Black hole superradiance to search for new particles

Diego Blas

w./ Sam Witte 2009.10074 (PRD), 2009.10075 (PRD)
+ 2102.11280 (PRD) w/ Caputo, Pani and Witte)

Universitat Autònoma
de Barcelona

Barcelona Institute of
Science and Technology

Outline of the talk

Succinct review of BH superradiance

‘Classical’ tests (based only on the existence of a ultralight boson)

Photon superradiance & tests in the CMB if $F(\gamma, X)$ exists

Black hole rotational superradiance*

Zel'dovich 71, Press & Teukolsky, '72; Bekenstein & Schiffer'98,
Cardoso et al '04
Brito, Cardoso, Pani 1501.06570 [gr-qc]

Wave **amplified** if scattered by absorbing rotating bodies (e.g. BH) if

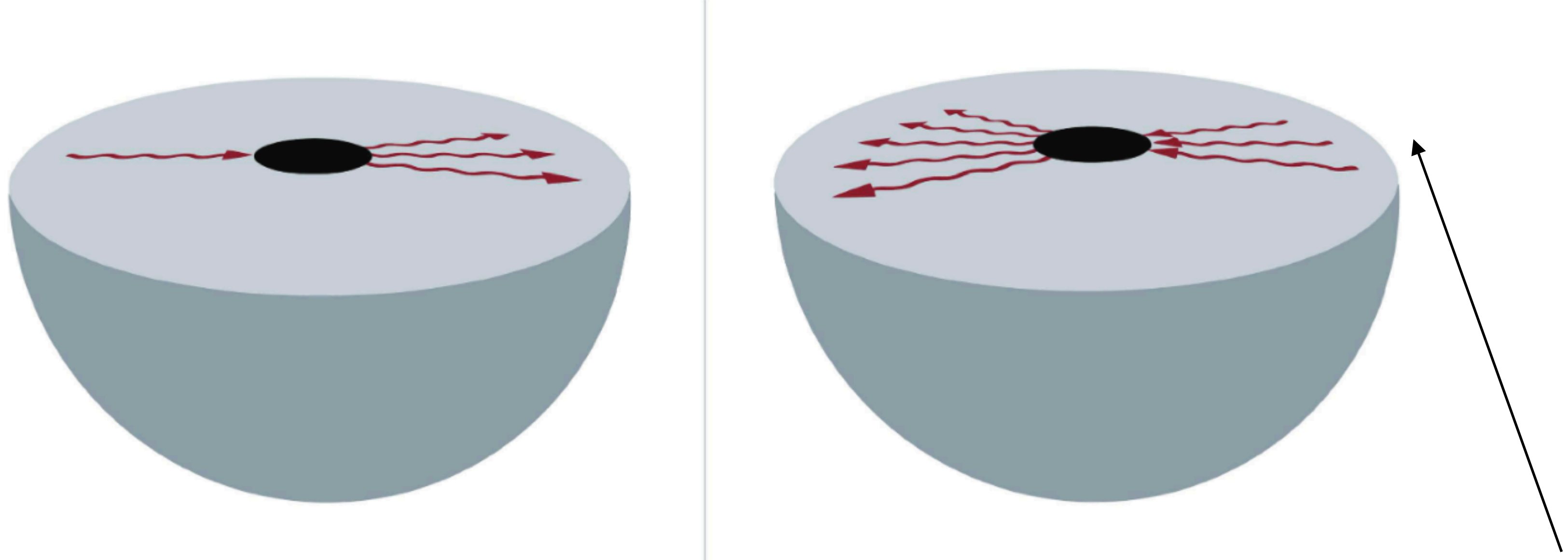
$$\Phi \sim A_i e^{-i\omega(t+r)} e^{im\phi} S(\theta)$$

$$\omega < m\Omega$$

rotational frequency

wave-frequency

azimuthal number



If waves are massive, they 'reflect' back, and will keep amplifying!

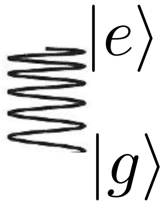
*Not to be confused with quantum (Dicke) superradiance

Black hole superradiance

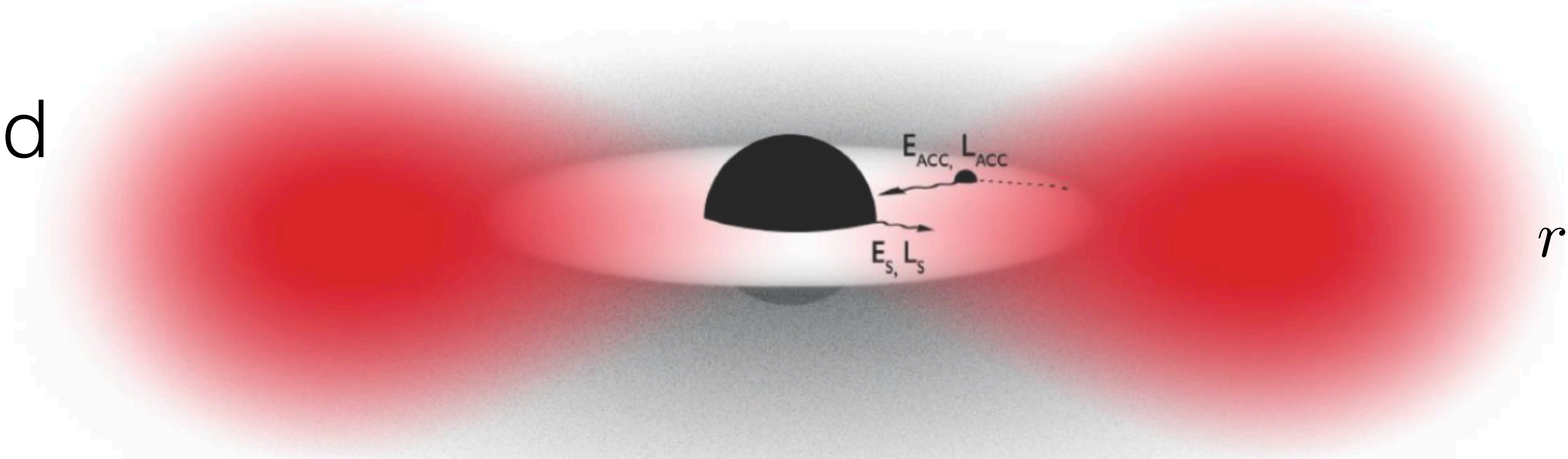
If nothing else happens, a (bosonic) wave will grow a cloud around the BH (at the expense of rotational energy)

Brito, Cardoso, Pani 1501.06570 [gr-qc]

BH w/ cloud



BH w/o cloud



$$r_{\text{cloud}} \sim 1/m_b$$

$$\rho_b \sim \frac{M}{r^3} \sim 10^{48} \frac{M}{M_\odot} \left(\frac{m_b}{10^{-10}\,\text{eV}}\right)^3 \text{eV/cm}^3$$

efficient for $m_b M \sim \frac{m_b}{10^{-10}\,\text{eV}} \frac{M}{M_\odot} \sim O(1)$

$$\tau \sim 10^2 \left(\frac{M}{10\,M_\odot}\right) \left(\frac{0.2}{m_b M}\right)^9 \text{ seconds}$$

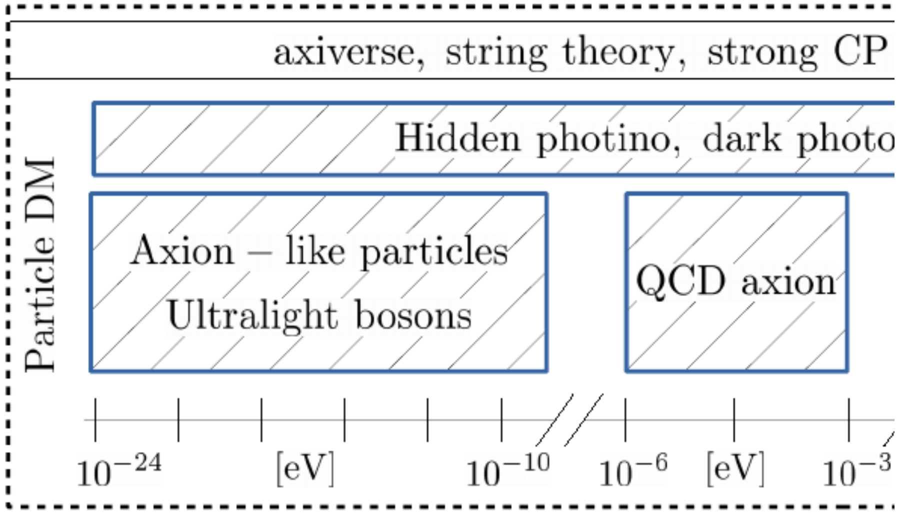
Black hole superradiance

Consequences: emission of GWs, spinning down of BHs, emission of bosons, perturbance of local gravitational potential…

But **astrophysical** BHs require very low masses, absent in the SM!

$$m_b M \sim \frac{m_b}{10^{-10}\,\mathrm{eV}}\frac{M}{M_\odot} \sim O(1)$$

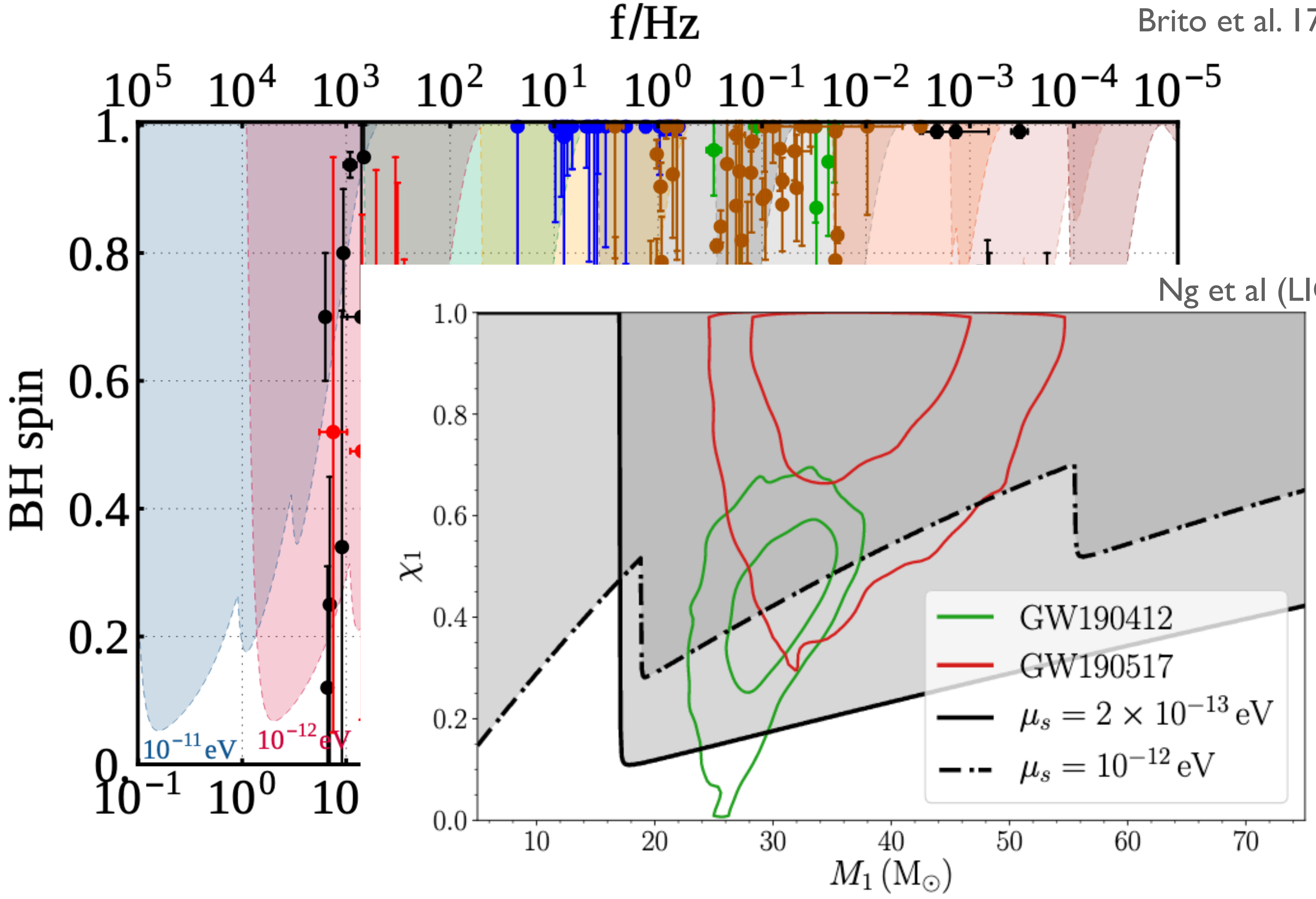
hence, this is a tool to ‘detect’ ultra-light fields beyond the SM



Effects on the Regge plane

$$m_b M \sim \frac{m_b}{10^{-10}\,\mathrm{eV}}\,\frac{M}{M_\odot} \sim O(1)$$

the clouds extract *J* from the BH

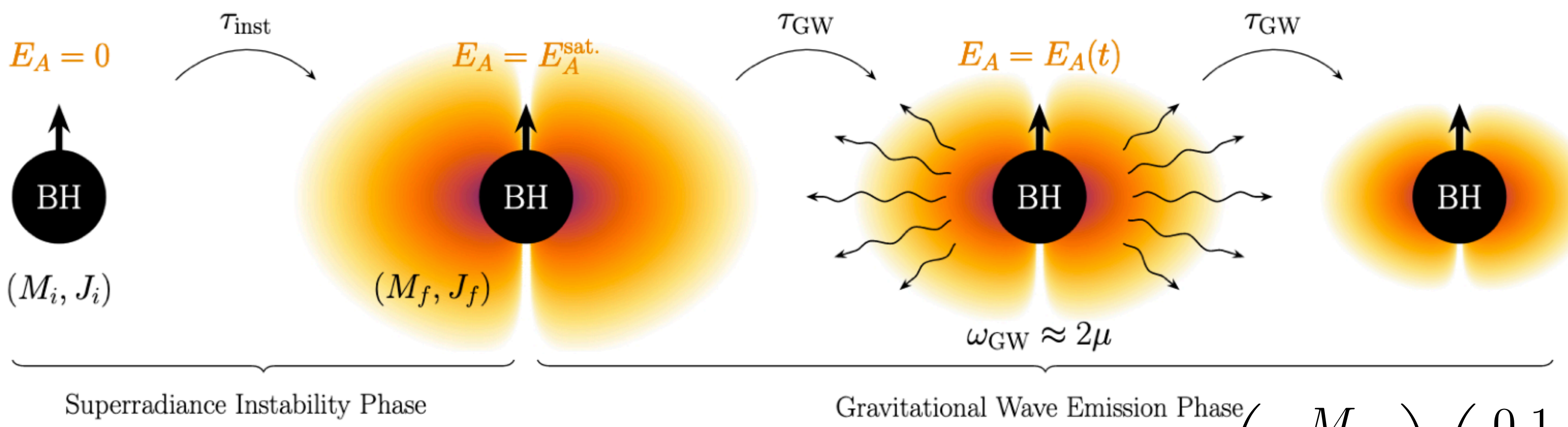


Brito et al. 17

Ng et al (LIGO) 20

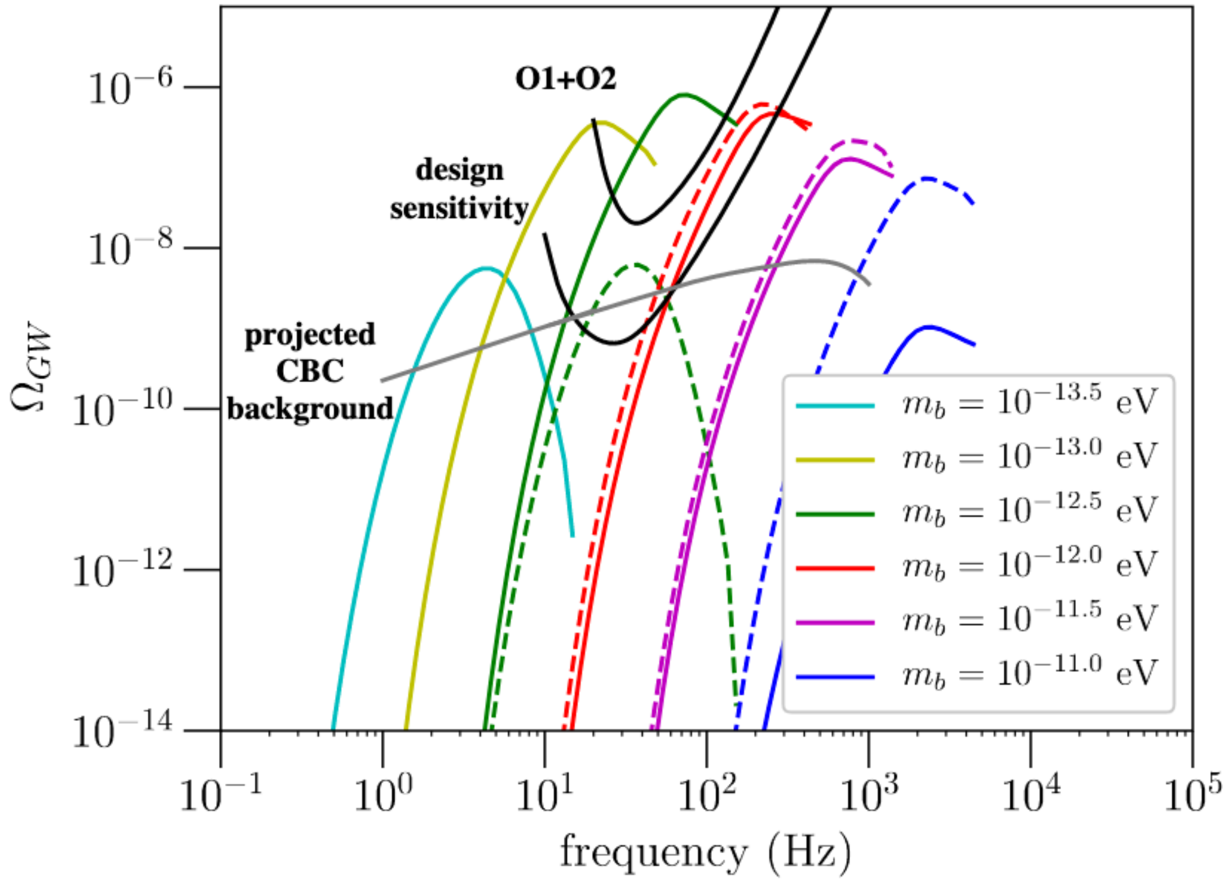
GW signal

from Tsukada et al, ‘20

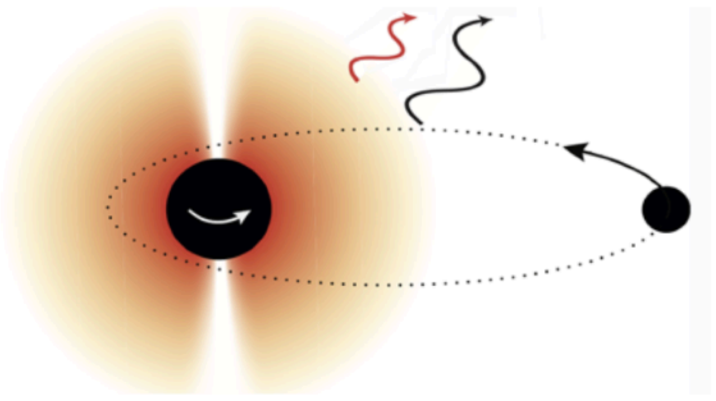


$$\tau^S_{\rm GW} \approx 10^5 \text{yr} \left(\frac{M}{10M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\chi_i-\chi_f}\right)$$

given a model for BH population one can predict the GW signal, eg.



Rich pheno in binaries



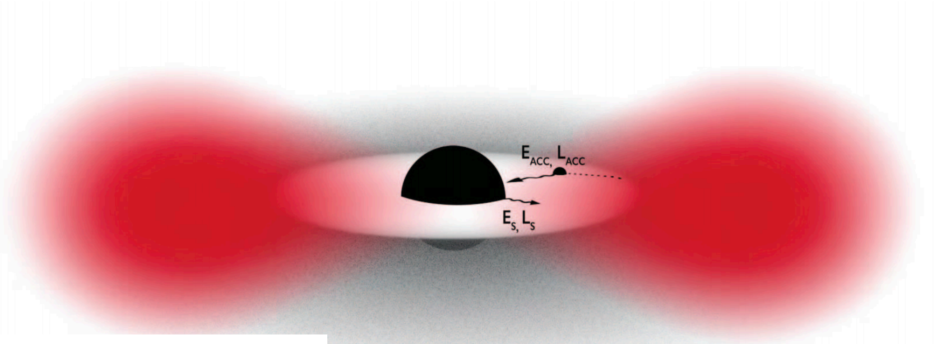
Credit: D. Baumann/University of Amsterdam

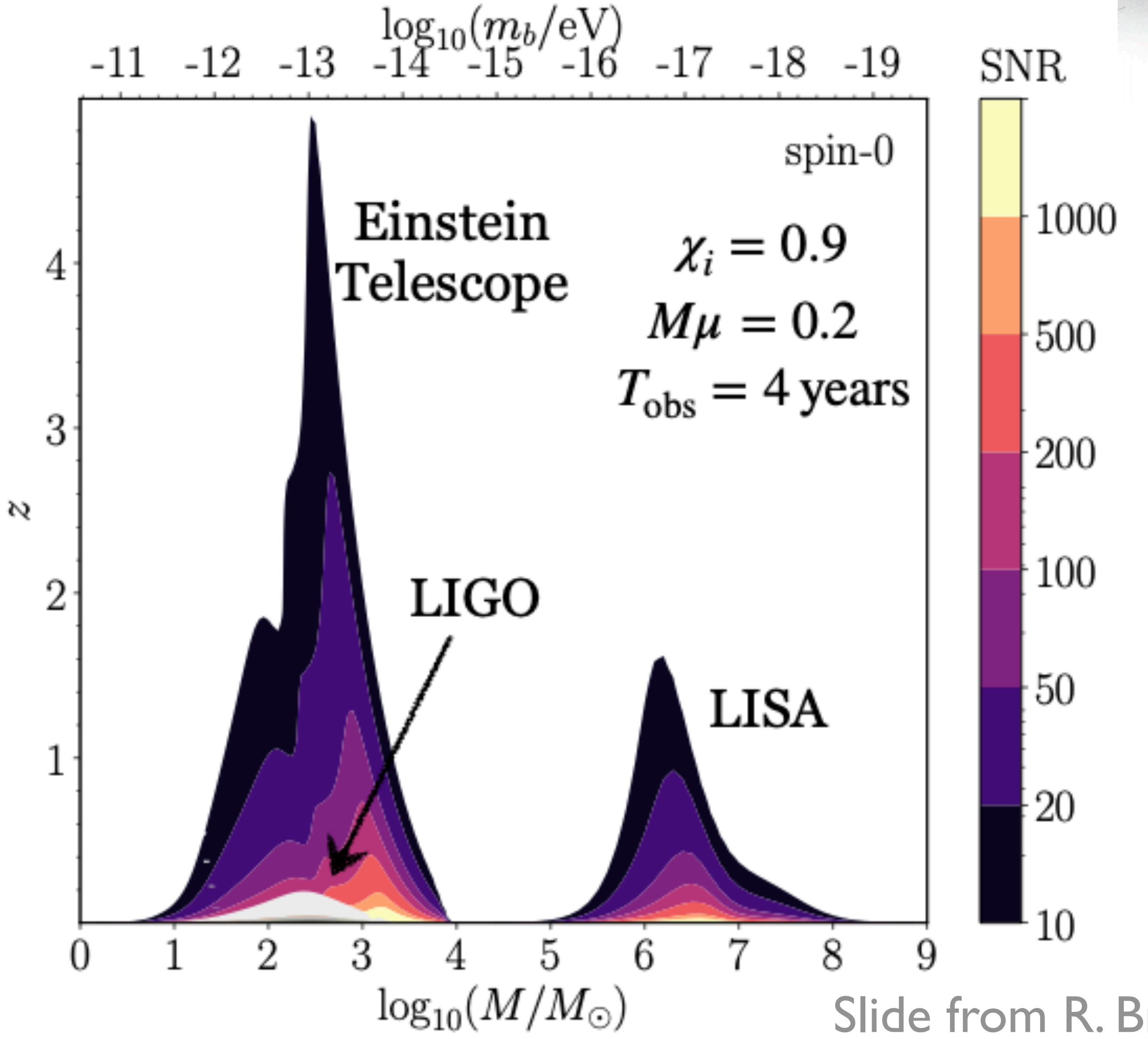
e.g. Baumann et al 20, 21
Berti, Brito el al 19
Hannuksela+ Nature Astron. 2019

Direct GWs searches

Arvanitaki *et al*’09; Yoshino & Kodama ’14; Arvanitaki, Baryakhtar & Huang, ’15; RB *et al ’17;* Baryakthar, Lasenby & Teo ’17; Siemonsen & East ’20; RB, Grillo & Pani ’20, Zhu *et al* ‘20…

Bosonic cloud itself emits **nearly monochromatic long-lived GWs** which could be directly detected.



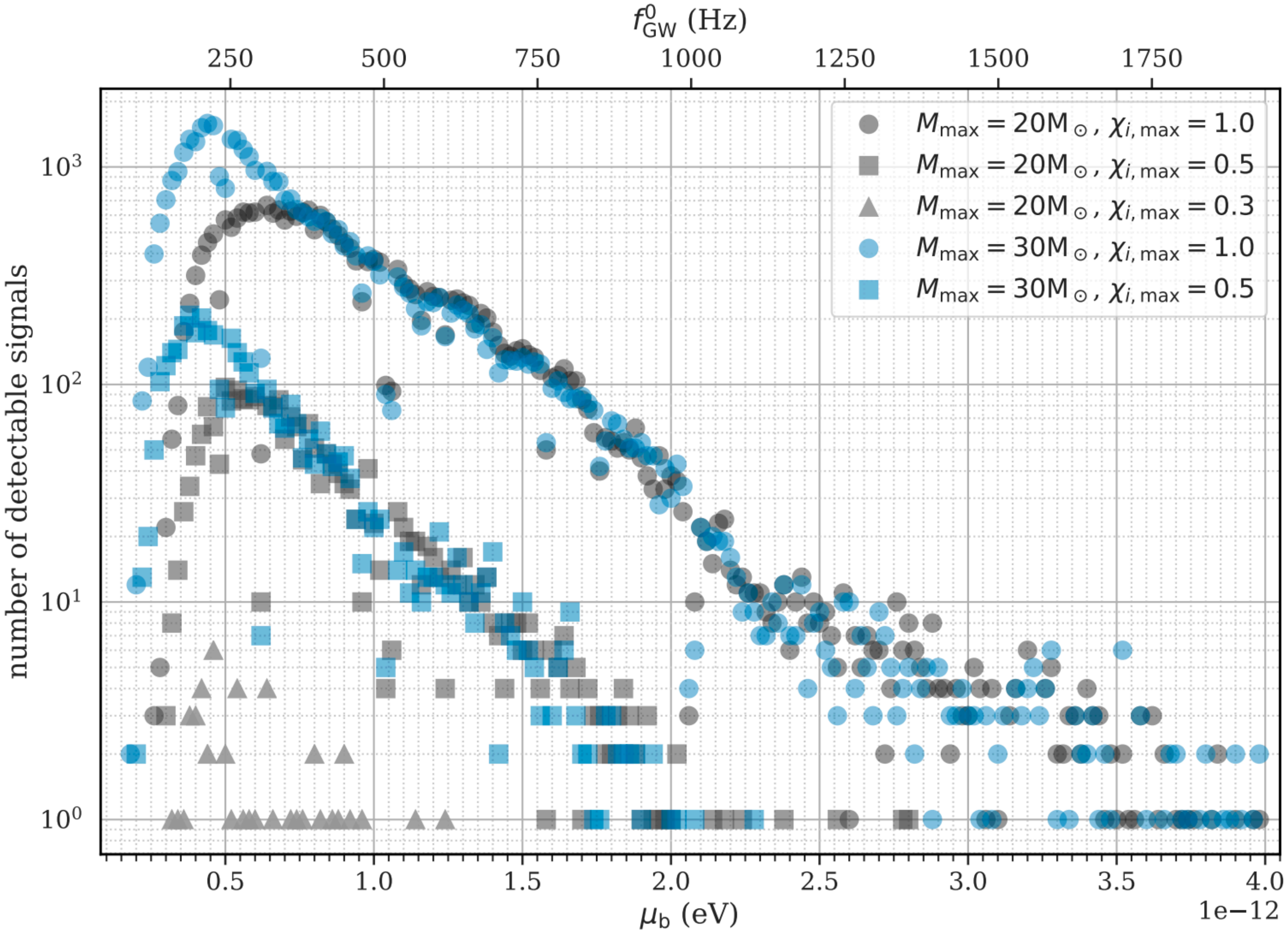


Slide from R. Brito,
Einstein Seminar, 22 University of Tübingen

All sky continuous GWs searches

Arvanitaki, Baryakhtar & Huang, '15; RB *et al* '17; Baryakthar, Lasenby & Teo '17; Palomba *et al*' 19; Zhu *et al* '20

- **Many BHs** in the Universe that we do not see. Estimated 10^8 black holes just in the Milky Way.
- **All-sky "blind" searches** could reveal the presence of a boson cloud around a black hole emitting continuous gravitational waves.



From: Zhu *et al* ' PRD102, 063020 (2020)

Null searches for continuous GWs in LIGO/Virgo data can be used to constrain bosonic fields.

Palomba *et al*, PRL 123, 171101 (2019)
Zhu *et al* ' PRD102, 063020 (2020)
LVC Collaboration, arXiv:2111.15507 (2021)

Slide from R. Brito,
Einstein Seminar, 22 University of Tübingen

Black hole superradiance

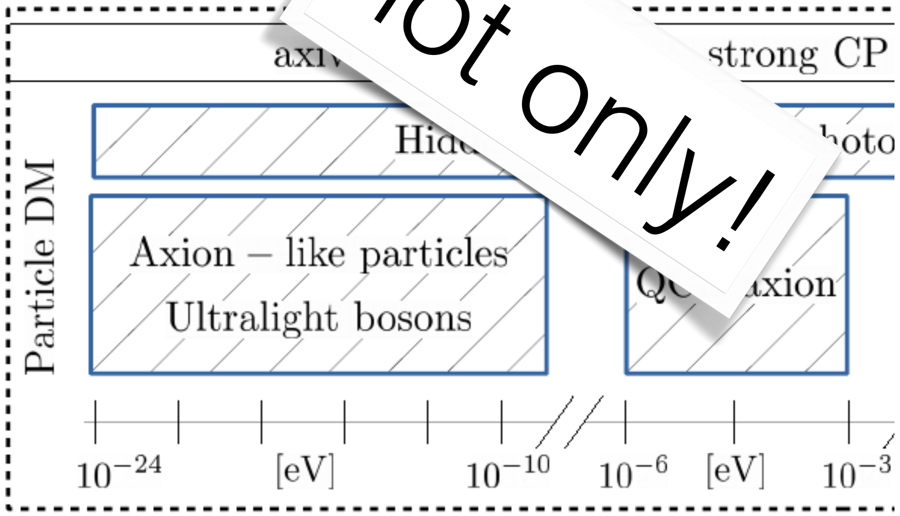
Consequences: emission of GWs, spinning down of BHs, emission of bosons, perturbance of local gravitational potential…

But **astrophysical** BHs require very low masses, absent in the SM!

$$m_b M \sim \frac{m_b}{10^{-10}\,\mathrm{eV}} \frac{M}{M_\odot} \sim O(1)$$

hence, this is a tool to 'detec ltra-light fields beyond the SM

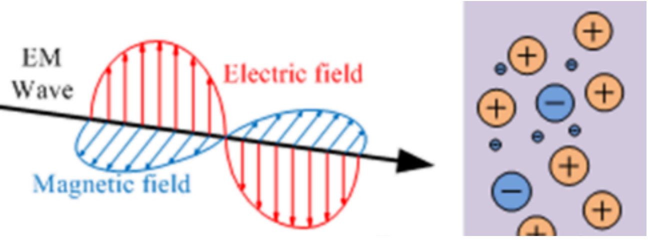
not only!



Black hole PHOTON superradiance

In the presence of a dilute plasma n_e

Pani, Loeb '13
Conlon, Herdeiro '17

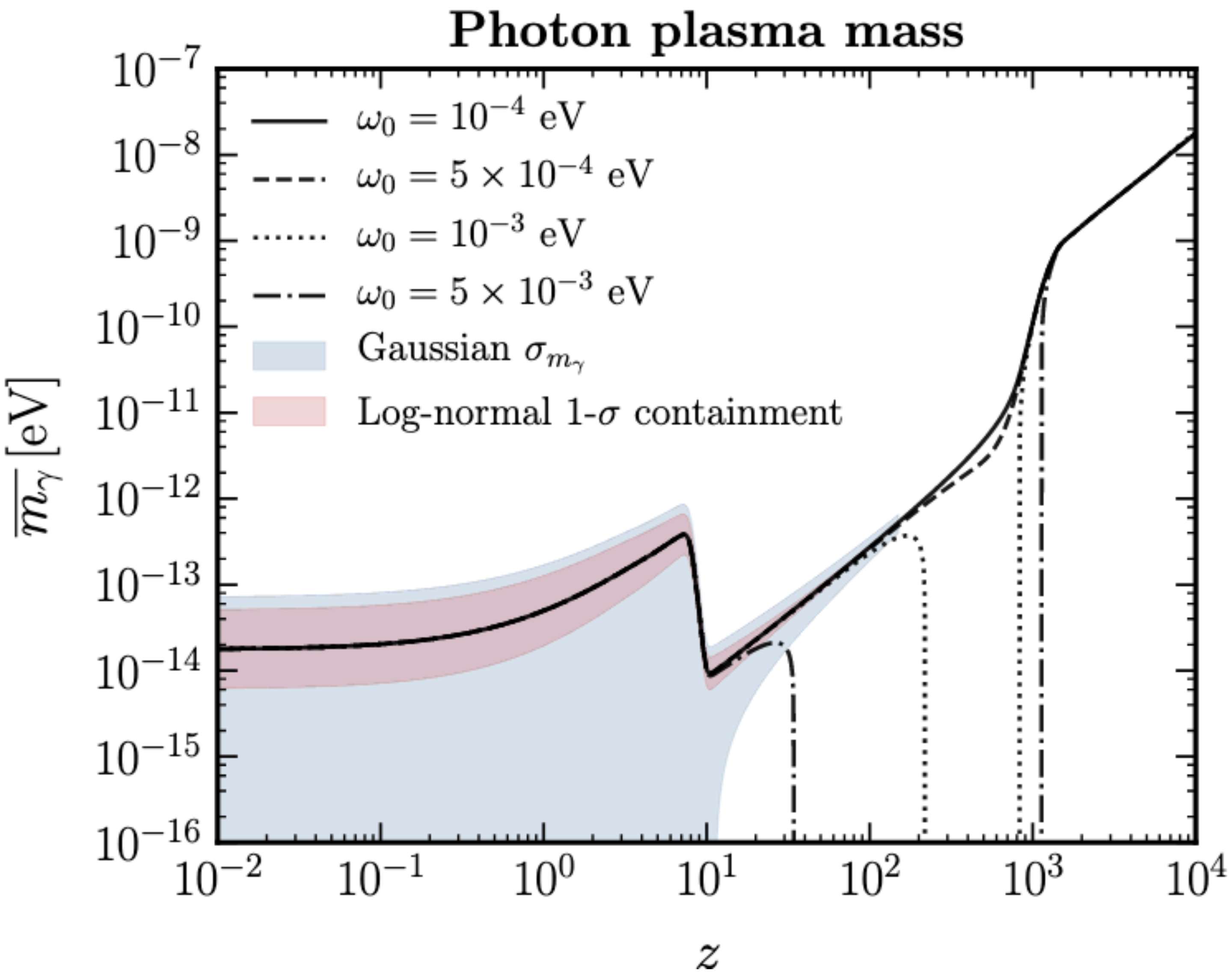


$$\omega^2 = \omega_p^2 + k^2$$

$$m_\gamma \simeq \omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \sim 10^{-10}\sqrt{\frac{n_e}{\mathrm{cm}^3}}\ \mathrm{eV}$$

in the inter-galactic medium

Caputo et al '20



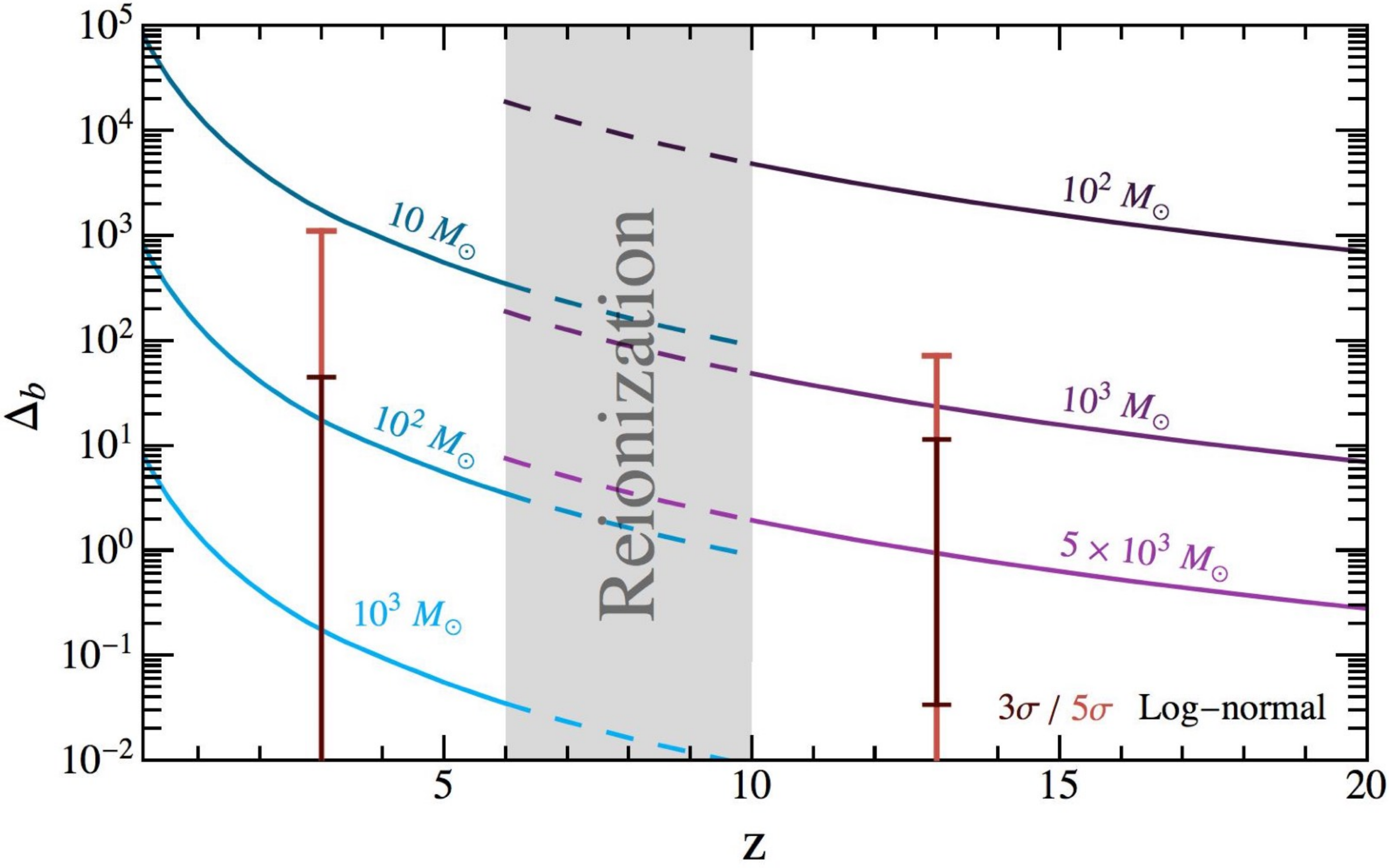
Photon plasma mass

Black hole PHOTON superradiance

Blas, Witte '20

$$m_b M \sim \frac{m_b}{10^{-10}\,\mathrm{eV}} \frac{M}{M_\odot} \sim O(1)$$

$$n_e = x_e \bar{n}_b \Delta_b$$



Black hole PHOTON superradiance II

does this really happen?

- (spinning) BHs typically do not live in the IGM, so higher n_e
  - The mass may have a profile from accretion $n_e(r)$

Dima, Barausse ‘20

both problems solved if BHs are ejected to the IGM! (likely)

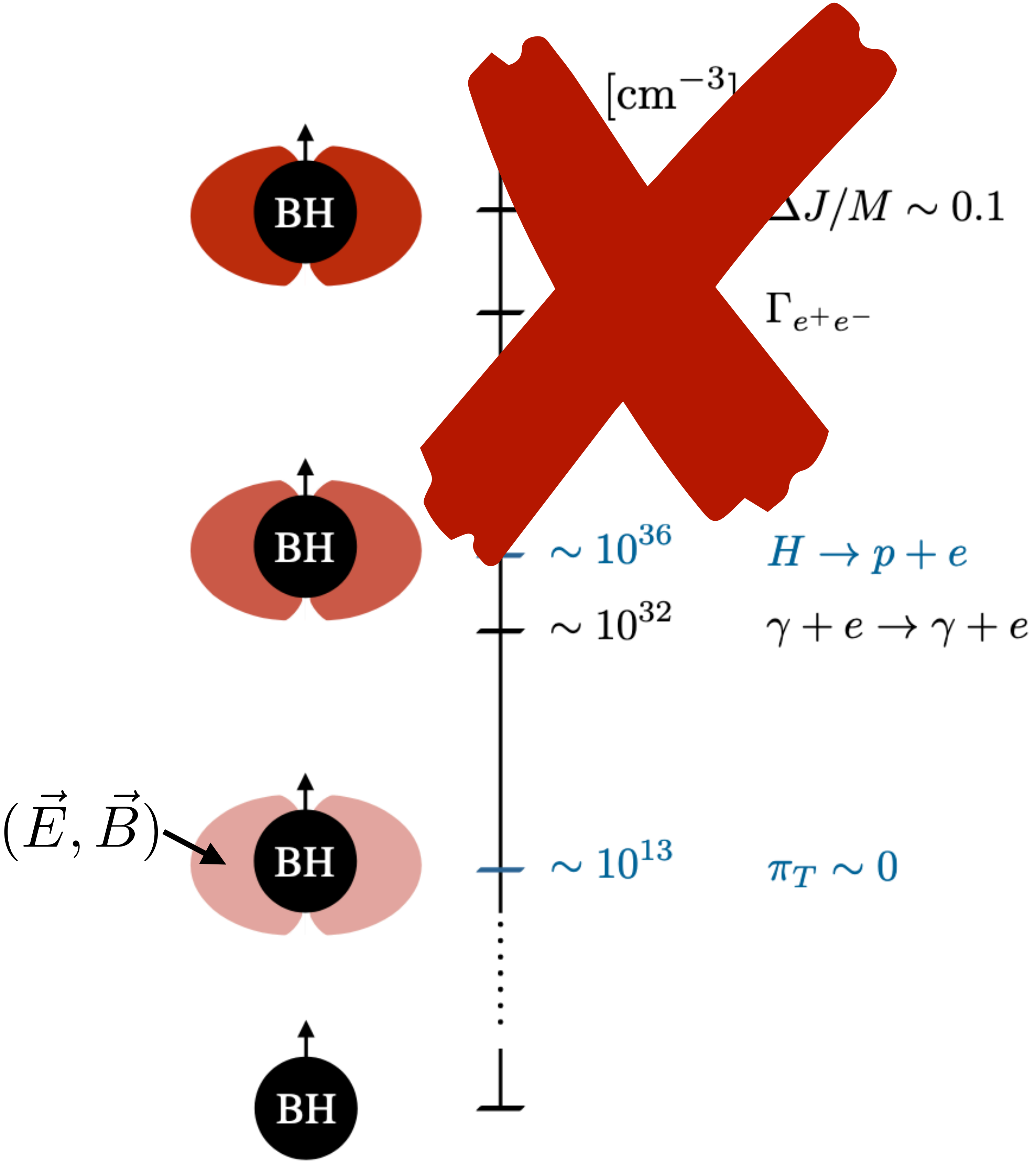
is that all?

$$\omega^2 = \omega_p^2 + k^2$$

$$m_\gamma \simeq \omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \sim 10^{-10}\sqrt{\frac{n_e}{\mathrm{cm}^3}}\ \mathrm{eV}$$

not always applicable + SR photons and plasma electrons interact!

Quenching mechanisms photon SR: Verdict



Fukuda, Nakayama '19

pair production

Blas and Witte 20

acceleration of *e*
not related to plasma mass
(relevant for Z')

Cardoso et al '20

non-linear corrections

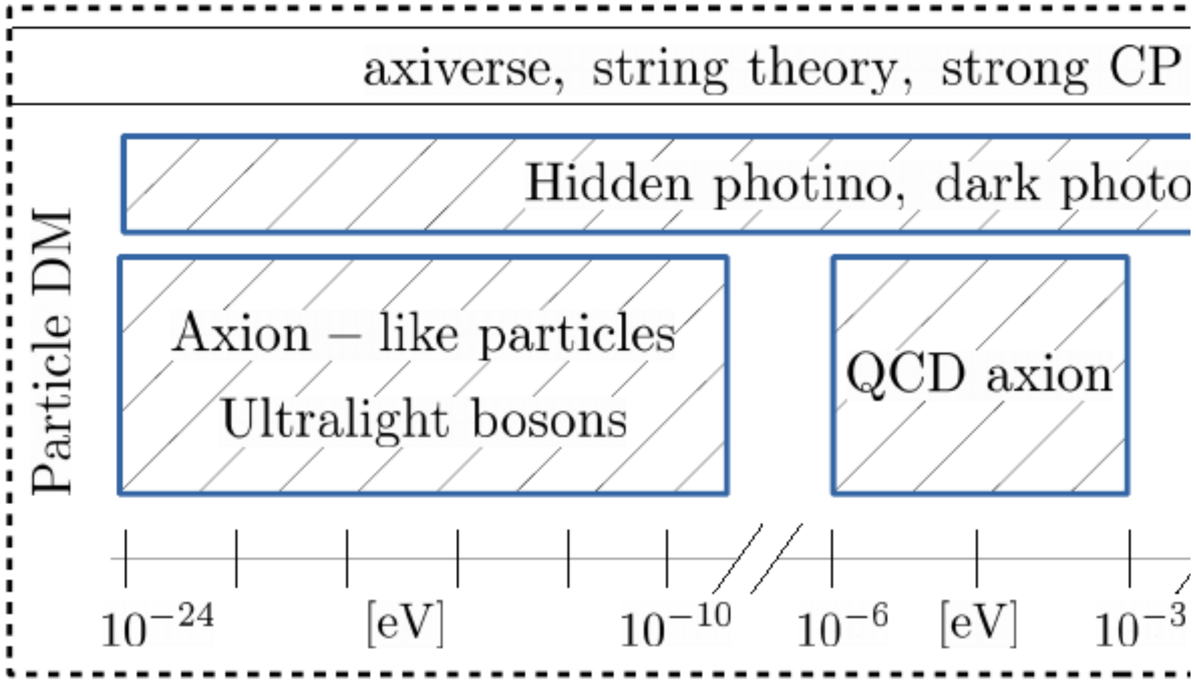
$$\omega^2 = k^2 + \frac{\omega_p^2}{1 + \frac{e^2 E^2}{m_e^2 \omega^2}}$$

Observing axion SR in the CMB

Blas and Witte 20

Observing axion SR in the CMB

$$m_a M \sim \frac{m_a}{10^{-10}\,\mathrm{eV}} \frac{M}{M_\odot} \sim O(1)$$



These particles may have (self) interactions that modify SR

axion self-interactions

$$V(a) = f_a^2 \mu^2 (1 - \cos(a/f_a))$$

Arvanitaki, Dubovsky 10

bosenova

axion-photon interactions

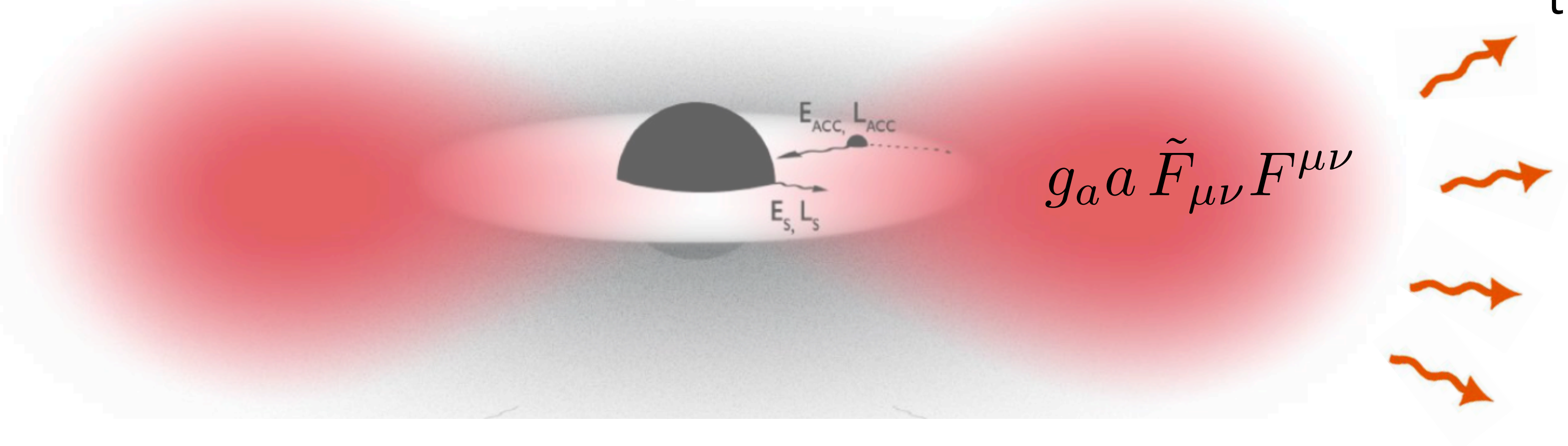
$$g_a a \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Rosa, Kephart 17
Ikeda, Brito, Cardoso 18

explosion of low-energy photons

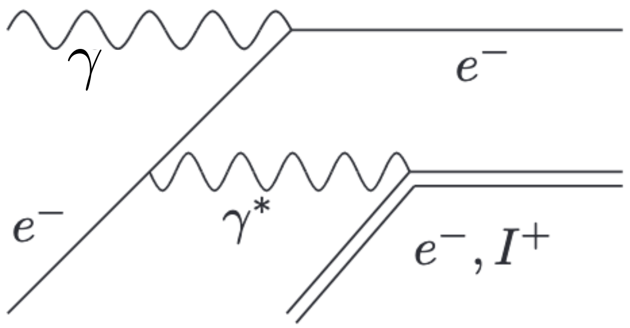
Observing axion SR in the CMB

Blas, Witte '20



$$g_a a\,\tilde{F}_{\mu\nu}F^{\mu\nu}$$

these photons heat the plasma



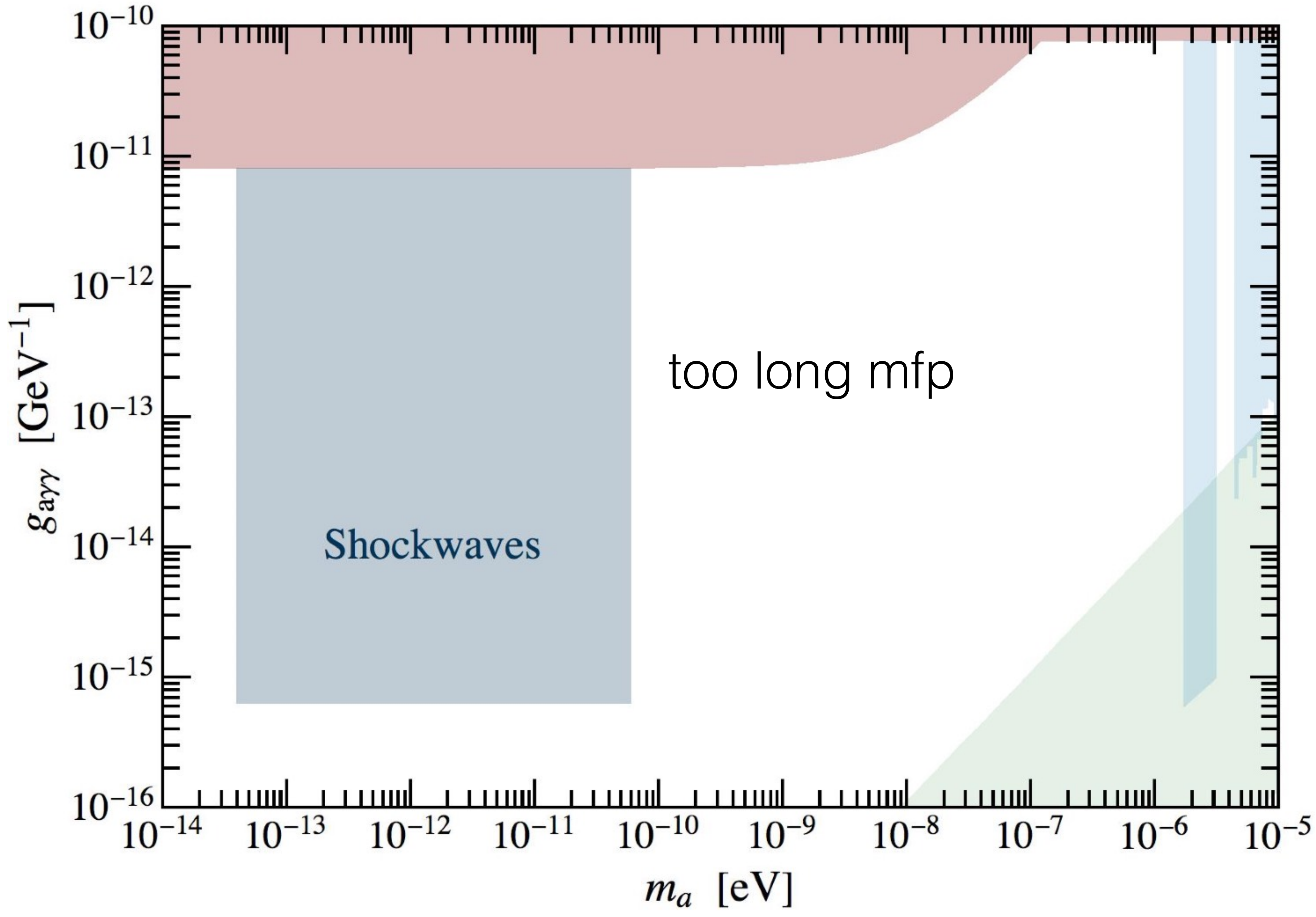
$$\sigma_{ff} \simeq \frac{4\pi^2\alpha\sigma_T}{\sqrt{6\pi}} n_p \sqrt{\frac{m_e}{T}} \frac{g_{ff}\left(E_\gamma, T\right)}{TE_\gamma^2}$$

this happens for $g_a \gtrsim 10^{-19}\sqrt{\frac{M}{M_a}}\frac{1}{\left(m_a M\right)^2}\mathrm{GeV}^{-1}$

energy extracted $\frac{dE}{dt} \sim 10^{66}\left(\frac{M_a}{M}\right)\mathrm{eV/s}$

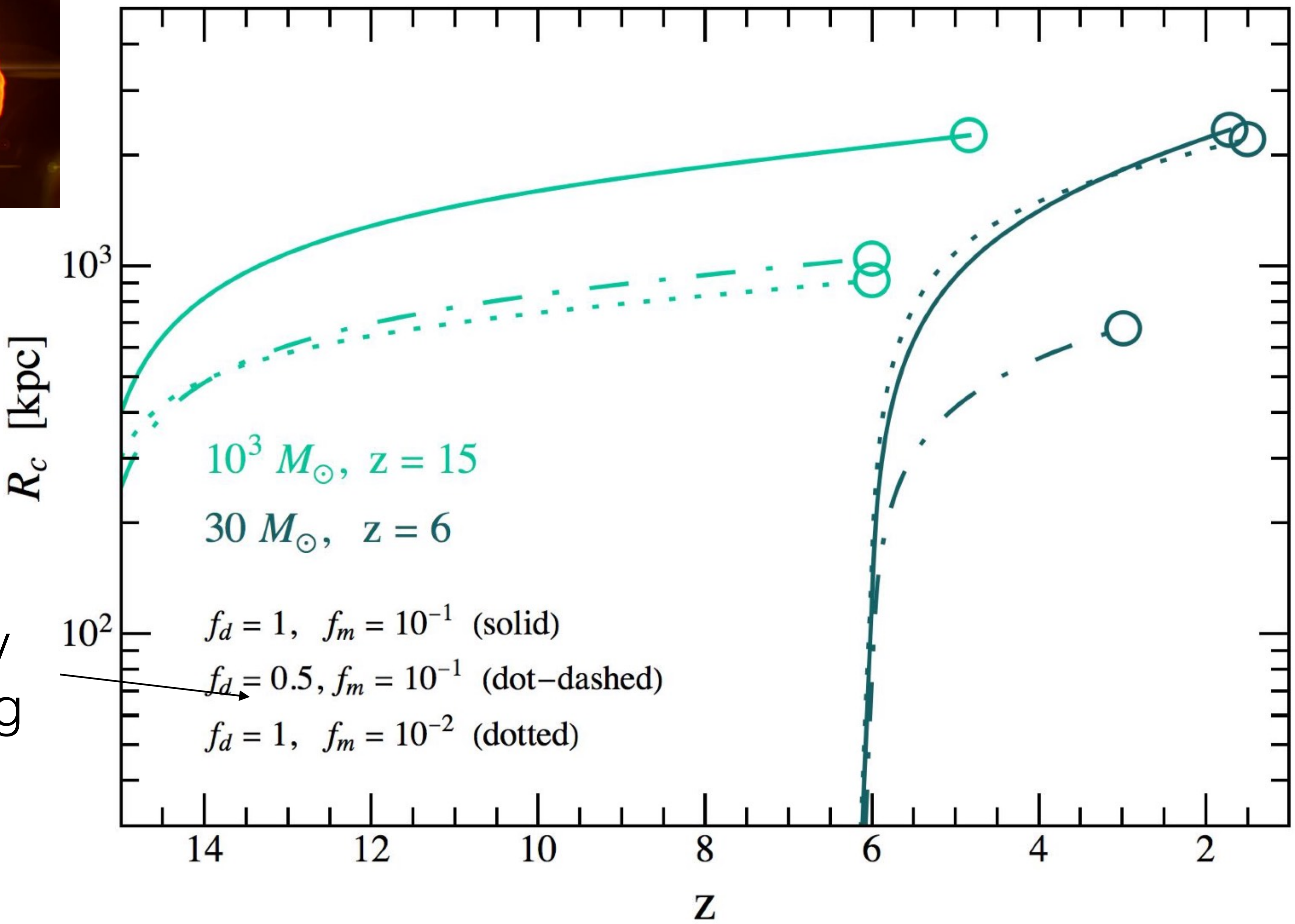
Observing axion SR in the CMB

Blas, Witte ’20



Shockwave evolution

Blas, Witte 20



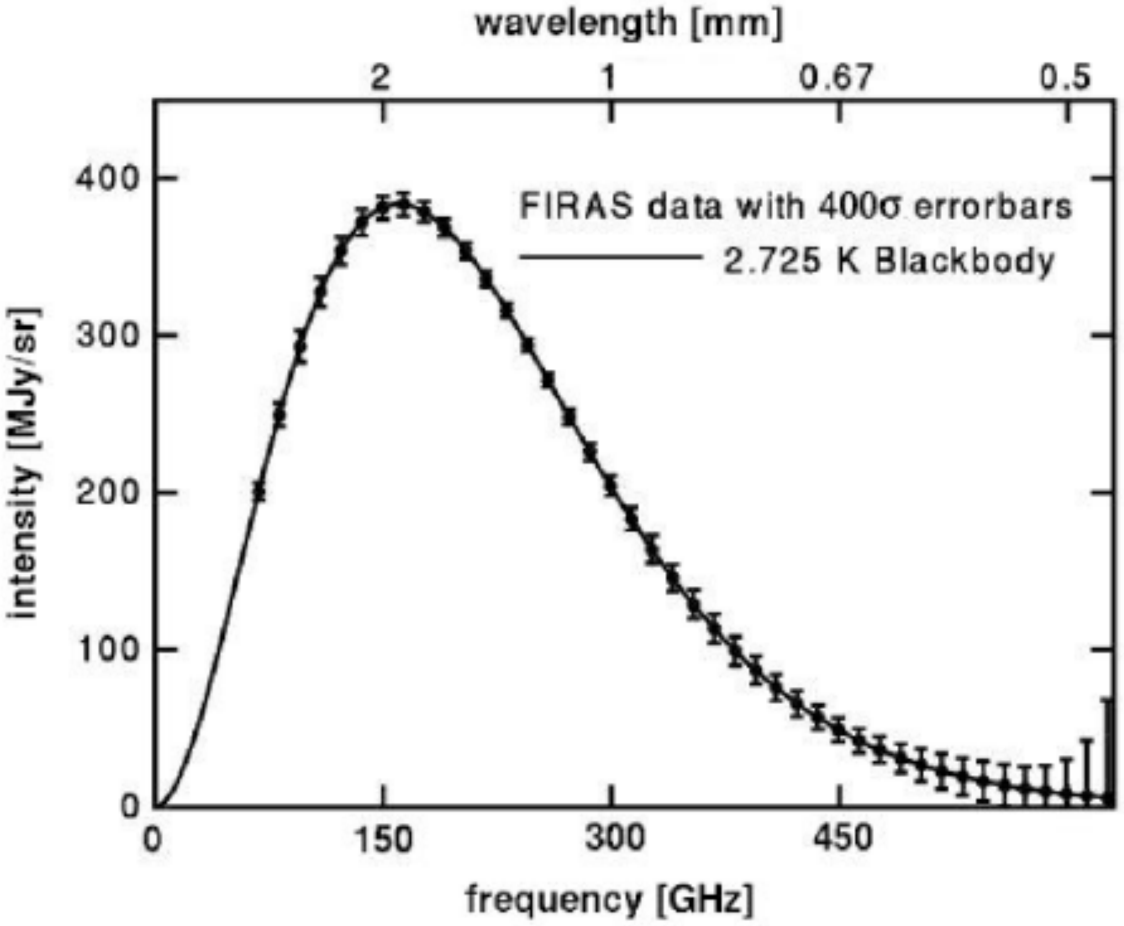
uncertainty in modelling

this leaves behind a Mpc size hot and ionised bubble!

Observable consequences

we focus on a **single** event*

i) a hot and ionized large bubble generates **CMB spectral distortions**

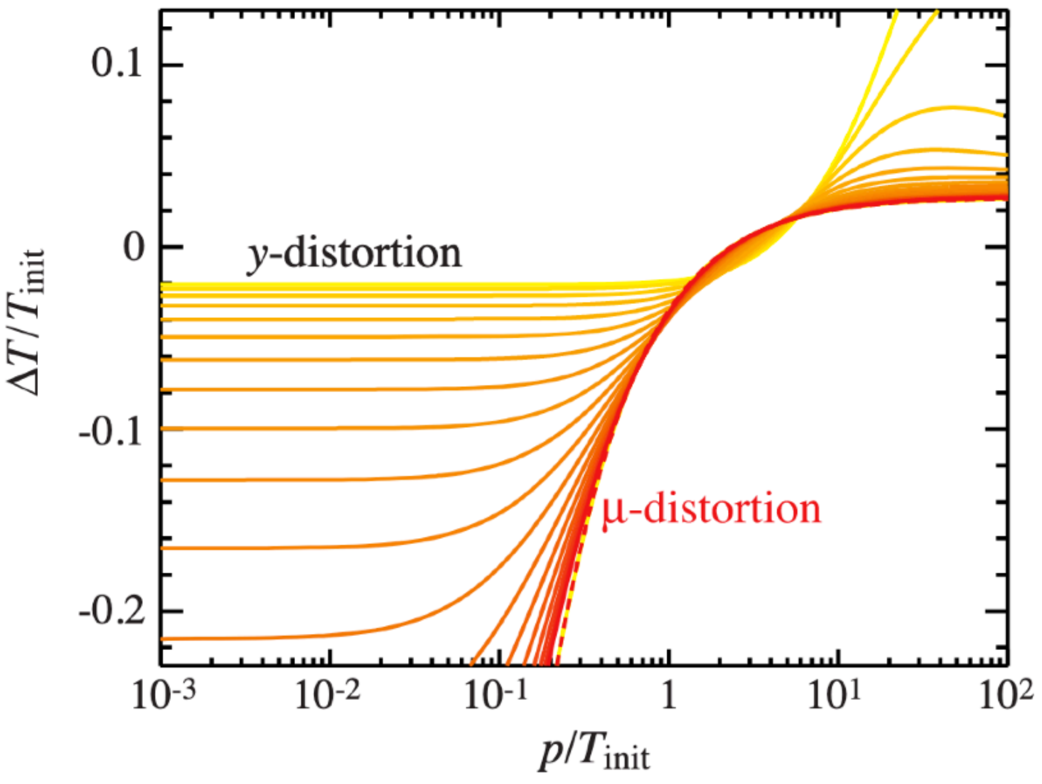


Observable consequences

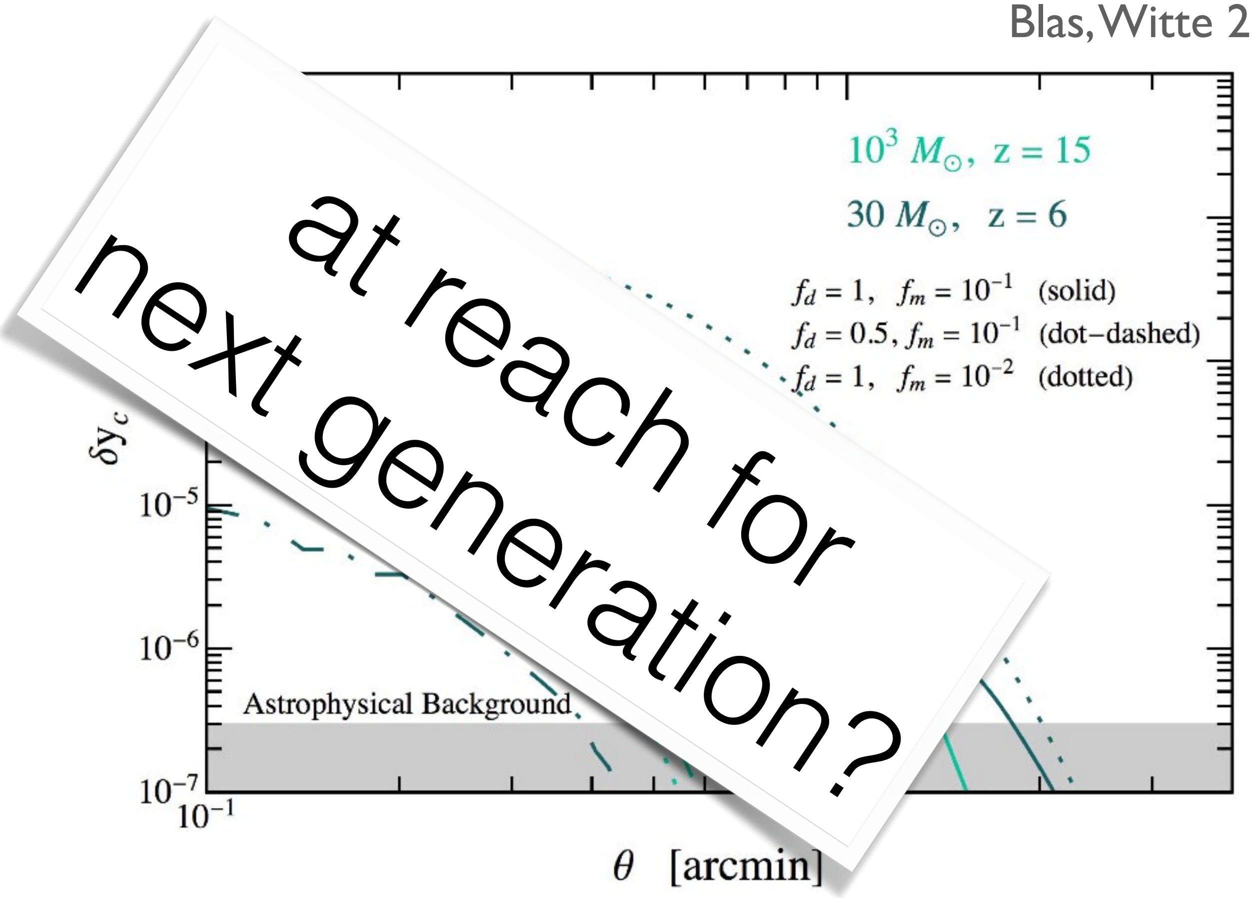
we focus on a **single** event*

i) a hot and ionized large bubble generates **CMB spectral distortions**

Hu 95



Blas, Witte 20



at reach for next generation?

$$y_c = \int dz \frac{(T - T_{\rm cmb})}{m_e} \frac{\sigma_T n_e}{H(z)(1+z)}$$

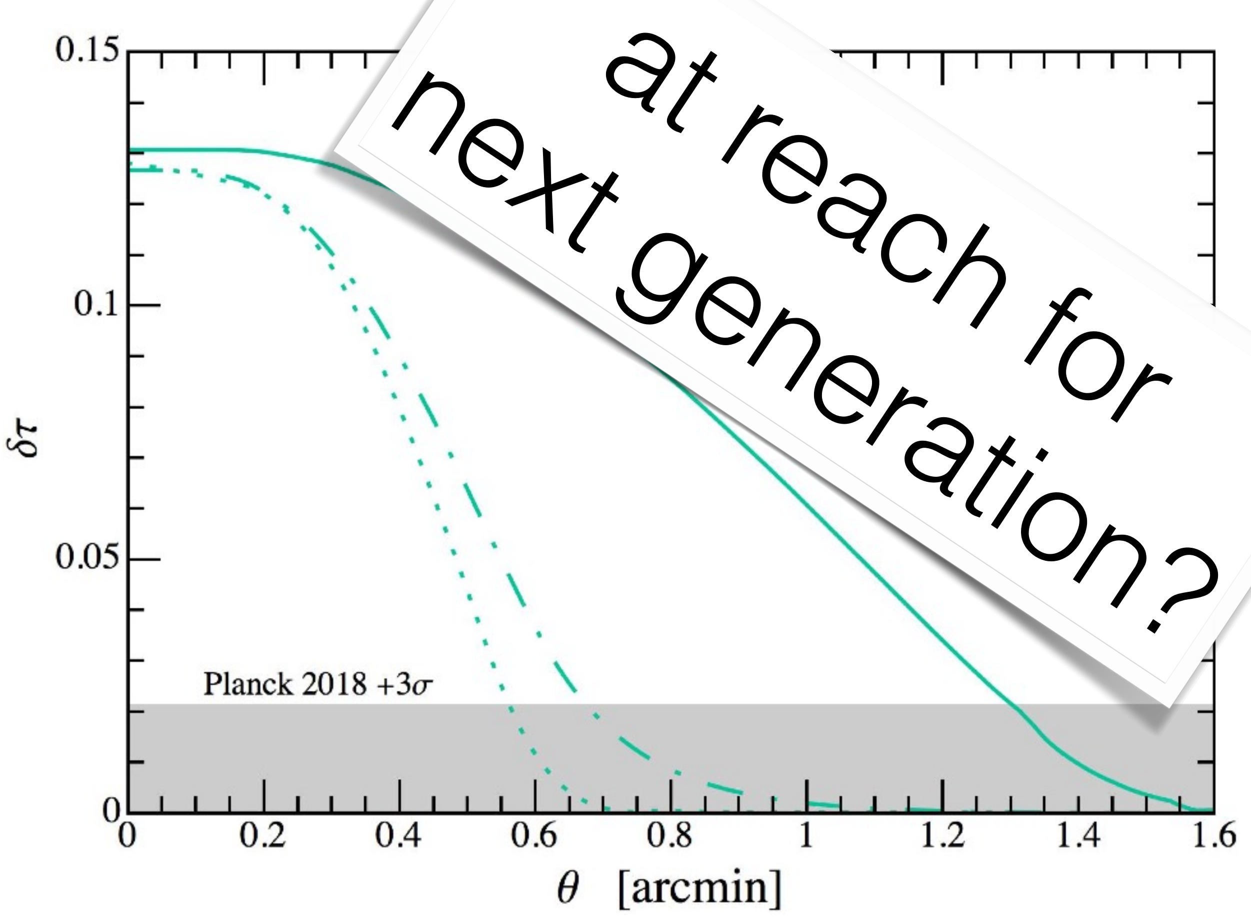
* if we knew the distribution of BHs one can do better

Blas, Witte in progress (?)

Observable consequences

ii) a hot and ionized large bubble modifies the **optical depth**

$$\delta\tau = \int dz \frac{1}{H(z \quad\quad + z)} \left[n_e(z) - n_{e,0}(z)\right] \sigma_T$$



at reach for
next generation?

we focus on a **single** event*

* if we knew the distribution of BHs one can do better

Blas, Witte in progress (?)

Conclusions

- Rotational superradiance: handle into light bosons: SGWB, Regge plane, direct GWs, explosions…

Intense activity!

- Right range for photons in the IGM! Can we use it?
  - Most likely not! SR quenched by interactions! (but Z'…)

Cardoso et al '20

Blas, Witte '20

- Explosive cloud for axions $g_a a\, \tilde{F}_{\mu\nu} F^{\mu\nu}$

Blas, Witte '20

  - Heats local environment and leaves signatures in CMB observables (TBC)
  - Many new possibilities for SR if interactions are included

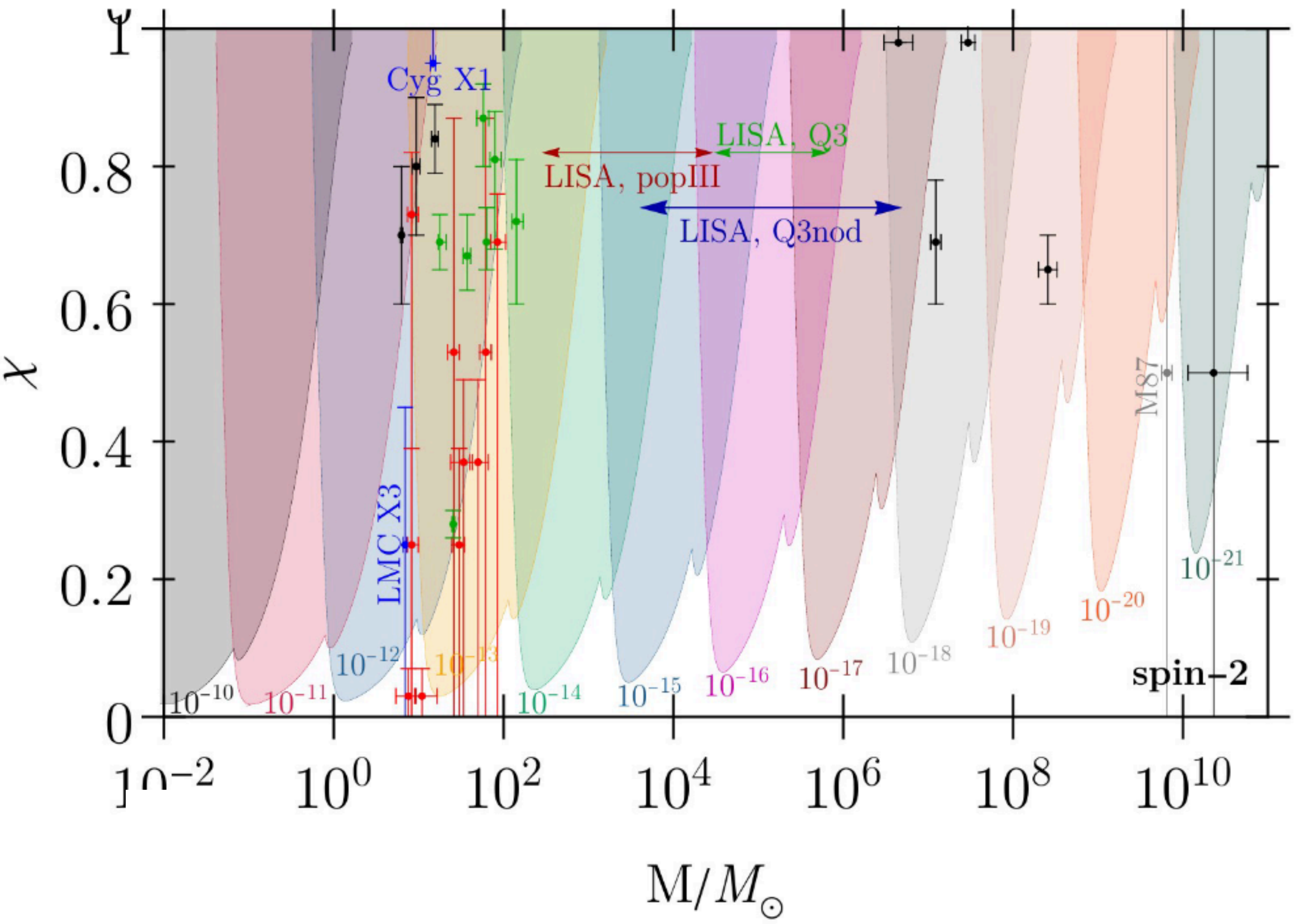
BH superradiant instability spectrum

- Instability depends on spin of the BH & particle spin (S):

$$\omega_R \sim \mu - \frac{\mu (M\mu)^2}{2(1+\ell+n+S)^2} \qquad \omega_I \sim -\left(\omega_R - m\Omega_H\right)(M\mu)^{4\ell+5+2S}$$

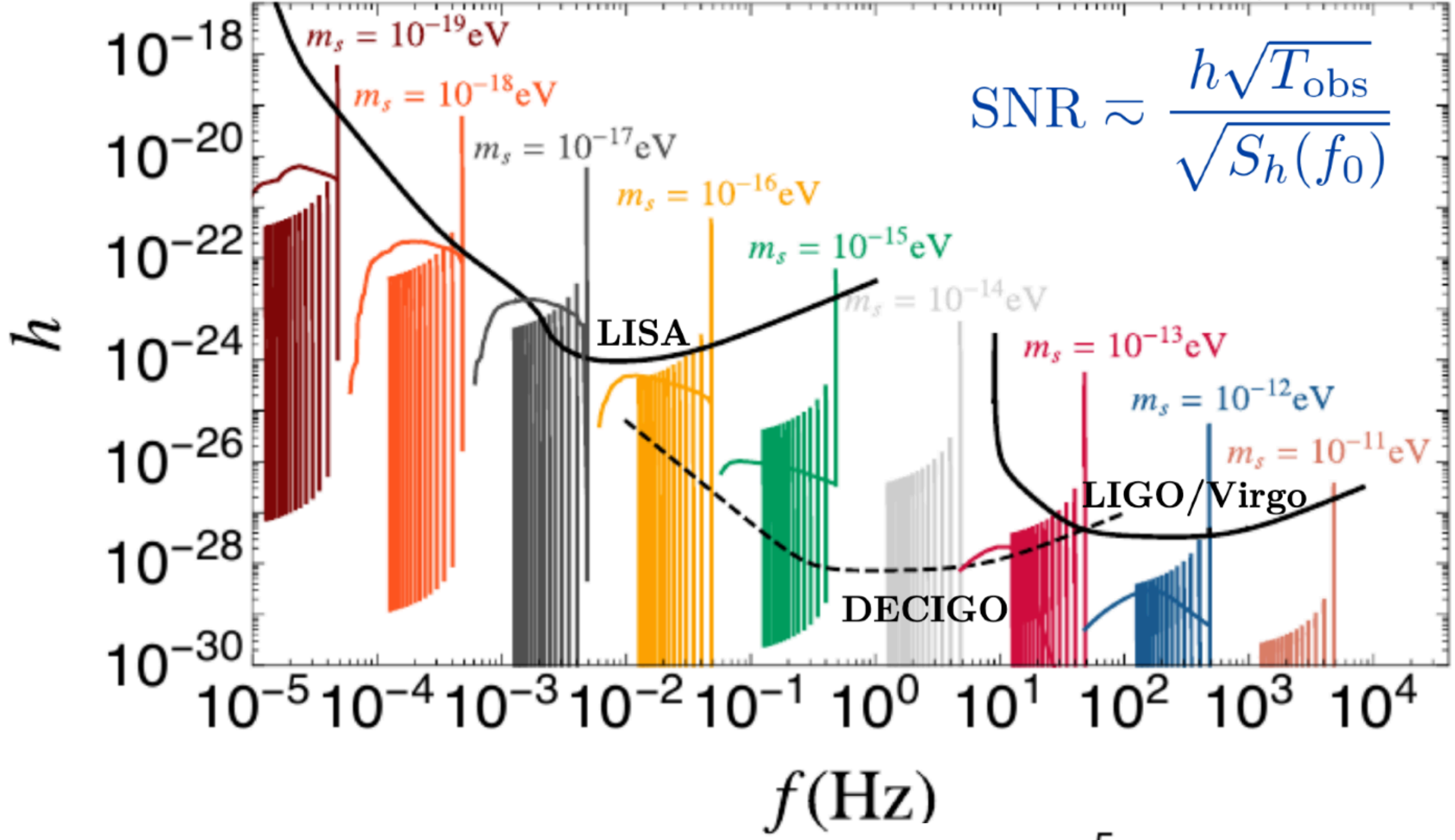
- Incomplete timeline of progress on the superradiant-mode spectrum:
  - Scalar, numerical spectrum [Dolan PRD 2007]
  - Vector, nonspinning case [Rosa & Dolan PRD 2012]
  - Vector, quadratic in spin [Pani+ PRL 2012]
  - Scalar/vector, time-domain, any spin [Witek+ PRD 2013]
  - Tensor, linear in spin → special non-hydrogenic mode! [Brito, Cardoso, Pani PRD 2013]
  - EFT approach [Endlich & Penco, JHEP 2017]
  - Vector, Newtonian approximation [Baryakhtar+ PRD 2017]
  - Vector, frequency domain, PDEs, any spin [Cardoso+ JCAP 2018]
  - Vector, separability, any spin [Frolov+ PRL 2018]
  - Vector, ODEs, numerical spectrum [Dolan PRD 2018]
  - Tensor, Newtonian approximation [Brito, Grillo, Pani PRL 2020]

From P. Pain
2022 KIAS



Brito, Cardoso, PP gr-qc/1501.06570v8

Brito+, PRL 2017, PRD 2017



$$\mathrm{SNR} \approx \frac{h\sqrt{T_{\rm obs}}}{\sqrt{S_h(f_0)}}$$