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Black-hole spins as gravitational and cosmological probes

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Outline

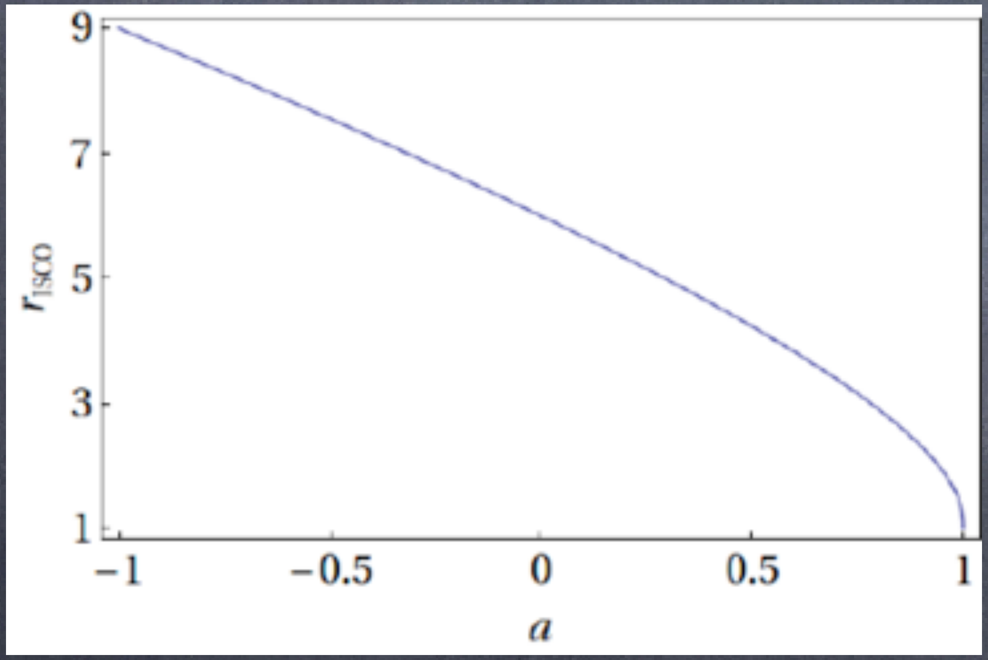
- Why bother about BH spins? (in gravity & cosmology)
  - BH spins probe strong field gravity (frame dragging, Bardeen-Petterson effect, precession & GW modulation...)
  - Massive BH spins trace galaxy evolution (accretion, mergers, jets ...)
- The cosmological evolution of the spins of massive BHs: electromagnetic vs GW observations

BHs: the relativist's vs astrophysicist's view

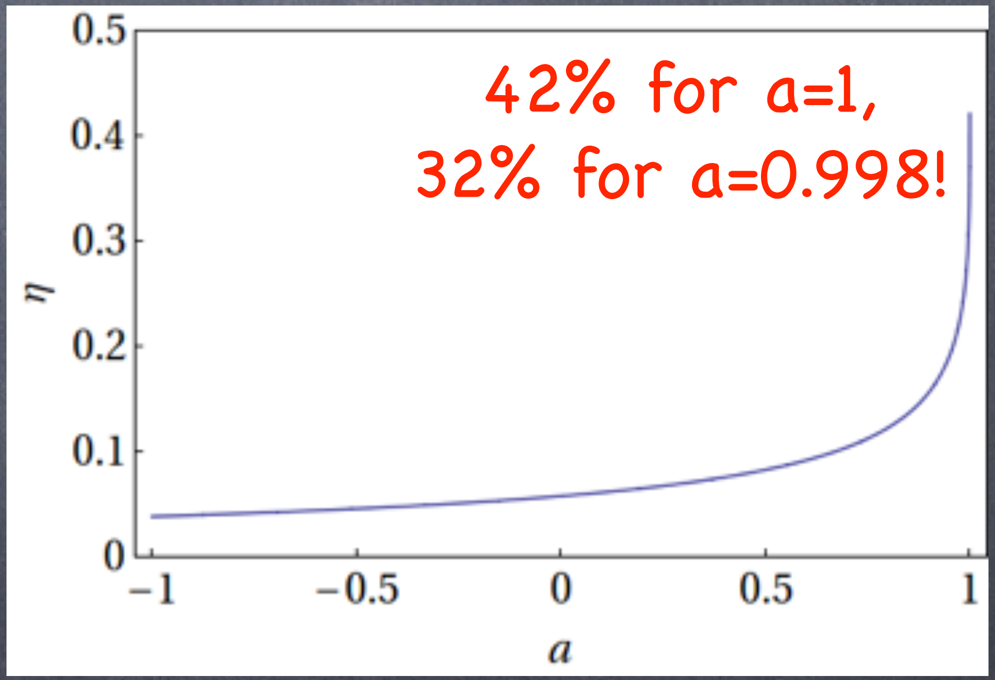
- A vacuum solution to the field equations that is regular outside an event horizon (located at $R \sim GM/c^2$)
- In GR, characterized by mass M, electric charge Q (= 0 astrophysically) and spin $S=a\,GM^2/c$ (with $-1 \le a \le 1$)...
- ... but more exotic charges present if gravity not described by GR (cf tests of GR with GWs, eg EMRIs)

The effect of BH spins: frame-dragging in isolated BHs

- Mass behaves qualitatively like in Newtonian gravity
- Spin affects motion around BHs (“frame dragging”):



Innermost Stable Circular Orbit
(i.e. inner edge of thin disks)

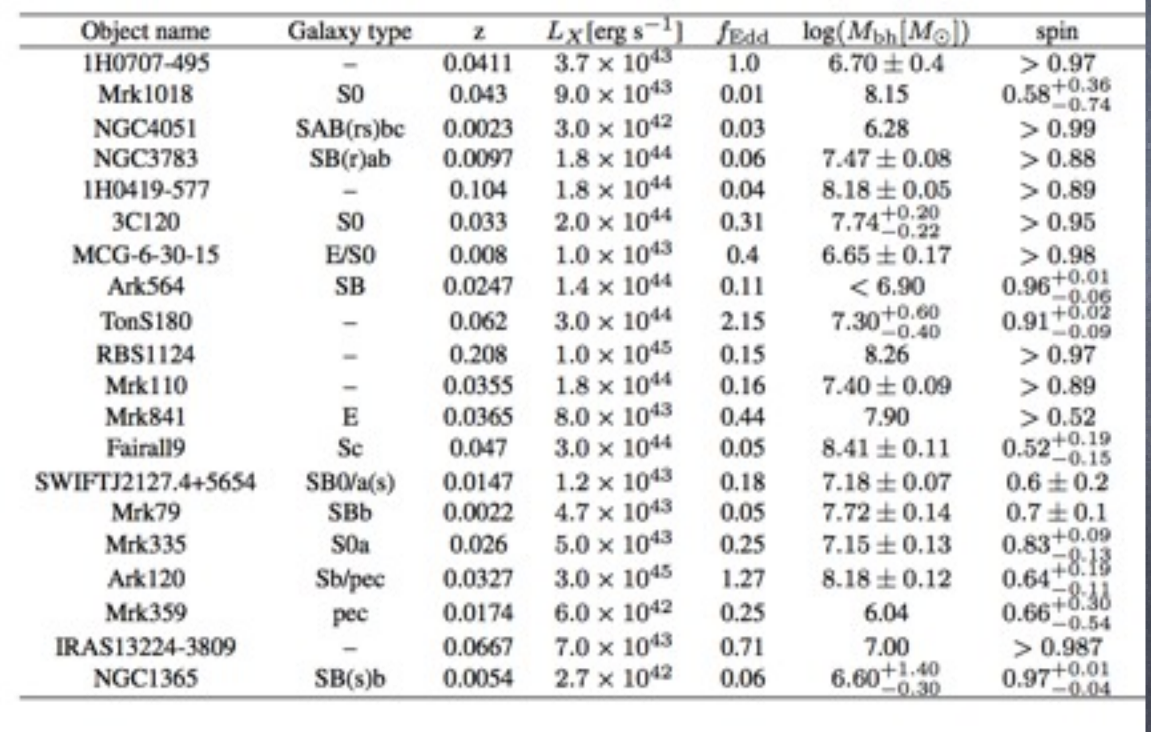


42% for a=1,
32% for a=0.998!

Efficiency of EM
emission from thin disks

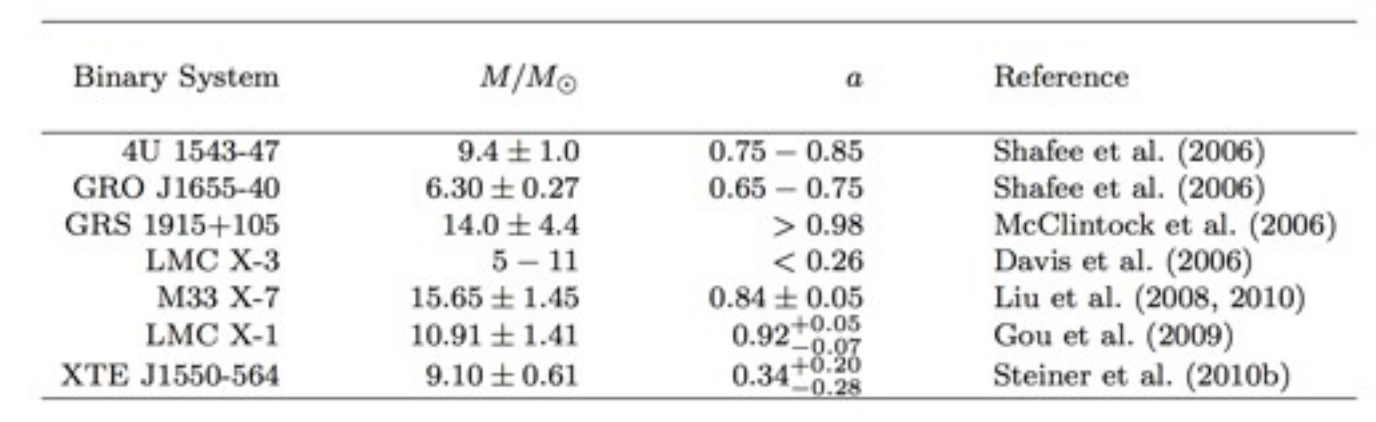
The effect of BH spins: frame-dragging in isolated BHs

- Effects are testable with electromagnetic observations
- Continuum fitting (micro-quasars only) and relativistic iron lines (both AGNs and micro-quasars)



Object name	Galaxy type	z	L_X[erg s^{-1}]	$f_{\rm Edd}$	$\log(M_{\rm bh}[M_\odot])$	spin
1H0707-495	–	0.0411	3.7×10^{43}	1.0	6.70 ± 0.4	> 0.97
Mrk1018	S0	0.043	9.0×10^{43}	0.01	8.15	$0.58^{+0.36}_{-0.74}$
NGC4051	SAB(rs)bc	0.0023	3.0×10^{42}	0.03	6.28	> 0.99
NGC3783	SB(r)ab	0.0097	1.8×10^{44}	0.06	7.47 ± 0.08	> 0.88
1H0419-577	–	0.104	1.8×10^{44}	0.04	8.18 ± 0.05	> 0.89
3C120	S0	0.033	2.0×10^{44}	0.31	$7.74^{+0.20}_{-0.22}$	> 0.95
MCG-6-30-15	E/S0	0.008	1.0×10^{43}	0.4	6.65 ± 0.17	> 0.98
Ark564	SB	0.0247	1.4×10^{44}	0.11	< 6.90	$0.96^{+0.01}_{-0.06}$
TonS180	–	0.062	3.0×10^{44}	2.15	$7.30^{+0.60}_{-0.40}$	$0.91^{+0.02}_{-0.09}$
RBS1124	–	0.208	1.0×10^{45}	0.15	8.26	> 0.97
Mrk110	–	0.0355	1.8×10^{44}	0.16	7.40 ± 0.09	> 0.89
Mrk841	E	0.0365	8.0×10^{43}	0.44	7.90	> 0.52
Fairall9	Sc	0.047	3.0×10^{44}	0.05	8.41 ± 0.11	$0.52^{+0.19}_{-0.15}$
SWIFTJ2127.4+5654	SB0/a(s)	0.0147	1.2×10^{43}	0.18	7.18 ± 0.07	0.6 ± 0.2
Mrk79	SBb	0.0022	4.7×10^{43}	0.05	7.72 ± 0.14	0.7 ± 0.1
Mrk335	S0a	0.026	5.0×10^{43}	0.25	7.15 ± 0.13	$0.83^{+0.09}_{-0.13}$
Ark120	Sb/pec	0.0327	3.0×10^{45}	1.27	8.18 ± 0.12	$0.64^{+0.19}_{-0.11}$
Mrk359	pec	0.0174	6.0×10^{42}	0.25	6.04	$0.66^{+0.30}_{-0.54}$
IRAS13224-3809	–	0.0667	7.0×10^{43}	0.71	7.00	> 0.987
NGC1365	SB(s)b	0.0054	2.7×10^{42}	0.06	$6.60^{+1.40}_{-0.30}$	$0.97^{+0.01}_{-0.04}$

Compilations (Reynolds, Brenneman,...) of massive BH spins

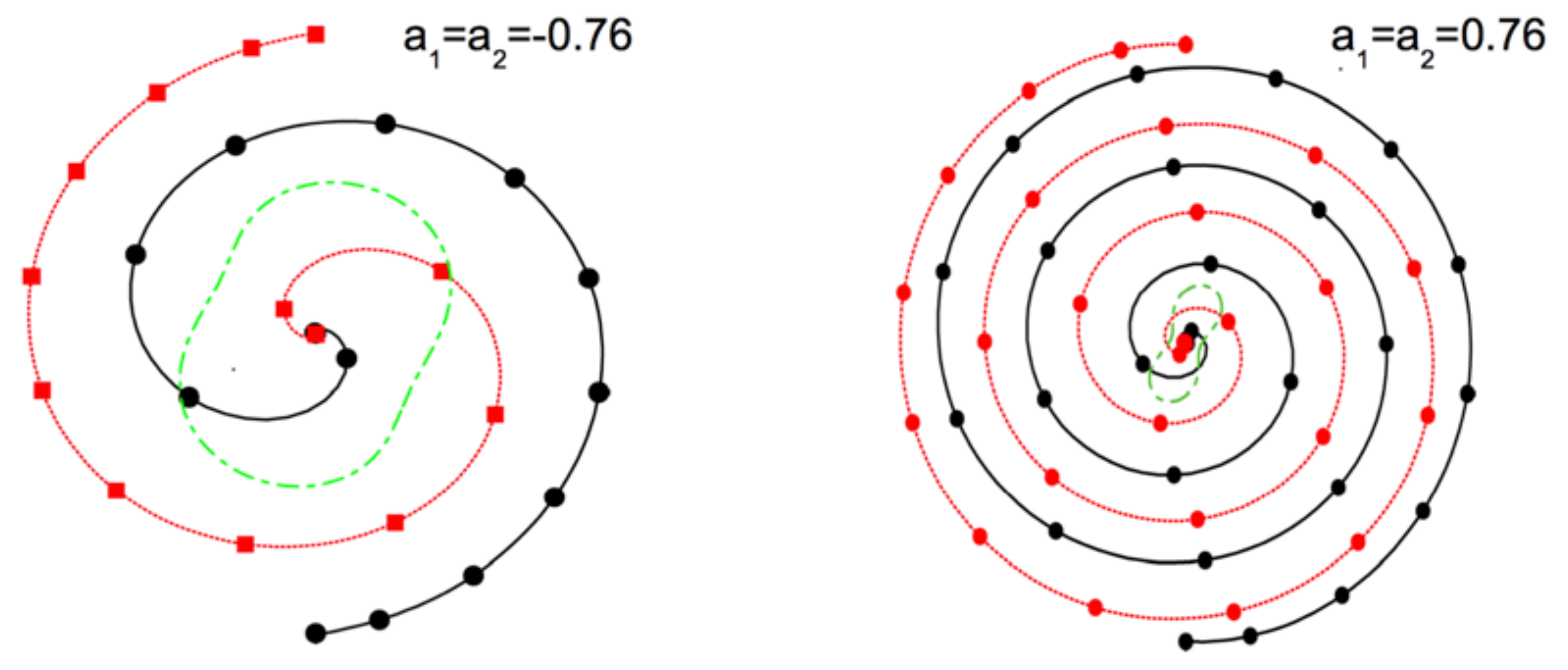


Binary System	$M/M_\odot$	a	Reference
4U 1543-47	9.4 ± 1.0	$0.75 - 0.85$	Shafee et al. (2006)
GRO J1655-40	6.30 ± 0.27	$0.65 - 0.75$	Shafee et al. (2006)
GRS 1915+105	14.0 ± 4.4	> 0.98	McClintock et al. (2006)
LMC X-3	$5 - 11$	< 0.26	Davis et al. (2006)
M33 X-7	15.65 ± 1.45	0.84 ± 0.05	Liu et al. (2008, 2010)
LMC X-1	10.91 ± 1.41	$0.92^{+0.05}_{-0.07}$	Gou et al. (2009)
XTE J1550-564	9.10 ± 0.61	$0.34^{+0.20}_{-0.28}$	Steiner et al. (2010b)

Stellar-mass BH spins

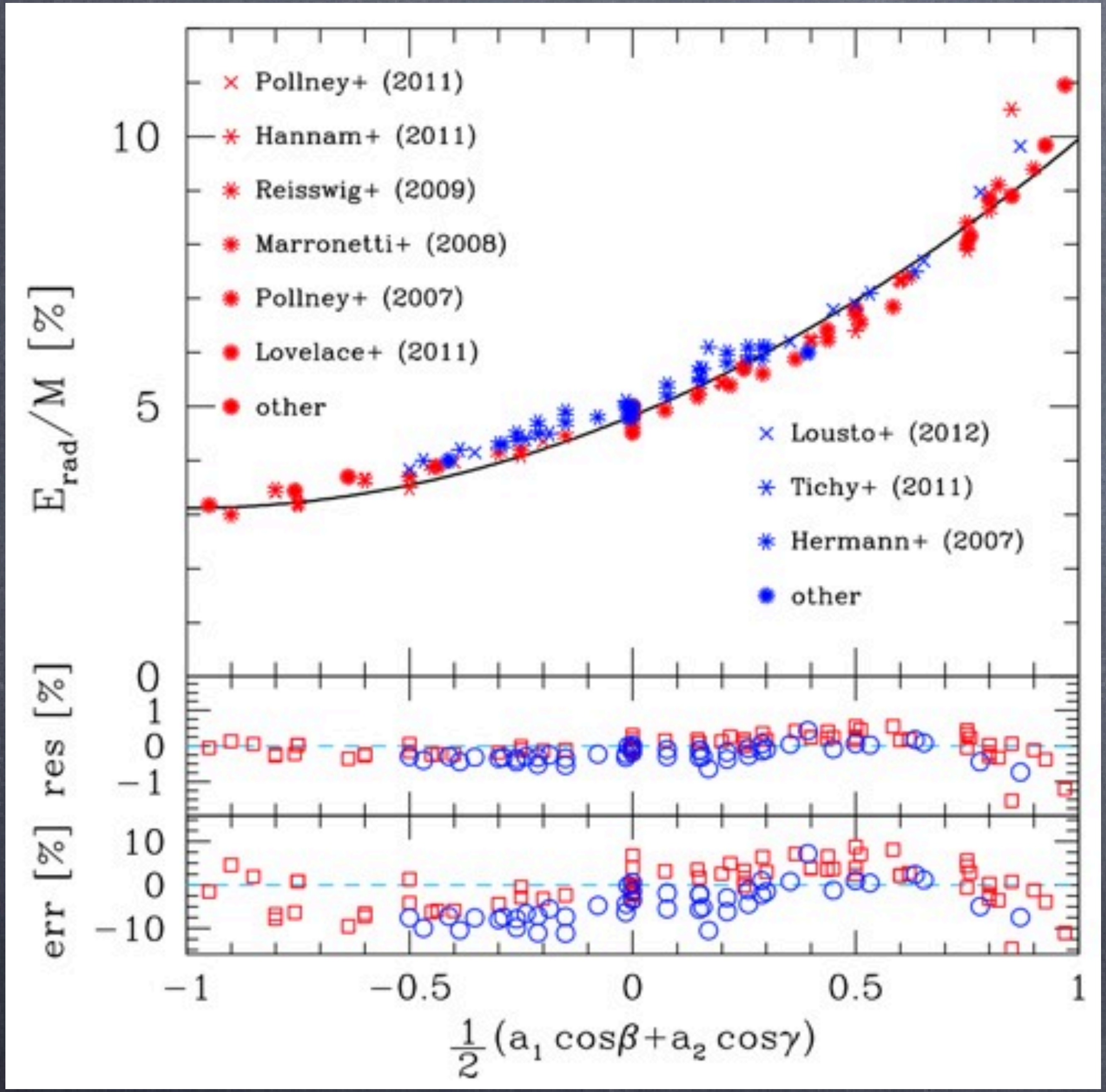
The effect of BH spins: frame-dragging in binaries

- Spin-orbit coupling or "hang-up" effect: for large spins aligned with L, effective ISCO moves inward ...



Figures from Lousto, Campanelli & Zlochower (2006)

The effect of BH spins: frame-dragging in binaries



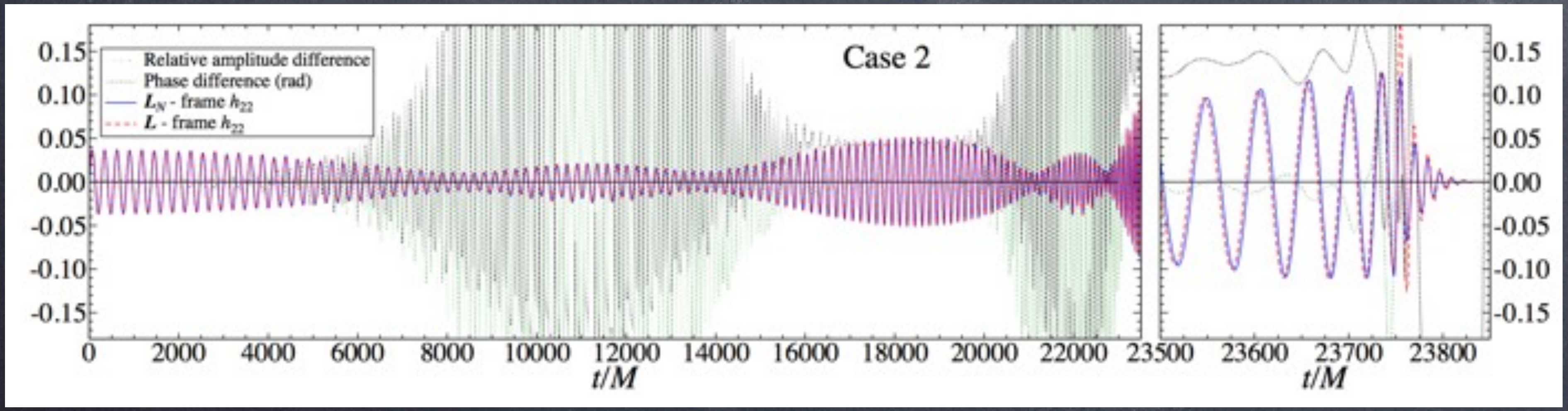
- … and GW "efficiency" gets larger

Testable with GWs!

Figure from EB, Morozova & Rezzolla (2012)

The effect of BH spins on the waveforms

- GW amplitude at merger increases with spins (because ISCO moves inward for larger spins)
- Spin precesses around total angular momentum $J=L+S_1+S_2$
- Precession-induced modulations observable with GW detectors:
  - increase SNR and improve measurements of binary parameters (e.g. luminosity distance and sky localization, cf eg Hughes, Lang & Cornish 2011)
  - Allow measurements of angle between spins (cf Vitale et al 2014 for Adv LIGO/Virgo)

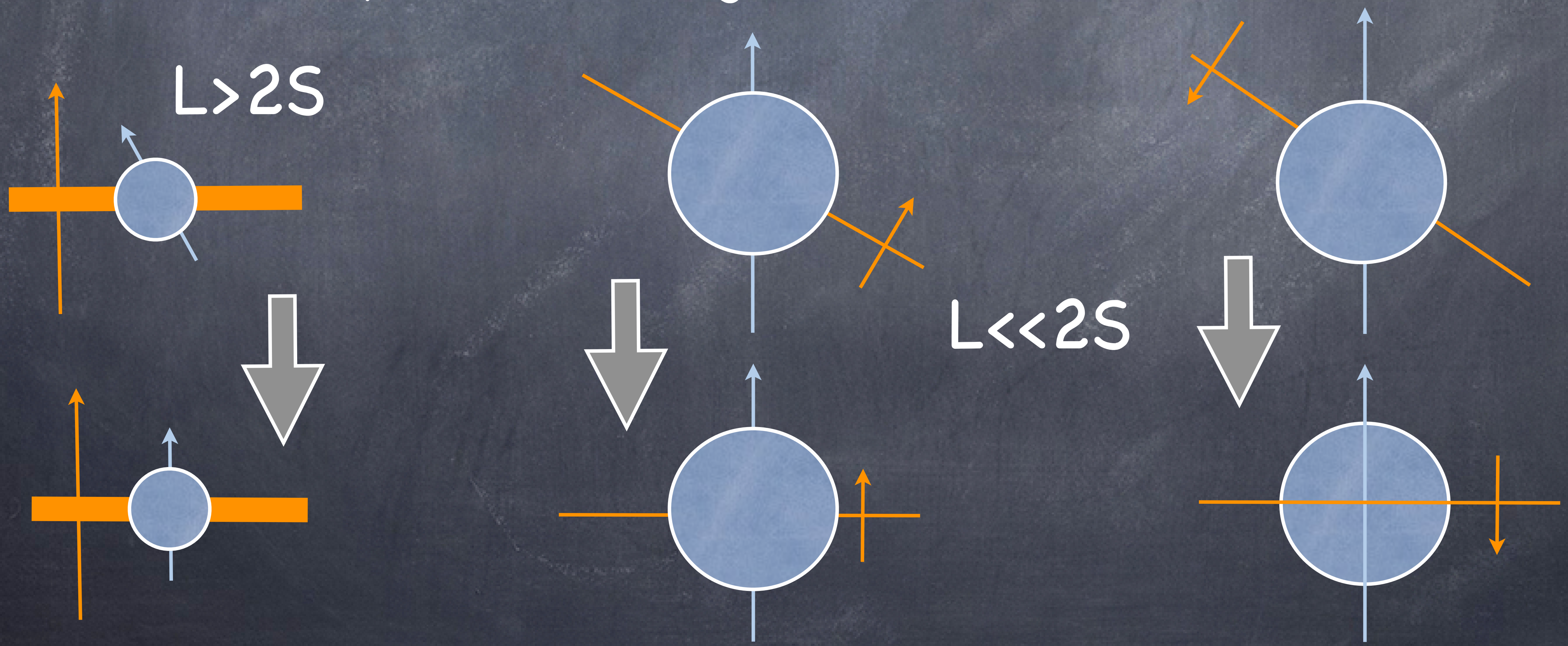


EOB waveforms for BH binary with mass ratio 1:6 and spins 0.6 and 0.8, from Pan et al (2013)

The Bardeen Petterson effect

(see also King, Pringle, Dotti, Volonteri, Perego, Colpi, ...)

- Coupling between BH spin S and angular momentum L of misaligned accretion disk + dissipation
- Either aligns or anti-aligns S and L in ~10^5 yrs (for MBHs) << accretion timescale
- Anti-alignment only if disk carries little angular momentum (L < 2S) and is initially counterrotating



The environment's influence on the evolution of BH spins

- Accretion (and spin!) depends on local supply of gas.

  For massive BHs, gas supply depends on galactic properties (e.g. morphology) & history (e.g. star formation, supernovae, AGN activity)

- In gas-rich environments, spins are aligned to disk's angular momentum by Bardeed Petterson effect.

  "Wet" mergers (aligned spins) vs "dry" mergers (isotropic spins, but partial alignment during PN inspiral, cf Schnittman, Berti, Kesden, Sperhake, ...)

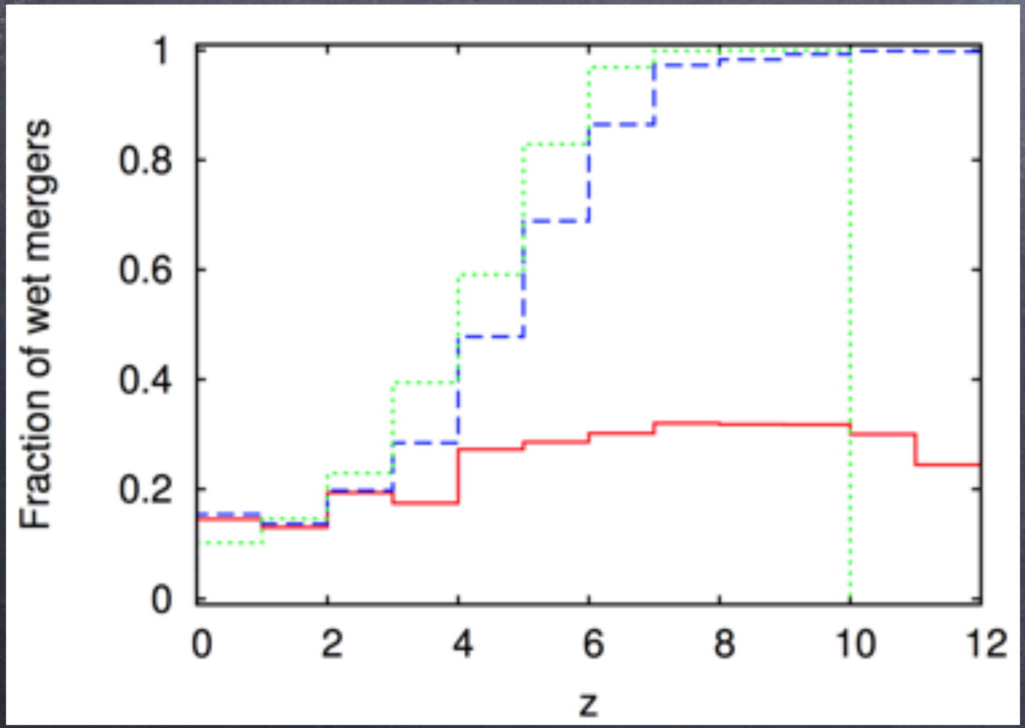
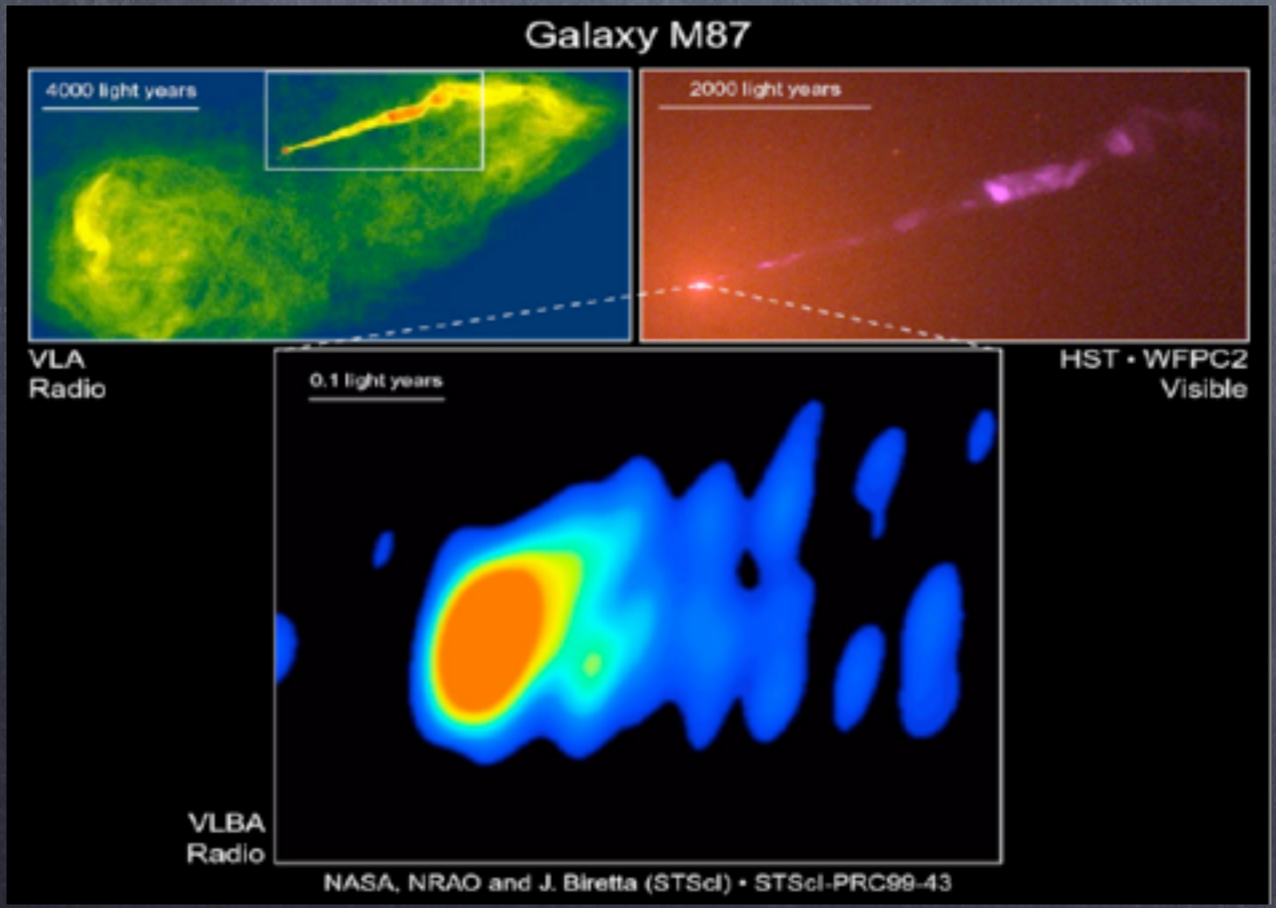


Figure from EB 2012
cf also work in progress by A. Klein

Feedback of the spins on the environment?

Massive BHs transfer energy to galaxy through jets (trigged by spin and/or binary motion + magnetic field) and quench star formation (AGN feedback)

- Surprising due to scales (BHs ~10^{-6} pc vs galaxy ~1-100s kpc)
- Invoked to explain "cosmic downsizing" (most massive galaxies, where strongest AGNs live, have older stars and weaker star formation than smaller galaxies)



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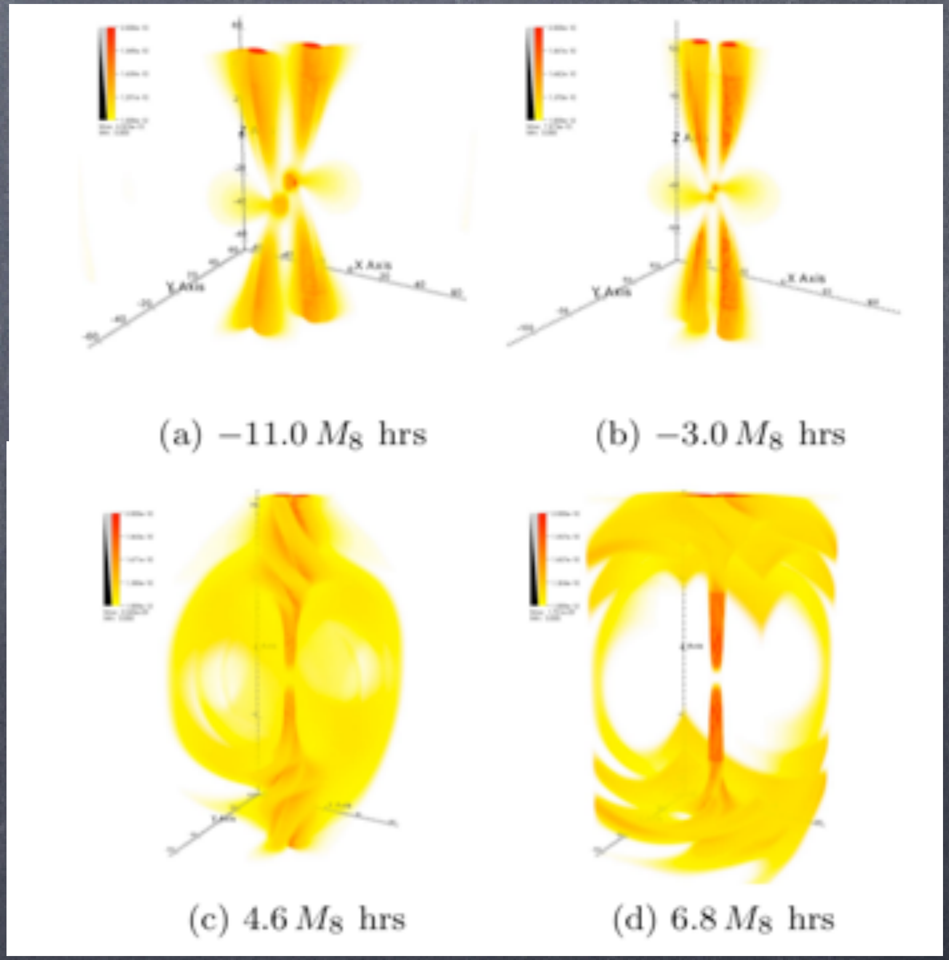
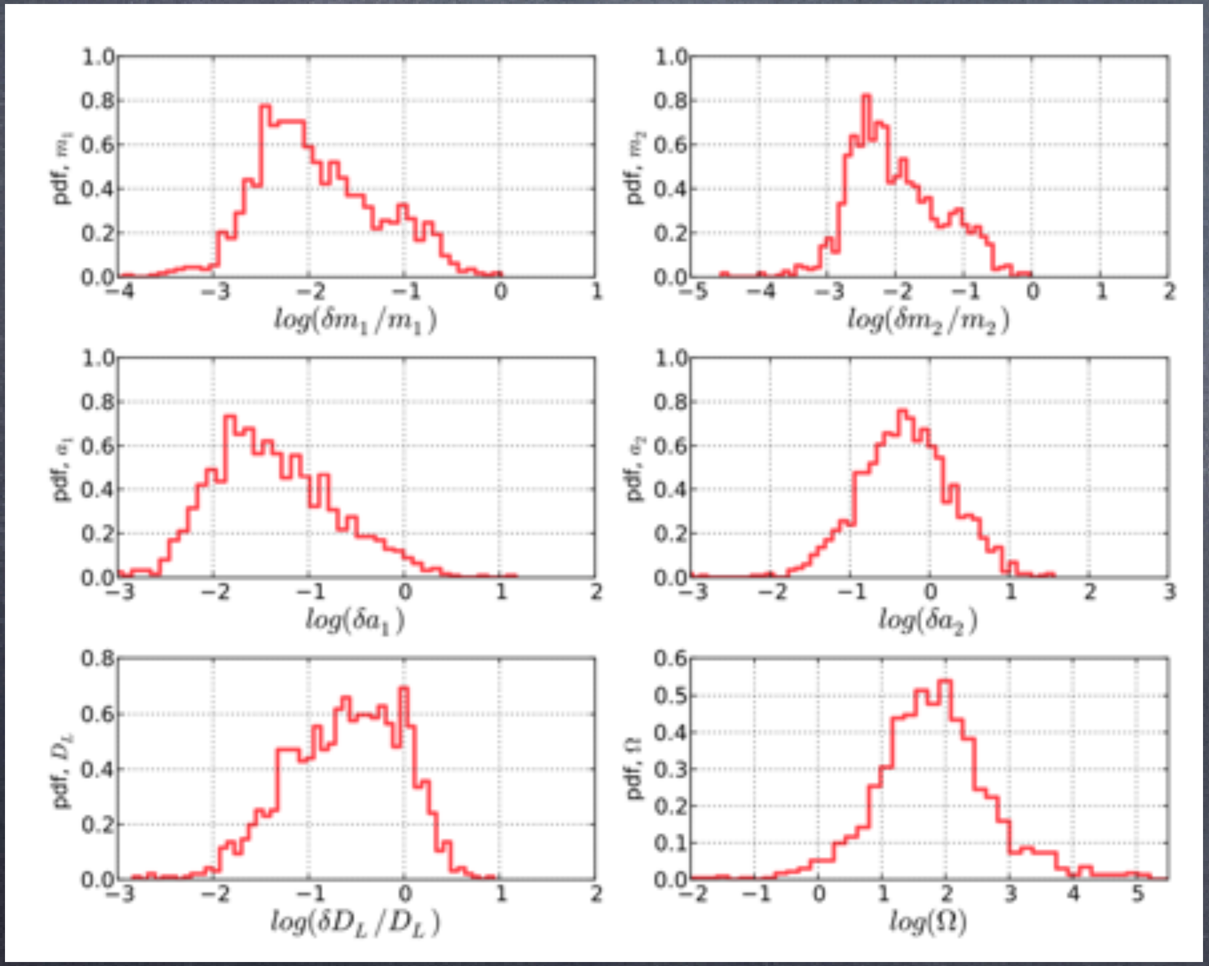

(a) $-11.0\,M_8$ hrs (b) $-3.0\,M_8$ hrs

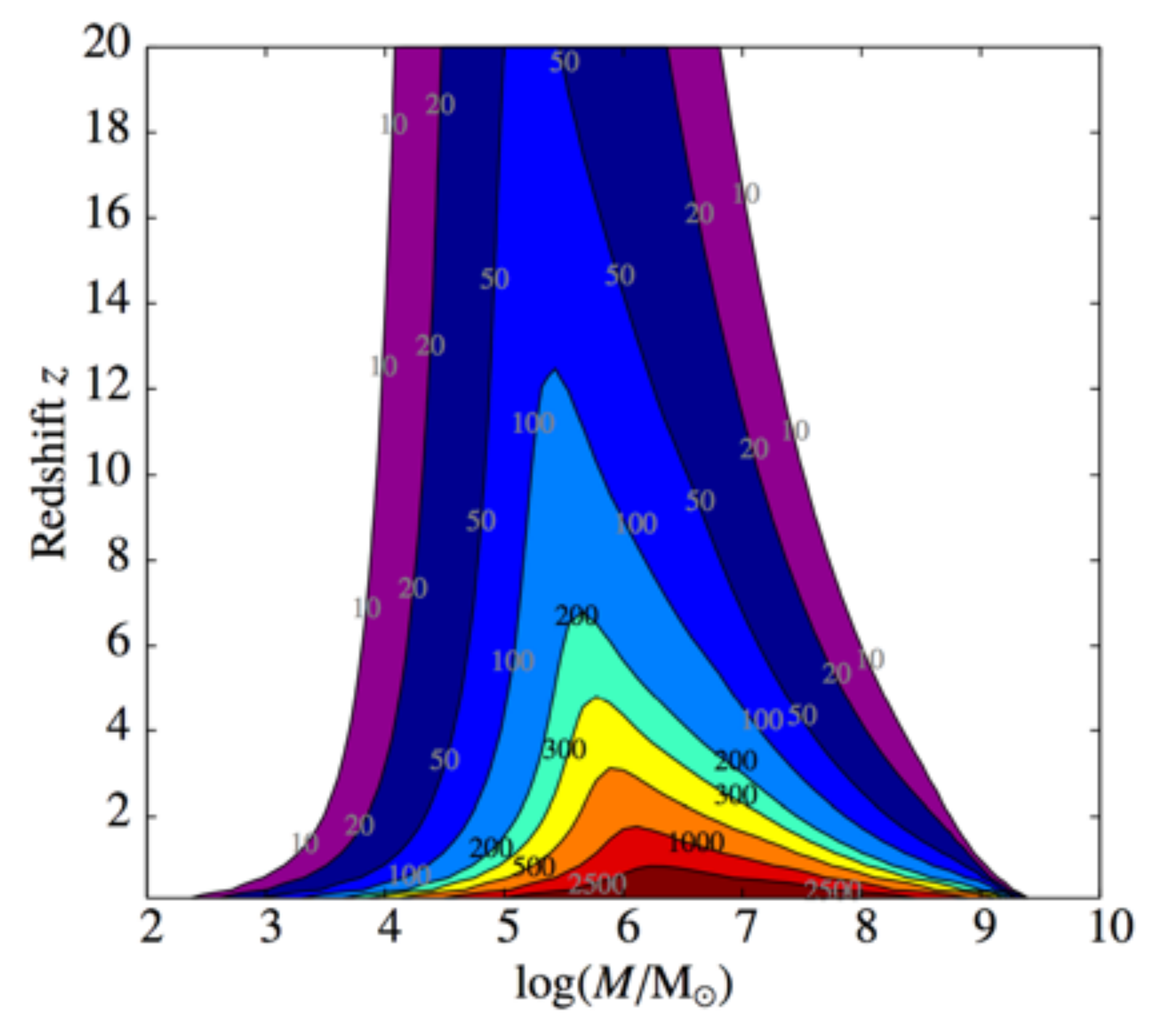
(c) $4.6\,M_8$ hrs (d) $6.8\,M_8$ hrs

simulation by Palenzuela, Lehner and Liebling 2010; cf also Blandford & Znajek (1977)

BH mass & spin measurements with eLISA

- Masses measured to within 0.1% for massive BHs up to high z
- Massive BH spins measured to within 0.01 - 0.1 (improvable with better waveforms)
- No redshift, poor sky localization if no EM counterparts



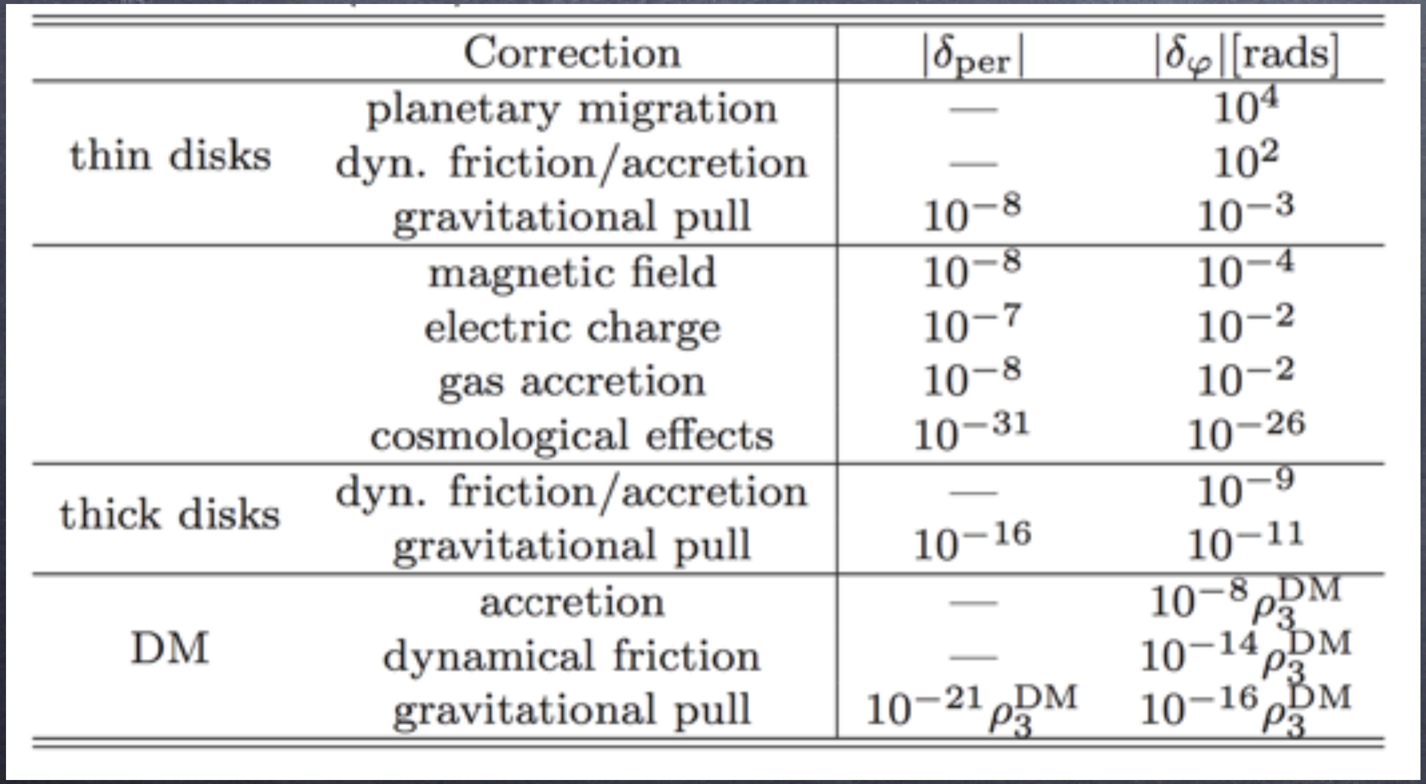


Figures from the eLISA science case

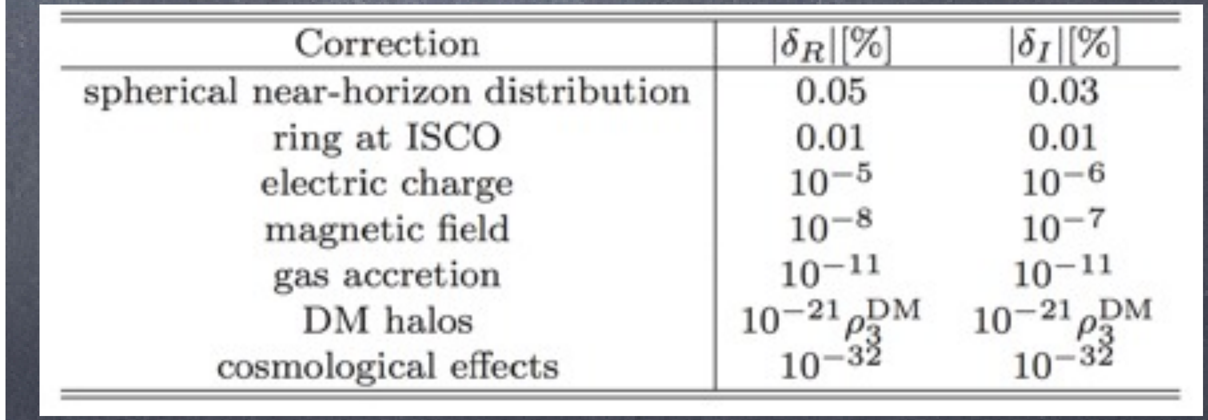
Environmental pollution on eLISA signals

- Evolution of BH masses and spins is driven by interaction with galactic environment on long (i.e. cosmological) timescales and large separations >> GM/c^2
- At small separation relevant for GW emission, environmental effects are typically negligible, except for a few % of EMRI population

GW measurements of BH masses and spin are clean!



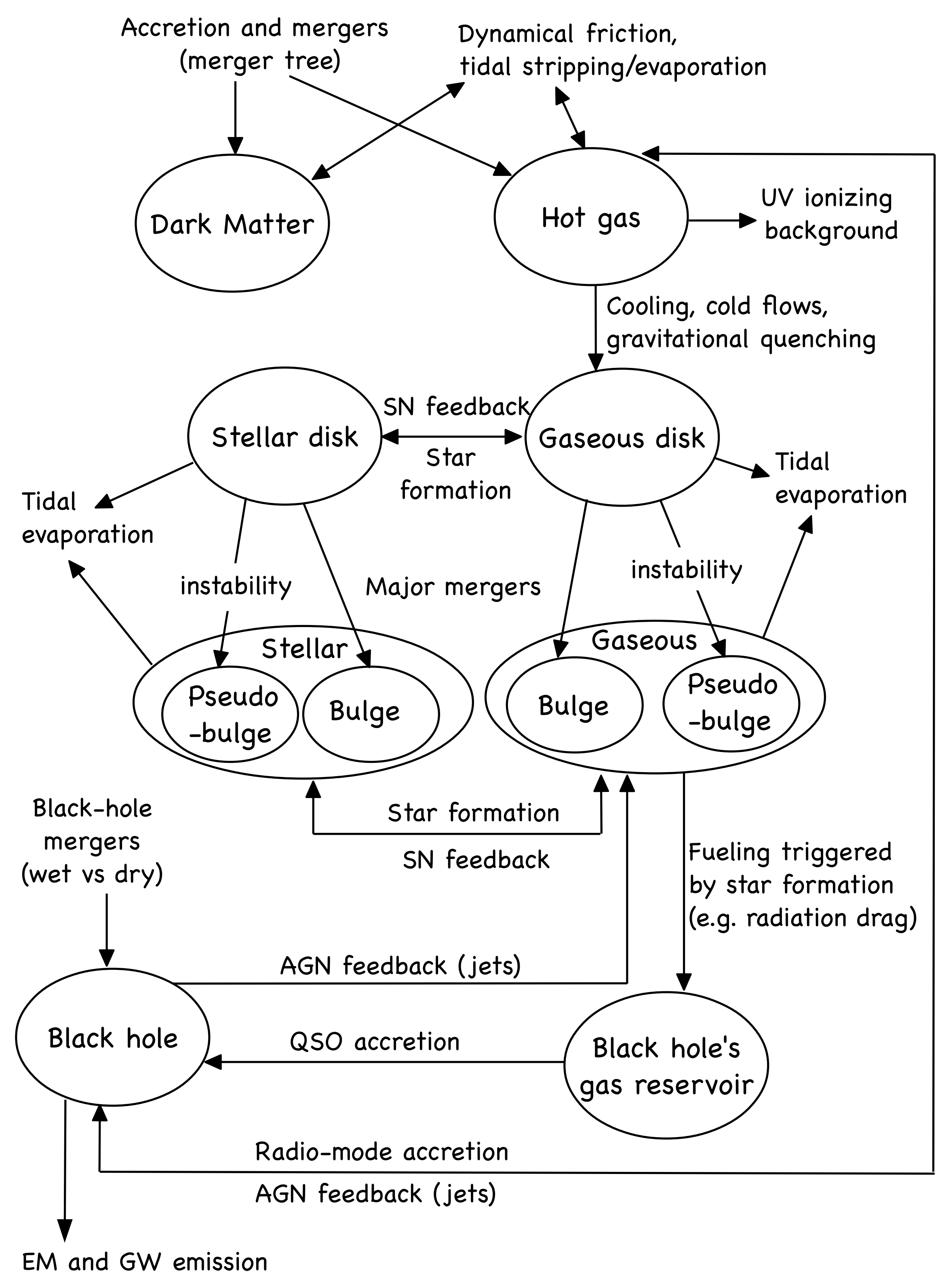
Correction		$\lvert\delta_{\rm per}\rvert$	$\lvert\delta_\varphi\rvert$[rads]
thin disks	planetary migration	—	10^4
	dyn. friction/accretion	—	10^2
	gravitational pull	10^{-8}	10^{-3}
	magnetic field	10^{-8}	10^{-4}
	electric charge	10^{-7}	10^{-2}
	gas accretion	10^{-8}	10^{-2}
	cosmological effects	10^{-31}	10^{-26}
thick disks	dyn. friction/accretion	—	10^{-9}
	gravitational pull	10^{-16}	10^{-11}
DM	accretion	—	$10^{-8}\rho_3^{\rm DM}$
	dynamical friction	—	$10^{-14}\rho_3^{\rm DM}$
	gravitational pull	$10^{-21}\rho_3^{\rm DM}$	$10^{-16}\rho_3^{\rm DM}$



Correction	$\lvert\delta_R\rvert$[%]	$\lvert\delta_I\rvert$[%]
spherical near-horizon distribution	0.05	0.03
ring at ISCO	0.01	0.01
electric charge	10^{-5}	10^{-6}
magnetic field	10^{-8}	10^{-7}
gas accretion	10^{-11}	10^{-11}
DM halos	$10^{-21}\rho_3^{\rm DM}$	$10^{-21}\rho_3^{\rm DM}$
cosmological effects	10^{-32}	10^{-32}

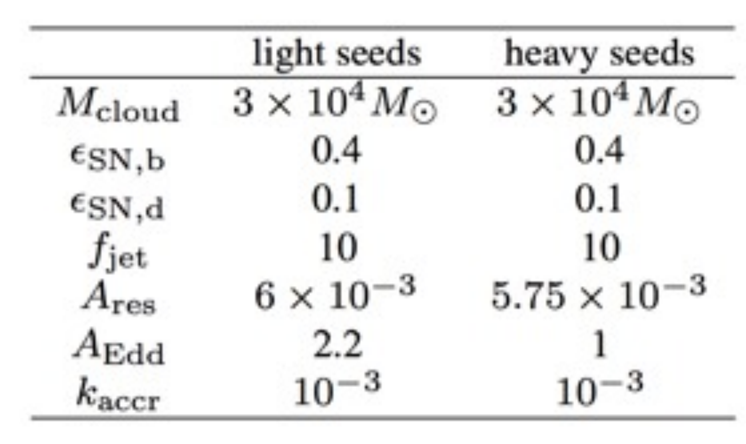
EB, Cardoso & Pani 2014

How to model BH-galaxy coevolution



- Purely numerical simulations impossible due to sheer separation of scales (10^{-6} pc to Mpc) and dissipative/nonlinear processes at sub-grid scales

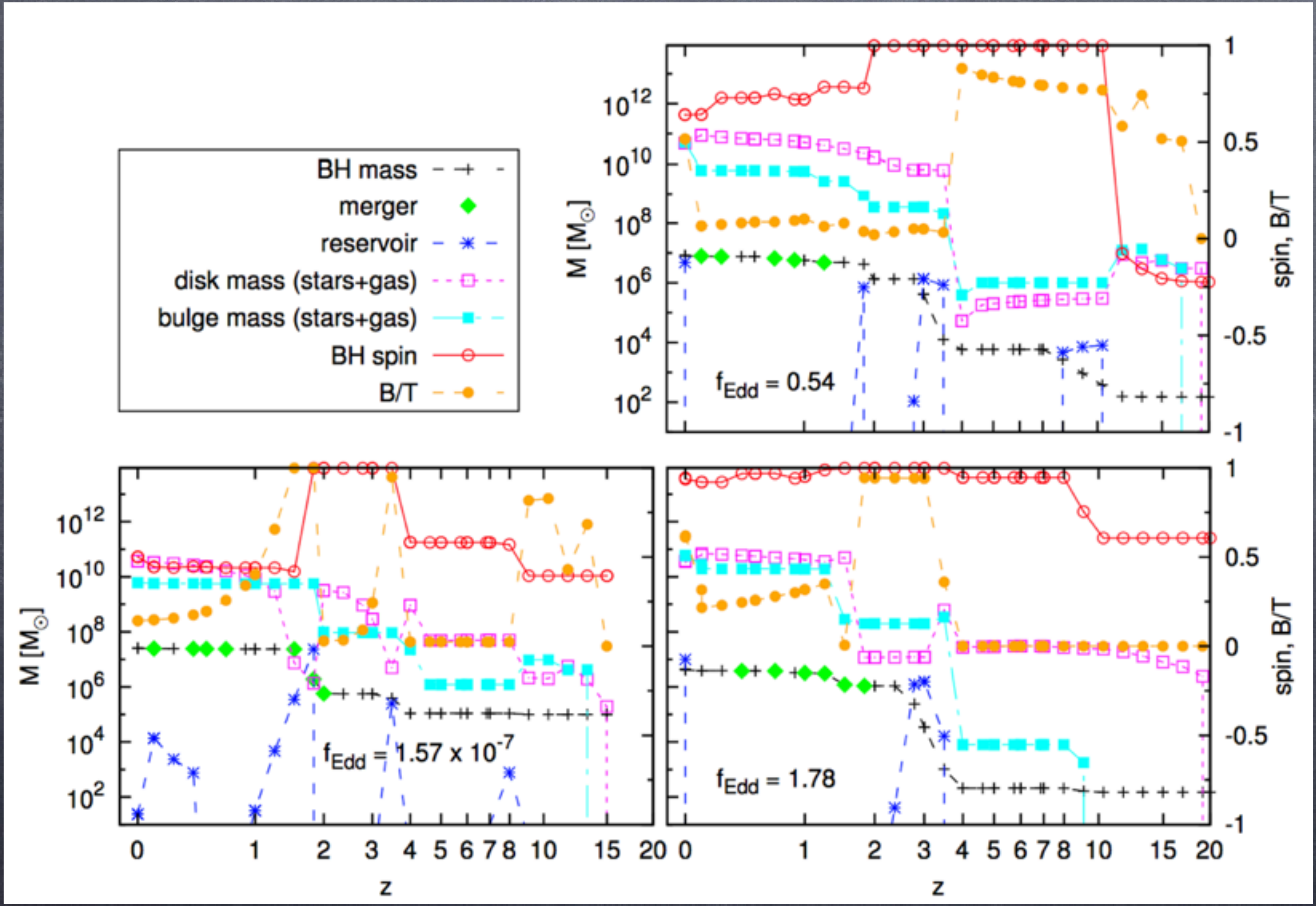
- Semi-analytical model with 7 free parameters, calibrated vs data at z = 0 and z > 0
(e.g. BH luminosity & mass function, stellar/baryonic mass function, SF history, M – σ relation, etc)



	light seeds	heavy seeds
$M_{\rm cloud}$	$3 \times 10^4 M_\odot$	$3 \times 10^4 M_\odot$
$\epsilon_{\rm SN,b}$	0.4	0.4
$\epsilon_{\rm SN,d}$	0.1	0.1
$f_{\rm jet}$	10	10
$A_{\rm res}$	6×10^{-3}	5.75×10^{-3}
$A_{\rm Edd}$	2.2	1
$k_{\rm accr}$	10^{-3}	10^{-3}

EB (2012); Sesana, EB, Dotti & Rossi (2014)

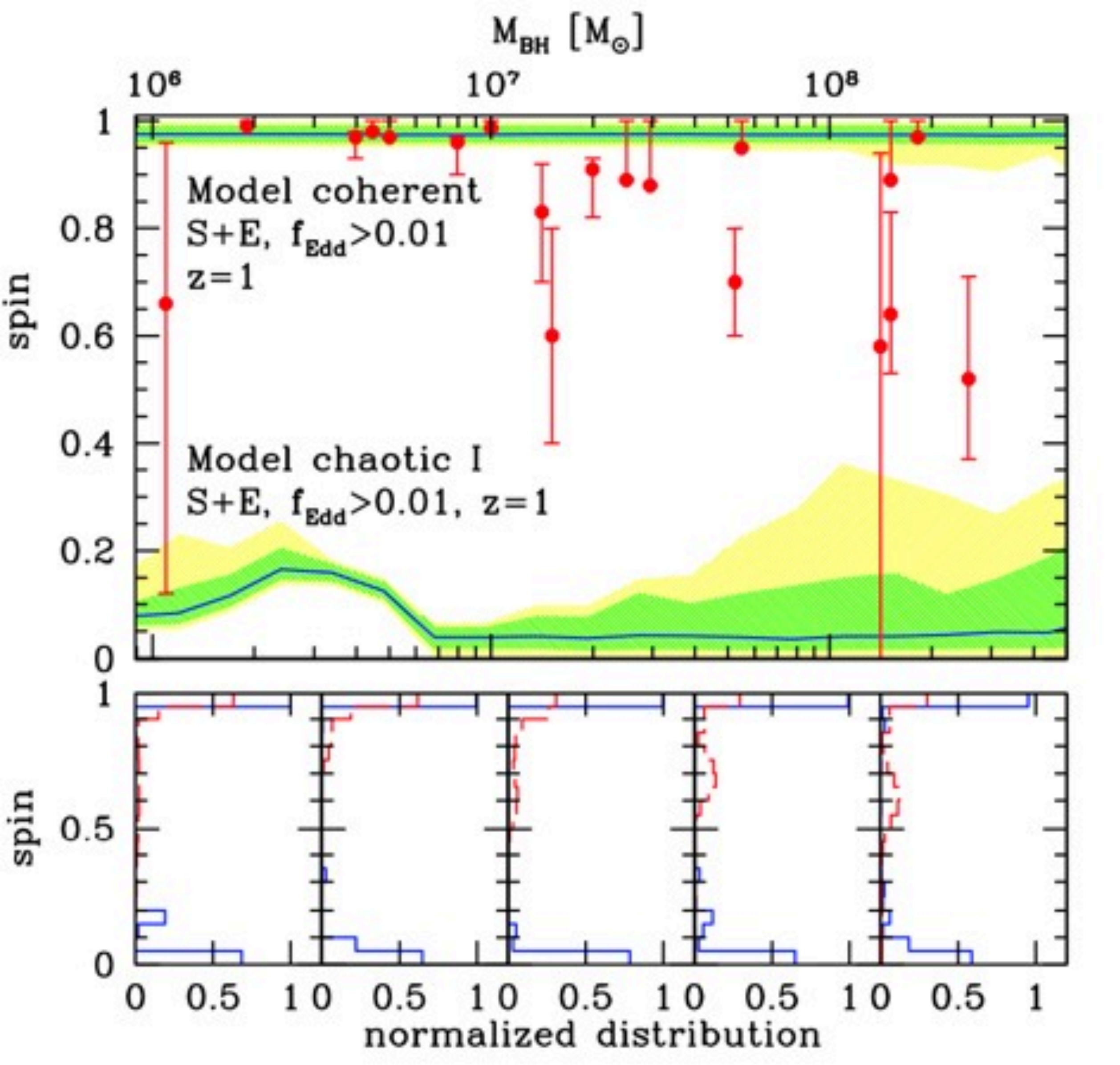
Some examples of BH-galaxy coevolution

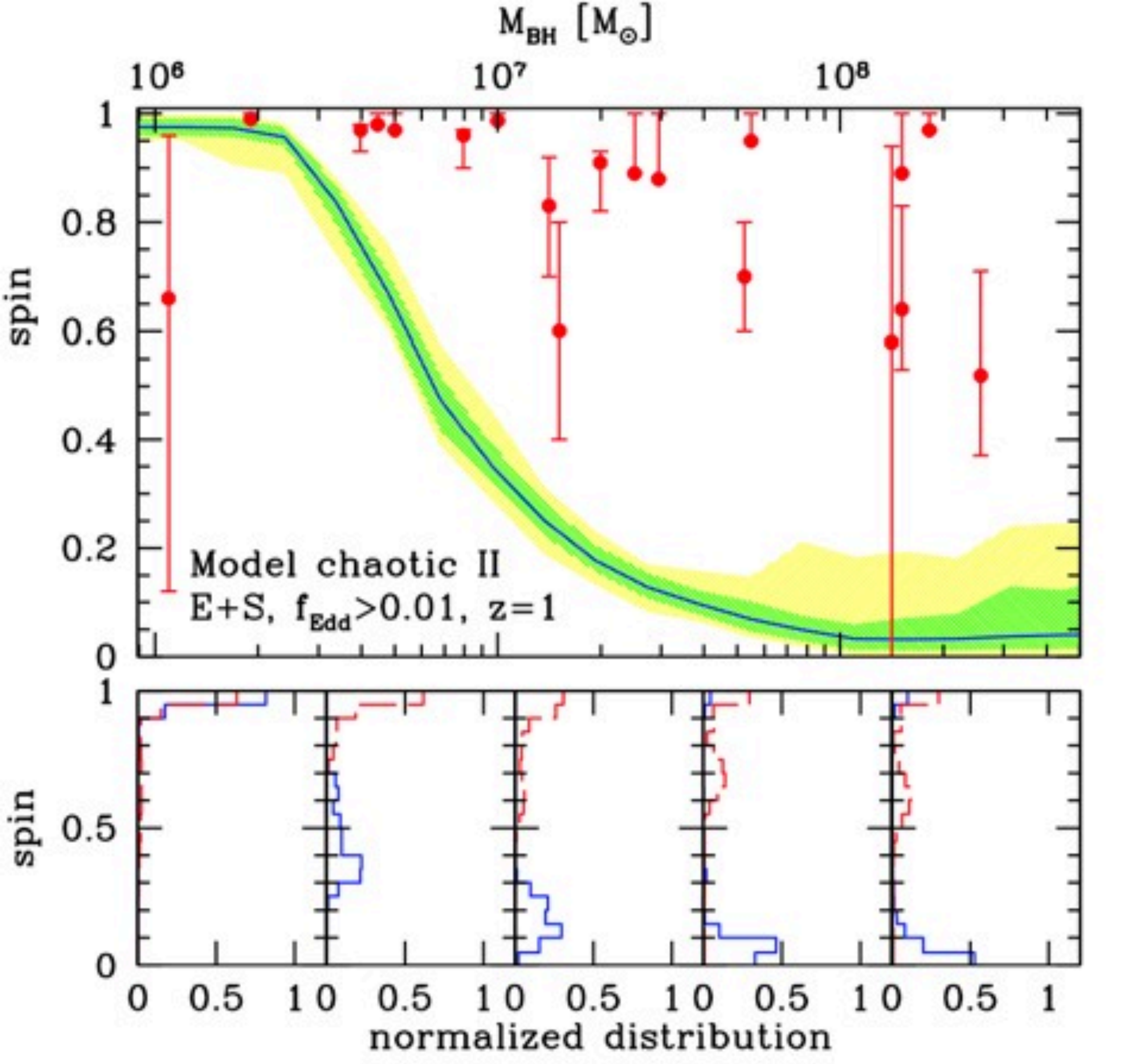


How about spin evolution?

- Observations: growing number of spin measurements using relativistic iron lines
- Theory (King, Pringle, Volonteri, Berti, ...): main driver of spin evolution is radiatively efficient accretion and **NOT** mergers:
  - Coherent accretion (gas accretes with fixed L)
  - Chaotic accretion (of clouds with randomly oriented L)

Neither works!



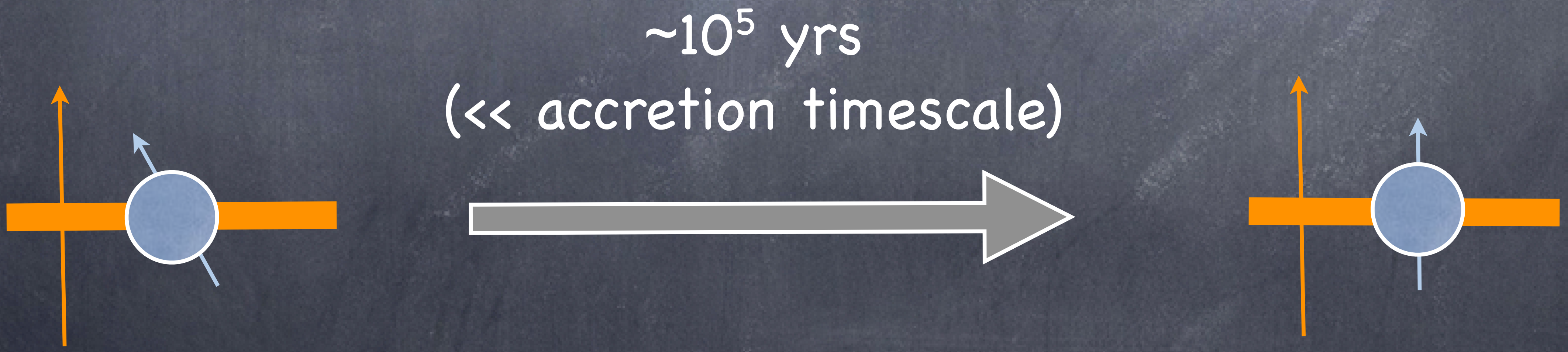


Sesana, EB, Dotti & Rossi (2014)

A mix of coherent and chaotic?

(Dotti, Colpi et al 2012)

- Accretion by clouds of gas, with mass set by minimum of a "typical" cloud mass ~10^4 - 10^5 M_{sun}, and "fragmentation" mass scale set by self gravity
- If $J_{cloud} > 2 J_{bh}$, Bardeen Petterson effect aligns BH spin to accretion disk: coherent accretion



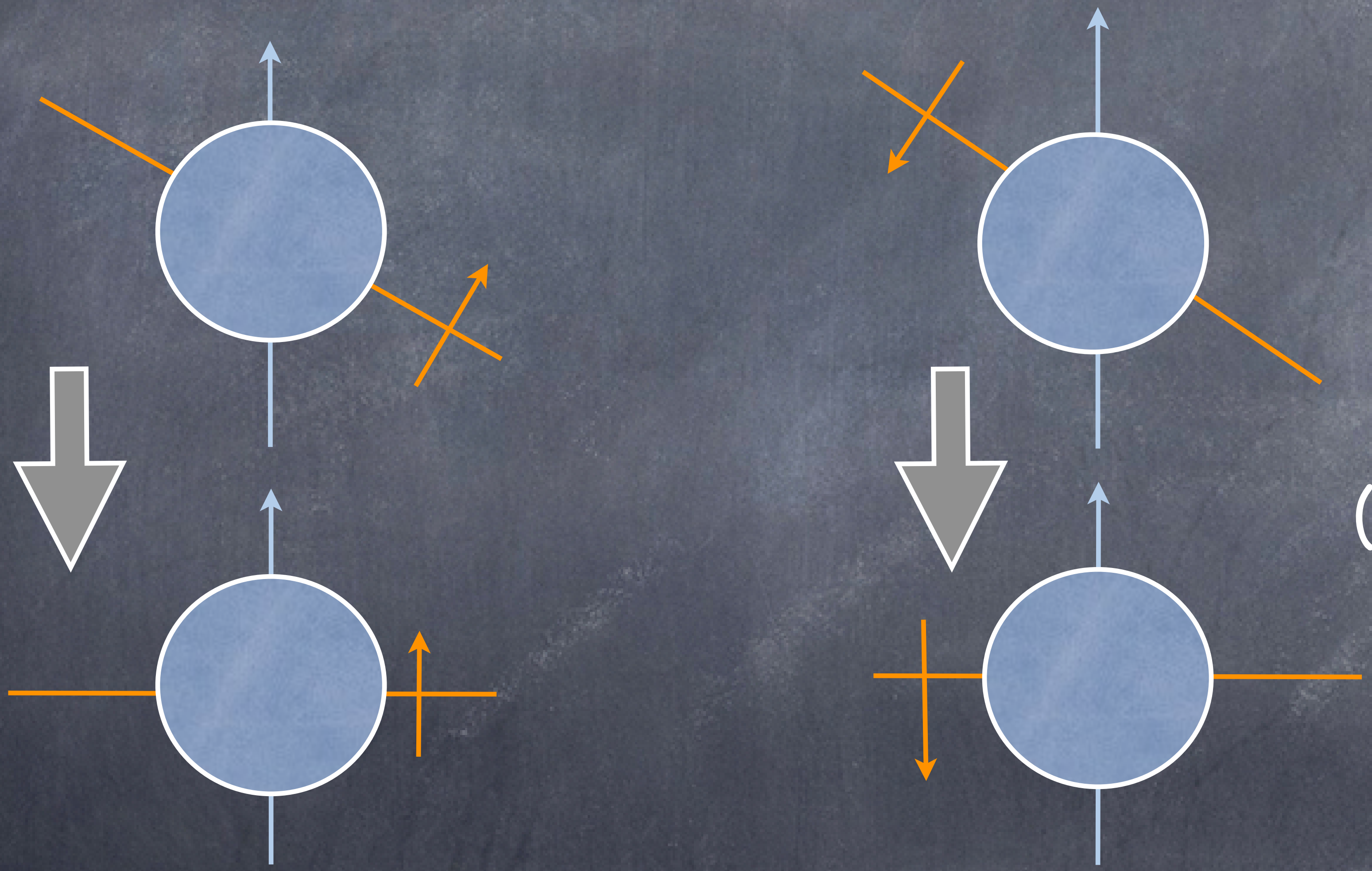
~10^5 yrs

(<< accretion timescale)

A mix of coherent and chaotic?

(Dotti, Colpi et al 2012)

- If $J_{cloud} < 2\, J_{bh}$, either alignment or anti-alignment can happen, depending on initial orientation of J_{cloud}: spin evolution depends on "isotropy" of J_{cloud} distribution



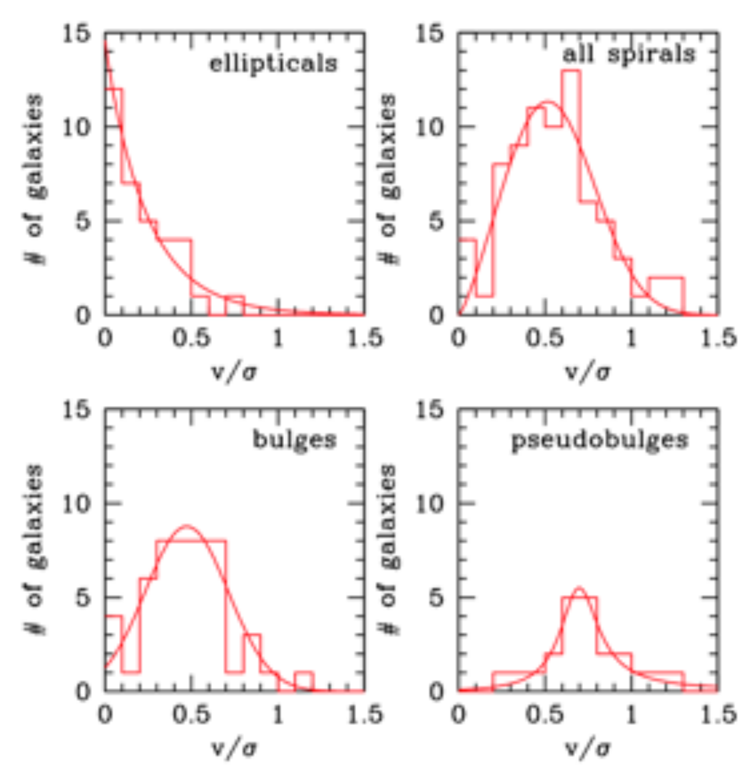
~10^5 yrs
(<< accretion timescale)

- We just need fraction of clouds with $J_{bh} \cdot J_{cloud} > 0$

Linking accretion to galactic morphology

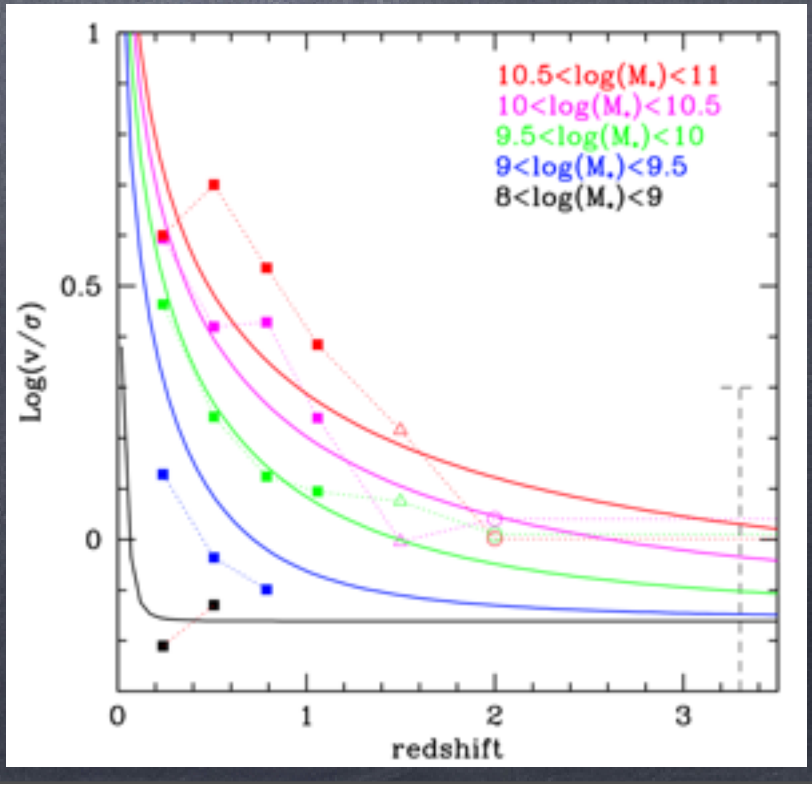
(Sesana, EB & Dotti 2014)

- $J_{\rm cloud}$ has "coherent" part (due to rotational velocity v) and "chaotic" part (due to velocity dispersion σ)
- Extract from observations of v / σ
  - for stars in ellipticals and in classical/pseudo-bulges hosted in spirals
  - for gas in spiral disks, on scales > 100 pc



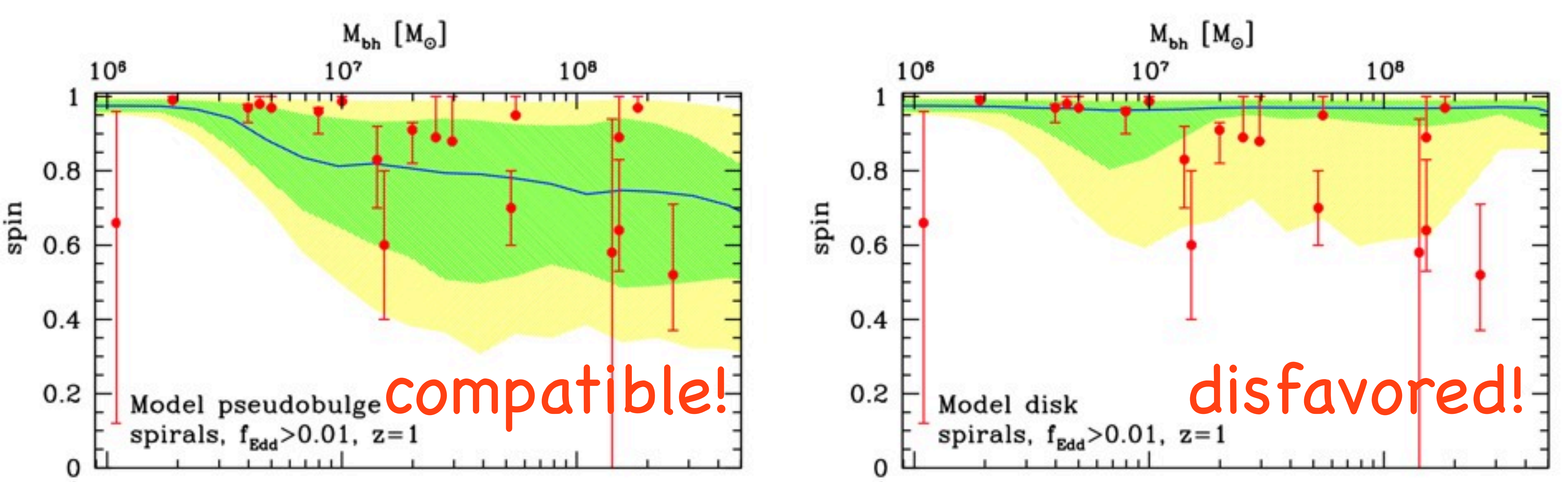
Stars

Gas



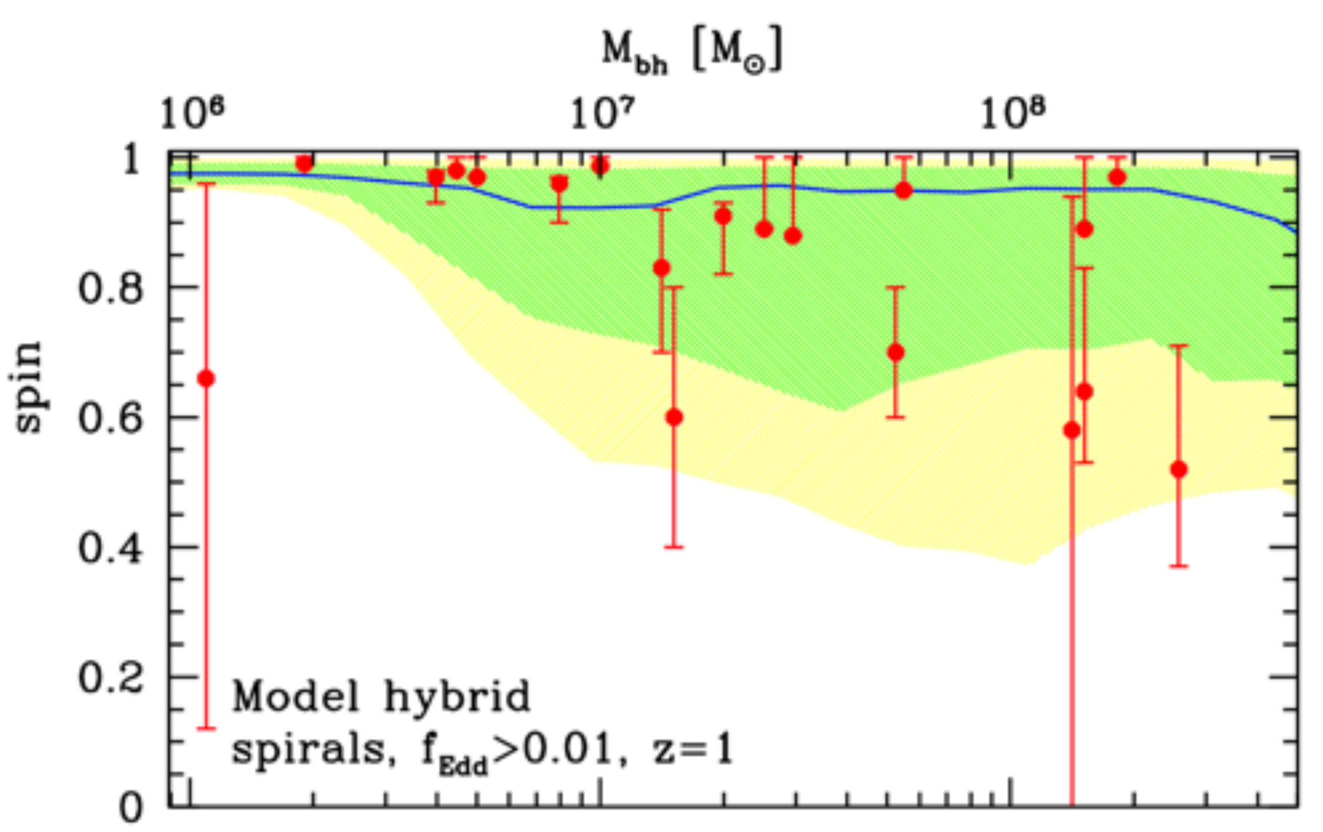
Comparison to data

- When comparing to observed sample morphology matters (spins measured for accreting BHs in spirals)
- Ellipticals: accretion linked to stellar dynamics
- Spirals: accretion linked to stellar dynamics ("bulge/pseudobulge" model) or to gas dynamics ("disk" model)



Sesana, EB, Dotti & Rossi (2014)

The best model



Sesana, EB, Dotti & Rossi (2014)

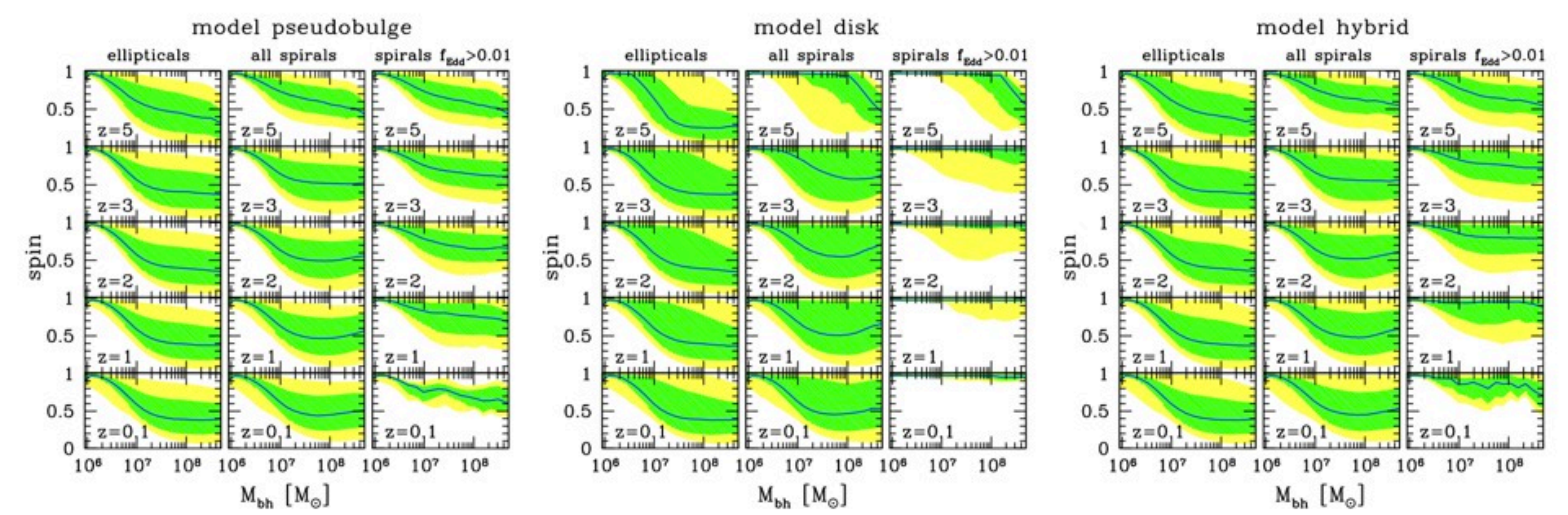
Are there 2 fueling channels (bulge stars + disk gas)?

Data favor hybrid model linking accretion to

- Stellar dynamics in ellipticals and in spirals with a classical bulge
- Gas dynamics in spirals with a pseudo-bulge formed from bar instabilities

Testing BH spin evolution with GWs?

- eLISA/ET will measure masses to within 0.1% and spins to within 0.01-0.1 (at least)
- Clean measurements (no environmental effects; cf EB, Pani & Cardoso 2014)
- Will test correlation between BH spins & morphology, redshift evolution



Sesana, EB, Dotti & Rossi (2014)

Conclusions

- BH spins produce genuinely relativistic effects detectable in GW signals (frame-dragging, spin-orbit precession, waveform modulations)
- Their cosmological evolution is entangled with galaxy evolution (accretion, Bardeen-Petterson effect, mergers, AGN feedback)
- GW detectors will test astrophysical models for coevolution of massive BH spins and galaxies with better accuracy/different selection effects than electromagnetic probes

Thank you!