Axions-2020

Sergey Troitsky
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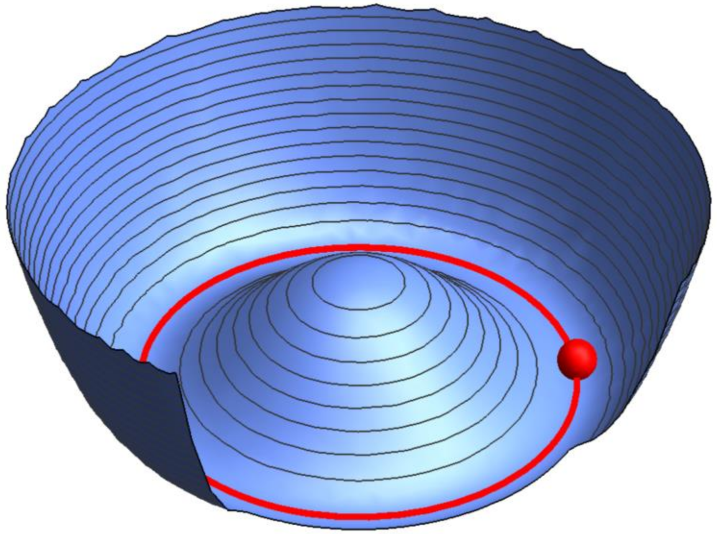
ICCPA-2020, October 6

Some of the original results obtained jointly with
A. Korochkin, G. Rubtsov, M. Libanov,
D. Gorbunov, P. Tinyakov, I. Tkachev,
M. Fairbairn, T. Rashba

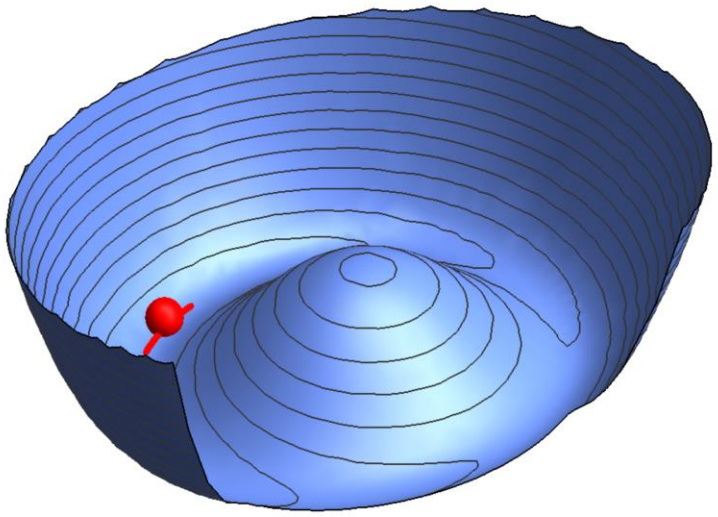
Supported in part by the Russian Science Foundation

A general U(1): axion-like particles (ALPs)



spontaneous breaking of U(1):
Goldstone boson (massless)

(one scale)

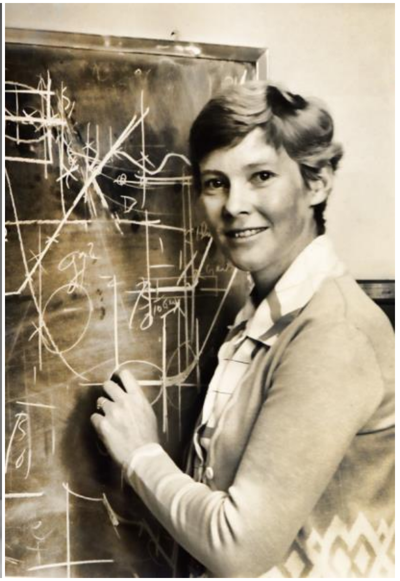


spontaneous + small explicit breaking:
pseudo-Goldstone boson (light)

(two scales)

The U(1): Peccei & Quinn 1977

Photo: Quanta Magazine



VOLUME 38, NUMBER 25 PHYSICAL REVIEW LETTERS 20 JUNE 1977

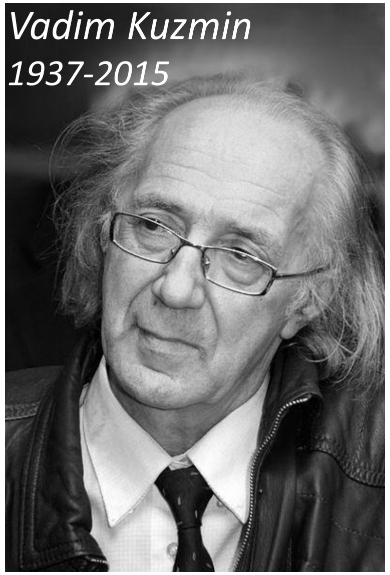
CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

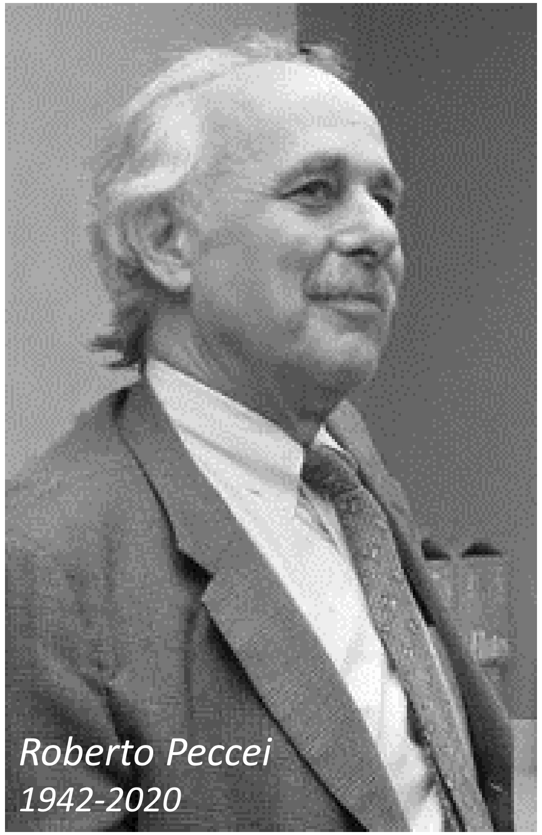
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

Roberto
PECCEI
1942 – 2020

Personal: “Peccei’s money” 1993



Vadim Kuzmin
1937-2015



Roberto Peccei
1942-2020

Nuclear Physics B412 (1994) 607–620
North-Holland

NUCLEAR PHYSICS B

Tree amplitudes at multiparticle threshold in a model with softly broken O(2) symmetry

M.V. Libanov, V.A. Rubakov and S.V. Troitsky

Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect, 7a, 117 312 Moscow, Russian Federation

Received 13 July 1993
Accepted for publication 26 July 1993

The work of M.L. and S.T. is supported in part by the Weingart Foundation through a cooperative agreement with the Department of Physics at UCLA.

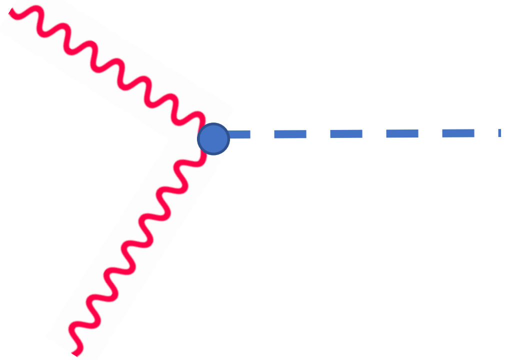
Axions and ALPs are popular…

- strong CP problem
- fundamental symmetries
- string theories
- dark matter
- cosmological structure formation
- topological defects
- stellar evolution
- supernovae
- gamma-ray astronomy
- UHE cosmic rays
- solar corona heating

……

ALP-photon interaction

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m^2 a^2 - \boxed{\frac{1}{4}gaF_{\mu\nu}\tilde{F}^{\mu\nu}}$$

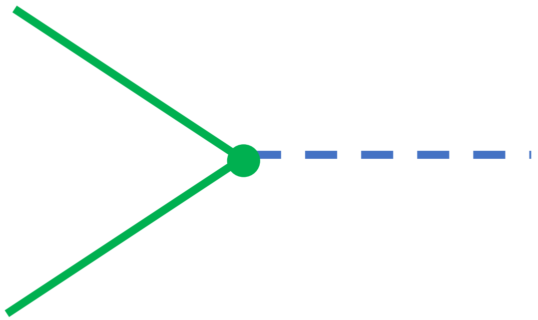


- allowed by all symmetries, hence appears
- dimensionful coupling g suppressed by the U(1) breaking scale
  - ✓ related to the ALPmass for a particular model, e.g. the QCD axion

$$\frac{a}{M}F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad M \sim f_A \sim \frac{\Lambda^2_{\mathrm{QCD}}}{m}$$

- photon/ALP mixing in the external magnetic field
- conversion probability depends on the mass, coupling, energy and field

ALP-fermion interaction

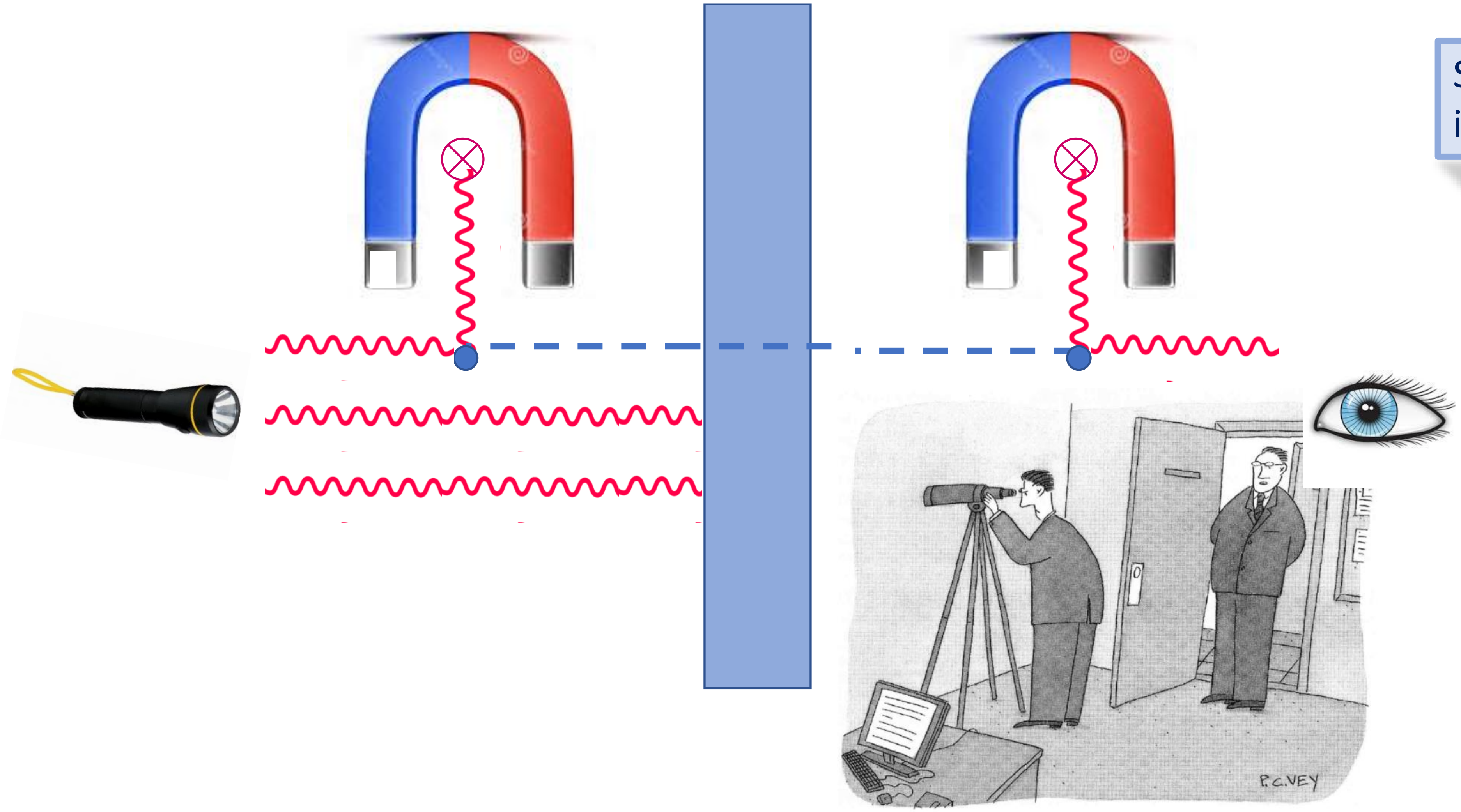


- coupling of a (pseudo)Goldstone boson determined by the current algebra
- dimensionless coupling suppressed by the U(1) breaking scale
  - ✓ related to the ALP mass for a particular model, e.g. the QCD axion

$$\sim \frac{m_\psi}{f_A} a\bar{\psi}\gamma_5\psi$$

- zero or not, depending on particular quantum numbers
- electron-ALP coupling of particular interest

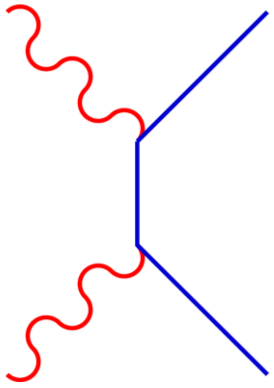
ALP-photon: shining light through walls



Search for axions
in a laboratory

Pair production: the Universe is opaque to gamma rays

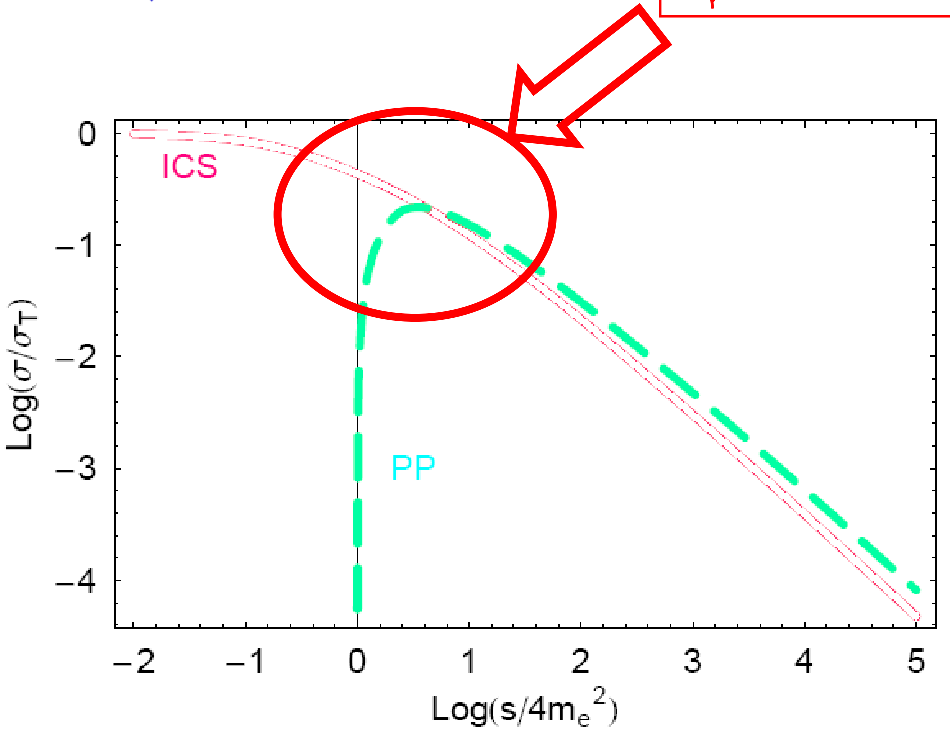
Nikishov 1962

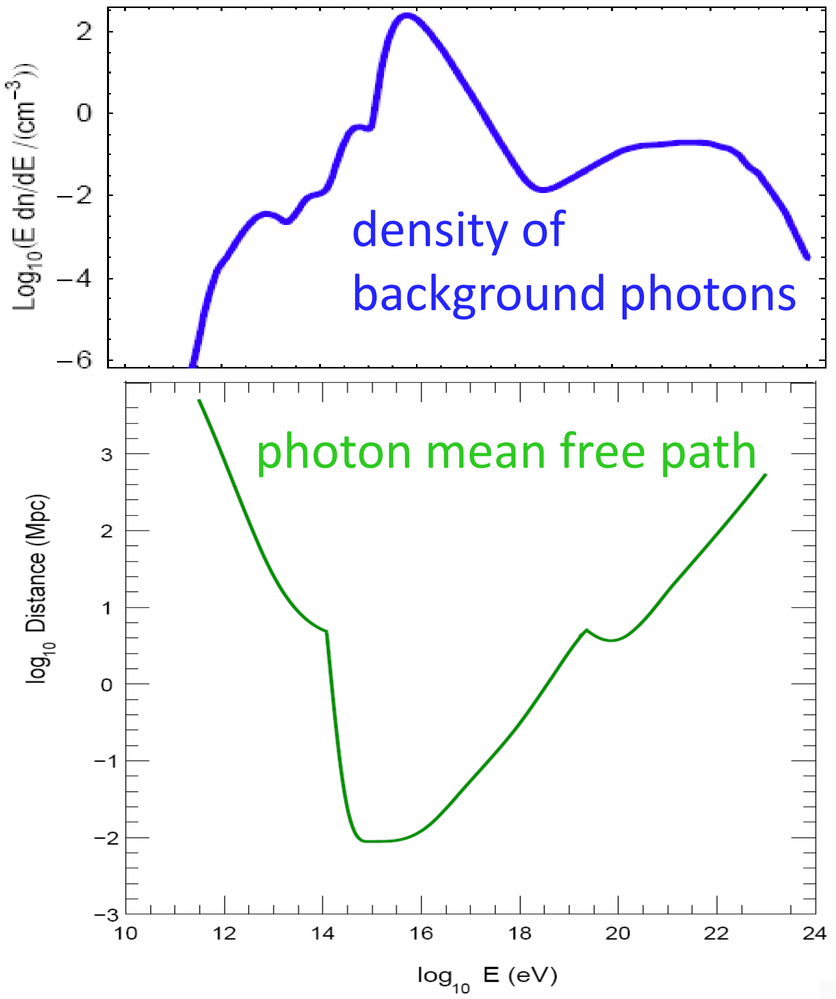


the most intense pair production:

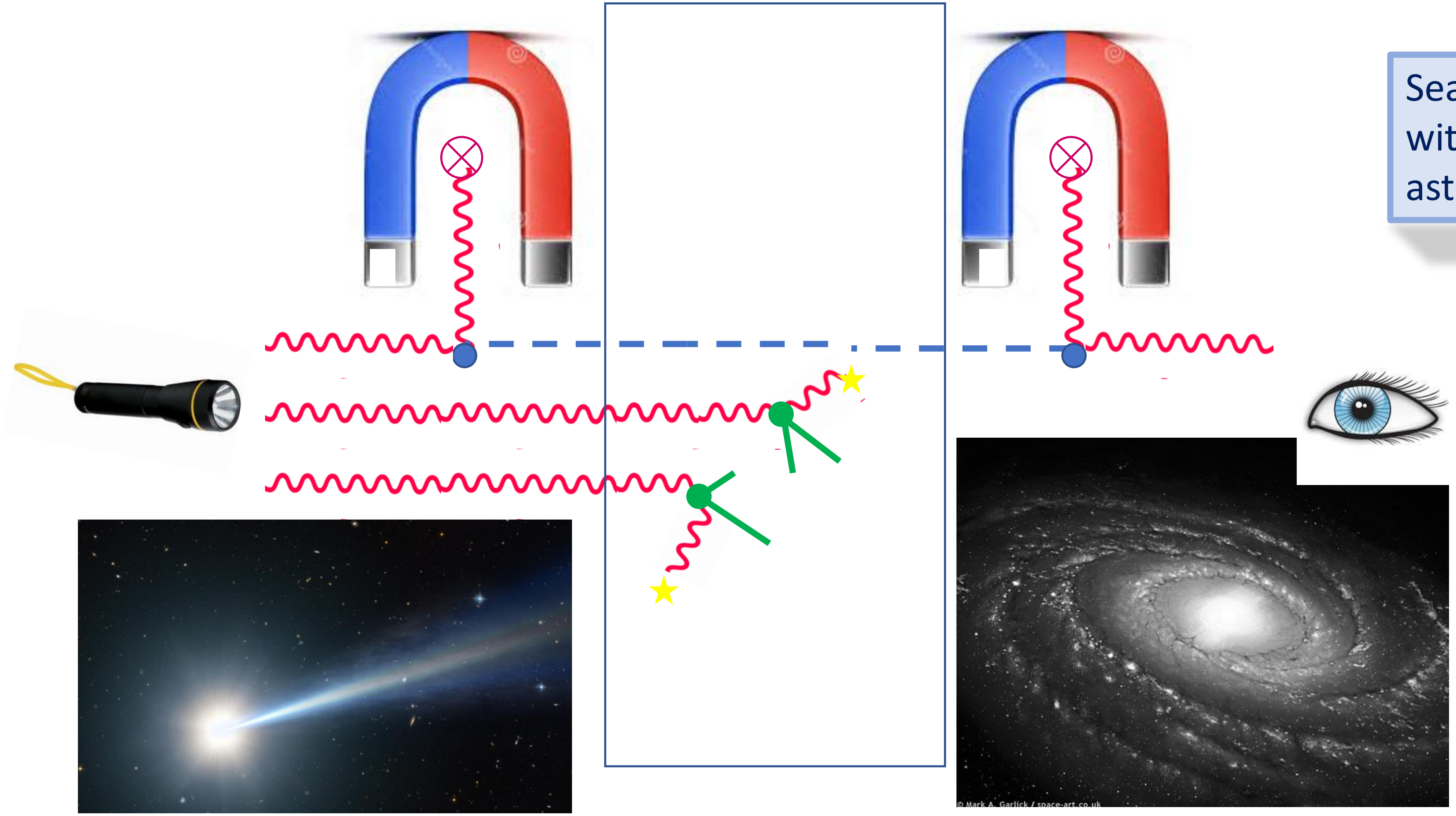
$s/4m_e^2 \sim 2 \ldots 4$

$E_\gamma \sim 5\times10^{11}\ (\omega/\mathrm{eV})^{-1}$ eV



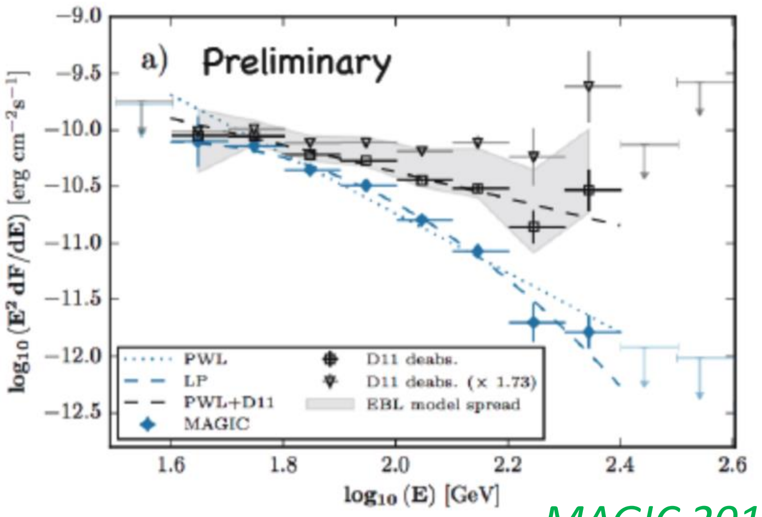


ALP-photon: shining light through the Universe



Search for axions with gamma-ray astronomy

ALP: “anomalous transparency of the Universe”?



MAGIC 2016

- “IR/TeV crisis” – individual sources *Protheroe, Meyer 2000 + ……*

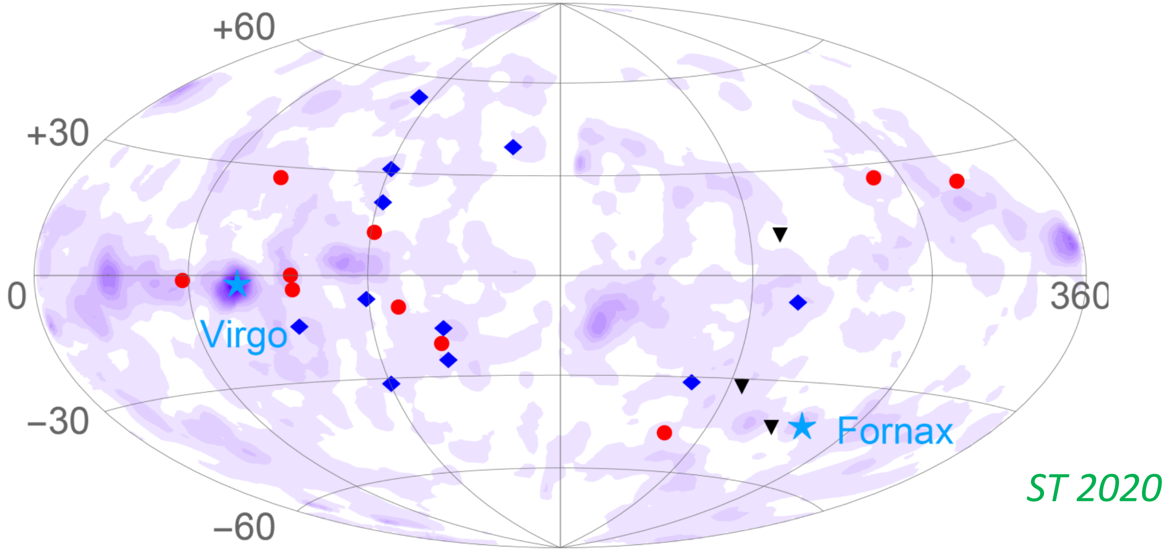
- spectra of distant sources look differently compared to physically similar nearby ones *Kneiske, unpublished*

- statistics of “deabsorbed” spectra:
  features right at the energies for which the correction becomes important! *Horns, Meyer 2012* *Rubtsov, ST 2014*

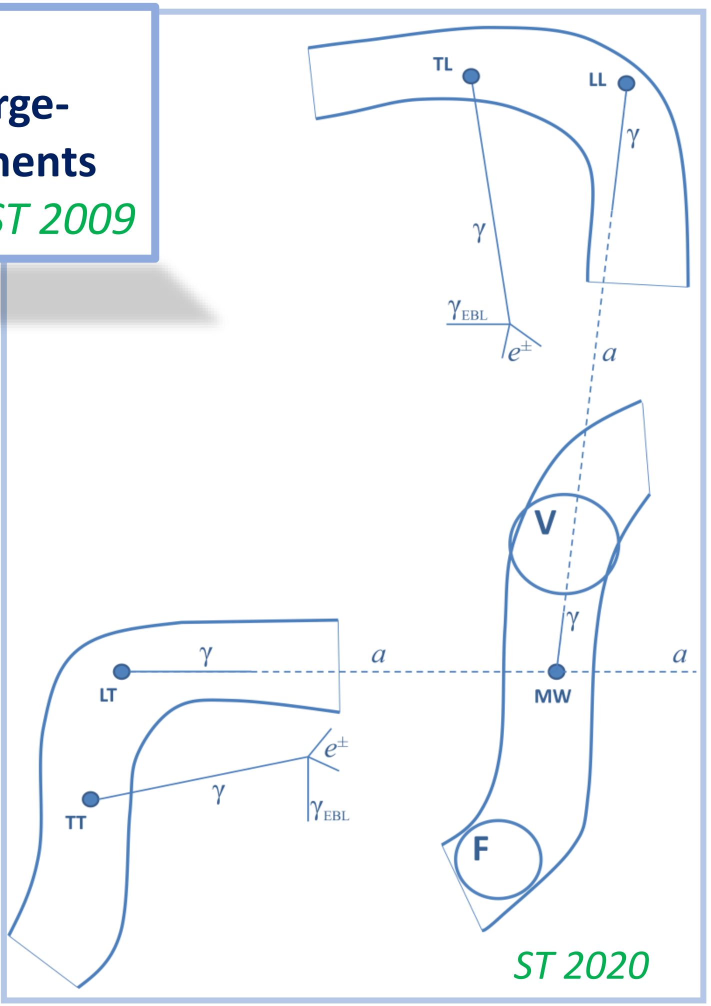
State of the art – increasing statistics, better known distances:
- the anomaly is confirmed for a part of sources – both “old” and “new” ones
- many new, weaker sources do not demonstrate any problem
- modest overall statistical significance of the anomaly

Korochkin, Rubtsov, ST 2019

Anisotropy: anomalous sources point to the local filament!



Supports the axion-photon mixing in large-scale structure filaments *Fairbairn, Rashba, ST 2009*



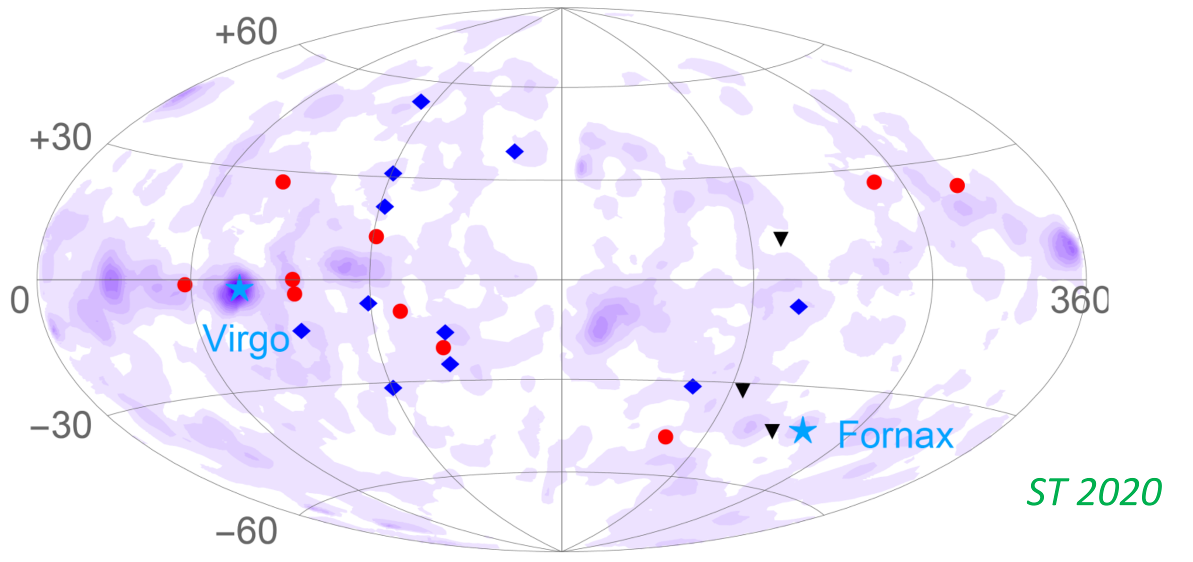
Red: 4.1 σ "anomalous" gamma-ray blazars, E>100 GeV *Korochkin, Rubtsov, ST 2019*

Blue: BL Lacs correlated with HiRes cosmic rays, E>10^{19} eV *Gorbunov, Tinyakov, Tkachev, ST 2004; HiRes Collaboration 2005*

Black: VHE GRB *(not in the statistical analysis)* *HESS 2020, MAGIC 2020*

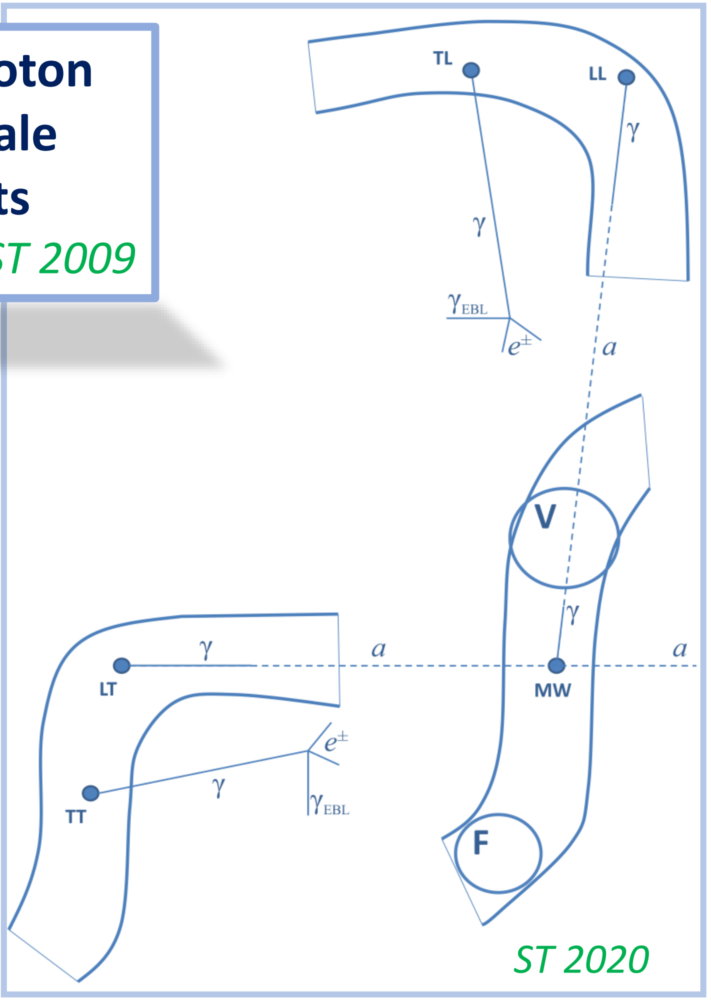
Shadow: weighted density of nearby galaxies *2MRS 2019*

Future tests of the anisotropy and its ALP explanation



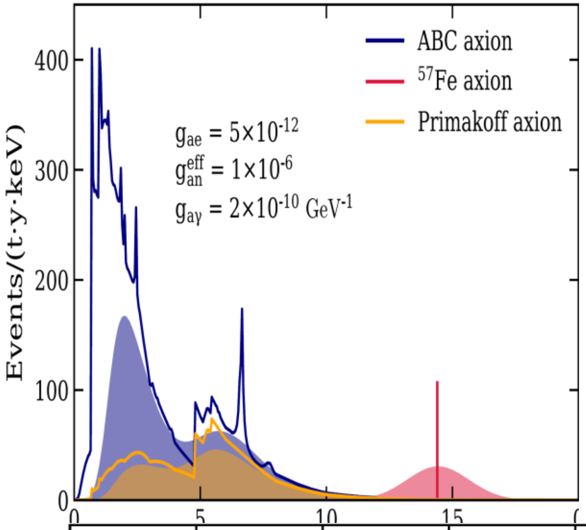
- isotropic samples of blazars
- tests of *HiRes* BL Lac correlations with *Telescope Array*
- search for the ALP in a lab
  - ✓ *ALPS-IIc* in DESY (light through walls)
  - ✓ *babyIAXO* (solar axions/ALPs)

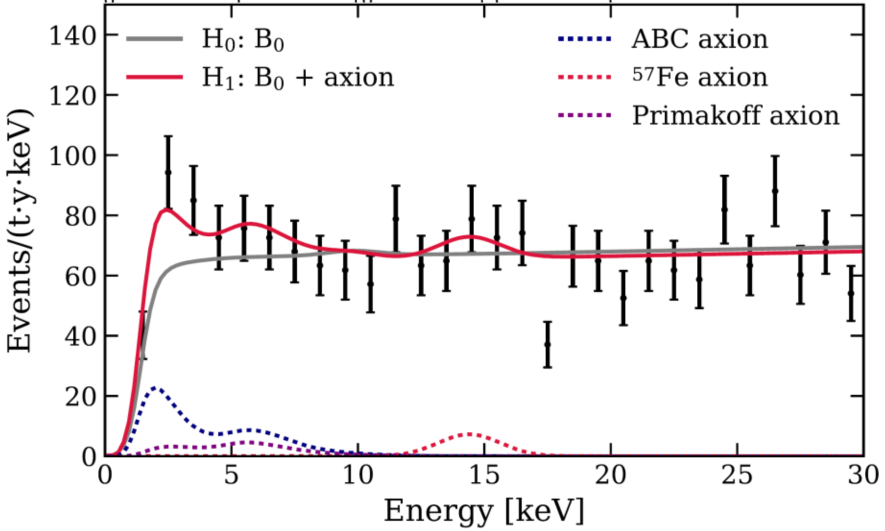
Test the axion-photon mixing in large-scale structure filaments
Fairbairn, Rashba, ST 2009



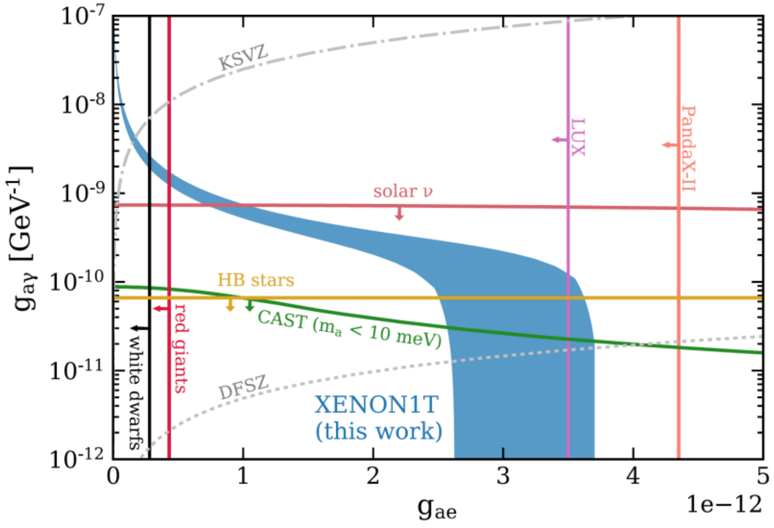
XENON1T 2020 – a claim for a solar ALP

- liquid xenon experiment for dark-matter search in Gran Sasso
- electronic recoil
- excess of counts at low energies (2-3 keV, range 1-30 keV)
- consistent with a signal from solar ALP interacting with electrons
- axion explanation preferred over known systematics/backgrounds





XENON1T 2020



ALPs affect stellar evolution

light particles with very suppressed interactions remove energy from stellar interiors
evolutionary timescales shorten
*
light particles with stronger but suppressed interactions result in energy transfer between parts of a star
mechanical construction of a star changes

relevant for the electron coupling:

white-dwarf luminosity function
average rate of WD cooling
Blinnikov, Vysotsky 1990

HB stars to red giants ratio
time scale of helium burning
Dicus et al. 1978

pulsating white dwarf period change
rate of individual WD cooling
Isern et al. 1992

tip of the red-giant branch
time of helium ignition
Raffelt 1990

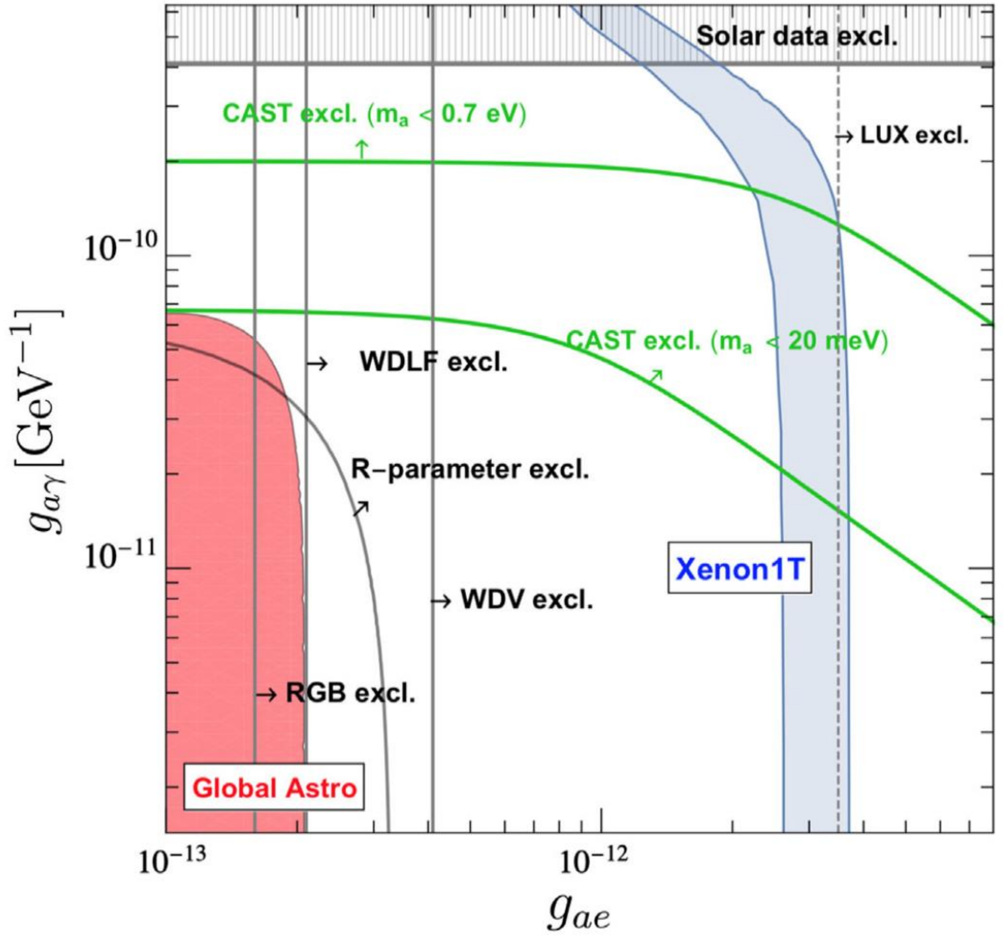
constrains much stronger than from laboratory experiments
reviews: *Raffelt 1996 (book), Giannotti et al. 2015, 2017*

XENON1T 2020 – axion explanation excluded from stars

- ALP-electron coupling too large!
- no helium-burning stars form at all…
- solar lifetime OK
- exclusion significances:

Observable	Measured	Expected	Tension
R parameter	1.39 ± 0.03	$\leq 0.83(g_{e13} = 9)$	$19\sigma^\star$
$M_{I,\mathrm{TRGB}}^{\mathrm{LMC}}$ (mag)	-4.047 ± 0.045	$\leq -4.92(g_{e13} = 9)$	$19\sigma^\star$
g_{e13}^{WDLF}	$\leq 2.8(3\sigma)$	29.7 ± 4.8	5.6σ
$\dot{\Pi}_{\mathrm{L19-2}}^{(113)}$	3.0 ± 0.6	57 ± 16	3.4σ
$\dot{\Pi}_{\mathrm{L19-2}}^{(192)}$	3.0 ± 0.6	95 ± 27	3.4σ
$\dot{\Pi}_{\mathrm{PG1351+489}}$	200 ± 90	19620 ± 5730	3.4σ
$\dot{\Pi}_{\mathrm{G117-B15A}}$	4.2 ± 0.7	113 ± 33	3.3σ
$\dot{\Pi}_{\mathrm{R548}}$	3.3 ± 1.1	87 ± 25	3.3σ

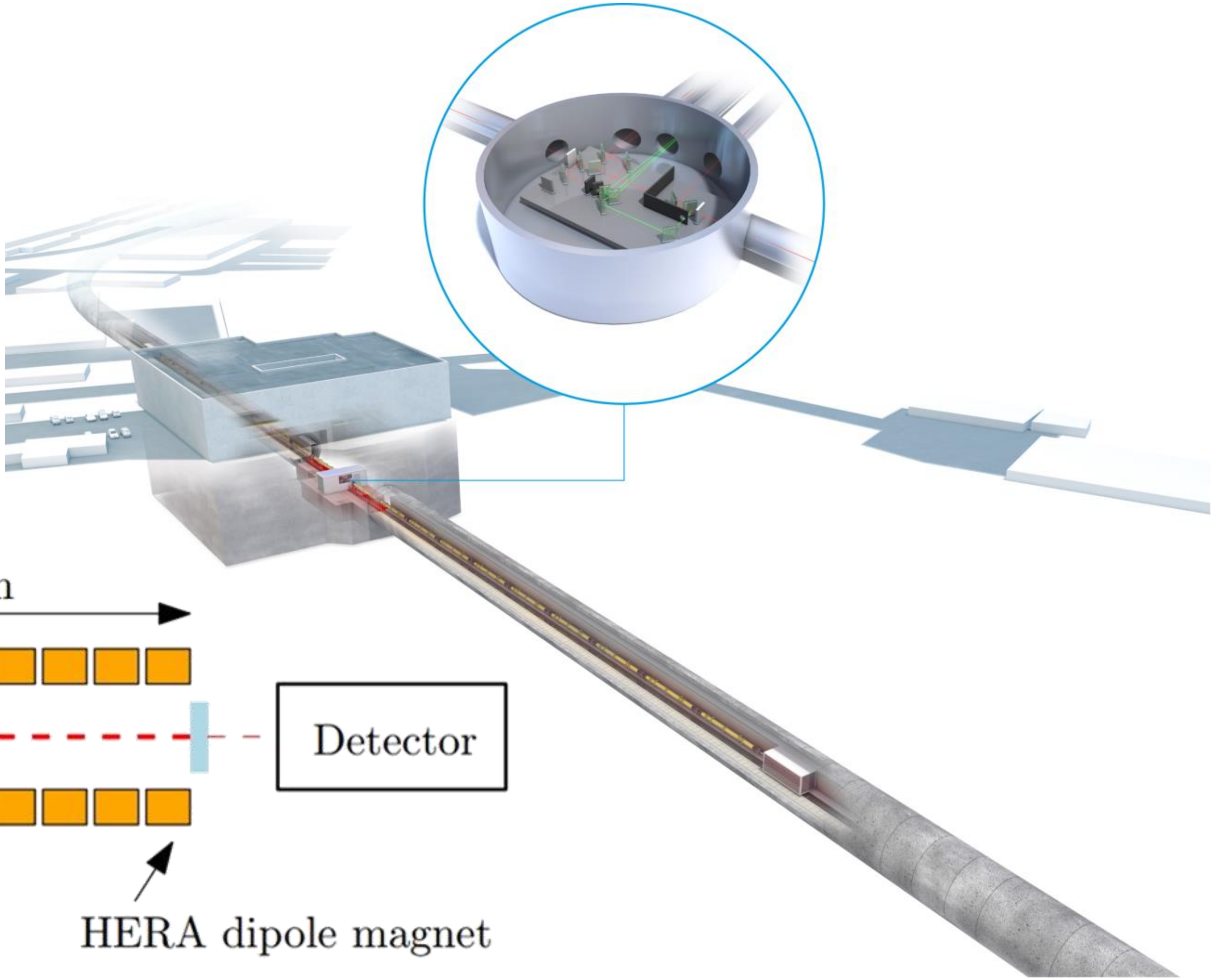
Di Luzio et al. 2020

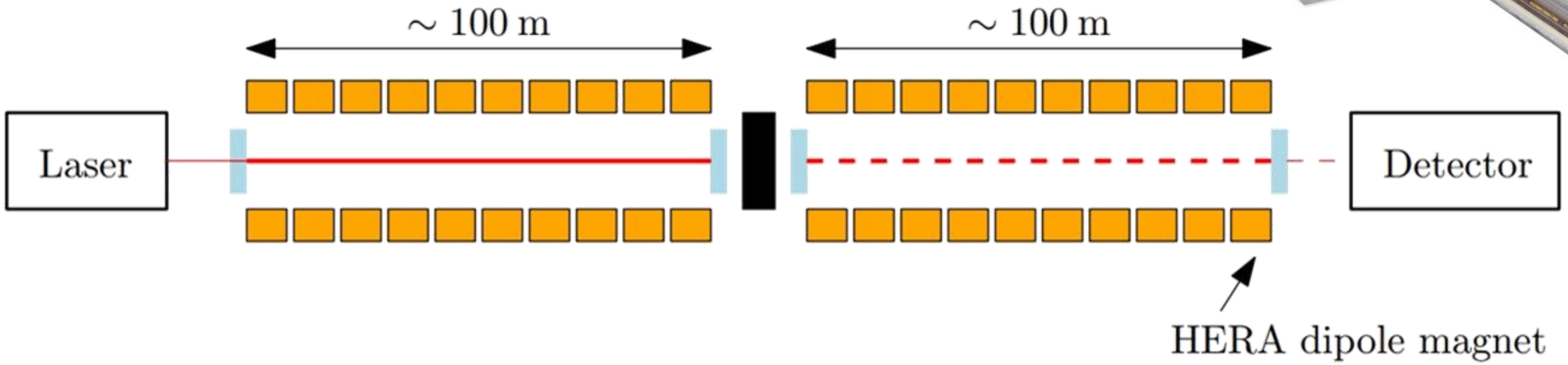


19 sigma exclusion. **10 times lower coupling already excluded at 99% CL**

Purely laboratory axion experiment: ALPS-IIc

- light shining through the wall
- straightened HERA magnets
- locked cavities
  (resonant generation and regeneration)
- data taking soon

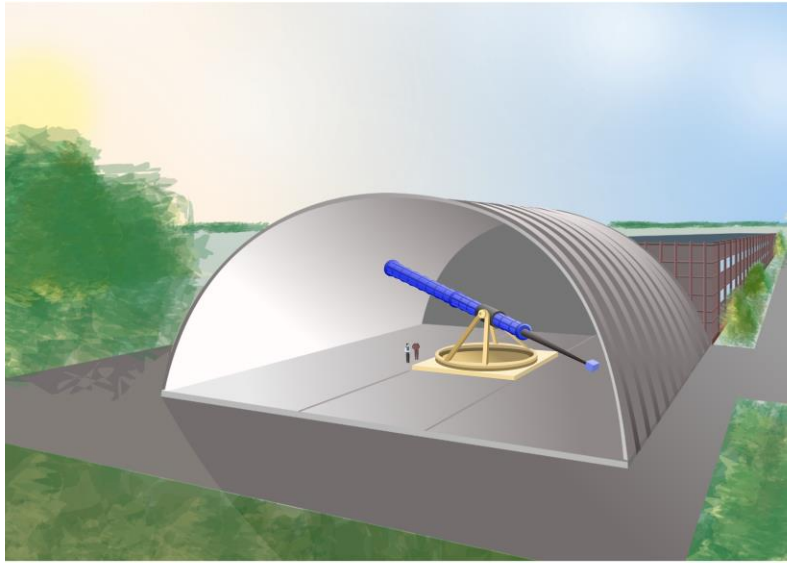


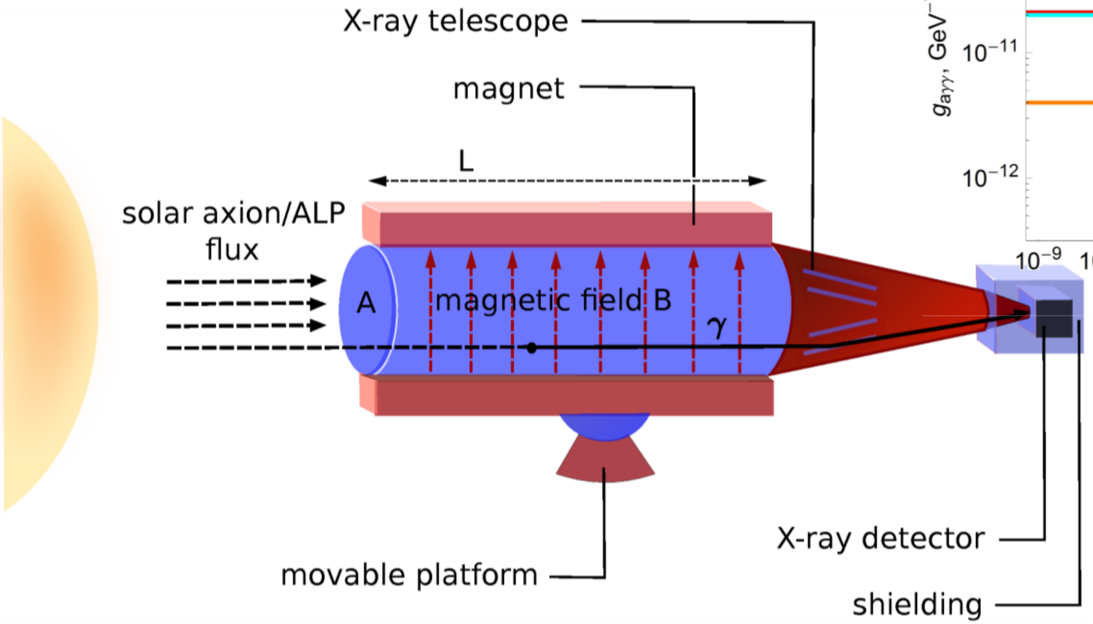


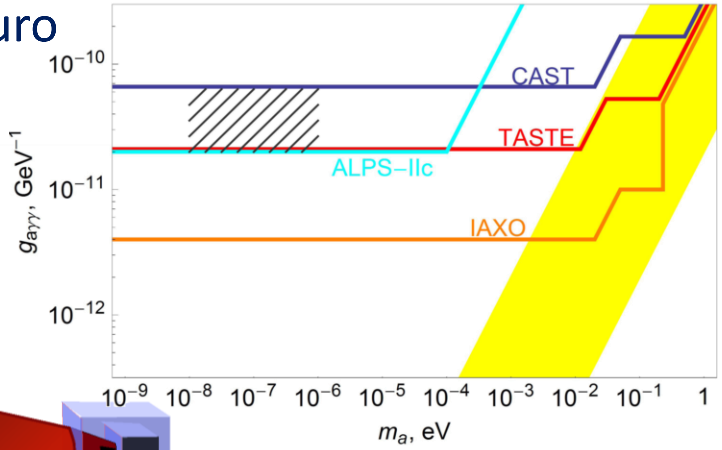
Russian axion helioscope not funded

- helioscopes: detection of solar axions in a lab
- CAST in CERN – world-best limits on the photon coupling
- TASTE proposed in 2017 – x100 S/N improvement with refurbished equipment, cost 3 MEuro
- not funded in 3 years

Troitsk
Axion
Solar
Telescope
Experiment







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Towards a medium-scale axion helioscope and haloscope

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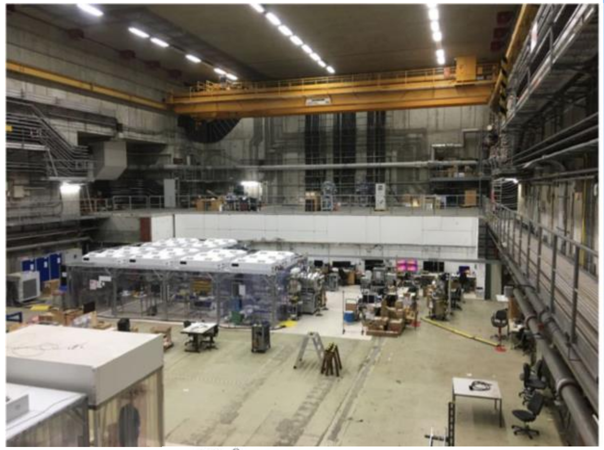
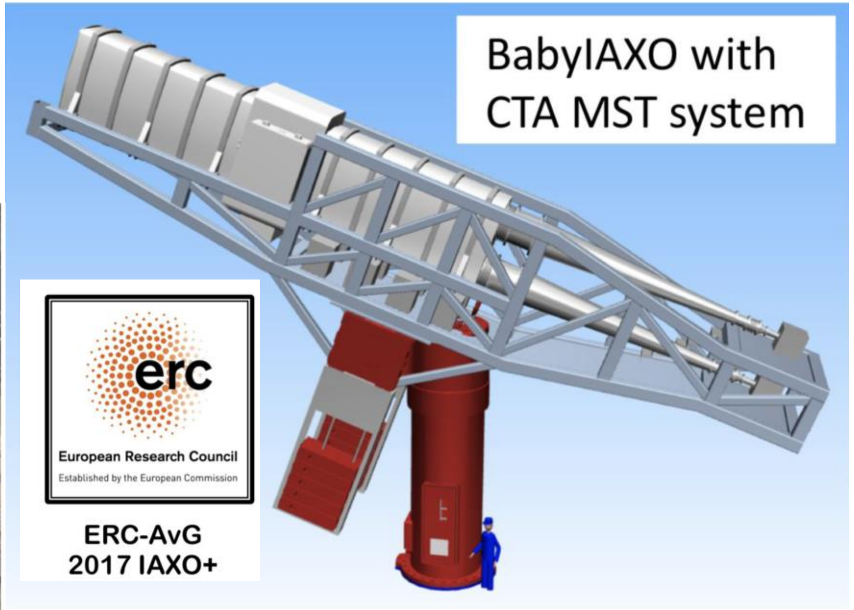
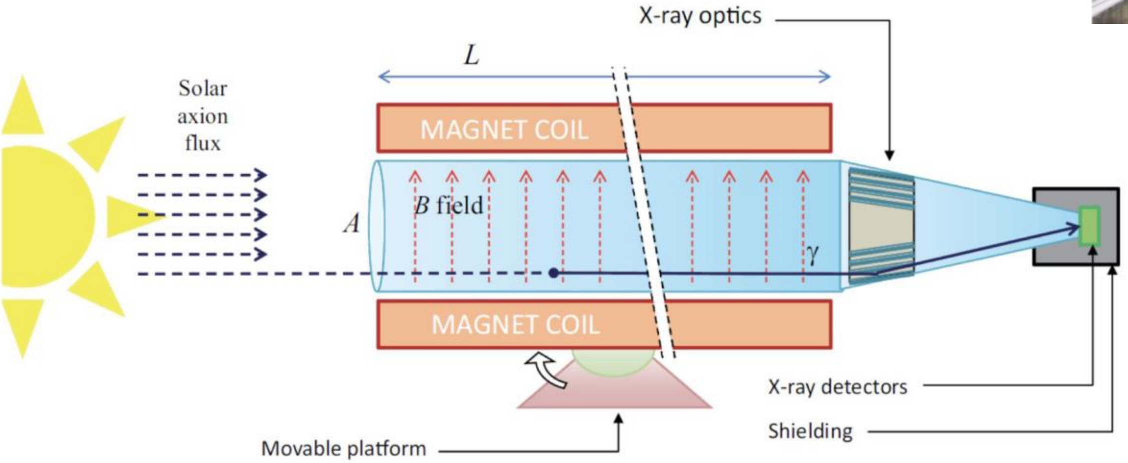
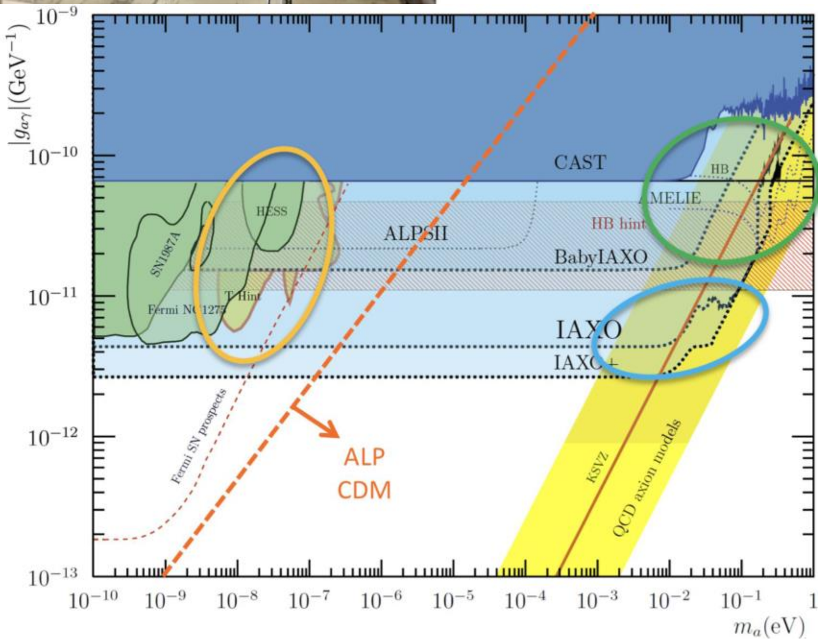
European axion helioscope funded: babyIAXO

- similar concept and sensitivity as TASTE
- proposed in 2017, few months after TASTE
- 6.5 MEuro received from European grants
- construction started in DESY
- former TASTE groups joining babyIAXO now



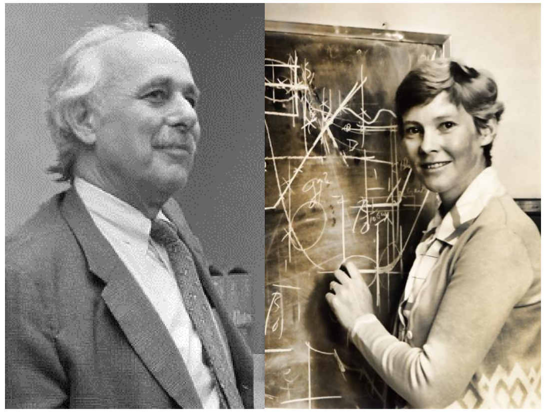


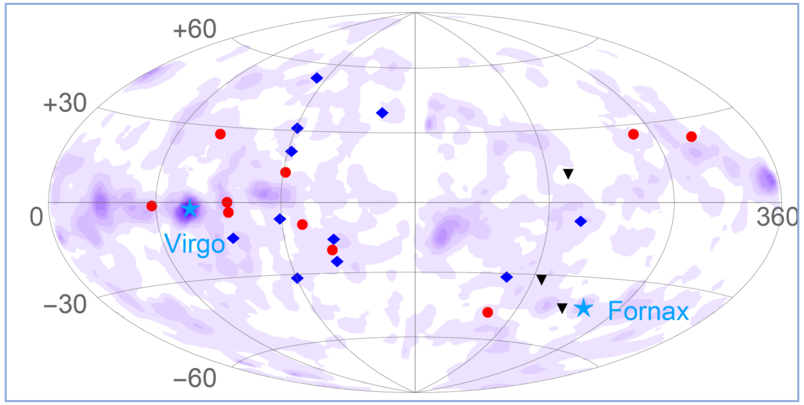




Axions-2020

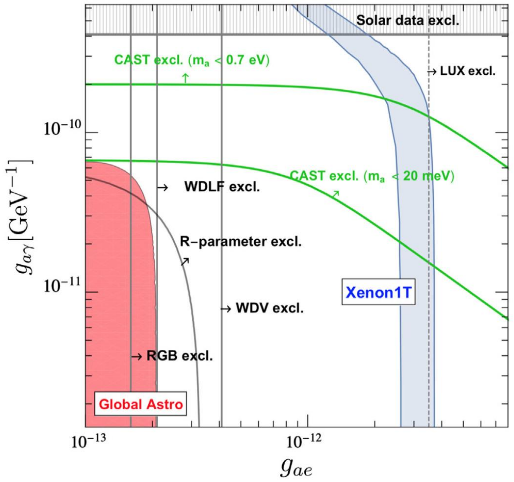
- tribute to late Roberto Peccei, wish more discoveries to Helen Quinn

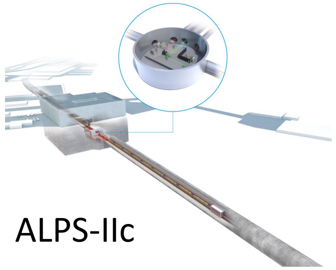


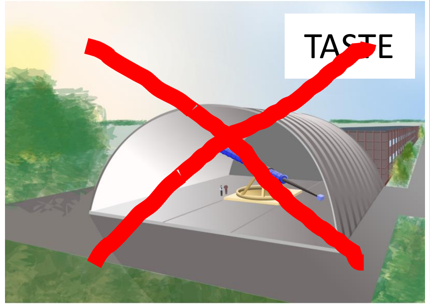


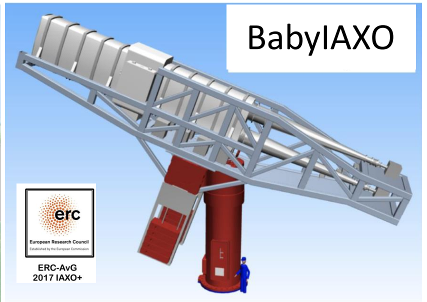
- axions in gamma-ray astronomy: some hints and more tests to come

- XENON1T excess: axion explanation excluded from stars by 19 sigma









- new laboratory experiments are coming, but not in Russia