CA21106 General Meeting, Istanbul, 04/09/2024

Boson Cloud Atlas: Direct Observation of Superradiance Clouds

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Based on
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2408.16051

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האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Dark mass around dark objects

BHs are dark but we can “see” them via:
X-ray emission from accretion disks,
lensing, star motion, GWs …

Kerr BHs spacetimes are characterized by..

- mass M
- spin $J = \chi G M^2$

But what if some other extended dark mass
is there around BH? DM Spikes, clouds…

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Luminous vs Dynamical

Luminous and **dynamical** mass measurements of the Coma cluster hinted at **Dark Matter**

$$M_{\rm Coma}^{\rm lum} \sim 800 \times 10^9\ M_\odot$$

$$M_{\rm Coma}^{\rm dyn} \sim \frac{5}{3}\frac{R_{\rm Coma}}{G}v^2 \sim 400 M_{\rm Coma}^{\rm lum}$$

Two measurements to find dark mass

(Zwicky 1933)

Goal of the talk:

Spin measurements of the same BH with two EM techniques can reveal dark mass around the BH

Outline

Measuring BH spins in accreting systems

Weighing a dark cloud

Dark mass around BHs: superradiance

Weighing a boson cloud

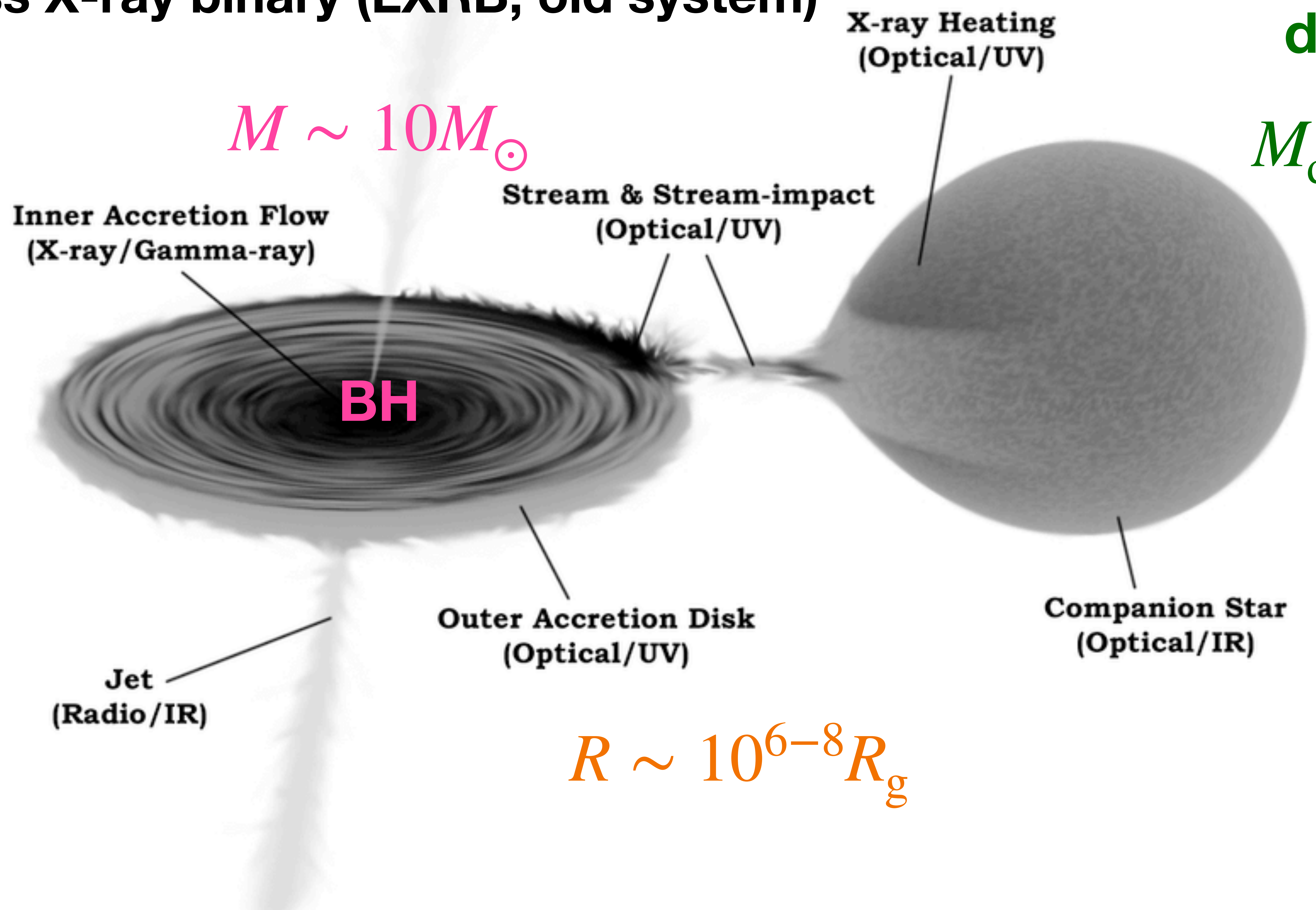
Measuring BH spins in accreting systems

E.g. low mass X-ray binary (LXRB, old system)

donor star

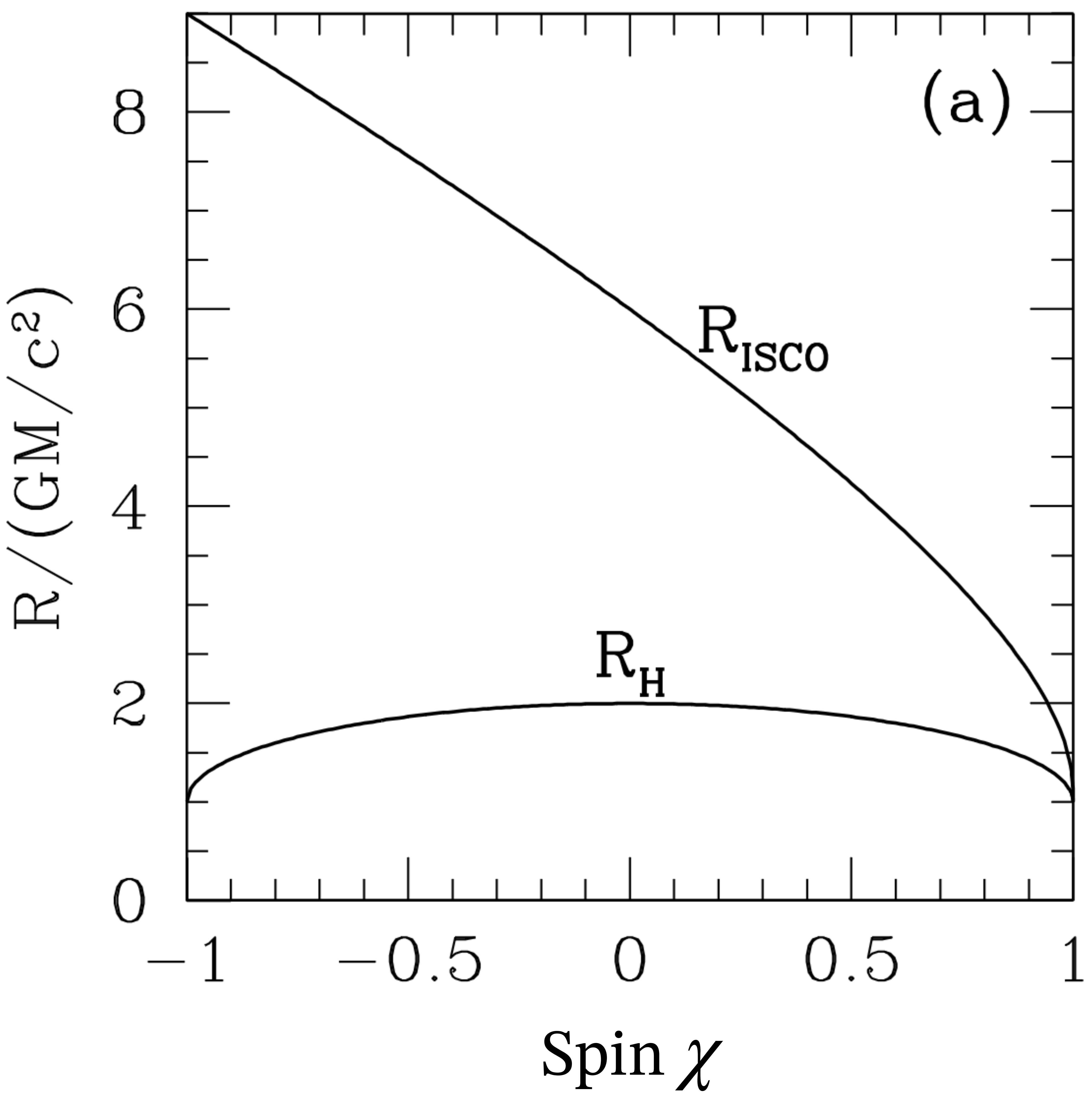
$M_{\rm donor} \sim 5 M_\odot$

$M \sim 10 M_\odot$



$R \sim 10^{6-8} R_{\rm g}$

Spin and the ISCO (Kerr BH)



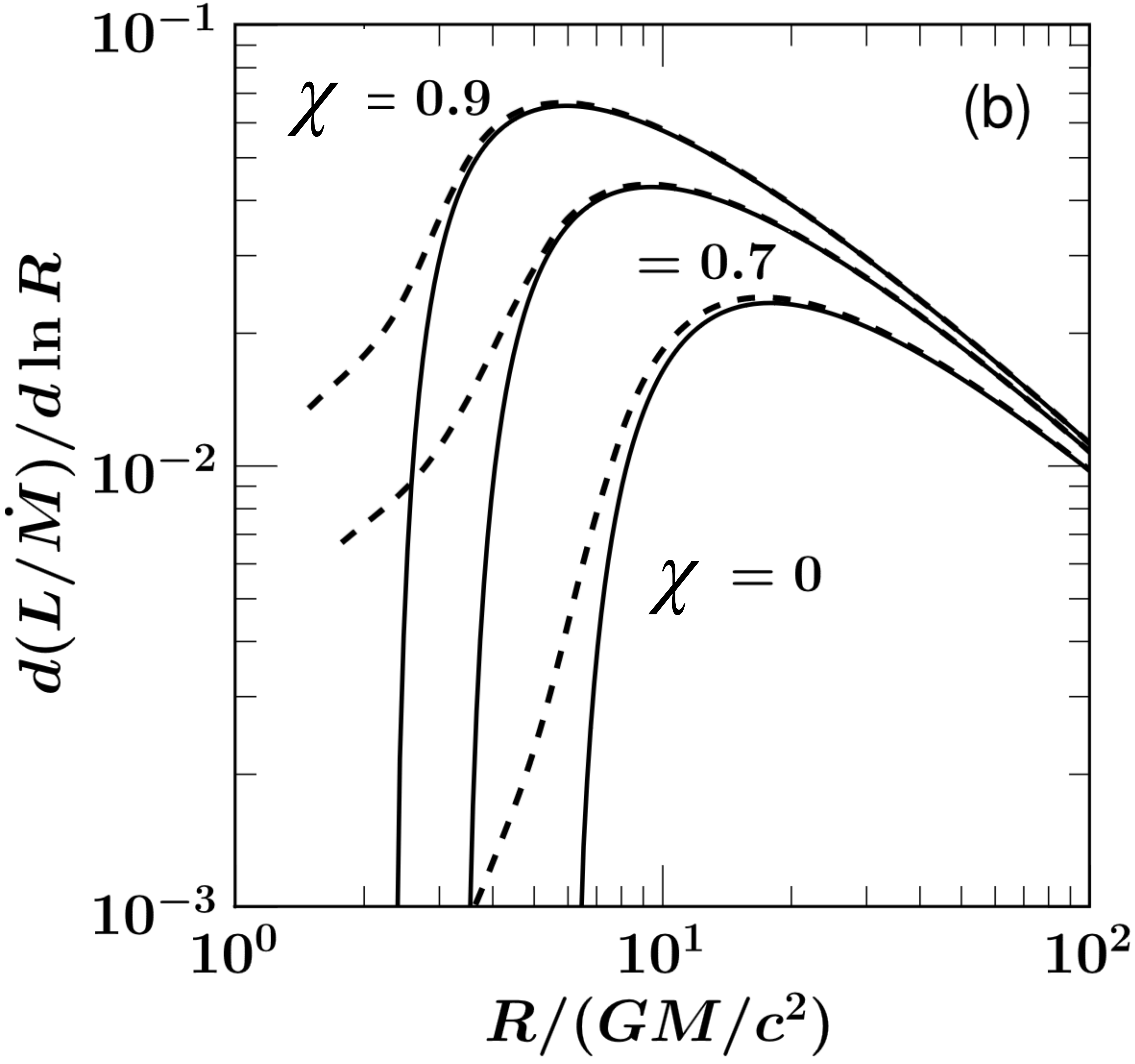
[McClintok+, 1303.1583]

non-linear region

(easier to measure $\chi \sim 1$)

Novikov-Thorne **thin disk*** model

Radiation flux



* Geometrically thin, optically thick disk, valid for systems accreting at

$$L \sim (0.01 - 0.3) L_{\text{edd}}$$

[McClintok+, 1303.1583]
Dashed lines: MHD simulations [Zhu+, 2012]

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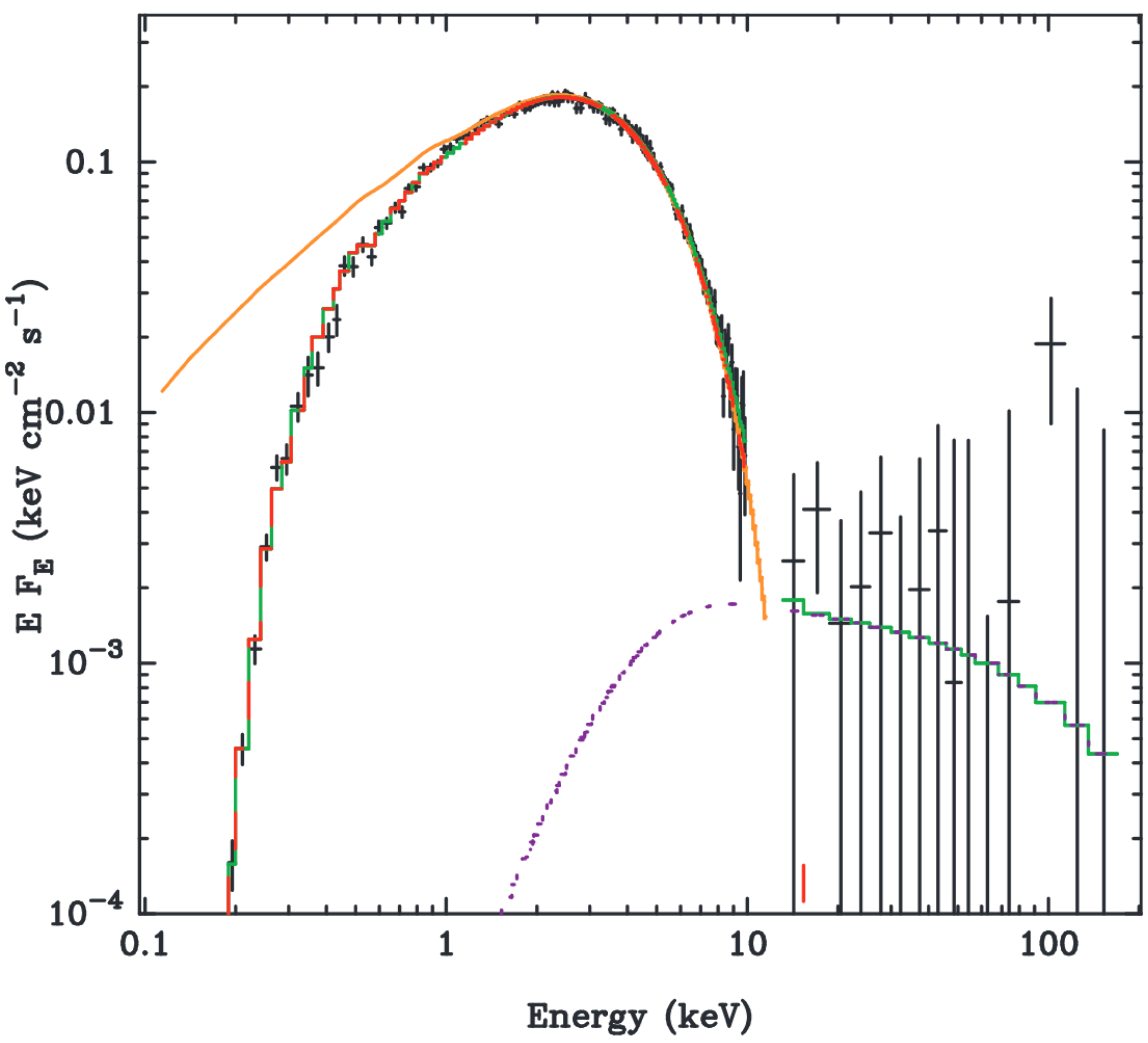
Method 1: Continuum fitting (CF)



Total CF model
Thermal component
Compton component
No interstellar absorption

External parameters:

M **BH mass**

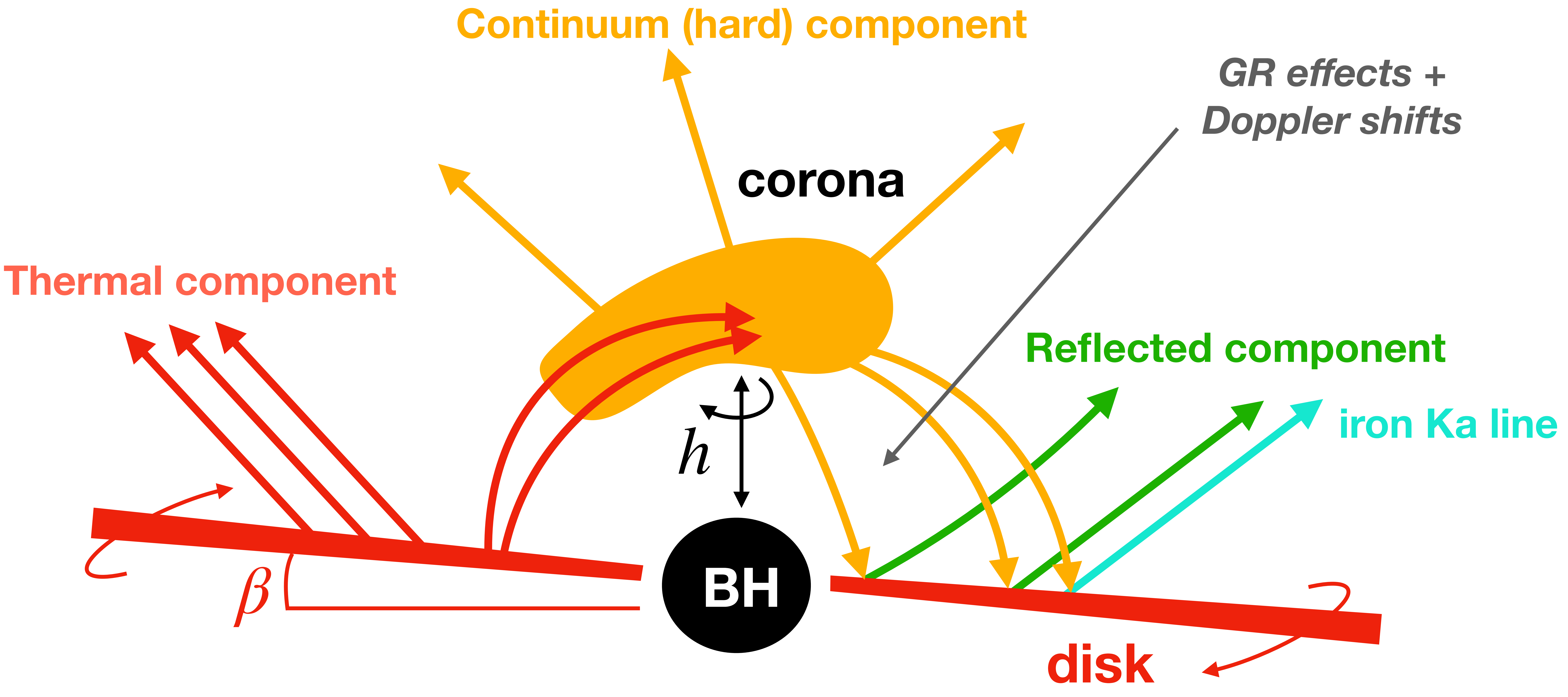
D **distance to source**

ι **disk inclination to us**

...

[McClintok+, 1303.1583]

Method 2: X-ray reflection



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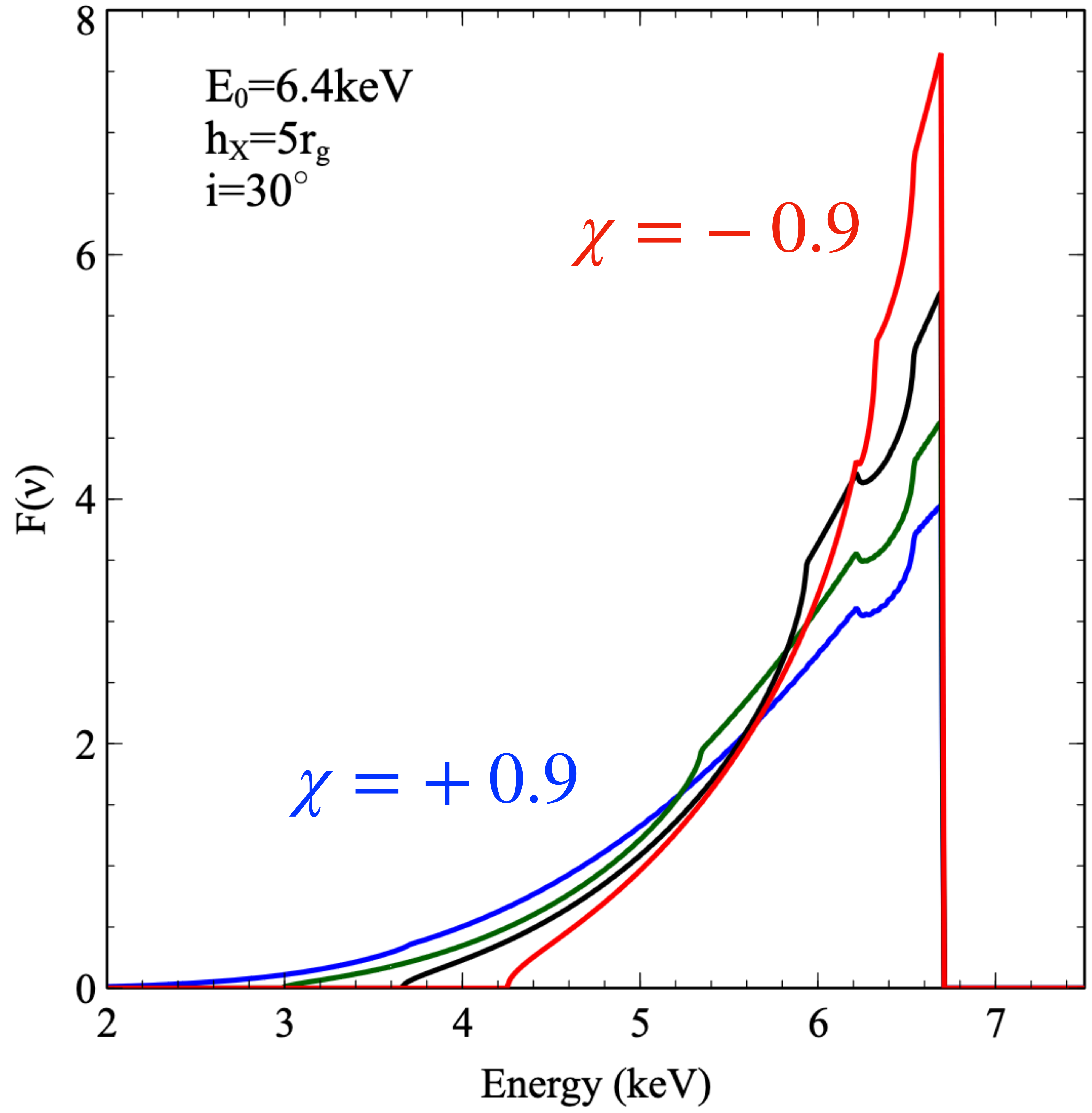
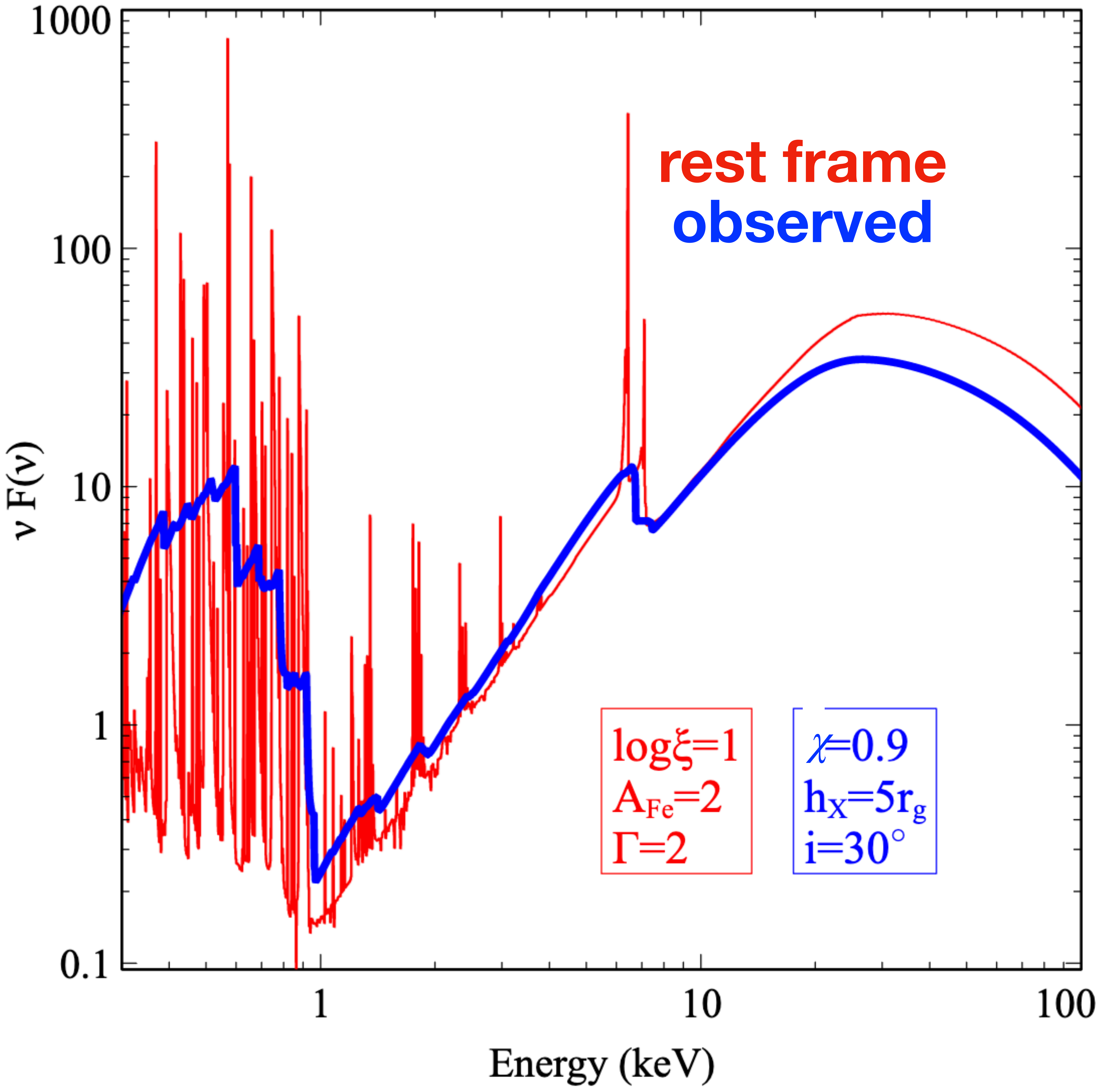
Method (2): X-ray reflection (iron Ka line)





[Reynolds, 2020]

CF

- Measures the **physical** $R_{\mathrm{ISCO}} = GMf(\chi)$
- Needs a measure of BH mass to infer spin **
- Needs external measurements of D, ι
- Reliable and understood
- Non-equatorial disk? Sub-ISCO emission?
- Applied only to XRB so far: $M \sim 10M_{\odot}$

Iron Ka

- Measures the **dimensionless** $\frac{R_{\mathrm{ISCO}}}{R_{\mathrm{g}}} = f(\chi)$
- Infers spin directly
- Geometry treated as nuisance/sanity check
- Uncertainties on geometry/plunging region
- Non-equatorial disk? Sub-ISCO reflection?
- Applicable to wide range of BHs: XRB & AGN

** M measured dynamically (enclosed mass),

e.g. via Kepler's 3rd law with donor star

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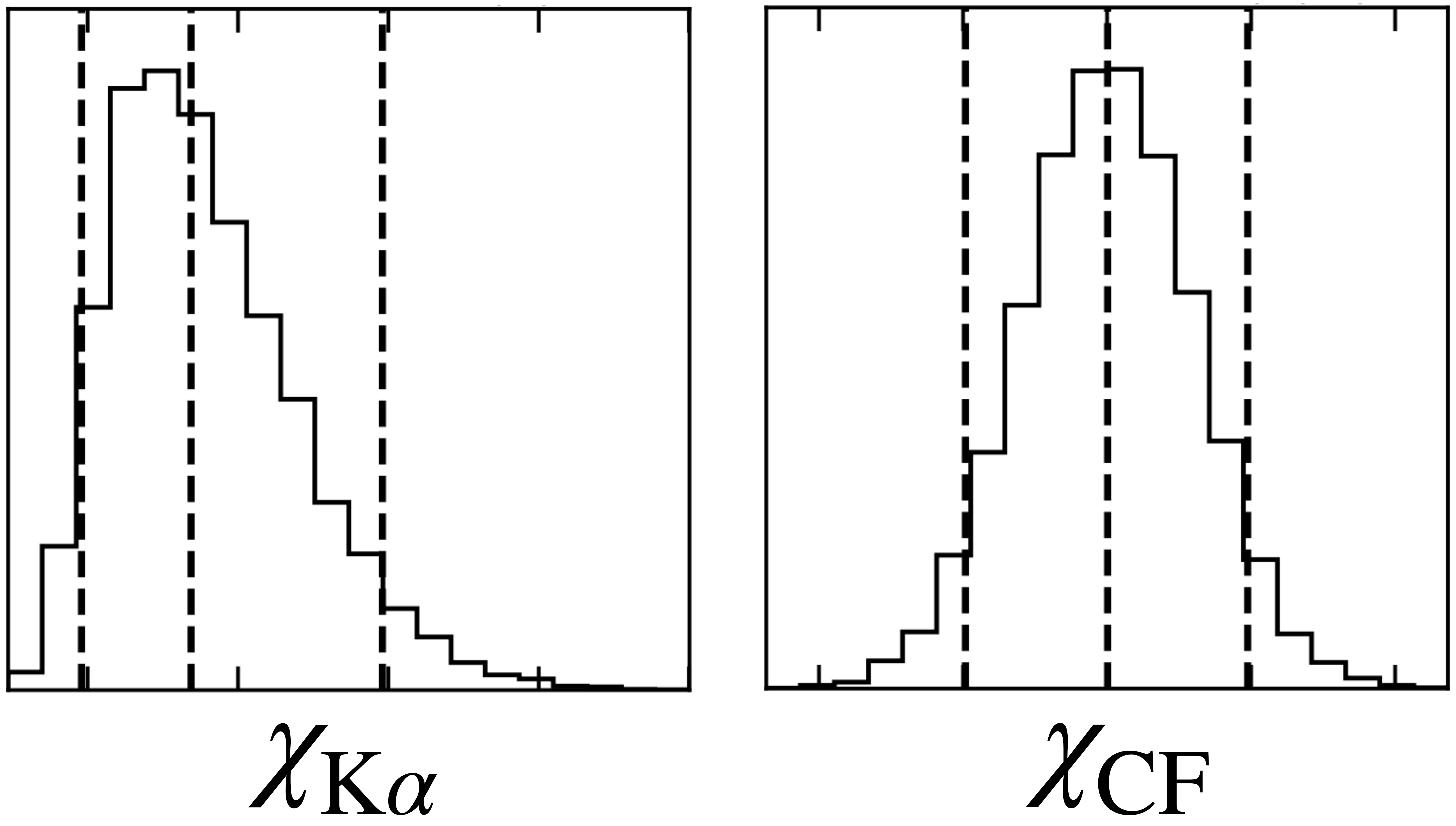
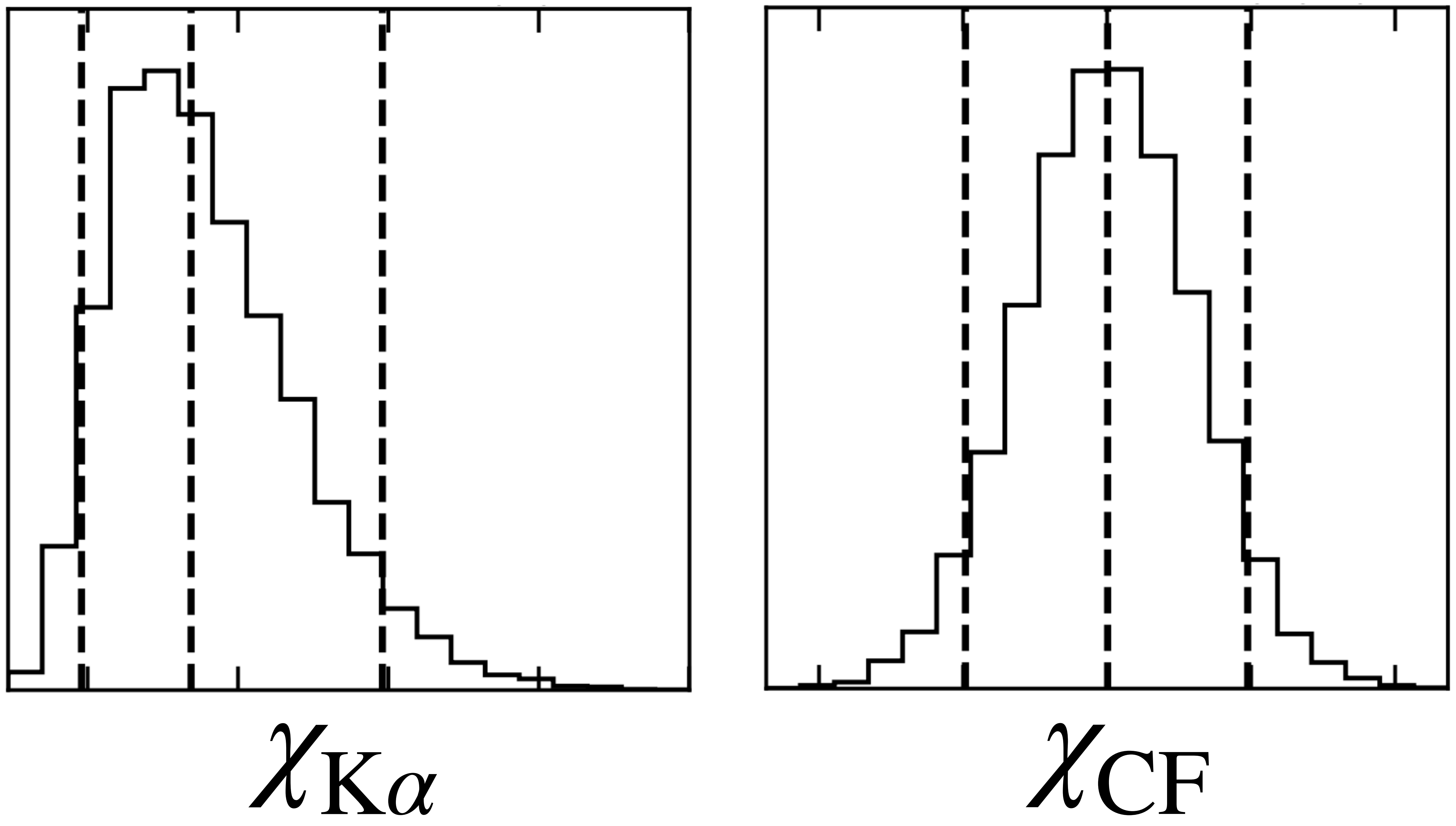
Weighing (fractional) dark mass



Weighing (fractional) dark mass

$$M_{\rm dyn} = M + M_d$$

$$\begin{aligned} R_{\rm ISCO} &= (M + M_d) f(\chi_{\rm CF}) \\ &= M f(\chi_{{\rm K}\alpha}) \end{aligned}$$

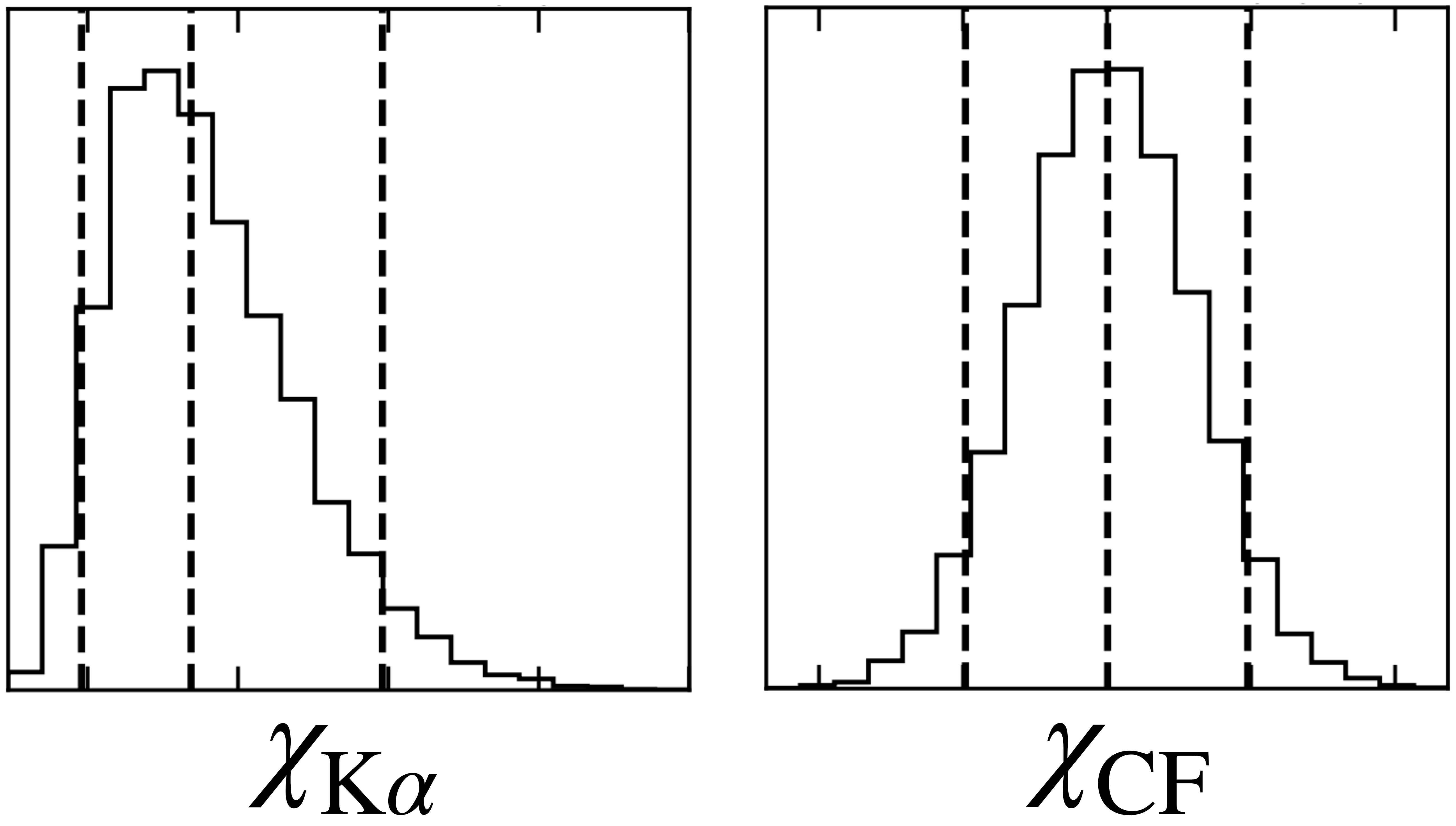


Weighing (fractional) dark mass

$$M_{\mathrm{dyn}} = M + M_d$$

$$R_{\mathrm{ISCO}} = (M + M_d) f(\chi_{\mathrm{CF}}) = M f(\chi_{\mathrm{K}\alpha})$$

$$\zeta = \frac{M_d}{M} = \frac{f(\chi_{\mathrm{K}\alpha})}{f(\chi_{\mathrm{CF}})} - 1$$



Dark mass only if

$$\chi_{\mathrm{K}\alpha} < \chi_{\mathrm{CF}}$$

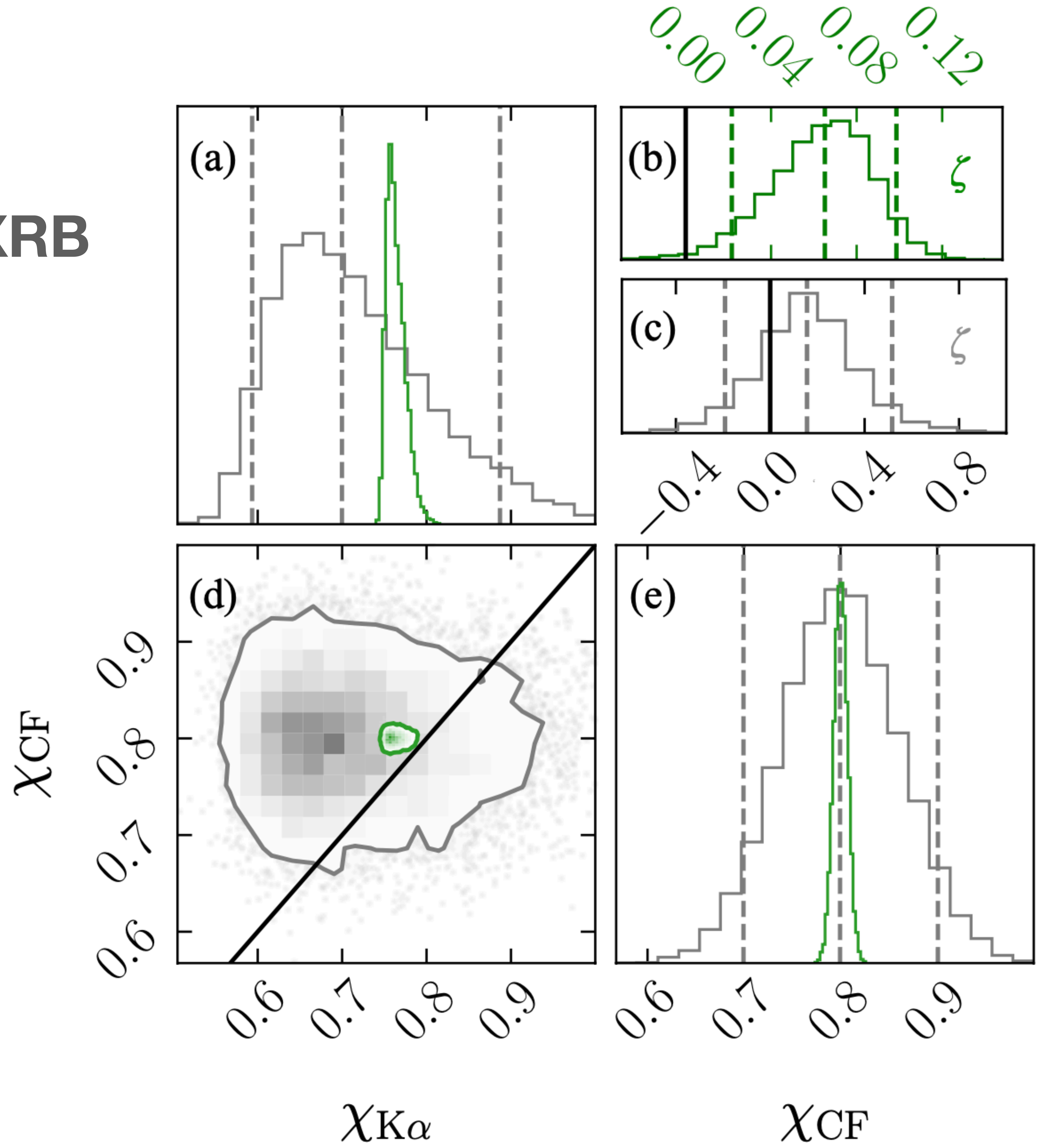
Example inspired by 4U 1543-475 XRB

$$\zeta = \frac{M_d}{M} = \frac{f(\chi_{K\alpha})}{f(\chi_{CF})} - 1$$

Actual distributions & errors

Errors reduced by factor 10

[Khalaf, Kuflik, AL, Stone 2408.16051]



Dark mass around BHs: superradiance

Consider an ultralight scalar field of mass μ

$$\lambda_{\mathrm{C}} \sim \frac{1}{\mu} \sim R_{\mathrm{g}} = GM$$

fine structure constant

$$\alpha \equiv \mu R_{\mathrm{g}} \sim \mathcal{O}(0.1)$$

we use the non-relativistic approximation, $\alpha < 1$

Dark mass around BHs: superradiance

Far away from the BH, the field eq. of motion is the Schrödinger eq.

$$\frac{\partial}{\partial t}\psi = \left[-\frac{\nabla^2}{2\mu} - \frac{\alpha}{r}\right]\psi$$

bound solutions are the hydrogen-like eigenstates

$$\psi = \sum_{n\ell m} c_{n\ell m}\psi_{n\ell m}$$

Dark mass around BHs: superradiance

But a BH is not a proton! Ingoing boundary conditions at the horizon impose

$$\omega_{n\ell m} = E_{n\ell m} + i\Gamma_{n\ell m}$$

instability rate

$\Gamma_{n\ell m} < 0$ usually but if

$$0 < \omega \leq m\boxed{\Omega_{+}(\alpha,\chi)}$$

Outer horizon angular velocity

Then we have superradiance (SR), i.e. $\Gamma_{n\ell m} > 0$
and a boson cloud forms at the expense of the BH mass and spin

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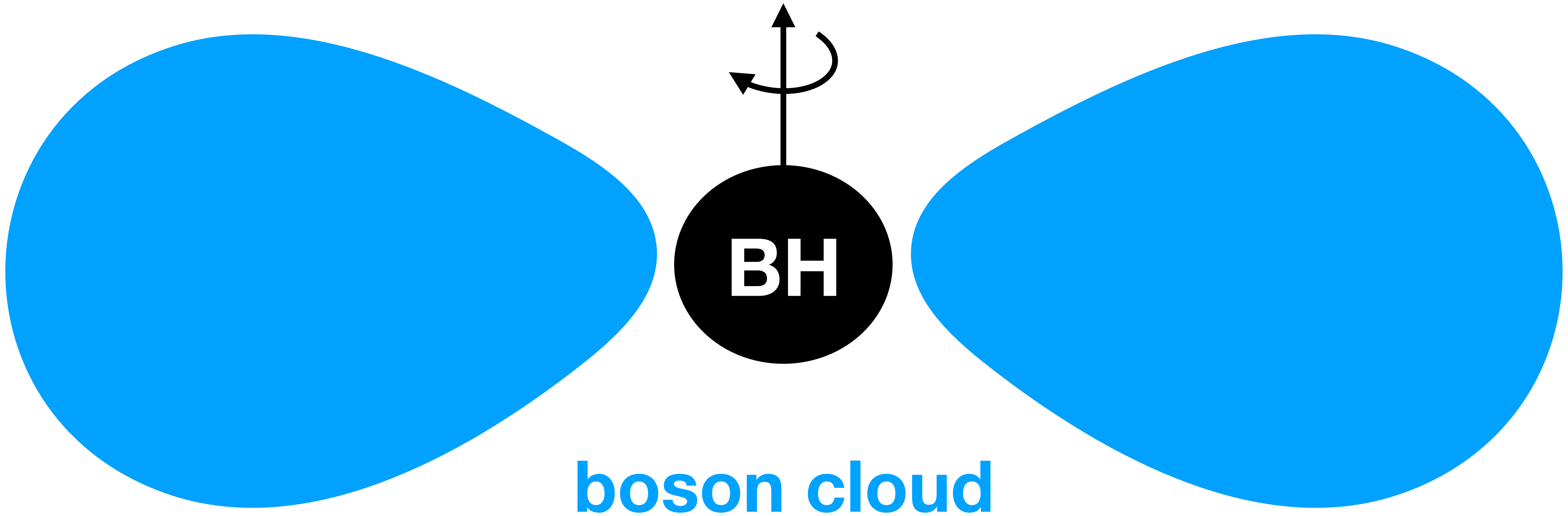
Dark mass around BHs: superradiance

The larger SR rate happens for $|n\ell m\rangle = |m+1, m, m\rangle$

SR stops when "saturation" is reached $\omega = m\Omega_+(\alpha, \chi)$

$$\chi_m = \frac{\alpha_m/m}{\alpha_m^2/m^2 + 1/4}$$

$M_c \lesssim 0.1M$



boson cloud

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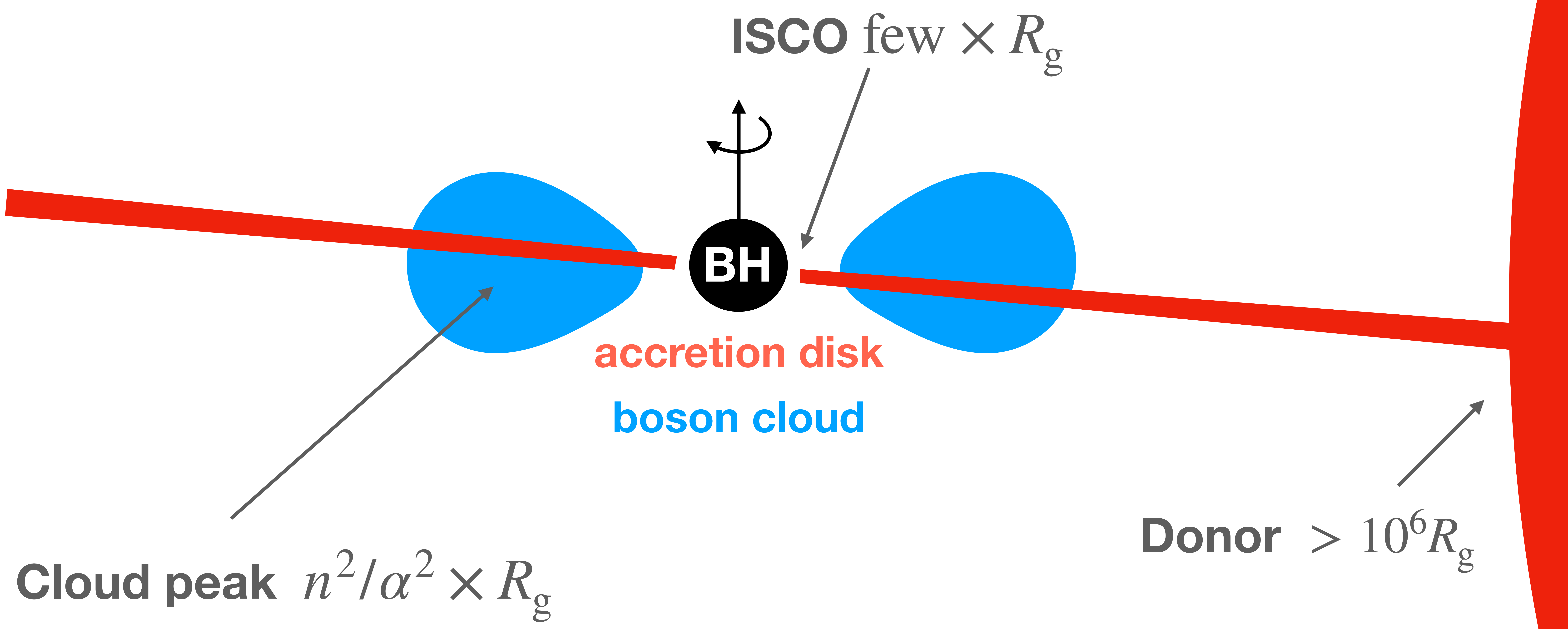
Geometry BH+cloud+donor+accretion disk



Cloud evolution for different boson masses

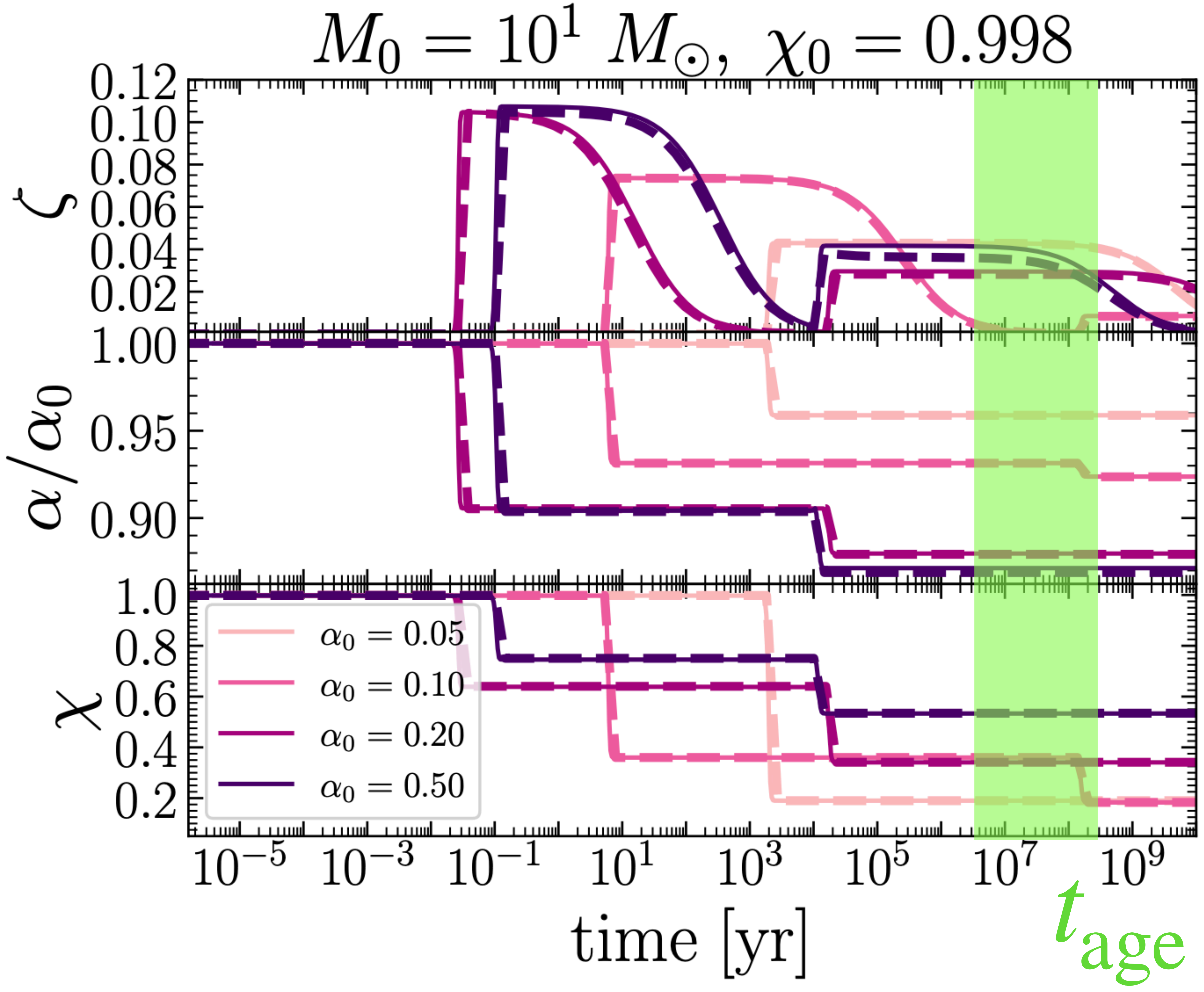
$$\dot{N}_i = \Gamma_i N_i - 2\Gamma_i^{\mathrm{GW}} N_i^2,$$

$$\dot{M} = -\sum_i E_i \Gamma_i N_i + \cancel{\dot{M}_{\mathrm{acc}}},$$

$$\dot{J} = -\sum_i m_i \Gamma_i N_i + \cancel{\dot{J}_{\mathrm{acc}}}\,.$$

boson cloud fractional mass

$$\zeta = \frac{M_c}{M} = \frac{\mu}{M}\sum_i N_i$$



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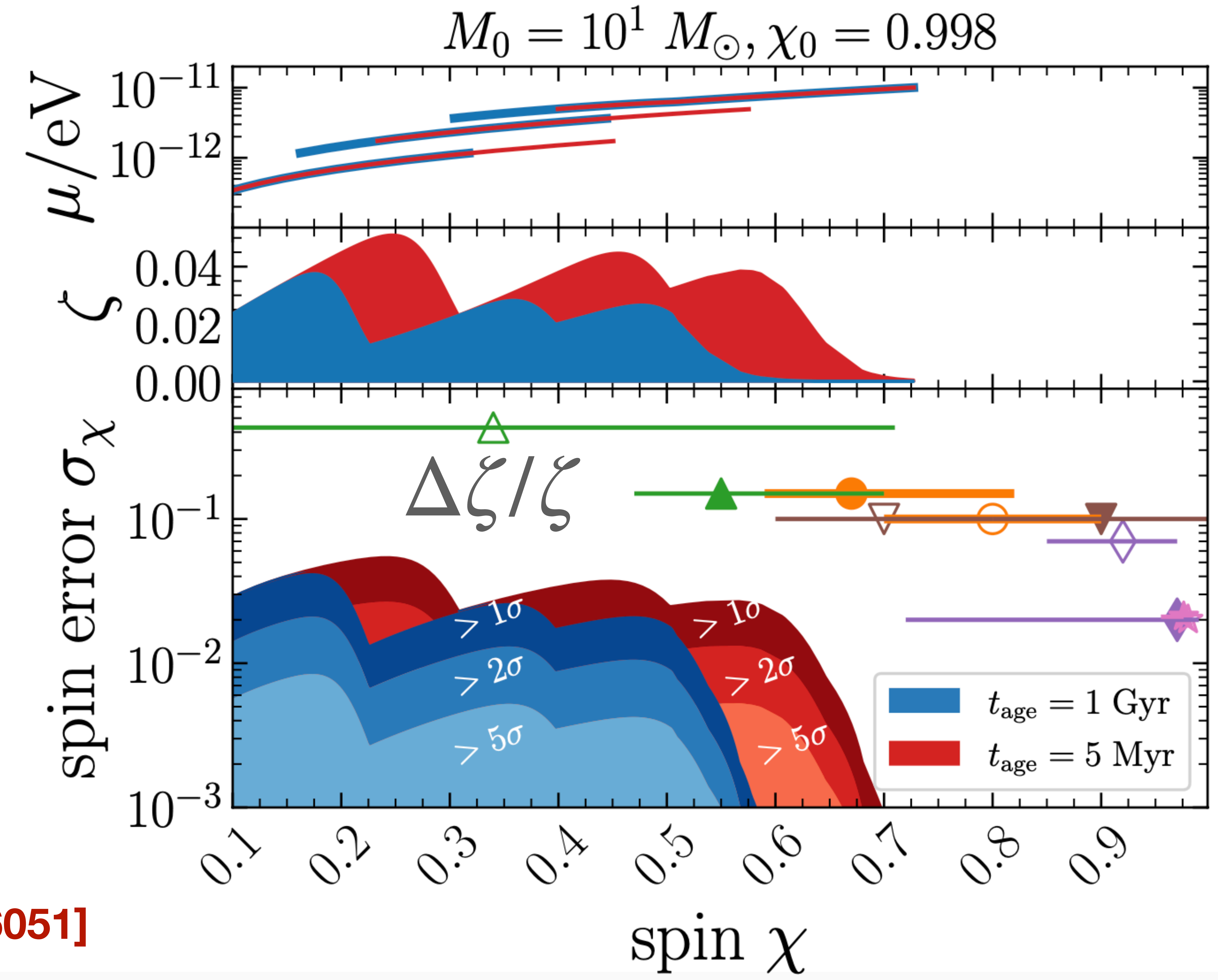
Solar mass BH.

Depending on M_{donor}:

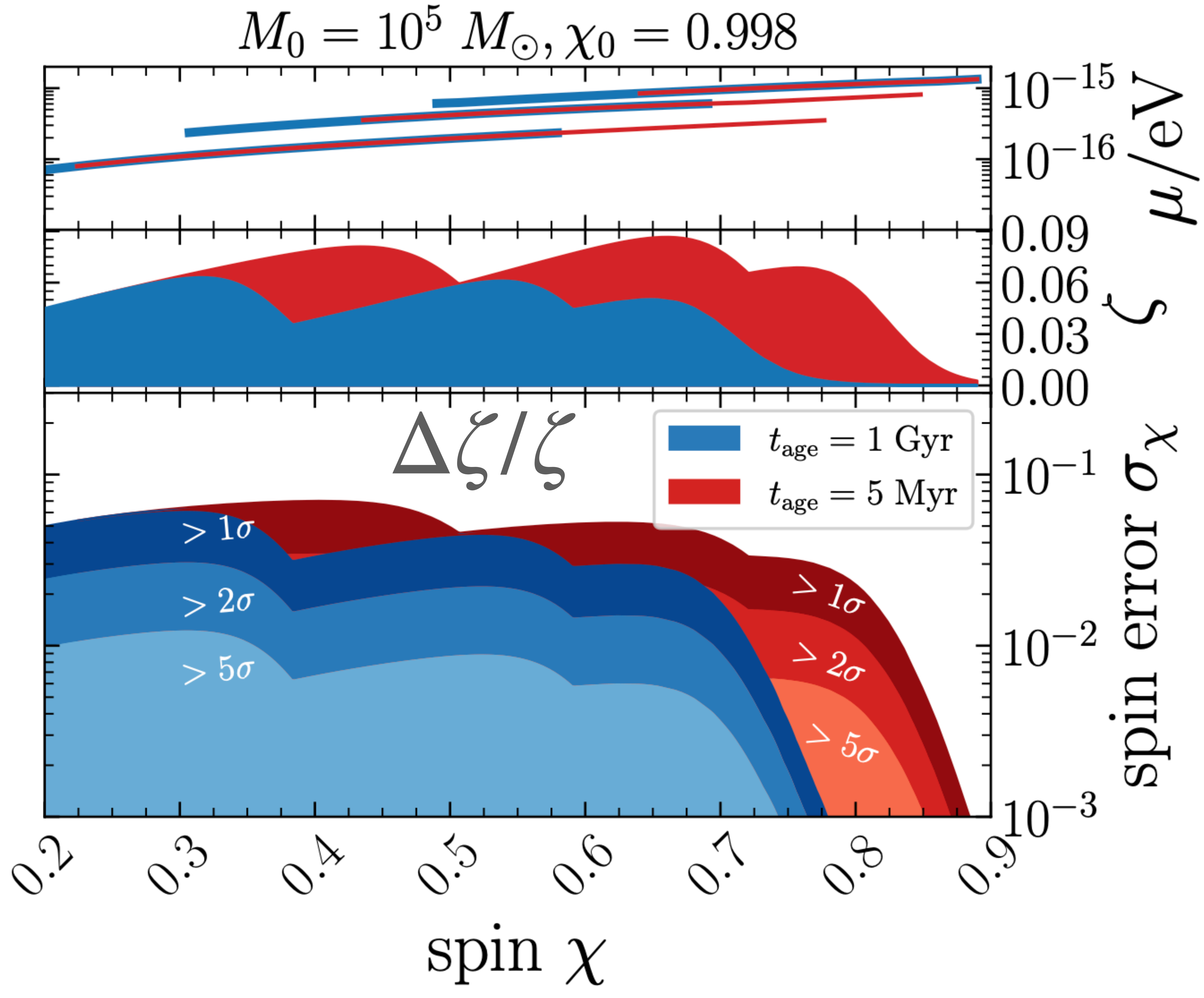
LXRB: old

HXRB: young



[Khalaf, Kuflik, AL, Stone 2408.16051]

Massive BH (IMBH),
old or young



[Khalaf, Kuflik, AL, Stone 2408.16051]

Conclusions

- In the future, spin measurements through **CF** and **iron Ka/reflection** might be used to infer **dark mass** $M_d \gtrsim \text{few} \times 0.01M$
- Scenario motivated in BH superradiance, depending on: **BH mass, boson mass** and **age of the system**
- Complementary **exclusion limits** for clouds around XRB $M \sim 10M_\odot$
- Massive BH (IMBHs?) may open a **direct discovery channel**

Conclusions

- In the future, spin measurements through **CF** and **iron Ka/reflection** might be used to infer **dark mass** $M_d \gtrsim \text{few} \times 0.01M$
- Scenario motivated in BH superradiance, depending on: **BH mass, boson mass** and **age of the system**
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& Outlook

- Bosons self-interactions? Vector bosons? Accretion-fueled SR?
- Other motivated scenarios? DM spikes?

Thank you!

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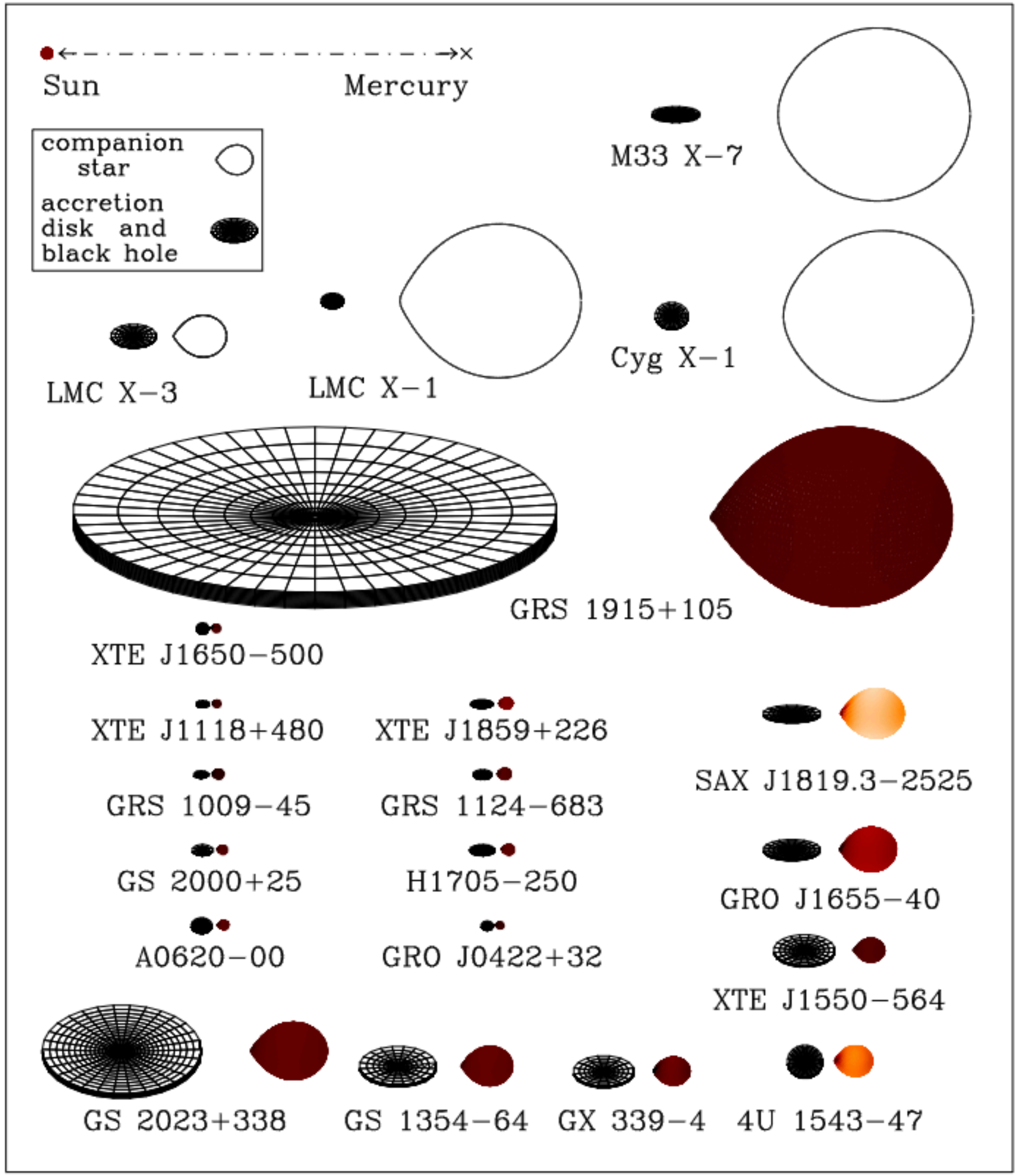
Backup

System	Age [Gyr]	Ref	χ Kα	ι [deg]	Ref	χ CF	$M_{\rm dyn}$ [$M_\odot$]	ι [deg]	D [kpc]	Ref
LMC X-1	0.005	[70]	$0.97^{+0.02}_{-0.25}$	fixed	[71]	$0.92^{+0.05}_{-0.07}$	10.91 ± 1.54	36.38 ± 2.02	48.10 ± 2.22	[72]
4U 1543-475	$0.1 - 0.5$	[73]	$0.67^{+0.15}_{-0.08}$	$36.3^{+5.3}_{-3.4}$	[74]	0.8 ± 0.1	9.4 ± 0.1	20.7 ± 1.5	7.5 ± 1.0	[75]
XTE J1550-564	$4.0 - 13.5$	[73]	$0.55^{+0.15}_{-0.22}$	$75 - 82$	[76]	$0.34^{+0.37}_{-0.43}$	9.10 ± 0.61	74.7 ± 3.8	$4.38^{+0.58}_{-0.41}$	[76]
GRO J1655-40	$0.2 - 0.6$	[73]	> 0.9	30^{+5}_{-10}	[77]	0.7 ± 0.1	6.30 ± 0.27	70.2 ± 1.2	3.2 ± 0.2[a]	[75]
GRS1915+105	$0.1 - 0.9$	[73]	$0.976_{-0.021}$	$67.1^{+1.9}_{-1.1}$	[79]	> 0.98	14.0 ± 4.4	66 ± 2	11.2 ± 0.8	[80]

[a] However, it has been argued in [78] that $D \lesssim 2$ kpc, driving $\chi_{\rm CF} \sim 0.91$, in agreement with the Kα method.

To have a look at the errors…

Backup


Sun
Mercury
companion star
accretion disk and black hole
M33 X−7
LMC X−3
LMC X−1
Cyg X−1
GRS 1915+105
XTE J1650−500
XTE J1118+480
XTE J1859+226
SAX J1819.3−2525
GRS 1009−45
GRS 1124−683
GS 2000+25
H1705−250
GRO J1655−40
A0620−00
GRO J0422+32
XTE J1550−564
GS 2023+338
GS 1354−64
GX 339−4
4U 1543−47