Dynamical complexity in disk-wind systems

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BHs: Chance or Necessity?

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Chance: result of galaxy evolution

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Chance: result of galaxy evolution

Necessity: the growth hormone of galaxy evolution

...a first glance to the monster: active galactic nuclei

Luminosity 10^{41} - 10^{48} erg/s ~ - - >> Lgal

Variability seconds - years ~ t_d

Size $R \sim ct_d \sim 10^{12}$-10^{18} cm << Rgal

Eddington Luminosity $L_{edd} = 4\pi GMm_p c/\sigma_T = 1.26 \times 10^{38}\ M/M_O$

$= 1.26 \times 10^{46}\ M_8$ erg/s

$L_{acc} = 1.26 \times 10^{46}\ M_8\ (L_{acc}/L_{edd})$ erg/s $L_{acc} = \varepsilon Mc^2$

Critical accr. $M_c = L_{edd}/c^2 = 4 \times 10^{-8}\ (M/M_O)\ M_O$/yr

$= 4\ M_8\ M_O$/yr if ε=0.057

Fueling AGNs

Conversion of mass to energy with some efficiency η

$$L = \eta \dot{m} c^2 \qquad \dot{m} = \frac{L}{\eta c^2} = 1.8\times10^{-3}\frac{L_{44}}{\eta} M_{\oplus} yr^{-1}$$

$$U = \frac{1}{2}\frac{GMm}{r} \qquad L \approx \frac{dU}{dt} = \frac{1}{2}\frac{GM}{r}\frac{dm}{dt} = \frac{GM\dot{m}}{r} \Rightarrow \eta \approx \frac{1}{2}\frac{GM}{rc^2} = \frac{1}{12} = 0.083 \text{ if}$$

$$R_S = 2\frac{GM}{c^2} \approx 3\times10^{13} M_8 cm \quad \text{last stable orbit} = 3R_S$$

and ignoring relativistic effects.

$$\Delta U = \frac{1}{2}\frac{GM}{3R_S} \text{ energy available from a particle falling to } 3R_S$$

$\eta = 0.057$ for a Schwarzschild metric and 0.42 for a Kerr metric (l.s.o.$=\frac{1}{2}R_S$)

$$\dot{m}_E = \frac{L_E}{\eta c^2} \equiv \text{ Critical mass accretion rate } \approx 2.2 M_8 M_{\oplus} yr^{-1}$$

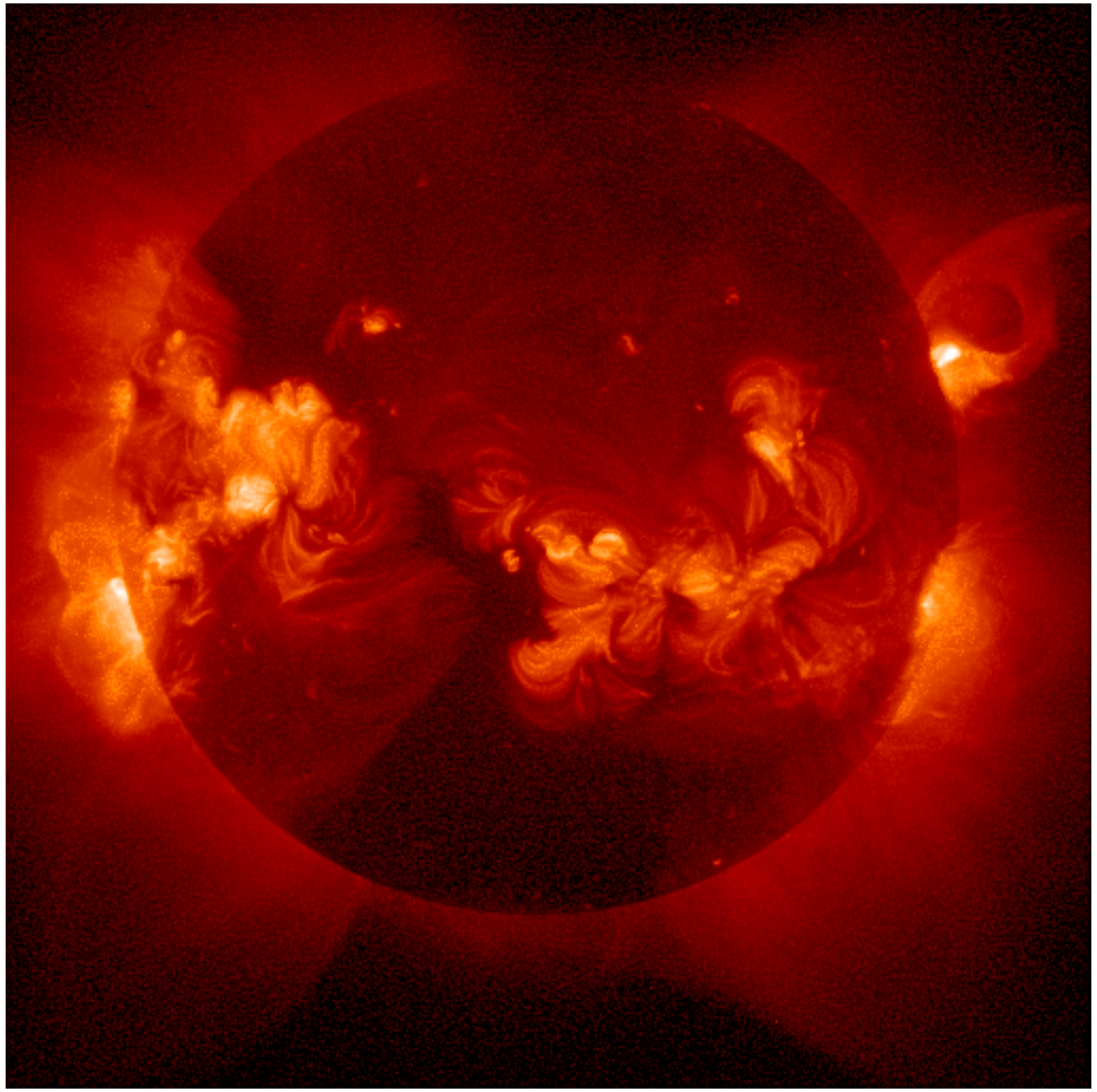
X-ray spectrum

- Dissipate energy in optically thick disk – cool, no hard X-rays
- MUST dissipate in optically thin material so that E >> kT (Compton)

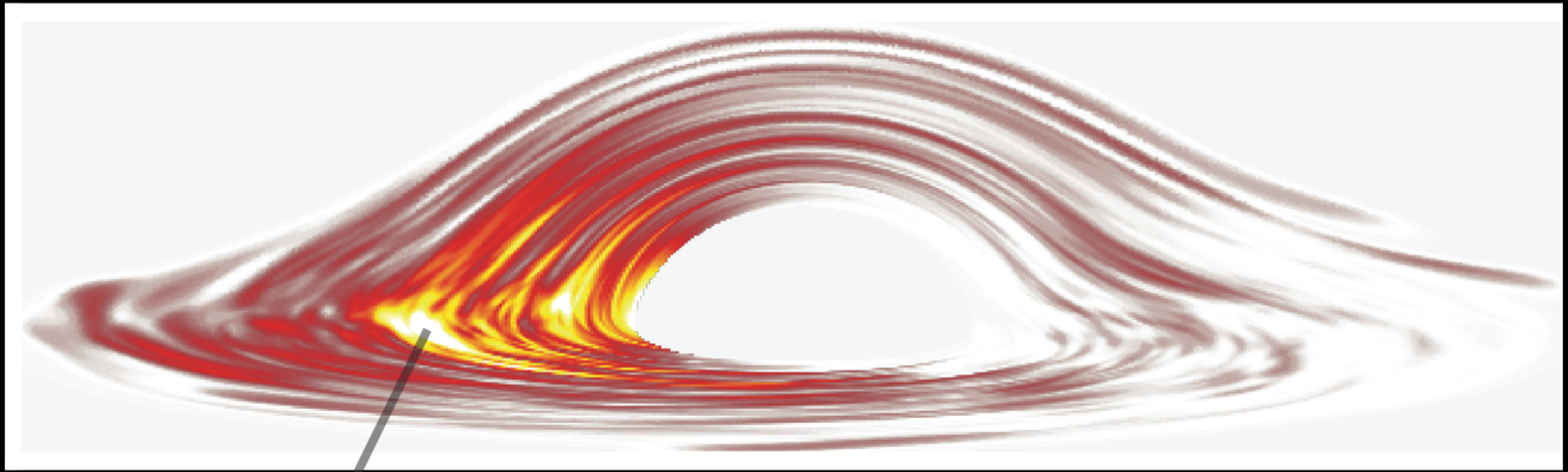
Optically thin accretion flow – low L/L_{Edd} only!

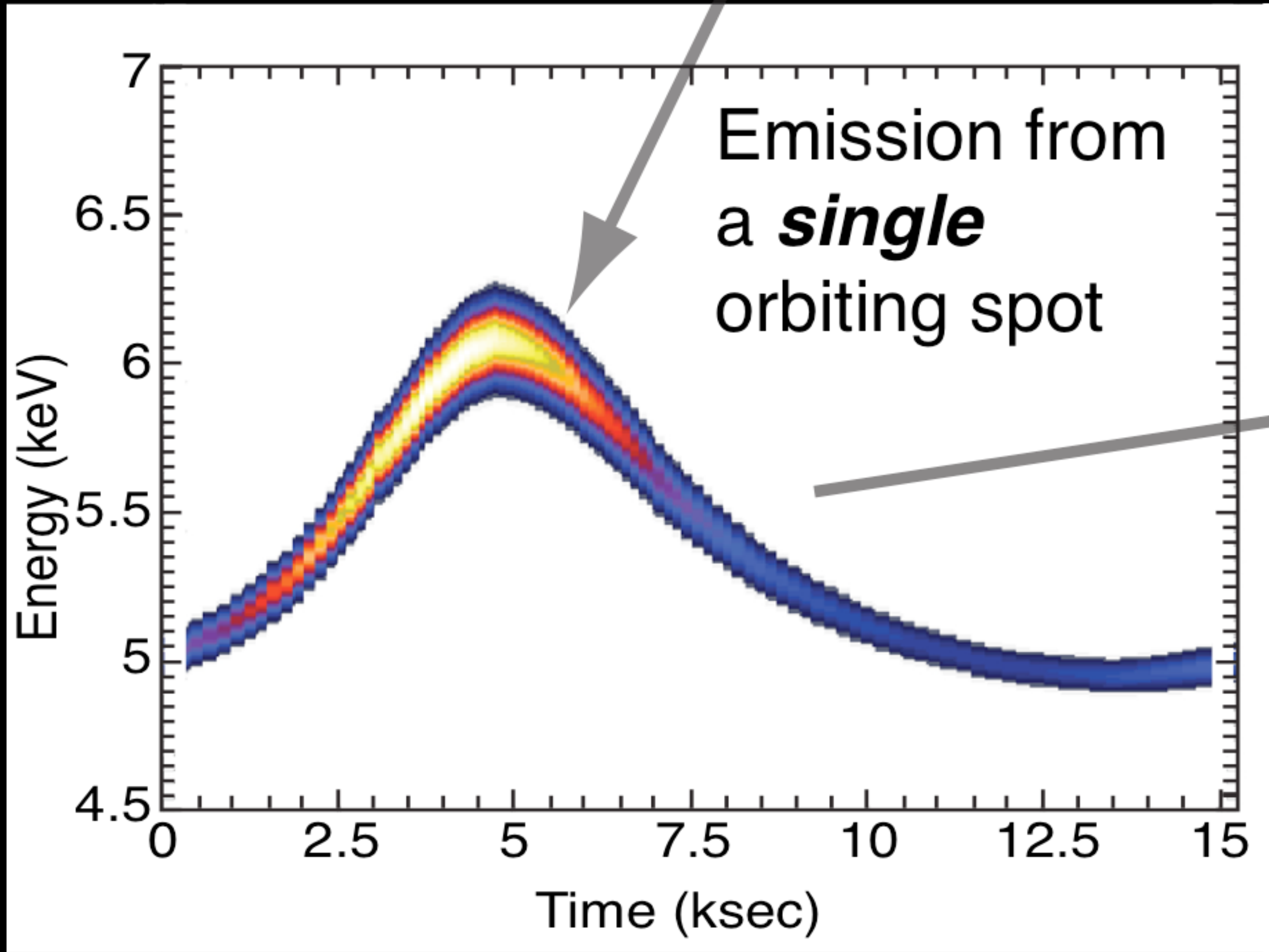
Magnetic reconnection above disk – no known alternatives at high L/L_{Edd}!

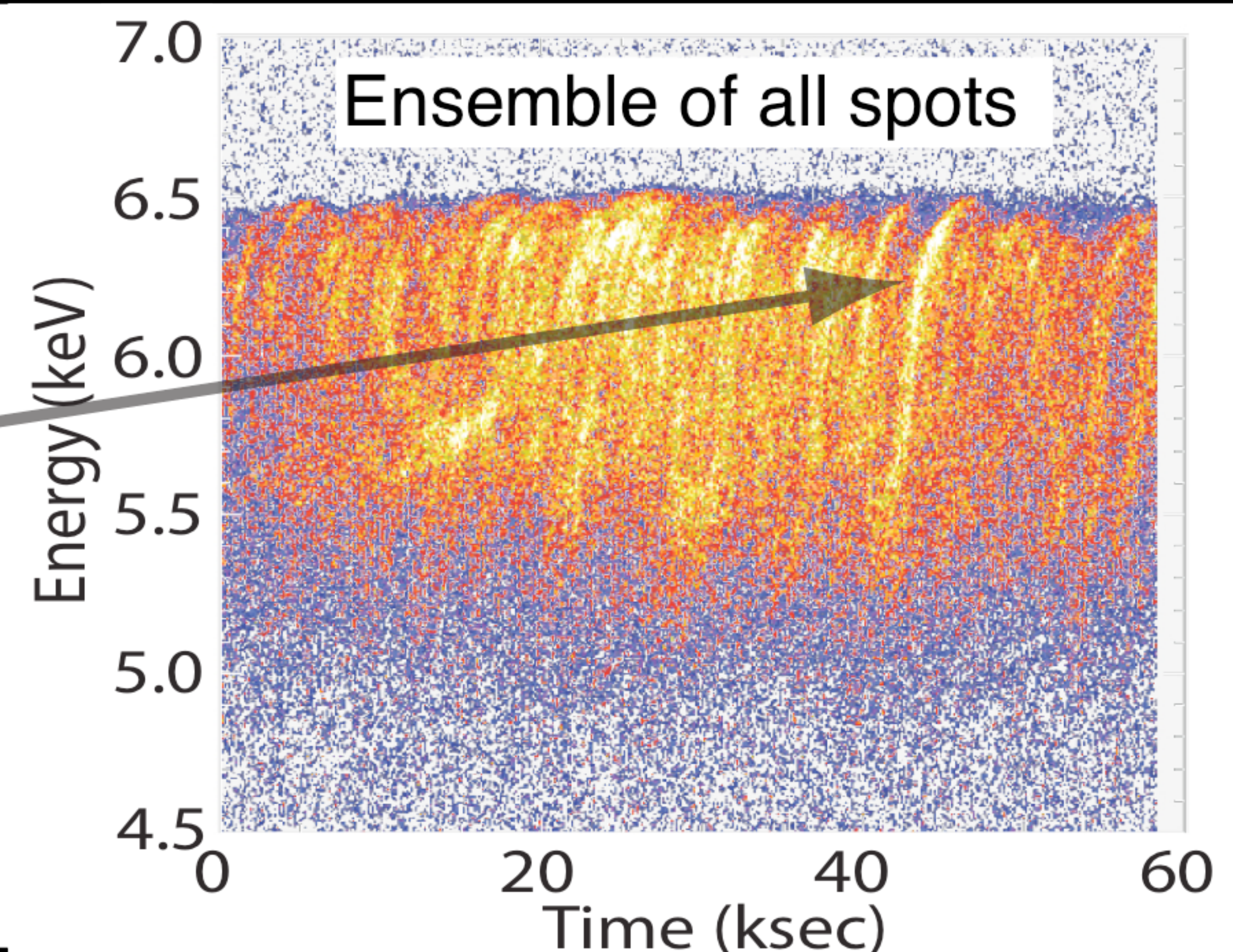
Inverse Compton scattering of lower energy photons by energetic electrons in a corona surrounding the disk



Accretion disks in galactic nuclei







Observational evidences of supermassive BHs

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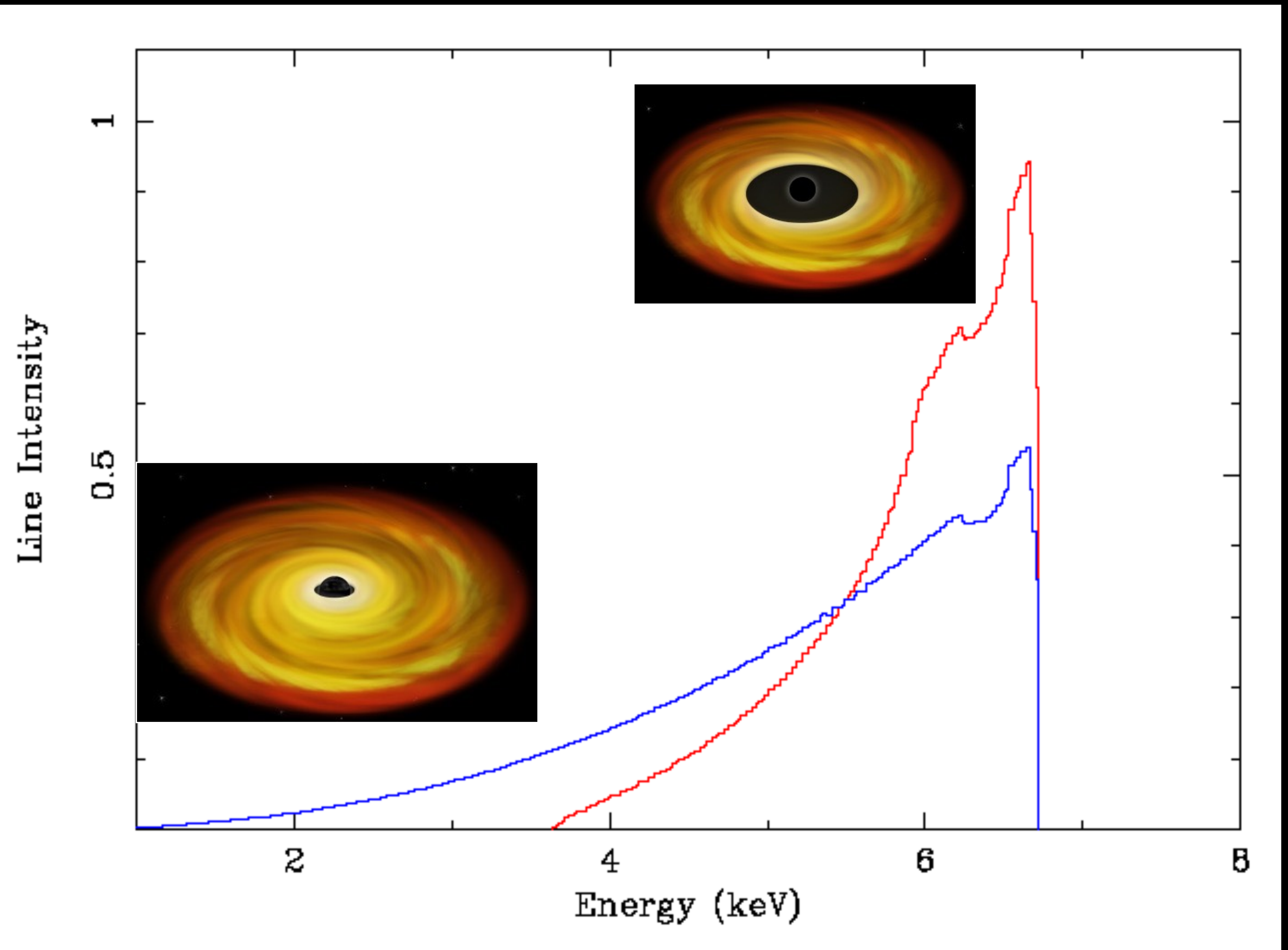
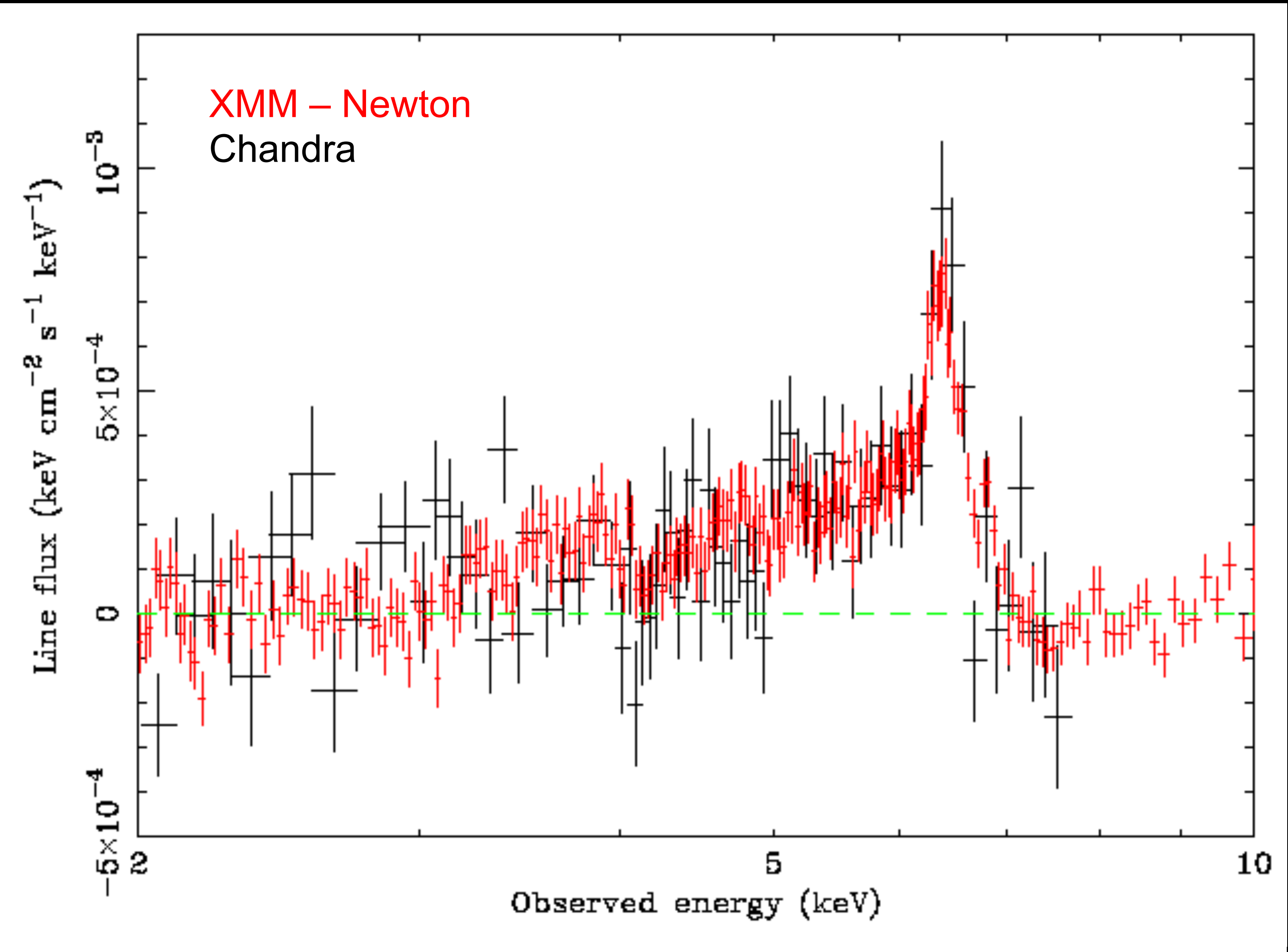
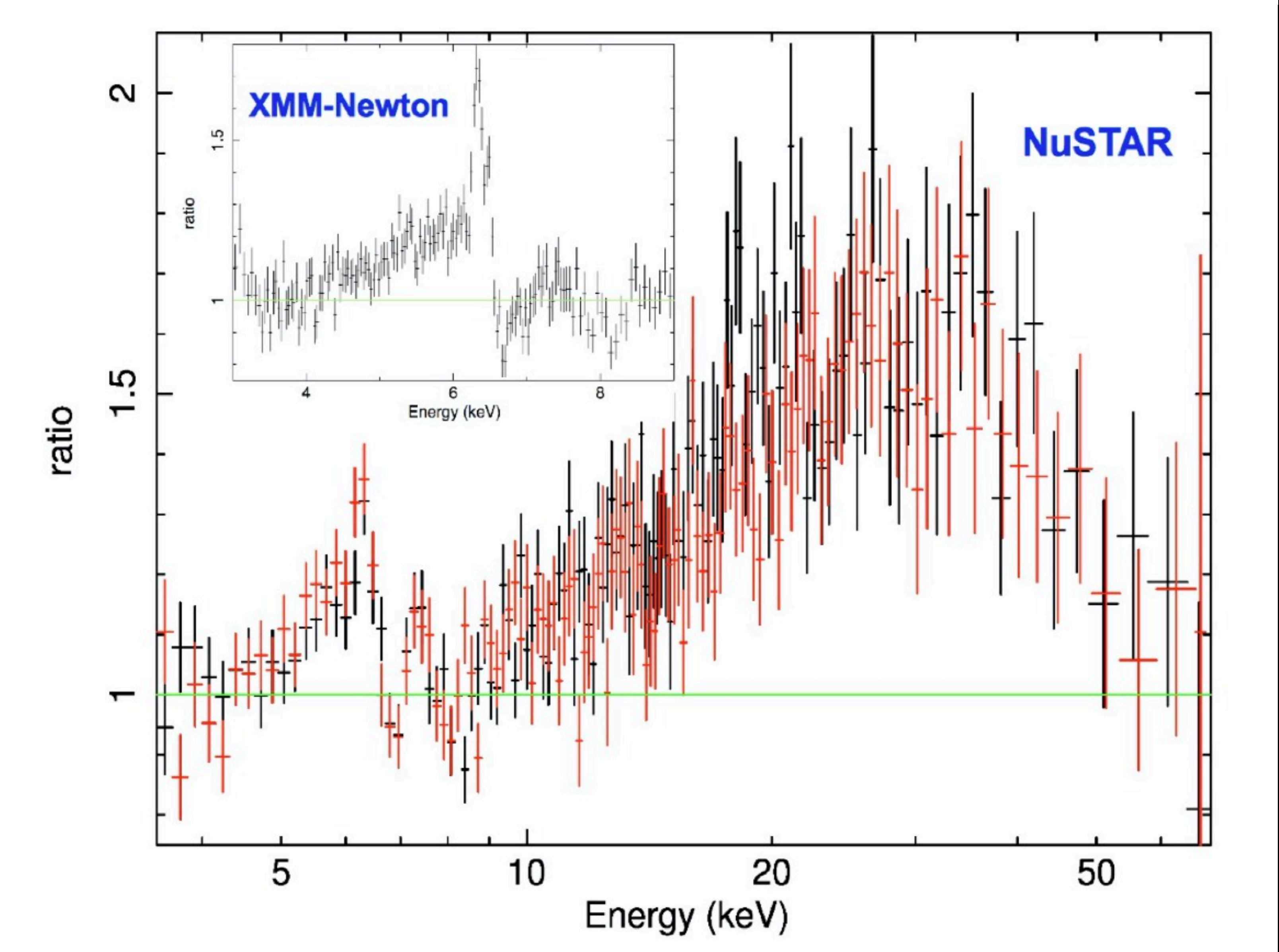
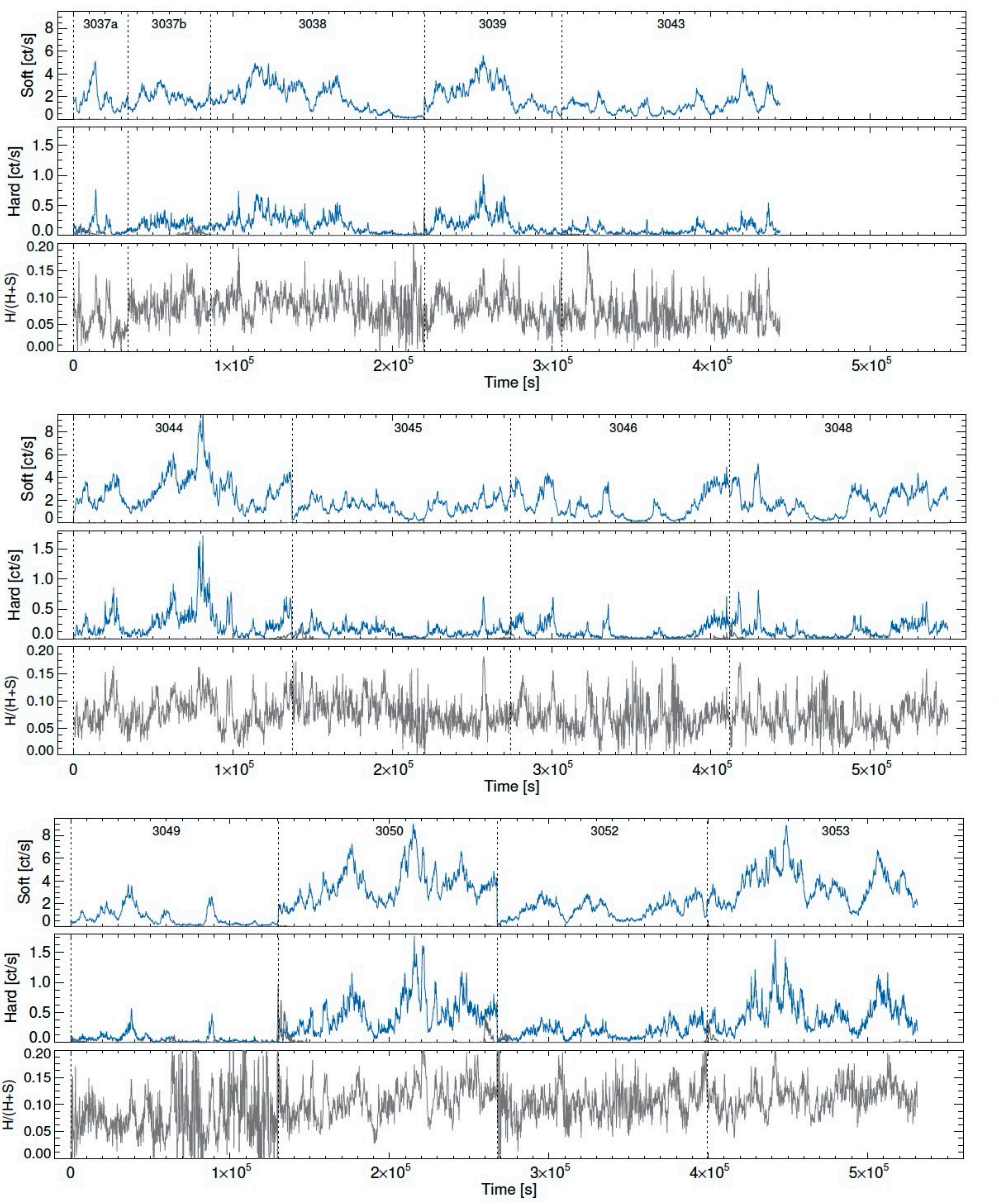
Observational evidences of nuclear disks



- $i = 33° \pm 1°$
- $r_{in} = 1.8 \pm 0.1\ R_g$ (ISCO)
- $a/M = 0.93 \pm 0.01$ →KERR
- $\xi < 30$ erg cm s^{-1}



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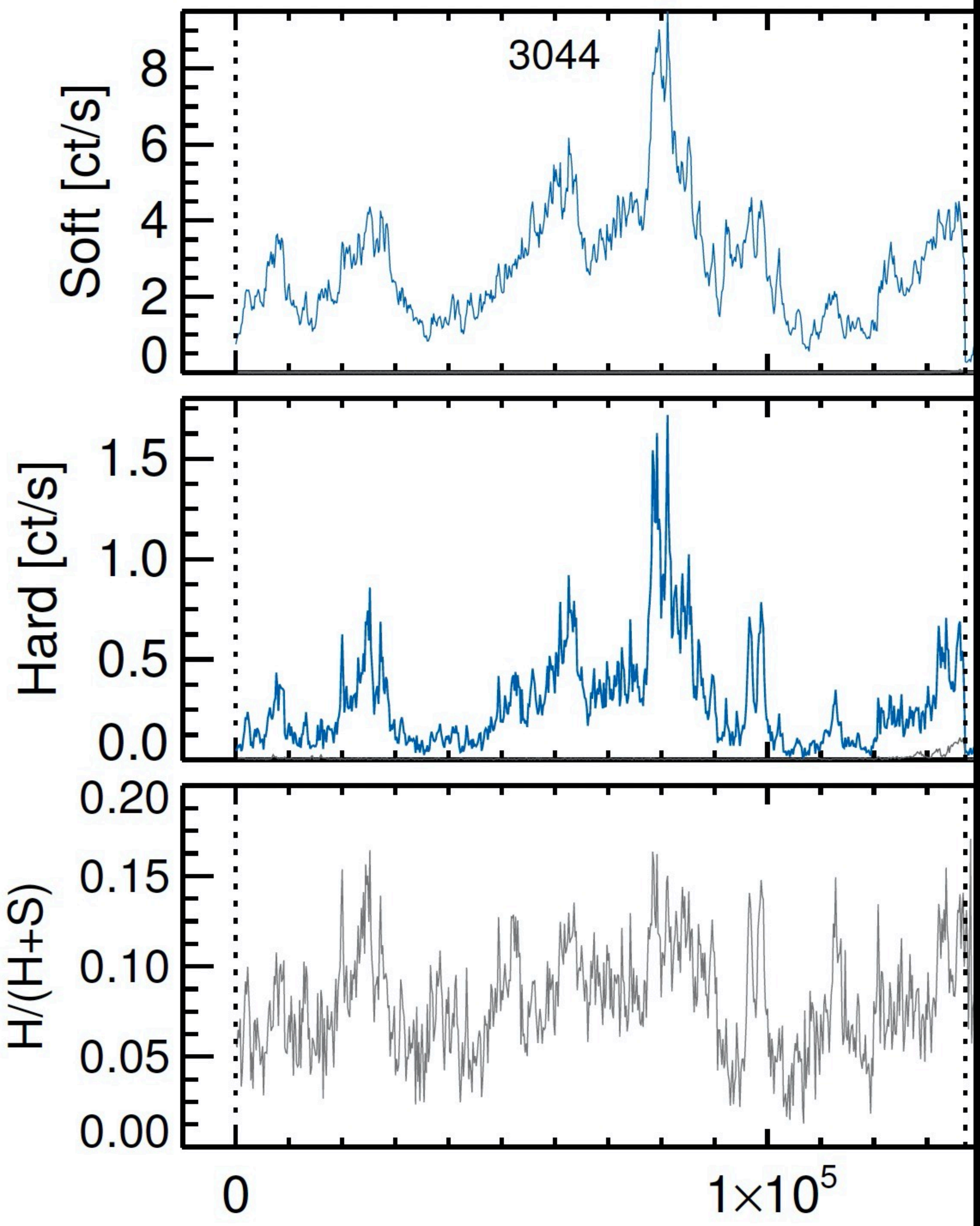
Soft [ct/s]
Hard [ct/s]
H/(H+S)
Time [s]


3044
Soft [ct/s]
Hard [ct/s]
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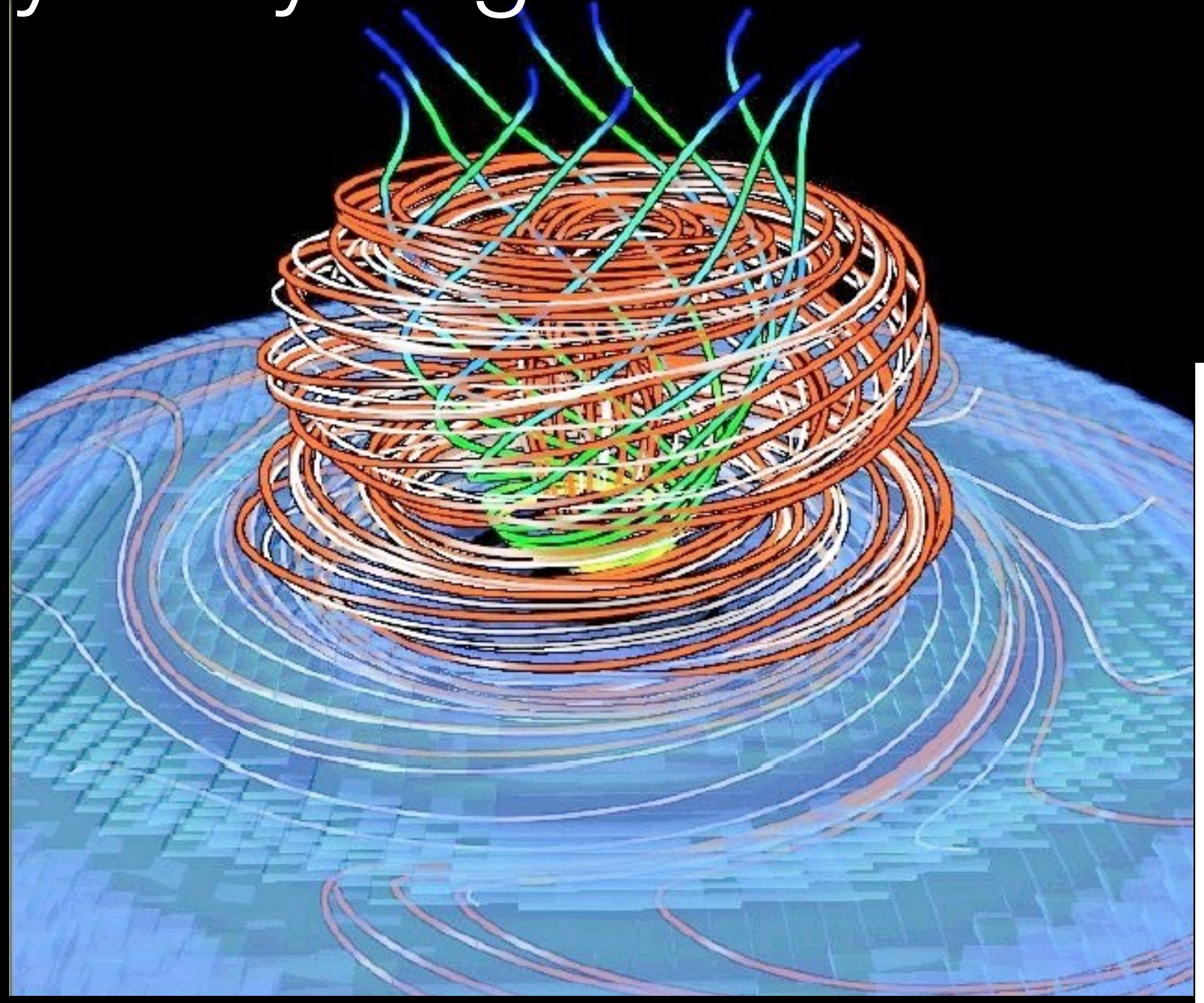
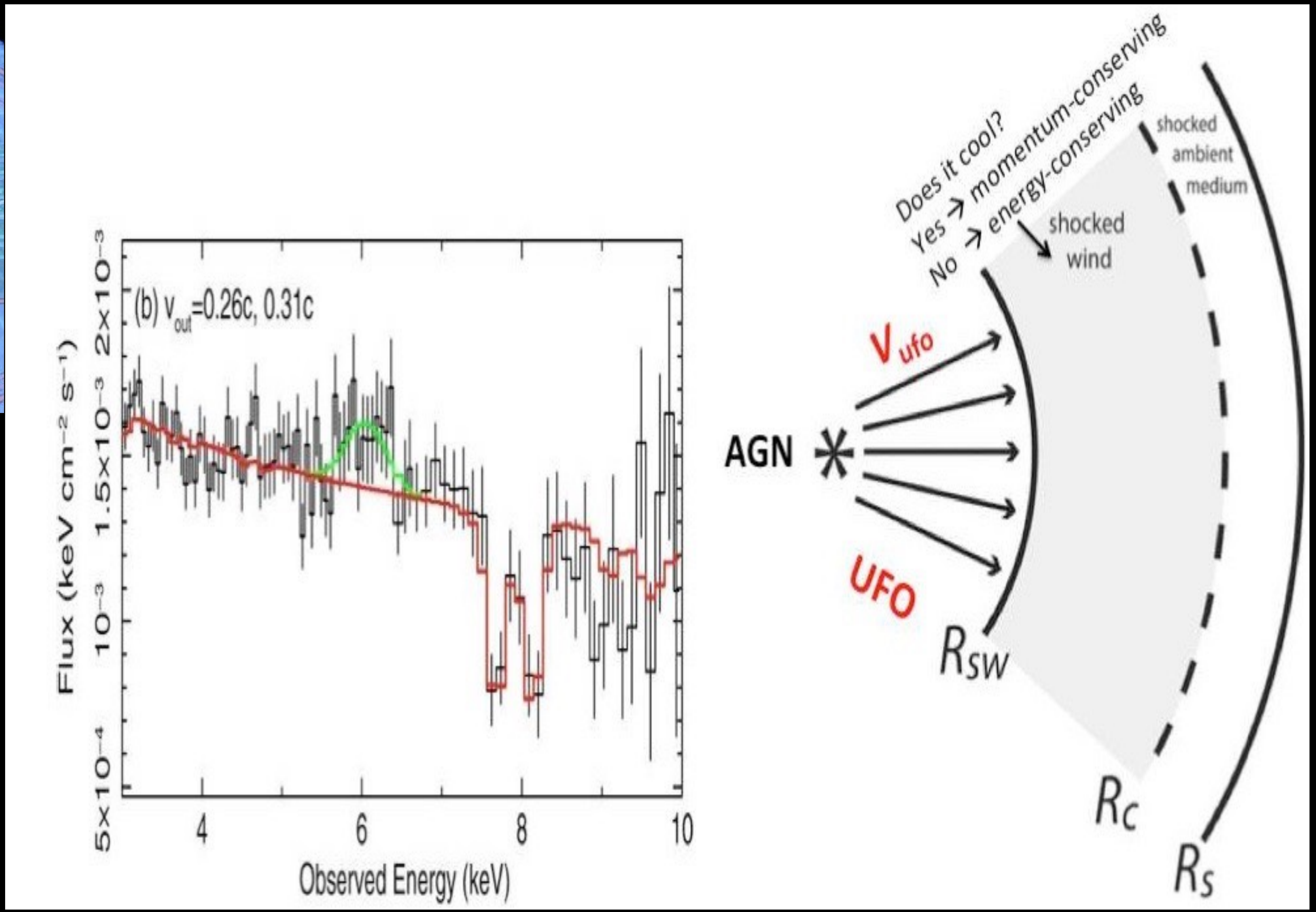
Observational evidences of nuclear winds

Ultra Fast Outlows (UFO) with velocity up to a fraction of c are observed in the central regions of AGNs; they likely originate from the acceleration of disk outflows





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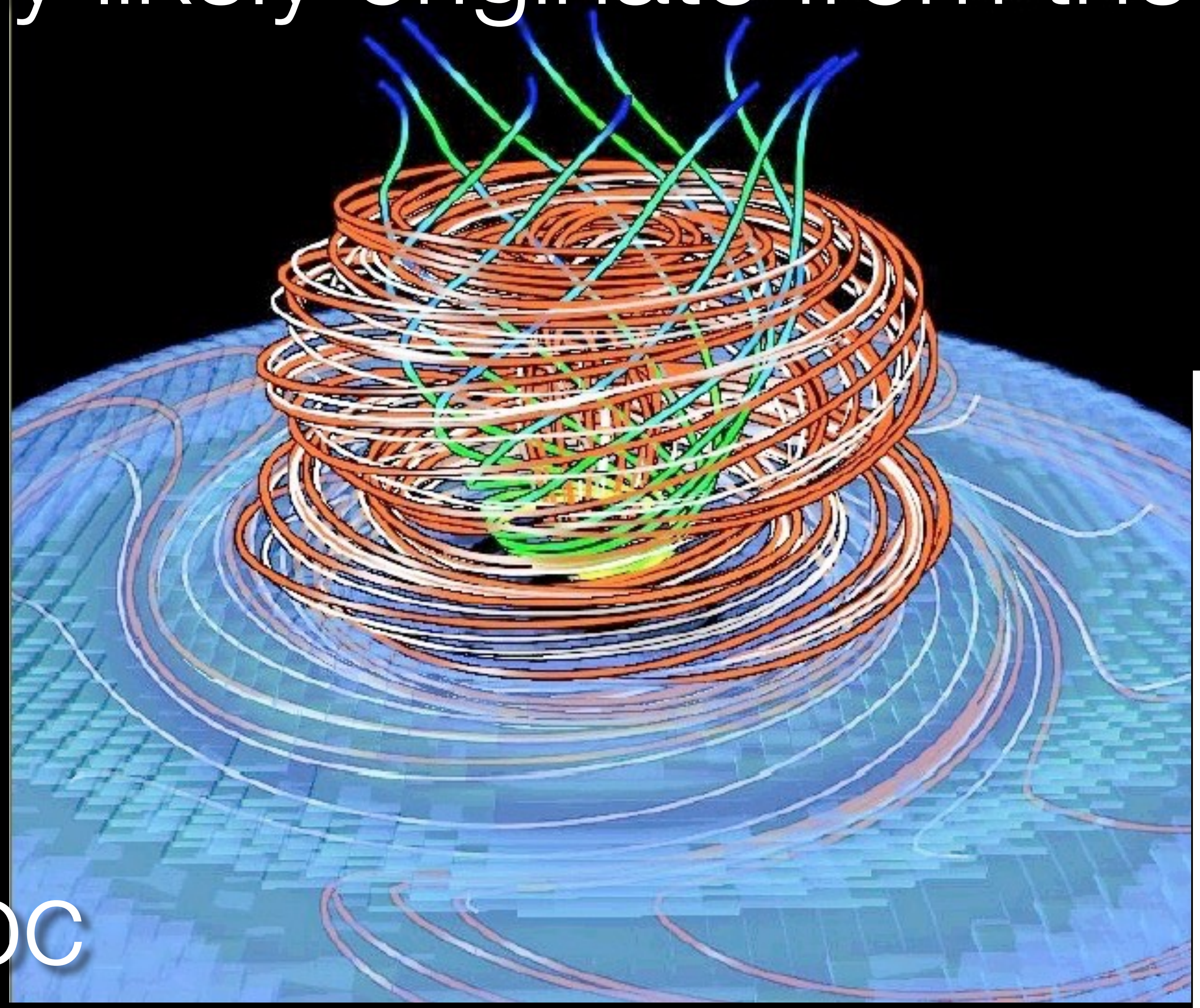


$\log\xi \sim 3\text{-}6$

$\log N_H \sim 22\text{-}24$

$v_{out} \sim 0.03\text{-}0.3$ c

$r_{max} < L_{ion}/N_H\xi \sim 0.03$pc

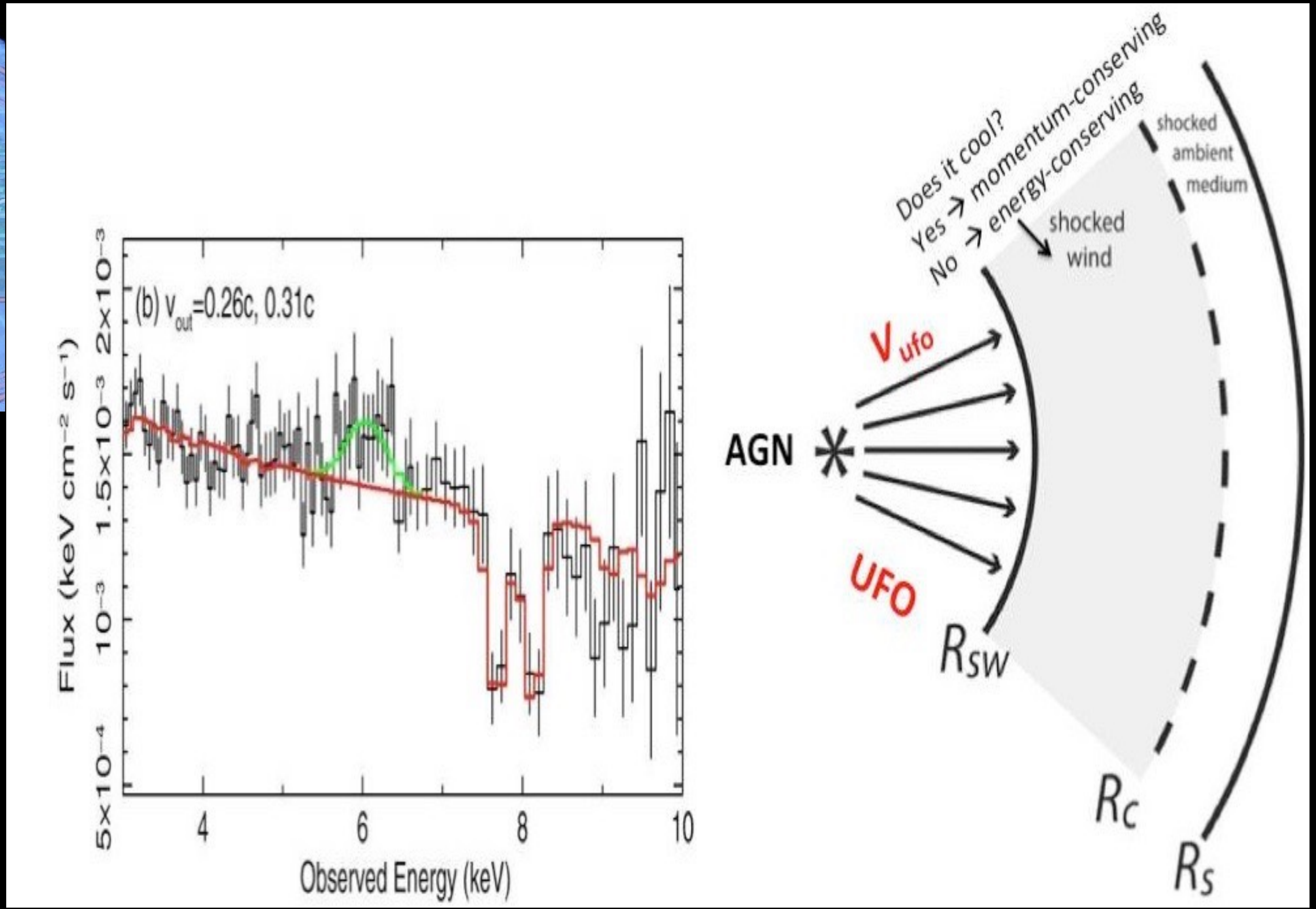
ionization par.

$r_{min} < 2GM_{BH}/v^2_{out} \sim 0.003$pc

escape vel.

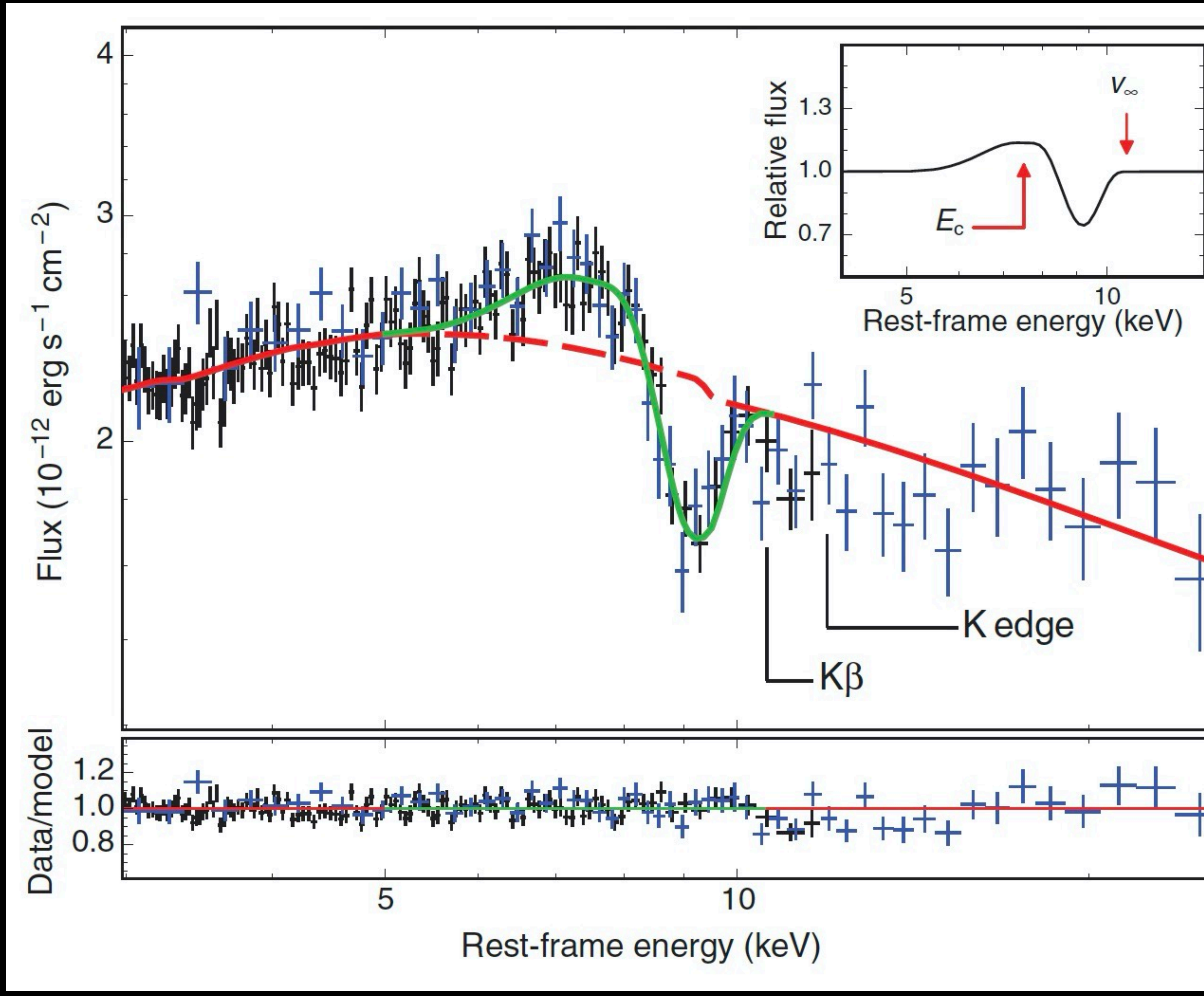
$M_{out} \approx m_p N_H r v_{out} \sim 0.01\text{-}1 M_{\otimes}$/yr

Mass outflow rate



A look at UFOs from a different perspective

- Intimatedly related to mass accretion because of the conservation of L
- Transport momentum/energy/entropy: ***feedback***
- Collect UFOs observations and interpret them in the framework of the MHDW
- Study their statistical properties as complex dynamical systems



MHDWinds

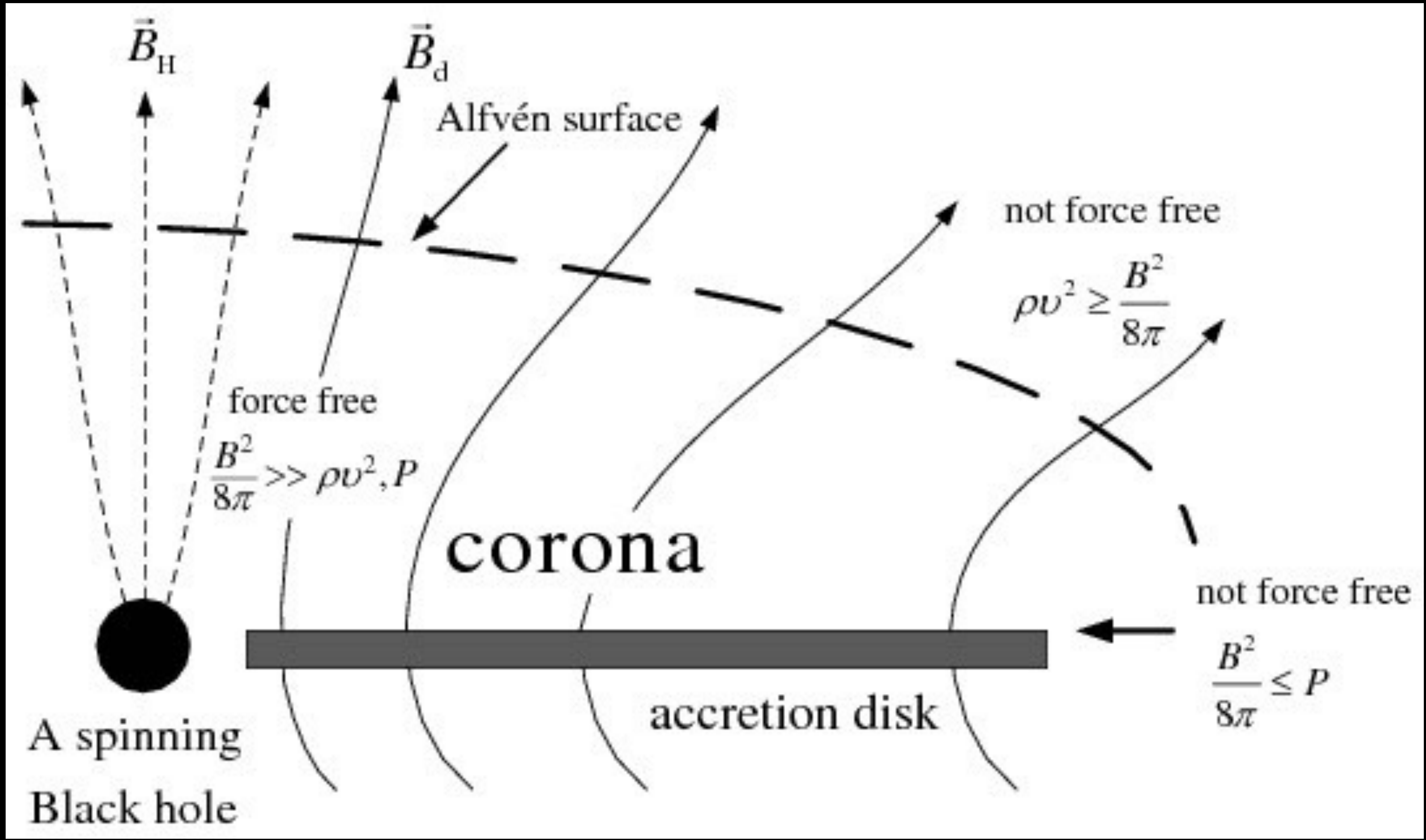
$$\dot{J}_d = \dot{M}_{in} r_0^2 \Omega_0 = \dot{J}_w = \dot{M}_{out} \Omega_0 r_A^2$$

$$r_A = \frac{B_p}{\Omega_0 (4\pi\rho)^{0.5}}$$

$$v_w = v_\infty = \sqrt{2} v_0 \frac{r_A}{r_0}$$

$$\bar{\omega} = \frac{\dot{M}_w}{\dot{M}_{accr}}$$

$$\bar{\omega} = \left(\frac{r_0}{r_A}\right)^2 = 0.01 - 1$$



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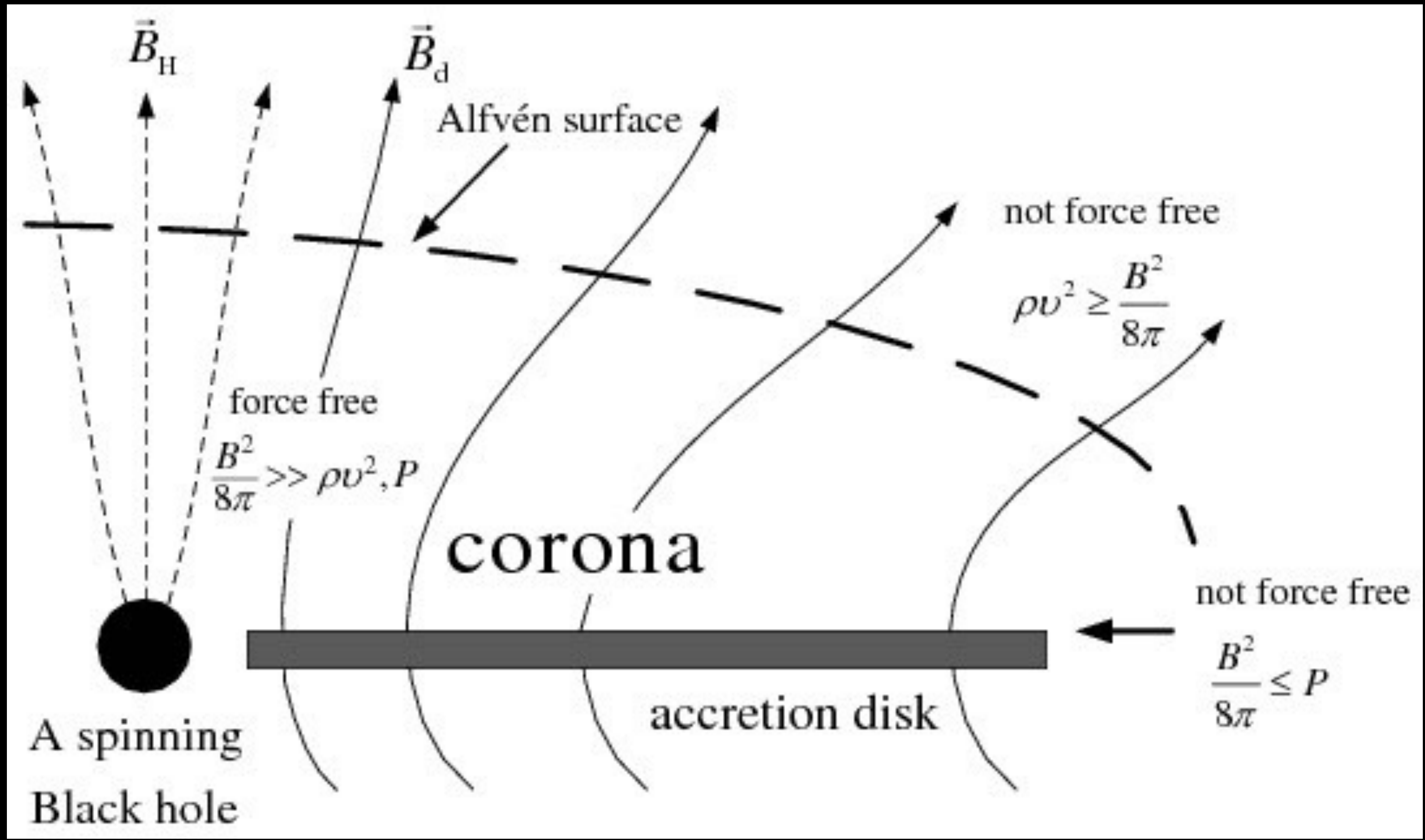

UFOs

Krongold et al. 2007

$$\dot{M}_w = 0.8 m_p f N_H v_w r = 6.3055 \times 10^{-24} N_H v_w r M_\odot$$

$$\dot{M}_w(r_{min}) = 0.88 \frac{N_H}{10^{24}} \frac{M_{BH}}{10^8} \left(\frac{v_w/c}{0.1}\right)^{-1} M_\odot/yr$$

$$\bar{\omega}(r_{min}) = 5.03 \frac{N_H}{10^{24}} \frac{M_{BH}}{10^8} \left(\frac{v_w/c}{0.1}\right)^{-1} \left(\frac{L_{bol}}{10^{45}}\right)^{-1} \frac{\epsilon}{0.1} M_\odot/yr$$

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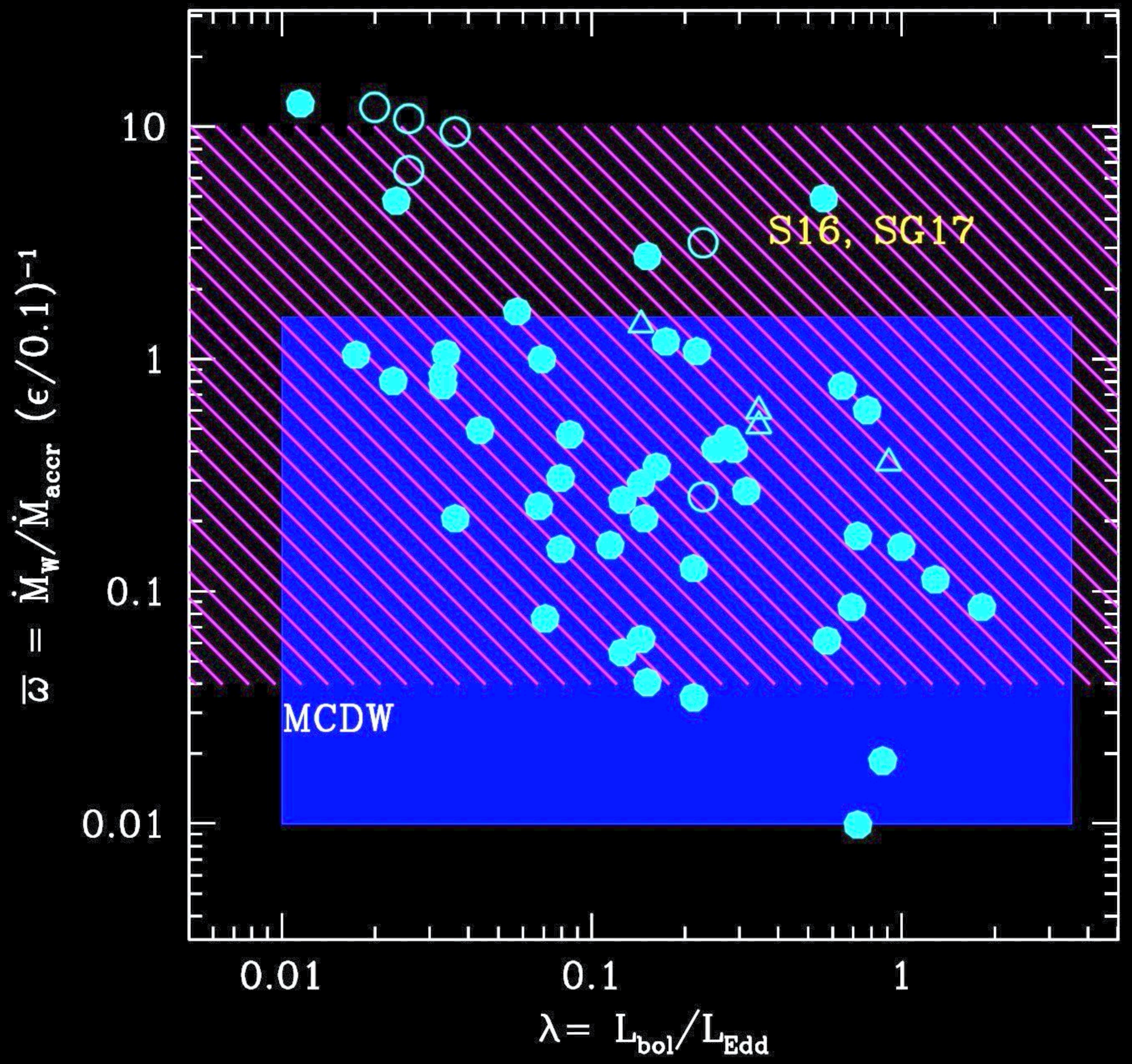
UFO winds: statistical sample

$$\bar{\omega} = \frac{1}{\lambda} \times \frac{\dot{M}_w}{\dot{M}_{Edd}} = \frac{\lambda_w}{\lambda}$$

$$L_w = 1/2 \dot{M}_w v_w^2 = \epsilon_w \dot{M}_\bullet c^2$$

$$\epsilon_w = \frac{L_w}{\dot{M}_{accr} c^2} \approx 0.005 - 0.01$$

span 3 orders of magnitude
>> statistical+systematic error



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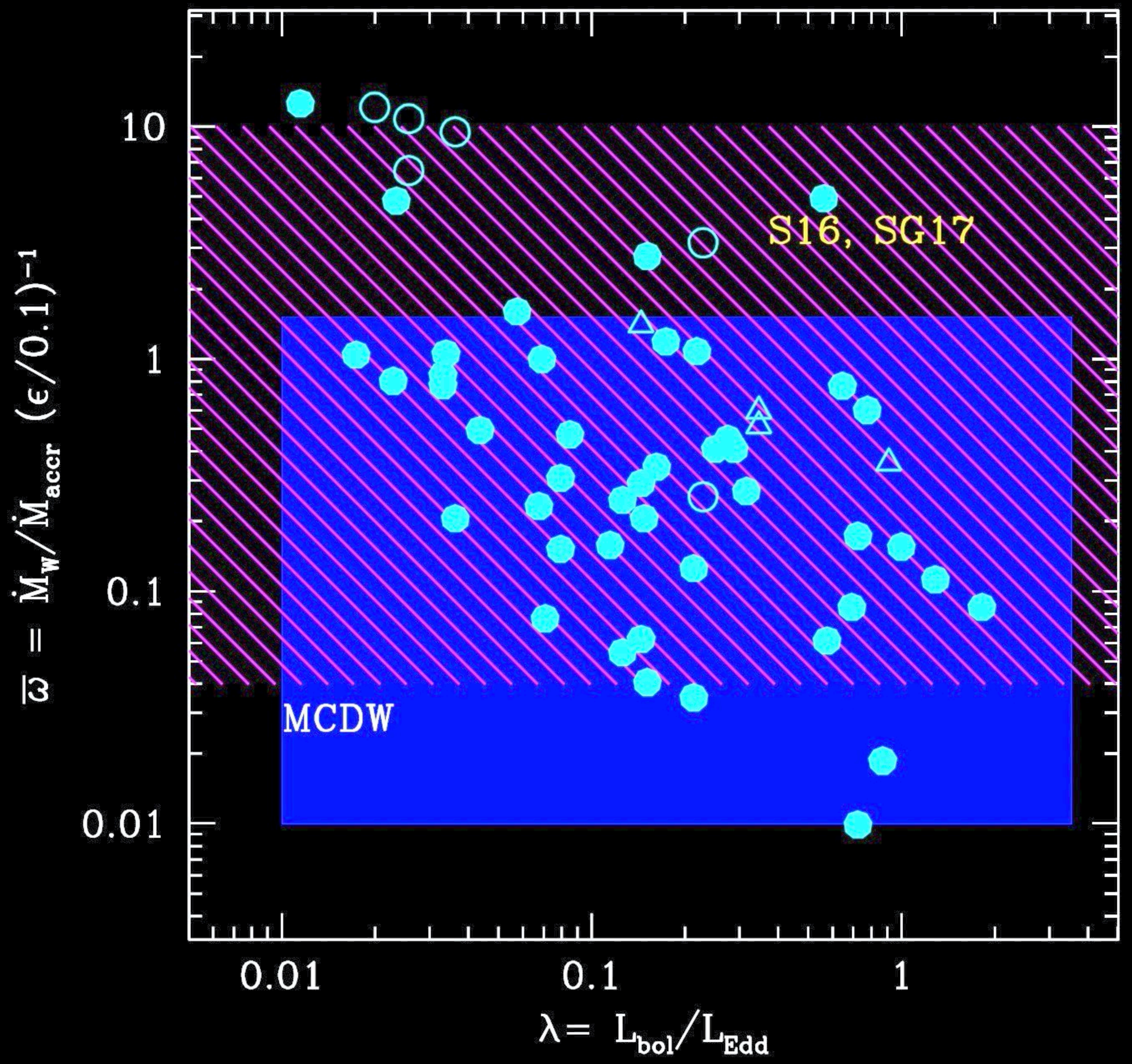
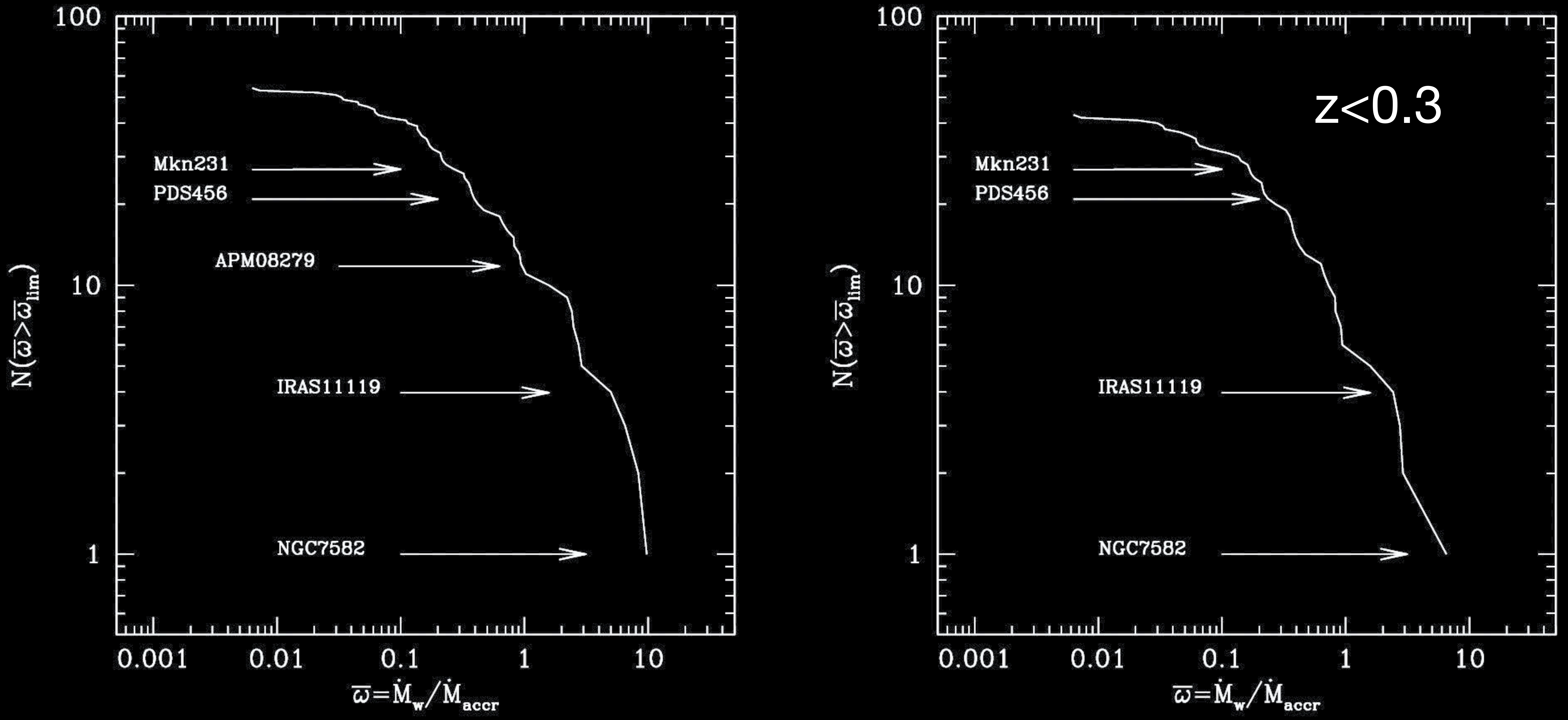
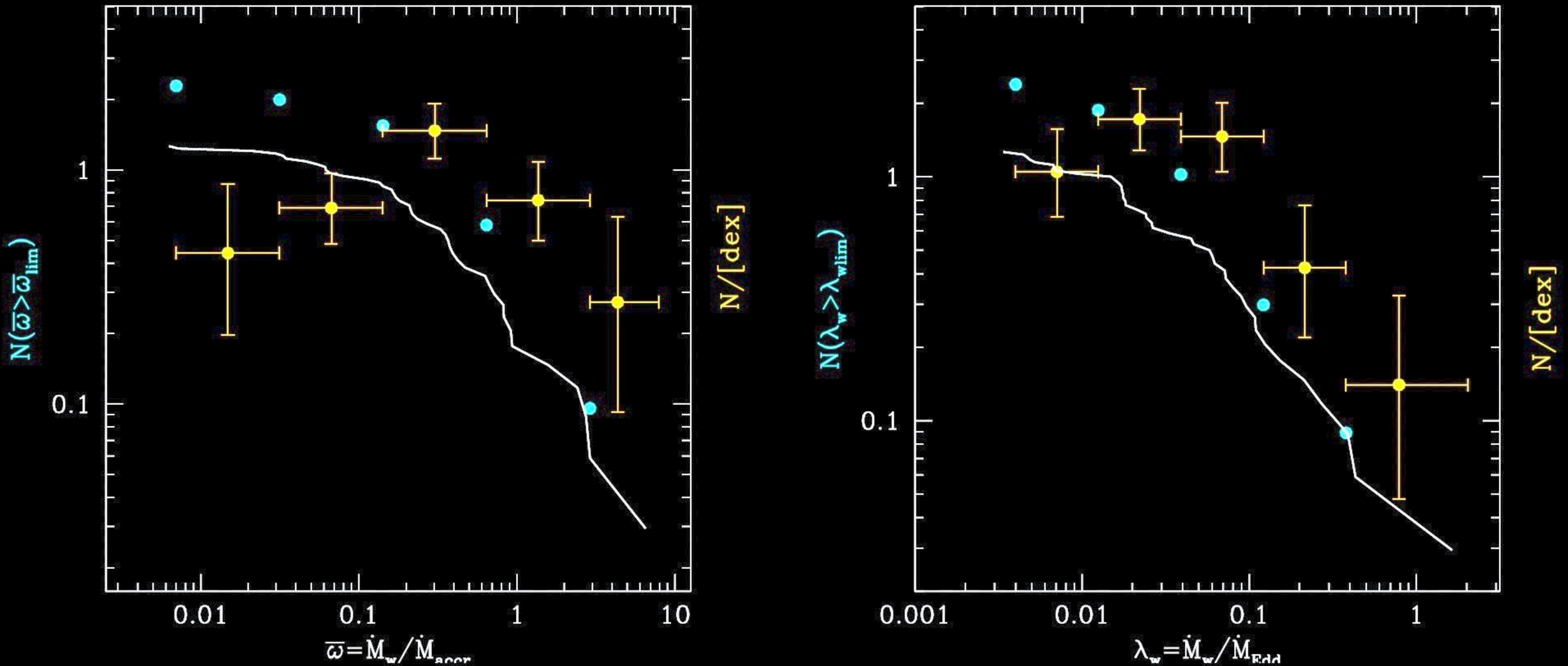


Cumulative distribution functions



Binned distribution functions

Correcting for selection effects, z<0.3



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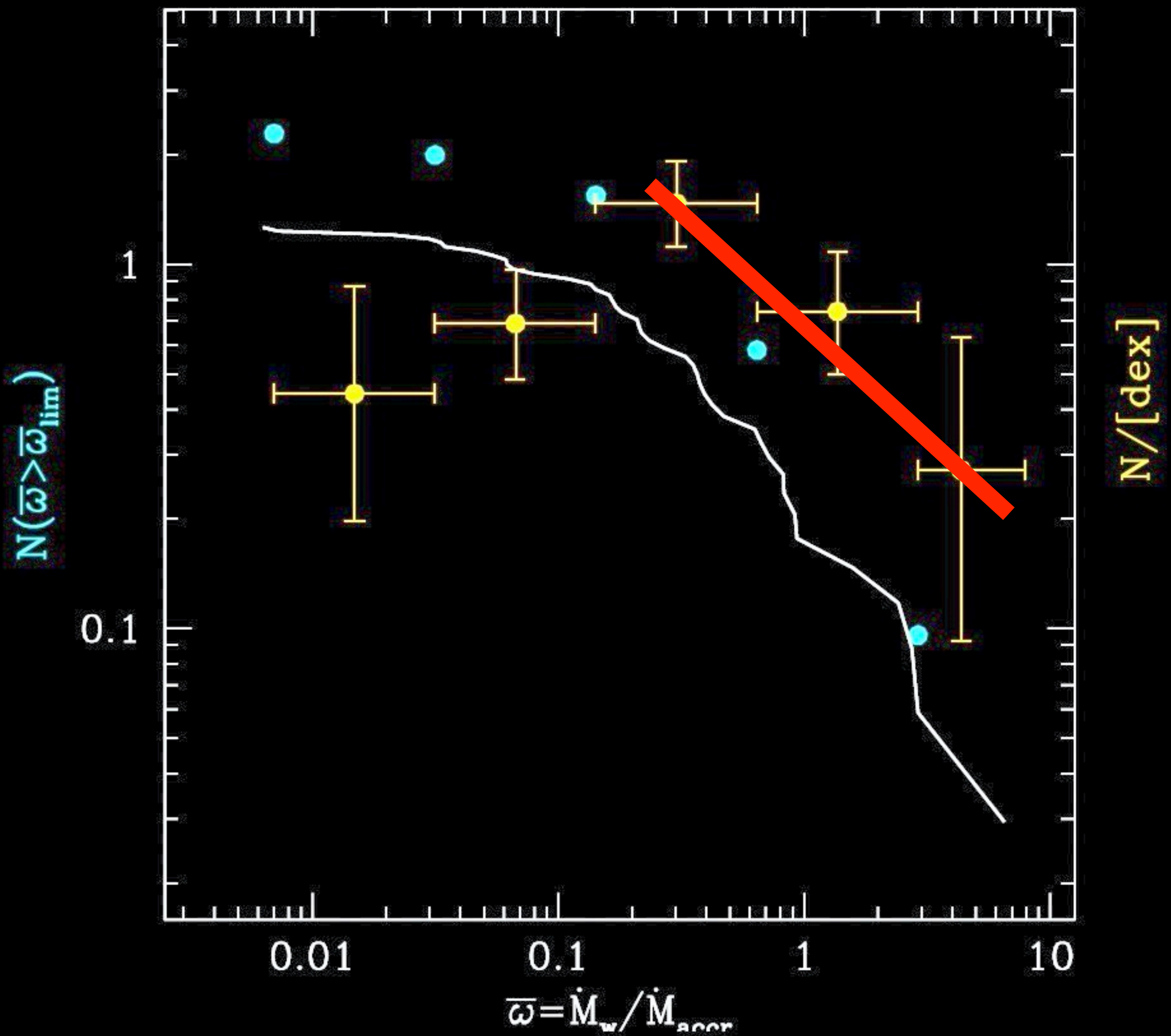
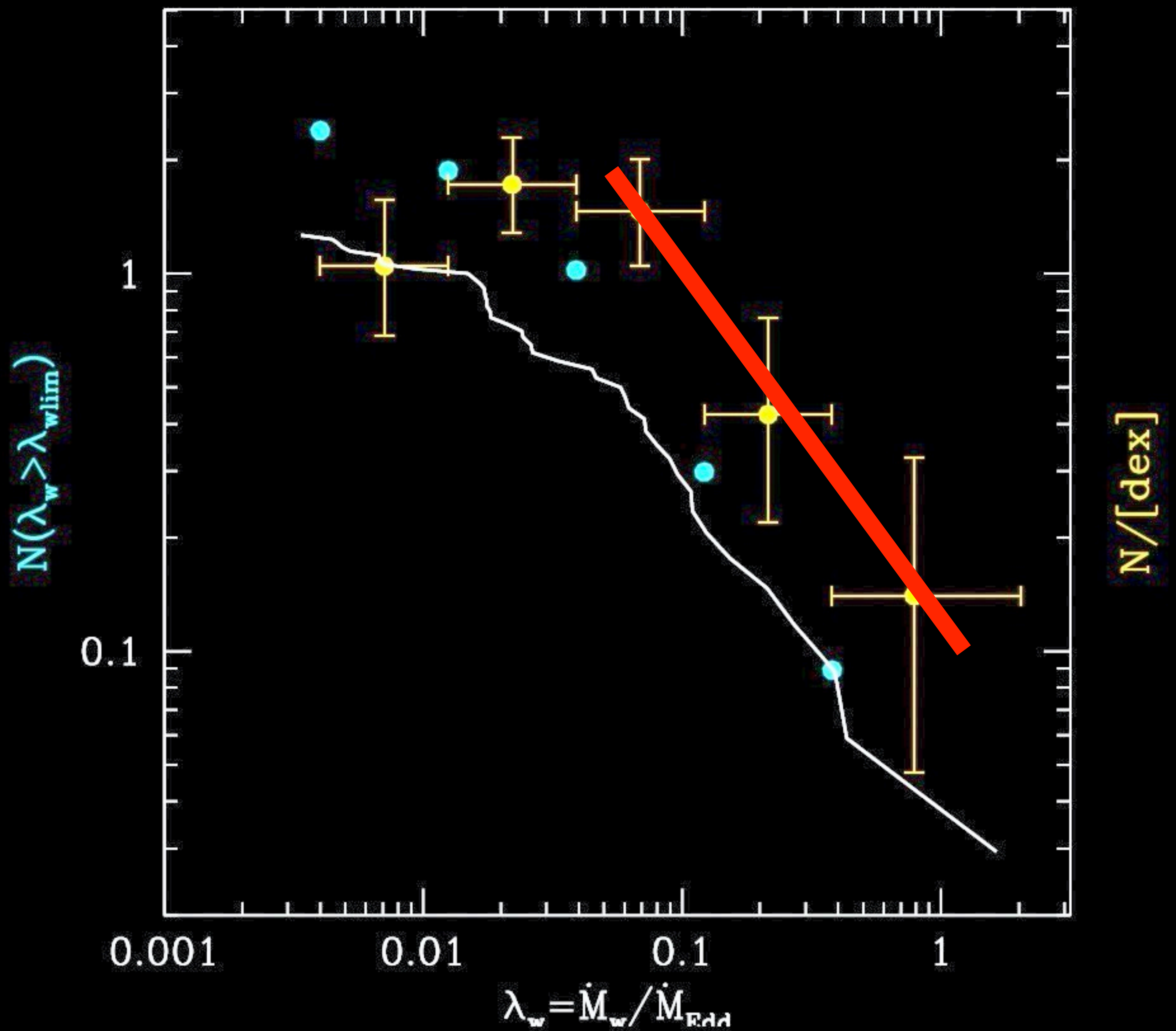




$$\dot{M}_w v_w = 4\pi r^2 P_b - 1/f(\bar{\omega})\frac{GM_{BH}M_{gas}}{r^2}$$

$$\dot{M}_w v_w = \frac{\dot{M}_w v_w^2}{2}\frac{\Delta t}{r} - 1/f(\bar{\omega})\frac{GM_{BH}M_{gas}}{r^2} =$$

$$\frac{\dot{M}_w v_w^2}{2}\frac{\Delta t}{r} - 1/f(\bar{\omega})\frac{GM_{BH}\dot{M}_\bullet \Delta t}{r^2} =$$

$$\frac{\dot{M}_w \Delta t}{r} \times (\frac{v_w^2}{2} - 1/f(\bar{\omega})\frac{GM_{BH}}{\bar{\omega} r})$$

$$\Delta t = \frac{f(\bar{\omega}) v_w r}{f(\bar{\omega})\frac{v_w^2}{2} - \frac{GM_{BH}}{\bar{\omega} r}}$$

$$\Delta t = \frac{R_B}{\frac{1\sqrt{2}v_0}{2\bar{\omega}} - \frac{c_\infty^2}{\sqrt{2}v_0 f(\bar{\omega})}} = \frac{R_B \bar{\omega}}{0.64 v_0 - \frac{c_\infty^2 \bar{\omega}}{\sqrt{2} v_0 f(\bar{\omega})}}$$

$$\boxed{\Delta t \approx 140 \text{ yr} \times \bar{\omega}(\frac{v_0/c}{0.1})^{-1}}$$

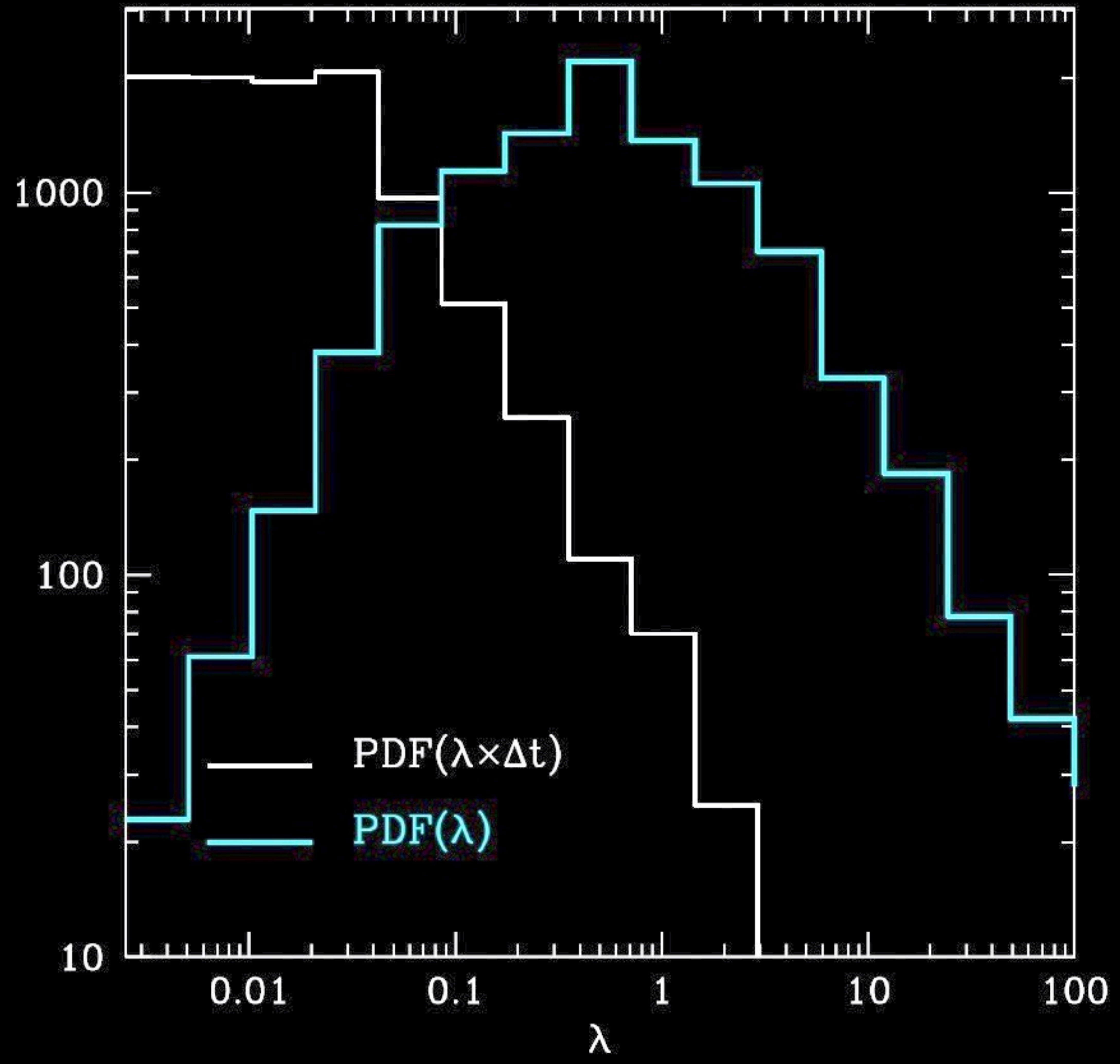
λ distribution function

$$\lambda = \frac{\dot{M}_\bullet}{\dot{M}_{Edd}} = \frac{\lambda_w}{\bar{\omega}}$$

$\Delta t \sim \bar{\omega}$ if wind trust contrast gas accretion at the Bondi radius

$\lambda \times \Delta t$ scales as λ_w

slope of λ_w distribution = $-1^{+0.7}_{-0.5}$



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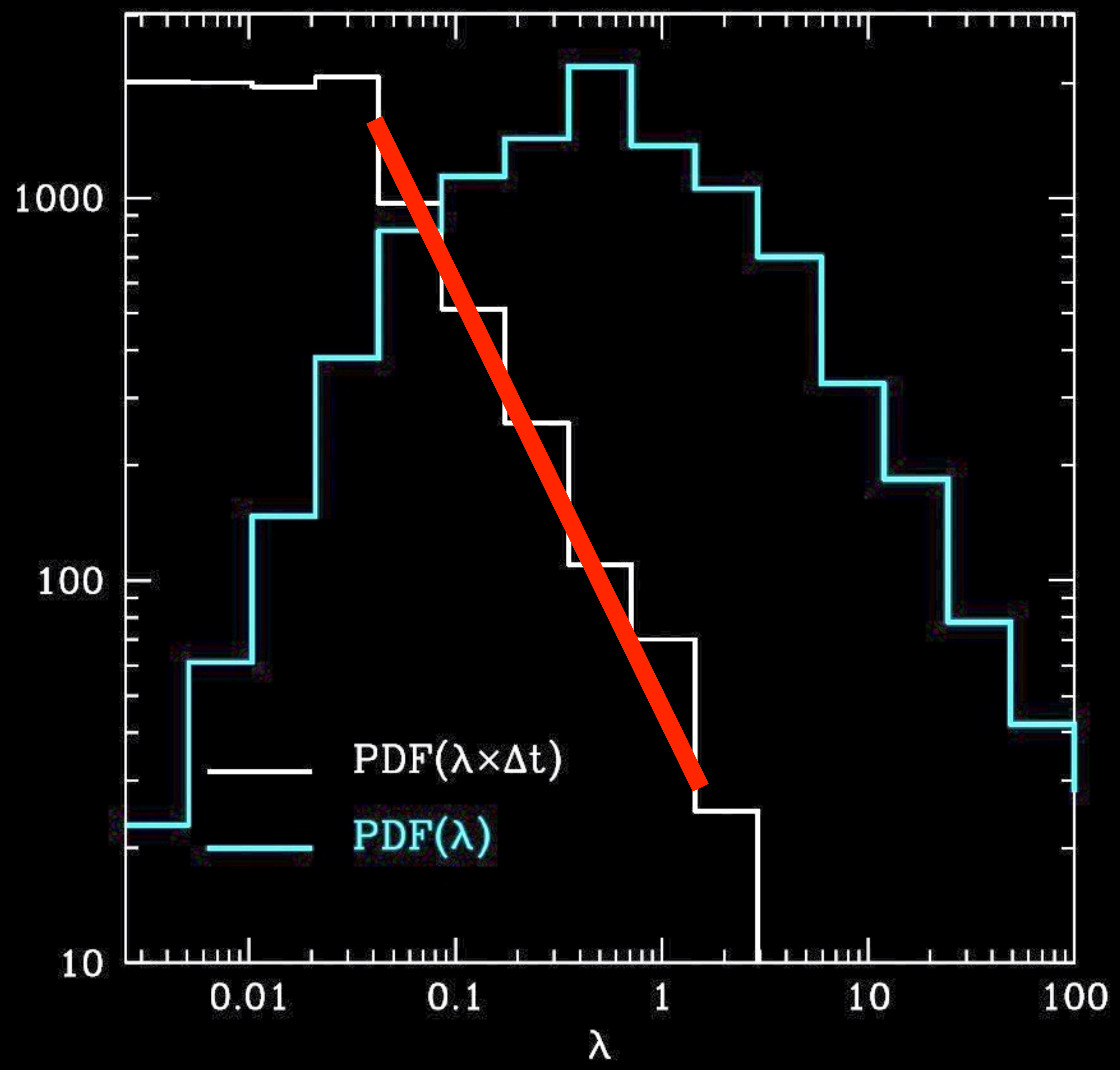


If the wind activity timescale is shorter than the AGN timescale, and if the population functions are drawn from independent snapshots

↓

wind activity history in each single sources can be statistically described by the population functions

Many relatively small wind events for each major wind event in each AGN activity cycle

↓

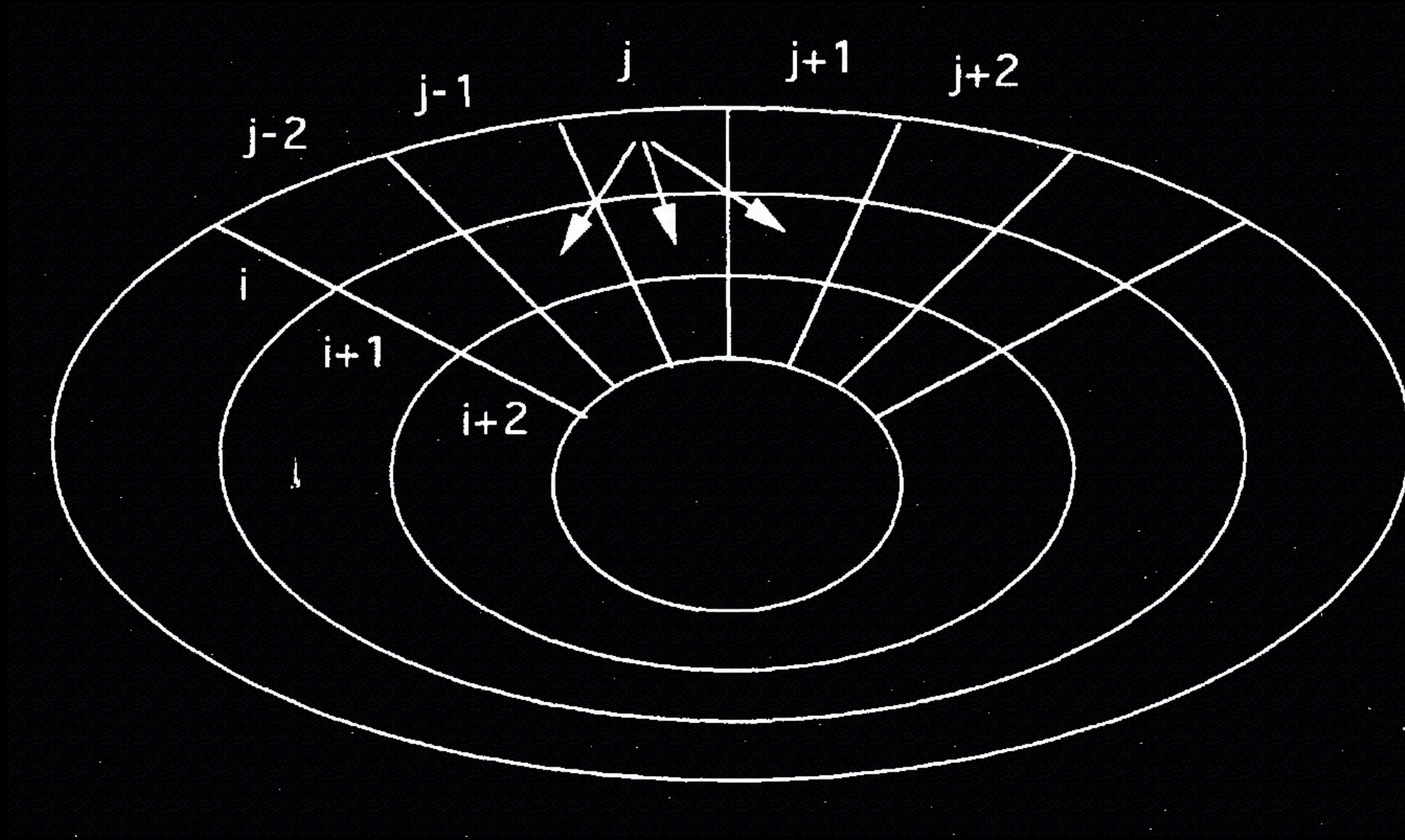
fractal behaviour, as e.g. CCA

BH growth equivalent to constant $\lambda \sim 0.1$ during AGN lifetime

A cellular automaton for disk-wind systems

$$M_{i,j} > M_{crit}$$

$$M_{i,j} = M_{i,j} - 3m$$
$$M_{i+1,j} = M_{i+1,j} + m$$
$$M_{i+1,j+1} = M_{i+1,j+1} + m$$
$$M_{i+1,j-1} = M_{i+1,j-1} + m$$



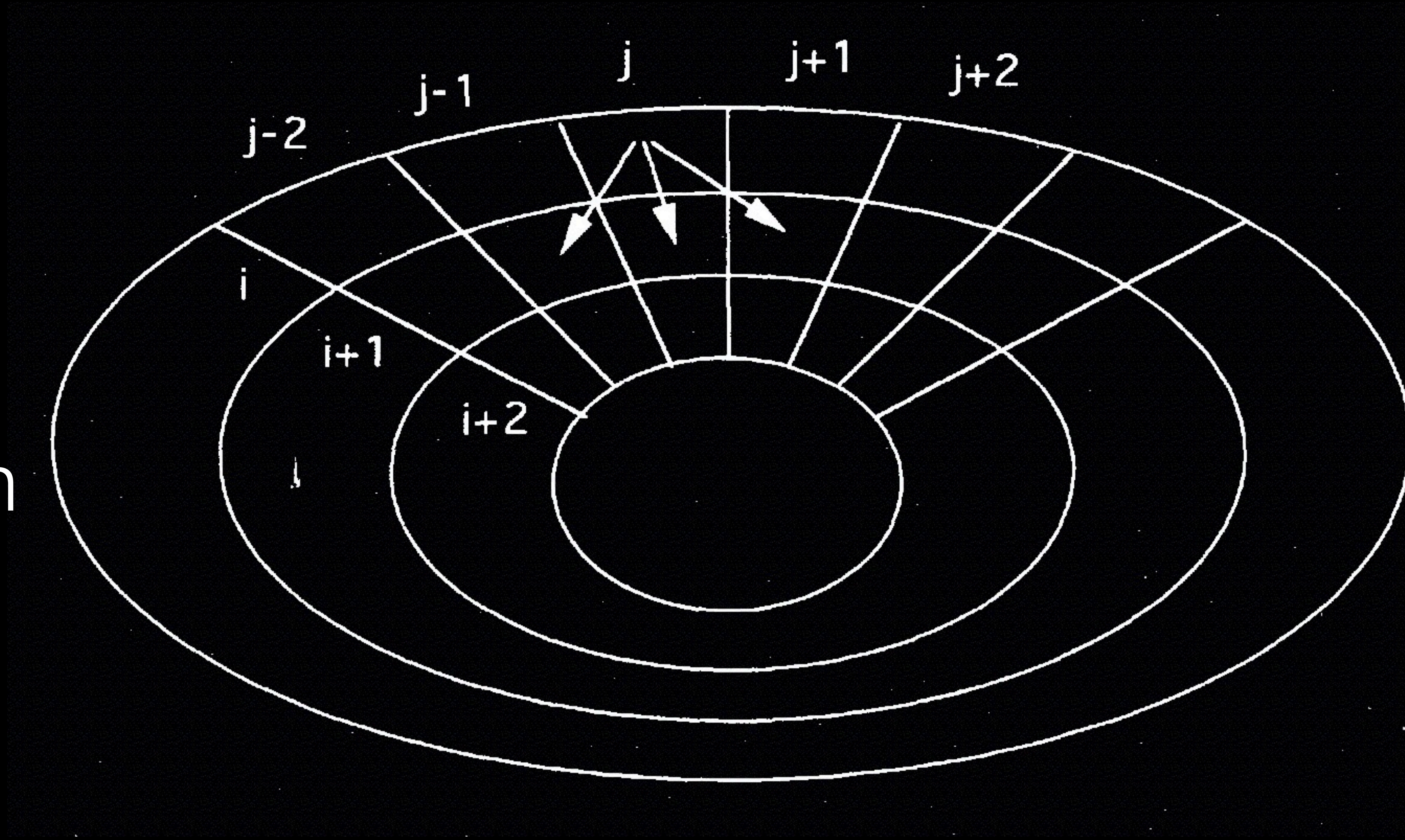
Mineshighe et al 1994-1999

A cellular automaton for disk-wind systems

Set-up 1 —> Mineshighe original setup, no feedback

Set-up 2 —> mass percolating inward $m_{in} = m/(1+\bar{\omega})$ mass in the wind $m_{out} = m\bar{\omega}/(1+\bar{\omega})$

Set-up 3 —> similar to set-up 2 but plus wind trust contrasting accretion at the outer radius



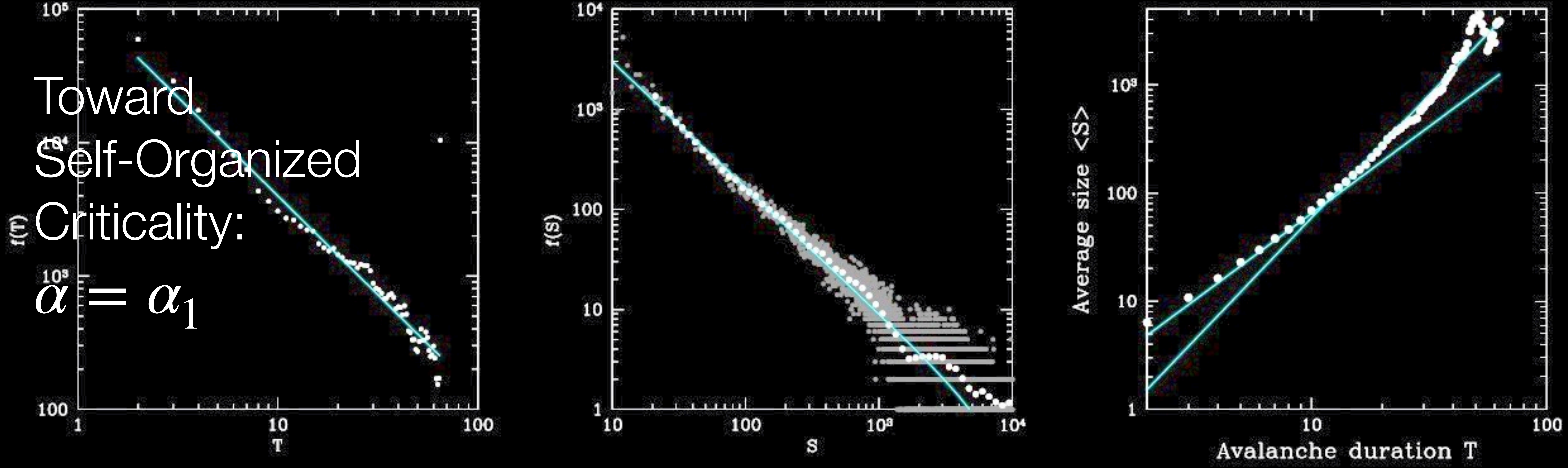
Mineshighe et al 1994-1999

$$f(S) \sim S^{-\tau},\ f(T) \sim T^{-\tau_t}$$

$$\alpha = \frac{(\tau_t - 1)}{(\tau - 1)}$$

Toward
Self-Organized
Criticality:

$\alpha = \alpha_1$



Theory of critical exponents

Bak et al. 1987, 1994; Kuntz & Sethna 2000; Sethna et al. 2001

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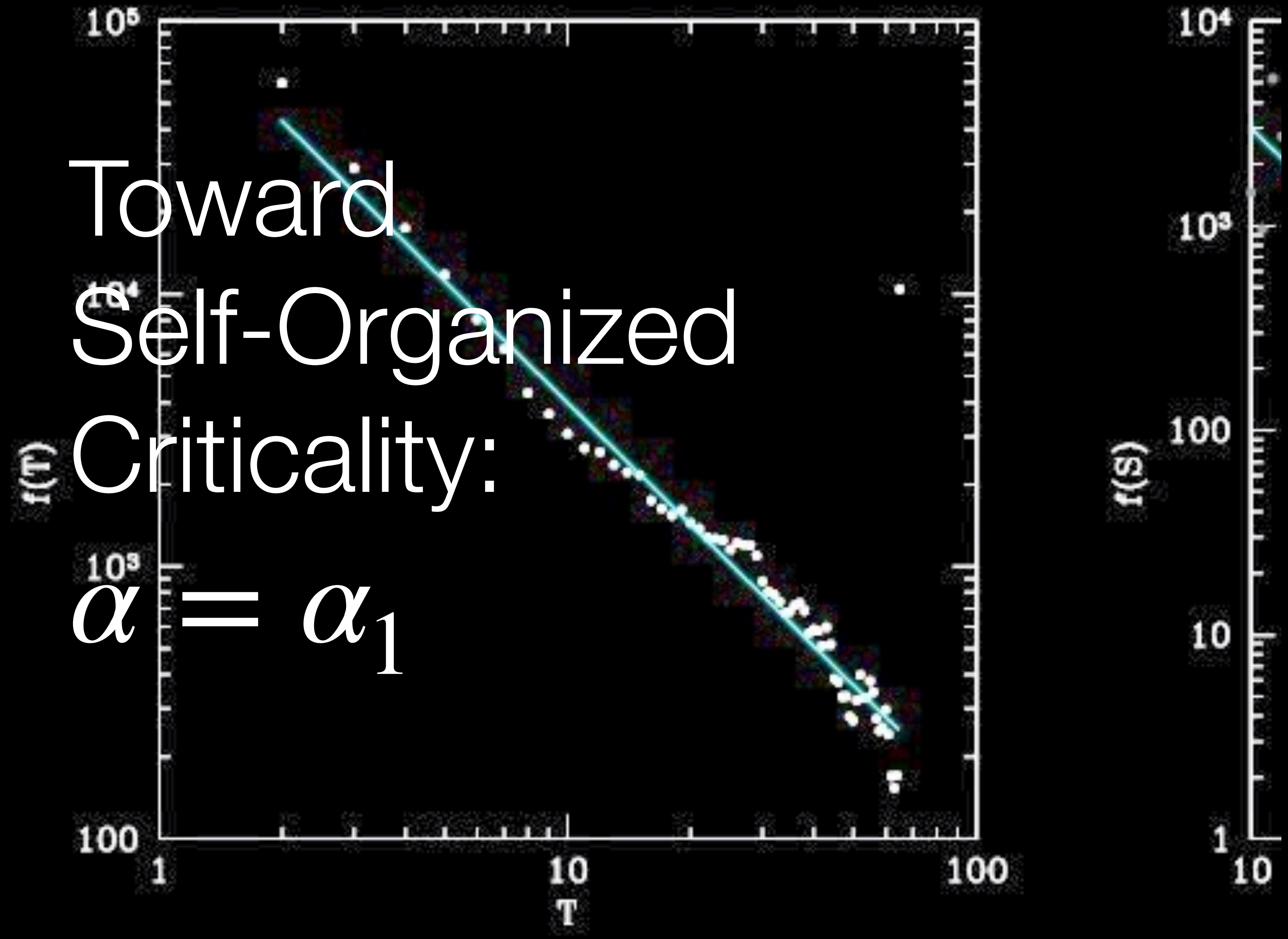

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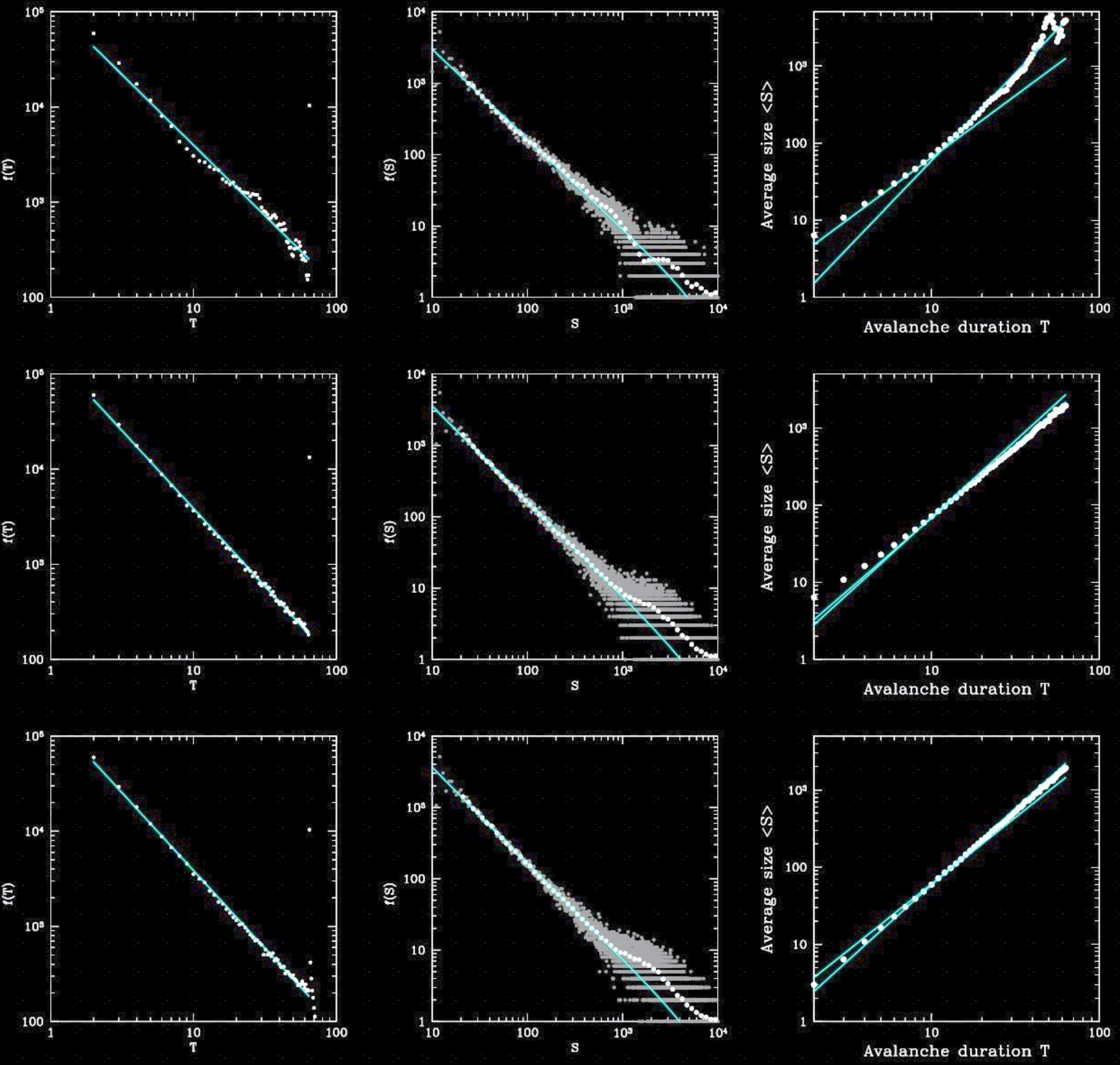

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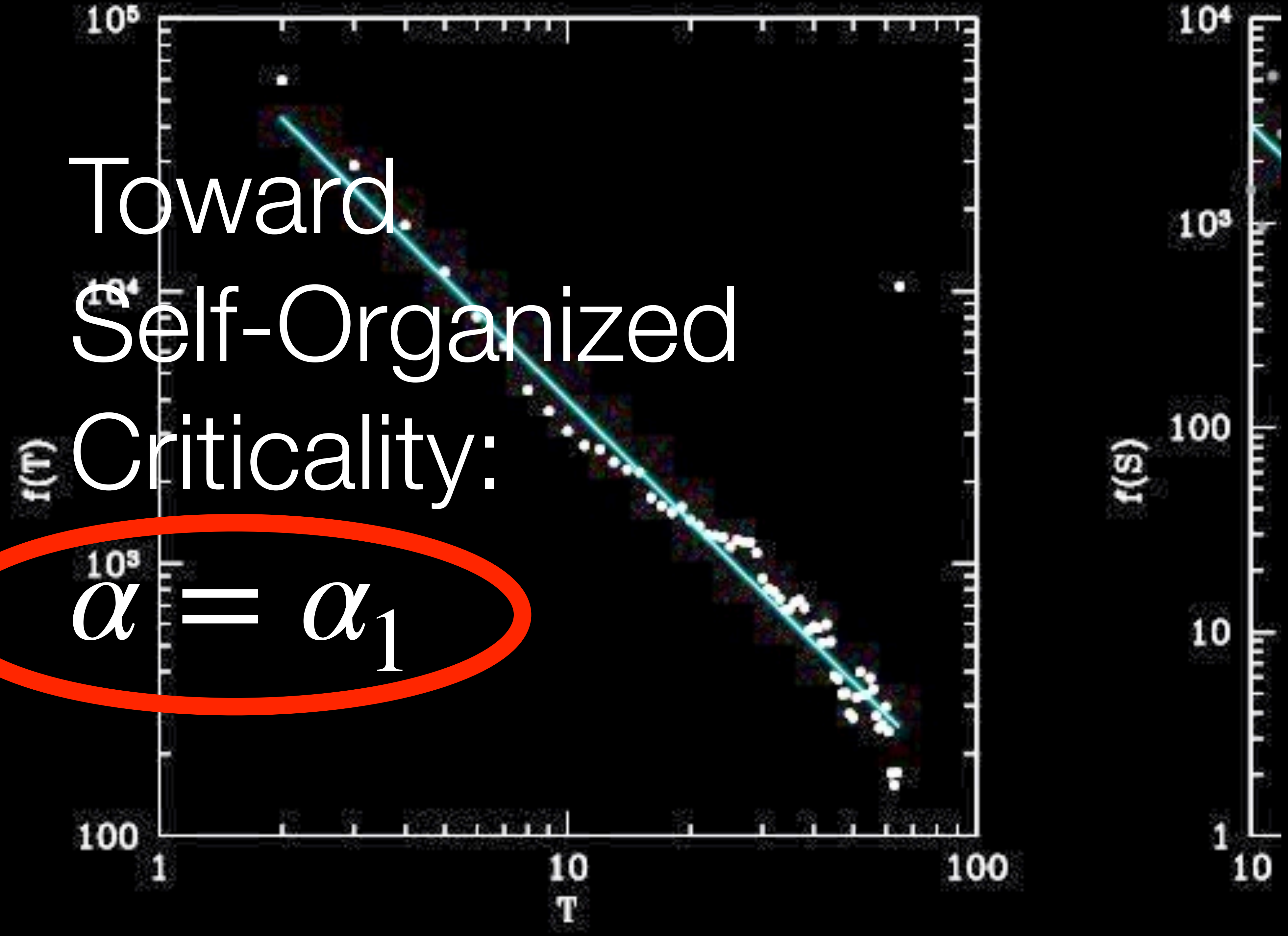

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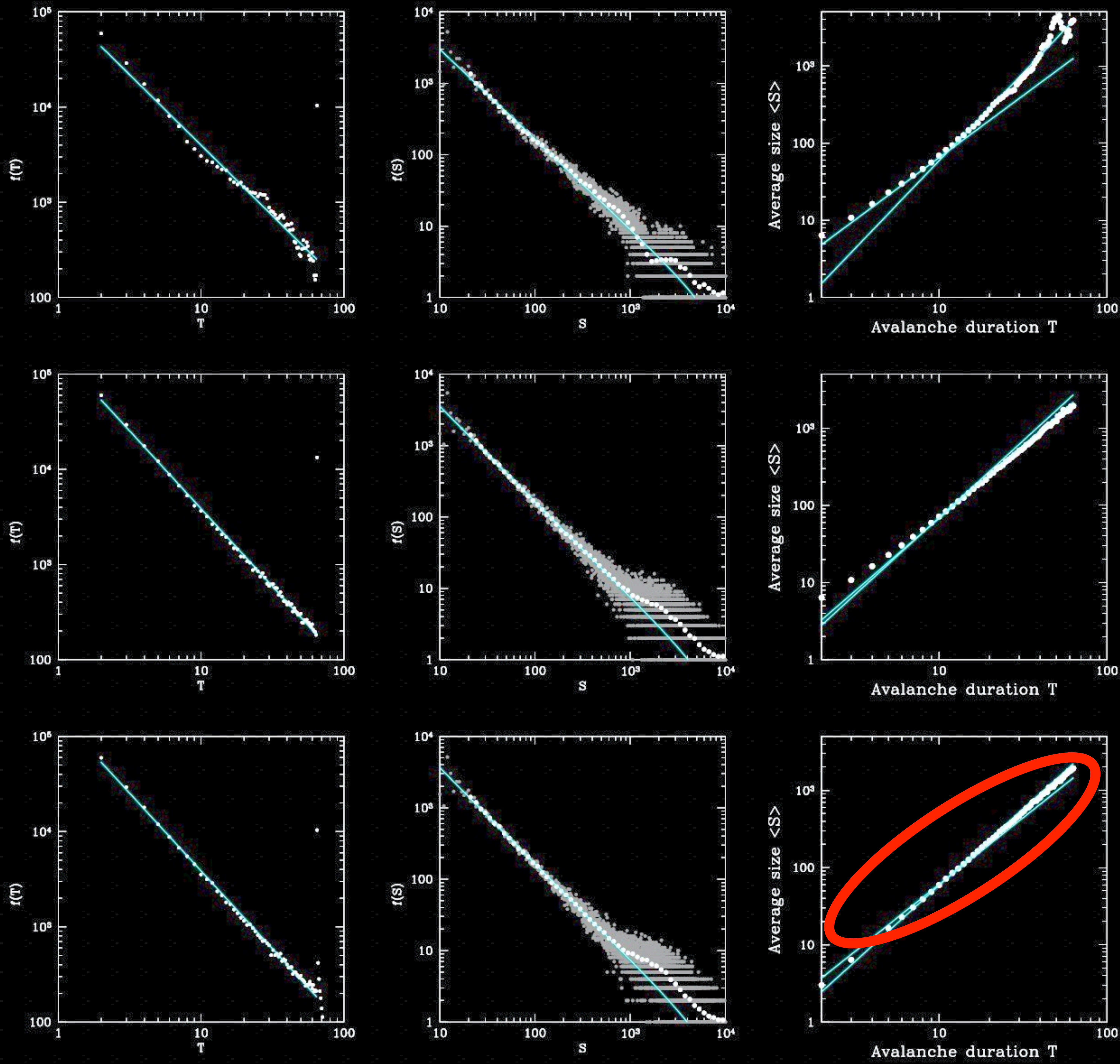
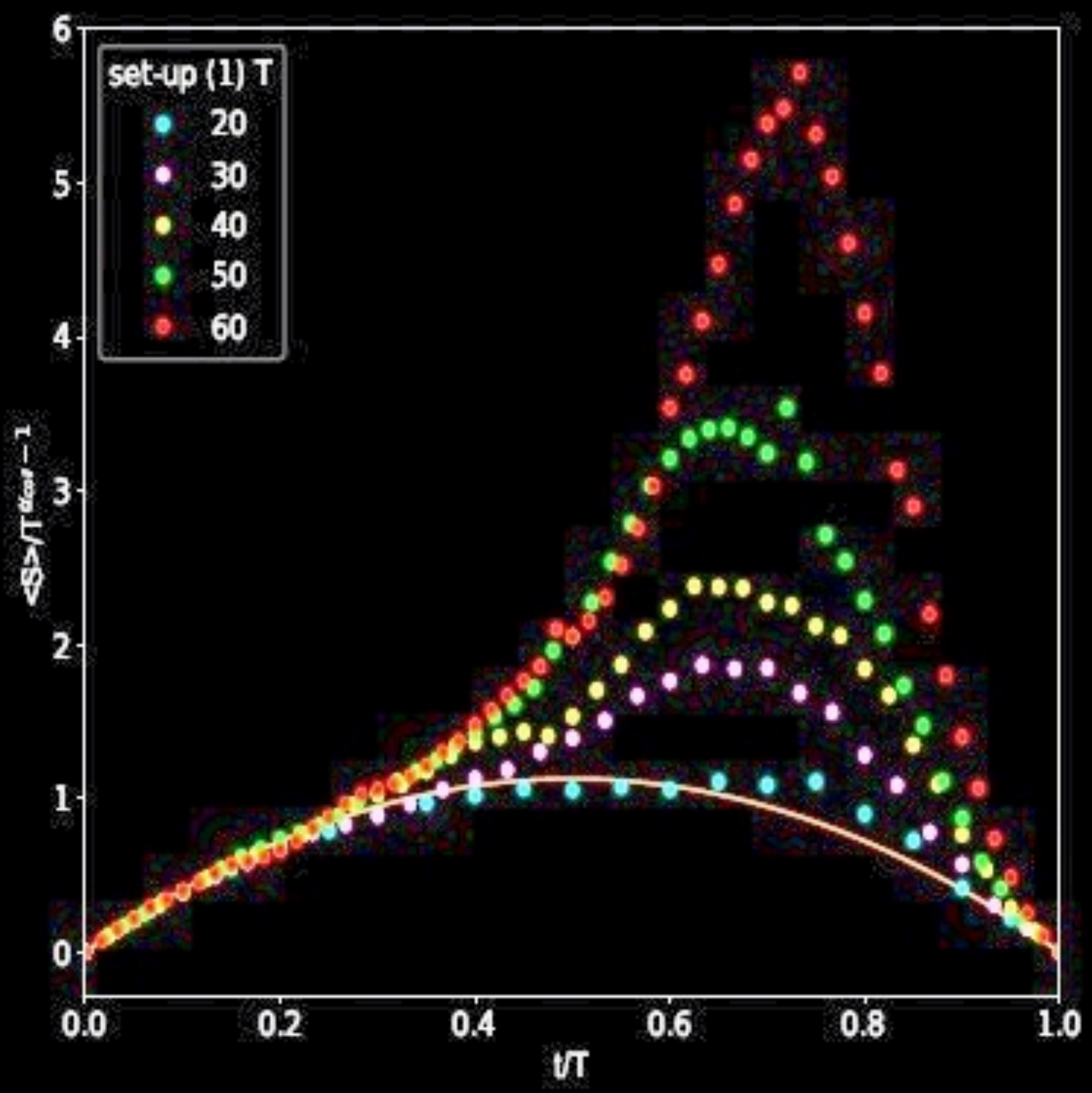
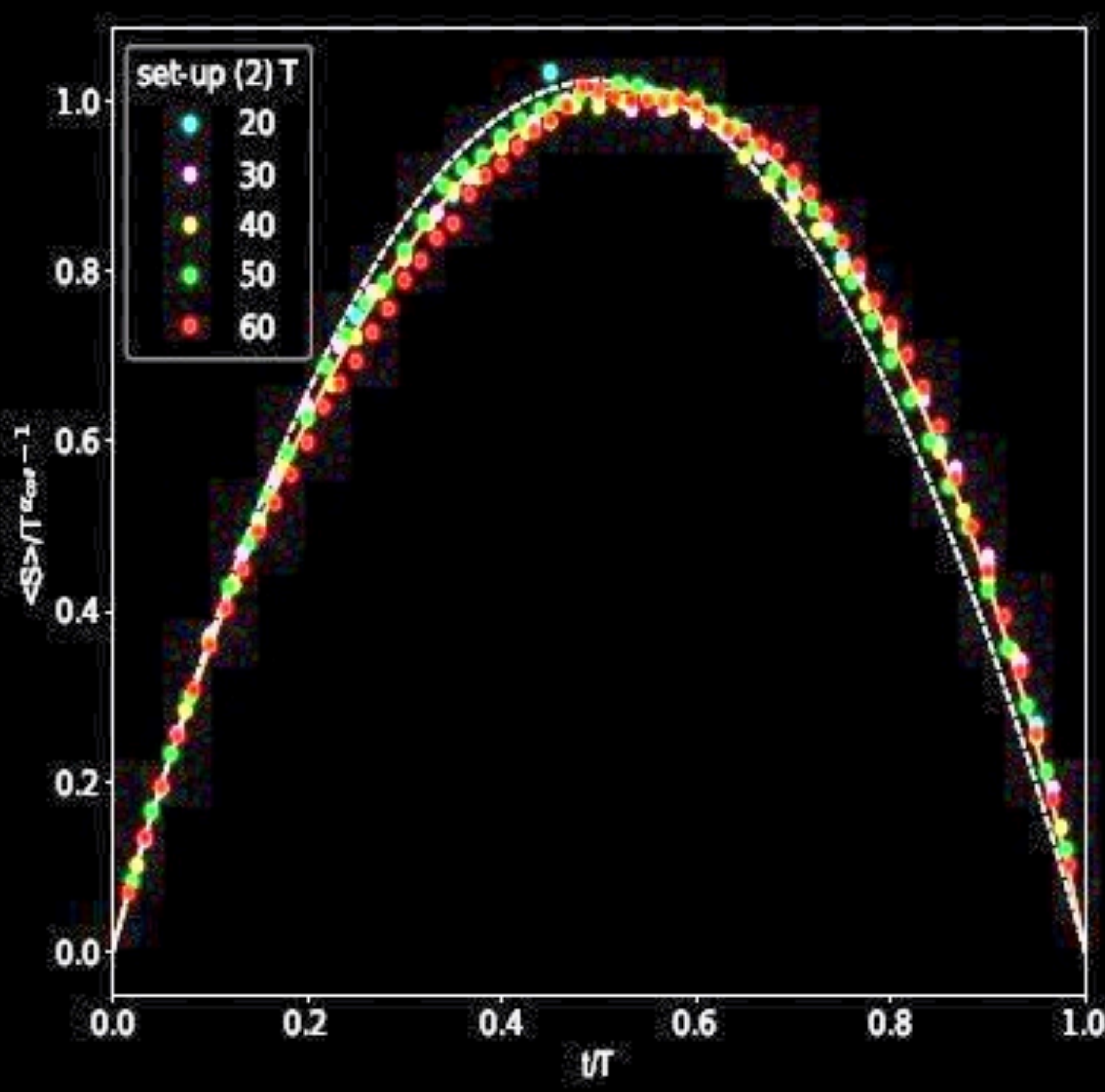


Toward
Self-Organized Criticality

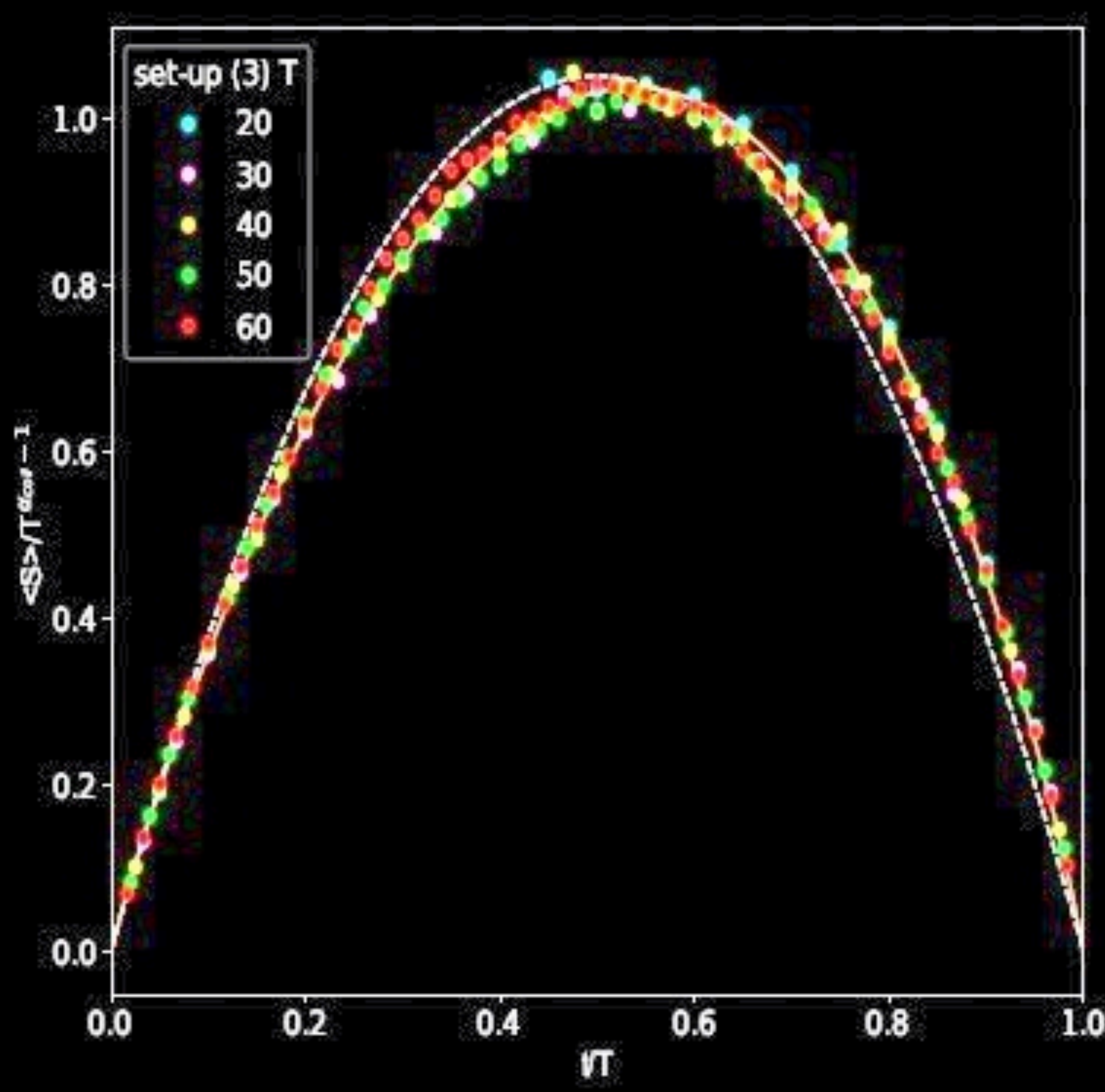
Set-up 1



Set-up 2



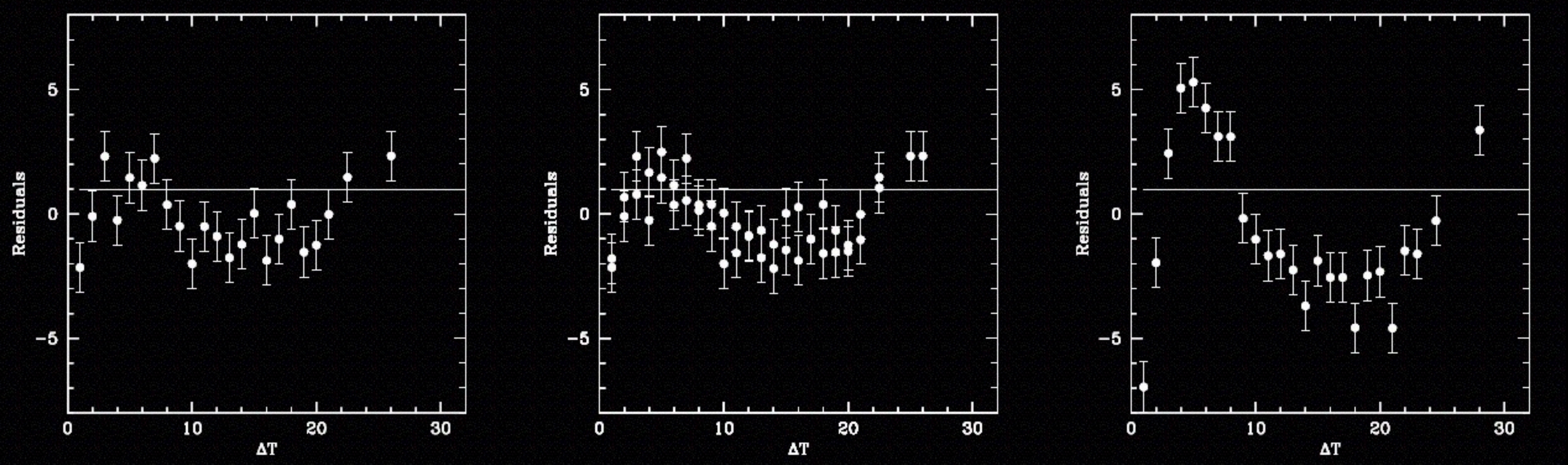
Set-up 3



Toward
Self-Organized Criticality

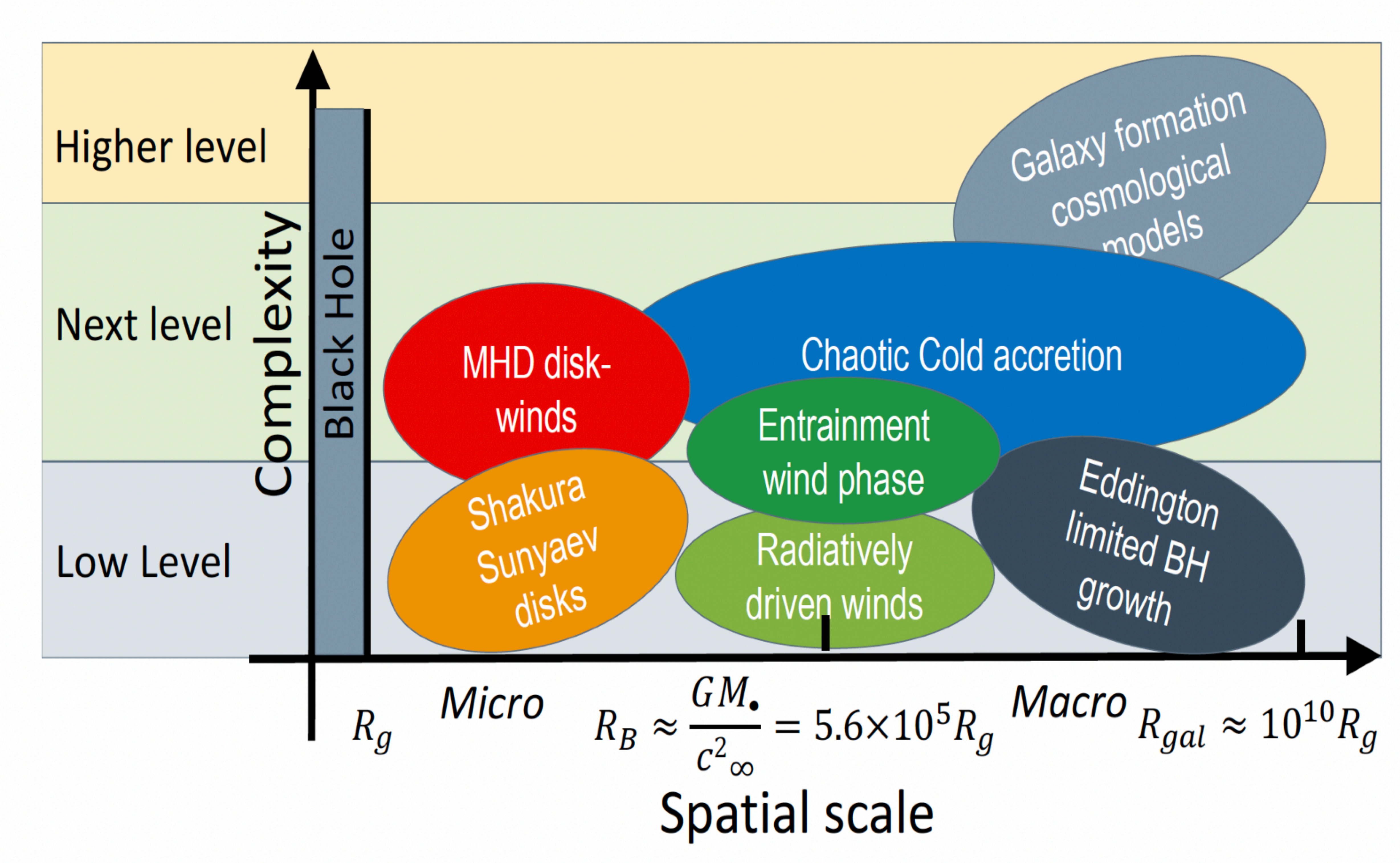
The residuals after subtracting the best t exponential model from the cumulative distribution function of the waiting times

Set-up 1 Set-up 2 Set-up 3



Complex dynamical systems

successful approach in evolutionary biology, neurology, condensed matter



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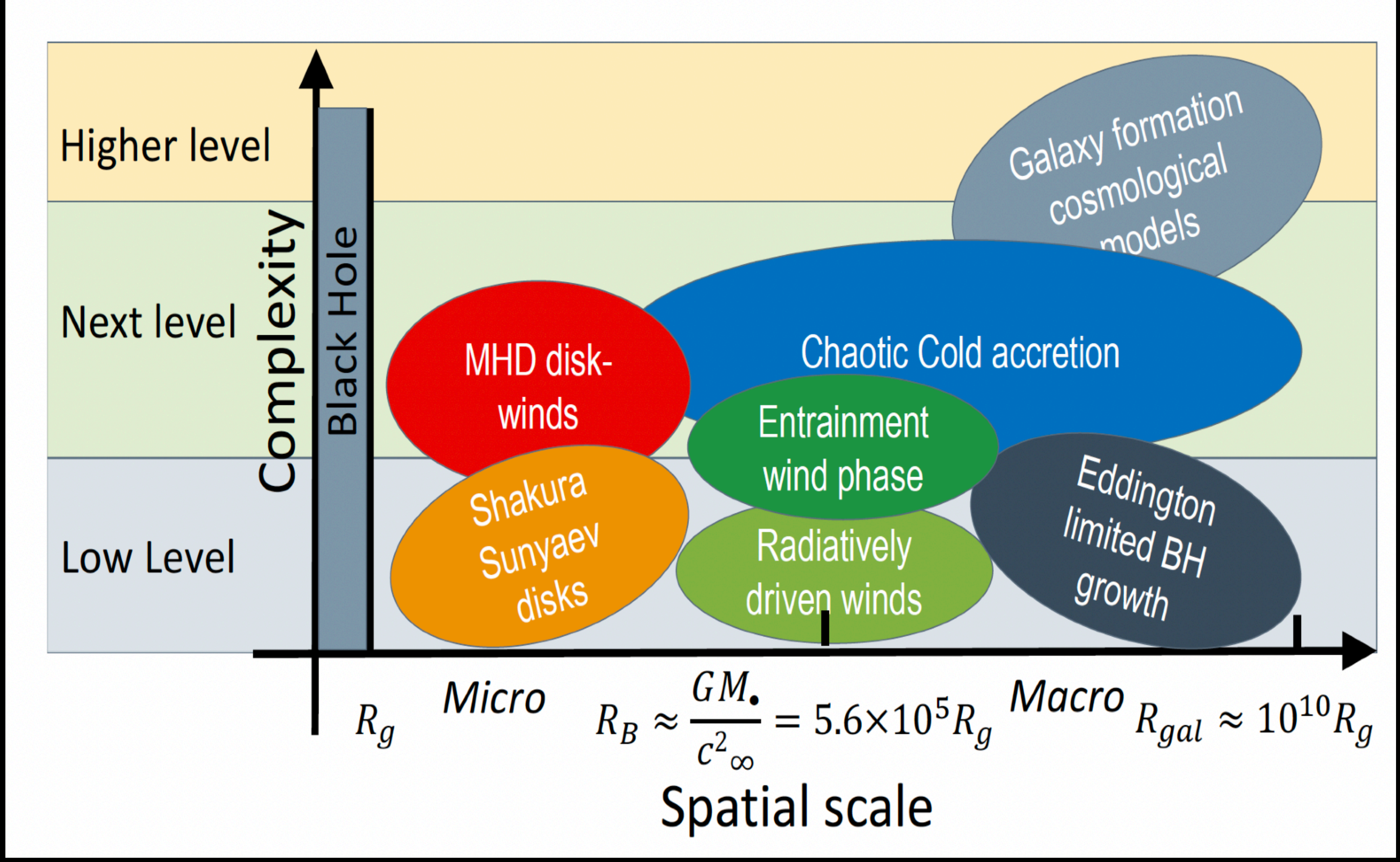
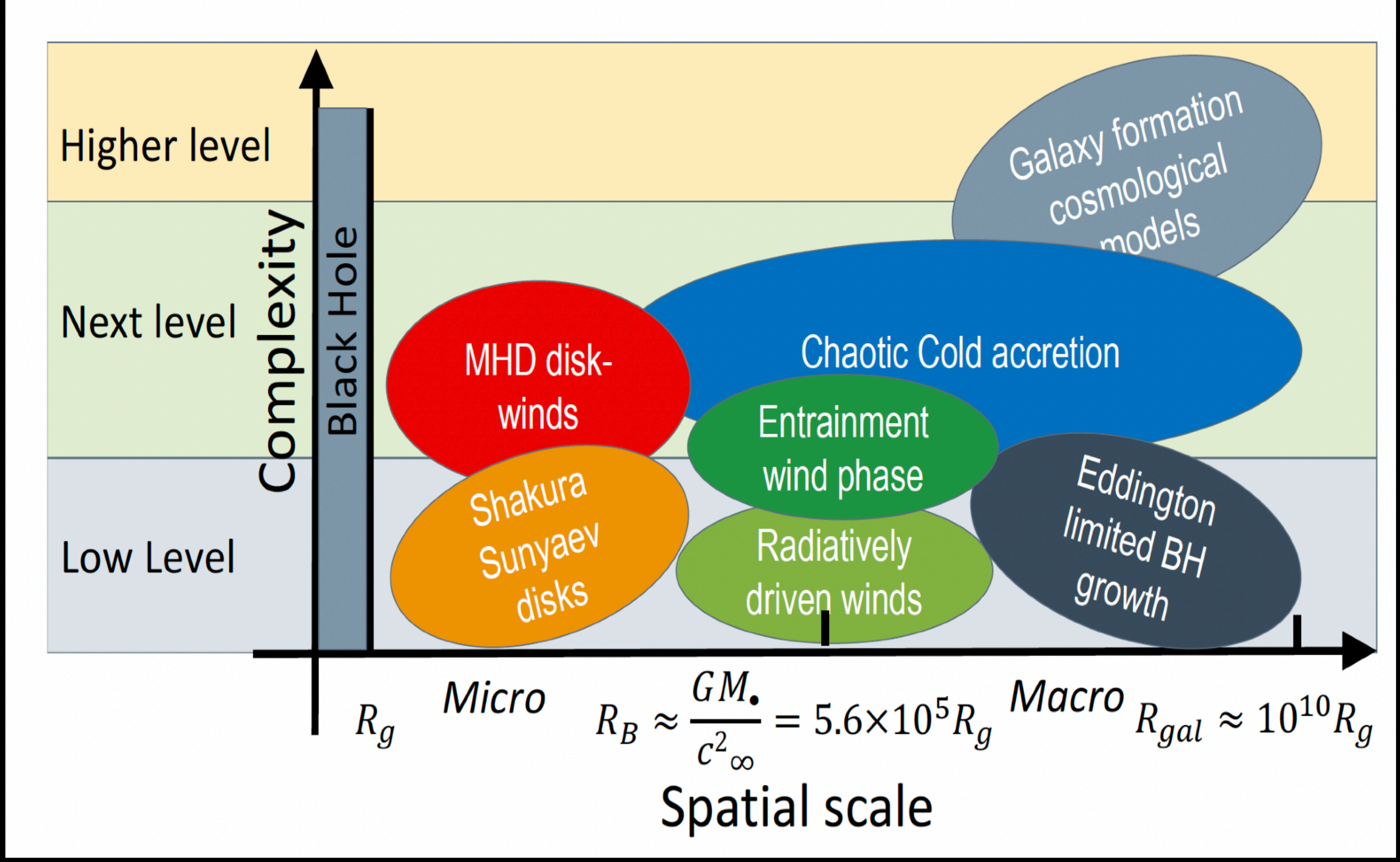


Complex dynamical systems

successful approach in evolutionary biology, neurology, condensed matter

- Non-linearity and sensitivity to initial conditions, stochastic variables
- Emergent properties produce a hierarchy of levels, developing power law scaling laws



Complex dynamical systems

successful approach in evolutionary biology, neurology, condensed matter

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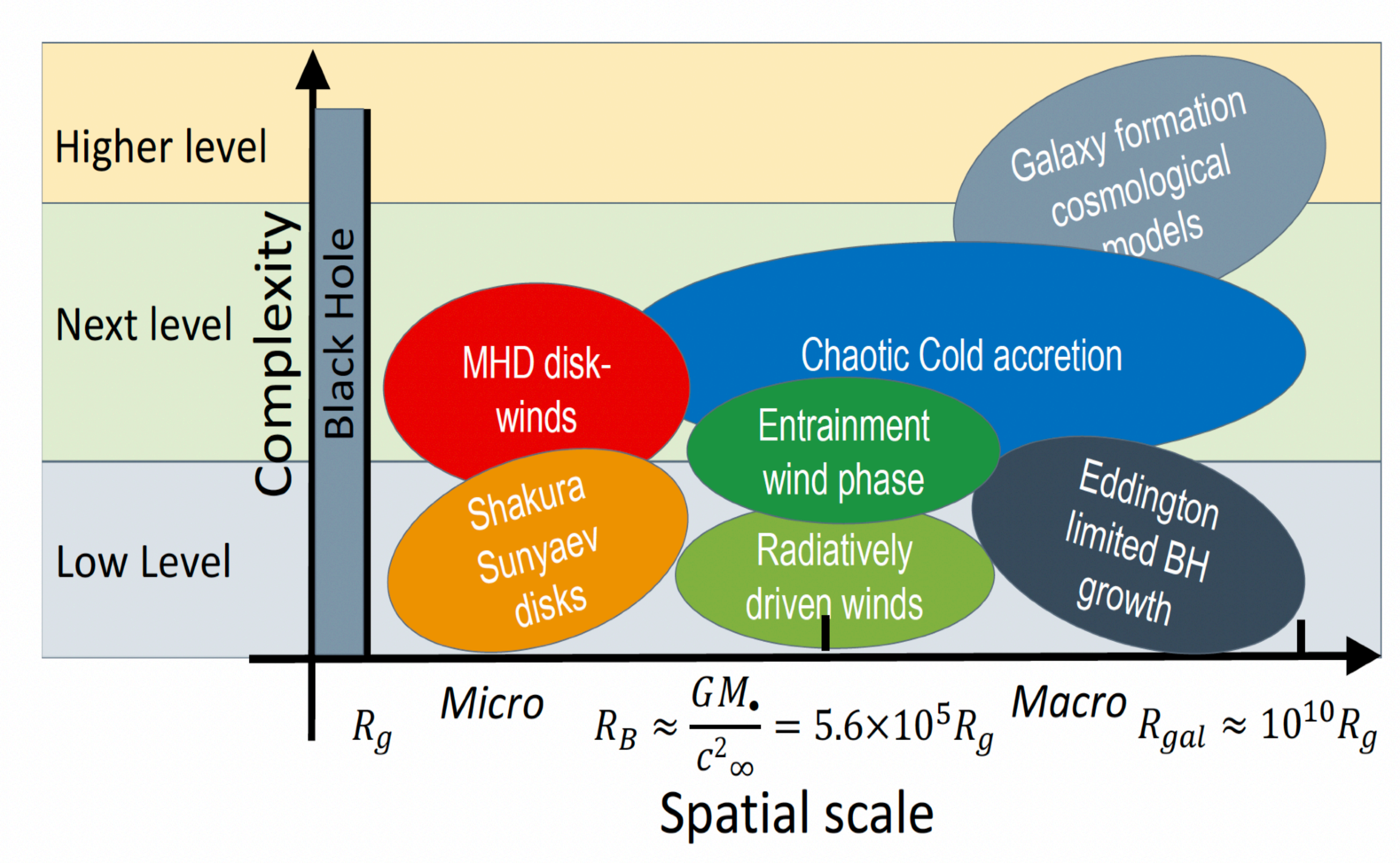
- Self-organization attained through feedback. *co-evolution* in evolutionary biology: organisms create their environment, which in turn influences the same organisms.



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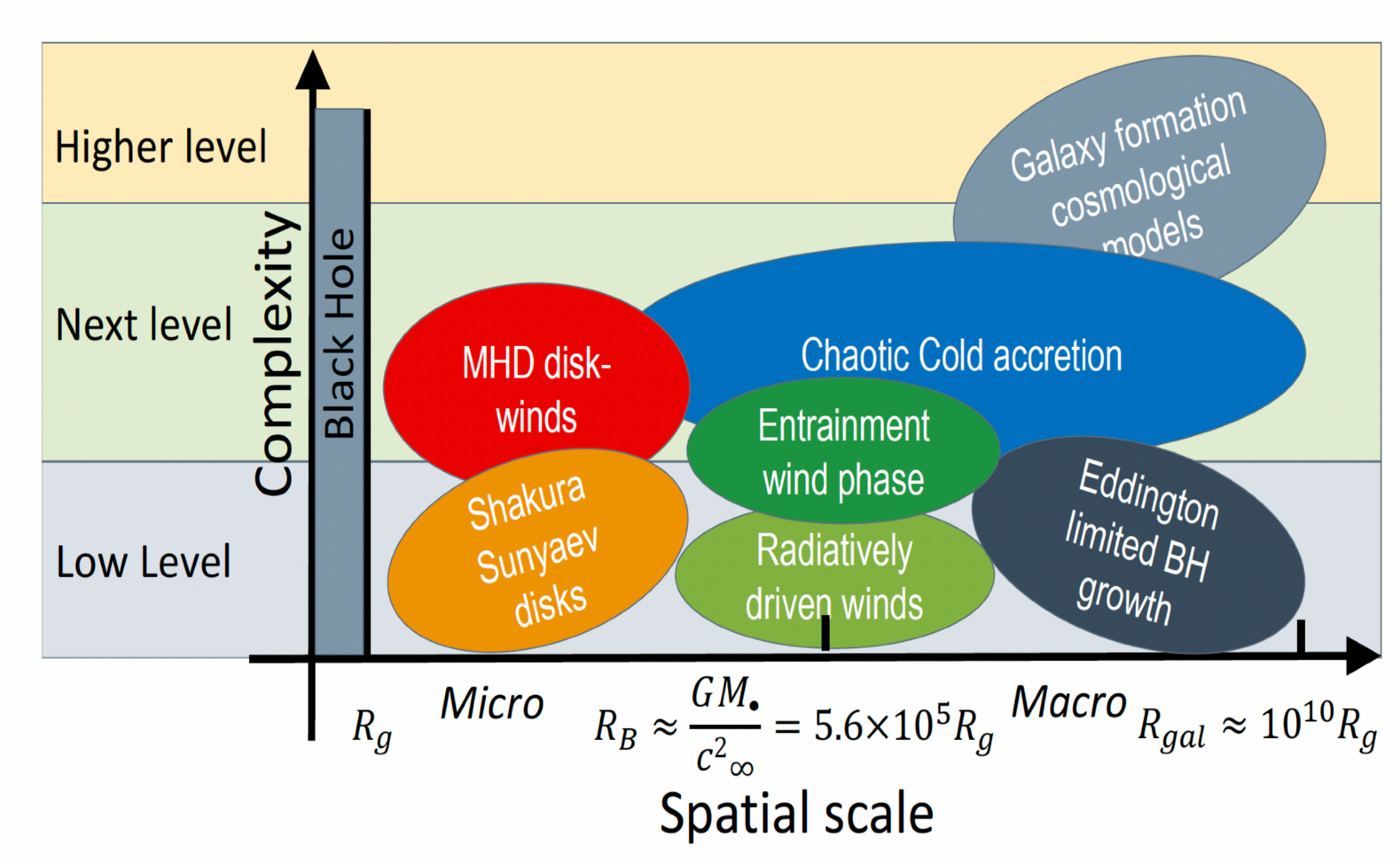
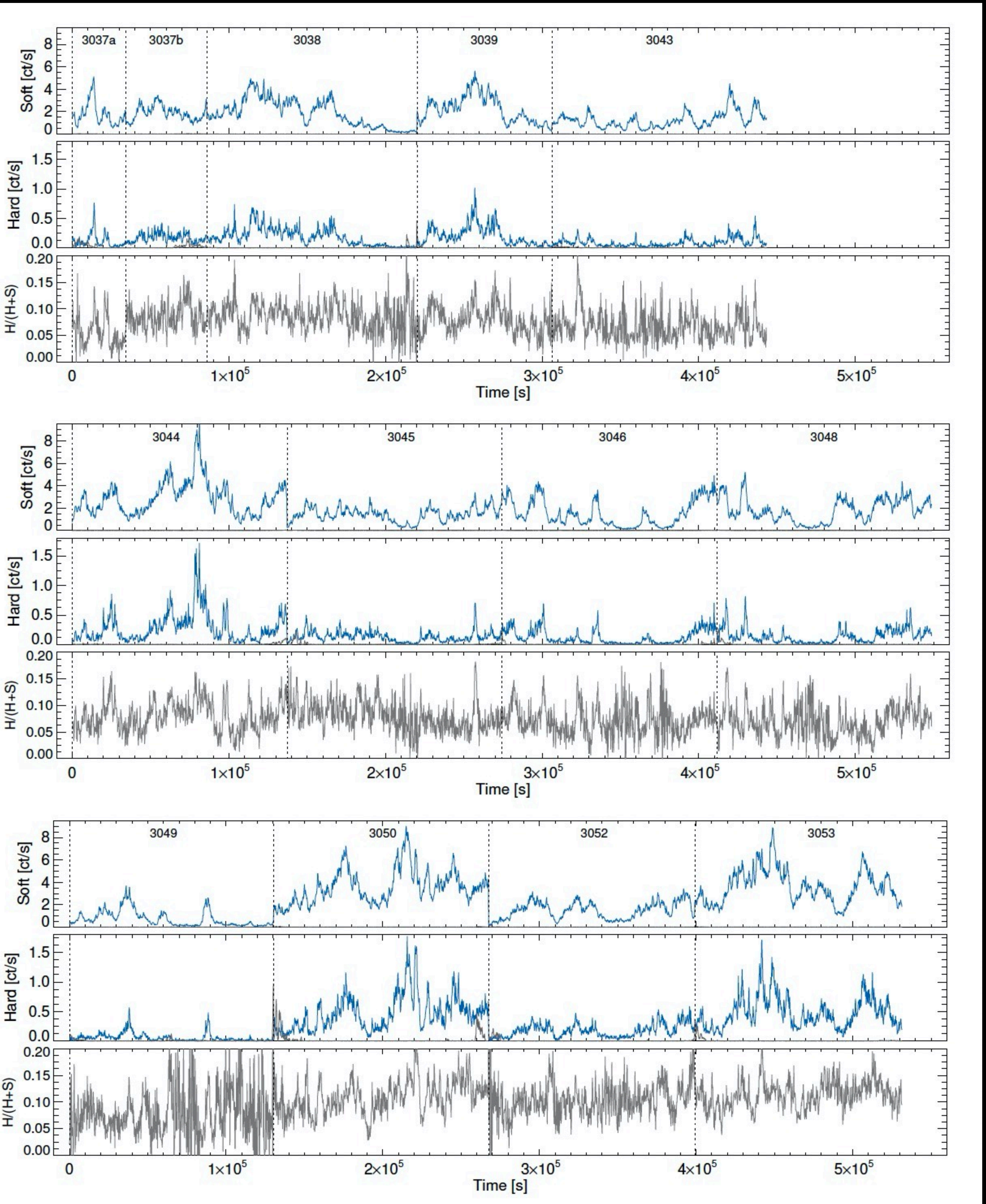


- Criticality, the status just in between the phases where activity is only local and where is so strong that spans always the full size of the system what next?

Accretion disk variability

- The leading model to explain this variability property is based on the inward propagation of random accretion rate fluctuations in the accretion flow
- Turbulent fluctuation in the local mass accretion rate at different radii propagate through the flow, with variability coupled together over a broad range in timescales.
- this fluctuation in mass accretion rate affects the next radial zone in, modulating its random fluctuations. This has the effect that the fluctuations at each radius are the product of the fluctuations from all previous radii, forming a fluctuation power spectrum $P(f) \propto f^{-1}$ down to the inner boundary of the flow, so modulating the region where most of the energy is released.
- The size of the rms fluctuations is linearly related to the source flux, such that that rms/F remains constant (Uttley & McHardy 2001). This is more or less equivalent to saying that the fluctuations have a log-normal distribution (Uttley, McHardy & Vaughan 2005). There is no way to do this in any model of variability which takes a sum of independent events, so all shot noise models are ruled out (Uttley et al. 2005).
- This also rules out self organized criticality models, where variability is propagated inwards only once the accretion flow at that radius crosses some critical threshold in properties. This produces a power law rather than lognormal distribution of fluctuations (Done et al. 2007).


3037a
3037b
3038
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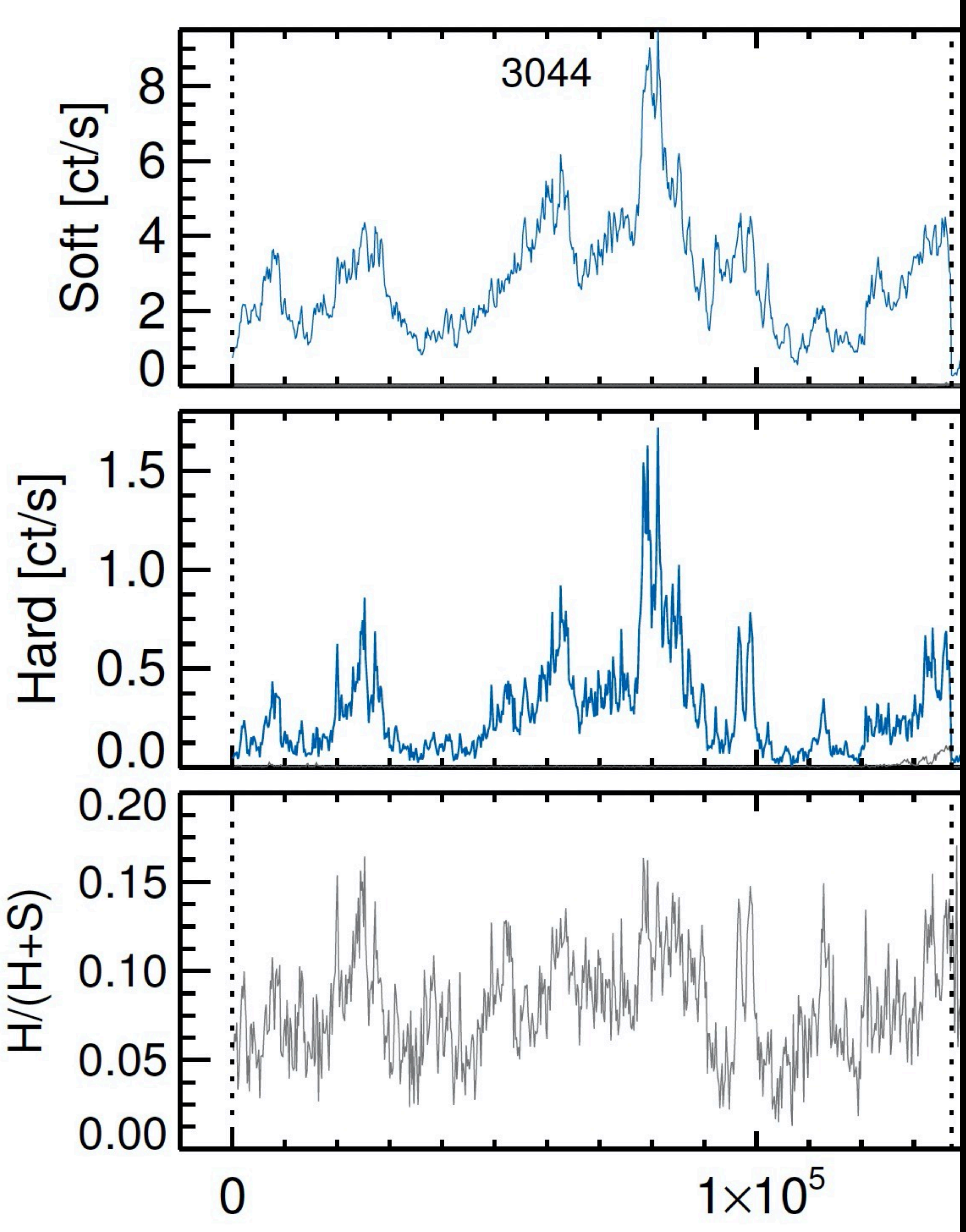
3052
3053
Soft [ct/s]
Hard [ct/s]
H/(H+S)
Time [s]
0
1×10^5
2×10^5
3×10^5
4×10^5
5×10^5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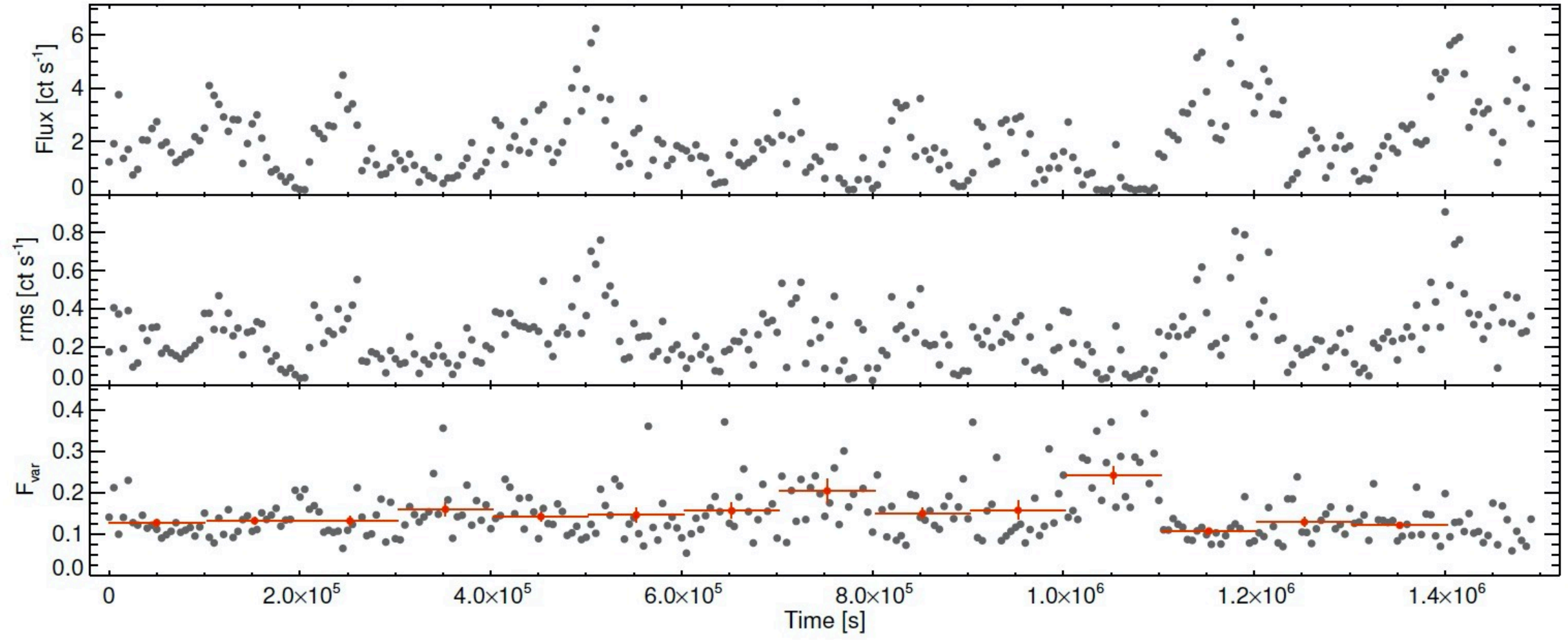
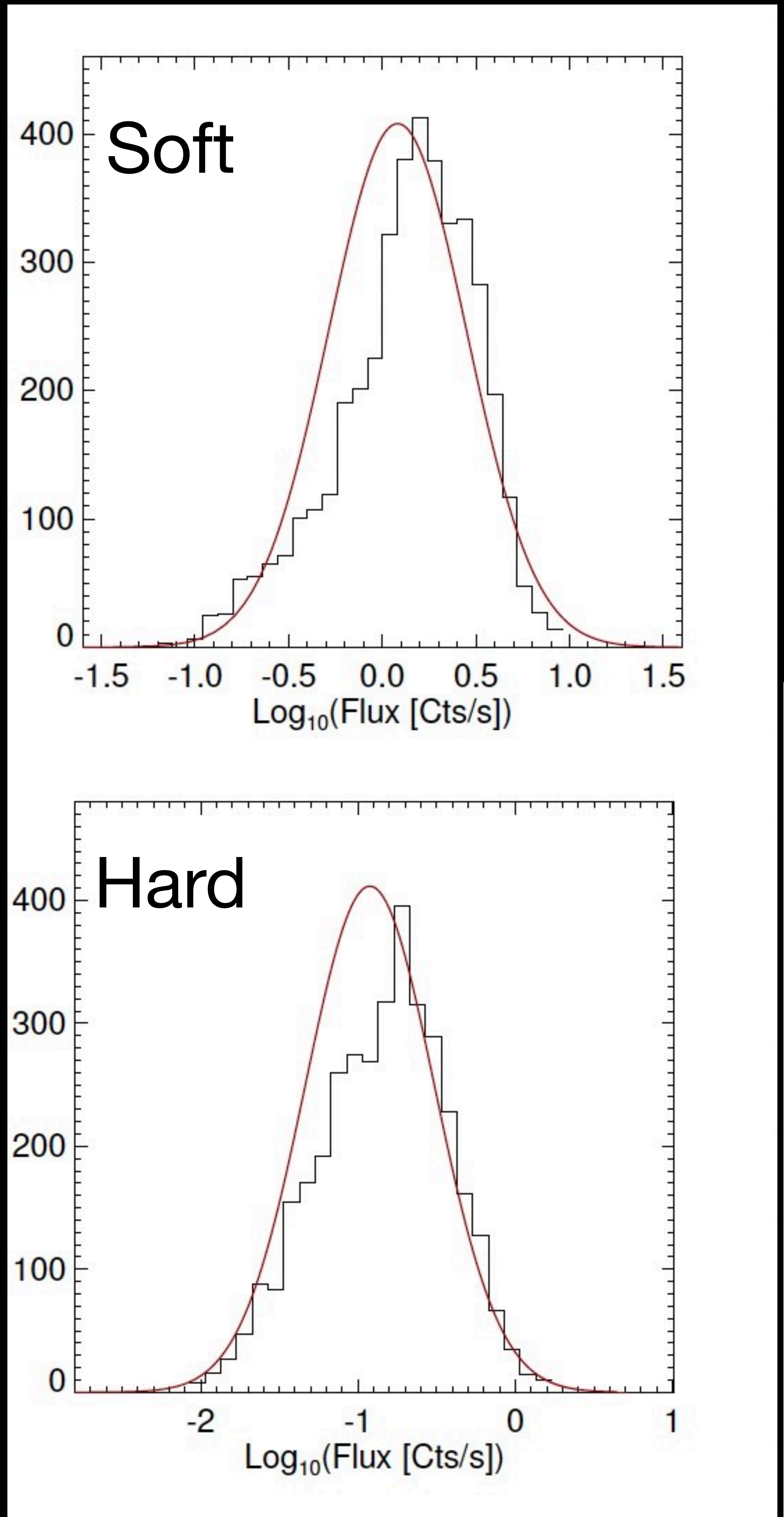
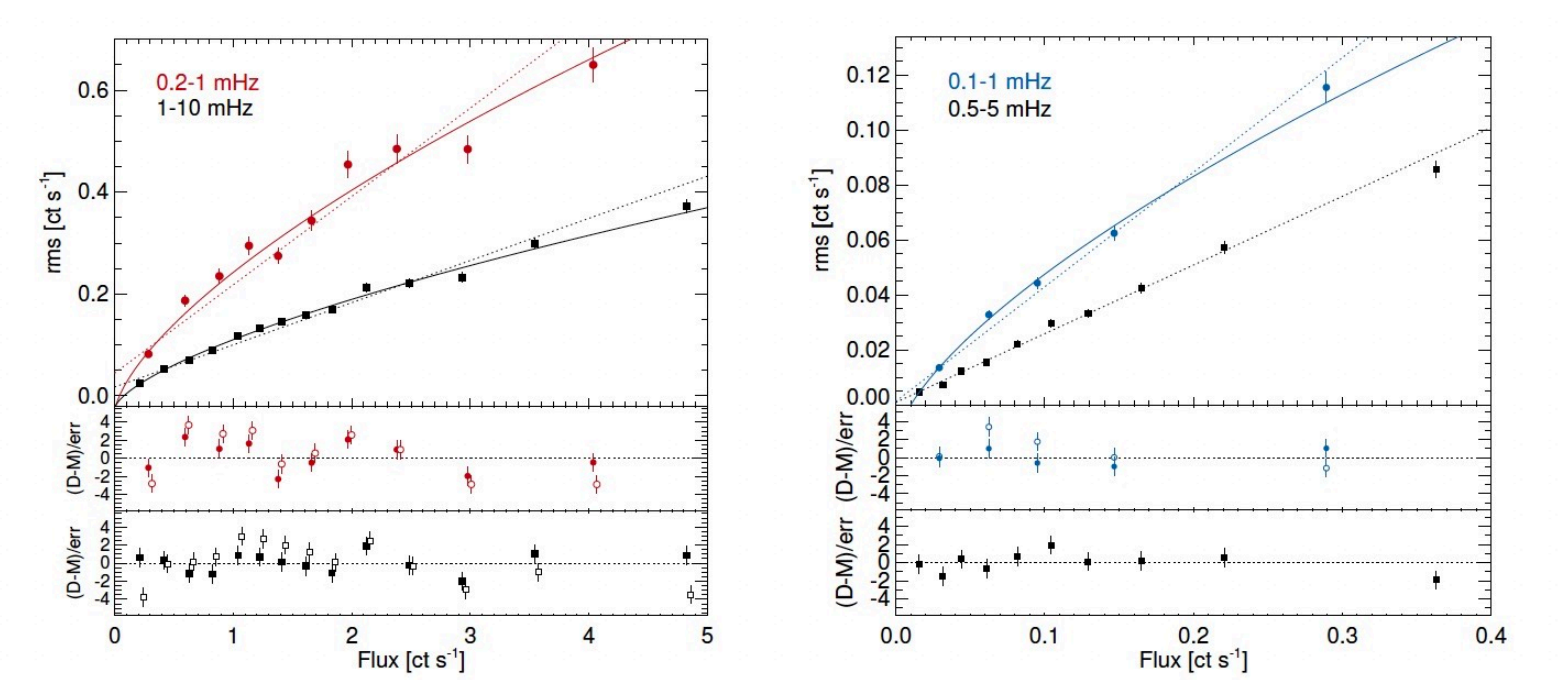


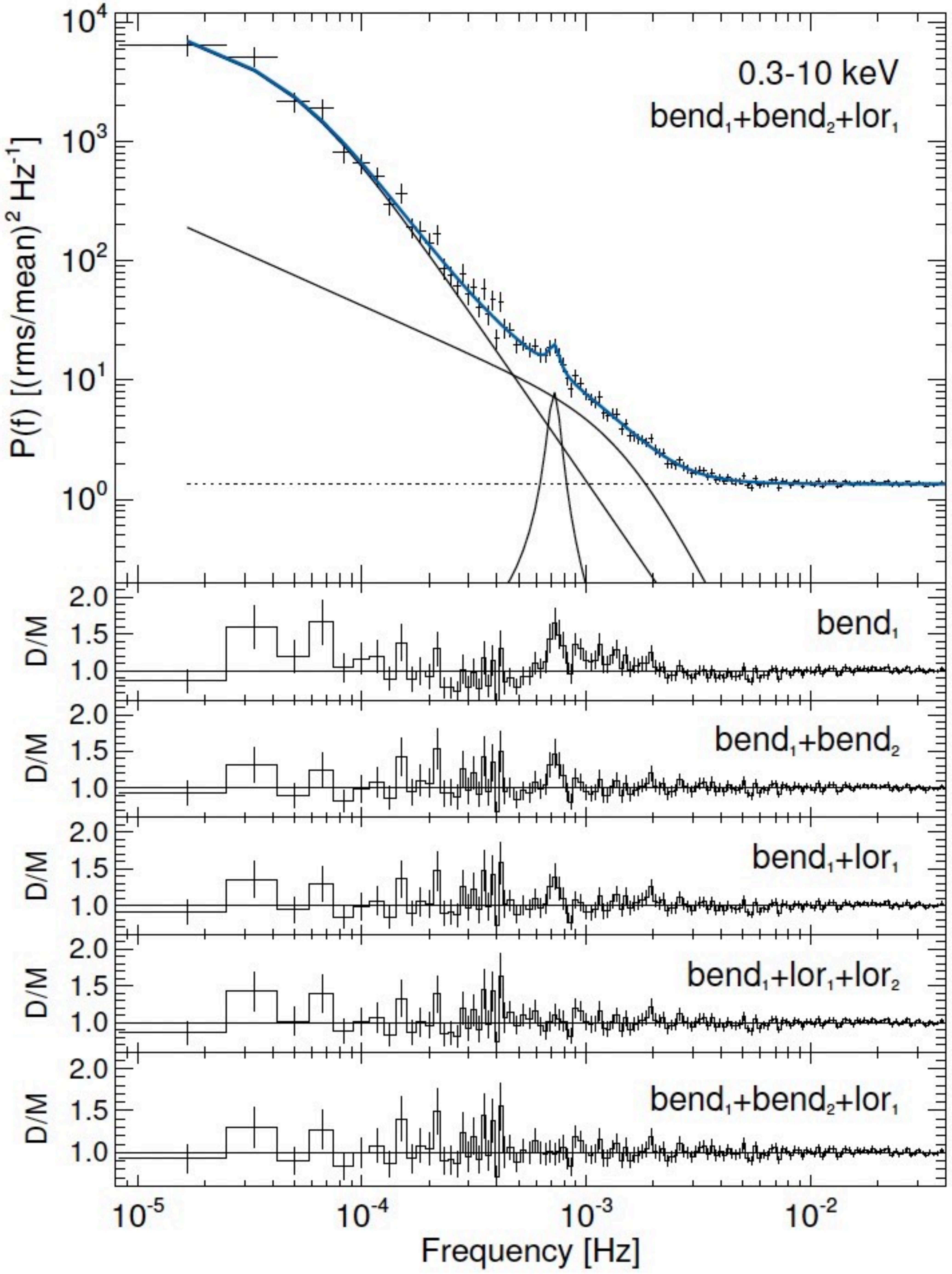
strong non-stationarity

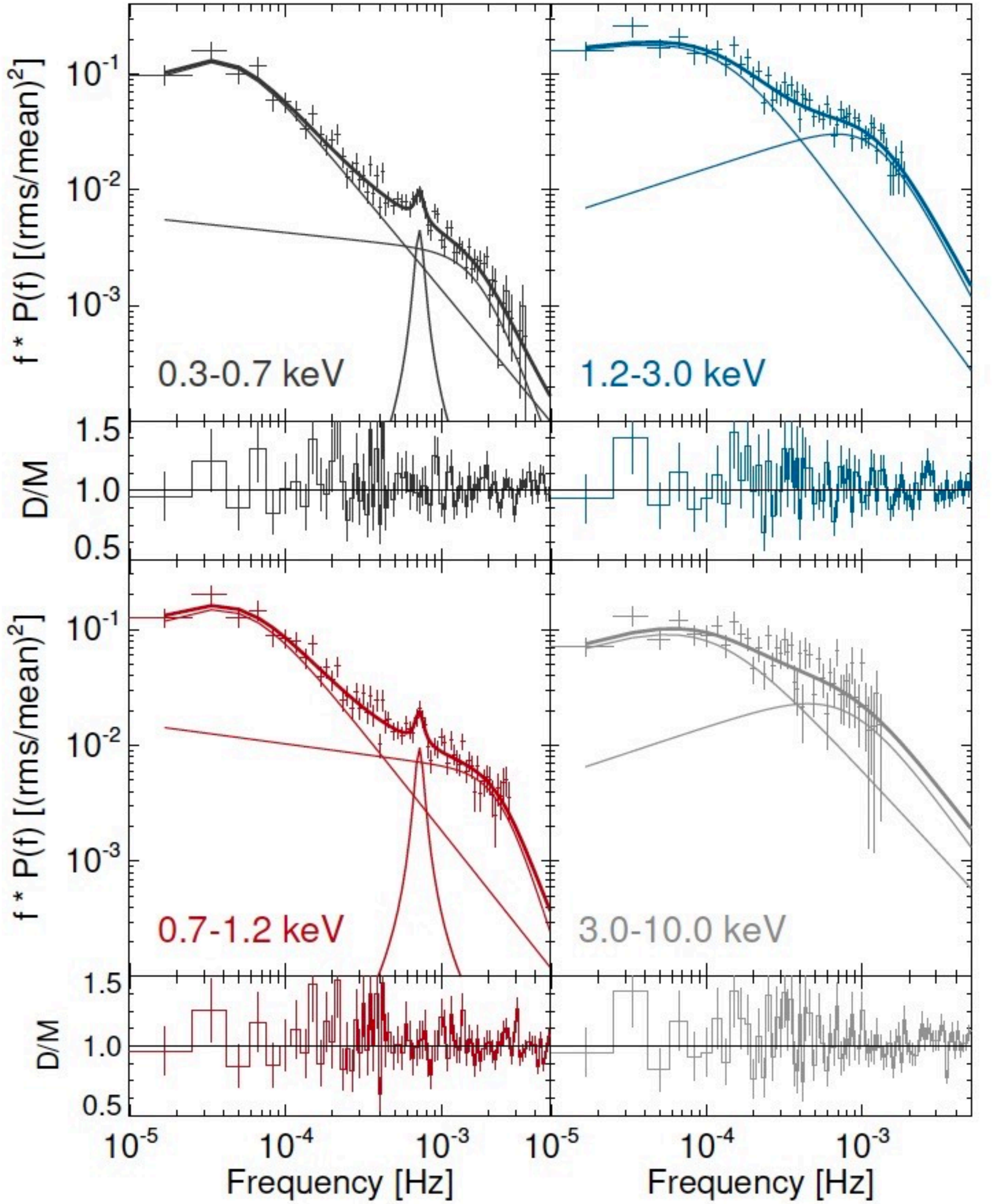


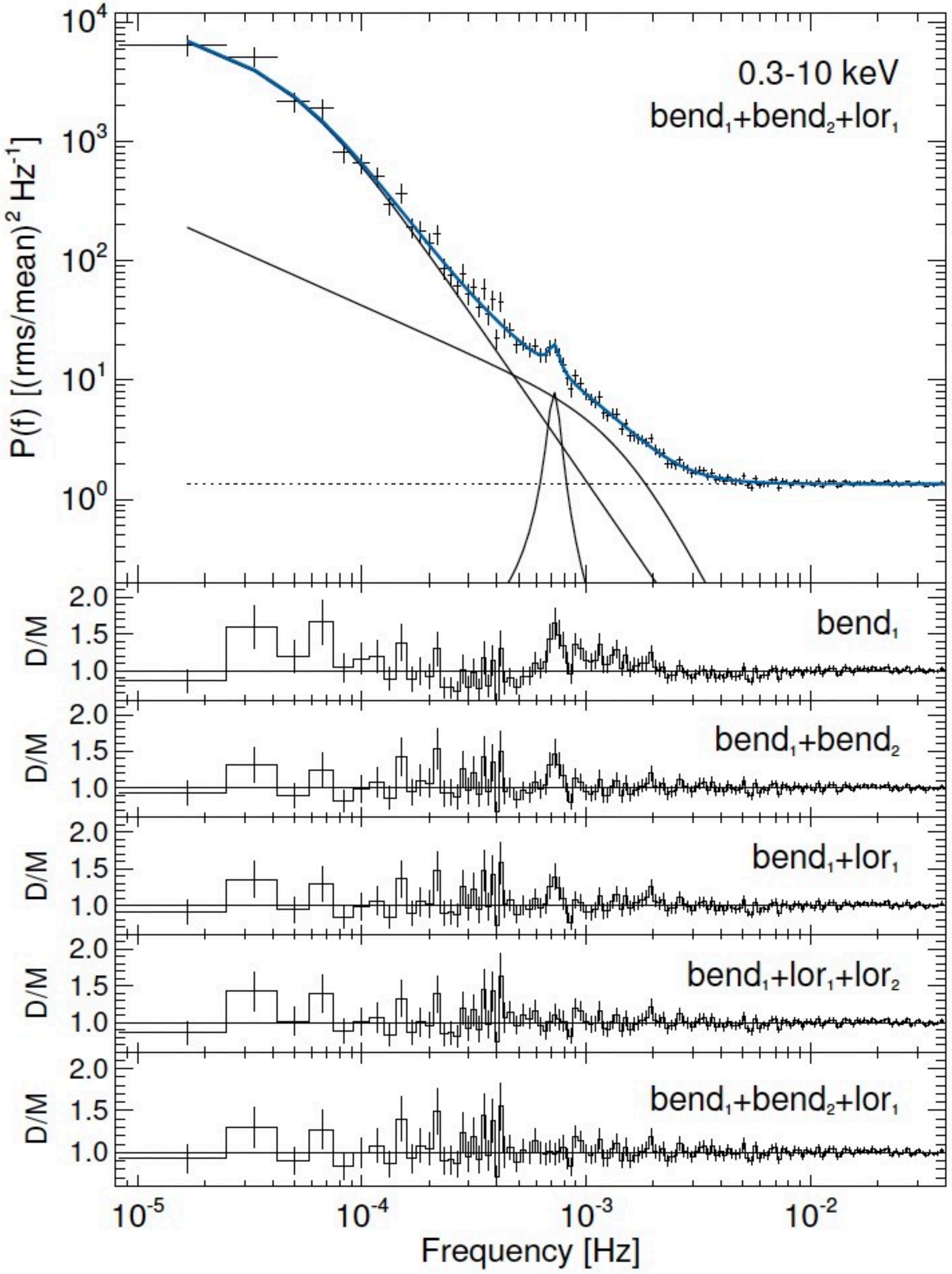
Flux distribution:
clear deviation
from log normal

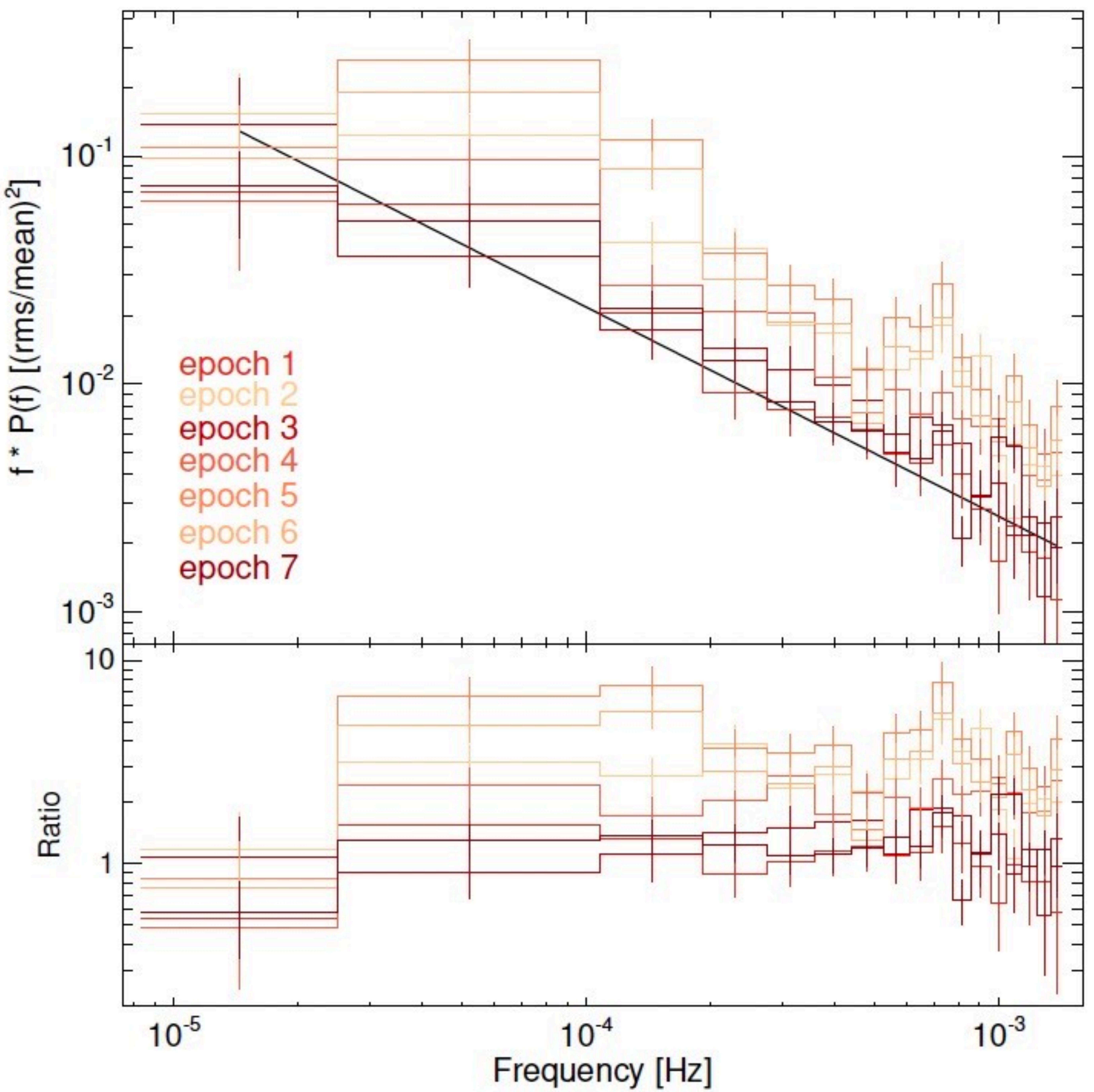
RMS-Flux NOT
linear




0.3-10 keV
bend₁+bend₂+lor₁
P(f) [(rms/mean)^2 Hz^{-1}]
D/M
bend₁
bend₁+bend₂
bend₁+lor₁
bend₁+lor₁+lor₂
bend₁+bend₂+lor₁
Frequency [Hz]


f * P(f) [(rms/mean)^2]
0.3-0.7 keV
1.2-3.0 keV
D/M
0.7-1.2 keV
3.0-10.0 keV
Frequency [Hz]
Frequency [Hz]


0.3-10 keV
bend1+bend2+lor1
P(f) [(rms/mean)^2 Hz^-1]
bend1
bend1+bend2
bend1+lor1
bend1+lor1+lor2
bend1+bend2+lor1
D/M
Frequency [Hz]


epoch 1
epoch 2
epoch 3
epoch 4
epoch 5
epoch 6
epoch 7
f * P(f) [(rms/mean)^2]
Ratio
Frequency [Hz]