Superradiance, Hawking Radiation, and Primordial Black Holes as Dark Matter

James Dent
Sam Houston State University

Corfu, September 8, 2023

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with collaborators Bhaskar Dutta and Tao Xu

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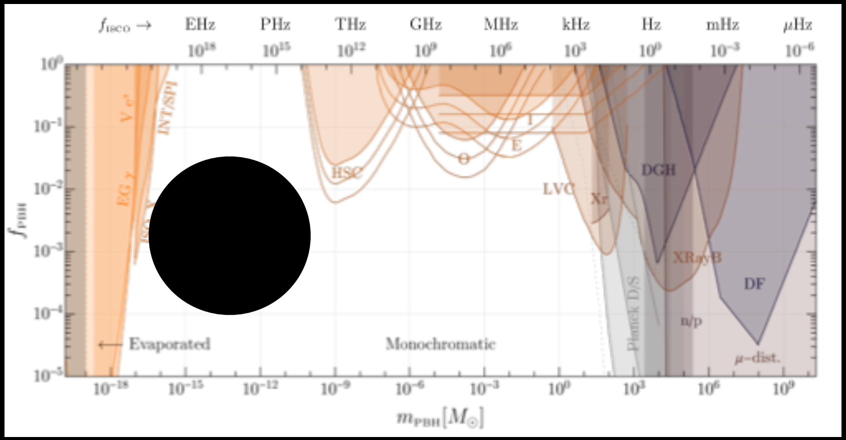
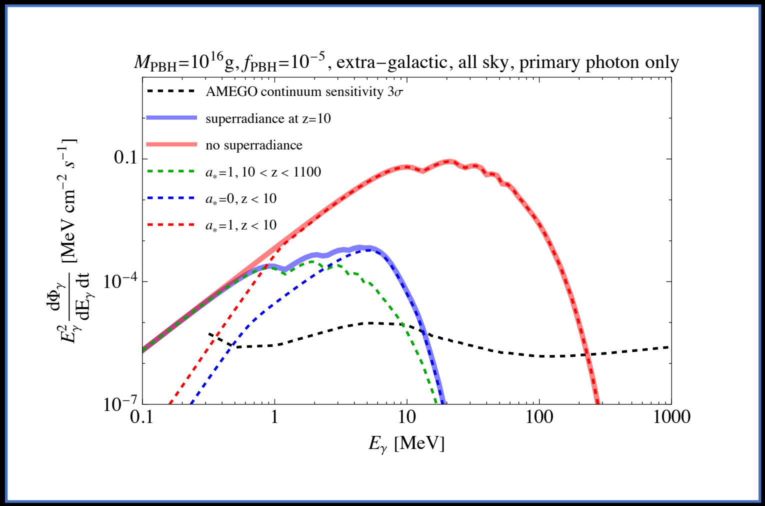
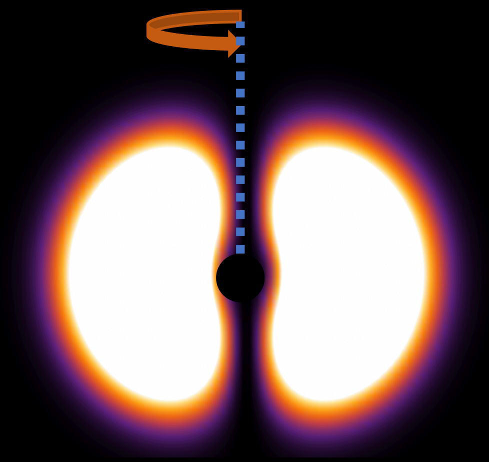
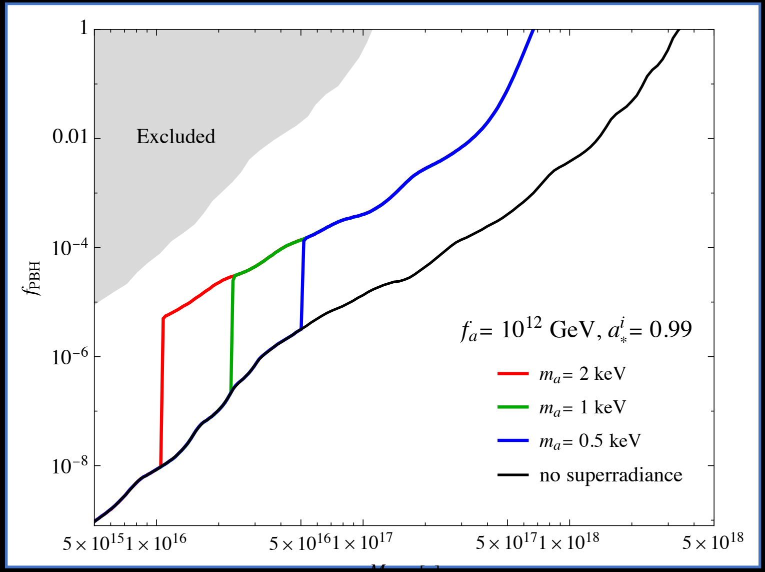


EHz
PHz
THz
GHz
MHz
kHz
Hz
mHz
μHz
HSC
LVC
Xr
DGH
XRayB
DF
n/p
μ-dist.
Evaporated
Monochromatic
$m_{\rm PBH}[M_\odot]$
$f_{\rm PBH}$



$M_{\rm PBH}$=10^{16}g, $f_{\rm PBH}$=10^{-5}, extra−galactic, all sky, primary photon only
AMEGO continuum sensitivity 3σ
superradiance at z=10
no superradiance
a_*=1, 10 < z < 1100
a_*=0, z < 10
a_*=1, z < 10
$E_\gamma^2 \frac{d\Phi_\gamma}{dE_\gamma dt}$ [MeV cm^{-2} s^{-1}]
E_γ [MeV]





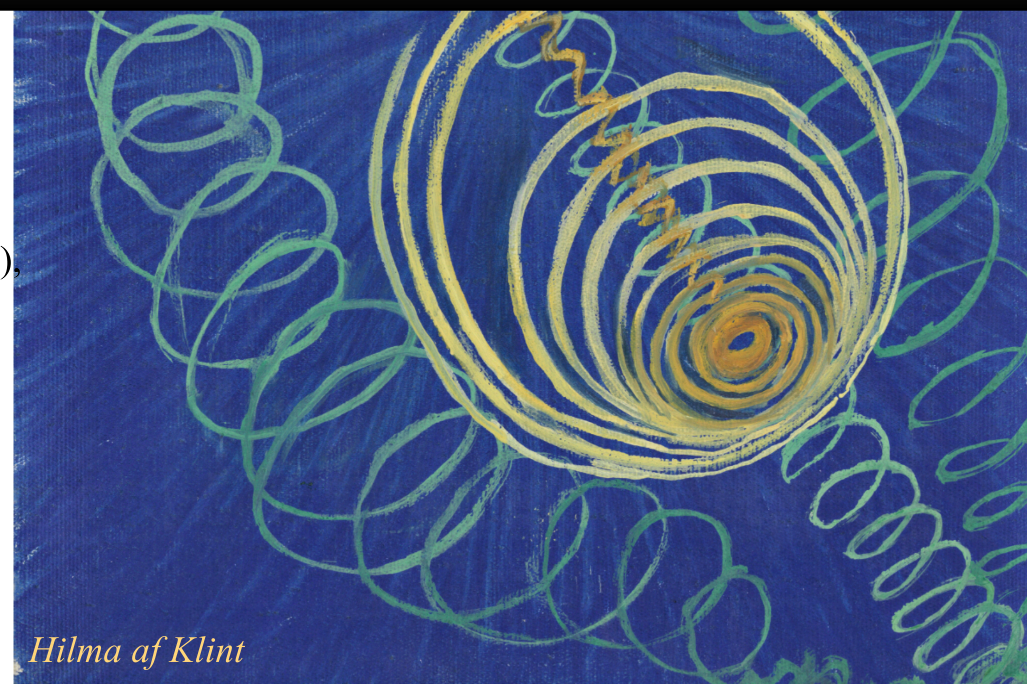
Excluded
$f_{\rm PBH}$
f_a= 10^{12} GeV, a_*^i= 0.99
m_a= 2 keV
m_a= 1 keV
m_a= 0.5 keV
no superradiance

Outline

Some Background

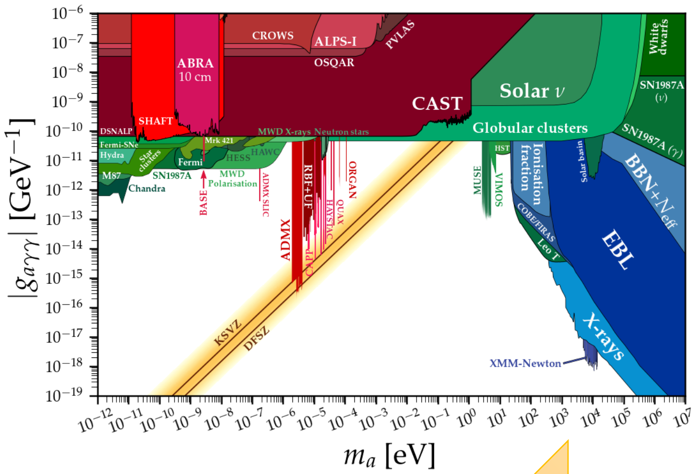
Primordial Black Holes

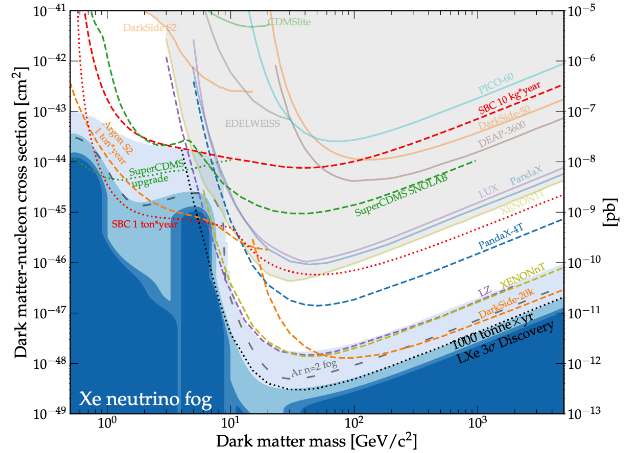
Y.B.Zel'dovich and I.D.Novikov, Soviet Astronomy **10** (1967)
S.Hawking, Mon.Not.Roy.Astron.Soc. **152** (1971)
B.J.Carr and S.W.Hawking, Mon.Not.Roy.Soc. **168** (1974),
B.J.Carr, Astrophys.J. **201** (1975)

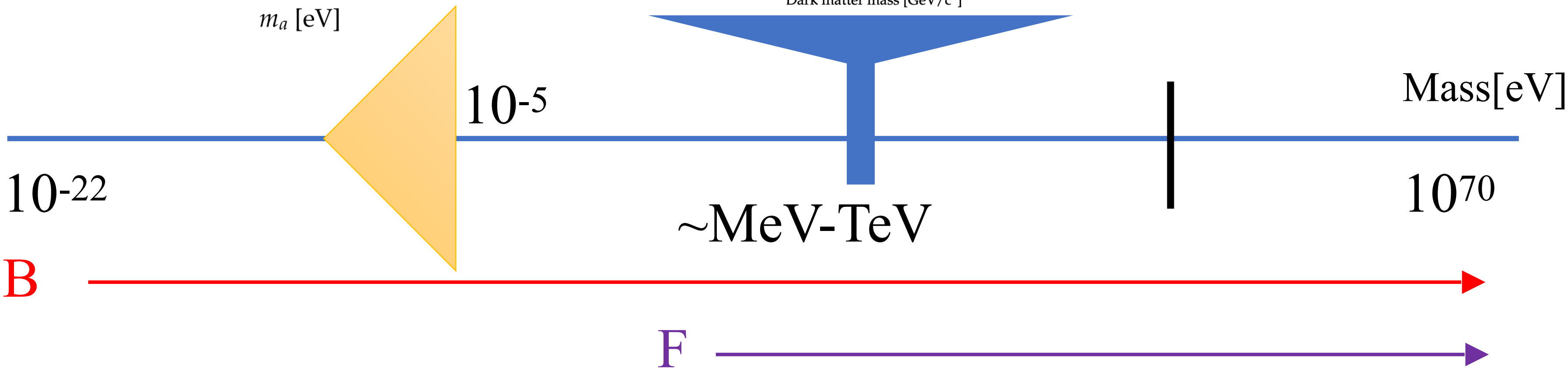


Hilma af Klint

DM Mass – an enormous range of possibilities







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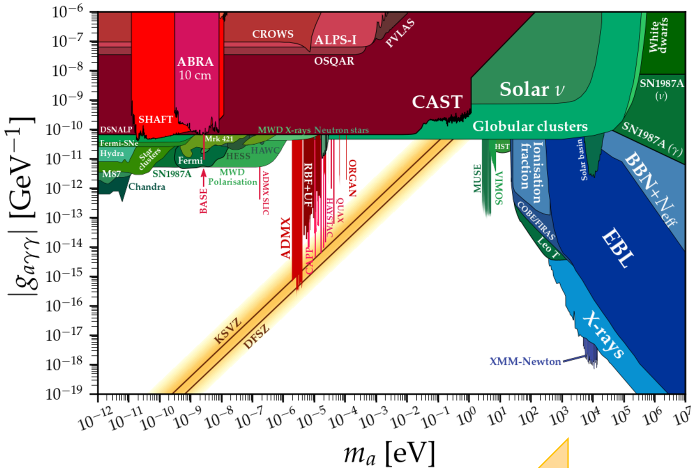
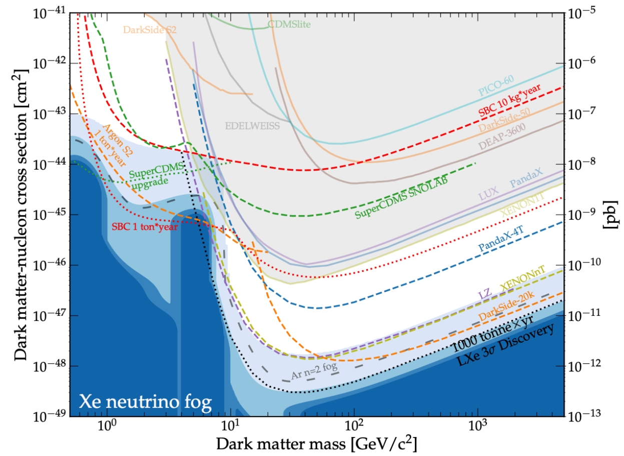
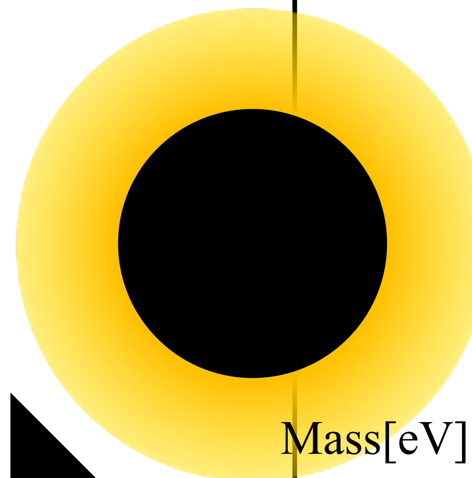
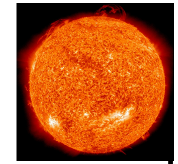








10^{-5}

Mass[eV]

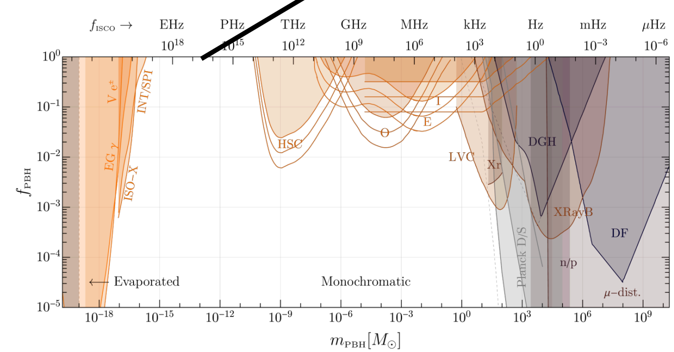
10^{-22}

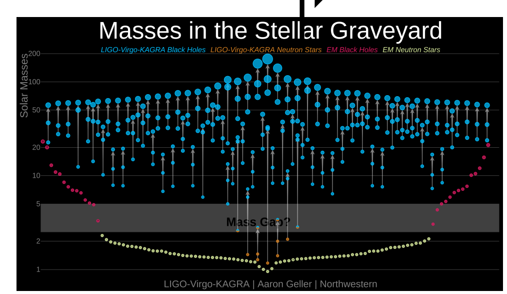
~MeV-TeV

10^{70}

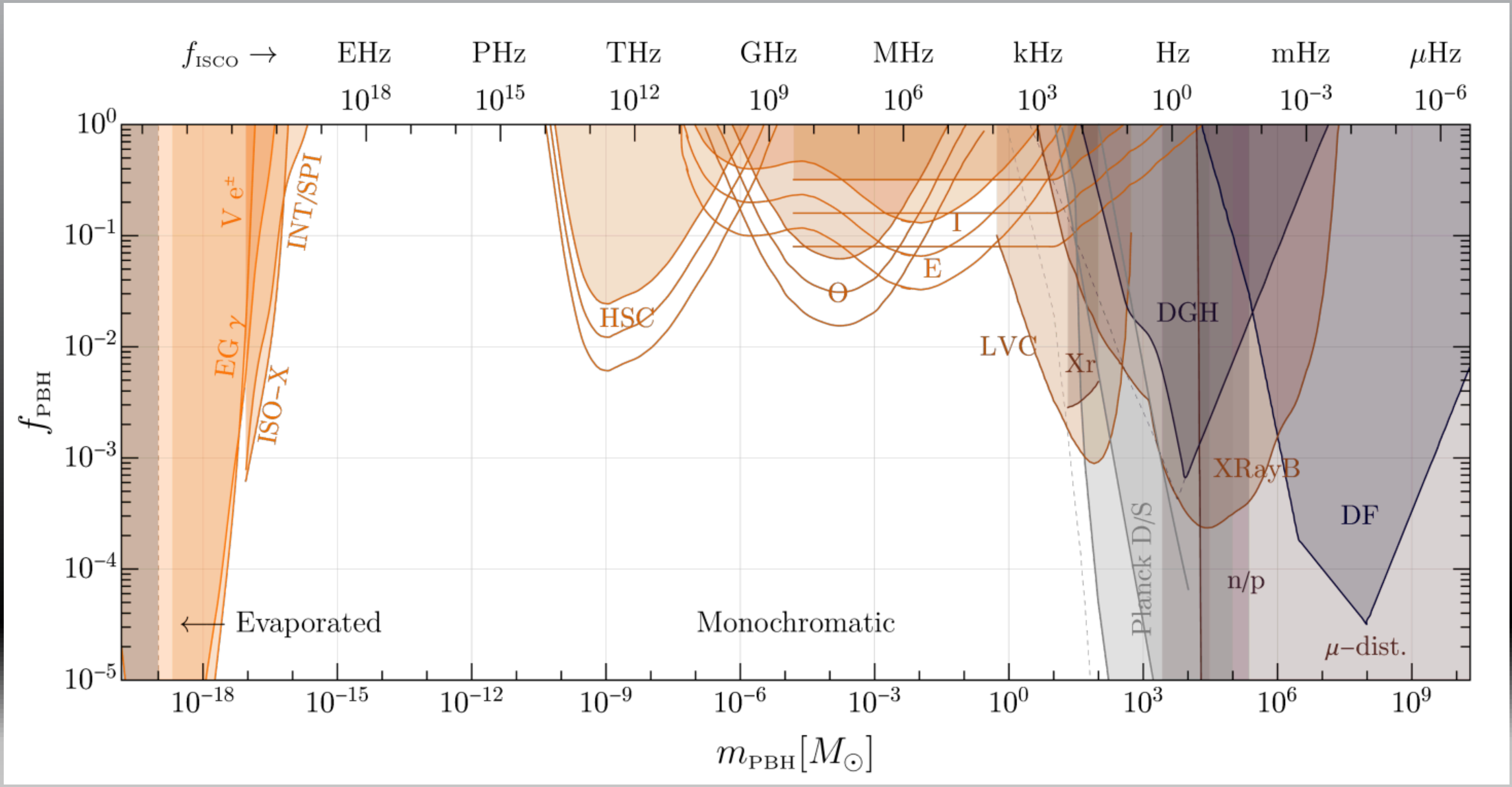
B

F





PBH –DM mass fraction



G.Franciolini, A.Maharana, and F.Muia, 2205.02153, constraints based on
B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, Rept.Prog.Phys. (2021), 2002.12778

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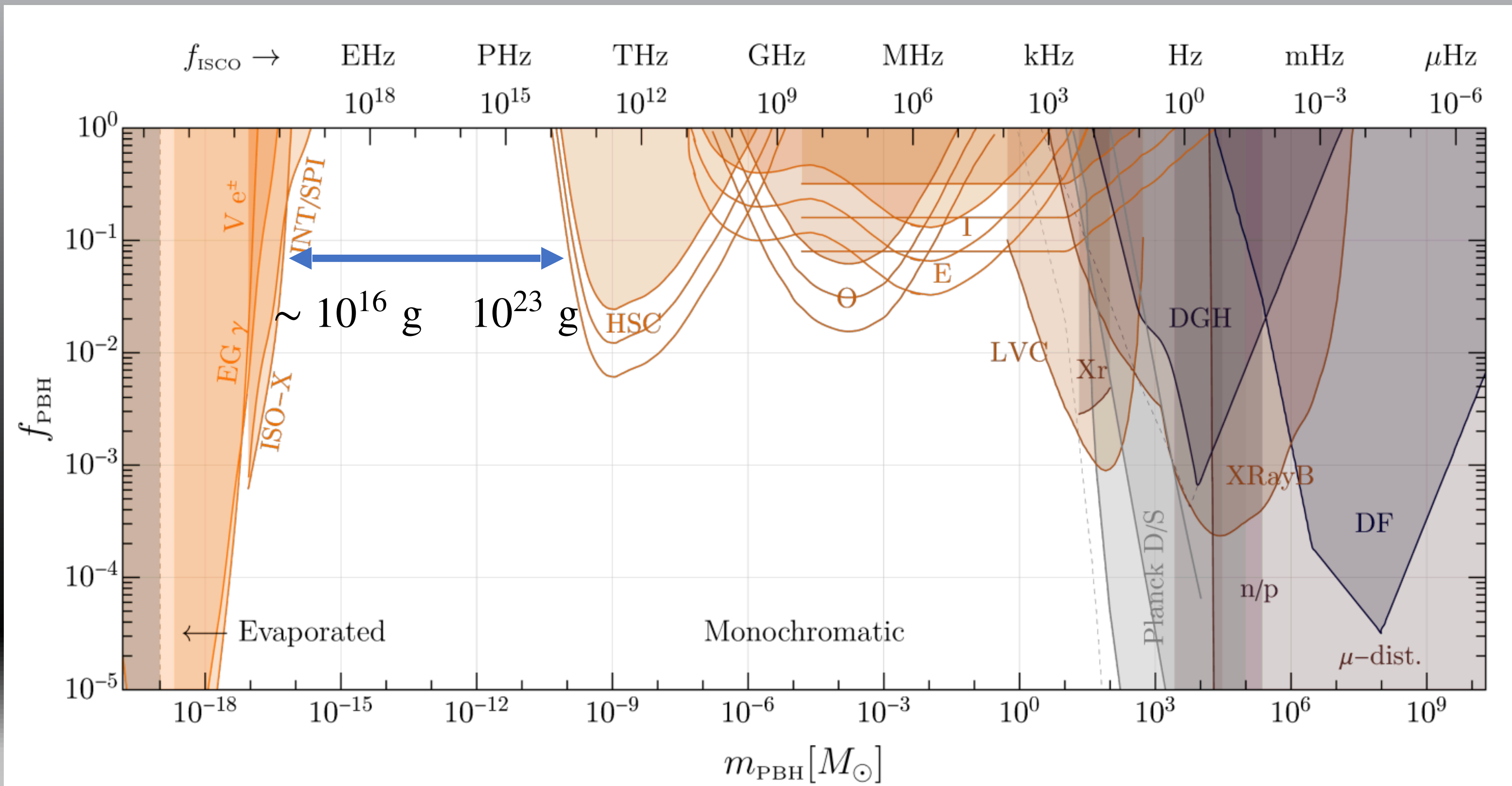

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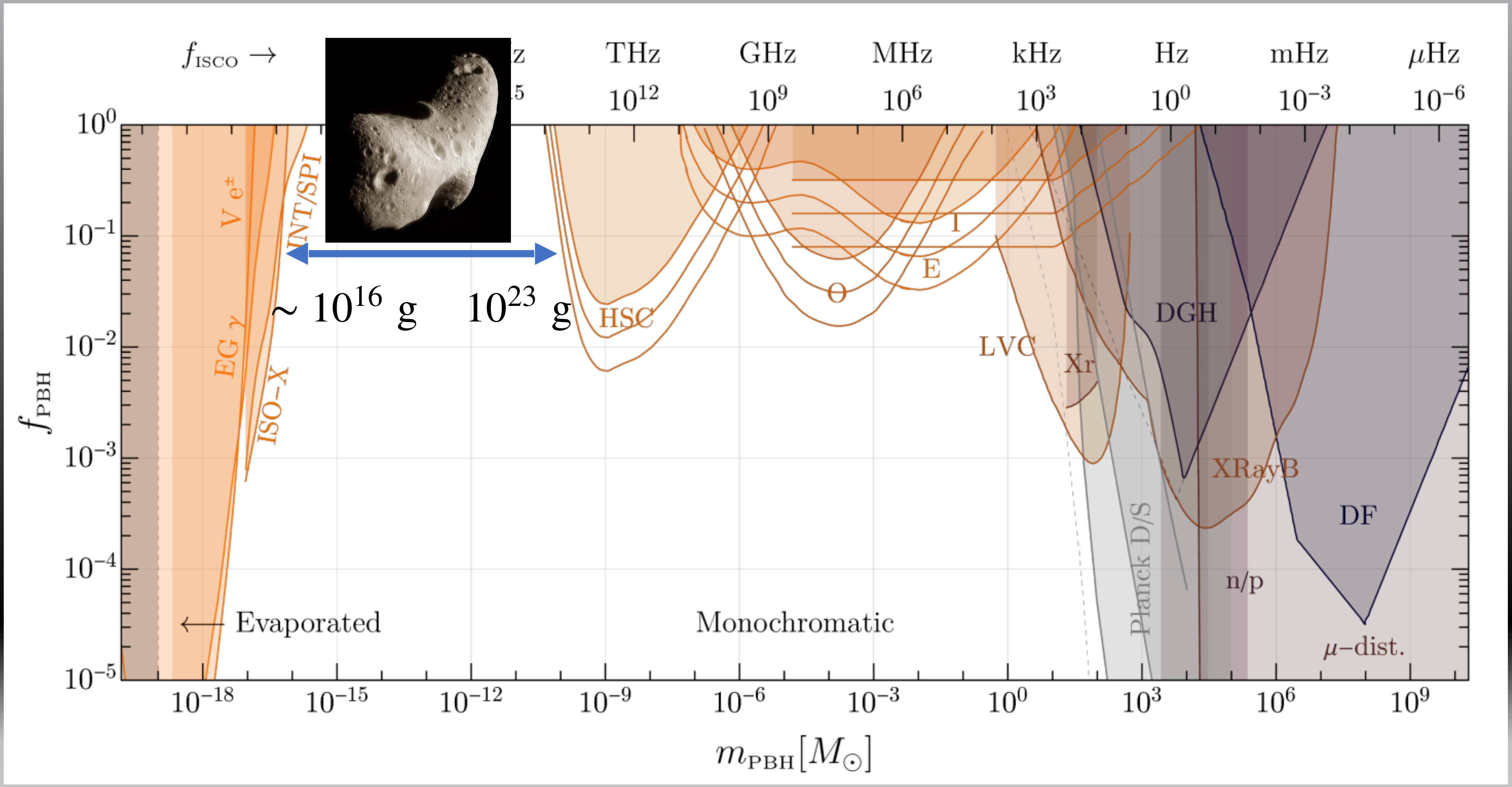

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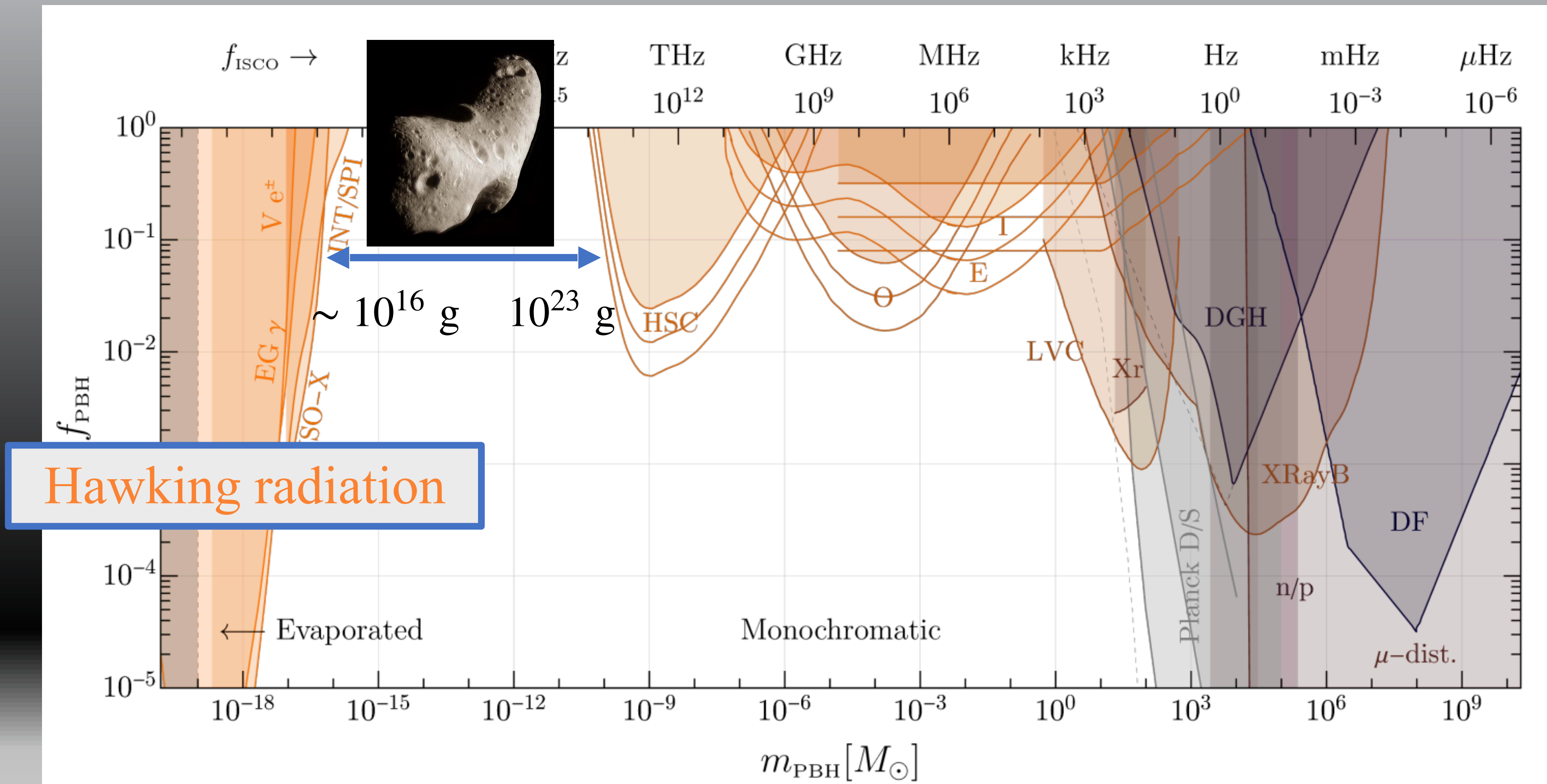

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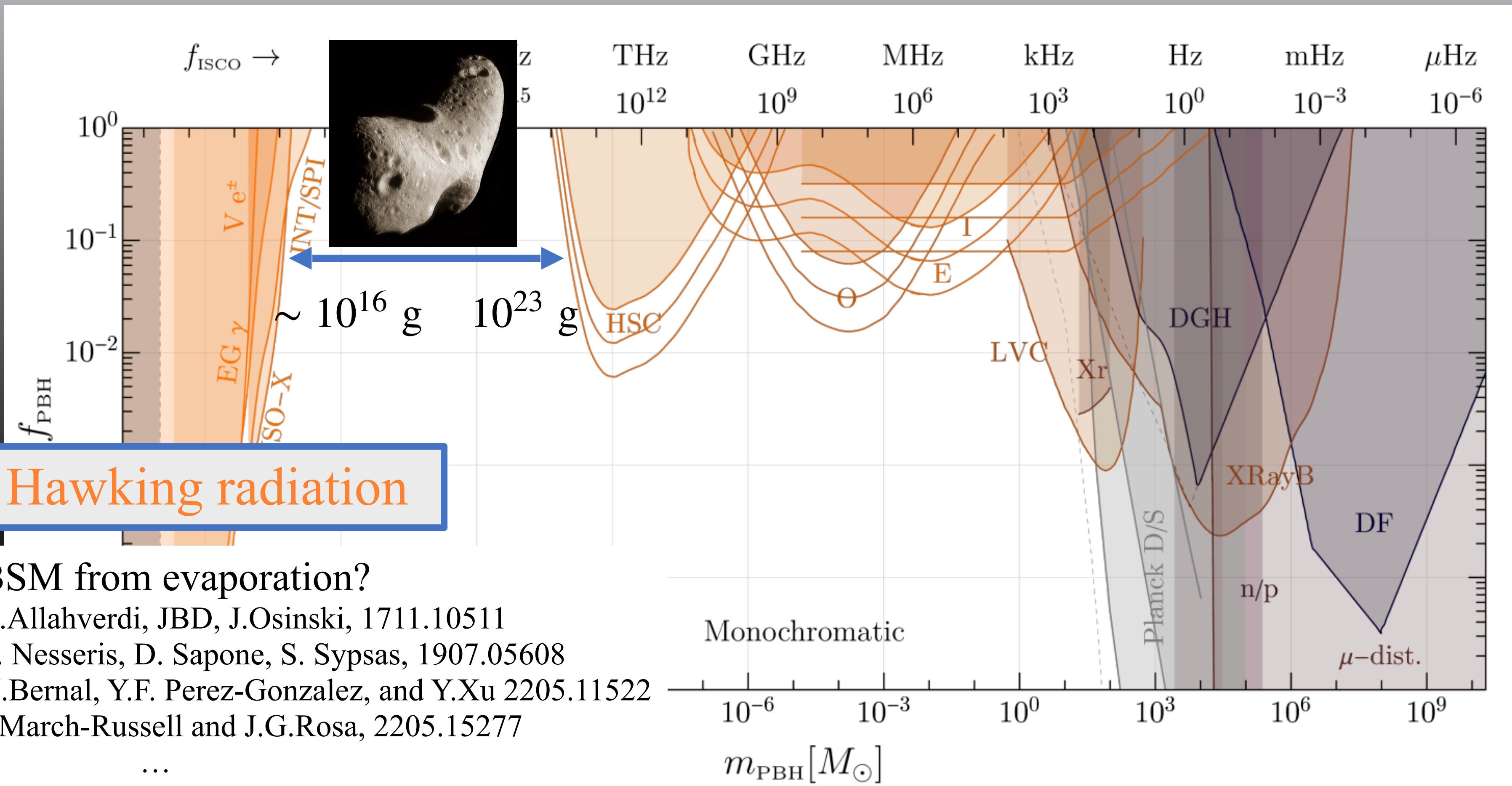

Hawking radiation

BSM from evaporation?

R.Allahverdi, JBD, J.Osinski, 1711.10511

S. Nesseris, D. Sapone, S. Sypsas, 1907.05608

N.Bernal, Y.F. Perez-Gonzalez, and Y.Xu 2205.11522

J.March-Russell and J.G.Rosa, 2205.15277

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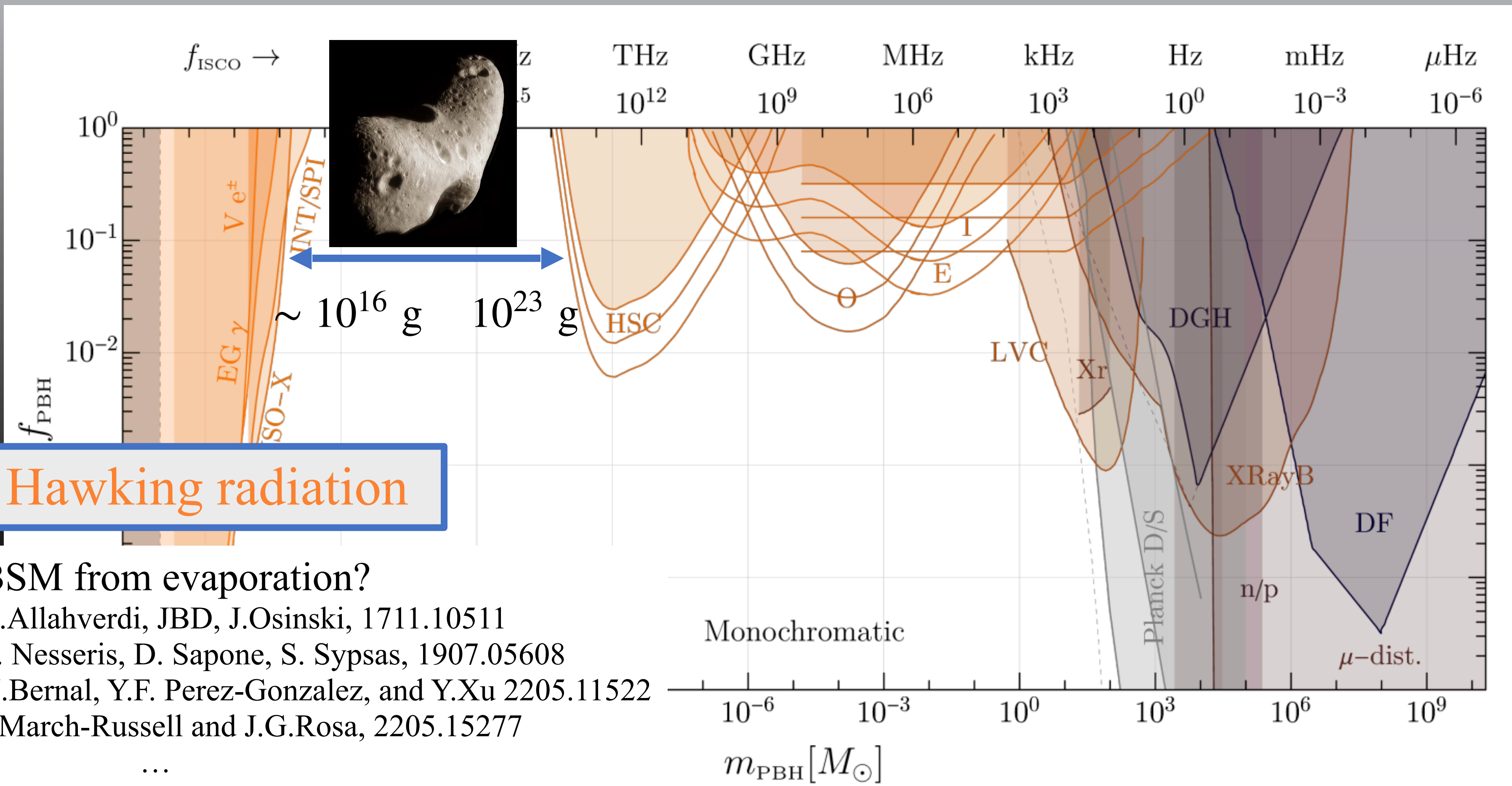

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See talk by C. Tzerefos

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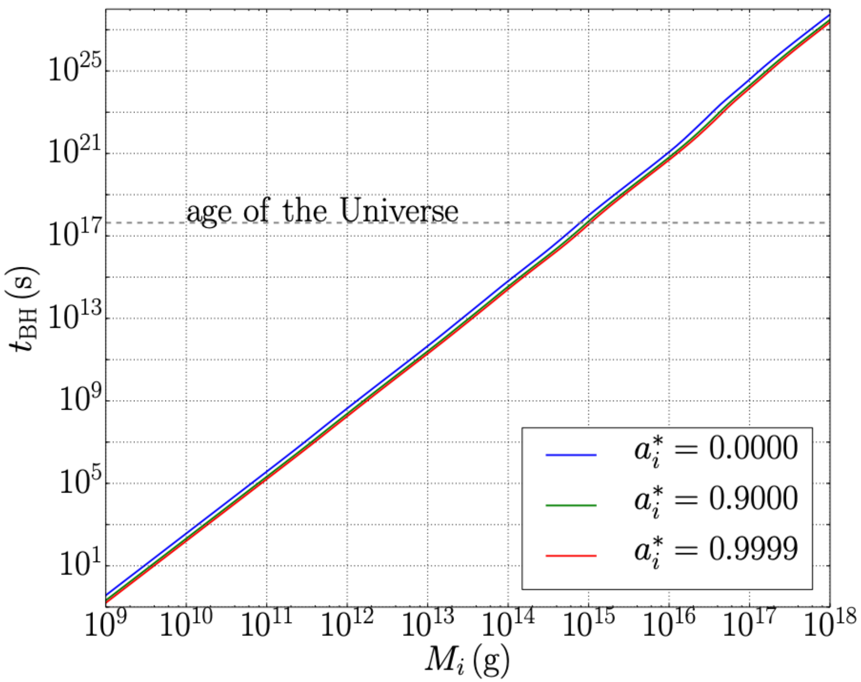
Survival to the Present

$m_{\rm BH} \gtrsim 10^{15}$ g

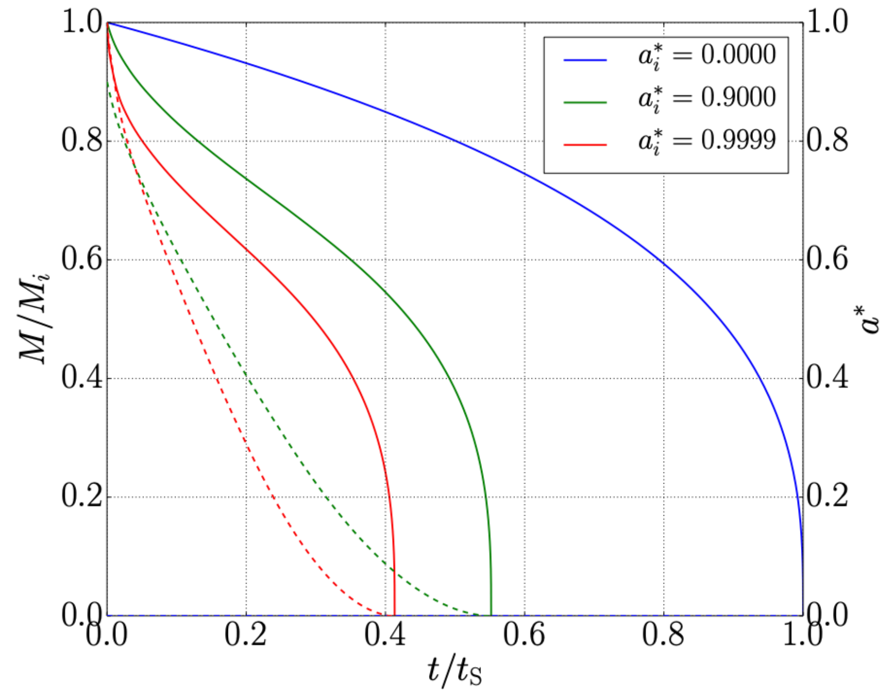


BBN : $M_{PBH} \simeq 3 \times 10^9$ g

CMB : $M_{PBH} \simeq 6.7 \times 10^{13}$ g

A.Arbey & J.Auffenger, MNRAS (2020) 1906.04196

Black Hole Evolution



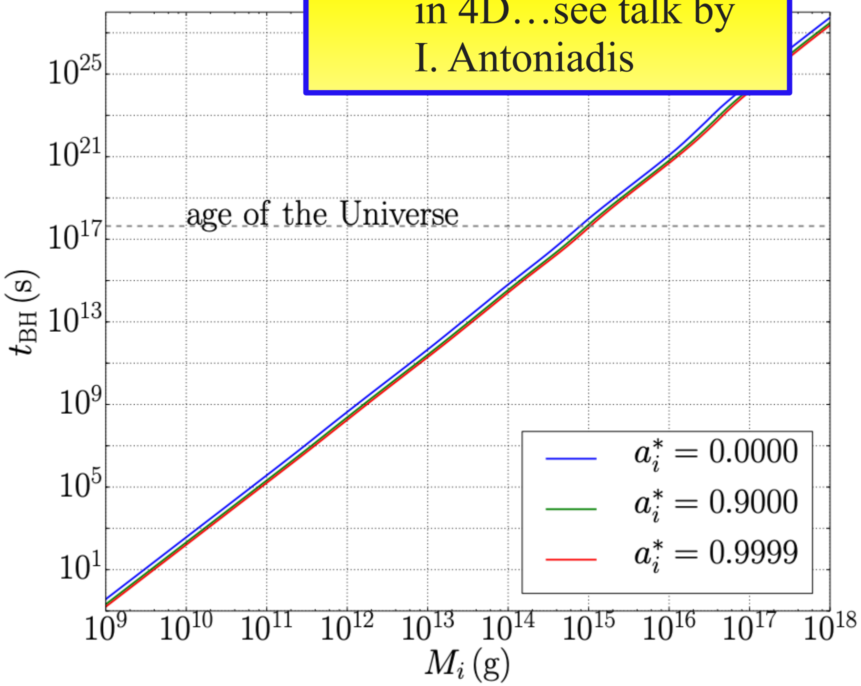
Spin alters fate

$$T = \frac{1}{4\pi M} \frac{\sqrt{1 - a_*^2}}{\left(1 + \sqrt{1 - a_*^2}\right)}$$

Survival to the Present

$m_{\rm BH} \gtrsim 10^{15}$ g

in 4D…see talk by I. Antoniadis



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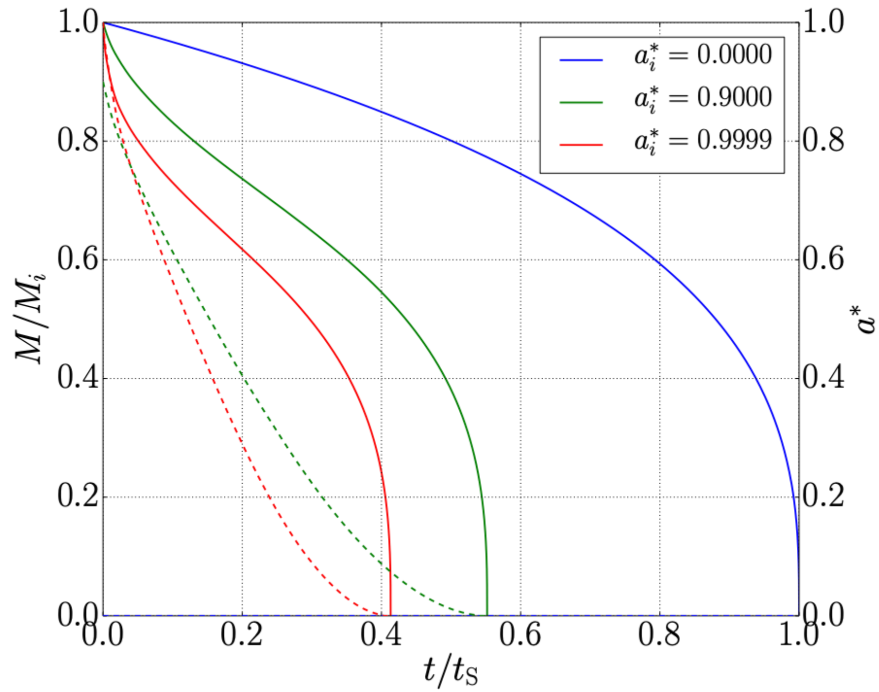
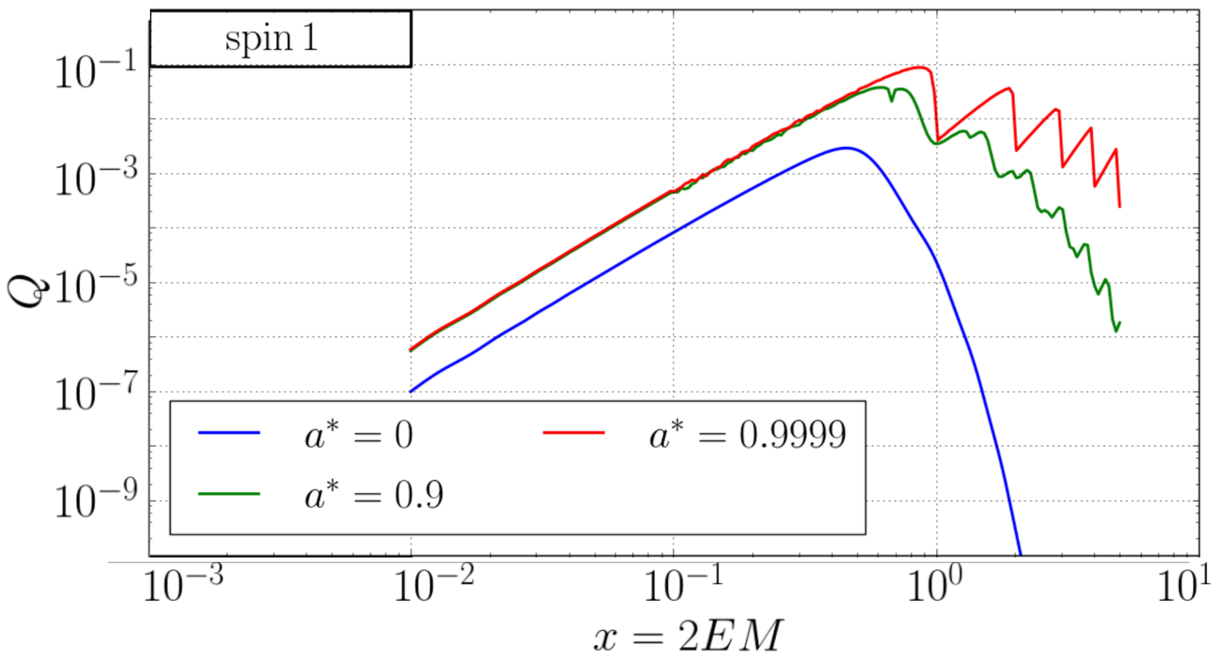


Spin alters fate

$$T = \frac{1}{4\pi M} \frac{\sqrt{1-a_*^2}}{\left(1+\sqrt{1-a_*^2}\right)}$$

Hawking Radiation

$$\frac{d^2 N_i}{dt\,dE} = \sum_{\text{dof}} \frac{\Gamma_i(E, M, x_j)/2\pi}{e^{E'(E,x_j)/T} - (-1)^{2s_i}}$$

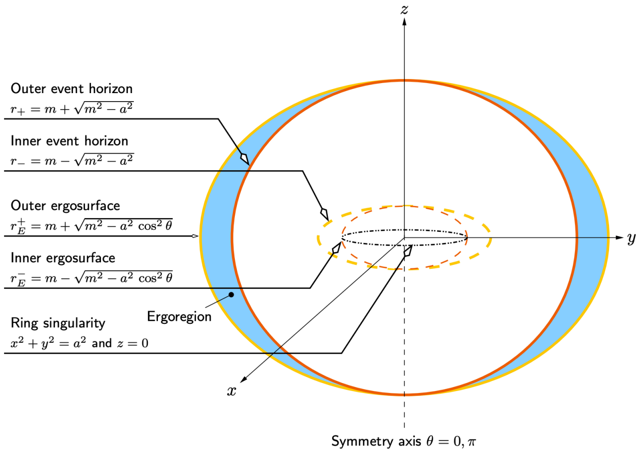


Spin alters fate

BlackHawk v2.0

A.Arbey & J.Auffinger, ICHEP2020 2012.14767, and Eur.Phys.J.C (2021) 2108.02737

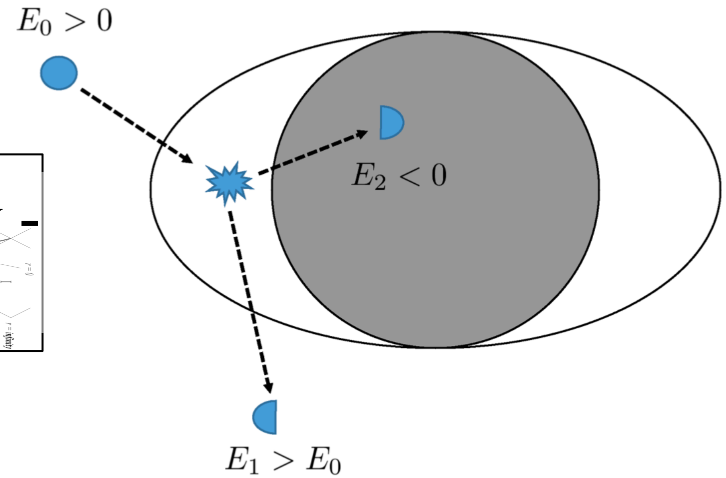
Superradiance - Boson Production



M.Visser, 0706.0622

Penrose process – energy and angular momentum extraction

Kerr geometry - ergoregion



R.Brito, V.Cardoso, and P.Pani, 1501.06570

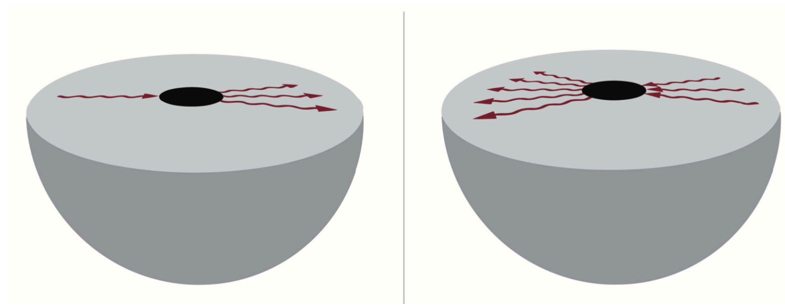
GENERATION OF WAVES BY A ROTATING BODY

Ya.B. Zel'dovich
Institute of Applied Mathematics, USSR Academy of Sciences
Submitted 9 July 1971
ZhETF Pis. Red. 14, No. 4, 270 - 272 (20 August 1971)

In this case the additional term in the wave equation inside the rotating body (under its surface) is equal to

$$\psi a \gamma (i\omega + \frac{i\beta n c}{r} (\psi = \psi i a \gamma(\omega + n\Omega)$$

Consequently, the additional term reverses sign at $n\Omega < -\omega$, where $n < 0$ and $|n| > \omega/\Omega$. The medium operates effectively as an amplifier and not as an absorber with respect to waves with such values of n.



LETTERS TO NATURE

PHYSICAL SCIENCES

Floating Orbits, Superradiant Scattering and the Black-hole Bomb

We now consider a w
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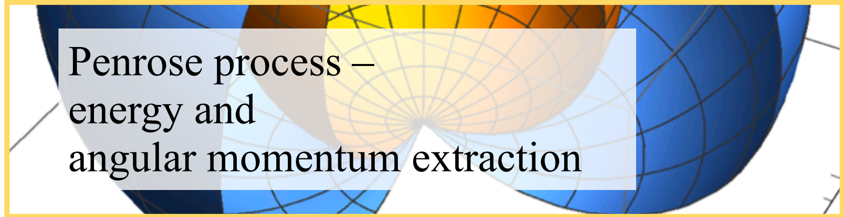
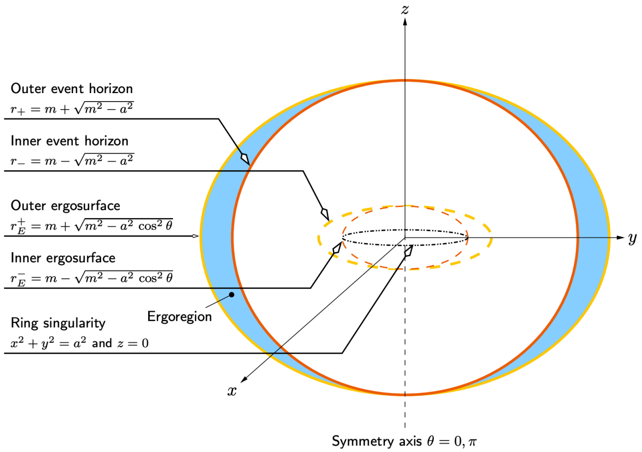
W.H. Press and S.A. Teukolsky, *Nature* **238** (1972)

Penrose process – energy and angular momentum extraction





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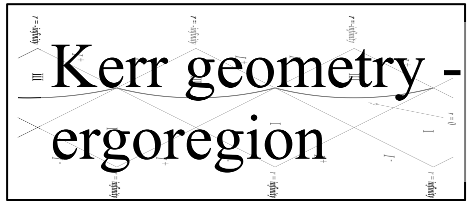
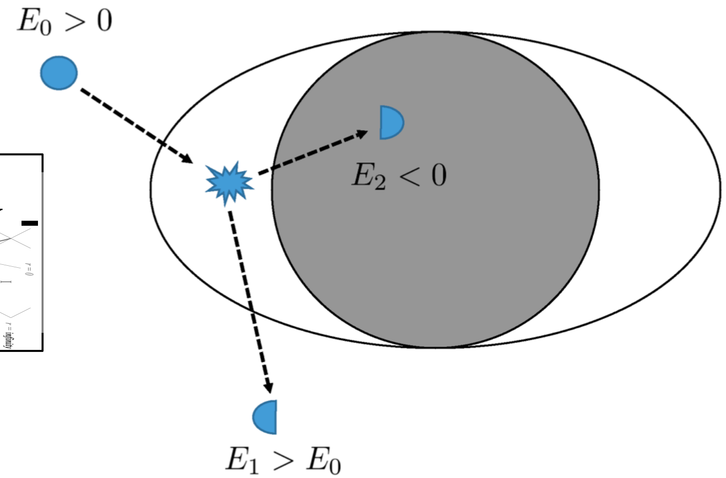
Kerr geometry - ergoregion





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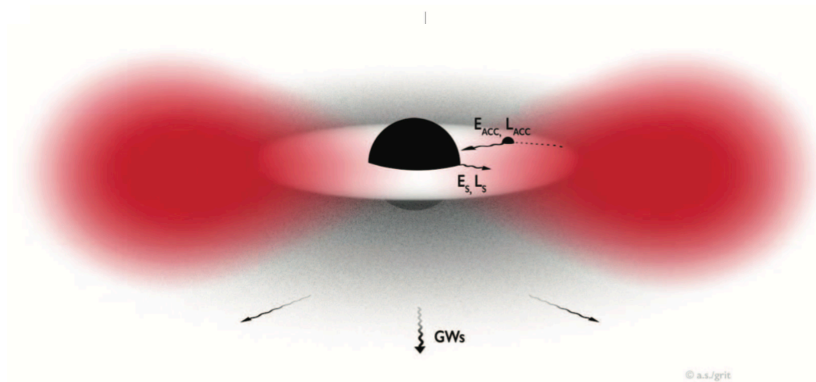

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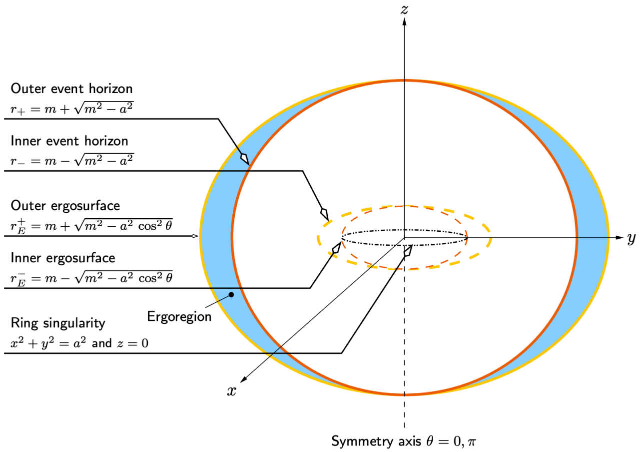
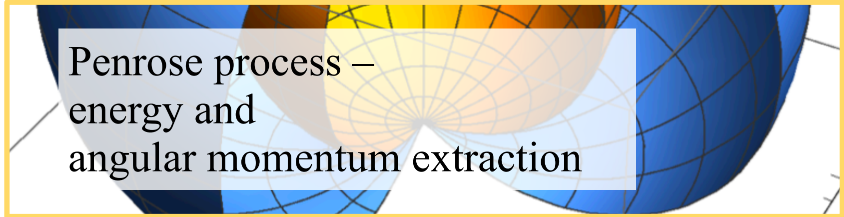
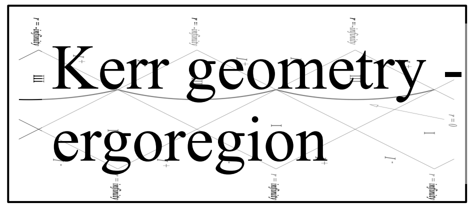
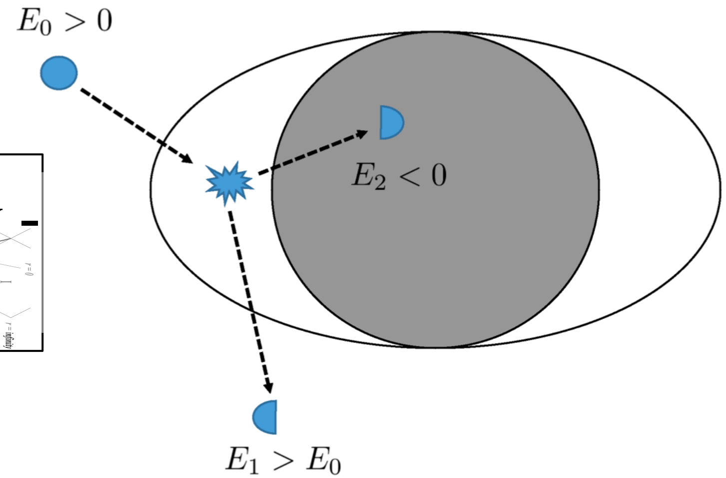


M.Visser, 0706.0622







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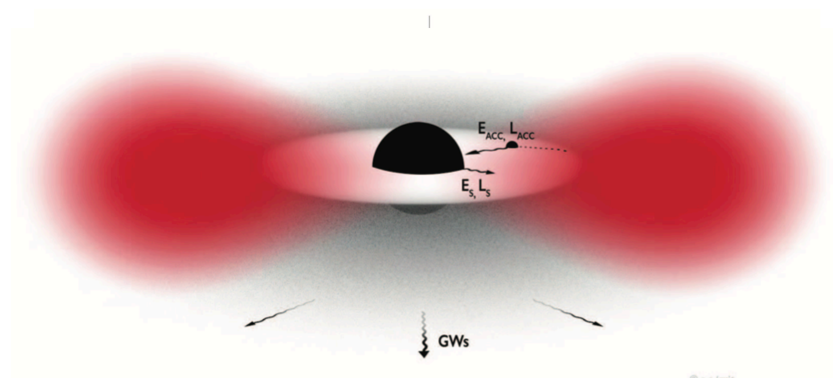
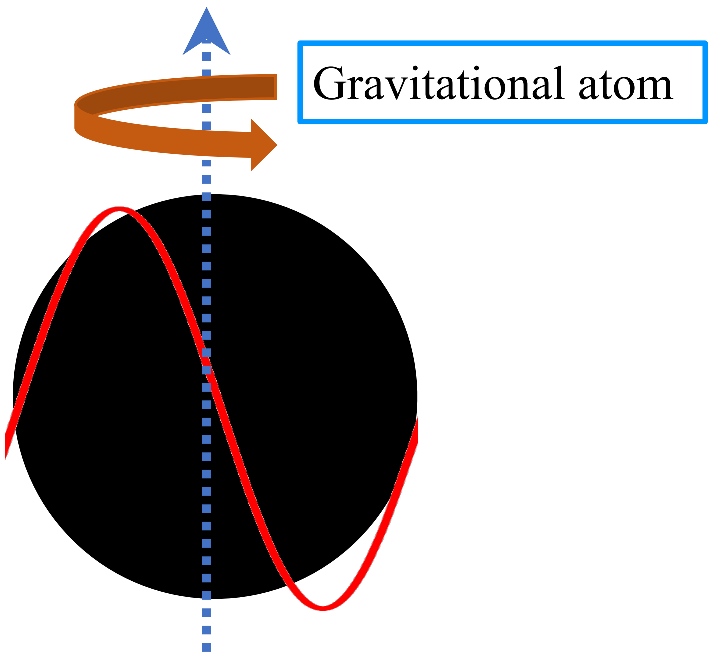


R.Penrose, *Riv.Nuovo Cim.* (1969), Y.B. Zel'dovich, *Pis'ma Zh. Eeksp. Teor. Fiz.* **14** [JETP Lett. **14** (1971)], Misner, C. W., Phys. Rev. Lett., 28, 994 (1972), T. Damour, N. Deruelle, and R. Ruffini, Lett.Nuovo Cim. **15** (1976), S.L. Detweiler, PRD **22** (1980), S.R.Dolan, PRD **76** (2007), A.Arvanitaki, S.Dimopoulos, S.Dubovsky, N.Kaloper, and J.March-Russell, 0905.4720, R.Brito, V.Cardoso, and P.Pani, *Lect.Notes Phys.* (2015), 1501.06570 ……

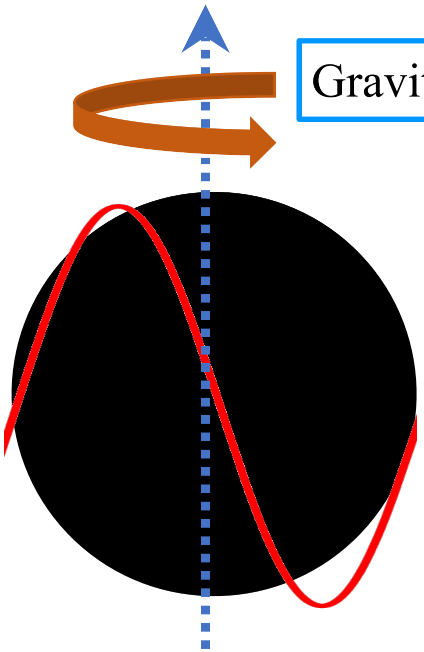
Superradiance - mechanism



$$\lambda_a \simeq r_g$$

Growth occurs for de Broglie wavelengths roughly matched with the BH crossing radius. Opens a window for probing ultralight weakly interacting bosons

Superradiance - mechanism



Gravitational atom

$$\psi_{n\ell m}(t,r,\theta,\phi) \simeq e^{-i\omega t} e^{imt} R_{\ell m}(r) S_{\ell m}(\theta)$$

Gravitational Fine Structure

$$\alpha = r_g m_a \qquad r_g \equiv G_N M$$

$$\alpha \lesssim 1/2$$

$$\lambda_a \simeq r_g$$

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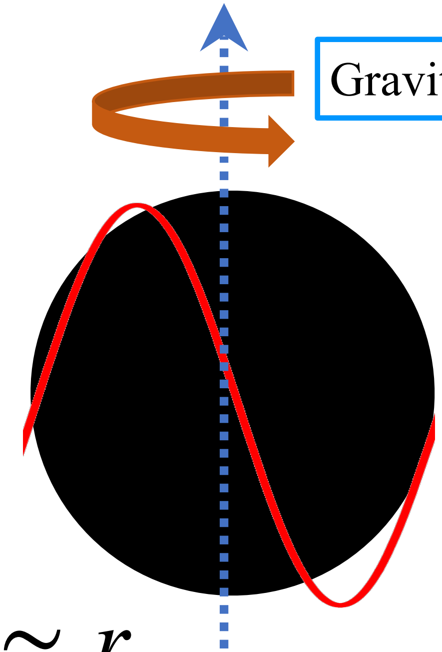
Superradiance - mechanism



$\lambda_a \simeq r_g$

Gravitational atom

$$\psi_{n\ell m}(t, r, \theta, \phi) \simeq e^{-i\omega t} e^{imt} R_{\ell m}(r) S_{\ell m}(\theta)$$

$$\omega = \omega_R + i\omega_I$$

$$\omega_R \simeq m_a \left(1 - \frac{\alpha^2}{2n^2}\right)$$

Gravitational Fine Structure

$$\alpha = r_g m_a \qquad r_g \equiv G_N M$$

$$\alpha \lesssim 1/2$$

Superradiance Condition

$$\omega_I > 0$$

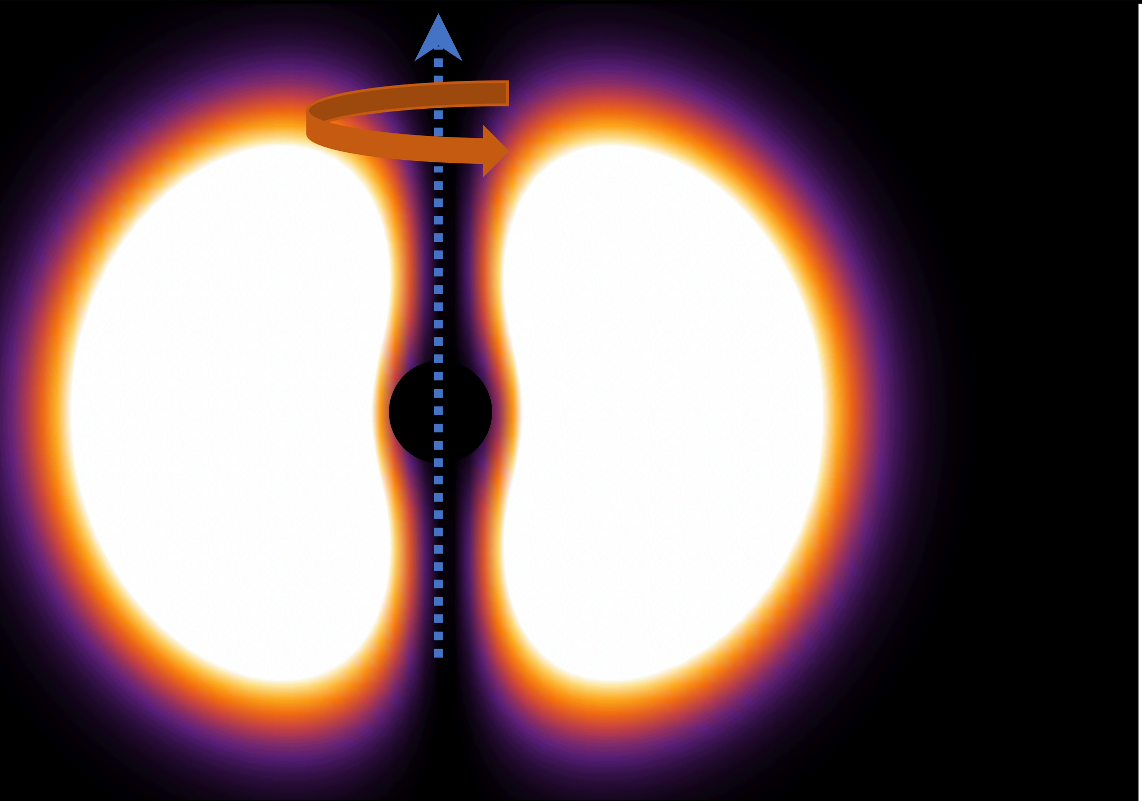
$$\Omega_H > \omega_R / m$$

Cloud Size

$$r \simeq \frac{4}{\alpha^2} r_g$$

Growth occurs for de Broglie wavelengths roughly matched with the BH crossing radius. Opens a window for probing ultralight weakly interacting bosons

Superradiance - mechanism



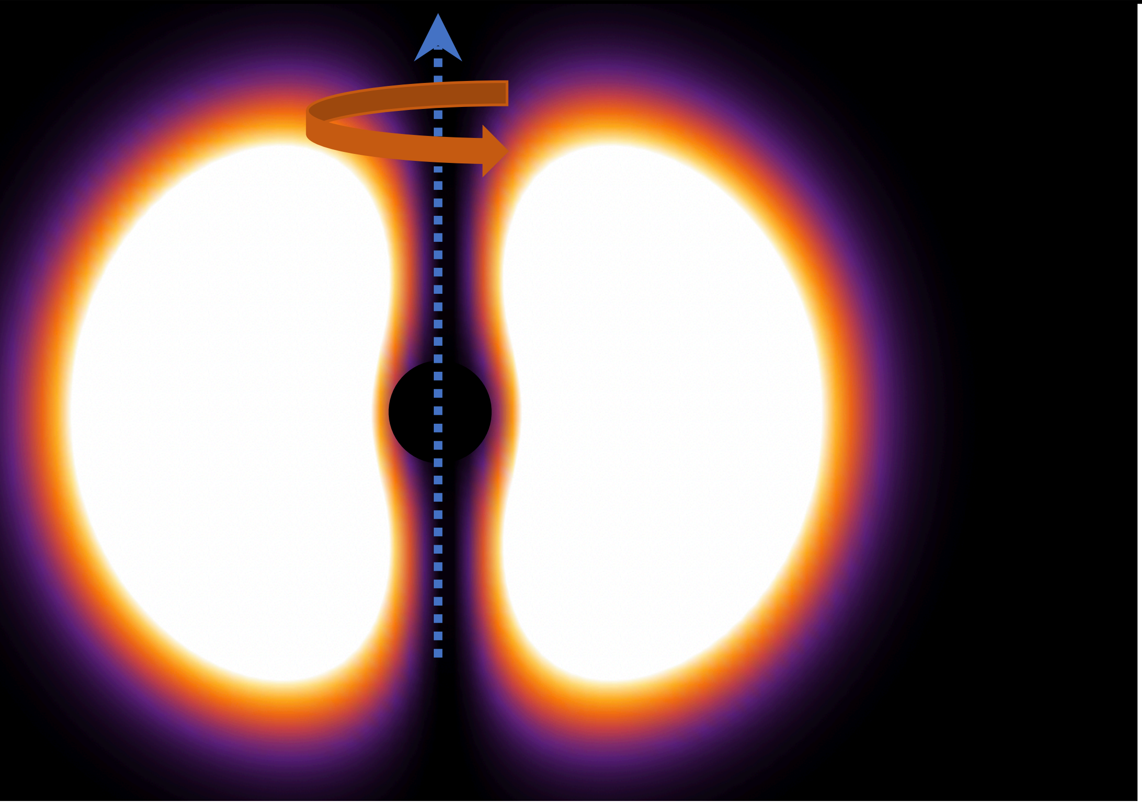
Unstable to exponential growth – energy and angular momentum extraction

$$\Gamma_{SR} \propto (m\Omega_H - \omega_R)\alpha^{4\ell+2s+5}$$

n, ℓ, m

$$N_{SR} \simeq 2 \times 10^{39} a_{*i} \frac{\Delta J}{J_0} \left(\frac{M_{PBH}}{10^{15}\ \mathrm{g}} \right)^2$$

Superradiance - mechanism



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n, ℓ, m

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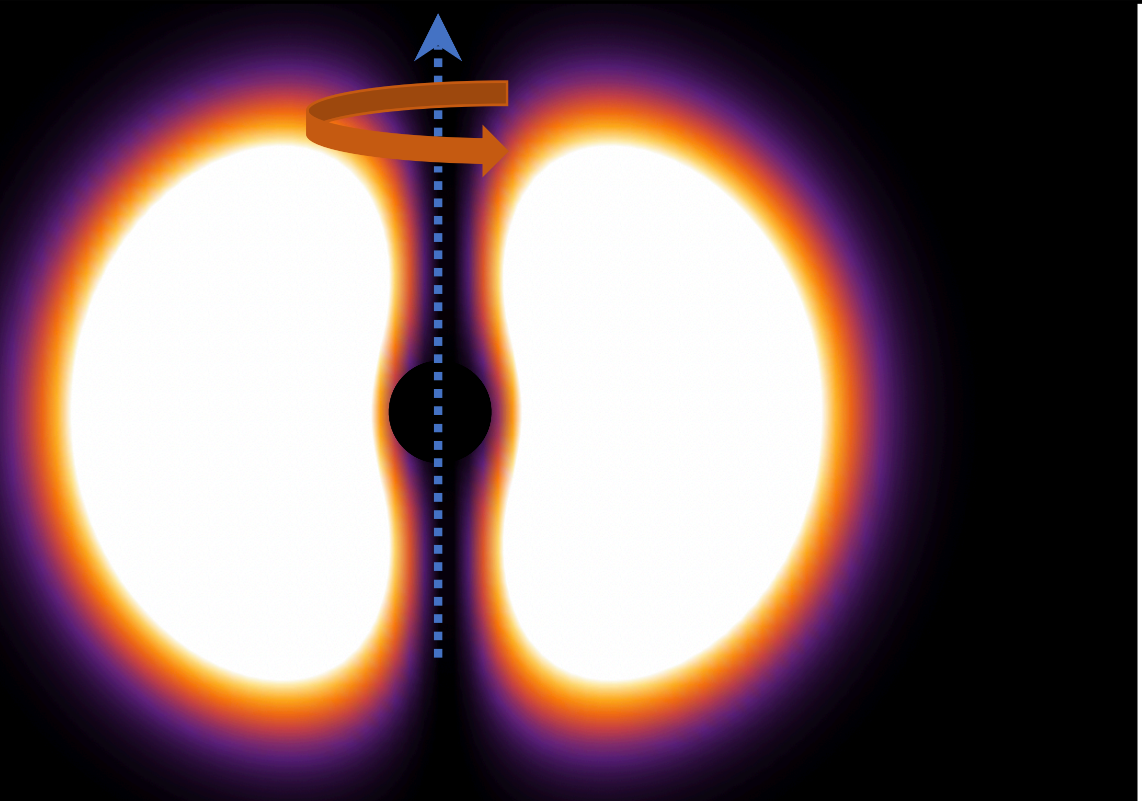
Spin-down of black holes until superradiance is cut off

$$a_{*f} \simeq 4\alpha \qquad \frac{\Delta J}{J_0} \simeq 1 - \frac{4\alpha}{a_{*i}}$$

Superradiance - mechanism



Unstable to exponential growth – energy and angular momentum extraction

$$\Gamma_{SR} \propto (m\Omega_H - \omega_R)\alpha^{4\ell+2s+5}$$

$$n, \ell, m$$

$$N_{SR} \simeq 2 \times 10^{39} a_{*i} \frac{\Delta J}{J_0} \left(\frac{M_{PBH}}{10^{15}\ \mathrm{g}} \right)^2$$

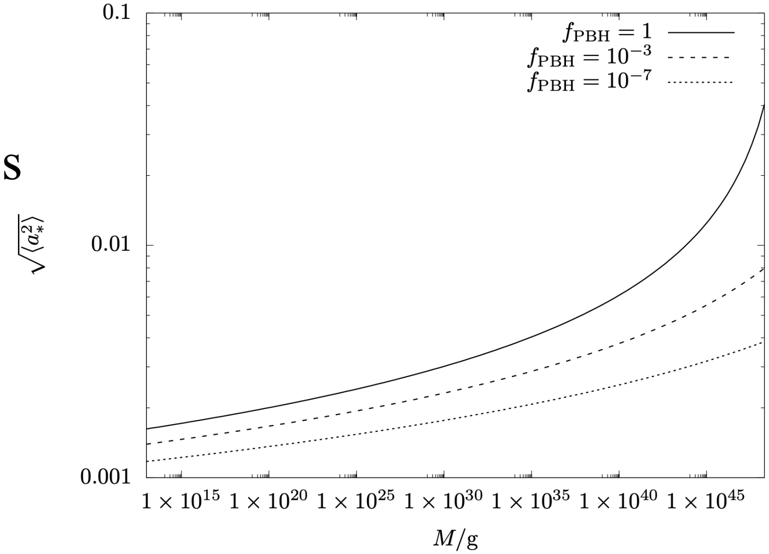
Spin-down of black holes until superradiance is cut off

$$a_{*f} \simeq 4\alpha \qquad \frac{\Delta J}{J_0} \simeq 1 - \frac{4\alpha}{a_{*i}}$$

Quasi-monochromatic GW emission

$$f_{GW} \simeq \frac{m_a}{\pi}$$

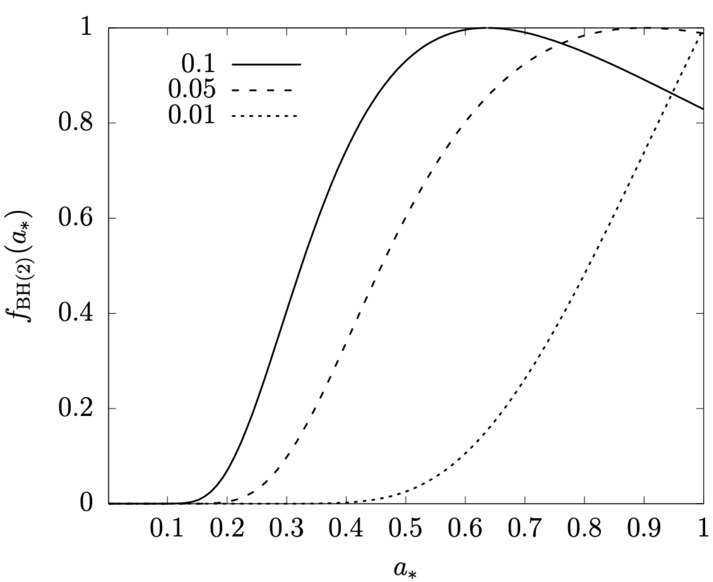
PBH Formation with high spin ?

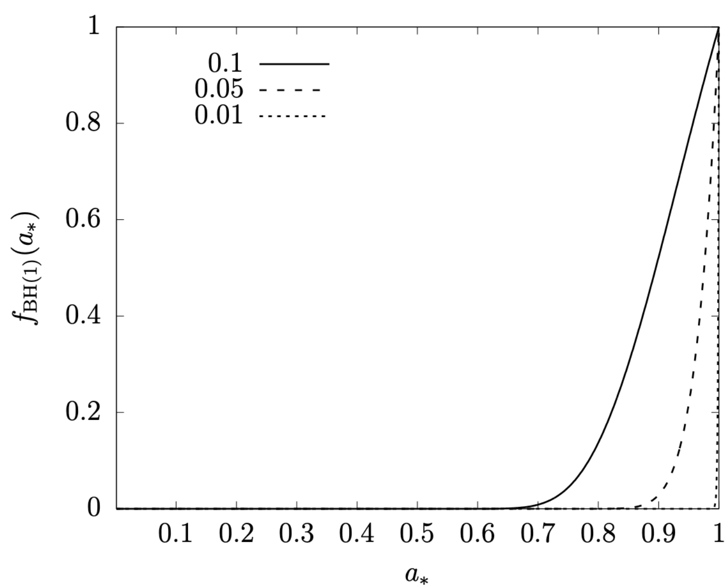


Radiation Dominated Era - Typically produces a PBH population with low spin

T. Harada, C.-M. Yoo, K. Kohri, Y. Koga, and T. Monobe, 2011.00710
V. De Luca, V. Desjacques, G. Franciolini, A. Malhotra, A. Riotto, 1903.01179

Early Matter Dominated Eras





M. Y. Khlopov and A. G. Polnarev, Phys. Lett. B 97 383 (1980), T. Harada, C.-M. Yoo, K. Kohri and K.-I. Nakao, 1707.03595.

Spin and Formation Mechanisms

Formation mechanism	Mass range	PBH spin
Inflationary perturbations [106]	DM, LIGO, supermassive	small
Inhomogeneous baryogenesis [51–53, 98]	LIGO, supermassive	small
Yukawa "fifth force" [89, 226]	DM, LIGO, supermassive	small
Supersymmetry, Q-balls, no long-range [79, 80, 82]	DM ($10^{-16} - 10^{-6} M_\odot$)	large
Supersymmetry, long-range scalar forces [90]	DM ($10^{-16} - 10^{-6} M_\odot$)	small
Light scalar Q-balls (not SUSY) [80]	DM, LIGO, supermassive	large
Oscillons from the inflaton [81]	DM, LIGO, supermassive	large
Multiverse bubbles [55–57]	DM, LIGO, supermassive	small

S. Bird et al. *Snowmass 2021: PBH DM,* 2203.08967

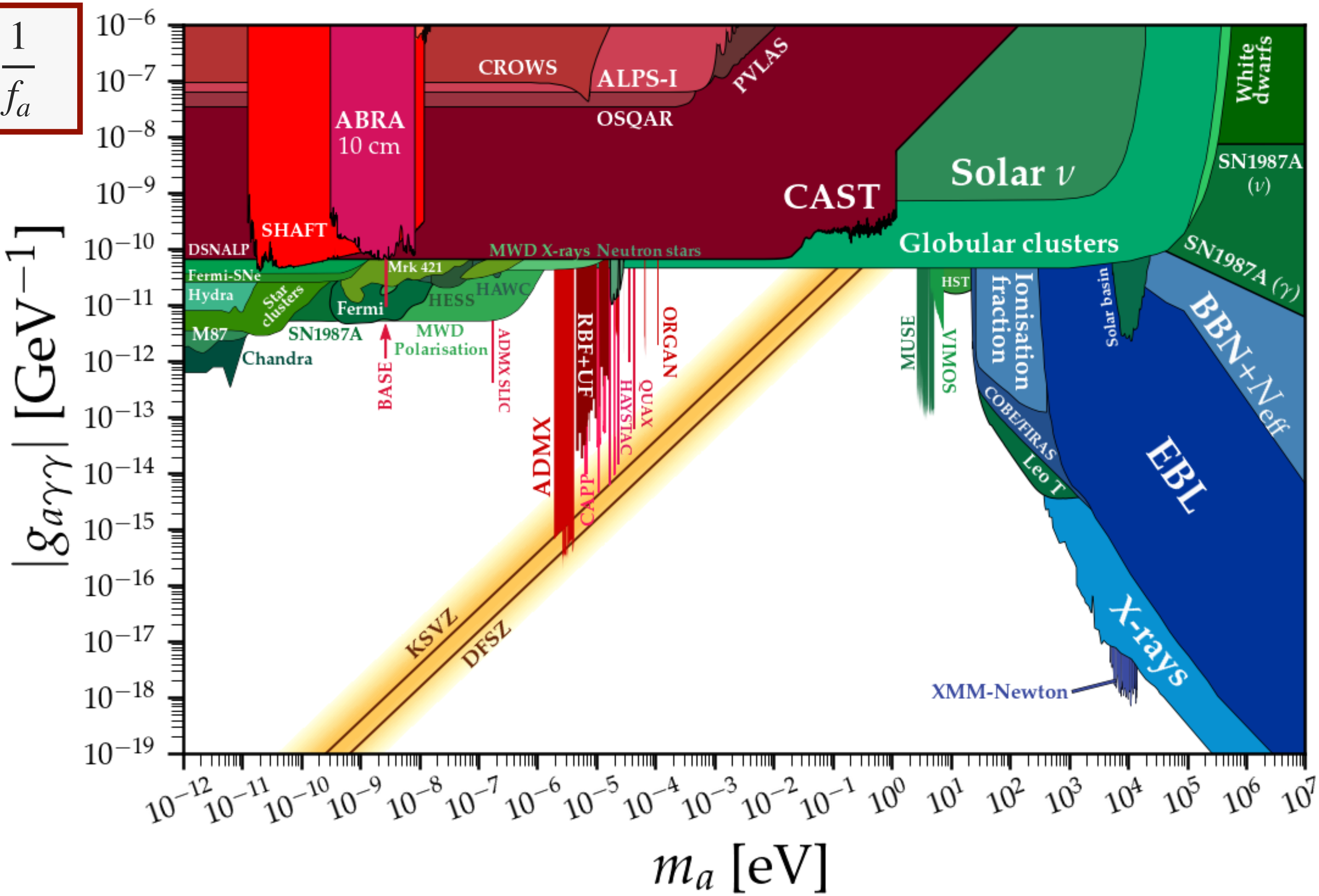
PBHs formed from collapsing domain walls have been shown to possibly have large, $O(1)$ spins

Y.N. Eroshenko, JCAP (2021) 2111.03403

	PBH Production Scenario	
	Inflationary Perturbations *(common mechanism)*	Field Fragmentation *(our mechanism)*
Source and type of large (CMB-scale) perturbations	inflaton fluctuations, curvature	inflaton fluctuations, curvature
Source and type of small (PBH-scale) perturbations	inflaton fluctuations, curvature	stochastic field fragmentation, isocurvature (fragment-lumps)
PBH source field	inflaton	inflaton or spectator field
Required potential condition	inflaton potential fine tuning	no new restrictions on inflaton potential, scalar field potential shallower than quadratic (attractive self-interactions)
PBH formation era ($t_{\rm PBH}$) and type	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm reh}$, after reheating, radiation-dominated era	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm inf}$, before or after reheating, temporary matter-dominated era
PBH size ($r_{\rm BH}$) vs. horizon ($r_{\rm H}$) at formation	$r_{\rm BH} \sim r_{\rm H} \sim H^{-1}$	$r_{\rm BH} \ll r_{\rm H} \sim H^{-1}$
PBH spin (a_s)	$a_s \sim 0$	$a_s \sim \mathcal{O}(1)$ possible

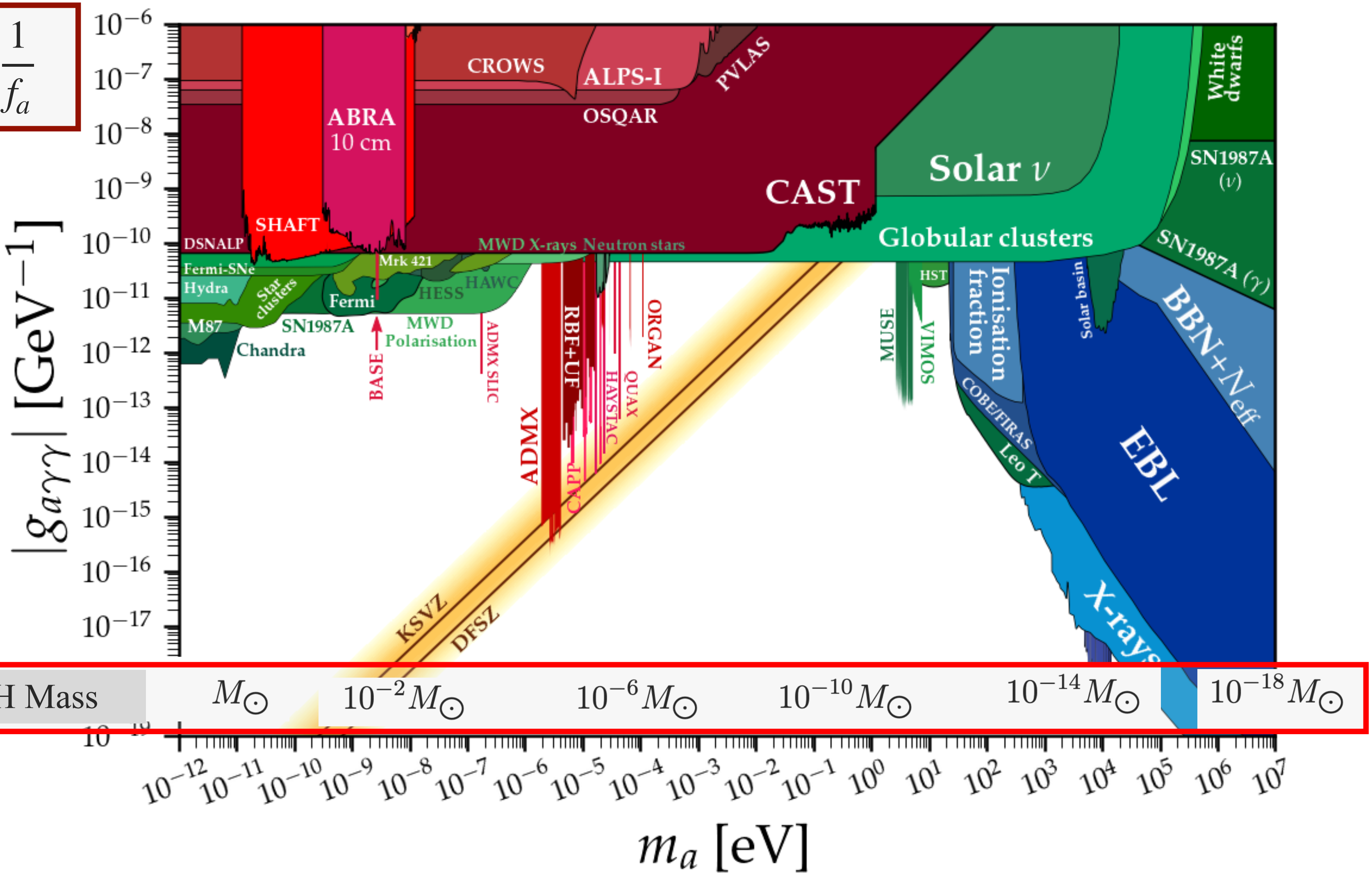
E.Cotner, A.Kusensko, M.Sasaki, V.Takhistov, JCAP (2019) 1907.10613

$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$



Ciaran O'Hare - https://cajohare.github.io/AxionLimits/

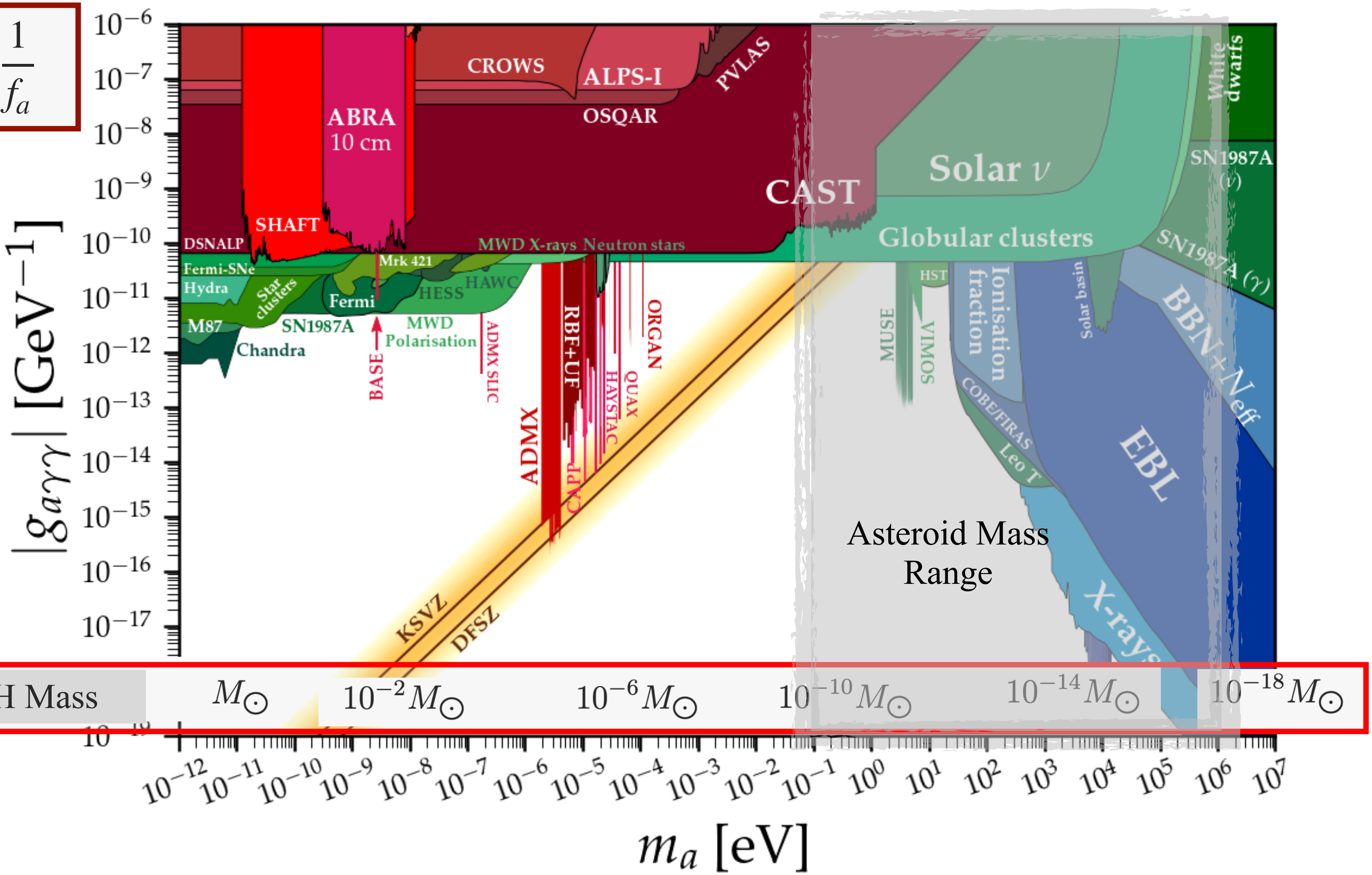
$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$



$$\frac{2GMm_a}{c\hbar} = 1.5 \frac{M}{10^6 M_\odot} \frac{m_a c^2}{10^{-16}\ \text{eV}}$$

GW frequency from superradiance $f_{\mathrm{GW}} \sim 5 \times 10^{13}$ Hz $\sim 5 \times 10^{20}$ Hz

$g_{a\gamma\gamma} \propto \frac{1}{f_a}$



$$\frac{2GMm_a}{c\hbar} = 1.5 \frac{M}{10^6 M_\odot} \frac{m_a c^2}{10^{-16}\ \mathrm{eV}}$$

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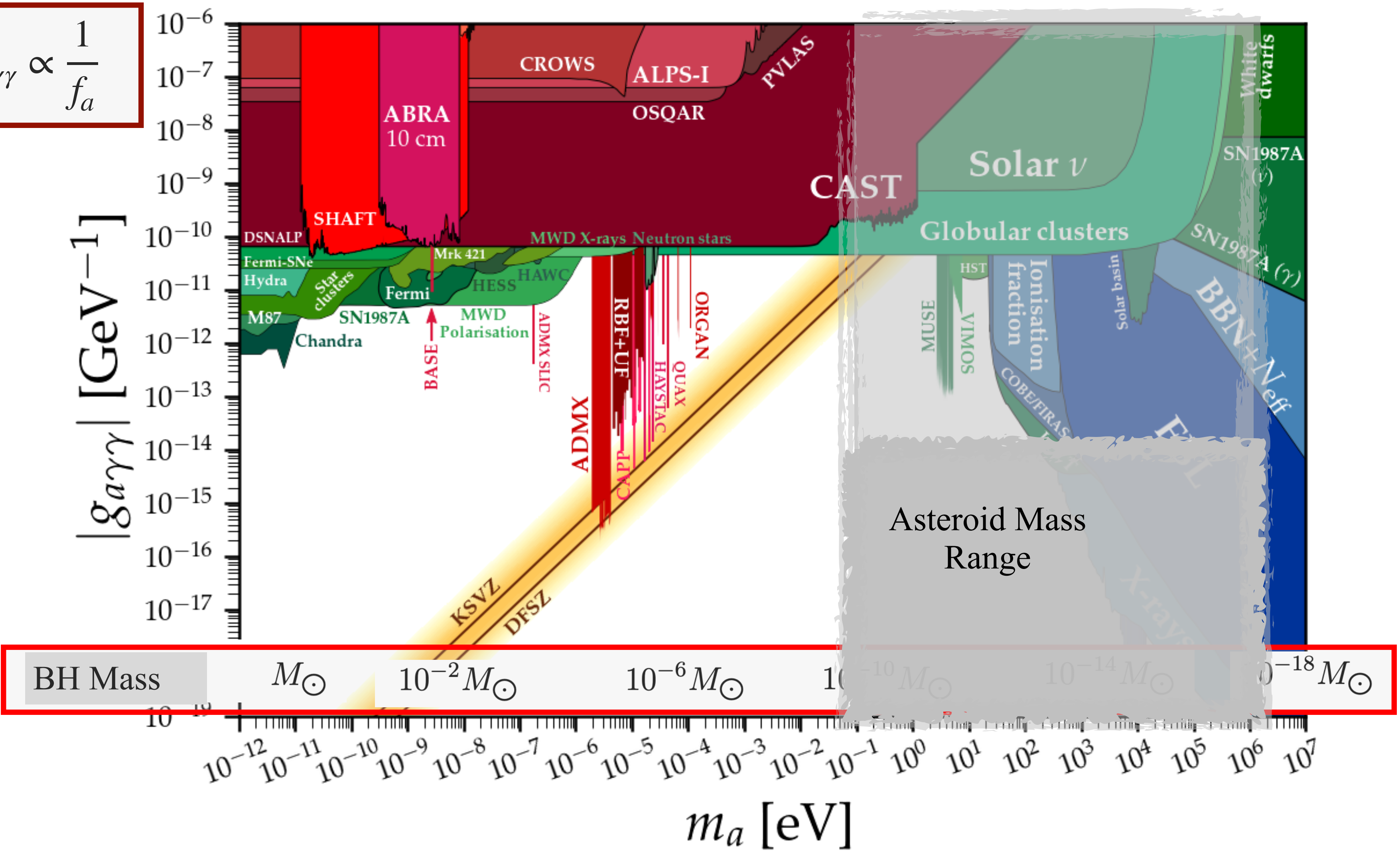
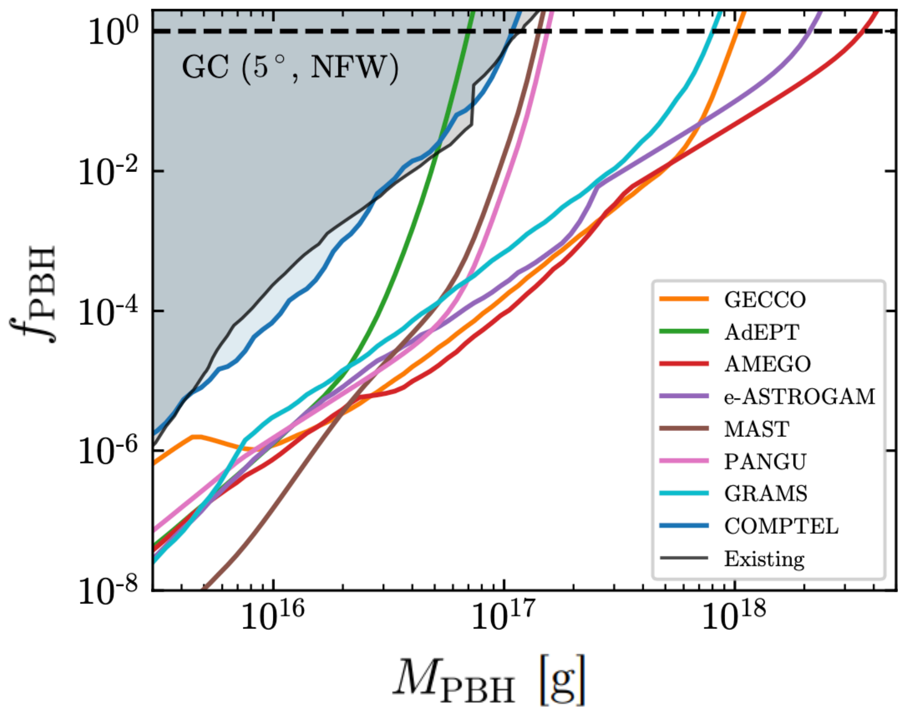
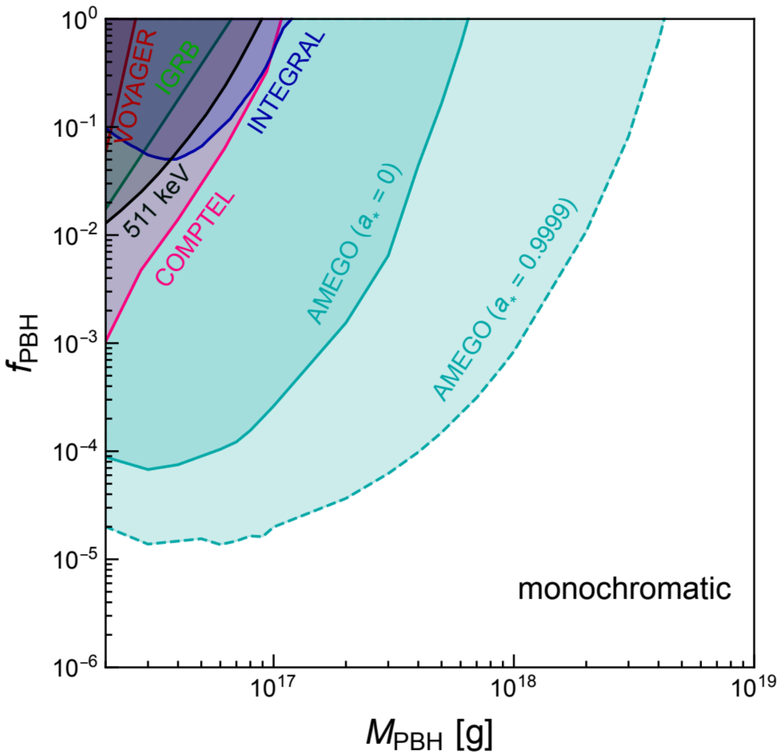


$$\frac{2GMm_a}{c\hbar} = 1.5 \frac{M}{10^6 M_\odot} \frac{m_a c^2}{10^{-16}\ \text{eV}}$$

Constraints from Hawking Radiation

PBH – MeV Sky - including the effects of spin





A.Coogan, L.Morrison, and S.Profumo, 2010.04797

A. Ray, R. Laha, J.B. Muñoz, and R. Caputo, PRD (2021) 2102.06714

See also: D. Ghosh, D. Sachdeva, and P. Singh, PRD (2022) 2110.03333, D. Malyshev, E. Moulin, and A. Santangelo, PRD (2022) 2208.05705 for XMM-Newton, THESEUS, +

Constraints from Hawking Radiation with Superradiance

with collaborators Bhaskar Dutta and Tao Xu - to appear

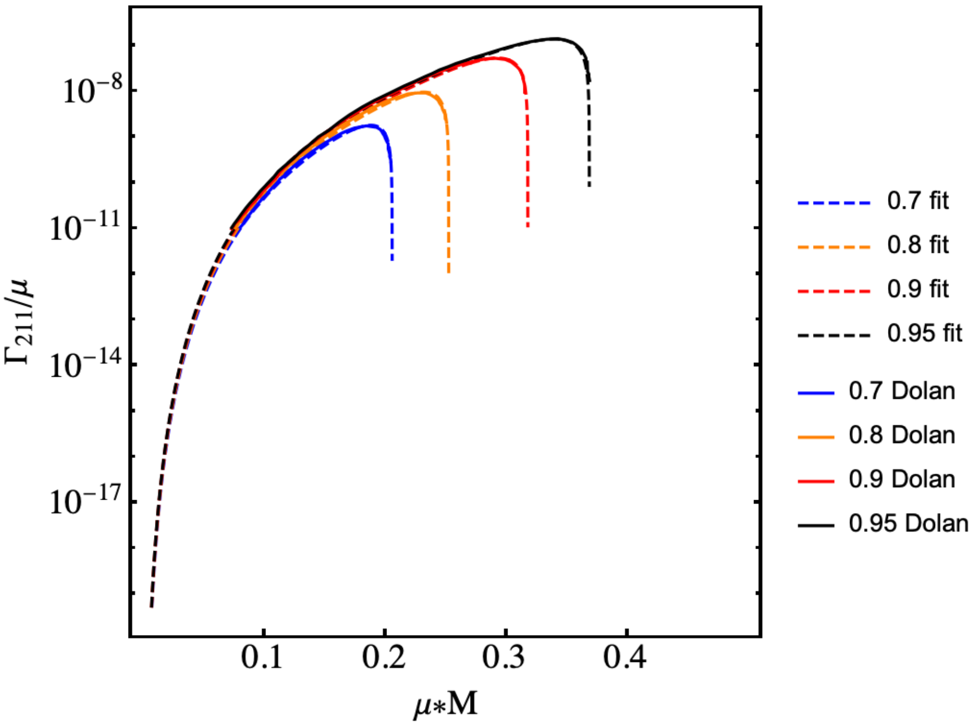
Constraints from Hawking Radiation with Superradiance

The parameter set

$$\{m_a, f_a, a_*, M_{PBH}, f_{PBH}\}$$

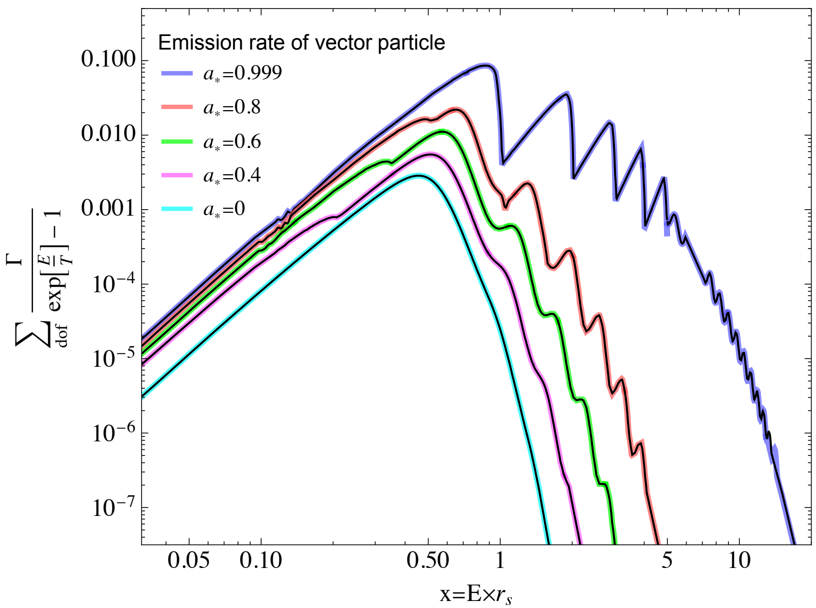
with collaborators Bhaskar Dutta and Tao Xu - to appear

Reproduction of Numerical Results



Matching to S. Dolan, PRD (2007) 0705.02880

Interpolate BlackHawk output for dynamical spin

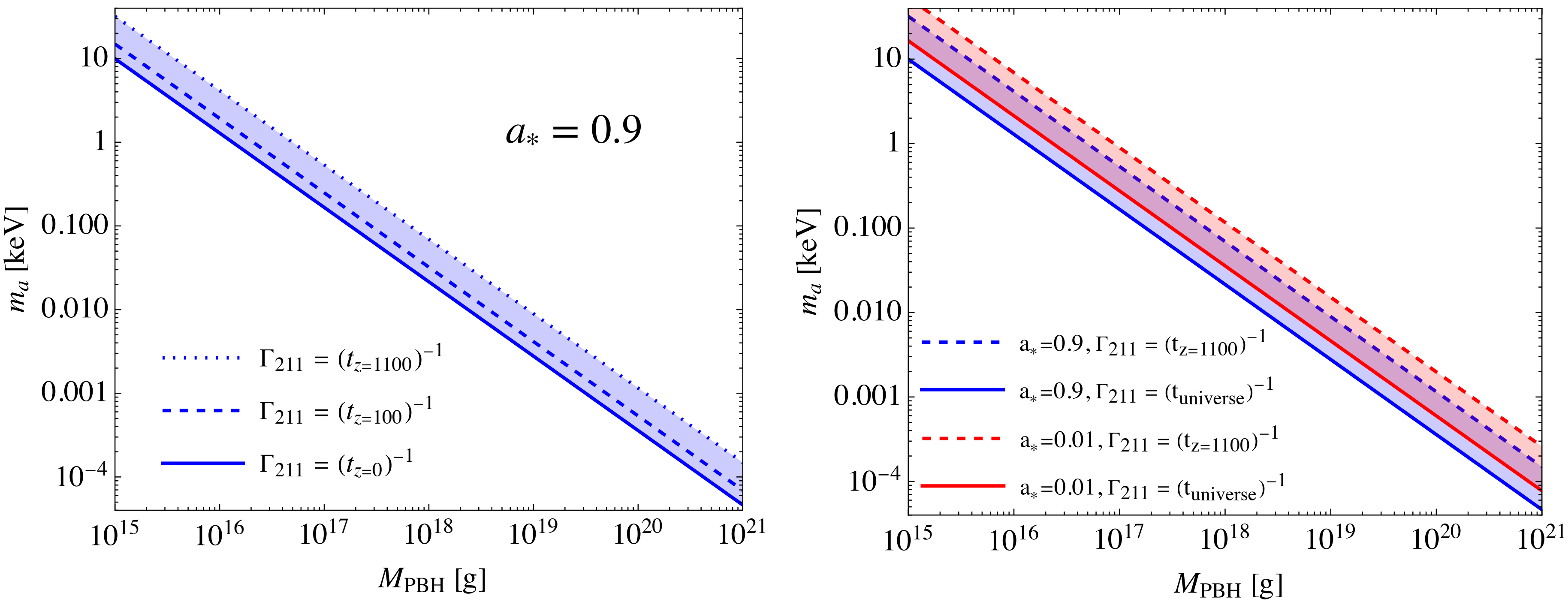


Checks and Software

Incorporated the SuperRad code: N. Siemonsen, T. May, and W.E. East, PRD (2023) 2211.03845 into Mathematica

Axion mass vs. PBH mass with time for superradiance

Superradiance after
CMB

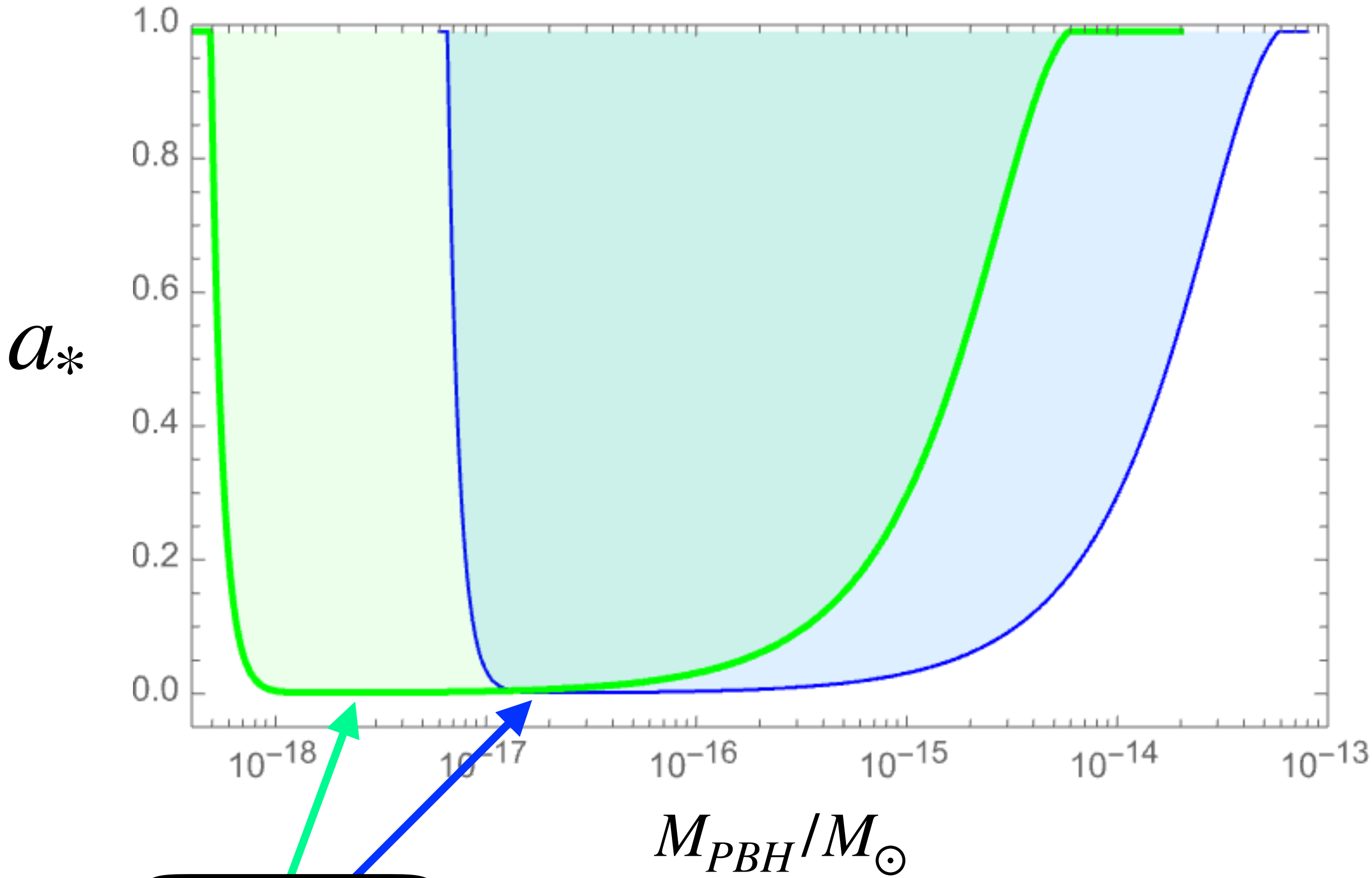


$$\alpha = m_a M_{PBH} G$$

JBD, B. Dutta, T. Xu

Example Regge plot in the asteroid mass range

$m_a = 10$ keV $m_a = 1$ keV



$\tau_{SR} > \tau_{uni}$

$a_{*,min} \sim 10^{-3}$

JBD, B. Dutta, T. Xu

The effects of spin and self-interactions on superradiance

$$\lambda = \frac{m_a^2}{f_a^2}$$

Γ_{D}: 211 + 211 → 322 + BH

322 + 322 → 211 + ∞ : Γ_{R}

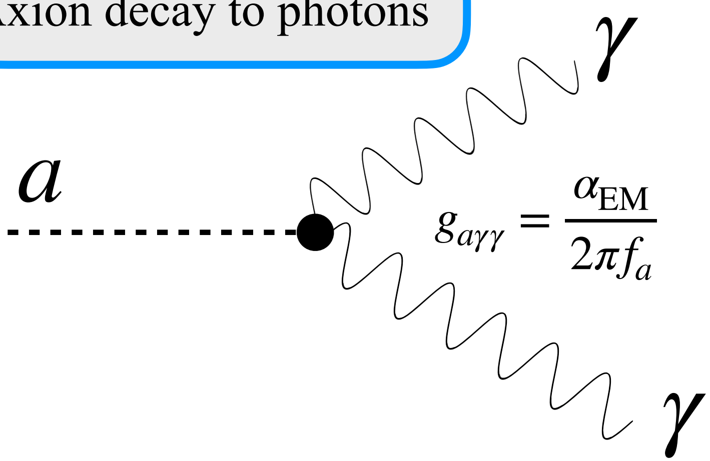
Population dynamics of the super radiant states

$$\Gamma_{\mathrm{D}} = 4 \times 10^{-7} \alpha^7 \lambda^2 m_a \left(1 + \sqrt{1 - a_*^2}\right)$$

$$\Gamma_{\mathrm{R}} = 1 \times 10^{-8} \alpha^4 \lambda^2 m_a$$

Strong enough self-coupling can quench the superradiant growth

Axion decay to photons



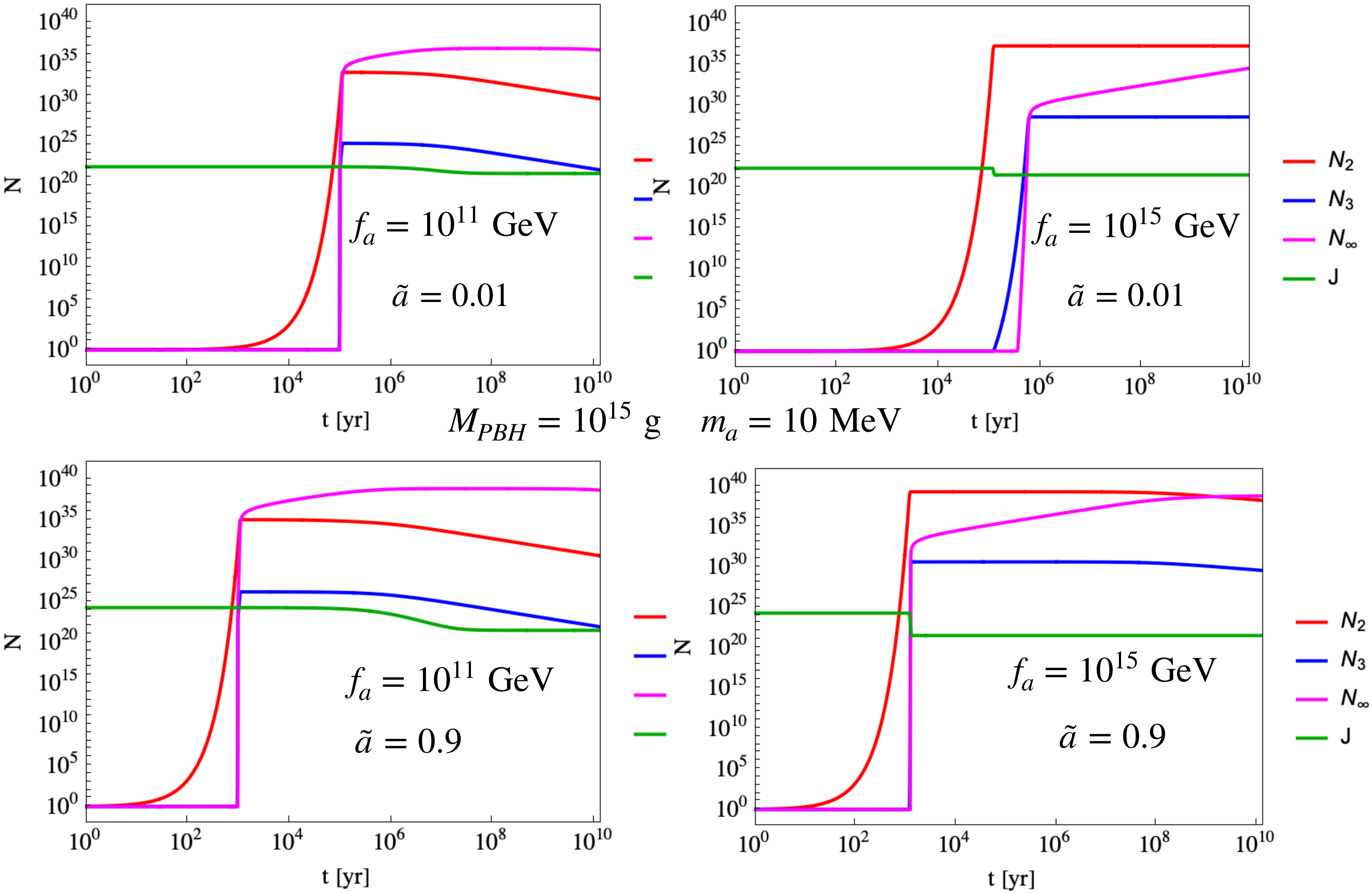
$$g_{a\gamma\gamma} = \frac{\alpha_{\mathrm{EM}}}{2\pi f_a}$$

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

Also enhances decay to photons

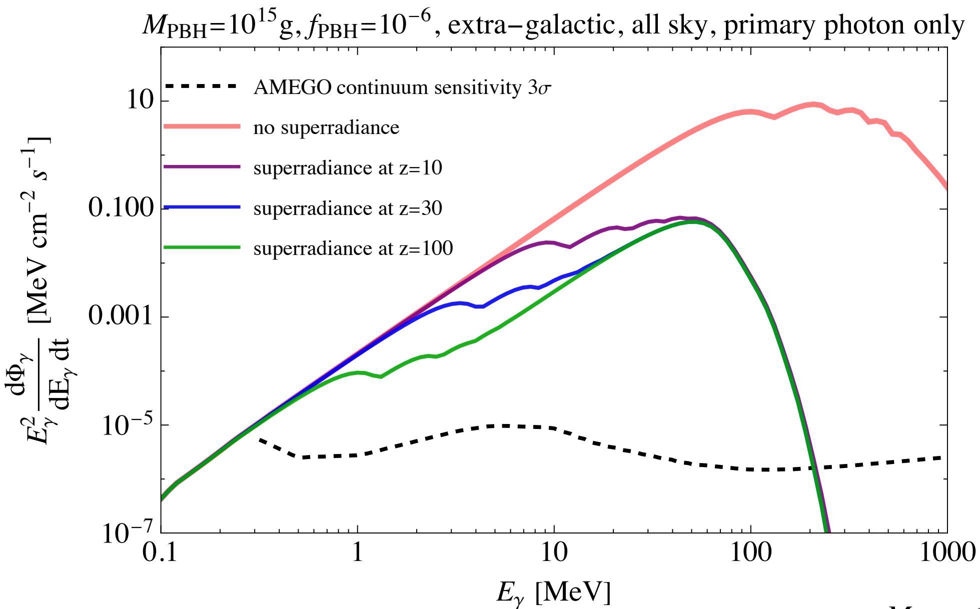
M. Baryakhtar, M. Galanis, R. Lazenby, and O. Simon, PRD (2021) 2011.11646
H. Omiya, T. Takahashi, T. Tanaka, and H. Yoshino, JCAP (2023) 2211.01949
N.P.Branco, R.Z.Ferreira, and J.G.Rosa, JCAP (2023) 2301.01780

The effects of spin and self-interactions on superradiance



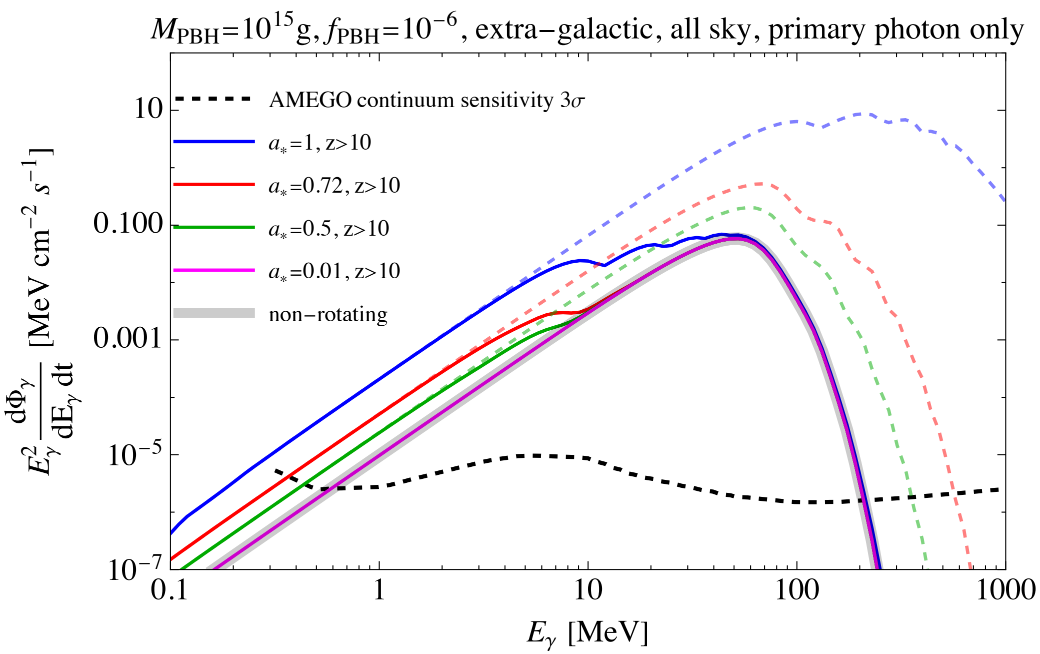
J.B.Dent, B.Dutta, and T.Xu, Following the work of: N.P.Branco, R.Z.Ferreira, and J.G.Rosa, JCAP (2023) 2301.01780

The effects of superradiance and axion decay on Hawking radiation - spin and superradiance



BH will spin down, reducing the Hawking radiation signal

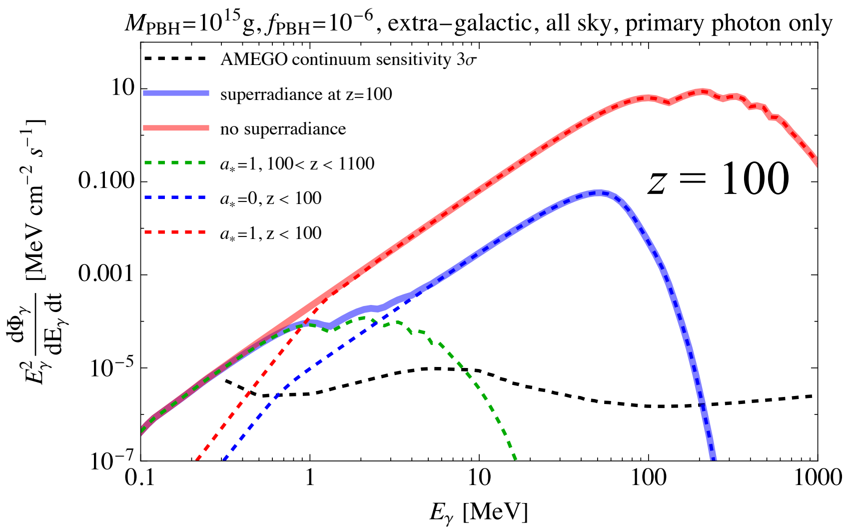
Caputo et al., AMEGO-X, 2208.04990

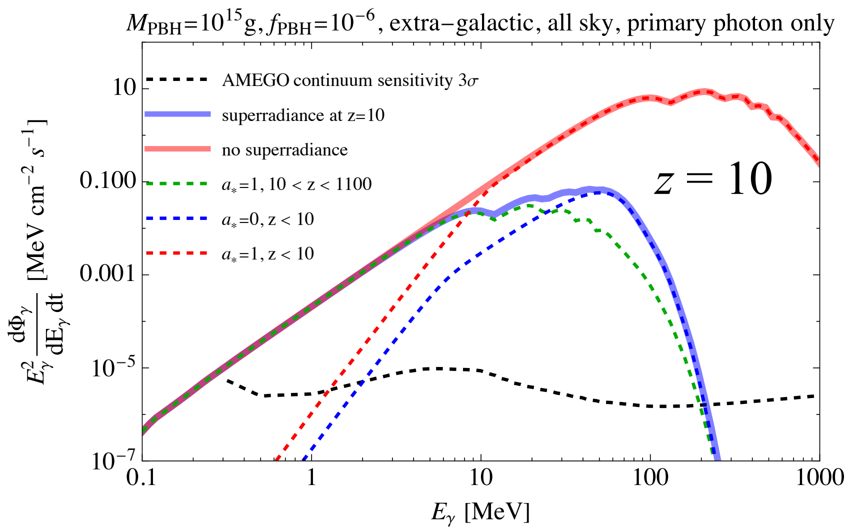


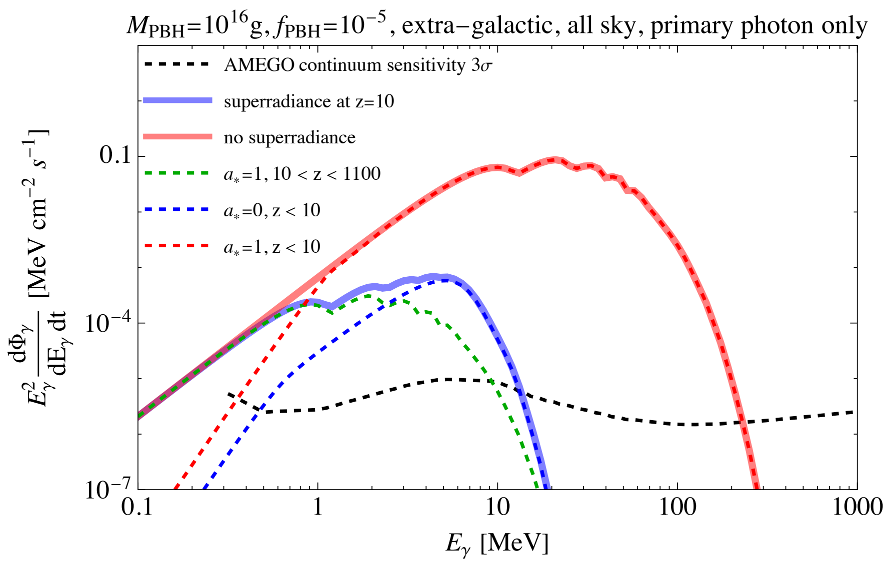
Combination of spin and superradiance

JBD, B. Dutta, T. Xu

The effects of superradiance and axion decay on Hawking radiation - spin and superradiance







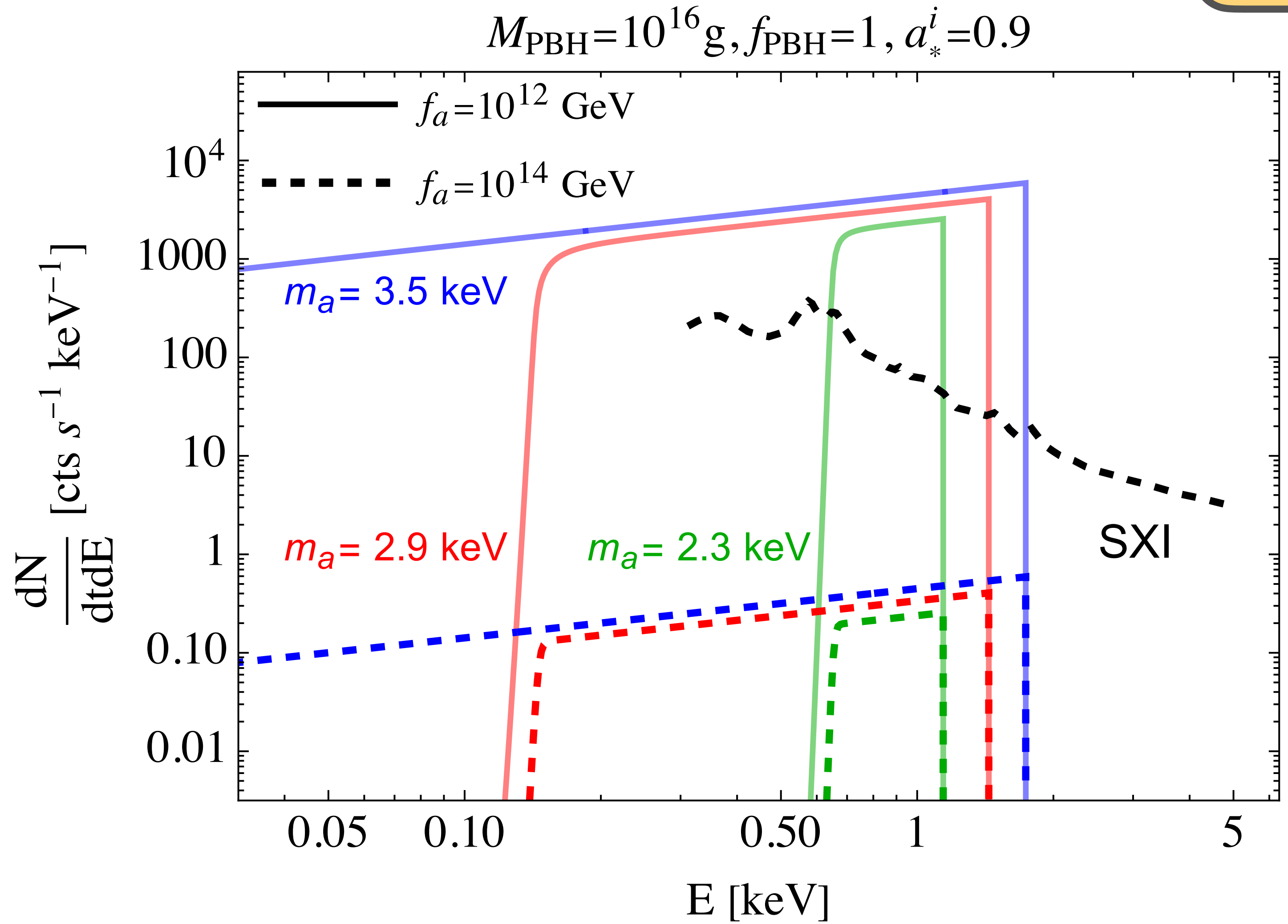
Mass, *z*,
and superradiance

Decrease the
PBH mass

JBD, B. Dutta, T. Xu

X-ray line search constraints

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

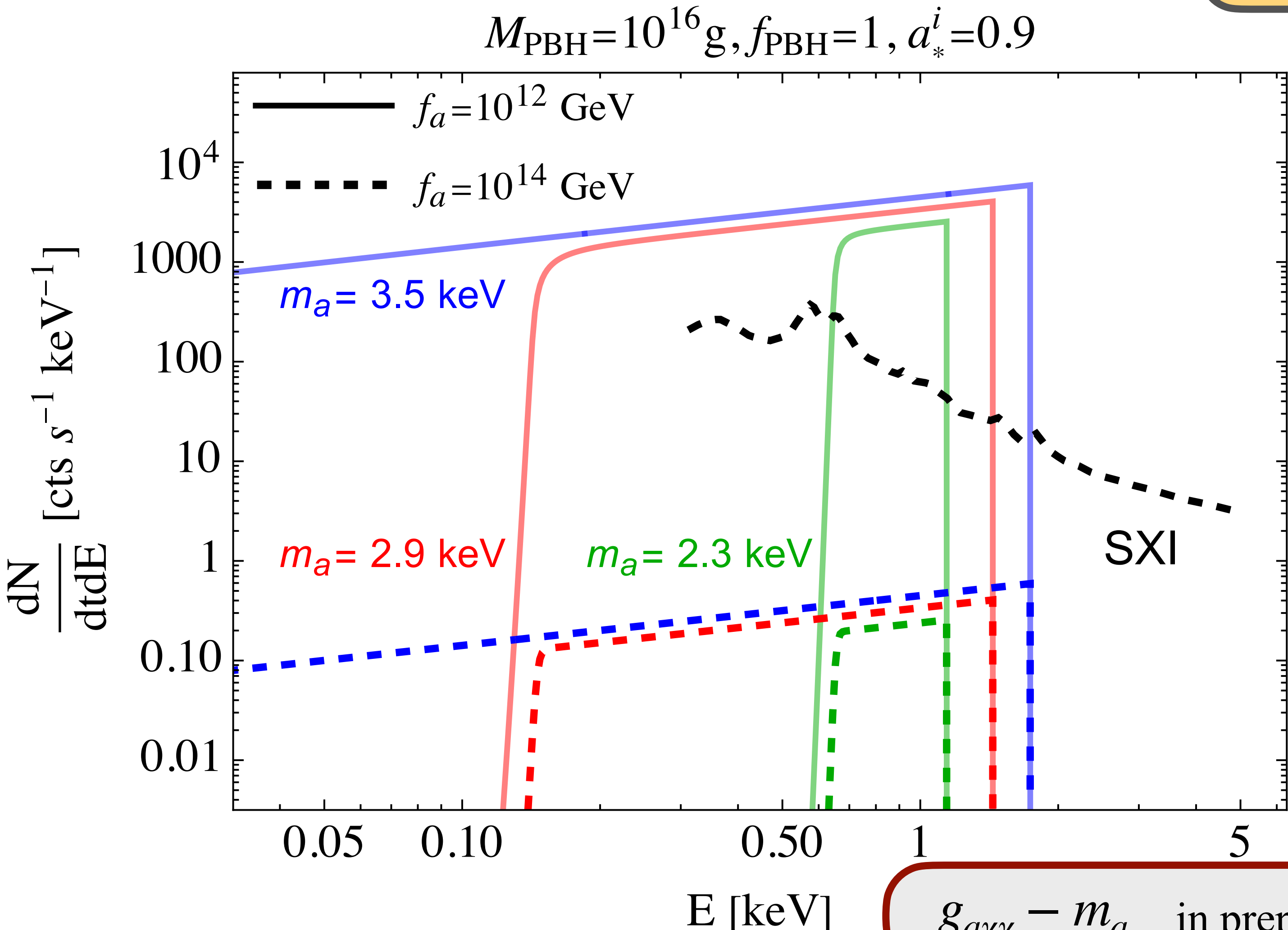


JBD, B. Dutta, T. Xu

Using the Theseus-SXI sensitivity: C. Thorpe-Morgan, D. Malyshev, A. Santangelo, J. Jochum, B. Jäger, M. Sasaki, and S. Saeedi, PRD (2020) 2008.08306

X-ray line search constraints

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

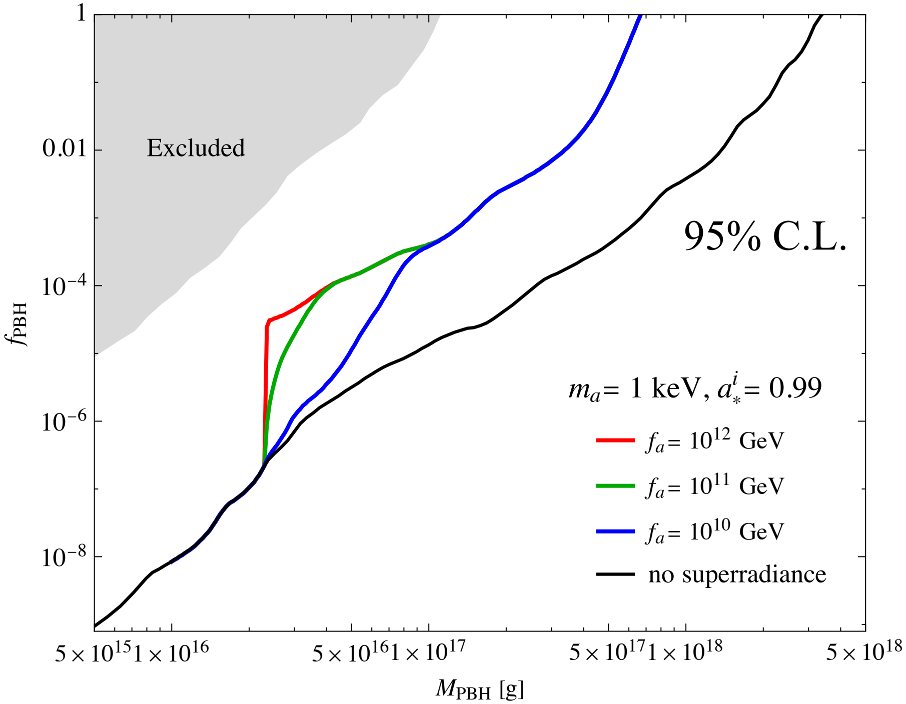


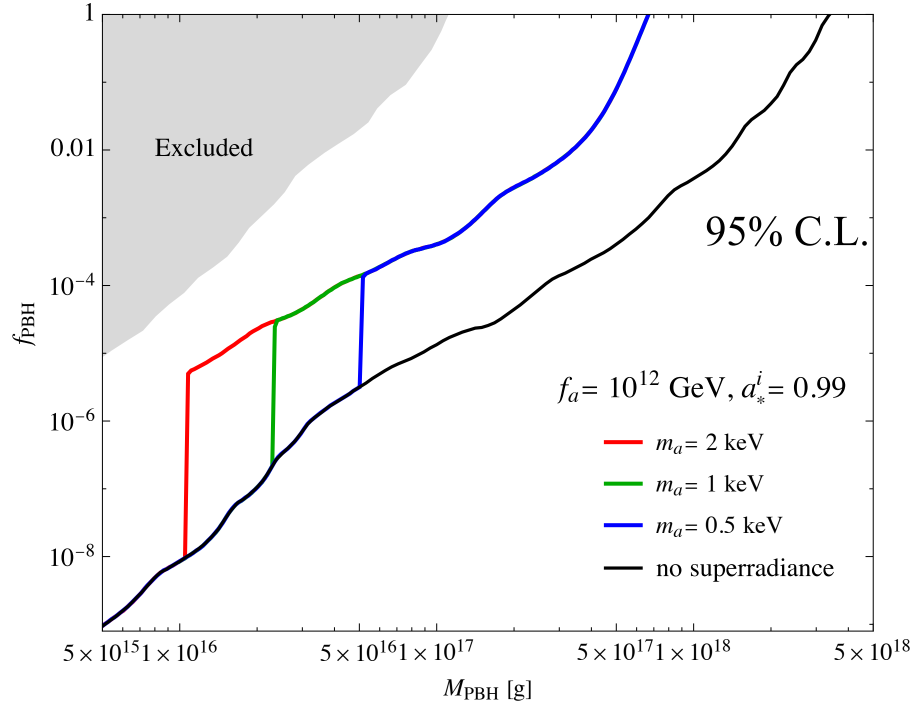
$g_{a\gamma\gamma} - m_a$ in preparation

JBD, B. Dutta, T. Xu

Using the Theseus-SXI sensitivity: C. Thorpe-Morgan, D. Malyshev, A. Santangelo, J. Jochum, B. Jäger, M. Sasaki, and S. Saeedi, PRD (2020) 2008.08306

PBH constraints



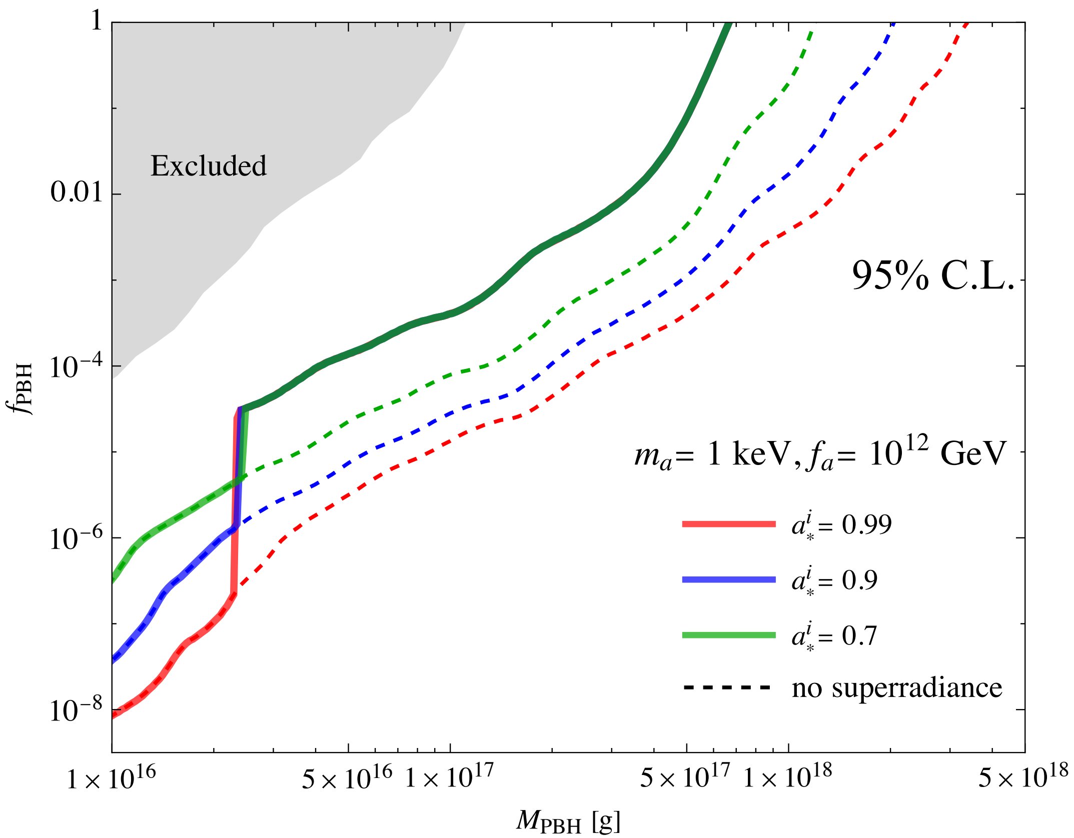


Given axion mass
Different self-couplings

Given self-couplings
Different axion mass

JBD, B. Dutta, T. Xu

PBH constraints



Given axion mass and self-coupling
Different spins

JBD, B. Dutta, T. Xu

GW Signals?

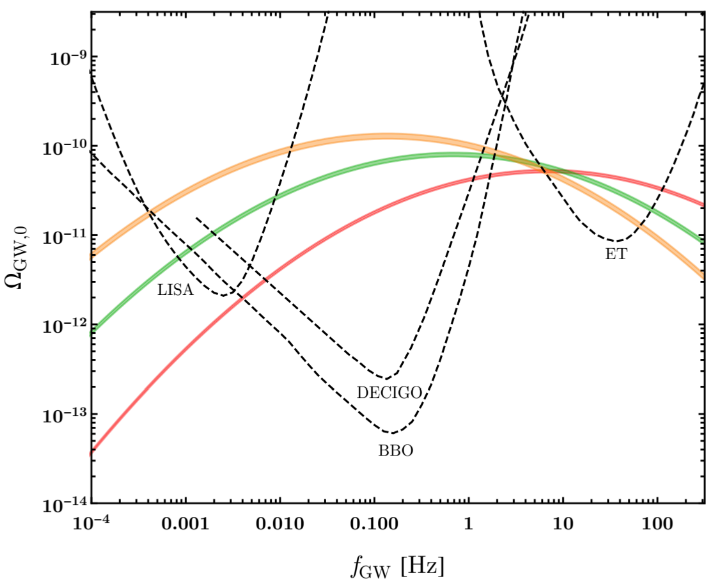
Monochromatic signal from the axion cloud

Binary signal

$f_{GW} \sim 5 \times 10^{13}$ Hz – 5×10^{20} Hz

Scalar Induced Gravitational Waves

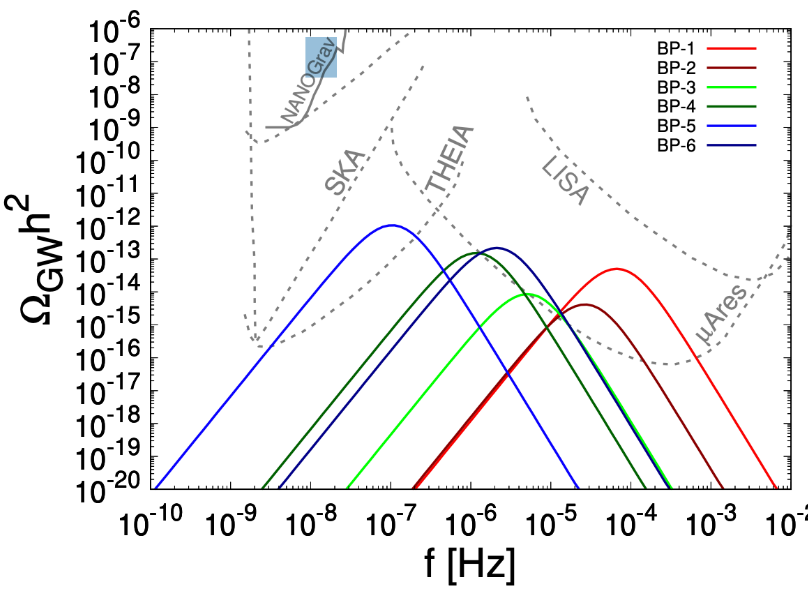
FOPT - spin?



$M_{PBH} \sim 10^{19}$ g

$M_{PBH} \sim 10^{17}$ g

$M_{PBH} \sim 10^{15}$ g

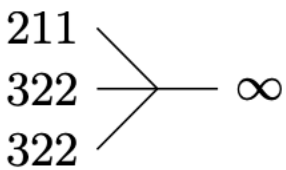


$10^{-20} \lesssim M_{PBH}/M_\odot \lesssim 10^{-16}$

K.Agashe, J.H.Chang, S.J.Clark, B.Dutta, Y.Tsai, and T.Xu, 2202.04653

D.Marfatia, P.-Y. Seng, JHEP (2022) 2112.14588

Direct Flux on Earth?



The energy of the ionized axion is

$$E_{ion} = 2\omega_{322} - \omega_{211} \simeq \frac{\alpha^2 \mu}{72}$$

Leading to a non-rel velocity

$$v \simeq \frac{\alpha}{6}$$

M. Baryakhtar, M. Galanis, R. Lasenby, and O. Simon, PRD (2021) 2011.11646.

The maximum flux from these axions is roughly

$$\Phi_a = n_a v_a \qquad \Phi_{a,max} \simeq \frac{10}{\text{cm}^3} \frac{M_{PBH}}{10^{17}\ \text{g}} \frac{\alpha}{6} c$$

J.Dent, B. Dutta, and T. Xu in progress

Which leads to a flux on Earth of about

$$7.5 \times 10^8 \ \frac{1}{\text{cm}^2\,\text{s}}$$

For a 10 keV axion with a 10^{17}g PBH

This is ~10^2 that of the solar axion flux at 1 keV from the Primakoff process

J. Redondo, JCAP (2013) 1310.0823

Discussion

Superradiance and Hawking radiation combined create interesting search opportunities for PBHs in the asteroid mass range

Extra-galactic and galactic searches across the MeV sky along with X-ray line searches provide correlations in the PBH and axion parameter spaces

There are a variety of possible additional correlative signals such as gravitational waves and direct detection of ionized axons

Vector superradiance can also be considered

Superradiance and Hawking radiation combined create interesting search opportunities for PBHs in the asteroid mass range

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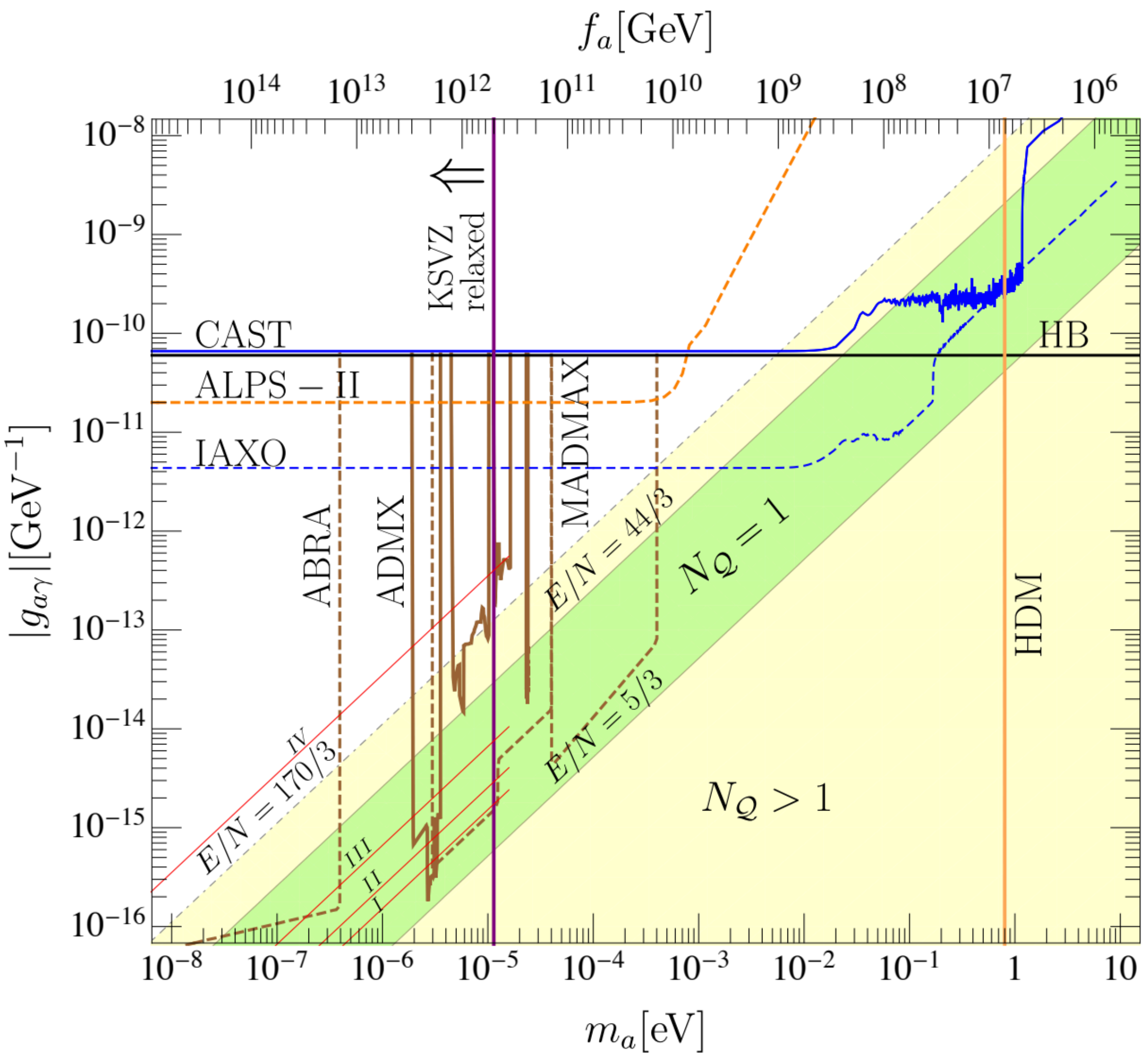
Thank you

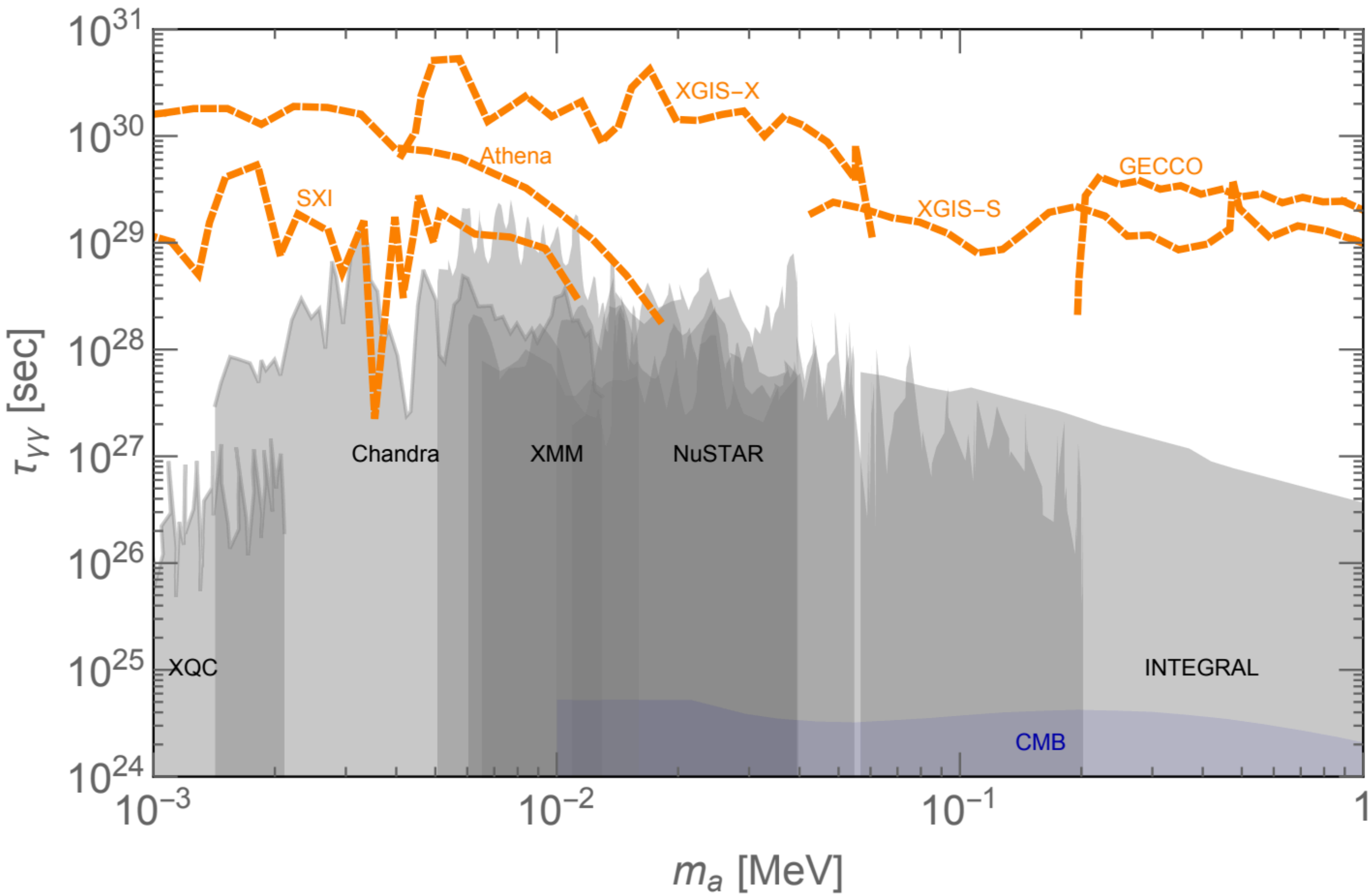
Back-up Slides

Axion Models - Parameter Space Coverage



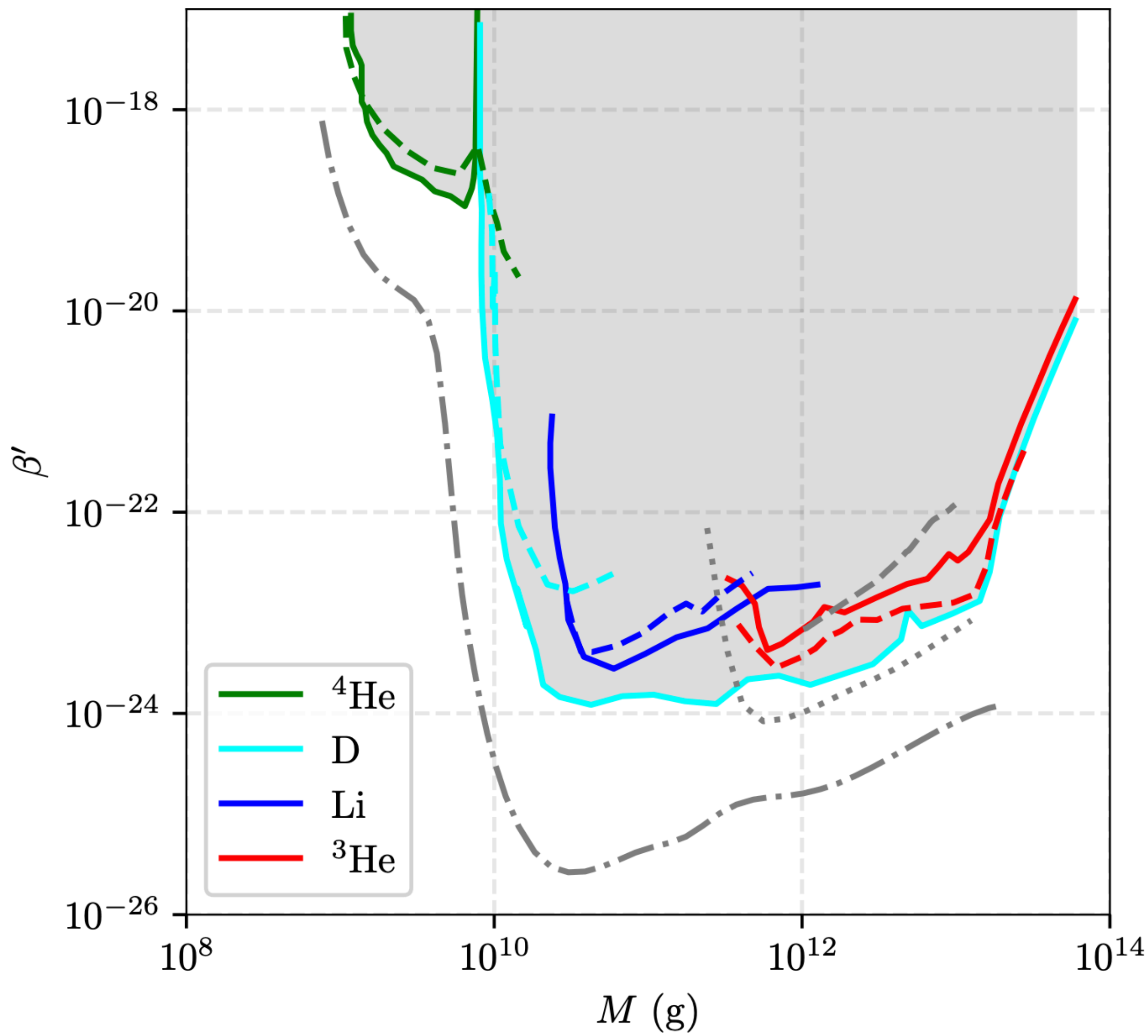
L. Di Lucio, M. Giannotti, E. Nardi, and L. Visinelli, Phys.Rept. (2020) 2003.01100

X-ray Line searches current and future



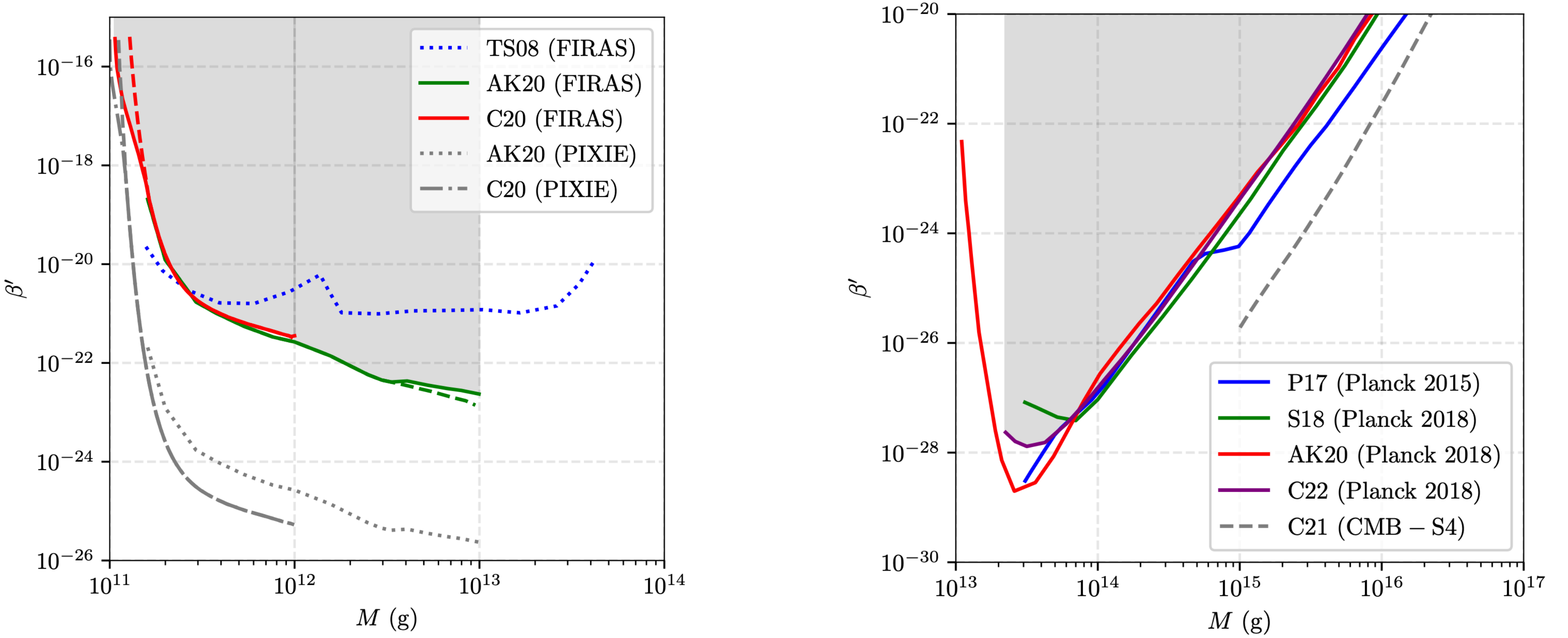
P. Panic, D. Redigolo, T. Schwetz, and R. Ziegler, PLB (2023) 2209.03371

PBH constraints - BBN



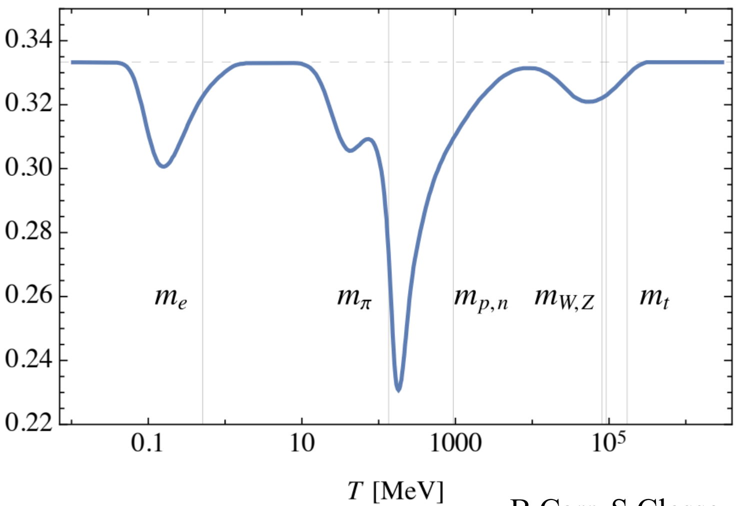
J. Auffinger, *Prog.Part.Nucl.Phys.* (2023) 2206.02672

PBH constraints - CMB

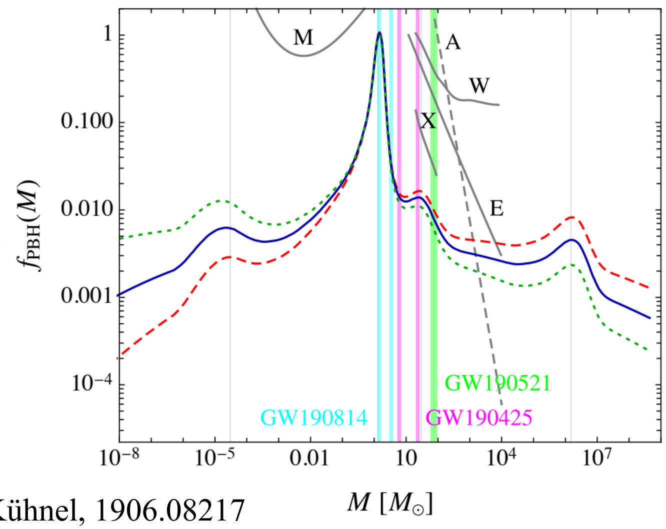


J. Auffinger, *Prog.Part.Nucl.Phys.* (2023) 2206.02672

Spin distributions as a function of EoS



Mass



B.Carr, S.Clesse, J.Garcia-Bellido, and F.Kühnel, 1906.08217

Spin

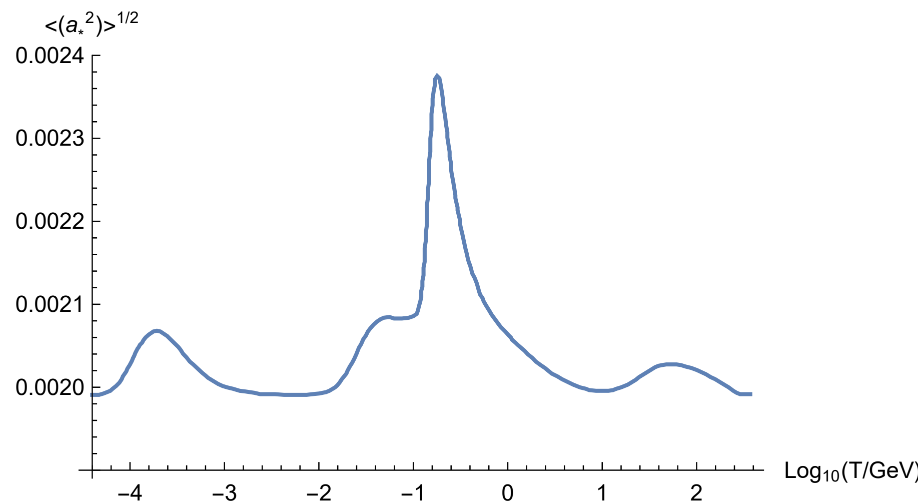


Figure produced by: Phuc Duc Loc Ngo using the approach of D. Saito, T. Harada, Y. Koga, and C.-M. Yoo, JCAP (2023) 2305.13830

Effects of accretion - negligible for sub-solar masses

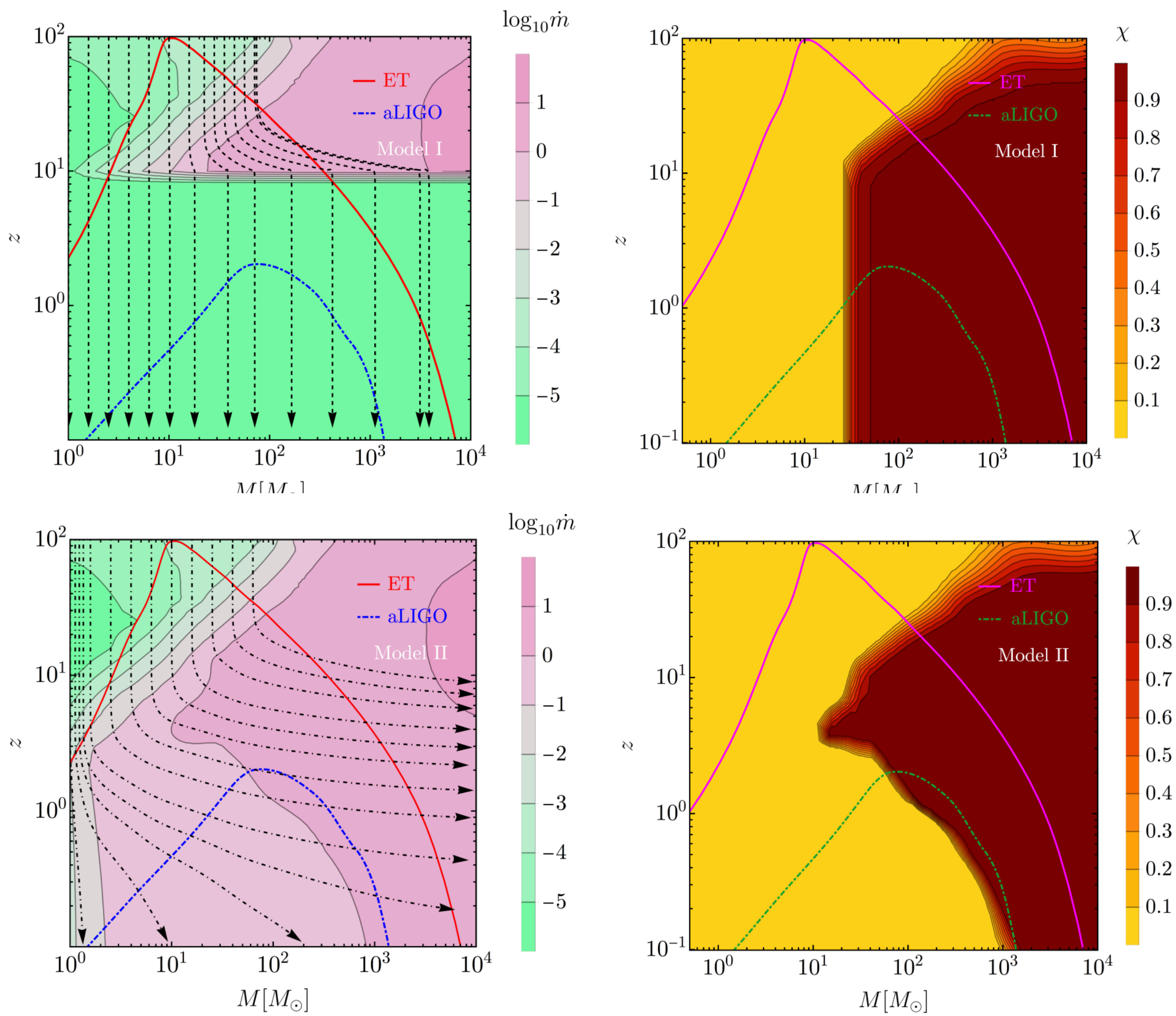


Figure 5. *Same as in Fig. 4 but for Model II, i.e. assuming a sustained accretion also when* $z < 10$.

V. De Luca, G. Franciolini, P. Pani, and A. Rito, JCAP (2020) 2003.02778

BH Temperature

$$T = \frac{\hbar c^3}{8\pi G M k} \approx 8.6 \times 10^{-12} \left(\frac{M_\odot}{M} \right) \text{ eV}$$

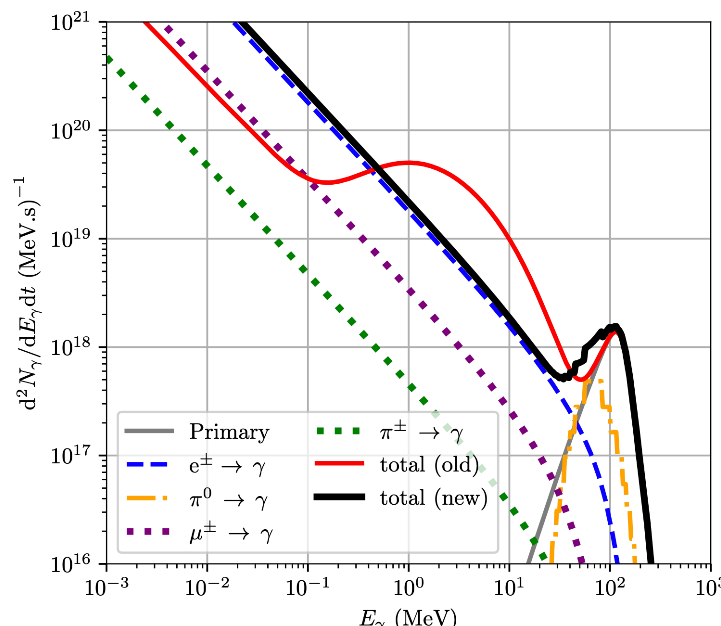
(no spin)

BH lifetimes

$$\tau(M) \approx \frac{\hbar c^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_\odot} \right)^3 \text{ yr}$$

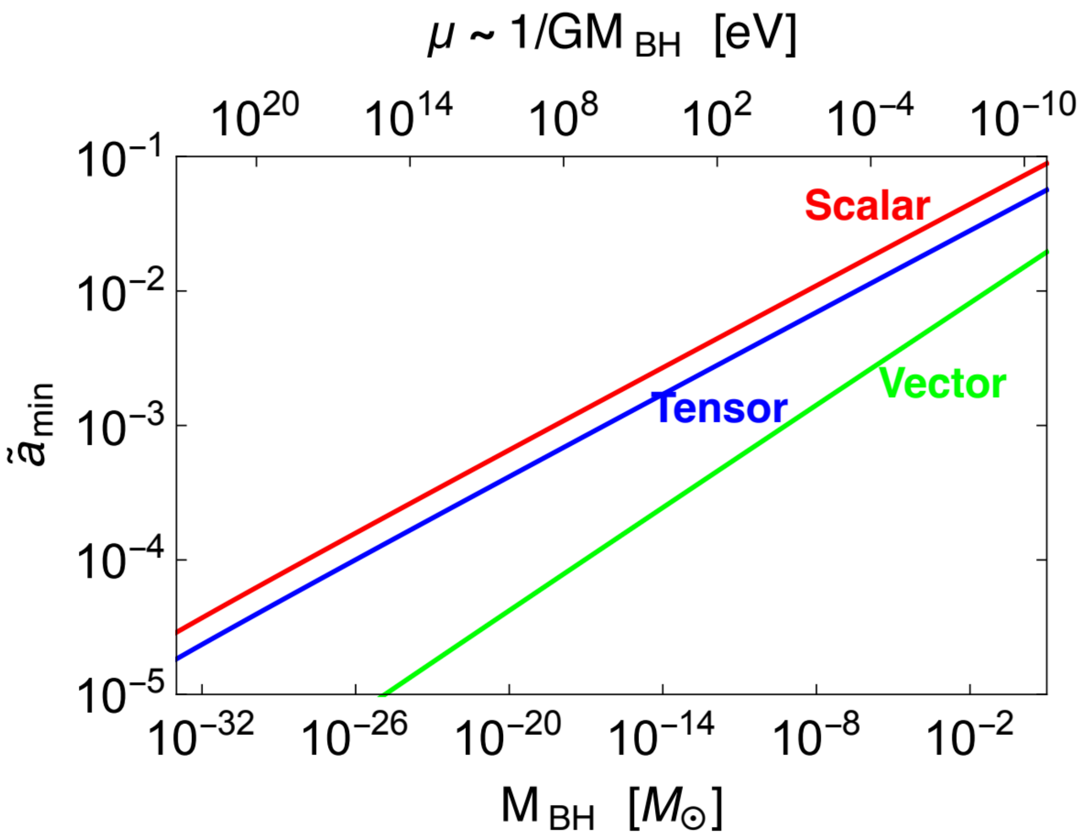
Survival to the present

$$m_{\rm BH} \gtrsim 10^{15} \text{ g}$$



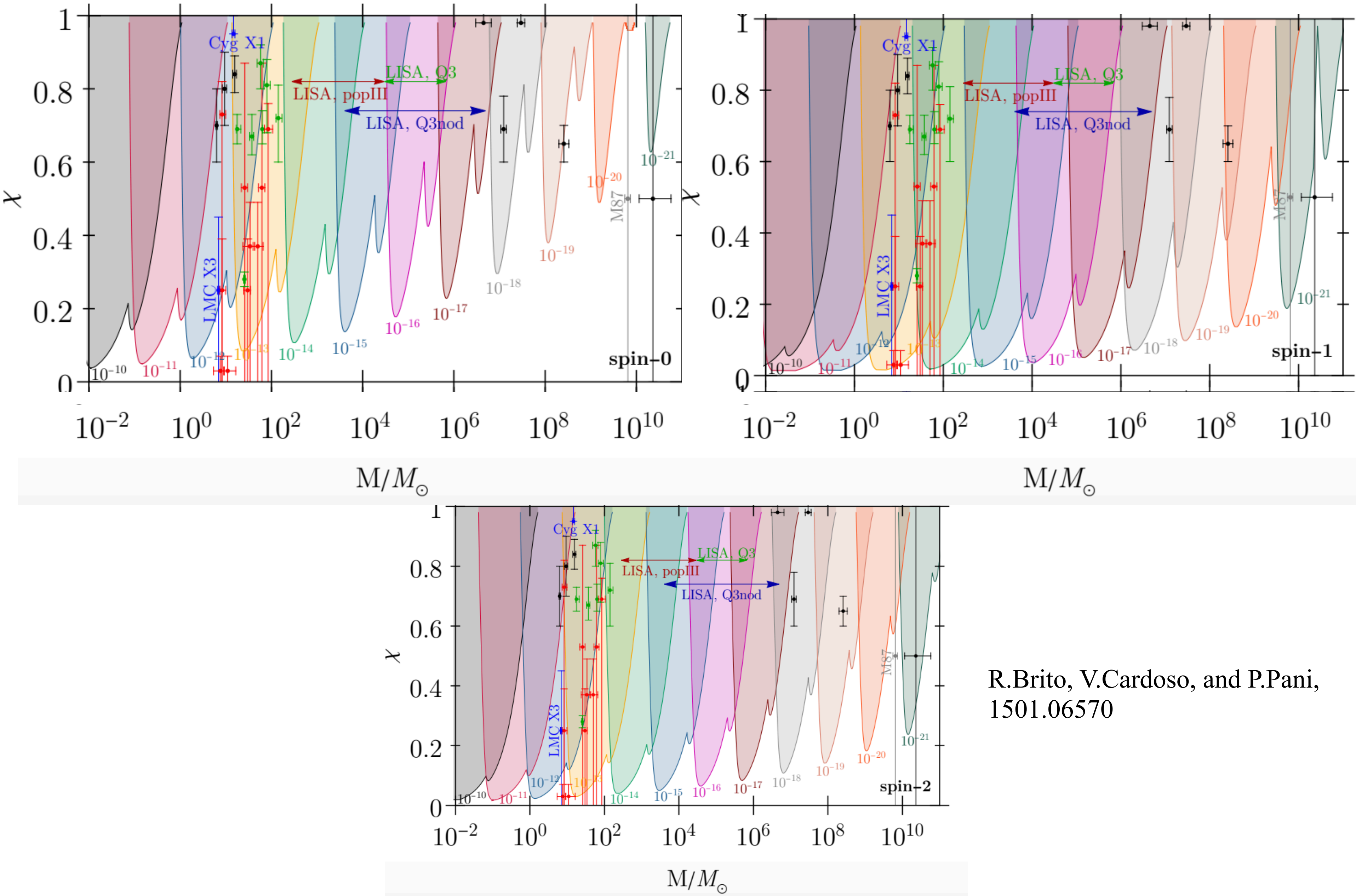
A.Arbey & J.Auffenger, 2108.02737

Minimal spins for Superradiance



C. Ünal 2301.08267

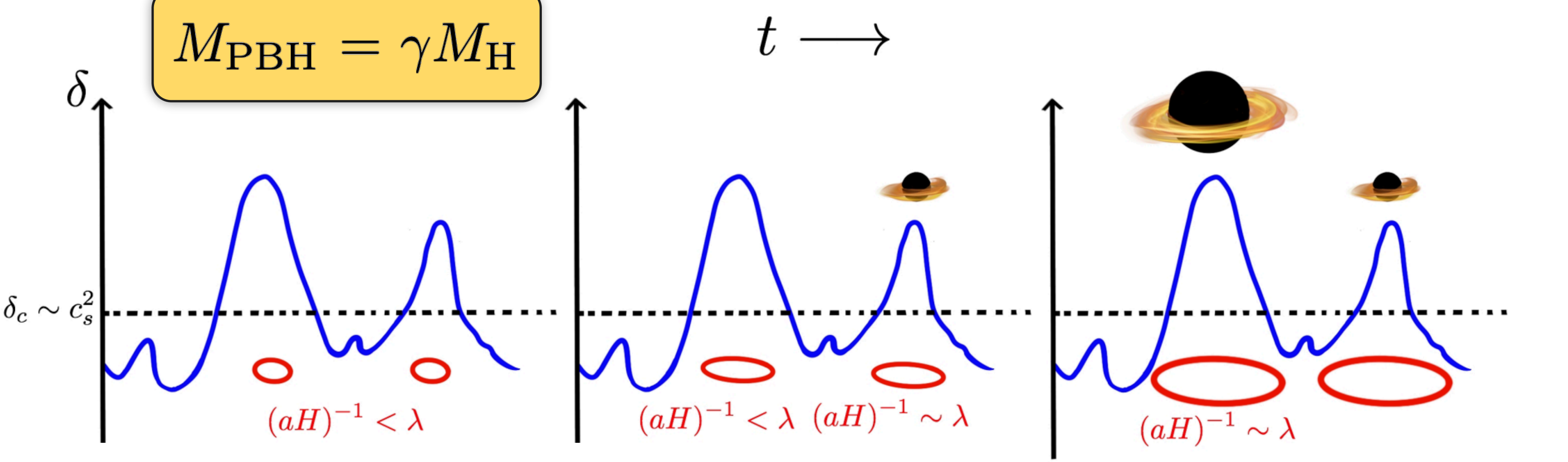
Regge Plots spin-0, 1, 2



R.Brito, V.Cardoso, and P.Pani, 1501.06570

Formation

$$M_{\rm PBH} = \gamma M_{\rm H}$$



$$M_{\rm H} = \frac{4}{3}\bar{\rho}\left(\frac{c}{H}\right)^3 = \frac{c^3}{2GH} \sim 10^{15}\,{\rm g}\left(\frac{t}{10^{-23}{\rm s}}\right)$$

P.Villanueva-Domingo, O.Mena, S.Palomares-Ruiz, 2103.12087

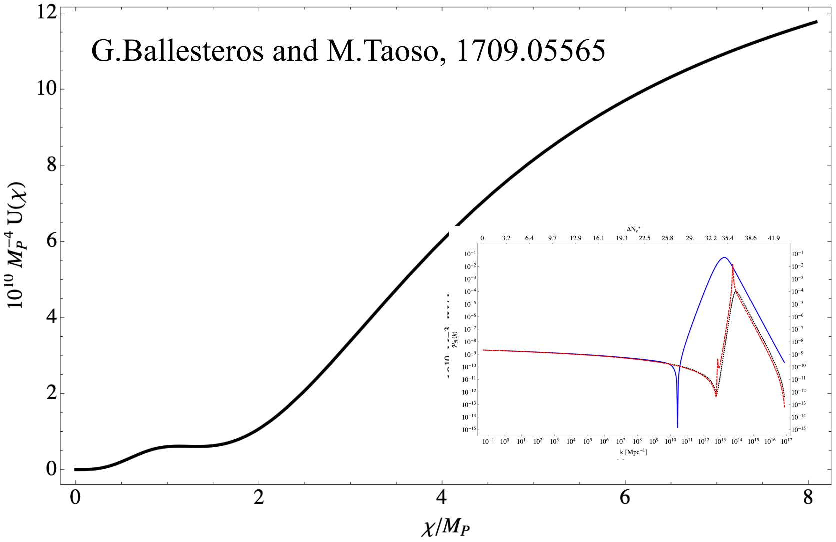
$$\beta(M) \equiv \frac{\rho_{\rm PBH}}{\rho(t_i)}$$

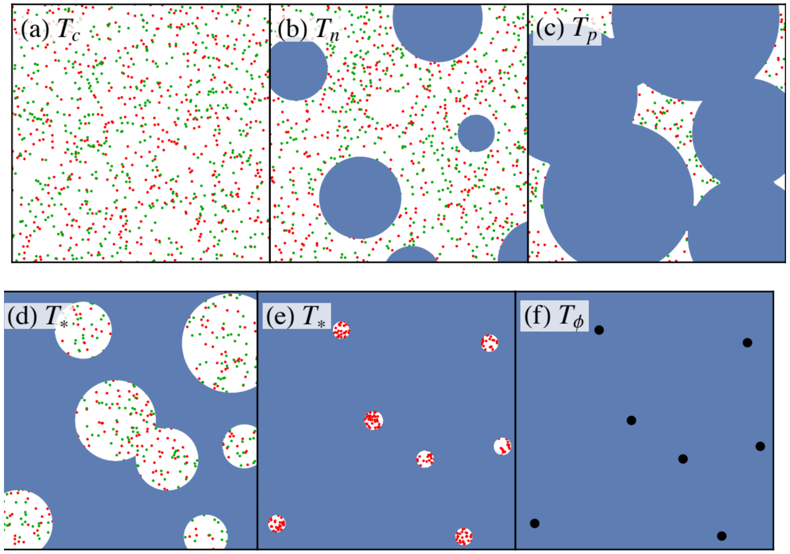
$$\beta'(M) \equiv \gamma^{1/2}\left(\frac{g_{*{\rm i}}}{106.75}\right)^{-1/4}\left(\frac{h}{0.67}\right)^{-2}\beta(M)$$

$$f(M) \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 3.81 \times 10^8 \beta'(M)\left(\frac{M}{M_\odot}\right)^{-1/2}$$

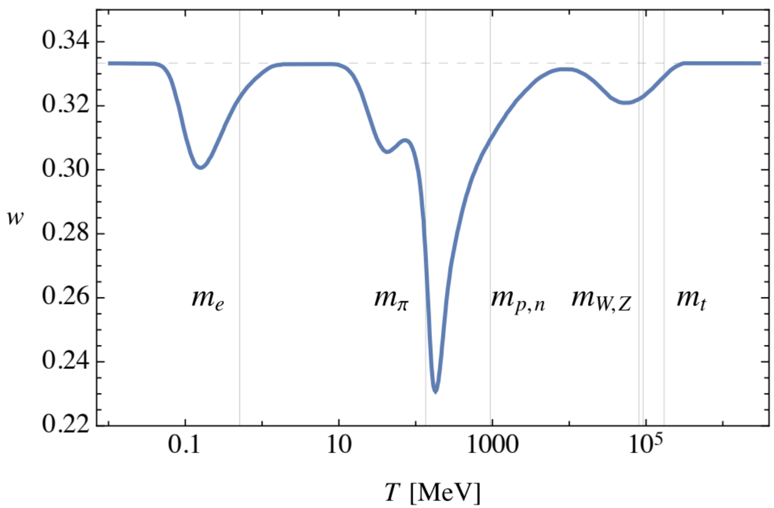
B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, Rept.Prog.Phys. (2021), 2002.12778

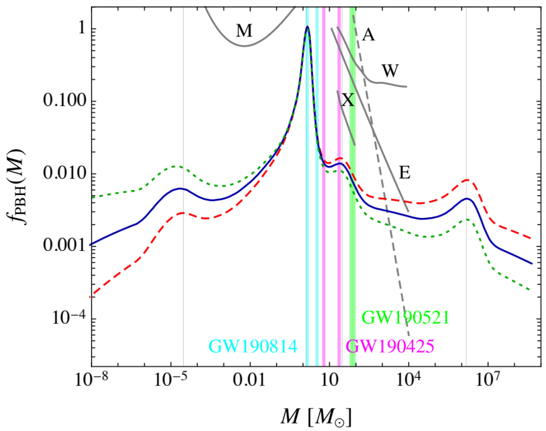
Formation mechanisms and mass distributions





J.-P.Hong, S.Jung, and K.-P. Xie, 2008.04430
K.Kawana, K.-P. Xie, 2106.00111

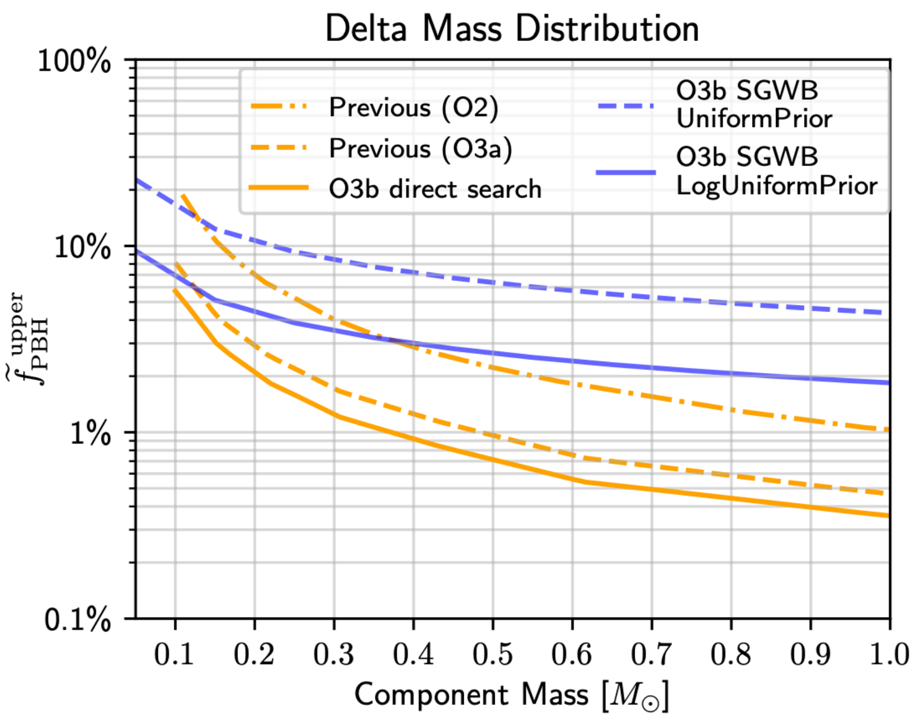


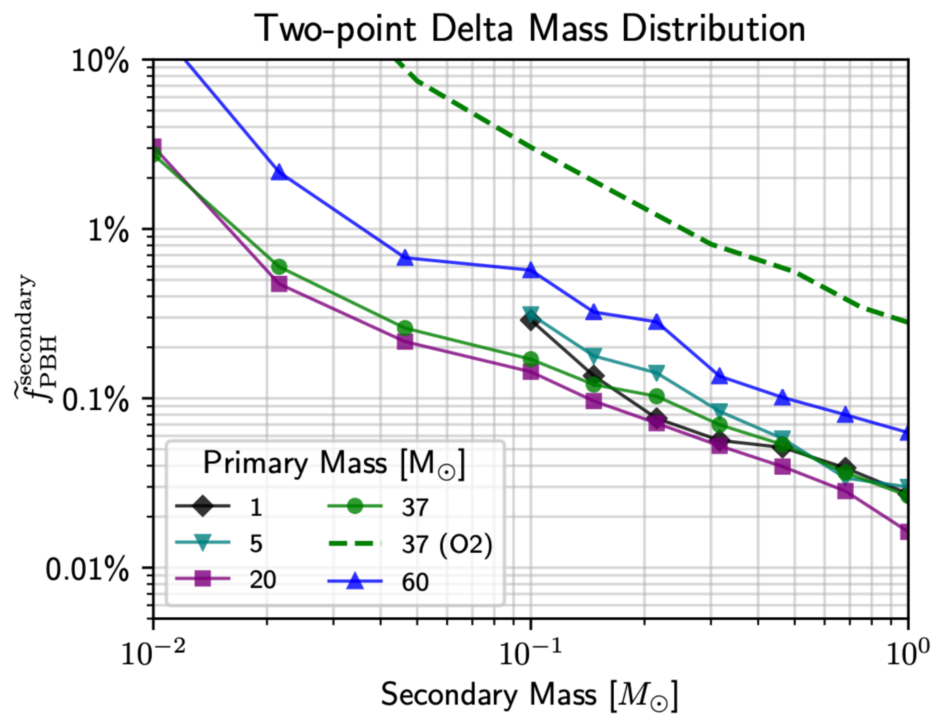


Etc…many others

B.Carr, S.Clesse, J.Garcia-Bellido, and F.Kühnel, 1906.08217

PBH – sub-solar mass merger

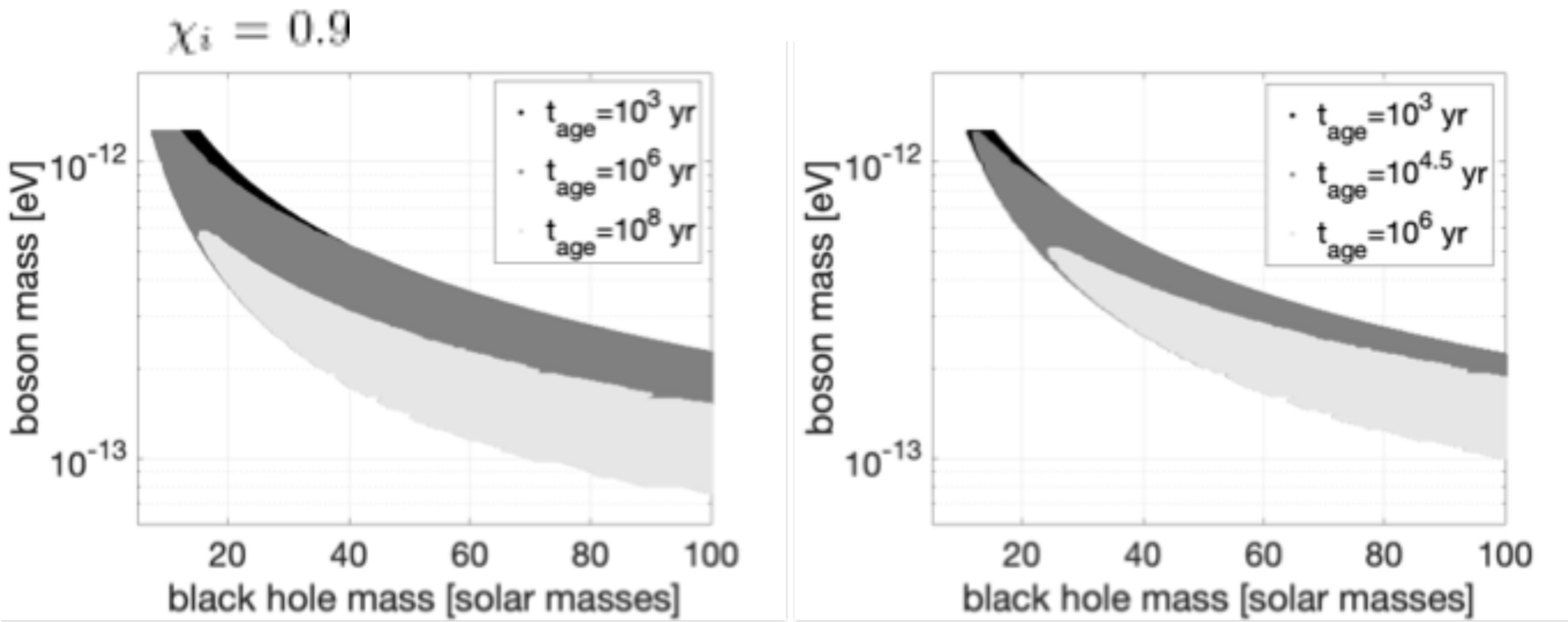




A.H.Nitz and Y.-F.Wang, 2202.11024

Superradiance – GW Searches

All-sky for quasi-monochromatic, long-duration from scalar boson clouds



LIGO Scientific, Virgo, and KAGRA, R.Abbott *et al.*, 2111.15507

$$h_0 \approx 6 \times 10^{-24}\ \mathrm{yr} \left(\frac{M}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\ \mathrm{kpc}}{D}\right)(\chi_i - \chi_f)$$

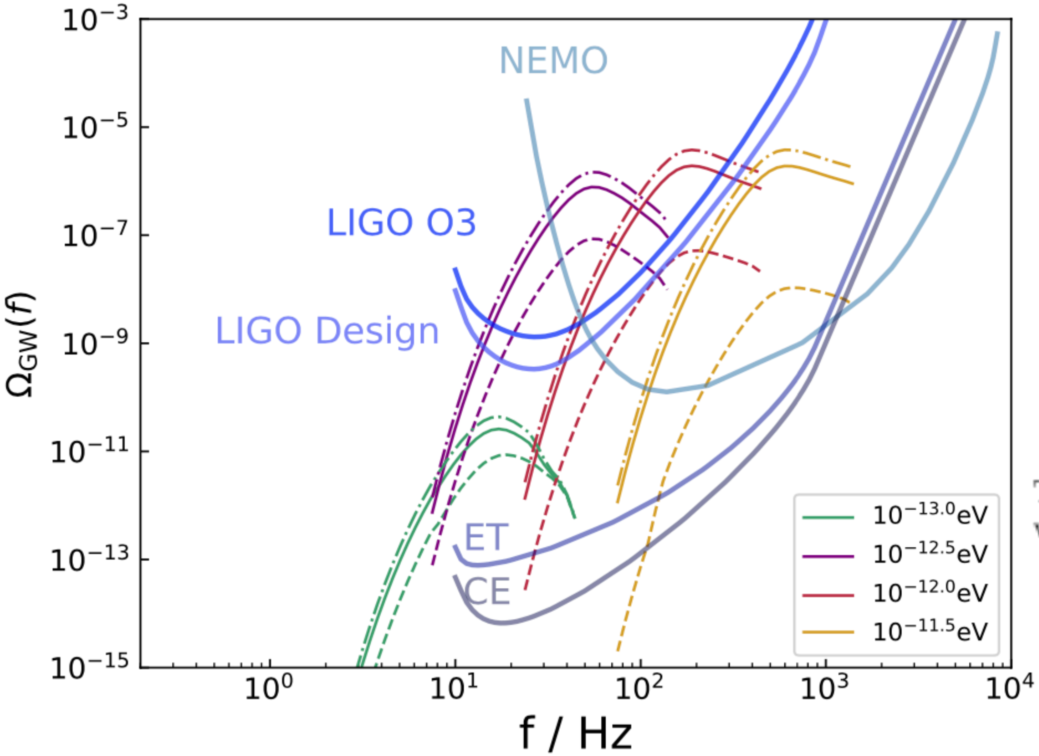
R.Brito, V.Cardoso, and P.Pani, *Lect.Notes Phys.* (2015), 1501.06570

$$\tau_{\mathrm{GW}}^S \approx 1.3 \times 10^5\ \mathrm{yr}\left(\frac{M}{10M_\odot}\right)\left(\frac{0.1}{M\mu_S}\right)^{15}\left(\frac{0.5}{\chi_i - \chi_f}\right)$$

Superradiance – SGWB search

SGWB search with O3 including all higher modes

$$\Omega_{GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln(f)}$$



χ_i	$\log\mathcal{B}$	m_s (eV)
Uniform[0, 1]	-0.27	$[1.5, 16] \times 10^{-13}$
Uniform[0, 0.5]	-0.15	$[1.9, 8.3] \times 10^{-13}$
Uniform[0.5, 1]	-0.30	$[1.3, 17] \times 10^{-13}$

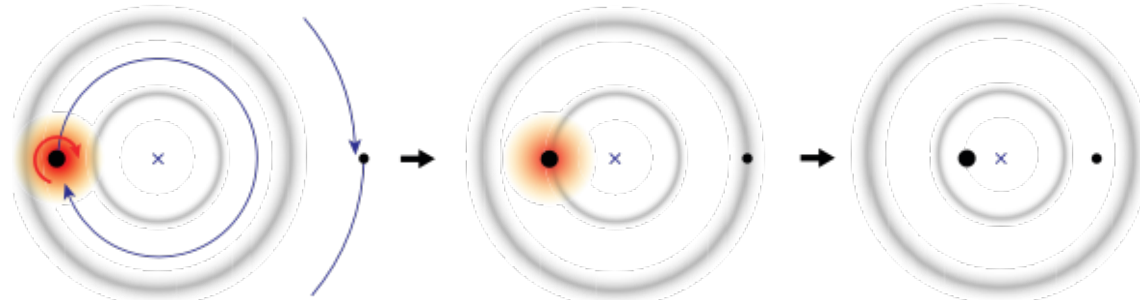
TABLE I. Results of Bayesian inference and exclusion intervals for the mass of boson at 95% credible level.

C.Yuan, Y.Jiang, Q.-G.Huang, 2204.03482 – O3 search

C.Yuan, R. Brito, and V.Cardoso, 2106.00021 – SGWB predictions

Superradiance – further issues

Environmental effects (binaries)
Resonances, multipole moments, etc.

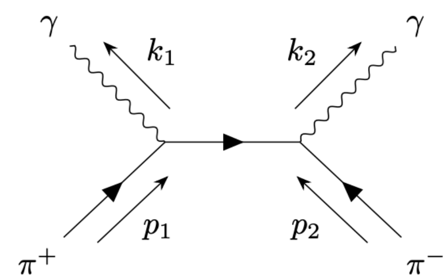


D.Baumann, H.S.Chia, and R.A.Porto, 1804.03208

Self-interactions $\frac{g}{3!}\varphi^3 + \frac{\lambda}{4!}\varphi^4$ can saturate the superradiant growth

M.Baryakhtar, M.Galanis, R.Lasenby, and O.Simon, 2011.11646
H.Omiya, T.Takahashi, T.Tanaka, and H.Yoshino, 2211.01949

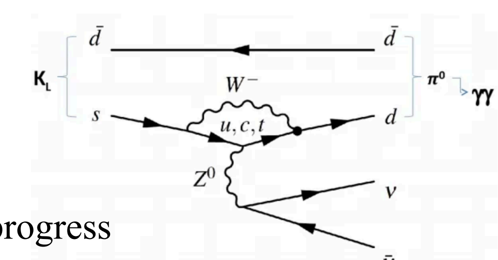
Mesons‘



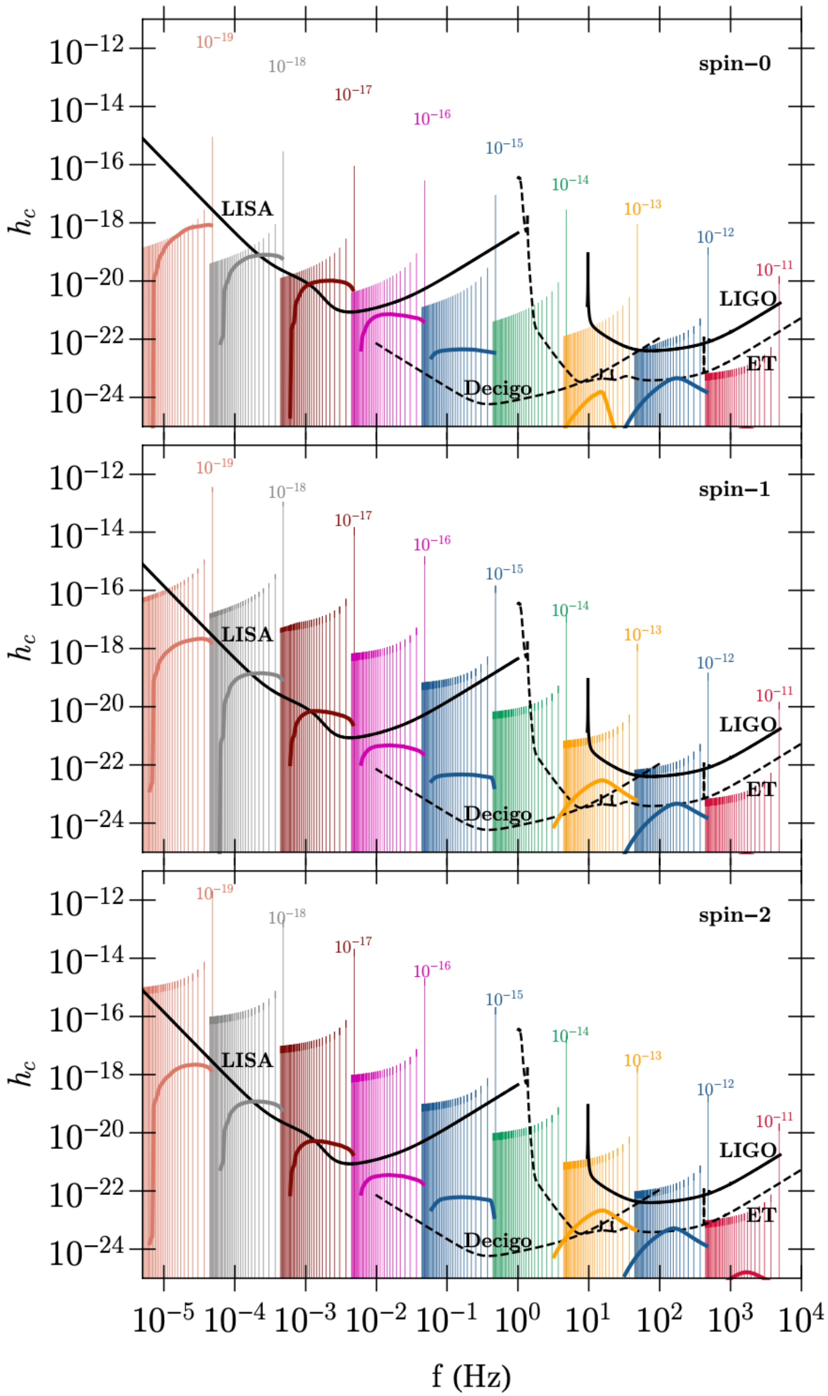
Other signals – (Lasing axions?)

T.W.Kephart and J.Rosa, 1709.06581

P.B.Ferraz, T.W.Kephart and J.Rosa, 2004.11303



JBD, T.W.Kephart, J.Rosa, in progress



SVT sensitivities

R.Brito, V.Cardoso, and P.Pani, *Lect.Notes Phys.* (2015), 1501.06570

PBH – LVK GWTC-3 PBH merger constraints

LVK GW results constrain PBH fractions and merger rates for different mass functions

	LN	PL	BPL	CC
$\mathrm{BF}_{\mathrm{1st}}^{\mathrm{2nd}}$	0.9	0.4	0.69	1.2
$\mathrm{BF}_{\mathrm{PL}}$	166	1	2	139
$10^3 f_{\mathrm{pbh}}$	$1.8^{+0.3}_{-0.3}$	$2.3^{+0.3}_{-0.3}$	$2.2^{+0.3}_{-0.4}$	$1.5^{+0.2}_{-0.2}$
$10^2 R_2/R_1$	$1.0^{+0.2}_{-0.1}$	$0.9^{+0.1}_{-0.1}$	$0.9^{+0.3}_{-0.1}$	$2.2^{+1.3}_{-0.5}$

L.Liu, Z.-Q.You, Y.Wu, and Z.-C.Chen, 2210.16094

Formation mechanisms and mass distributions

$$f_{\rm peak} \simeq (1.8\times 10^{16}\,{\rm Hz})\left(\frac{M}{10^5\,{\rm g}}\right)^{1/2}$$

Monochromatic $\psi_{\rm mon}(M) \equiv f_{\rm PBH}(M_c)\delta(M-M_c)$

lognormal $\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\,\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$

K.Kannike, L.Marzola, M.Raidal, H.Veermae, 1705.06225

Power law $\psi(M) \propto M^{\gamma-1}$

H.Deng, 2101.11098

• • •

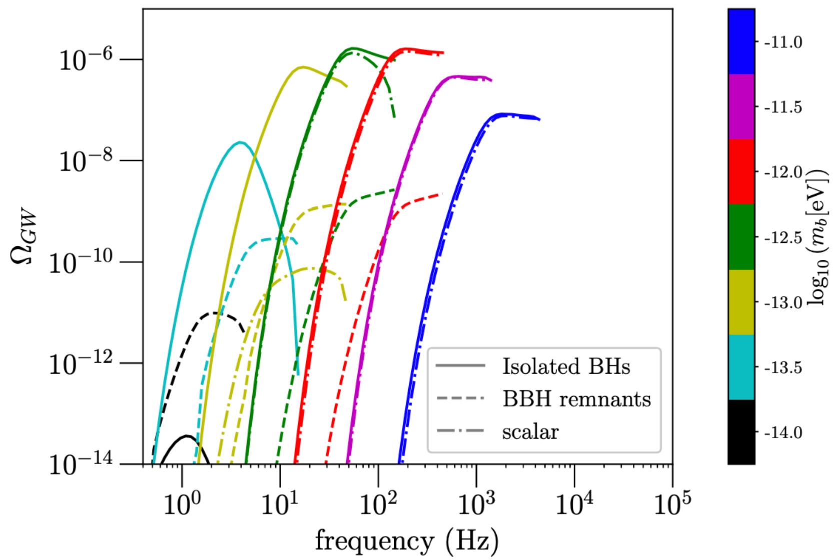
B.J.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, 0912.5297, B.J.Carr, M.Raidal, T.Tenkanen, V.Vaskonen, and H.Veermae, 1705.05567.

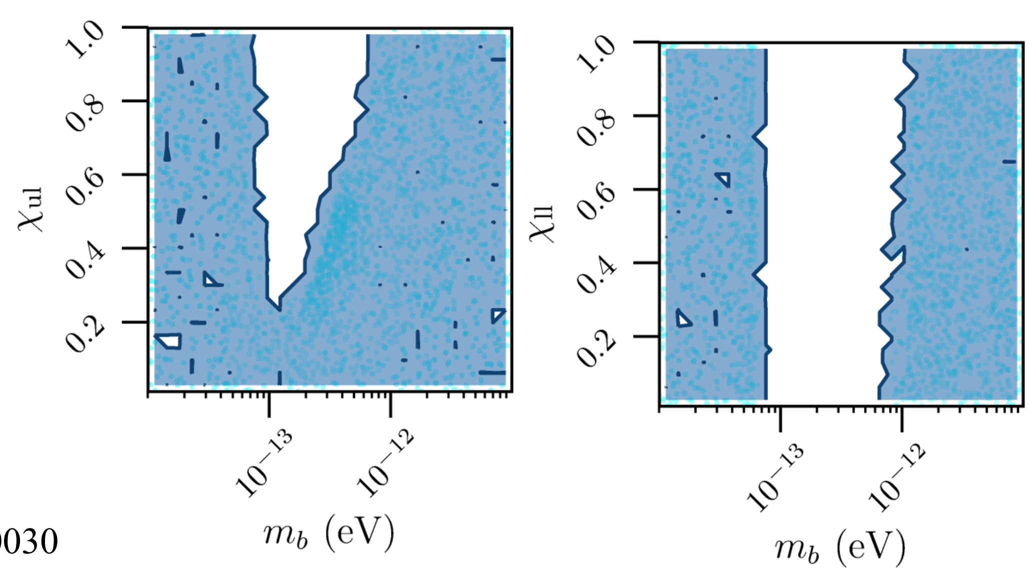
Superradiance – SGWB search

SGWB search with O2 for ULVectors

$$\tau^S_{\rm inst} \approx 30\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{\chi_i}\right)$$
$$\tau^V_{\rm inst} \approx 280\,{\rm s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{\chi_i}\right),$$

$$\tau^S_{\rm GW} \approx 10^5\,{\rm yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\chi_i-\chi_f}\right)$$
$$\tau^V_{\rm GW} \approx 8\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{11}\left(\frac{0.5}{\chi_i-\chi_f}\right)$$

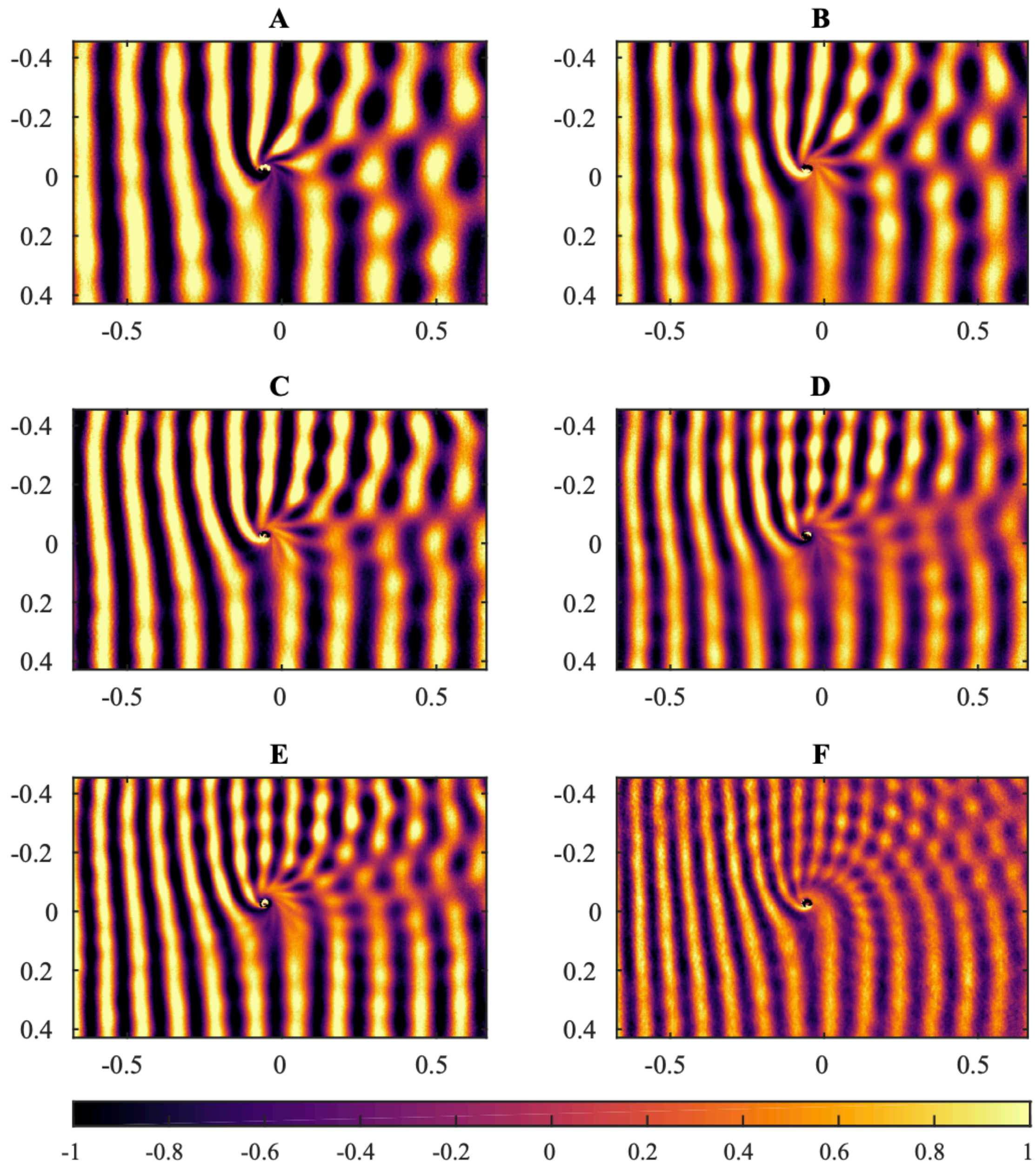




$$\nabla_\alpha F^{\alpha\beta} = \mu^2 A^\beta$$

W.E.East and F.Pretorious, 1704.04791
V.Frolov, P.Krtous, D.Kubiznak, and J.Santos, 1804.00030

L.Tsukada, R.Brito, W.E.East, N.Siemonson 2011.06995



Observation in laboratory vortex flow

Theo Torres, Sam Patrick, Antonin Coutant, Mauricio Richartz, Edmund W. Tedford et al. (Dec 19, 2016)
Published in: *Nature Phys.* 13 (2017) 833-836 • e-Print: 1612.06180 [gr-qc]