CENTRA, May 8, 2012

Enrico Barausse
(University of Guelph &
CITA National Fellow)

The evolution of the spins of massive black holes

Outline

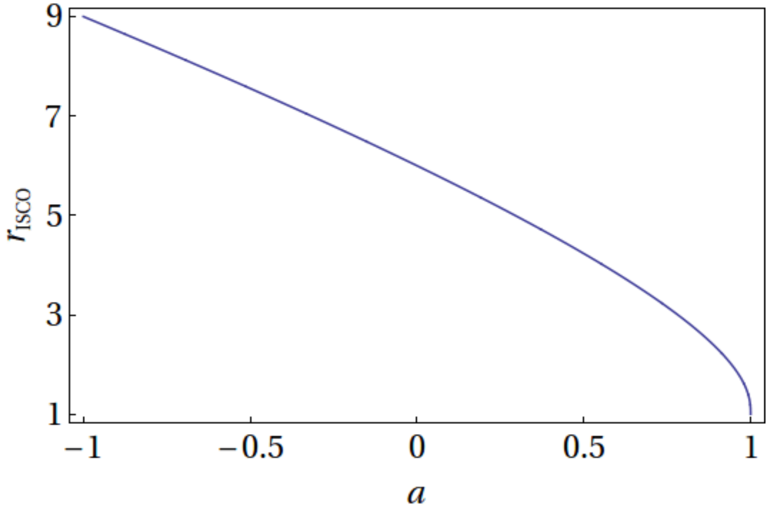
- Why are BH spins important?
  - Frame dragging (in isolated/binary BHs) → EM and GW emission efficiency
  - Bardeen Petterson effect → GW modulation
  - Jets and their effect on galaxies
- A semianalytical model for coevolution of massive BHs and their host galaxies:
  - The MBH spin evolution
  - Implications for future GW detectors (e.g. eLISA, DECIGO, Einstein Telescope)

BHs for a relativist

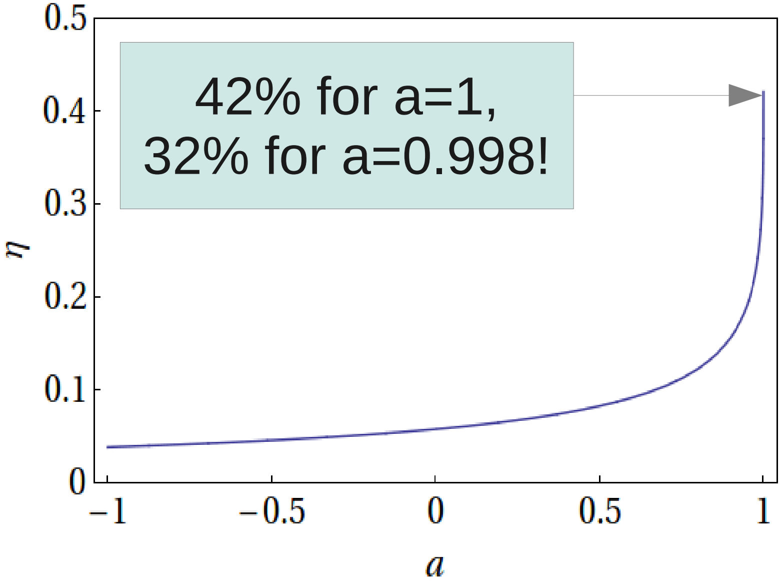
- Simple: 3 hairs
  - -Mass M
  - -Spin S (a=S/M^2)
  - -Electric charge Q (~ 0)
- Dynamics regulated by these 3 (2) hairs
- M and Q act like in Newton's/Maxwell's theory
- How about the spin?

Frame dragging in isolated BHs

- ISCO depends on spin...



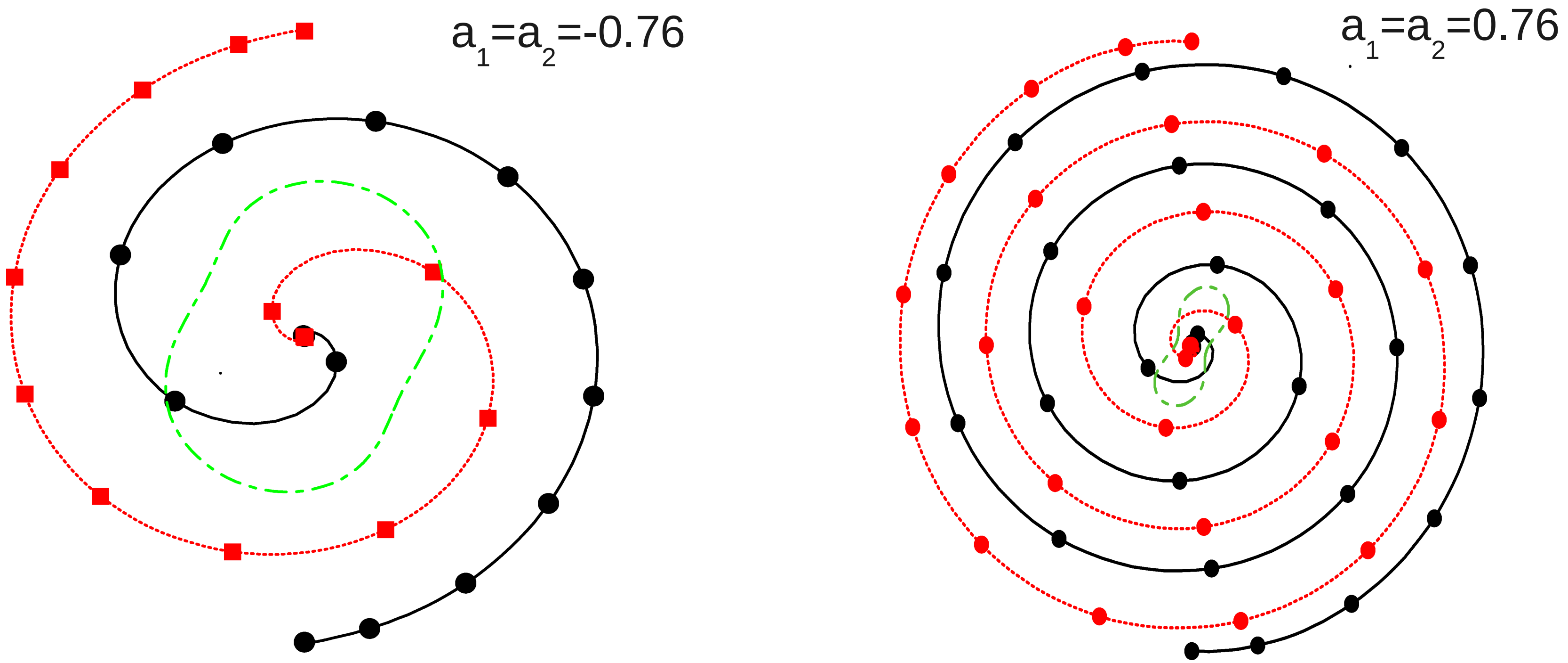
- … and so does EM efficiency (under coherent accretion)


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

Testable with iron Kα lines, continuum fitting!

Frame dragging in BH binaries

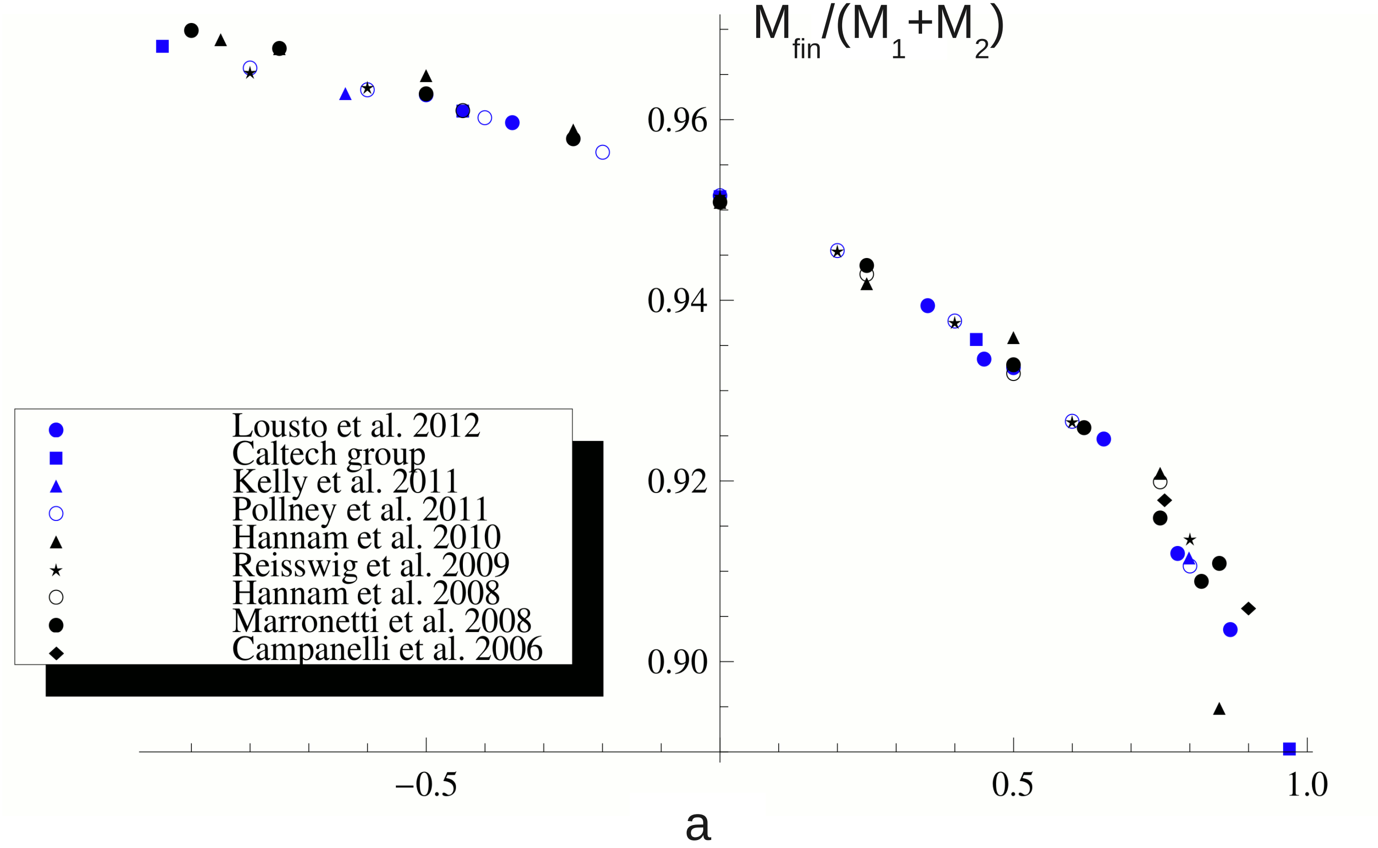
- Spin-orbit coupling or “hang-up” effect: for large spins aligned with L, effective ISCO moves inward …



Figures from Campanelli, Lousto & Zlochower 2006

Frame dragging in BH binaries

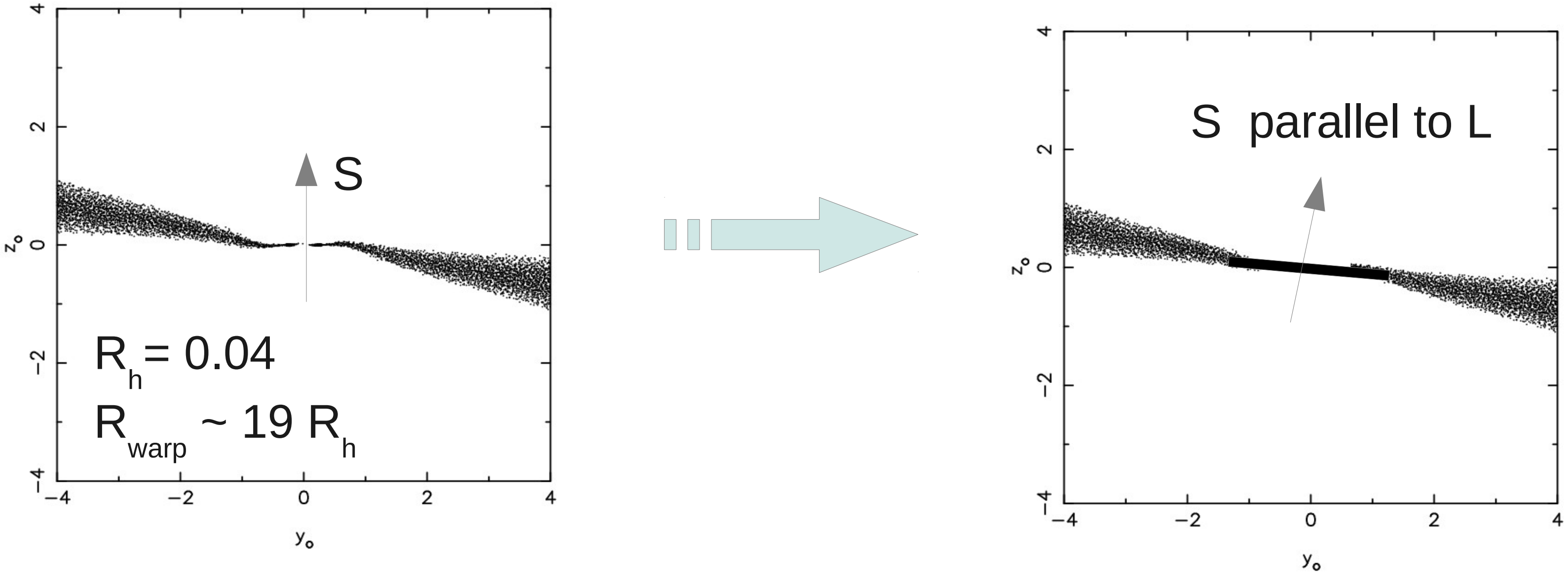
- …and GW “efficiency” larger



Effect testable with GW detectors!

The Bardeen-Petterson effect

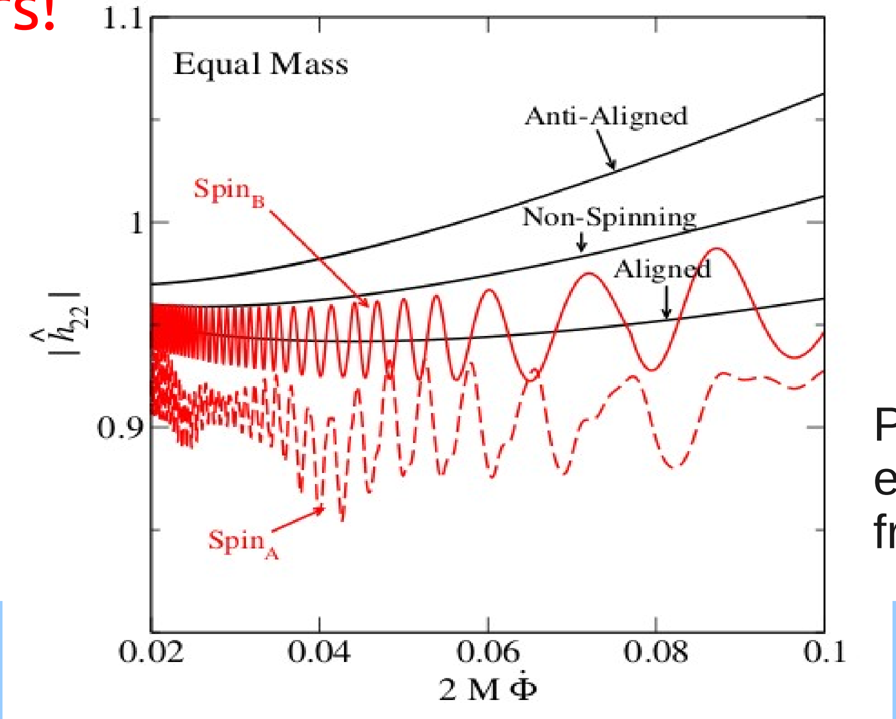
- If disk's angular momentum misaligned with BH's spin, spin-orbit coupling and dissipation realign S and L near BH (Bardeen-Petterson effect)
- On longer timescales ($\sim 10^5$ yrs for MBHs) warp torques spin and aligns it with L of external disk



SPH simulation from Nelson & Papaloizou 2000

Frame dragging and the spin direction

- MBH mergers in gas-rich (“wet”) enviroment have aligned spins because they align with circumnuclear disk
- For BH binaries in gas-poor (“dry”) environments, spin-orbit coupling make spins precess around total angular momentum $J=L+S_1+S_2$ → modulations in gravitational waveforms visible with GW detectors!



PN waveforms for BH binaries with equal masses and maximal spins, from Arun et al 2009

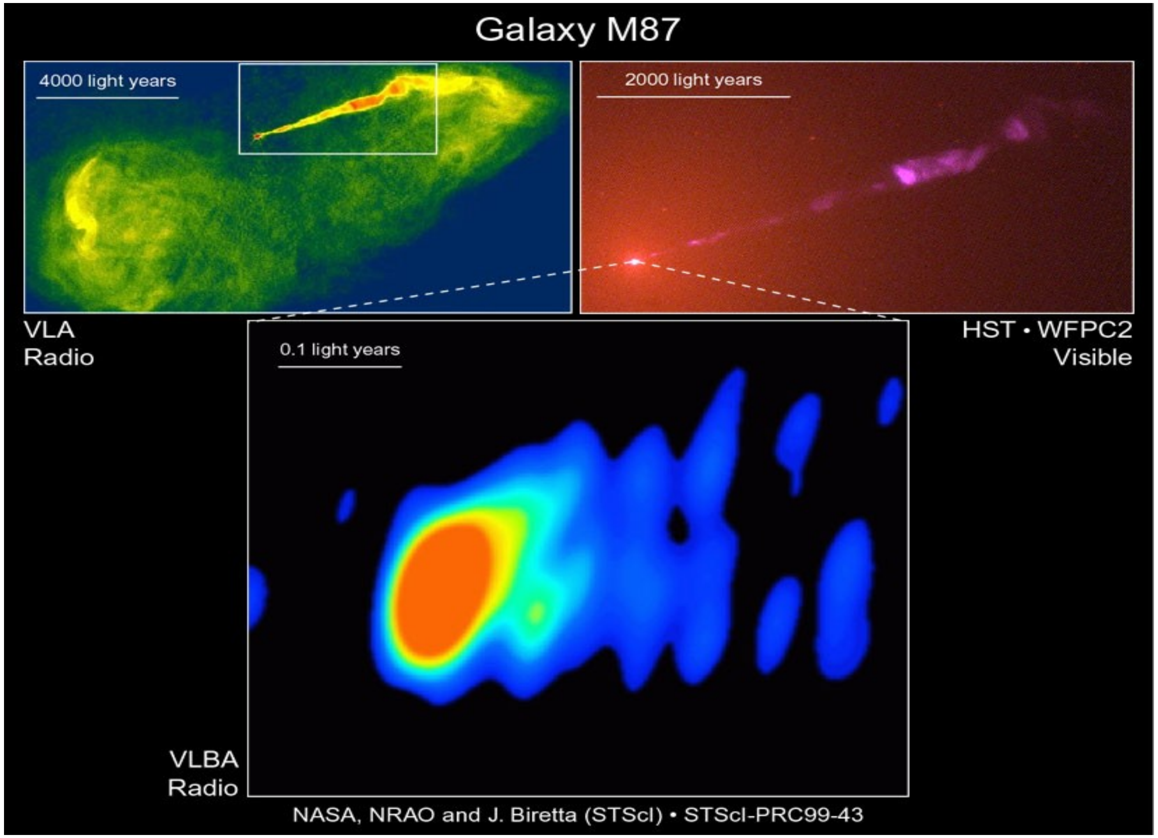
What does galaxy formation care about BHs?

Typical scales:

- MBH ~ $10^{-6} – 10^{-7}$ pc
- MBH accretion disk ~ pc
- Circumbinary disk ~ 100 pc
- Galactic bulge ~ kpc
- Galactic disk ~ 10 kpc
- Dark-matter halo ~ Mpc

What does galaxy formation care about MBHs?

- MBHs in AGNs can produce jets that reach far into the galaxy

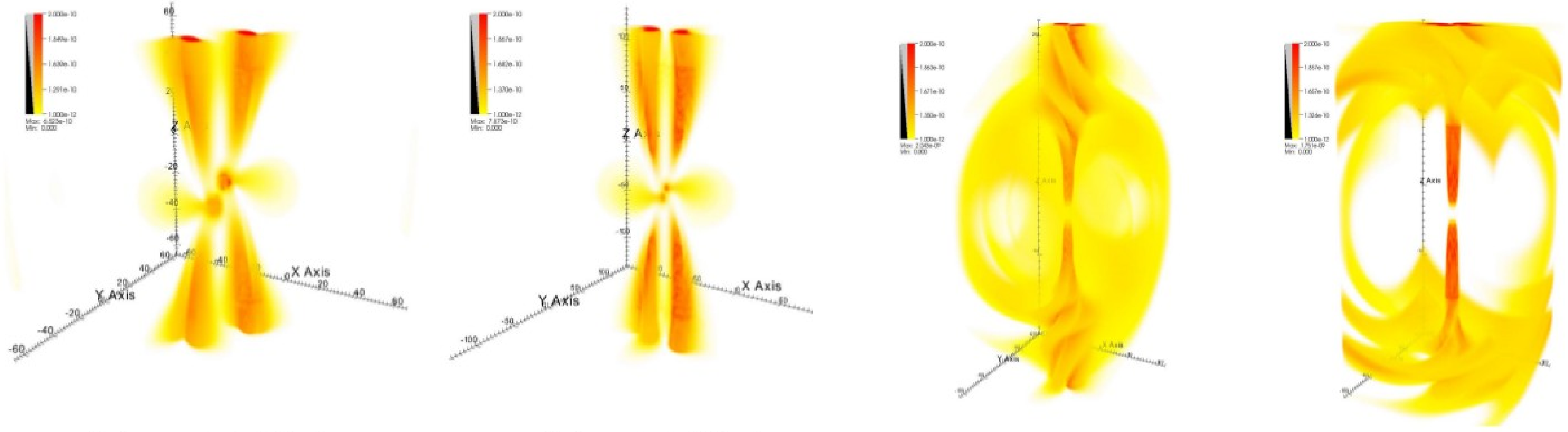


NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

- The kinetic energy of the jets is transferred to the galaxy and keeps it "hot", quenching star formation (AGN feedback)

What does galaxy formation care about MBHs?

- Jets can be produced by isolated spinnning BHs in a magnetic field anchored to accretion disk (Blandford & Znajek 1977)...
- … or by BHs (even non spinning ones) moving a magnetic fields anchored to circumbinary disk (Palenzuela, Lehner and Liebling 2010)



(a) $-11.0\ M_8$ hrs (b) $-3.0\ M_8$ hrs (c) $4.6\ M_8$ hrs (d) $6.8\ M_8$ hrs

What does galaxy formation care about MBHs?

- Galaxy formation is bottom-up: smaller systems form first and merger in larger ones...
- ...but most massive galaxies have older stars and weaker SF than smaller galaxies (cosmic downsizing)
- AGN feedback stronger in massive galaxies (which host the most massive BHs) → star formation shut down earlier in massive galaxies

1) AGN feedback (and therefore BH spins and mergers) crucial in modern galaxy formation models
2) Galaxy formation regulates gas available to MBHs for growing

Galaxy formation

- Range of scales involved (from MBHs to Hubble scale) and non-linear, dissipative microphysics prevents purely numerical approach
- Use semianalytical galaxy-formation model:

  - Dark Matter (halos)

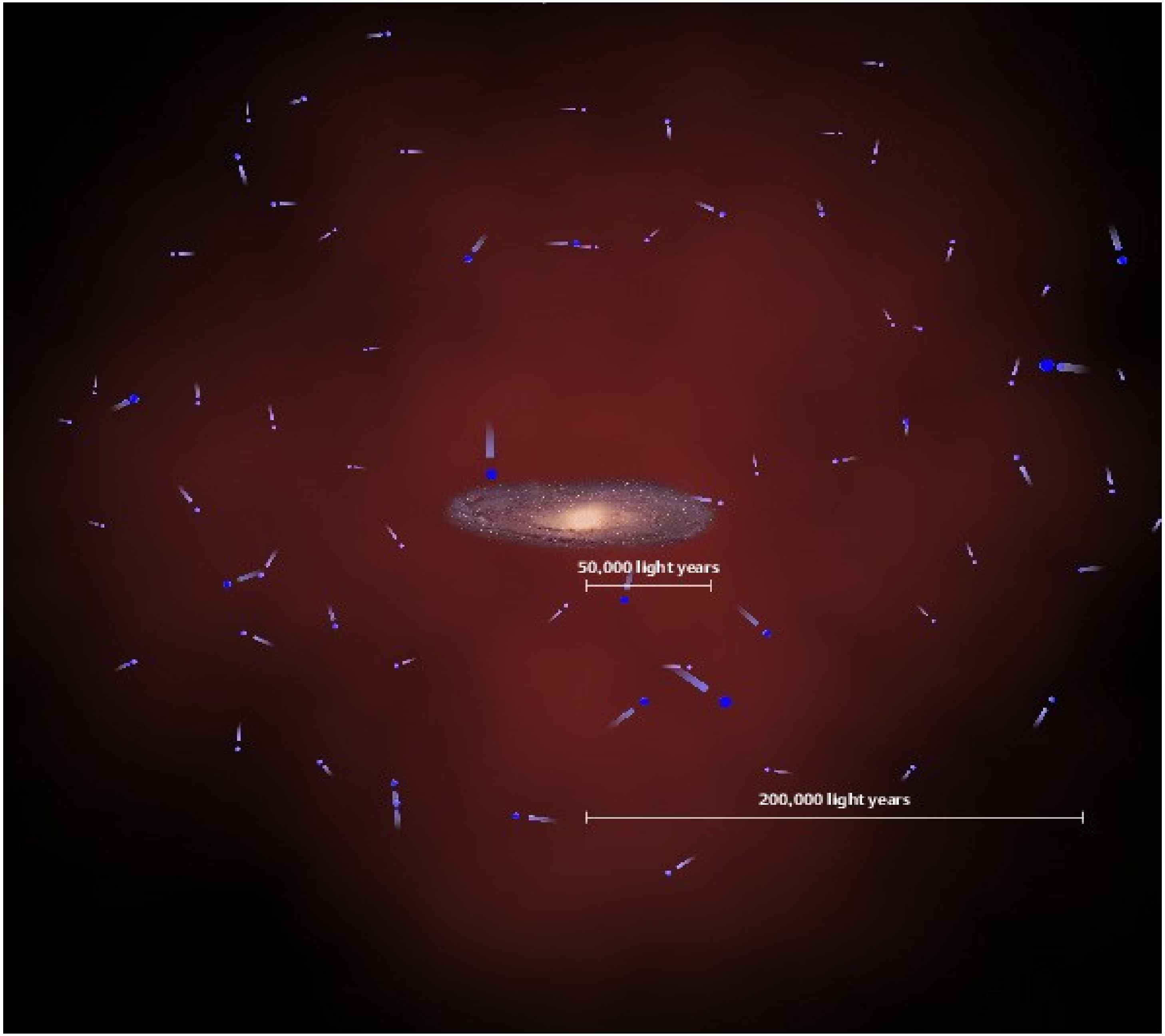
  - Hot gas (IGM)

  - Cold gas: bulges and disks

  - Stars: bulges and disks

  - Circumnuclear reservoir and MBH accretion disk

  - MBHs


50,000 light years
200,000 light years

Dark Matter

- Extended Press Schechter merger trees, modified to reproduce results of N-body simulations (Parkinson et al 2008)
- Based on gaussianity of primordial cosmological perturbations and their linear growth (corrected with top-hat collapse model)
- DM halos described by NFW density profile

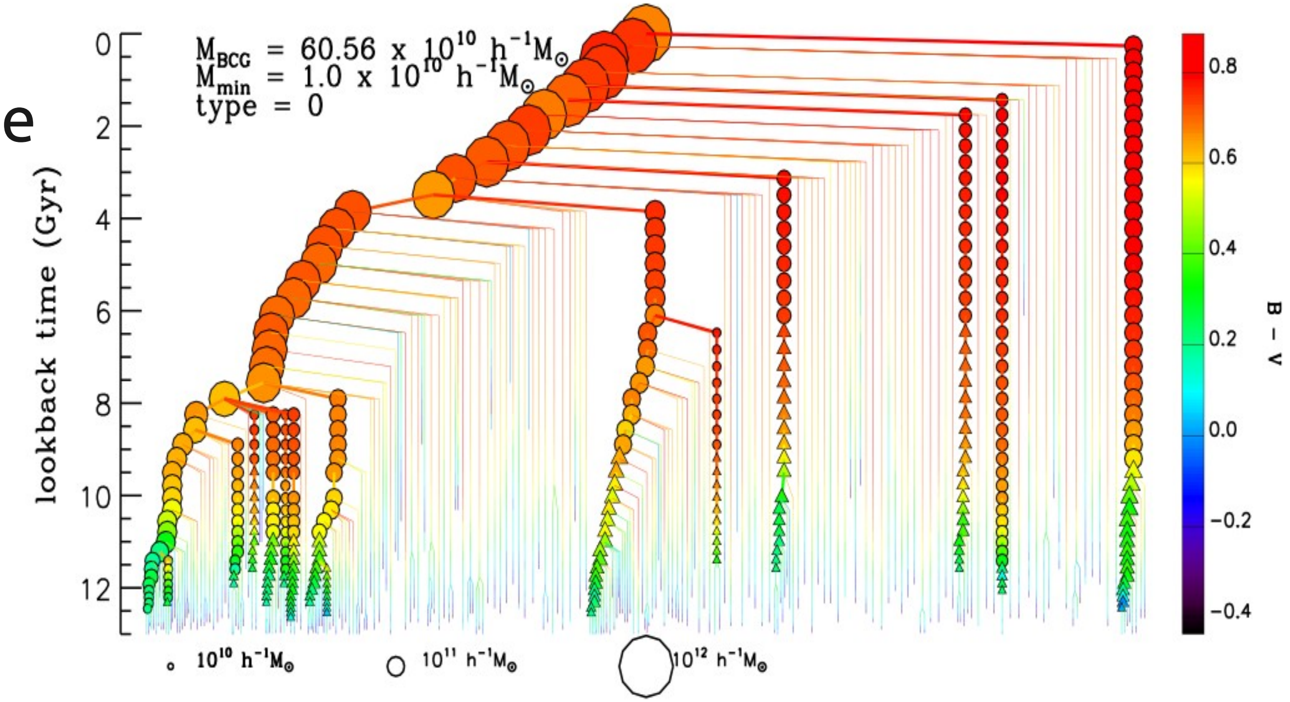
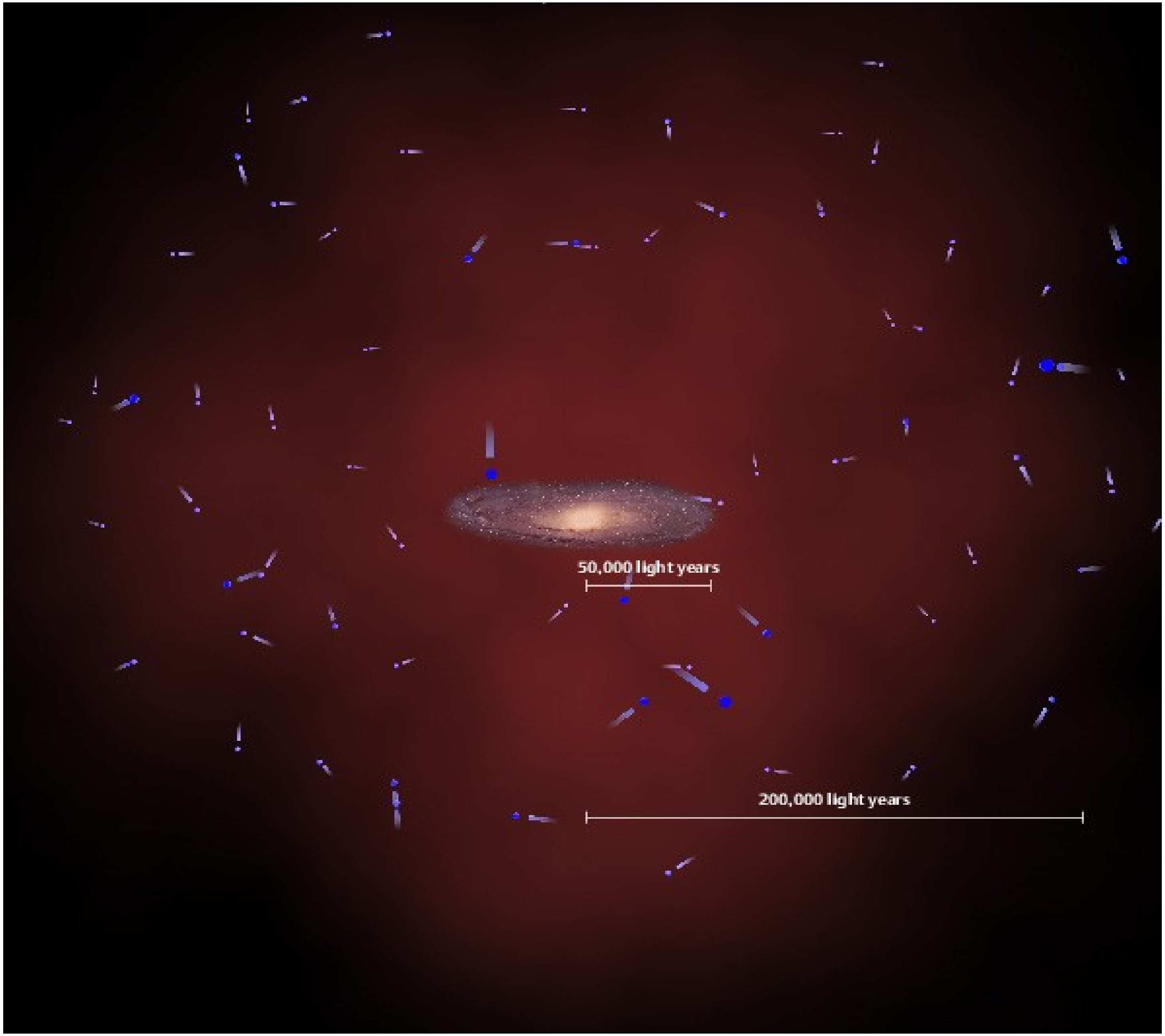


Figure from De Lucia & Blaizot 2007


50,000 light years
200,000 light years

The baryonic components: the hot gas

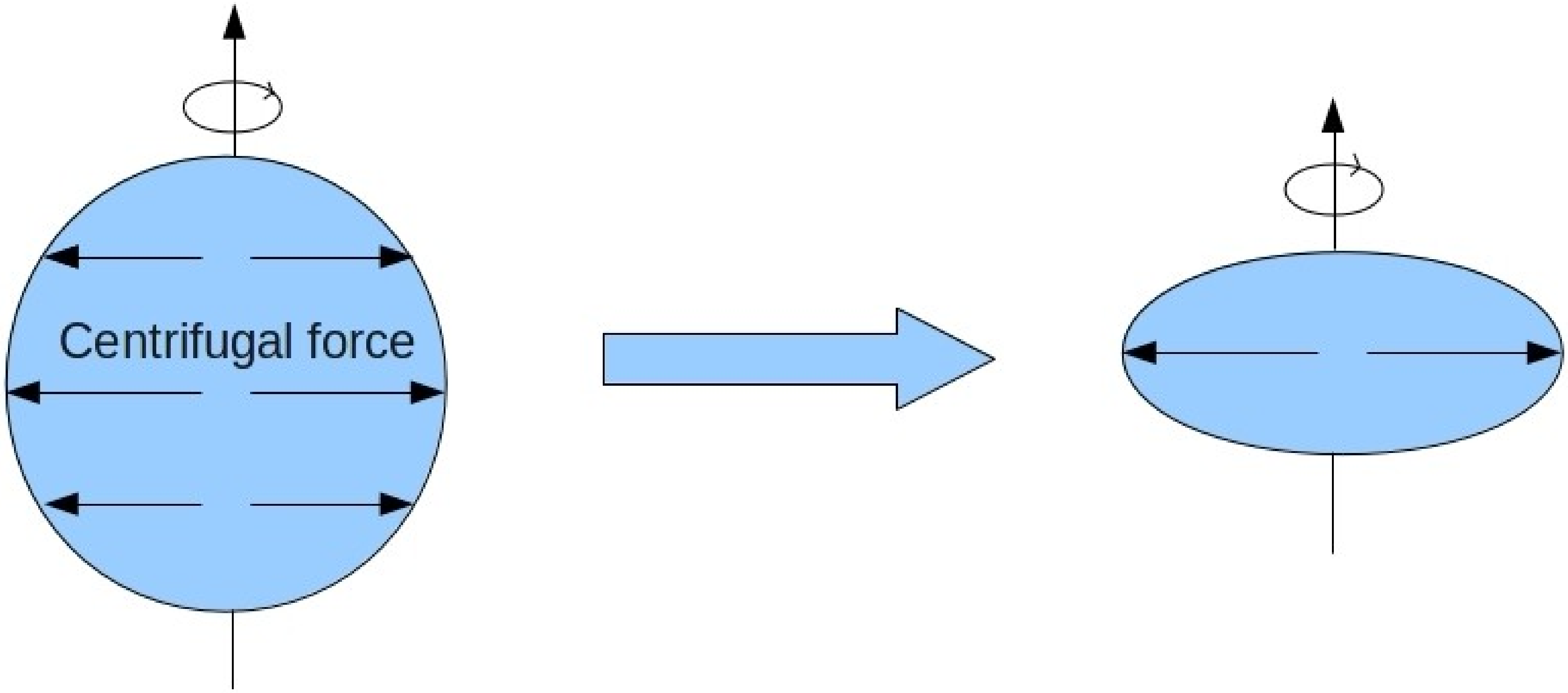
- Hot gas: primordial metallicity, brought in by DM accreting on halos between mergers

$$\dot{M}_{hot} = f_b \dot{M}_{DM}$$

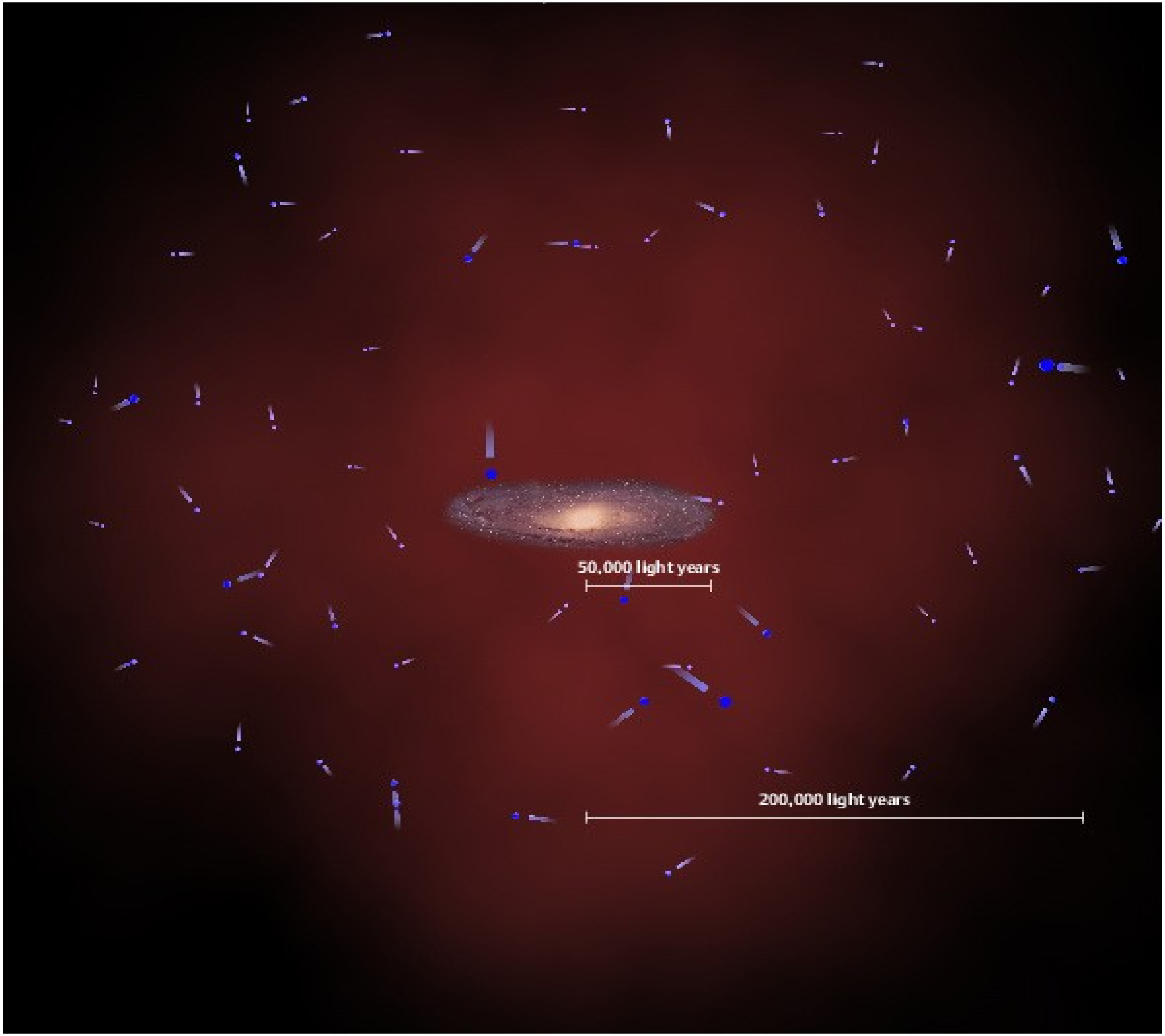
with baryon fraction $f_b \leqslant \Omega_b / \Omega_{DM}$
including effect of UV background

- Hot gas shock-heated to virial T, unless in low-mass halos at high z, where it streams in on dynamical time (cold accretion flows)
- Hot gas collapses in gaseous disks on dynamical timescale (if it cools “rapidly”) or on cooling timescale (if it cools “slowly”).

The collapse of the hot gas



Centrifugal force


50,000 light years
200,000 light years

The Sombrero galaxy

Galactic disks

- Gaseous disk: exponential density profile, scale radius calculated by L and M of collapsing hot has
- Star formation in molecular clouds: SFR depends on Σ_{mol}(r), which is related to disk's mid-plane pressure (Blitz & Rosolowsky 2006)
- Fraction of forming stars are SN: kinetic energy $E_{SN}=10^{44}$ J transferred to disk's gas, ejects it if $E_{SN}>E_{bind}$ (SN feedback)

$$\dot{\Sigma}_{\rm SN}(r,z) = -\frac{\epsilon_{\rm SN} E_{\rm SN} \eta_{\rm SN} \dot{\Sigma}_{\rm sfr}(r,z)}{\phi(r,z)}$$

- Stellar disk: exponential density profile with scale radius $R_d^{star} = R_d^{gas}/2$
- Both stellar and gaseous disks can develop bar instability when they become self-gravitating: disrupted in dynamical time and form bulges

The Sombrero galaxy

Galactic bulges

- Form from disk disruption due to bar instabilities or major mergers
- Both gaseous and stellar bulges described by Hernquist density profile (scale radius related to mass using fits to observations)
- Star formation more efficient than in disks (happens on dynamical timescale)
- SN feedback as in disks

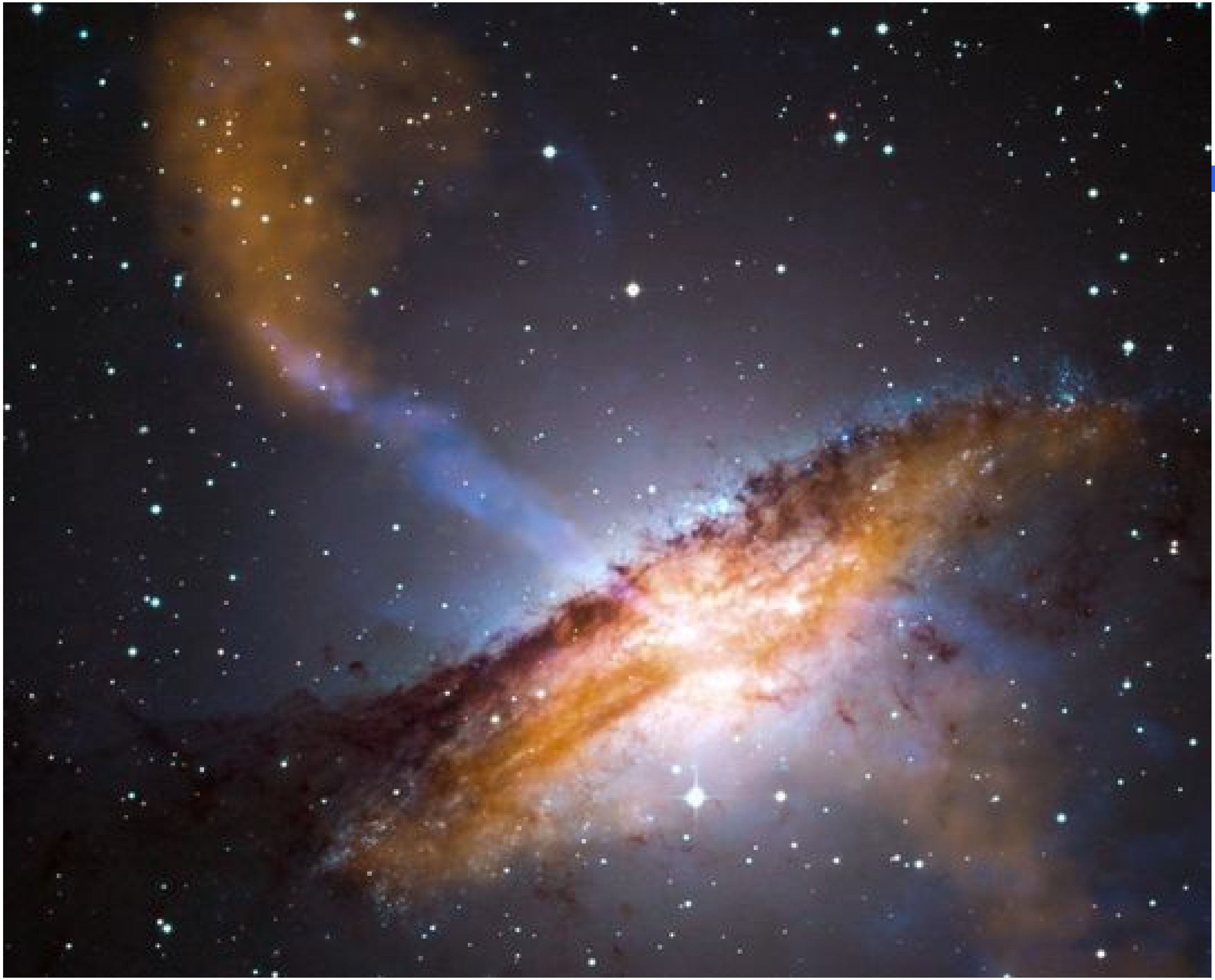
A galactic merger from Hubble

Galaxy mergers

- When two DM halos merge, baryonic structures (the “galaxies”) do not merge right away, but are slowly brought together by dynamical friction (~ Gyr)
- During dynamical friction time, satellite galaxy suffers from tidal stripping and evaporation
- When galaxy merge:

  - If $M_{sat}^{disk+bulge} / M_{main}^{disk+bulge} > 0.25$ (“major merger”) gasous and stellar disks disrupted and added to stellar and gaseous bulge

  - If $M_{sat}^{disk+bulge} / M_{main}^{disk+bulge} < 0.25$ (“minor merger”) disks survive



Composite image of Centaurus A

Massive black hole seeds

- Grow from 150 M_{sun} remnants of Pop III stars at z=15-20 (light seeds), or from 10^5 M_{sun} seeds forming at z=10-15 from collapse of massive protogalactic disks (heavy seeds)
- Seeds assigned random spin parameter from uniform distribution, but memory of initial spin lost when seed BH accretes $\gtrsim$ 3 times its initial mass

The QSO phase

- When SF happens in bulges (due to disk instabilities or major mergers), radiation drag forces cold gas into circumnuclear reservoir:

$$\dot{M}_{\rm res} = A_{\rm res}\psi_b(t)$$

- Circumnuclear reservoir accretes on MBH with rate

$$\dot{M}_{\rm QSO} = \frac{M_{\rm res}}{t_{\rm accr}}$$

t_{accr} is a free parameter

$$\dot{M}_{\rm bh,QSO} = \dot{M}_{\rm QSO}(1-\eta(a_{\rm bh}))$$

- If $M_{res} > M_{bh}$: coherent coherent (i.e. thin disk)

  If $M_{res} < M_{bh}$: chaotic accretion (i.e. accretion of clouds with random L)

- $\dot{M}$ can be super-Eddington, but luminosity cannot

$$L_{\rm bh,QSO} = \min\left\{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2\ ,\ L_{\rm Edd}\left[1+\ln\left(\frac{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2}{L_{\rm Edd}}\right)\right]\right\}$$

The MBH spin evolution

- Coherent accretion = prograde (thin disk accretion)
  → spin up

$$\dot{a}^{\rm coherent}_{\rm bh,QSO} = [L_{\rm ISCO}(a_{\rm bh}) - 2a_{\rm bh}E_{\rm ISCO}(a_{\rm bh})]\frac{\dot{M}_{\rm QSO}}{M_{\rm bh}}$$

$$\eta(a_{\rm bh}) = 1 - E_{\rm ISCO}(a_{\rm bh})$$

- Chaotic accretion: half of gas accretes on prograde orbits, half on retrograde orbits → spin down

$$\begin{aligned}\dot{a}^{\rm chaotic}_{\rm bh,QSO} = \Bigg\{ & \frac{L_{\rm ISCO}(a_{\rm bh}) + L_{\rm ISCO}(-a_{\rm bh})}{2} \\ & - a_{\rm bh}[E_{\rm ISCO}(a_{\rm bh}) + E_{\rm ISCO}(-a_{\rm bh})]\Bigg\}\frac{\dot{M}_{\rm QSO}}{M_{\rm bh}}\end{aligned}$$

$$\eta(a_{\rm bh}) = 1 - \frac{E_{\rm ISCO}(a_{\rm bh}) + E_{\rm ISCO}(-a_{\rm bh})}{2}$$

Radio-mode accretion

- If hot gas is in quasi-hydrostatic equilibrium with galaxy (i.e. in massive halos, z≲2), MBHs also accrete à la Bondi

$$\dot{M}_{\rm bh,radio} = 4\pi\lambda_B\rho_{\rm hot}(GM_{\rm bh})^2/v_{\rm s}^3$$

- Luminosity suppressed wrt QSO phase: Advection Dominated Accretion Flow

$$L_{\rm bol,radio} = 1.3\times10^{38}\left(\frac{M_{\rm bh}}{M_\odot}\right)\left(\frac{\dot{m}^2}{\alpha^2}\right)\left(\frac{\beta}{0.5}\right)\ {\rm erg\ s^{-1}}$$

- Effect on mass and spin paltry

$$\dot{a}_{\rm bh,radio} = -2a_{\rm bh}\frac{\dot{M}_{\rm bh,radio}}{M_{\rm bh}}$$

The AGN feedback

- Jets stronger for ADAFs (radio-mode accretion) than for thin disks (QSO-mode accretion), depend on spin

$$
\begin{aligned}
L_{\rm jet}^{\rm radio} &\approx f_{\rm jet} \times 10^{45.1} {\rm erg\ s}^{-1} \left(\frac{\alpha}{0.3}\right)^{-1} m_9 \left(\frac{\dot{m}}{0.1}\right) g^2 \\
&\times (0.55 f^2 + 1.5 f a_{\rm bh} + a_{\rm bh}^2)
\end{aligned}
$$

$$
\begin{aligned}
L_{\rm jet,QSO} &\approx f_{\rm jet} \times 10^{42.7} {\rm erg\ s}^{-1} \left(\frac{\alpha}{0.01}\right)^{-0.1} m_9^{0.9} \left(\frac{\dot{m}}{0.1}\right)^{6/5} \\
&\times (1 + 1.1 a_{\rm bh} + 0.29 a_{\rm bh}^2)
\end{aligned}
$$

- Jets eject hot gas and bulge cold gas with rates

$$
\dot{M}_{\rm b,gas}^{QSO} = \frac{2}{3} \frac{L_{\rm jet,QSO}}{\sigma^2} \frac{M_{\rm b,gas}}{M_{\rm hot} + M_{\rm b,gas}} \qquad \dot{M}_{\rm hot}^{QSO} = \frac{2}{3} \frac{L_{\rm jet,QSO}}{\sigma^2} \frac{M_{\rm hot}}{M_{\rm hot} + M_{\rm b,gas}}
$$

$$
\sigma = 0.65 V_{\rm vir}
$$

MBH mergers

- Final mass, spin and kick velocity of BH remnant calculated with phenological formulas reproducing numerical-relativity results (Tichy & Marronetti 2008, EB & Rezzolla 2009, van Meter et al 2010)
- Results depend strongly on spins and their orientation (e.g. kick velocity ~ 2500-5000 km/s for certain misaligned configurations, cf Lousto et al 2012)
- If $M_{res} > M_{bh1} + M_{bh2}$ ("wet merger"): Bardeen Petterson effect aligns spins
- If $M_{res} < M_{bh1} + M_{bh2}$ ("dry merger"): randomly oriented spins
- If $v_{kick} > v_{escape}$: BH ejected from galaxy

Calibration of the model

4 free parameters:

- Supernova feedback efficiency
  (fraction of SN kinetic energy transferred to gas)
- AGN feedback efficiency
  (fudge factor parametrizing uncertainties of jet production)
- Radiation drag efficiency
- BH accretion timescale

Galactic disks

- Gaseous disk: exponential density profile, scale radius calculated by L and M of collapsing hot has
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- Jets eject hot gas and bulge cold gas with rates

$$\dot{M}^{QSO}_{\rm b,gas} = \frac{2}{3} \frac{L_{\rm jet,QSO}}{\sigma^2} \frac{M_{\rm b,gas}}{M_{\rm hot} + M_{\rm b,gas}} \qquad \dot{M}^{QSO}_{\rm hot} = \frac{2}{3} \frac{L_{\rm jet,QSO}}{\sigma^2} \frac{M_{\rm hot}}{M_{\rm hot} + M_{\rm b,gas}}$$

$$\sigma = 0.65 V_{\rm vir}$$

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The QSO phase

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$$\dot{M}_{\rm res} = A_{\rm res}\psi_b(t)$$

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$$\dot{M}_{\rm bh,QSO} = \dot{M}_{\rm QSO}(1 - \eta(a_{\rm bh}))$$

- Accretion is coherent if $M_{res} > M_{bh}$, chaotic otherwise
- $\dot{M}$ can be super-Eddington, but L cannot

$$L_{\rm bh,QSO} = \min\left\{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2\,,\ \ L_{\rm Edd}\left[1 + \ln\left(\frac{\eta(a_{\rm bh})\dot{M}_{\rm QSO}c^2}{L_{\rm Edd}}\right)\right]\right\}$$

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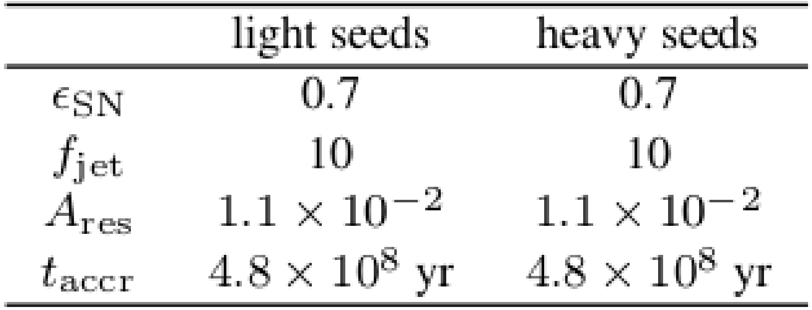
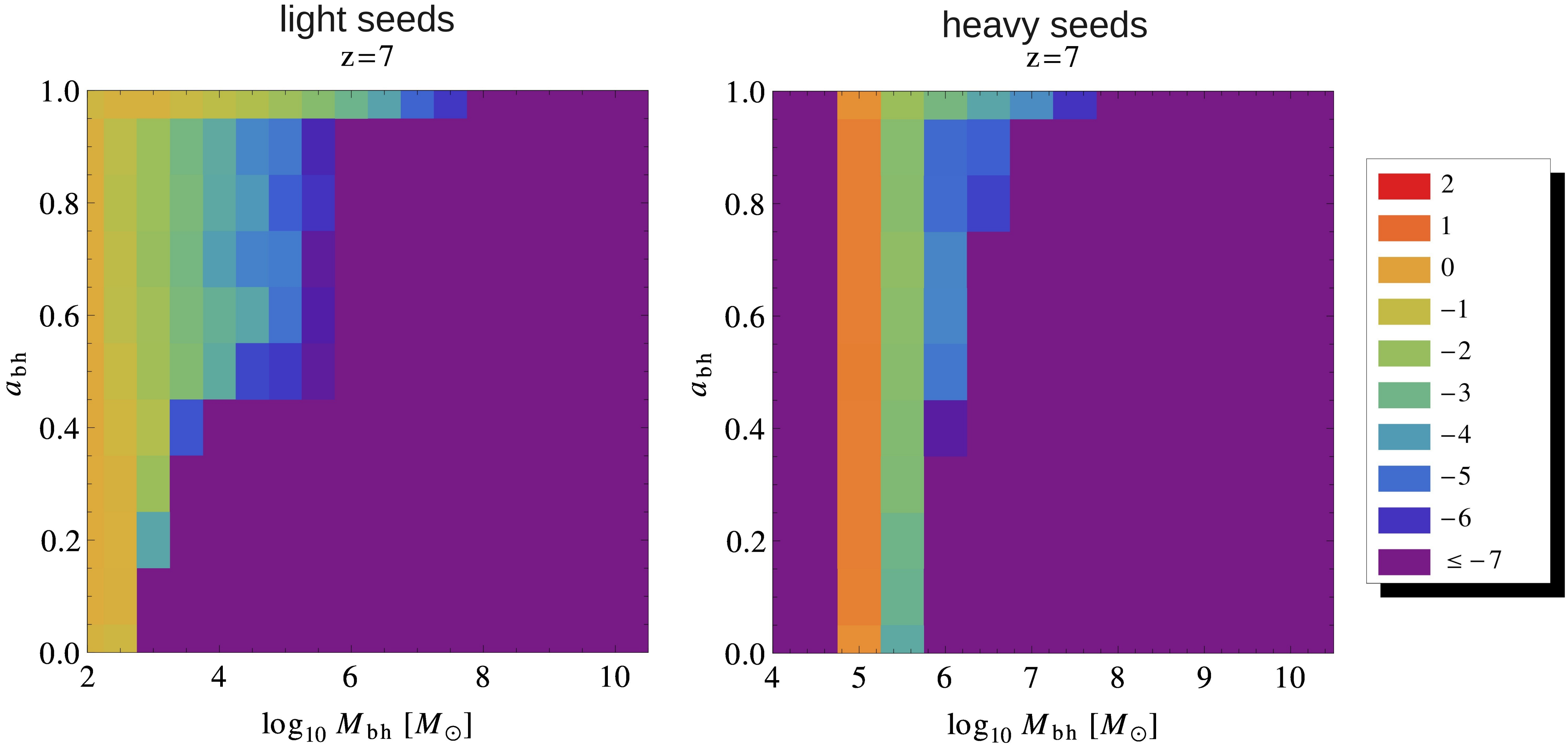
Calibration of the model

- **Observables at z=0**
  - Stellar and baryonic mass function
  - Gas fraction
  - Star formation rate
  - MBH mass function
  - Morphologies (fractions of spirals, ellipticals, irregulars)
  - M-σ and M_{bh}-M_{bulge} relations
- **Observables at z>0**
  - Quasar bolometric luminosity
  - Star formation history



	light seeds	heavy seeds
ϵ_{SN}	0.7	0.7
f_{jet}	10	10
A_{res}	1.1×10^{-2}	1.1×10^{-2}
t_{accr}	4.8×10^8 yr	4.8×10^8 yr

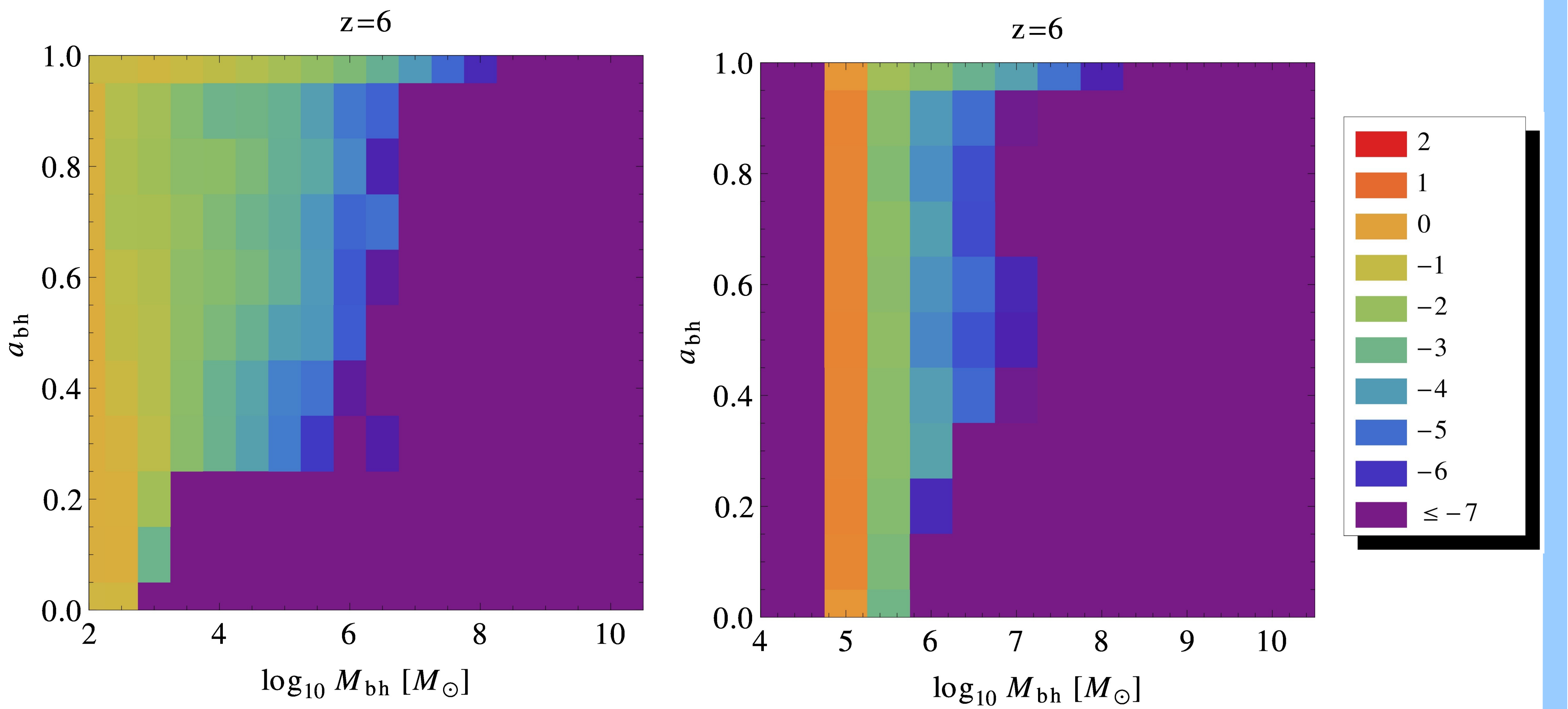
The spin evolution: z=7



Color code = $\log_{10}$ of number density of MBHs per unit log-mass and unit spin, i.e

$$\log_{10}(\mathrm{d}\phi_{\rm bh}[\mathrm{Mpc}^{-3}]/\mathrm{d}a) = \log_{10}(\mathrm{d}^2 n_{\rm bh}[\mathrm{Mpc}^{-3}]/(\mathrm{d}\log_{10} M_{\rm bh}[M_\odot]\,\mathrm{d}a))$$

The spin evolution: z=6



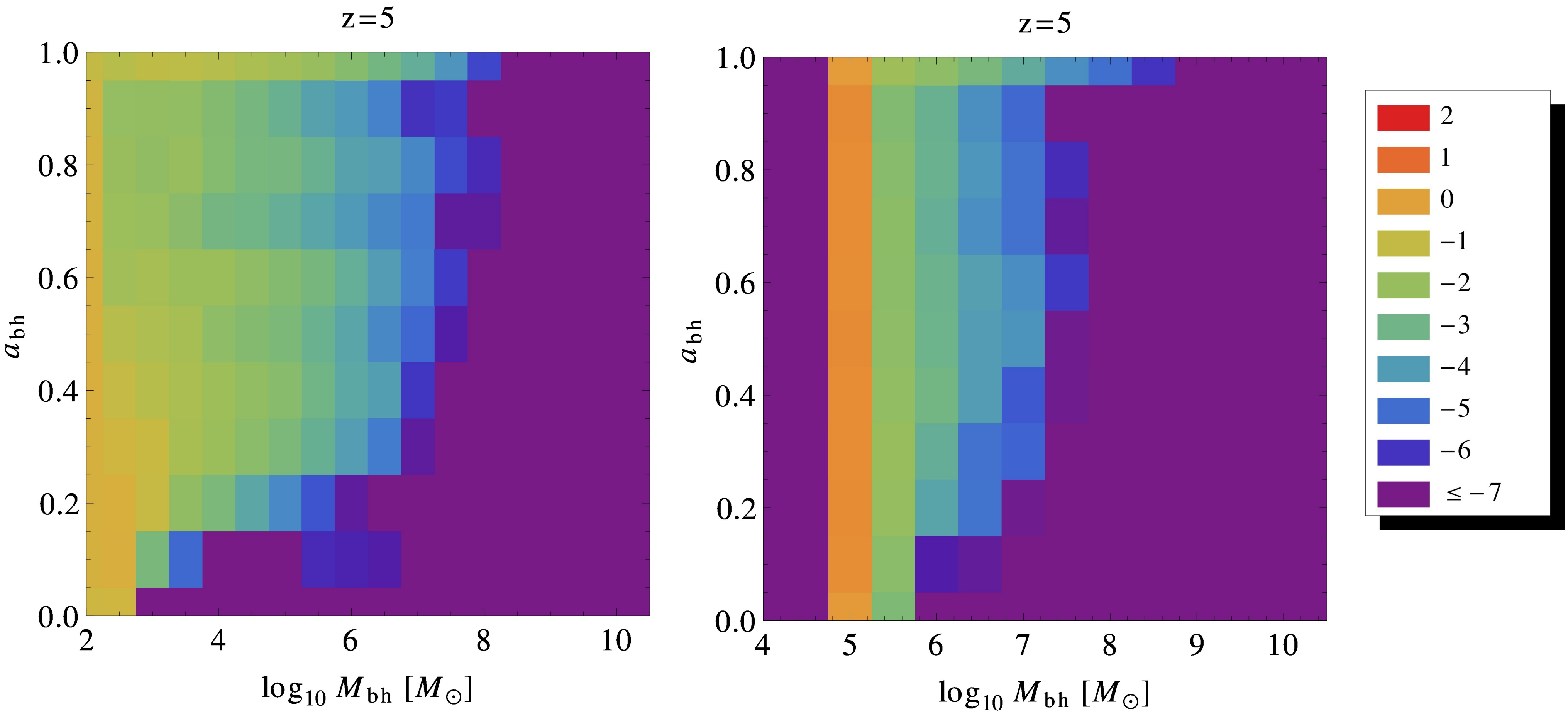
light seeds

heavy seeds

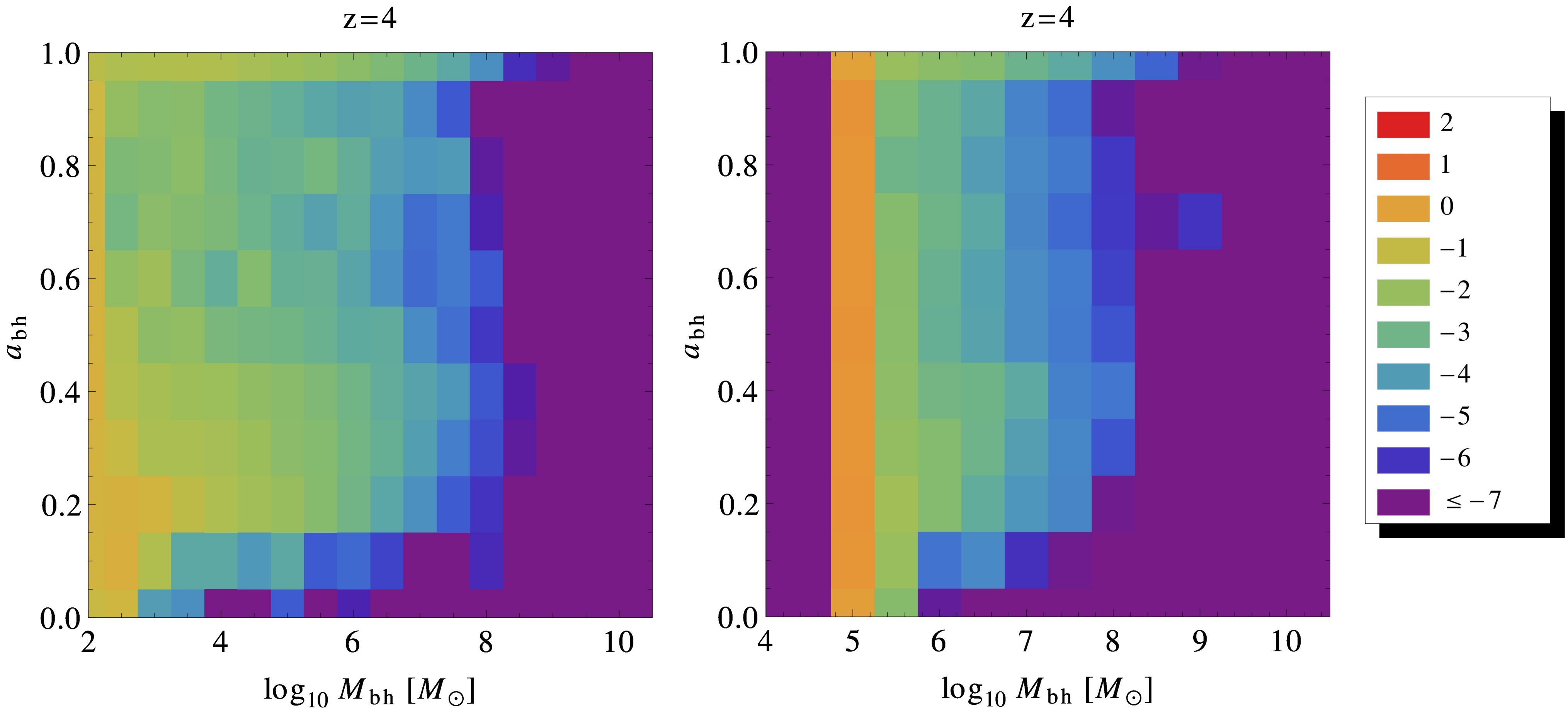
The spin evolution: z=5

light seeds

heavy seeds



The spin evolution: z=4

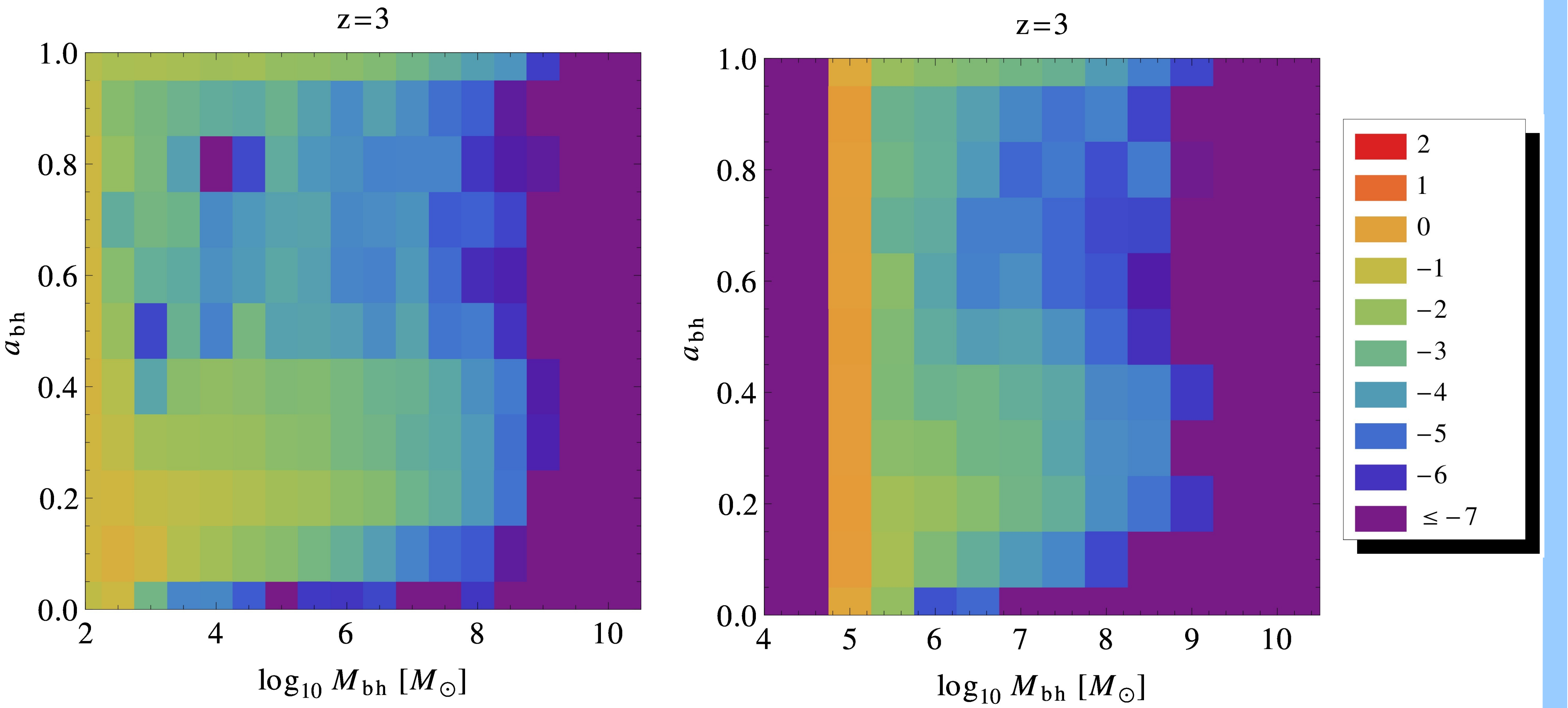

light seeds

heavy seeds

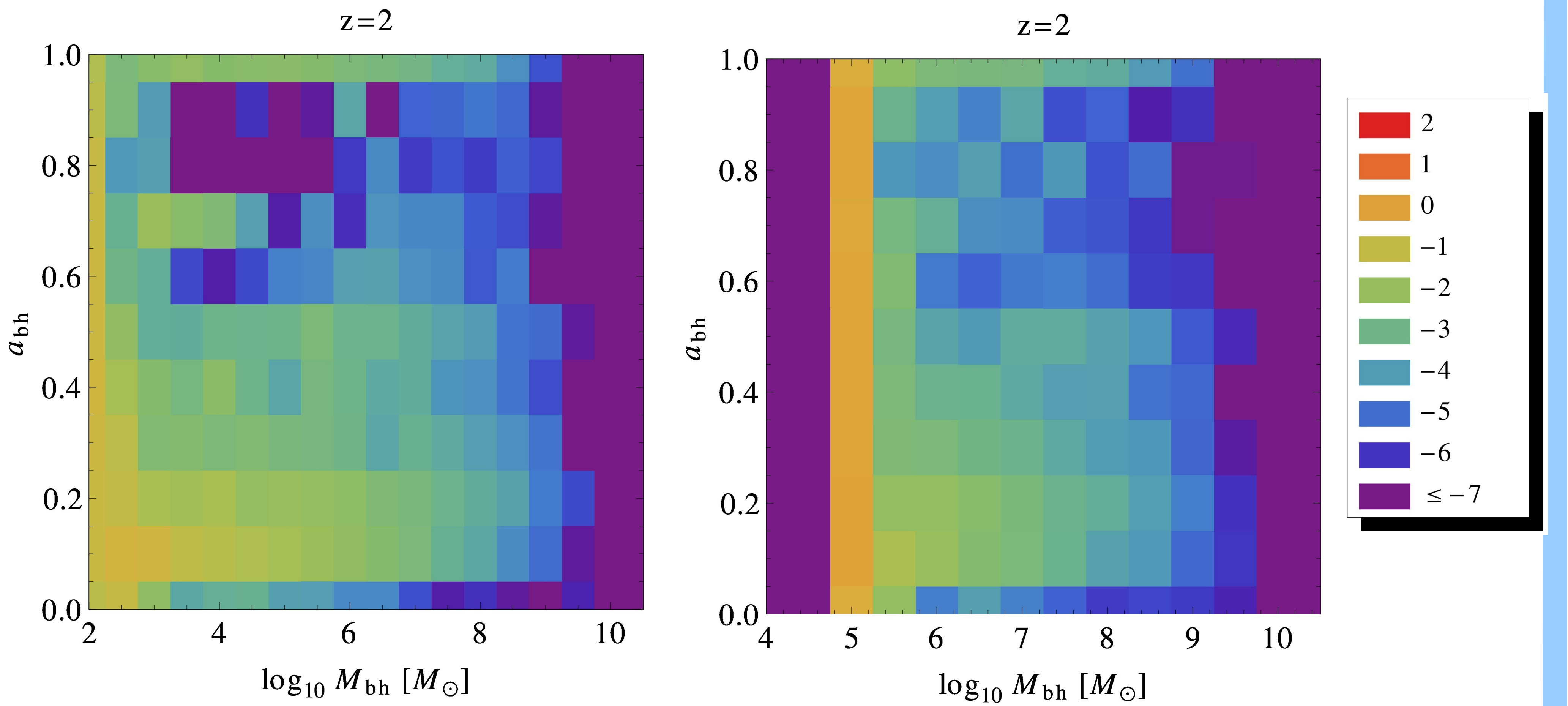
The spin evolution: z=3

light seeds

heavy seeds



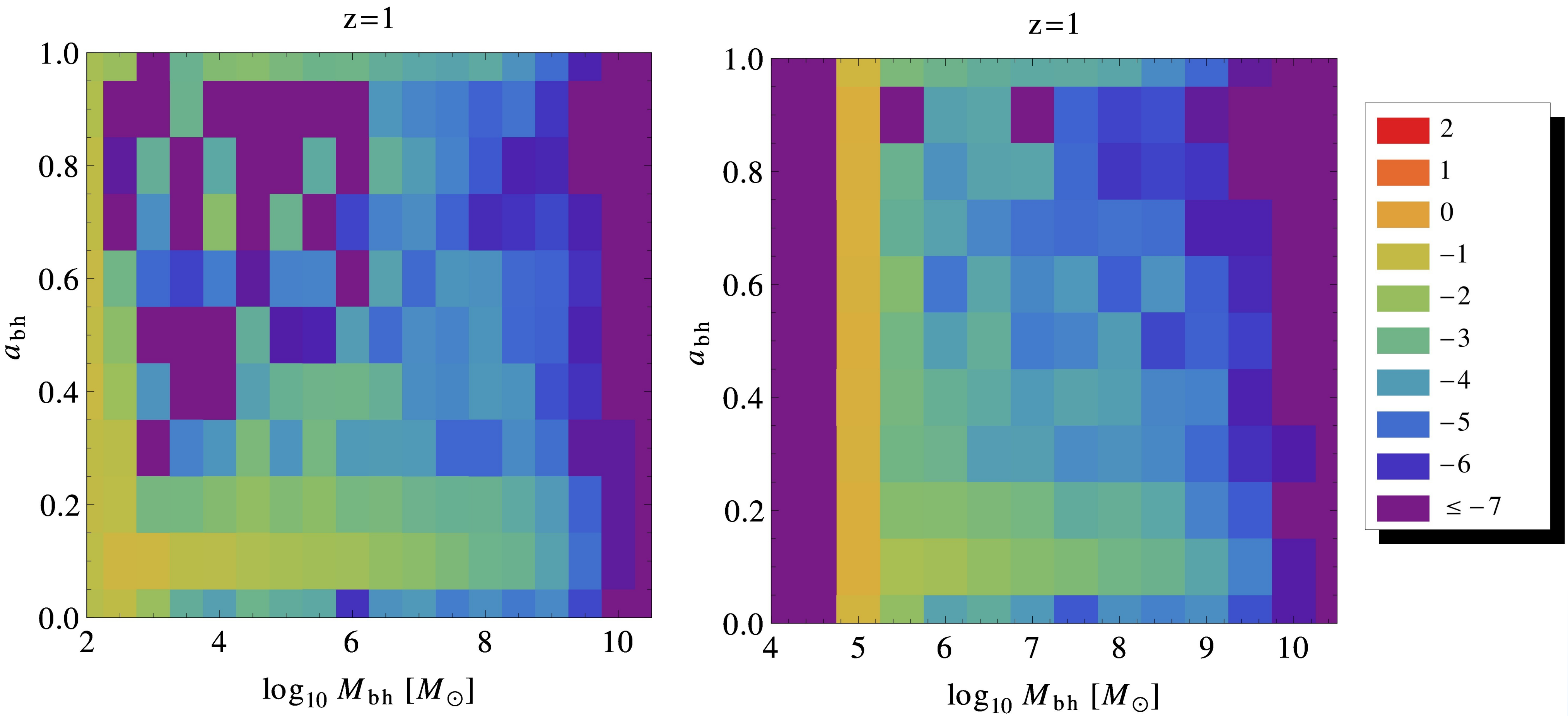
The spin evolution: z=2



light seeds

heavy seeds

The spin evolution: z=1



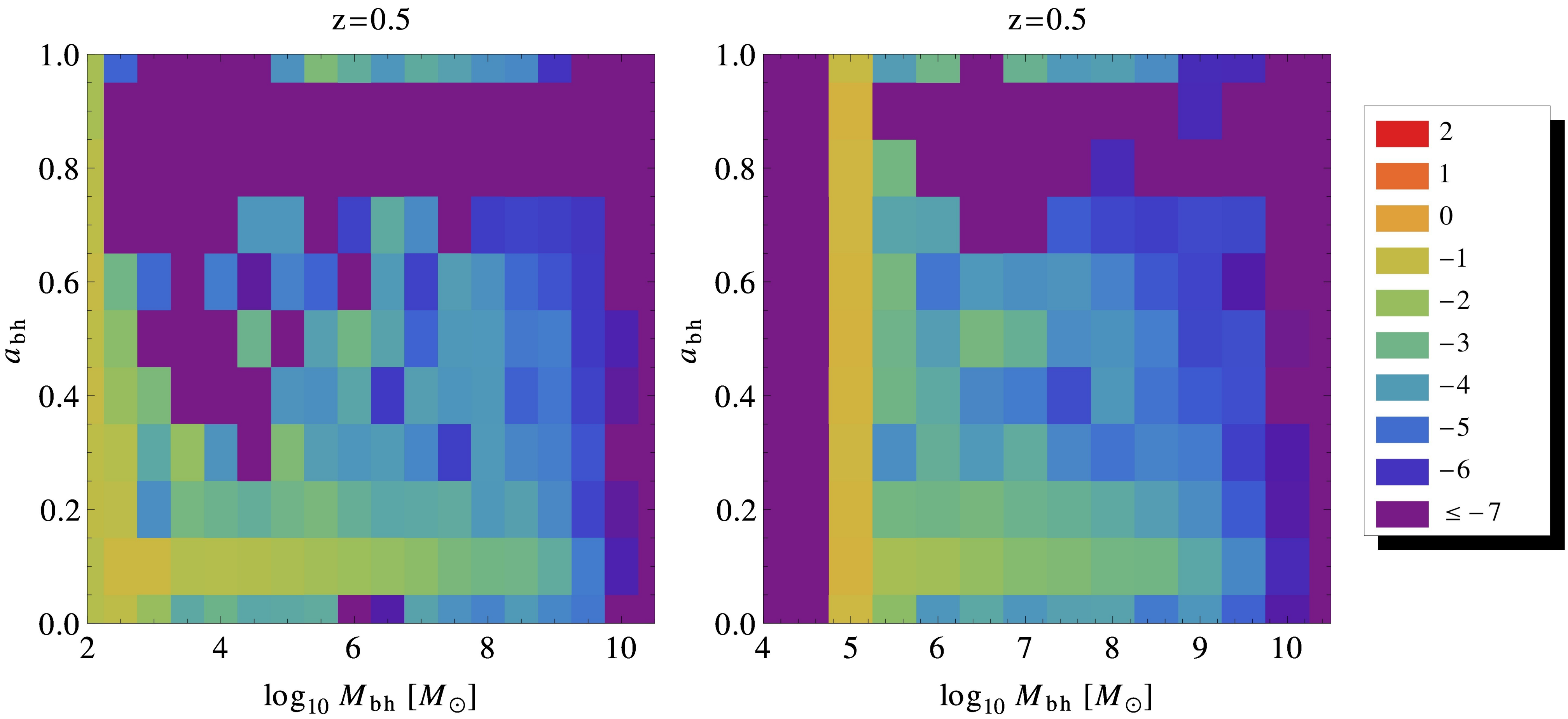
light seeds

heavy seeds

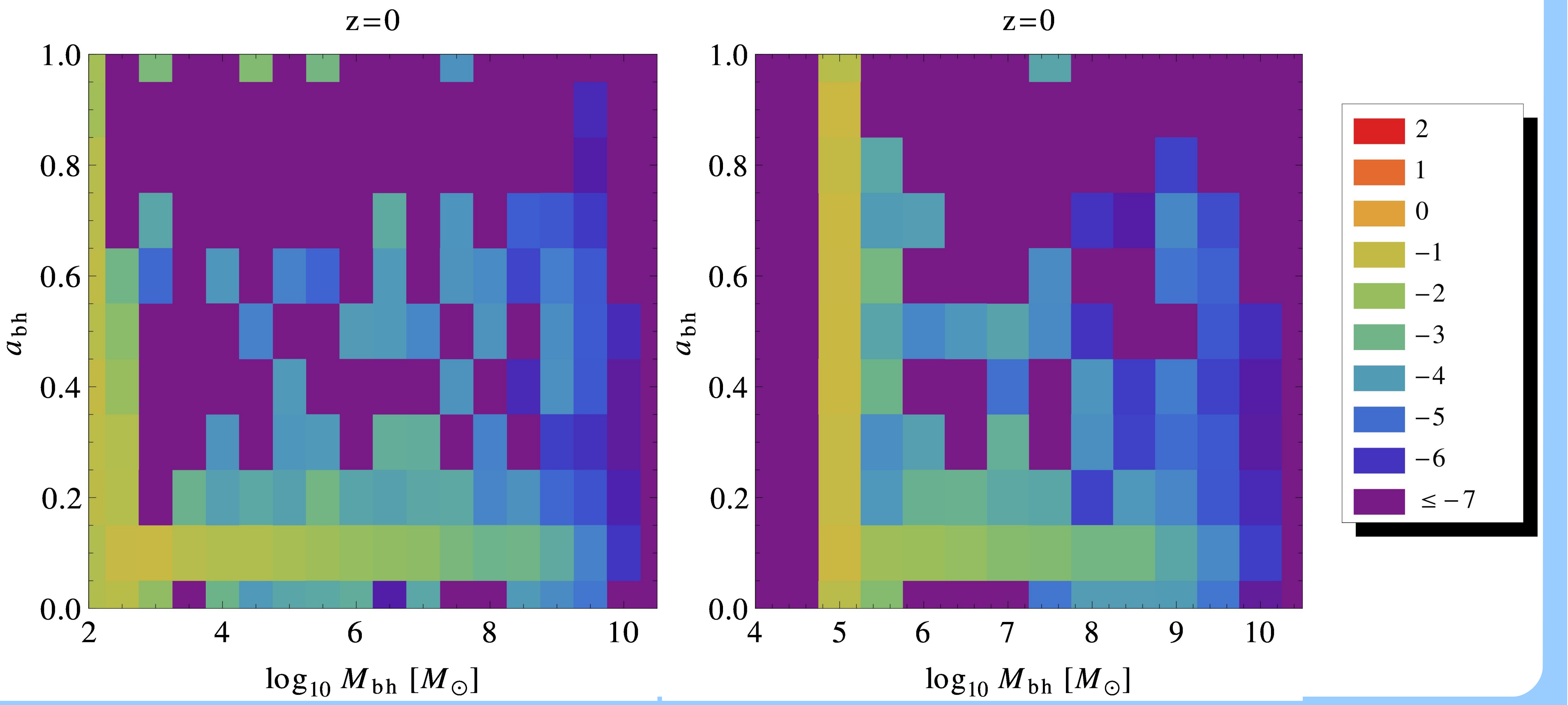
The spin evolution: z=0.5

light seeds

heavy seeds



The spin evolution: z=0



light seeds

heavy seeds

How can we measure MBH spins?

Iron Kα lines: measure inner edge of accretion disk (i.e. ISCO) with X ray telescopes

- Today: only few sources, effect of systematics uncertain
- ~ 2020s: ATHENA (Advanced Telescope for High ENergy Astrophysics): candidate mission for Europe's Cosmic Vision Program

- Higher resolution spectra in iron Kα region

- Will measure spins in sources at $z<0.3$

Problems: only sensitive to BHs in AGNs, low z, selection bias toward large spins, systematics?

A cleaner probe: gravitational waves

- GW detectors will

  - measure masses to within 0.1% and spins to within 1%

  - tell spin-aligned from precessing binaries thanks to spin induced modulation

- Today: sensitive to stellar-mass BHs (few events per yr at low z)

Future GW detectors

Ground based:

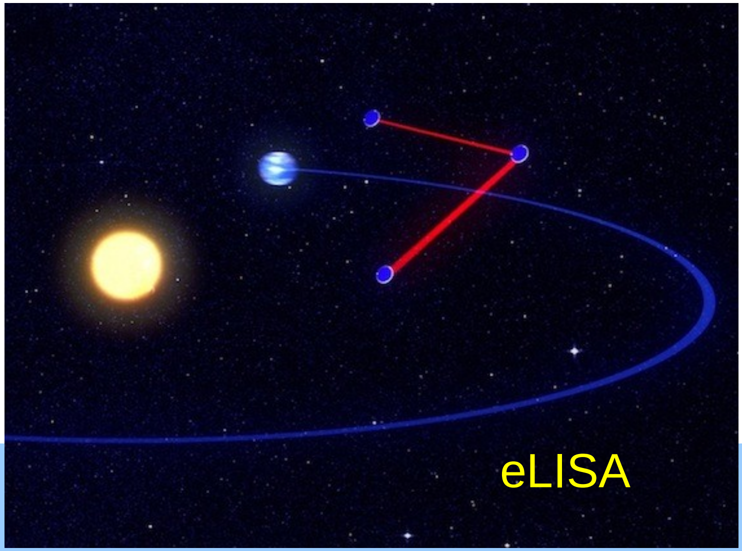
- ~2020s: Einstein Telescope, sensitive to IMBH binaries, z<10-15

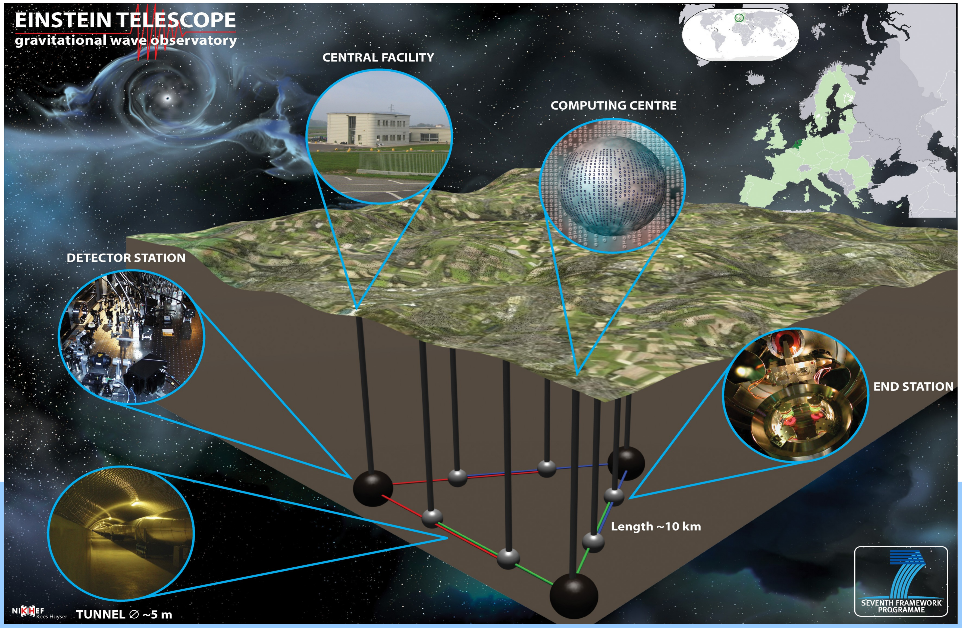
Space based:

- 2020s: eLISA/LISA (evolved Laser Interferometer Space Antenna): candidate mission for Europe's Cosmic Vision program

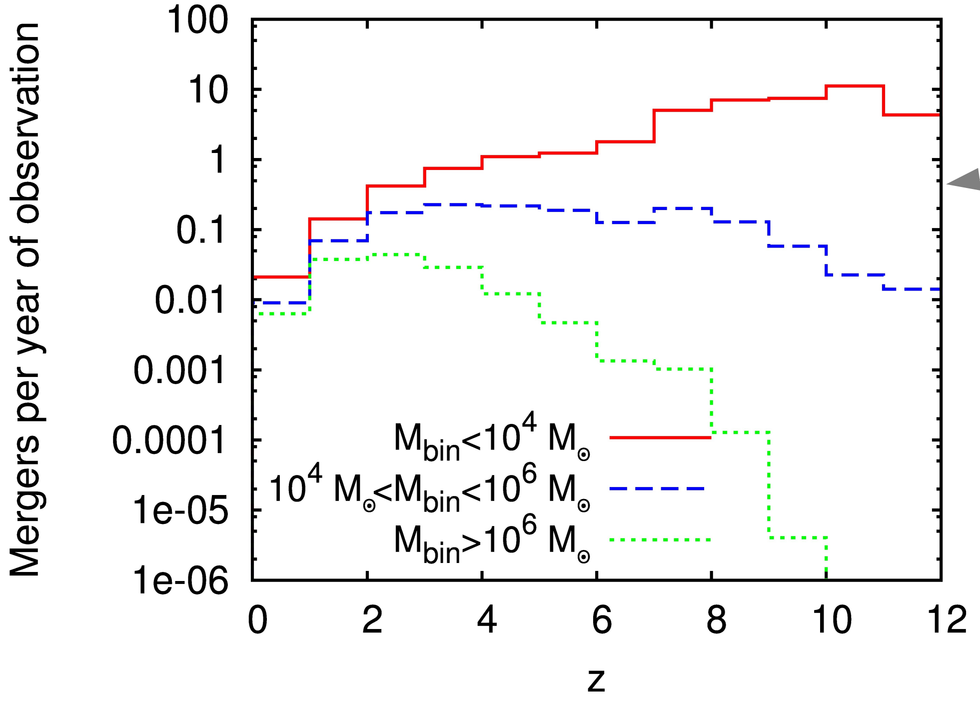
  Sensitive to MBH binaries of ~10^6 M_{sun} for z<10

- DECIGO, BBO (~ 2030s): IMBH and MBH binaries at z<15



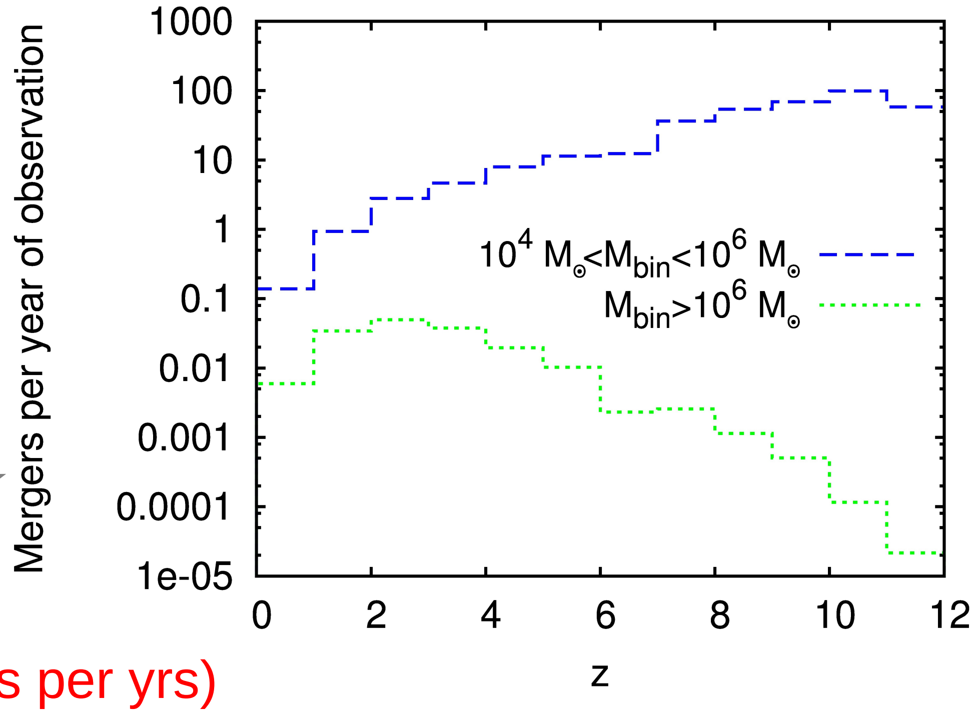


MBH mergers: how many?



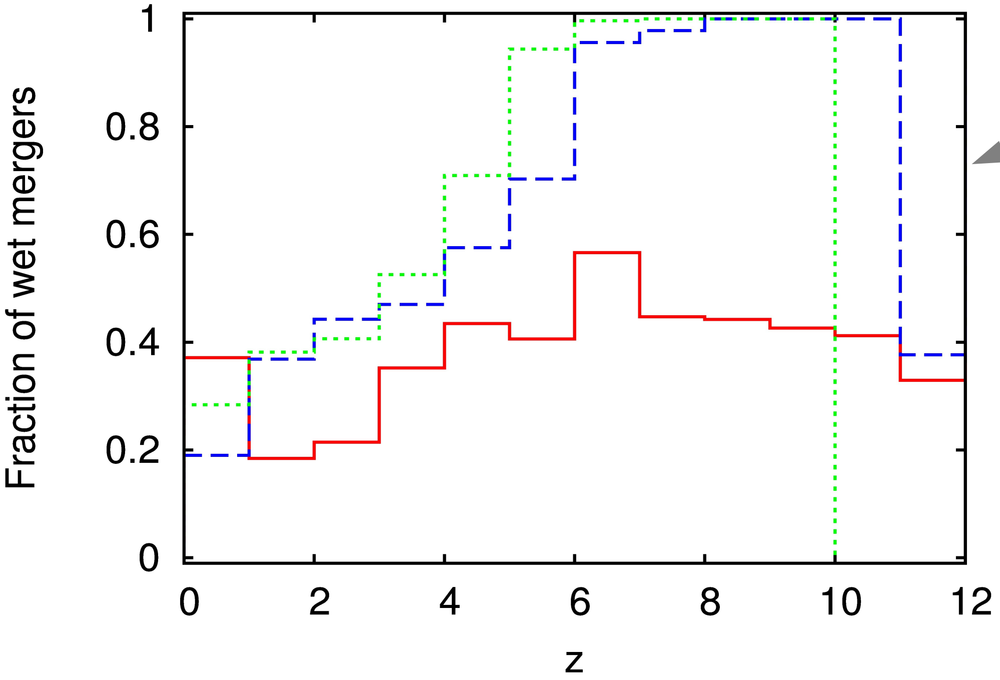
light seeds

heavy seeds



ET sources ~ red (up to hundreds of events per yrs)
eLISA sources ~ blue and green (1-200 events per yr)
DECIGO sources ~ all (hundreds of events per yr)

MBH mergers: wet vs dry



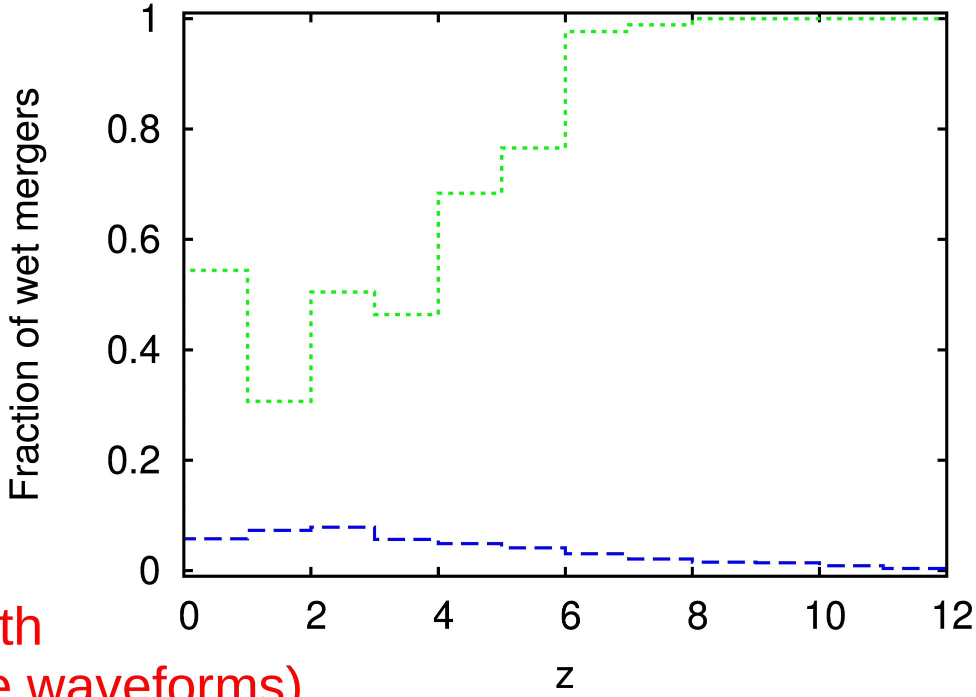
light seeds

Red = $M_{bin} < 10^4\, M_{sun}$

Blue = $10^4\, M_{sun} < M_{bin} < 10^6\, M_{sun}$

Green = $M_{bin} > 10^6\, M_{sun}$

heavy seeds

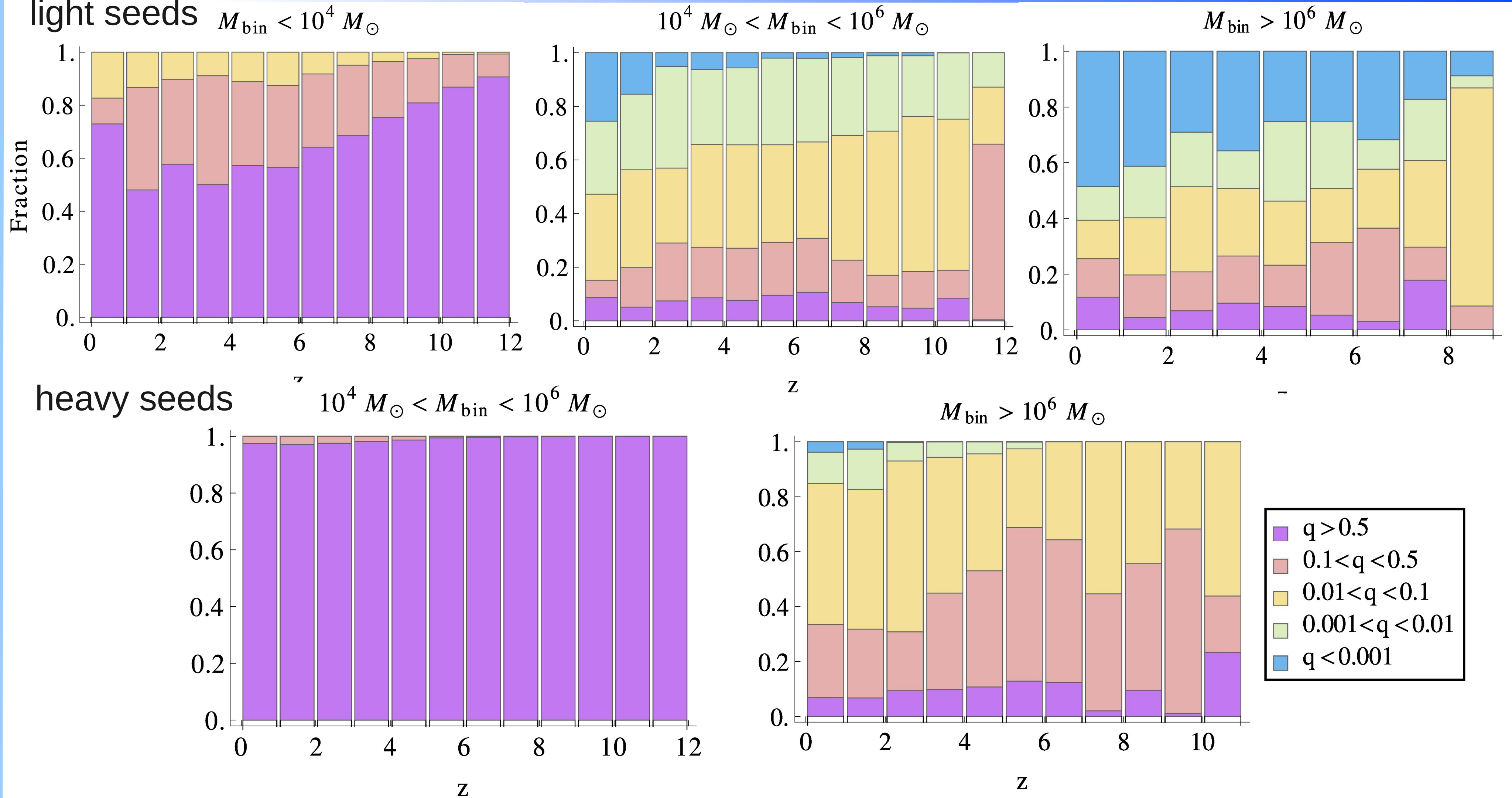


Fraction of wet/dry mergers observable with eLISA/ET/DECIGO (spin modulation in the waveforms)

MBH mergers: the mass ratios

light seeds

heavy seeds

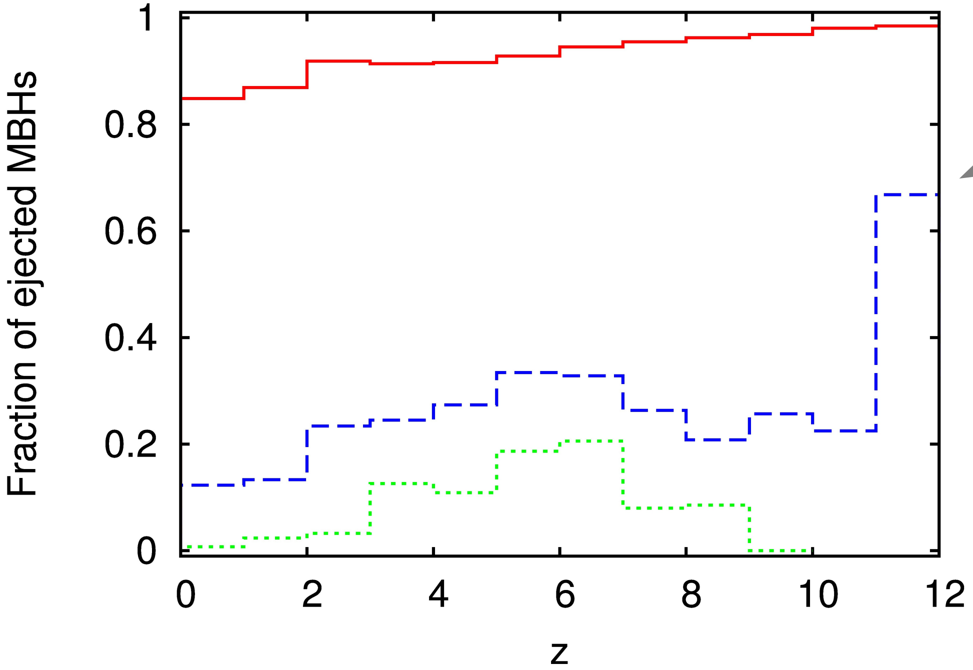


Testable with eLISA/ET/DECIGO

Conclusions and future work

- Evolution of MBH masses and spins entangled with galaxy evolution (AGN feedback on galaxy, gas regulates accretion and spin alignment)
- High spins and wet mergers at $z \gtrsim 3$ (when galaxies are gas rich), low spins and dry mergers at $z \lesssim 3$ (when galaxies sterilized by AGN feedback)
- Confirm that eLISA/NGO will see at least a few events per yr, and will be able to test MBH-gas interaction (by telling aligned binaries from precessing ones)
- Future work:
- ➔ Calculate more precise event rates for LISA account for spin effects in the waveforms (eg with EOB model, EB & Buonanno 2010,2011)
- ➔ Consider alternative galaxy formation models (Cook, EB et al 2010) and their impact on MBH spins and eLISA/NGO rates

How many wandering MBHs?



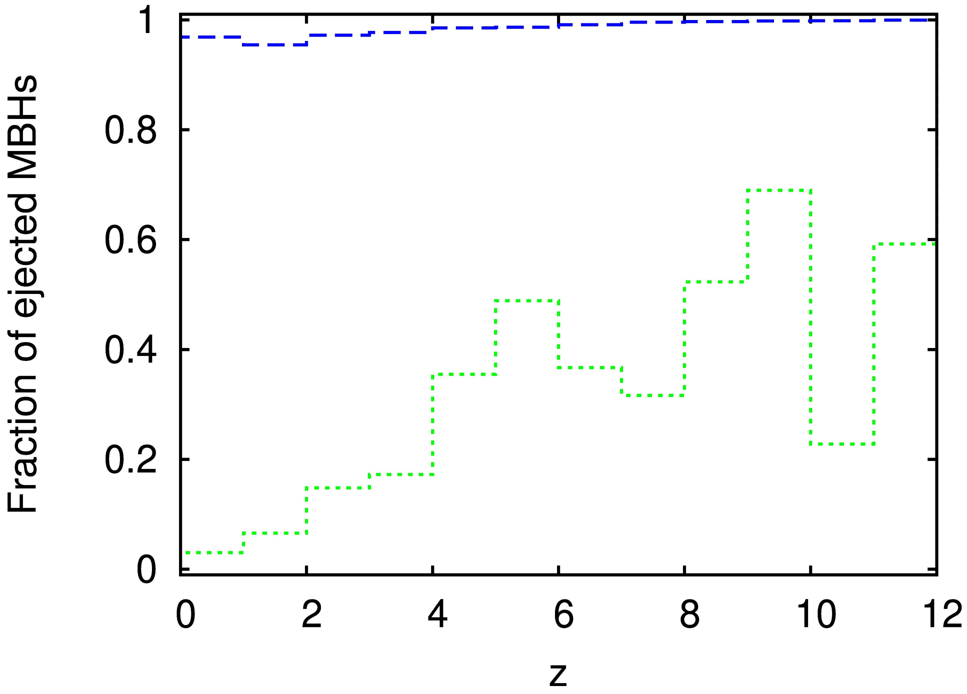
light seeds

Red = $M_{bin} < 10^4\,M_{sun}$

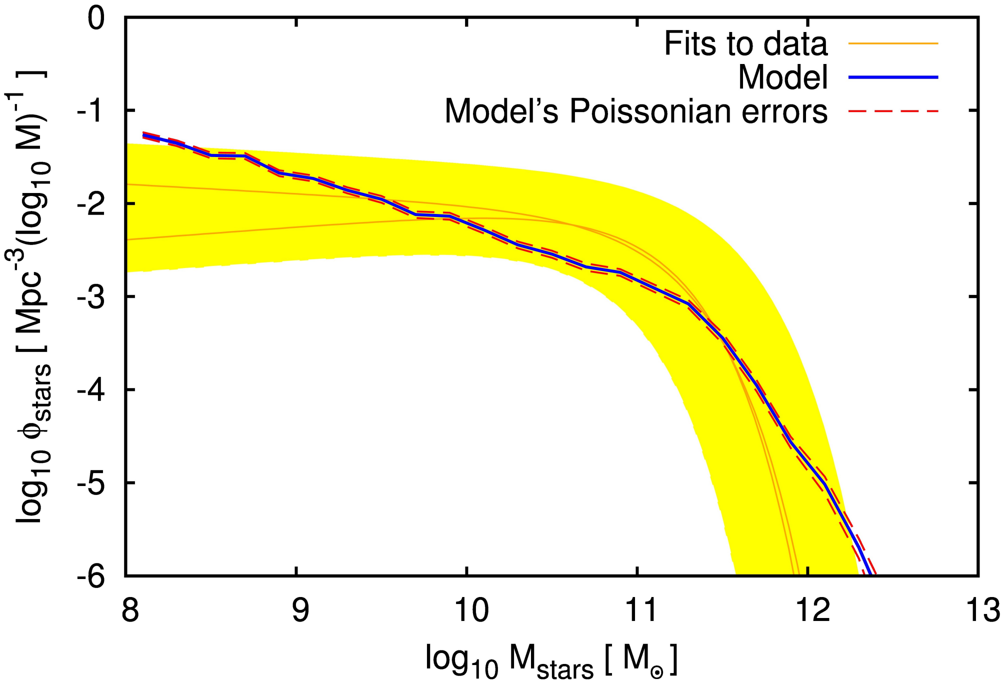
Blue = $10^4\,M_{sun} < M_{bin} < 10^6\,M_{sun}$

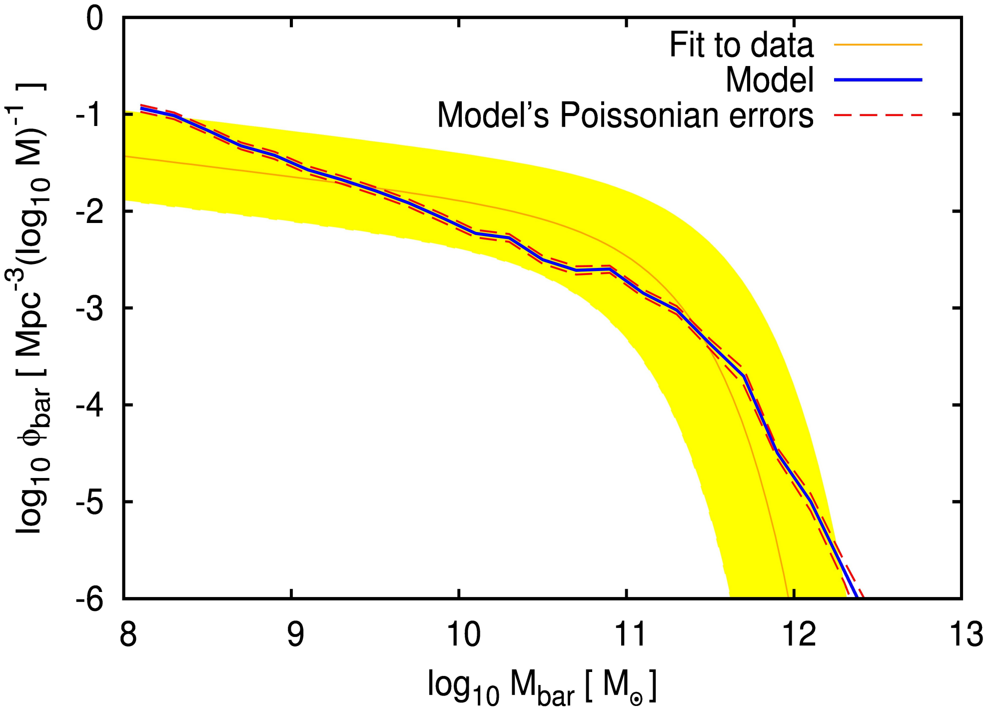
Green = $M_{bin} > 10^6\,M_{sun}$

heavy seeds



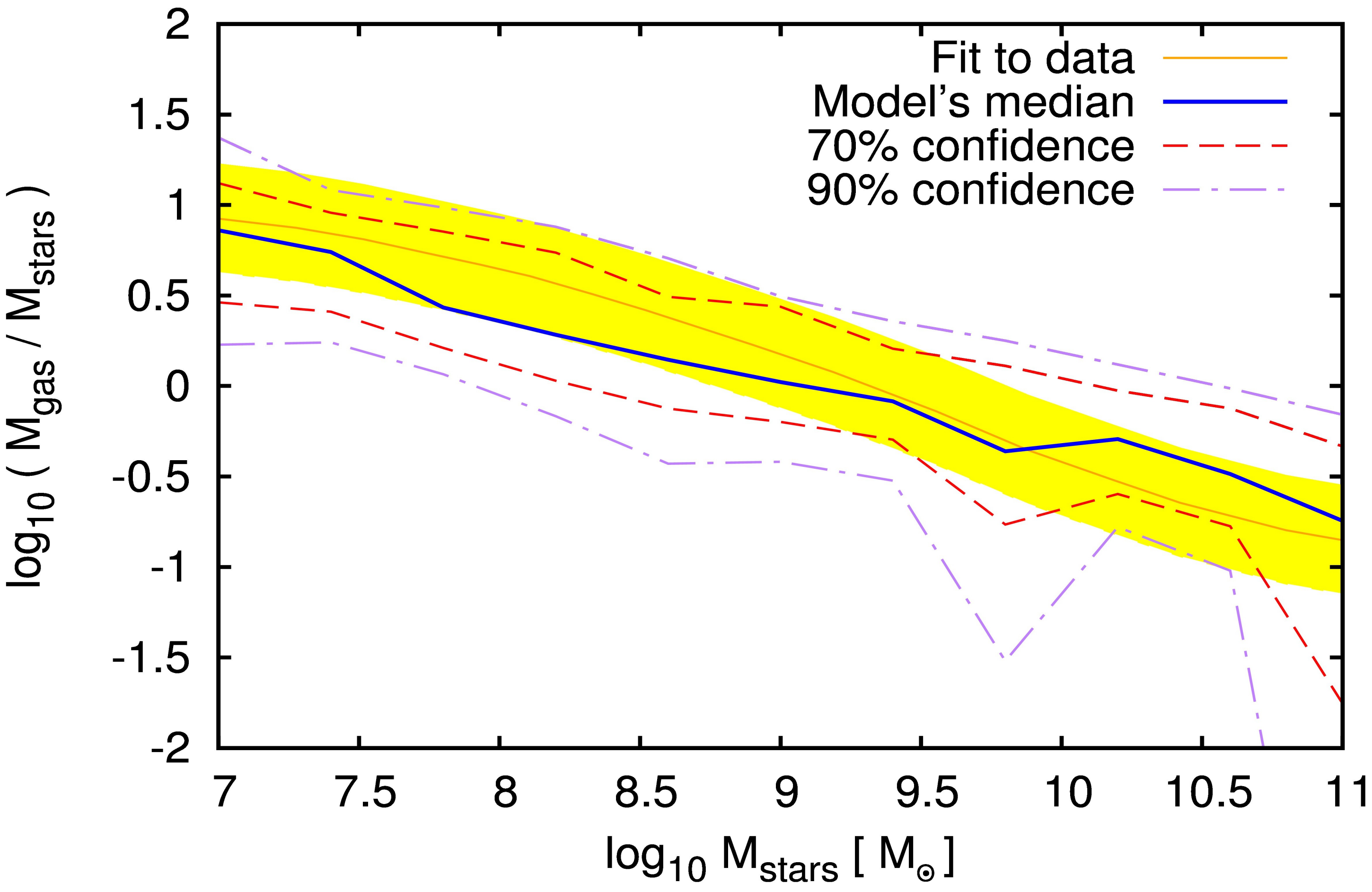
Stellar and baryonic mass function at z=0





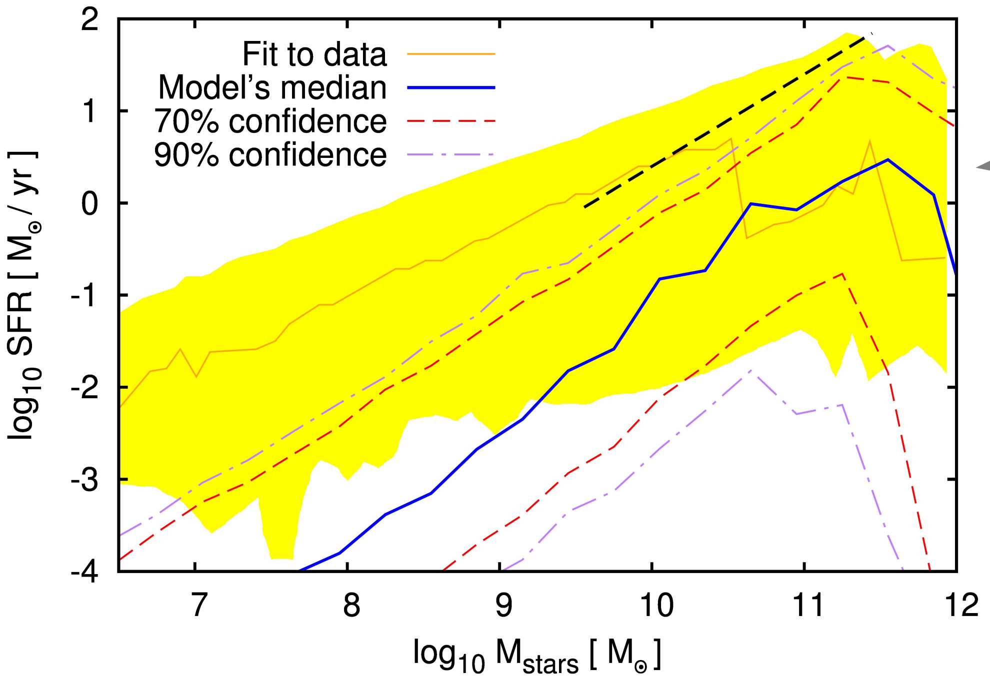
Observational fits from Bell et al 2003

Gas fraction at z=0



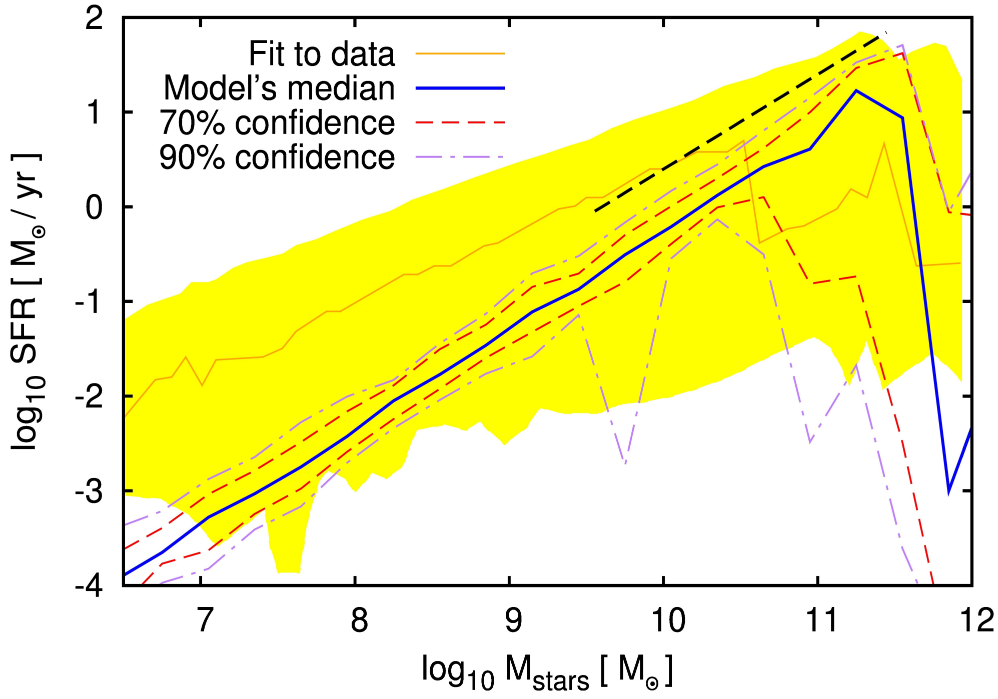
Observational fit from Baldry, Glazebrook, & Driver (2008)

Star formation rate at z=0



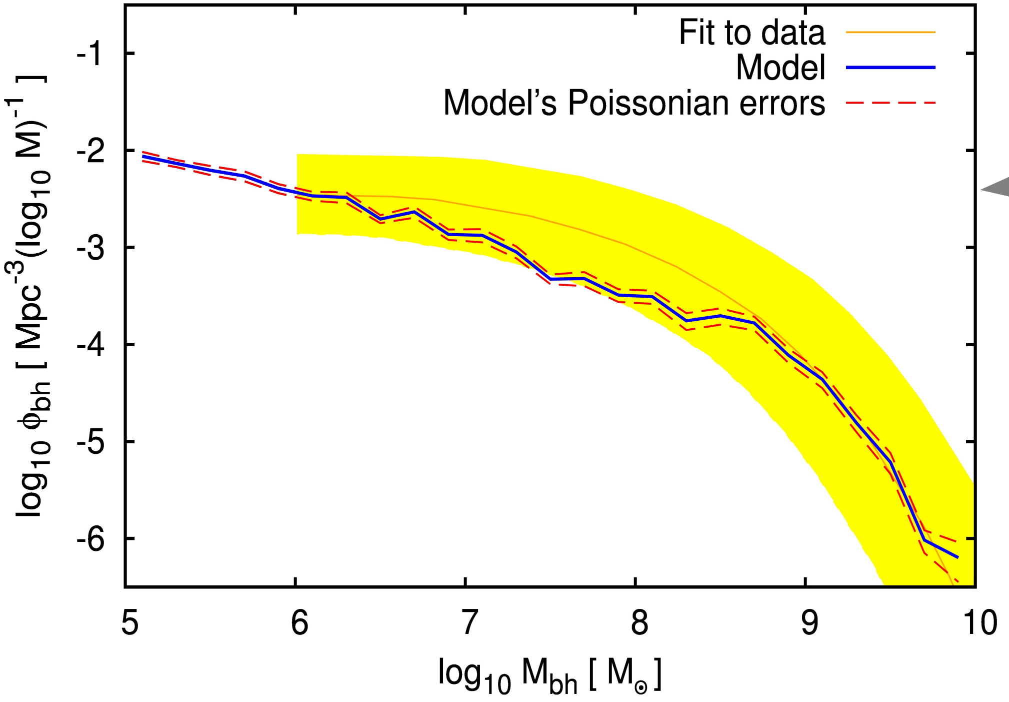
All galaxies (including satellites)

Only central galaxies (no satellites)



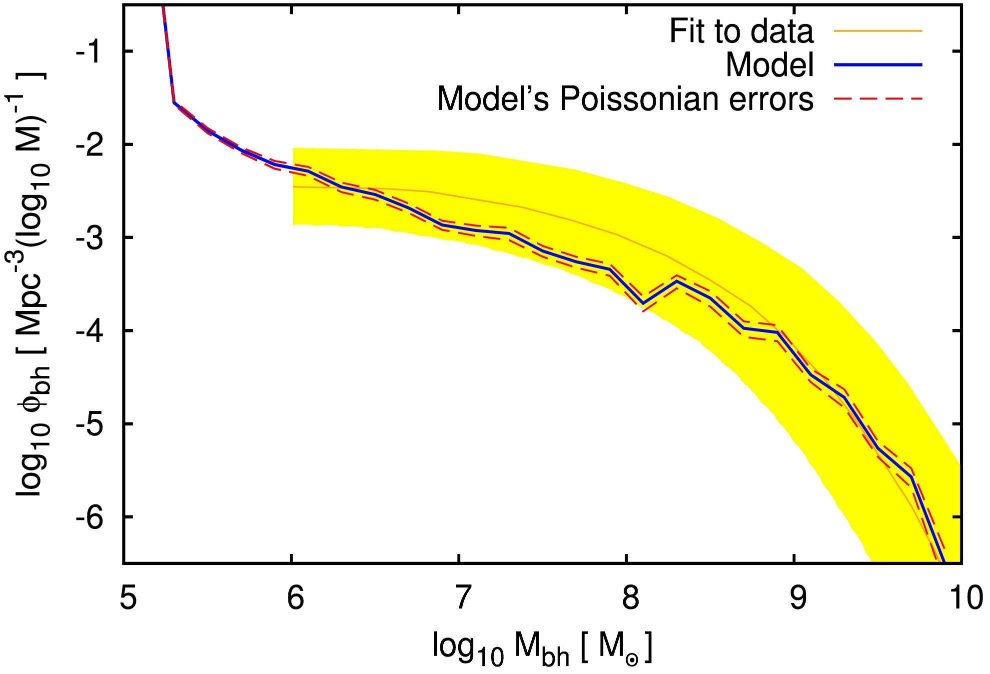
Observational data and fits from
Brinchmann et al 2004 and Elbaz et al 2011

MBH mass function at z=0



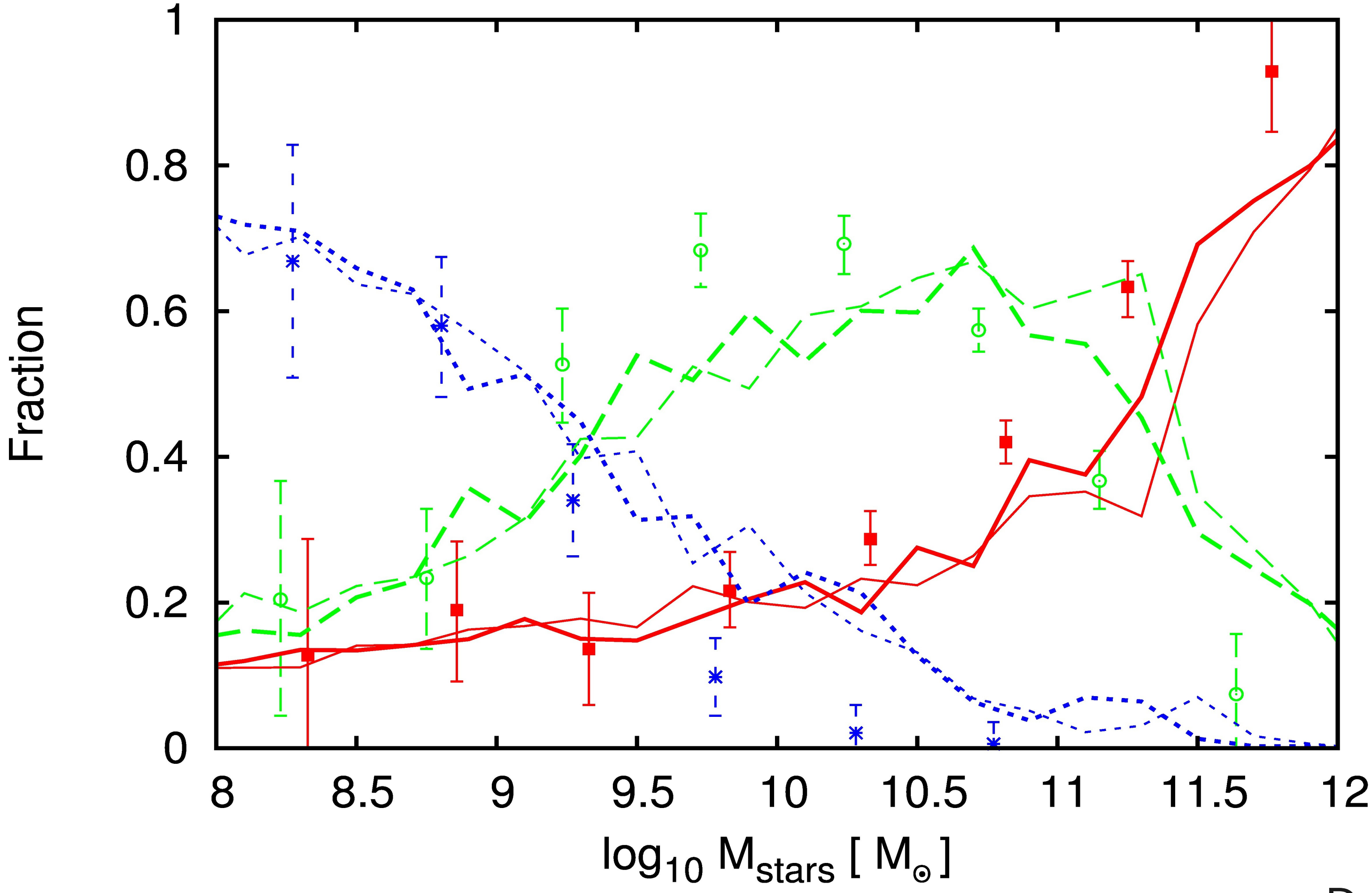
light seeds

heavy seeds



Observational fit from Marconi et al 2004

Morphologies at z=0

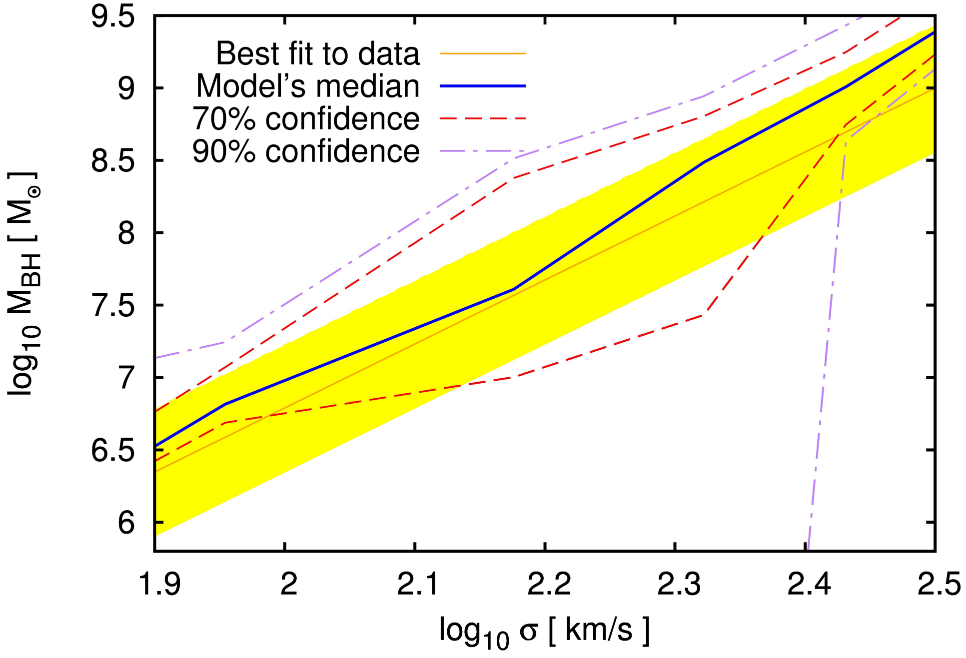


red=ellipticalls
green=spirals
blue=irregulars

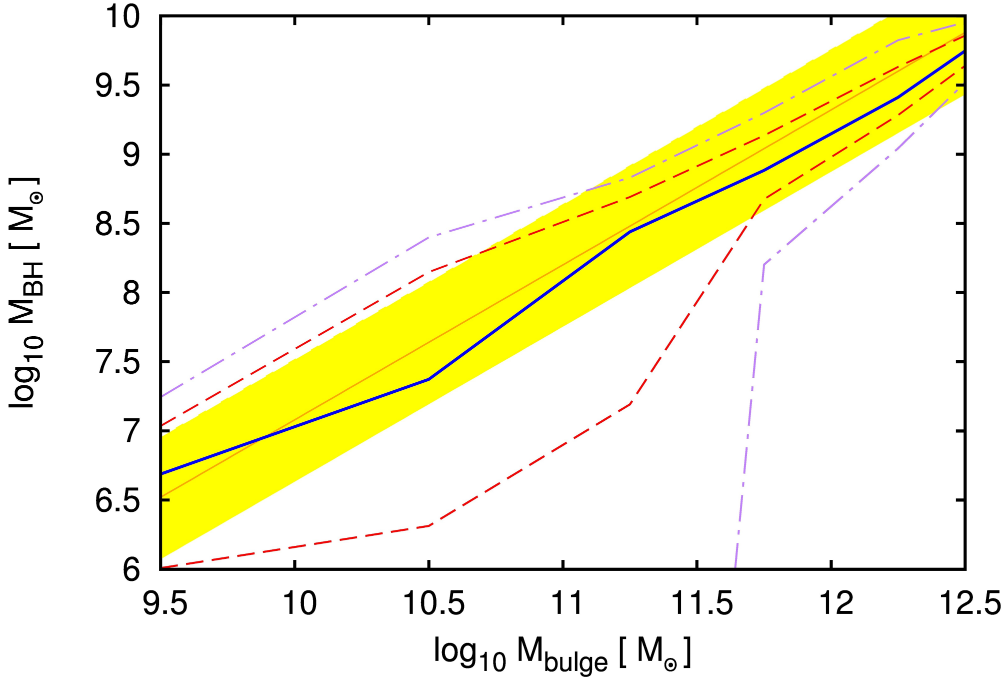
thick=heavy seeds
thin=light seeds

Data from Conselice 2006

M-σ and "Magorrian" relations at z=0

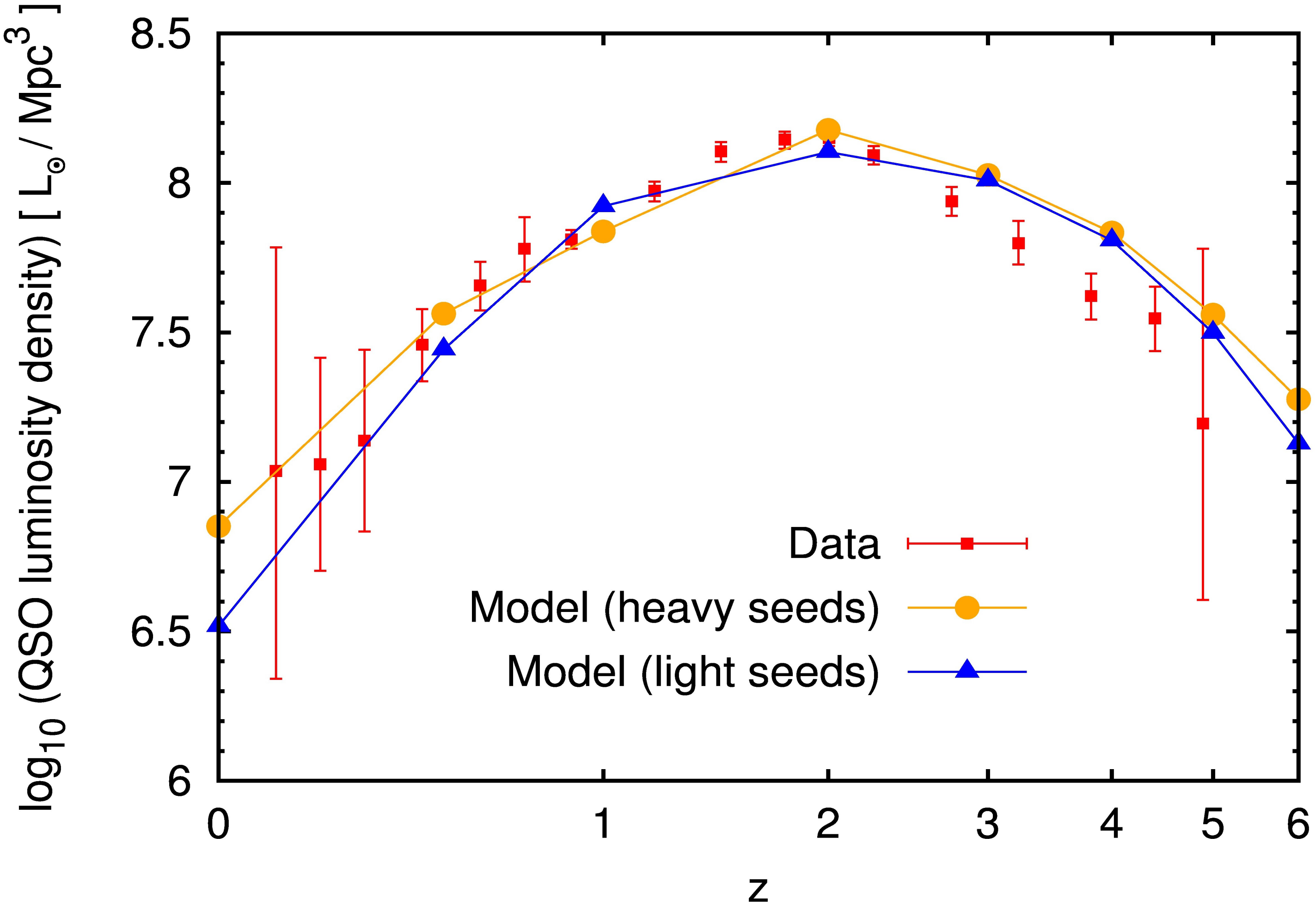


Observational fits from Gultekin et al 2009 and Haring & Rix 2004



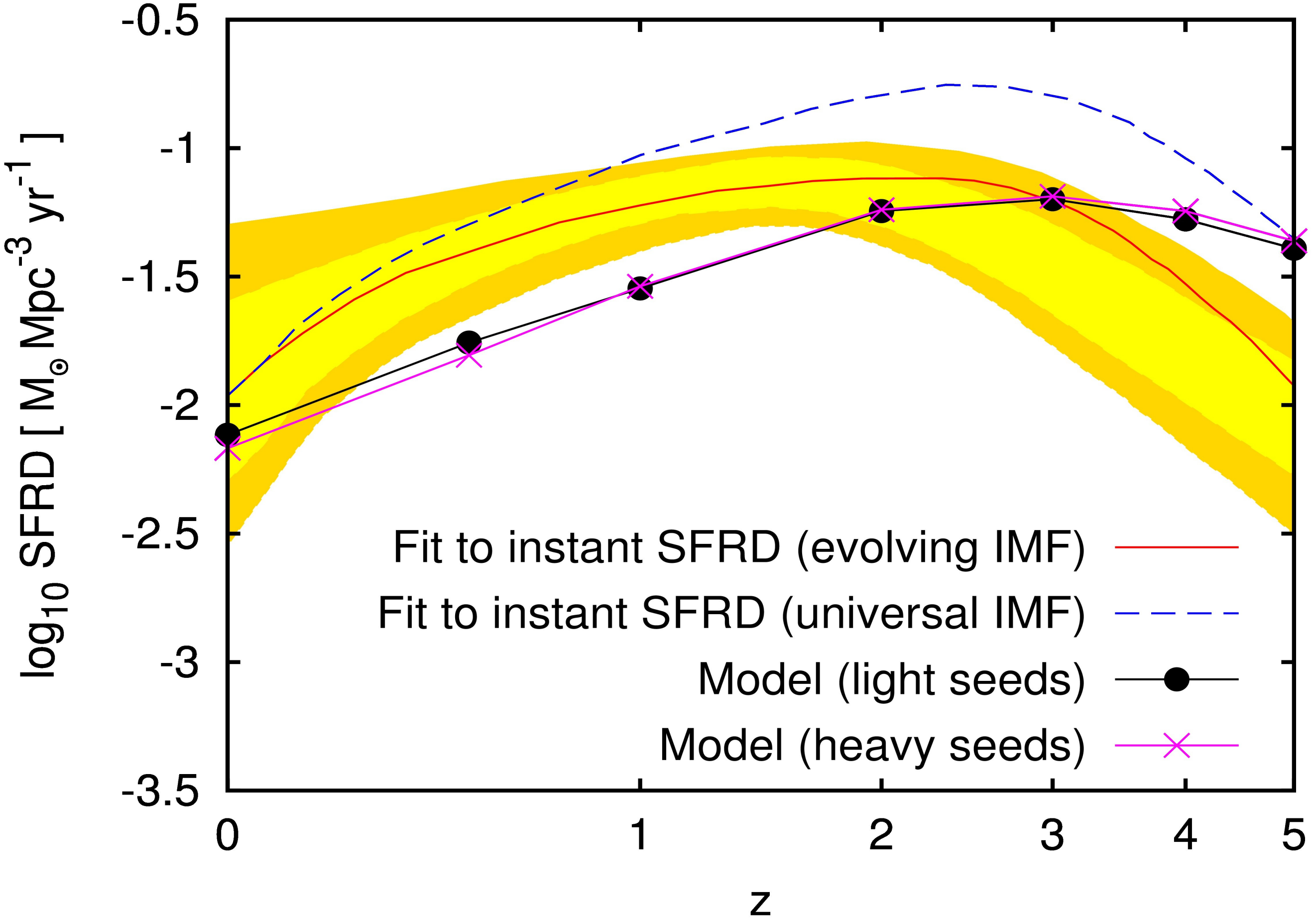
- Includes only central ellipticals
- Significant number of outliers, increased if satellites and disk galaxies are included

QSO luminosity



Observations from Hopkins, Richards & Hernquist 2007

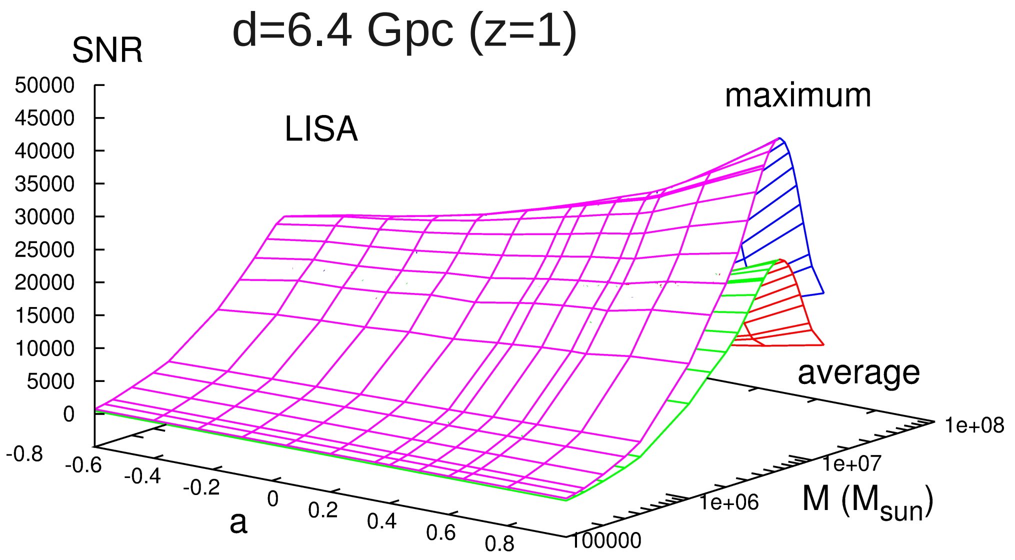
Star formation history



Data and observational fits from Wilkins, Trentham & Hopkins 2008

A cleaner probe: gravitational waves

- GW detectors will
  - measure masses to within 0.1% and spins to within 1%
  - tell spin-aligned from precessing binaries thanks to spin induced modulation
- GW event rates and SNR strongly dependent on BH spins



A cleaner probe: gravitational waves

Ground-base detectors

- 2015: Adv LIGO/Virgo, GEO600, TAMA300 sensitive to stellar-mass BH binaries at low z's, events ~ a few
- ~2020s: Einstein Telescope, sensitive to IMBH binaries (up to hundred of events), z<10-15

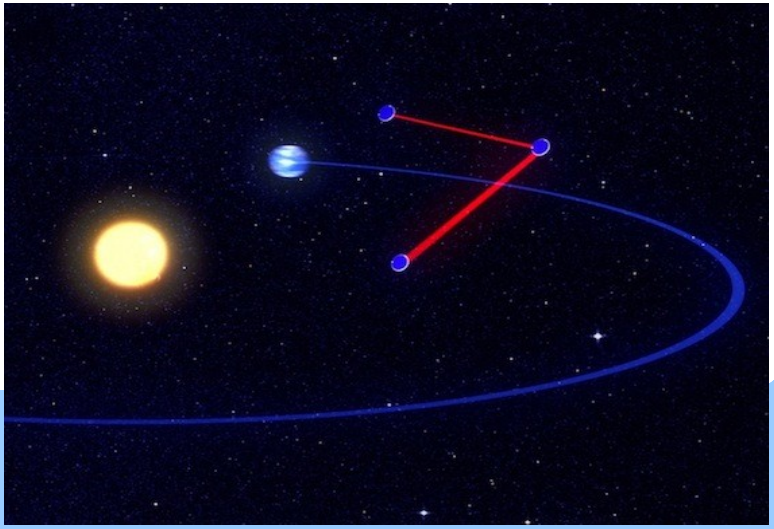
A cleaner probe: gravitational waves

Space based missions:

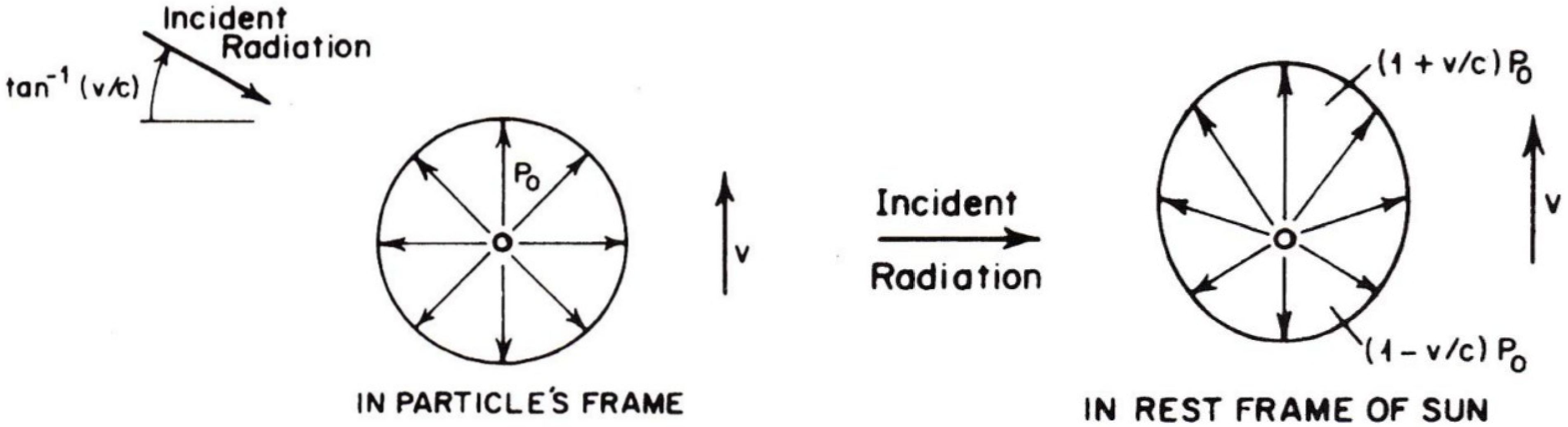
- 2020s: eLISA (evolved Laser Interferometer Space Antenna): 1 of 3 candidates for flagship mission of Europe's Cosmic Vision program

  Sensitive to MBH binaries of ~10^6 M_{sun} (few-100 events at z<10)

- DECIGO, BBO (2nd gen space-based dectors, 2030?): IMBH and MBH binaries at z<15 (hundreds of events)



Radiation drag



THE END