Black hole spin measurements of Cygnus X-1 using the continuum-fitting method

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Outline

- Background introduction
- The X-ray continuum-fitting method
- Cygnus X-1
- Summary

Background

- **No-Hair Theorem**

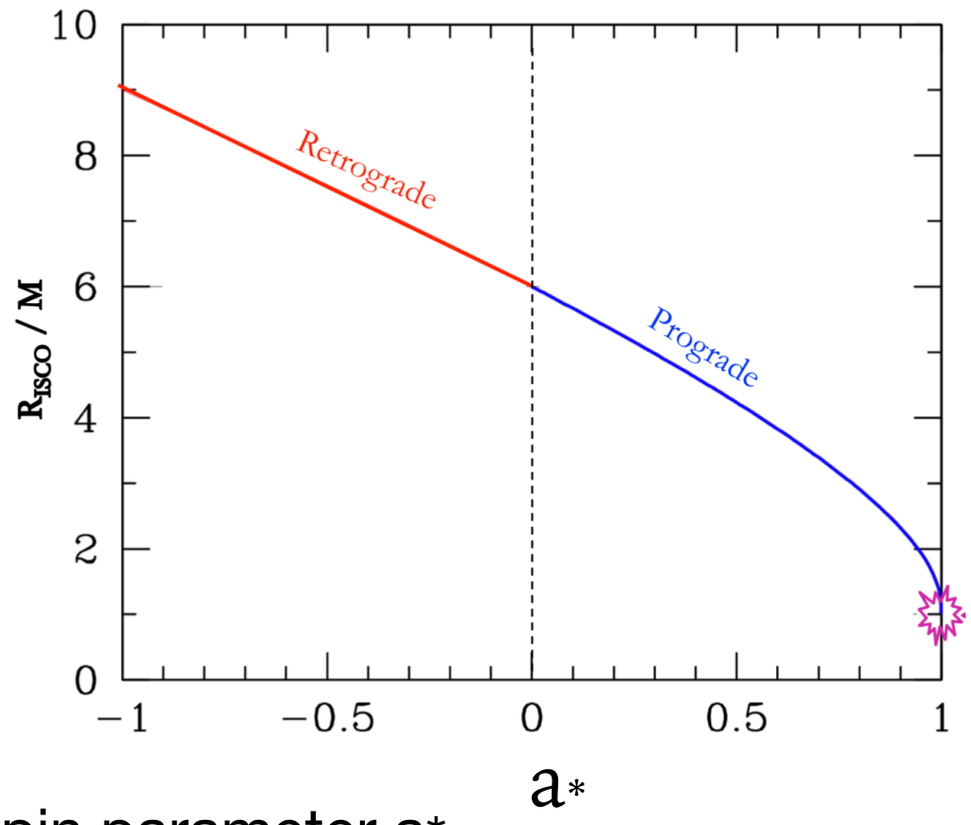
  1. Mass: M

  IMPORTANT

  2. Spin: $a_* = ac/GM = J(c/GM^2)$ $-1 \leq a_* \leq 1$

  3. Charge neutralized and unimportant

- **Theoretical Foundation**



R_{ISCO} (ISCO: inner-most stable circular orbit)

R_{in} (the inner radius of the disk) $=R_{ISCO}$

R_{ISCO} is directly related to the dimensionless spin parameter a_*

(Bardeen et al. 1972)

Background

- **Two Widely-used Methods of Measuring Spin**

1. Fe line Method （X-ray reflection fitting method）

(Fabian at al. 1989)

Fitting the relativistically-broadened profile of the 6.4 keV **Fe K line**

Both **stellar and supermassive** black holes

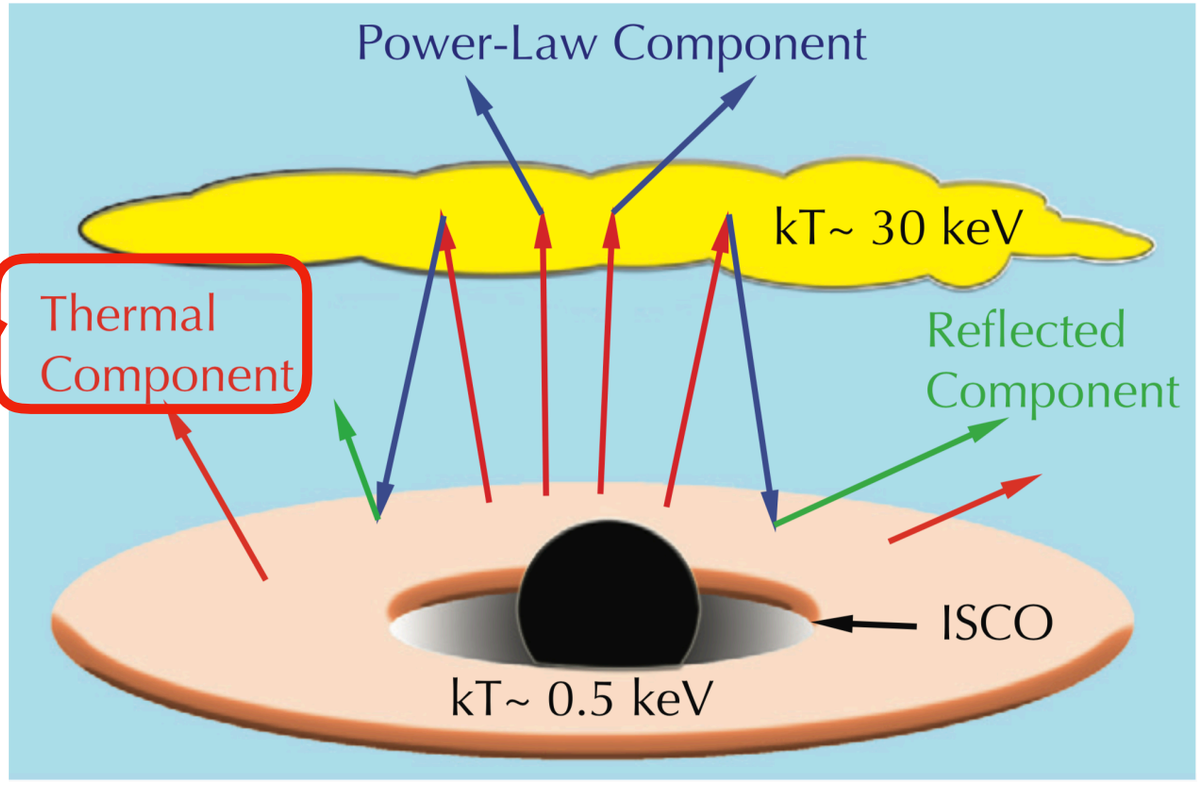
2. Continuum Fitting Method

(Zhang, Cui & Chen 1997)

Fitting the **thermal component** of the accretion disk

Stellar black holes

Our adopted method



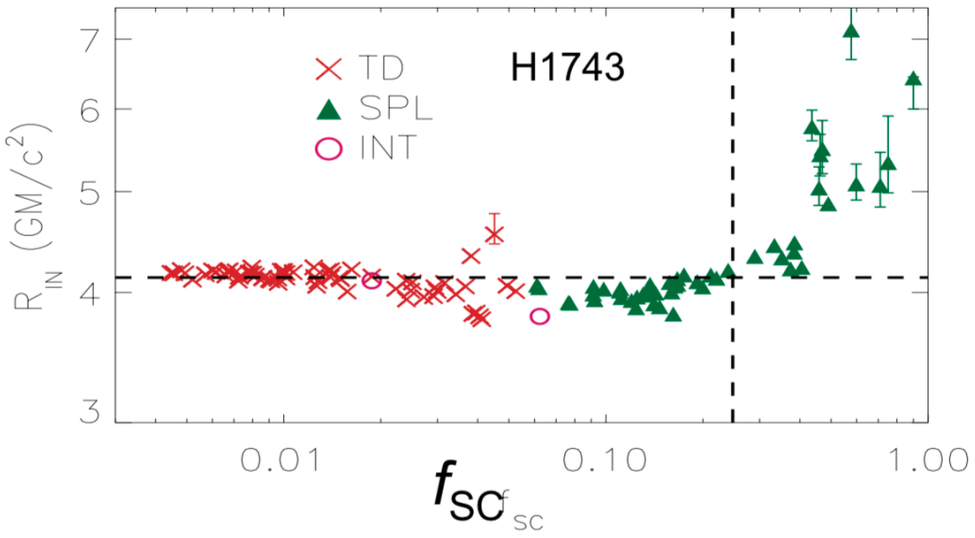
(Gou et al. 2011)

Continuum-fitting Method

- **Requirements**

1、 **Thin disk**: H/R < 0.1 equivalent to L/L_{Edd} < 0.3 (McClintock et al. 2006)

2、Spectrum dominated by **accretion disk component**



simpl: fsc<=25%

fsc：scattering fraction, The fraction of the seed photons that are scattered into the power-law tail (Steiner et al. 2009a,b)

3、Accurate system parameters: **M, i and D**

Cygnus X-1

- Galactic high mass BH X-ray binary
- One of the brightest and most persistent celestial X-ray sources
- The compact primary in Cygnus X-1 was the first black hole to be established via dynamical observations.

Distance (kpc)	Inclination (deg)	Mass ($M_\odot$)	Reference
1.86	27.1	14.8	Reid et al. 2011; Orosz et al. 2011

- **The History of Spin Measurement**

a rapidly spinning black hole

continuum-fitting method	
>0.95	Gou et al. 2011
>0.983	Gou et al. 2014

Fe-Ka line fitting method	
0.95-0.984	Fabian et al. 2012
>0.83	Tomsick et al. 2014
~0.9	Duro et al. 2016
0.93-0.96	Walton et al. 2016

Cygnus X-1 (Galactic high mass BH X-ray binary)

- **Newly-obtained Dynamical Parameters**

	Distance (kpc)	Inclination (deg)	Mass ($M_\odot$)	Reference
Old	1.86	27.1	14.8	Reid et al. 2011; Orosz et al. 2011
New	2.22	27.5	21.2	Miller-Jones et al. 2021

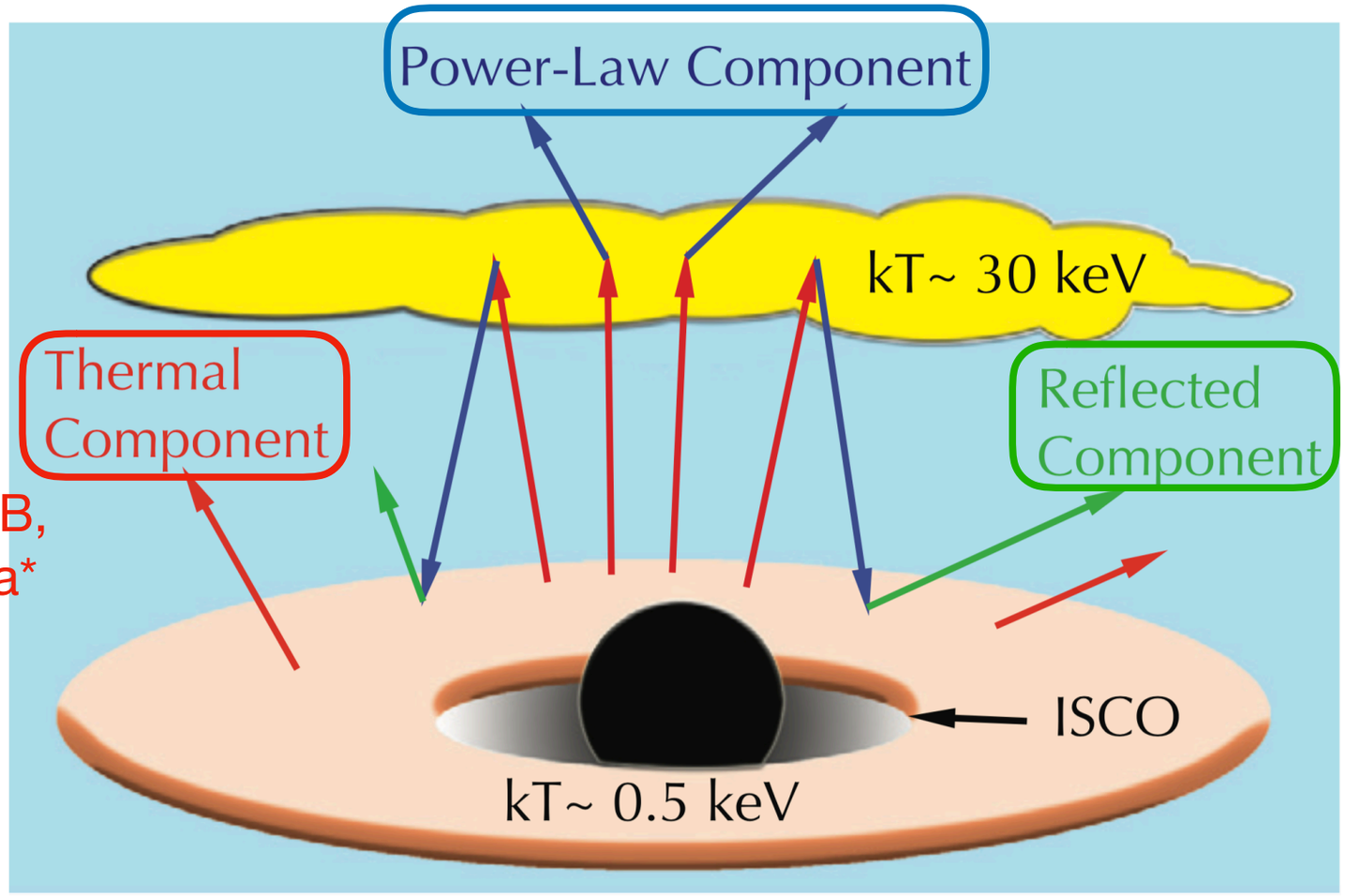
a_* ?

Spectra Fit

Xspec Model：

$$\mathrm{CRABCOR} * \mathrm{CONSTANT} * \mathrm{TBABS}\,[\mathrm{SIMPLR} \otimes \mathrm{KERRBB2} + \mathrm{KERRDISK} + \mathrm{KERRCONV} \otimes (\mathrm{IREFLECT} \otimes \mathrm{SIMPLC})]$$

KERRBB2
(a fully relativistic thin disk model, BHSPEC+KERRBB, the upper limit of a* is set to 0.9999)



(Gou et al. 2011)

SIMPL
(an advanced empirical Comptonization model)

IREFLECT
(a convolution model for reflection from ionized material)

KERRDISK
(accretion disk line emission)

Others:

CRABCOR (correcting for calibration deviations)

CONSTANT (reconciling calibration discrepancies between different detectors)

TBABS (an ISM absorption model)

KERRCONV (smearing the spectrum)

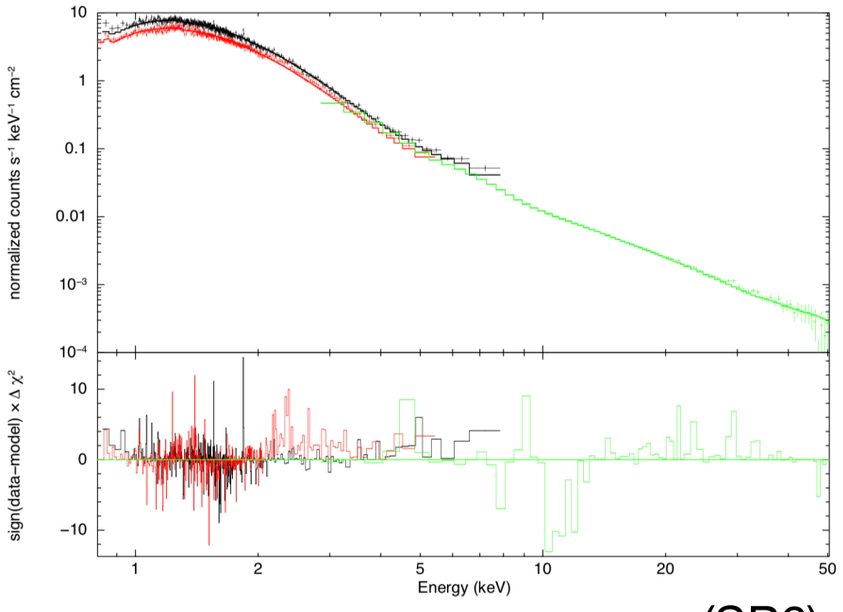
Results

- **Data：** Presented in Gou et al. (2011) and Gou et al. (2014)

Number	ObsID	Mission	Detector	Energy Band (keV)	UT	T_{exp} (s)	I (Crab)
SP1	10408000 & P10412	ASCA & RXTE	GIS & PCA	0.7–8.0 & 2.5–45.0	1996 May 30 06:43:16 & 07:51:29	2547 & 2240	0.80
SP2	12472 & P96378	Chandra & RXTE	HETG(CC) & PCA	0.8–8.0 & 2.9–50	2011 Jan 6 14:06:40–14:35:44	455 & 1744	0.52
SP3	12472 & P96378	Chandra & RXTE	HETG(CC) & PCA	0.8–8.0 & 2.9–50	2011 Jan 6 15:44:16–16:09:52	398 & 1536	0.61
SP4	12472 & P96378	Chandra & RXTE	HETG(CC) & PCA	0.8–8.0 & 2.9–50	2011 Jan 6 17:15:28–17:43:44	455 & 1744	0.57
SP5	12472 & P96378	Chandra & RXTE	HETG(CC) & PCA	0.8–8.0 & 2.9–50	2011 Jan 6 18:19:44–19:17:52	455 & 1744	0.38
SP6	12472 & P96378	Chandra & RXTE	HETG(CC) & PCA	0.8–8.0 & 2.9–50	2011 Jan 6 19:53:36–20:50:08	455 & 1744	0.38

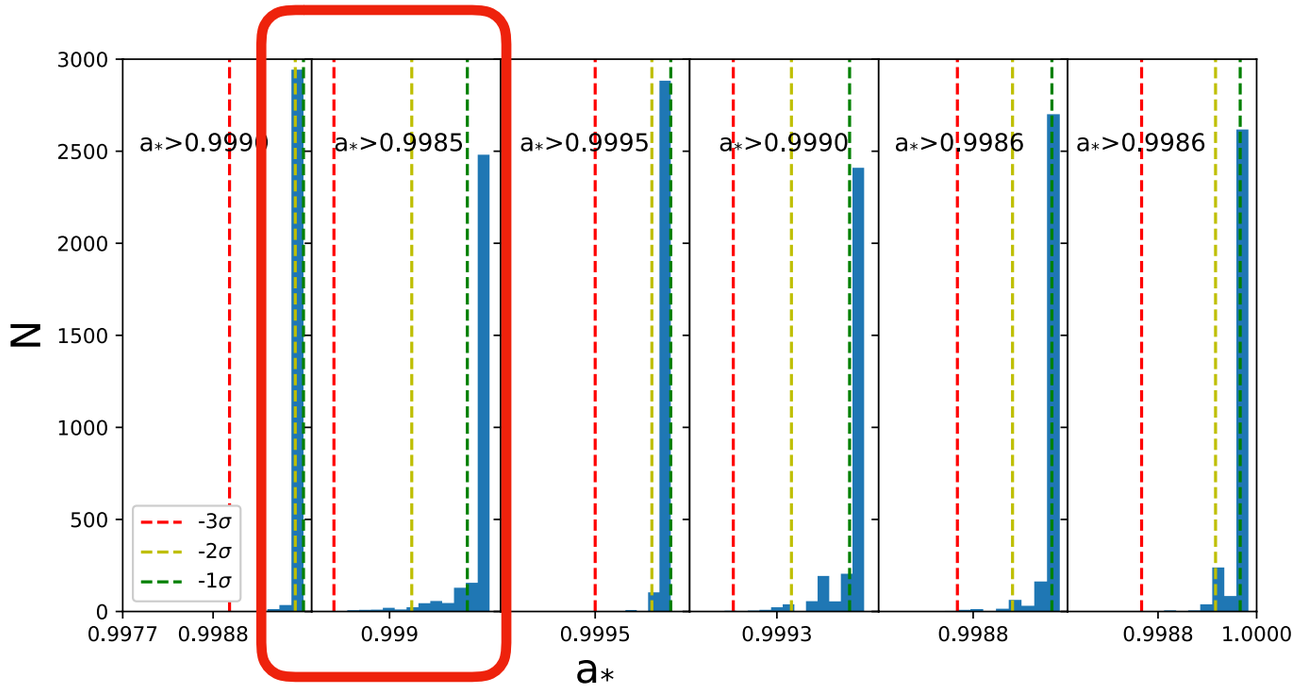
- **Parameters:** Newly-obtained parameters

- **Error Analysis:** Monte Carlo



(SP6)

- **Results:** a*>0.9985 (3σ)



Summary

1、We re-analyze six archival spectra of the black hole X-ray binary Cygnus X-1, which were originally presented in Gou et al. (2011) and Gou et al. (2014), to constrain the black hole spin. These data rigorously satisfy the selection criterion $f_{sc} <= 25\%$.

2、We adopt up-to-date values of three key dynamical parameters M, i, and D.

3、The key model we utilized is a fully relativistic thin disk model KERRBB2.

4、Monte Carlo simulations are performed in order to estimate the error in a_* due to the combined uncertainties of M, i, and D.

5、We arrive at our final result, $a_* > 0.9985$ at the 3σ level of confidence, which confirms the extreme spin of the black hole in Cygnus X-1.

Thanks!