# Stochastic and resolvable gravitational waves from ultralight bosons

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(mainly) based on

arxiv: 1706.05097; 1706.06311; 1805.08229;

see also arXiv:1404.7149; 1811.07786

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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
- Constraints on BH mimickers

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# Why light bosons?

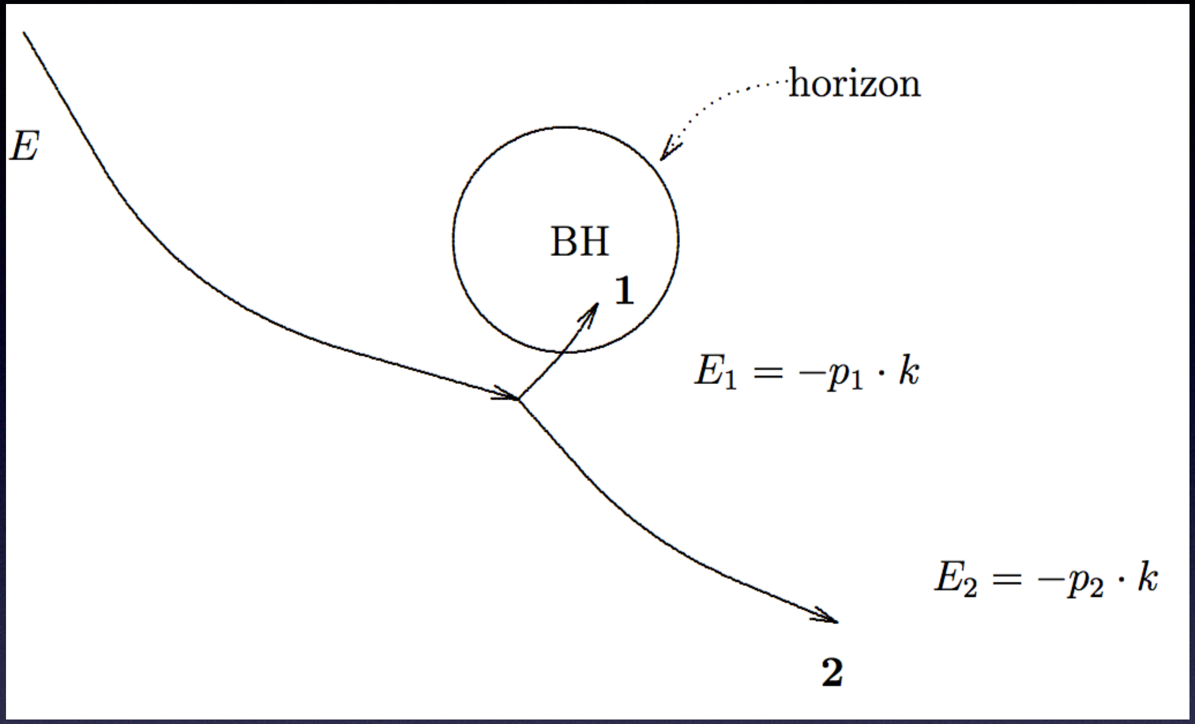
- Scalars ubiquitous in string theory, inflation, dark matter models (e.g. fuzzy/axionic dark matter)
- Useful as toy models for unknown phenomena/ interactions (e.g. modifications of GR)
- “Light” means <~ 1.e-10 eV
- Effect of mass term expected to be qualitatively similar for all boson degrees of freedom

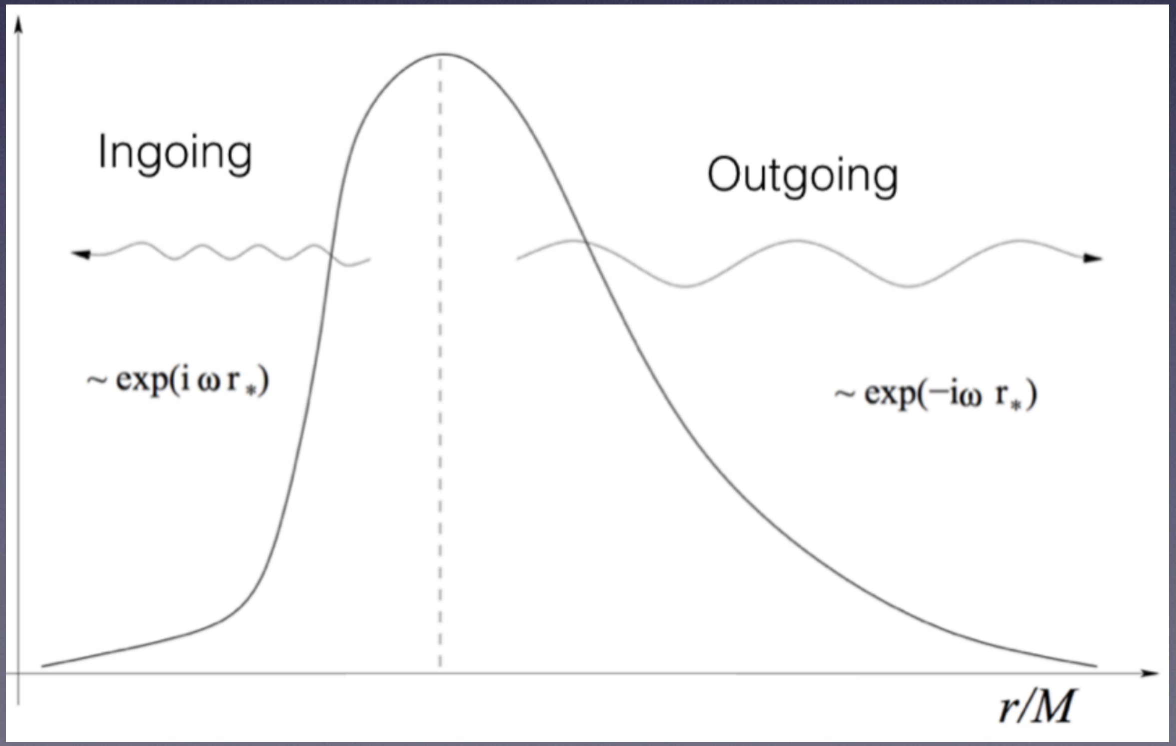
# Self-gravitating scalar configurations

- 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 (amplification of scattered waves with $\omega < m\Omega_H$)
- BH with high enough spin and “mirror” are superradiance unstable (BH bomb; Zeldovich 71, Press & Teukolsky 72, Cardoso et al 04)
- In ergoregion, negative energy modes can be produced but are confined (only positive energy modes can travel to infinity)
- By energy conservation, more and more negative energy modes can be produced, which may cause instability according to boundary conditions (at horizon and spatial infinity)



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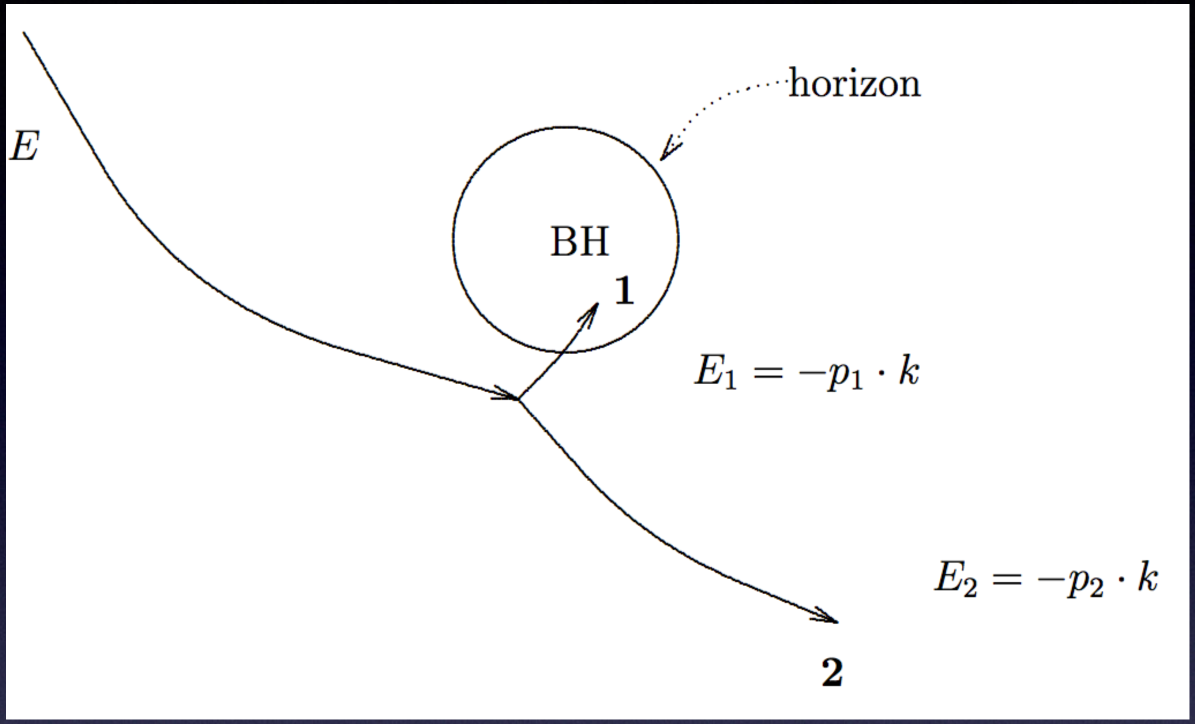
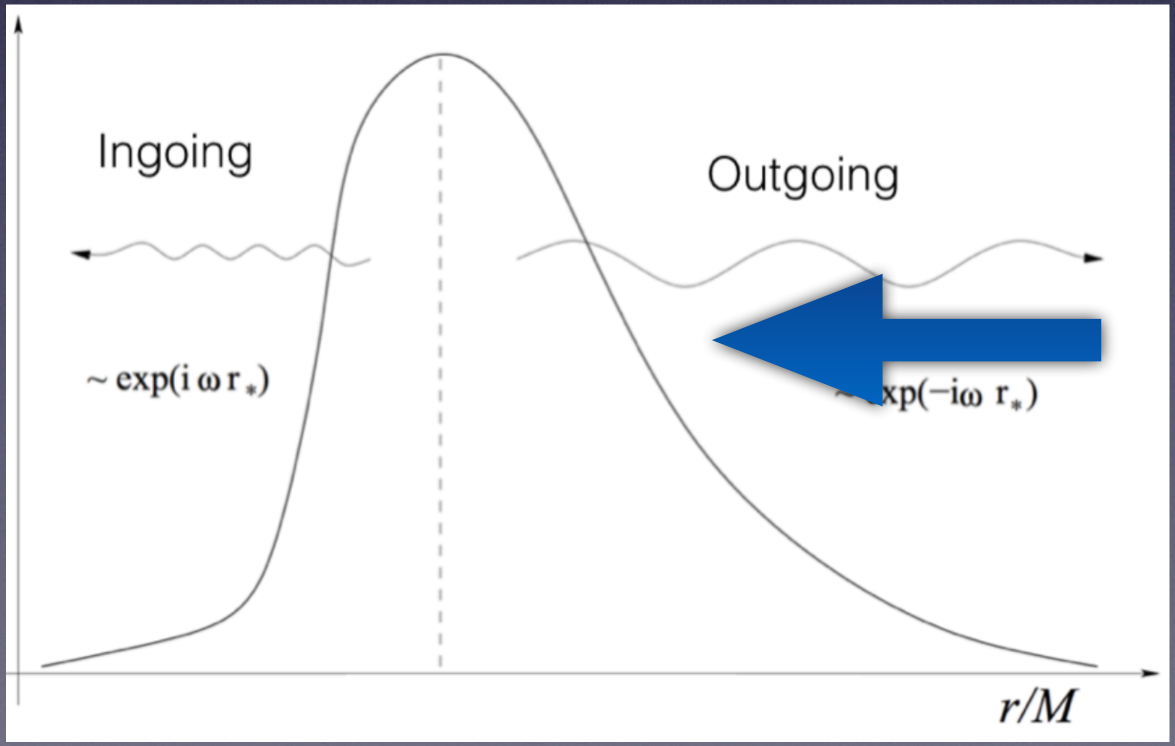
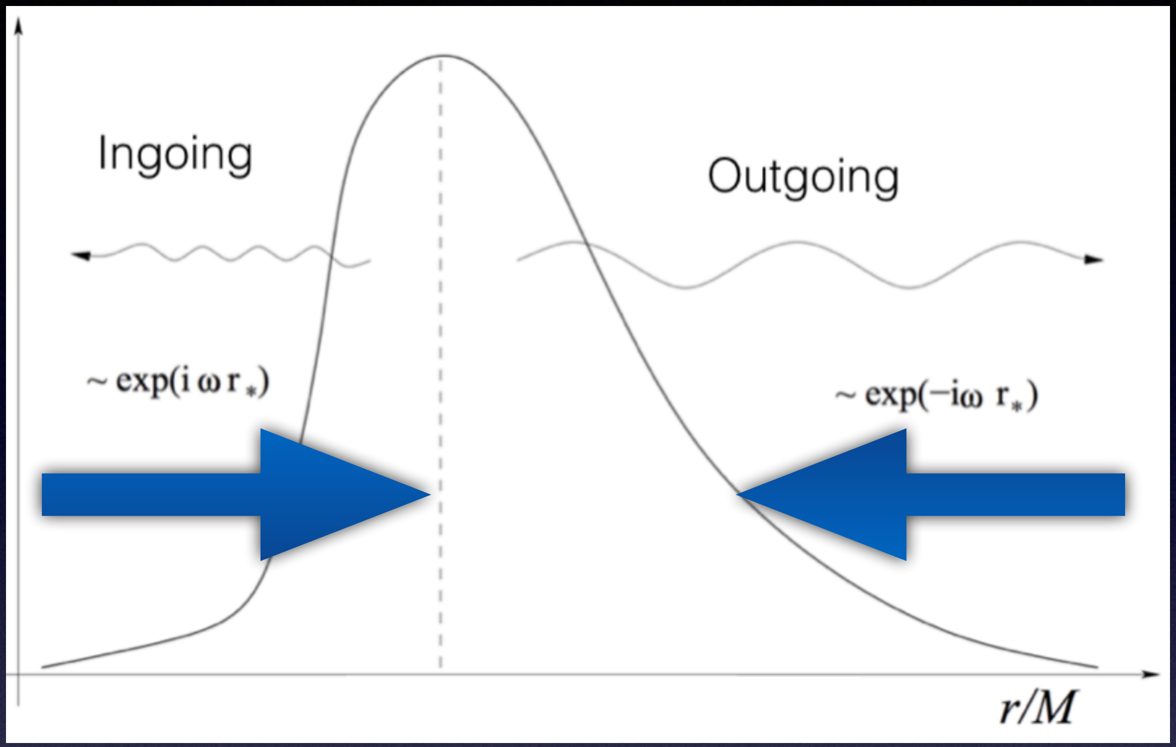


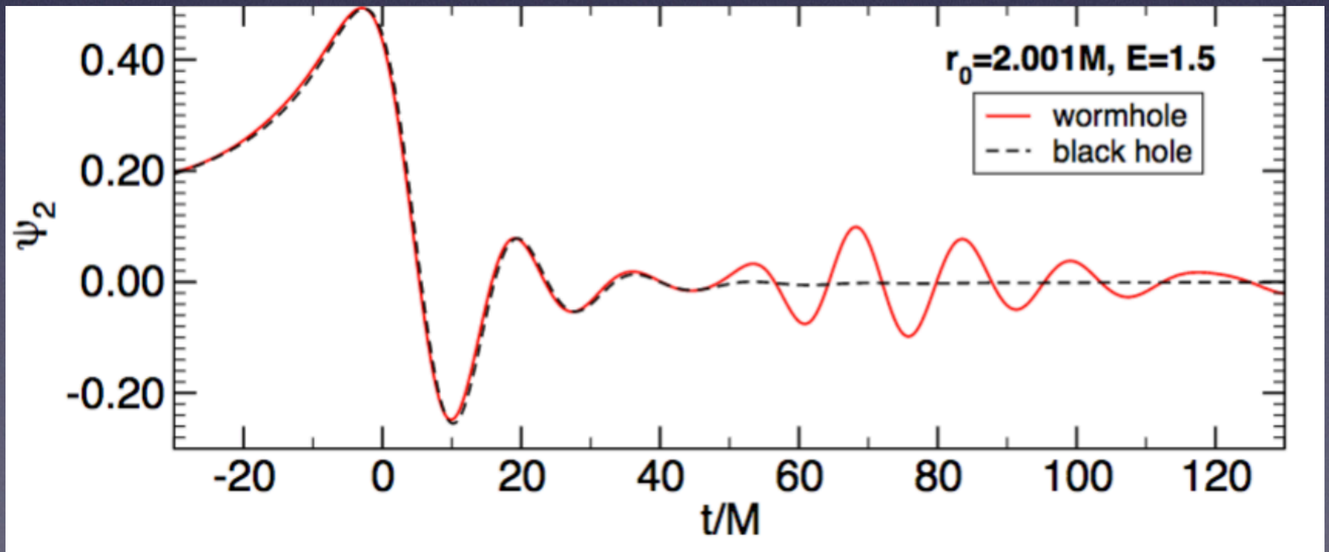



# Superradiance from near horizon physics

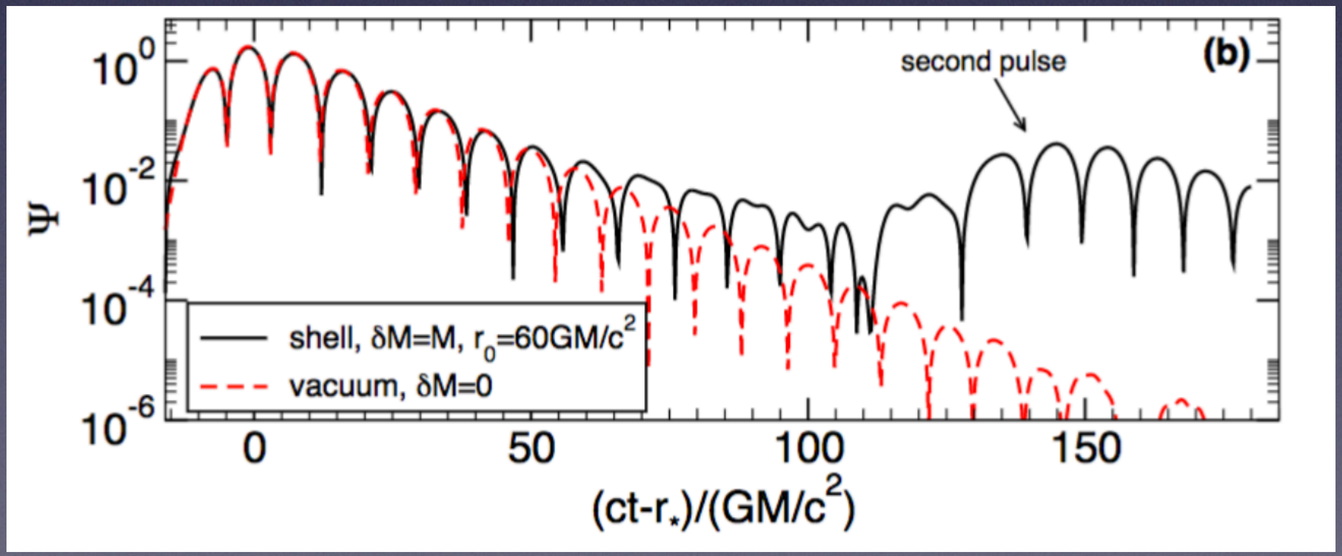



- Deviations away from Kerr geometry near horizon (e.g. firewalls, gravastars, wormholes, Lorentz violations, etc) can produce significant changes in QNM spectrum

- Delays $\Delta t \sim \log[r_0/(2M) - 1]$



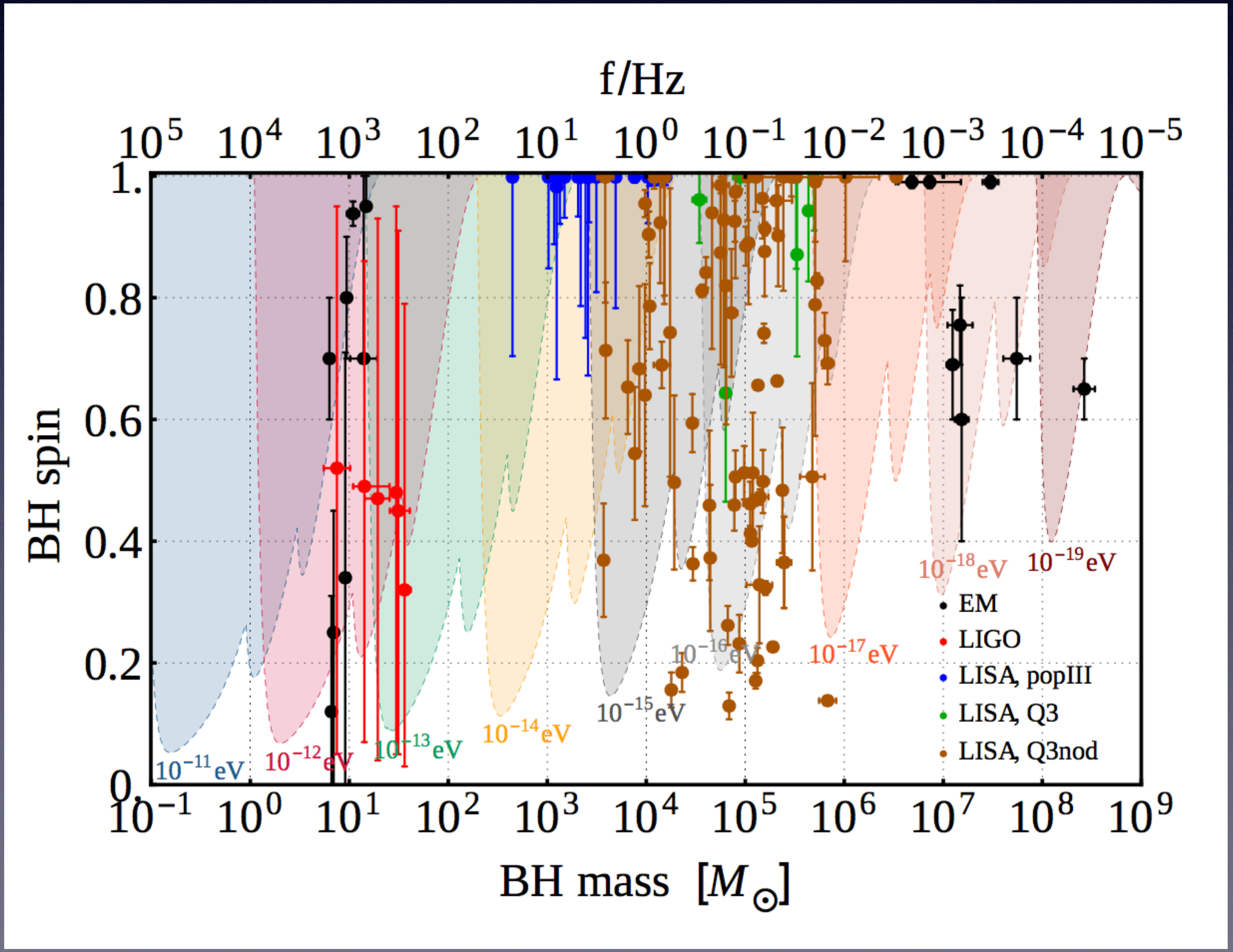

Cardoso, Franzin & Pani 2016




EB, Cardoso & Pani 2014

# 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



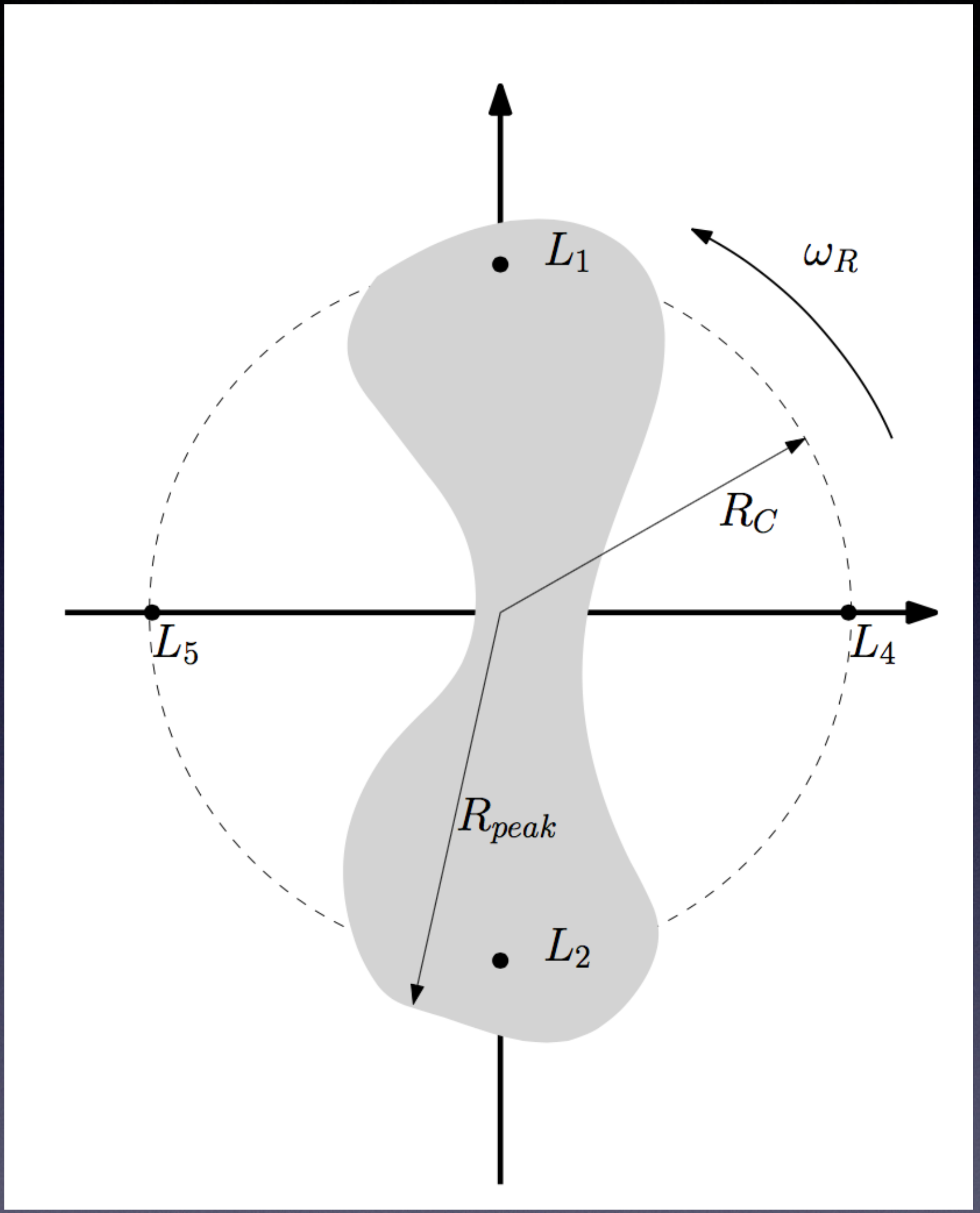
# Instability end point

- 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

# Background from isolated spinning BHs

energy emission efficiency

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

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

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

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

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

# 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 $M_{sun}$, $m_s$~$10^{-13}$ - $10^{-12}$ eV

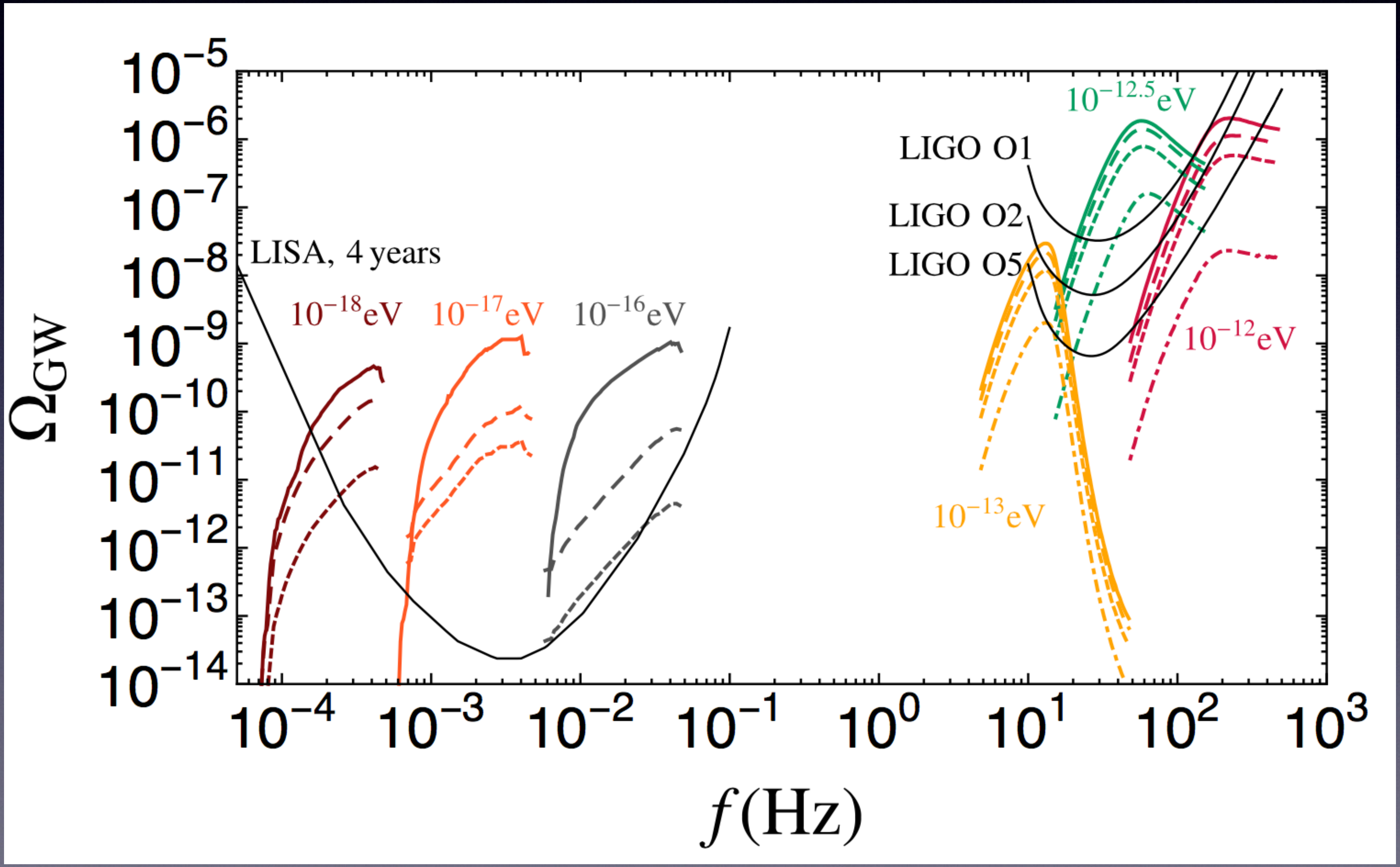
$$\Omega_{\rm GW,\,bin} \sim f_{\rm GW} f_{\rm m} \rho_{\rm BH}/\rho_c$$

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

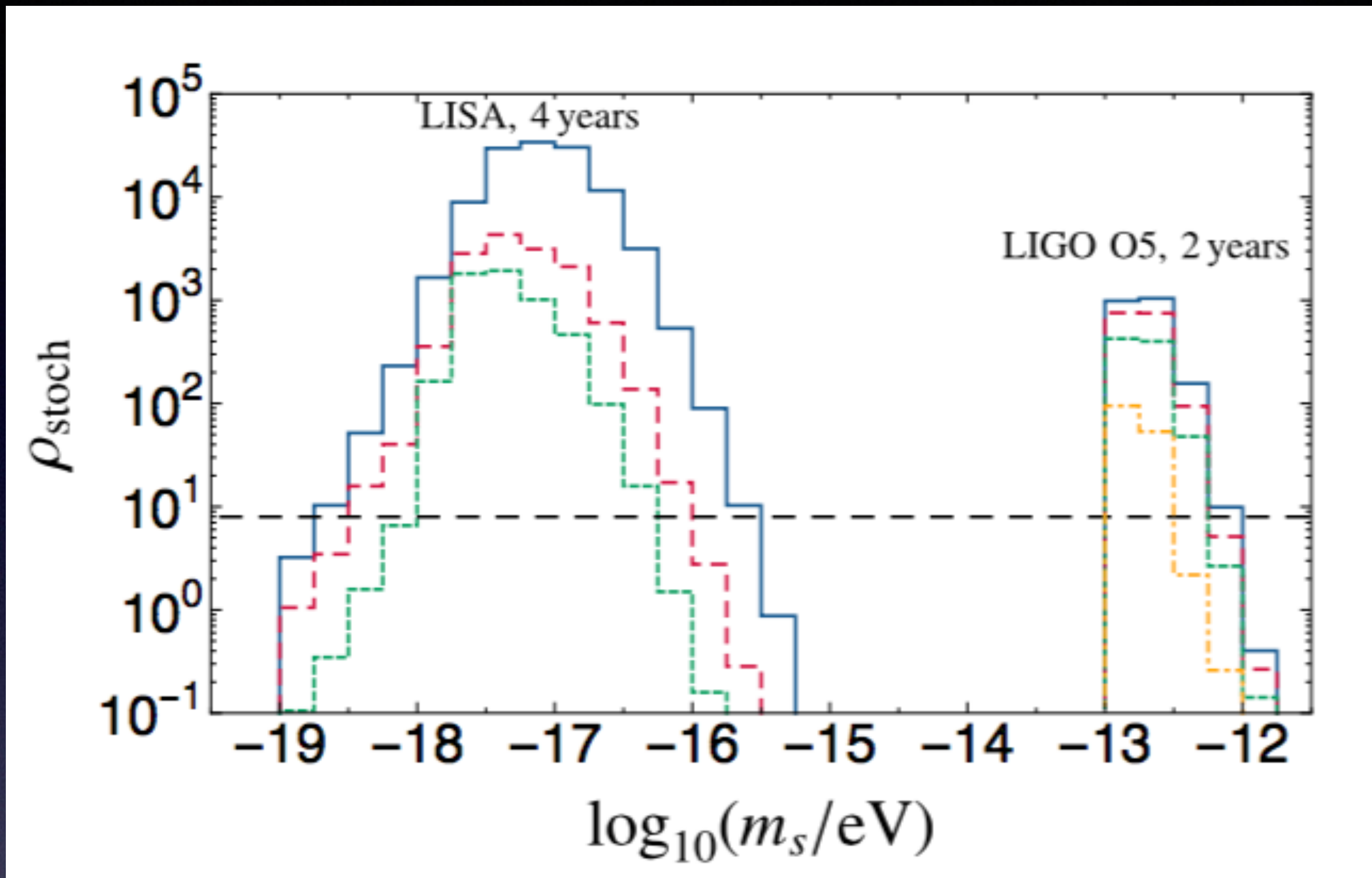
$$\Omega_{\rm GW,\,ax}/\Omega_{\rm GW,\,bin} \sim f_{\rm ax}/(f_{\rm GW} f_{\rm m}) \sim 10^2$$

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

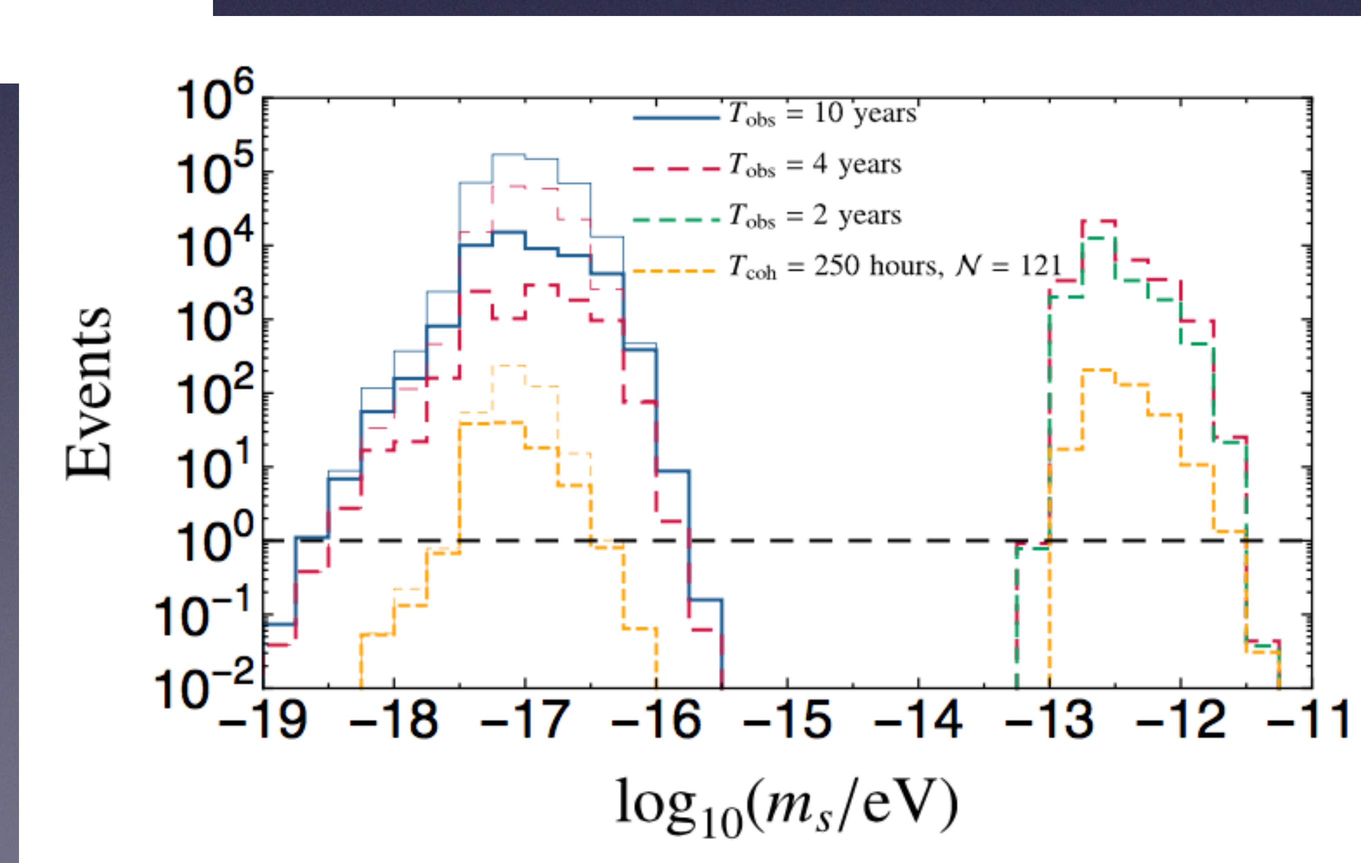
# Background from isolated spinning BHs



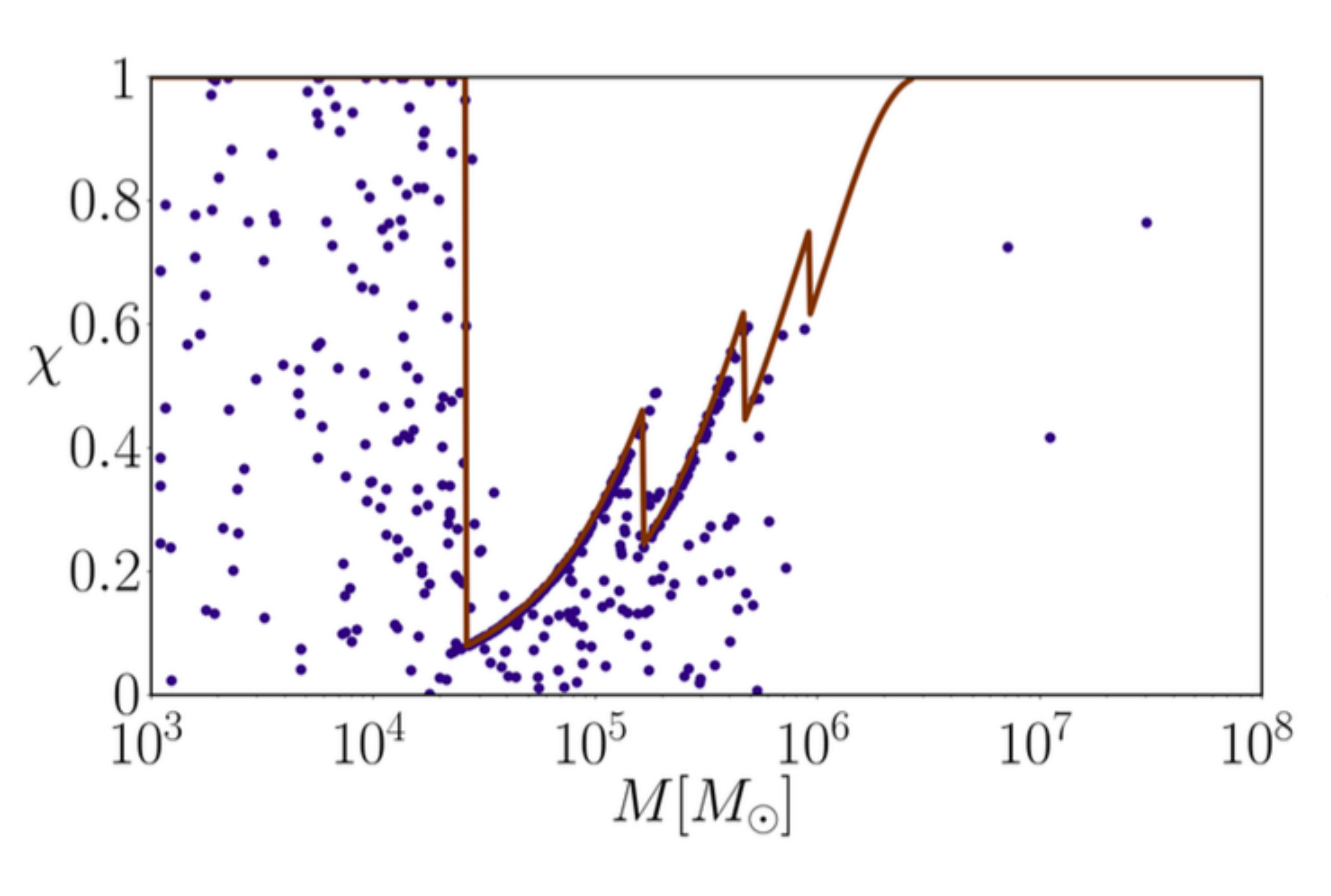
# Background and resolved sources




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



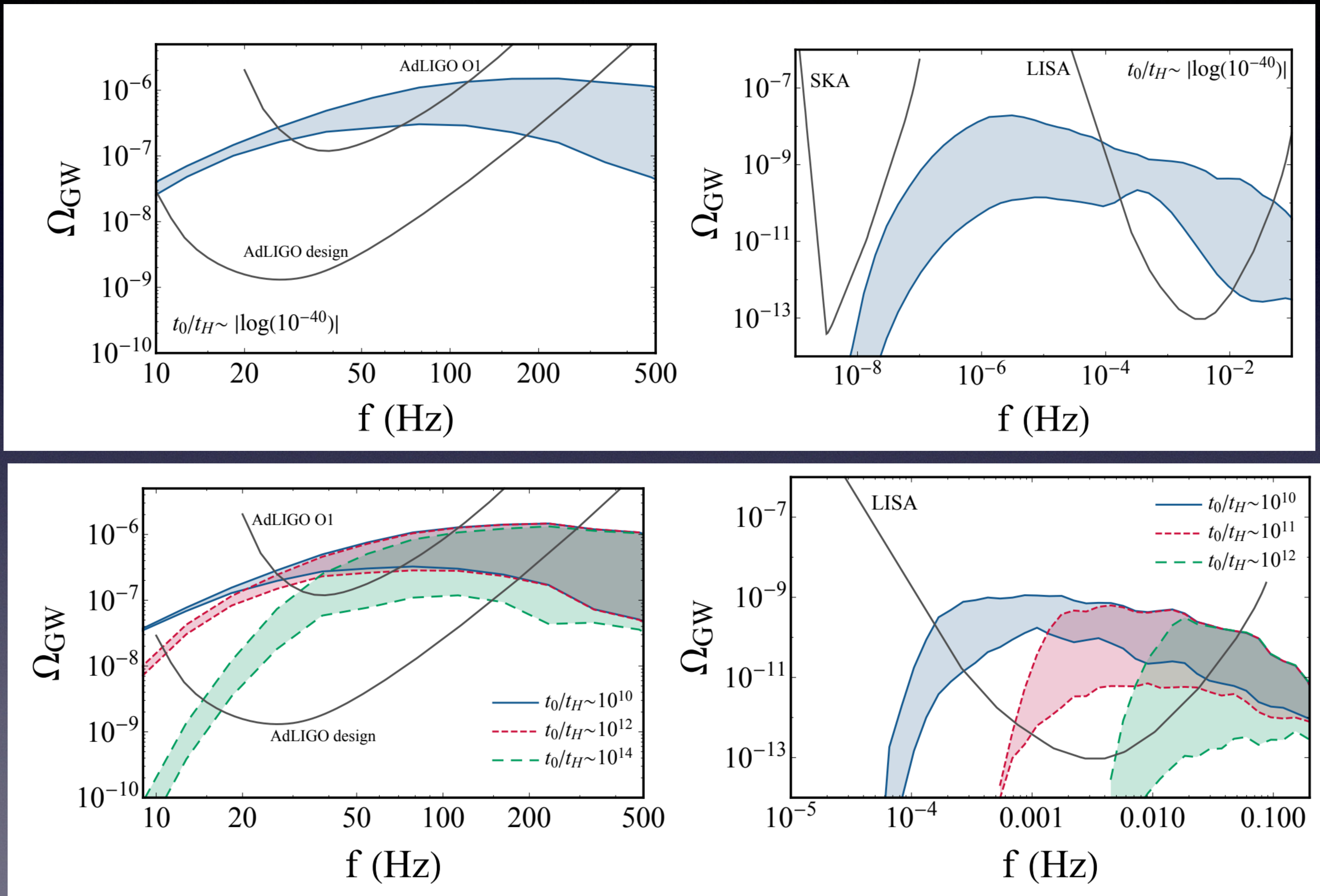
# Regge plane "holes"




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

# Bounds on BH mimickers

BH mimickers with no horizon are unstable to superradiance




EB, Brito, Cardoso, Dvorkin, Pani 2018

# Lorentz violations and horizons

- Lorentz violations introduce "asymmetry" between space and time (e.g. Horava, Einstein-aether)
- Dispersion relations imply diverging group velocity in UV:

$$\omega^2 = c^2 k^2 + \alpha k^4 + \dots$$

- Event horizon definition still possible because of preferred time foliation: universal horizon
  (EB, Jacobson and Sotiriou 2011; Blas, Sibiryakov 2011
- Universal horizon may be unstable and form finite area curvature singularity away from spherical symmetry: echoes/near horizon exotica?
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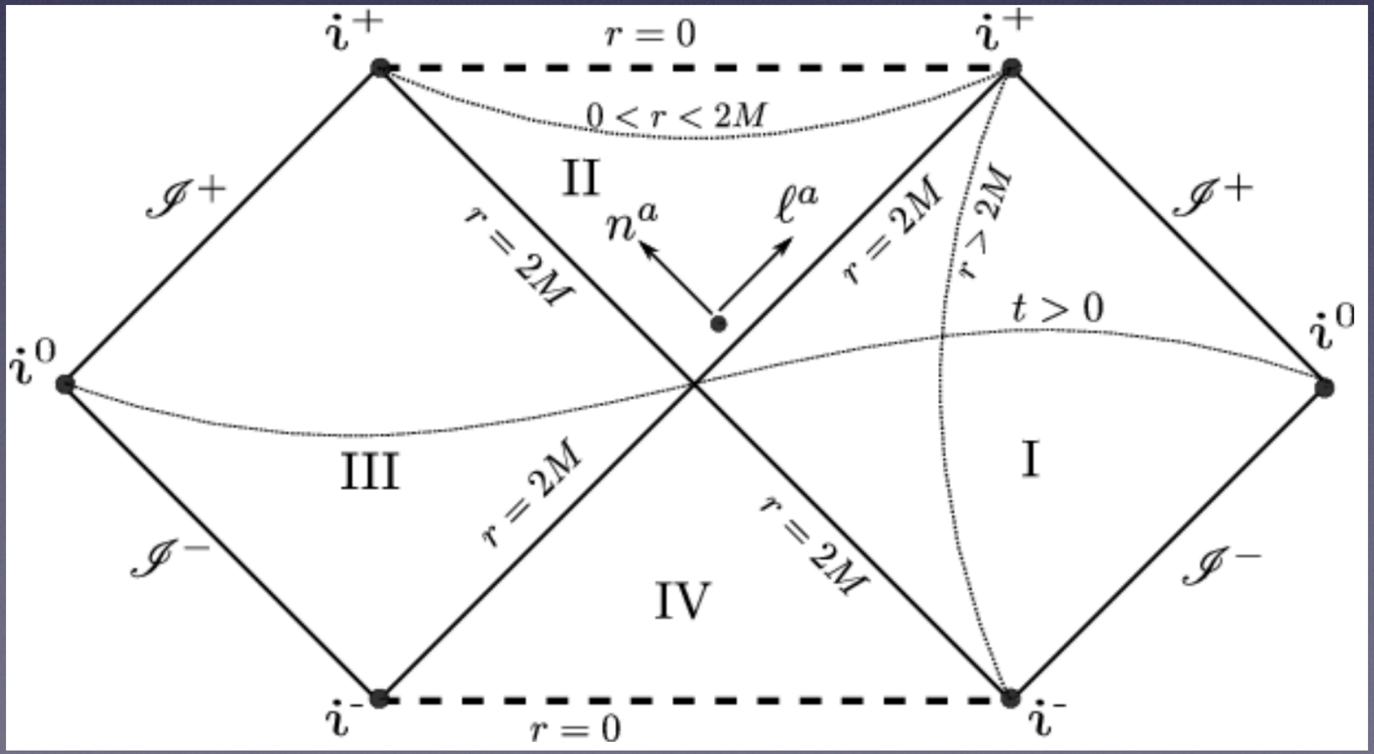


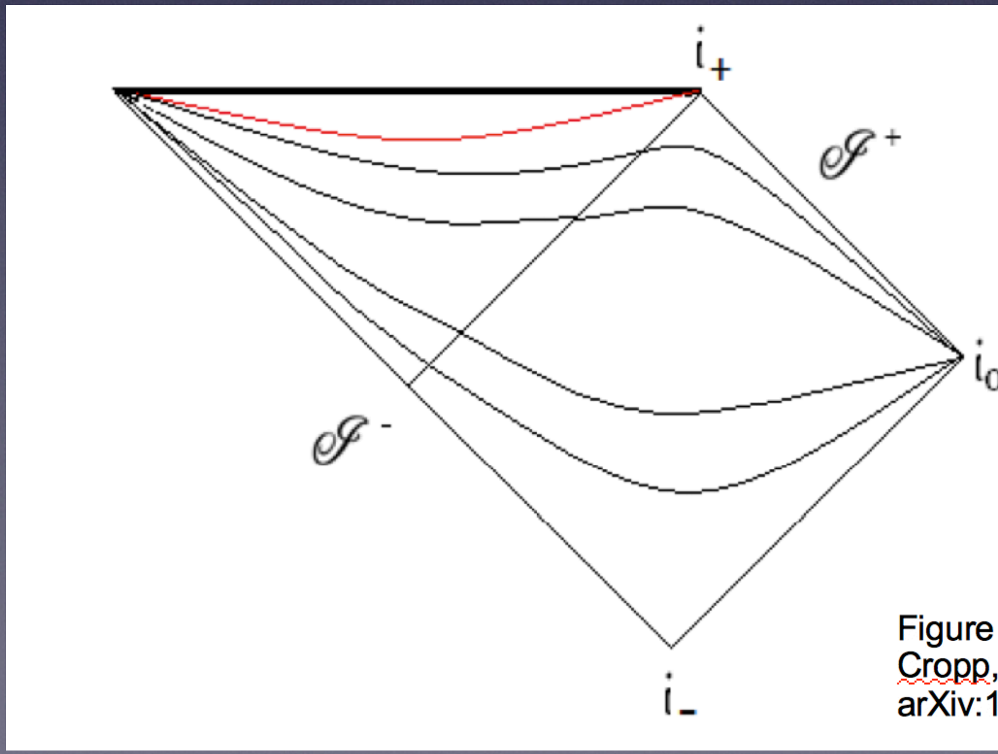


Figure adapted from Cropp, Liberati and Mohd, arXiv:1312.0405

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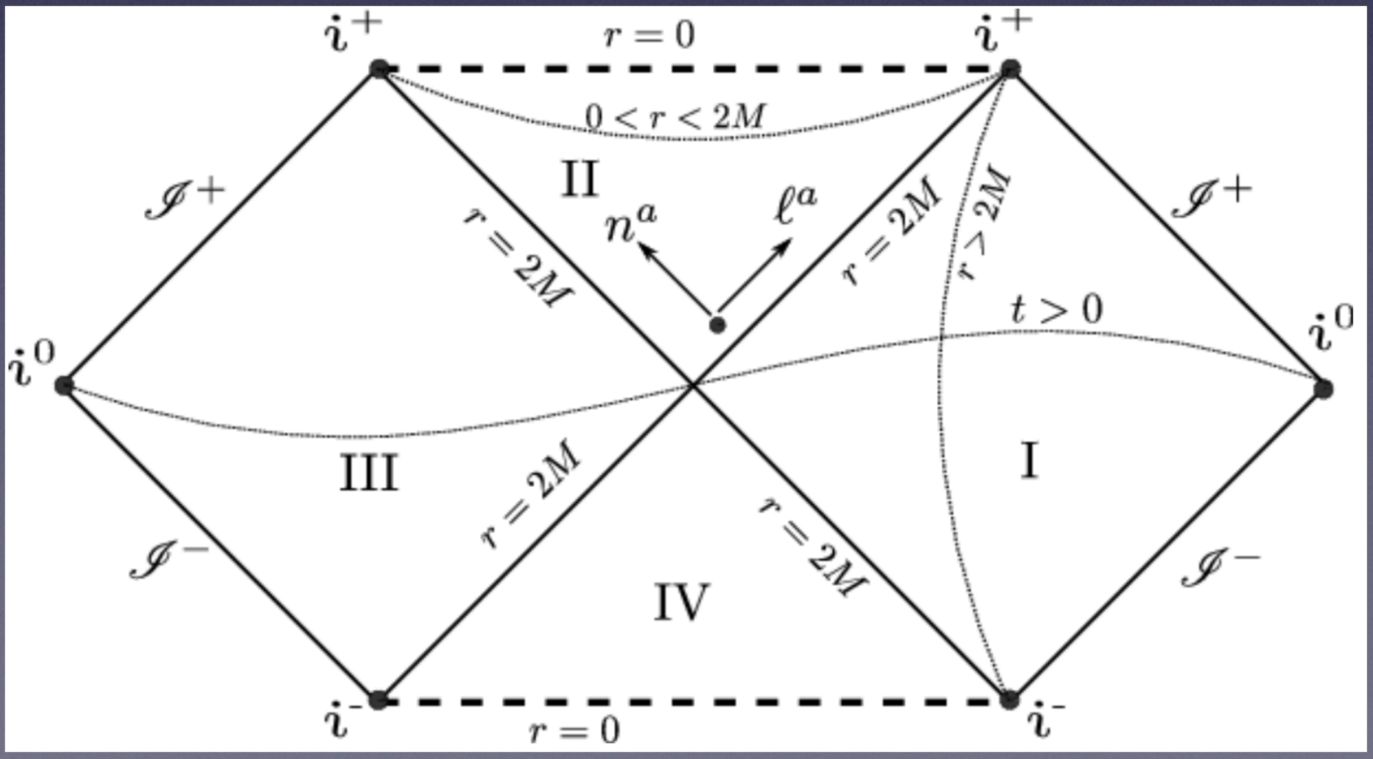


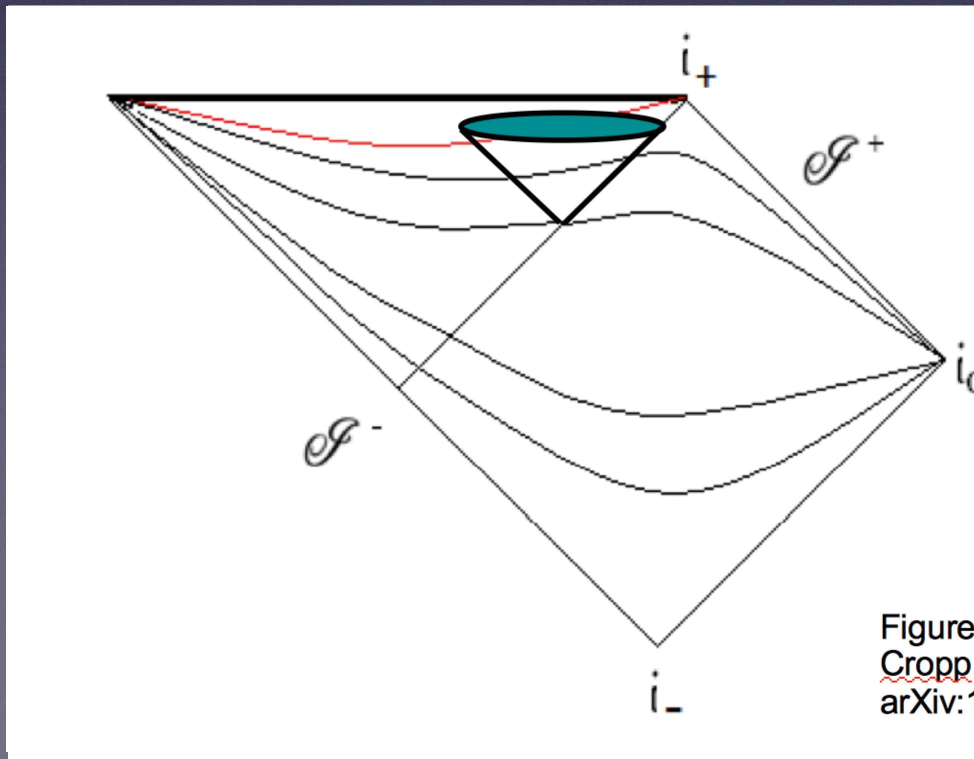


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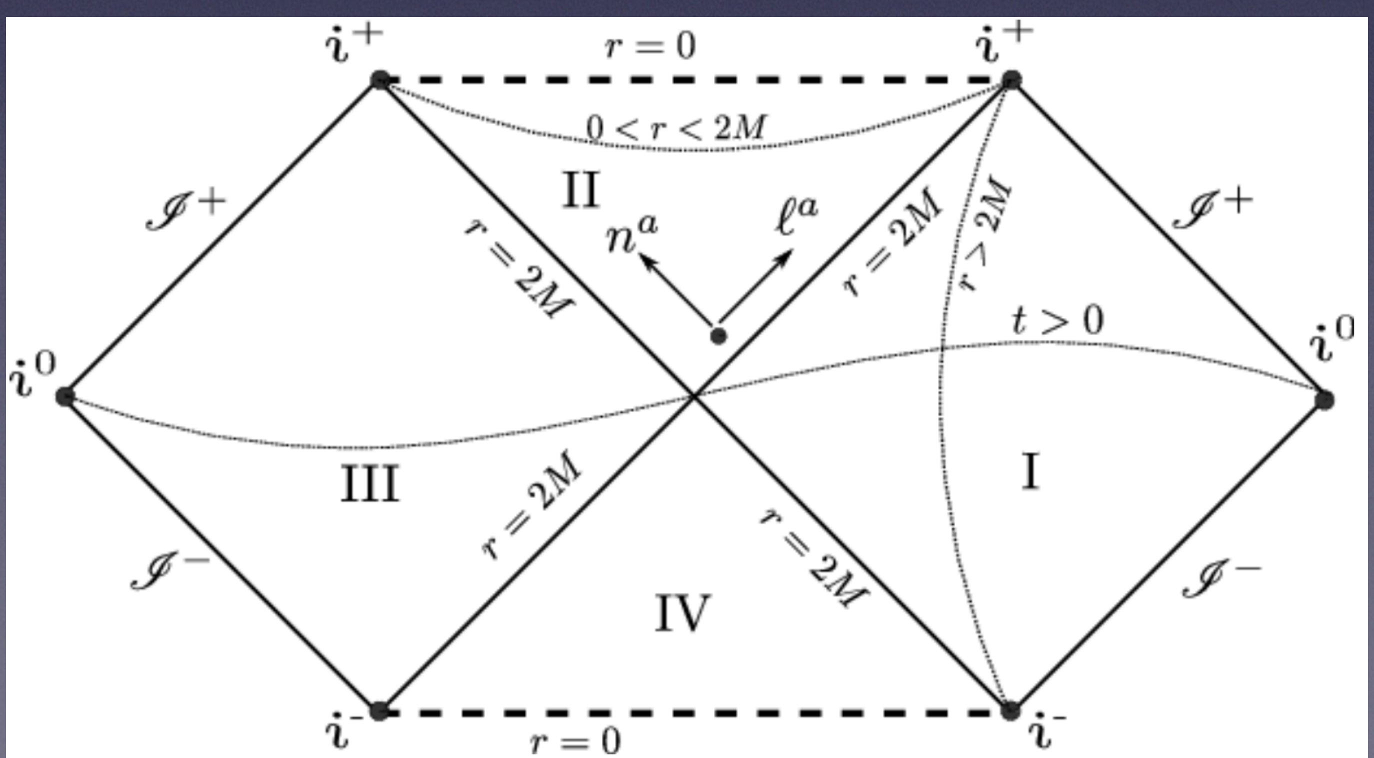


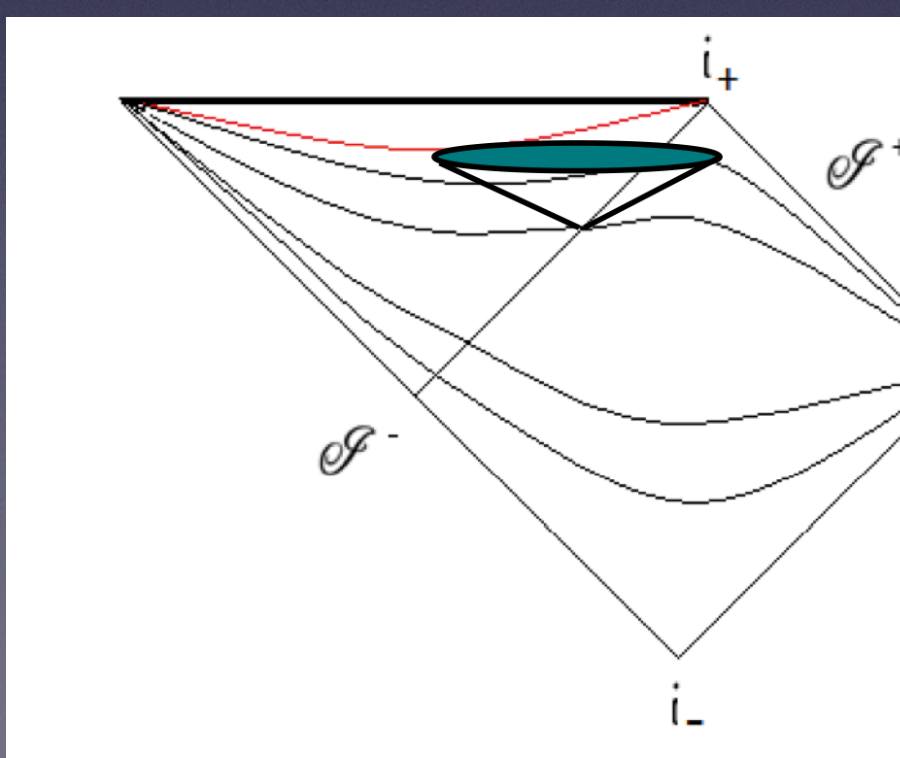


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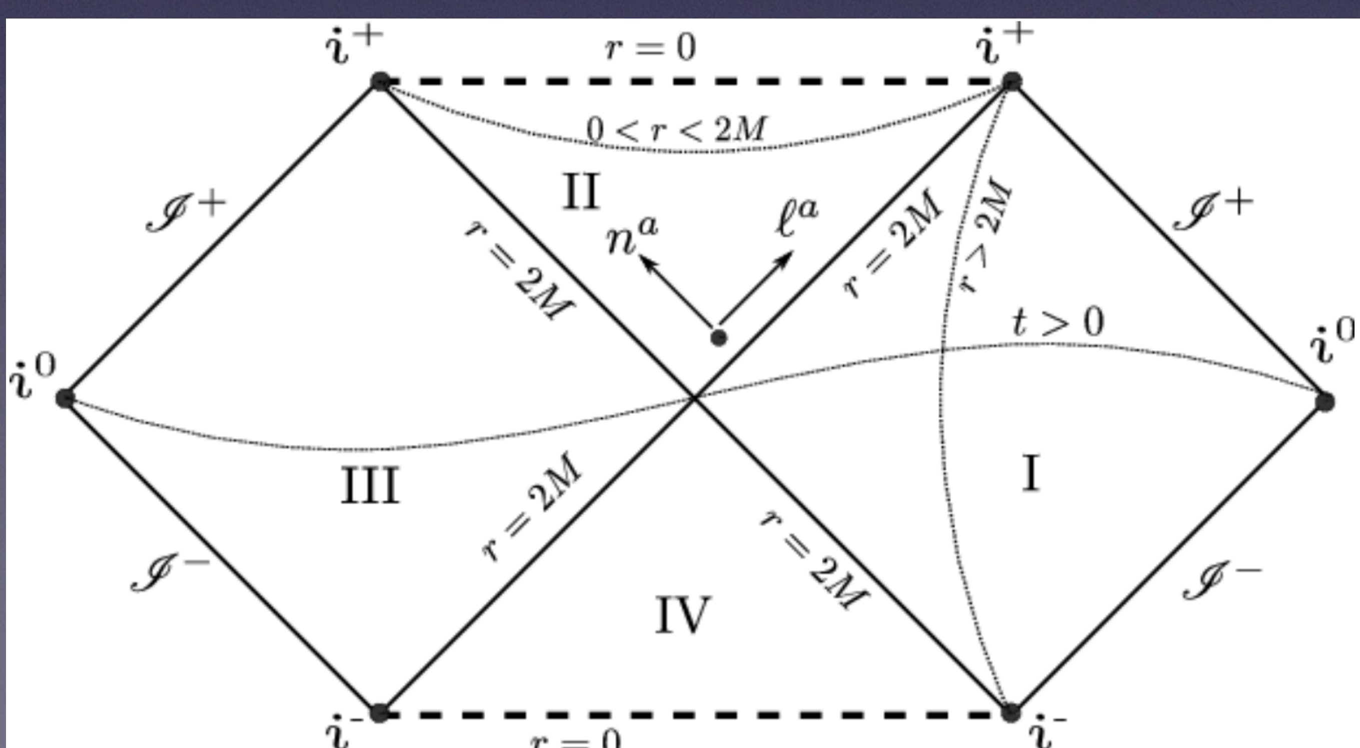


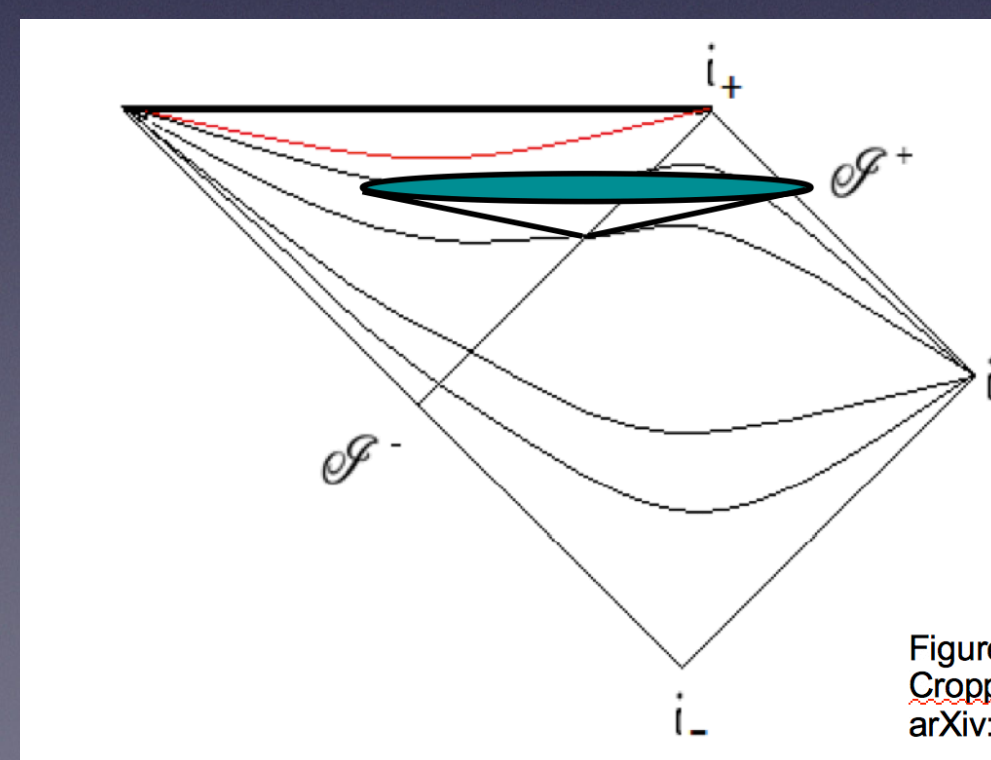


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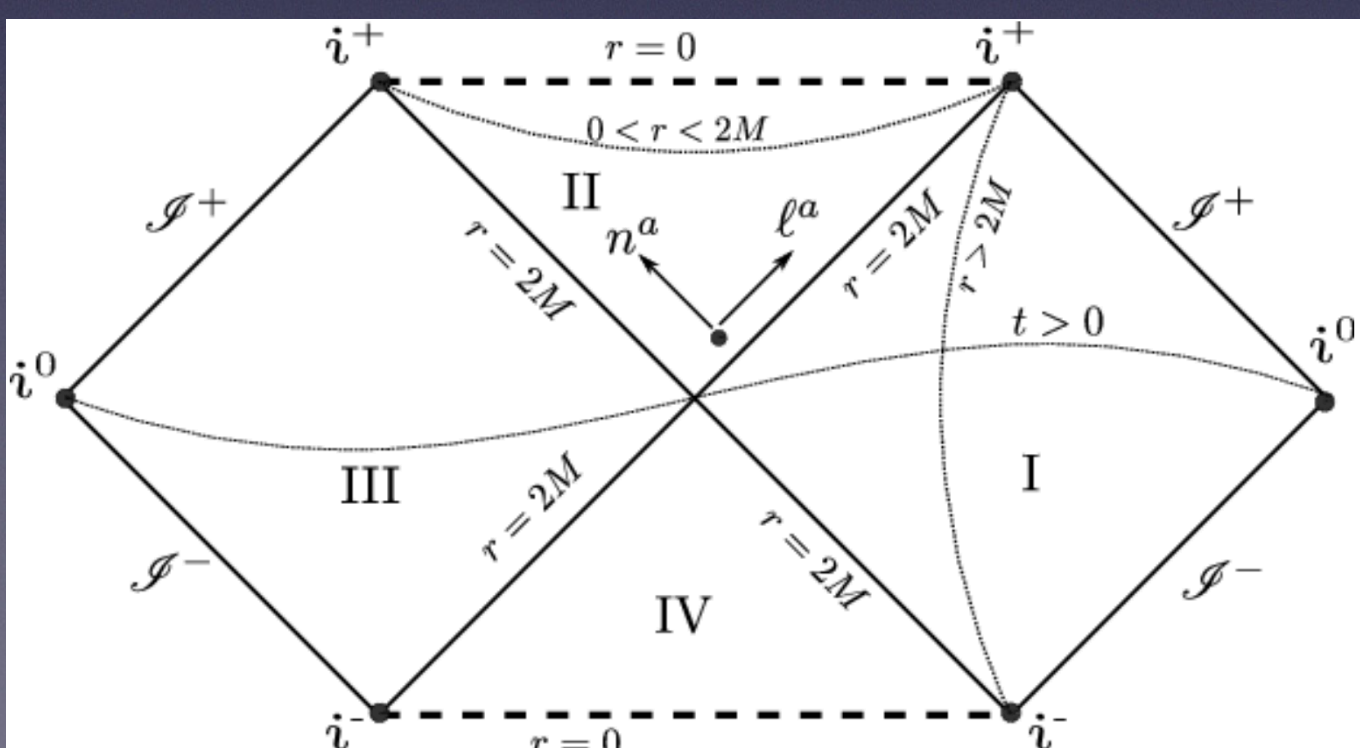


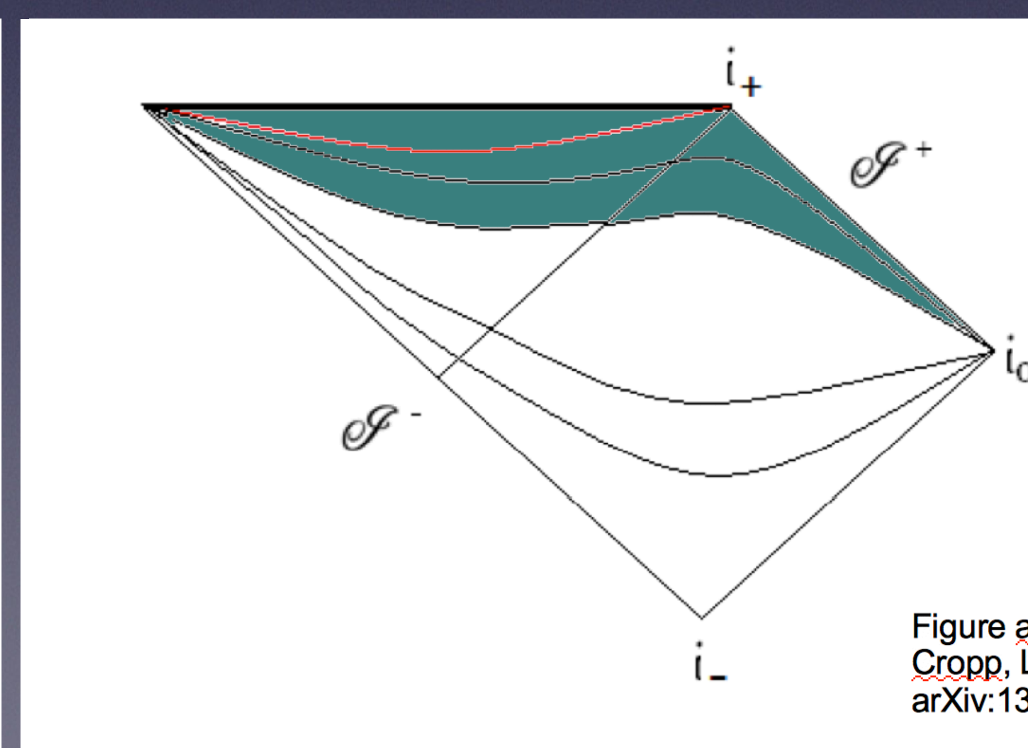


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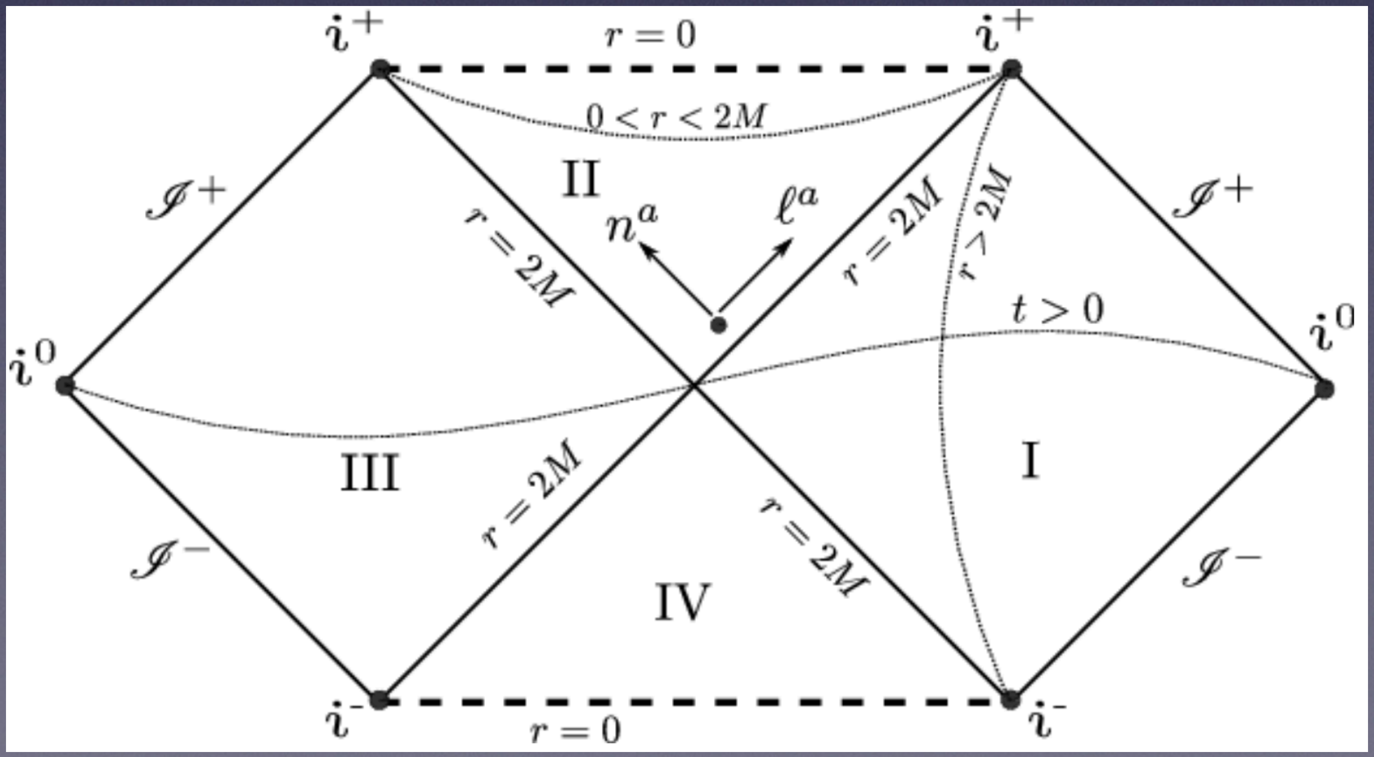


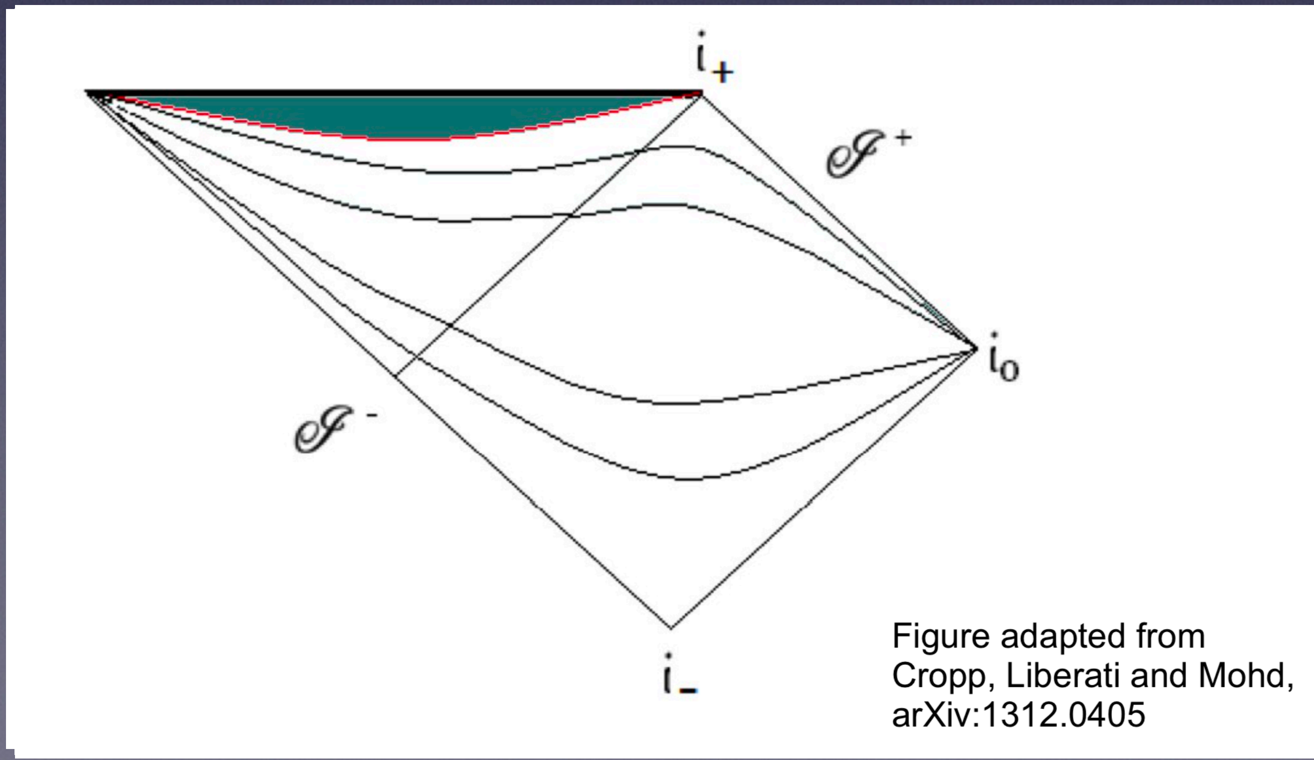


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# Conclusions

- 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, LISA will extend to ~ $10^{-18}$ eV
- Similar bounds on BH mimickers (and possibly Lorentz symmetry) from stochastic background