Stochastic and resolvable gravitational waves from ultralight bosons

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based on

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Outline

- A review of boson condensate formation around spinning BHs and their GW emission

- ~~Astrophysical models for spinning BHs~~

- Constraints on boson masses in the LISA and LIGO bands by

  - Direct detections

  - Stochastic backgrounds

  - “Holes” in Regge plane

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Why light bosons?

- Scalars ubiquitous in string theory, inflation, dark matter models
- Useful as toy models for unknown phenomena/ interactions (e.g. modifications of GR)
- Effect of mass term expected to be qualitatively the same as for vector/tensor degrees of freedom

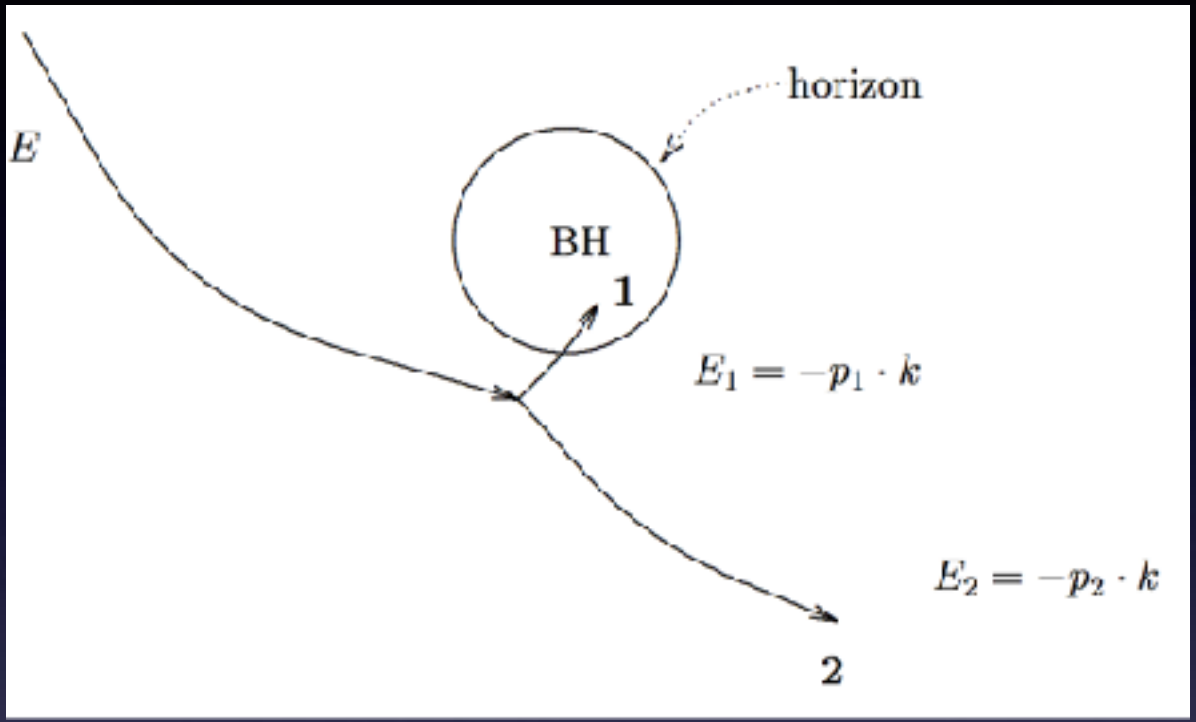
Self-gravitating scalar configurations

- Scalars can form self-gravitating configurations, especially if complex, massive (to avoid dispersion to infinity) and time dependent (to provide pressure): boson stars, oscillatons

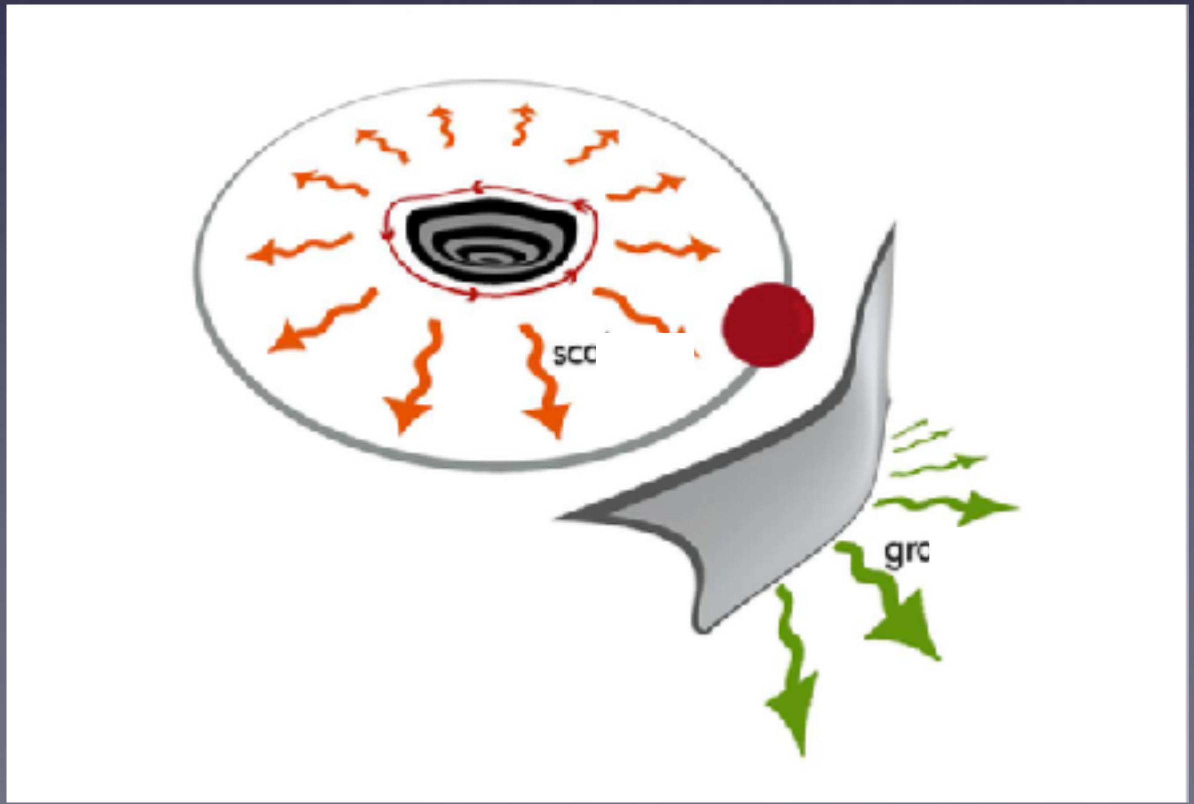
- Around BHs, massive real (complex) scalars can form quasi-stationary (stationary) configurations: boson clouds or condensates, hairy BHs

BH-boson condensates

- Formation linked to superradiant instabilities/Penrose process (amplifications of scattered waves with $\omega < m\Omega_H$

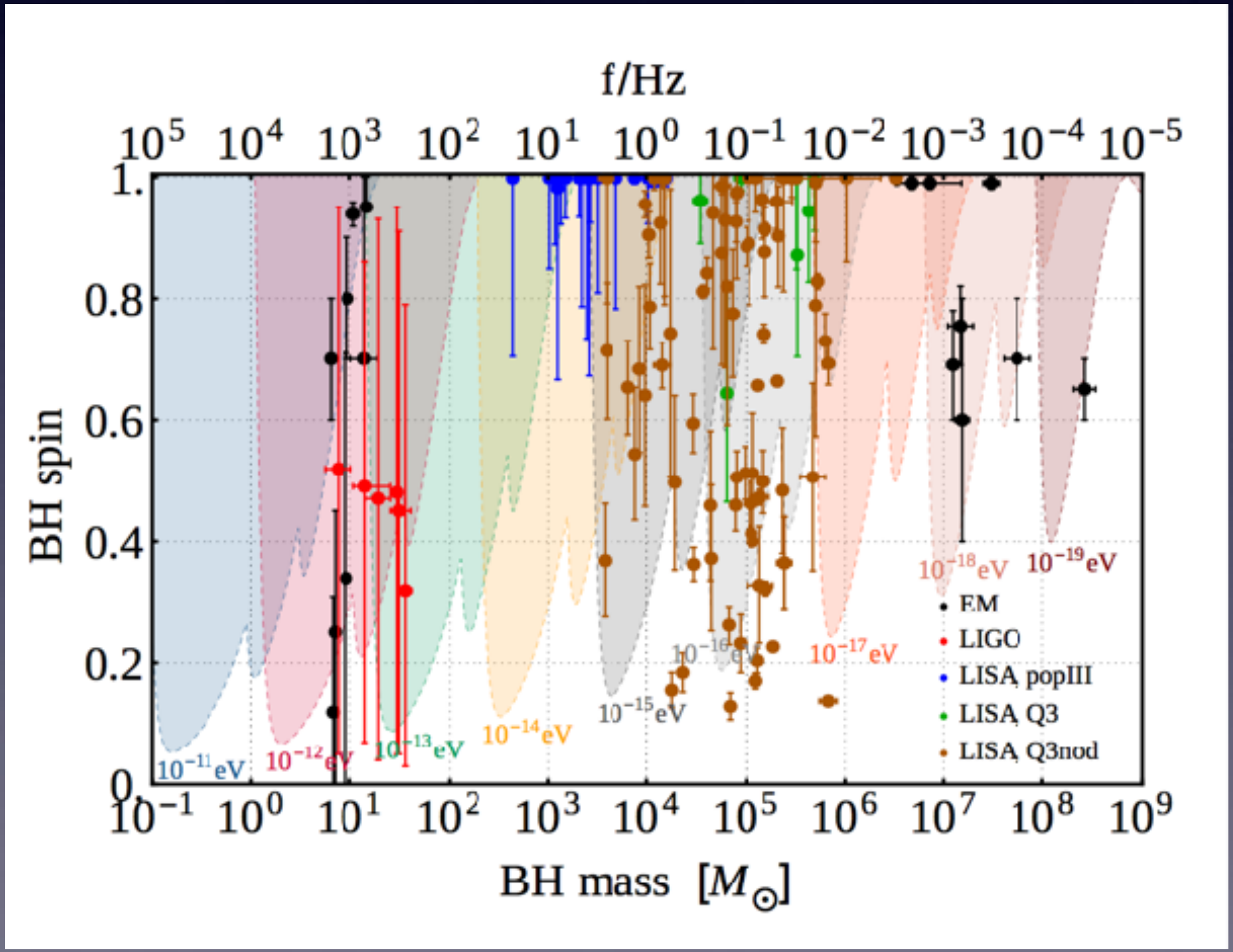


- BH with high enough spin in a mirror box are superradiance unstable (BH bomb; Zeldovich 71, Press & Teukolsky 72, Cardoso et al 04)



BH-boson condensates

- Same instability of spinning BH + massive boson (mass acts as “mirror” and allows for bound states), but NOT for fermions. Cf Damour, Deruelle & Ruffini 76



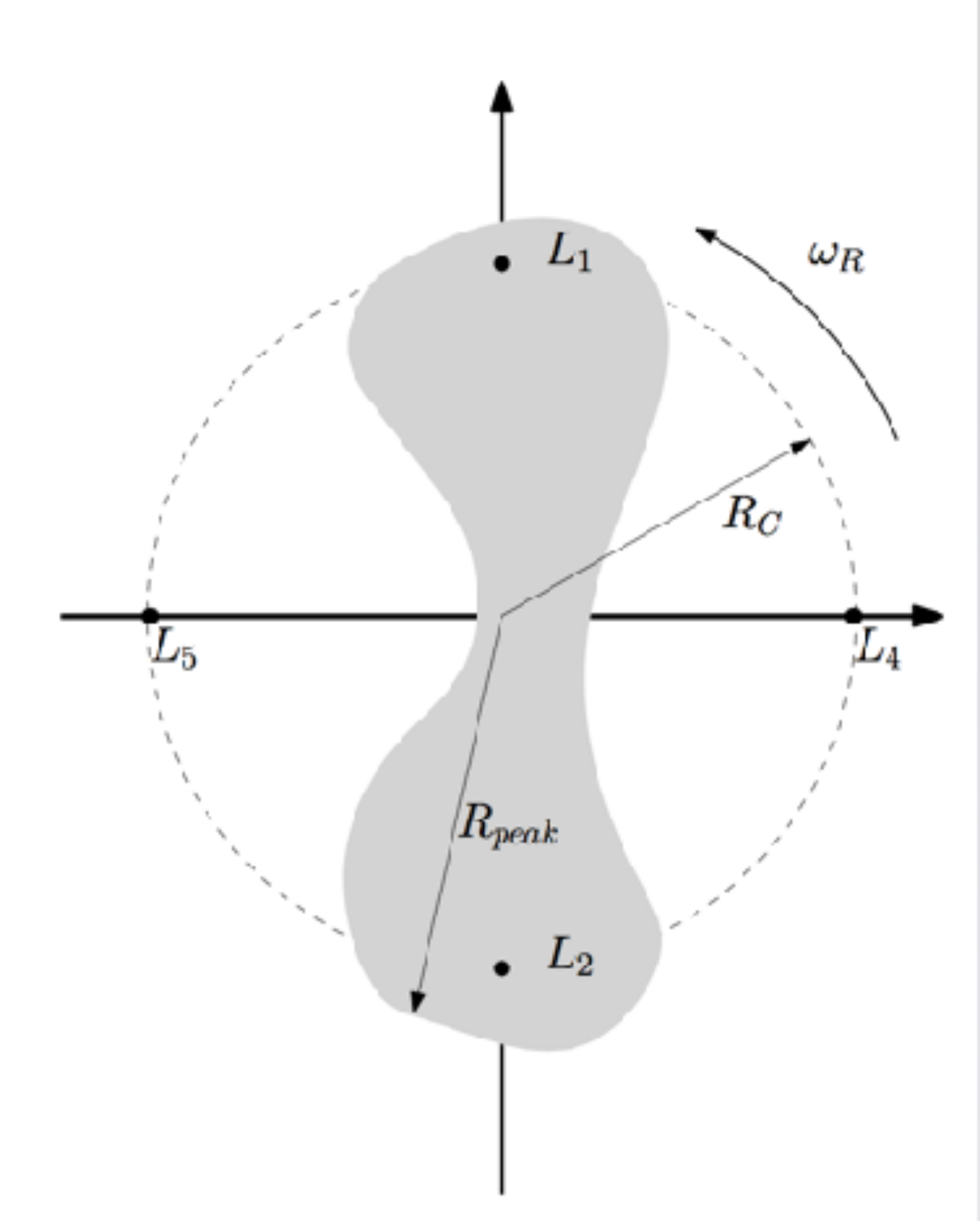
Instability end point

- BH sheds excess spin (and to a lesser degree mass) into a mostly dipolar rotating boson cloud …

$$m_s \equiv \mu\hbar,$$

$$\omega_R \sim \mu - \frac{M^2\mu^3}{8}$$

$$\Phi = A_0 g(r)\cos(m_\phi \phi - \omega_R t)\sin\theta\,,$$



- … till instability saturates

$$\mu \sim m\Omega_{\rm H}$$

$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9 \,{\rm yr}\,,$$

(for Mμ<<1 and χ<<1; max instability for Mμ=0.42)

GW emission

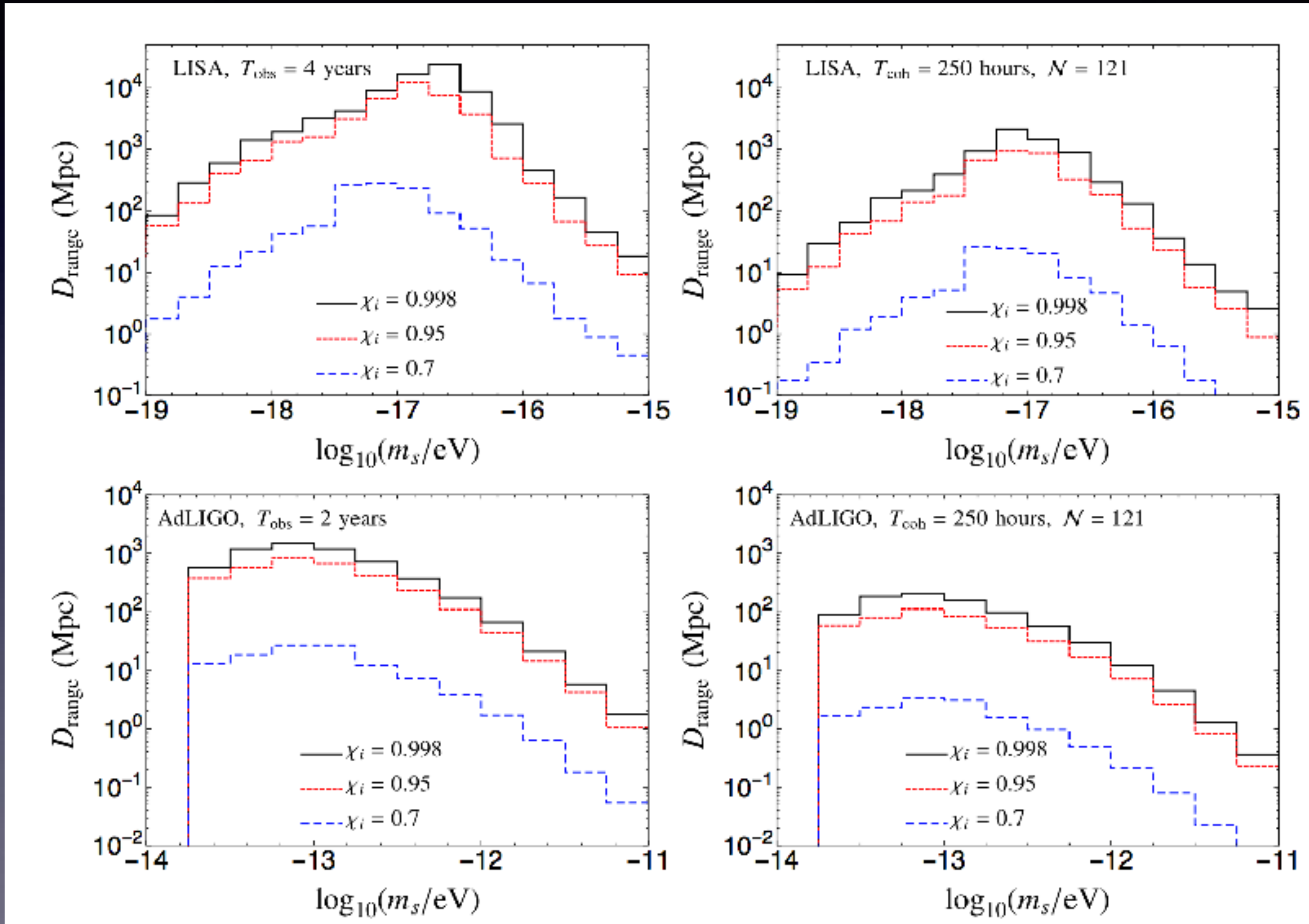
- Long-lived rotating scalar dipole produces almost monochromatic GWs via quadrupole formula on timescale

$$\tau_{\rm GW} \sim 6 \times 10^4 \, \chi^{-1} \left(\frac{M}{10\, M_\odot}\right) \left(\frac{0.1}{M\mu}\right)^{15} \, \mathrm{yr}$$

$$h = \sqrt{\frac{2}{5\pi}\frac{GM}{c^2 r}} \left(\frac{M_S}{M}\right) A(\chi, f_s M)\,,$$ rms strain amplitude

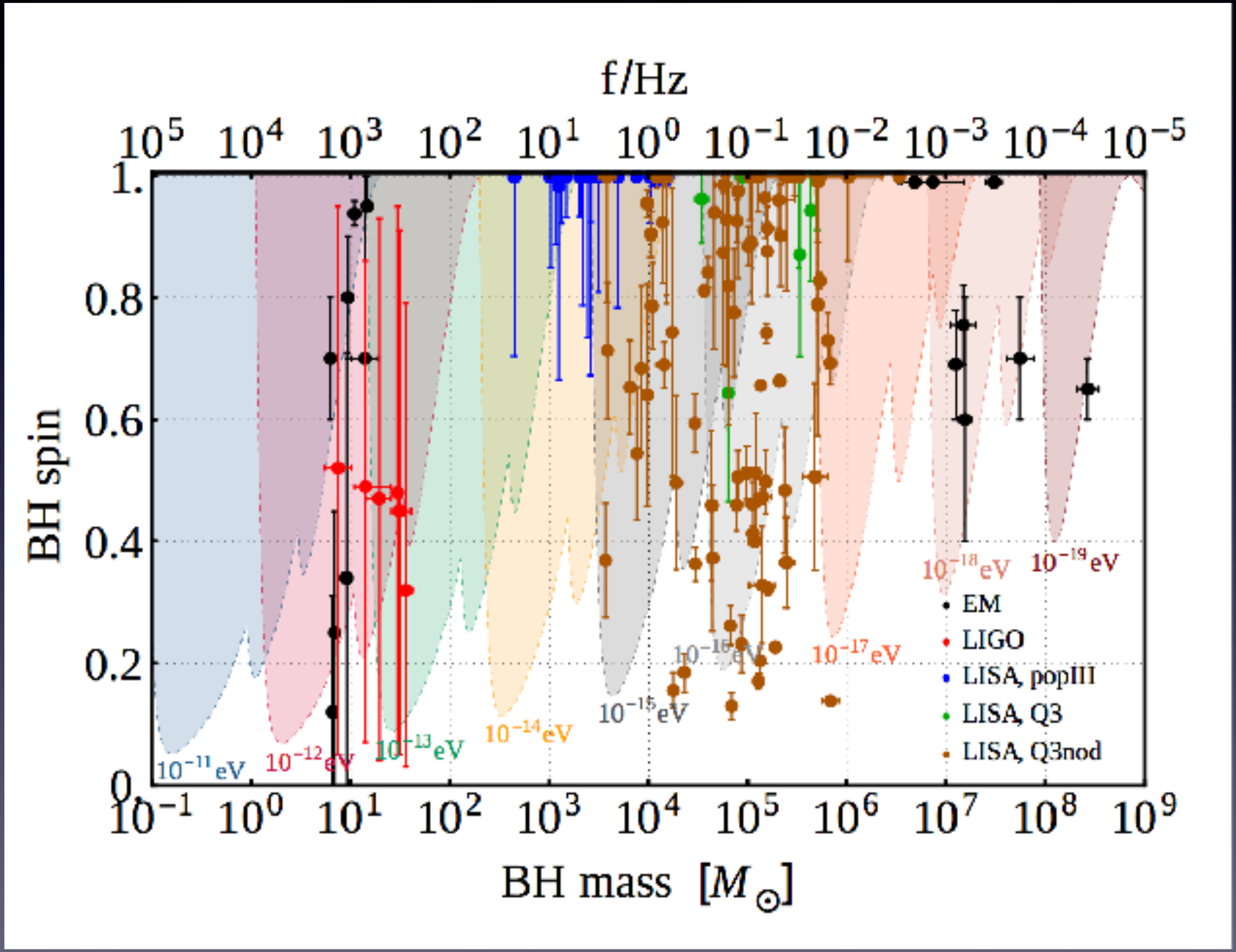
$$\omega \sim \mu$$ frequency

GW ranges



LISA, T_{obs} = 4 years
LISA, T_{coh} = 250 hours, $\mathcal{N}$ = 121
AdLIGO, T_{obs} = 2 years
AdLIGO, T_{coh} = 250 hours, $\mathcal{N}$ = 121
D_{range} (Mpc)
$\log_{10}(m_s/\mathrm{eV})$
$\chi_i = 0.998$
$\chi_i = 0.95$
$\chi_i = 0.7$

Indirect probe: BH spins



Problems:

- Systematic errors on measurements,
- Astrophysical intrinsic spin distribution unknown

Background from isolated spinning BHs

energy emission efficiency

$$f_{\rm ax} \sim \mathcal{O}(1\%)$$

monochromatic GW
in source frame

$$\Delta \ln f \;\sim\; 1$$

LISA band
massive BHs ~ 10^4-10^7 M_{sun}, m_s~10^{-16} - 10^{-18} eV

$$\rho_{\rm BH} \;\sim\; \mathcal{O}(10^4) M_\odot/{\rm Mpc}^3$$

$$\Omega_{\rm GW,\,ax} = (1/\rho_{\rm c})(d\rho_{\rm GW}/d\ln f) \sim f_{\rm ax}\rho_{\rm BH}/\rho_{\rm c}$$

$$\Omega^{\rm LISA}_{\rm GW,\,ax} \;\sim\; 10^{-9}$$

Background from isolated spinning BHs

energy emission efficiency

$$f_{\rm ax} \sim \mathcal{O}(1\%)$$

monochromatic GW
in source frame

$$\Delta \ln f \ \sim \ 1$$

LIGO/Virgo band
stellar-mass BHs ~ 10-50 M_{sun}, $m_s \sim 10^{-13}$ - 10^{-12} eV

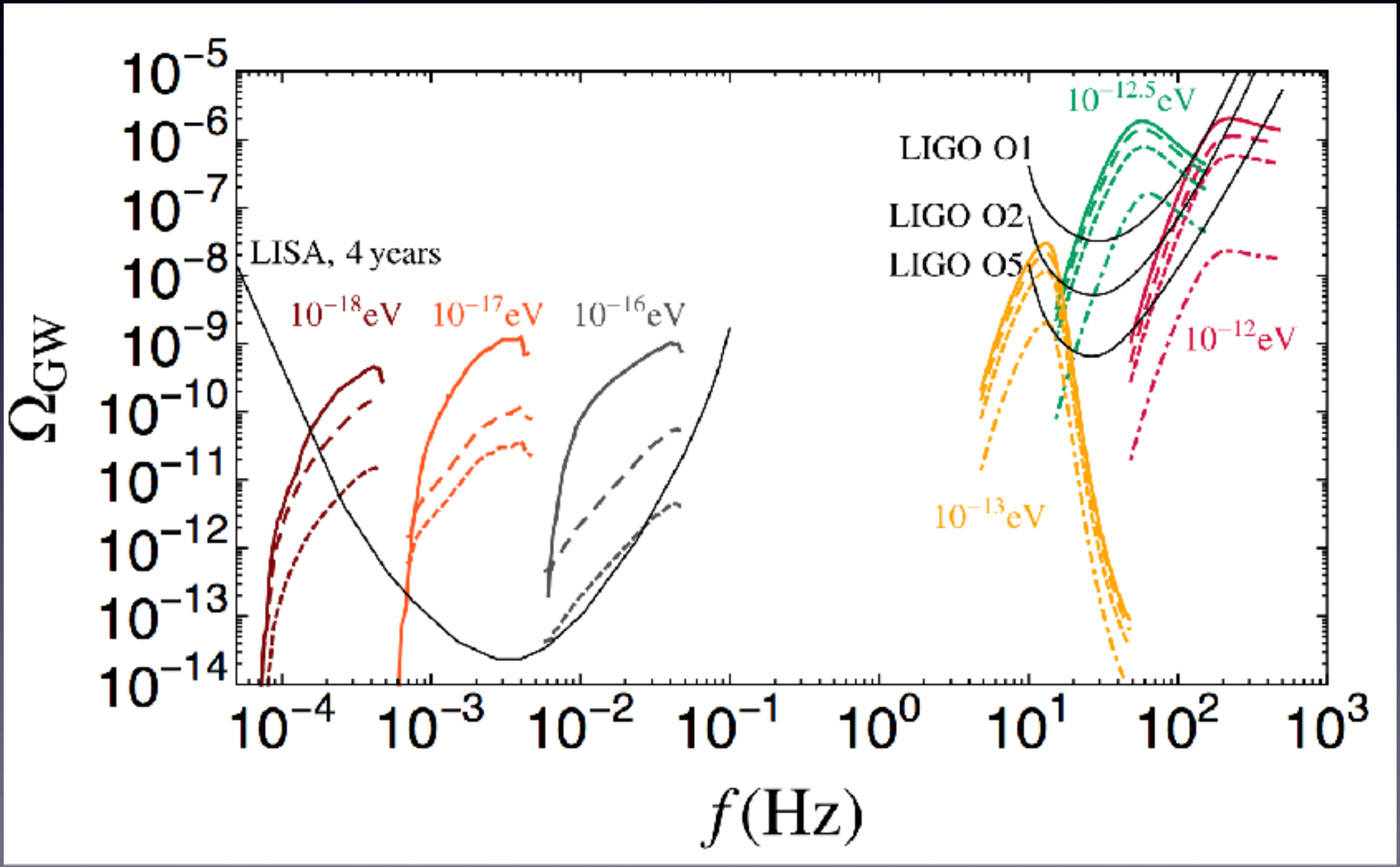
$$\Omega_{\rm GW,\,bin} \ \sim f_{\rm GW} f_{\rm m} \rho_{\rm BH}/\rho_c$$

$$f_{\rm GW} \ \sim \ \mathcal{O}(1\%) \qquad f_{\rm m} \ \sim \ \mathcal{O}(1\%)$$

$$\Omega_{\rm GW,\,ax}/\Omega_{\rm GW,\,bin} \ \sim \ f_{\rm ax}/(f_{\rm GW} f_{\rm m}) \ \sim \ 10^2$$

$$\Omega_{\rm GW,\,bin} \ \sim \ 10^{-9} - 10^{-8} \qquad \Omega^{\rm LIGO}_{\rm GW,\,ax} \sim 10^{-7} - 10^{-6}$$

Background from isolated spinning BHs



BH spin & mass modeling is crucial

Use state-of-the-art astrophysical models with input from continuum fitting/iron-Kα spin measurements

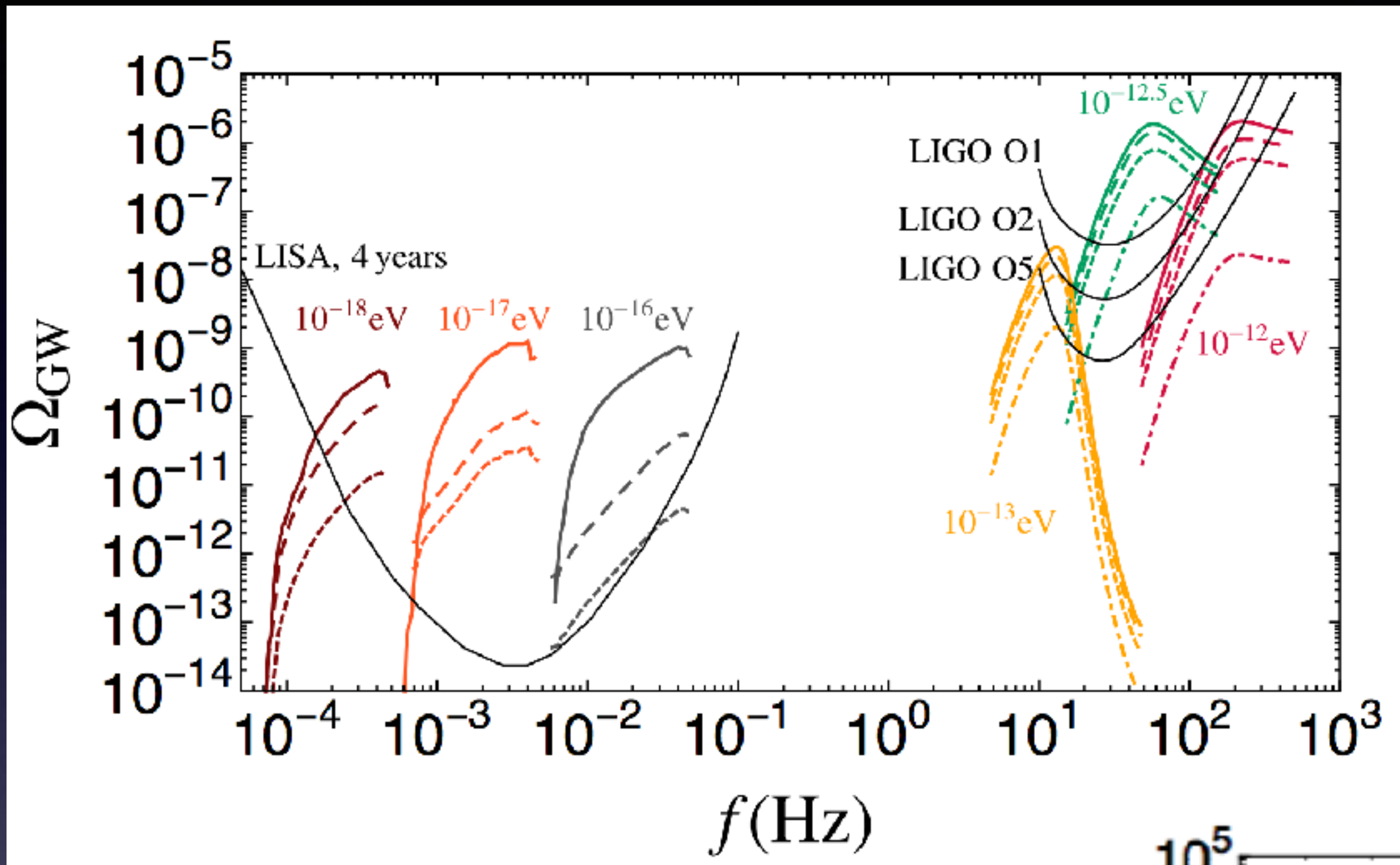
Object name	Galaxy type	z	L_X [erg s^{-1}]	$f_{\rm Edd}$	$\log(M_{\rm BH}[M_\odot])$	spin
1H0707-495	–	0.0411	3.7×10^{43}	1.0	6.70 ± 0.4	>0.97
Mrk1018	S0	0.043	9.0×10^{43}	0.01	8.15	$0.58^{+0.36}_{-0.74}$
NGC4051	SAB(rs)bc	0.0023	3.0×10^{42}	0.03	6.28	>0.99
NGC3783	SB(r)ab	0.0097	1.8×10^{44}	0.06	7.47 ± 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	$6.60^{+1.40}_{-0.30}$	$0.97^{+0.01}_{-0.04}$

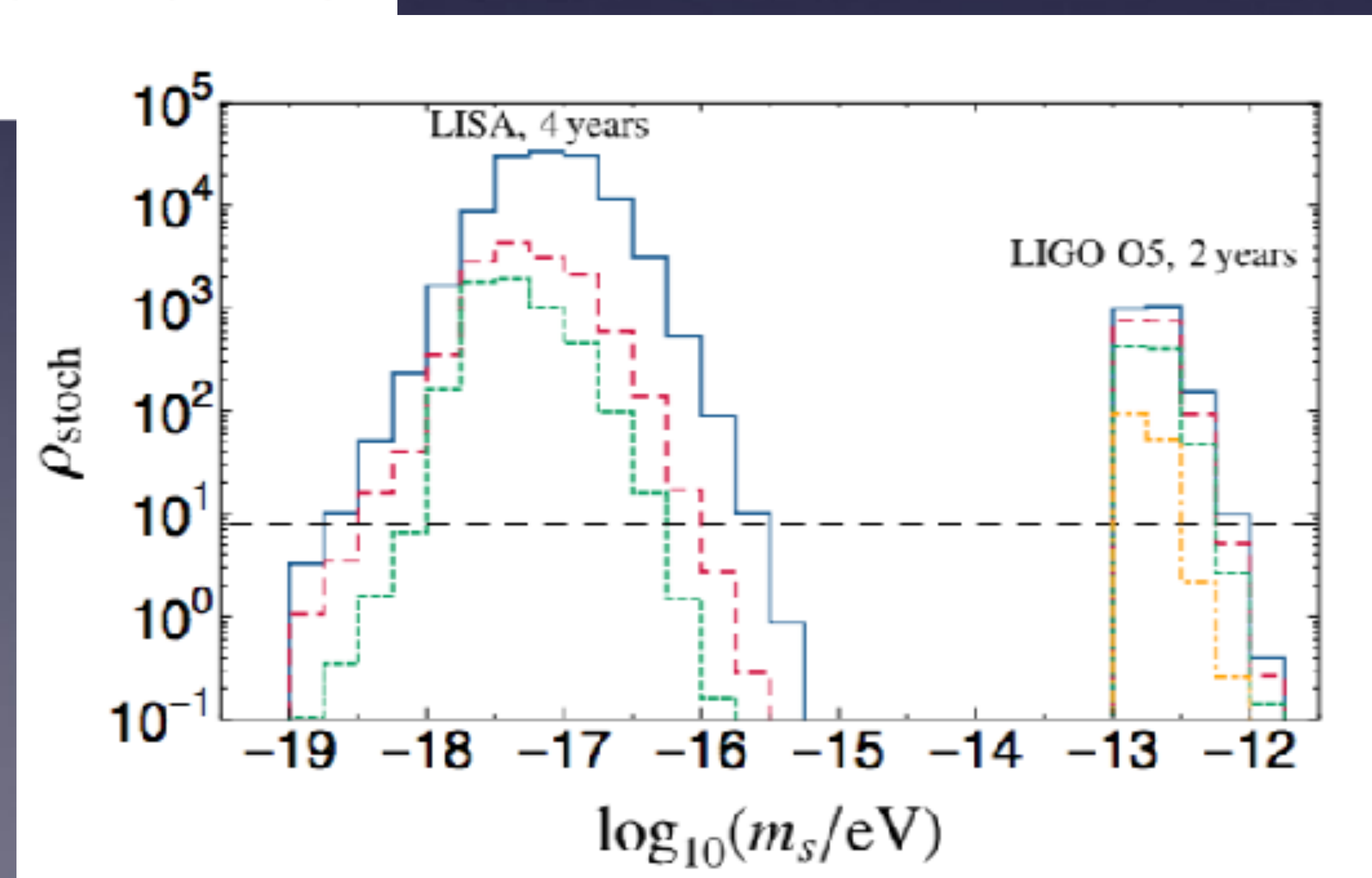
Compilations (Reynolds, Brenneman,...) of massive BH spins

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

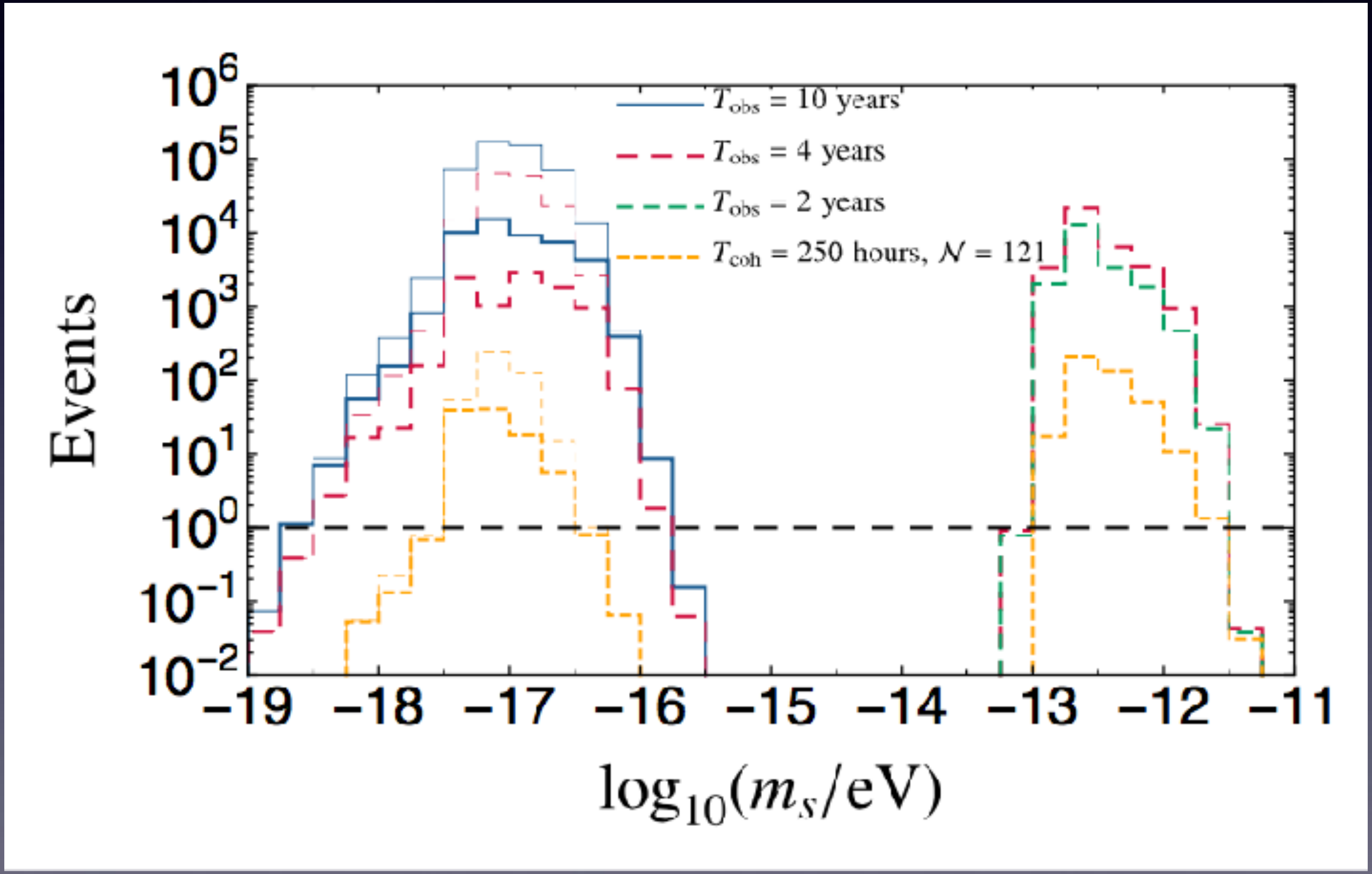
Stochastic background





Resolved events

Need to account for effect of stochastic background on sensitivity (cf e.g. WD binaries)



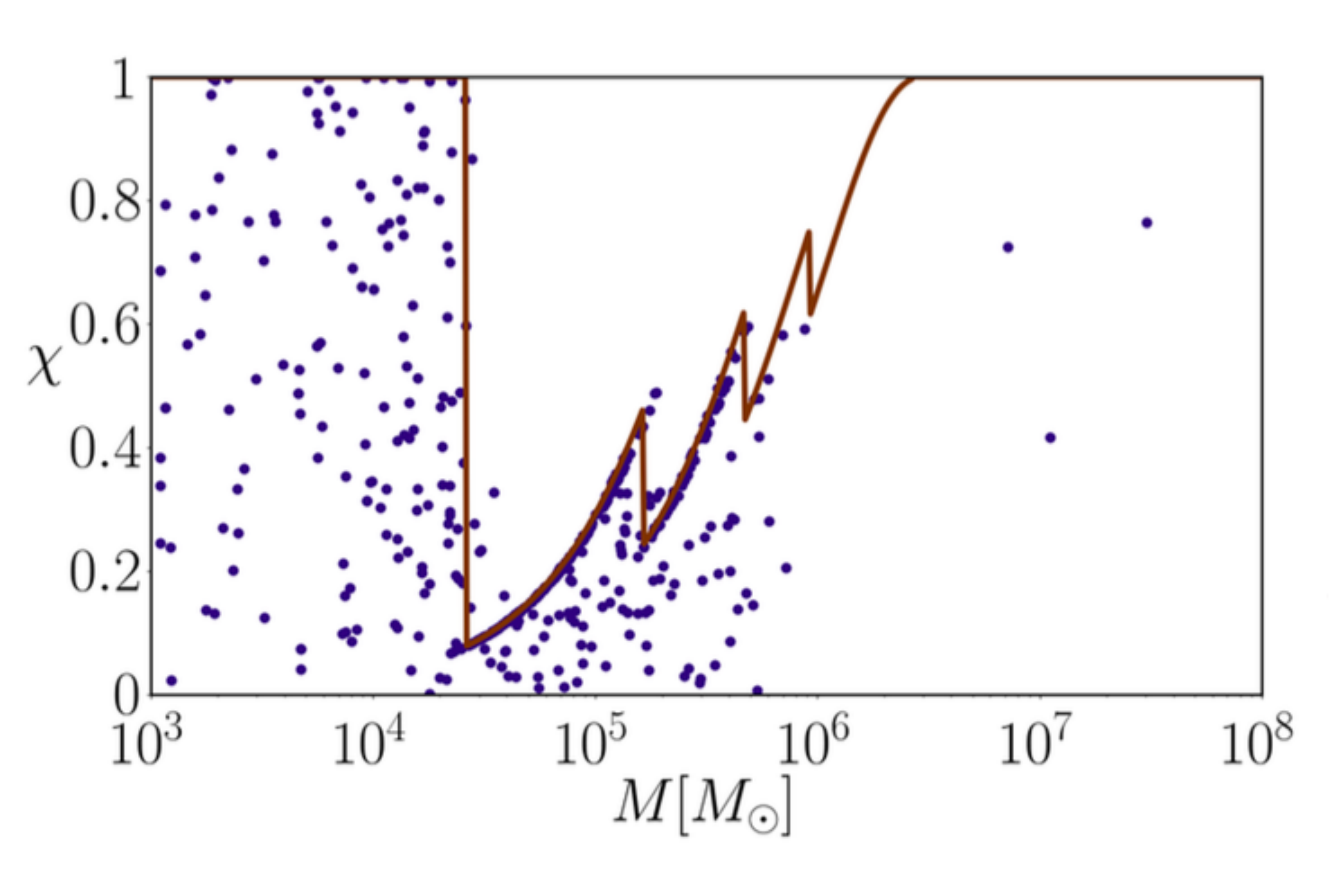
most optimistic models

Resolved events

m_s[eV]	Search method	Accretion model	Events
10^{-16}	Coherent	(C.1)	75 – 0
	Semicoherent		0
	Coherent	(C.2)	75 – 0
	Semicoherent		0
	Coherent	(C.3)	75 – 0
	Semicoherent		0
10^{-17}	Coherent	(C.1)	1329 – 1022
	Semicoherent		39 – 5
	Coherent	(C.2)	3865 – 1277
	Semicoherent		36 – 4
	Coherent	(C.3)	5629 – 1429
	Semicoherent		39 – 5
10^{-18}	Coherent	(C.1)	17 – 1
	Semicoherent		0
	Coherent	(C.2)	18 – 1
	Semicoherent		0
	Coherent	(C.3)	20 – 0
	Semicoherent		0

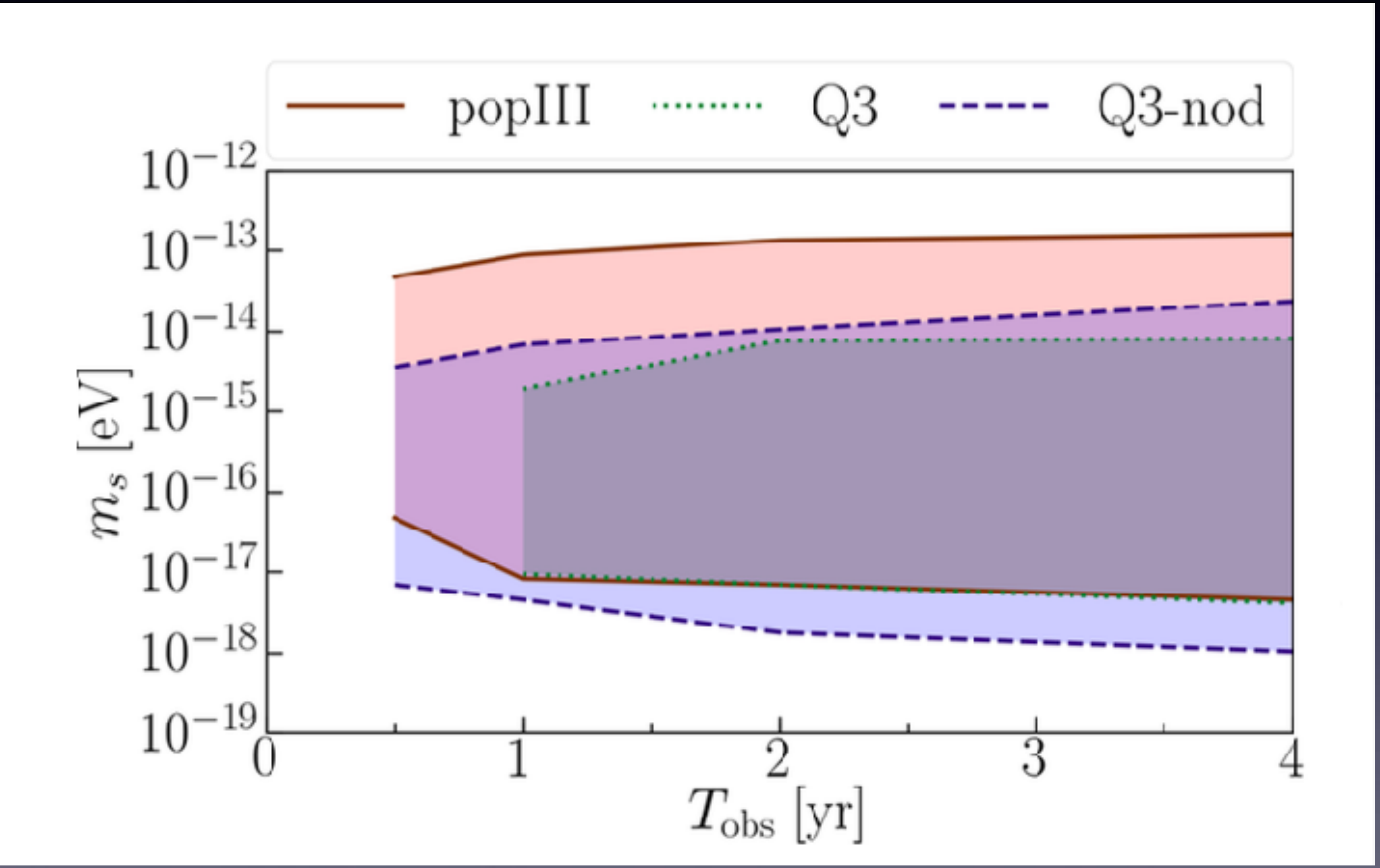
m_s[eV]	Search method	Events
$10^{-11.5}$	Coherent	21 – 2
	Semicoherent	1 – 0
10^{-12}	Coherent	1837 – 193
	Semicoherent	50 – 2
$10^{-12.5}$	Coherent	12556 – 1429
	Semicoherent	205 – 15

Regge plane “holes”



Look for “accumulation” near instability threshold
to avoid having to make assumptions
on astrophysical model

Regge plane “holes”

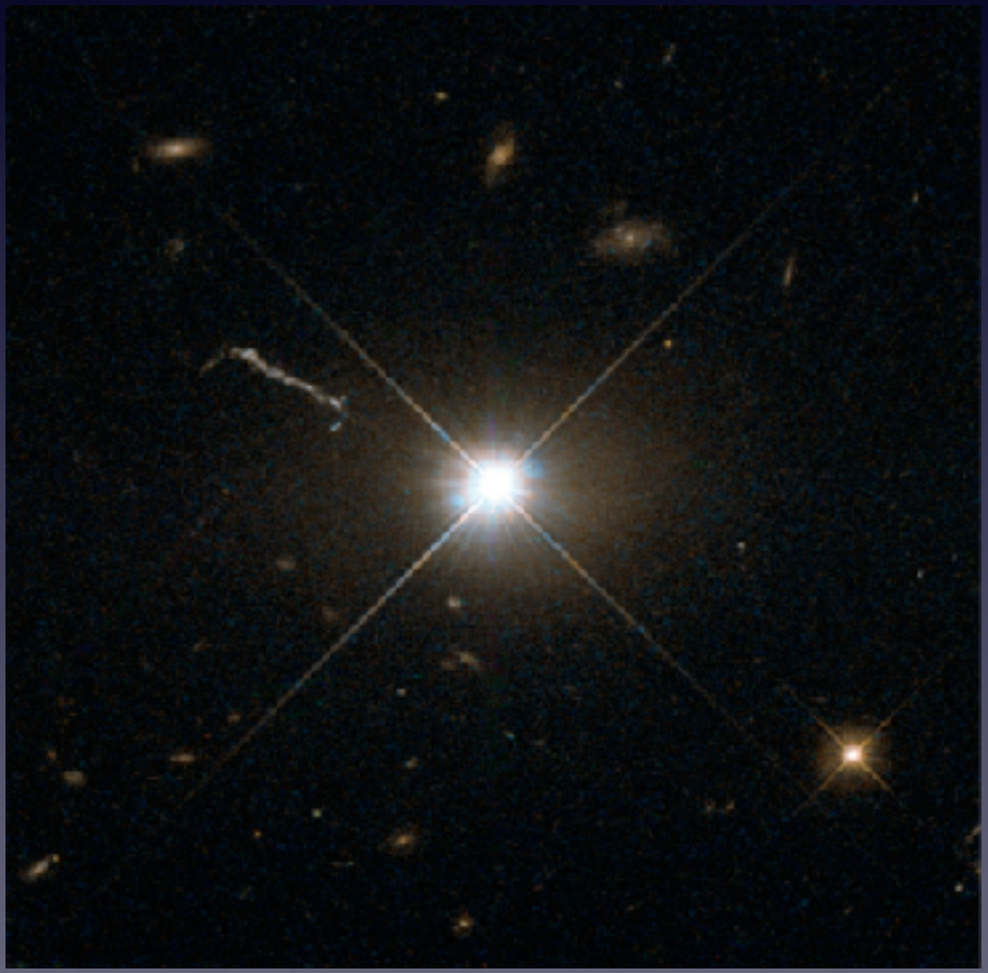


Conclusions

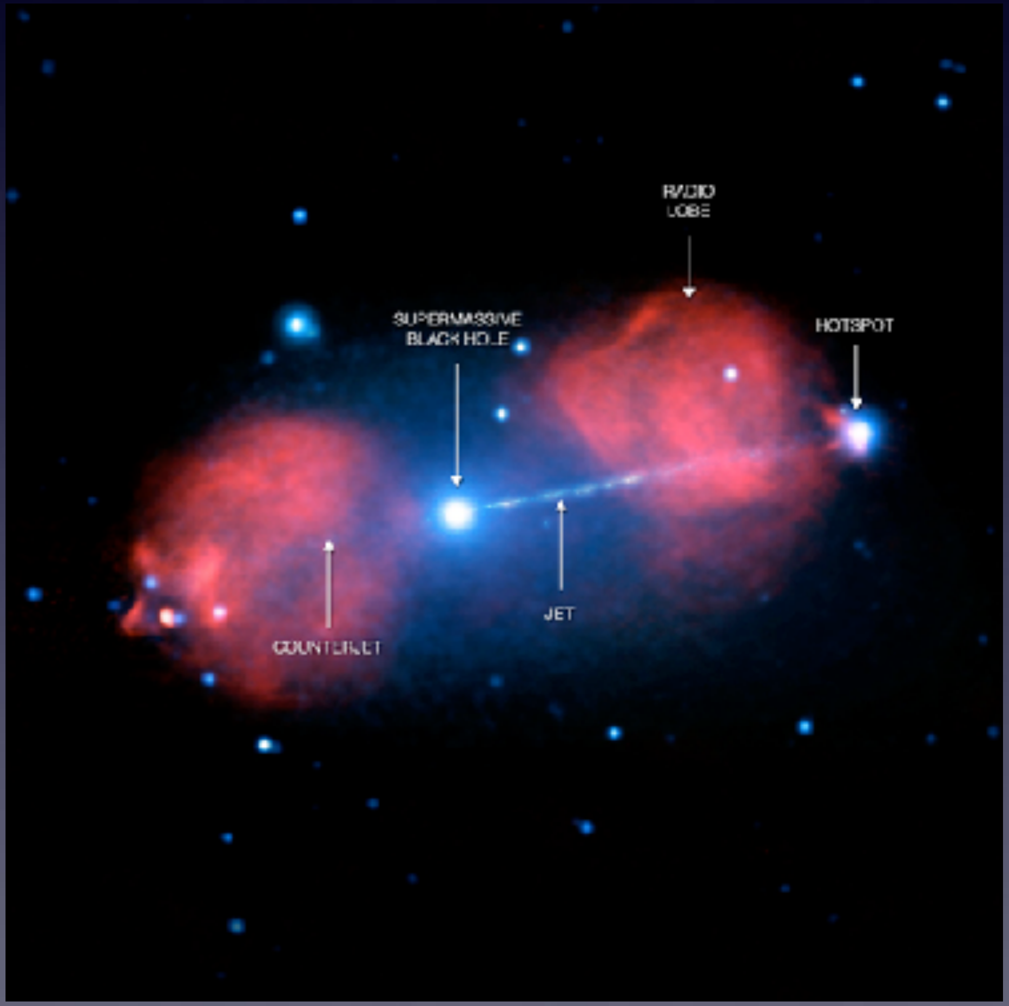
- Ultralight bosons can induce superradiant instabilities in spinning black holes, tapping their rotational energy to trigger the growth of a bosonic condensate
- Boson condensates emit almost monochromatic GWs
- GWs are LISA/LIGO band if boson's Compton wavelength is Gm/km scale
- Main observable is stochastic background, but resolved sources and Regge plane "holes" also possible
- LIGO rules out already masses ~ a few x 10^{-12} eV

Massive black holes are hosted in (nearly) all galaxies

They power quasars and active galactic nuclei (AGN) that outshine host galaxy



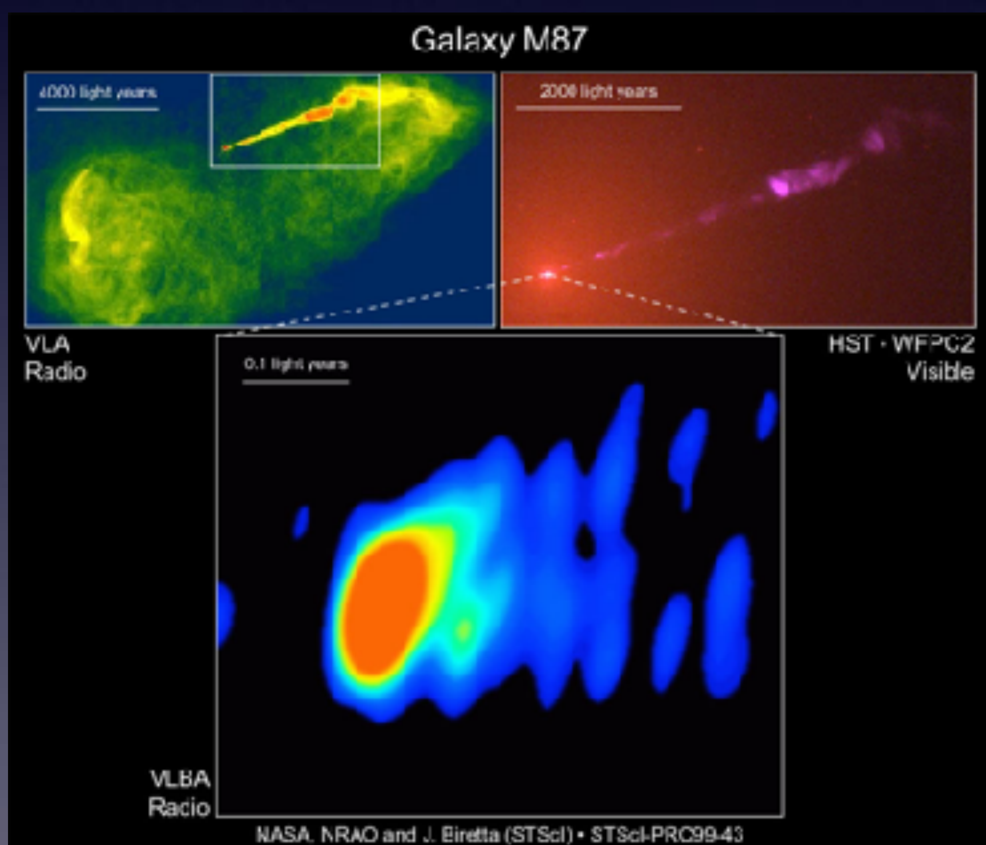
3C 273: 2.6 billion light years away, would shine as bright as Sun if at Proxima Centauri distance



Pictor A: giant jet spanning continuously for over 570,000 light years (red=radio, blue=x-ray)

What links large and small scale?

- Small to large: BH jets or disk winds transfer kinetic energy to the galaxy and keep it “hot”, quenching star formation (”AGN feedback”). Needed to reconcile ΛCDM bottom-up structure formation with observed “downsizing” of cosmic galaxies



Disk of dust and gas around the massive BH in NGC 7052

- Large to small: galaxies provide fuel to BHs to grow (”accretion”)

Galaxies merge…

… so massive BHs must merge too!

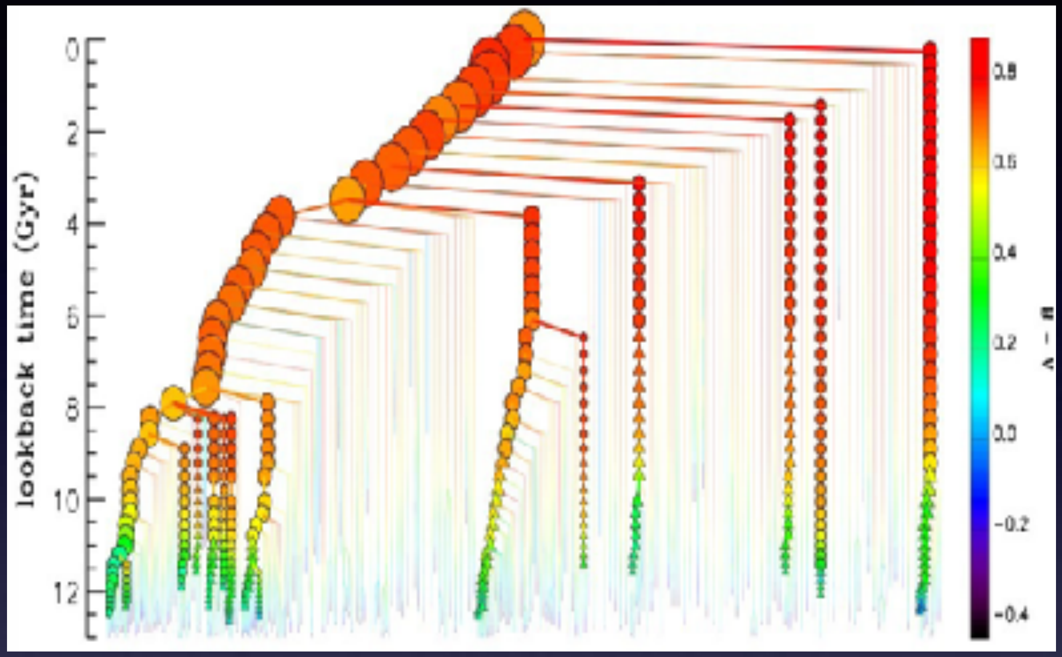


Figure from De Lucia & Blaizot 2007

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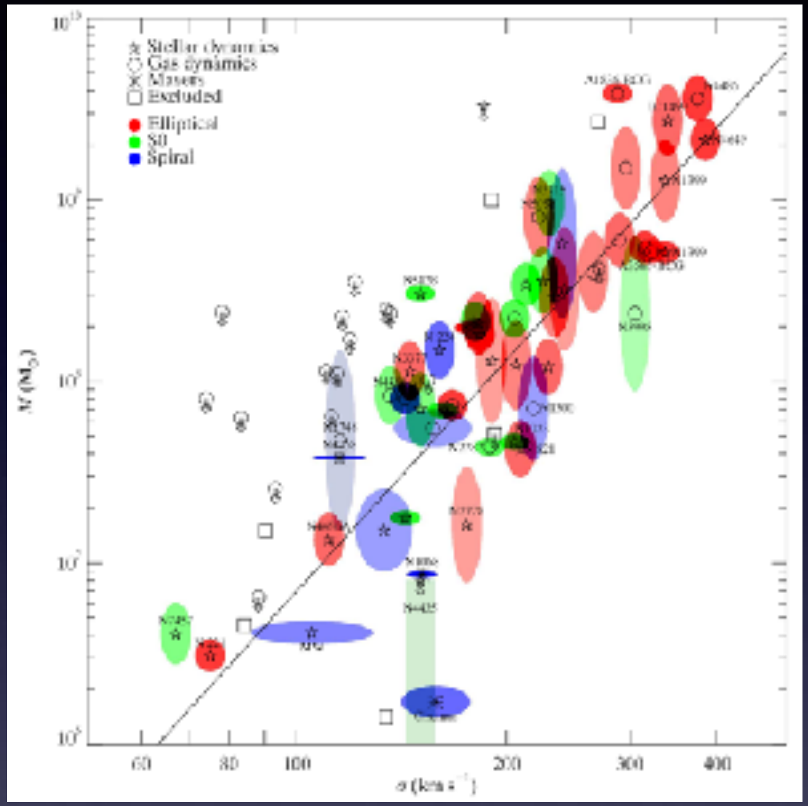

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

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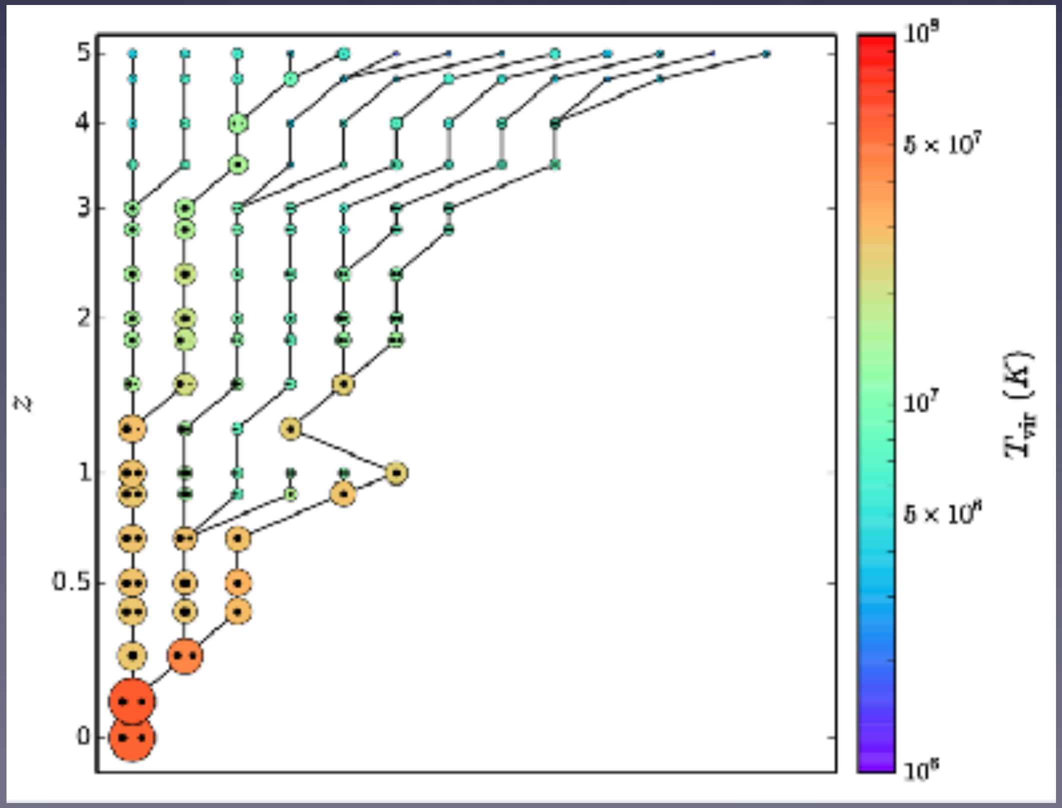
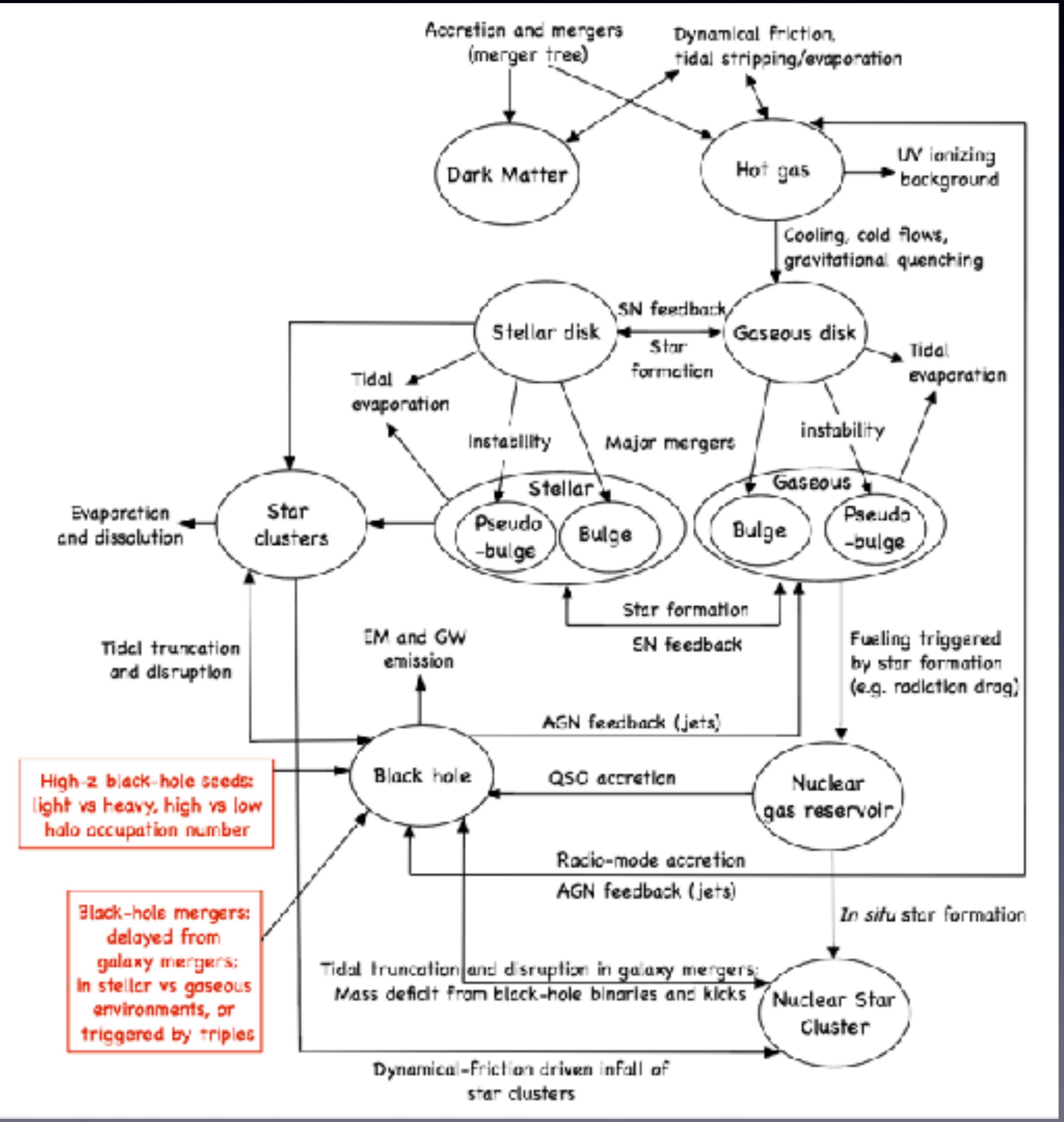


EB 2012
Figure credits: Lucy Ward

Semi-analytic galaxy-BH co-evolution

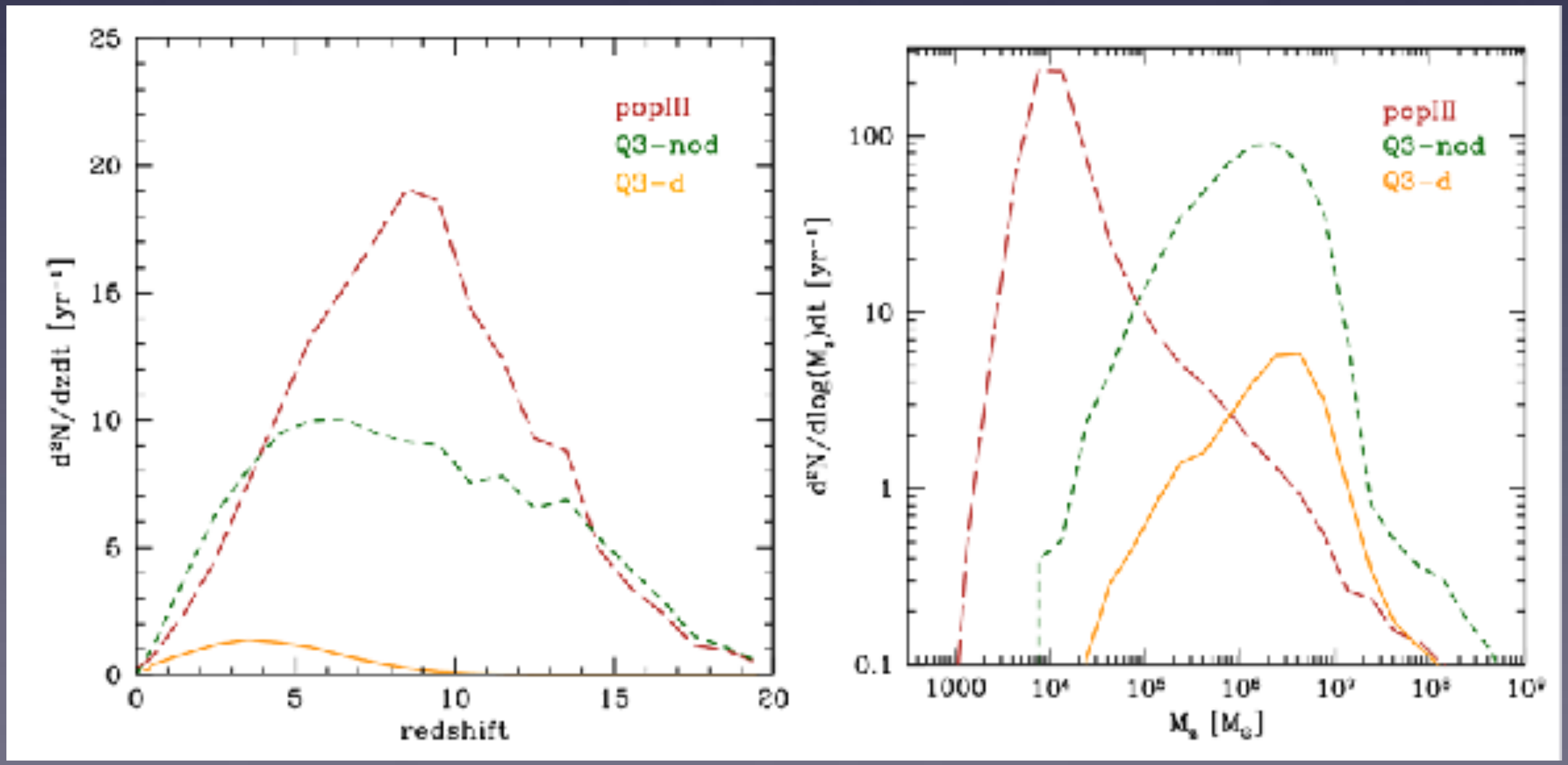
- Evolution of massive BHs difficult to predict because co-evolution with galaxies (c.f. M-σ relation, accretion, jets, feedback, etc)
- Purely numerical simulations impossible due to sheer separation of scales (10^{-6} pc to Mpc) and dissipative/nonlinear processes at sub-grid scales
- Semi-analytical model (EB 2012) 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)



EB 2012

Massive BH model's uncertainties

- Seed model: light seeds from PopIII stars (~100 M_{sun}) vs heavy seeds from instabilities of protogalactic disks (~10^5 M_{sun})
- No delays between galaxy and BH mergers, or delays depending on environment/presence of gas:
  - 3-body interactions with stars on timescales of 1-10 Gyr
  - Gas-driven planetary-like migration on timescales ≳ 10 Myr
  - Triple massive BH systems on timescales of 0.1-1 Gyr

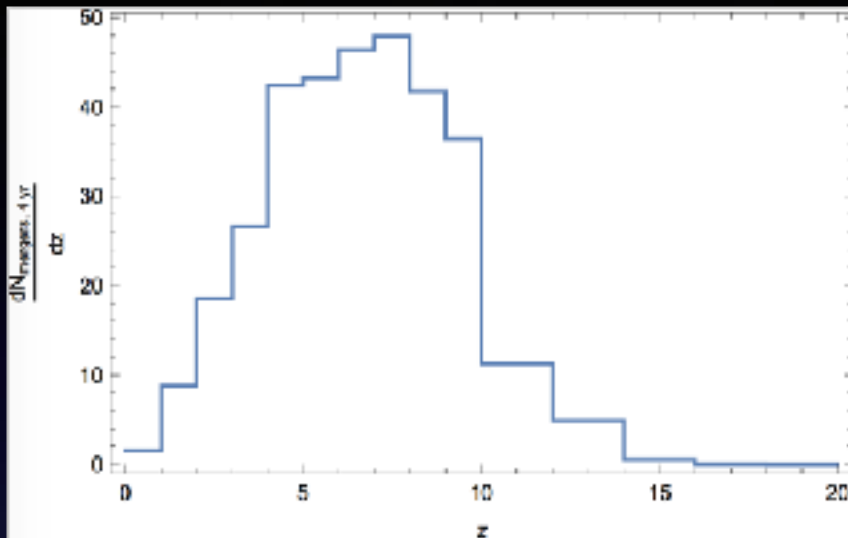


PopIII=light seeds, delays
(but similar results with no delays)

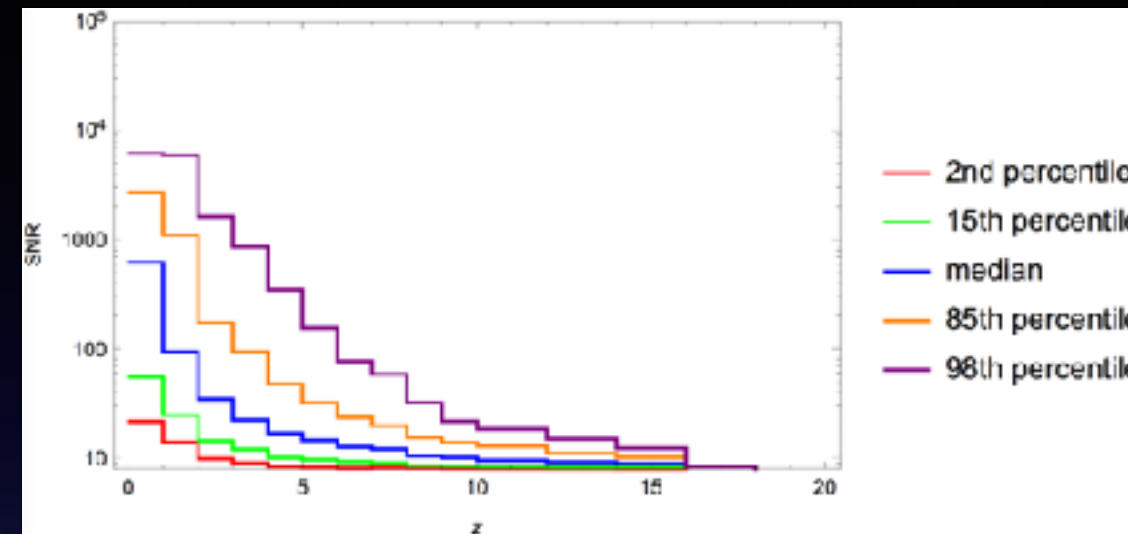
Q3-d= heavy seeds, delays
Q3-nod= heavy seeds, no delays

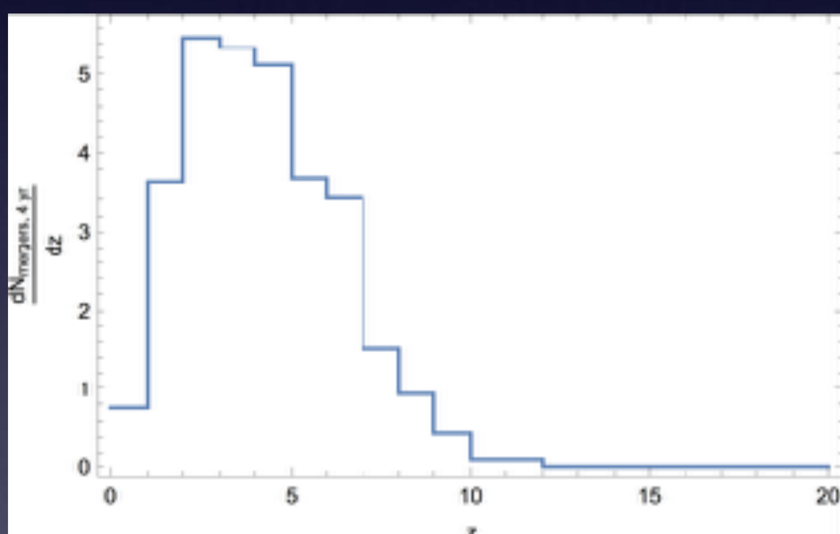
From Klein EB et al 2015

ESA proposal’s design

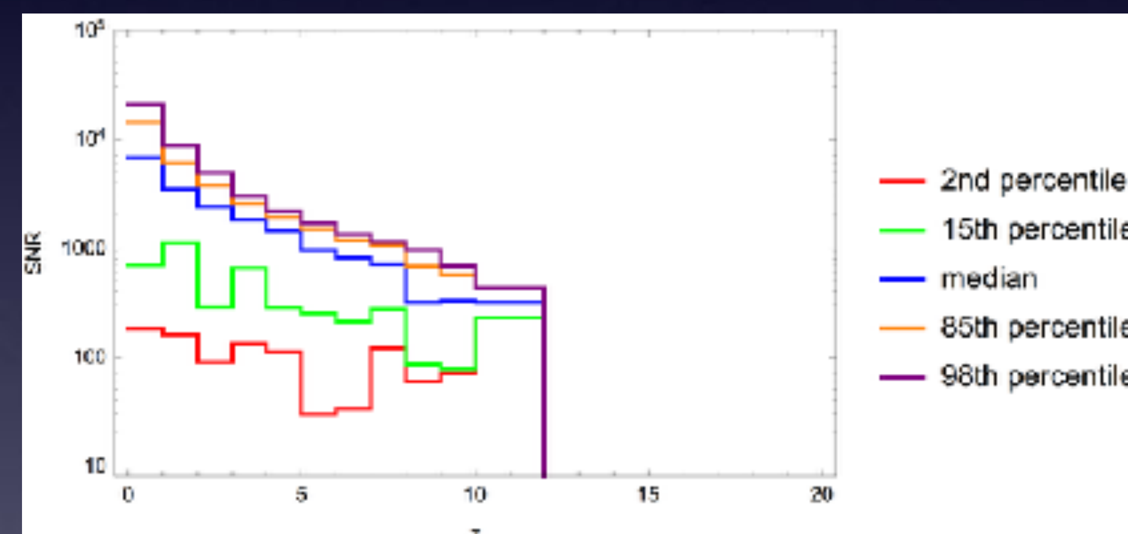


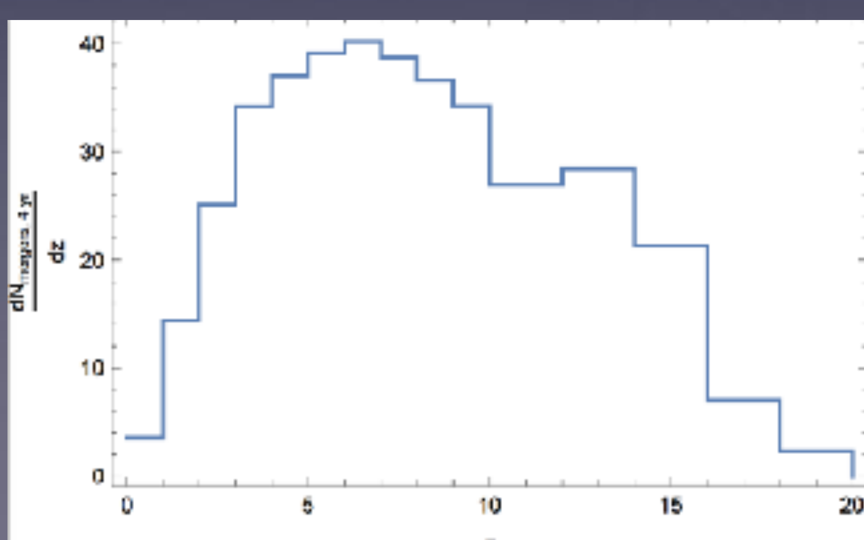
PopIII



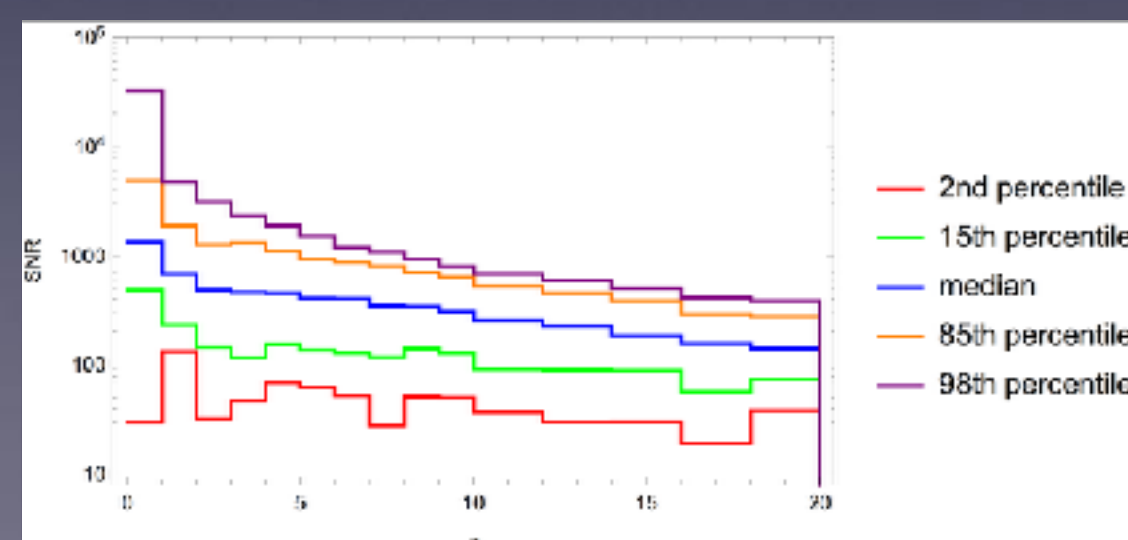


Q3-d



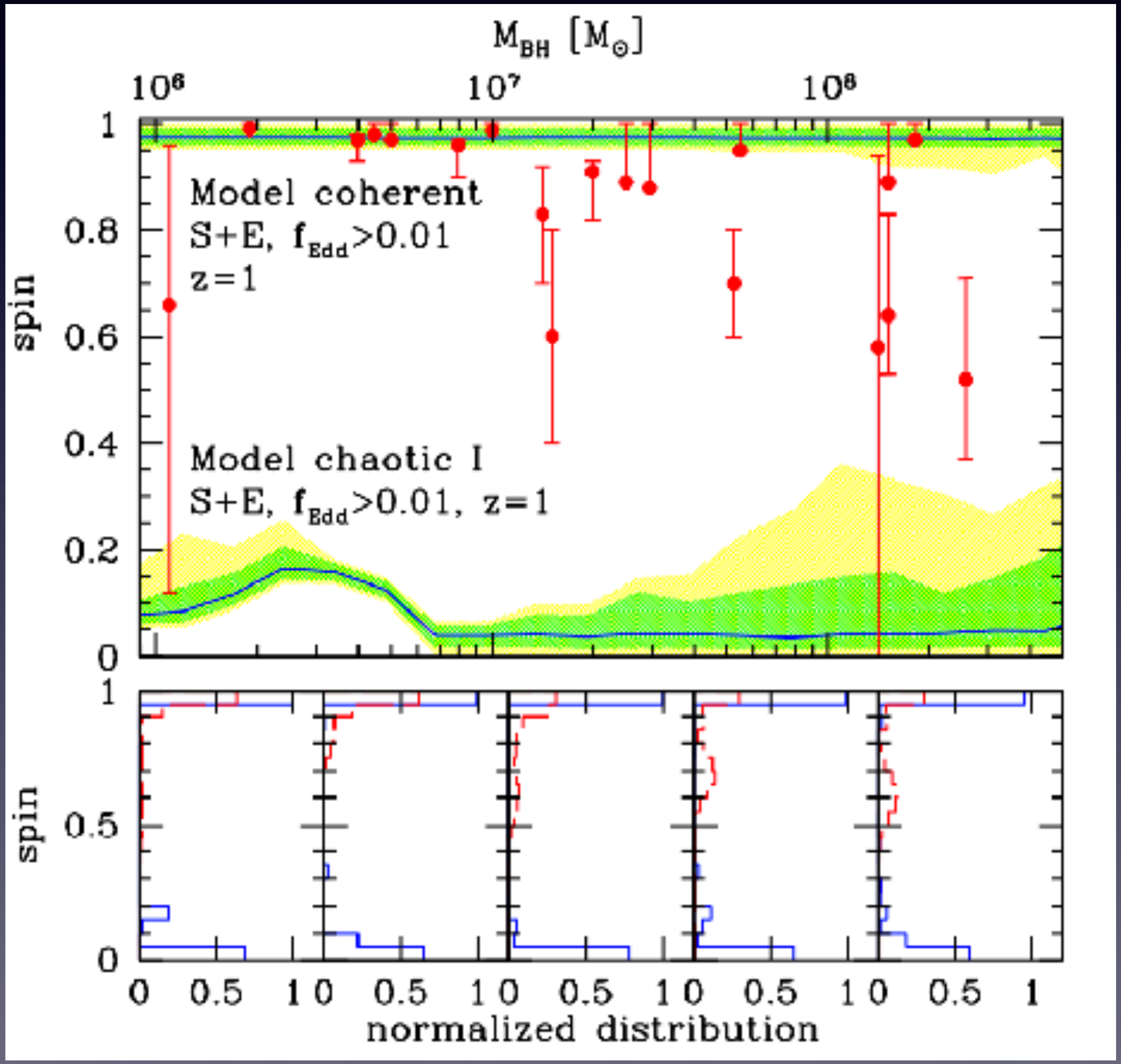


Q3-nod



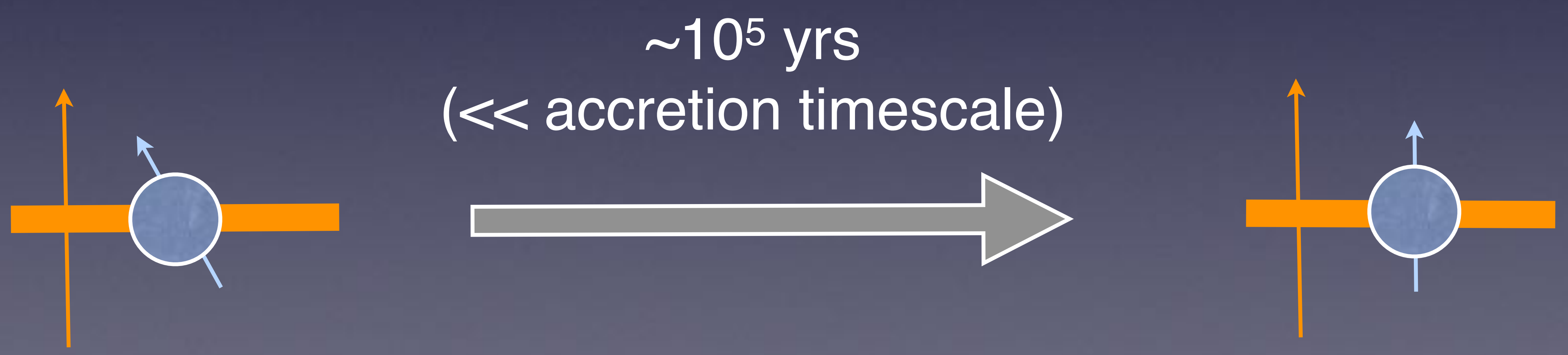
Spin evolution

- 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)



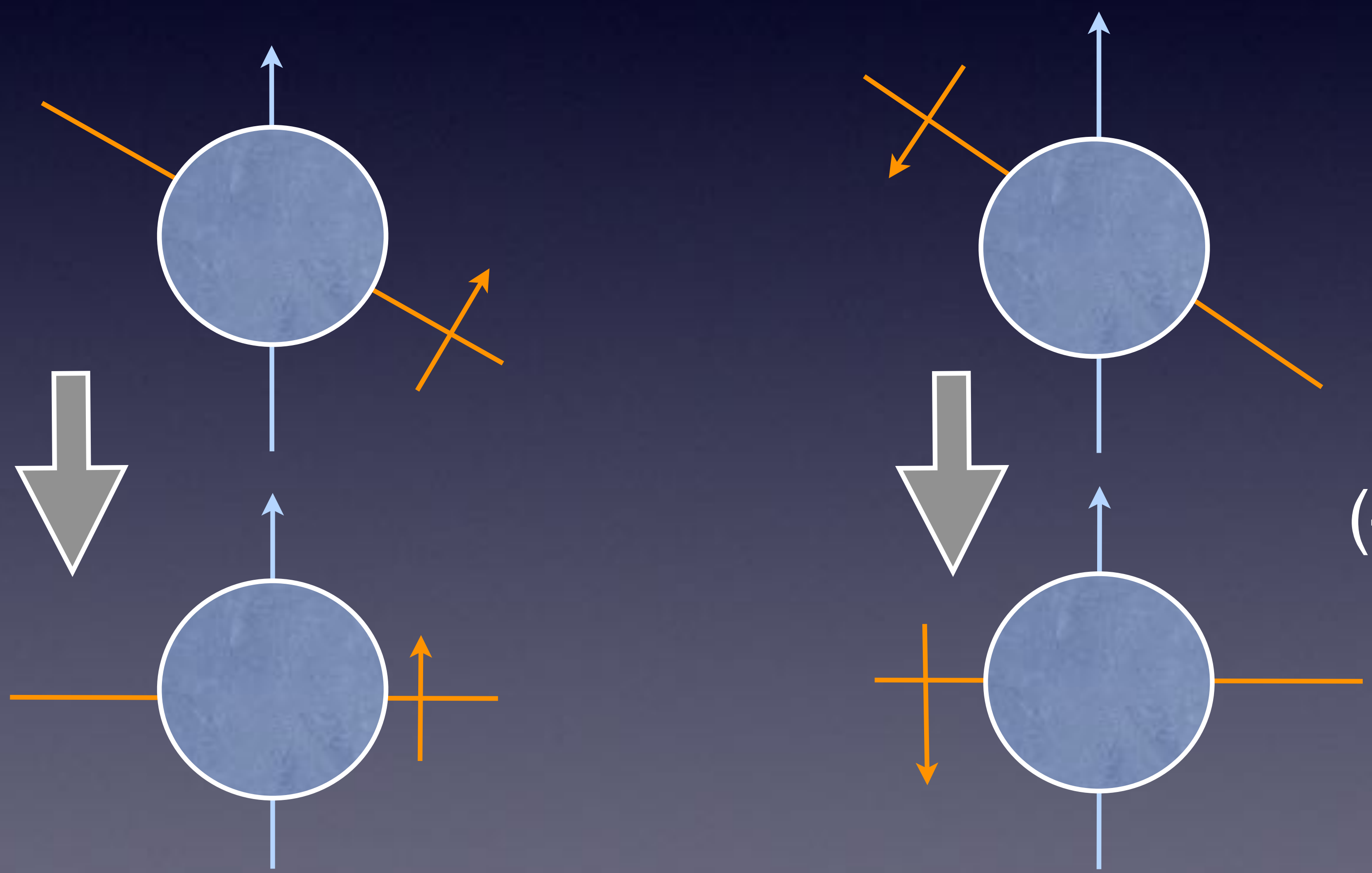
A mix of coherent and chaotic?

- Accretion by clouds of gas, with mass set by minimum of a "typical" cloud mass $\sim 10^4$ - 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



A mix of coherent and chaotic?

- 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



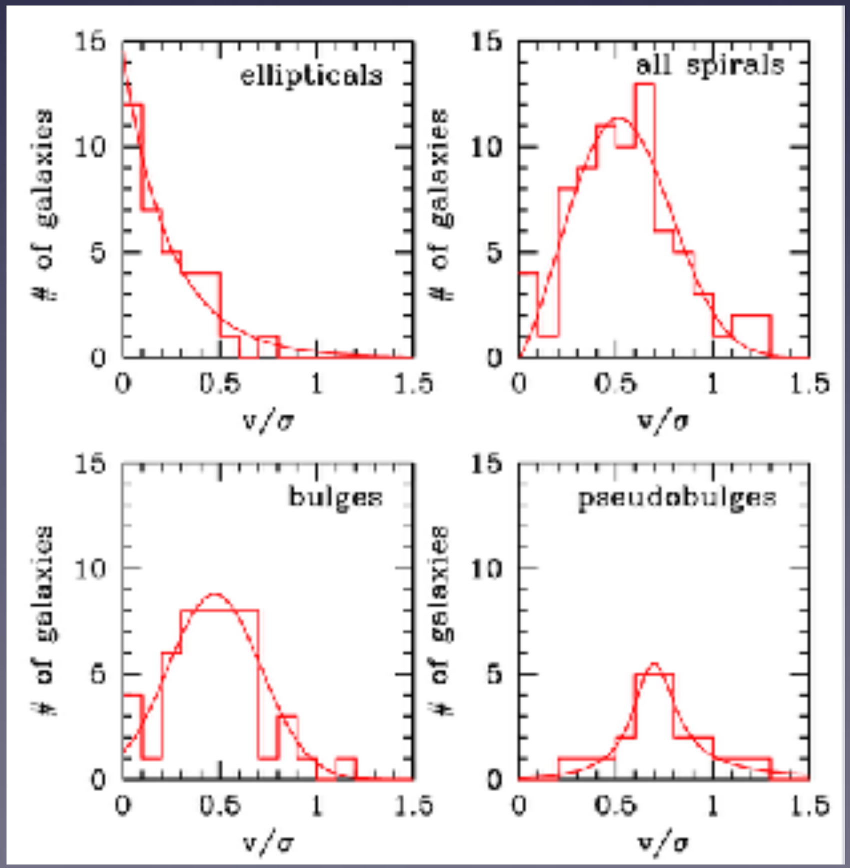
~10^5 yrs
(<< accretion timescale)

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

Linking accretion to galactic morphology

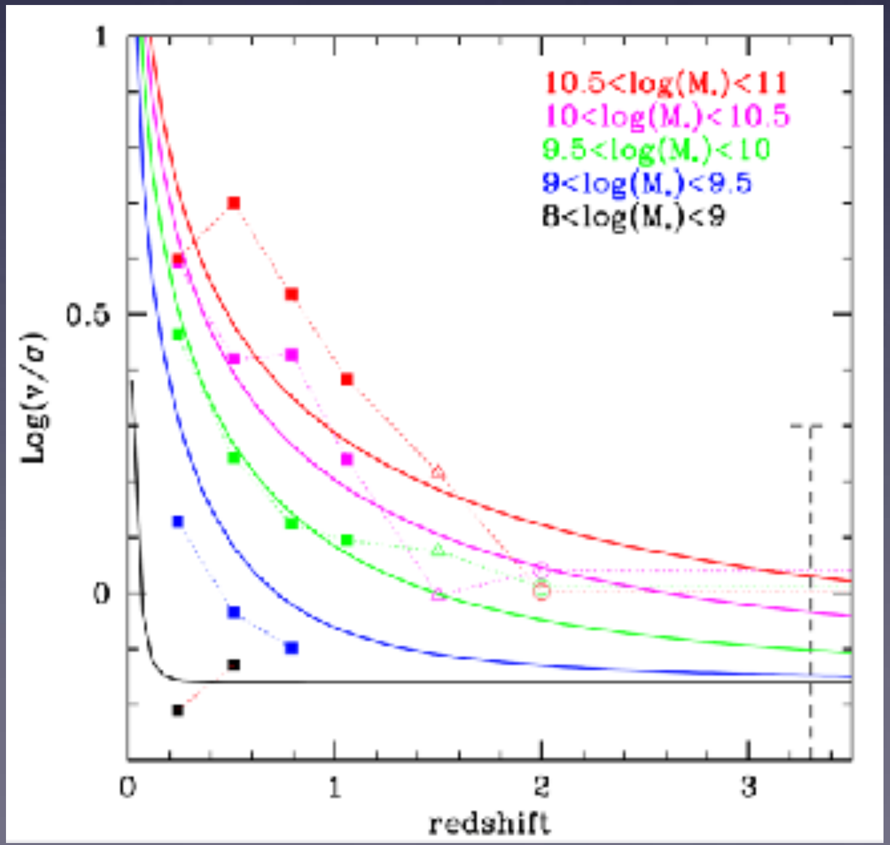
(Sesana, EB & Dotti 2014)

- J_{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



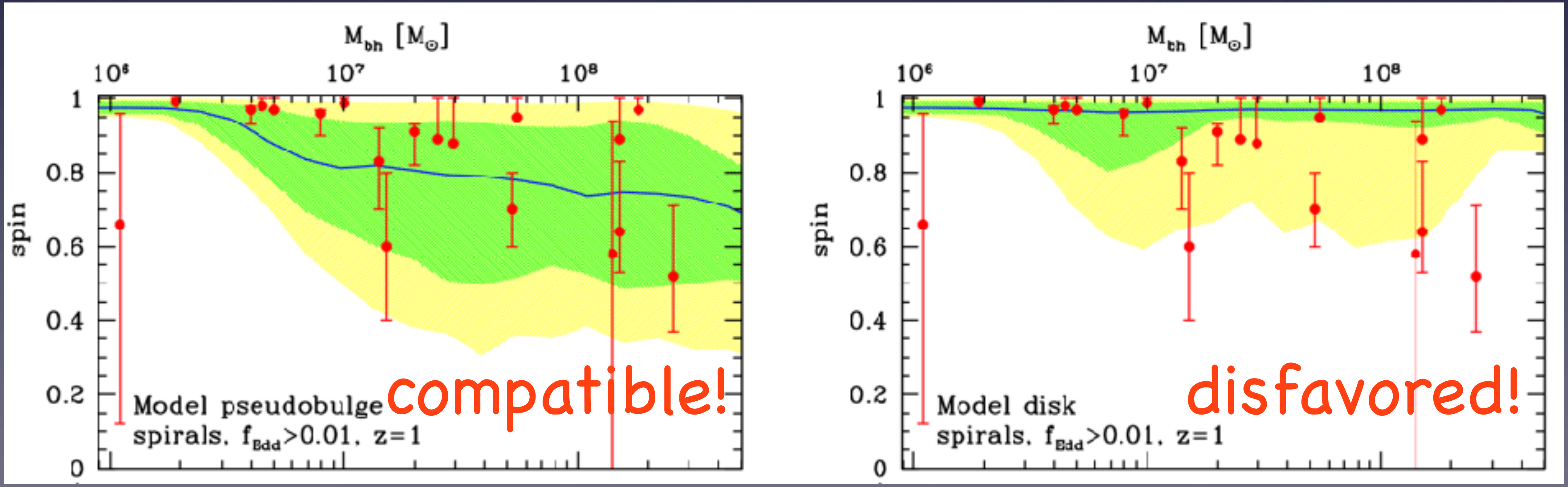
Stars

Gas



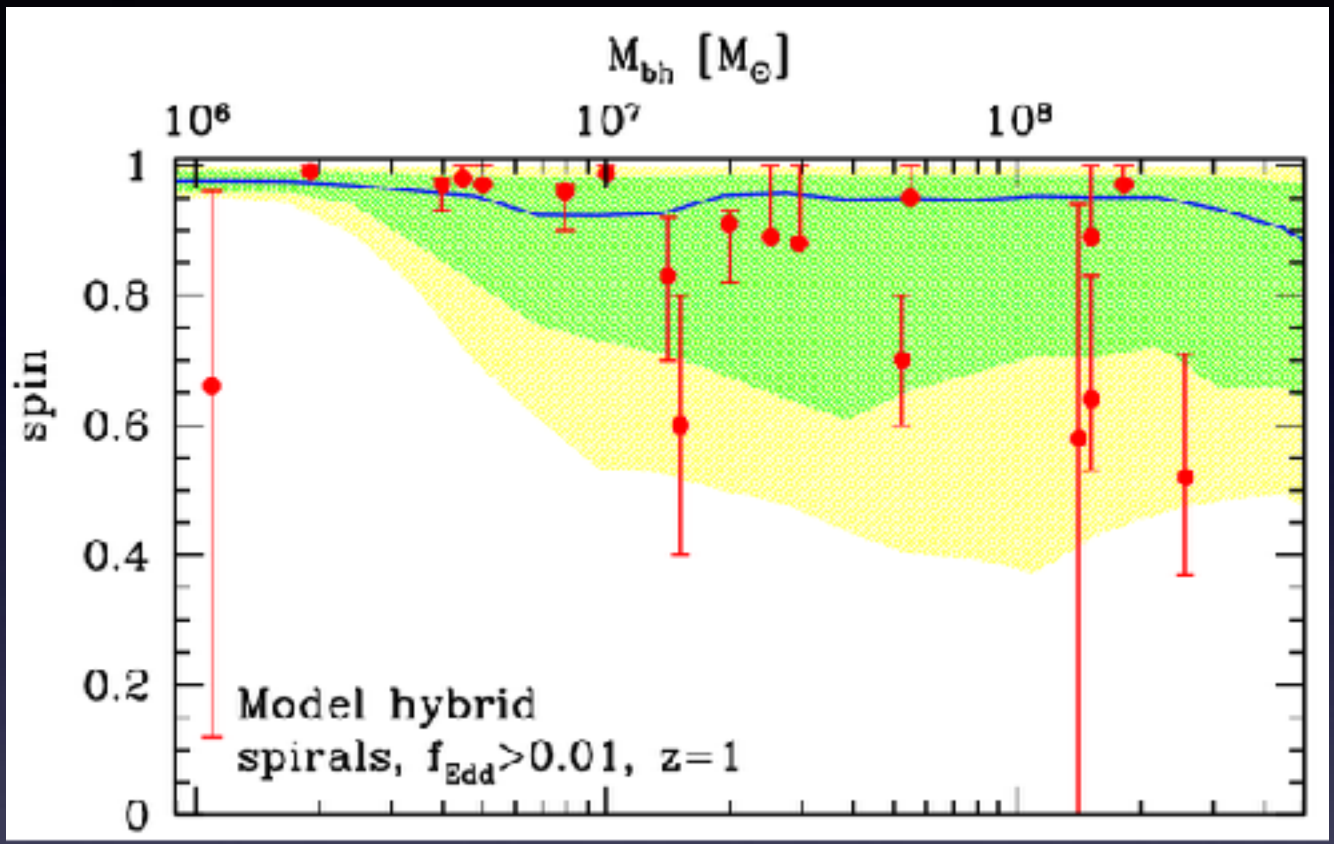
Comparison to data

- 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



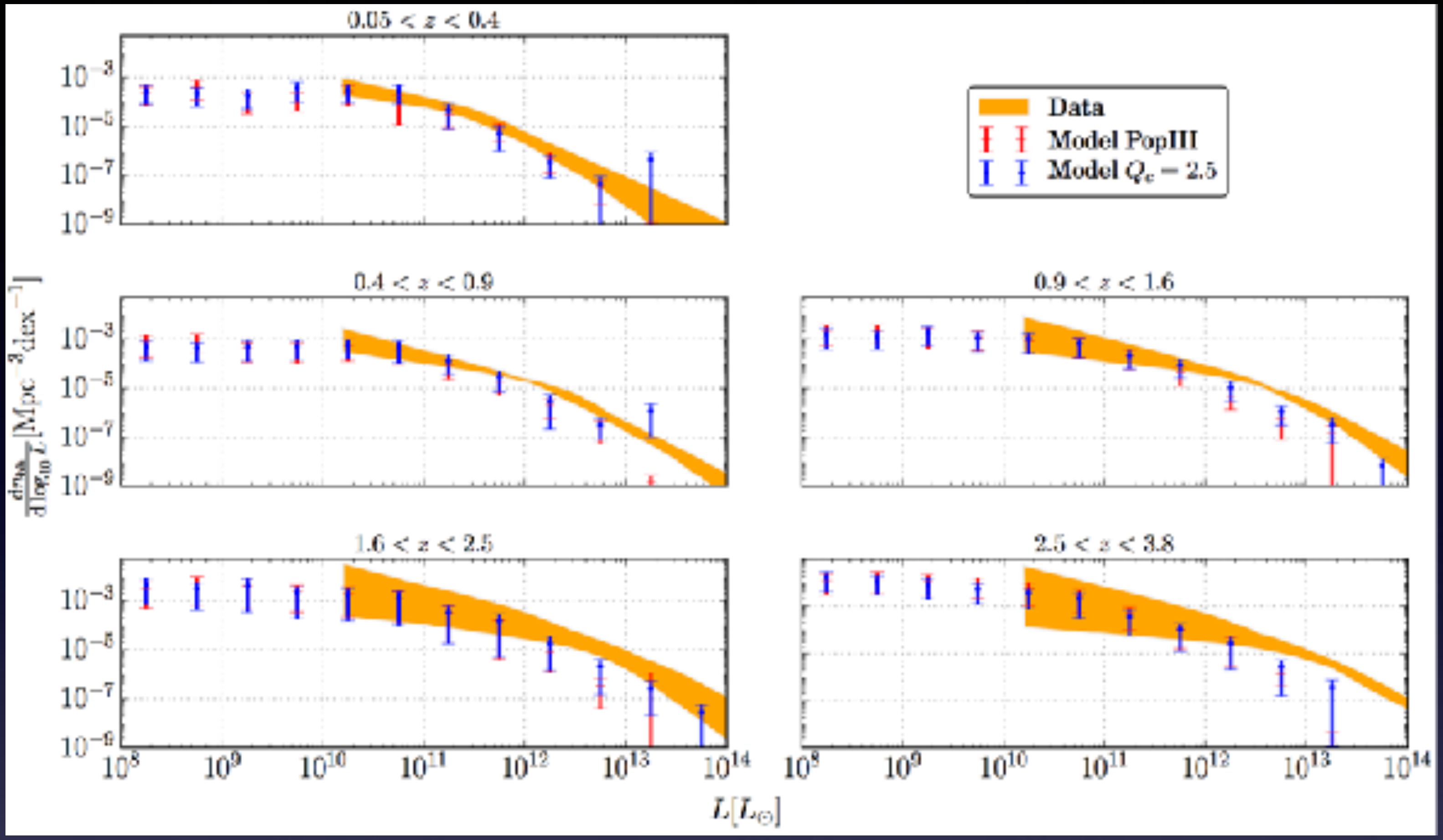
Sesana, EB, Dotti & Rossi (2014)

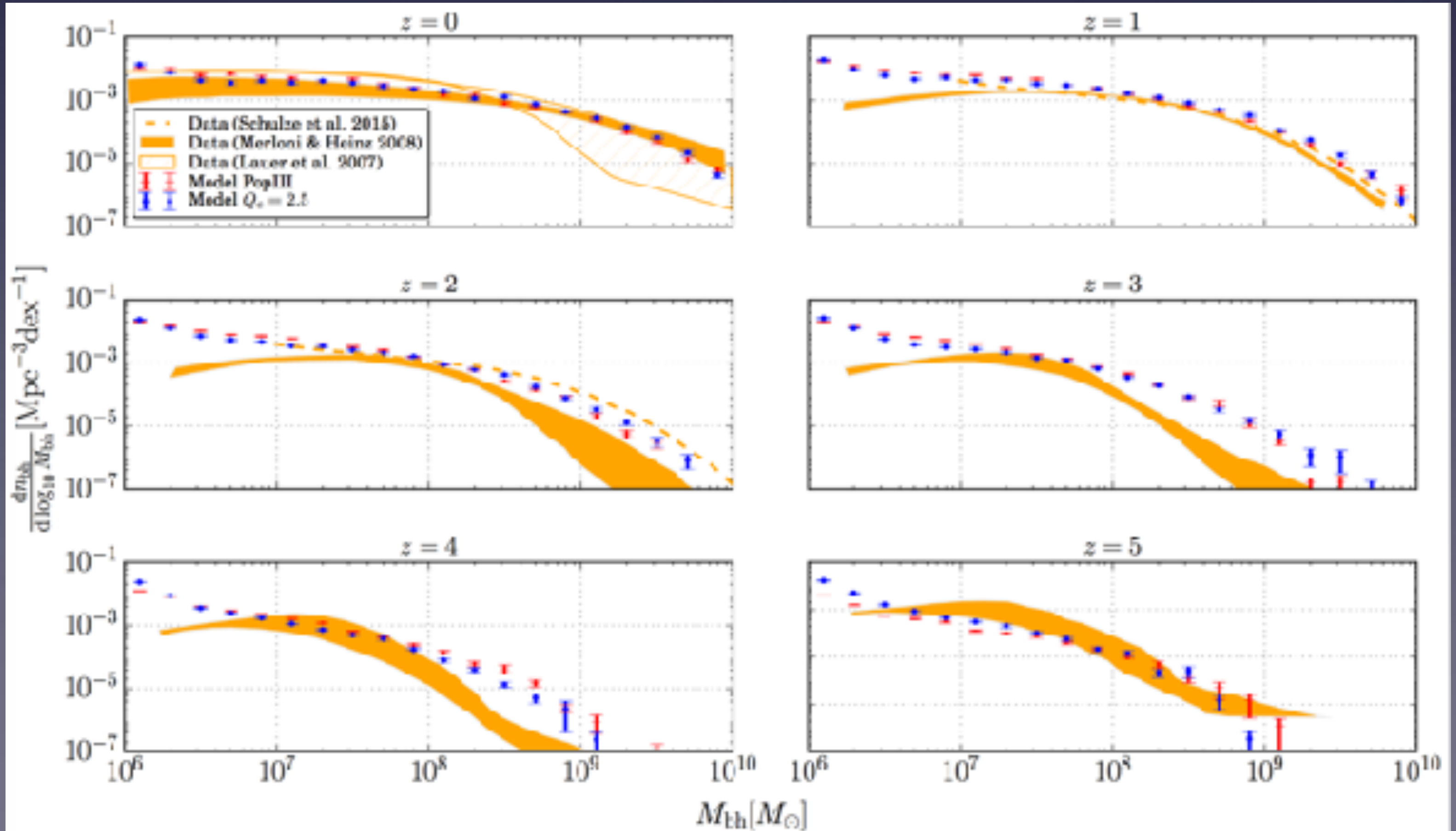
Data favor hybrid model linking accretion to

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

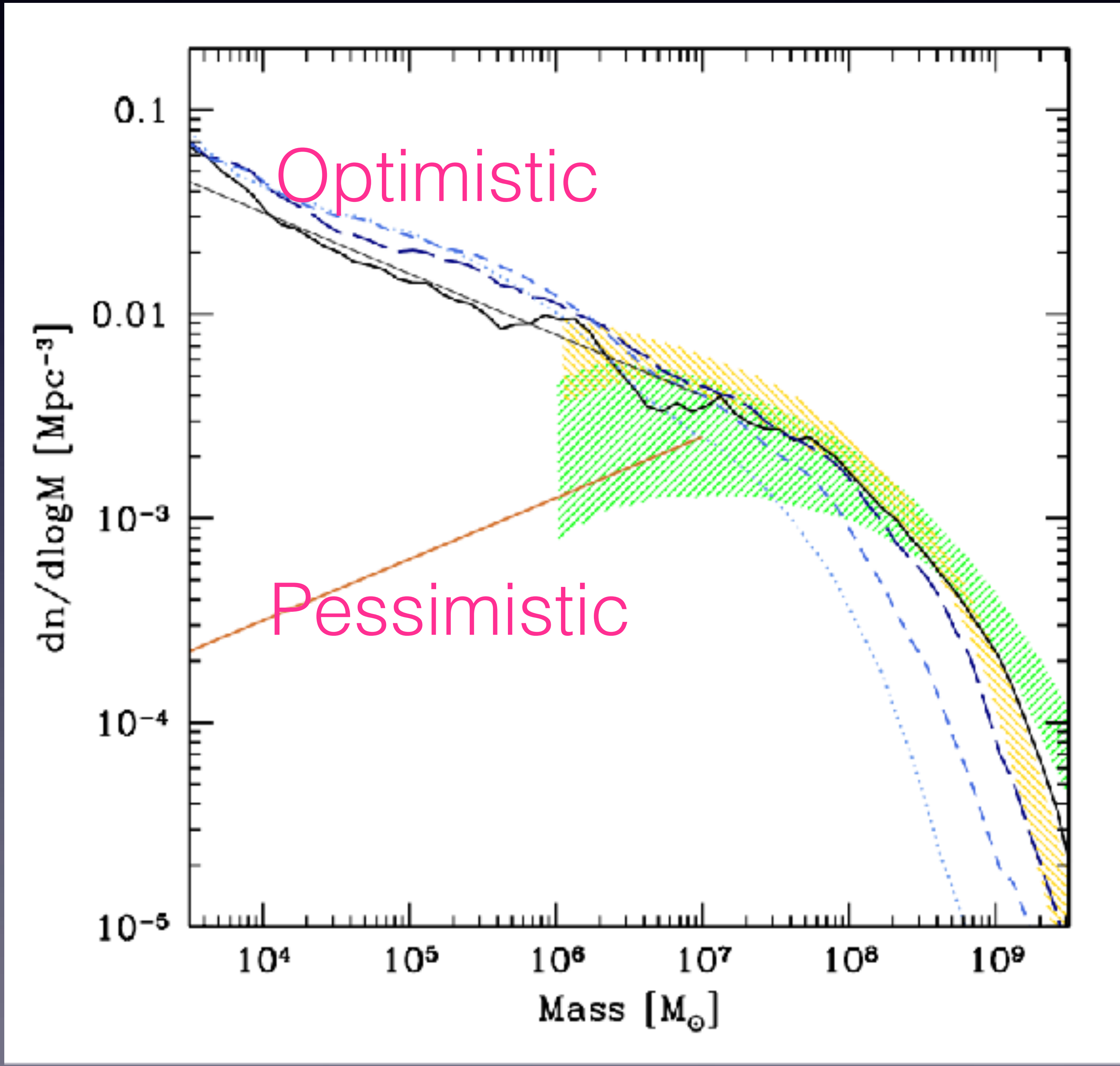
We also consider more pessimistic models with spins distributed uniformly between 0 and 1

MBH luminosity & mass functions





The slope/normalization of the low-mass end of the MBH mass function



Mergers/accretion

- Treatment of GW emission from bosonic clouds valid for isolated stationary BHs

- Mergers and accretion perturb GW emission, hence we cut GW short at the timescale corresponding to mergers or accretion, whichever shorter

- Impact on our conclusions negligible irrespective of seed model, and even if we assume fEdd=1 for all MBHs at all times,

Stellar-mass BHs

Extra-galactic BHs (Dvorkin et al 2016, 2017)

- Population synthesis+ semianalytic galaxy evolution model describing production of metals by stars and ISM metallicity
- SFR calibrated to observations
- Analytic fits for BH mass as function of ZAMS mass and metallicity

$$\frac{d\dot{n}_{\rm eg}}{dM} = \int \mathrm{d}\mathcal{M}_\star \psi[t-\tau(\mathcal{M}_\star)]\phi(\mathcal{M}_\star)\delta[\mathcal{M}_\star - g^{-1}(M)]\,,$$

Galactic BH (mostly important for resolved events)

$$\frac{dN_{\rm MW}}{dM} = \int dt \frac{\mathrm{SFR}(z)}{\mathcal{M}_\star}\frac{dp}{d\mathcal{M}_\star}\left|\frac{dM}{d\mathcal{M}_\star}\right|^{-1}$$

Spins chosen uniformly in [0.8,1], [0.5,1], [0,1], [0,0.5]