Axion Searches from Black Holes to the Basement

Saturday Morning of Theoretical Physics, Nov 2022

John March-Russell

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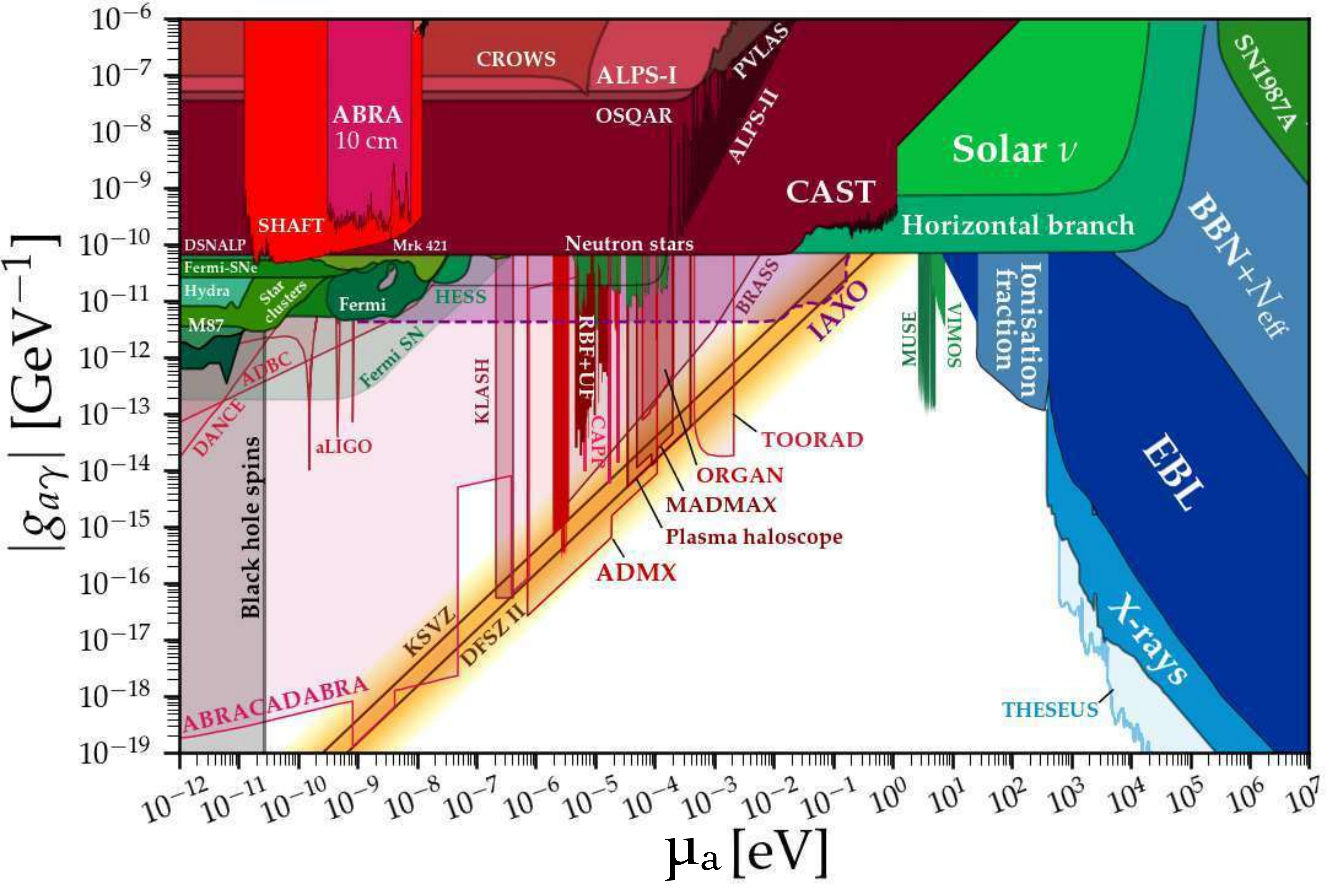
There are a *huge* range of possibilities

eg, every one of these regions is a different probe (current, or near-future) of just one possible axion coupling



As Joe Conlon explained axions are expected to often be *very light* with mass $\mu_a \ll m_e$ and are also expected (& constrained) to be *very feebly interacting*

As Joe Conlon explained axions are expected to often be *very light* with mass $\mu_a << m_e$ and are also expected (& constrained) to be *very feebly interacting*

(They also have a variety of *types* of interaction with normal matter - more on this later)

QCD axion mass μ_a set by "axion decay constant" f_a

$$\mu_a \simeq 6 \times 10^{-11}\mathrm{eV}\left(\frac{10^{17}\mathrm{GeV}}{f_a}\right) \simeq (3\mathrm{km})^{-1}\left(\frac{10^{17}\mathrm{GeV}}{f_a}\right)$$

Weinberg 1978; Wilczek 1978

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Axion-like-particles (ALPs) that generalize QCD axion occur very often in string theory. They share many features of QCD axion except tight relationship of mass and f_a - so μ_a and f_a now *independent parameters*

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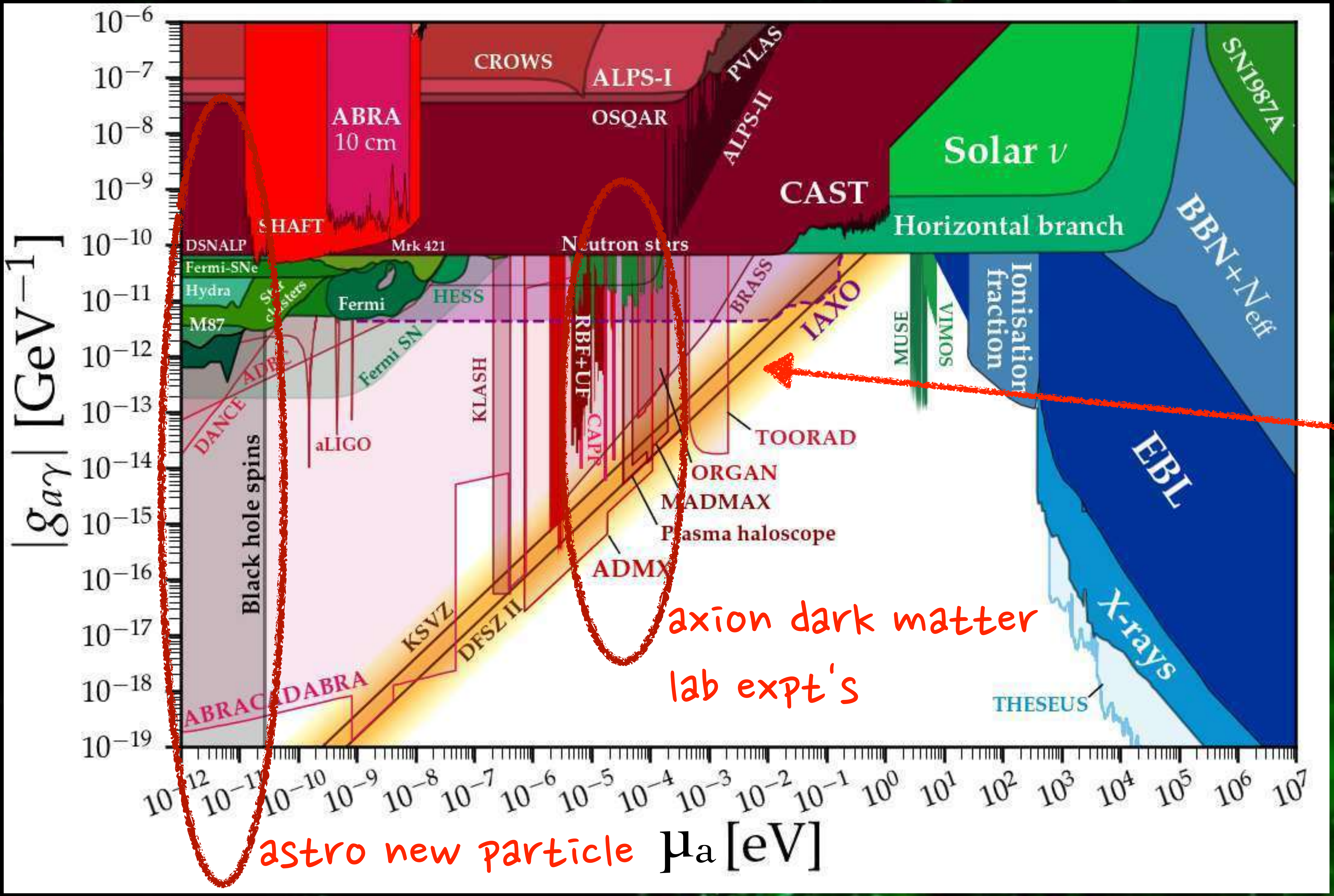
These are two of the most sensitive probes of axions, even reaching the QCD-axion mass-coupling region (and Oxford Phys is involved in both!)



QCD-axion mass-coupling region

axion dark matter lab expt's

astro new particle

First astro....

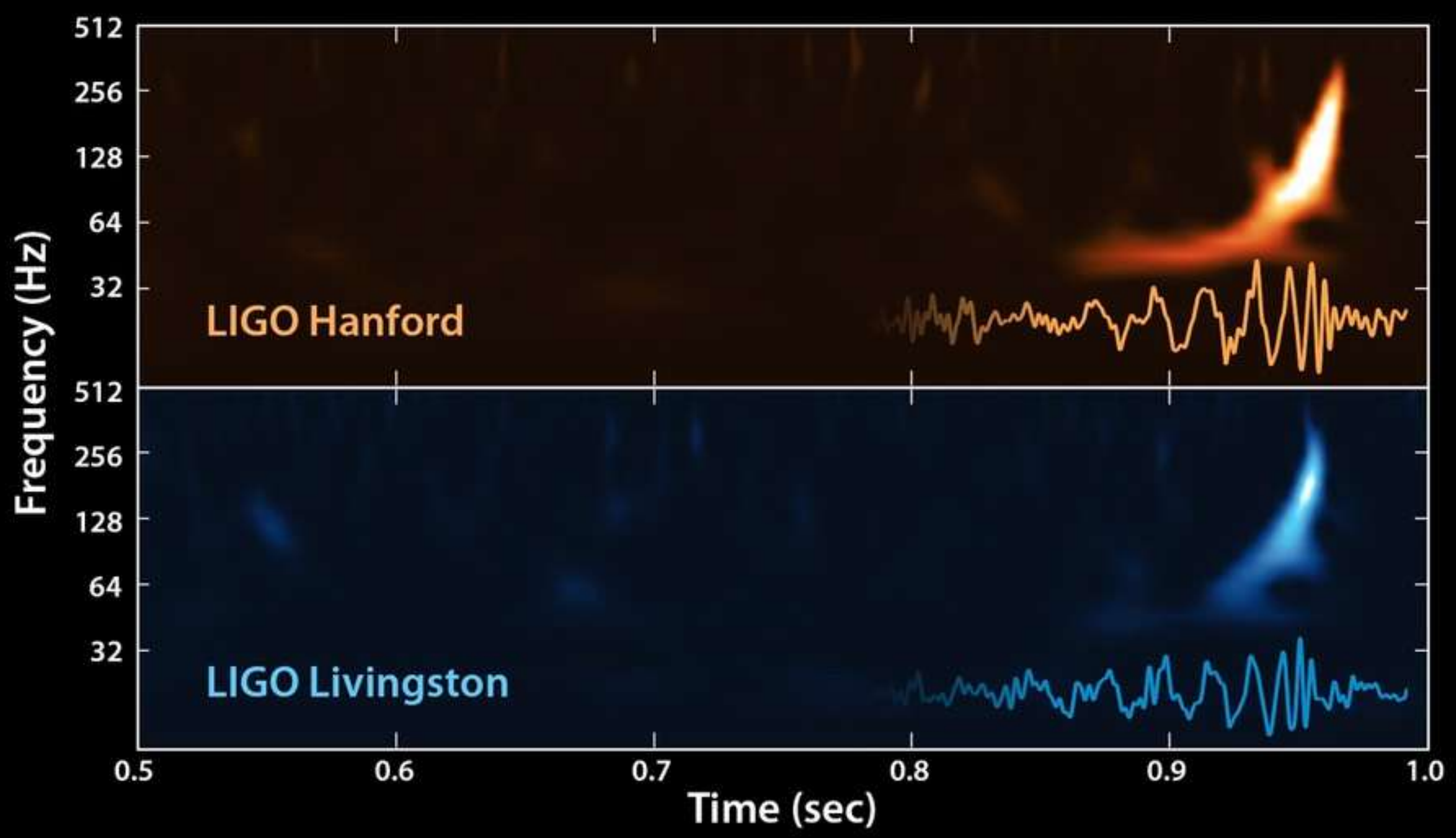
First astro....

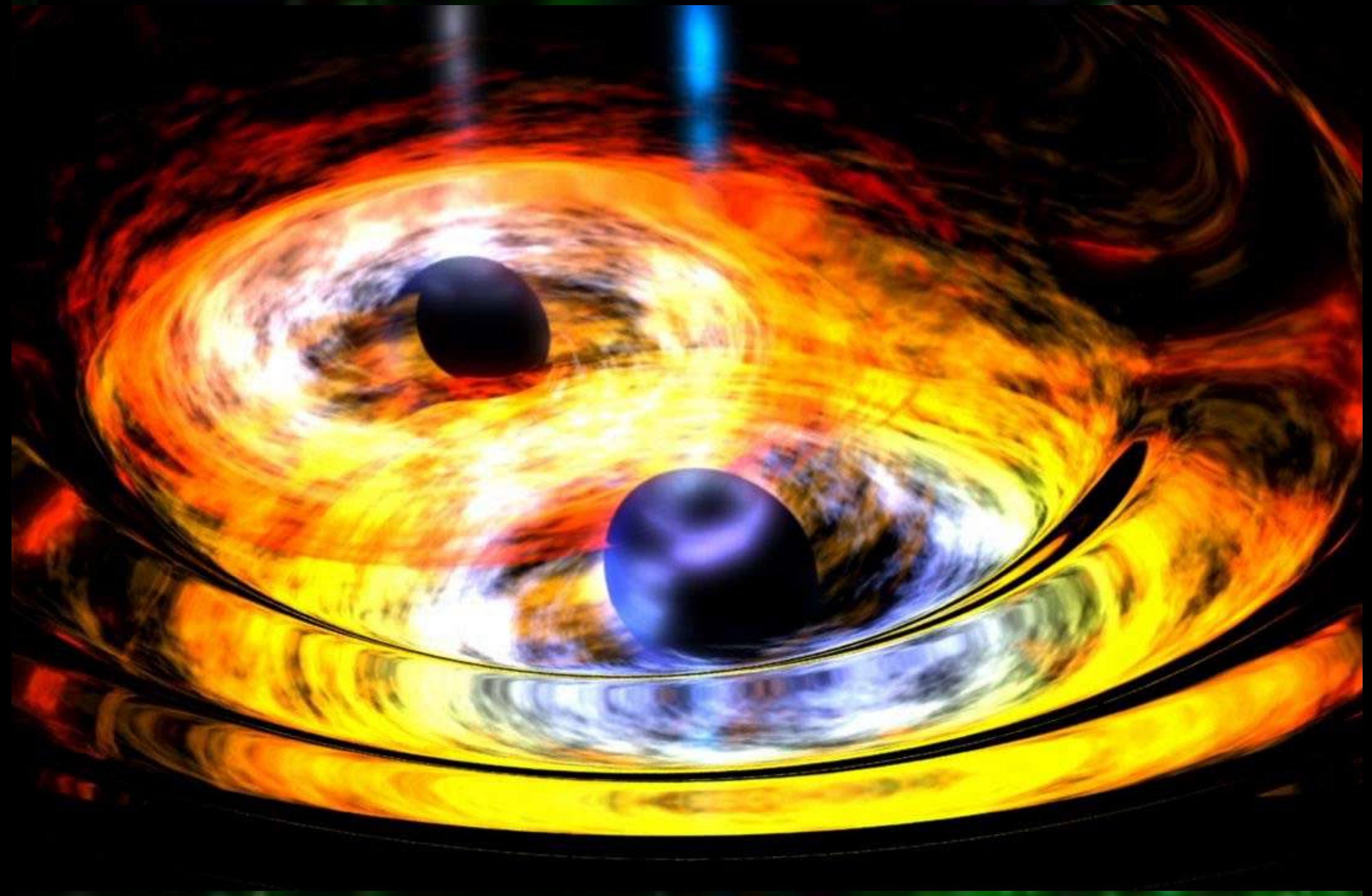
> Remarkably, astrophysical black holes provide a way to search for light axions that only depends on their absolutely mandated gravitational interaction

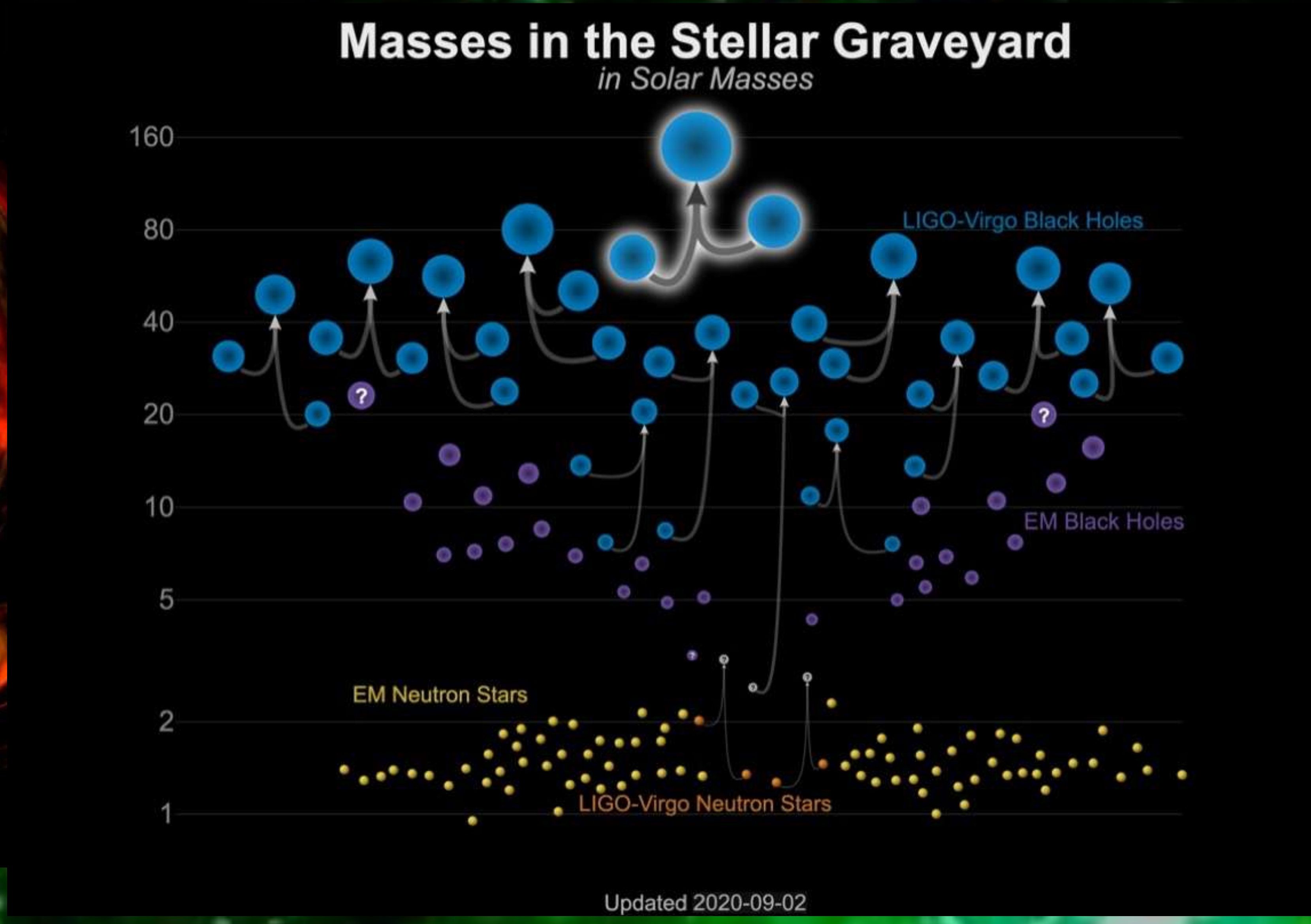
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell; arXiv hep-th/0905.4270

Black Hole Superradiance and Axions
or "BHs as Nature's detectors"

We know that astrophysical BHs exist!







Schwarzschild radii vary from ~few km to ~10^{10} km

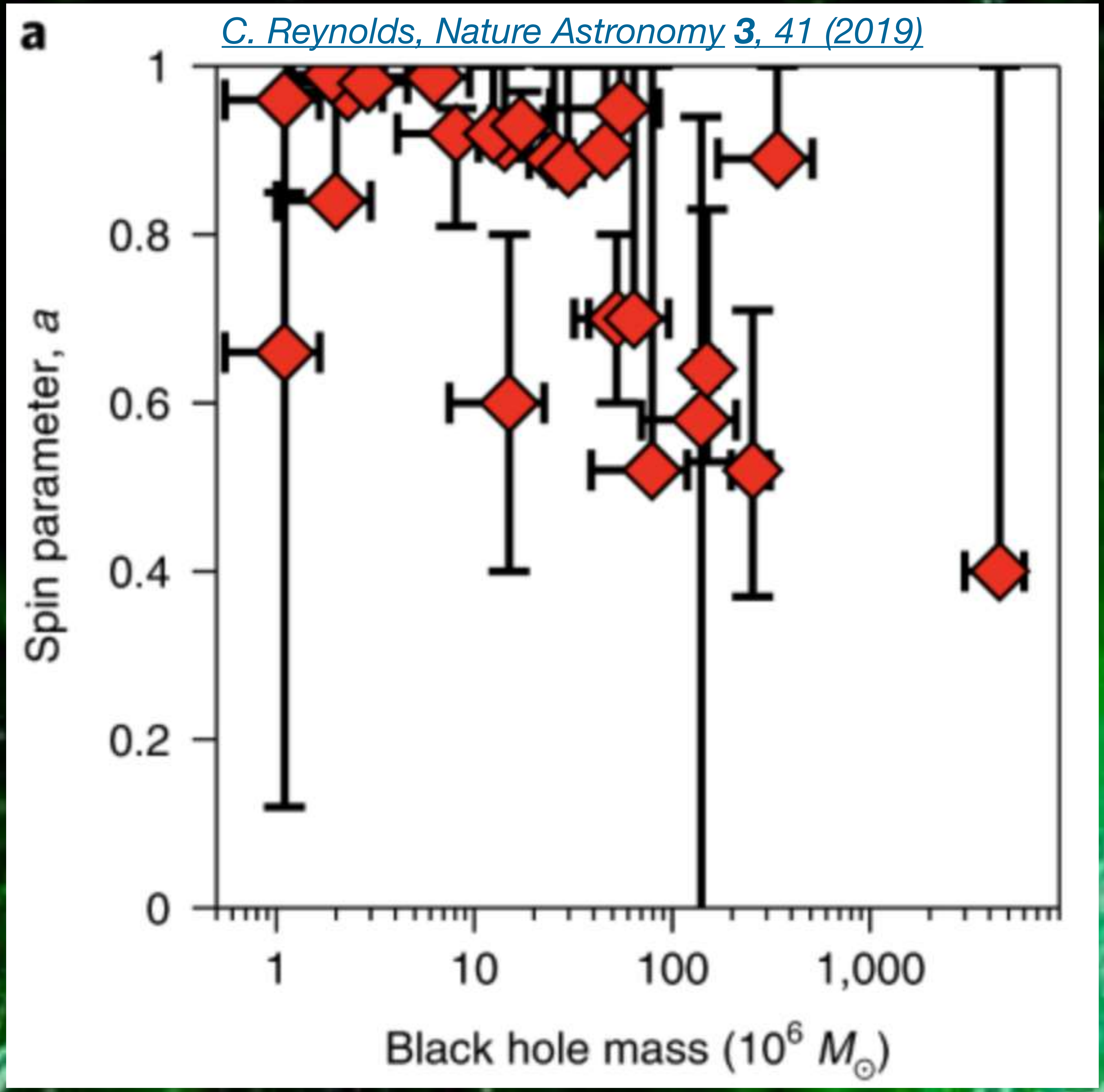
Black Hole Superradiance and Axions

Importantly astrophysical BHs are *rotating* (Kerr BHs)

`spin parameter' $$a_* \equiv \frac{J}{G_N M^2}$$

a_*=1: BH horizon velocity=c

a_*=0: non-rotating



C. Reynolds, Nature Astronomy **3**, 41 (2019)

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This angular momentum & rotational KE can be *extracted*

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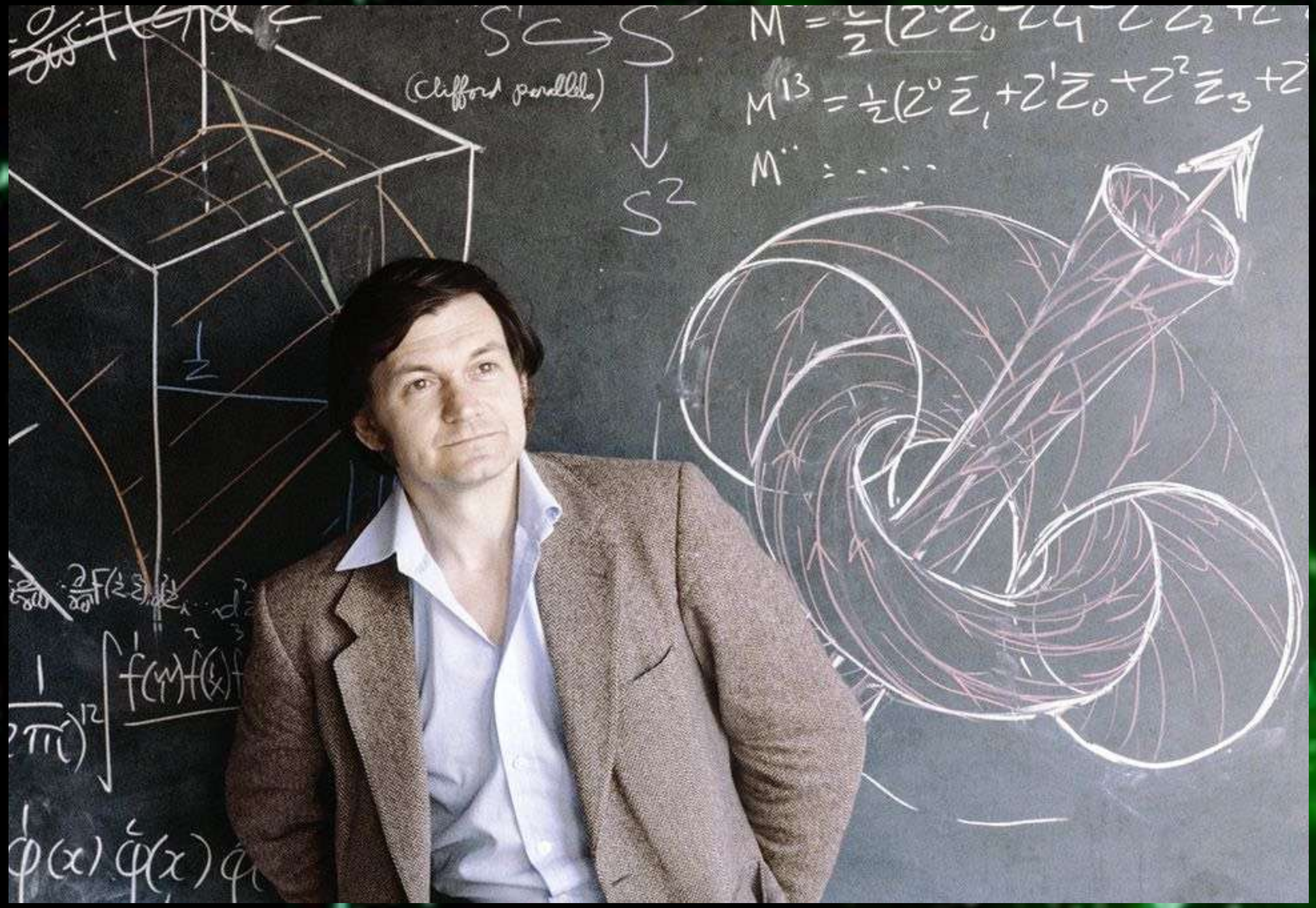
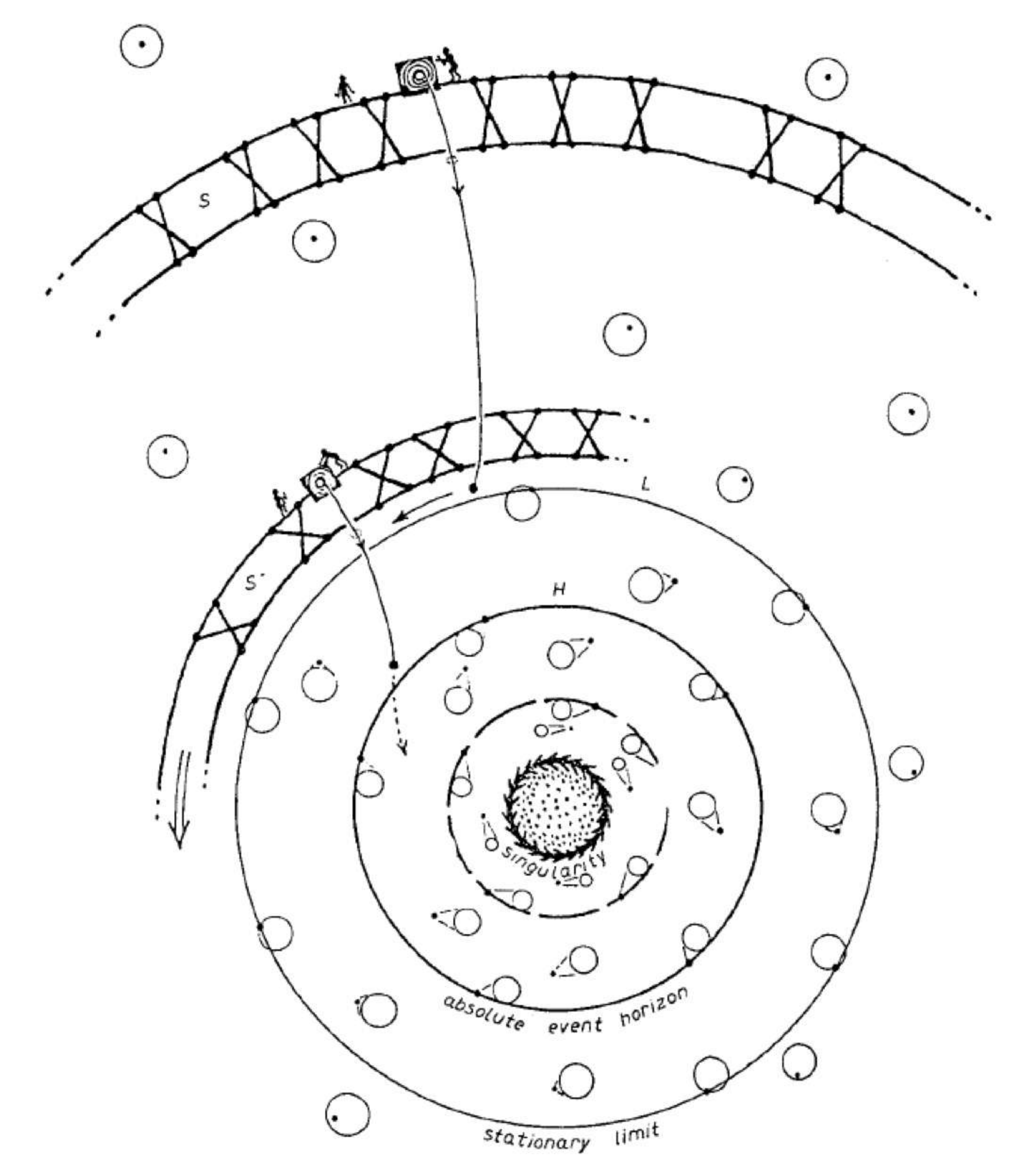
This angular momentum & rotational KE can be *extracted*

- classically by the *Penrose process* and its close relatives





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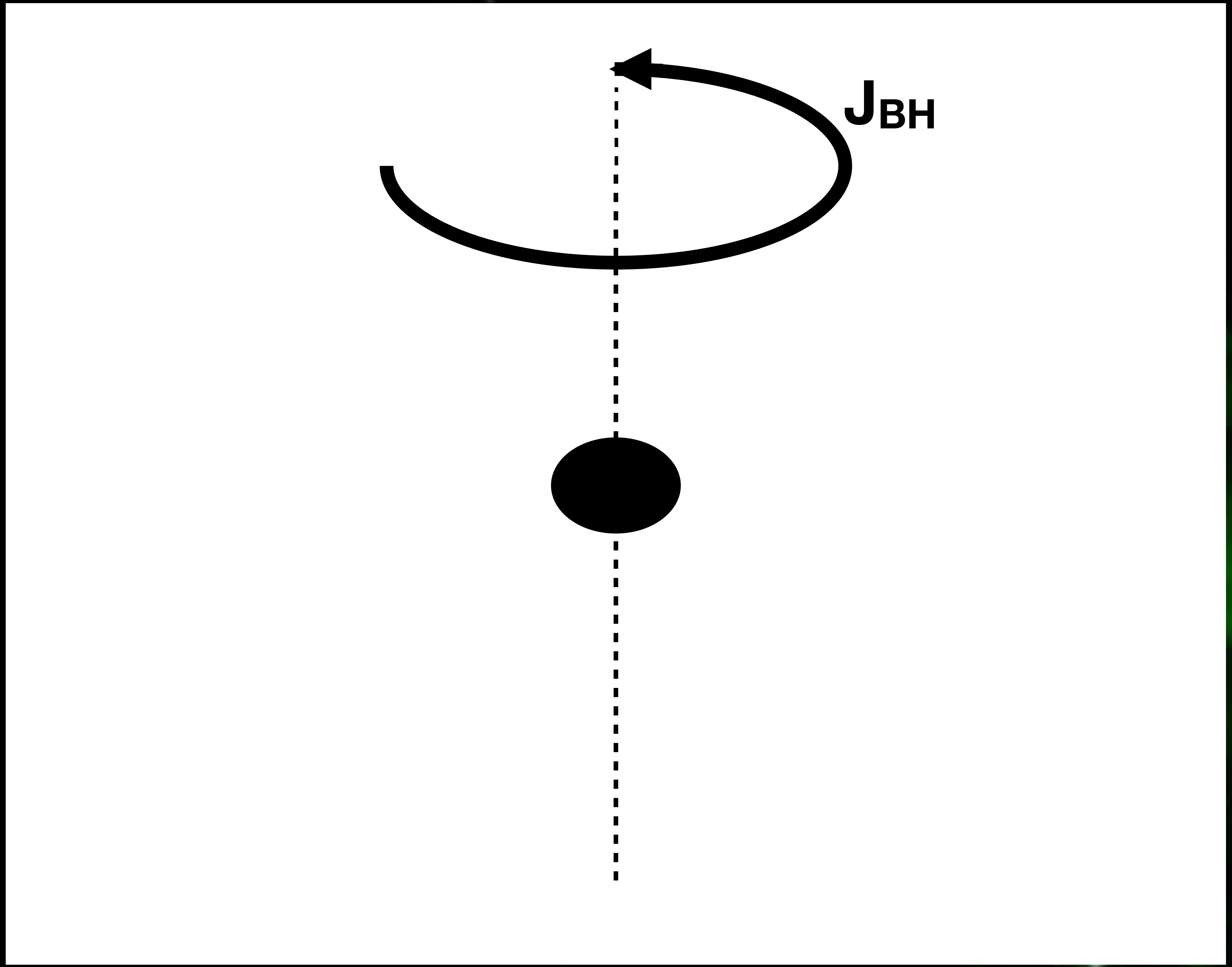
a `cloud' of bosons in non-zero angular momentum bound states around BH grows due to a form of `lasing' instability of Kerr BHs

Black Hole Superradiance and Axions



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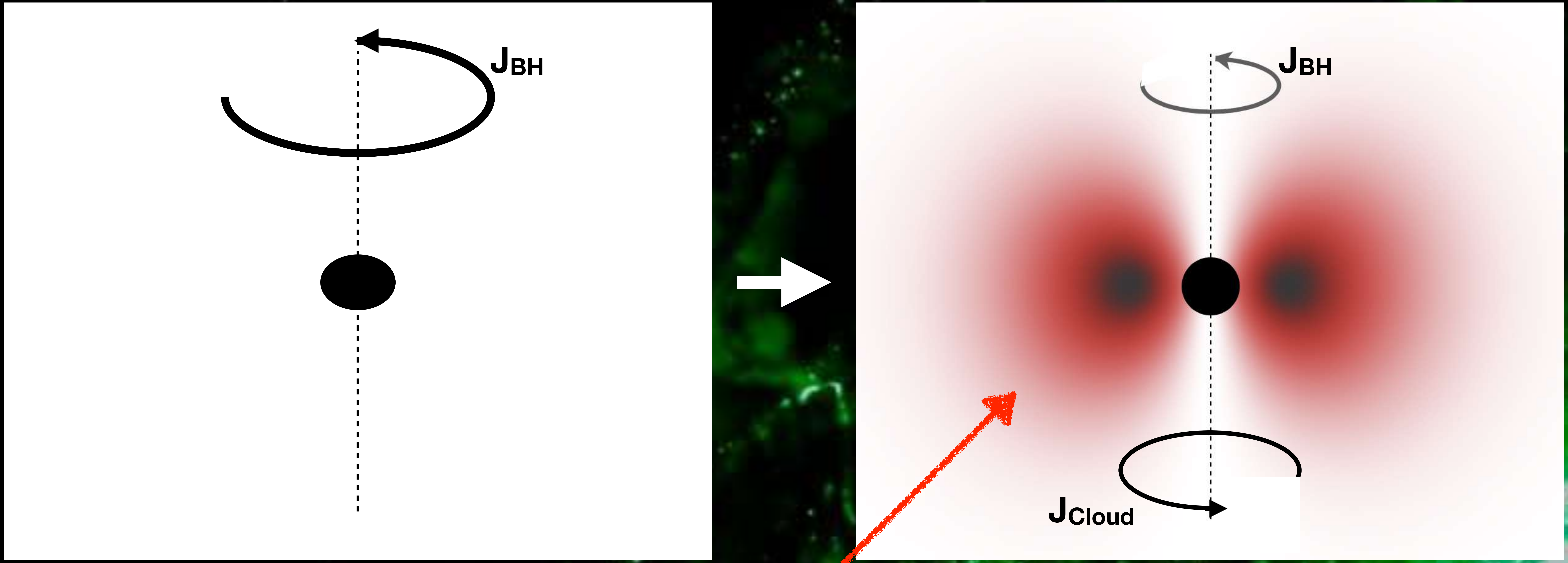

axion cloud containing large
angular momentum & energy

Quantumly: massive Bose field in a Kerr BH background has bound states with Im(E)=-Γ>0 - exponentially *growing* states!

Damour etal; Zouros & Eardly; Detweiler; Dolan;...

cf. Black hole 'bomb' of Press & Teukolsky

$$|\psi|^2 \sim |\mathrm{e}^{-iEt}|^2|f(r,\theta,\phi)|^2 \sim \mathrm{e}^{2|\Gamma|t}|f(r,\theta,\phi)|^2$$

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spatial part of state very similar to L>0 orbitals in Hydrogen atom!

Can understand this by studying QM solutions in the effective potential that a L>0 massive boson sees in Kerr BH background

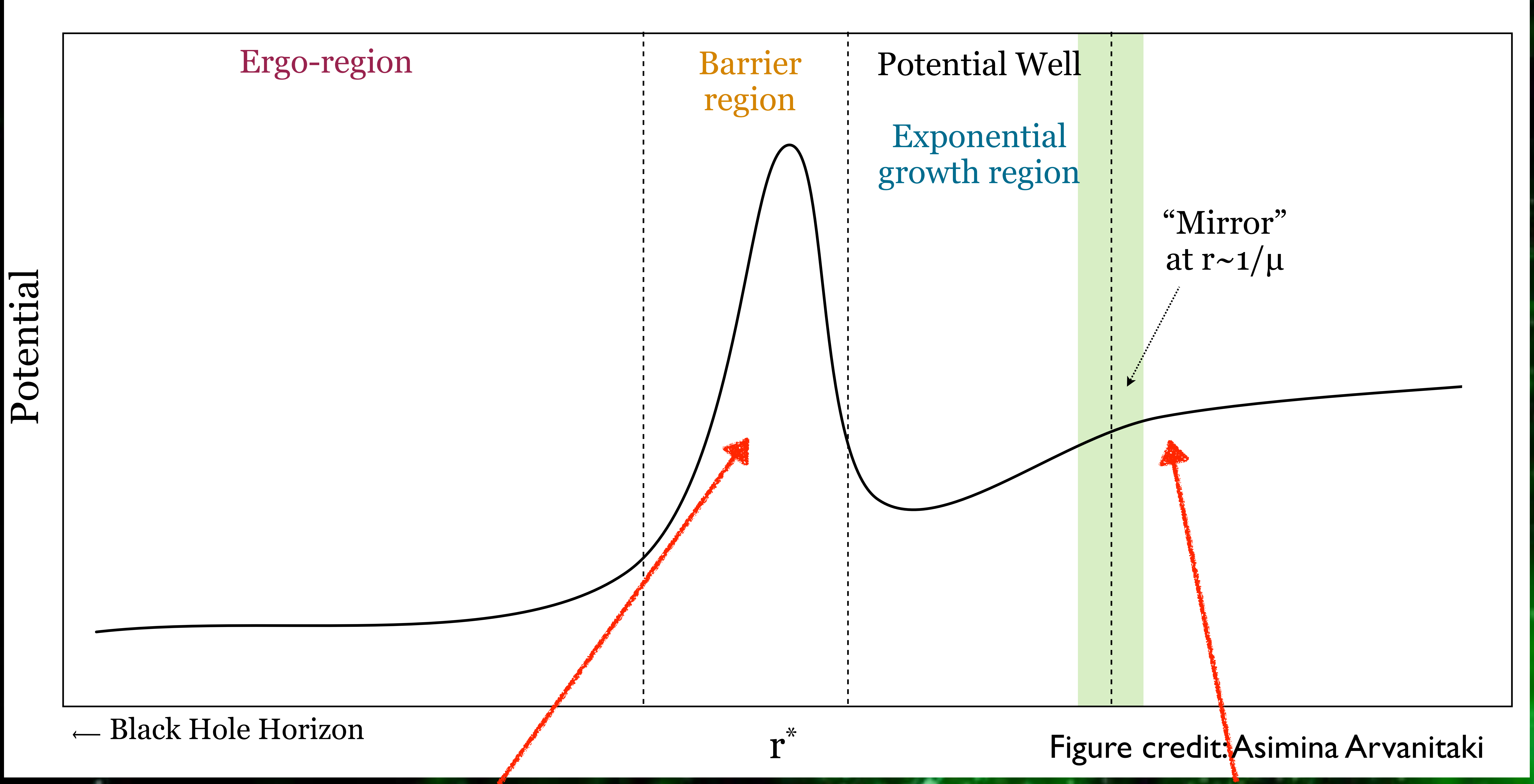

Figure credit: Asimina Arvanitaki

barrier due to state having non-zero L & L_z

this coulomb-like rise in potential due to mass

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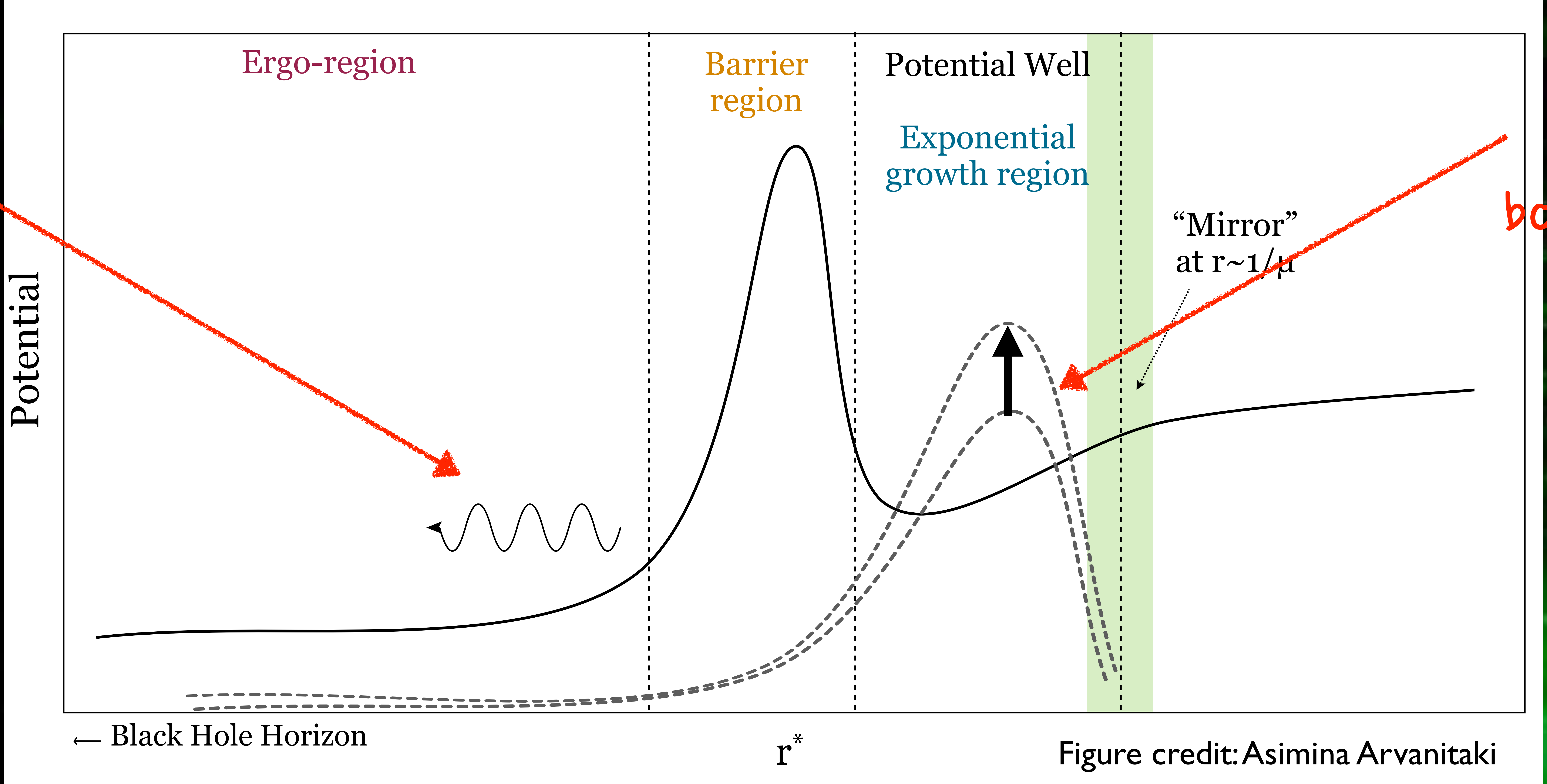
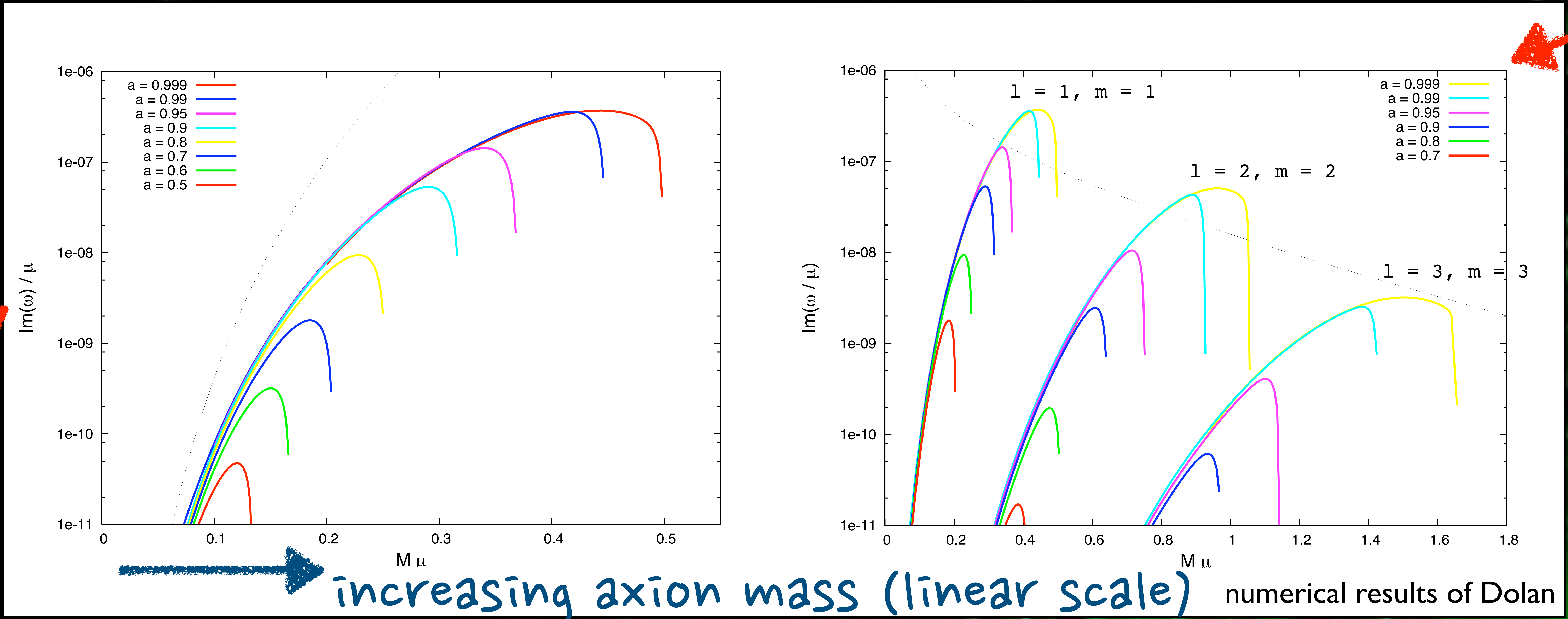


Figure credit: Asimina Arvanitaki

quantum fluctuation of axion

exponentially growing 'atomic' bound state

Can calculate growth rates for all the various'atomic' bound states as function of BH spin a_* (fastest for high BH spin), and μR_g (axion mass μ times the BH gravitational length scale $R_g = M\,G_N$)



numerical results of Dolan

size of Γ/μ (log scale)

increasing axion mass (linear scale)

growth rates of various bound states ($L=L_z=1$ wins)

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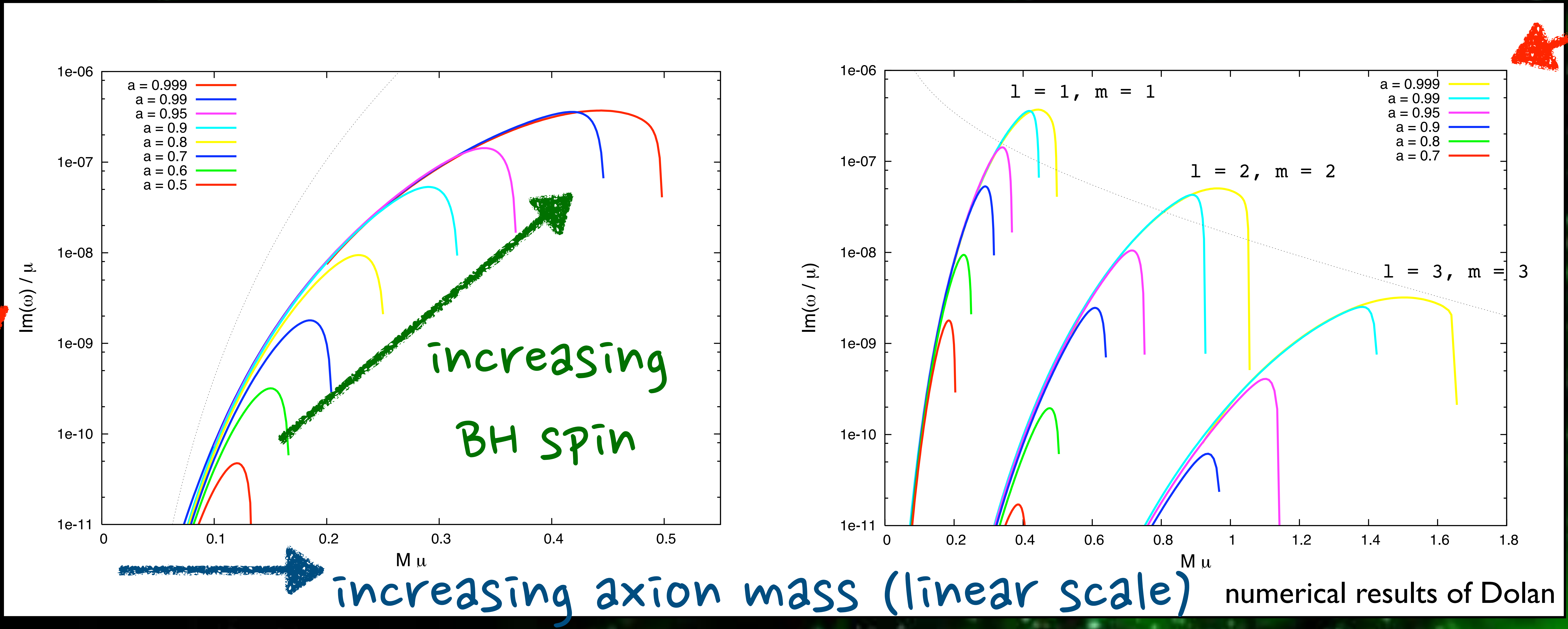

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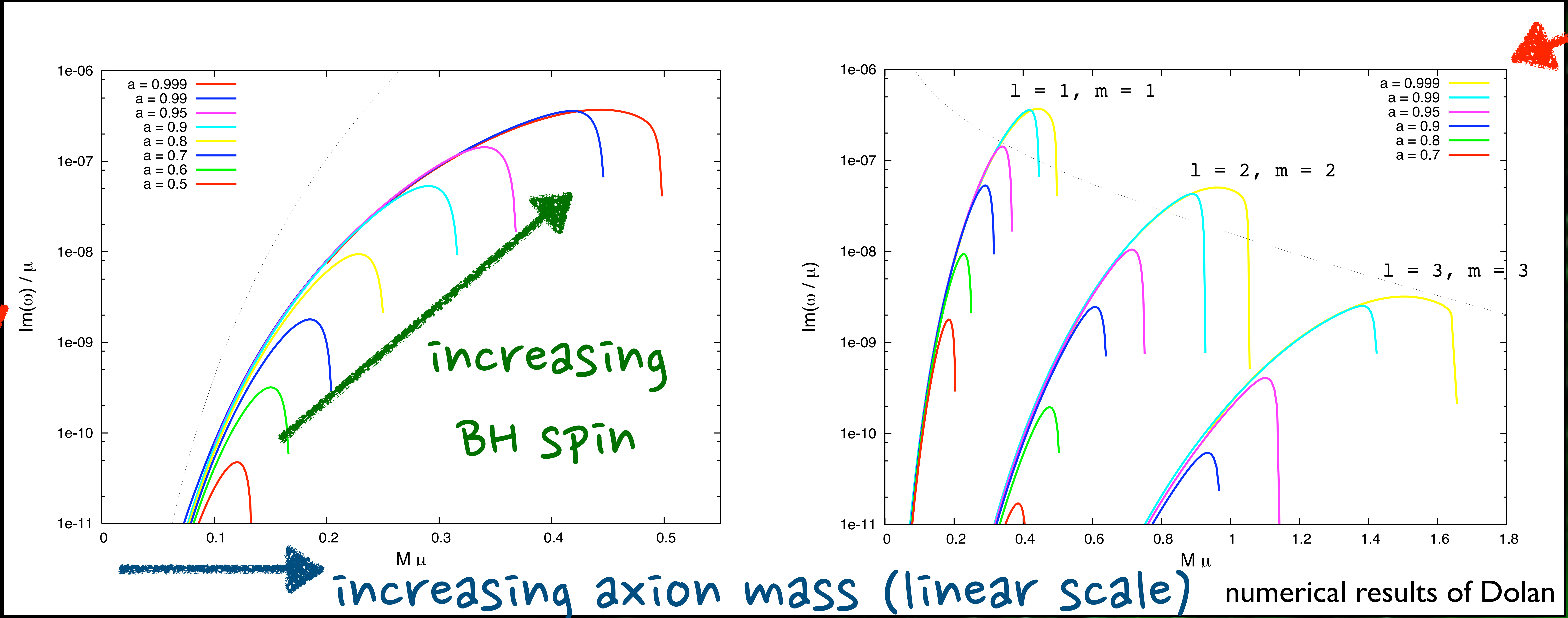

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Only a fast process for massive field with Compton wavelength close to BH size

Superradiance timescales (here assuming BH spin $a_* > 0.9$):

$$\tau \; [illegible] \times 10^6 R [illegible]$$

(as [illegible] as 100s v[illegible] 10[illegible])

Superradiance timescales (here assuming BH spin $a_* > 0.9$):

Optimal match between $1/\mu_a$ and R_g when $\mu_a R_g \sim 0.4$ giving

$$\tau_{sr} \simeq 6 \times 10^6 R_g$$

(as short as 100s vs $\tau_{\text{accretion}} \sim 10^{15}$s)

When $R_g \mu_a >> 1$,

$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g \mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

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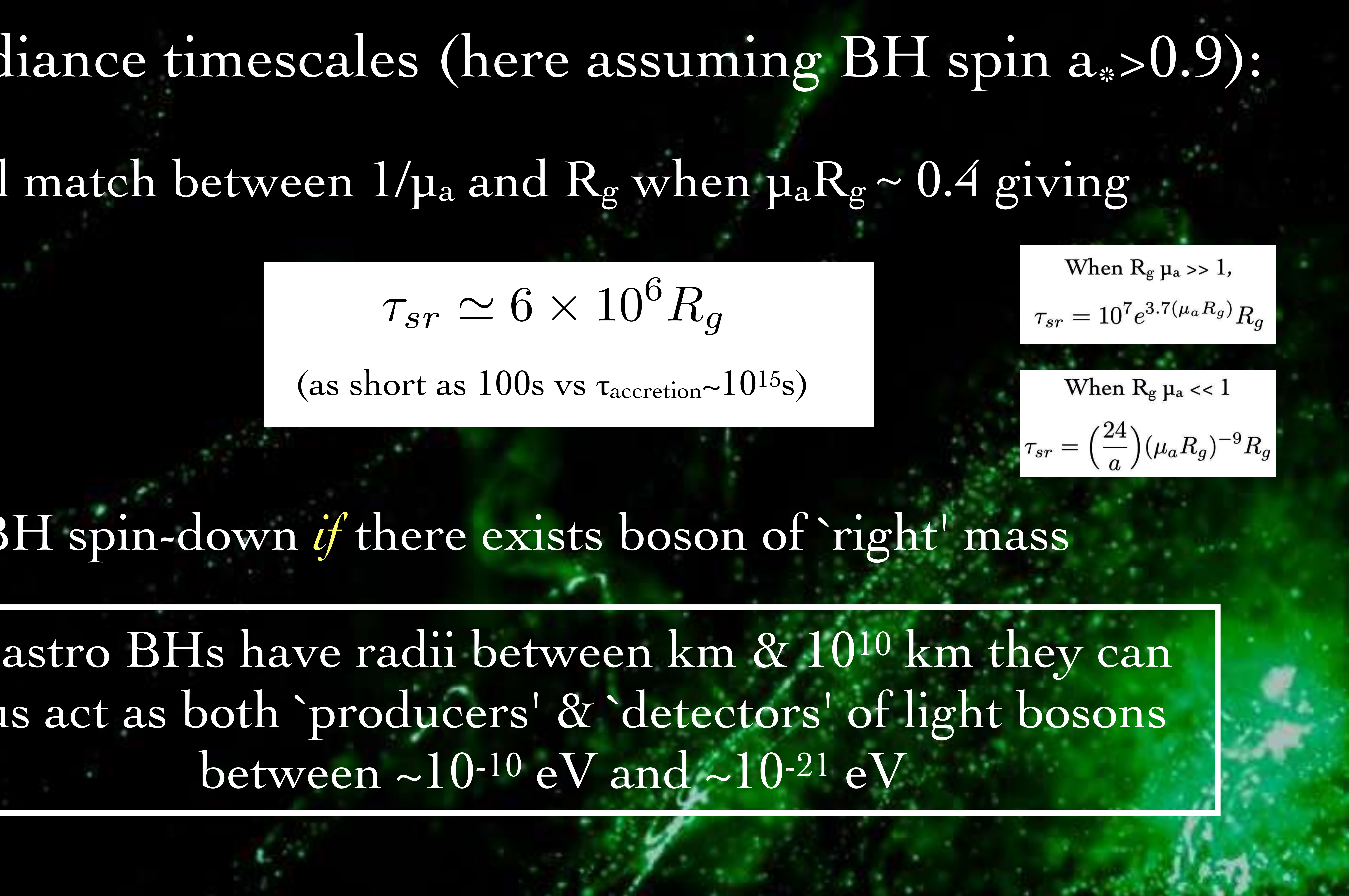
As astro BHs have radii between km & 10^{10} km they can thus act as both \`producers' & \`detectors' of light bosons between $\sim 10^{-10}$ eV and $\sim 10^{-21}$ eV



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"Gravitational Atom in the Sky" but with occupation number of relevant energy level(s) ~ 10^{77} ! (c.f. 2 for spin-up/down electrons in usual atoms as dictated by Pauli Exclusion)

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Note: self-interactions of the bosons can quench this growth limiting cloud to small occupancy - so only get this maximal process for feebly-interacting bosons (axions!,...)

Axion superradiance signatures

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell; arXiv hep-th/0905.4270

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- Photon conversion of axions from the cloud in the magnetic field of the black hole (possible future radio telescopes)

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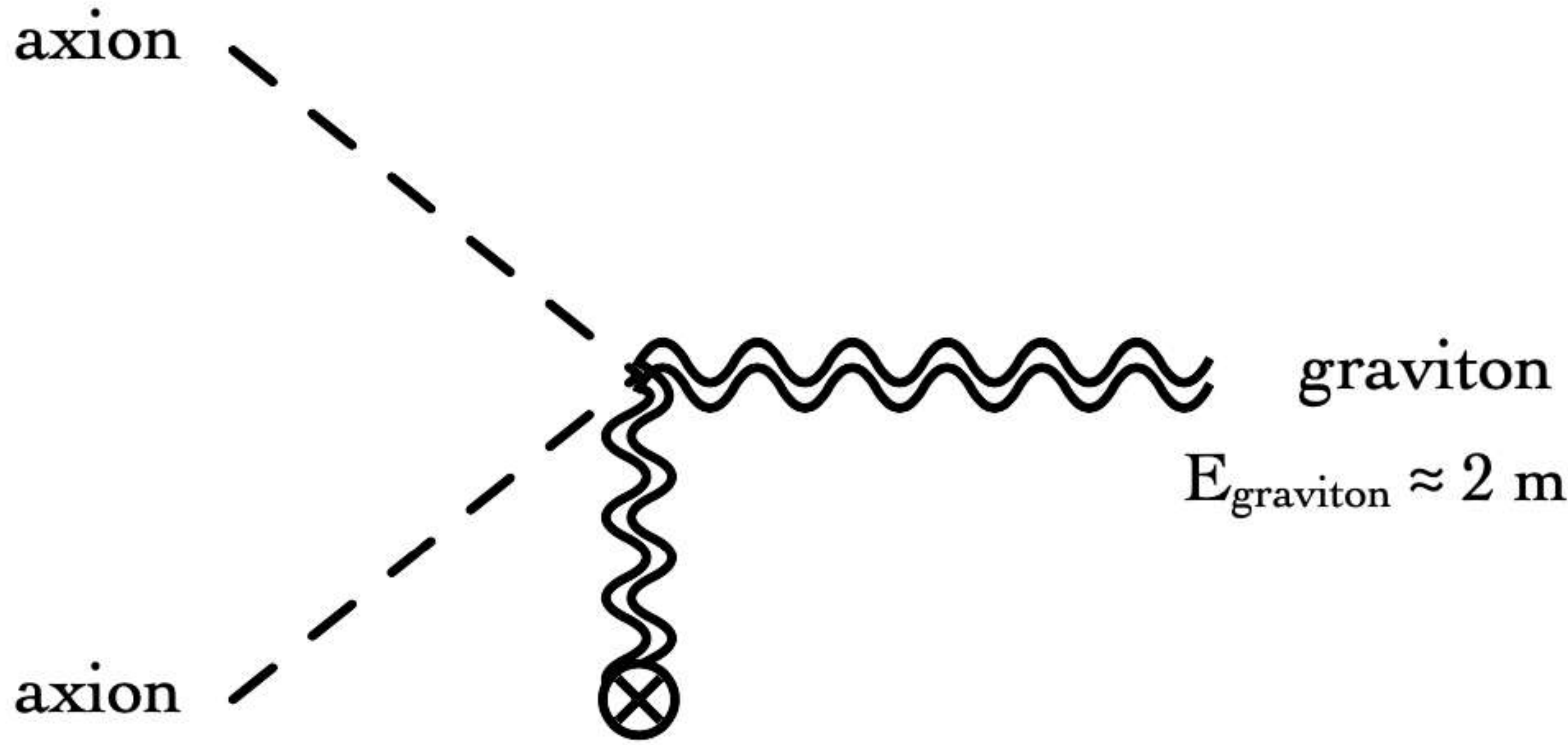

$E_{\text{graviton}} \approx 2\ m_{\text{axion}}$

$$f \;=\; 10\,\text{kHz} \times (\mu_a/10^{-11}\,\text{eV})$$

High frequency GWs

from Arvanitaki & Dubovsky: arXiv hep-th/1004.3558

signal enhanced by square of state occupation number; duration can be thousands of years

- *Many many* other signatures of axions in astro / cosmo environments being actively investigated…

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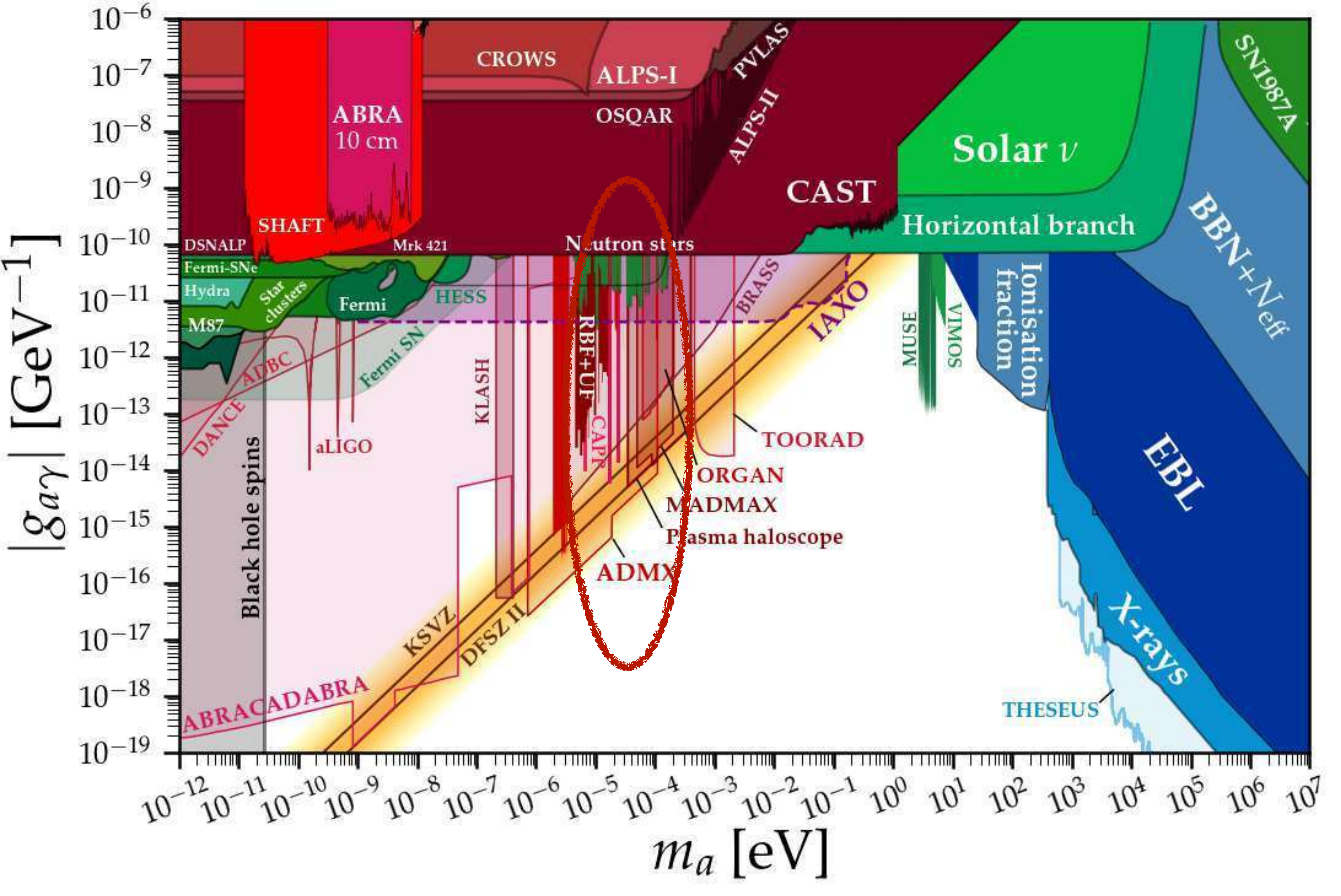
But now want to turn from the sky to the basement


$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
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10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
CROWS
ALPS-I
PVLAS
ALPS-II
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
SN1987A
Horizontal branch
BBN+$N_{\rm eff}$
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
Fermi SN
ADBC
DANCE
aLIGO
Black hole spins
KLASH
RBF+UF
CAPP
BRASS
IAXO
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
THESEUS
TOORAD
ORGAN
MADMAX
Plasma haloscope
ADMX
KSVZ
DFSZ II
ABRACADABRA

How do we search for (feebly-interacting) axions in labs?

$\ell \sim 1/mv$

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Well, first, the leading interactions of axions with ordinary matter come in three basic forms

$$g_{a\gamma\gamma}\, a\mathbf{E}.\mathbf{B}$$

electromagnetic E,B fields

$$g_{aff}\,(\nabla a).\mathbf{S}$$

fermion spin (e, p, n)

$$g_{EDM}\, a\mathbf{E}.\mathbf{S}_N$$

nucleon spin

where all the couplings, g~1/f_a

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where all the couplings, $g \sim 1/f_a$

Most commonly used coupling is a**E**.**B**

There are various ways of thinking about this a**E.B** term

If both "a" and "E,B" are well-described as classical fields then new term modifies two of Maxwell's Eqs - "Axion Electrodynamics"

Sikivie;Wilczek 1979-87

$\ell \sim 1/mv$

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$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\nabla a\cdot\mathbf{B}$$

$$\nabla\times\mathbf{B} - \dot{\mathbf{E}} = j + g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E})$$

ρ and j are the usual
charge density and
electric current

$\ell \sim 1/mv$

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New term effectively gives, *in the presence of* **B, E** *fields,* a $\ell \sim 1/mv$ new kind of charge density $-g_{a\gamma\gamma}\nabla a\cdot\mathbf{B}$ and a new kind of current $g_{a\gamma\gamma}(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E})$

OTOH if one or more of "a,**E,B**" is in quantum limit (axion quanta, and/or photons) then useful to think in terms of Feynman diags, eg,

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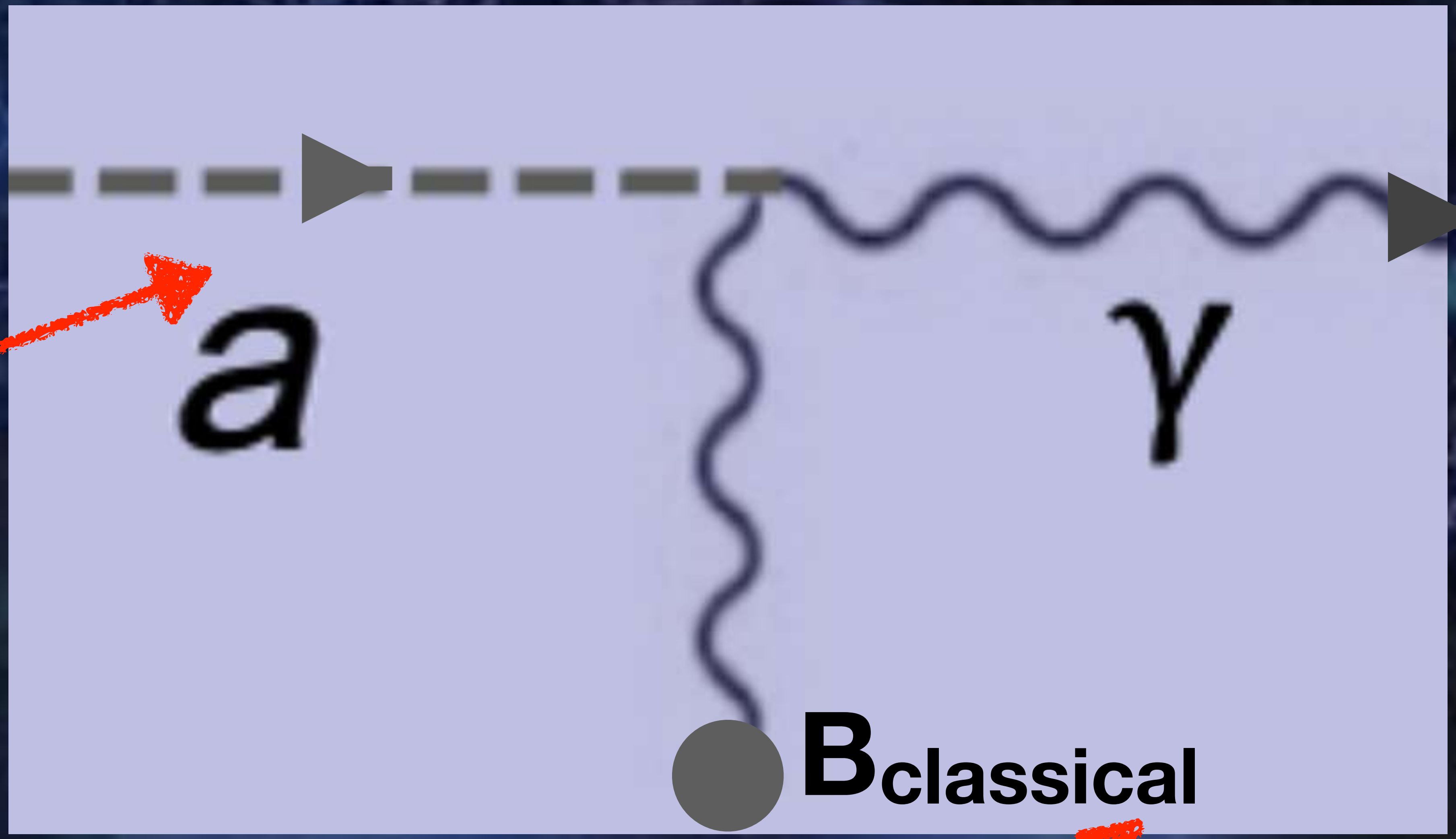

incoming axion quanta of energy ω

outgoing photon of energy ω

usually B as large classical B-fields easy to produce in laboratory

axion-photon conversion as Joe described so

Try to detect these (very tiny) new charges and currents sourced by axion field in presence of **E,B** - say by detecting anomalous "heating" of a cold shielded cavity

$\ell \sim 1/mv$

so

Try to detect these (very tiny) new charges and currents sourced by axion field in presence of **E,B** - say by detecting anomalous "heating" of a cold shielded cavity

or almost equivalently

Try to detect these (very rare) photons sourced by axion quanta in presence of **E,B** - say by detecting anomalous photon counts in a cold shielded cavity

$\ell \sim 1/mv$

But one major thing I haven't told you yet - where do the initial axions come from?!

cf. in BH case the BH itself produced the axions

$\ell \sim 1/mv$

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One important possibility: the Early Universe!

Preskill, Wilczek, Wise 1982; Abbott, Sikivie 1982

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The QCD axion and also axion-like-particles are now our leading candidates for dark matter!

$\ell \sim 1/mv$

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Quick aside on axion DM (many talks in itself...!)

Axions are excellent DM candidates as they are:

1) very feebly interacting - so "dark"

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Axions are excellent DM candidates as they are:

1) very feebly interacting - so "dark"
2) they are very long-lived so still around today

$\ell \sim 1/mv$

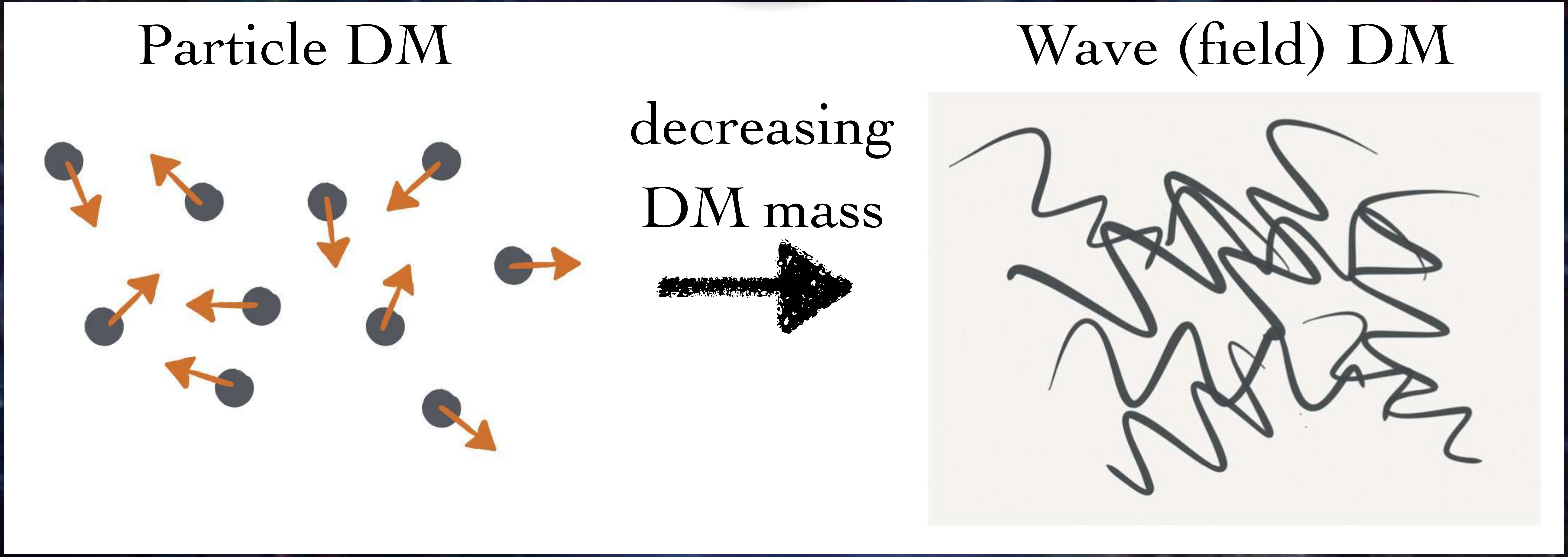
Quick aside on axion DM (many talks in itself...!)

Axions are excellent DM candidates as they are:

1) very feebly interacting - so "dark"
2) they are very long-lived so still around today
3) have production mechanisms that leave them "cold" (non-relativstic) as necessary for successful galaxy formation

$\ell \sim 1/mv$

However axion DM better described as field made of superposed waves



Particle DM

decreasing DM mass

Wave (field) DM

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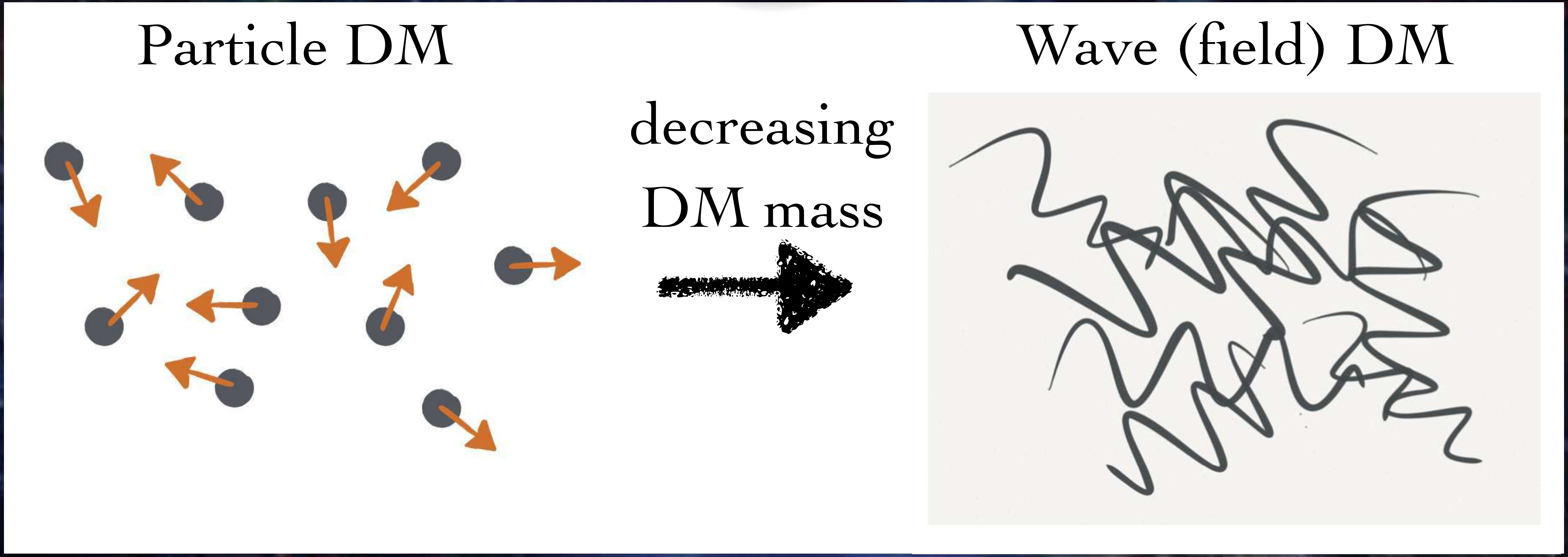

Particle DM

decreasing DM mass

Wave (field) DM

happens when $n_{dm} = \rho_{dm}/\mu > 1/(\lambda_{dB,dm})^3$ - for our galaxy when $\mu<1$ eV

Thus in our galaxy expect axion DM to be a everywhere present classical field oscillating at frequency $\nu_o=\mu c^2/h$

$$a(\vec{x},t) \simeq \mathrm{Re}\left\{2a_0 e^{i2\pi\nu_0 t}\int d^3\vec{v}\, f(\vec{v}) \exp\left(\frac{2\pi i m}{h}\left[\frac{v^2}{2}t - \vec{v}.\vec{x}\right]\right)\right\}$$

$$\ell \sim 1/mv$$

$$a_0 = \frac{\hbar}{\mu c}\sqrt{2\rho_{dm}}$$

Thus in our galaxy expect axion DM to be a everywhere present classical field oscillating at frequency $\nu_o=\mu c^2/h$

(but finite coherence time & length due to galactic DM velocity dispersion)

$$a(\vec{x},t) \simeq \mathrm{Re}\left\{2a_0 \mathrm{e}^{i2\pi\nu_0 t}\int d^3\vec{v}\, f(\vec{v}) \exp\left(\frac{2\pi i m}{h}\left[\frac{v^2}{2}t - \vec{v}.\vec{x}\right]\right)\right\}$$

$$a_0 = \frac{\hbar}{\mu c}\sqrt{2\rho_{dm}}$$

$$\ell \sim 1/mv$$

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Thus in our galaxy expect axion DM to be a everywhere present classical field oscillating at frequency $\nu_o=\mu c^2/h$

amplitude set by (roughly known) galactic DM density

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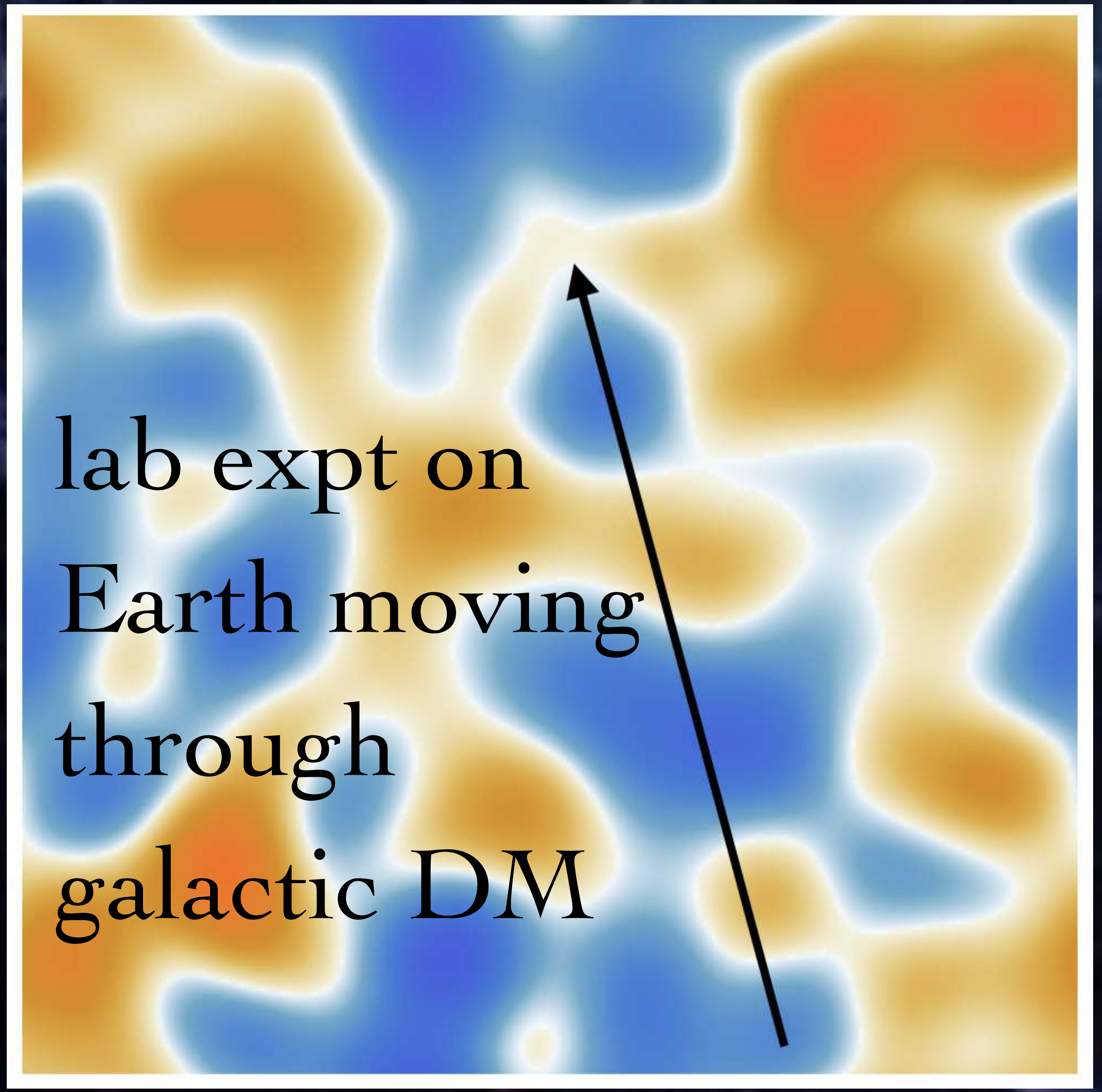
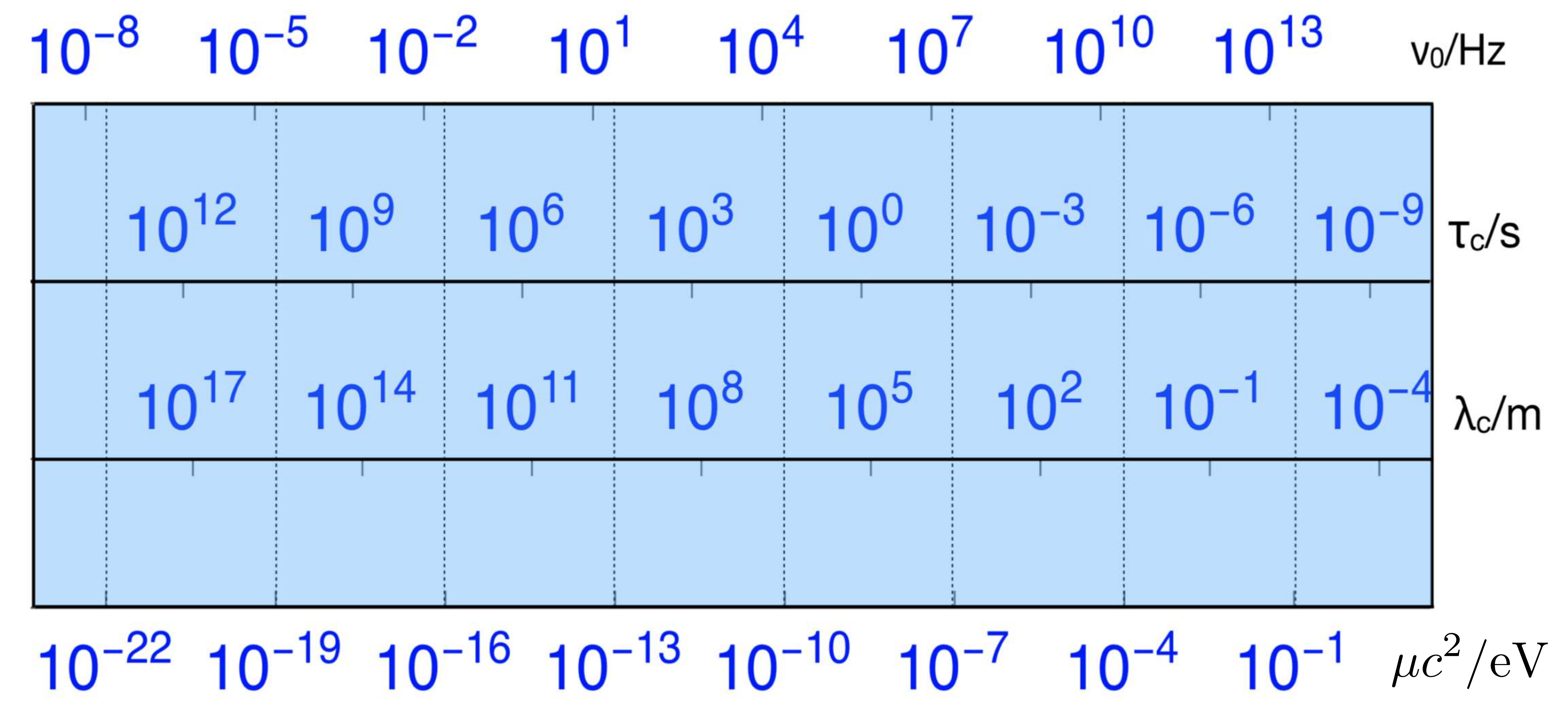


(freq. & expected coherence time/length as function of mass)



ν_0/Hz	10^{-8}	10^{-5}	10^{-2}	10^{1}	10^{4}	10^{7}	10^{10}	10^{13}
τ_c/s	10^{12}	10^{9}	10^{6}	10^{3}	10^{0}	10^{-3}	10^{-6}	10^{-9}
λ_c/m	10^{17}	10^{14}	10^{11}	10^{8}	10^{5}	10^{2}	10^{-1}	10^{-4}
μc^2/eV	10^{-22}	10^{-19}	10^{-16}	10^{-13}	10^{-10}	10^{-7}	10^{-4}	10^{-1}

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So, now we know where the axions are coming from (and that they are non-rel, v/c ~10^{-3}) how exactly do we search for DM axions?

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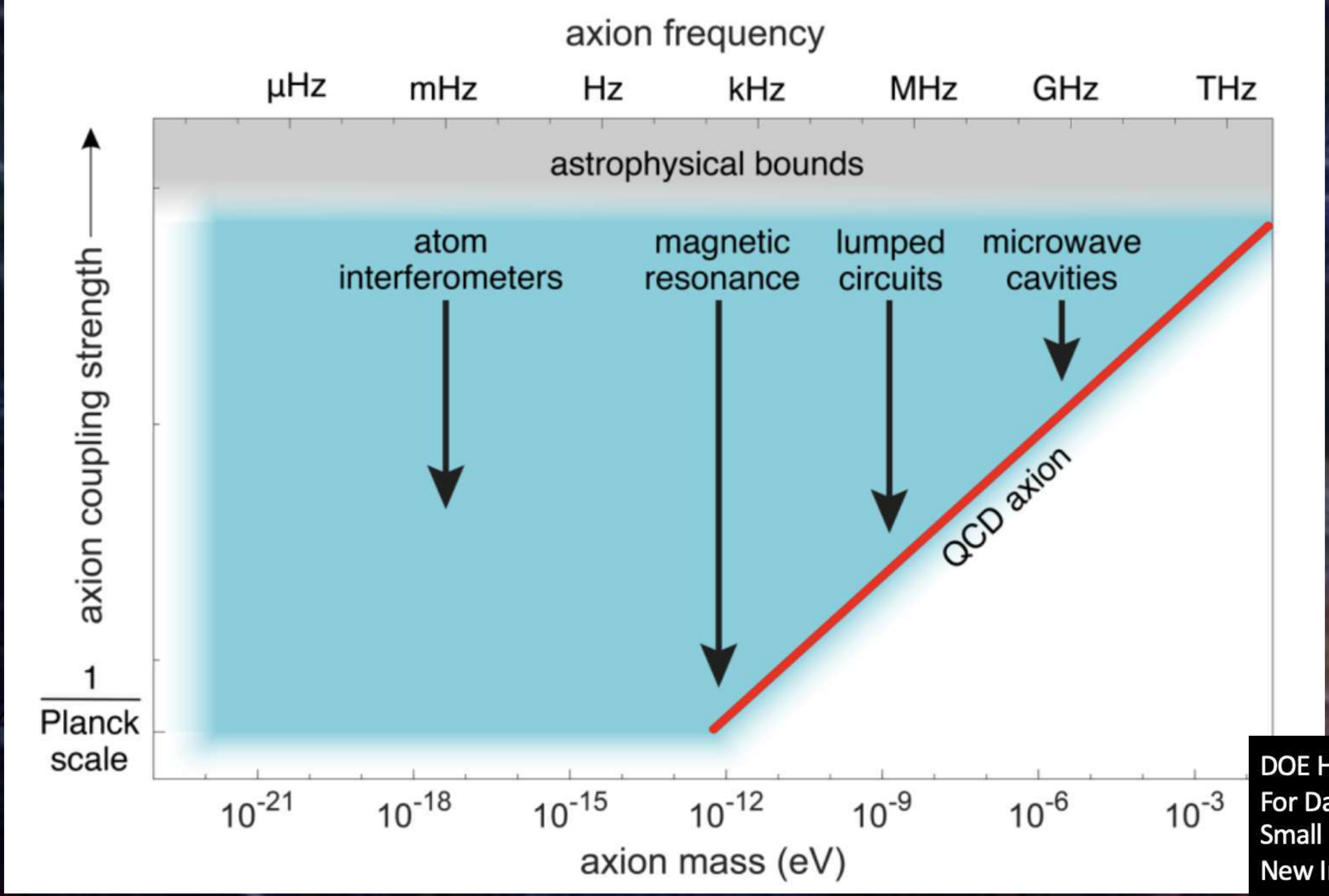
Answer depends on mass of axion - best technology varies!



DOE HEP BRN
For Dark Matter
Small Projects
New Initiatives

whole variety of different quantum technologies can be utilized

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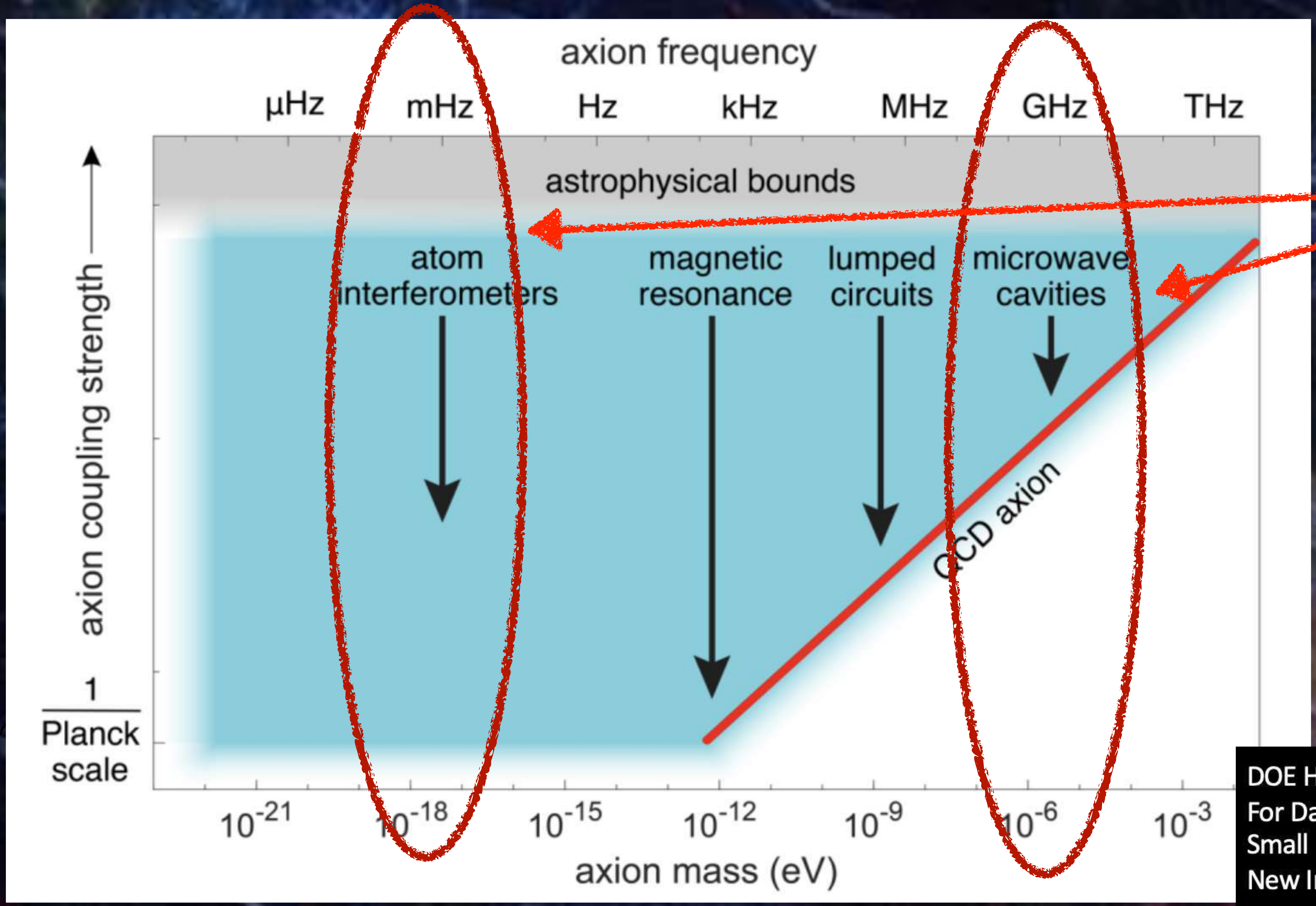

DOE HEP BRN
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Small Projects
New Initiatives

Oxford involved in both these leading techniques. Here focus on microwave cavities

whole variety of different quantum technologies can be utilized

Cavity searches for DM axions: (basic idea due to Sikivie 1983)

,

excitation of one of the cavity modes (freq resonant with axion mass) - enhanced photon occupation number

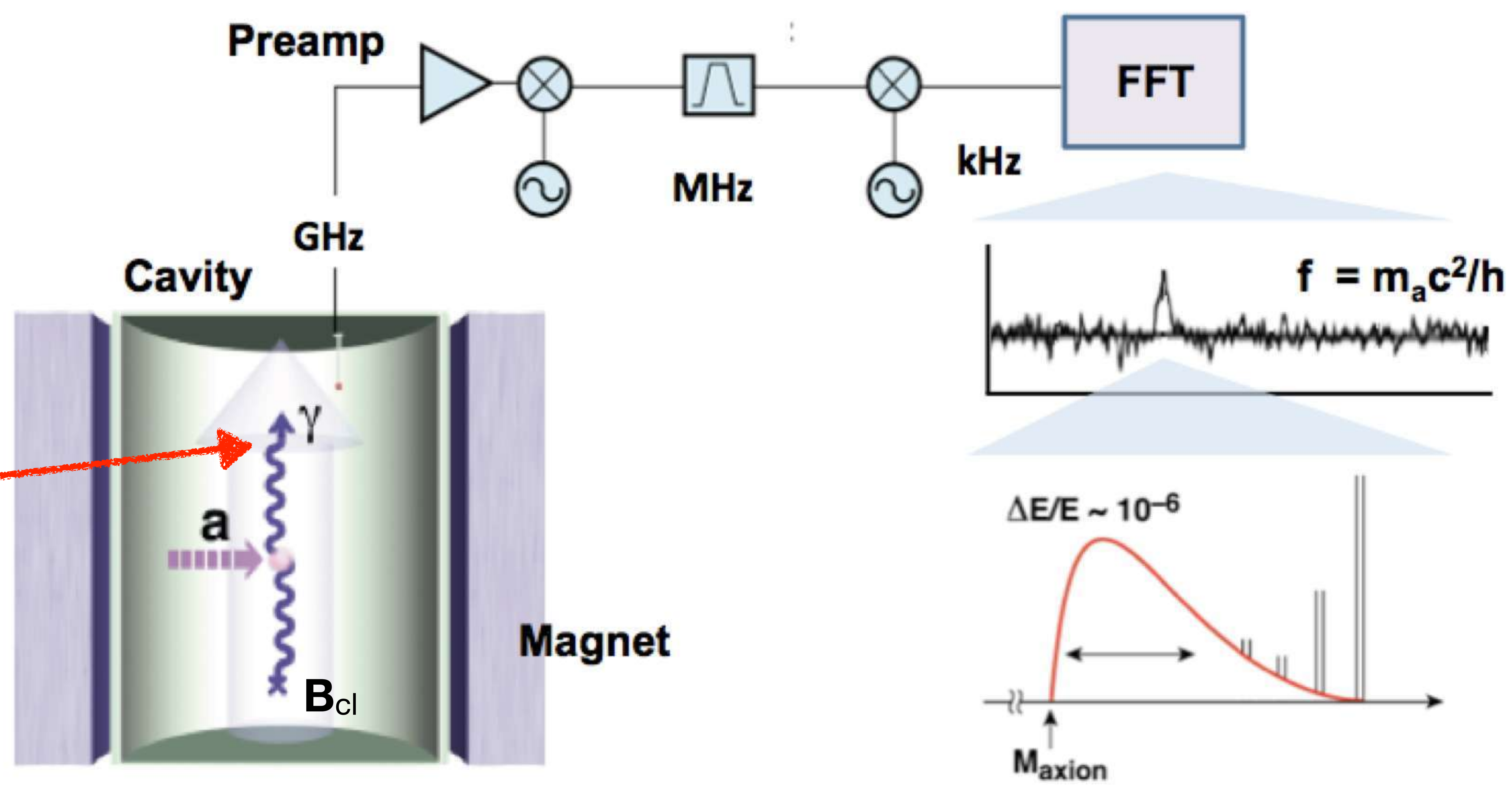

Figure 2

From P. Graham etal, arXiv:1602.00039

Schematic of the microwave cavity search for dark matter axions. Axions resonantly convert to a quasi-monochromatic microwave signal in a high-Q cavity in a strong magnetic field; the signal is extracted from the cavity by an antenna, amplified, mixed down to the audio range, and the power spectrum calculated by a FFT. Possible fine structure on top of the thermalized axion spectrum would reveal important information about the formation of our galaxy.

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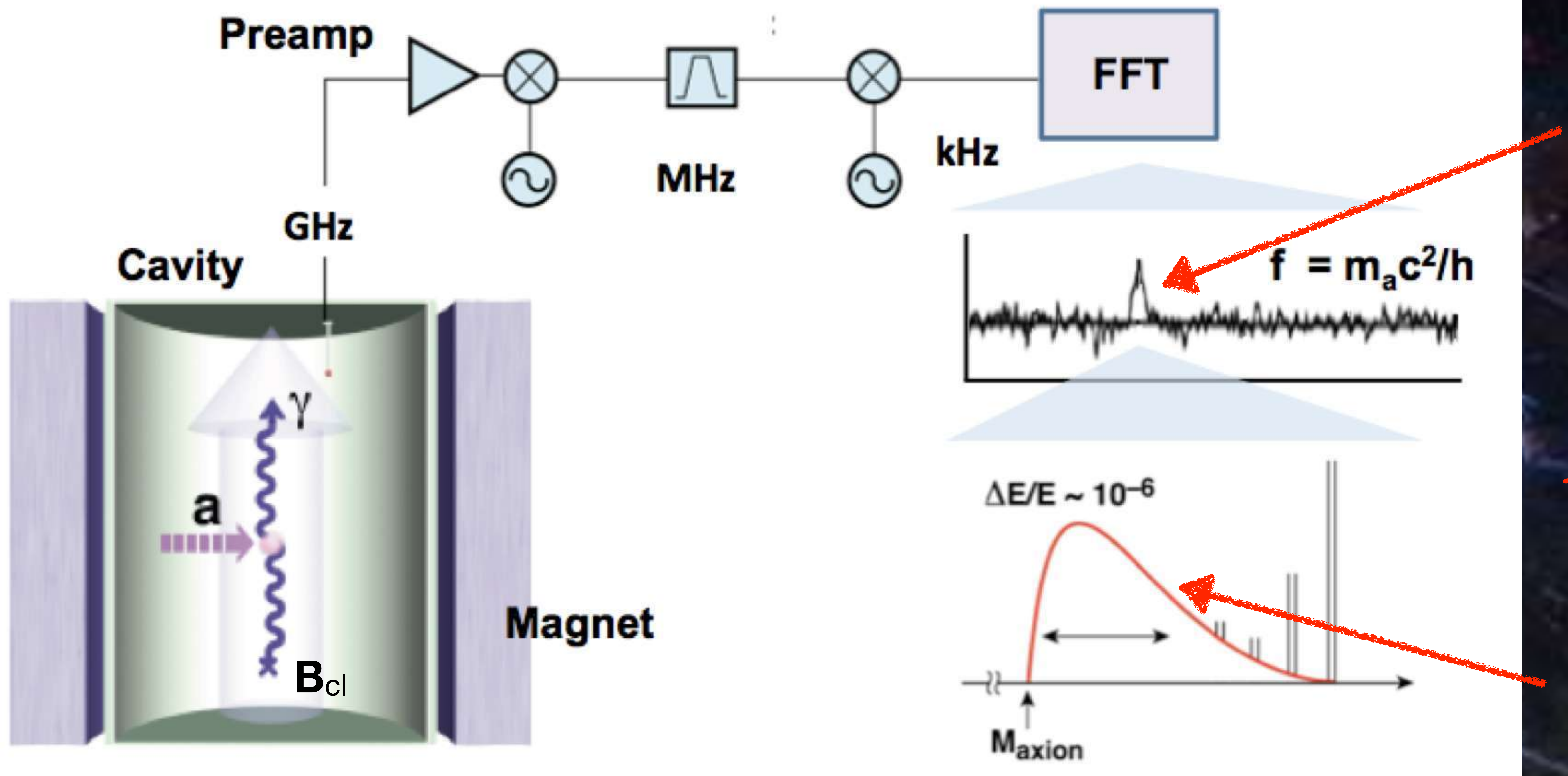

look for excess B-dept power (above thermal & quantum noise) with particular line shape

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Looking for *extremely* small excess power ~10^{-23} W in case of QCD axion

$$P_{a\gamma\gamma} = 5.0 \times 10^{-23}\,\mathrm{W}\left(\frac{C_\gamma}{0.75}\right)^2\left(\frac{\rho_a}{0.45\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\left(\frac{\nu_a}{1\ \mathrm{GHz}}\right)\left(\frac{B_0}{10\ \mathrm{T}}\right)^2\left(\frac{V}{30\ \mathrm{liters}}\right)\left(\frac{G}{0.5}\right)\left(\frac{Q_c}{10^5}\right)$$

From Semertzidis & Youn, *Sci. Adv.* **8**

so maximizing B-field strength, cavity parameters, and minimizing thermal and quantum noise vital

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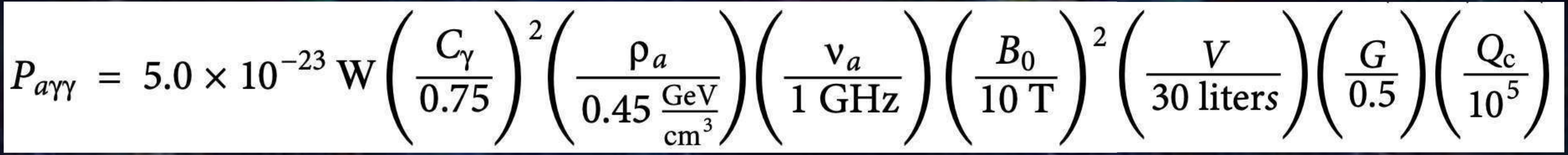

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Experiments worldwide now reaching this sensitivity but as *resonant* search must scan over the unknown axion mass (= freq) - this is present roadblock to efficiently cover all the most attractive parameter space

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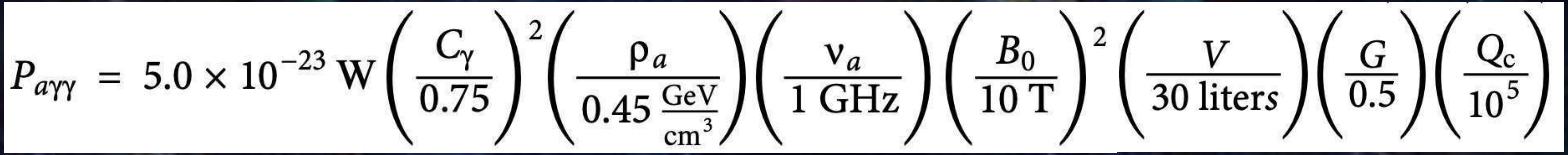

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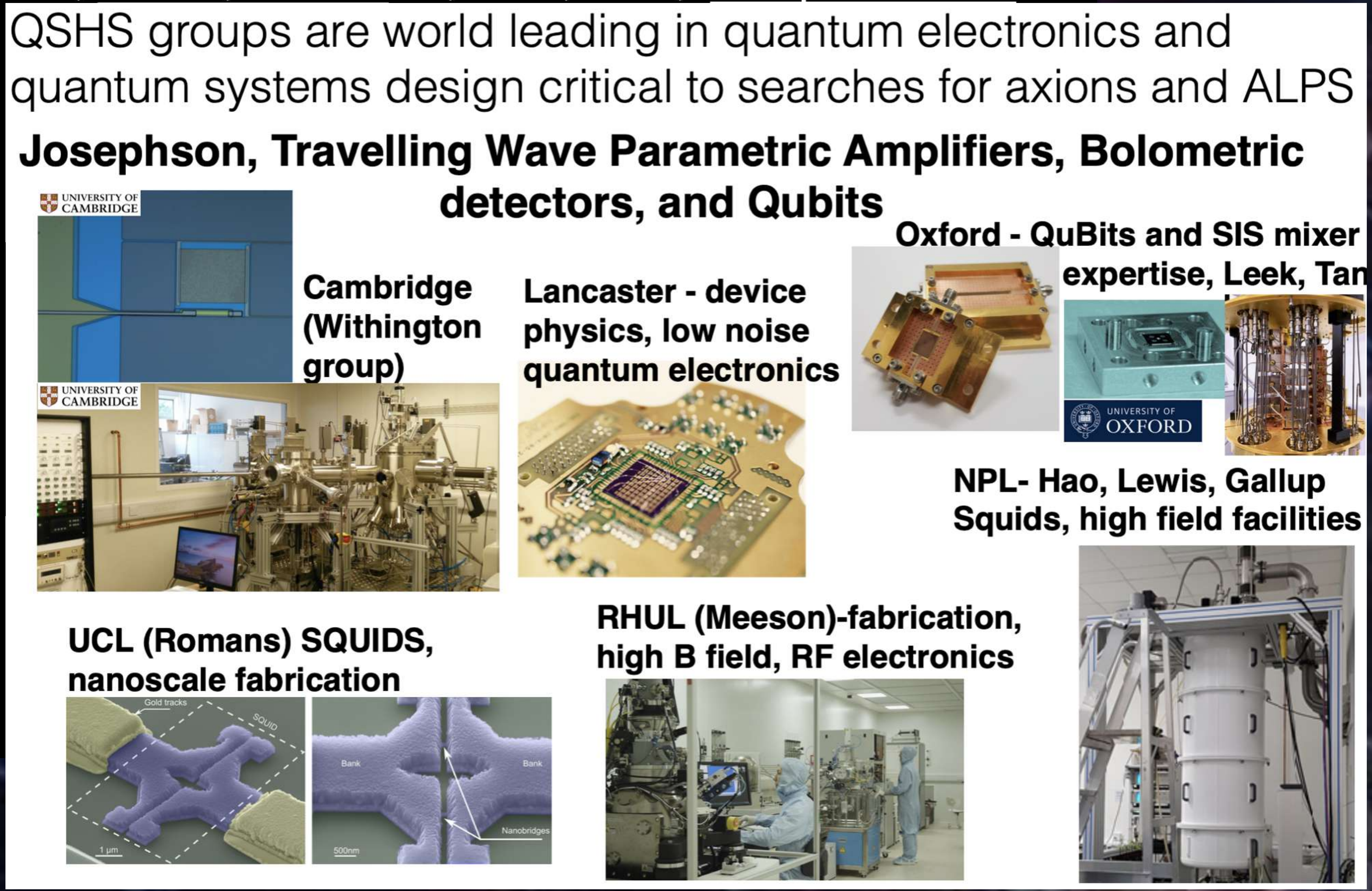
$\ell \sim 1/mv$

Fortunately, UK now involved in major project in this area - "QSHS" - with significant Oxford involvement (Sarkar, JMR, theory; Leek, Tan, expt.)

Quantum Sensors for the Hidden Sector

Sheffield, Cambridge, Oxford, RHUL, Lancaster, UCL, NPL, Liverpool

- A search for axions/ALPs using resonant conversion to microwave photons in high magnetic fields
- Initial focus on QCD axion, mass range 25-40μeV
- Collaboration with U.S. Axion Dark Matter eXperiment group, who operate the worlds most sensitive axion search, ADMX.
- **Ambition to build a UK high field (8T) low temperature (10mK) facility at Daresbury.**



QSHS groups are world leading in quantum electronics and quantum systems design critical to searches for axions and ALPS

Josephson, Travelling Wave Parametric Amplifiers, Bolometric detectors, and Qubits

Cambridge (Withington group)

Lancaster - device physics, low noise quantum electronics

Oxford - QuBits and SIS mixer expertise, Leek, Tan

NPL- Hao, Lewis, Gallup Squids, high field facilities

UCL (Romans) SQUIDS, nanoscale fabrication

RHUL (Meeson)-fabrication, high B field, RF electronics

Slide credit: Ed Daw (Sheffield)

World-leading QCD axion/ALP/ hidden photon DM searches possible in accessible mass range(s)

(PDG, 2020)

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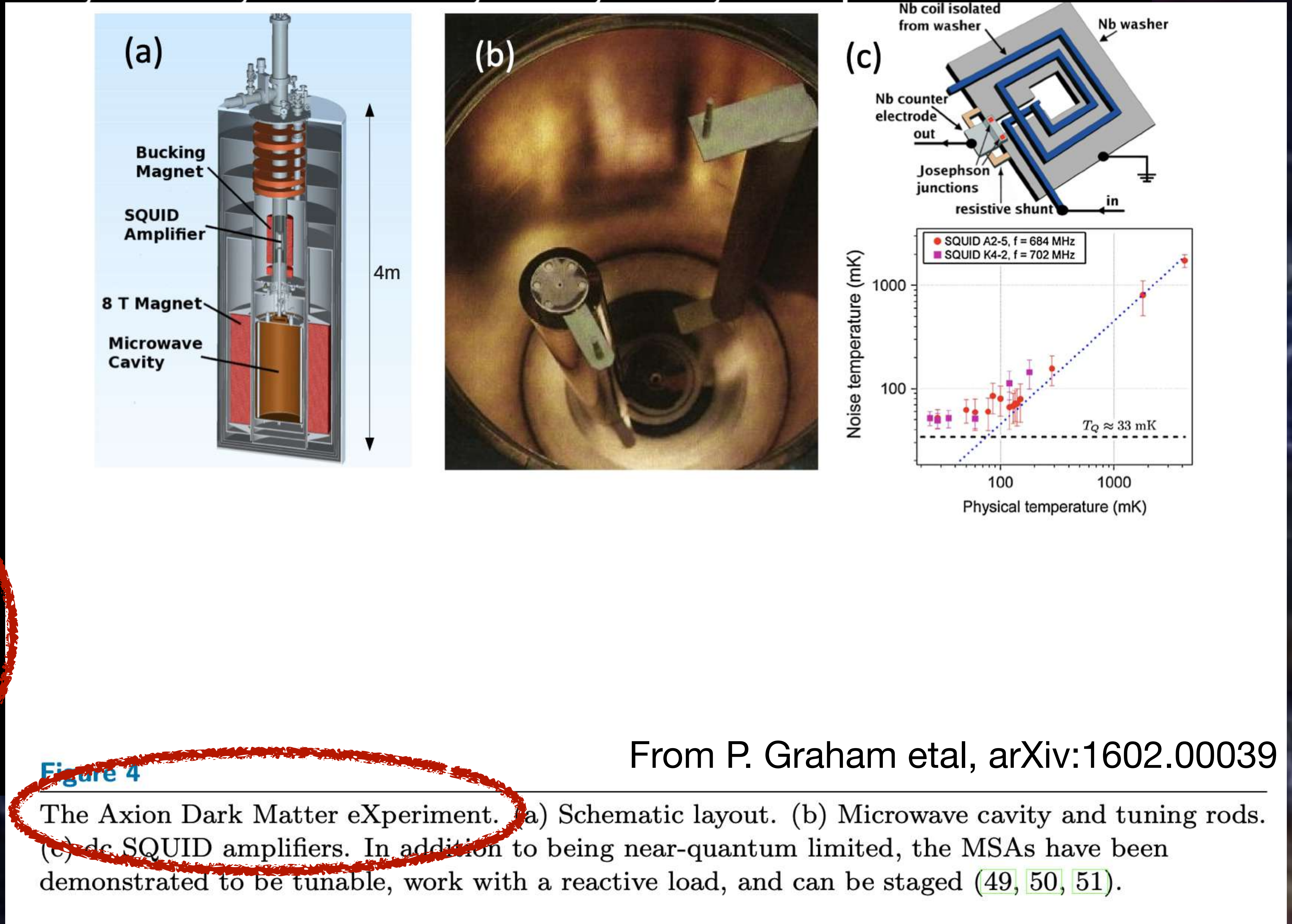


From P. Graham etal, arXiv:1602.00039

Figure 4

The Axion Dark Matter eXperiment. (a) Schematic layout. (b) Microwave cavity and tuning rods. (c) dc SQUID amplifiers. In addition to being near-quantum limited, the MSAs have been demonstrated to be tunable, work with a reactive load, and can be staged (49, 50, 51).

World-leading QCD axion/ALP/
hidden photon DM searches possible
in accessible mass range(s)

(PDG, 2020)

In conclusion

Many major new experiments & theory ideas in axion physics worldwide

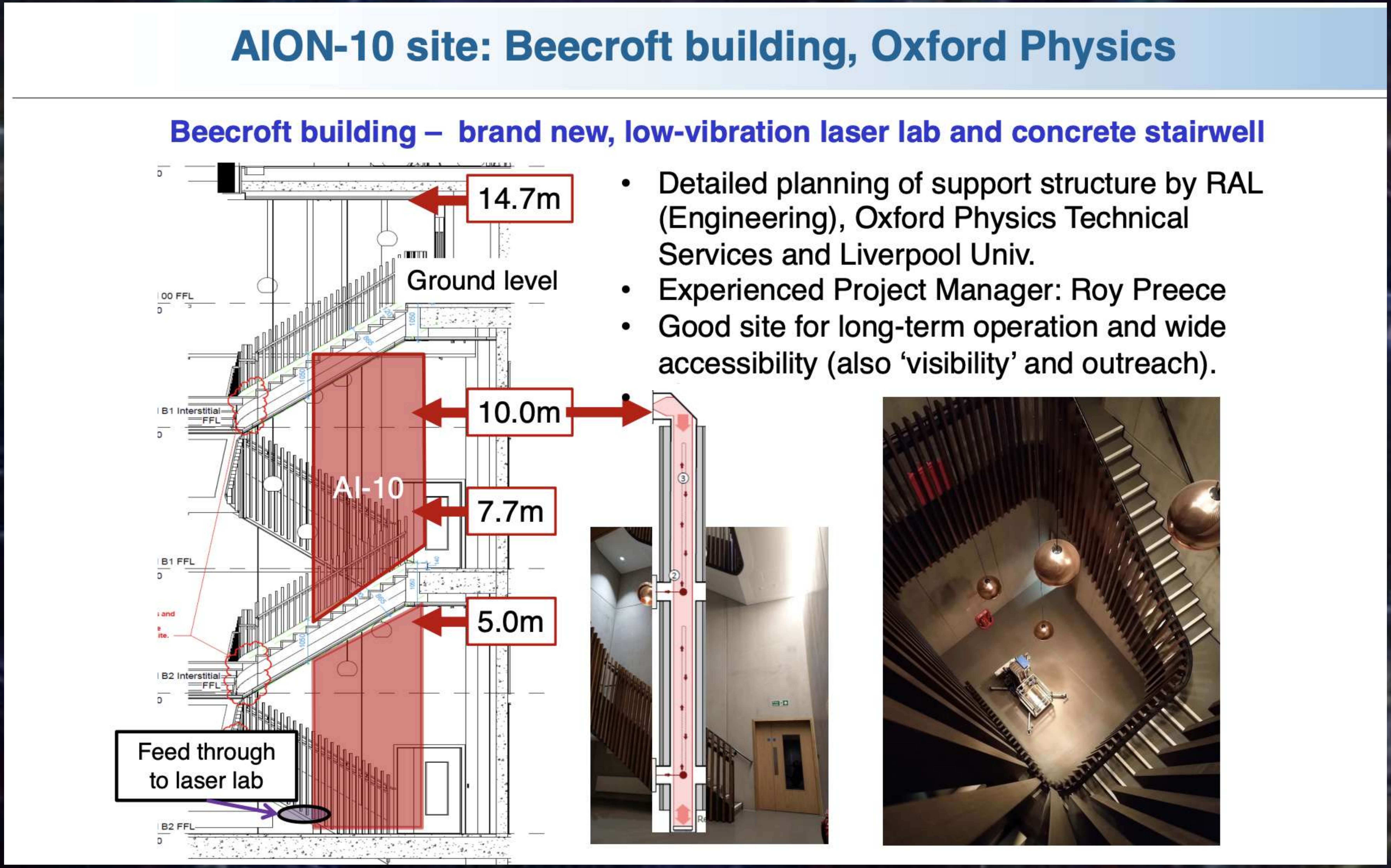
An extremely exciting and active area - stay tuned!

$\ell \sim 1/mv$

Backup Slides

$\ell \sim 1/mv$

also in Beecroft basement an atom-interferometer experiment....

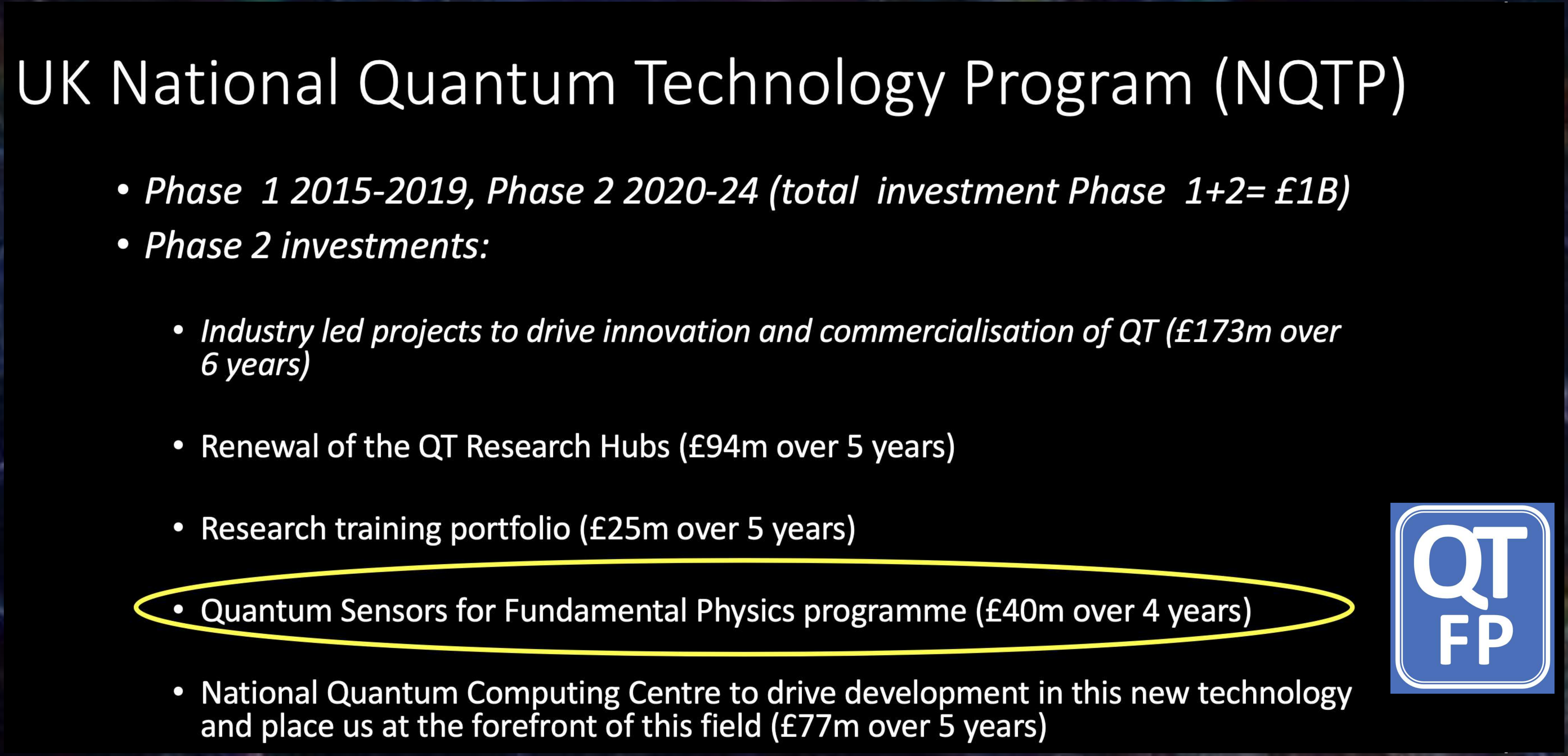


AION-10 site: Beecroft building, Oxford Physics

Beecroft building – brand new, low-vibration laser lab and concrete stairwell

- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also 'visibility' and outreach).

Funding from



UK National Quantum Technology Program (NQTP)

- *Phase 1 2015-2019, Phase 2 2020-24 (total investment Phase 1+2= £1B)*
- *Phase 2 investments:*
  - *Industry led projects to drive innovation and commercialisation of QT (£173m over 6 years)*
  - Renewal of the QT Research Hubs (£94m over 5 years)
  - Research training portfolio (£25m over 5 years)
  - Quantum Sensors for Fundamental Physics programme (£40m over 4 years)
  - National Quantum Computing Centre to drive development in this new technology and place us at the forefront of this field (£77m over 5 years)

QT FP

Slide (and much other QTFP) credit: Ian Shipsey

Can also use the coupling of axion to fermion spin to search

$$g_{a\gamma\gamma}\; a\mathbf{E}.\mathbf{B}$$

$$g_{aff}\;(\nabla a).\mathbf{S}$$

$$g_{EDM}\; a\mathbf{E}.\mathbf{S}_N$$

fermion spin (often electron)

nucleon spin

For these couplings use NMR techniques to measure the precession of the spins in effective oscillating "magnetic" field of axion dark matter

$\ell \sim 1/mv$

"CASPEr-Wind" & "CASPEr-Electric" experiments

Cosmic Axion Spin Precession Experiment (CASPEr)

New field of axion direct detection, similar to early stages of WIMP direct detection

No other way to search for light axions

Would be the discovery of dark matter and glimpse into physics at high energies ~ 10^{16} - 10^{19} GeV

already have data & initial limits

~~under construction~~ at Mainz and BU

BOSTON UNIVERSITY
Berkeley UNIVERSITY OF CALIFORNIA
Stanford
CALIFORNIA STATE UNIVERSITY EAST BAY
HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

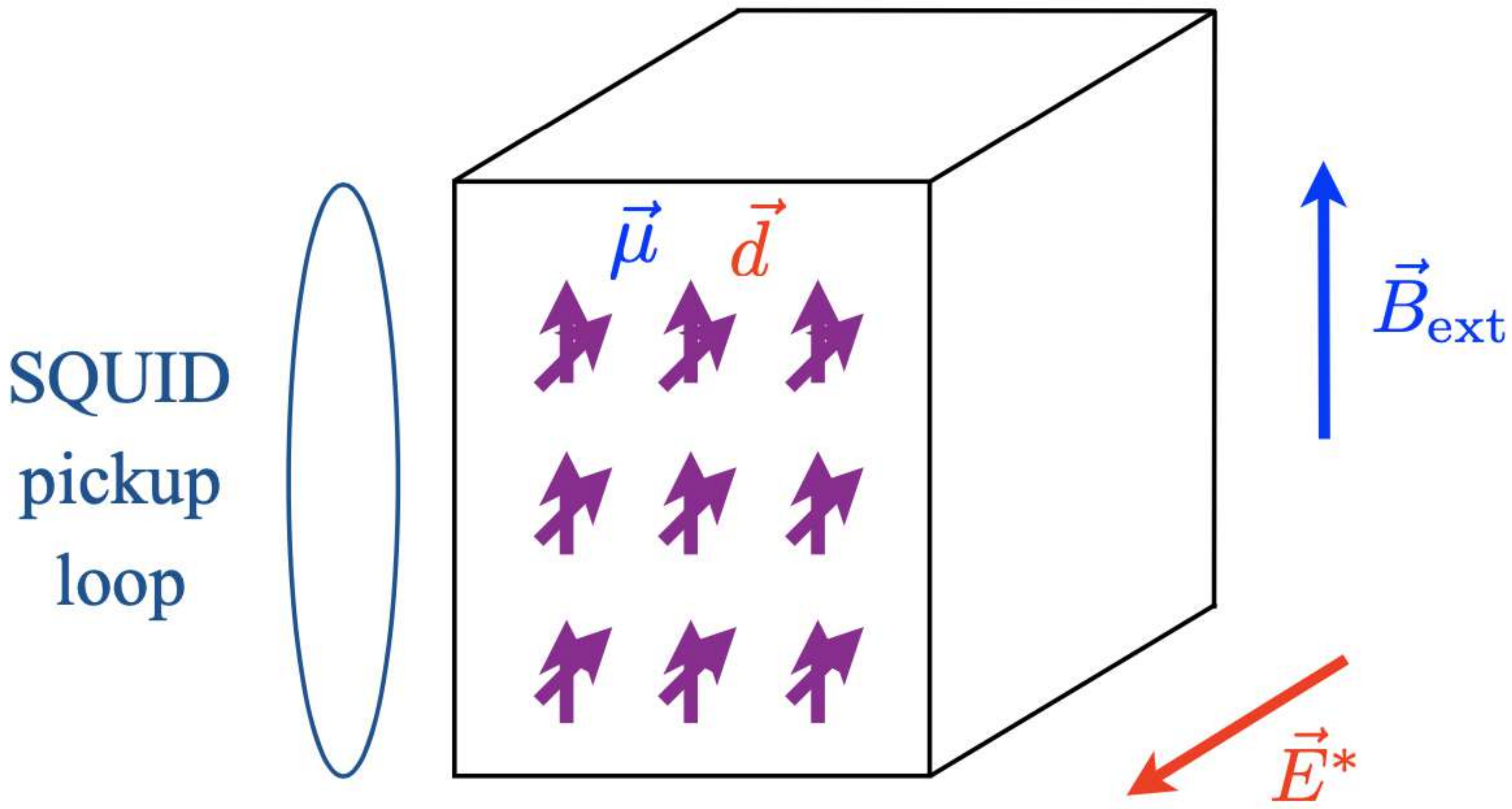
Dmitry Budker
Alexander Sushkov
Peter W. Graham
Surjeet Rajendran
Derek J. Kimball
Arne Wickenbrock
John Blanchard
Marina Gil Sendra
Gary Centers
Nataniel Figueroa
Deniz Aybas
Adam Pearson
Hannah Mekbib
Tao Wang

Slide credit Peter Graham

SIMONS FOUNDATION
HEISING - SIMONS FOUNDATION
Alfred P. Sloan FOUNDATION
DFG Deutsche Forschungsgemeinschaft

Cosmic Axion Spin Precession Experiment (CASPEr)

NMR techniques + high precision magnetometry



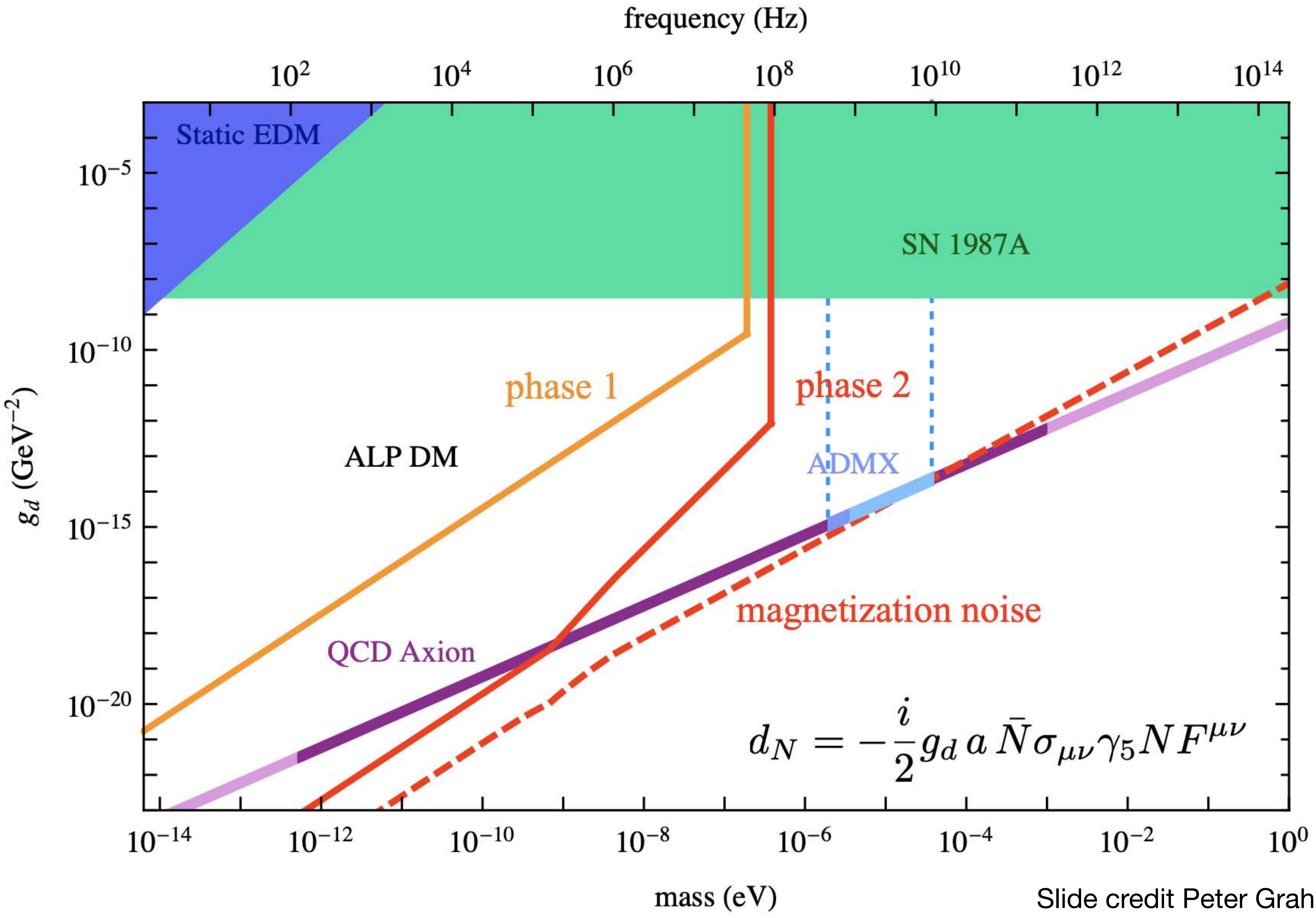
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

ferroelectric (e.g. $PbTiO_3$), NMR pulse sequences (spin-echo,…),…
quantum spin projection (magnetization) noise small enough

Slide credit Peter Graham

CASPEr Sensitivity



$$d_N = -\frac{i}{2} g_d \, a \, \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

Slide credit Peter Graham

$\ell \sim 1/mv$