Axion Searches

Javier Redondo

Probing the Dark Universe

6/11/2018

Dep. Theoretical Physics
Universidad de Zaragoza

MAX-PLANCK-GESELLSCHAFT

MPP Munich

New experimental approaches in the search for axion-like particles

Igor G. Irastorza[1,2] and Javier Redondo[1,3]

[1]Departamento de Física Teórica, Universidad de Zaragoza, 50009 Zaragoza, Spain
[2]Laboratorio Subterráneo de Canfranc, 22880 Canfranc Estación, Spain
[3]Max-Planck-Institut für Physik, 80805 München, Germany

May 7, 2018

Abstract

Axions and other very light axion-like particles appear in many extensions of the Standard Model, and are leading candidates to compose part or all of the missing matter of the Universe. They also appear in models of inflation, dark radiation, or even dark energy, and could solve some long-standing astrophysical anomalies. The physics case of these particles has been considerably developed in recent years, and there are now useful guidelines and powerful motivations to attempt experimental detection. Admittedly, the lack of a positive signal of new physics at the high energy frontier, and in underground detectors searching for weakly interacting massive particles, is also contributing to the increase of interest in axion searches. The experimental landscape is rapidly evolving, with many novel detection concepts and new experimental proposals. An updated account of those initiatives is lacking in the literature. In this review we attempt to provide such an update. We will focus on the new experimental approaches and their complementarity, but will also review the most relevant recent results from the consolidated strategies and the prospects of new generation experiments under consideration in the field. We will also briefly review the latest developments of the theory, cosmology and astrophysics of axions and we will discuss the prospects to probe a large fraction of relevant parameter space in the coming decade.

Axions in hep-th

STRONG CP PROBLEM

SHIFT SYMMETRY

NEW ENERGY SCALE f_A

Social strata Axion-like particles and the QCD axion

Axions in hep-ex

SPIN 0 BOSONS

LOW MASS

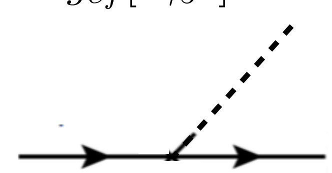
FEEBLE COUPLINGS

photon coupling

$$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

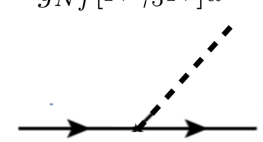
electron coupling

$$g_{ef}[\bar{e}\gamma_5 e]a$$



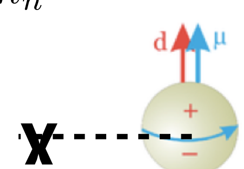
nucleon coupling

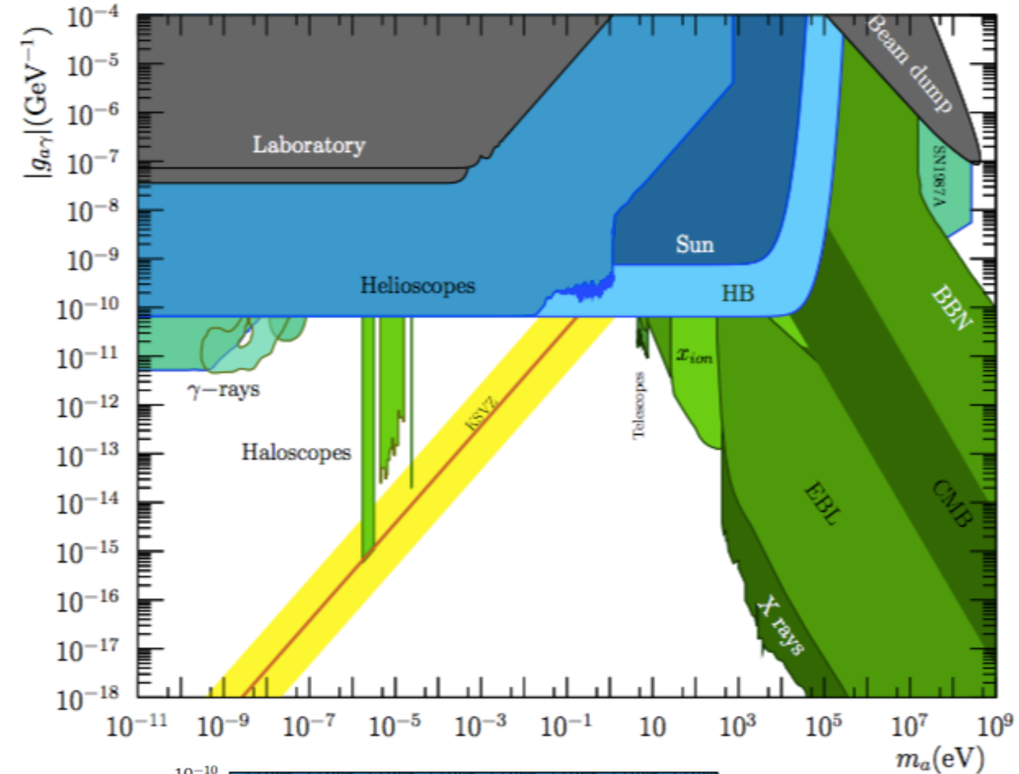
$$g_{Nf}[\bar{N}\gamma_5 N]a$$

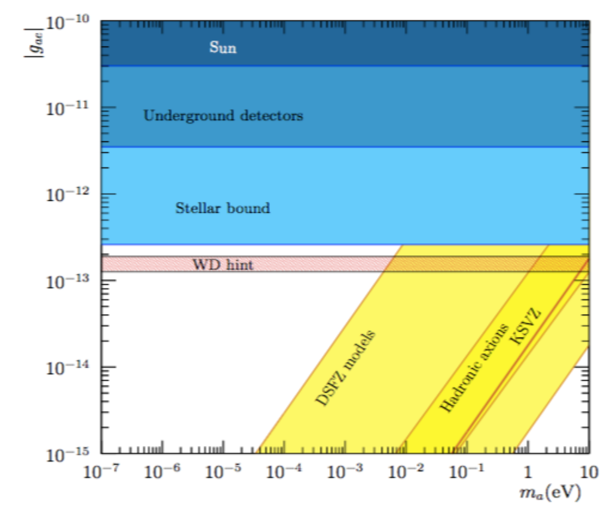


CP Neutron electric dipole

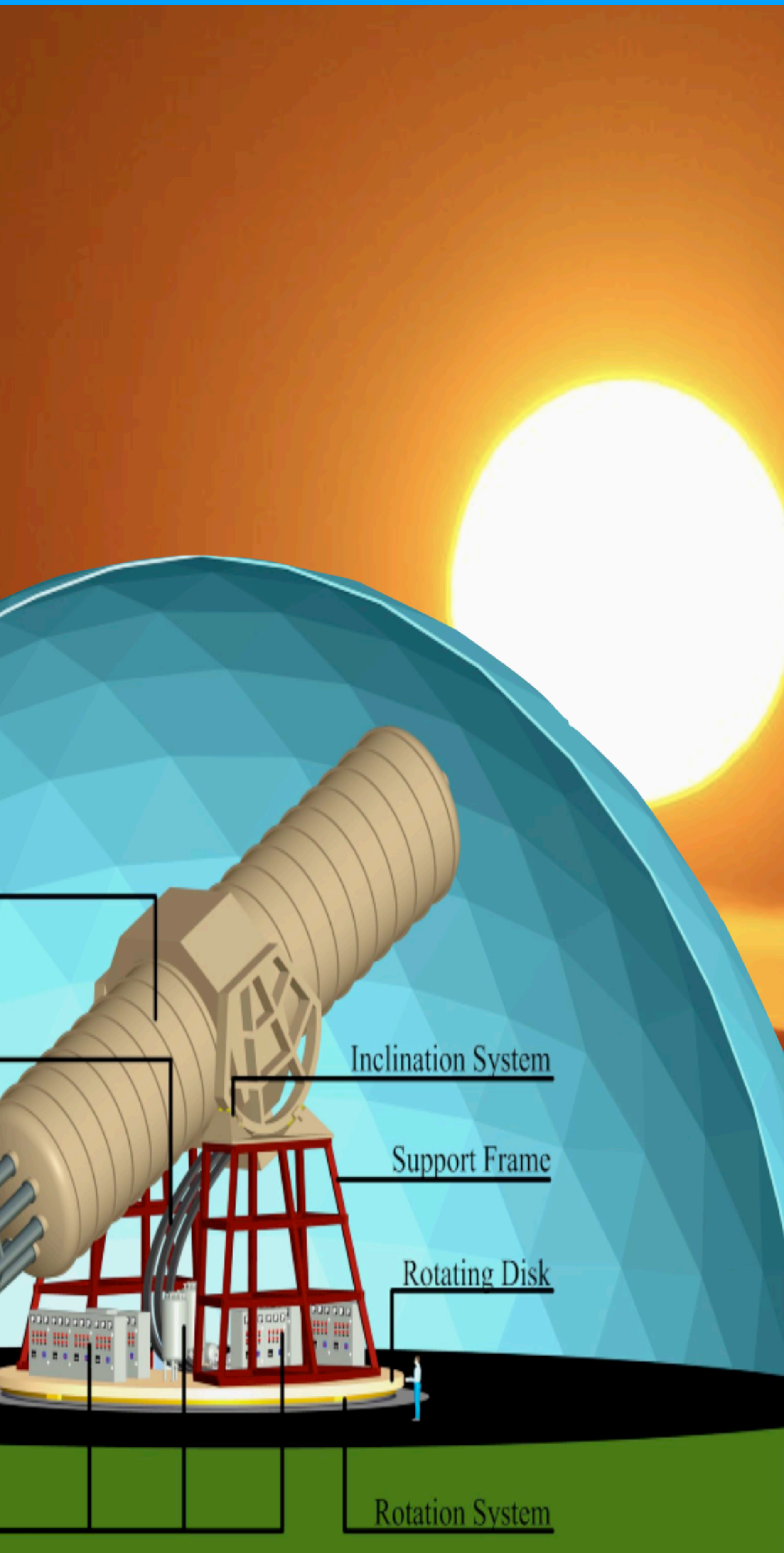
$$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$$



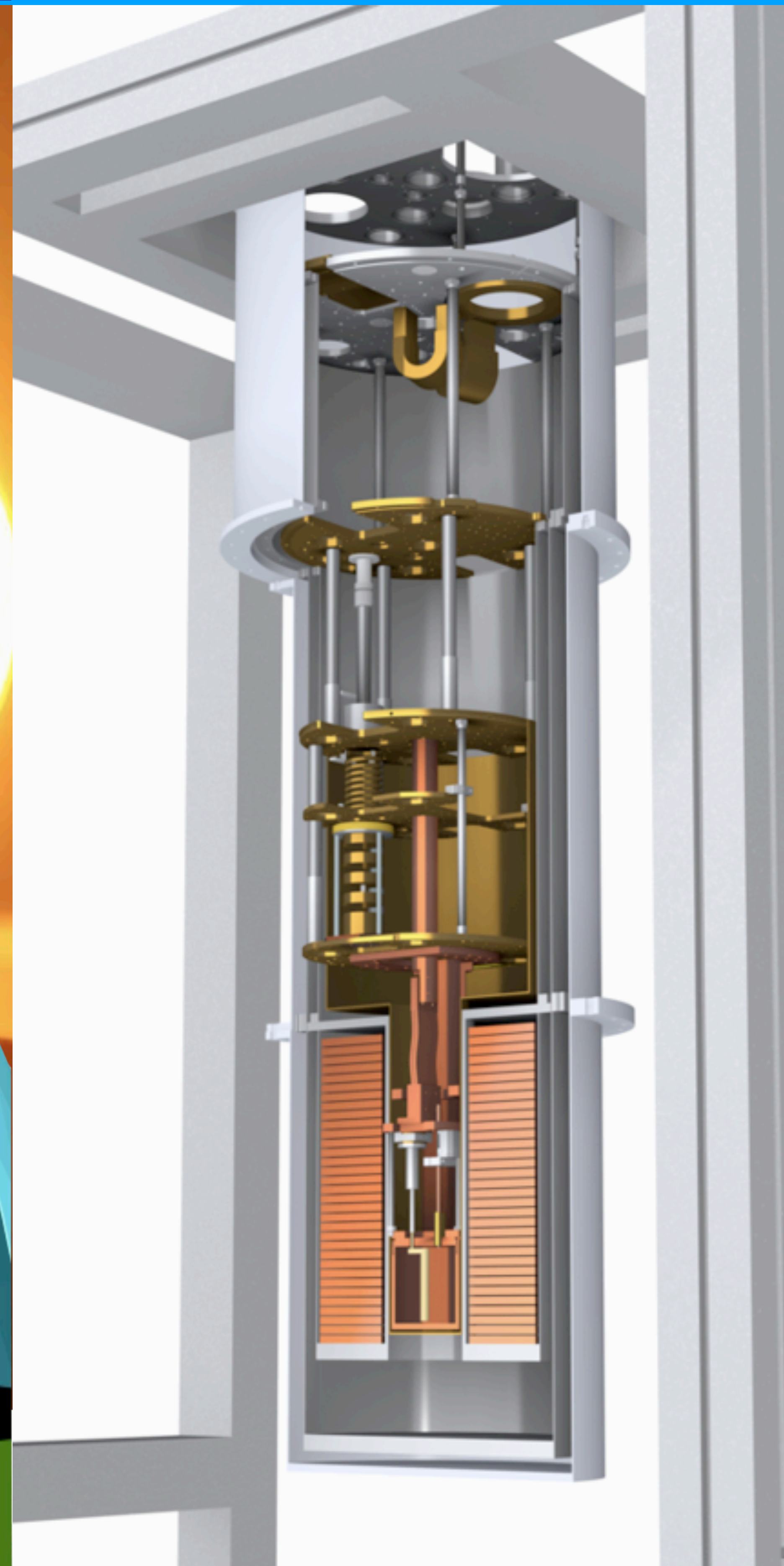




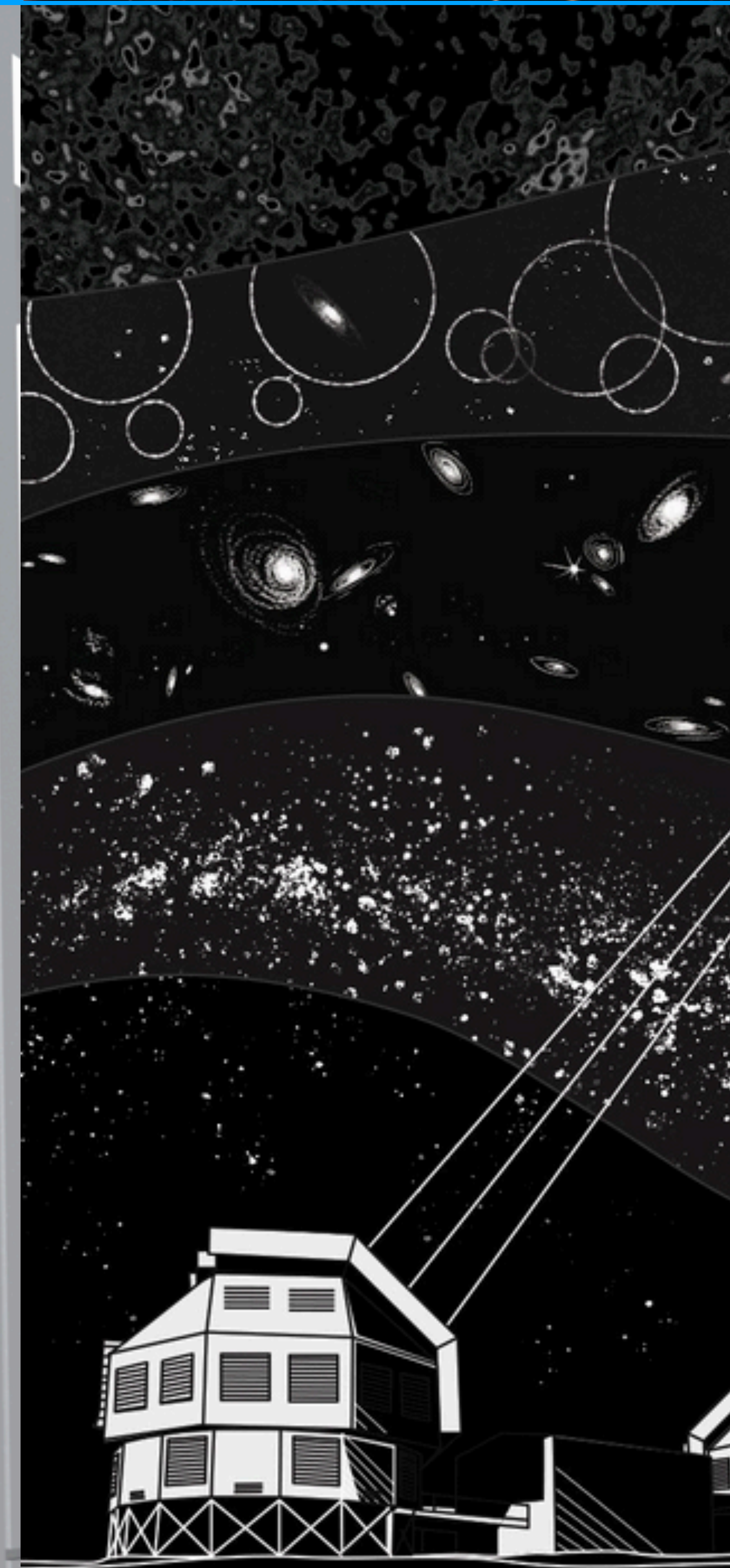
Stars



Lab



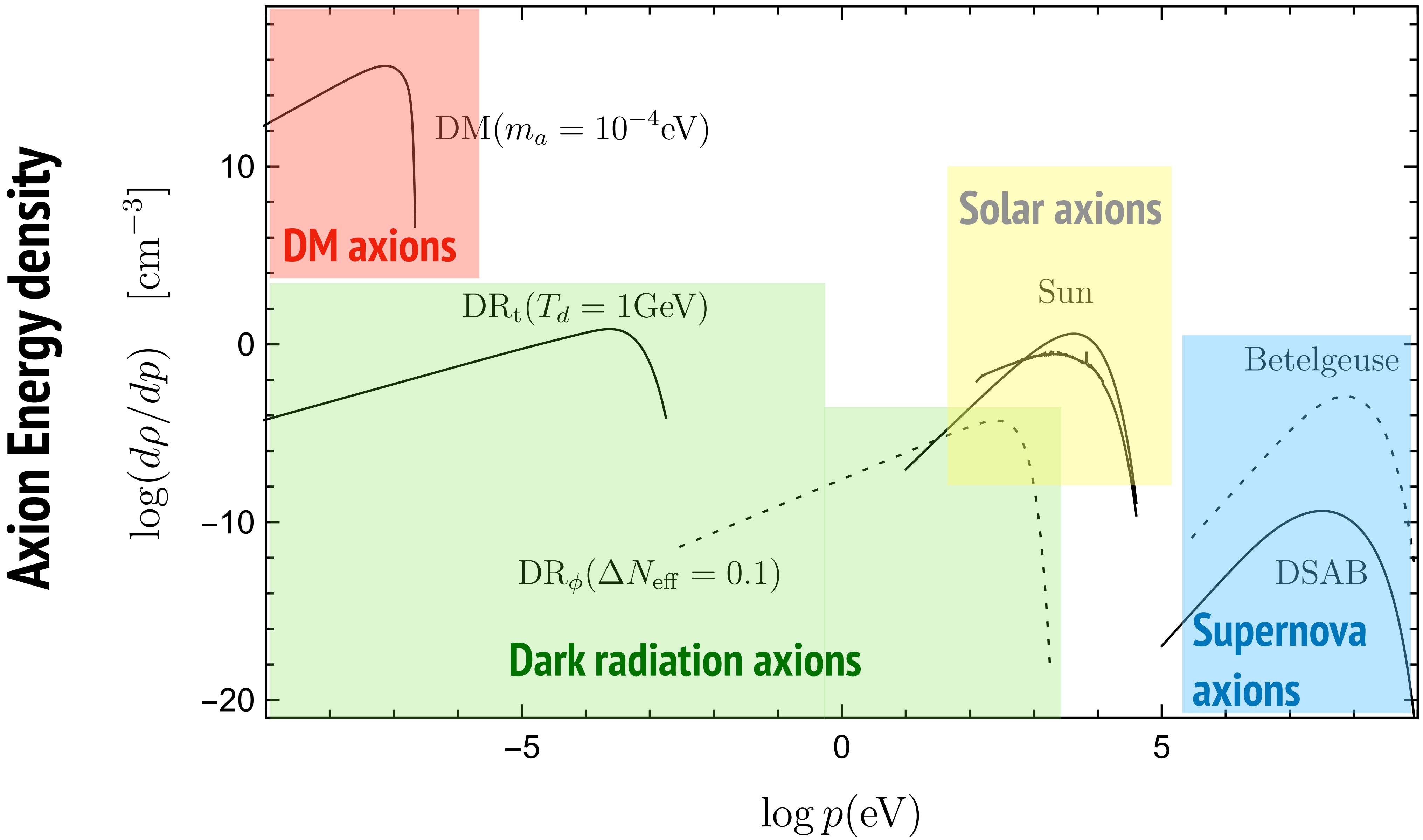
Cosmos



Search for Axions : Natural sources

- Naturally produced axions could be quite copious, save production and focus on detection!

Irastorza 2018

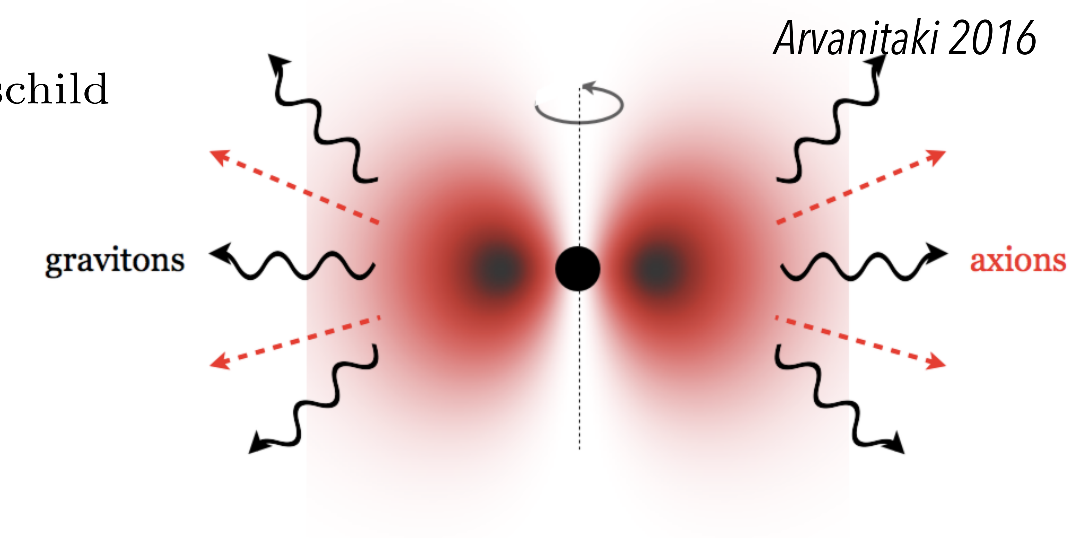


Axion momentum

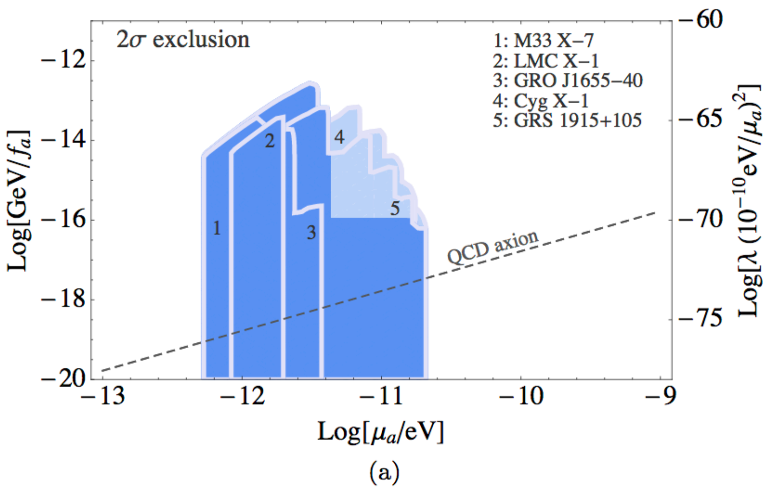
Black holes

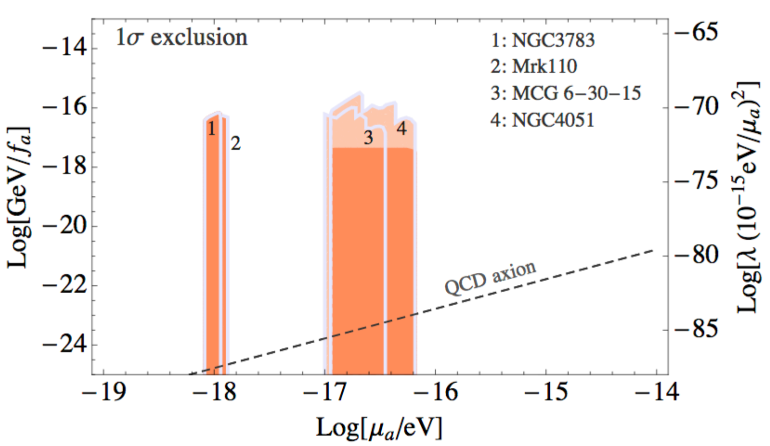
- Kerr Black holes superradiate ALPs of $m_a \sim 1/R_{\mathrm{Schwarzschild}}$

Arvanitaki 2016

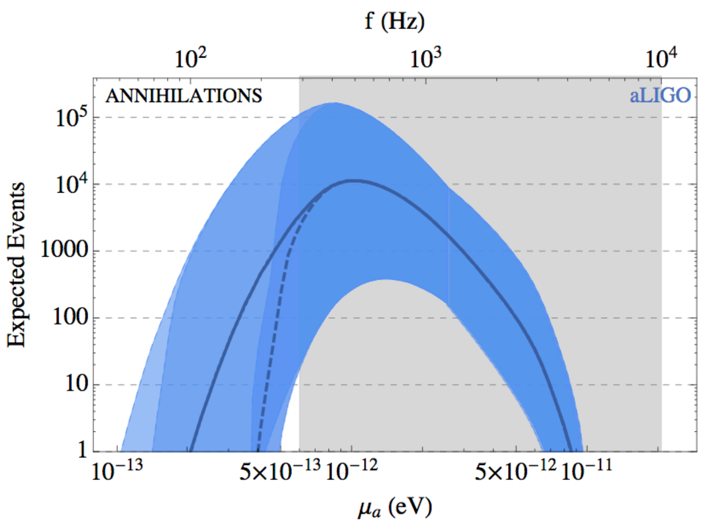


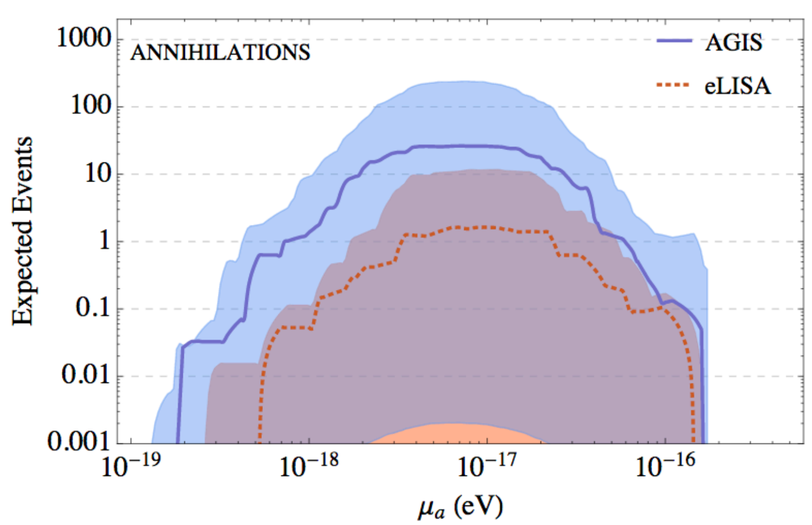
- Spin radiated >> discovery/constraints?





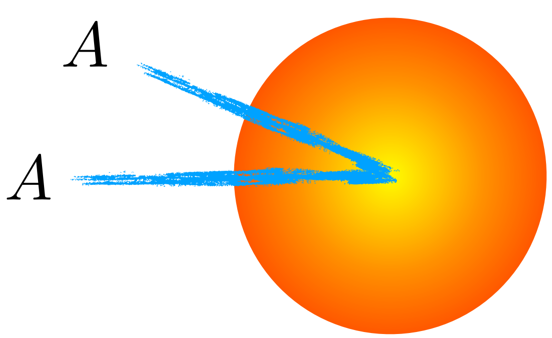
- Axion "atomic transitions" >> gravitational waves >> discovery/constraints





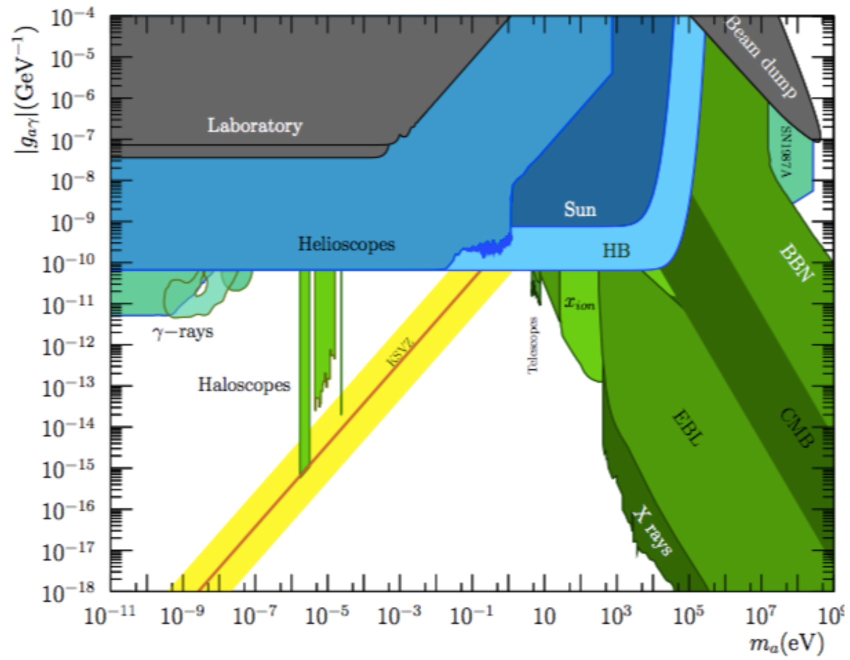
Stellar evolution

- ALP emission accelerates stelar evolution time scales: compare observations and predictions

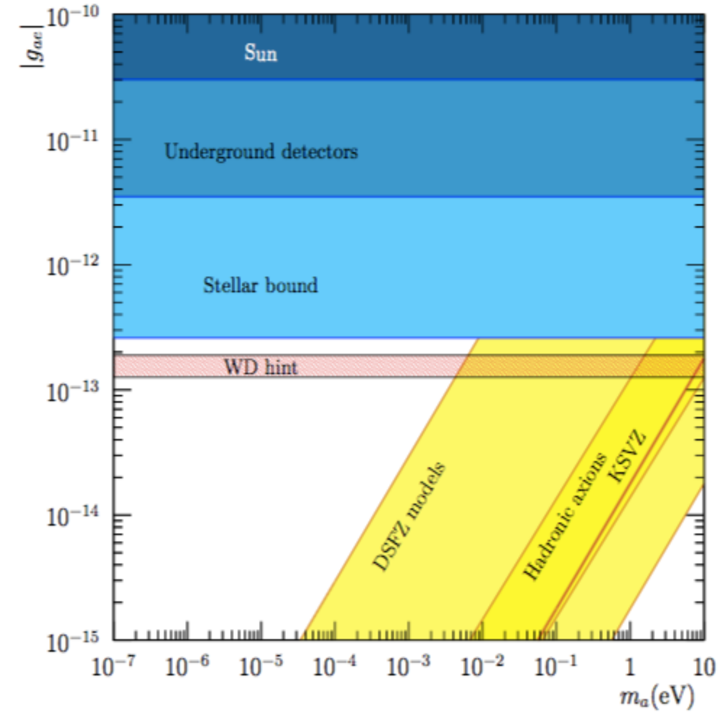


STRONG CONSTRAINTS

HBs in Gcs

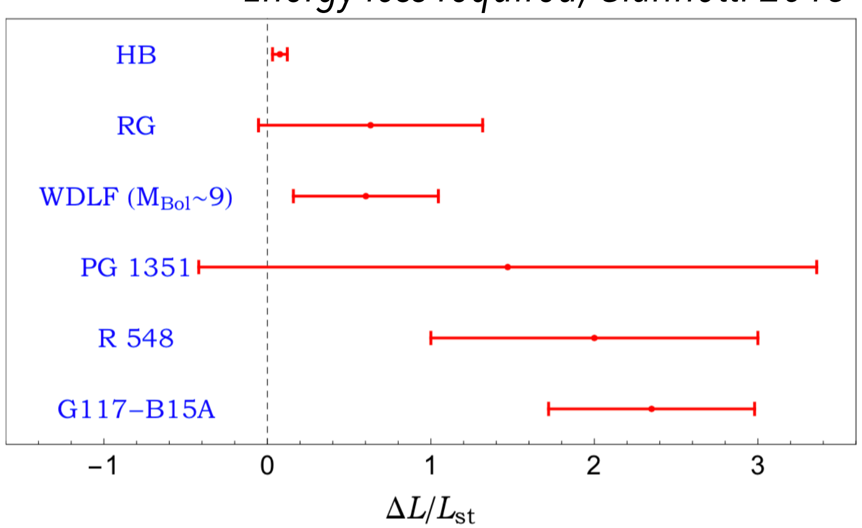


WDs, RGs in GCs

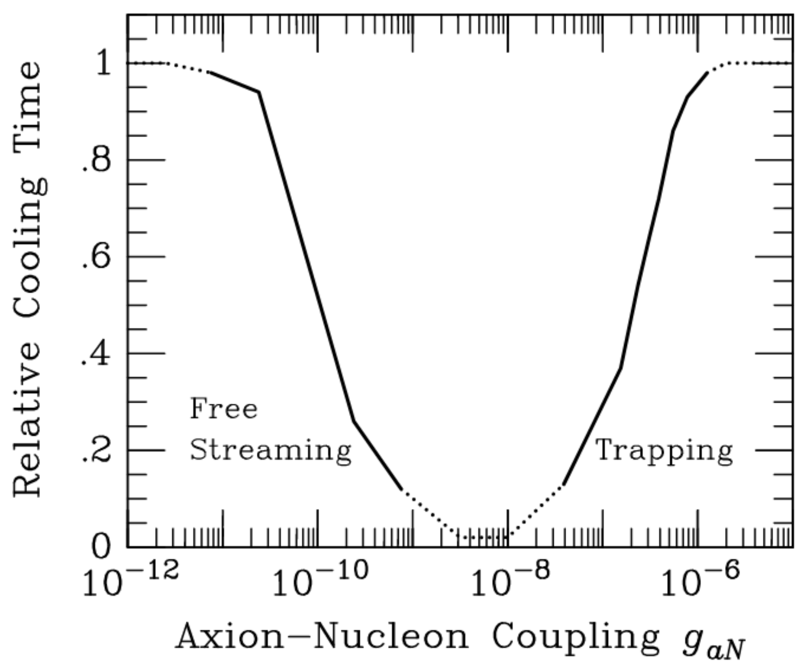


SOME ANOMALIES

Energy loss required, Giannotti 2015

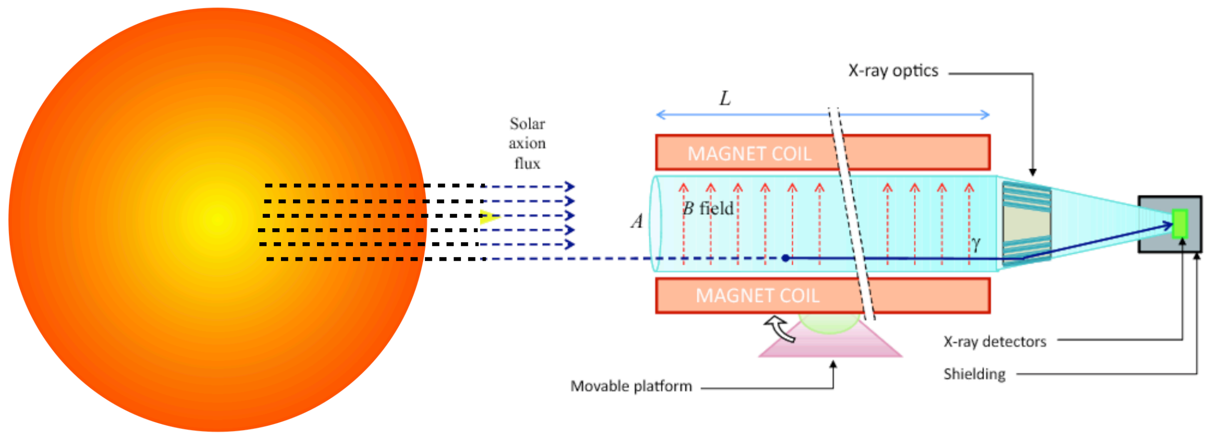


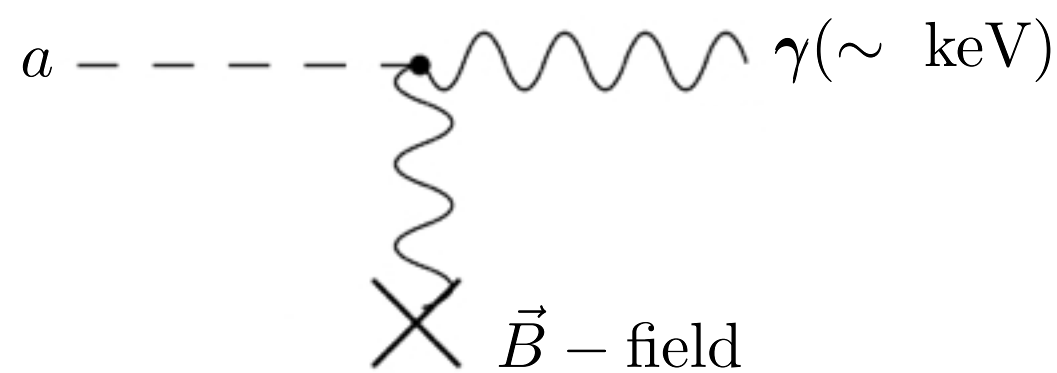
SN1987, Next Galactic SN



Solar axions

- Sun is brighter source of axions
- Haloscopes use inverse Primakoff (coherent conversion) in strong transverse fields



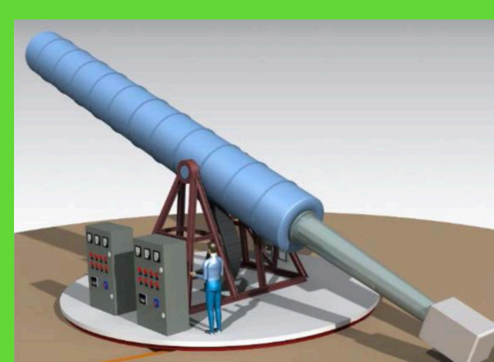


- Evolution from … to CAST (CERN) … to proposed IAXO (DESY)

CAST

- 1~2 h tracking/day (sunset,dawn)
- 3 Detectors (2 bores)
- X-ray optics
- small aperture

BABY IAXO

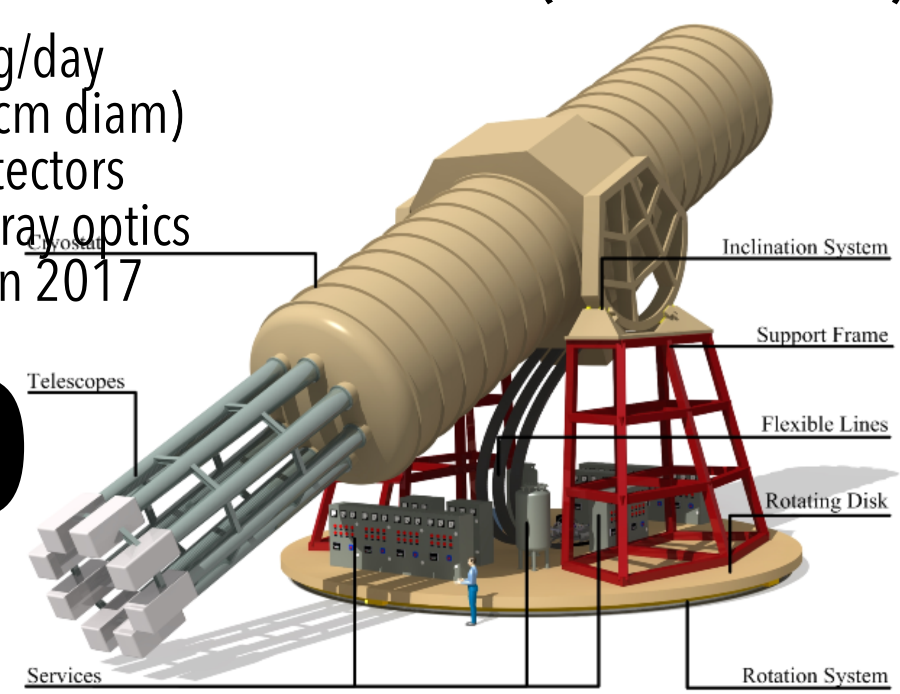


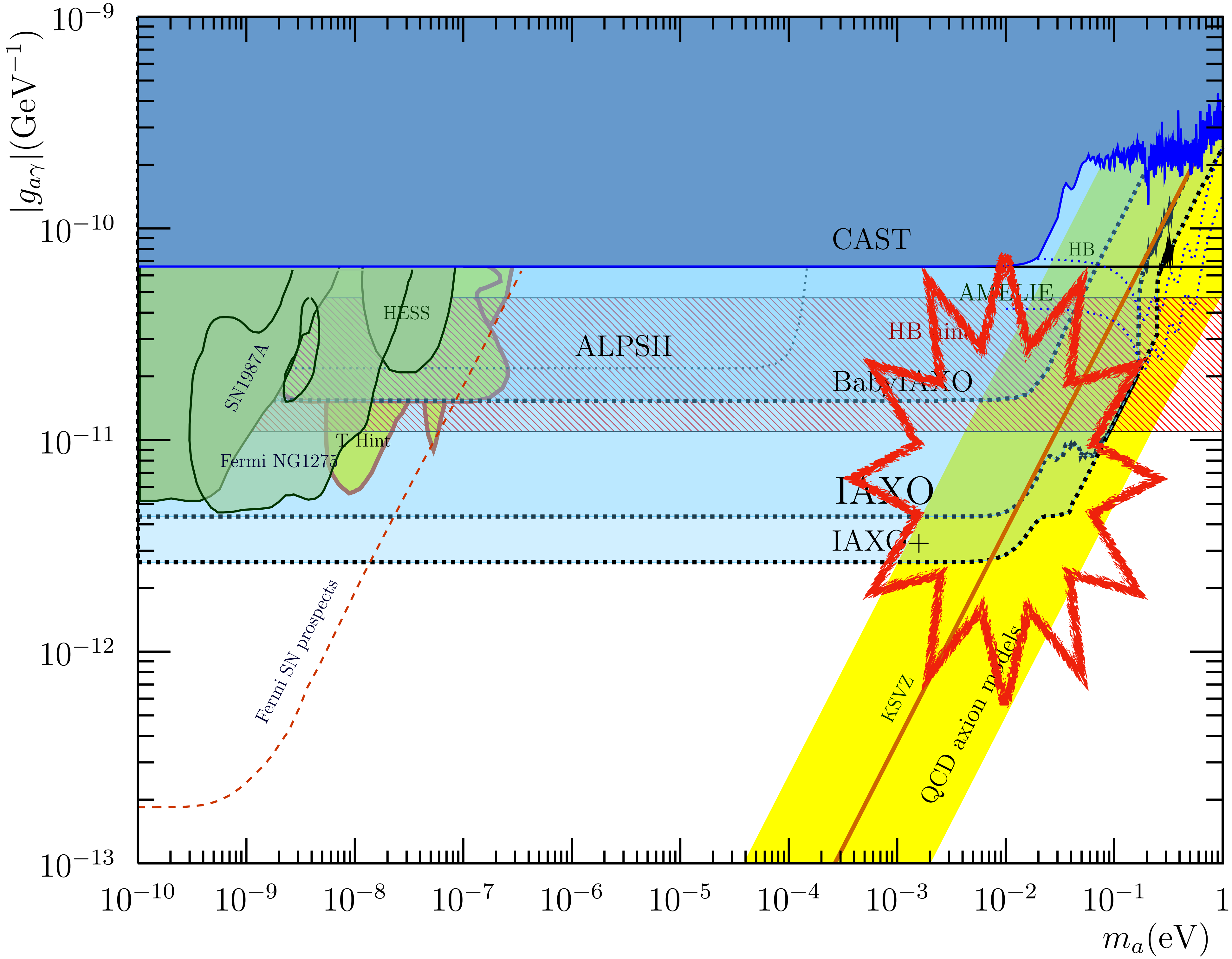
- Intermediate step to IAXO
- Full field/length
- X-ray optics
- Medium aperture

INTERNATIONAL AXION OBSERVATORY (DESY HAMBURG)

- 12 h tracking/day
- 8 bores (60 cm diam)
- different Detectors
- dedicated X-ray optics
- Collaboration 2017

IAXO

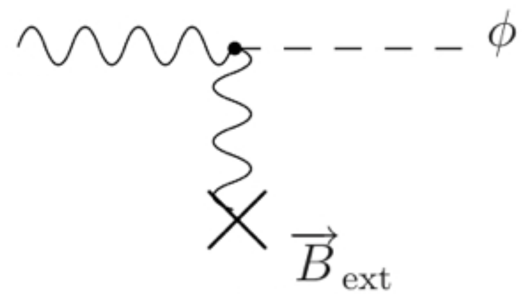


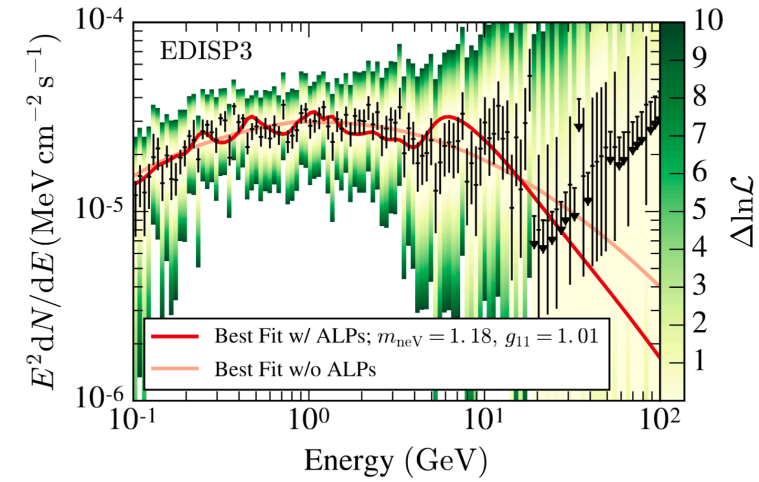


Other Helioscopes: Underground DM/nuless 2beta detectors SOLAX, COSME, DAMA, CDMS, EDELWEISS>> CUORE, GERDA, MAJORANA XENON, XMASS, PANDAX-II, LUX >> DARWIN

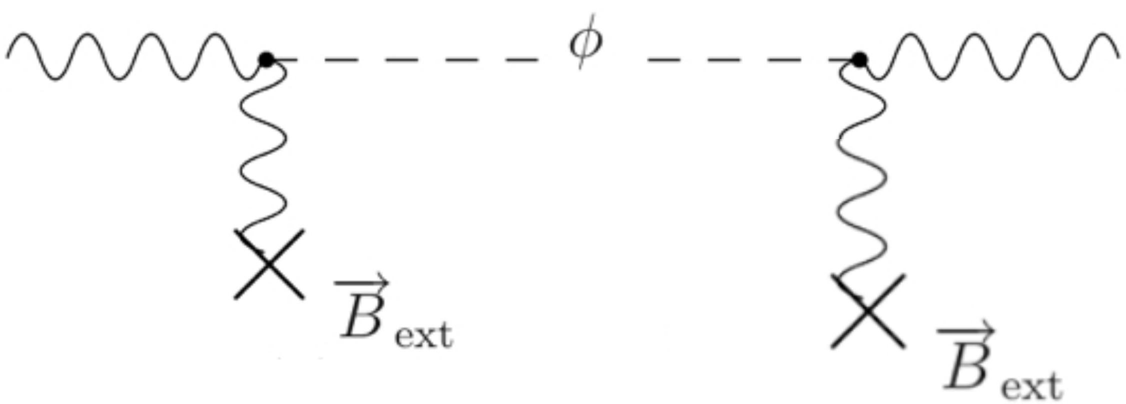
Photon propagation

- **Photon ALP conversion is energy dependent**

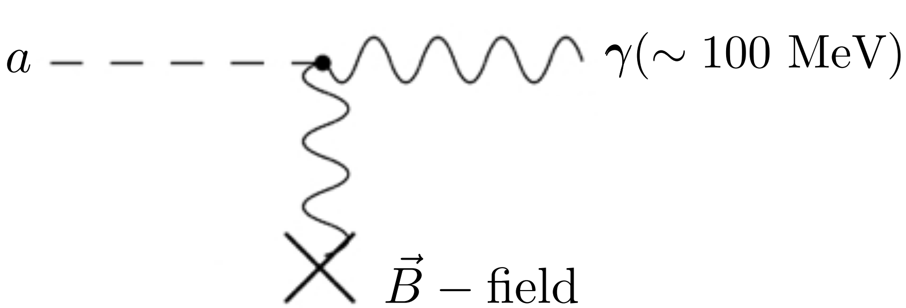




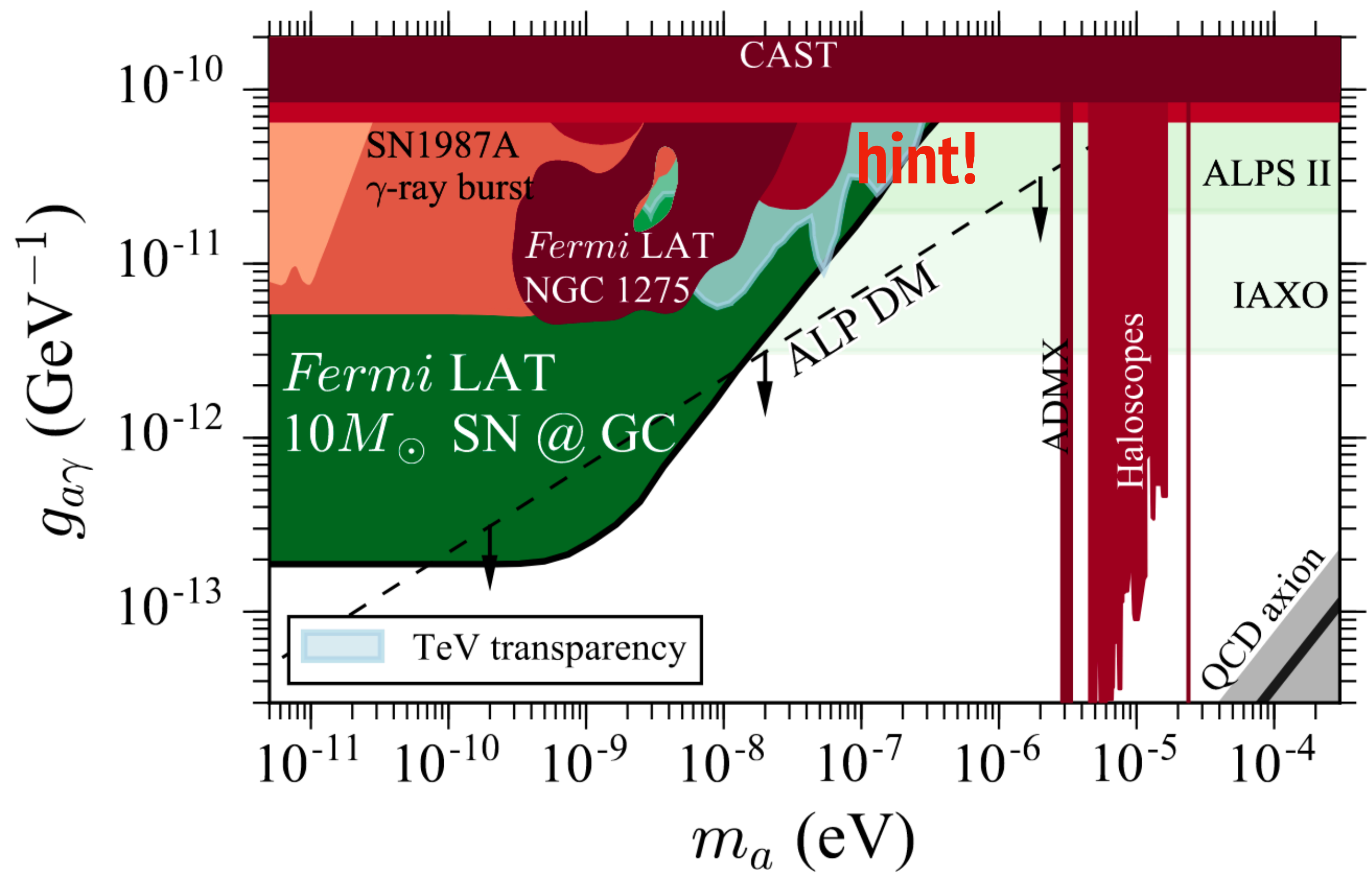
- **Reconversion decreases effective opacity (anomalous transparency to TeV gammas)**



- **Supernova-axions >> gamma ray burst**

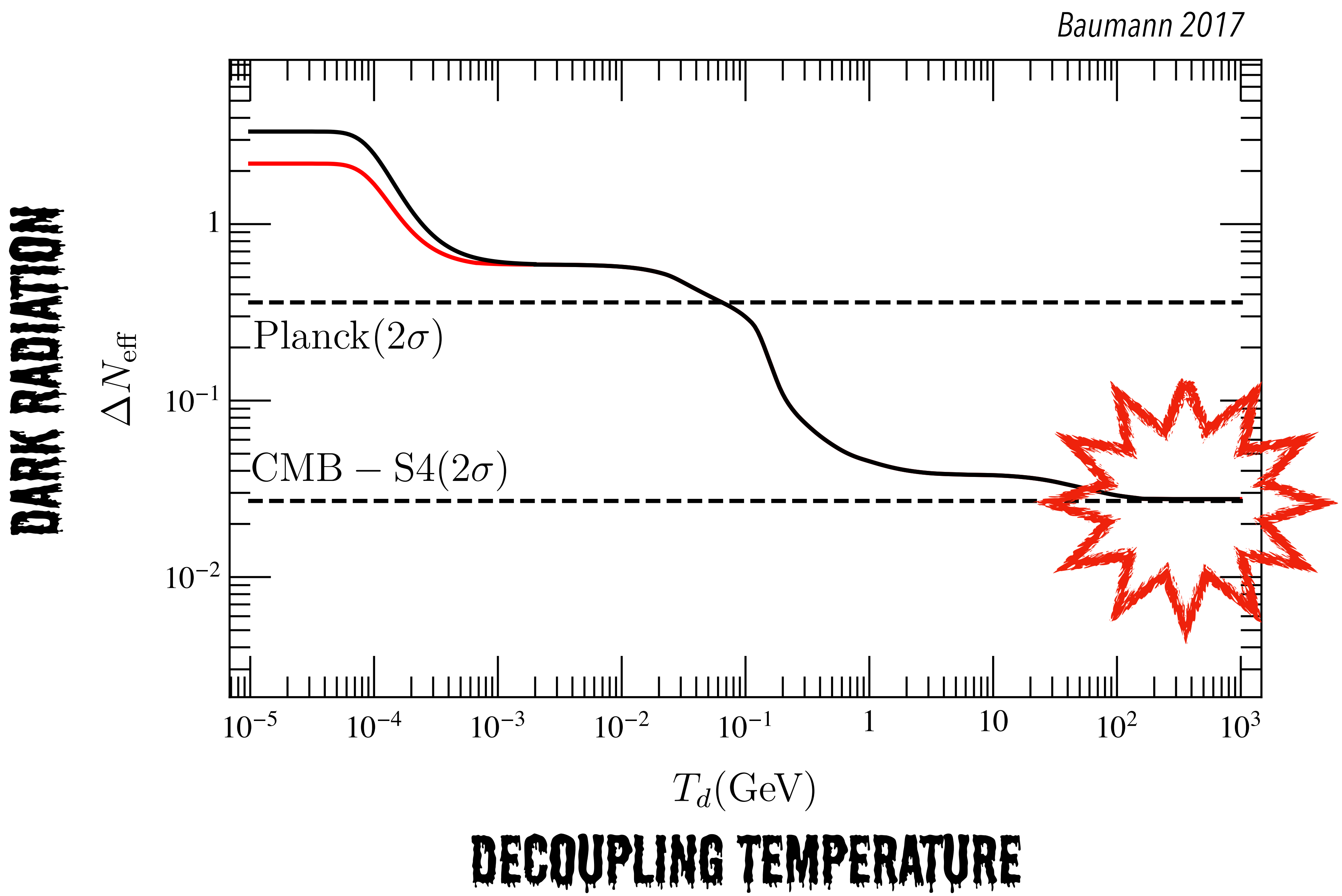


Meyer 2017



Dark radiation

- ALPs produced in the Big band at decoupled at a high-T >>> Dark radiation (extra neutrino species)
- Next generation CMB polarisation experiments can have the sensitivity to discover BSM



ALP Dark matter is (can be) different

QUANTUM PRESSURE

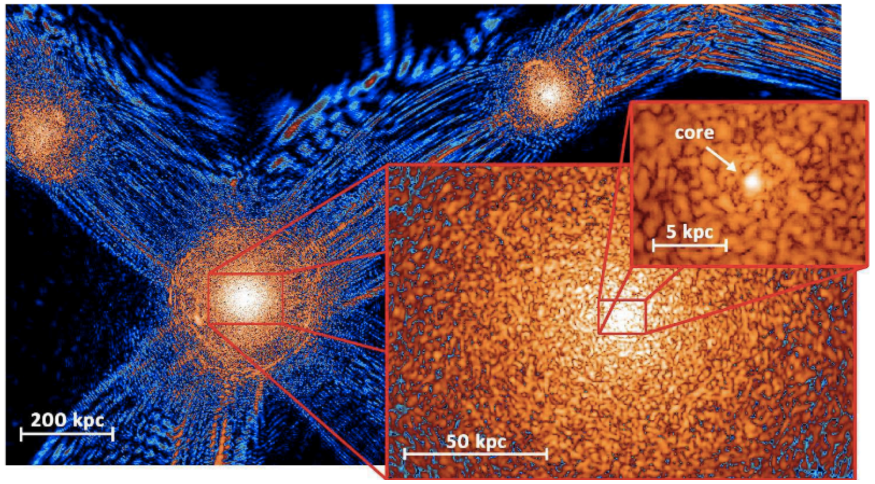
DECAYING DM

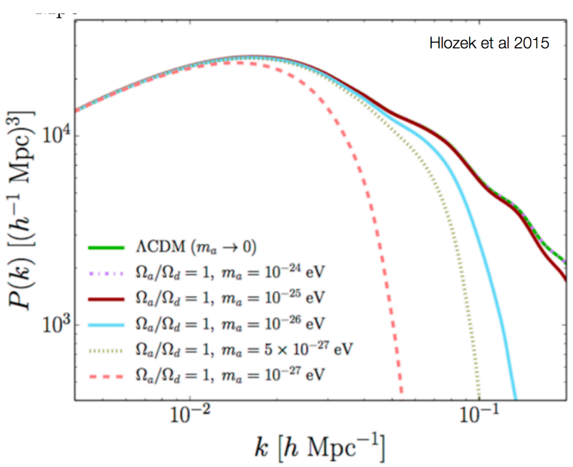
MINICLUSTERS

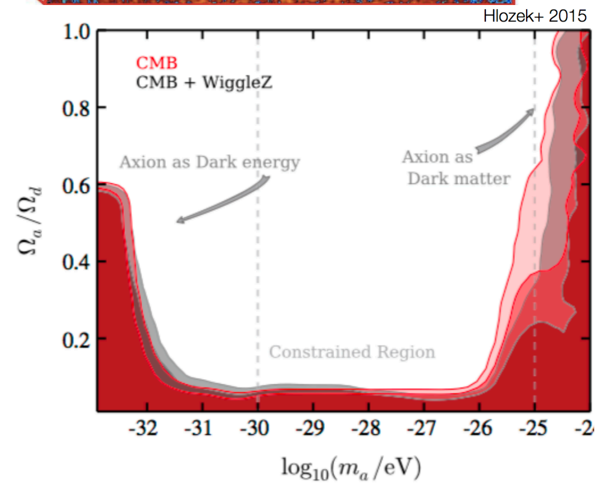
FEMTO,PICO,MICROLENSING

ISOCURVATURE T-FLUCTUATIONS

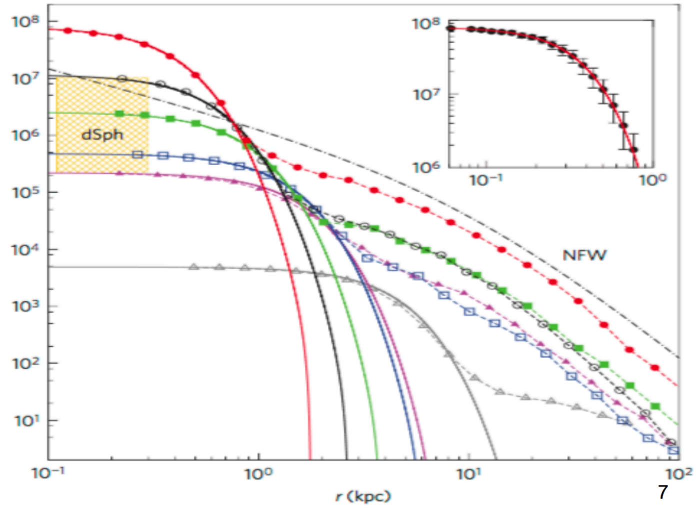
$$k_J = 67\, a^{1/4} \left(\frac{\Omega_a h^2}{0.12}\right)^{1/4} \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \mathrm{Mpc}^{-1}$$





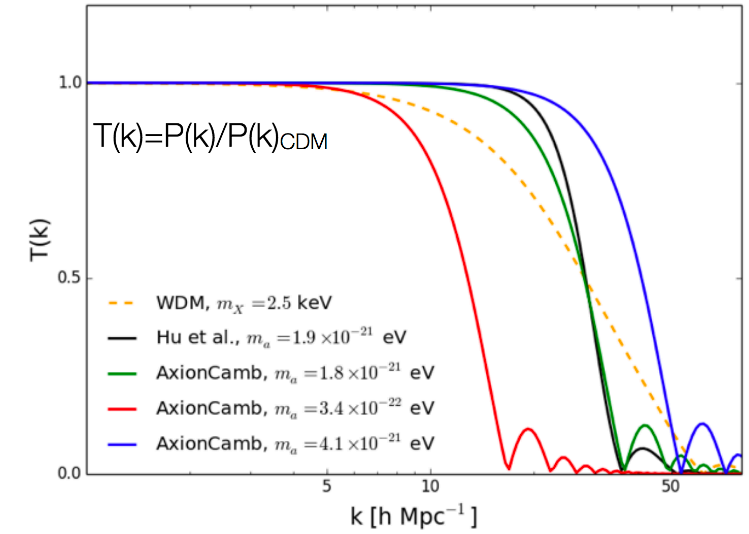


HALOS are CORED



VS.

Ly-alpha constraints



ALP Dark matter is (can be) different

QUANTUM PRESSURE

DECAYING DM $a \rightarrow \gamma\gamma$

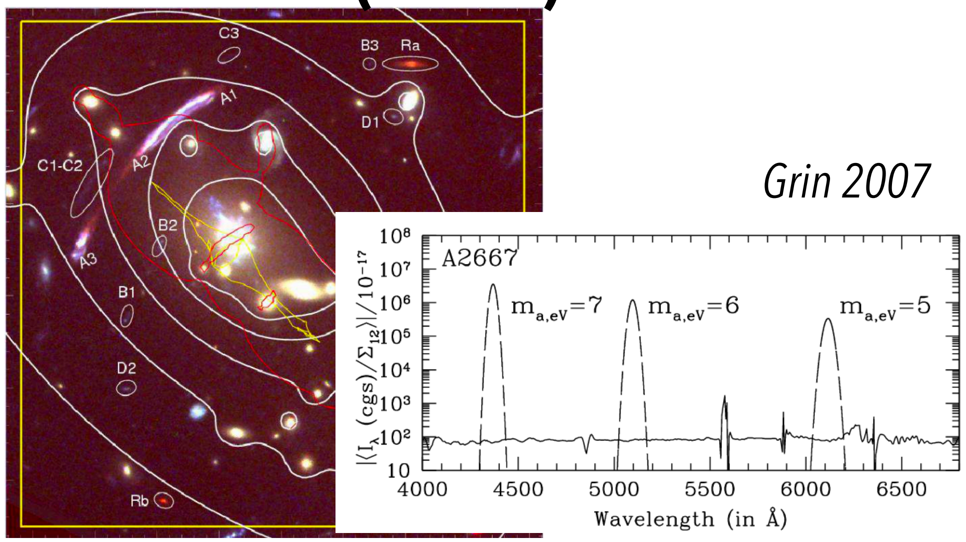
MINICLUSTERS

FEMTO,PICO,MICROLENSING

ISOCURVATURE T-FLUCTUATIONS

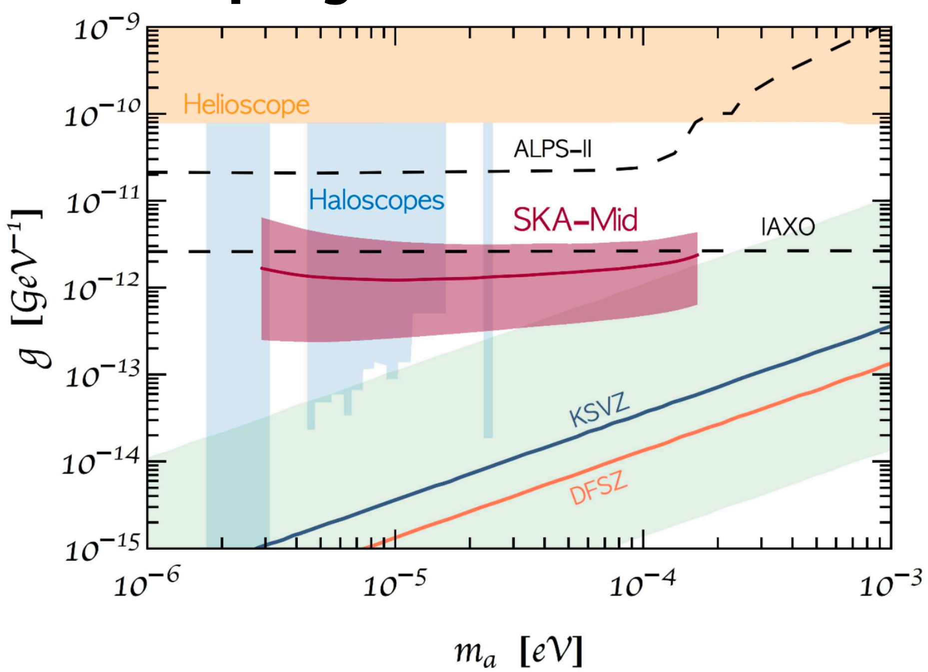
- Search for monochromatic lines at DM-rich structures

Abel cluster (visible)

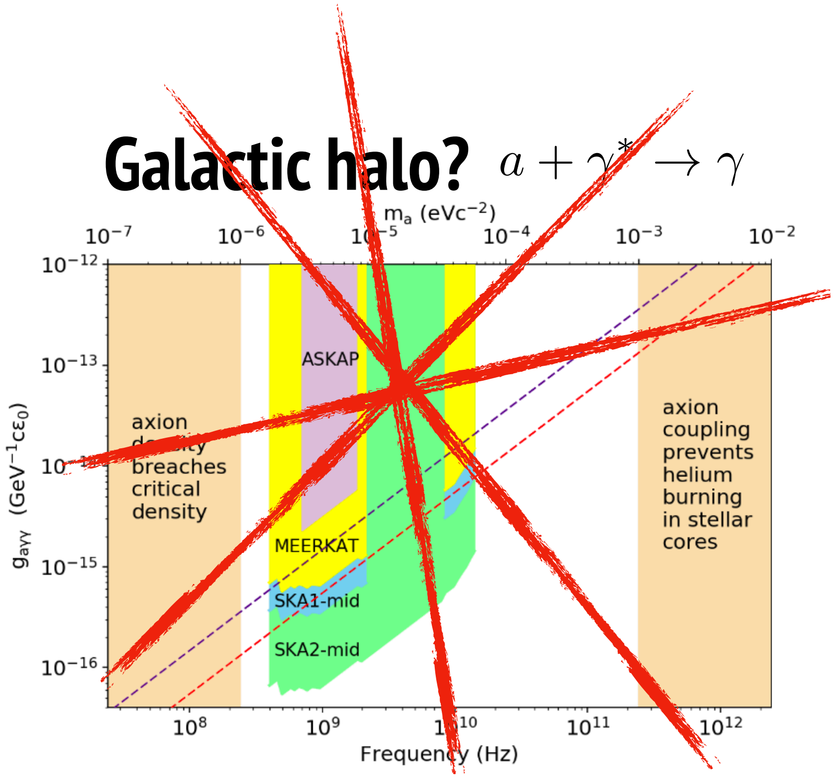


Grin 2007

Dsph. gal. *Caputo 2007*

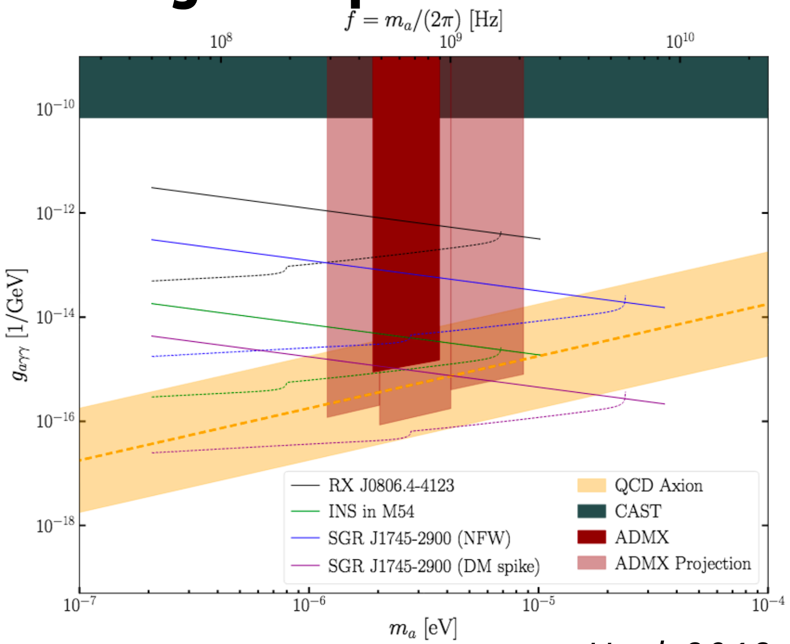


Galactic halo? $a + \gamma^* \rightarrow \gamma$



Quinn 2017, Sigl 2018

Magnetospheres $a + \gamma^* \rightarrow \gamma$



Hook 2018

ALP Dark matter is (can be) different

QUANTUM PRESSURE

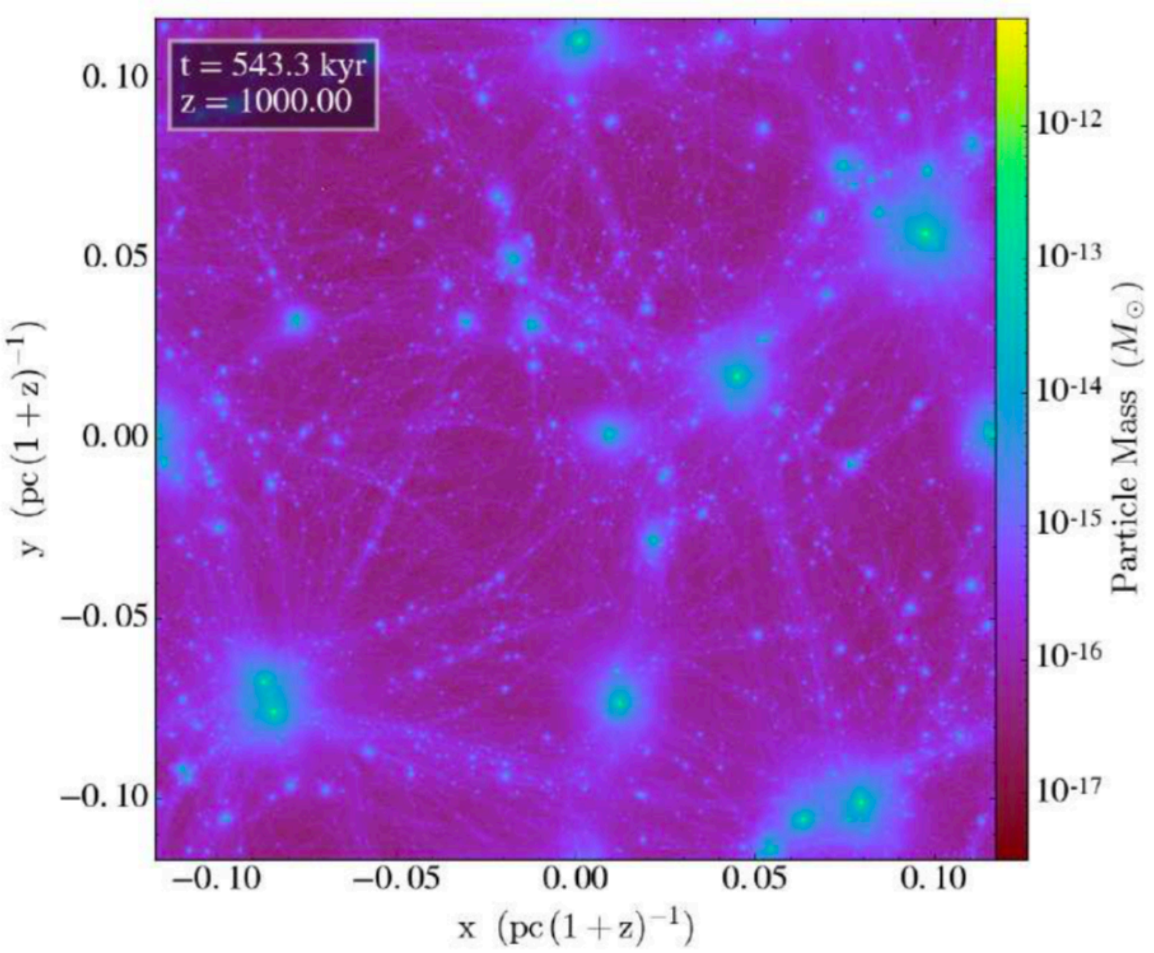
DECAYING DM

MINICLUSTERS

FEMTO,PICO,MICROLENSING

ISOCURVATURE T-FLUCTUATIONS

- post-inflation phase transition
- ultracold dark matter >>> miniclusters
- low mass, small DM clusters
- most of the DM can be in those
- only QCD axion miniclusters studied



ALP Dark matter is (can be) different

QUANTUM PRESSURE

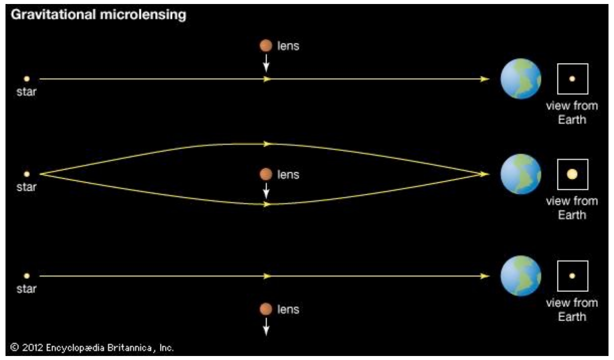
DECAYING DM

MINICLUSTERS

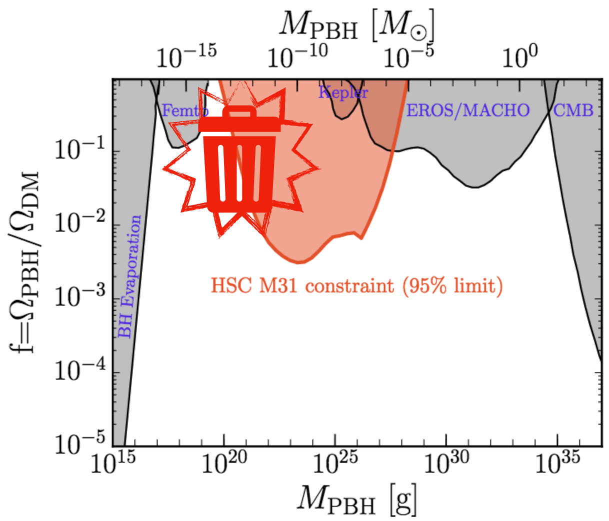
FEMTO,PICO,MICROLENSING

ISOCURVATURE T-FLUCTUATIONS

- miniclusters as gravitational lenses

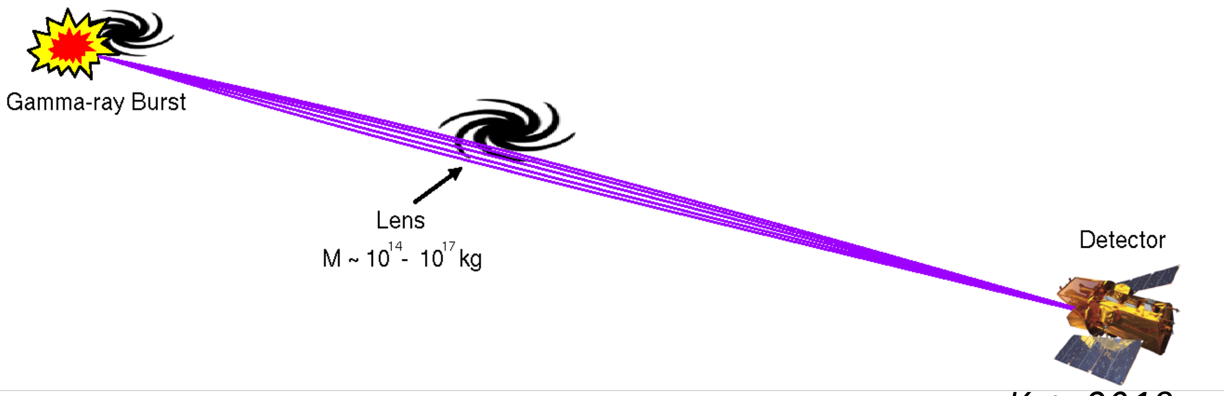


HSC M31 PBHs *Niikura 2017*

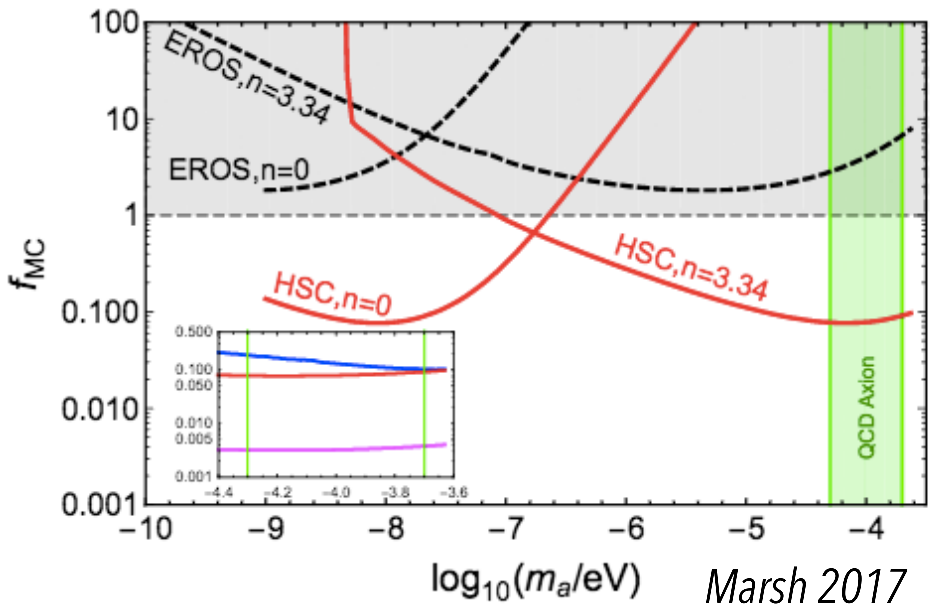


Inomata 2018

Femtolensing for smallest Minicluster masses



see Katz 2018



Marsh 2017

ALP Dark matter is (can be) different

QUANTUM PRESSURE

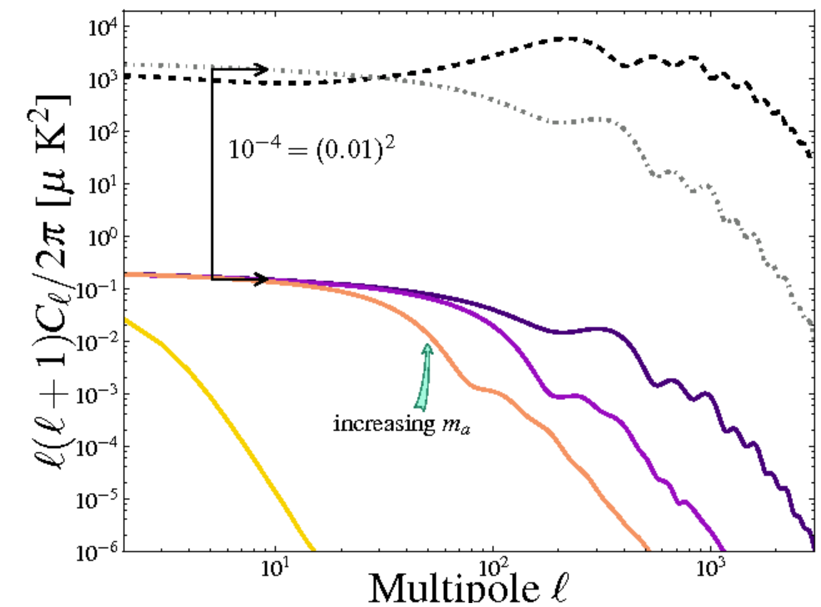
DECAYING DM

MINICLUSTERS

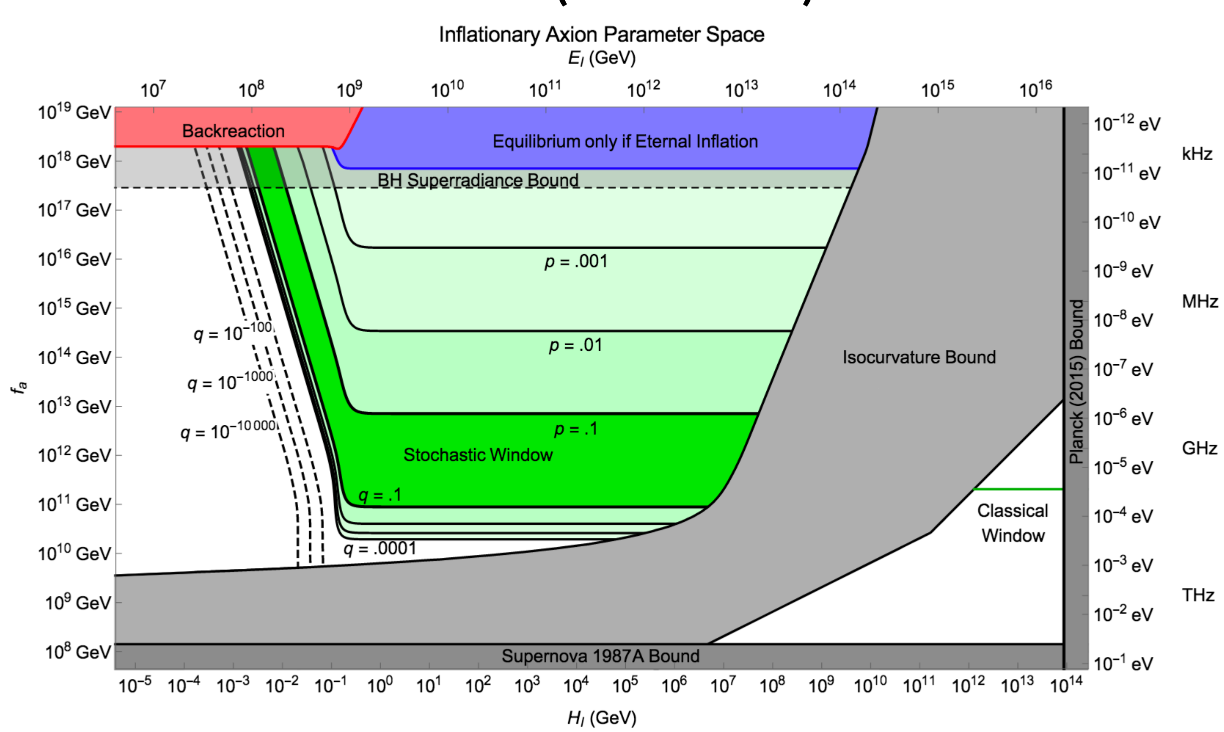
FEMTO,PICO,MICROLENSING

ISOCURVATURE T-FLUCTUATIONS

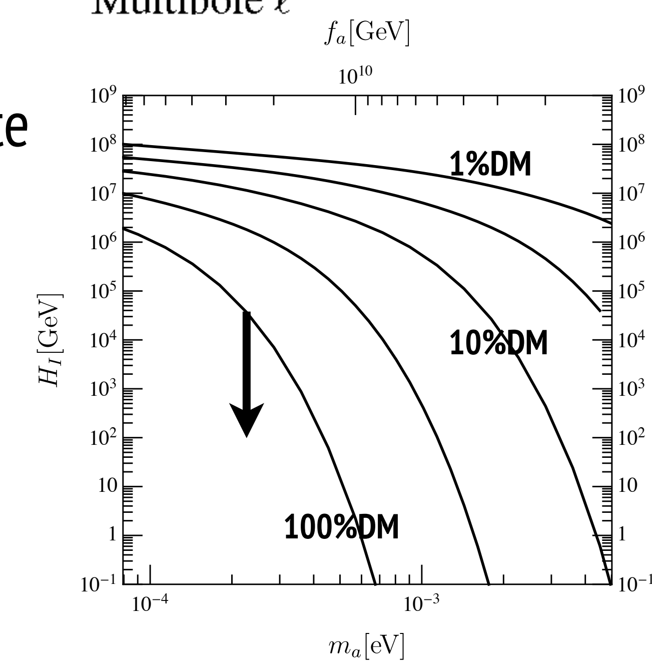
- Axion field fluctuations during inflation
- Axion DM fluctuations >>> T-isocurvature fluct



- Stochastic Axion scenario (Scherlis 2018) Low-scale of inflation

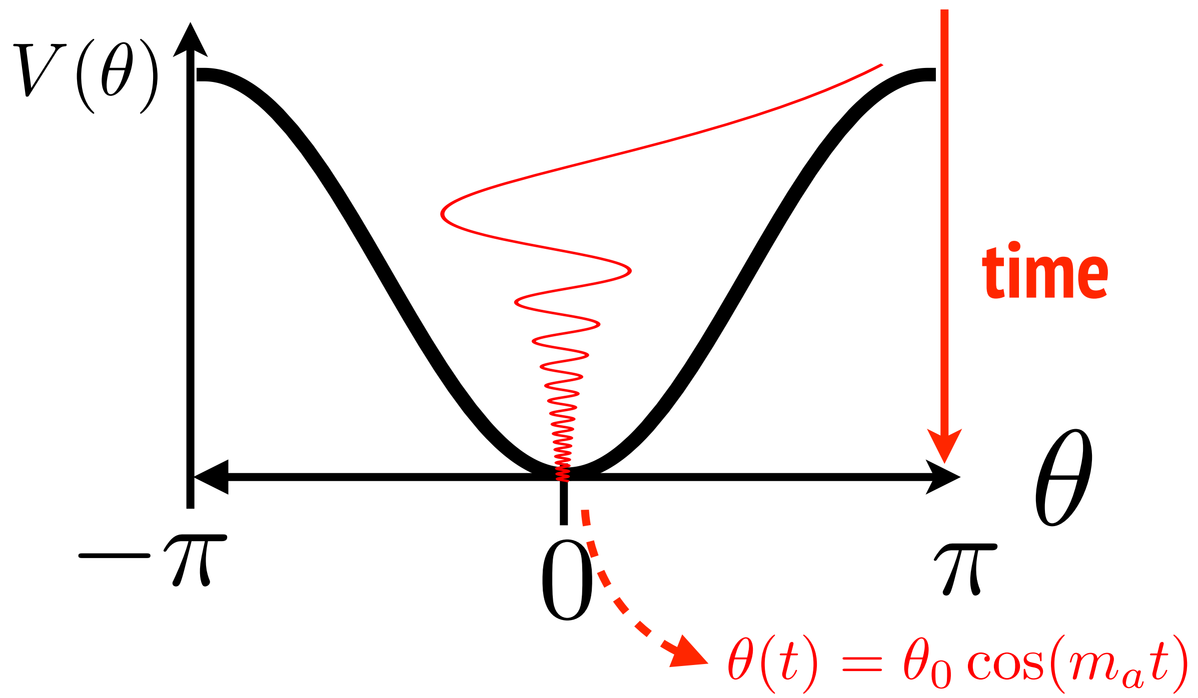


Depends on Hubble rate during inflation ... H_I



- If H_I is measured by next generation CMB Polarisation axion DM is excluded (avoided in some models)

Axion DM is also different in the lab

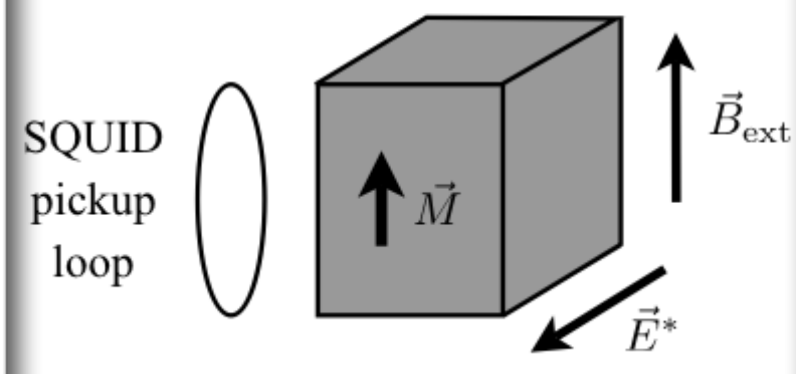


Local Dark Matter density*

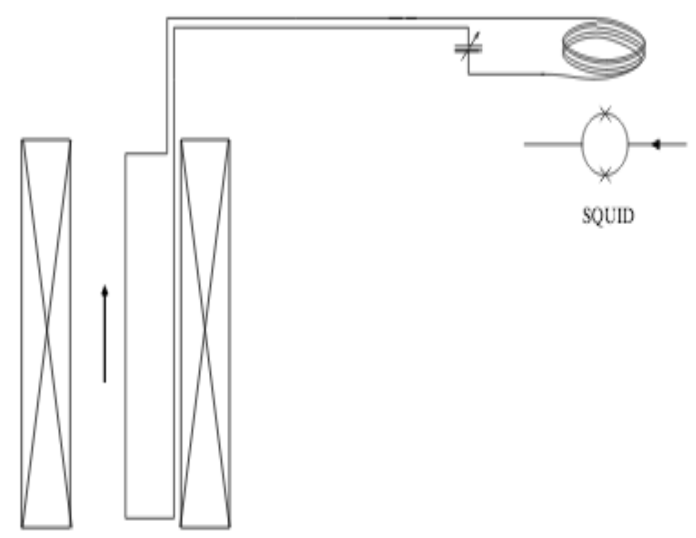
$$\rho_{\rm aDM} = 0.3 \frac{\rm GeV}{\rm cm^3}$$

$$\theta_0 = 3.6 \times 10^{-19}$$

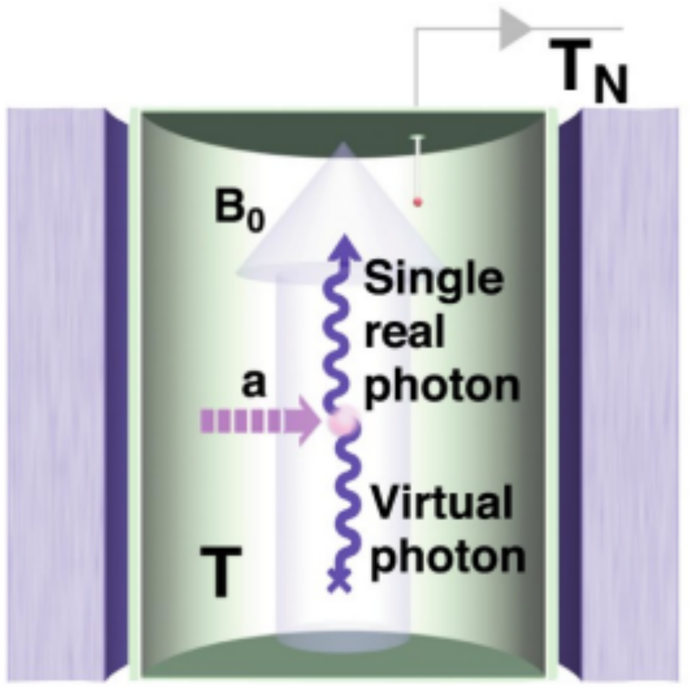
Oscillating EDM



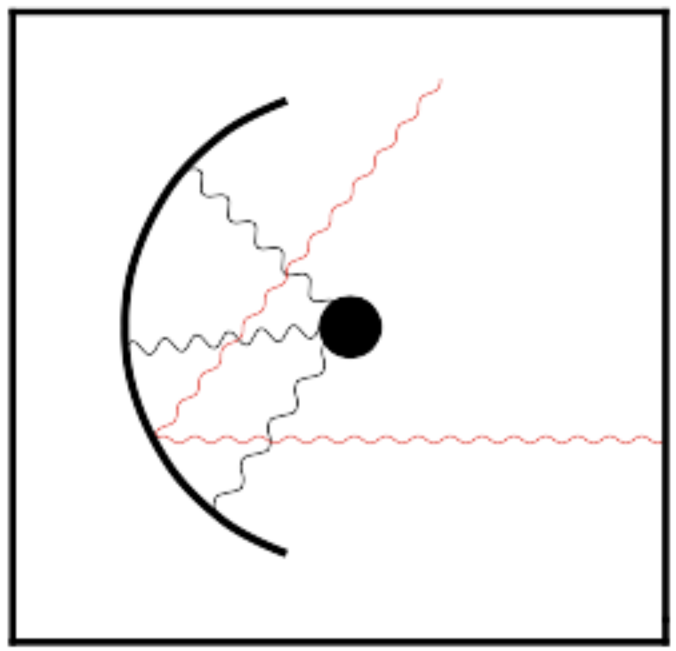
LC-circuit



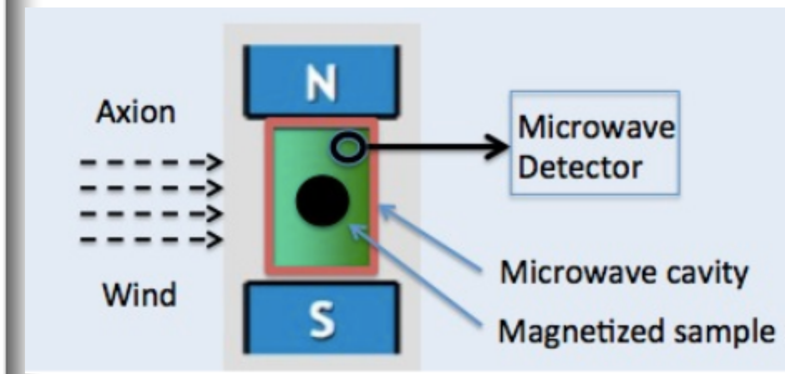
Cavities



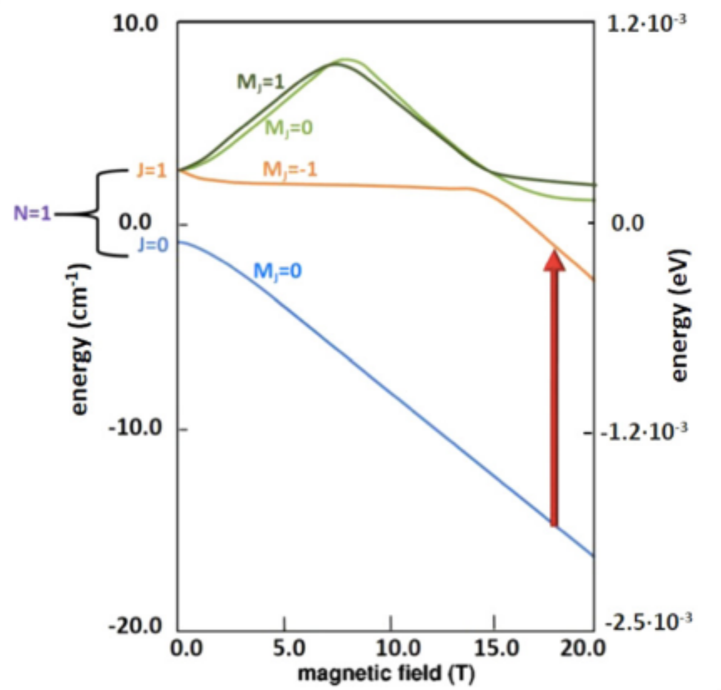
Mirrors



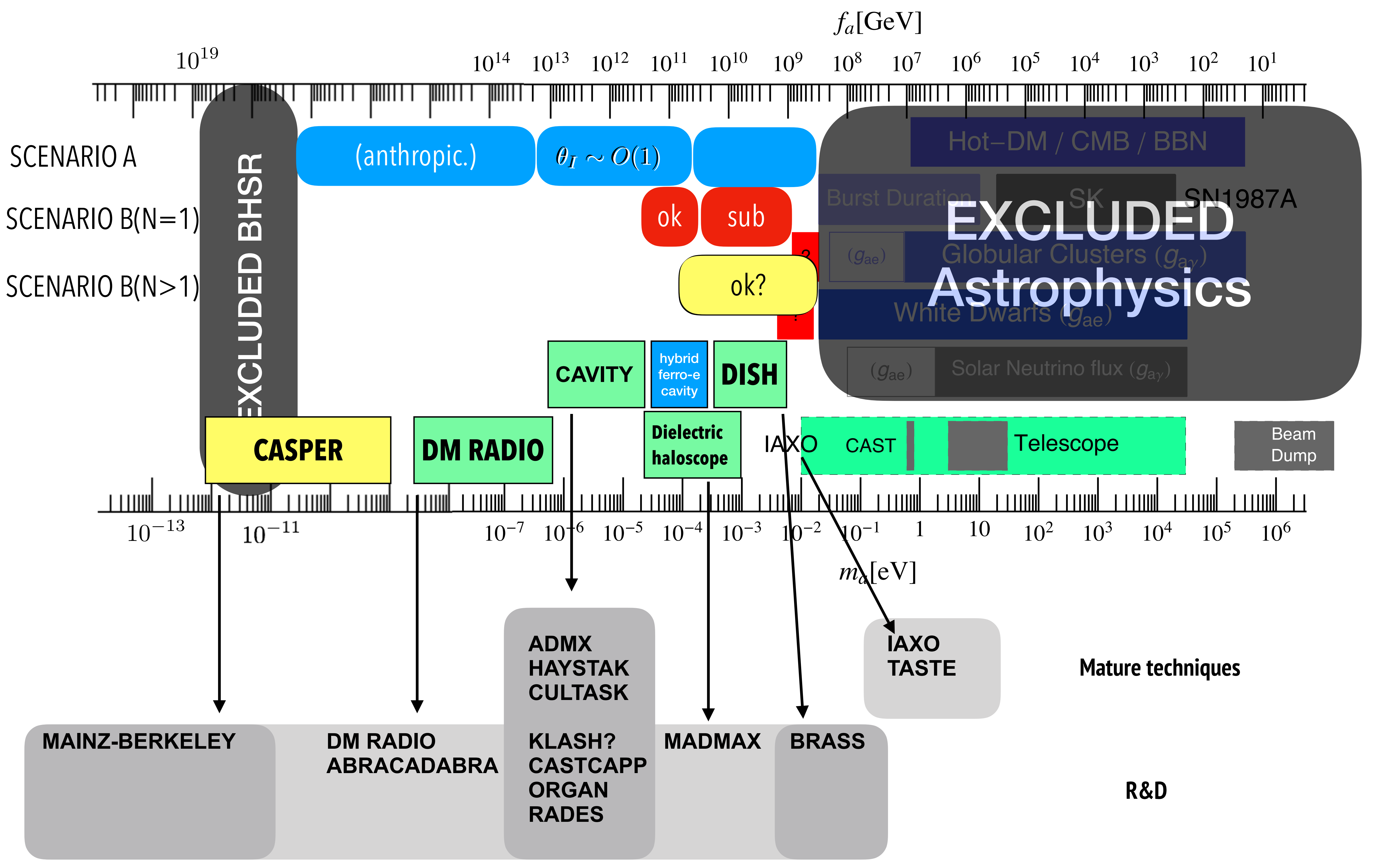
Ferromagnetic resonance



Atomic transitions



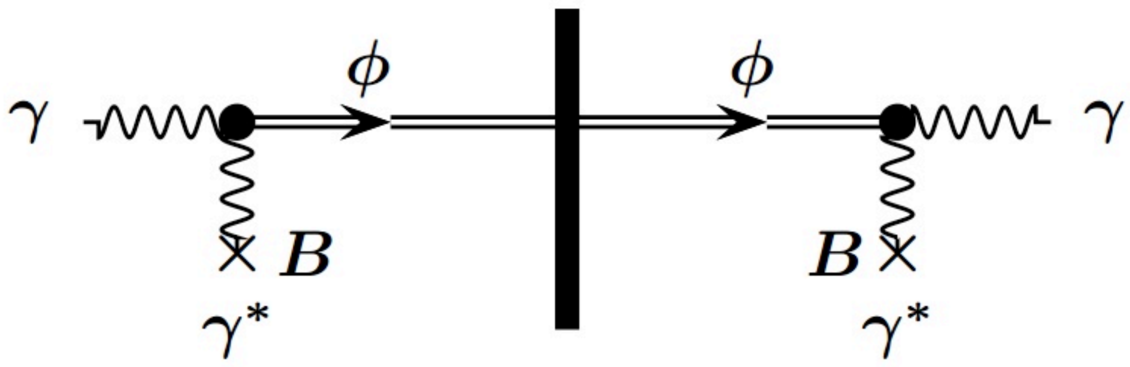
DM experiments (and lab experiments)



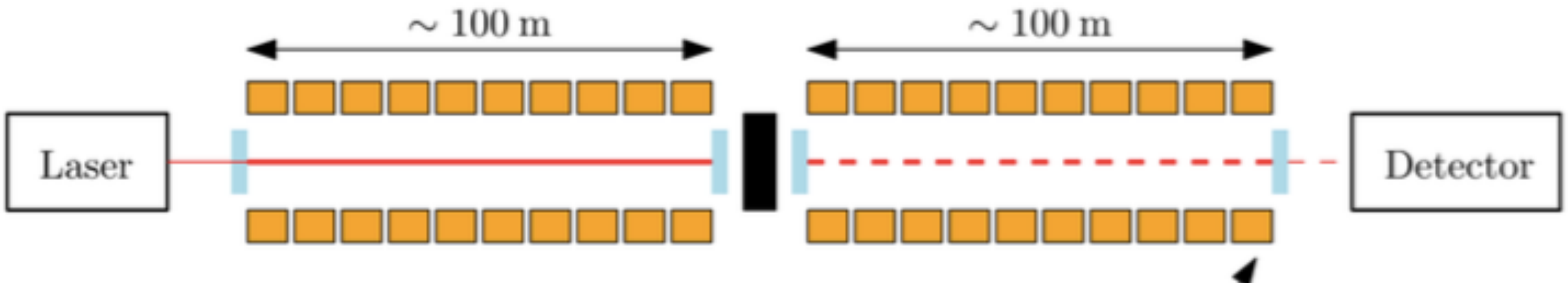
purely lab experiments

the ANY-Light-Particle-Search

Light shining through walls



Resonant regeneration in the receiving cavity



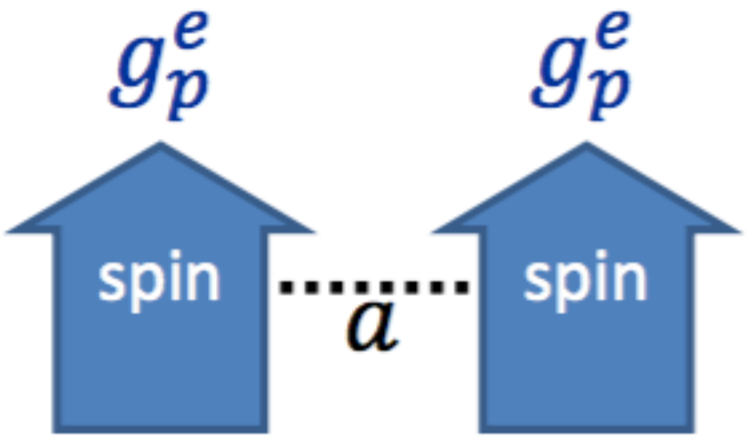
(d) ALPS-IIc

Exp.	Photon flux (1/s)	Photon E (eV)	B (T)	L (m)	B·L (Tm)	PB reg.cav.	Sens. (rel.)
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS II	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1
"ALPS III"	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27

Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}$[GeV^{-1}]
ALPS-I [427]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [429]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [428]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [430]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [431]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [432]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [432]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

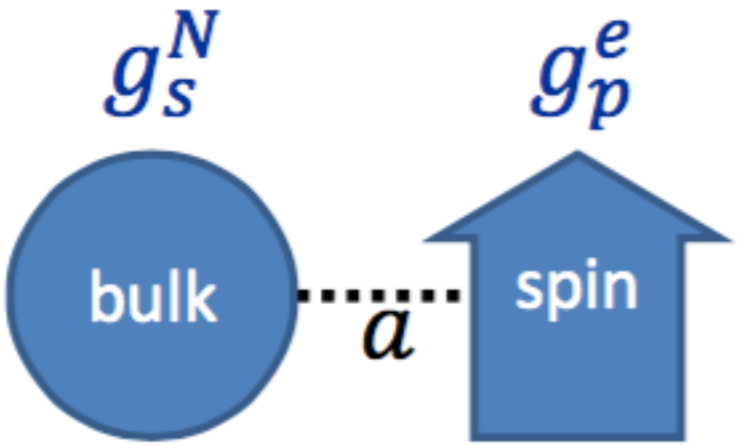
Long-range forces

Wilczek '84, Geraci 14



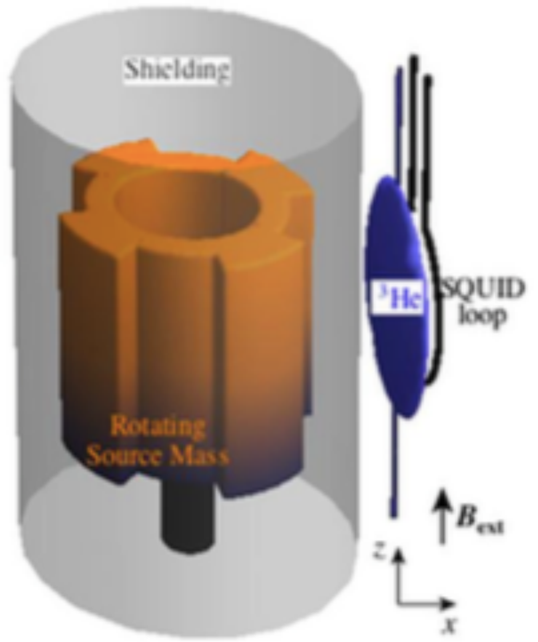
Long-range forces between macroscopic bodies

p-p forces are spin-spin ... very hard to measure!



In some case a tiny s-coupling can lead to a larger effect

s-p forces are number-spin ... much easier



ARIADNE, University of Nevada in Reno

Flavoured axions

- Axions related to flavour/family symmetries induce Flavour violating decays

$$\Gamma(K^+ \to \pi^+ a) \simeq \frac{m_K}{64\pi} g^2_{aff'}$$

$$BR(\pi^+ a) < 7.3 \times 10^{-11} \quad (E787, E949)$$

(NA62, ORKA, KOTO improvement by ~ 70 on BR)

$$f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}\,,$$

model dependent coefficient

$$BR(B^+ \to K^+ a) < 10^{-8} \sim 10^{-6} \quad (Belle2?)$$