022

Stanford

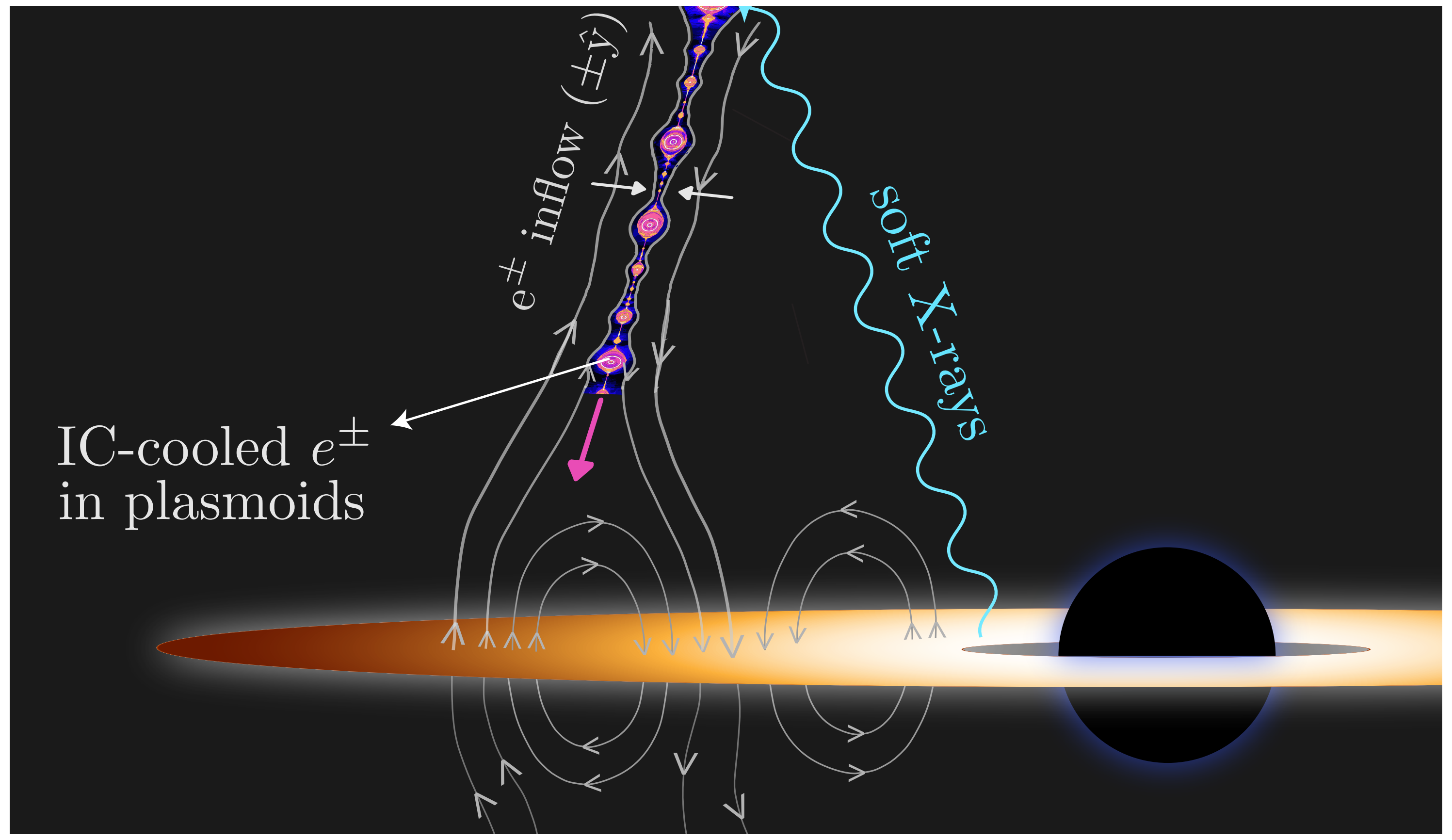
How is the corona formed?

Magnetically heated region on surface of accretion disk



Liska et al. 2022

Magnetic reconnection in black hole magnetosphere



Sridhar et al. 2021

How is the corona formed?

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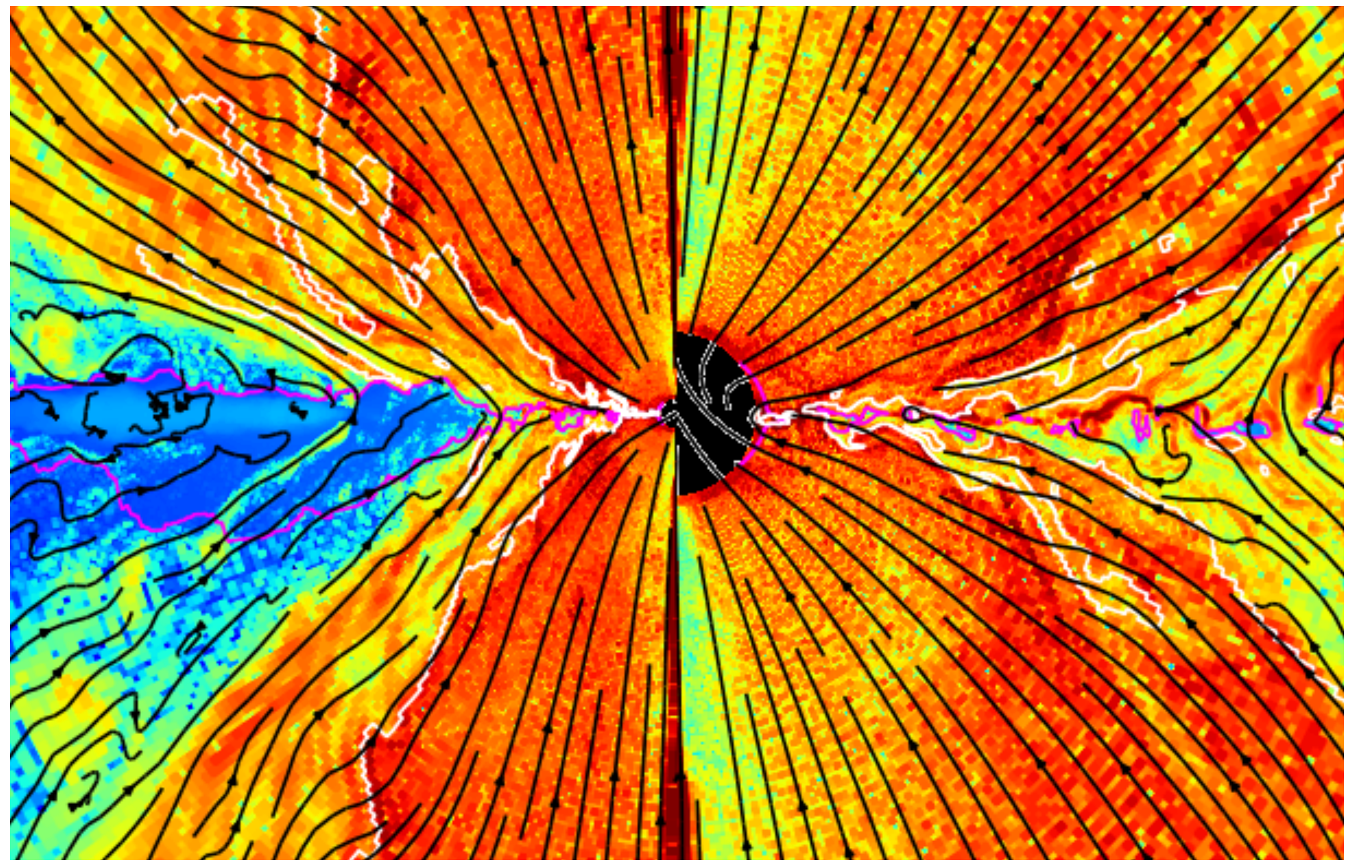

Liska et al. 2022

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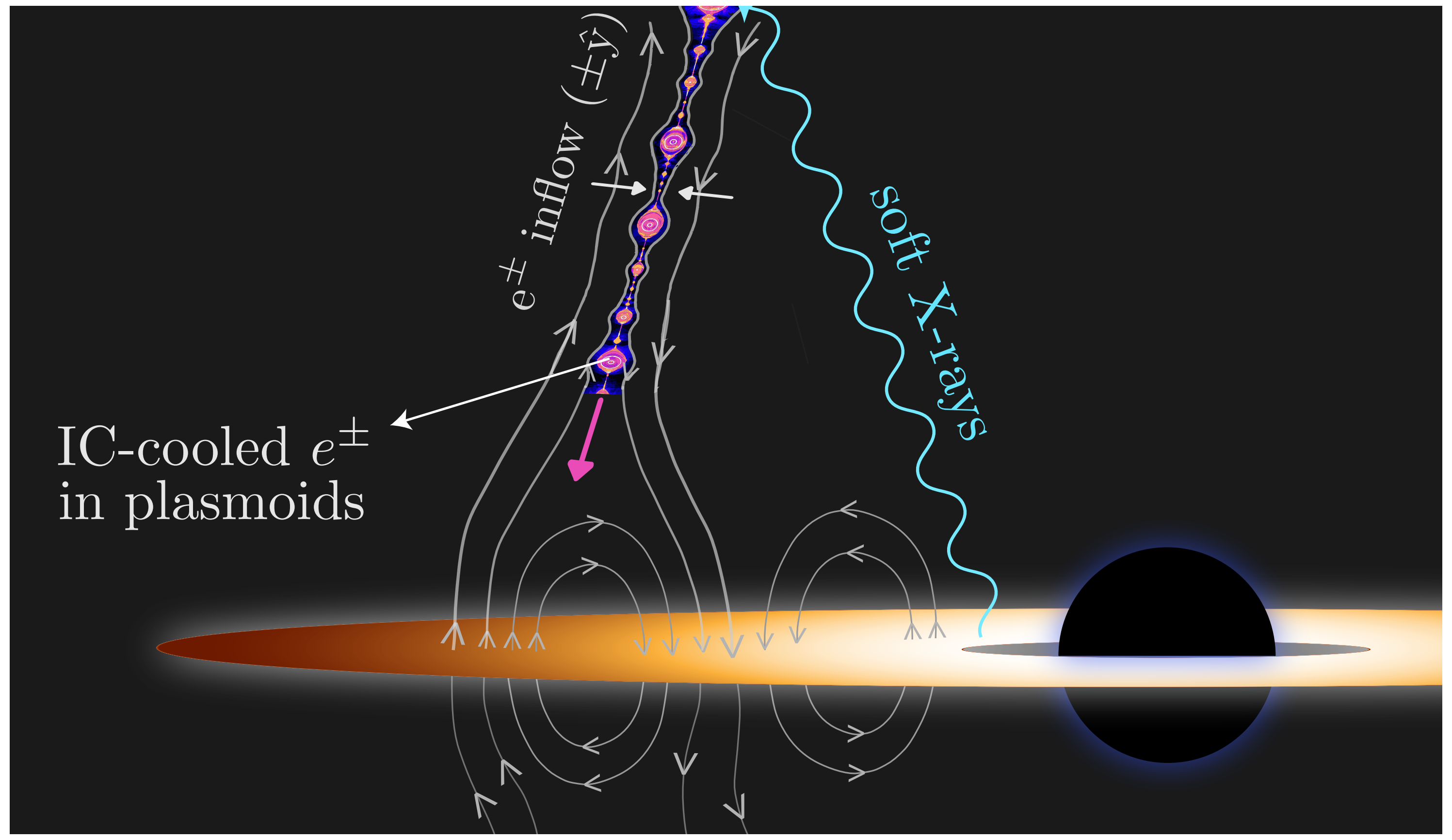
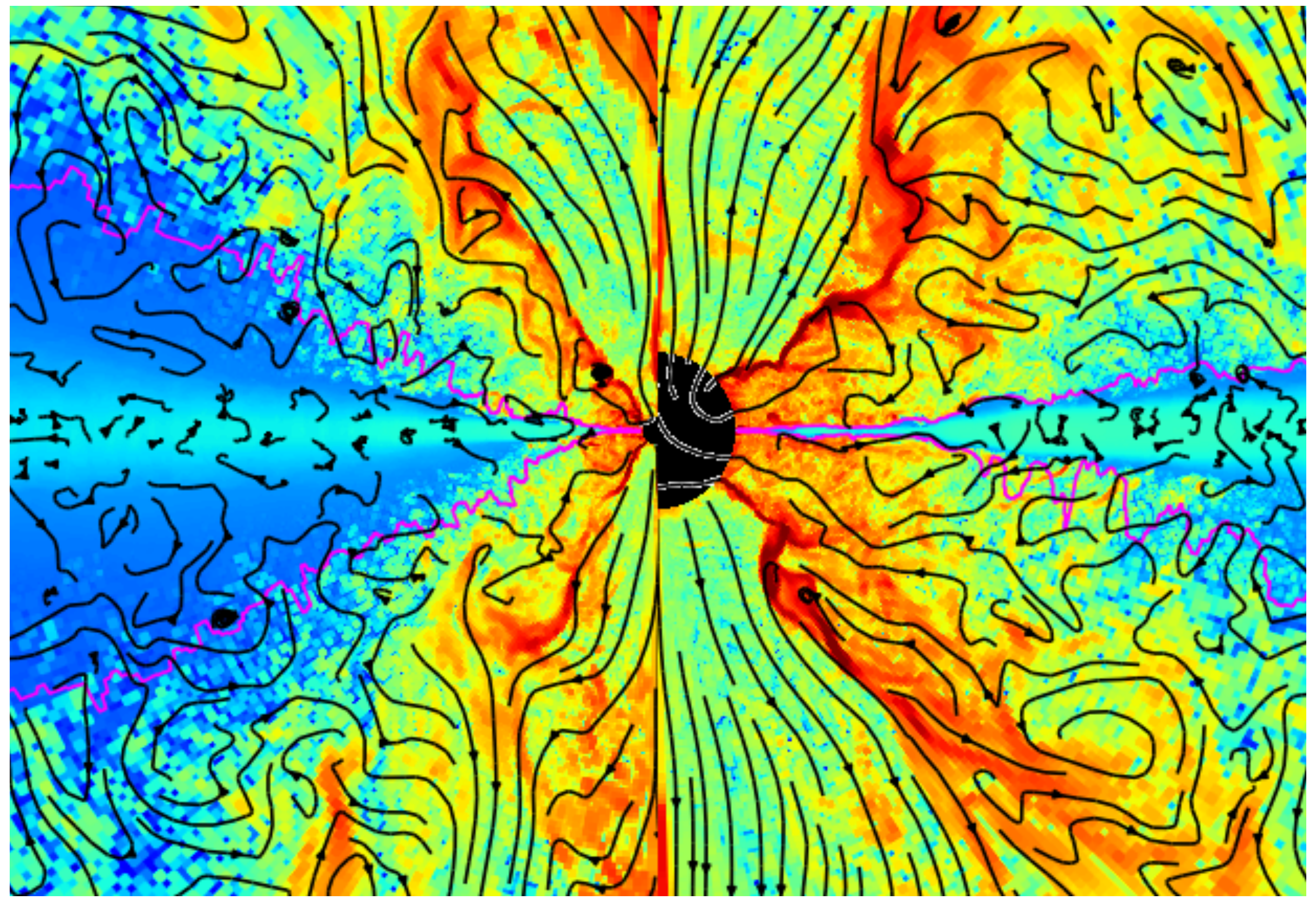


Sridhar et al. 2021

Dissipation at jet launching site



Liska et al. 2022

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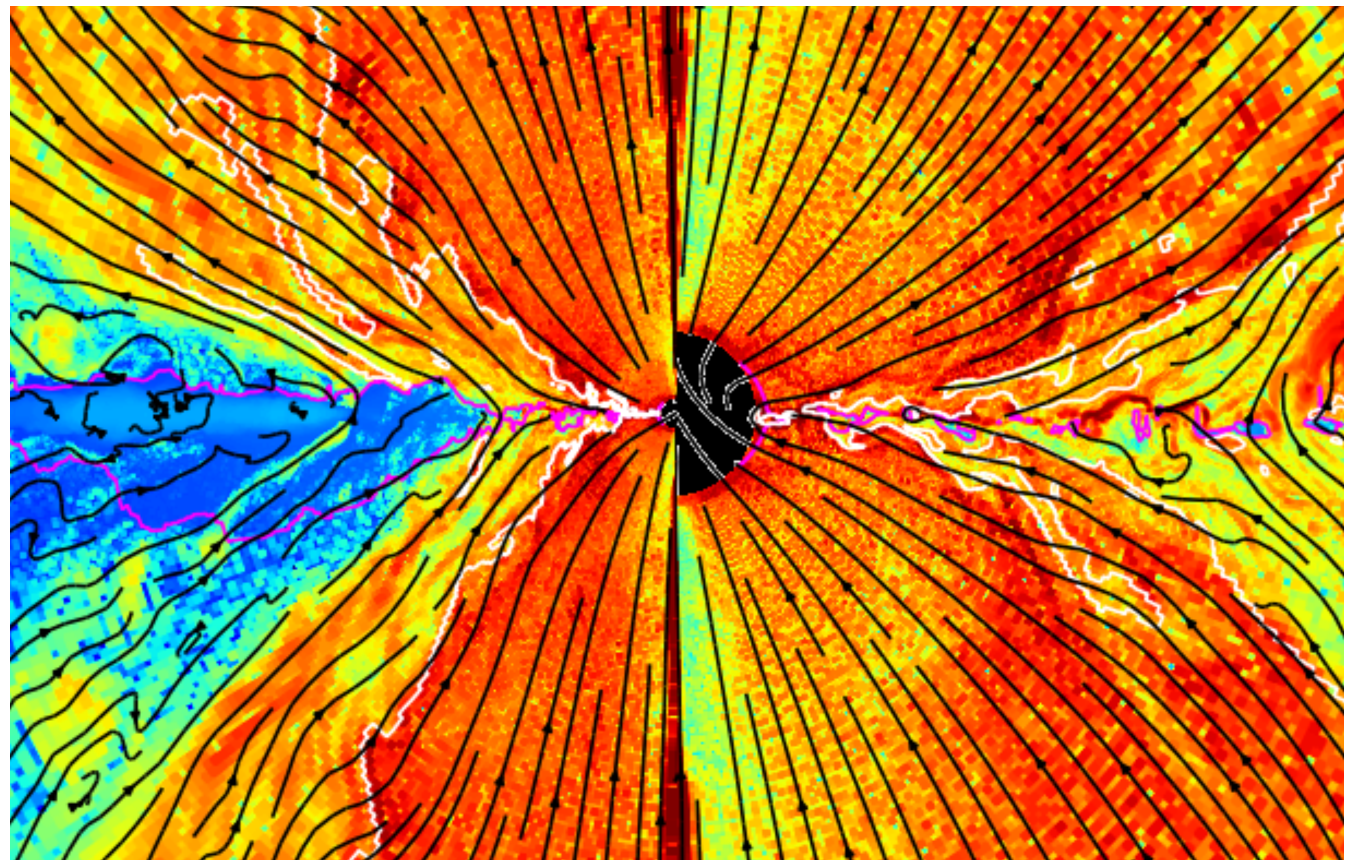

Liska et al. 2022

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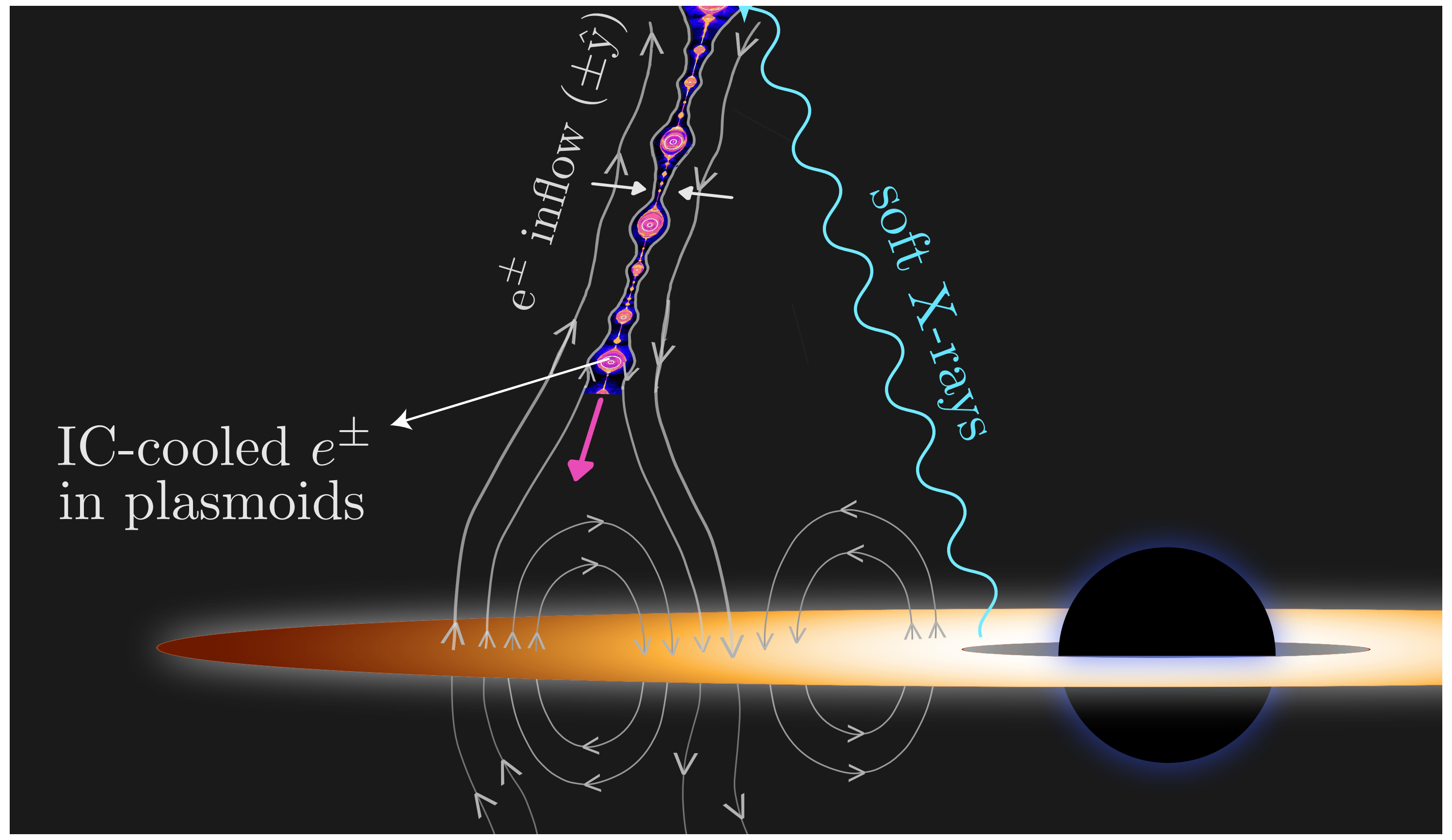

Sridhar et al. 2021

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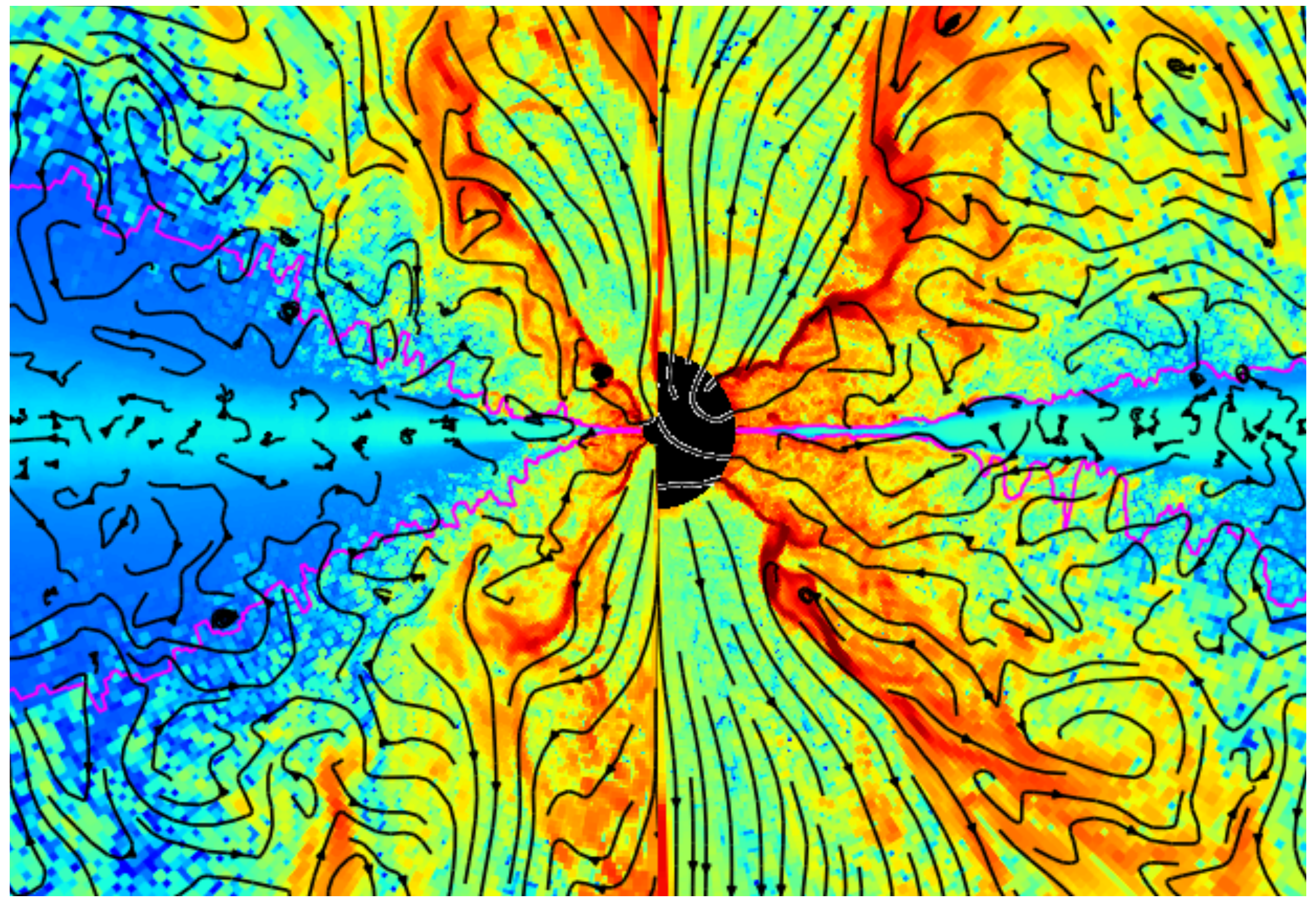
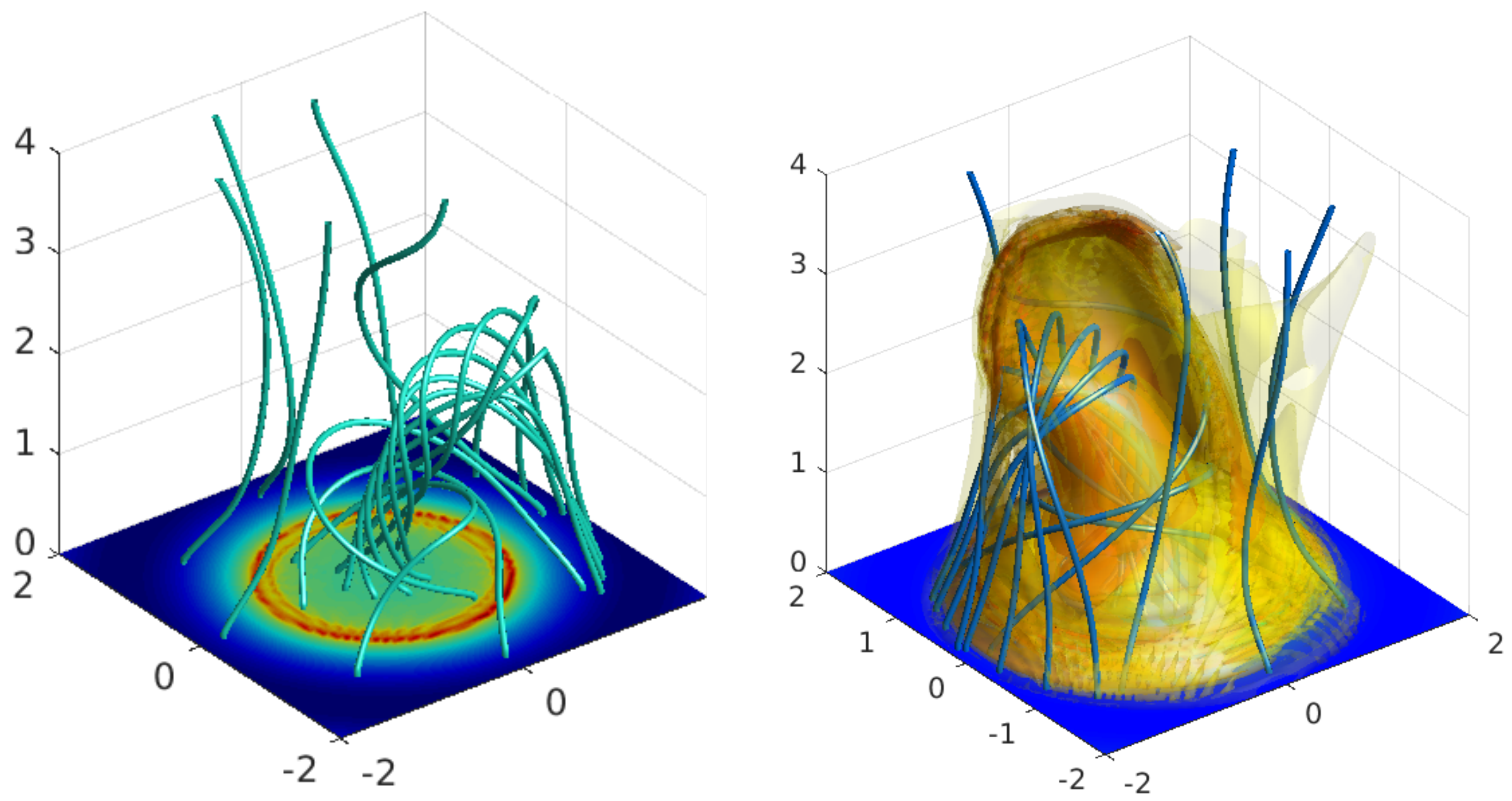


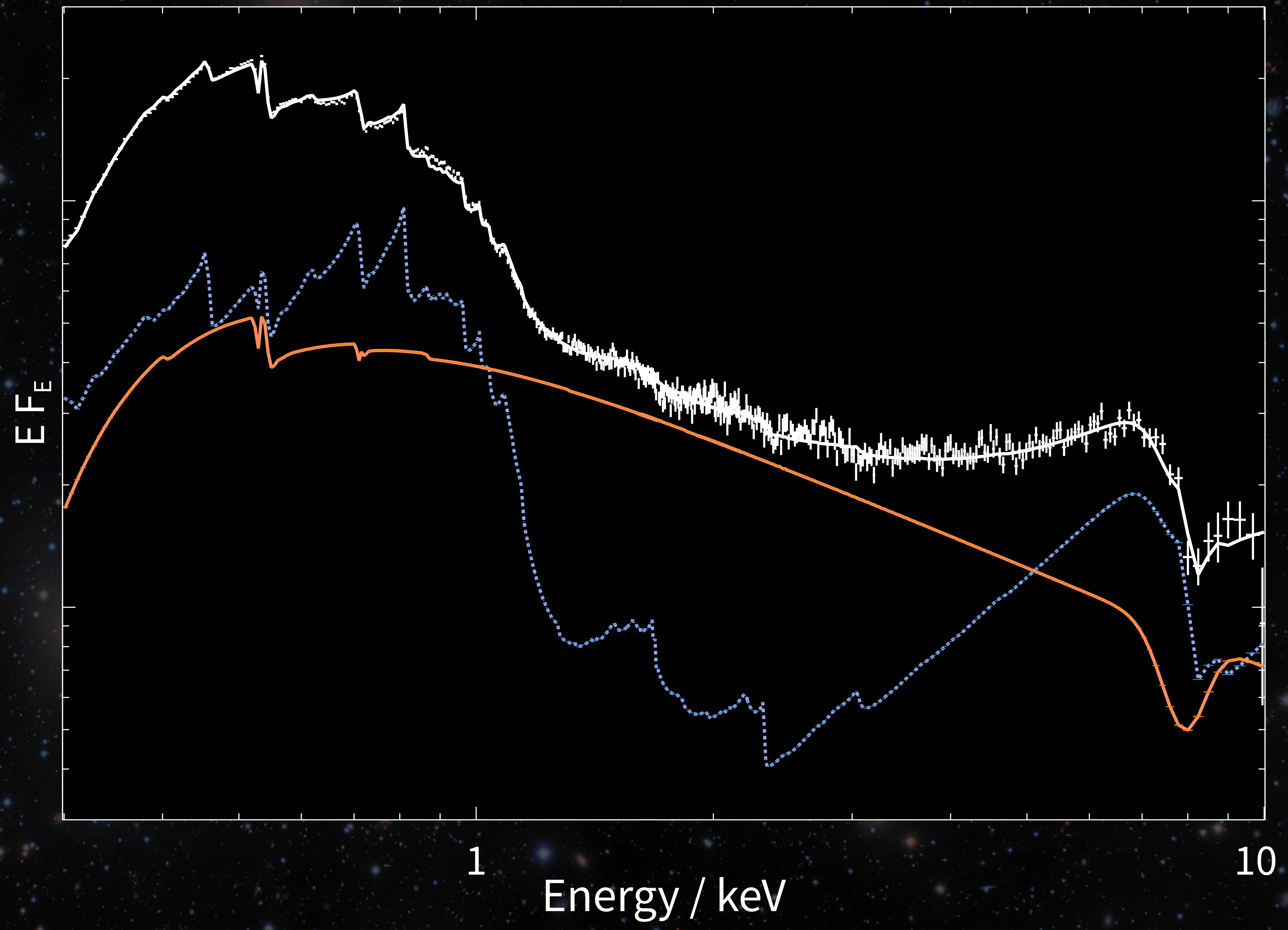
Liska et al. 2022

Dissipation in a failed jet



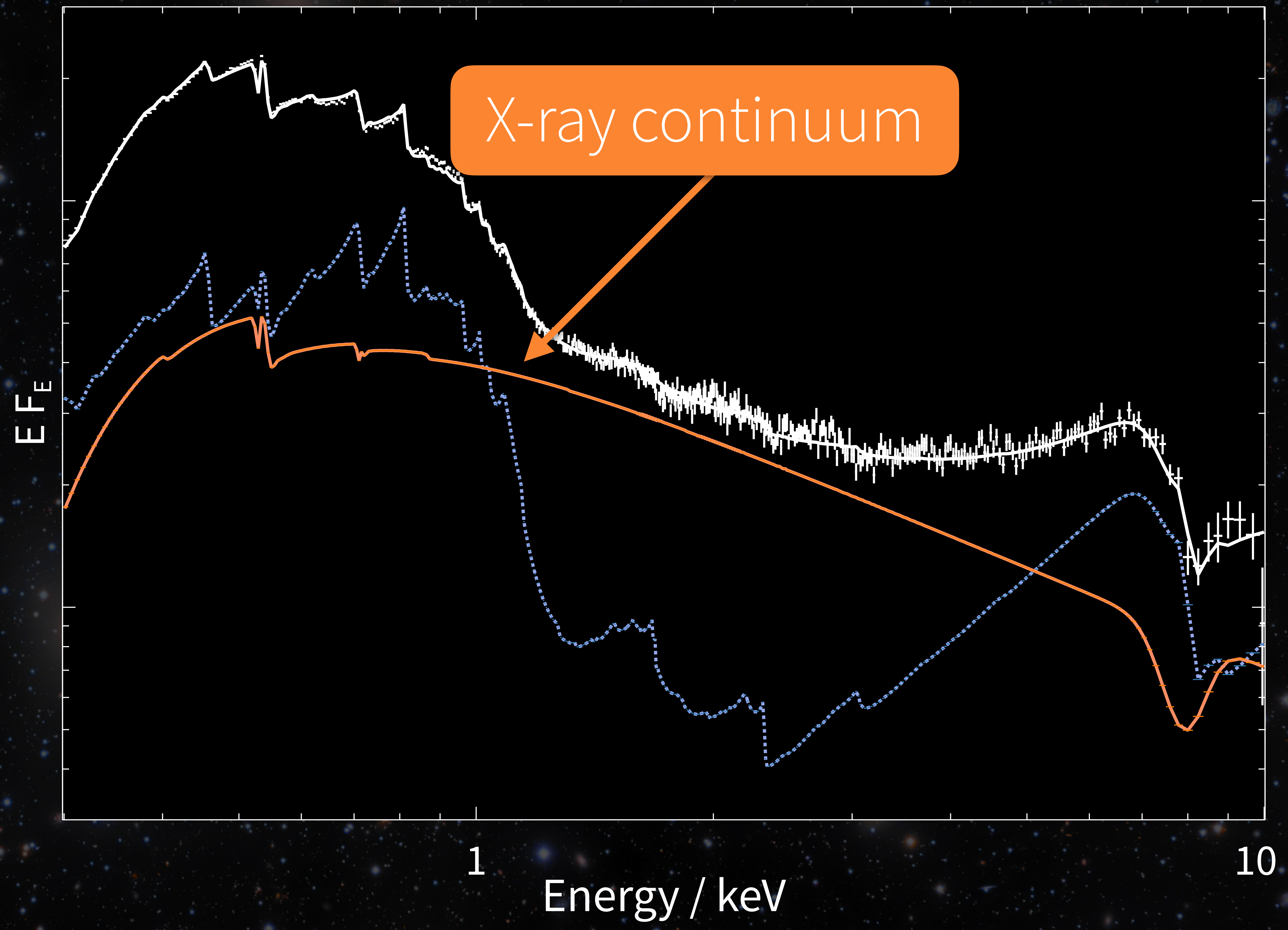
Yuan et al. 2019

The accretion disc (revisited)



esa XMM-Newton

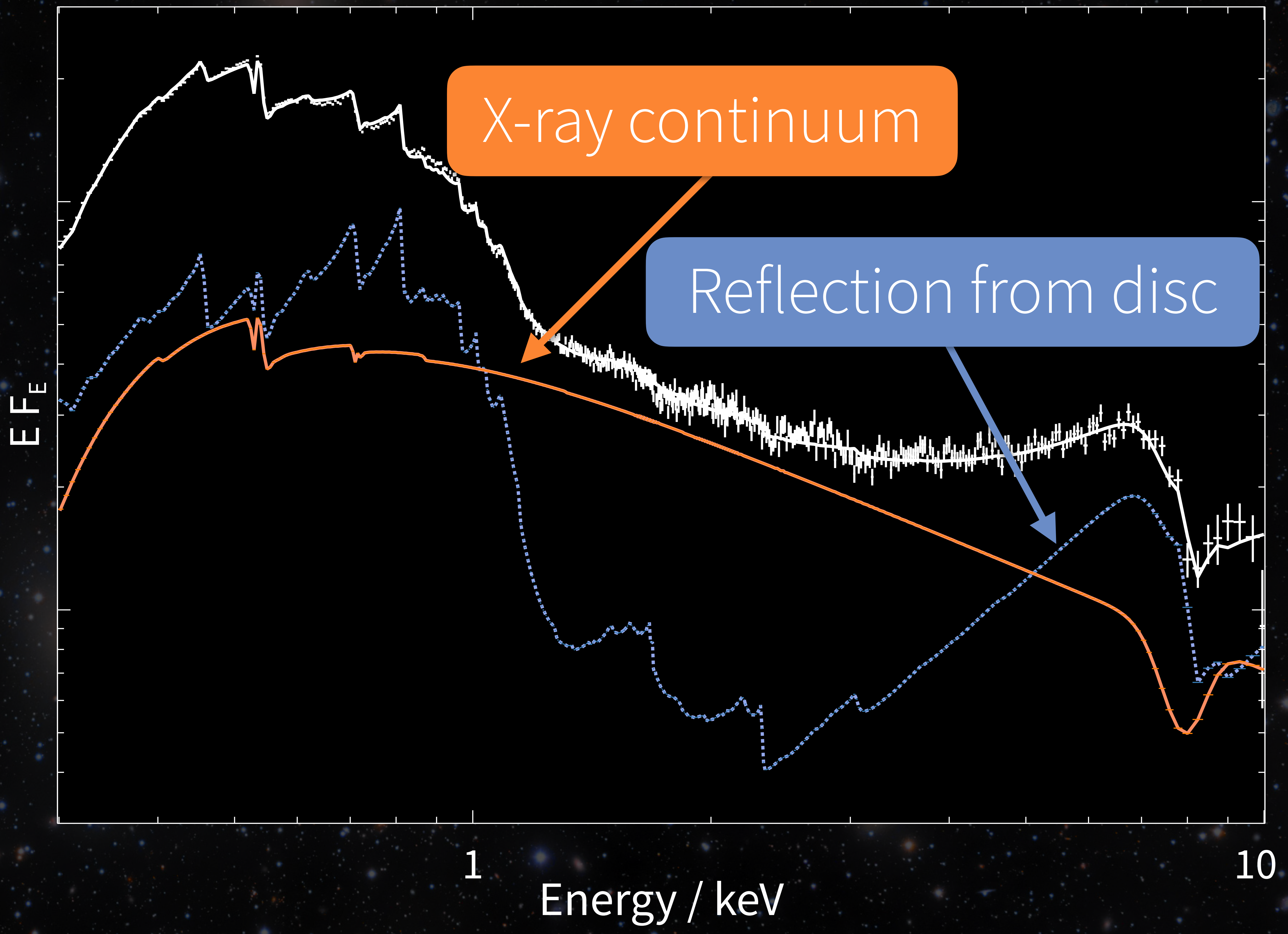
IRAS 13224–3809, observed for 1.5Ms



XMM-Newton

IRAS 13224–3809, observed for 1.5Ms

XMM-Newton



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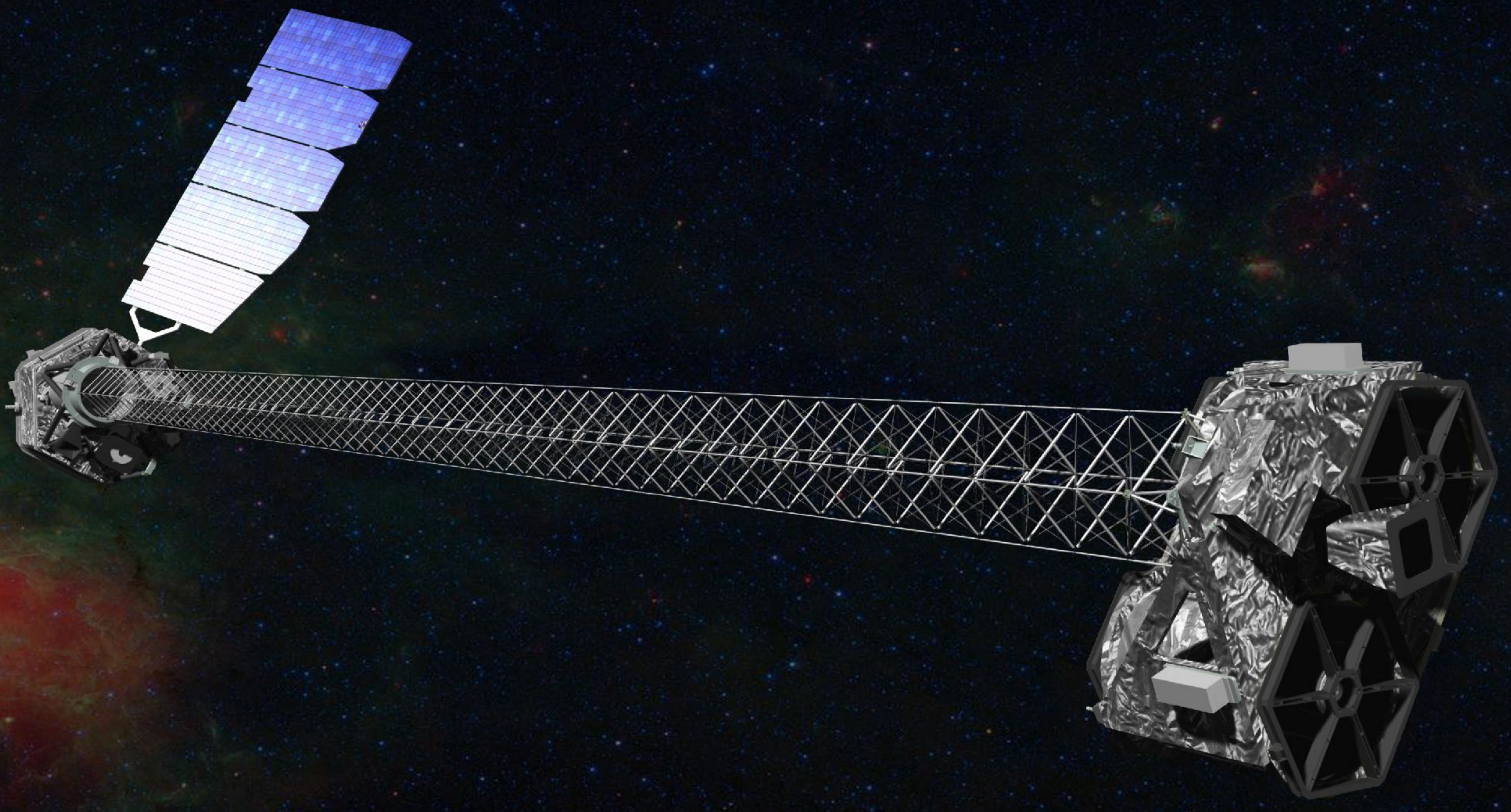
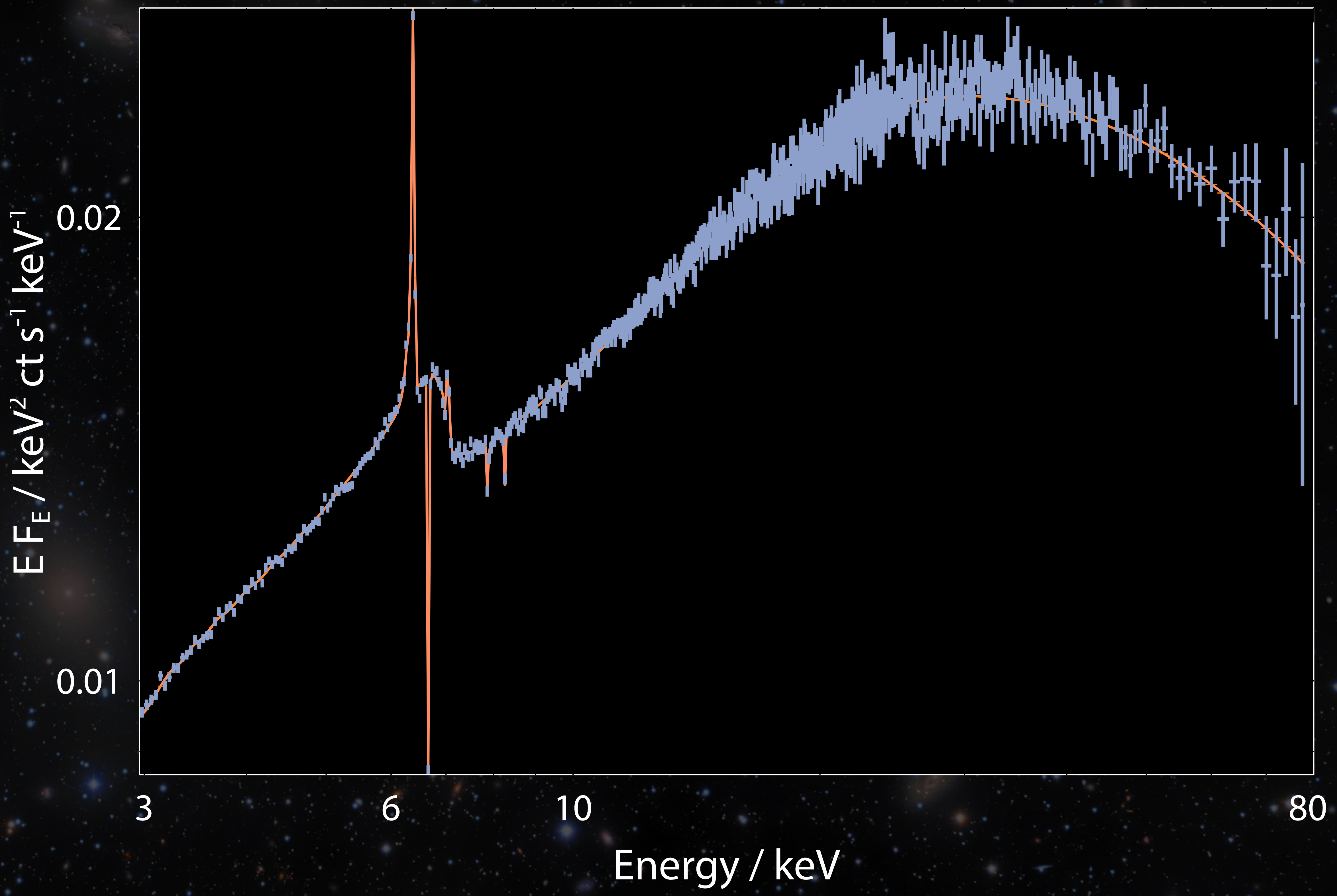
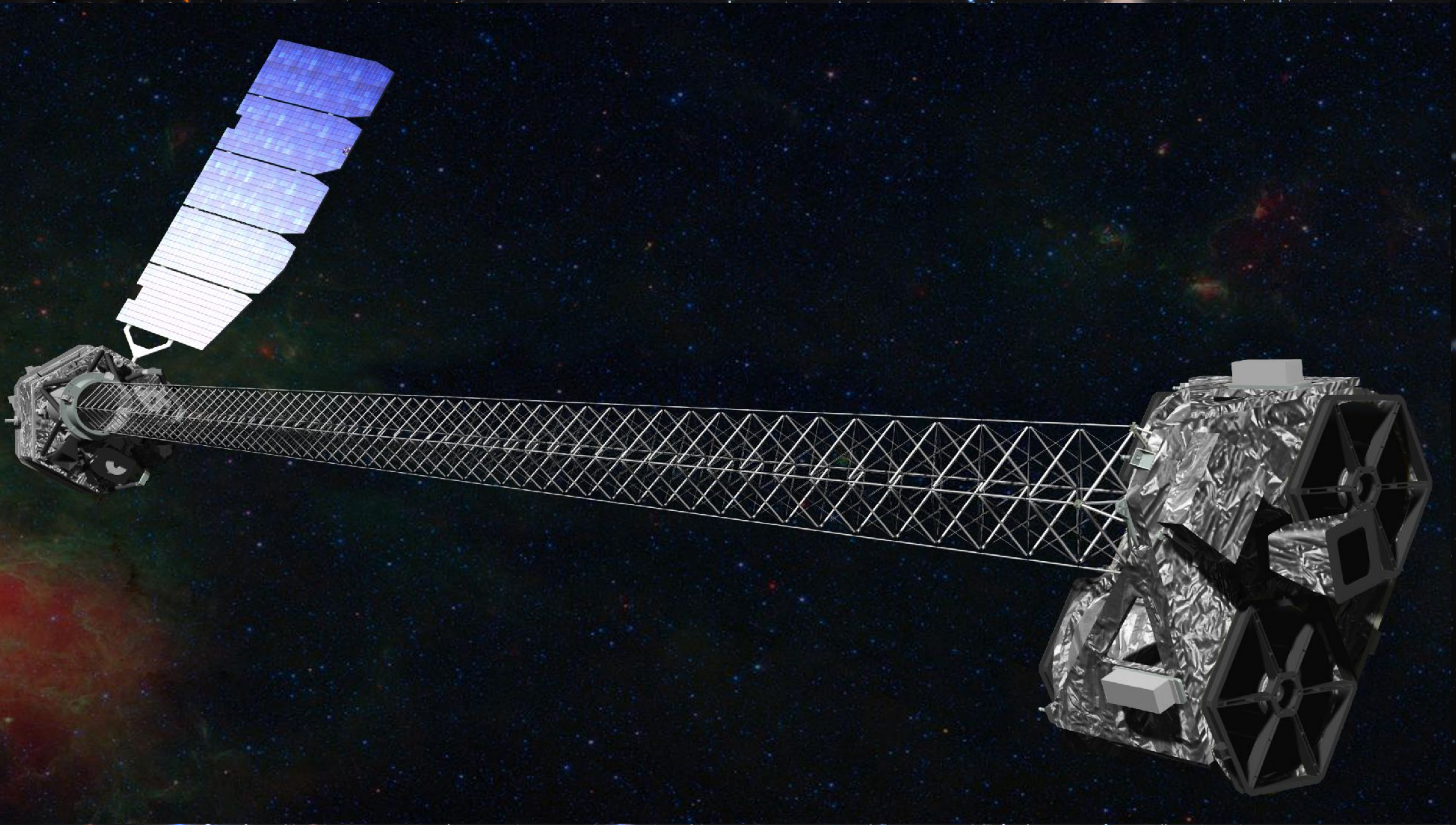
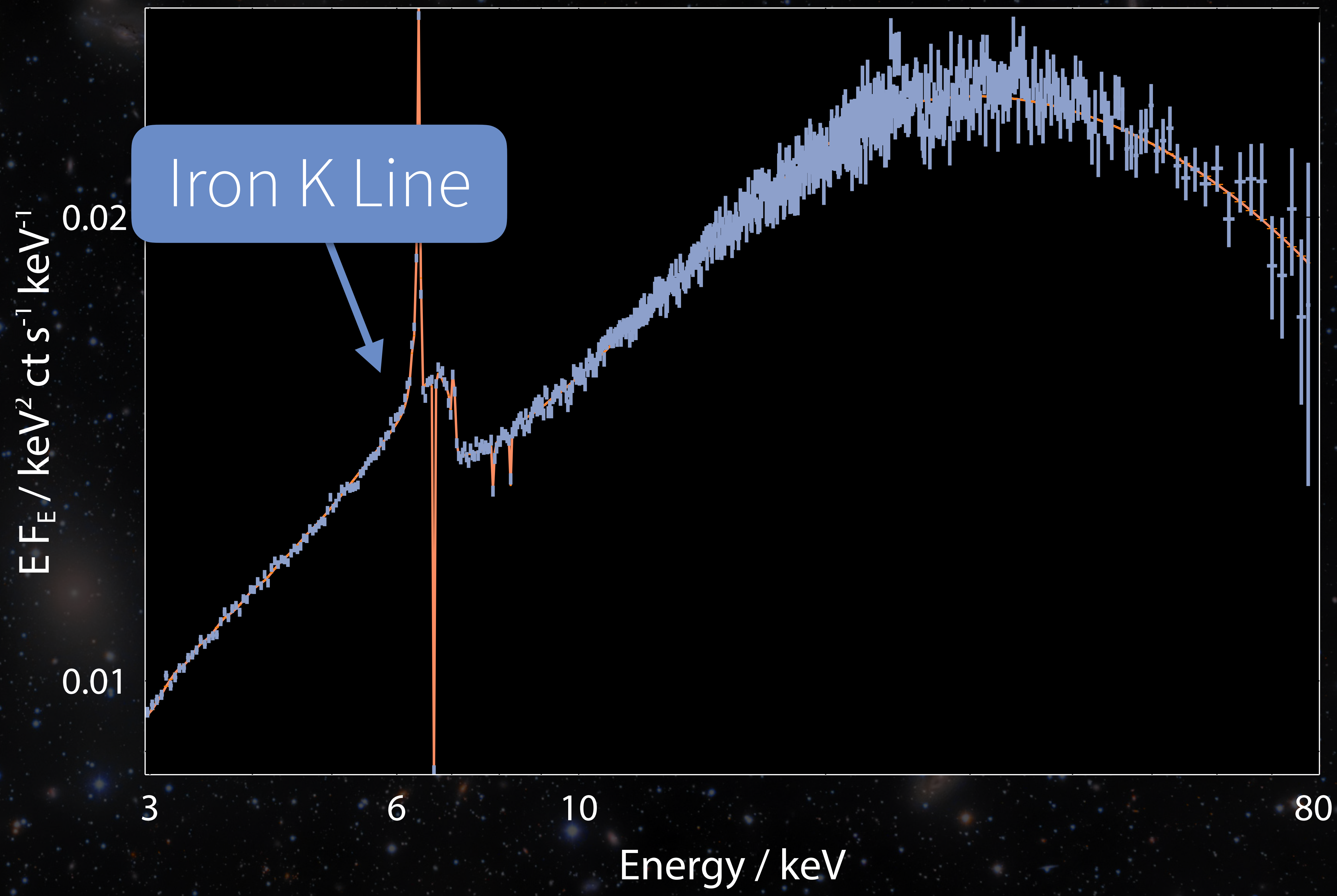




Stacked NuSTAR spectrum of the iron K reverberation sample of Seyfert galaxies

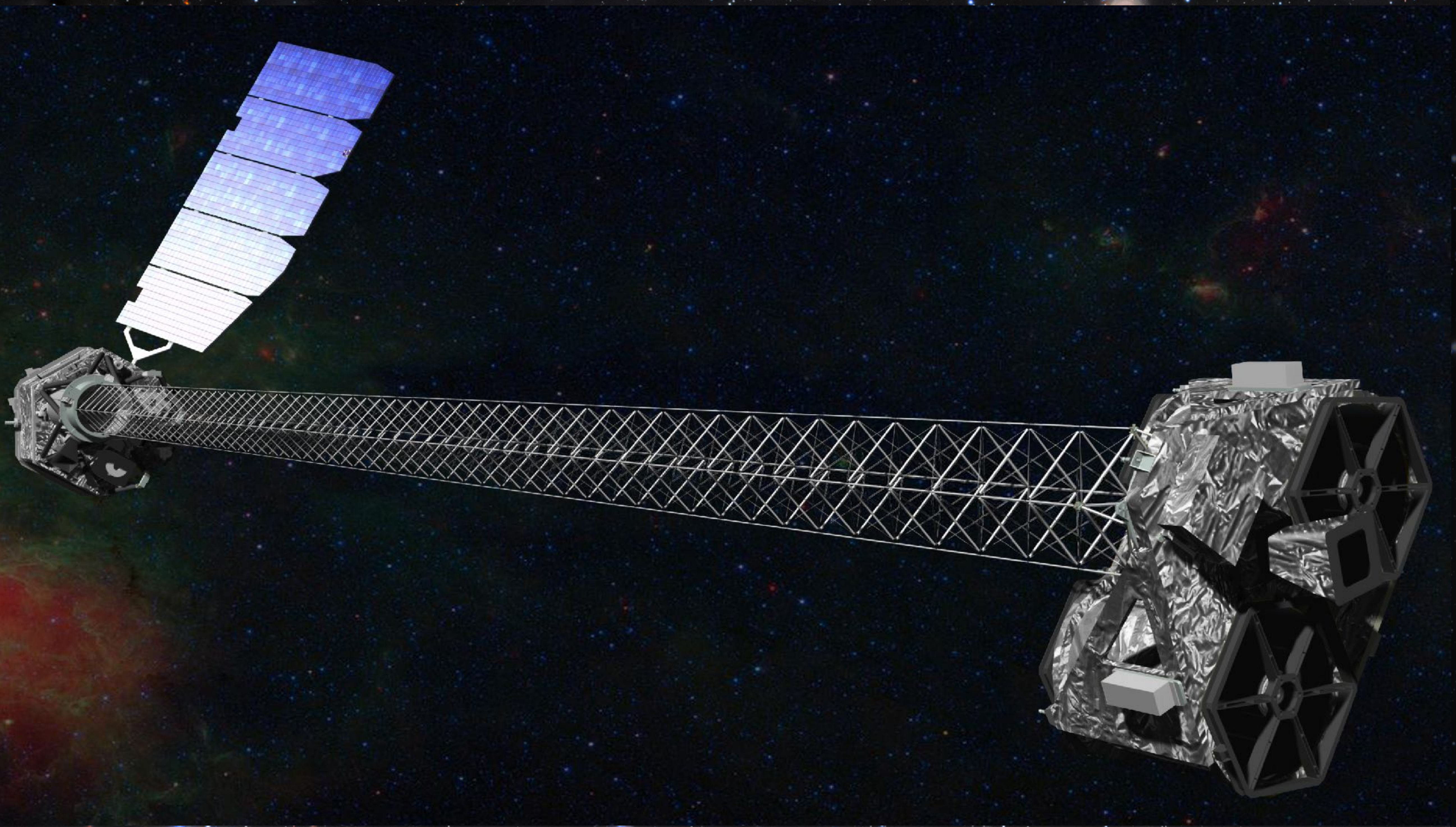
NuSTAR

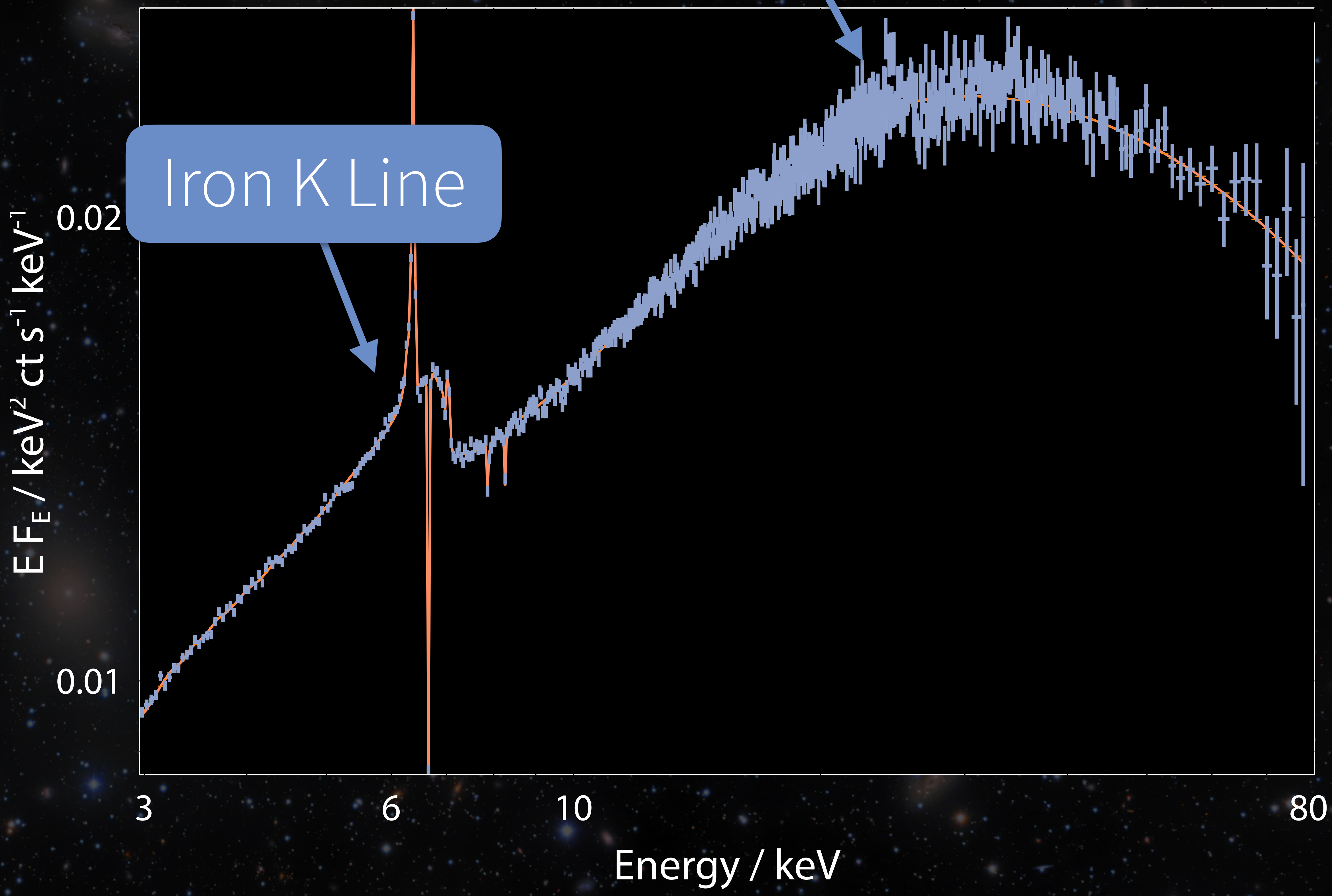




Stacked NuSTAR spectrum of the iron K reverberation sample of Seyfert galaxies

NuSTAR

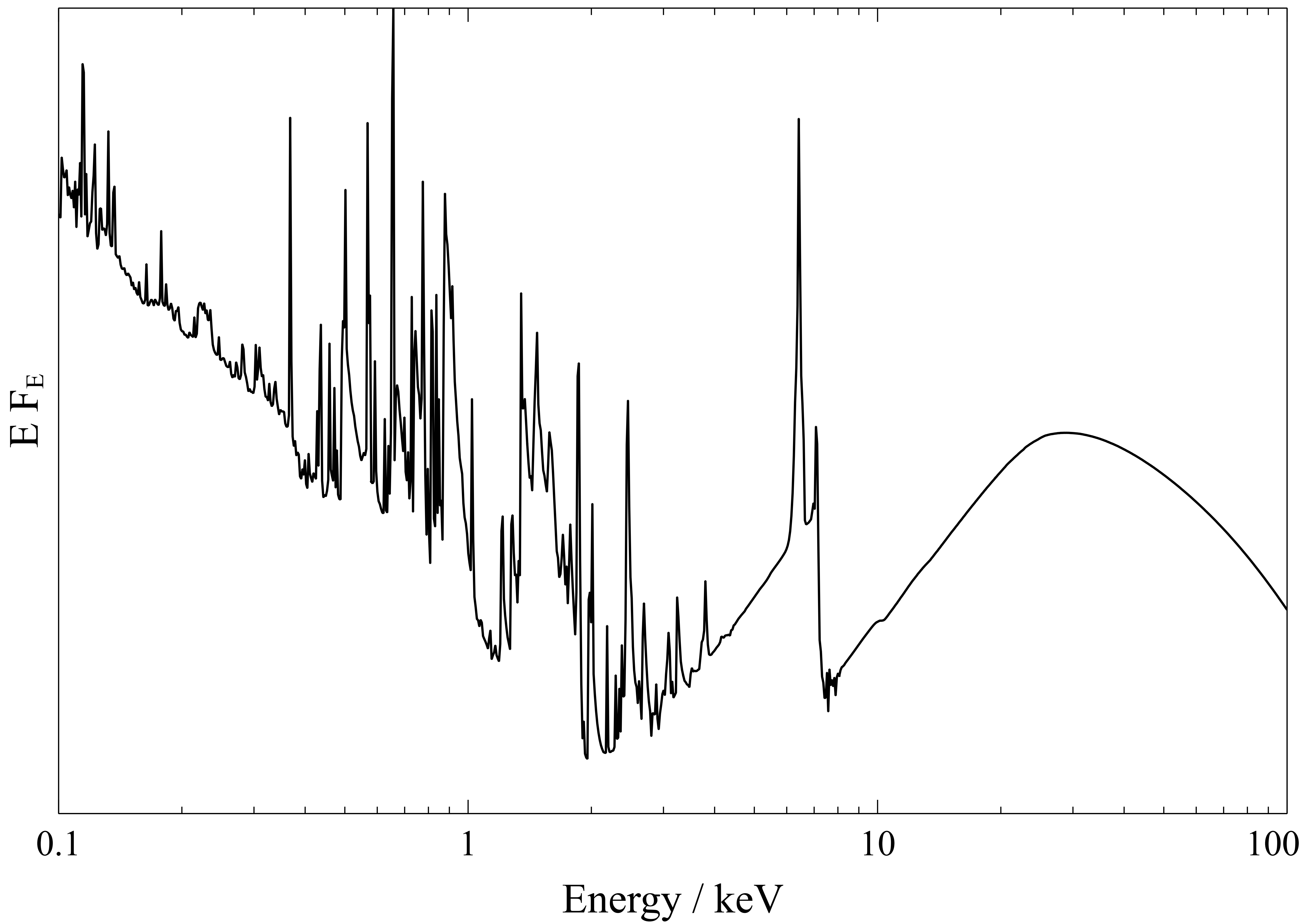




Stacked NuSTAR spectrum of the iron K reverberation sample of Seyfert galaxies

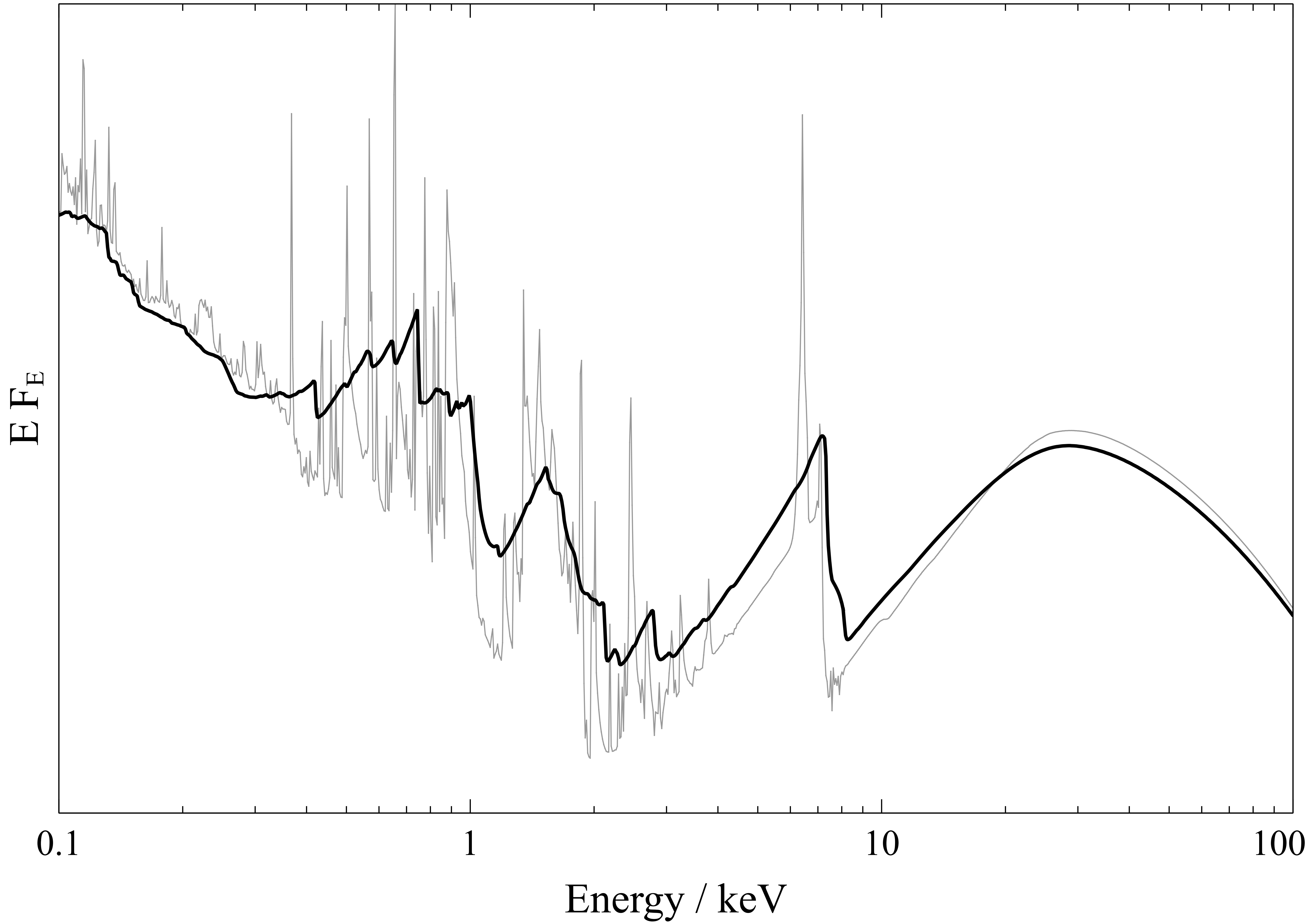
NuSTAR

Reflection from the accretion disc



- Reflection spectrum formed by reprocessing of X-ray continuum by plasma in accretion disc
  - Compton scattering
  - Thermal bremsstrahlung
  - Photoelectric absorption
  - Fluorescent line emission
- XILLVER model (García et al. 2013)

Reflection from the accretion disc



- Doppler shifts due to orbital motion of accretion disc
- Gravitational redshifts in proximity of black hole
- Relativistic blurring/broadening of reflection spectrum
  - Relativistic broad emission lines
  - Soft excess as emission lines are blended together
- RELXILL model (Dauser, García et al. 2014)

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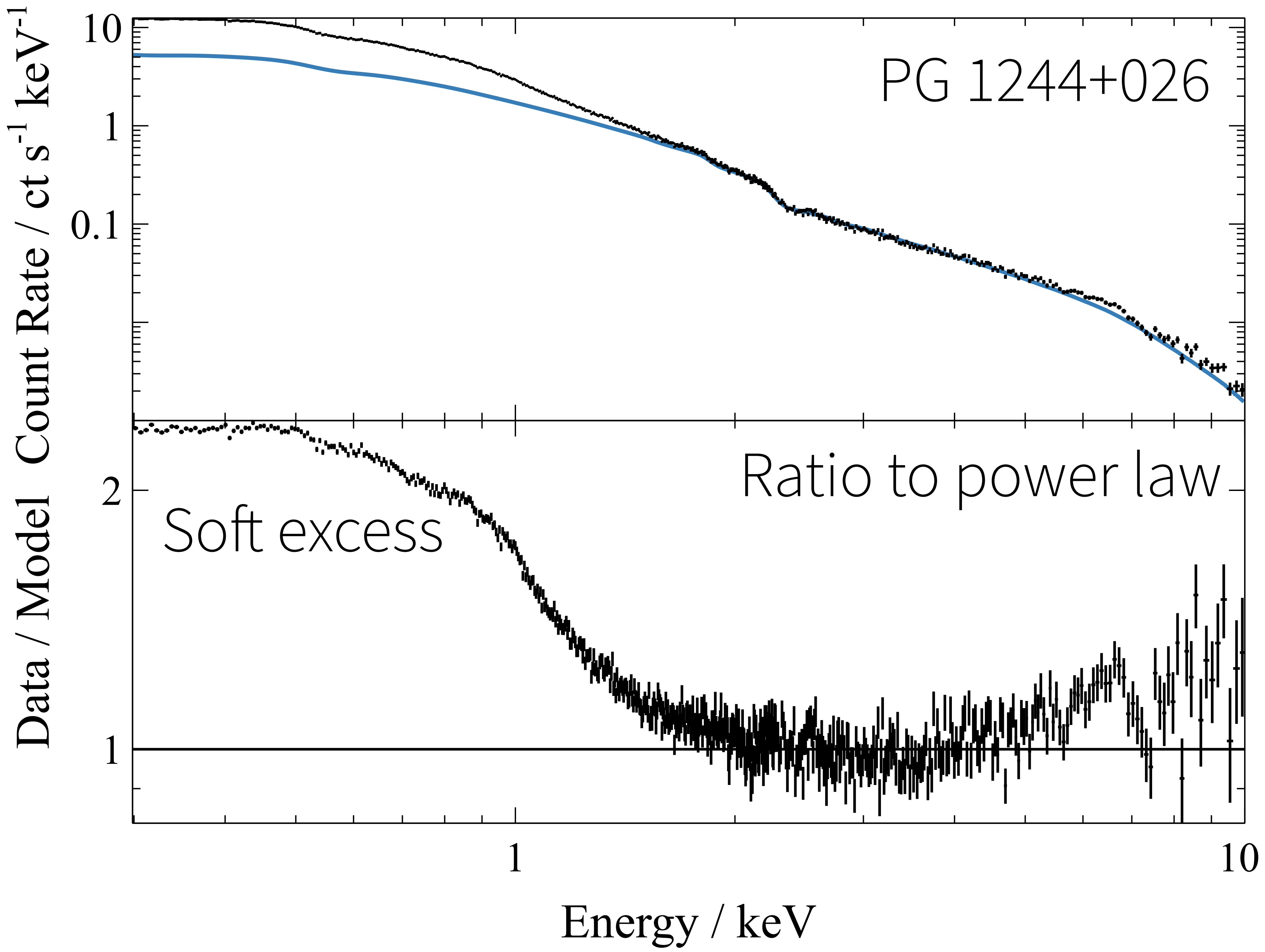
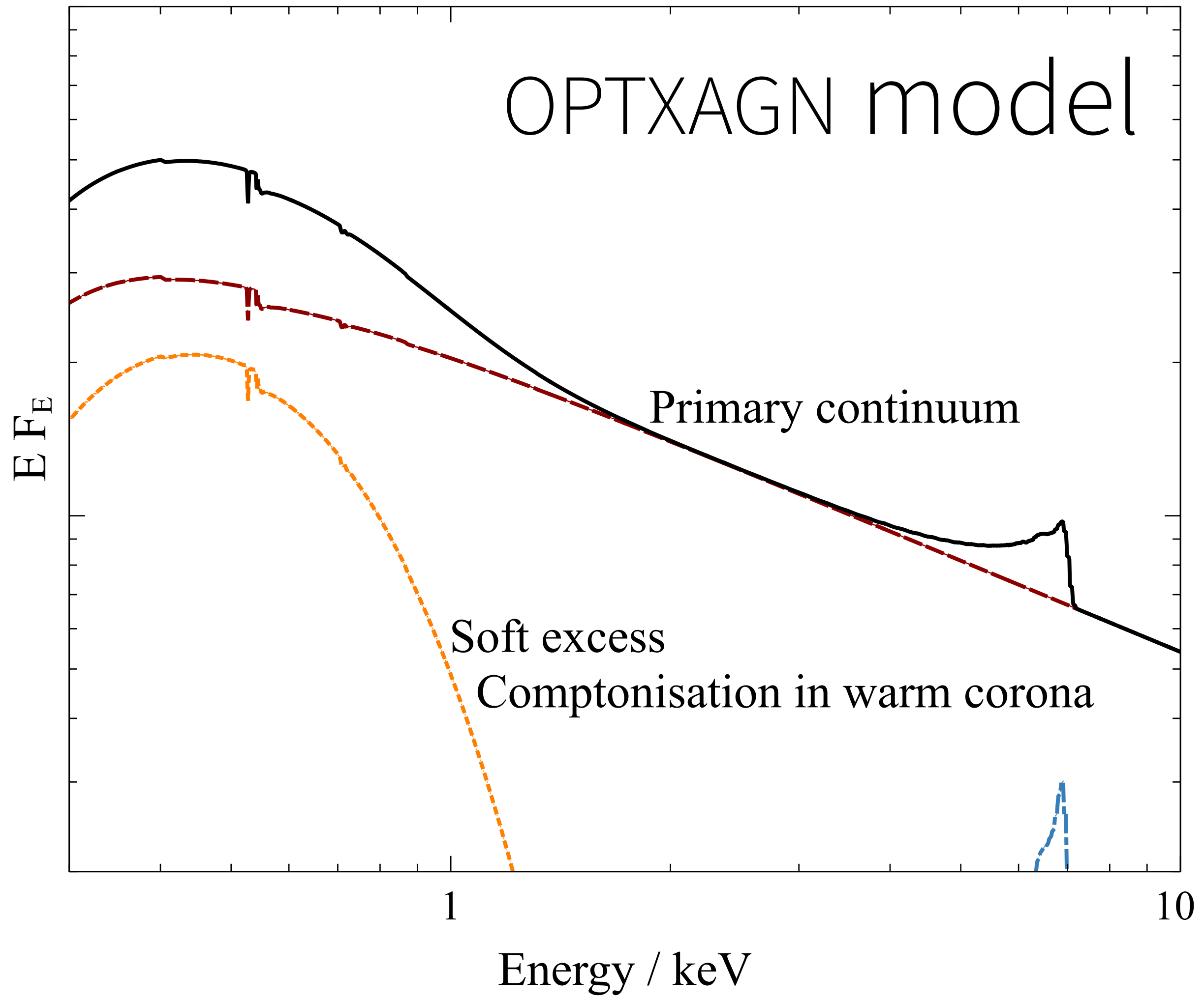
Soft excess

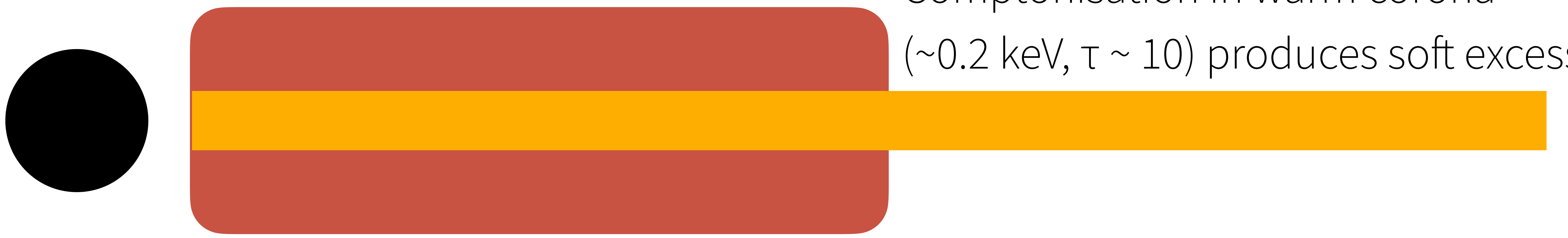


Done et al. 2012



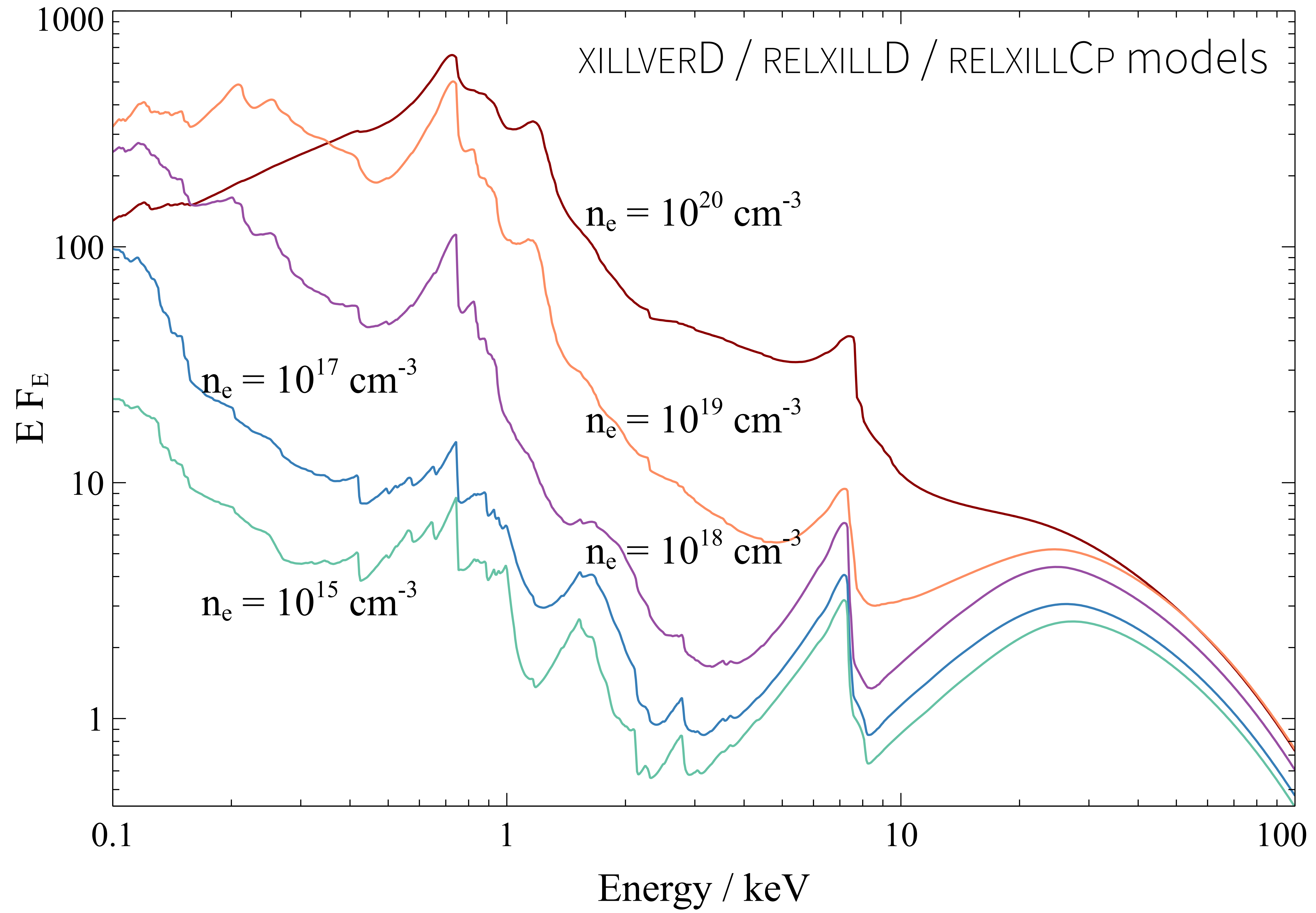
Comptonisation in hot corona (~100 keV) produces power law continuum

Comptonisation in warm corona (~0.2 keV, τ ~ 10) produces soft excess



- Some AGN show large soft excess that is not easily explained by standard reflection model
- Compton scattering by a warm atmosphere on the disc can produce soft excess (‘soft Comptonisation in a warm corona’)
- Or we don’t fully understand model radiative transfer in the disc…

The density of the accretion disc



García et al. 2016

- The standard reflection model assumes a disc density of $n_e = 10^{15}$ cm^{-3}, suitable for $M_{BH} \sim 10^8 M_\odot$
- Standard accretion discs around less massive black holes have higher disk densities
- Increased disc density increases Bremsstrahlung heating/cooling and suppresses radiative cooling, producing an enhanced soft excess
- The soft excess is also affected by variation in the disc ionisation parameter and ionisation gradients across the disc

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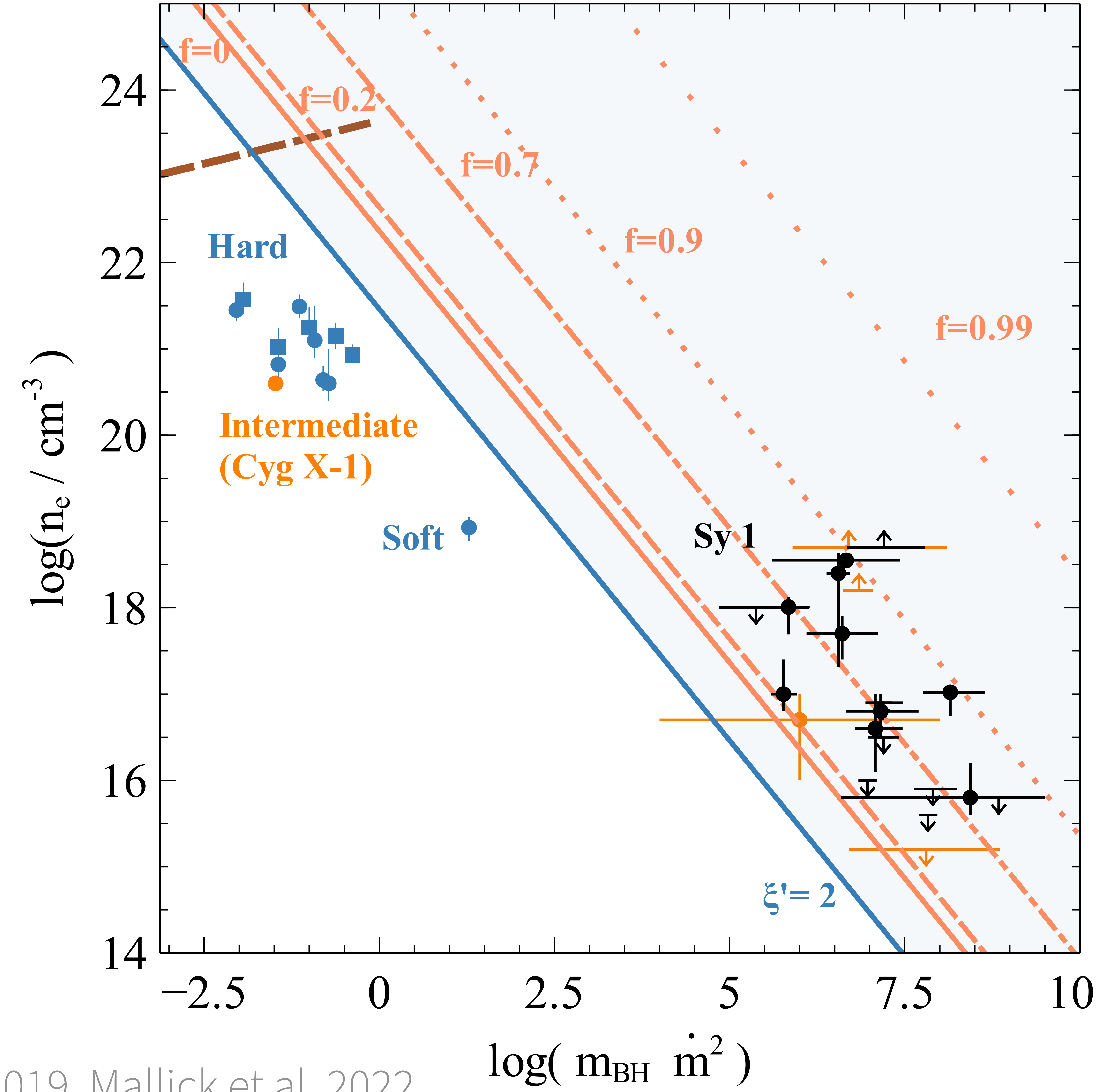
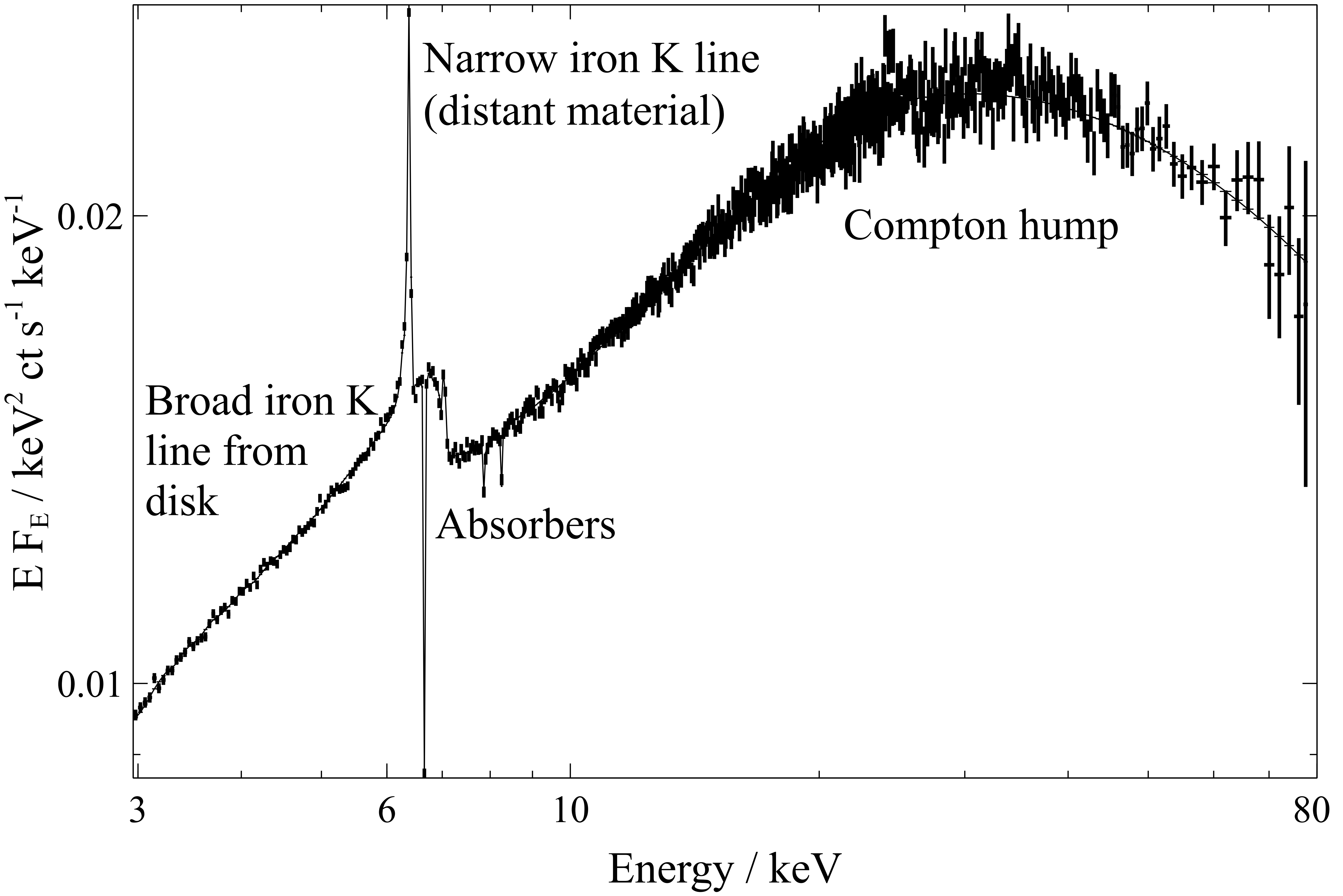
The density of the accretion disc



Jiang et al. 2019, Mallick et al. 2022

- We can compare density measured using reflection model to prediction from standard accretion disc model
- Density modified by fraction of power transferred to corona at each radius on disc

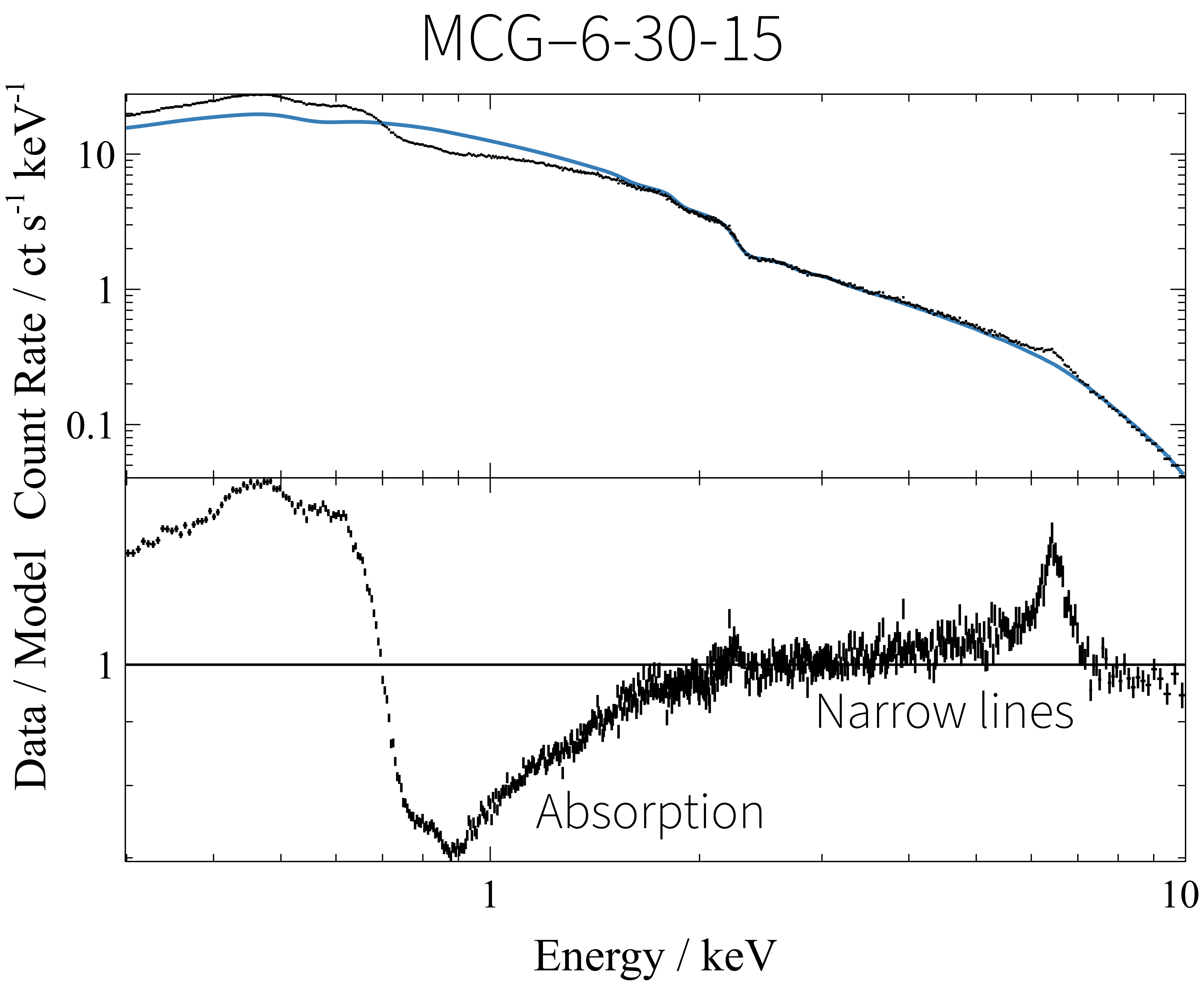
Distant reflection

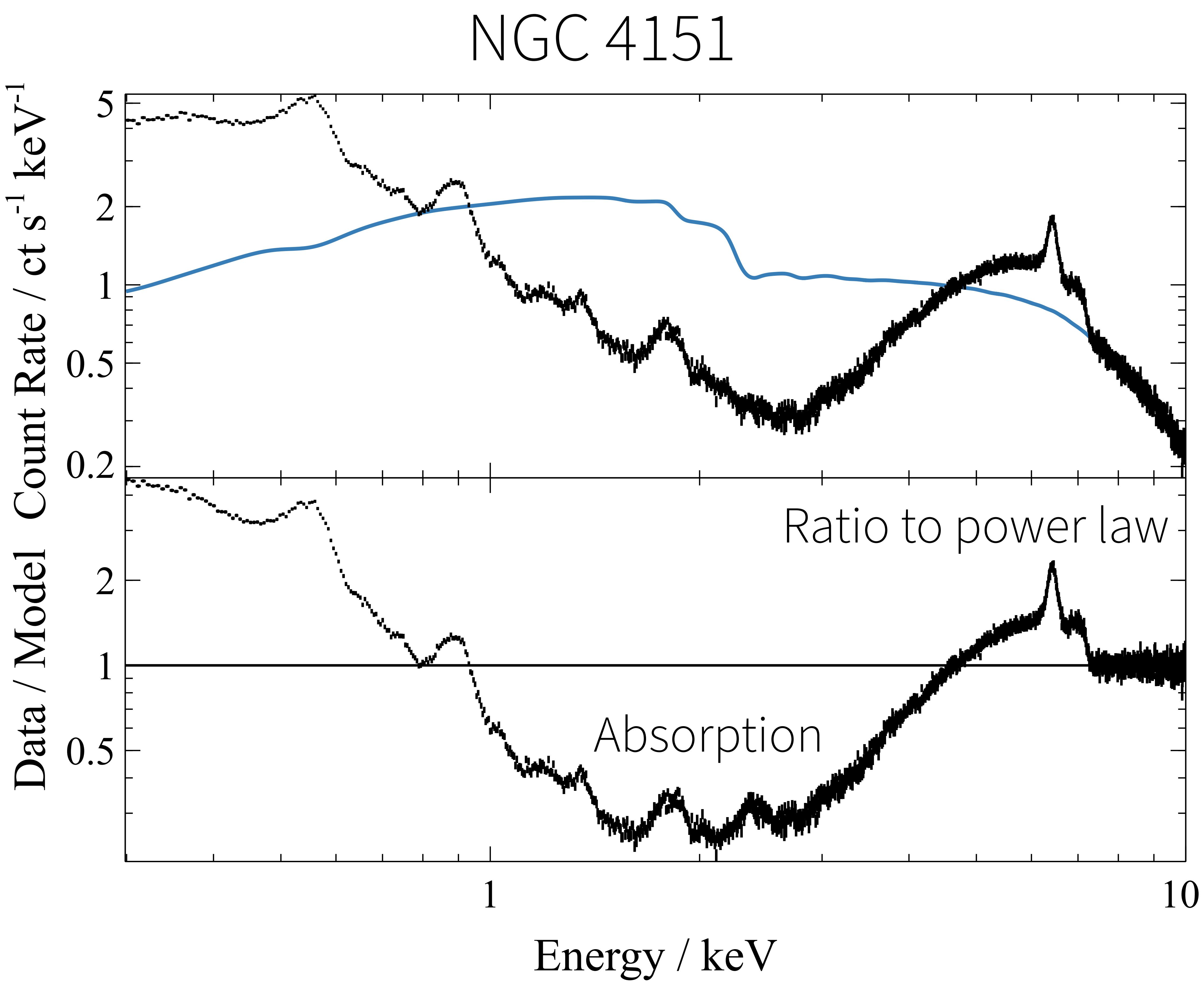


- In addition to broad iron K line from inner accretion disc, there may be a narrow component of the iron line
- Reflection from slowly moving material far from black hole (torus, BLR, etc.)
- Model using XILLVER or just a simple Gaussian line

Outflows and absorbers

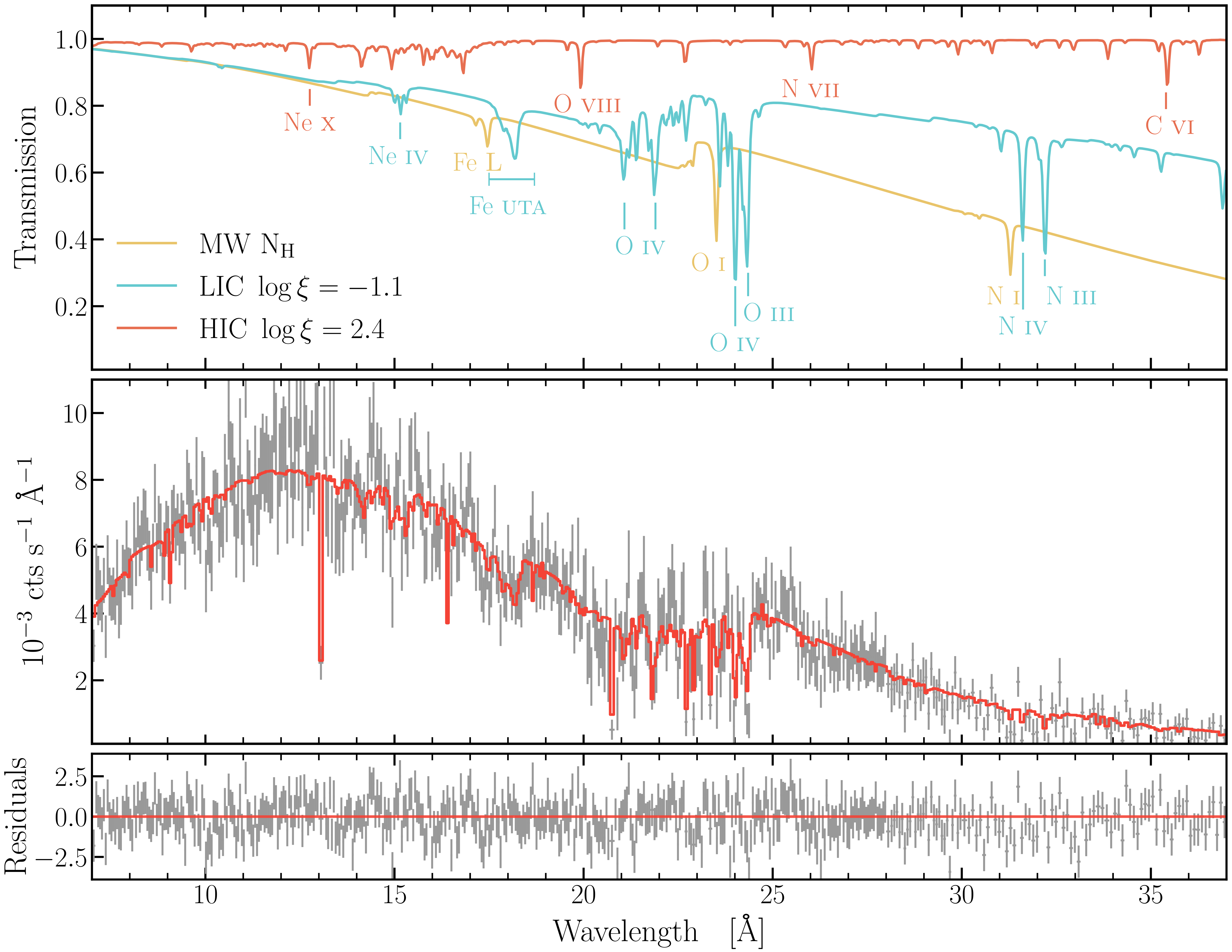
Warm Absorbers





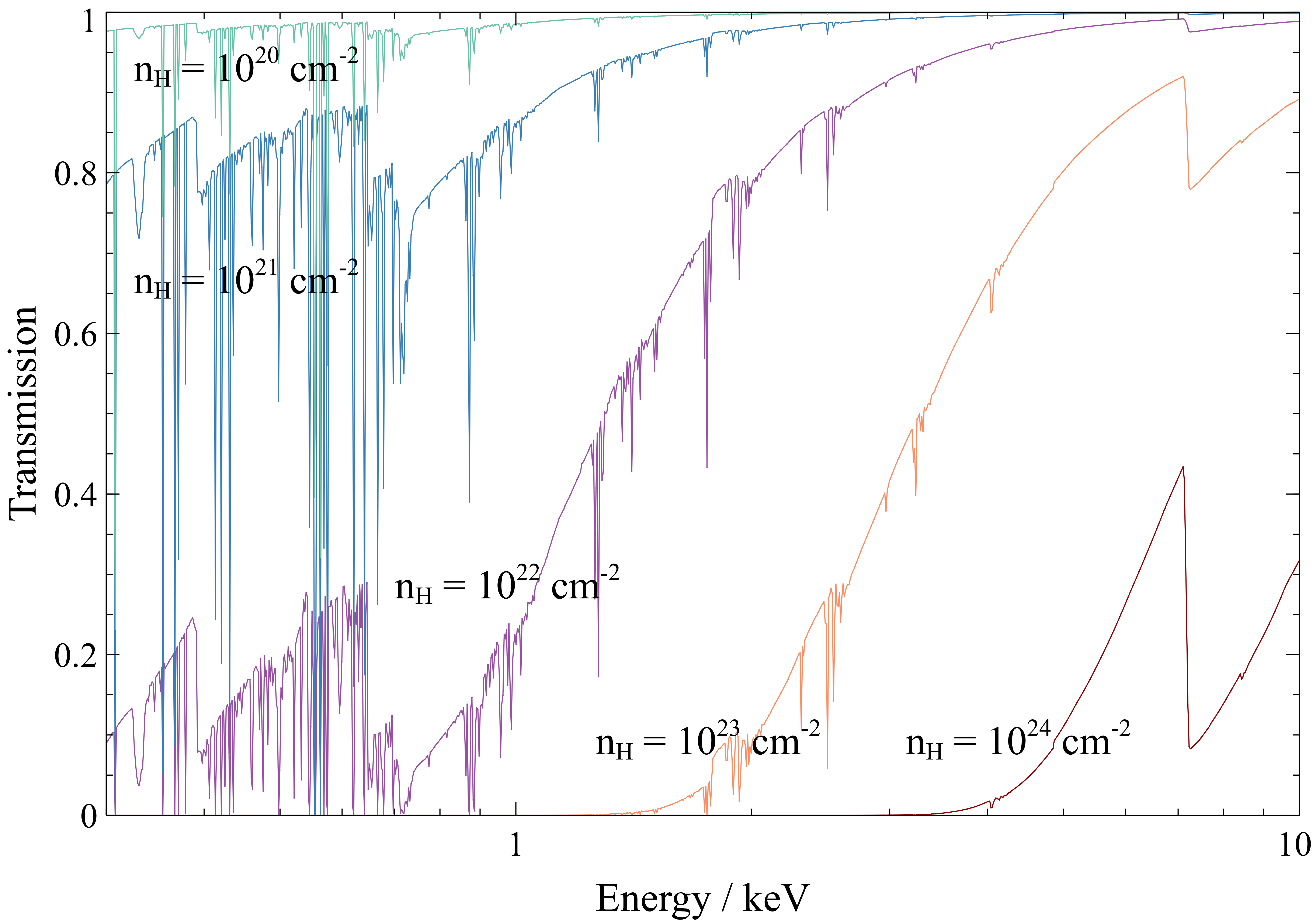
Warm absorbers

I Zw 1 – Rogantini et al. 2022



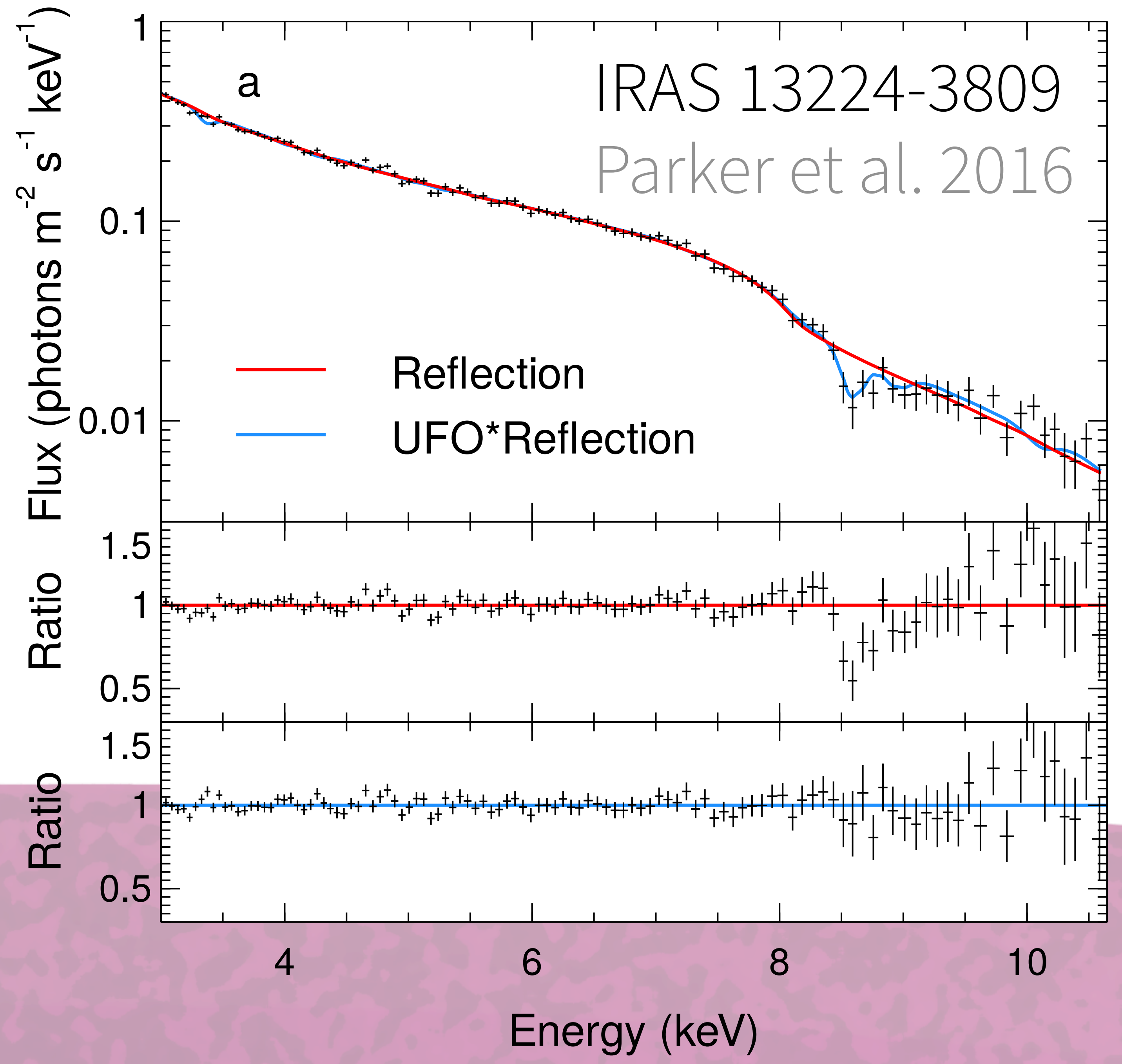
- High resolution spectra (e.g. XMM-Newton Reflection Grating Spectrometer) show narrow absorption lines from warm absorbers, blueshifted corresponding to outflow velocities 100 ~ 1000 km s^{-1}
- Model absorbers using photoionisation codes (e.g. XSTAR, CLOUDY, WARMABS)
  - Fit column density, ionisation parameter, velocity (and density)
- Often find multiple components in different ionisation states
- Warm absorbers are variable (and not simply related to change in flux), hinting at clumpy outflows connected to the disc

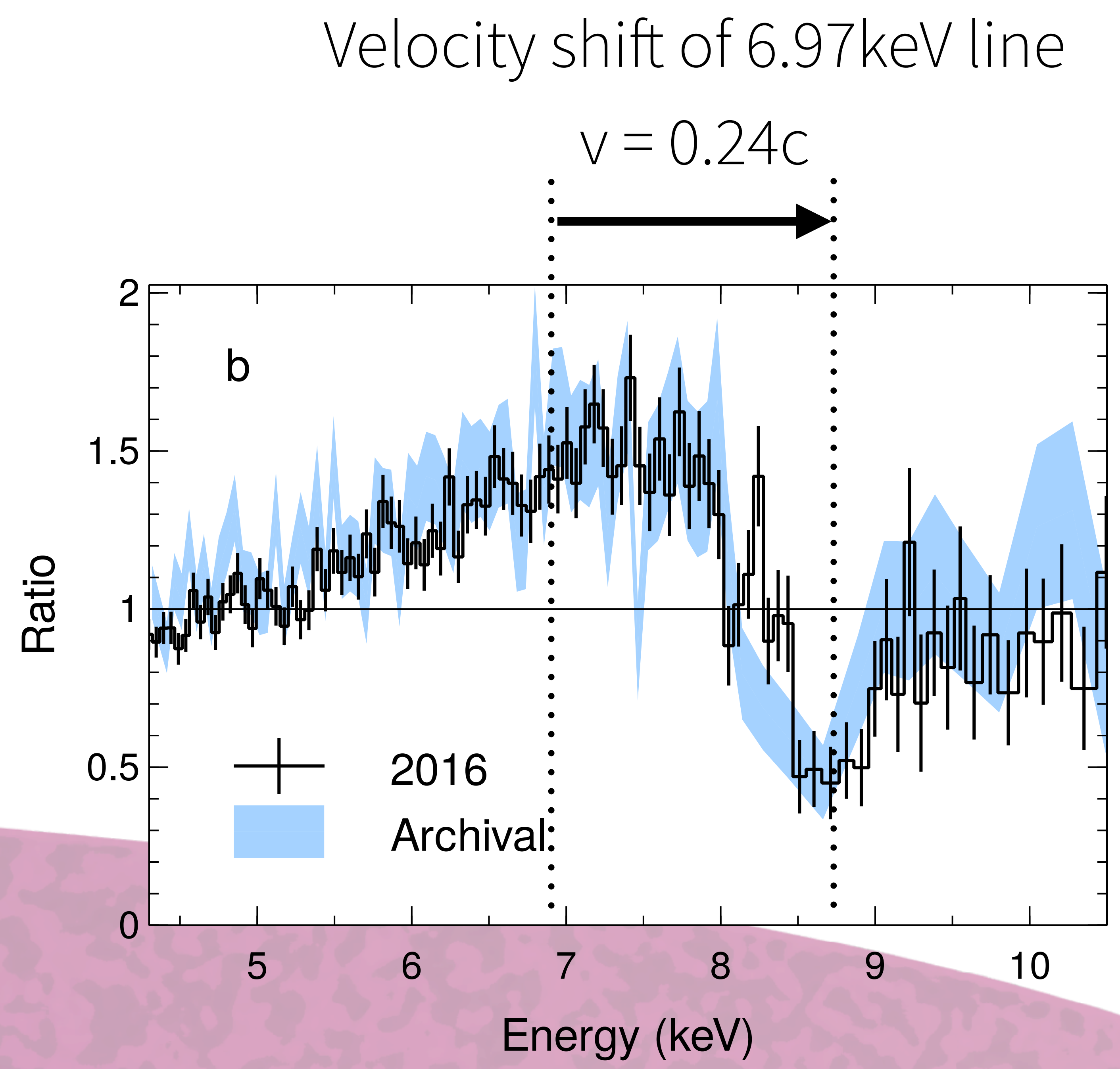
From mild absorption to obscuration



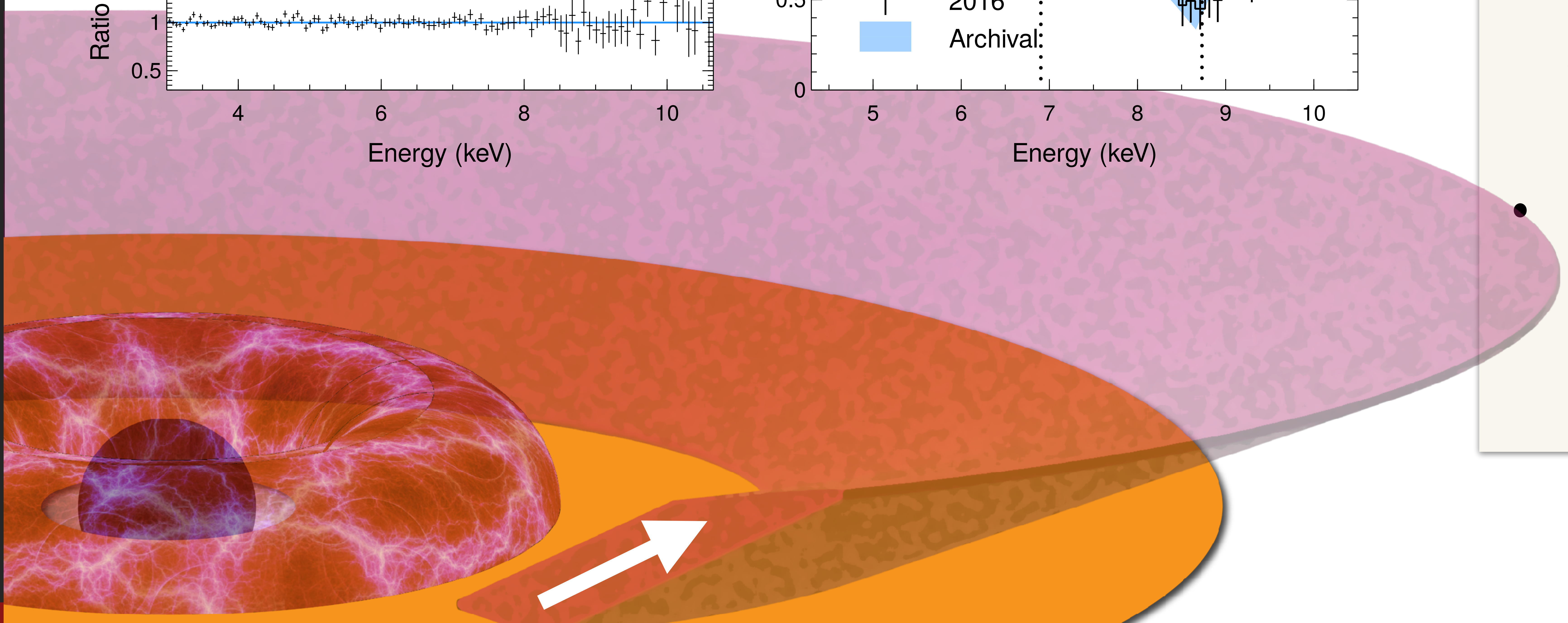
- At low column densities ($n_H \sim 10^{20}$ cm^{-2}), mild continuum absorption below ~1 keV, plus narrow absorption lines
- At increased column densities, significant absorption of continuum to higher energies
- When $n_H \sim 10^{24}$ cm^{-2}, optically thick to Compton scattering (Compton thick or obscured AGN, detectable in hard X-rays > 10 keV)

Ultrafast Outflows (UFOs)

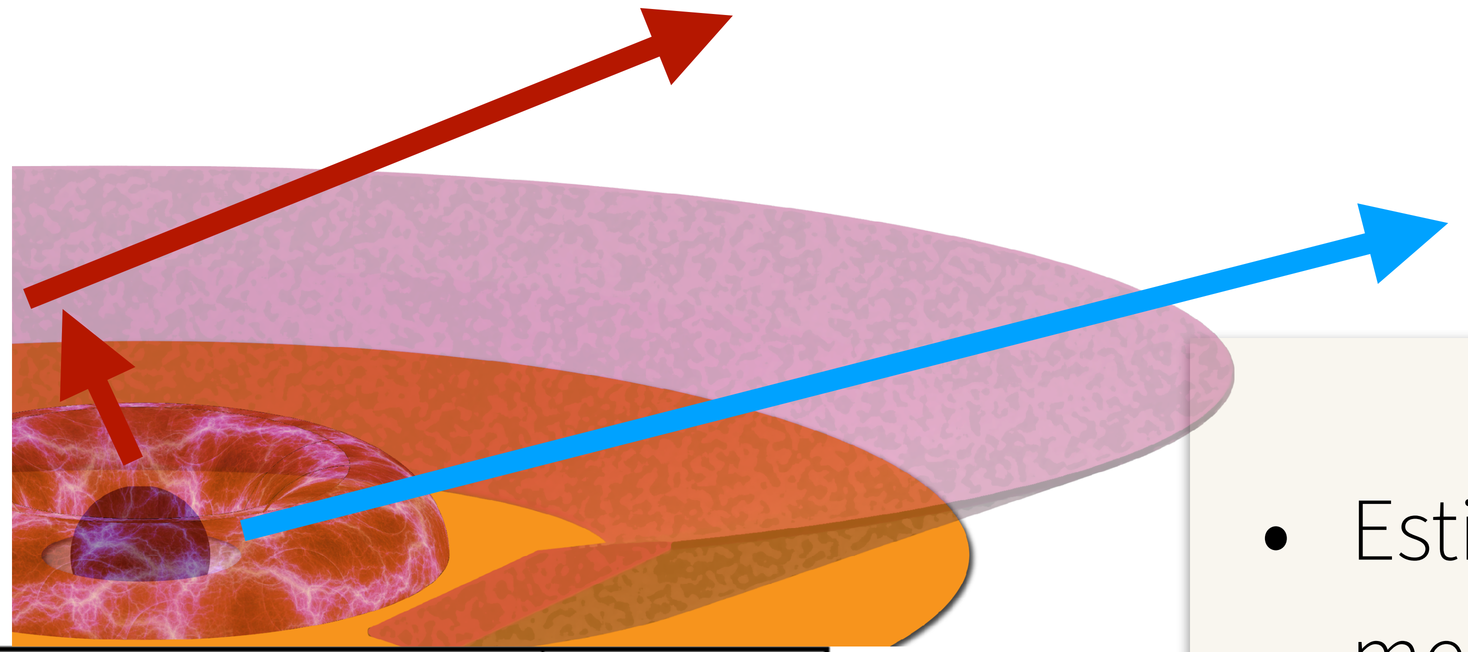


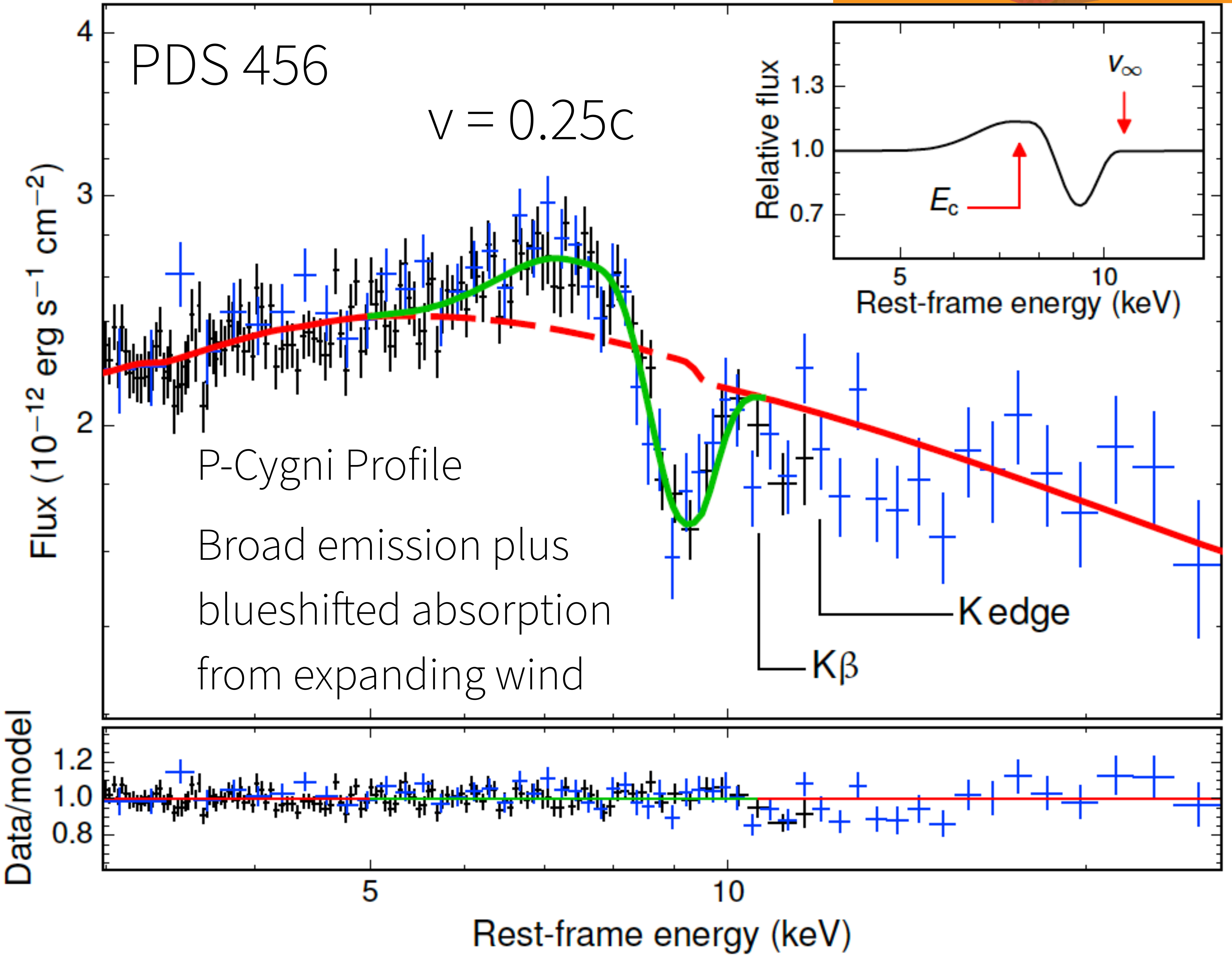


- Relativistic winds of highly ionised gas (velocity >0.1c) launched from inner accretion disc
- Absorption lines from highly-ionised FeXXV FeXXVI in the iron K band
- Radiation driven, or magnetically driven by Blandford-Payne process



UFOs and AGN Feedback





- Estimate mass outflow rate from measurement of column density and velocity, and estimate of opening angle

$$\dot{m}_{\rm out} = \Omega N_H m_{\rm p} v_{\rm out} r_{\rm in} \sim 10\, M_\odot\, {\rm yr}^{-1}$$

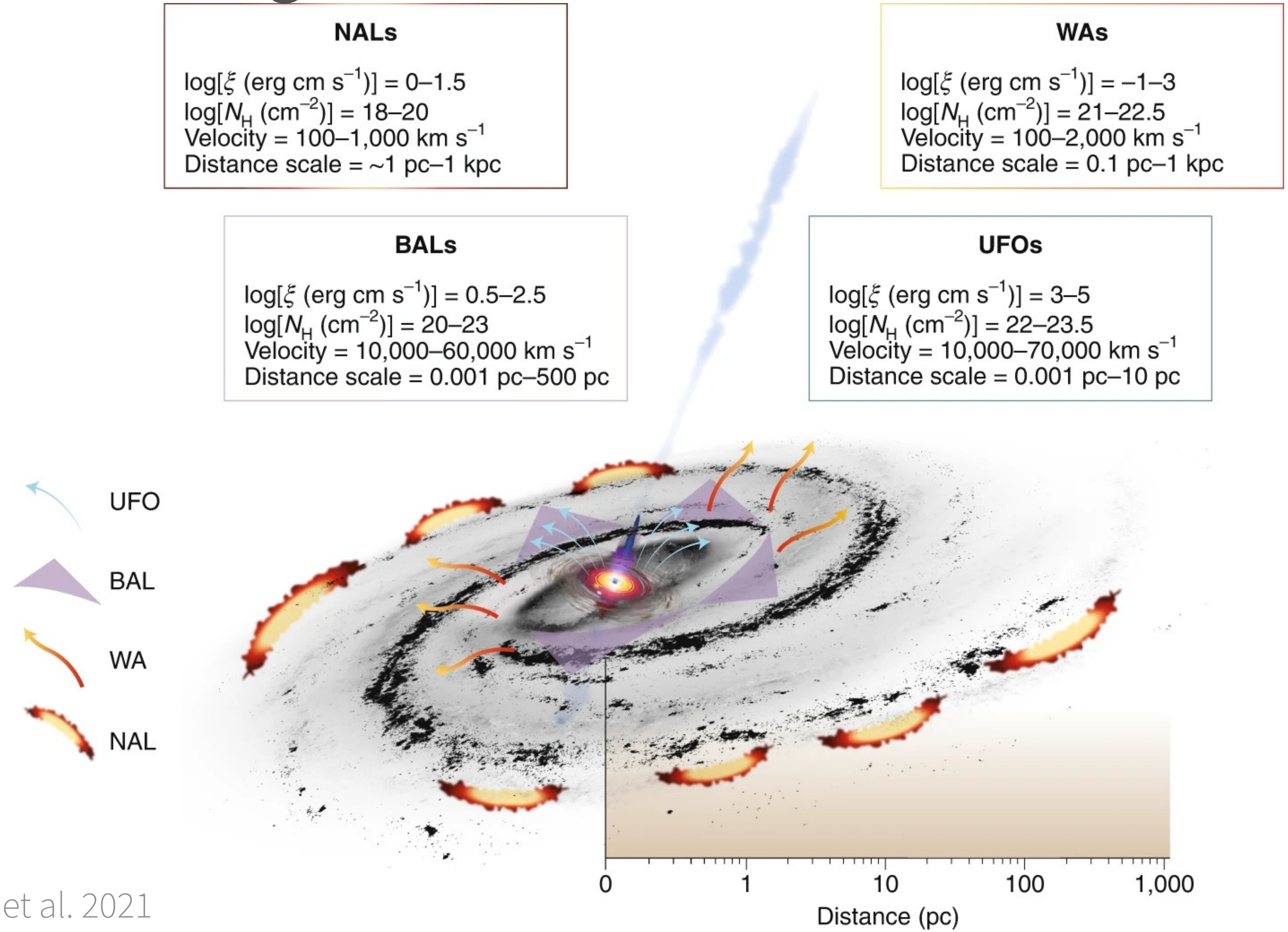
- Kinetic power

$$P_{\rm kin} = \frac{1}{2}\dot{m}_{\rm out} v_{\rm out}^2 \sim 10^{46}\,{\rm erg\,s^{-1}} \sim 0.2\, L_{\rm bol}$$

- Ultrafast outflows can carry significant momentum and kinetic energy into the host galaxy, and may represent a significant channel of AGN feedback

Nardini et al. 2015

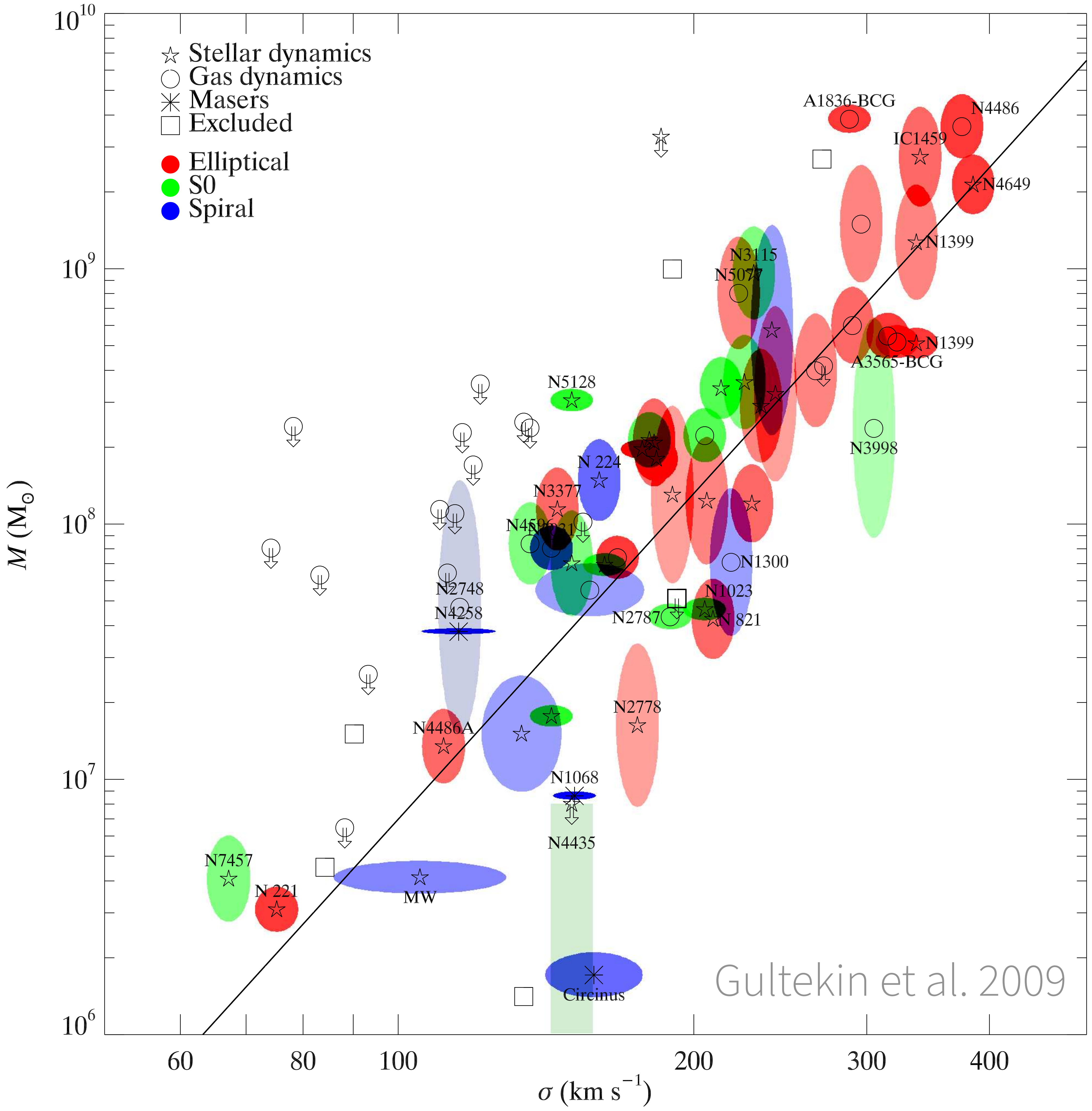
Connecting the outflows



Laha et al. 2021

AGN feedback

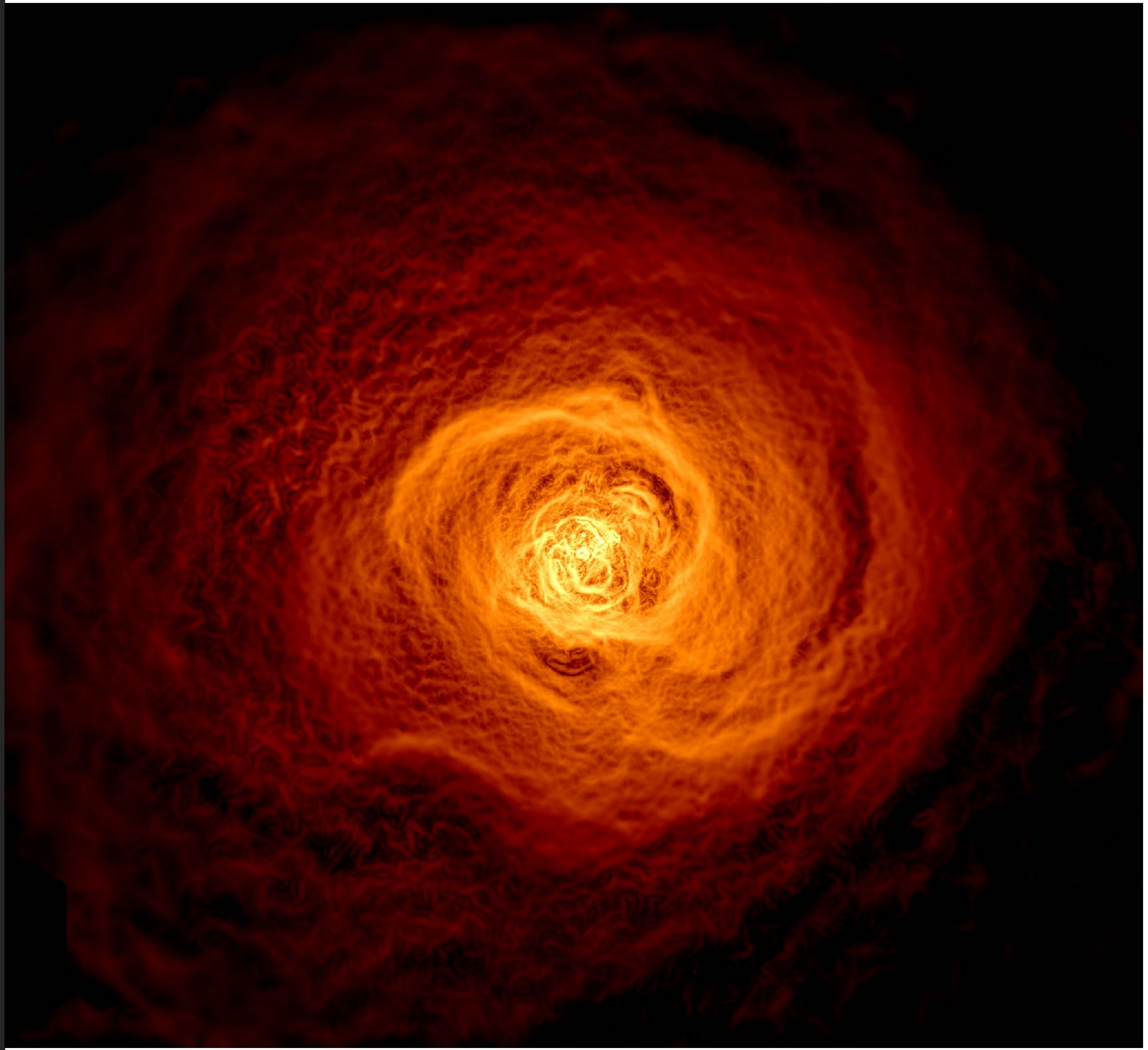
The M-σ relation



- The mass of the supermassive black hole is tightly correlated with the mass and velocity dispersion (σ) of the host galaxy's stellar bulge
- With little scatter, there must be coupling between the growth of the black hole and the growth of the galaxy

Stanford

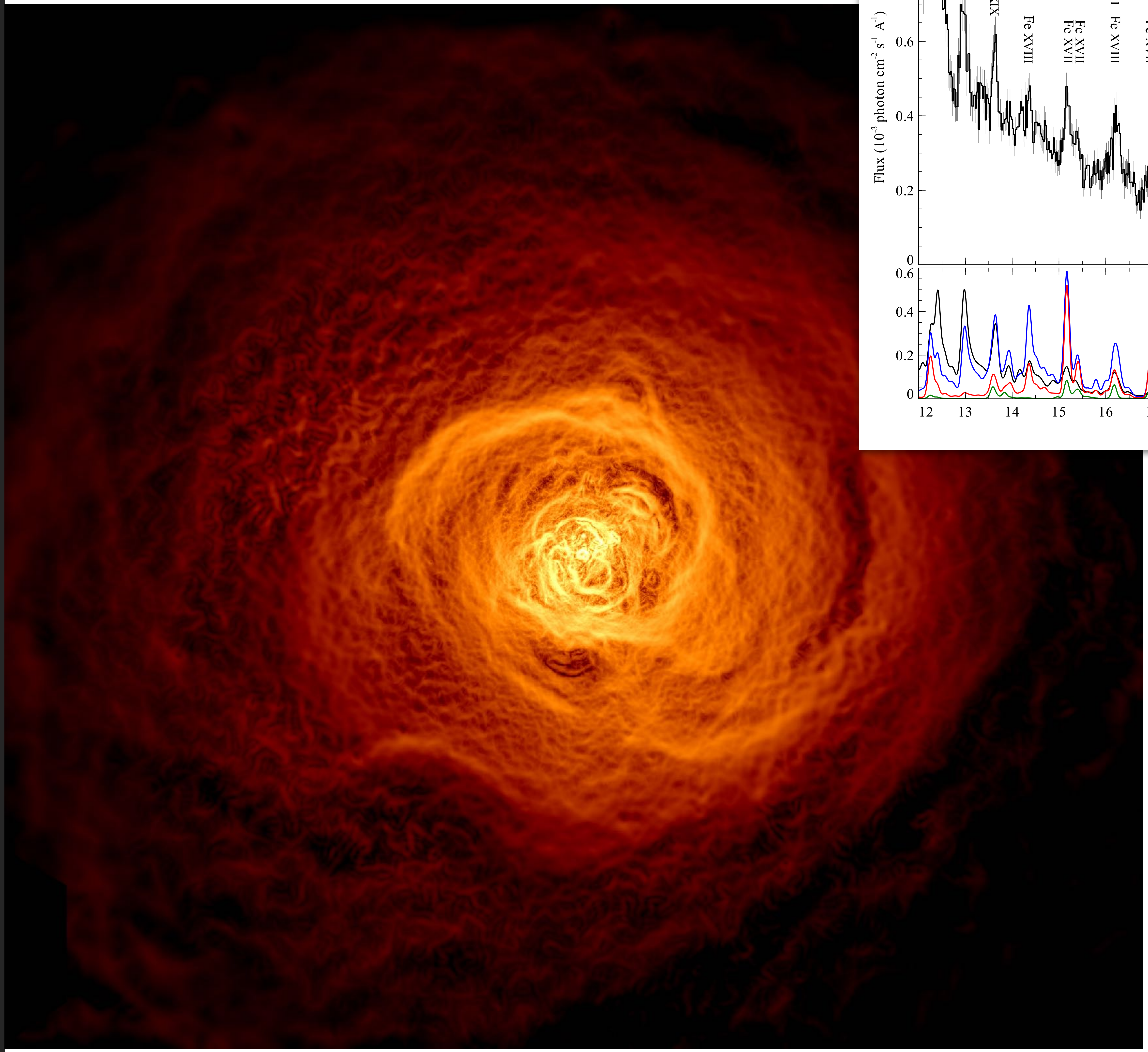
Cluster cooling flows

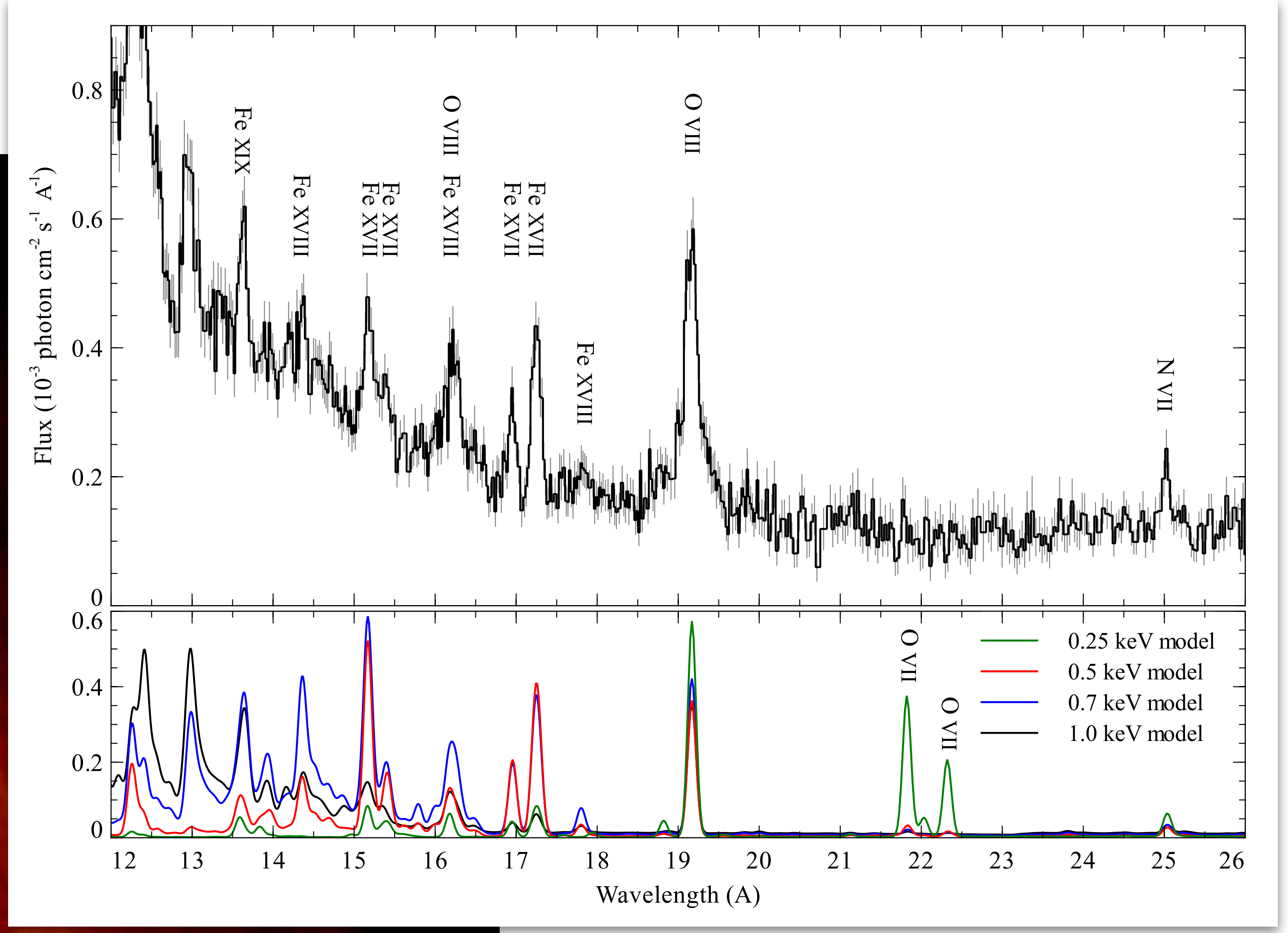


Fabian et al. 2012

- X-ray luminosity of cool core clusters implies cooling times
- Observe cooling flows of gas falling into cluster, implying cool gas should be accumulating in core
- This accumulating cool gas is not observed from the X-ray emission lines it should emit
- Solution if AGN in central brightest cluster galaxy is heating the gas

Cluster cooling flows





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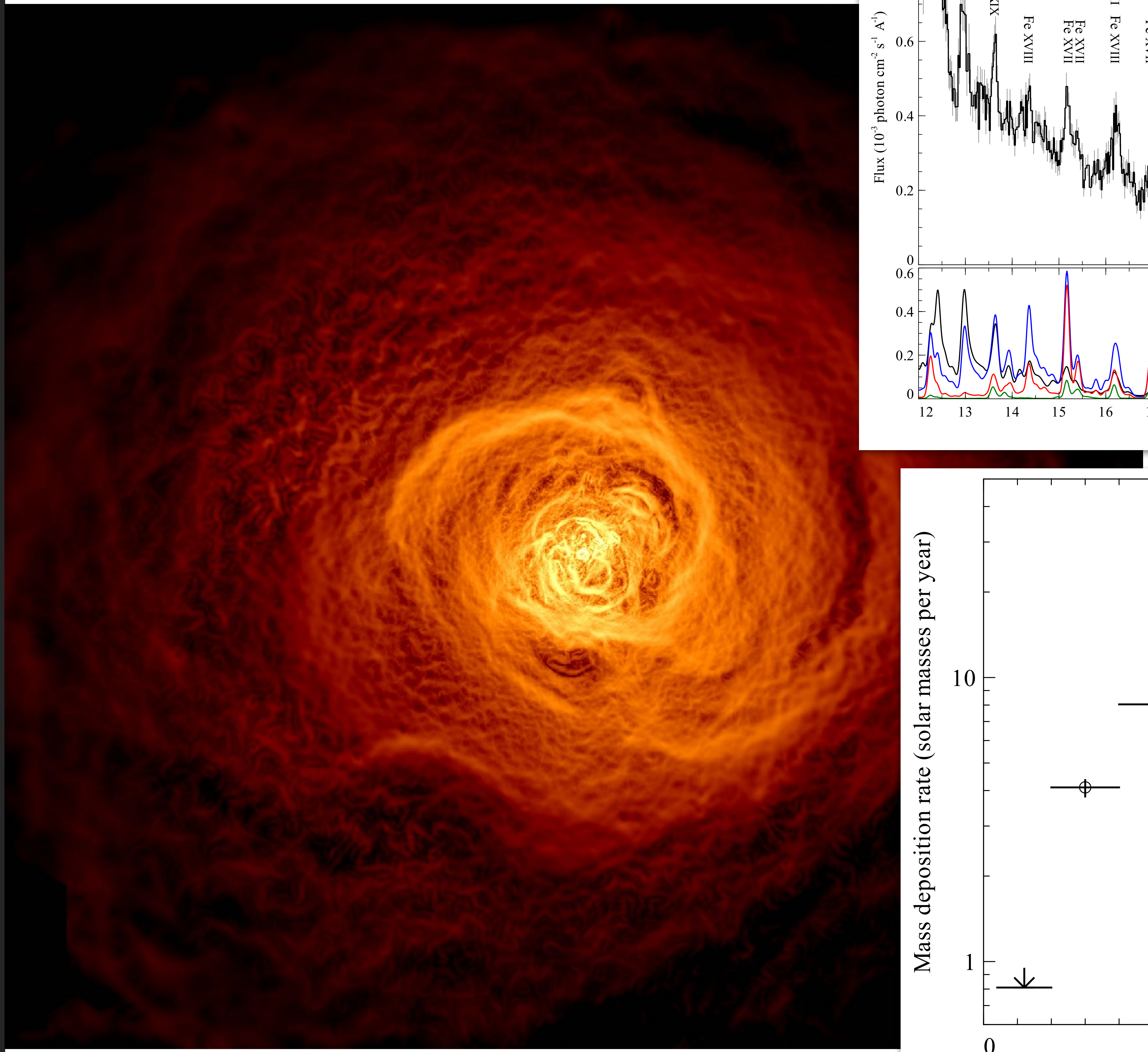

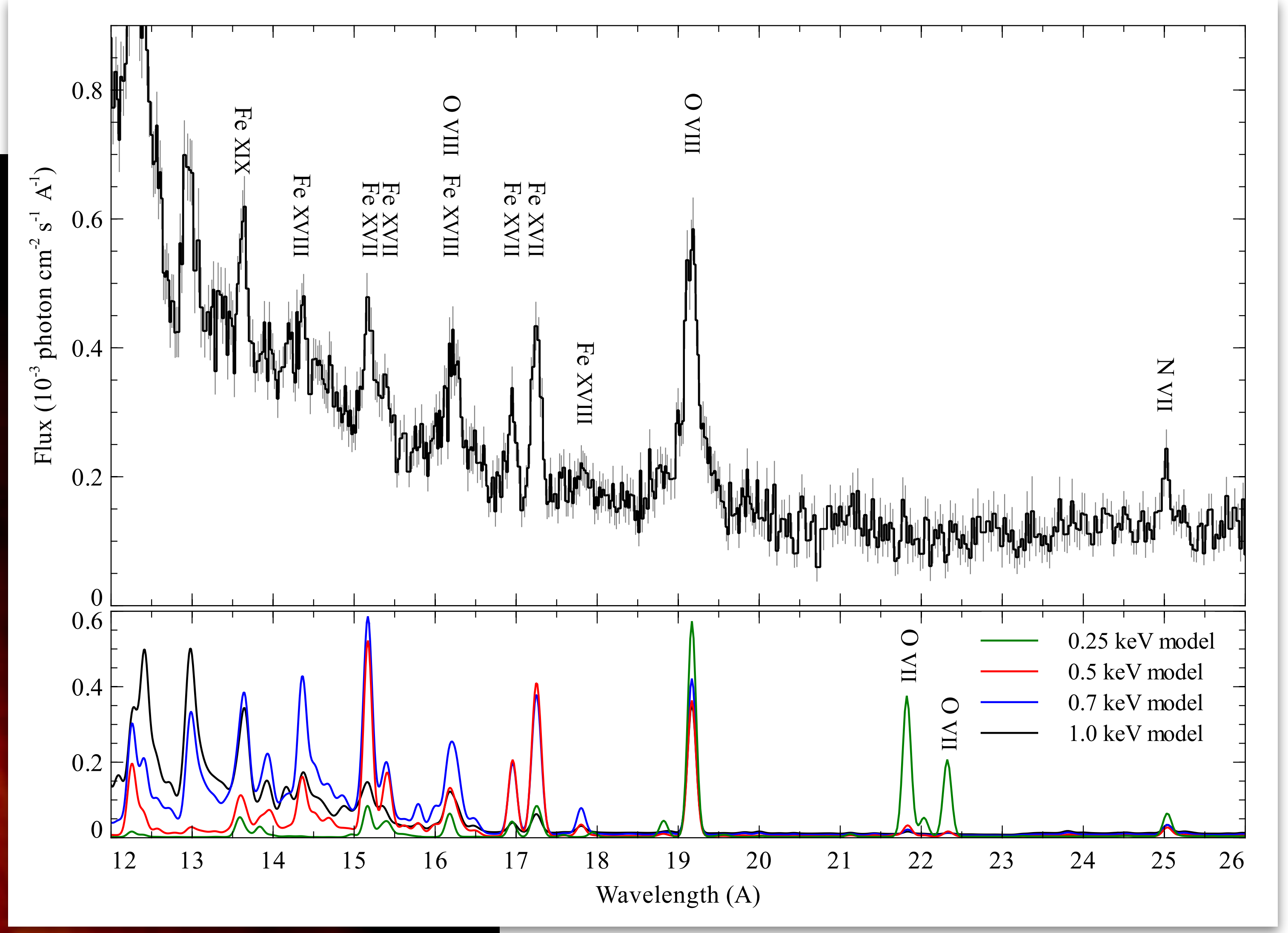

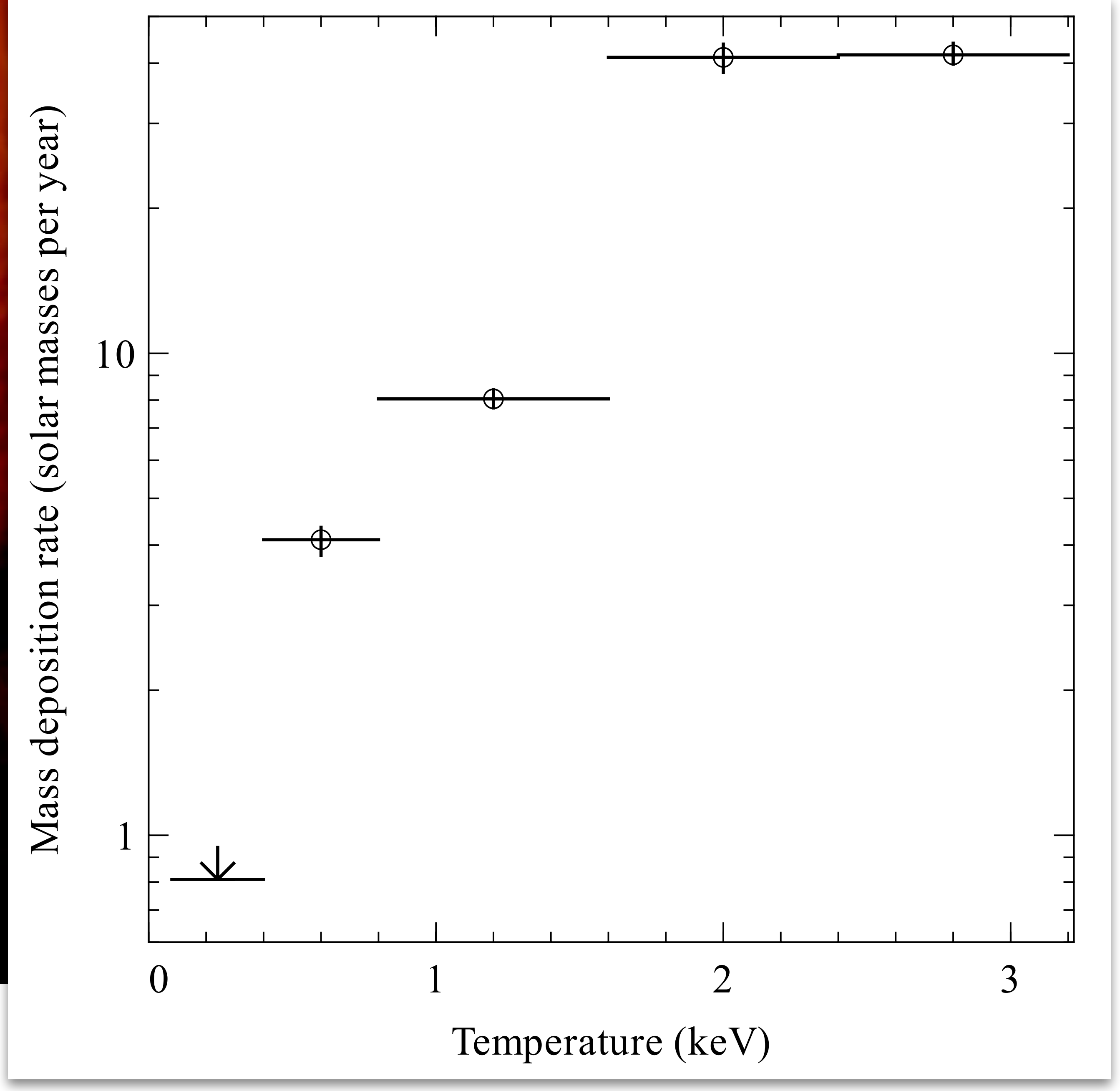

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Fabian et al. 2012

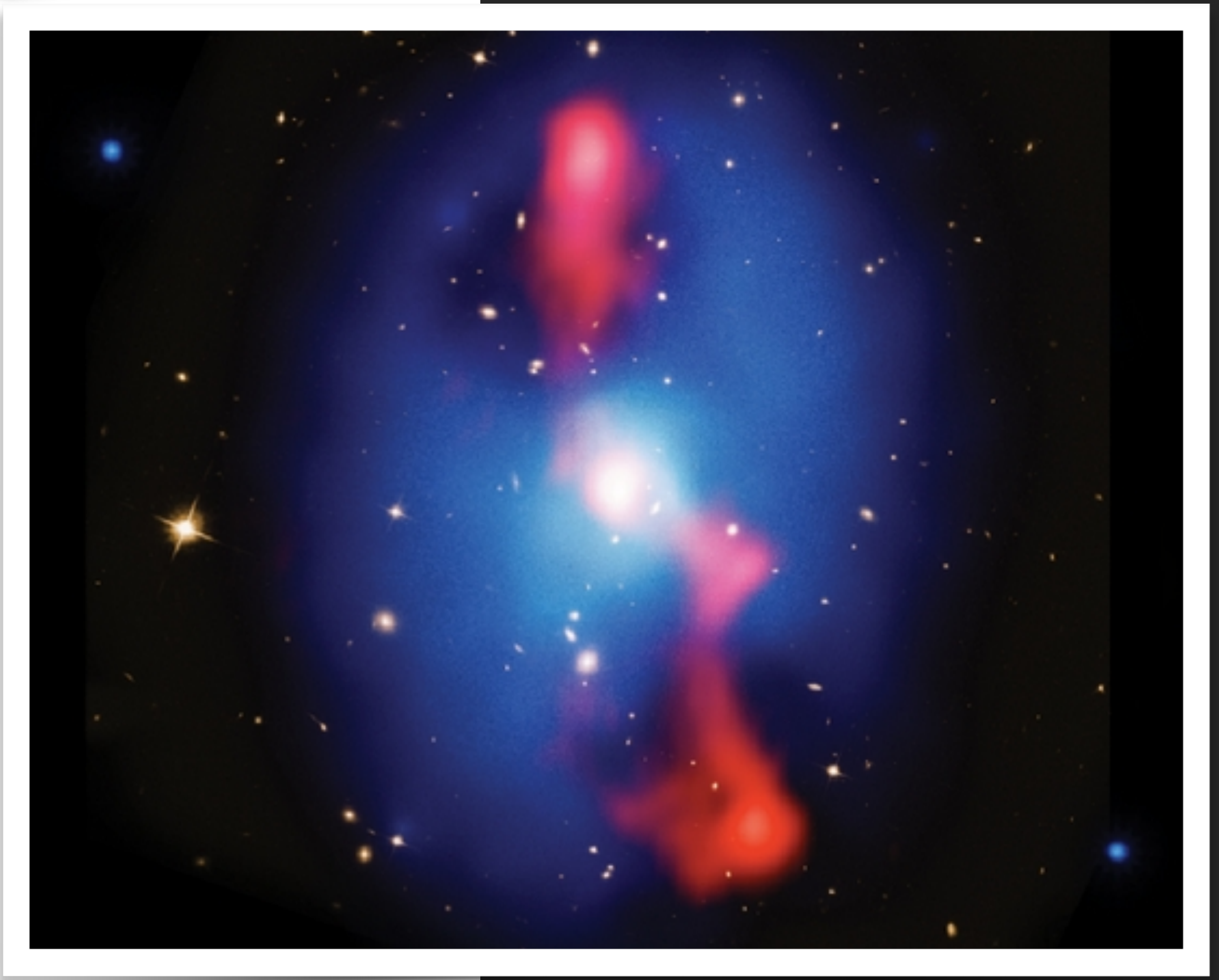
Modes of AGN feedback

Quasar (radiative or wind) mode

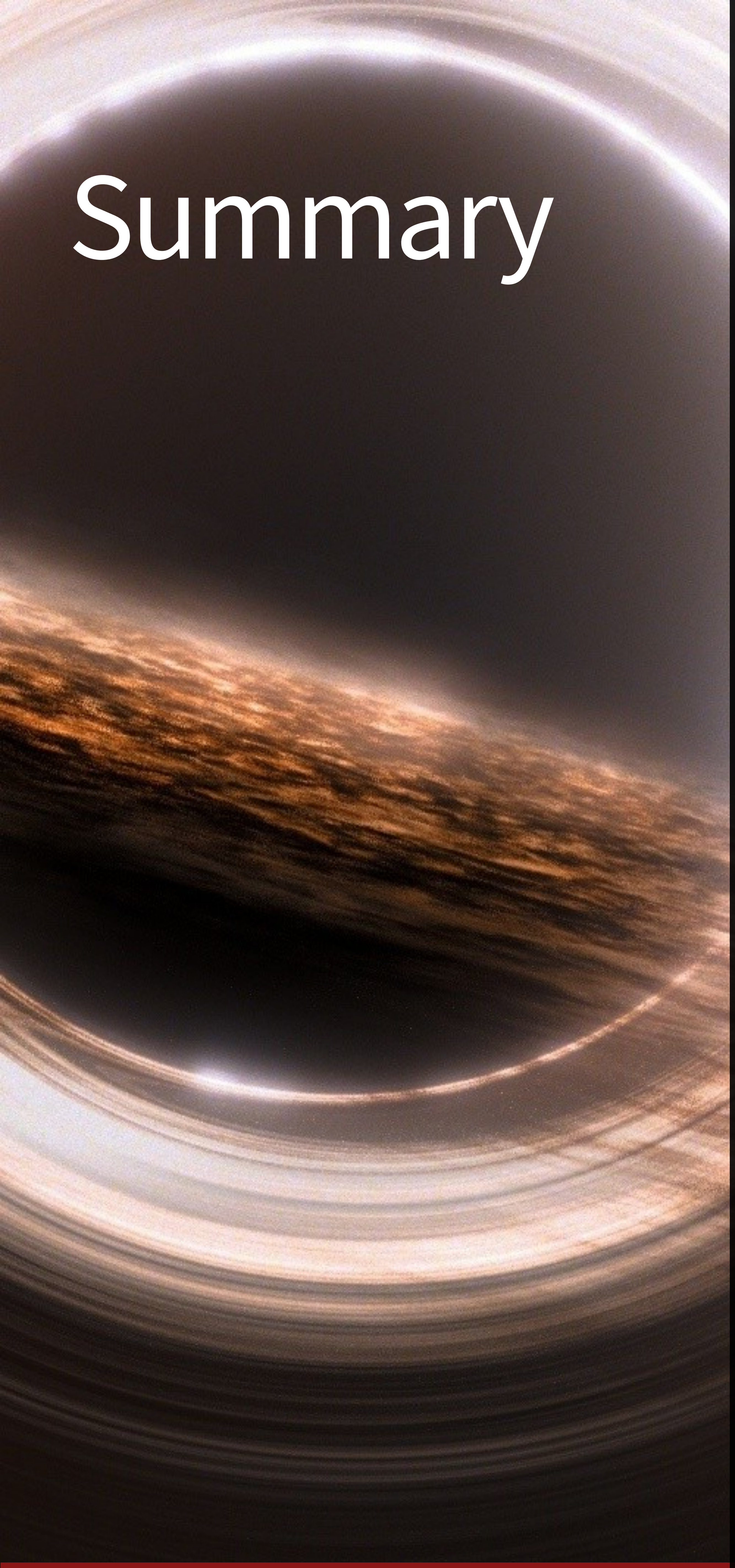
- Radiation pressure (especially on dust) drives winds
- Winds transport kinetic energy into ISM of host galaxy

Kinetic (radio) mode

- Kinetic energy transported into environment via jet
- Can span large distances out of host galaxy



Fabian et al. 2012

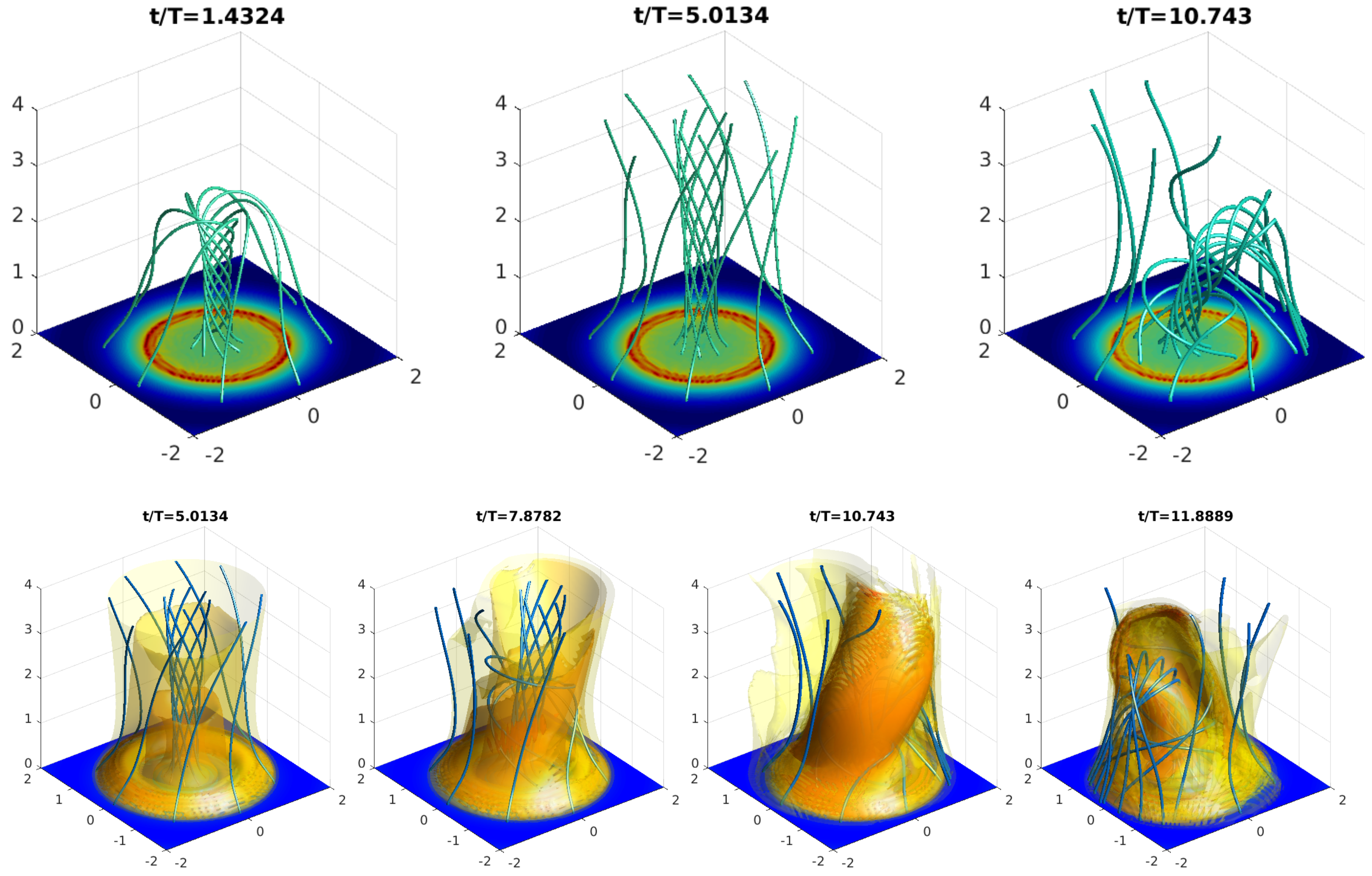


Summary

- Multi-wavelength observations let us piece together the structure of AGN
- Accretion disc dominates optical/UV emission, while X-ray emission is dominated by emission from a corona of accelerated particles close to black hole
- We observe reflection of the X-ray continuum from the inner accretion disc (more in Lecture II)
- AGN launch multi-scale outflows, from large-scale, moderately ionised warm absorbers, to ultra-fast, relativistic outflows (UFOs) launched from inner disc
- The energy released from an accreting supermassive back hole plays an important role in governing the formation of galaxies and structure in the Universe via AGN feedback

Backup slides

Lighting the Lamppost



Current density shows dissipation sites

- Why does a collimated jet-like core appear in the corona of a radio-quiet AGN?
- Differential rotation inflates tubes
- Strong confinement by ambient magnetic field leads to kink instability — causes jet to collapse
- Rotational energy from black hole dissipated in magnetosphere

Yuan, Spitkovsky, Blandford & Wilkins 2019