Gianni, Piero & Paola fest

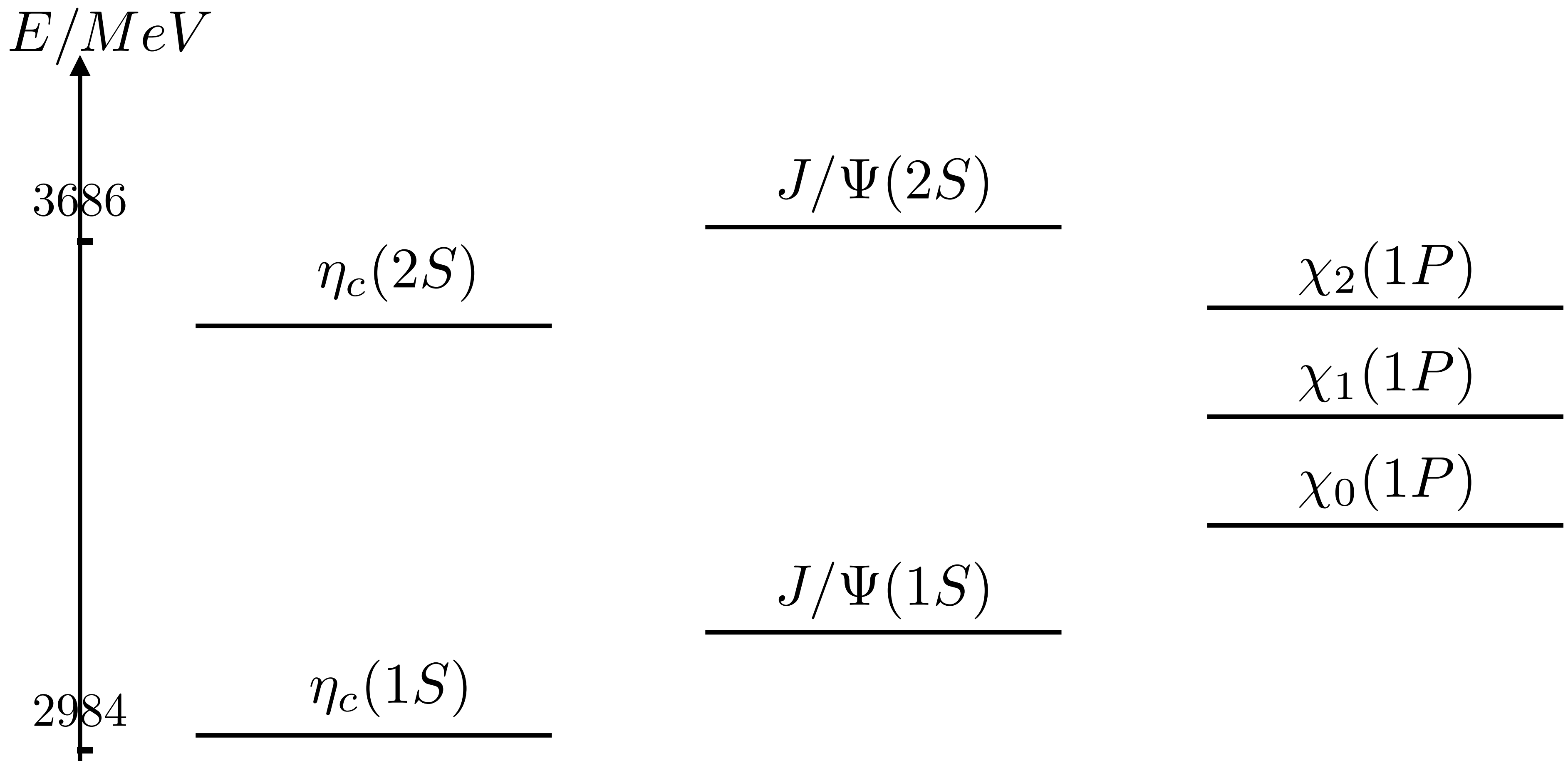
Charmonia and (mostly) axions

R. Barbieri

Ferrara, October 8-9, 2018

Charmonium spectroscopy

$e^+e^- \to J/\Psi \to e^+e^-$ Discovery: Nov 1974



Γ's between 100 keV and 30 MeV

$p\bar{p} \to (c\bar{c}) \to e^+e^-$

$p\bar{p} \to (c\bar{c}) \to \gamma\gamma$

R704 (CERN)
E760 (FNAL)
E835 (FNAL)

Piero & Paola

See Pordes talk

The narrowness of charmonia

Discovery: Nov 1974

Appelquist, Politzer (1975) and De Rujula, Glashow (1975) interpret the narrowness of $J/\Psi(1^{--})$ as a consequence of its 3 gluon decay

$$\frac{\Gamma(\psi \to \text{hadrons})}{\Gamma(\psi \to e^+e^-)} \approx \frac{5(\pi^2-9)}{18\pi} \frac{\alpha_s^3}{\alpha^2}$$

CALCULATION OF THE ANNIHILATION RATE OF P WAVE QUARK-ANTIQUARK BOUND STATES

R. BARBIERI, R. GATTO* and R. KÖGERLER
CERN, Geneva, Switzerland

Received 27 October 1975

In the framework of the gauge theory of strong interactions (in particular for the charm scheme) we calculate the annihilation rates of P wave quark-antiquark bound states of $J^{PC} = 0^{++}, 2^{++}$. Applications can be made to the decays of the $C = +1$ states lying between ψ and ψ', to their gluonic production, and to f′ decay. Annihilations into 2γ and the Primakoff productions are also discussed.

$^3P_{0,1,2}$ parameter measurements

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 533 (2002) 237–242

www.elsevier.com/locate/npe

New measurements of the resonance parameters of the $\chi_{c0}(1^3P_0)$ state of charmonium

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT

Nuclear Physics B 717 (2005) 34–47

NUCLEAR PHYSICS B

Measurement of the resonance parameters of the $\chi_1(1^3P_1)$ and $\chi_2(1^3P_2)$ states of charmonium formed in antiproton–proton annihilations

SINGULAR BINDING DEPENDENCE IN THE HADRONIC WIDTHS OF 1^{++} AND 1^{+-} HEAVY QUARK ANTIQUARK BOUND STATES

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and

E. REMIDDI
Istituto di Fisica dell'Università, Bologna,
Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy

Received 10 February 1976

The annihilation rates into hadrons of P-wave heavy quark-antiquark bound states are calculated within SU(3) colour gauge theory (in particular for the charm scheme). An interesting feature we find is a logarithmic divergence for small binding for the states 1^{++} and 1^{+-}. Implications for the asymptotic freedom approach to the decay rates of the new particles are discussed. An attempt to use quantitatively the obtained results for all the C-even P-waves gives $\Gamma_{ann}(0^{++}) : \Gamma_{ann}(2^{++}) : \Gamma_{ann}(1^{++}) \approx 15:4:1$.

Experimentally, mostly from E760, E835:

$$\Gamma(\chi_{c0}) = 10.5 \pm 0.6 \qquad \Gamma(\chi_{c2}) = 1.93 \pm 0.11 \qquad \Gamma(\chi_{c1}) = 0.84 \pm 0.04 \qquad MeV$$

$$\Gamma(0^{++}) : \Gamma(2^{++}) : \Gamma(1^{++}) = 12 : 2.4 : 1$$

Most recent

PHYSICAL REVIEW LETTERS **121,** 092002 (2018)

Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and Measurement of their Masses

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

(Received 28 May 2018; revised manuscript received 8 July 2018; published 29 August 2018)

Thanks to Piero & Paola

Why to look for axions?

One single coupling only ($\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$) refuses to show up in the SM!?!

How do we know that $\theta \lesssim 10^{-10}$?

$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ is T-odd and (almost) the only source of T-violation in the SM

	$\vec{\mu}\cdot\vec{B}$	$\vec{d}\cdot\vec{E}$
T	$+$	$-$

$$|\vec{\mu_N}| = 2\cdot 10^{-14} e\cdot cm$$

$$|\vec{d_N}| \approx \theta\cdot 10^{-15} e\cdot cm$$

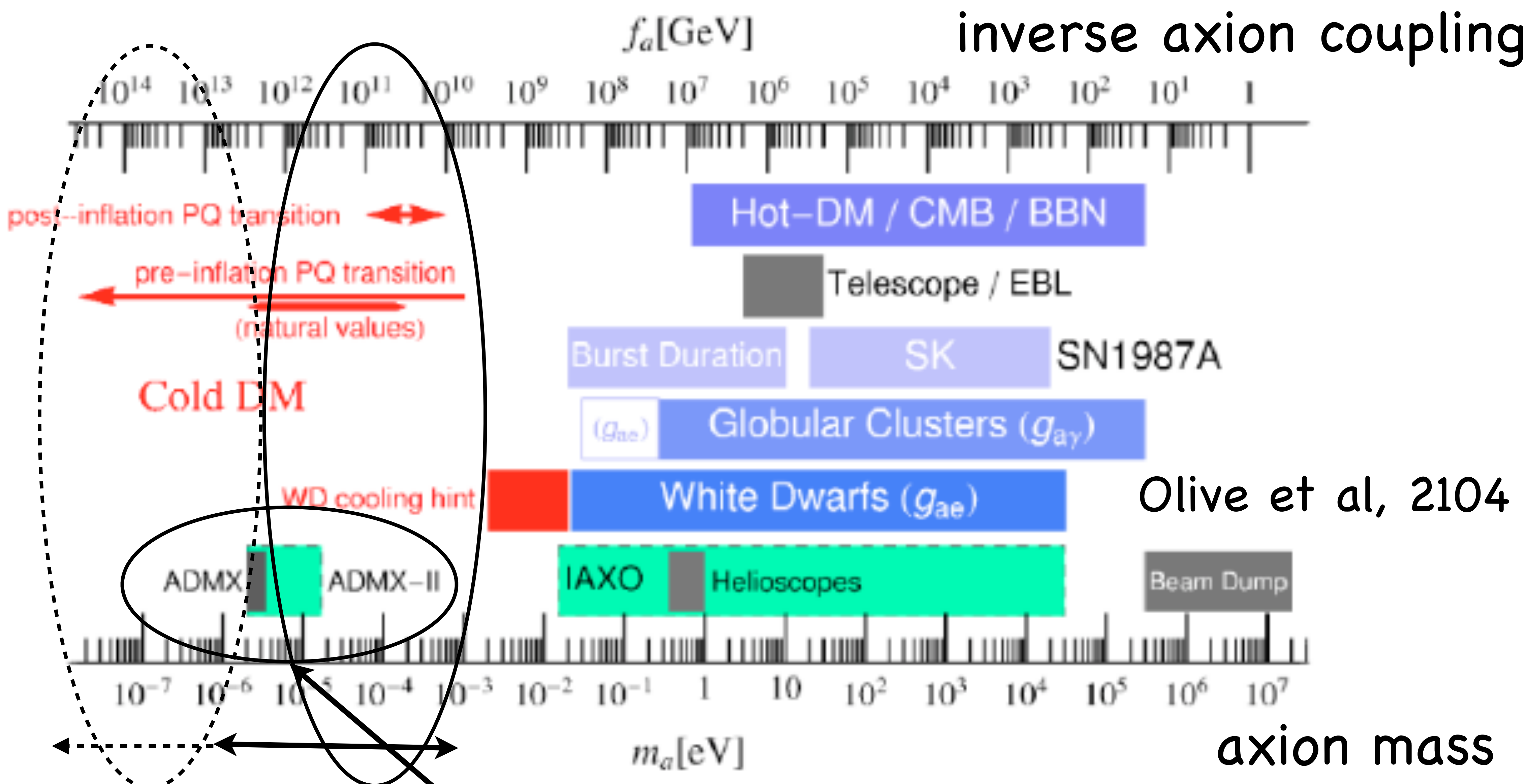
$$|\vec{d_N}|_{exp} < 3\cdot 10^{-26} e\cdot cm$$

$\Rightarrow$ Make θ a dynamical field forced in its cosmological history to relax to 0 (almost) and (possibly) appear as DM

Peccei, Quinn 1977

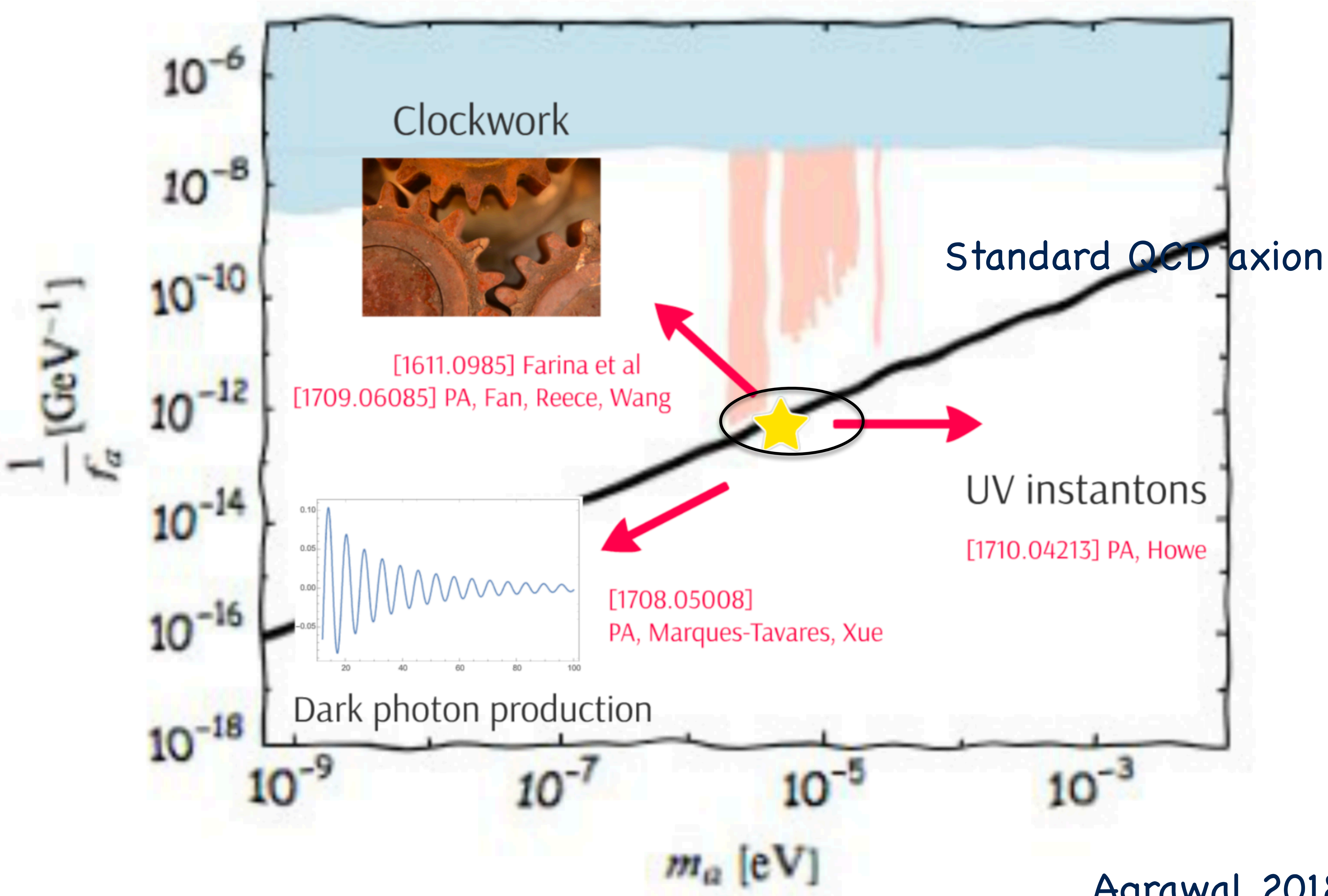
The dynamical field, a, is the "axion" and is very intensively searched for

(with the most interesting region still unaccessible)



$$\frac{a}{f_a}\frac{\alpha}{8\pi}C_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad a \xrightarrow{\vec{B}} \gamma$$

Attempts to expand the salient region



Agrawal 2018

The coupling to spin

$$L = \bar{\psi}(x)(i\hbar\not{\partial}_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \quad (g_s = 10^{-(12\div17)} g_p \frac{GeV}{m_\Psi})$$

DFSZ $g_p(e) \approx 1$

KSVZ $g_p(e) \approx 10^{-3}$

NRL: $$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma}$$

$$\gamma = \frac{e}{2m_\Psi}$$

B, Cerdonio, Fiorentini, Vitale 1989

The axion as a source of an effective $\vec{B}$

1. By the DM axion wind seen on earth moving in the galaxy $a \sim a_0 \sin(m_a t - m_a \vec{v} \cdot \vec{x})$

$$\vec{B}_{eff} = \frac{g_p}{e} \vec{\nabla} a = \frac{g_p}{e} m_a \vec{v}\, a_0 \cos m_a t$$

$$m_a \approx 6\ \mu eV \left(\frac{10^{12} GeV}{f_a}\right)$$

(as reference)

$$\omega = m_a \approx 100\ GHz$$

$$m_a\ a_0 \approx \sqrt{\rho_{DM}} \approx 0.3\ GeV/cm^3$$

$$v \approx 10^{-3}$$

coherence length $\lambda_a^C \approx \frac{1}{m_a v} \approx 10\ m$

coherence time $\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec$

$$B_{eff} \approx 10^{-22}\ Tesla \frac{m_a}{10^{-4} eV}$$

(on electrons)

(1000 bigger on nucleons)

The challenge illustrated

(From the DM axion wind)

$$\gamma_e B_{eff}(e) \approx \gamma_N B_{eff}(N) \approx 10^{-26} eV \frac{m_a}{10^{-4} eV}$$

$$d\ E \approx 10^{-27} eV \frac{E}{10^8 V/cm}$$ (CASPEr)

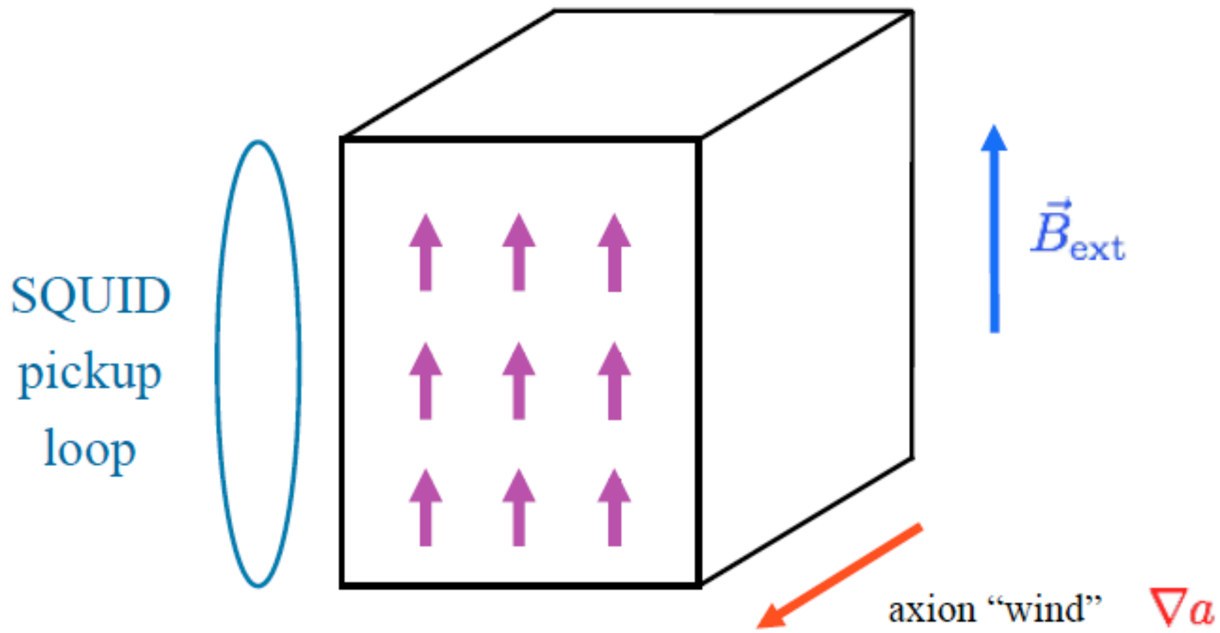
versus, e.g. (Gabrielse et al)

$$\Delta(g-2)_e < 10^{-13} \ \Rightarrow \ \gamma_e B \lesssim 10^{-17} eV \frac{B}{5\ Tesla}$$

$$d_e < 10^{-28} e \cdot cm \ \Rightarrow \ d_e E \lesssim 10^{-17} eV \frac{E}{10^{11} V/cm}$$

Need to work on some resonant phenomenon

Searching for the axion DM wind by way of their coupling to the spin



on electron spins
B, Cerdonio, Fiorentini, Vitale 1989

on nucleon spins
Graham, Rajendram 2010

Solving Block eq.s, at resonance

$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{B} - \frac{1}{T_1, T_2}\mathbf{M}$$

$$m_a = \begin{cases} e: & 2\gamma_e B^{ext} \approx 10^{-4}\ eV \dfrac{B^{ext}}{T} \\ N: & 2\gamma_N B^{ext} \approx 10^{-7}\ eV \dfrac{B^{ext}}{T} \end{cases}$$

$$M_T = \gamma^2_{e,N} B^{eff}_{e,N} n_S \tau \cos{(m_a t)} \begin{cases} N: & 10^{-19} T\ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec) \\ e: & 10^{-21} T\ (m_a = 10^{-4}\ eV,\ \tau = 10^{-6}\ sec) \end{cases}$$

$$\tau = min(\tau_a, \tau_{rel}, \tau_R)$$

$$n_S = 10^{22}/cm^3$$

About "radiation dumping"

Bloom 1957

Back to the transverse magnetization

(for axion wind only)

$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t) \qquad \tau = min(\tau_a, \tau_{rel}, \tau_R)$$

$$\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec \frac{10^{-4}\ eV}{m_a}$$

$\tau_{rel} \approx$ → $0.1\ sec\ for\ NMR$; → $10^{-6}\ sec\ for\ EMR$

$$\tau_R = \frac{1}{\gamma^2 n_S w^3 V} \approx (\frac{10^{-4} eV}{w})^3 \frac{mm^3}{V} \frac{10^{22}/cm^3}{n_S} \times$$

→ $10^{-9}\ sec\ for\ EMR$; → $10^{-3}\ sec\ for\ NMR$

$\Rightarrow \tau_R$ large, hence negligible, for NMR exp.s (CASPEr, static force)

$w = 200\ Hz$

$\Rightarrow \tau_R$ seriously relevant for EMR

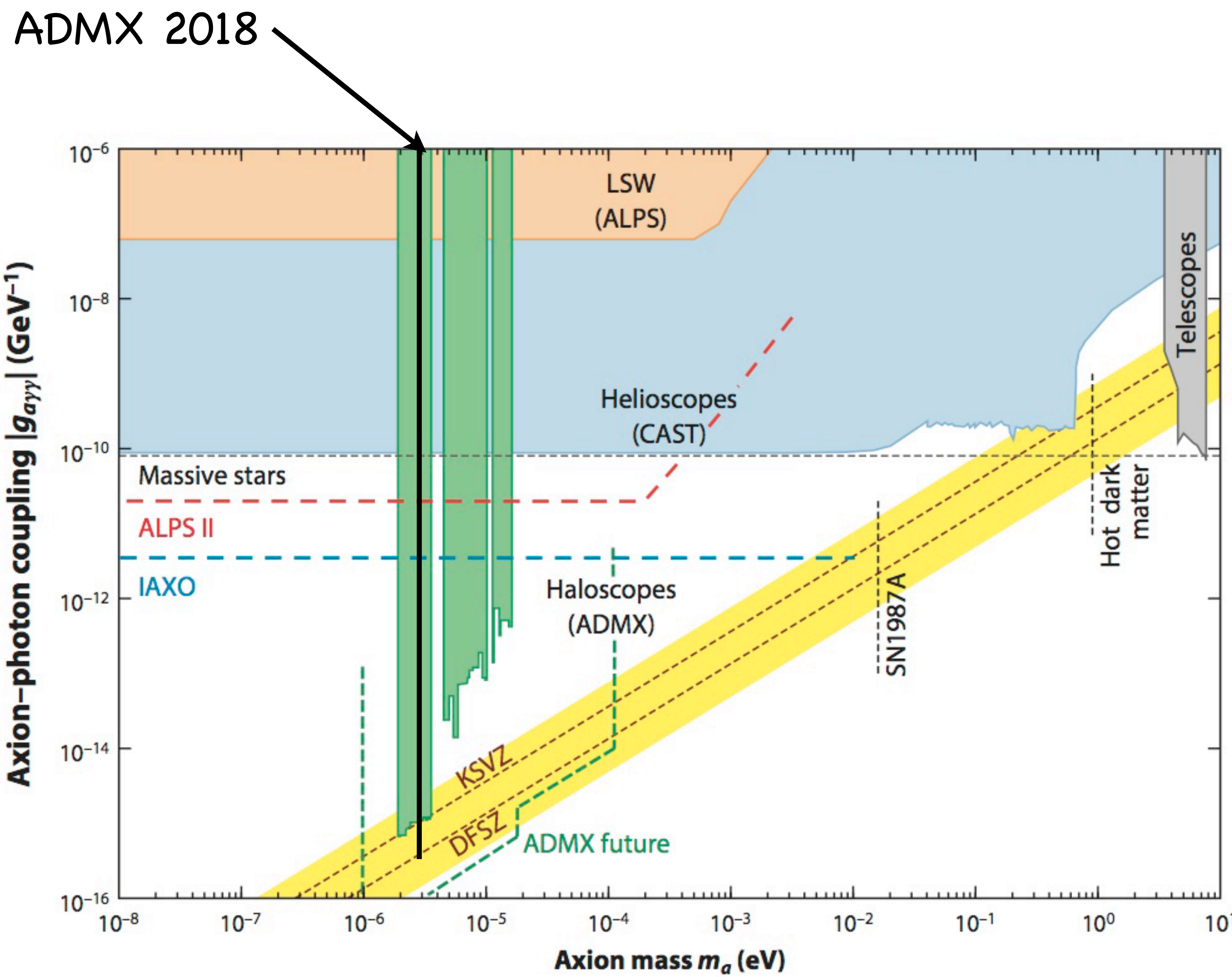
Need to work in a cavity

$$\mathcal{L}_a = -\frac{1}{2}|\partial_\mu a|^2 + \frac{\partial_\mu a}{f_a} J_\mu^{PQ} + \frac{a}{f_a}\frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{a}{f_a}\frac{\alpha}{8\pi} C_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$J_\mu^{PQ} = \sum_\Psi Q_\Psi^{PQ} \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

Source	Coupling: Photons	Coupling: Nucleons	Coupling: Electrons
Dark Matter (Cosmic) axions	ADMX, HAYSTACK, DM Radio, LC Circuit, MADMAX, ABRACADABRA	CASPEr	QUAX
Solar axions	CAST IAXO		
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE	

Axion searches: current

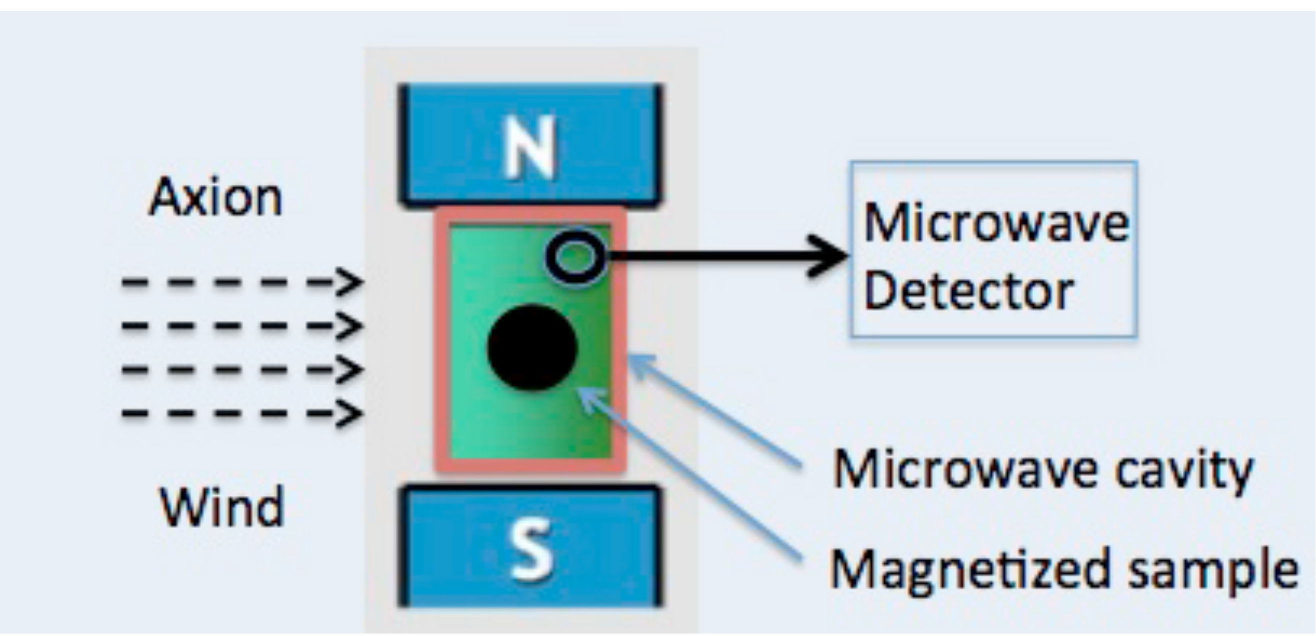


QUaerere AXions

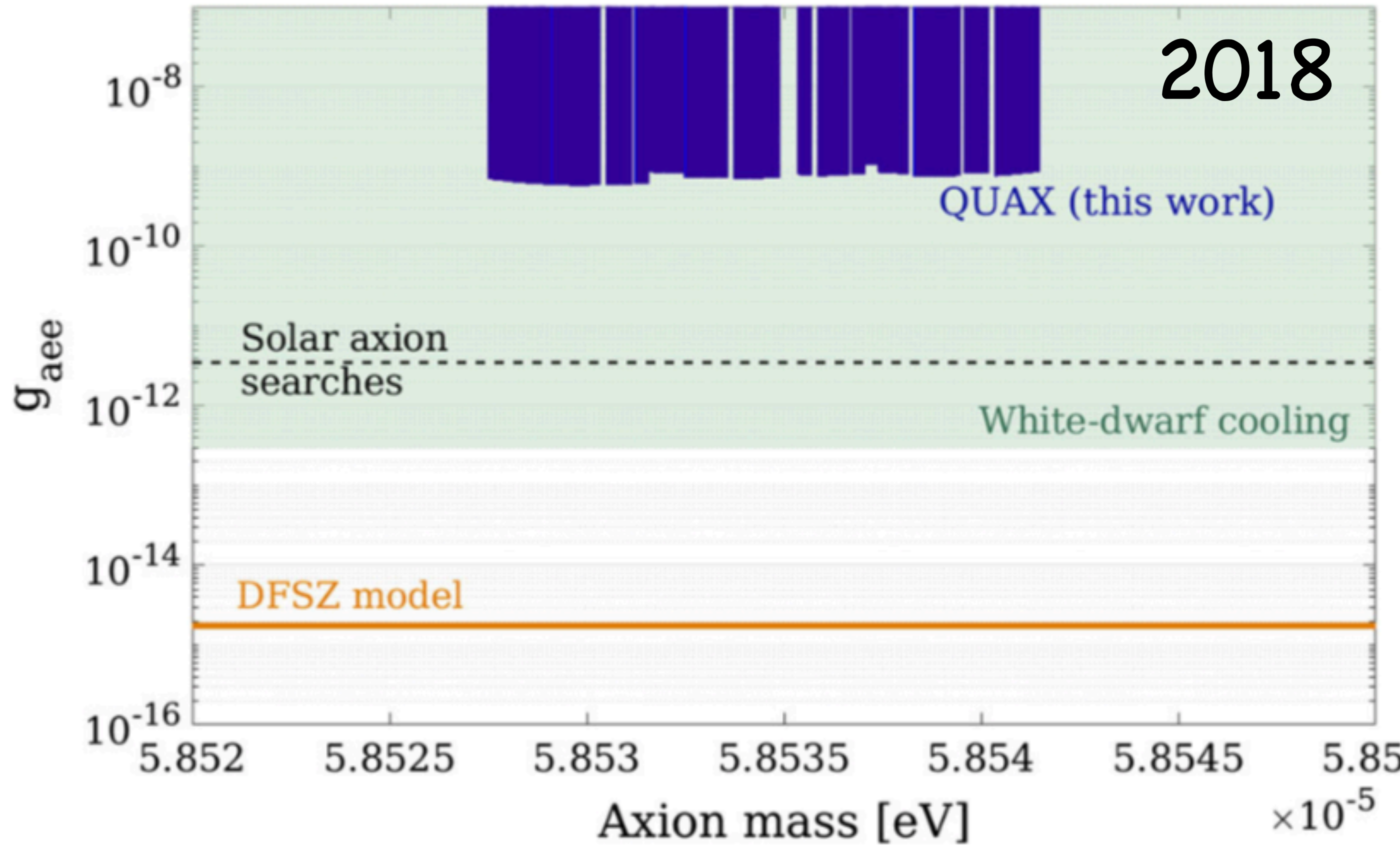
QUAX collaboration

Use the coupling to the electron spin (to avoid the frequency cutoff)

and (try to) detect the RF power emitted by the coherent magnetic dipole oscillating at $w = m_a$



The experiment in principle



The current status

Thanks to Gianni

(and to the QUAX Collaboration)

A quick introduction to axions

Suitably extend the SM to include an exact classical U(1)-symmetry (PQ) spontaneously broken at a scale f_a

Due to a mixed anomaly, a pseudo-GB, a, arises, so that

$$\mathcal{L}_a = -\frac{1}{2}|\partial_\mu a|^2 + \frac{\partial_\mu a}{f_a} J_\mu^{PQ} + \frac{a}{f_a}\frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{a}{f_a}\frac{\alpha}{8\pi} C_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu} \quad -V(a,\pi^0)$$

$$J_\mu^{PQ} = \sum_\Psi Q_\Psi^{PQ} \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

$\Rightarrow$ $< a >= 0$ hence $\theta = 0$

In the cosmic evolution, at $T \lesssim \Lambda_{QCD}$

$$m_a \approx 6\ \mu eV (\frac{10^{12} GeV}{f_a})$$

$\rho_a = m_a^2 a^2 \propto T^3 \propto 1/R^3$ hence Cold Dark Matter

$\Omega_a \approx (\frac{6\ \mu eV}{m_a})^{7/6}$ hence $\Omega_{DM} \approx 0.2$ at $m_a \approx 20\ \mu eV$