

New tests for ultra-light dark matter with black hole superradiance

Diego Blas

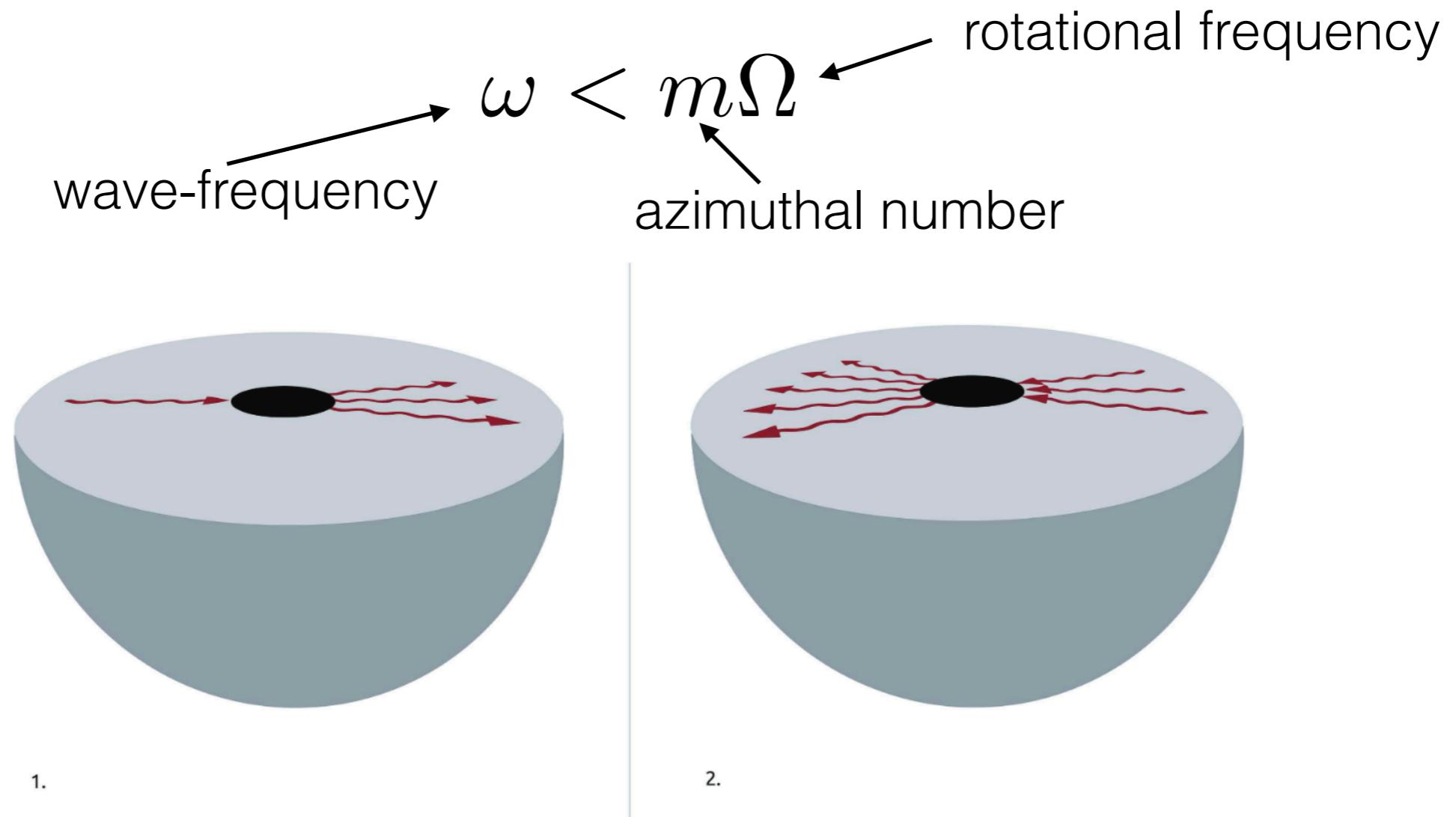
w./ Sam Witte 2009.10074, 2009.10075 (both to appear in PRD)

Black hole superradiance

Zel'dovich 71

Brito, Cardoso, Pani 1501.06570 [gr-qc]

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

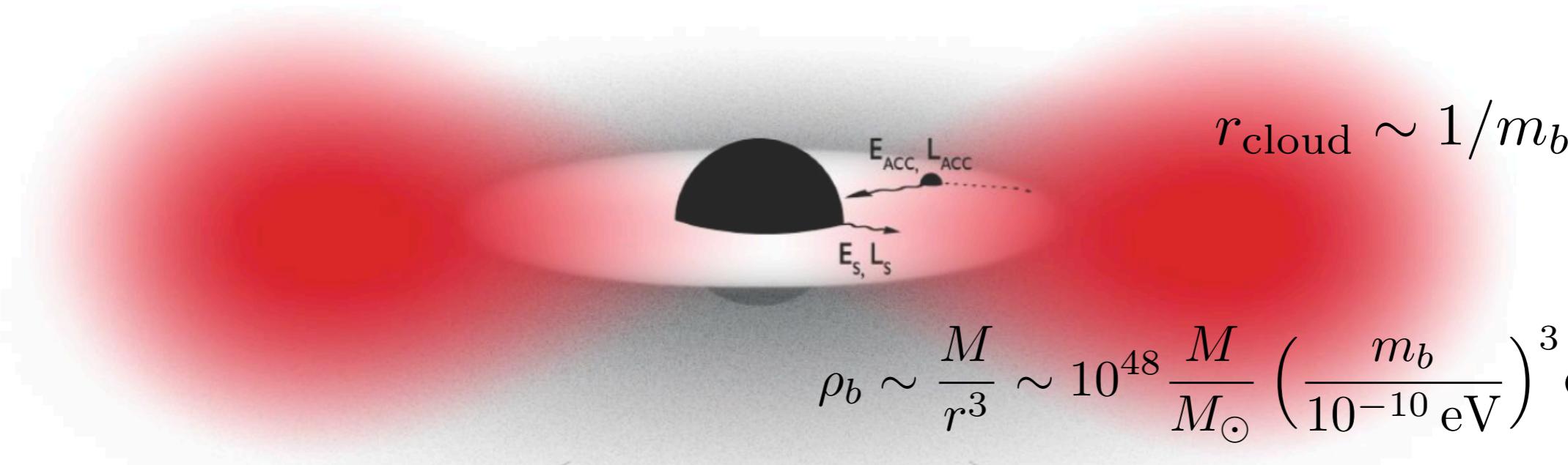


If waves are massive, they 'reflect' back, and will keep amplifying!

Black hole superradiance II

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]



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

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

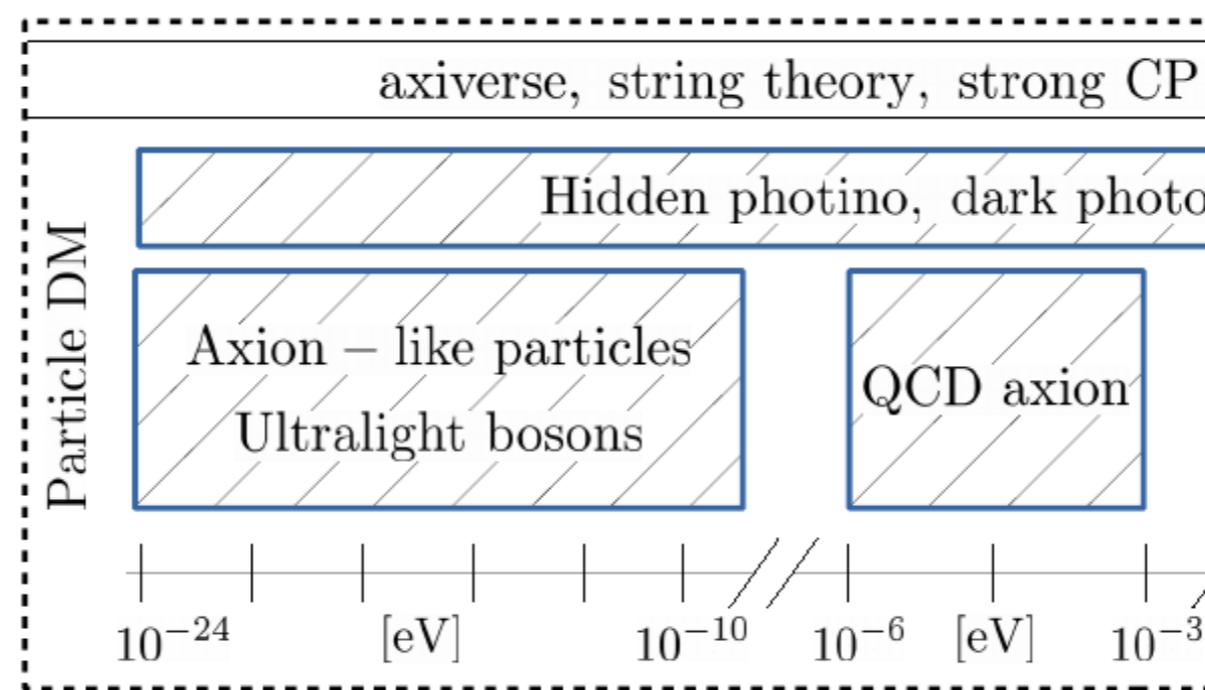
Black hole superradiance III

This has **consequences**: spinning down of BHs, emission of GWs, perturbation of local gravitational potential...

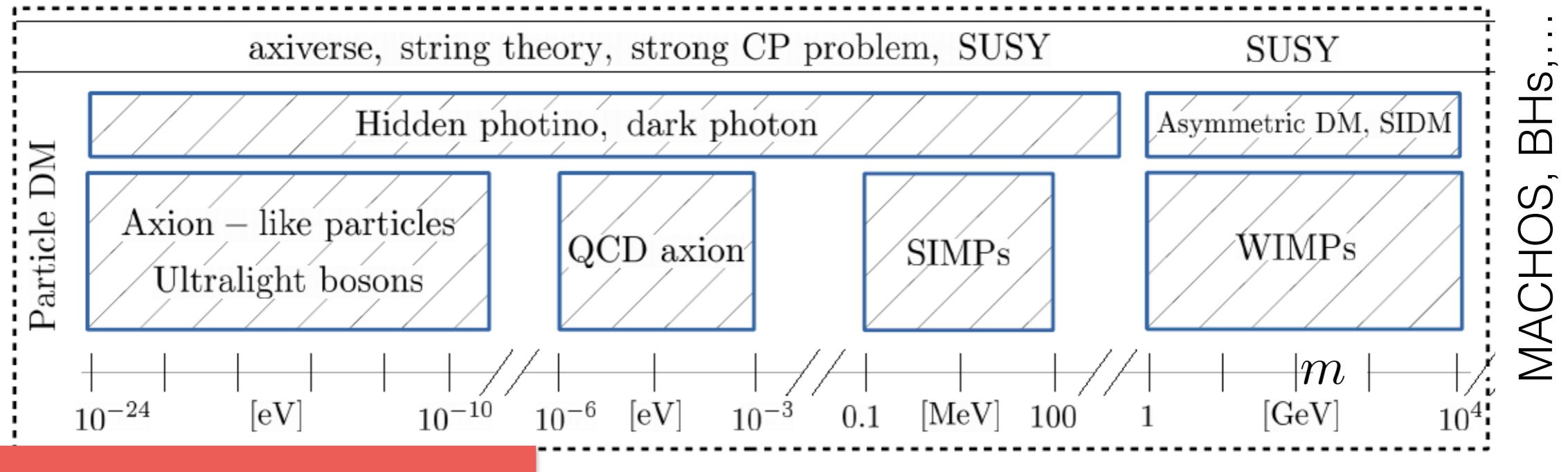
But astrophysical BHs require very low masses, absent in the SM!

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

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



Inset on dark matter candidates



these masses are well-motivated
theoretically and have their own ‘miracles’

i) generating mechanism inflation/misalignement/phase
transitions...

ii) (main) direct detection strategy $p \sim m_\chi \langle v \rangle \sim 10^{-3} m_\chi$

(many new ideas!)

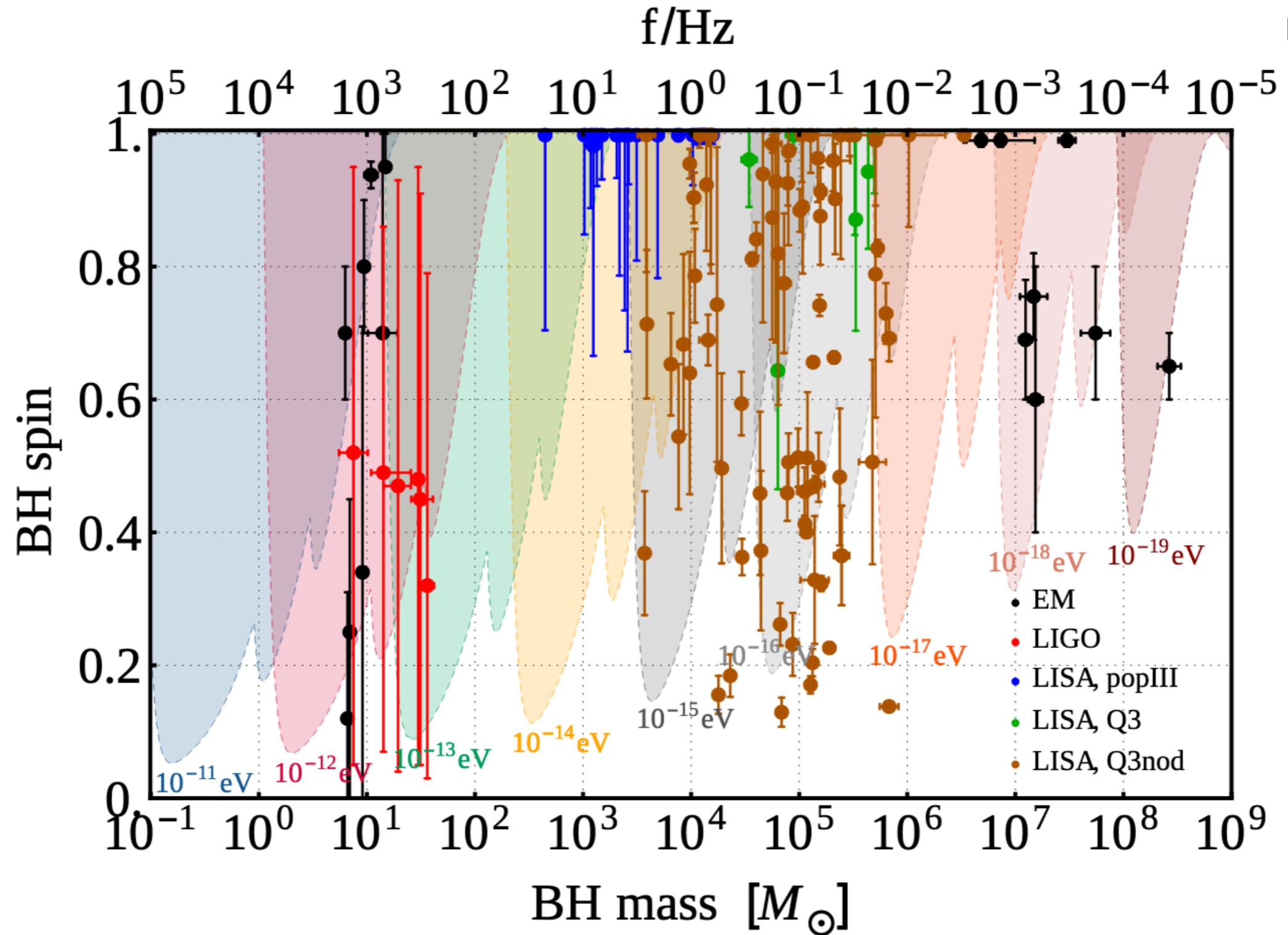
GeV nuclear recoil

Effects on the Regge plane

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

the clouds extract J from the BH

Brito et al. 17

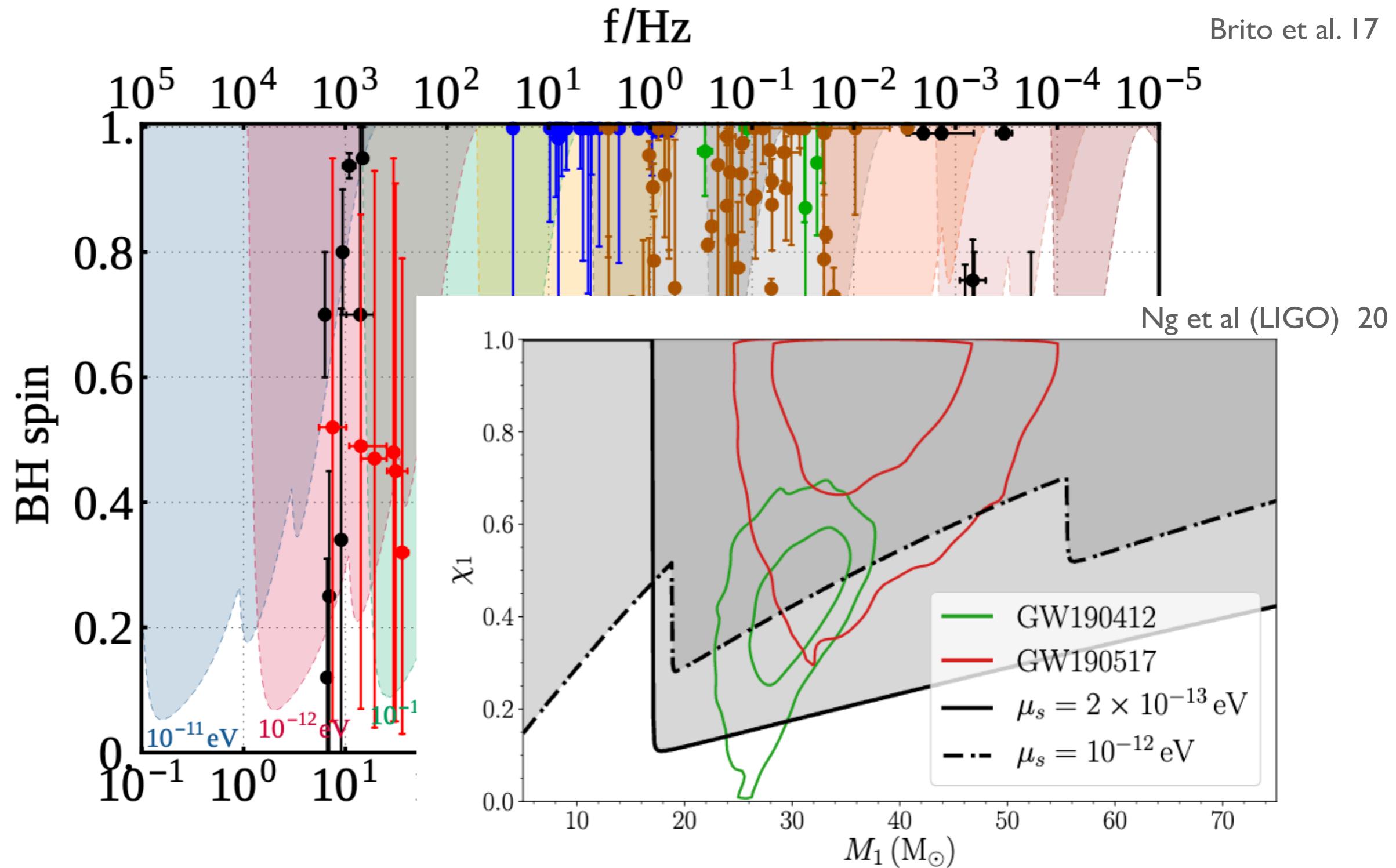


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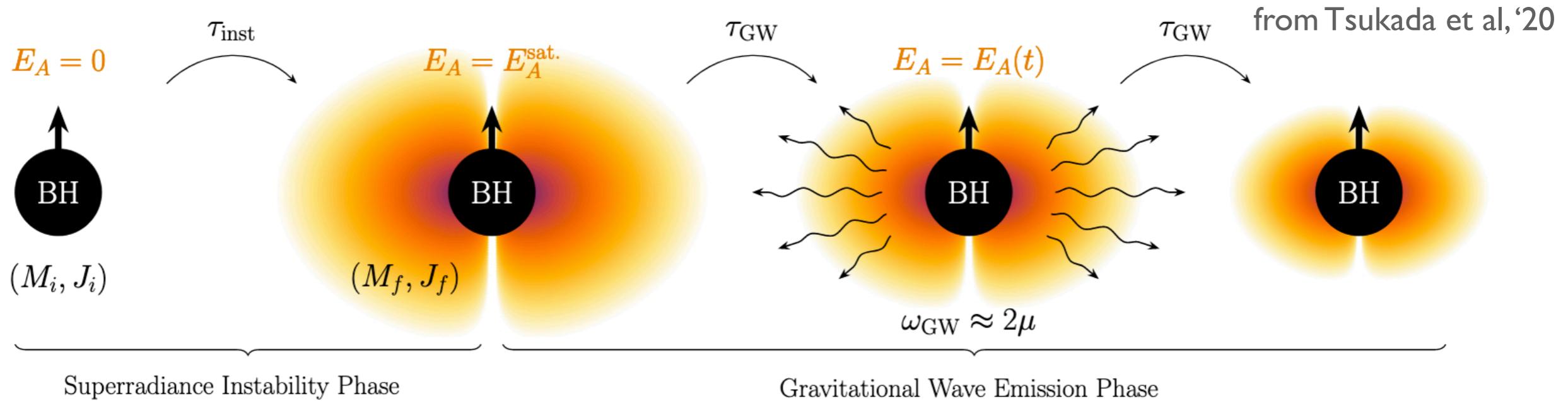
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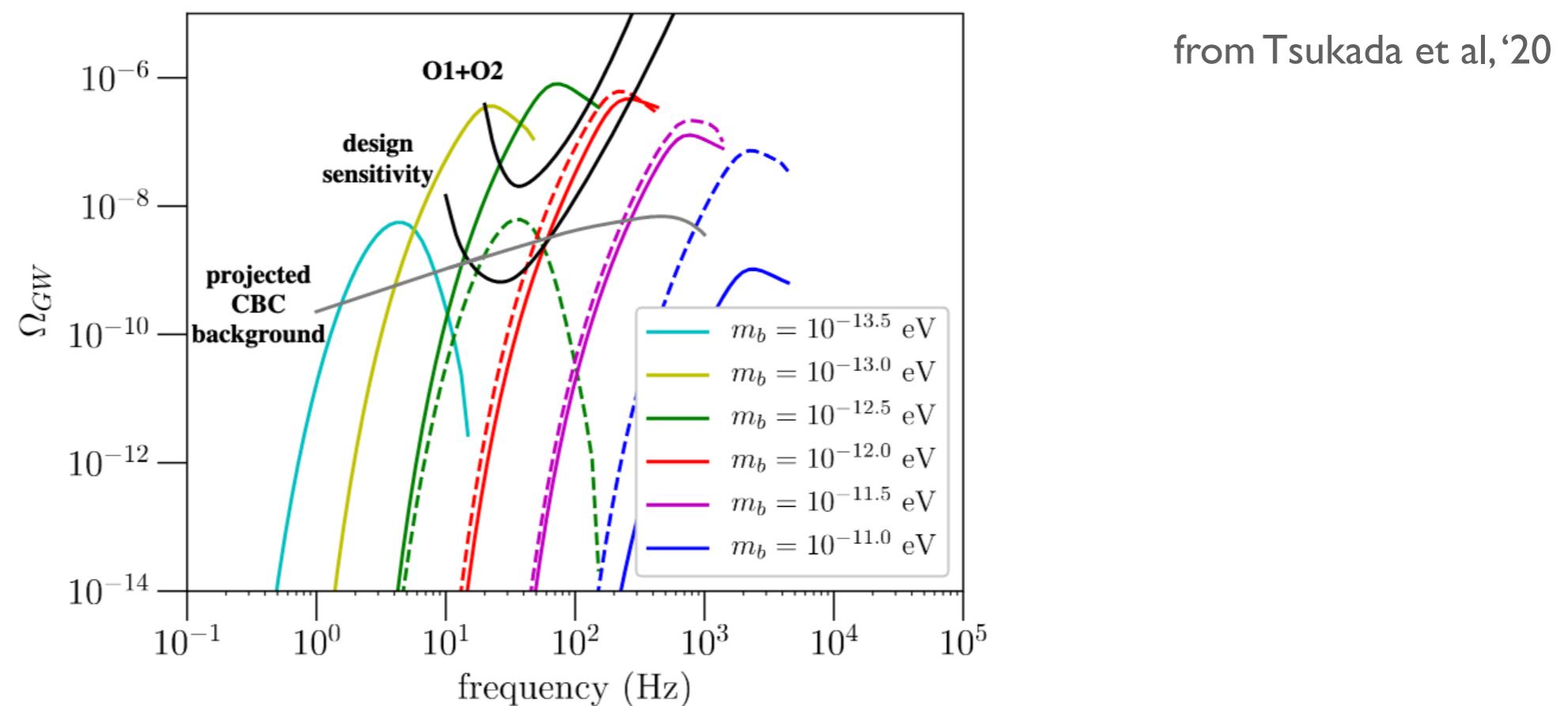
Brito et al. 17



GW signal

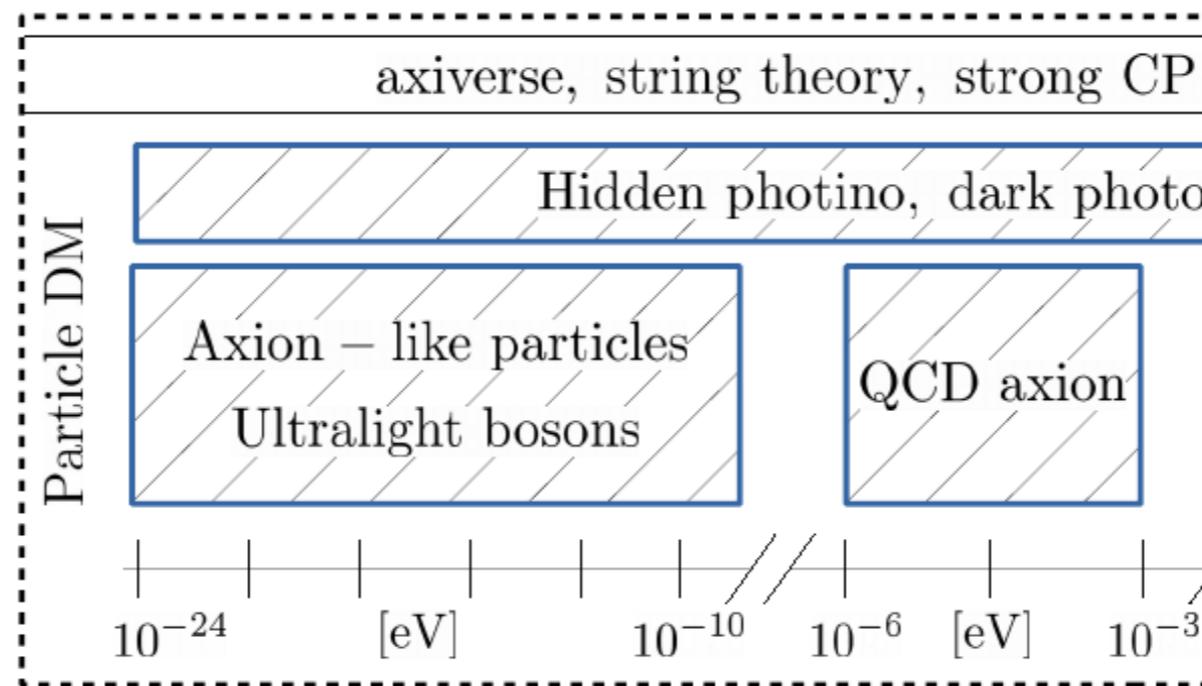


given a model for BH population one can predict the GW signal, eg.



Including interactions

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



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

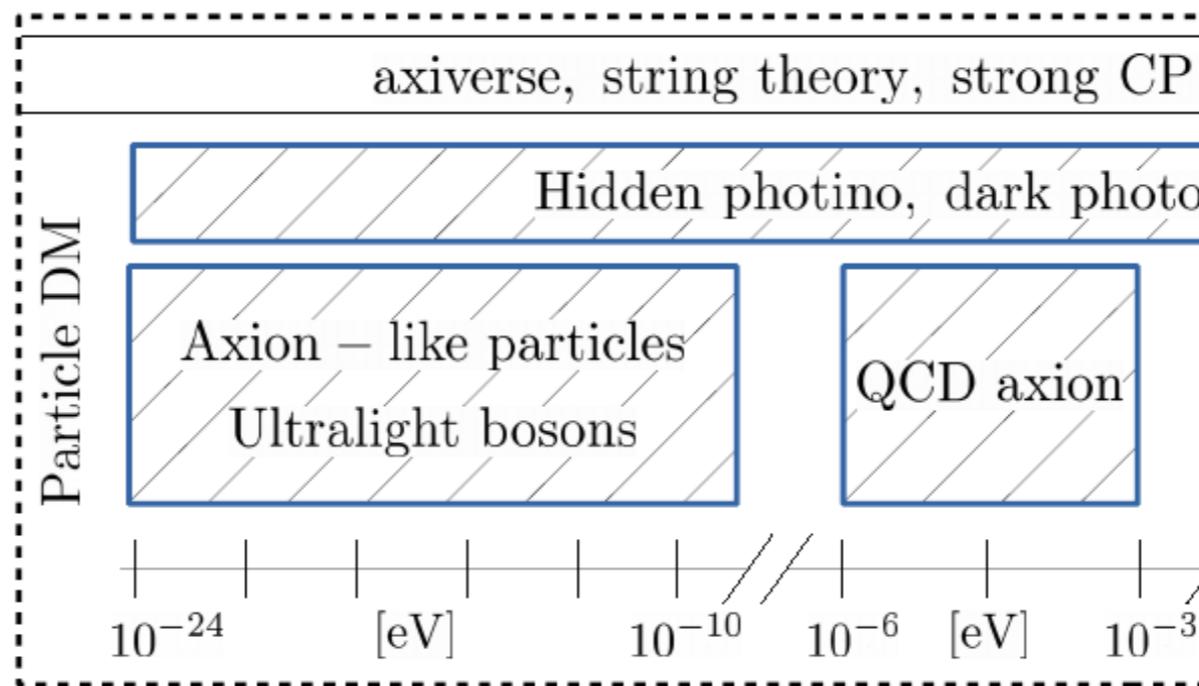
Ikeda, Brito, Cardoso 18

Baryakhtar 20

explosion of low-energy photons

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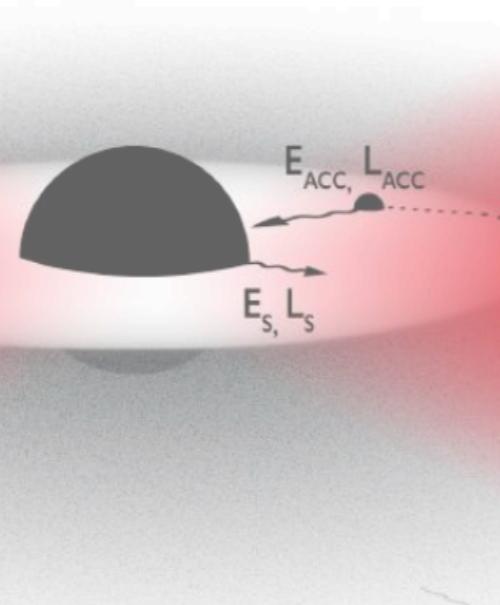
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explosion of low-energy photons

Observing axion SR in the CMB

Blas, Witte 20



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



low energy photons!*

this happens for

$$g_a \gtrsim 10^{-19} \sqrt{\frac{M}{M_a}} \frac{1}{(m_a M)^2} \text{ GeV}^{-1}$$

energy extracted

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

*(careful with plasma mass)

$$m_a > 10^{-13} \text{ eV}$$

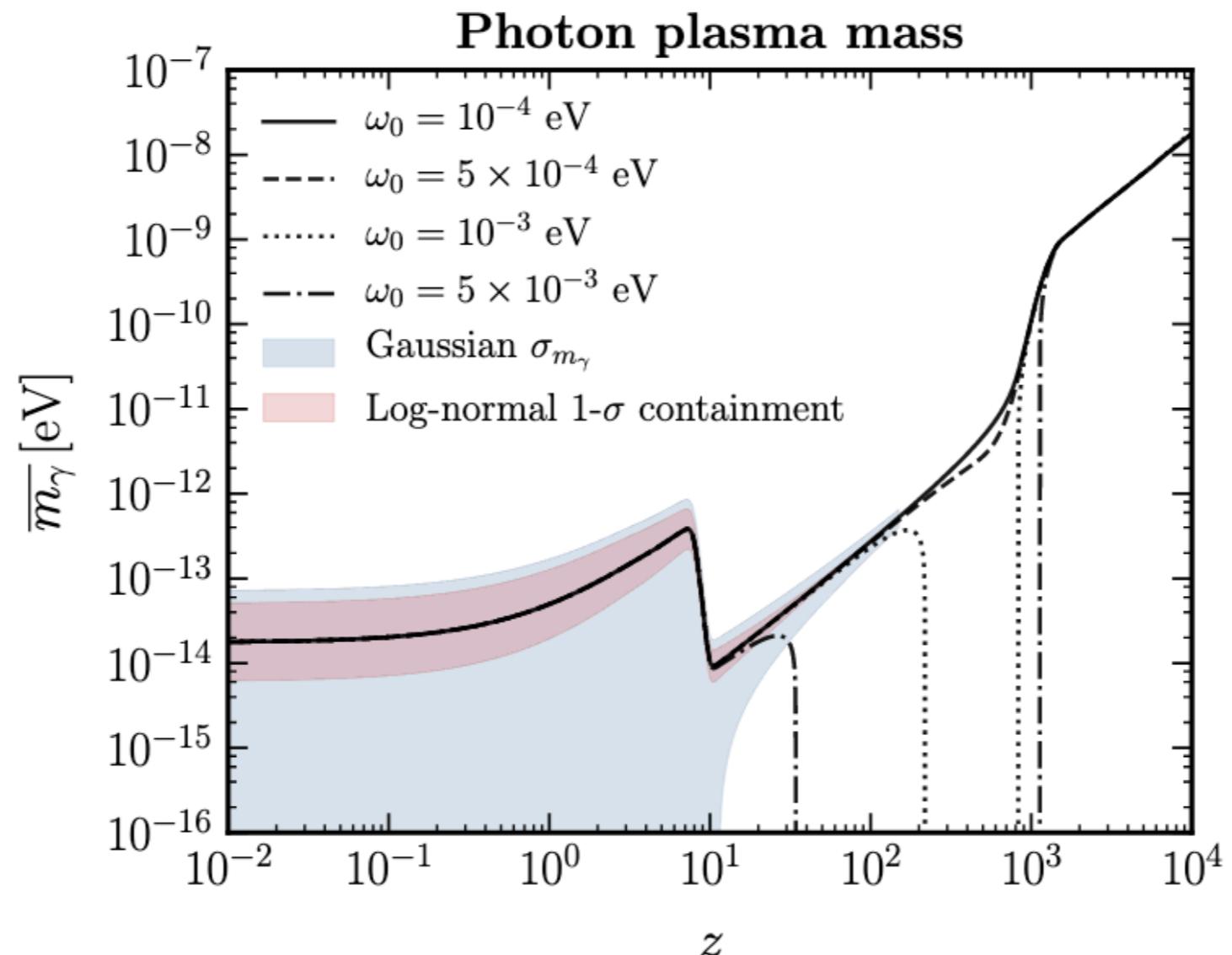
Plasma mass in the IGM

In the presence of a dilute plasma n_e

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

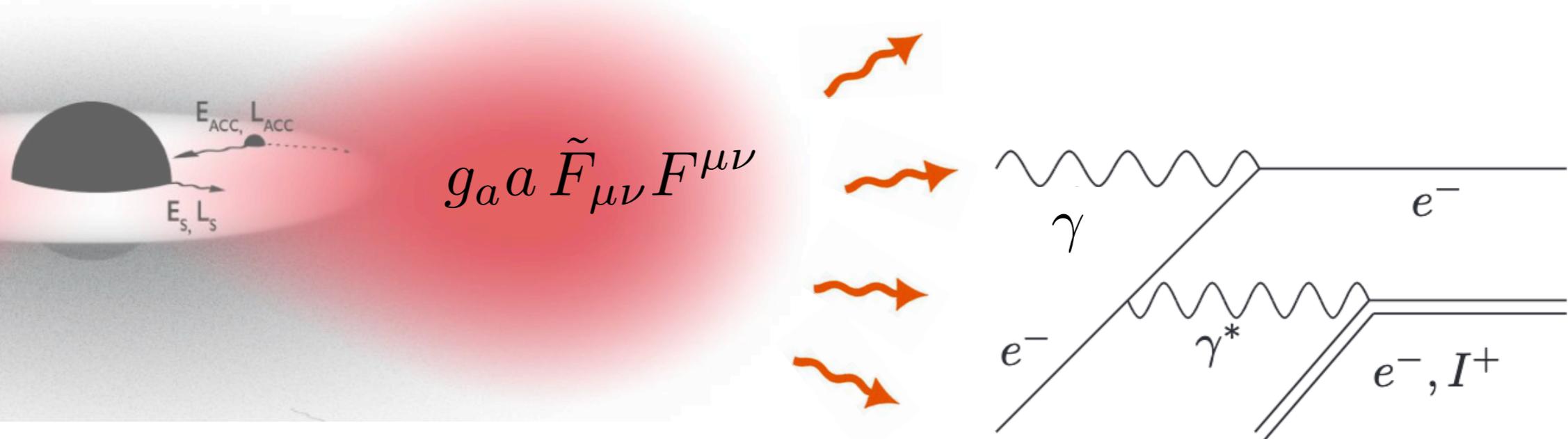
in the inter-galactic medium

Caputo et al '20



Observing axion SR in the CMB

Blas, Witte 20



these photons heat the plasma at a rate

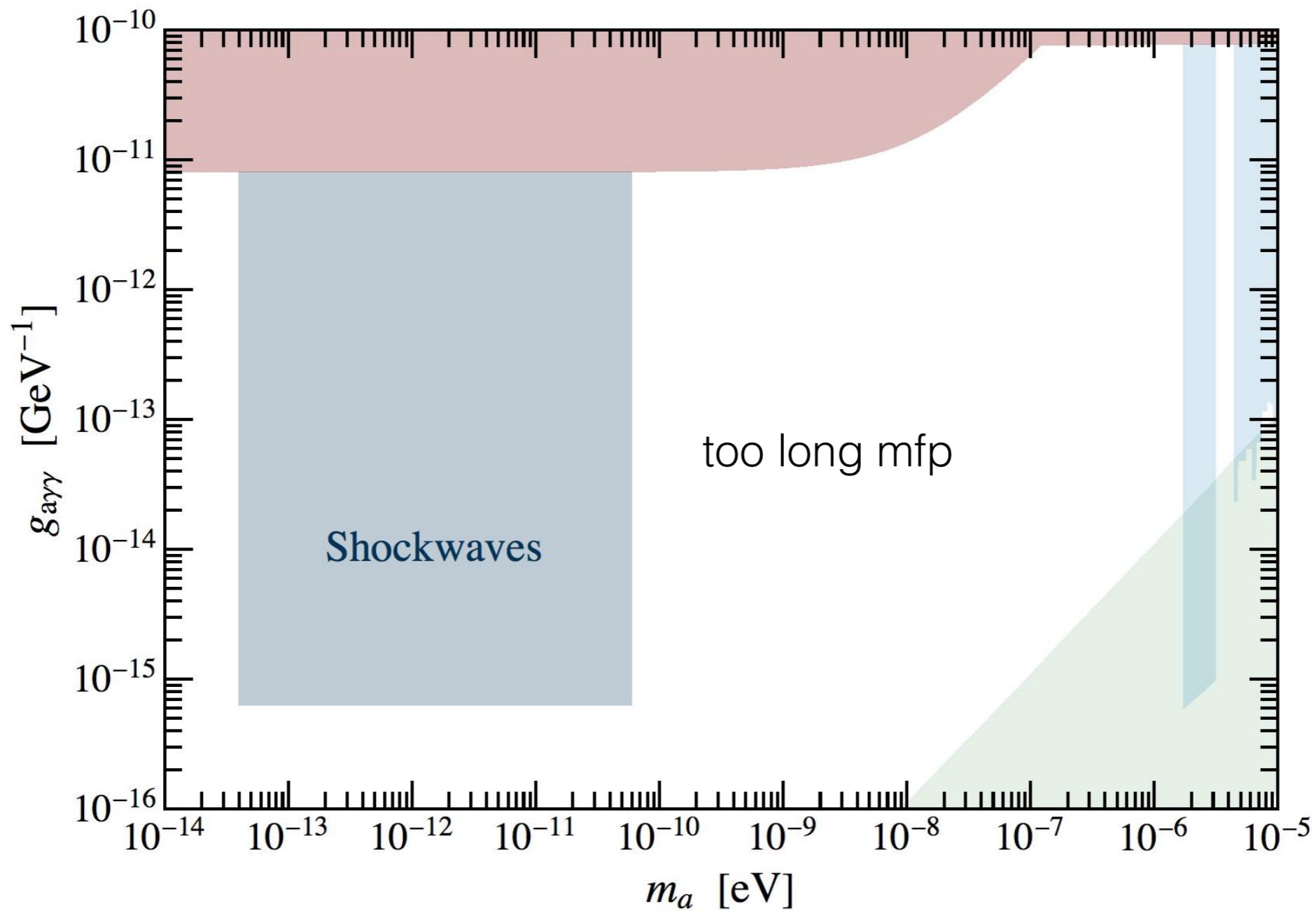
$$\Gamma_{ff} = n_\gamma n_e \sigma_{ff} , \quad \sigma_{ff} \simeq \frac{4\pi^2 \alpha \sigma_T}{\sqrt{6\pi}} n_p \sqrt{\frac{m_e}{T}} \frac{g_{ff}(E_\gamma, T)}{T E_\gamma^2}$$

this deposited energy rises the temperature in (for $M \sim 10M_\odot$)

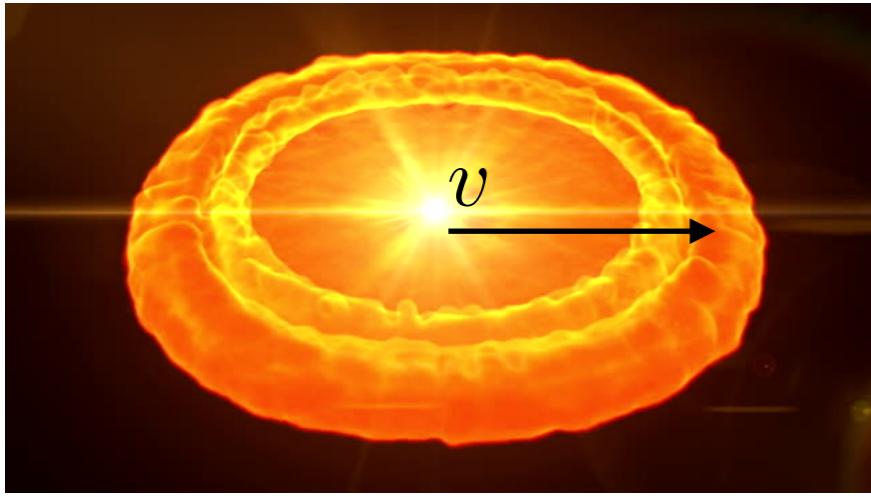
$l < \text{pc}$ to $T \sim 10^{12} \text{ K} \rightarrow$ shock wave (may) develop

Observing axion SR in the CMB

Blas, Witte 20



Shockwave evolution



Tegmark, Silk 93

$$\dot{v} = \frac{8\pi G p}{\Omega_b^2 H^2 R \gamma^3} - \frac{3}{R} (v - HR)^2 - \left(\Omega_{cdm} + \frac{\Omega_b}{2} \right) \frac{H^2 R}{2}$$

↑ ↑ ↑

pressure force braking from
accelerating surrounding material grav. deceleration

relativistic plasma , conservation of energy

$$E = \frac{3}{2} p \mathcal{V}_{sw} \quad \frac{dE}{dt} = L - p \frac{d\mathcal{V}_{sw}}{dt} = L - p 4\pi R^2 v$$

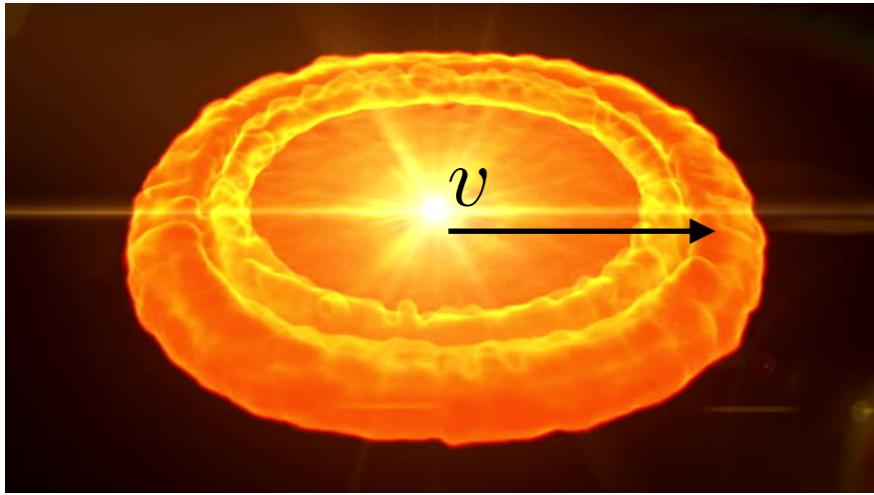
heating from collisions with medium

$$L = L_{SR} + \downarrow L_d - L_{comp} - L_{brem} - L_{ion}$$

↑ ↓

superradiance Compton cooling (CMB) thermal emission ionization of medium

Shockwave evolution



Tegmark, Silk 93

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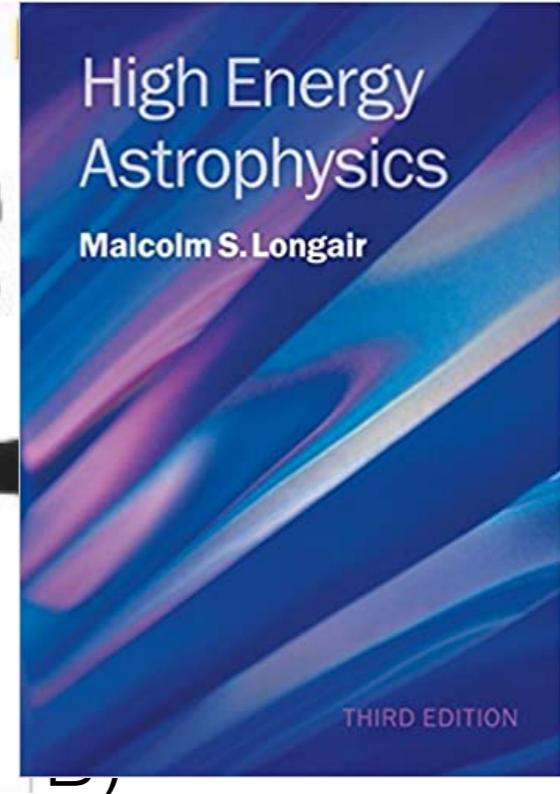
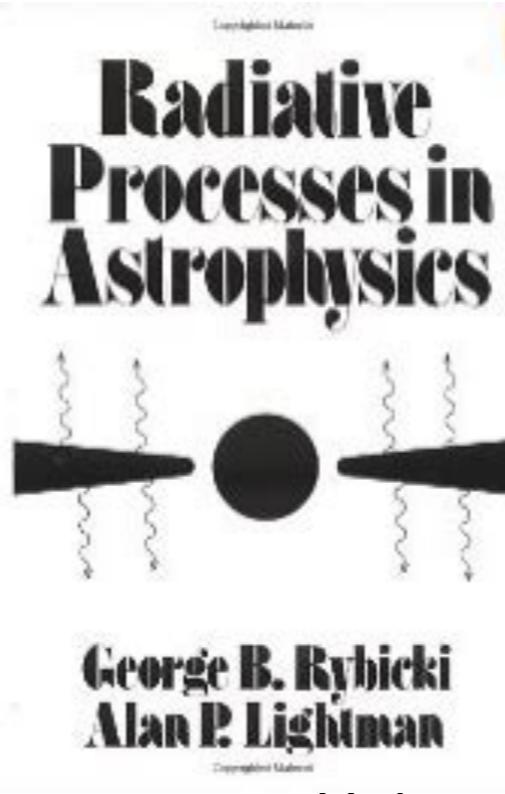
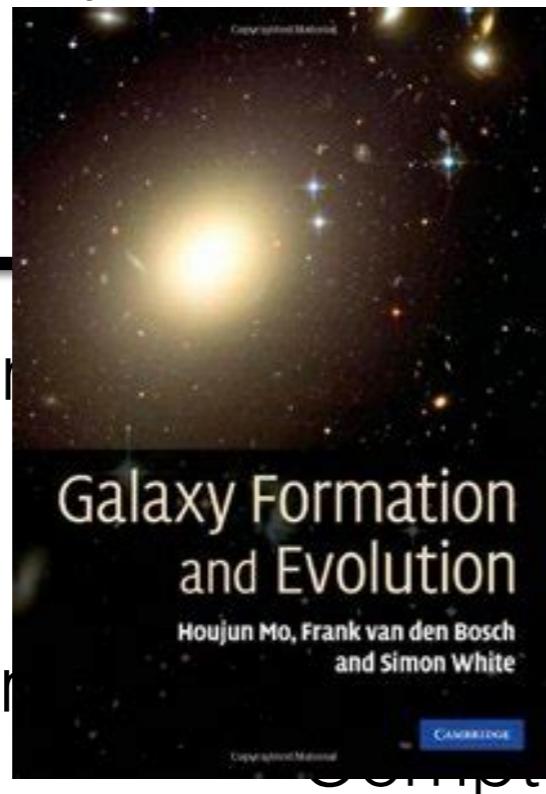
↑ ↑ ↑
pressure force braking from grav. deceleration
 accelerating surrounding material

relativistic plasma

E

heating from

superradiant



, conservation of energy

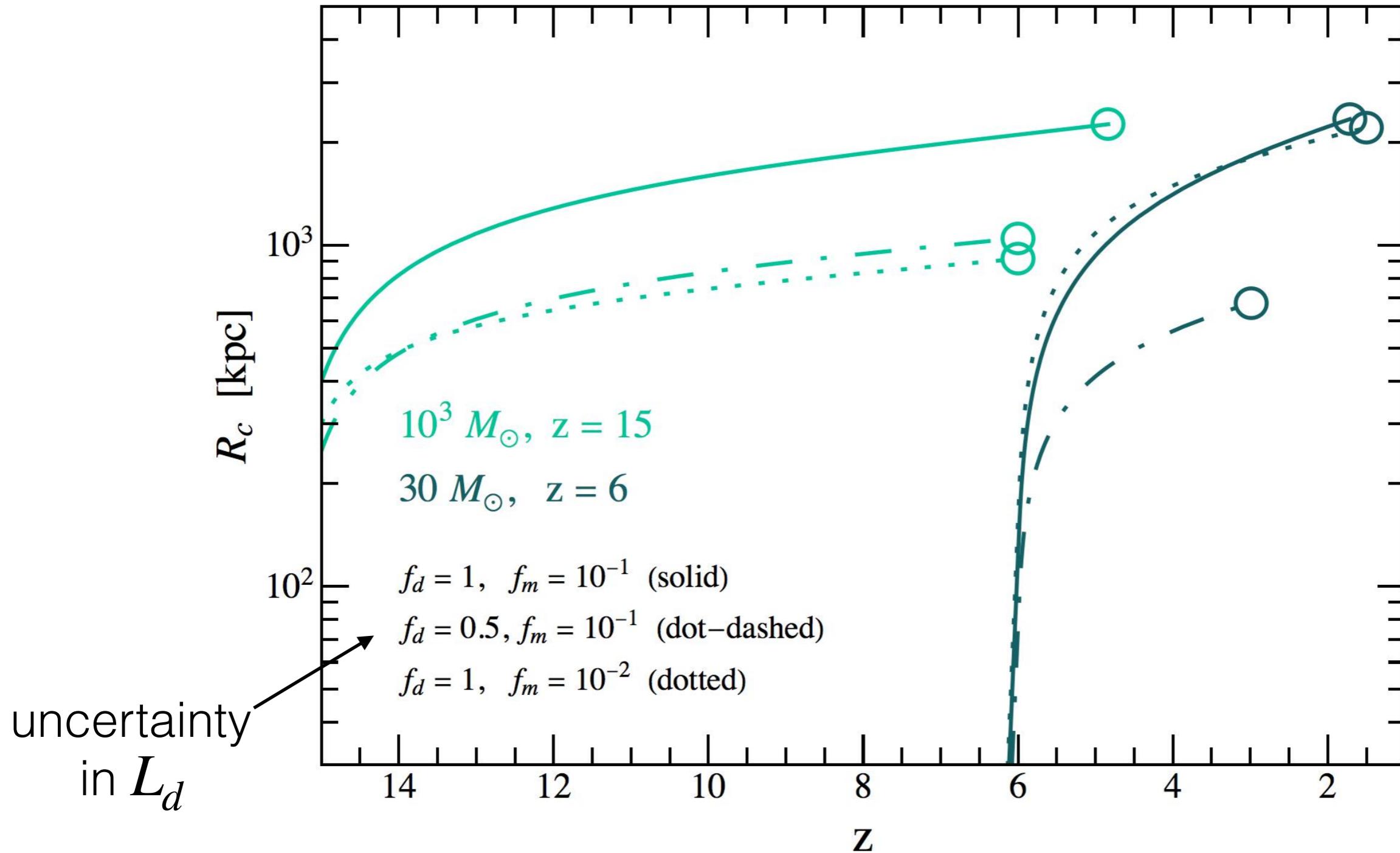
$- p 4\pi R^2 v$

usion

of medium

Shockwave evolution

Blas,Witte 20



this leaves behind a *Mpc* size hot and ionised bubble!

Observable consequences

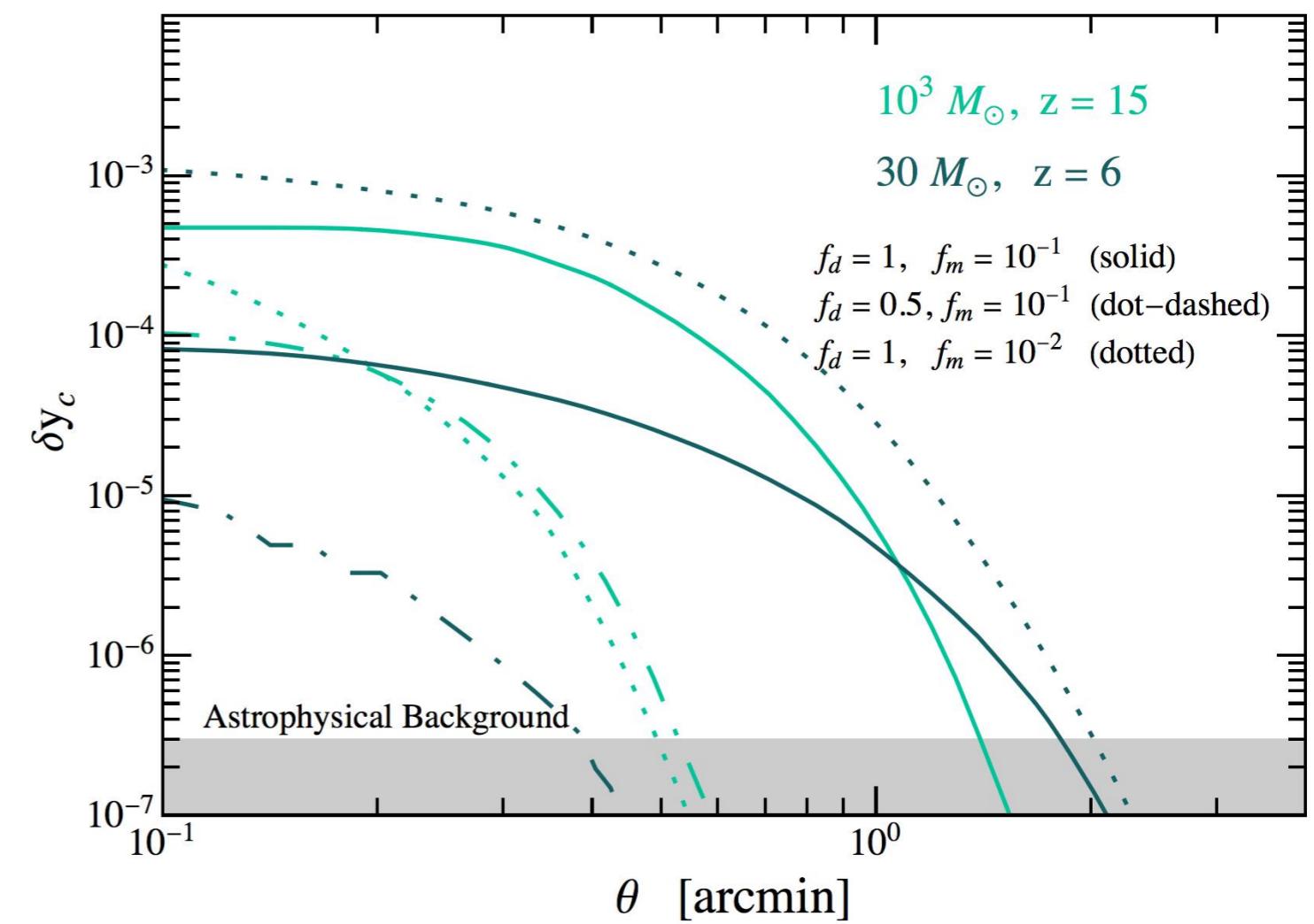
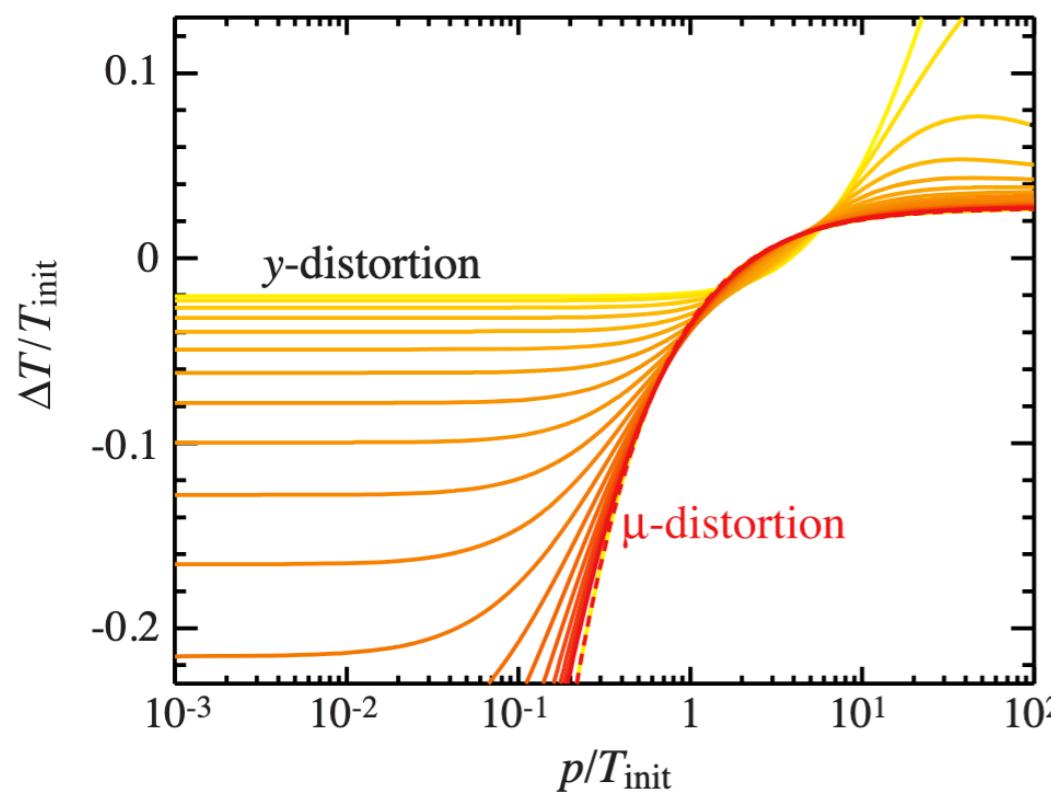
we focus on a **single** event*

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

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

Hu 95

Blas, Witte 20



* if we knew the distribution of BHs we may find stronger signals

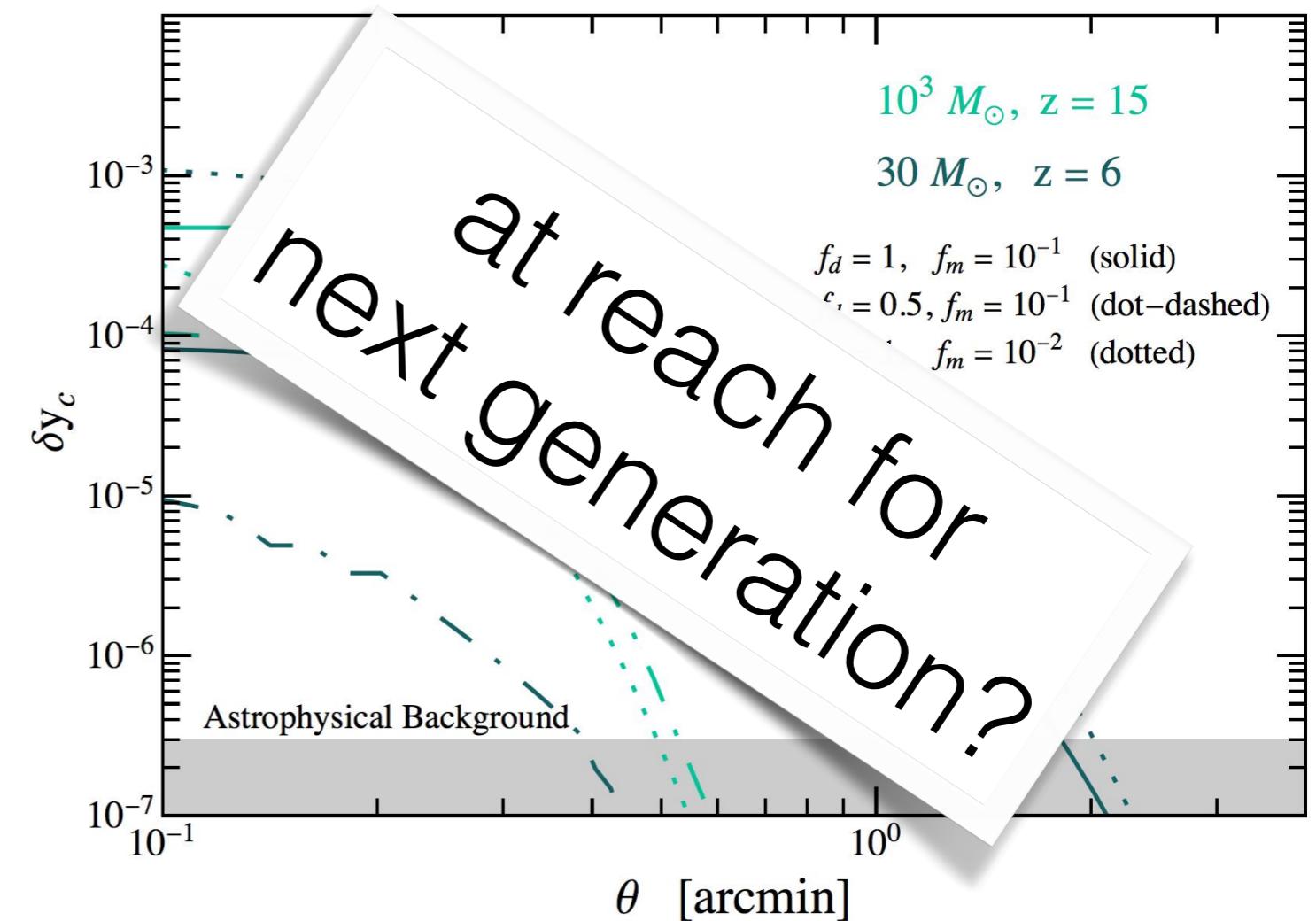
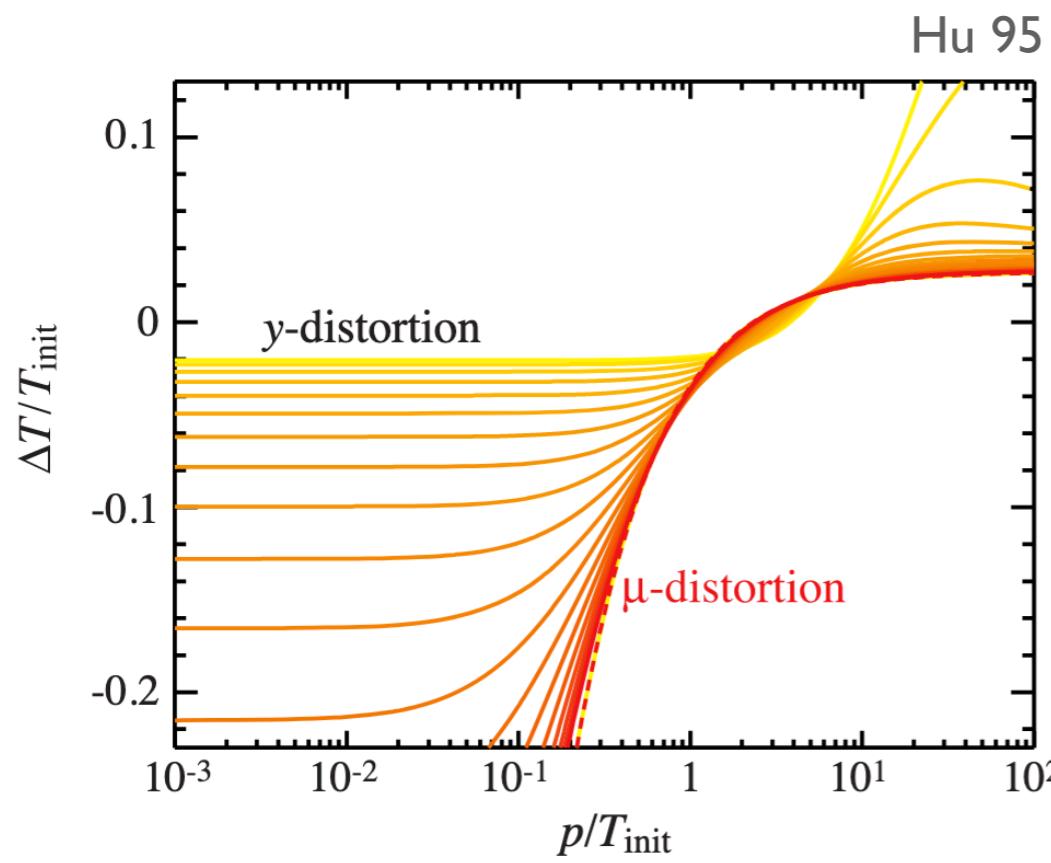
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Blas, Witte 20

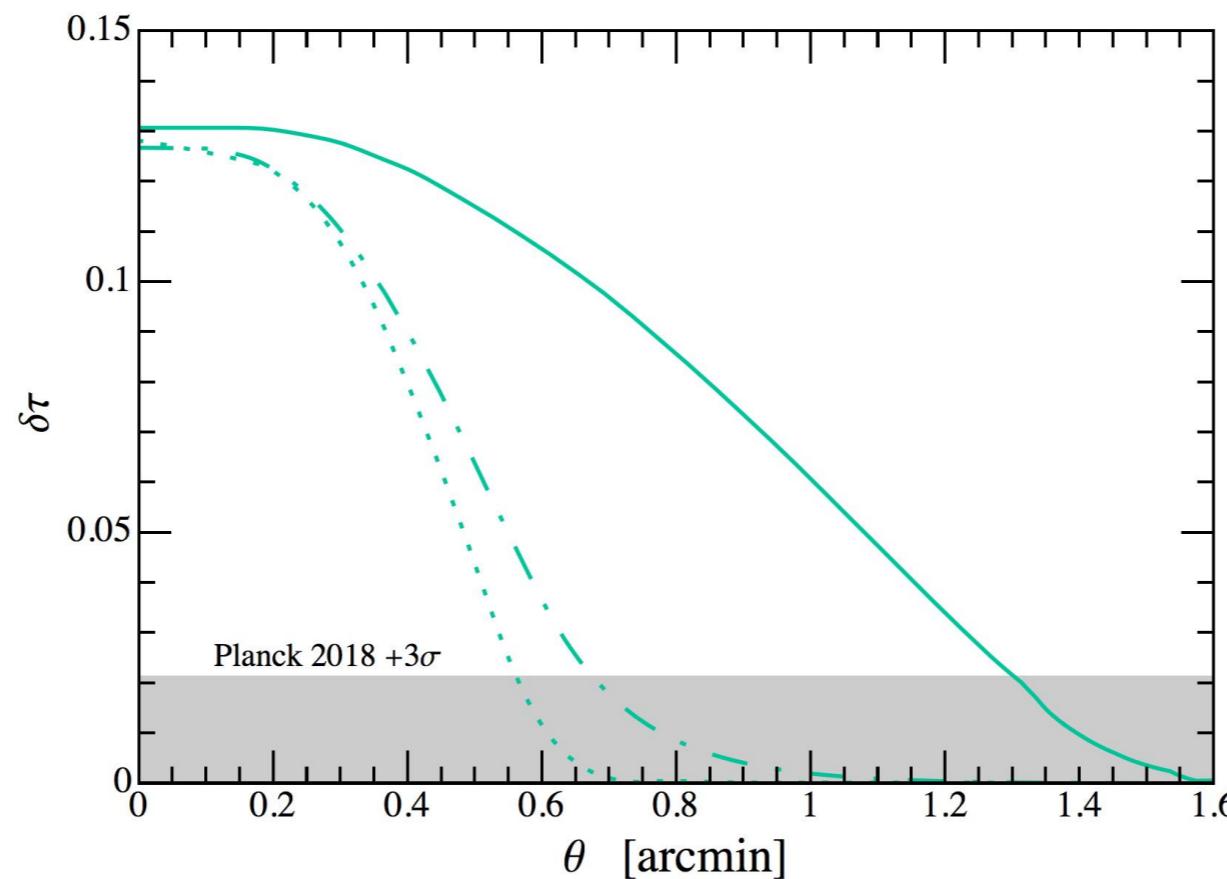


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Observable consequences

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

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



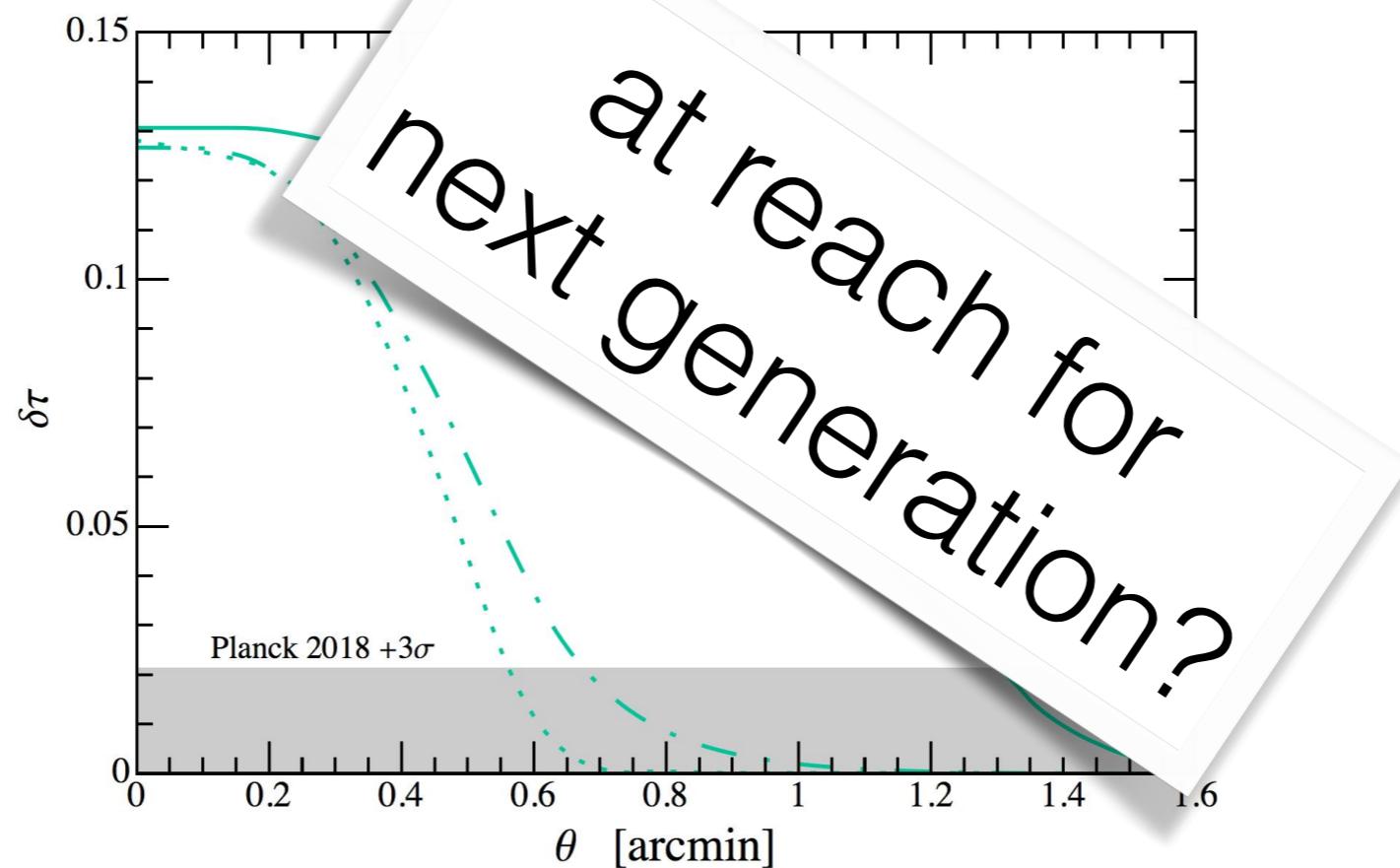
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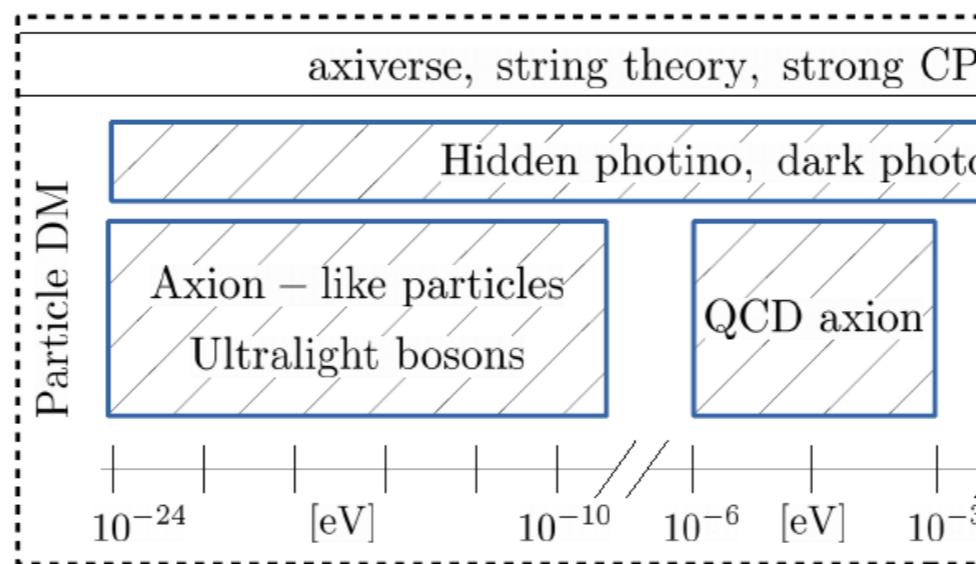
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Conclusions

- Rotational superradiance: unique handle into light bosons

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



- The cloud may blow for axions $g_a a \tilde{F}_{\mu\nu} F^{\mu\nu}$
 - This heats the local environment with (TBC) signatures in CMB observables for interesting ranges of g_a

Black hole PHOTON superradiance

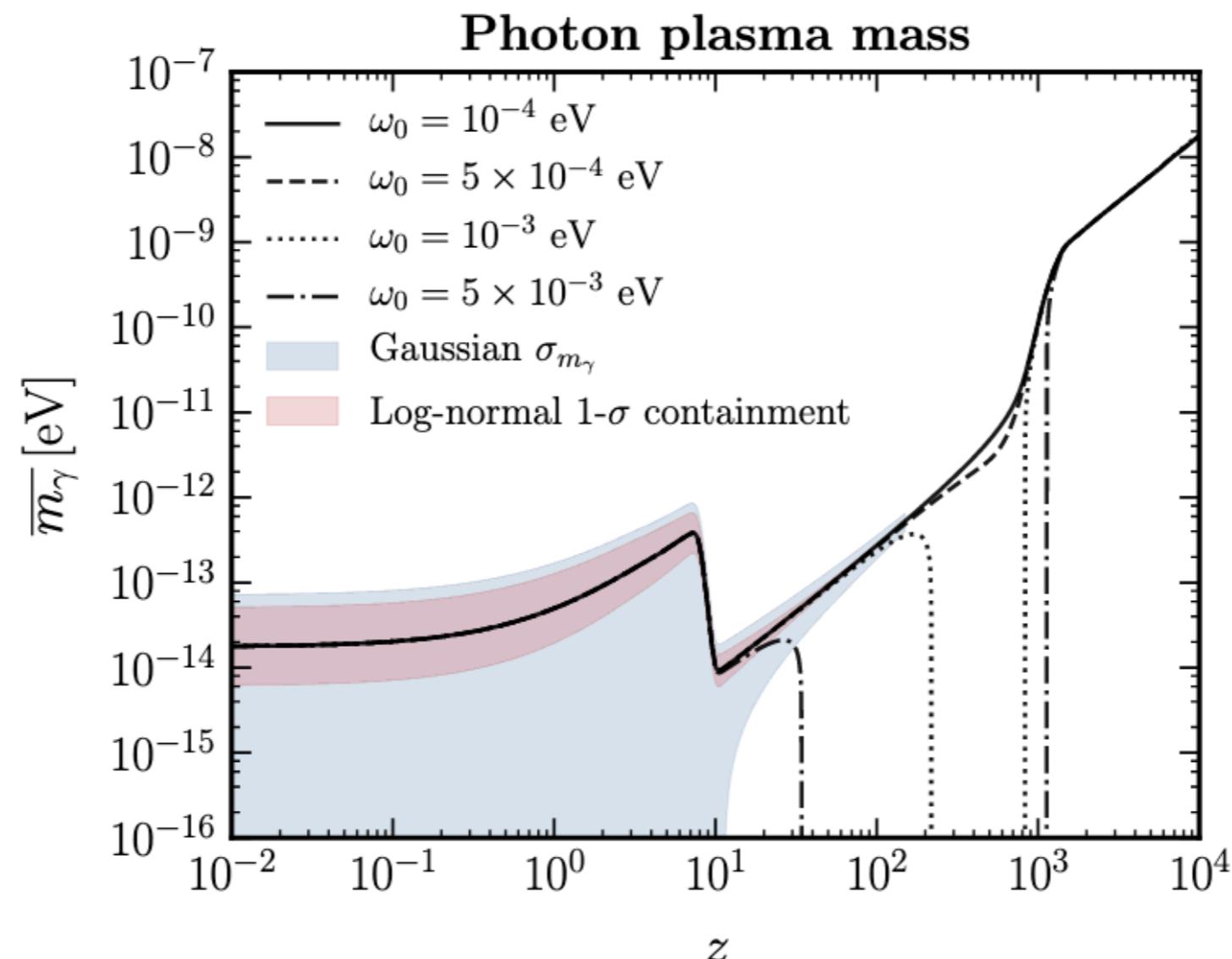
In the presence of a dilute plasma n_e

Pani, Loeb '13
Conlon, Herdeiro '17

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

in the inter-stellar medium

Caputo et al '20

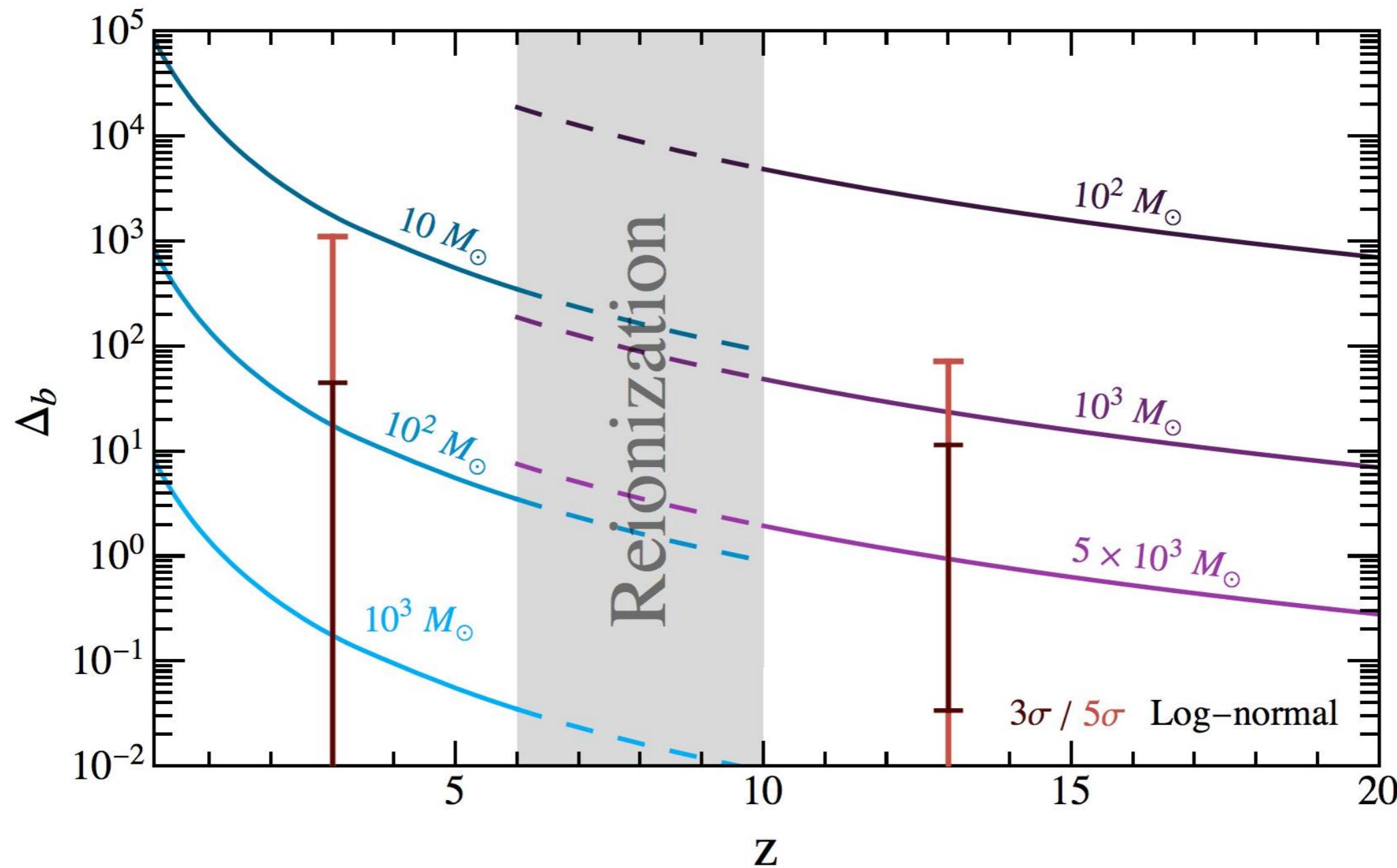


Black hole PHOTON superradiance

Blas, Witte '20

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

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



Black hole PHOTON superradiance II

does this really happen?

- (spinning) BHs typically do not live in the ISM, 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 ISM! (likely)

is that all?

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

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

not always applicable + SR photons and plasma electrons interact!

Quenching mechanisms of photon SR

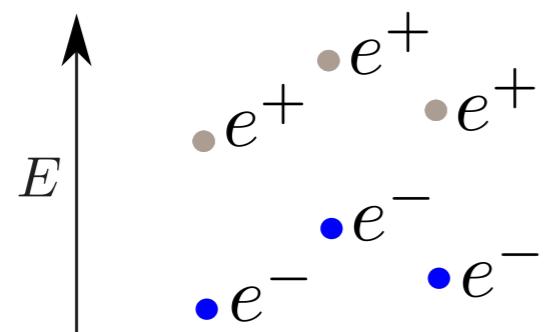
0) Thermal corrections or degeneracy negligible

Blas, Witte '20

i) Pair production

Fukuda, Nakayama '19

$$\rho_\gamma \sim 10^{36} \text{ eV/cm}^3$$



$$\Gamma = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{\pi m_e^2 n}{eE}}$$

extracted energy

$$E_{\max} \sim 10^{-10} \left(\frac{10^{-10} \text{ eV}}{m_\gamma} \right)^2 M$$

Cardoso et al '20

ii) Non-linear corrections

massless at

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

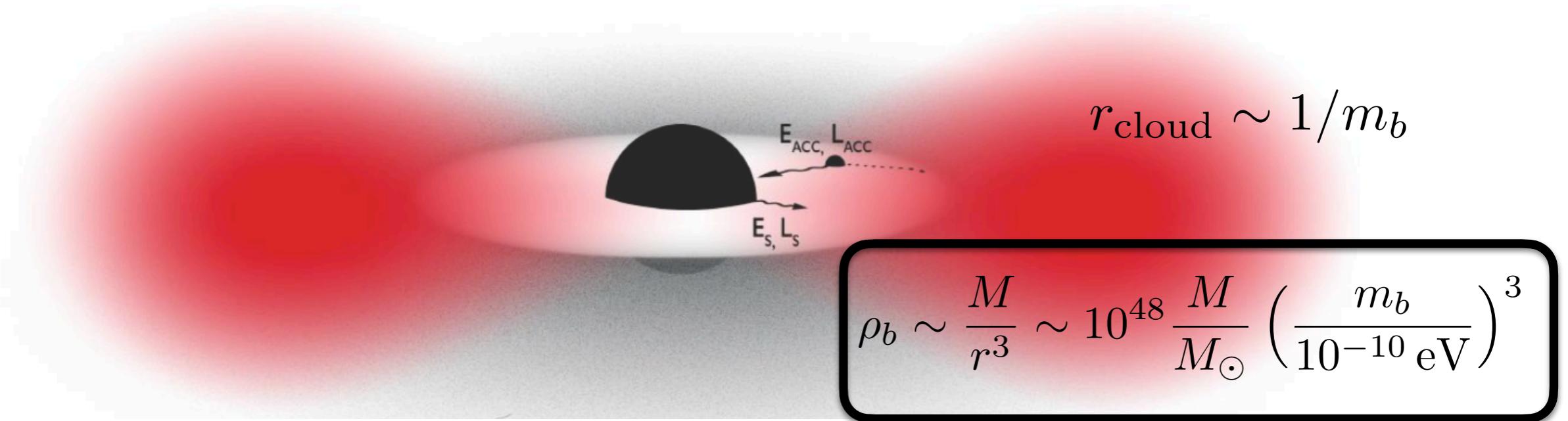
$$E \sim \sqrt{\rho_\gamma} \sim \sqrt{\omega_p n_\gamma} \gtrsim m_e \omega_p / e$$

$$\rho_\gamma \sim 10^2 \text{ eV/cm}^3$$

Black hole superradiance II

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Brito, Cardoso Pani 1501.06570 [gr-qc]



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Quenching mechanisms of photon SR I

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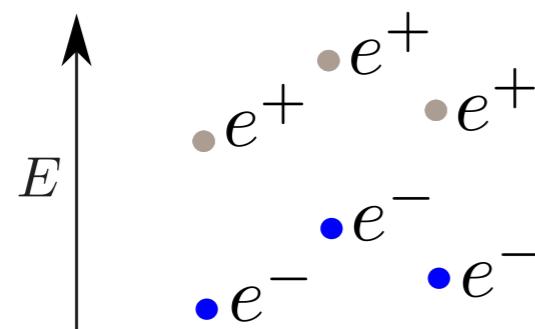
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Cardoso et al '20

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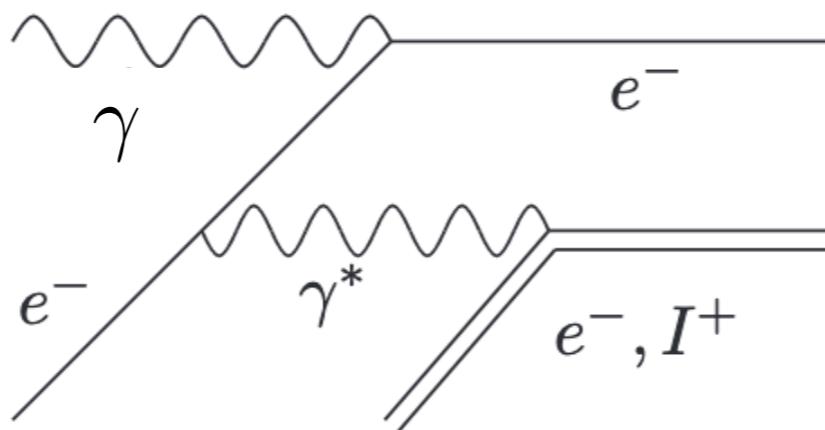
Quenching mechanisms of photon SR II

iii) Heating of neutral hydrogen

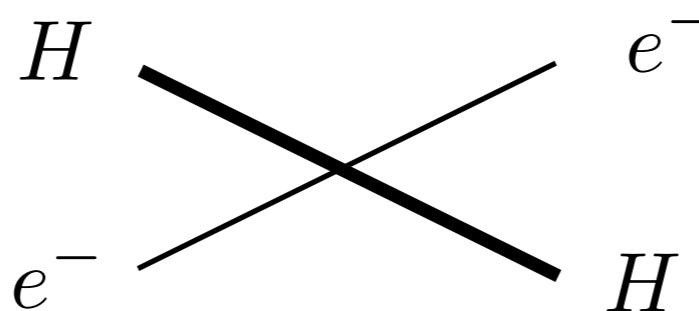
Blas,Witte '20



free-free scattering heats e^- to 10^4 K!



but the collisional excitation to heat H is never efficient!



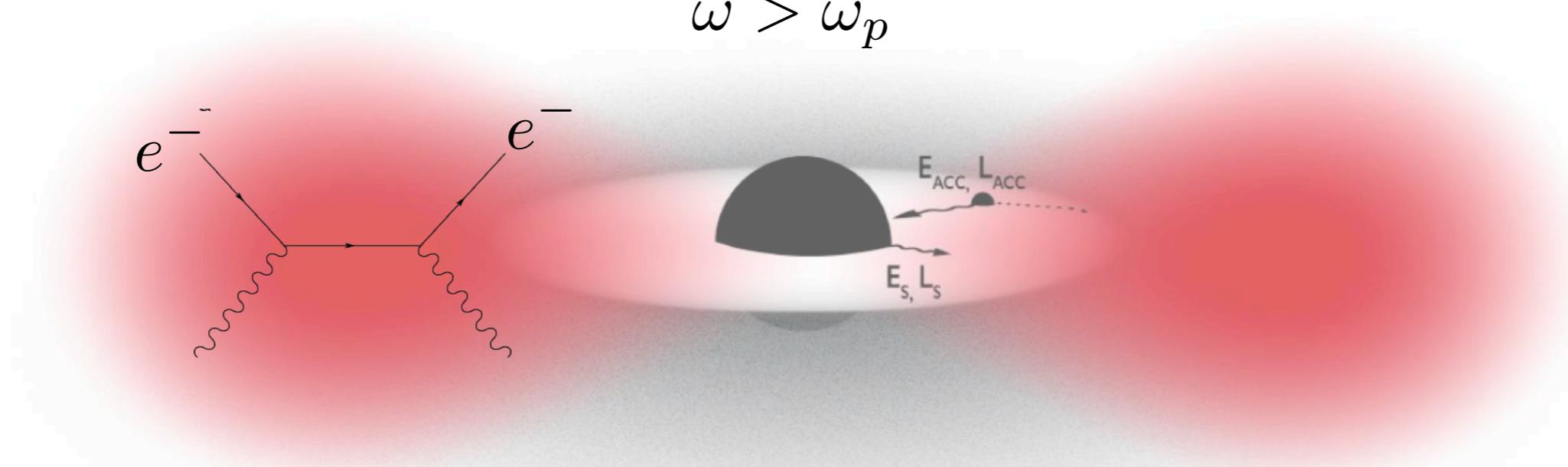
Quenching mechanisms of photon SR III

iv) The role of scattering

Blas,Witte '20

the hot electrons may upper-scatter the cloud!

$$\omega > \omega_p$$



these more energetic photons won't be bounded!

again, not a problem!

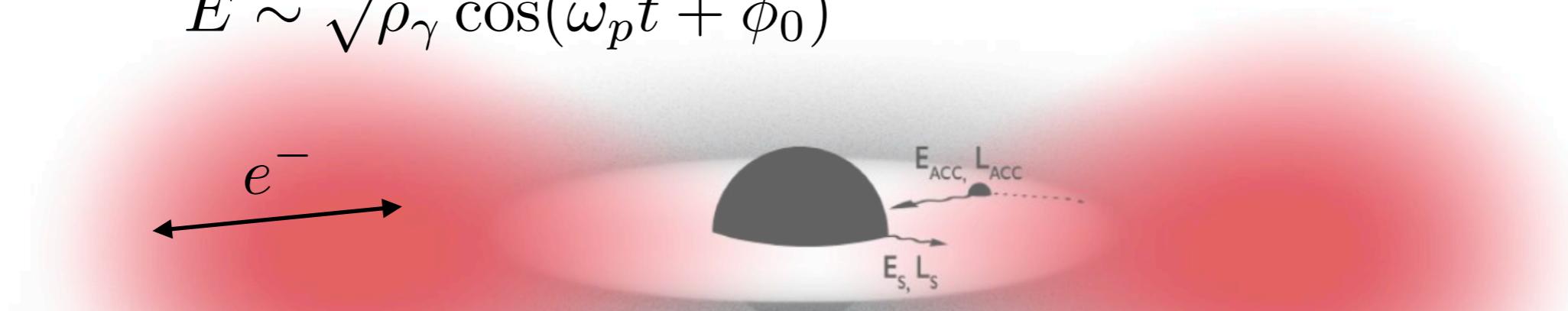
Quenching mechanisms of photon SR IV

v) Energy loss by accelerating e^-

Blas, Witte '20

the cloud has huge electric and magnetic fields!

$$E \sim \sqrt{\rho_\gamma} \cos(\omega_p t + \phi_0)$$



$$\langle \gamma \rangle \sim \sqrt{\rho}/(m_e m_\gamma)$$

This energy comes from the electric field of the cloud

$$\frac{dE_\gamma^{acc}}{dt} = \frac{dE_\gamma^{sr}}{dt} \rightarrow \rho_\gamma^{eq} \sim 10^{19} \frac{m_\gamma}{10^{-13} \text{ eV}} \text{ eV/cm}^3 \ll \rho_\gamma^{\text{pair}} \ll \rho_\gamma^{\text{sr}}$$

This stops the growth and generates high energy photons! (TBC)

$$L \sim 5 \times 10^{48} \left(\frac{10^{-13} \text{ eV}}{m_\gamma} \right) \frac{\text{eV}}{\text{s}}$$

Quenching mechanisms of photon: Verdict

Point ii) wins!!

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

BUT maybe for other light bosons v) is more efficient

$$\frac{dE_{\gamma}^{acc}}{dt} = \frac{dE_{\gamma}^{sr}}{dt}$$

Ultra-light (fuzzy) DM: the simplest DM?

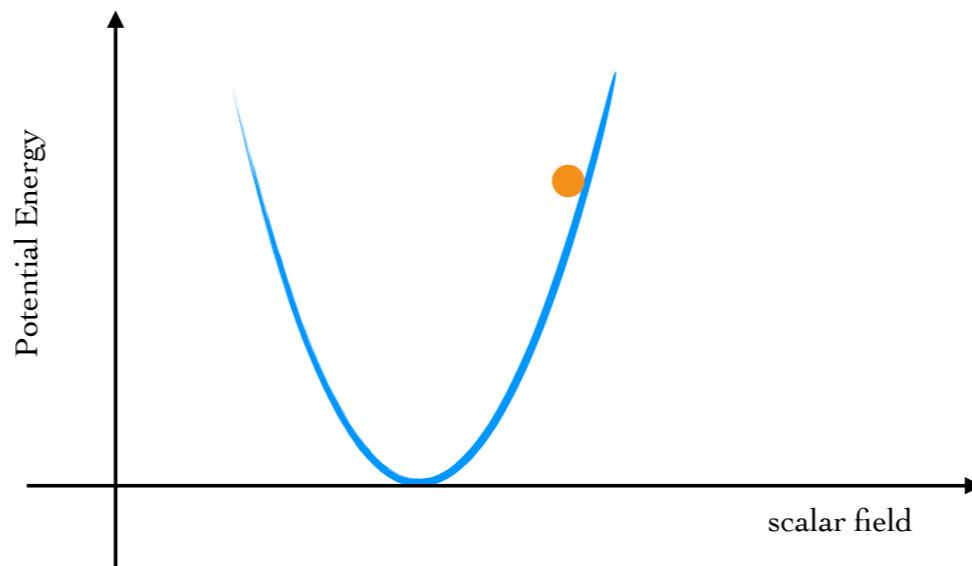
Massive scalar case $\phi(x, t)$

$$\square\phi(x, t) + m^2\phi(x, t) = 0$$

Initial conditions set by early universe:
phase transition/inflation yields a very homogeneous configuration

$$\ddot{\phi} + H\dot{\phi} + m^2\phi = 0$$

$$m \ll H$$



$\phi_0 \sim f_a$ high-energy scale

$$m \sim \frac{\Lambda}{f_a} M_{\text{Pl}} e^{-S}$$

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