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?

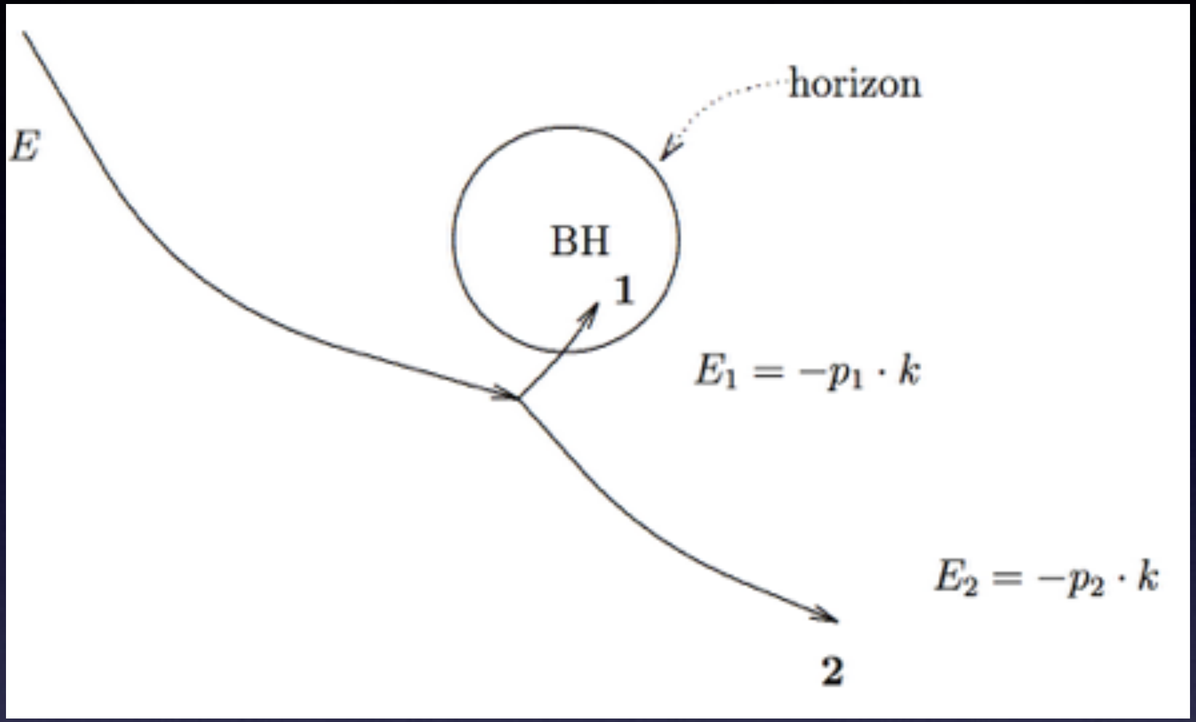
- Scalars ubiquitous in string theory, inflation, dark matter models
- Useful as toy models for unknown phenomena/interactions (e.g. modifications of GR)
- Effect of mass term expected to be qualitatively the same as for vector/tensor degrees of freedom

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

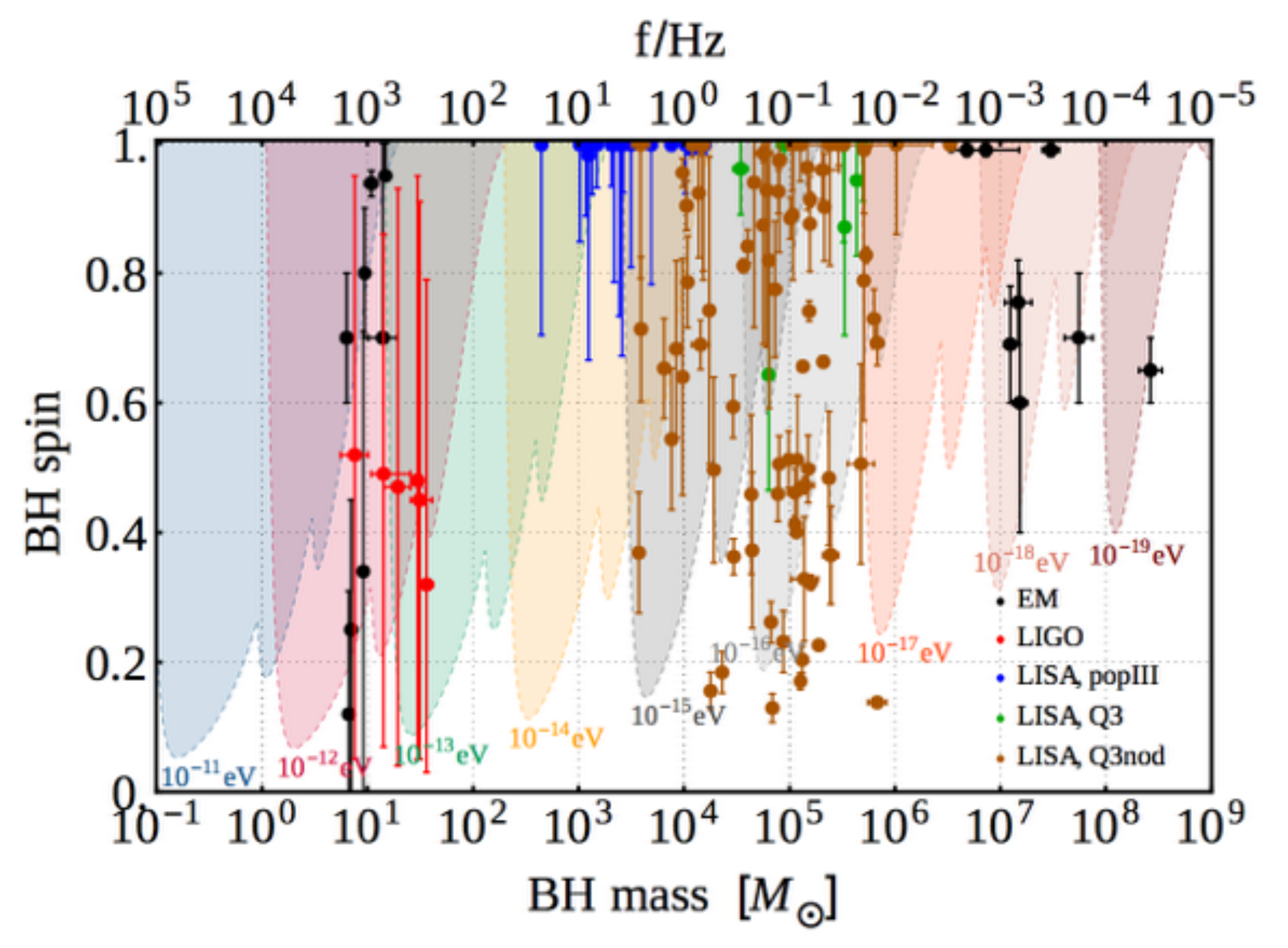
- Formation linked to superradiant instabilities/Penrose process (amplifications of scattered waves with $\omega < m\Omega_H$



- 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



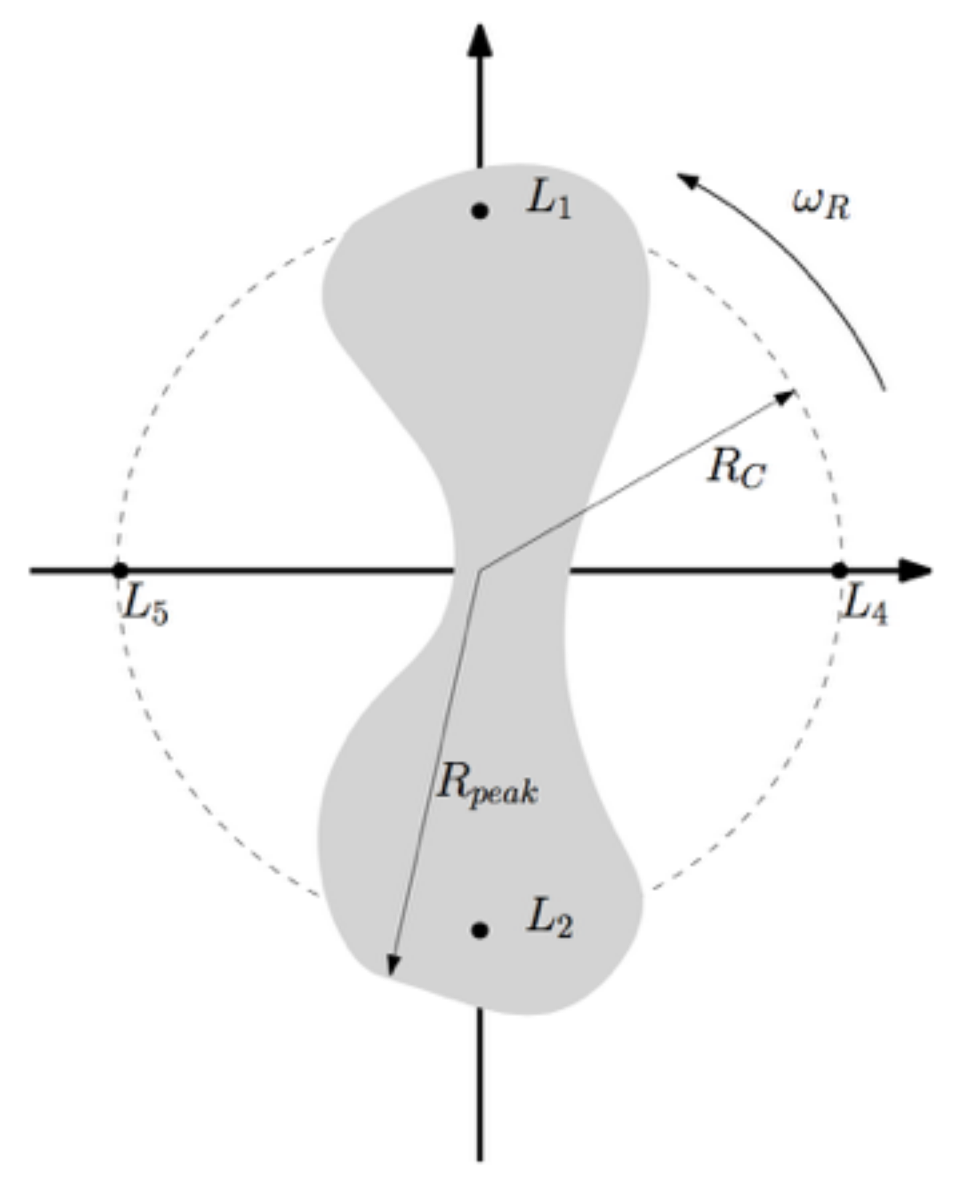
Instability end point

- 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

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

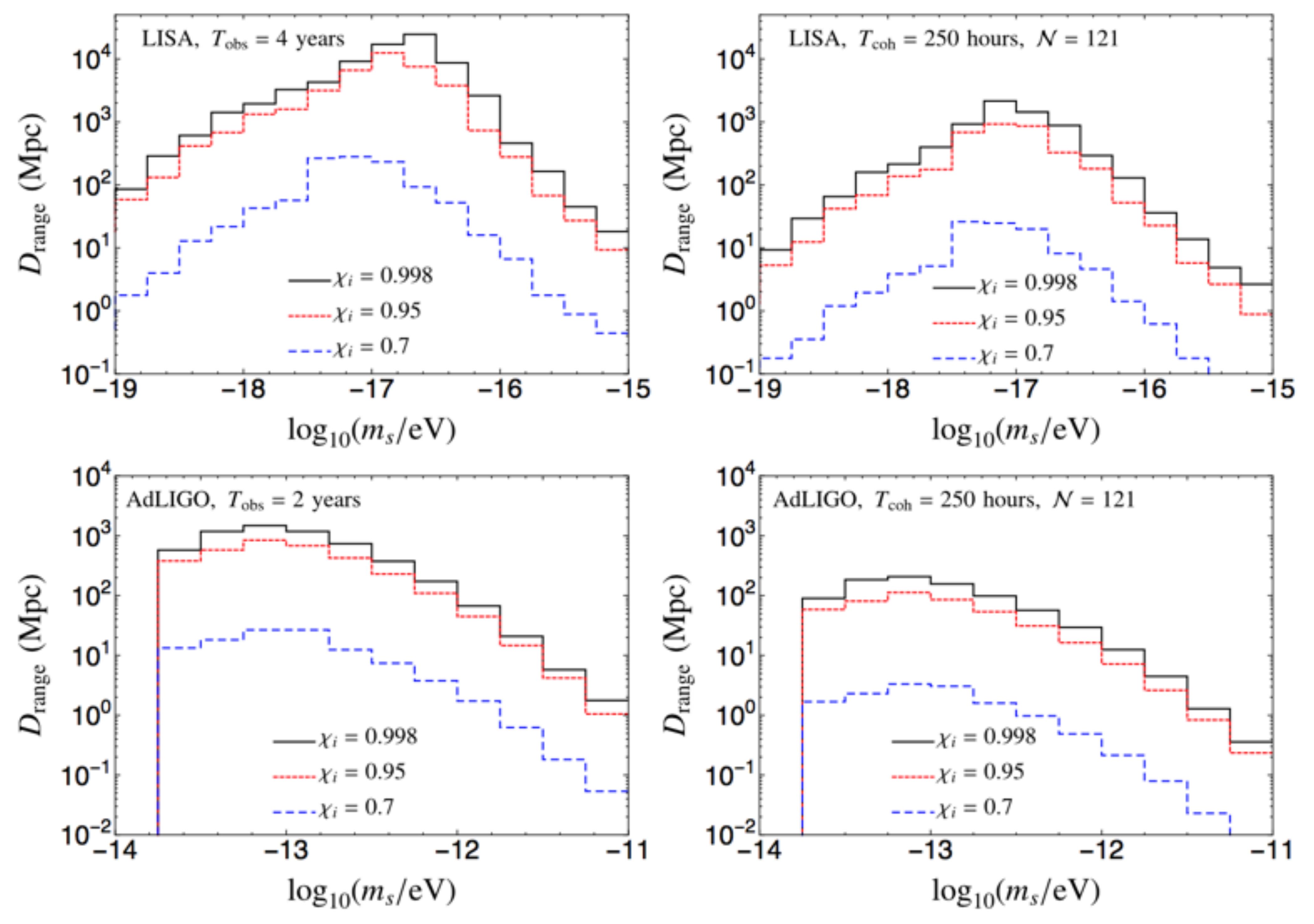
$$h = \sqrt{\frac{2}{5\pi}} \frac{GM}{c^2 r} \left(\frac{M_S}{M} \right) A(\chi, f_s M) \, ,$$

rms strain amplitude

$$\omega \sim \mu$$

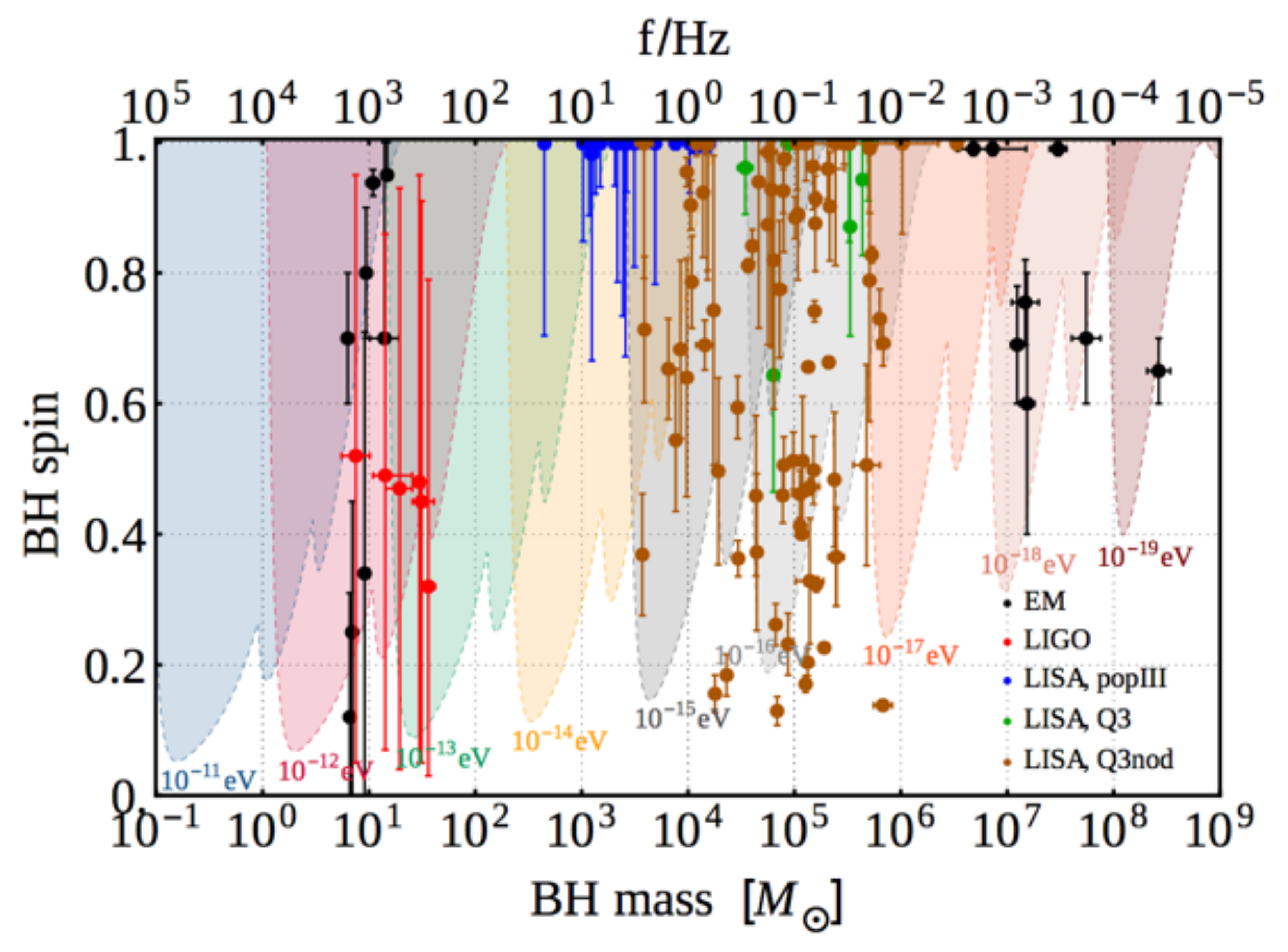
frequency

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)
$\log_{10}(m_s/\mathrm{eV})$
$\chi_i = 0.998$
$\chi_i = 0.95$
$\chi_i = 0.7$
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
−19
−18
−17
−16
−15
−14
−13
−12
−11

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 $M_{\rm sun}$, m_s~10^{-16} - 10^{-18} eV

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

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

$$\Omega_{\rm GW,\,ax}^{\rm LISA} \sim 10^{-9}$$

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 $M_{\rm sun}$, $m_s \sim 10^{-13}$ - 10^{-12} eV

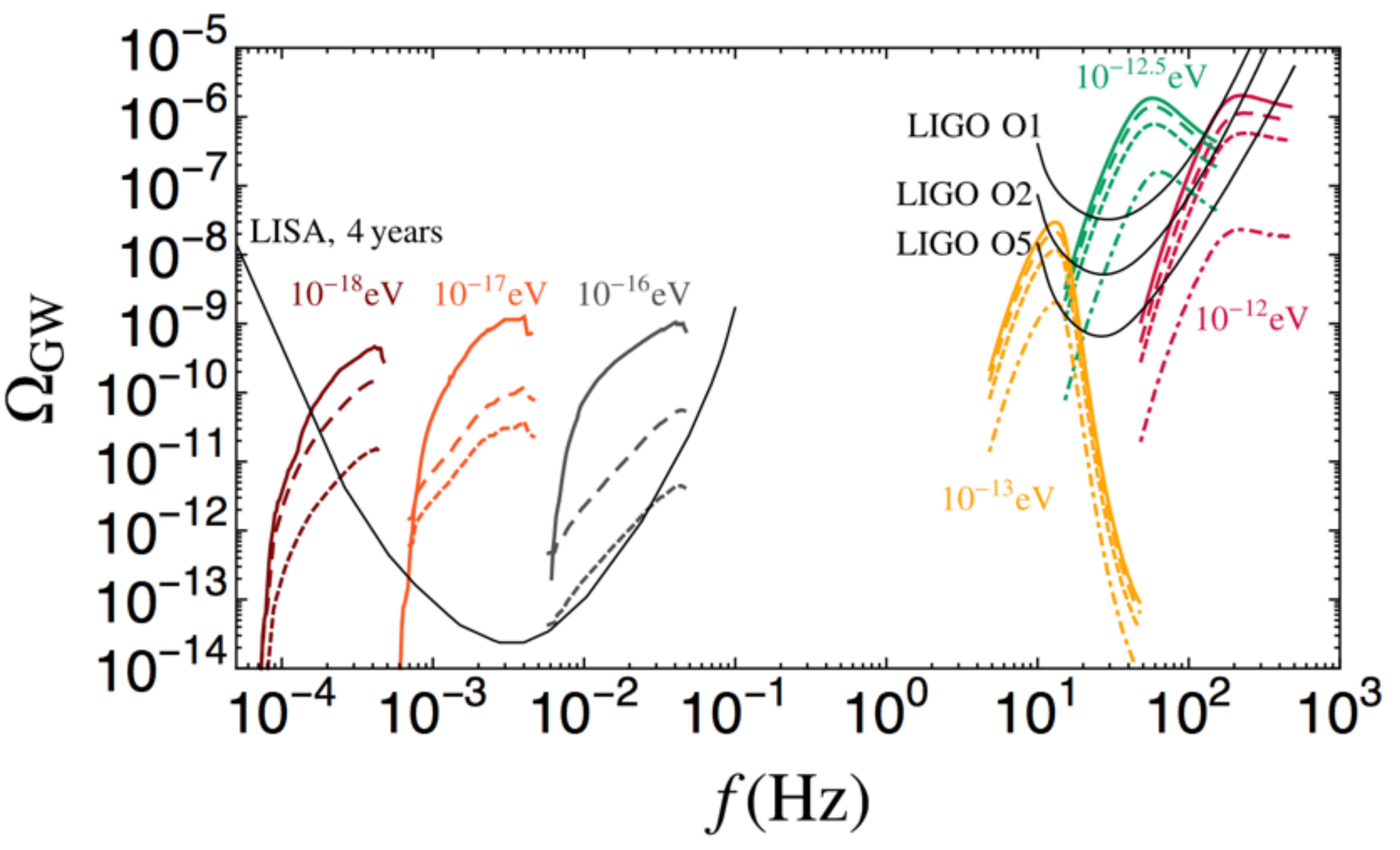
$$\Omega_{\rm GW,\, bin} \ \sim f_{\rm GW} f_{\rm m} \rho_{\rm BH}/\rho_c$$

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

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

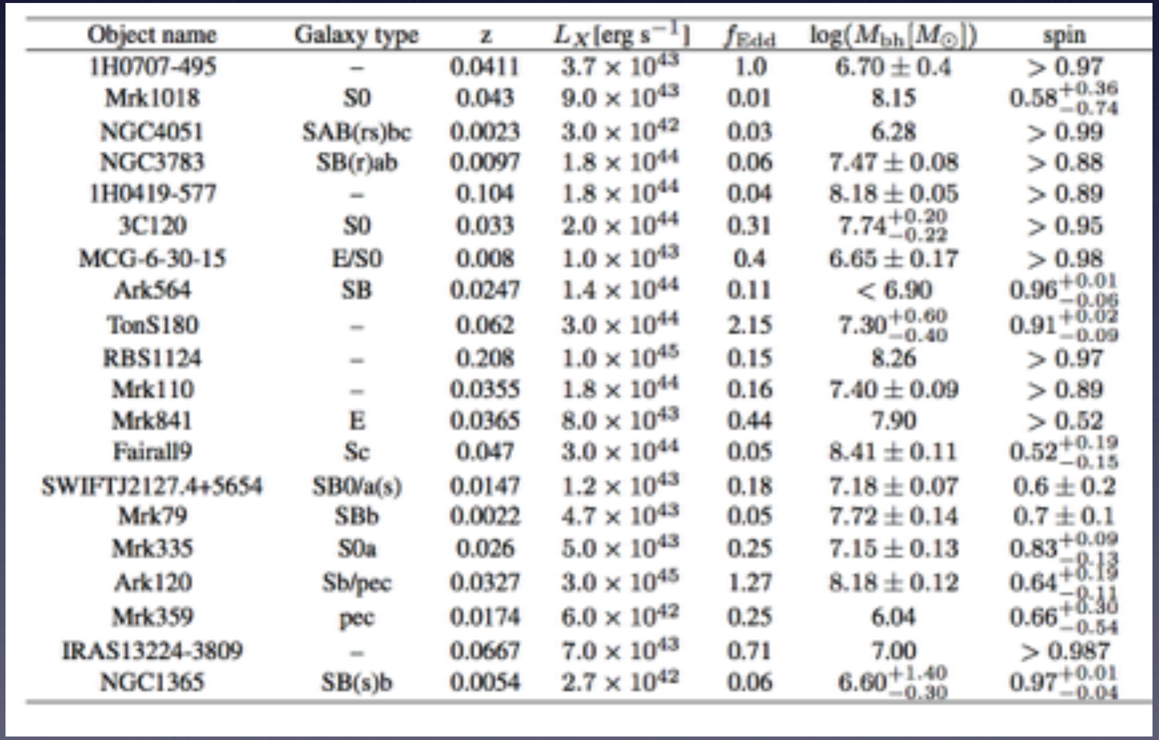
$$\Omega_{\rm GW,\, bin} \ \sim \ 10^{-9} - 10^{-8} \qquad \Omega^{\rm LIGO}_{\rm GW,\, ax} \sim 10^{-7} - 10^{-6}$$

Background from isolated spinning BHs



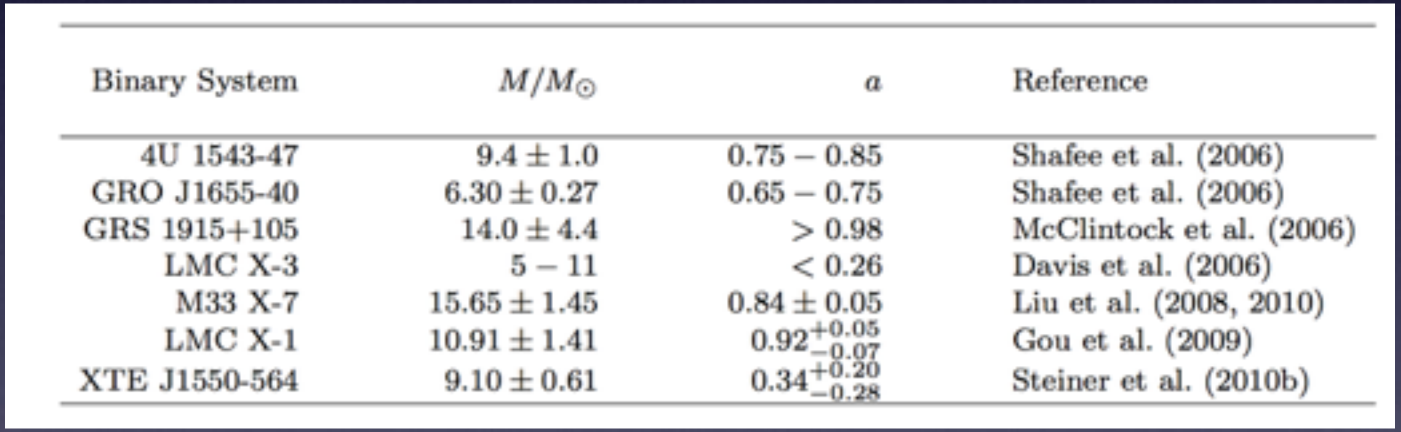
BH spin & mass modeling is crucial

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	$6.60^{+1.40}_{-0.30}$	$0.97^{+0.01}_{-0.04}$

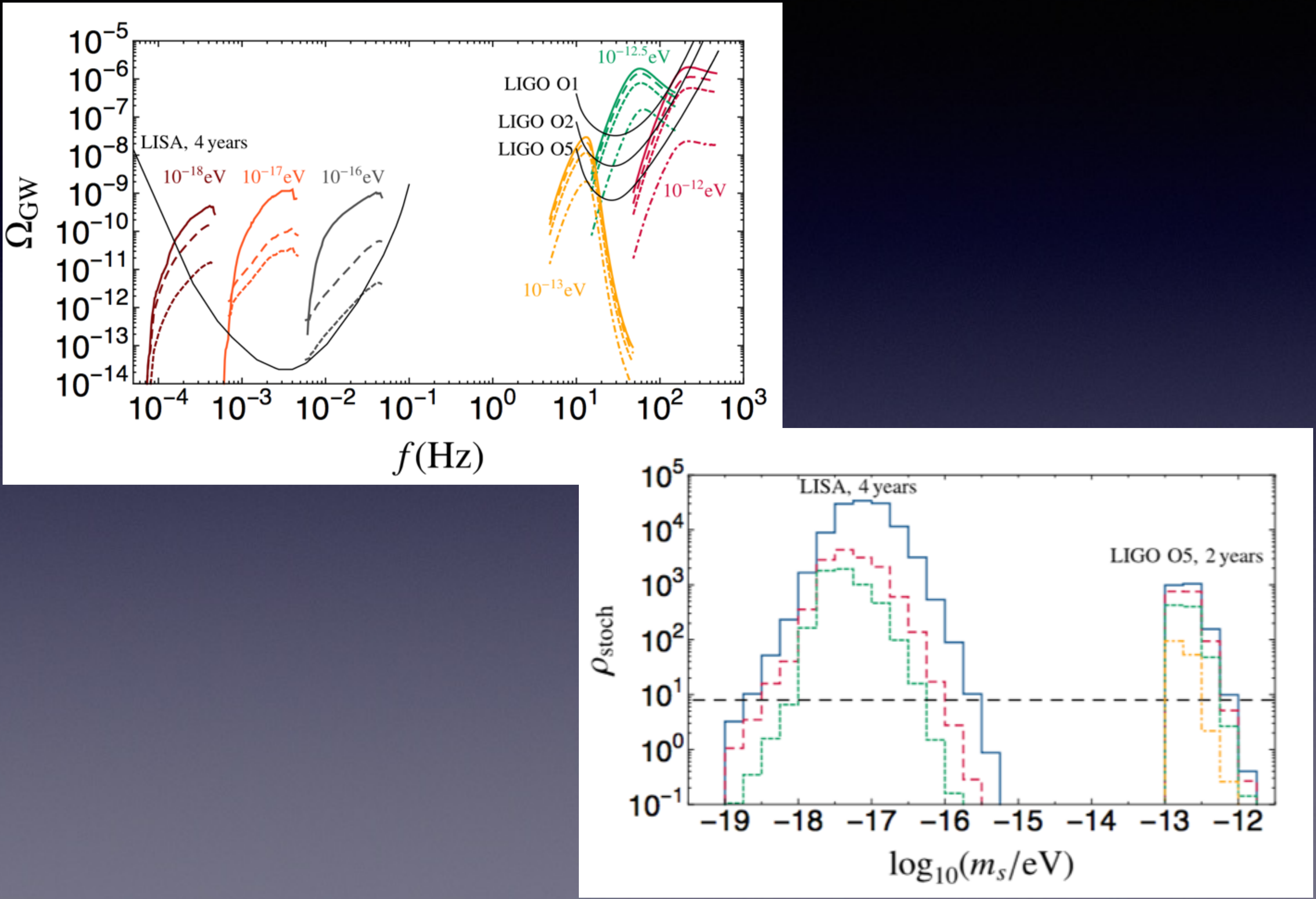
Compilations (Reynolds, Brenneman,...) of massive BH spins



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)

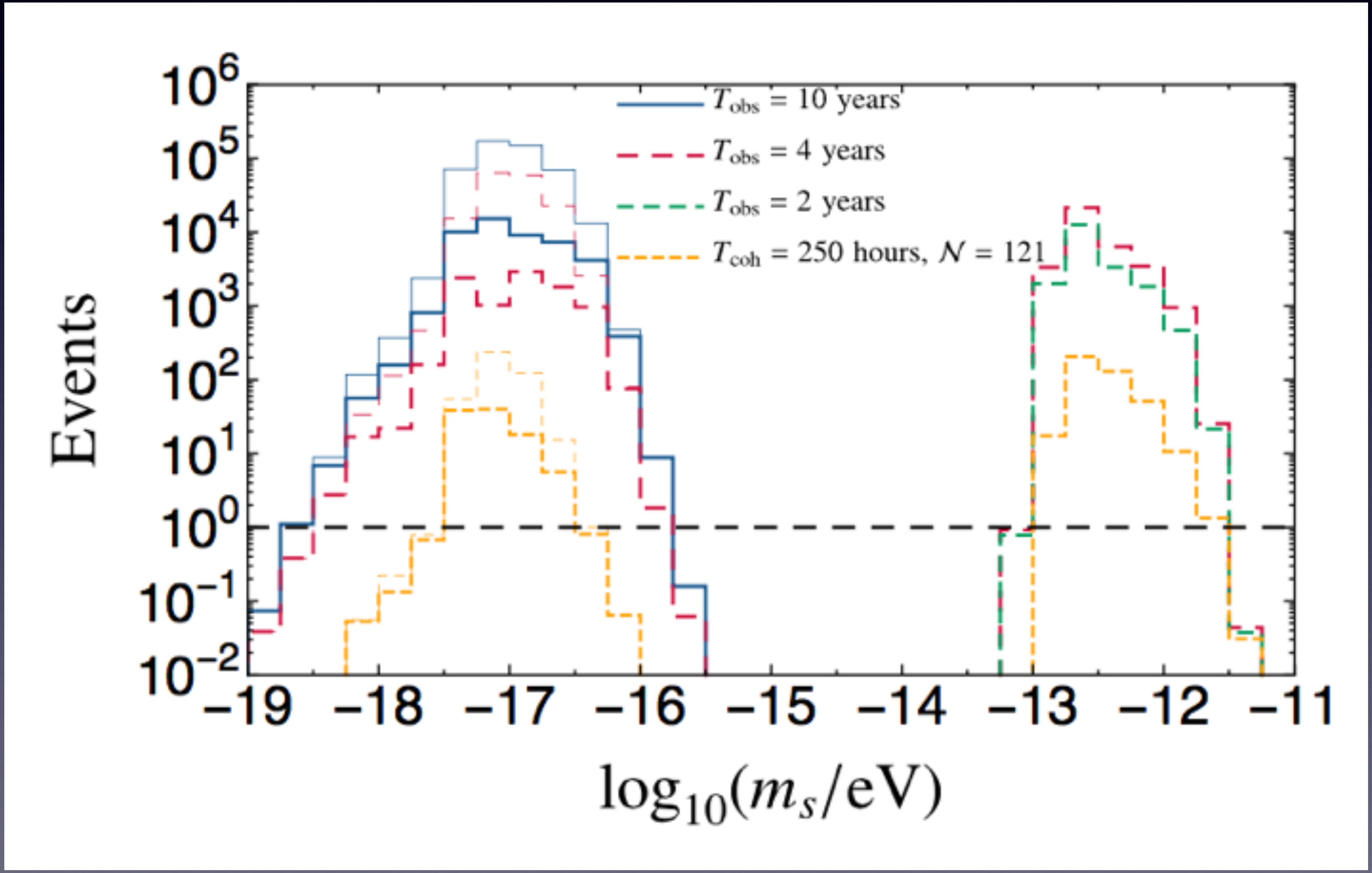
Stellar-mass BH spins

Stochastic background



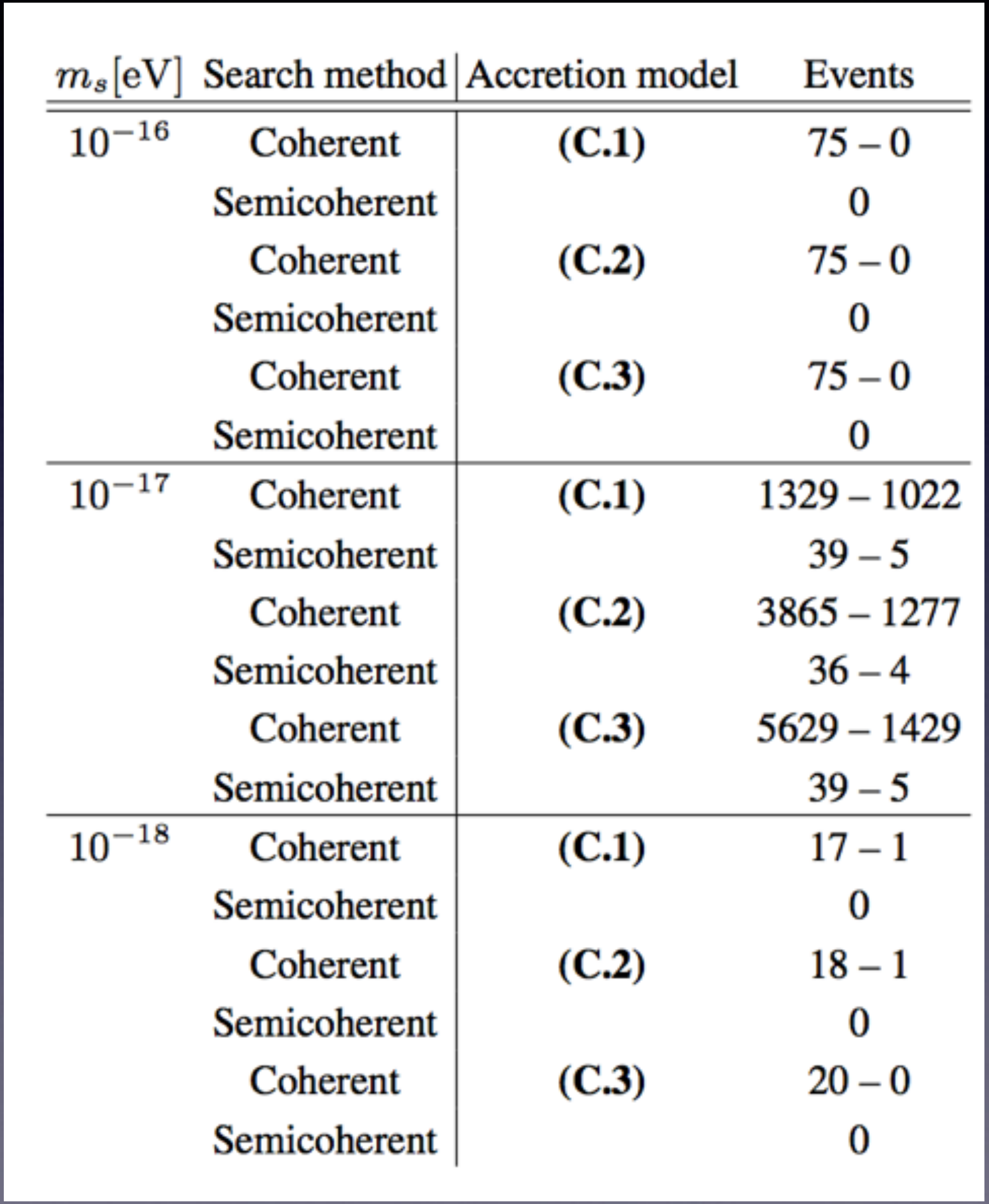
Resolved events

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

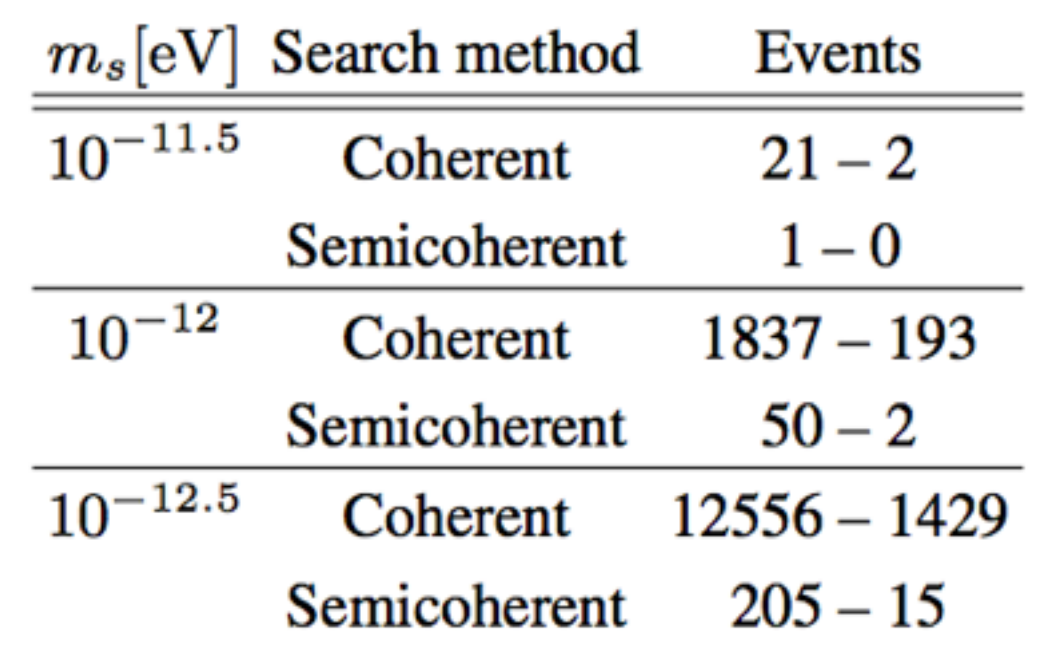


most optimistic models

Resolved events

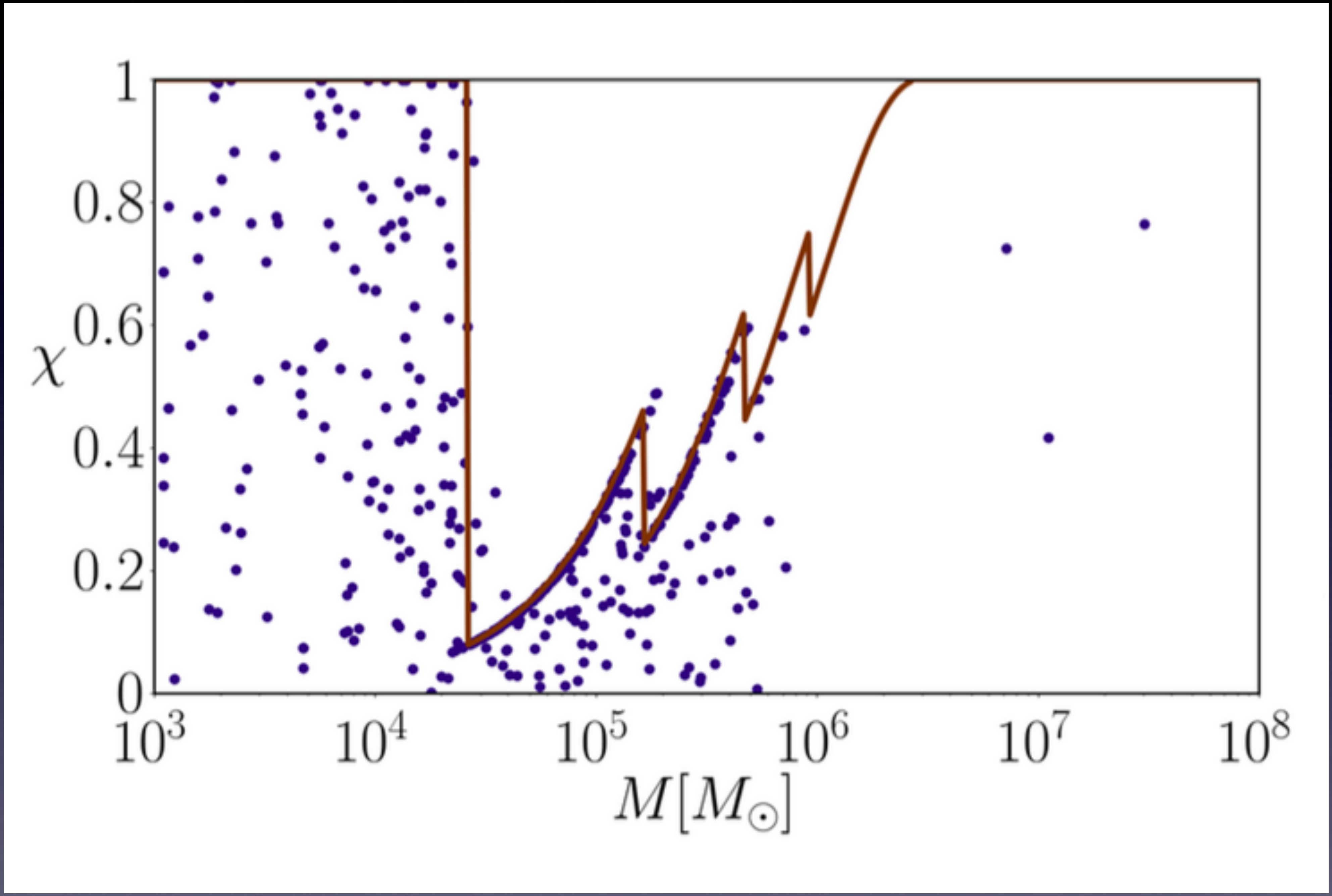


m_s[eV]	Search method	Accretion model	Events
10^{-16}	Coherent	**(C.1)**	75 – 0
	Semicoherent		0
	Coherent	**(C.2)**	75 – 0
	Semicoherent		0
	Coherent	**(C.3)**	75 – 0
	Semicoherent		0
10^{-17}	Coherent	**(C.1)**	1329 – 1022
	Semicoherent		39 – 5
	Coherent	**(C.2)**	3865 – 1277
	Semicoherent		36 – 4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



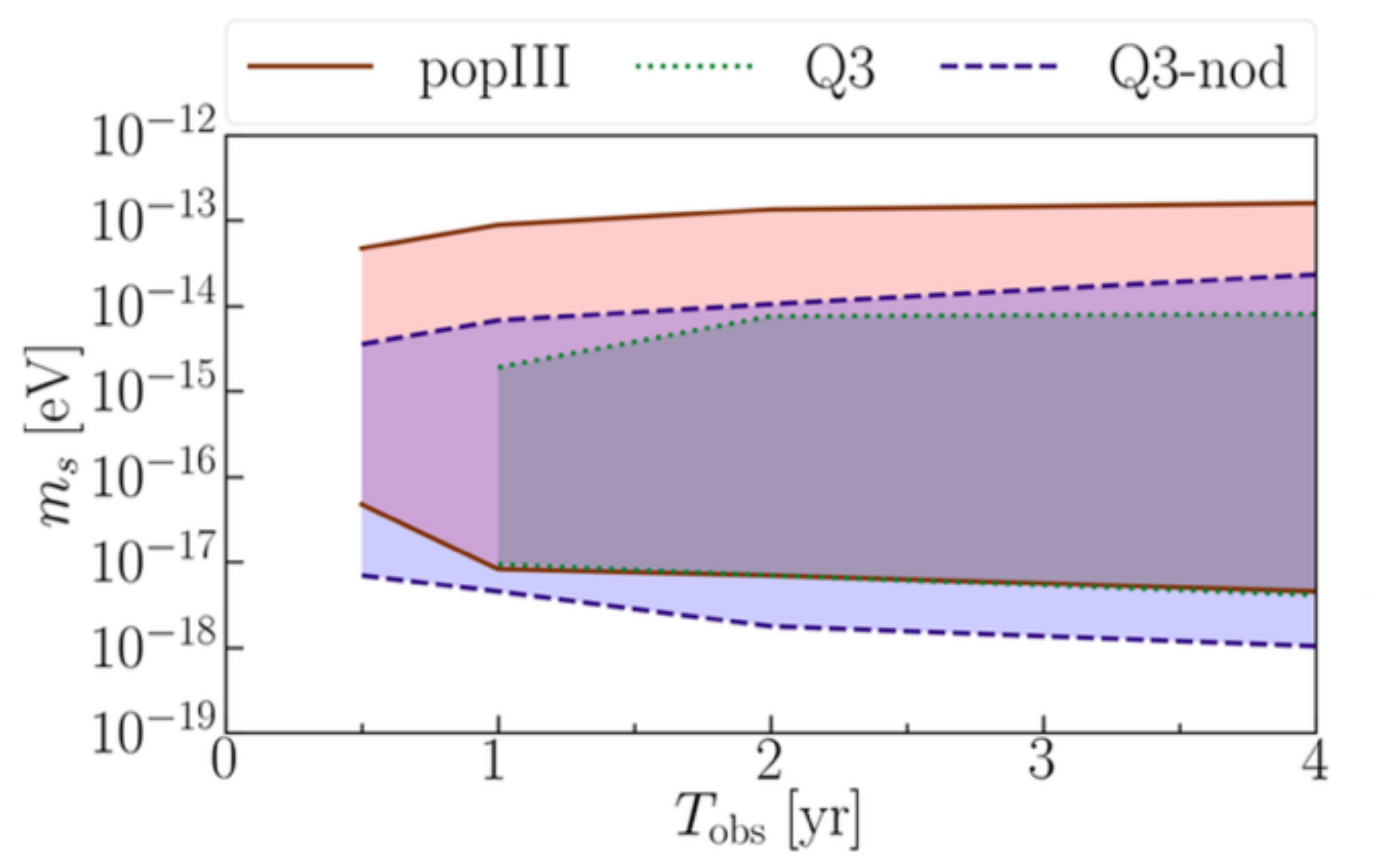
m_s[eV]	Search method	Events
$10^{-11.5}$	Coherent	21 – 2
	Semicoherent	1 – 0
10^{-12}	Coherent	1837 – 193
	Semicoherent	50 – 2
$10^{-12.5}$	Coherent	12556 – 1429
	Semicoherent	205 – 15

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