Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

The Axion & ALPs landscape:

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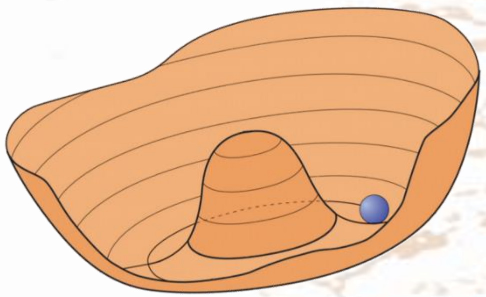
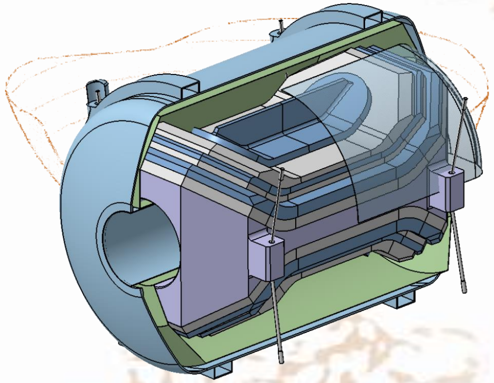
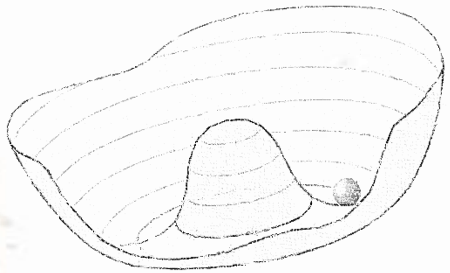
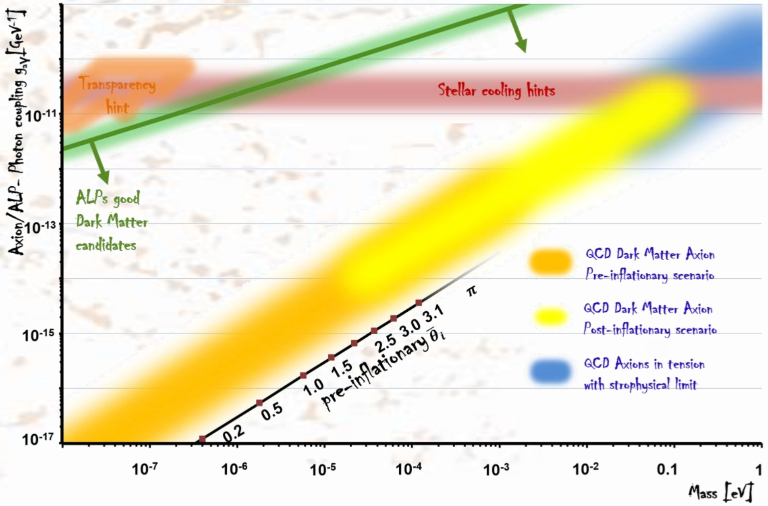
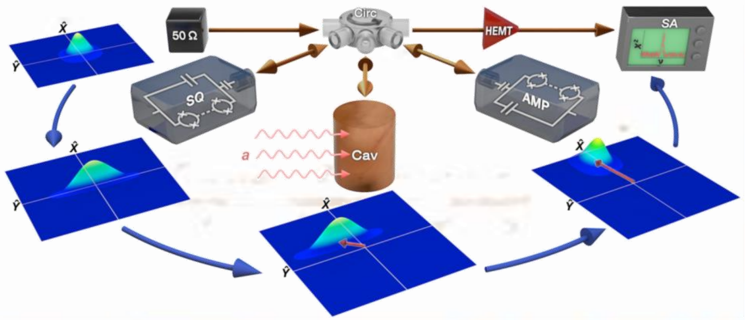




- Wanted !!
  Axion profile
- Navigating the axiverse: explore the vast range!
- The bounty hunters: Chose your arms!
- Surveying terra incognita







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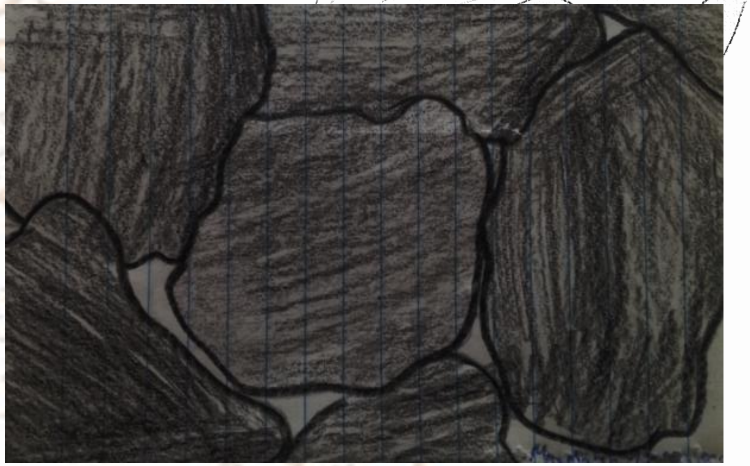
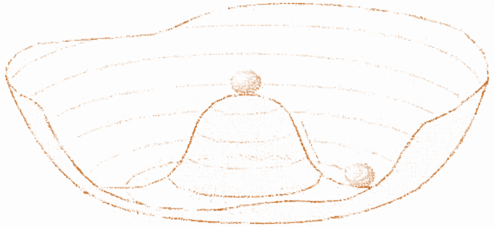
WANTED



the QCD Axion



Guilty for solving the strong CP problem!

$$\bar{\Theta} \cdot \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu} \; \epsilon \; \mathcal{L}_{QCD}$$

$$\bar{\Theta} = \Theta - \arg\det M_q \qquad -\pi < \bar{\Theta} < \pi$$

Random phase from Θ-vacuum

phases from Yukawa coupling: CKM matrix

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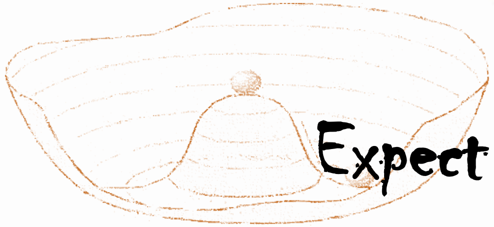
WANTED

the QCD Axion

Guilty for solving the strong CP problem!



Expect nEDM: $d_n \sim \overline{\Theta} \cdot 10^{-16}$ e cm

nEDM limit: $d_n < 3 \cdot 10^{-26}$ e cm

Phys. Rev. Lett. 124, 081803 (2020)

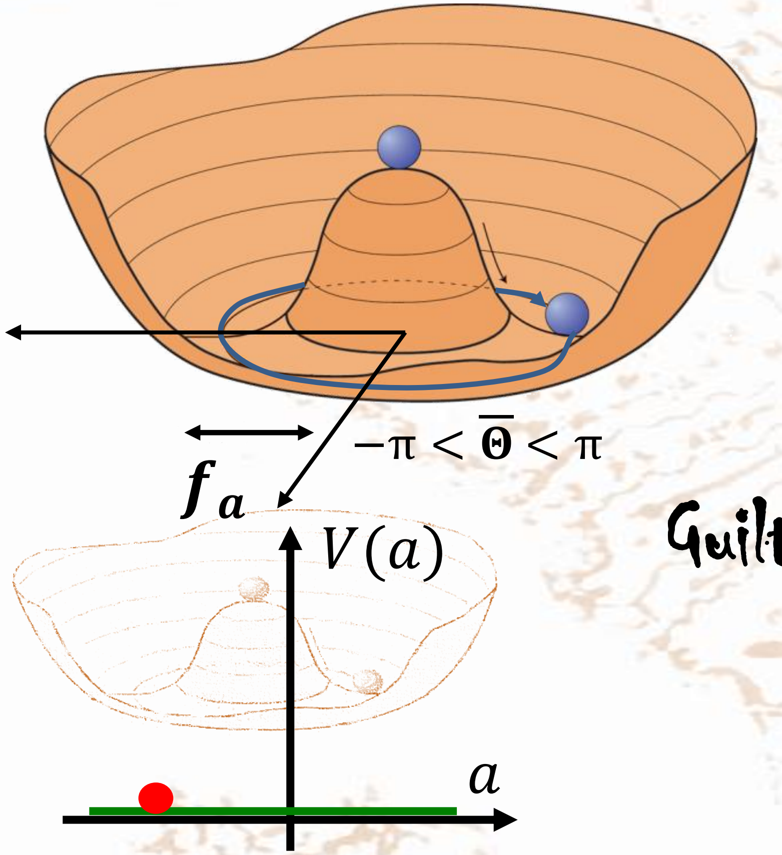
-> $\overline{\Theta} = \Theta - \arg\det M_q < 10^{-10}$

Random phase from Θ-vacuum

phases from Yukawa coupling: CKM matrix

WANTED

Peccei Quinn symmetry breaking of U(1)



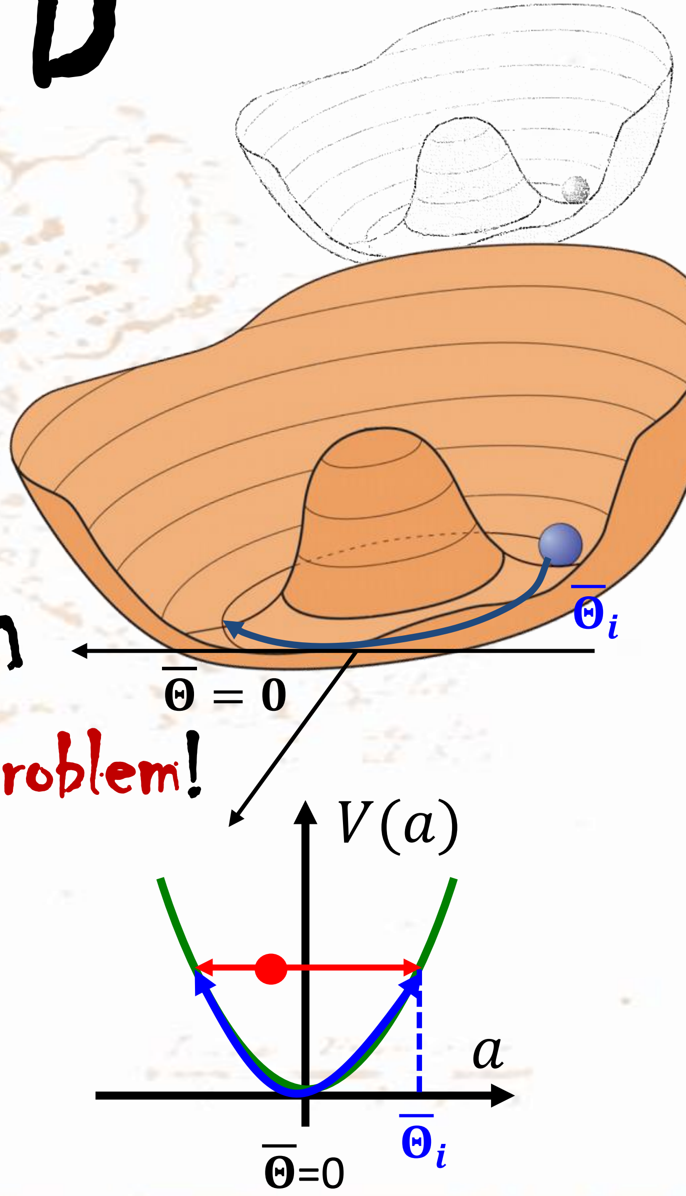
QCD:

Explicit symmetry breaking

the QCD Axion

Guilty for solving the strong CP problem!

$$m_a \sim 5.7 \mu eV \frac{10^{12} GeV}{f_a}$$



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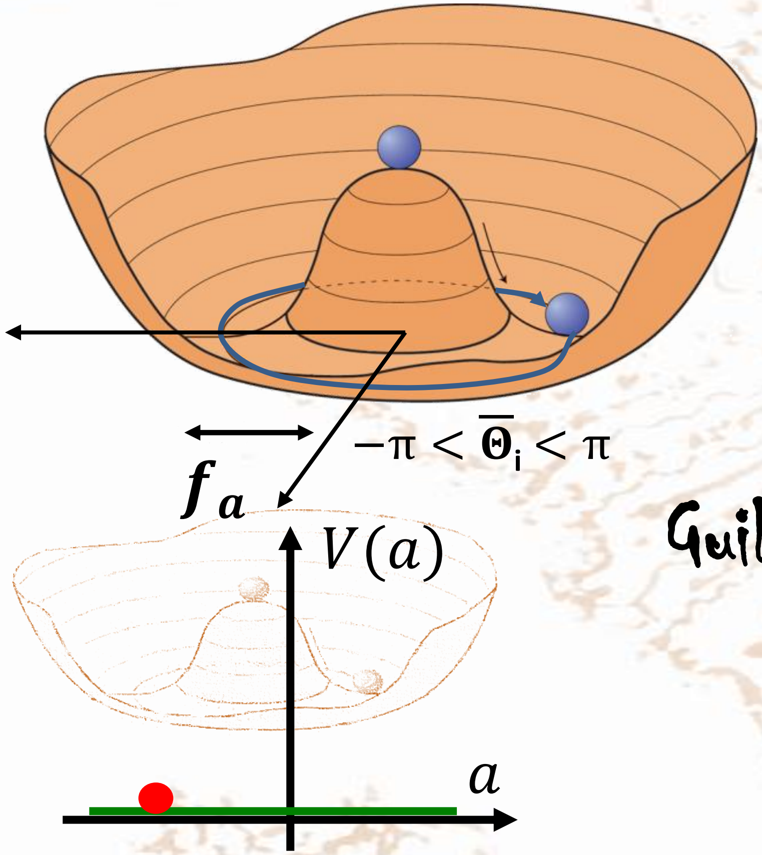
WANTED



QCD:

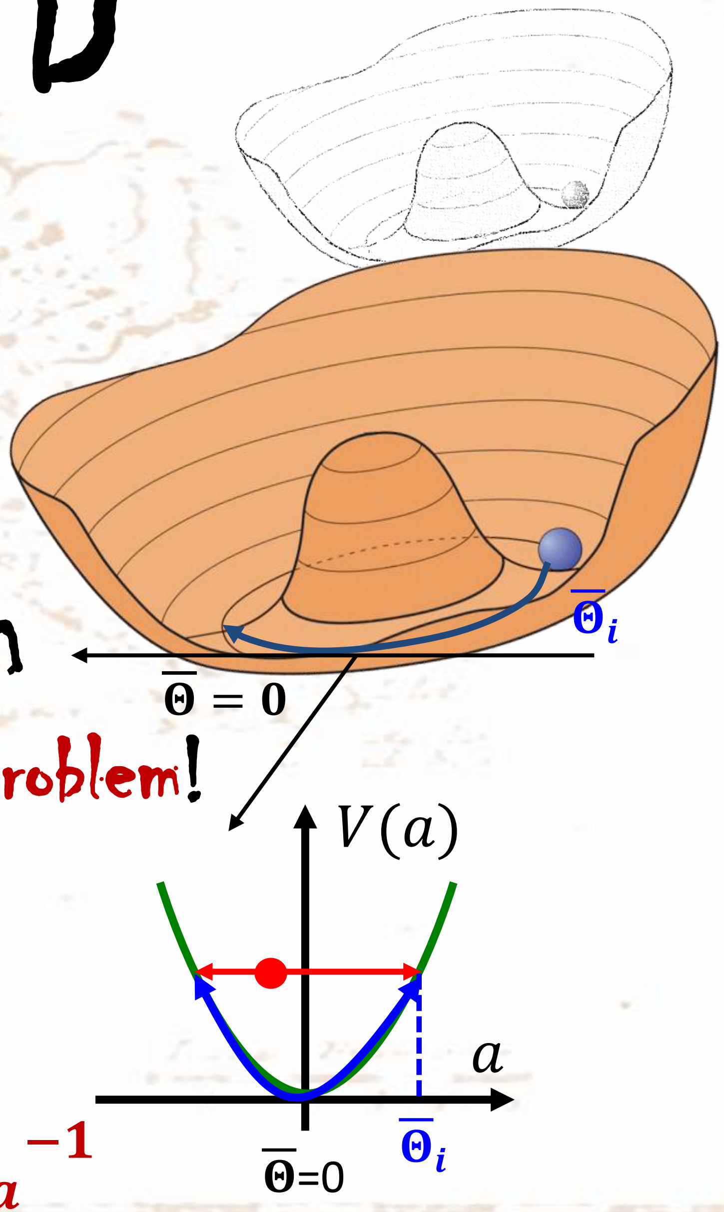
Explicit symmetry breaking

the QCD Axion

Guilty for solving the strong CP problem!

master of disguise!

$$m_a \sim 5.7 \mu eV \frac{10^{12} GeV}{f_a}$$



Coupling to photons suppressed: $g_{a\gamma} \propto f_a{}^{-1}$

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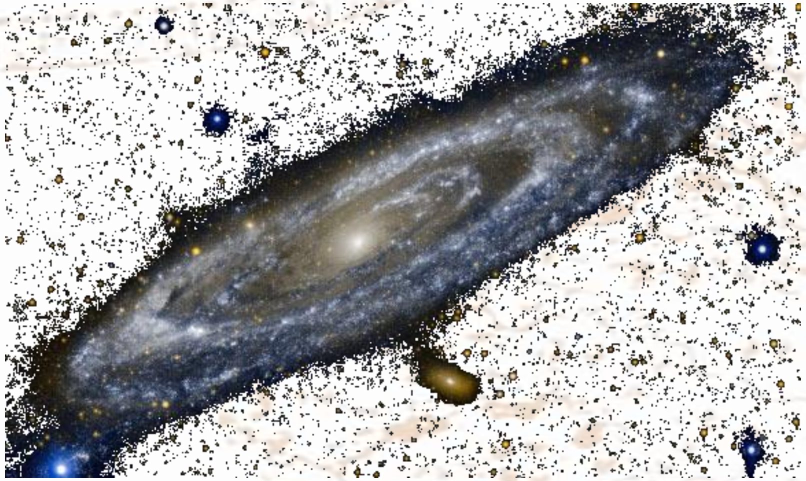
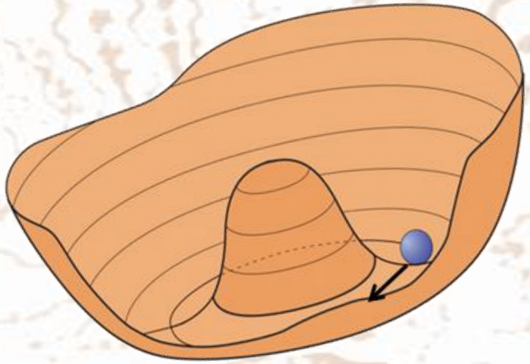
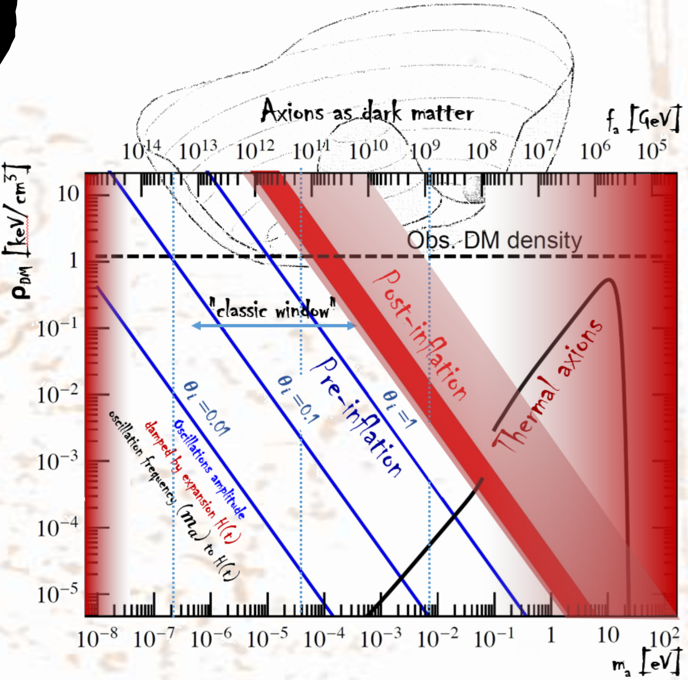
WANTED







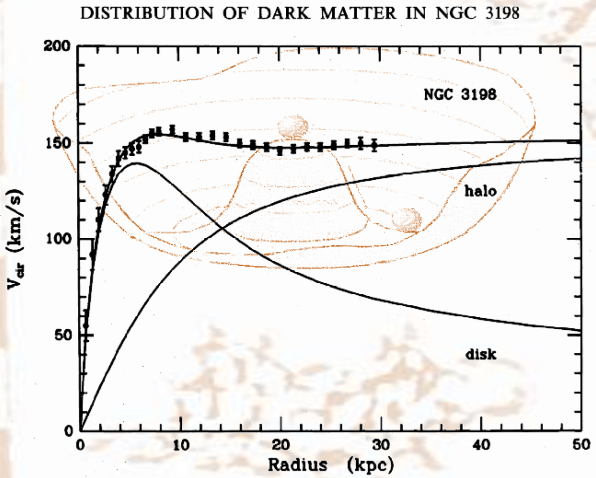
the QCD Axion

Guilty for solving the strong CP problem!

master of disguise!

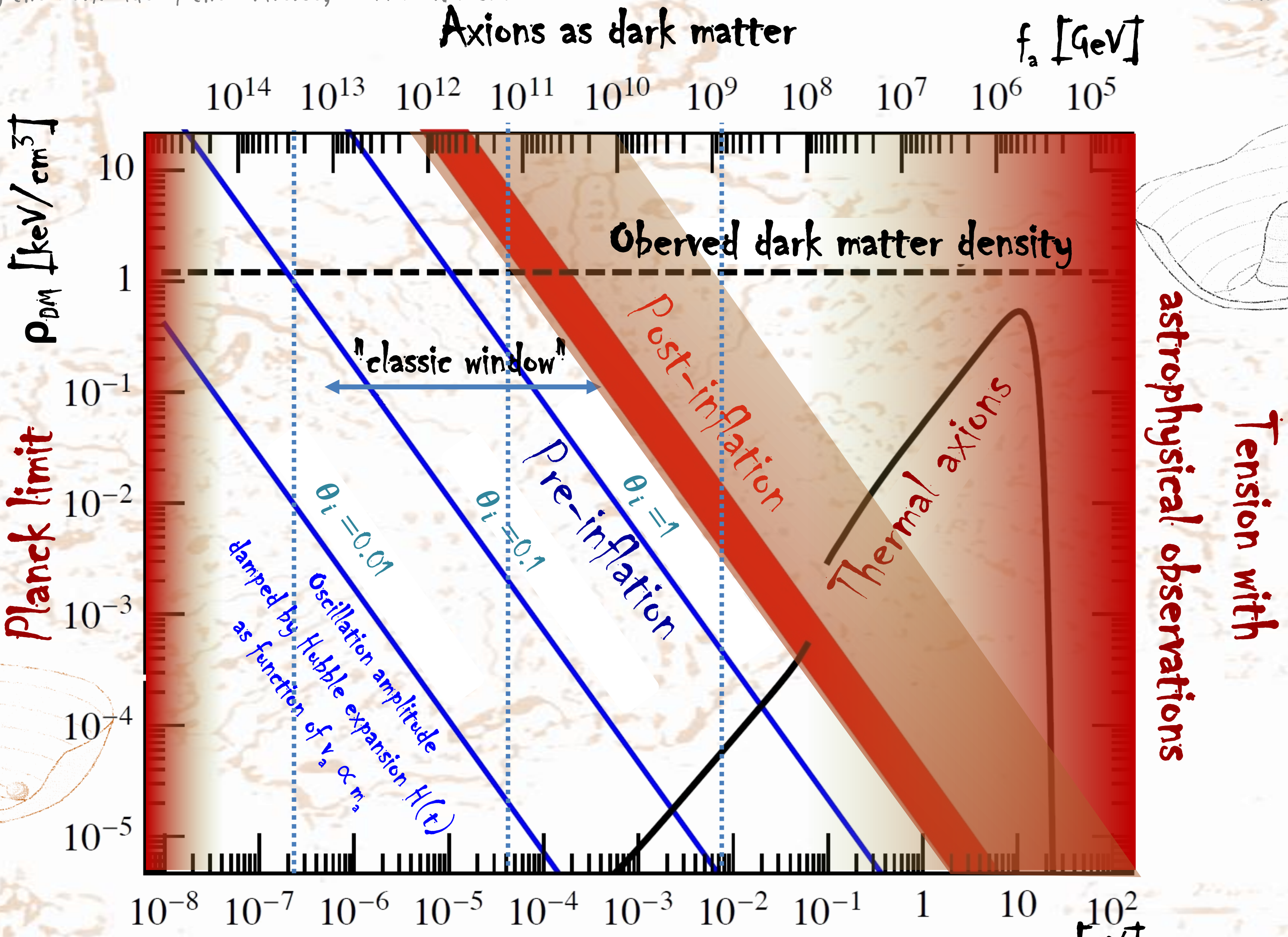
$$m_a \sim 5.7\mu eV \frac{10^{12} GeV}{f_a}$$

$$g_{a\gamma} \propto f_a^{-1}$$



REWARD: Solve the DM crisis?

Axions as dark matter



REWARD: Solve the DM crisis?

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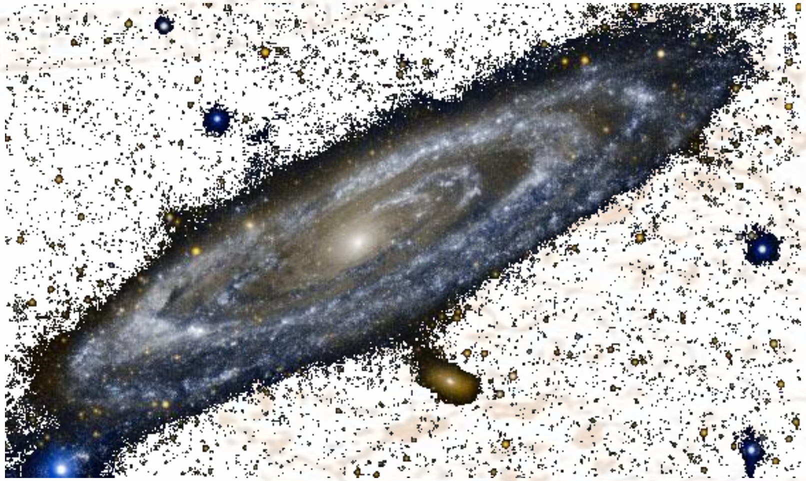
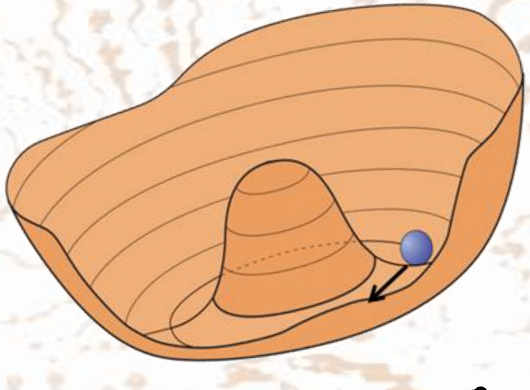
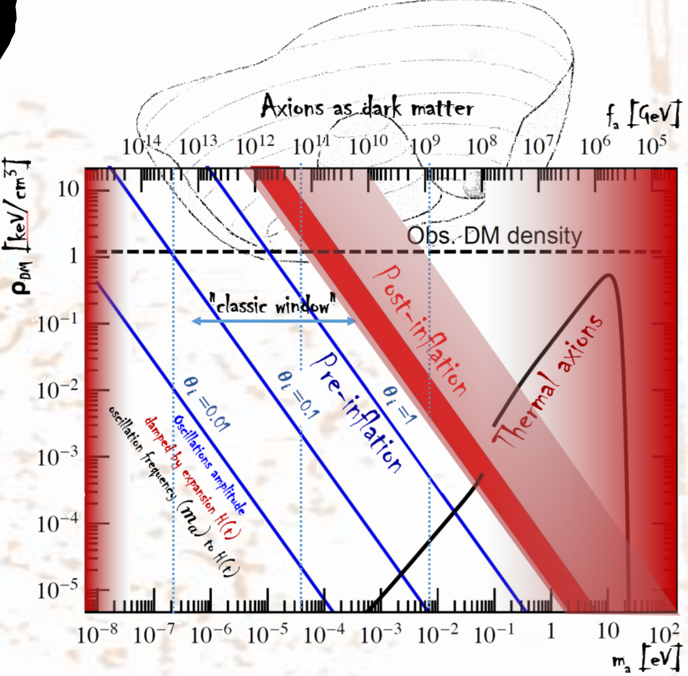
WANTED







the QCD Axion

Galactic dark matter:

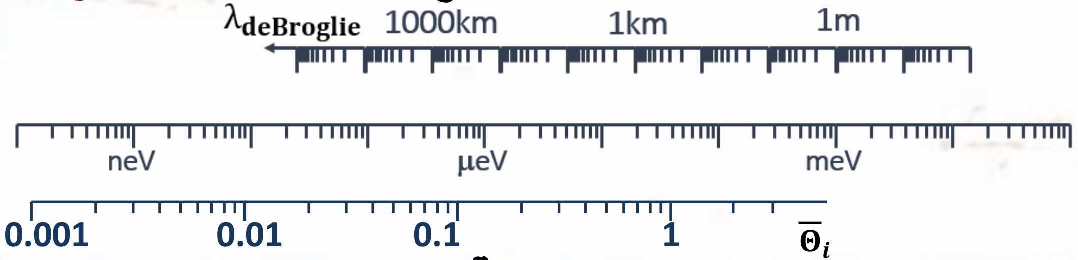
$\langle v_{DM} \rangle = 10^{-3} c$

Guilty for solving the strong CP problem!

master of disguise: (nearly) invisible & wave-like!

could hide anywhere

pre-inflation



post-inflation

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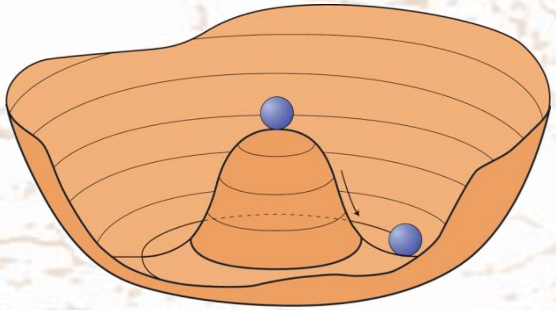
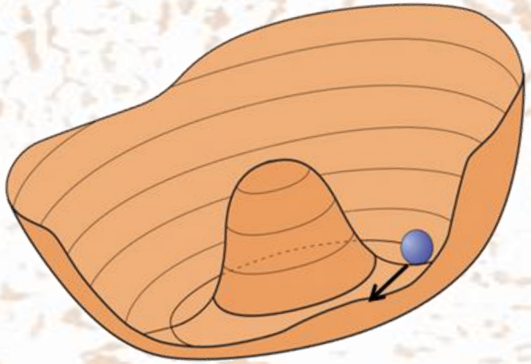
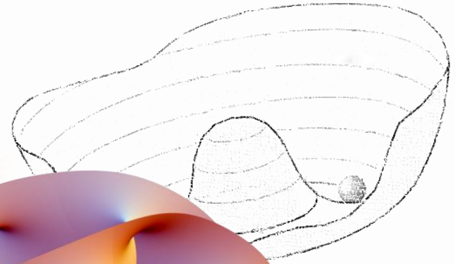
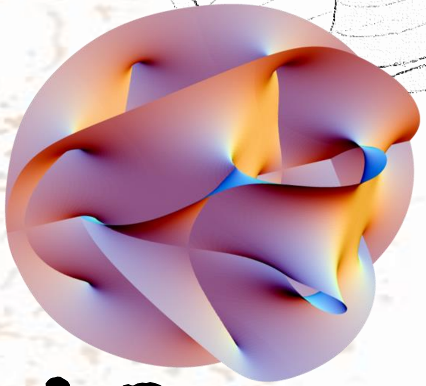
WANTED

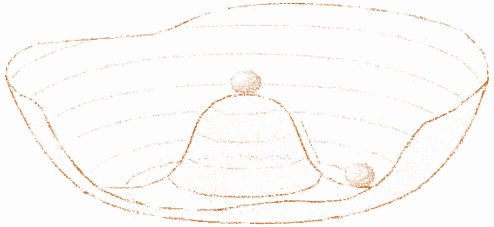
the QCD Axion & ALPs

Guilty for solving the strong CP problem!

Axions: masters of disguise!

Prime suspect for cause of DM crisis!

Compactification of dimensions → Axiverse!



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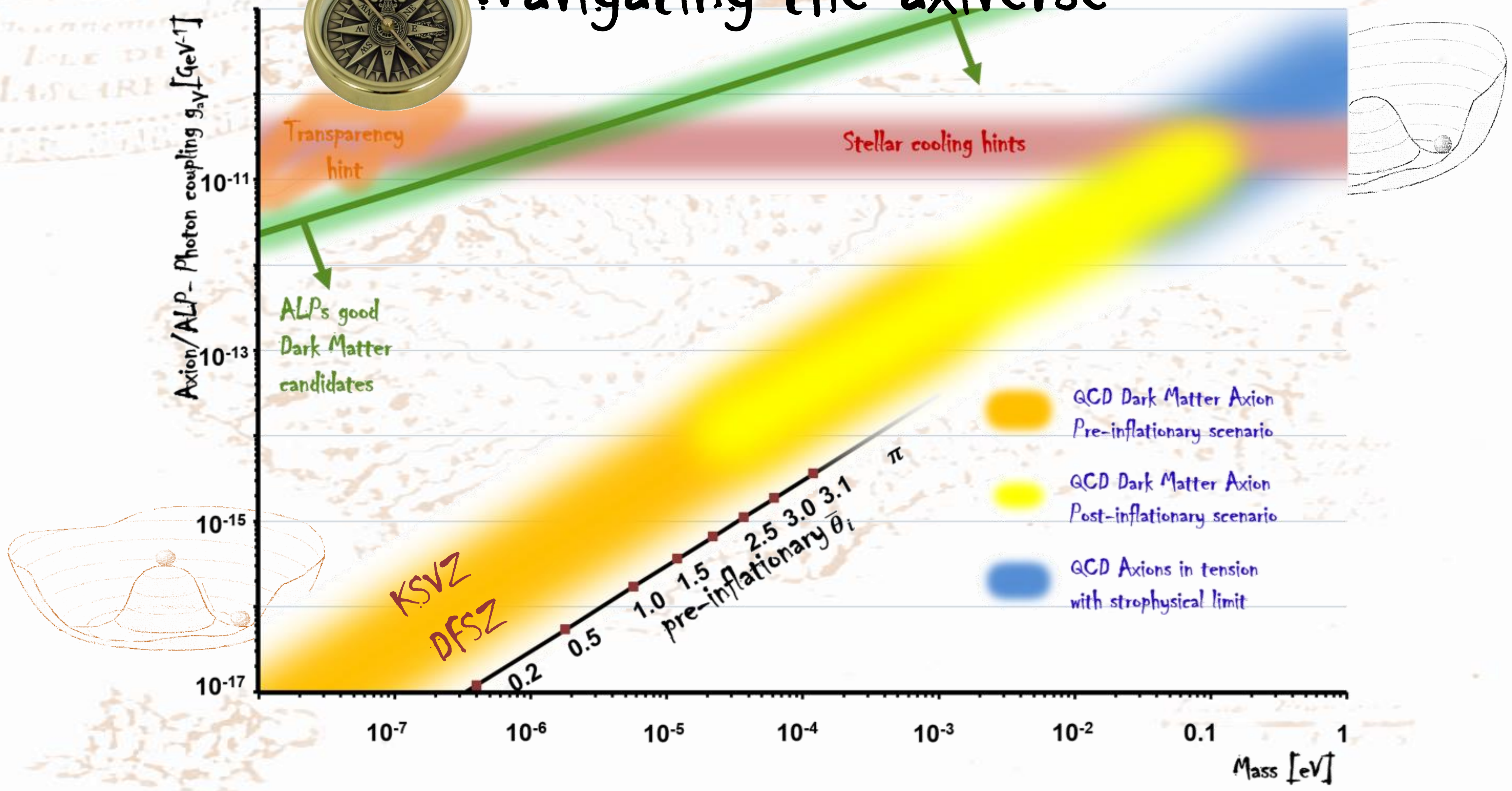
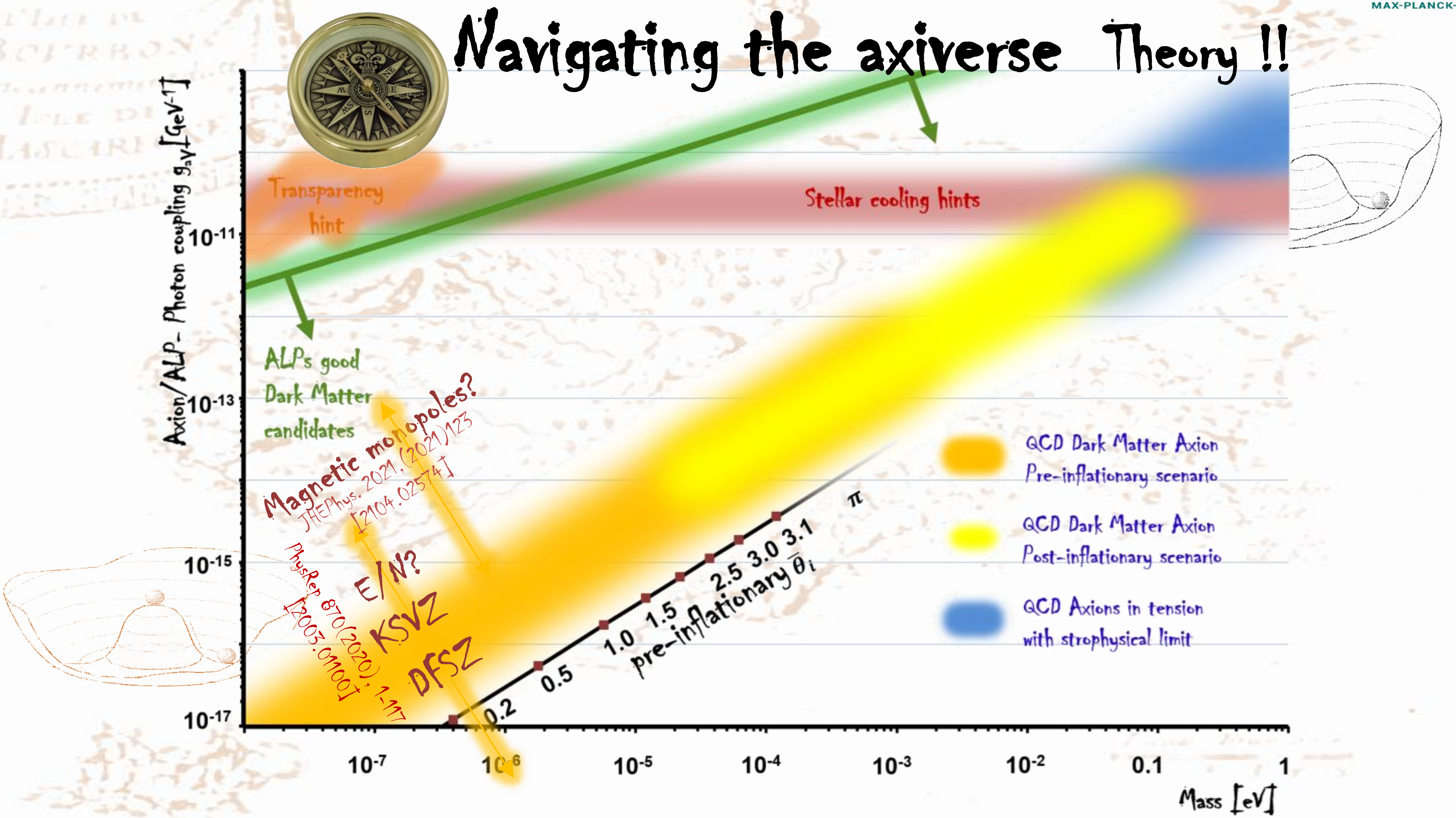
Navigating the axiverse



Navigating the axiverse Theory !!



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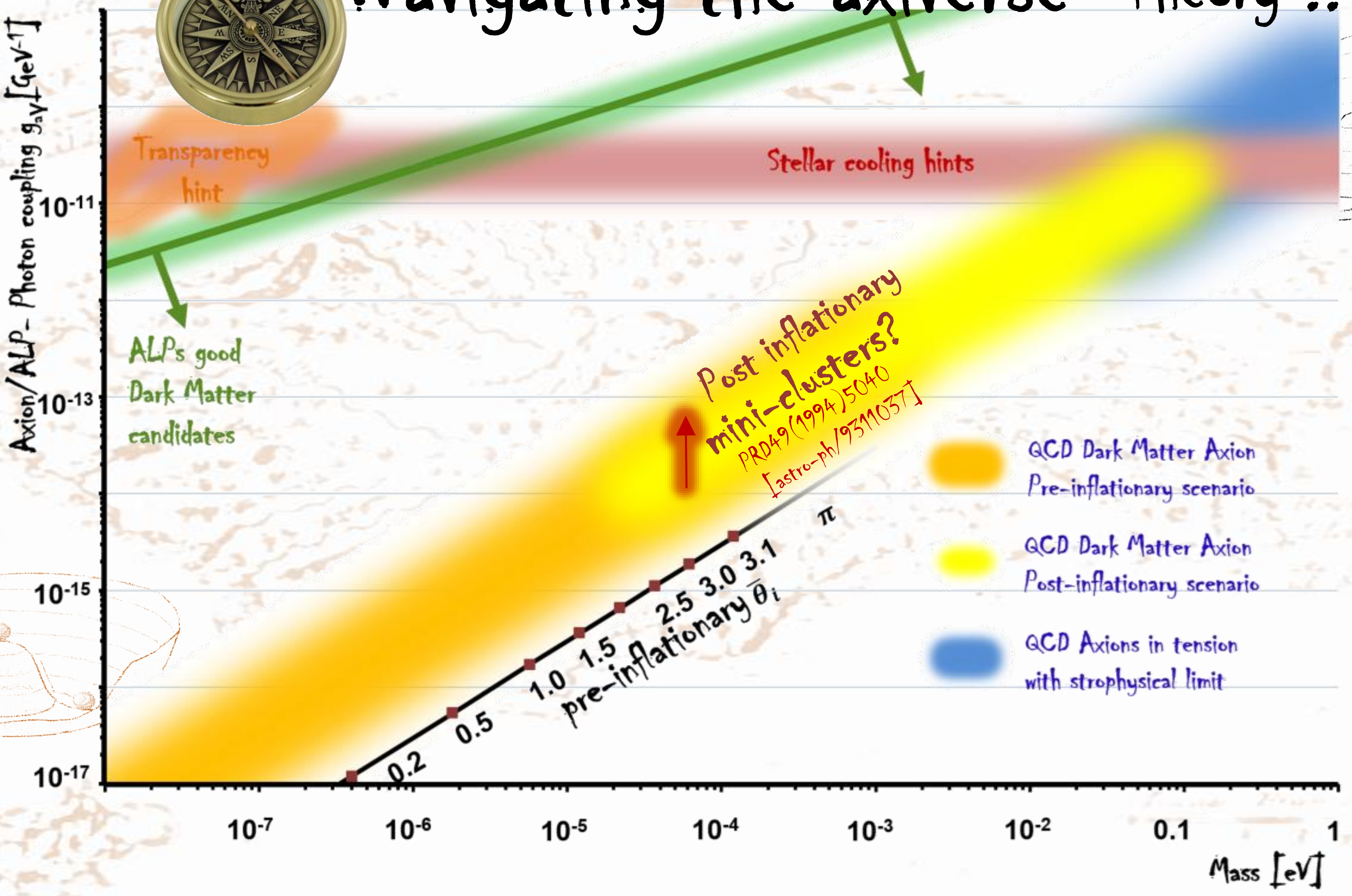
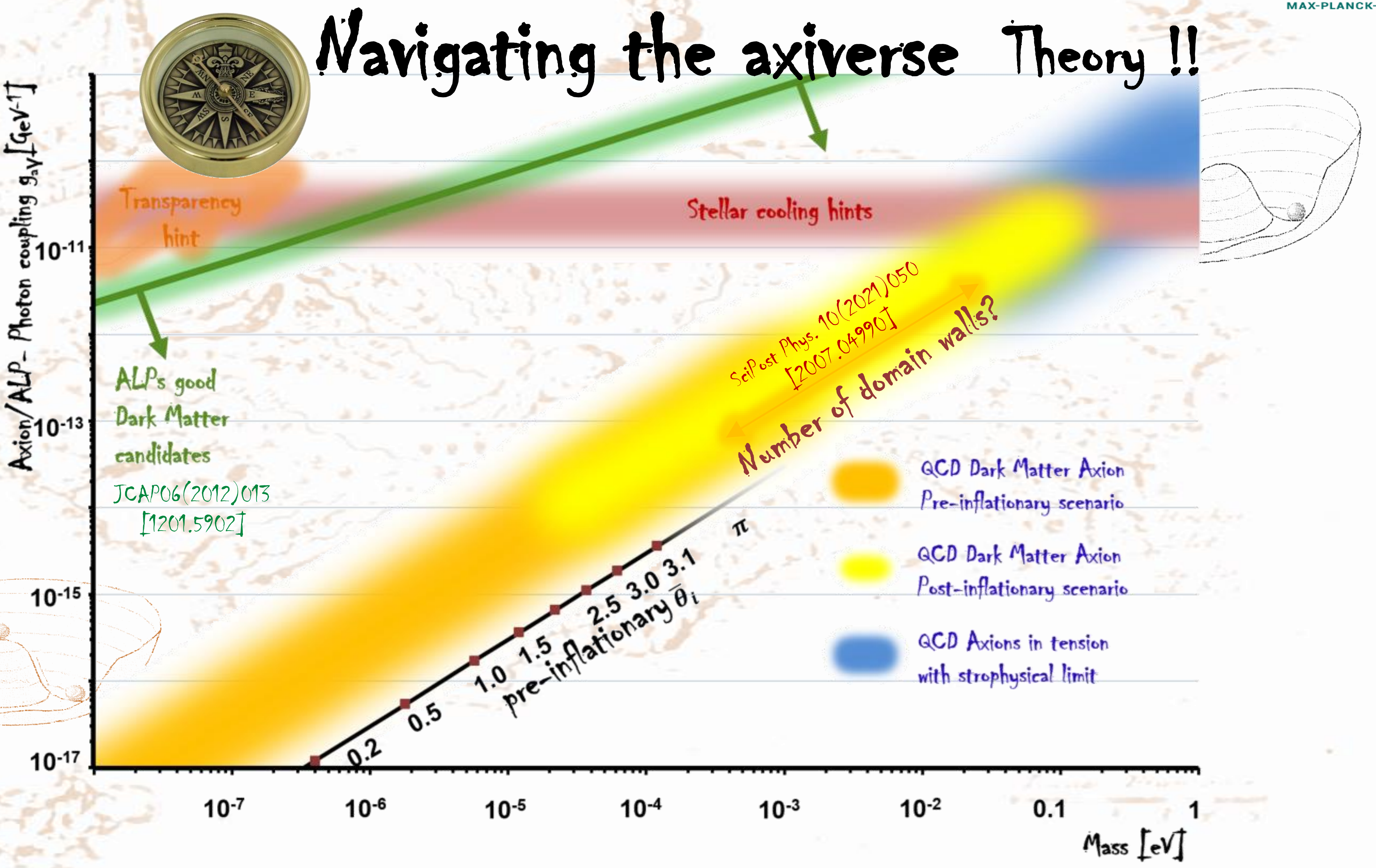
Navigating the axiverse Theory !!



Navigating the axiverse Theory !!



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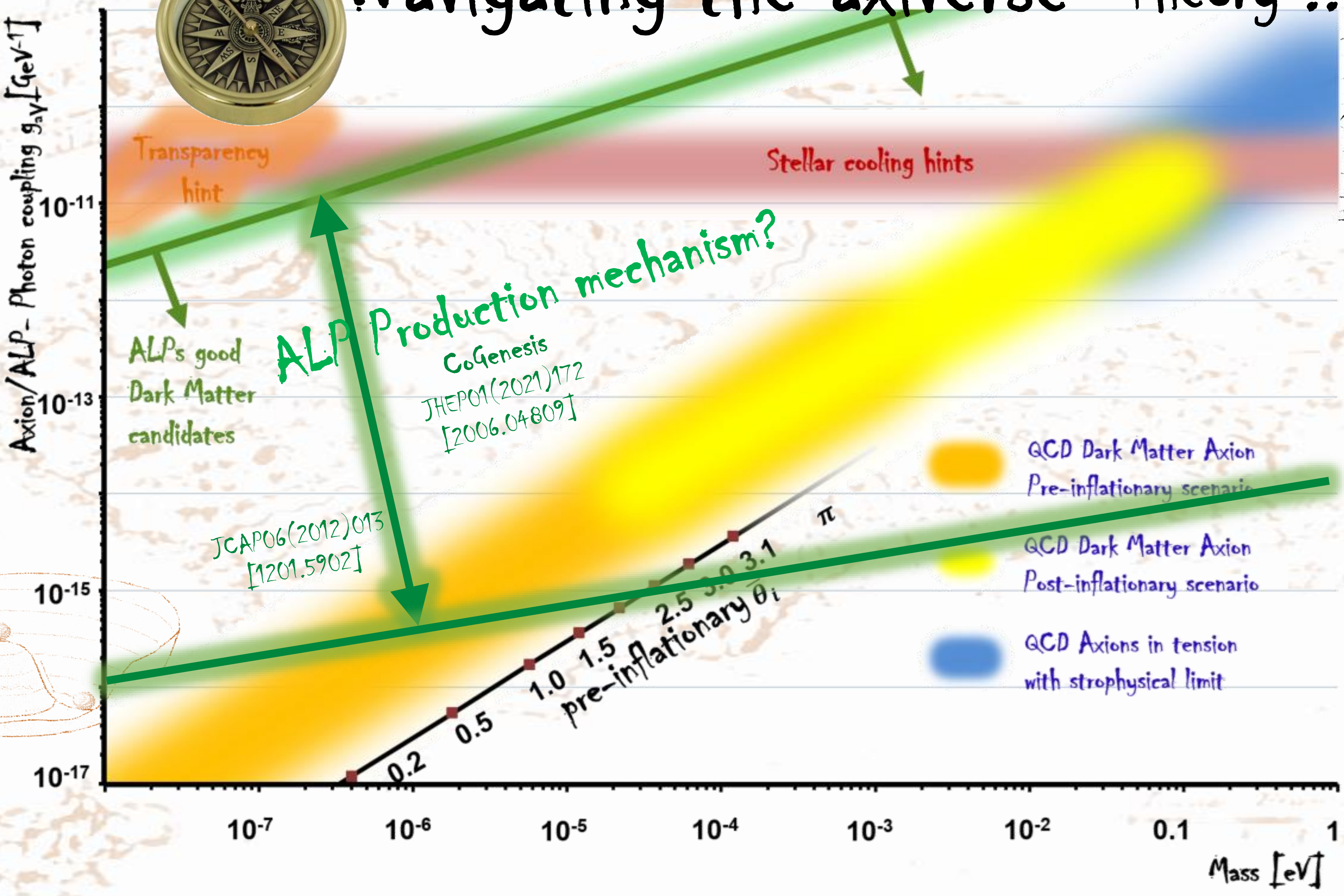
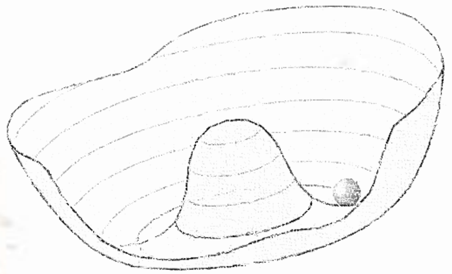
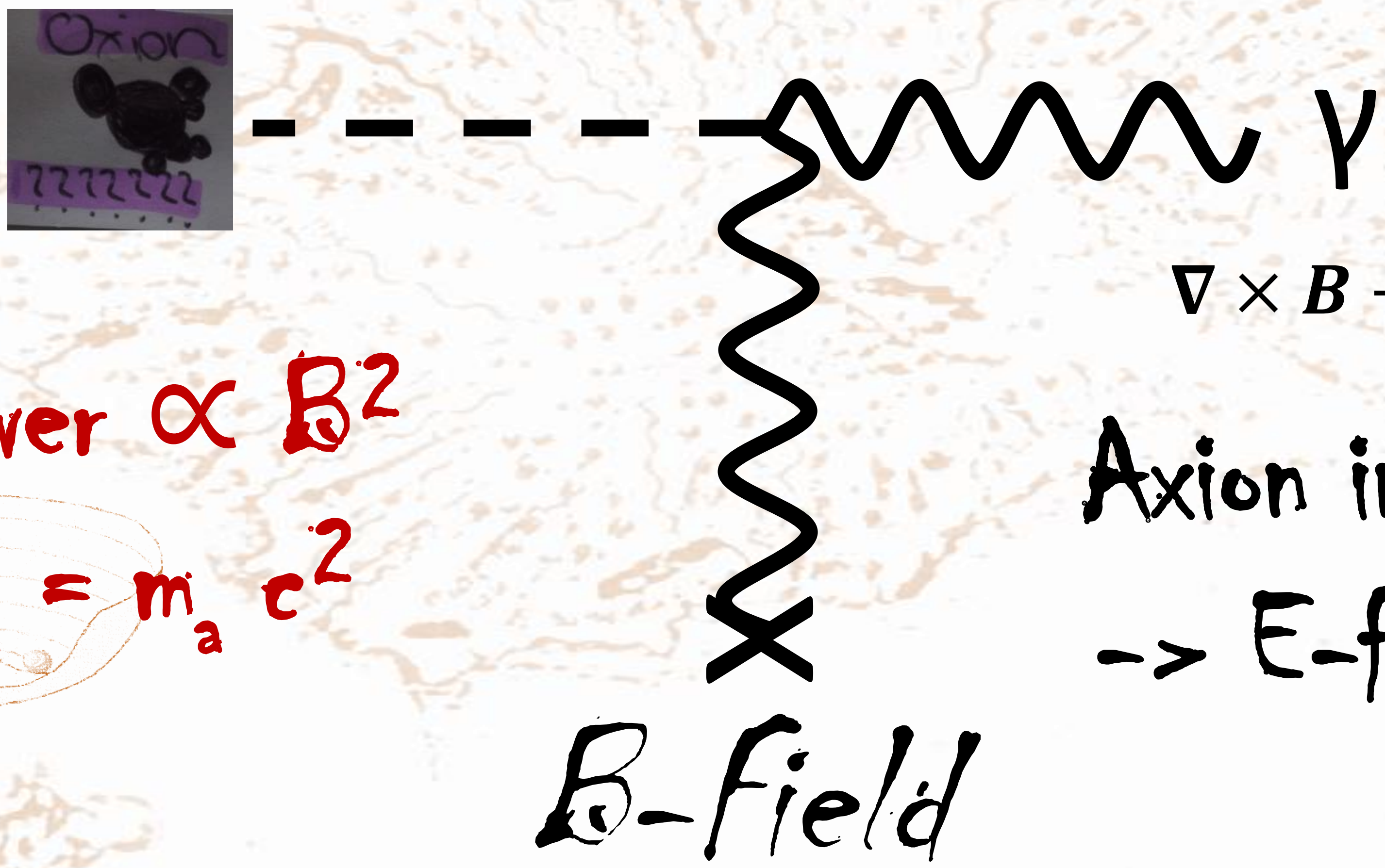
Navigating the axiverse Theory !!



The bounty hunters' most important arms:

The inverse Primakoff effect





$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = \boldsymbol{J} + g_{a\gamma}\, \boldsymbol{B}\dot{a}$$

Power $\propto B^2$

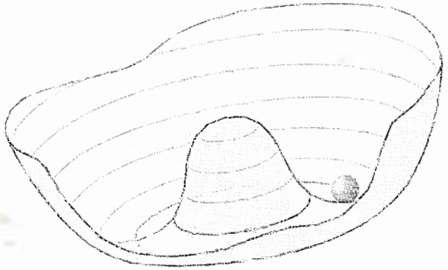
$h\nu_a = m_a c^2$

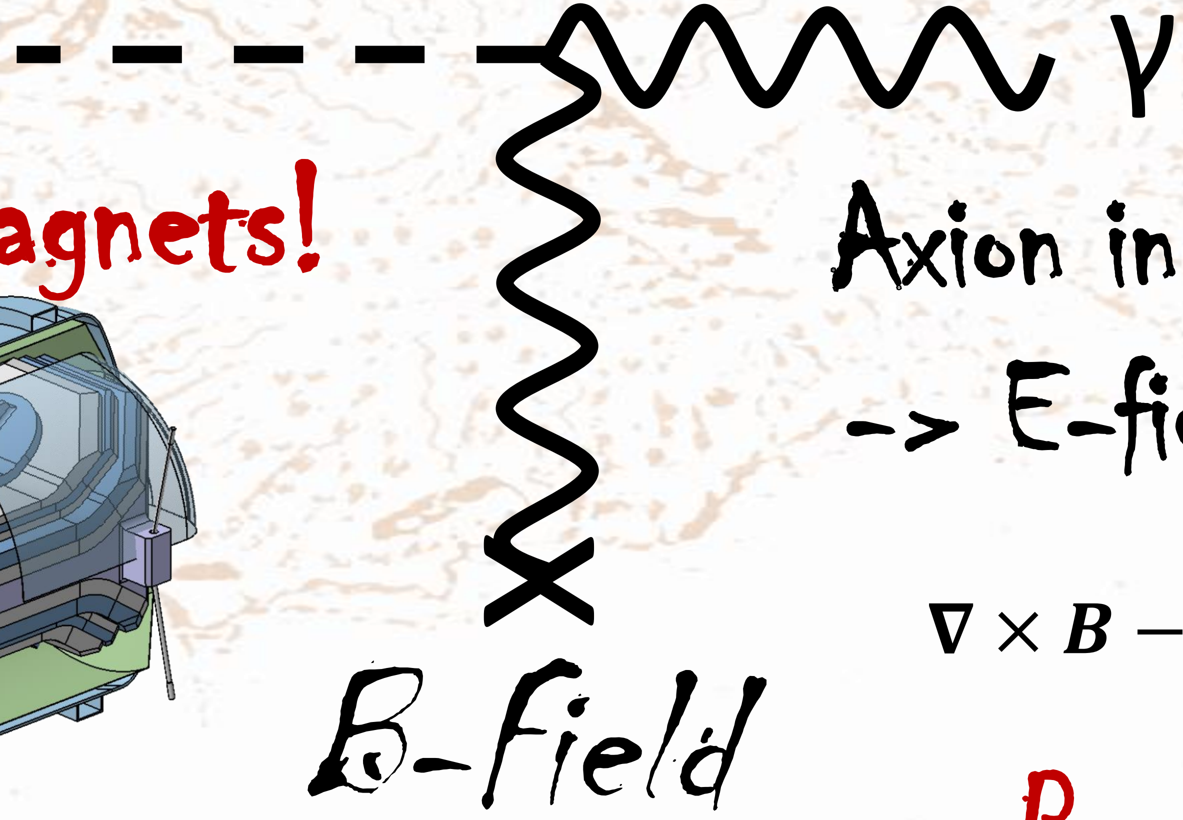
Axion in static B-field

-> E-field oscillation!

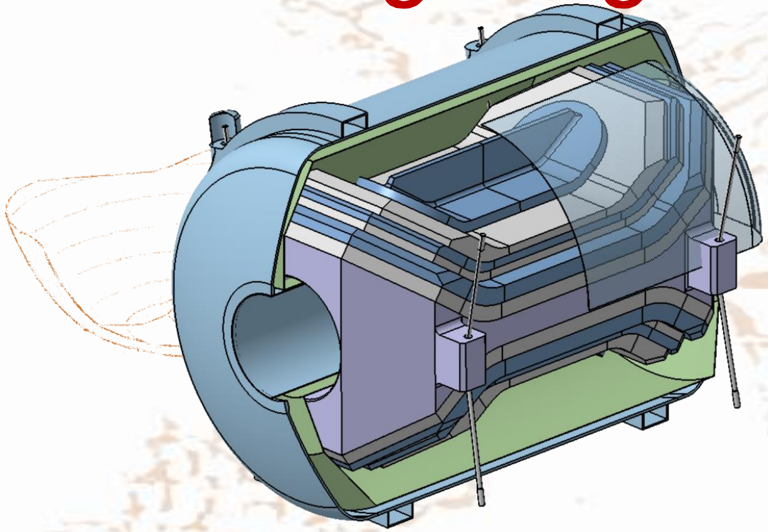
The bounty hunters' most important arms:

The inverse Primakoff effect





Strong magnets!



Axion in static B-field

-> E-field oscillation!

$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = \boldsymbol{J} + g_{a\gamma}\, \boldsymbol{B}\dot{a}$$

Power $\propto B^2$

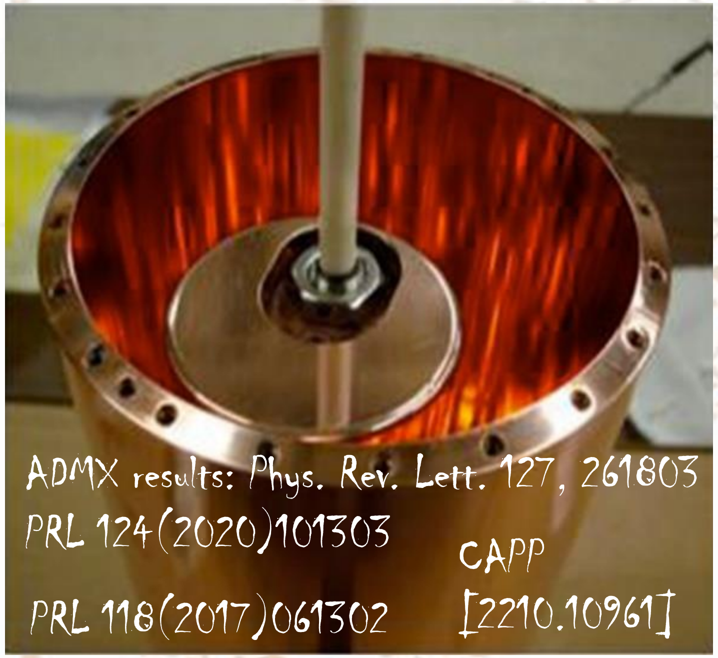
The bounty hunters' most important arms:

Axion induced E-field oscillations:

-> exploit wave mechanics & boost E-field

Tunable high Q- resonators

ADMX & CAPP & Haystac



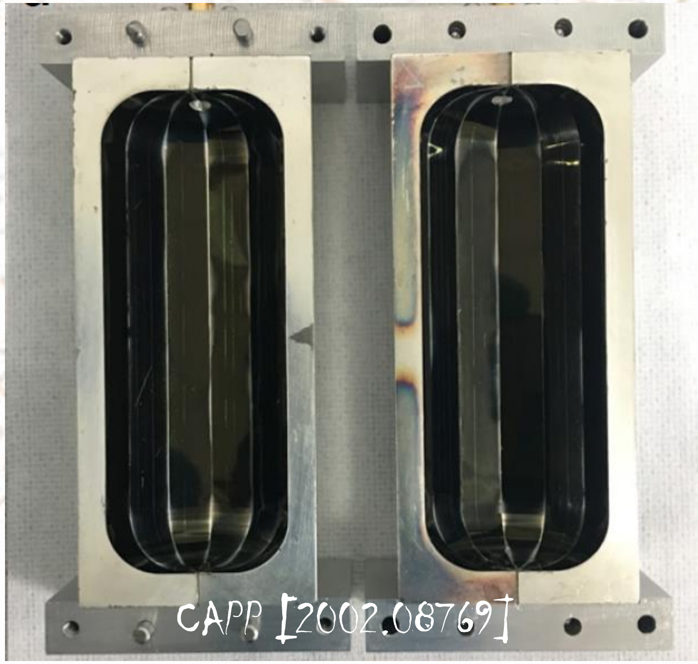
ADMX results: Phys. Rev. Lett. 127, 261803

PRL 124(2020)101303

PRL 118(2017)061302

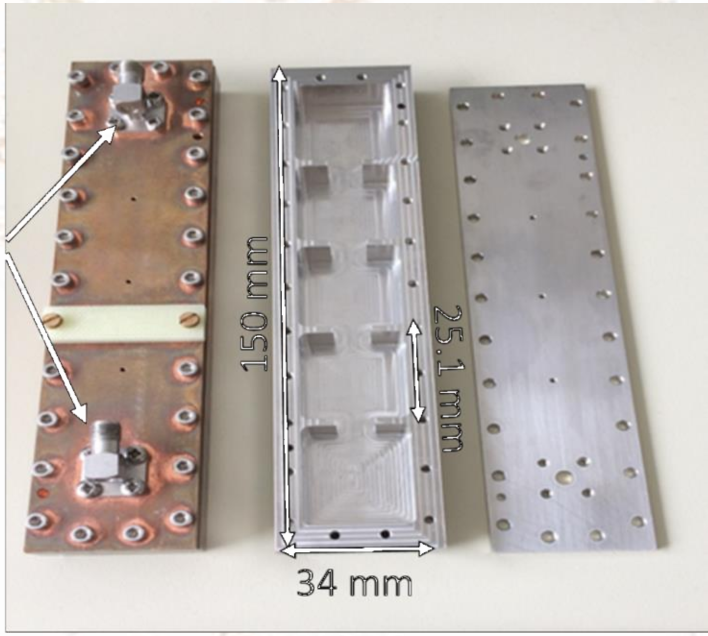
CAPP [2210.10961]

Superconducting cavities



CAPP [2002.08769]

Split cavities



RADES [2104.13798]

$$\text{Power} \propto B^2 \cdot V \cdot Q$$

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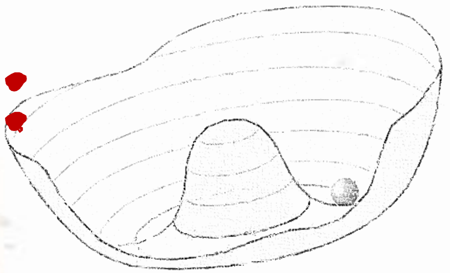
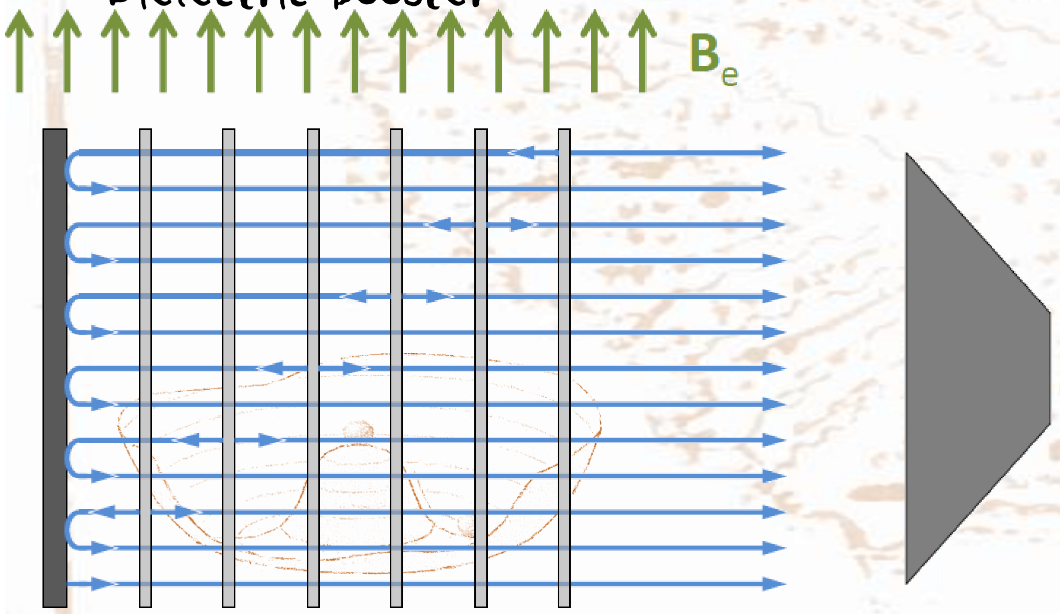
The bounty hunters' most important arms:

Axion induced E-field oscillations:



-> exploit wave mechanics

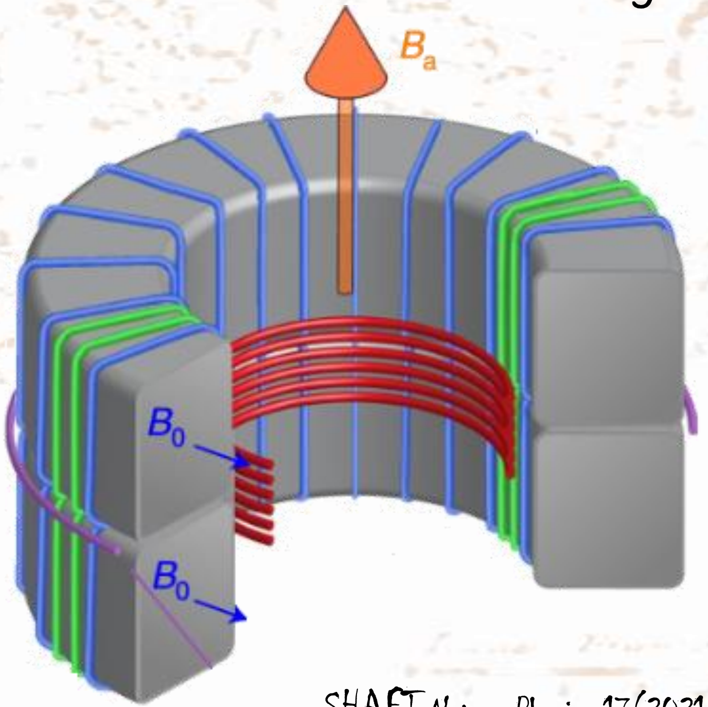
Dielectric booster



Constructive interference of coherent photon emission at dielectric layers

MADMAX PRL118 (2017)091801

LC circuits – toroidal magent



Detect B-field oscillations
Using QUID
Pickup loops

SHAFT Nature Physics 17(2021)79 [1901.10652]
DM radio – ADMX SLIC - ..

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The bounty hunters' most important arms:

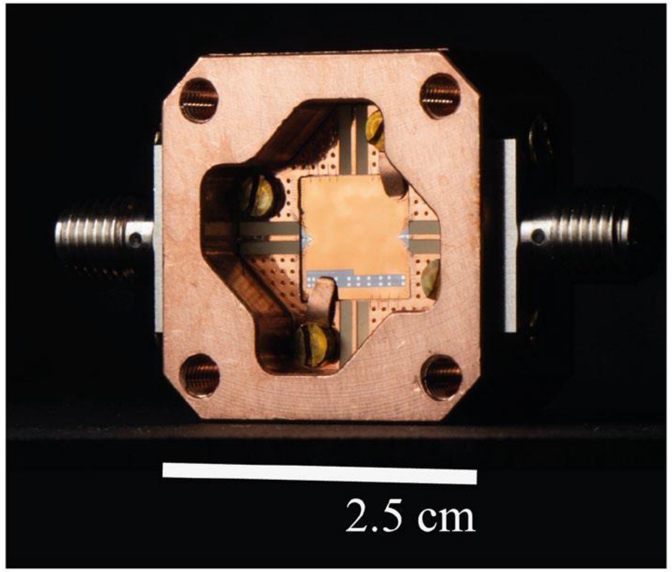
Low noise amplifiers

Quantum limited JPA
Haystac/ADMX

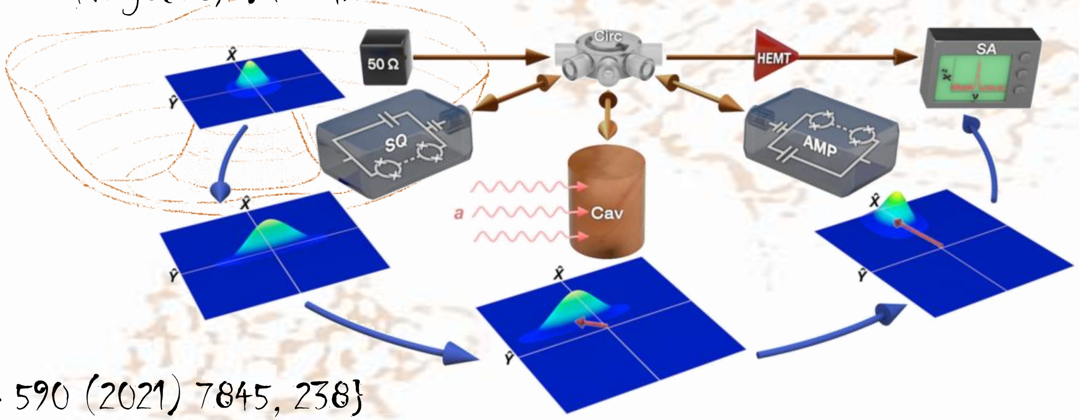
S.N.R. $\propto P/T_{sys}$

-> minimize noise

-> cryogenic temperatures

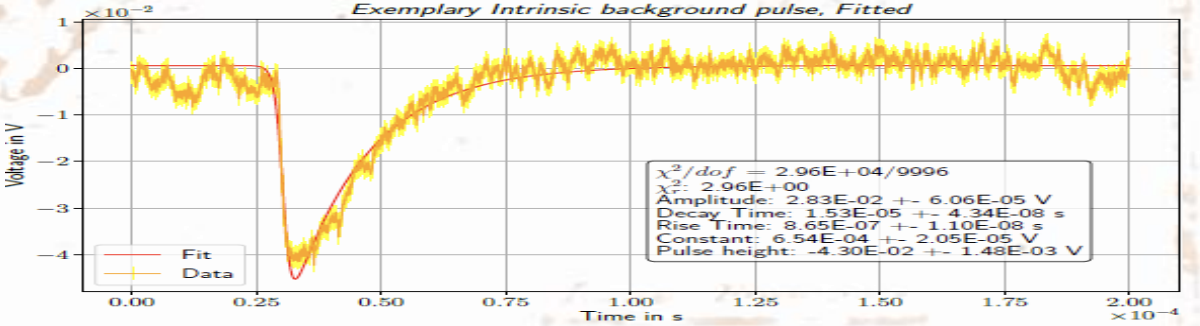


TWPA for MADMAX [2101.05815]



{Nature 590 (2021) 7845, 238}

squeezed states Haystac



Single photon detectors {2110.10654}
TES for ALPSII

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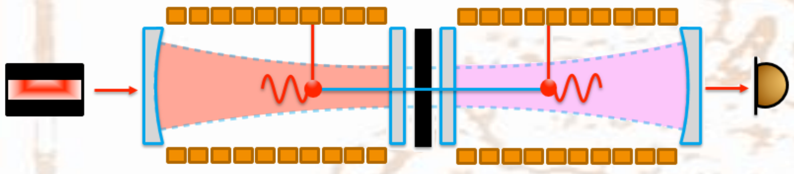
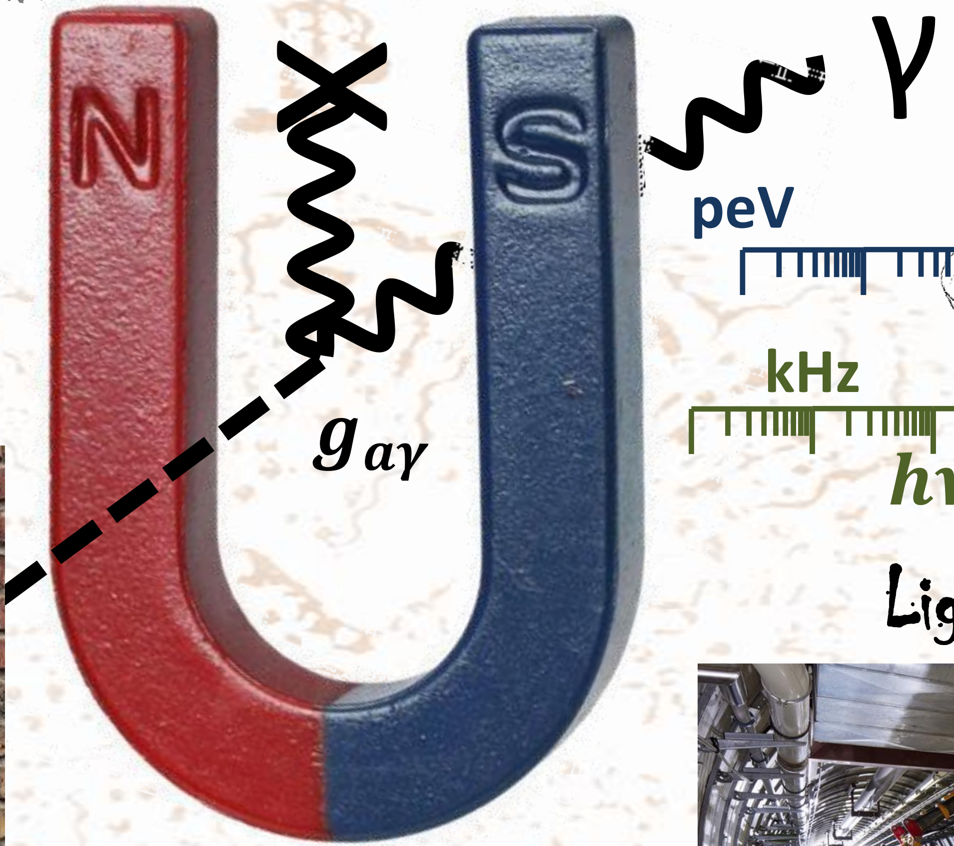
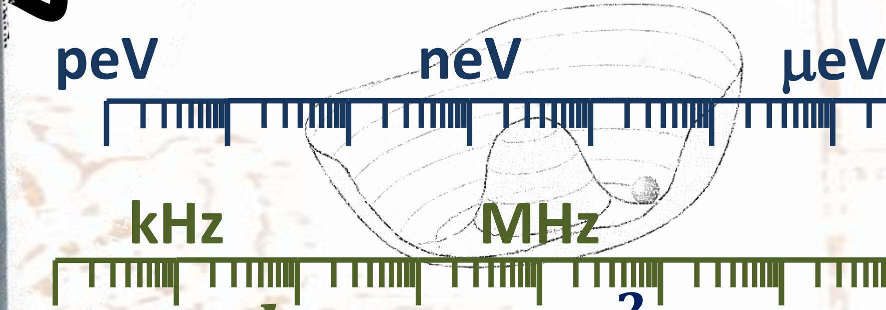
The bounty hunters: Lab experiment



[arXiv:1302.5647]

Light shining through the wall





$$h\nu_a = m_a c^2$$

Light detection

Laser as source

ALPSII at DESY

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ALPSII at DESY

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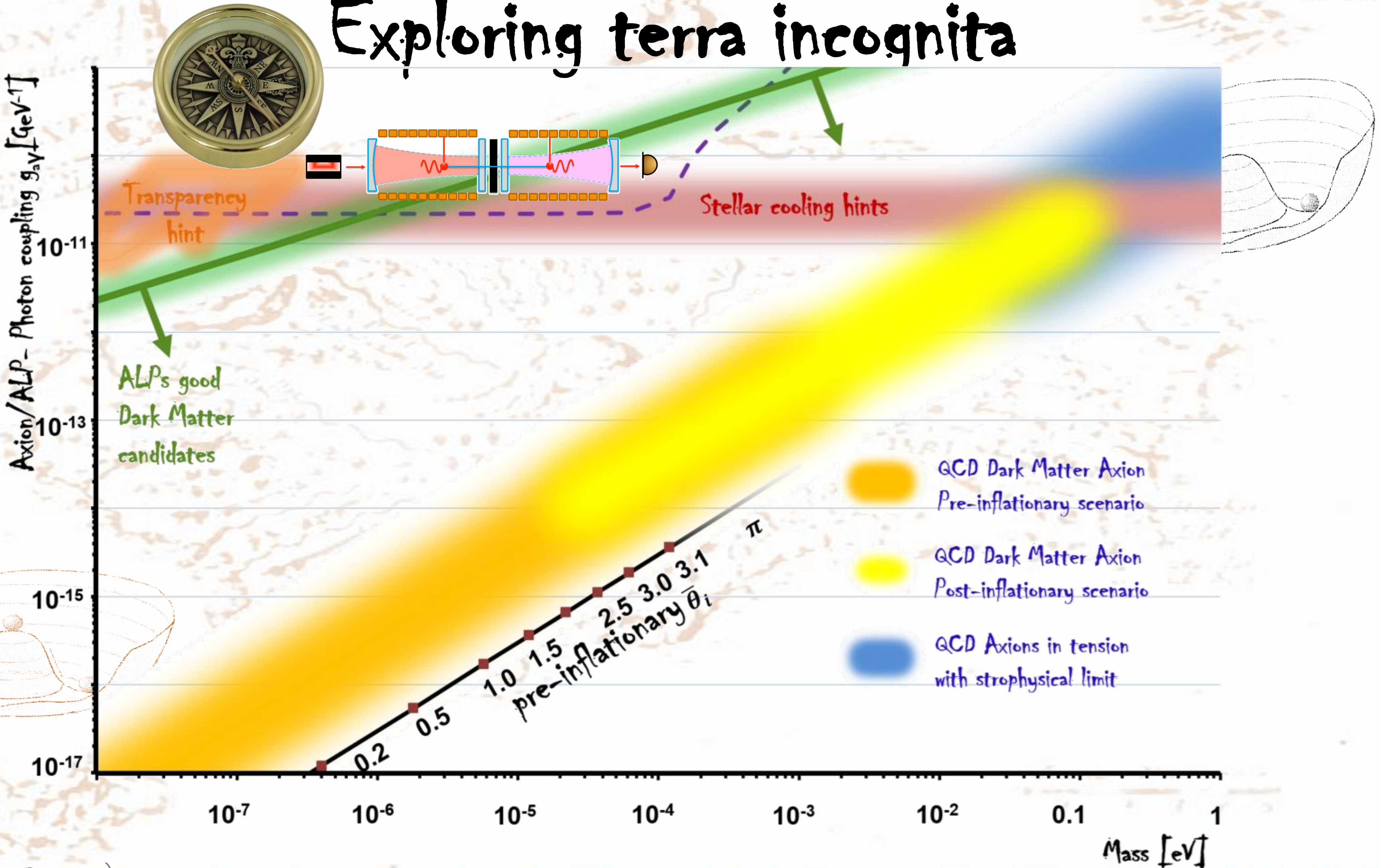
Exploring terra incognita



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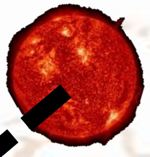
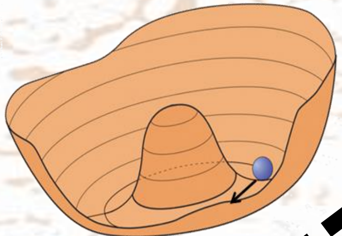
The bounty hunters:

Helioscope $g_{a\gamma}$ g_{ae}

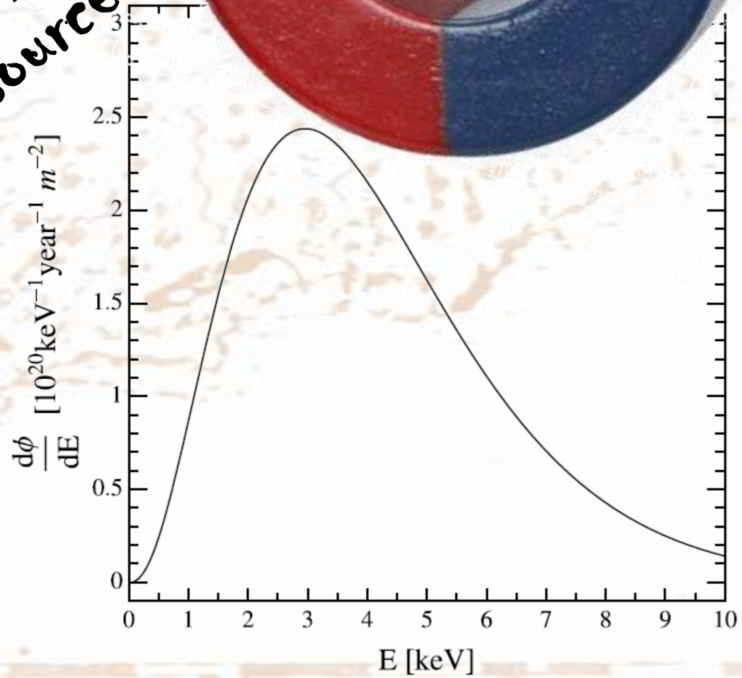


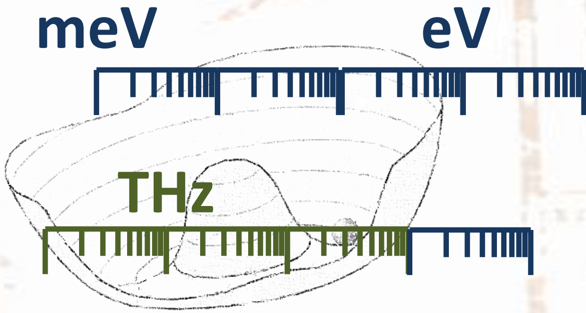


(baby)IAXO

JCAP06(2019)047
[arXiv:1904.09155]

Sun as source



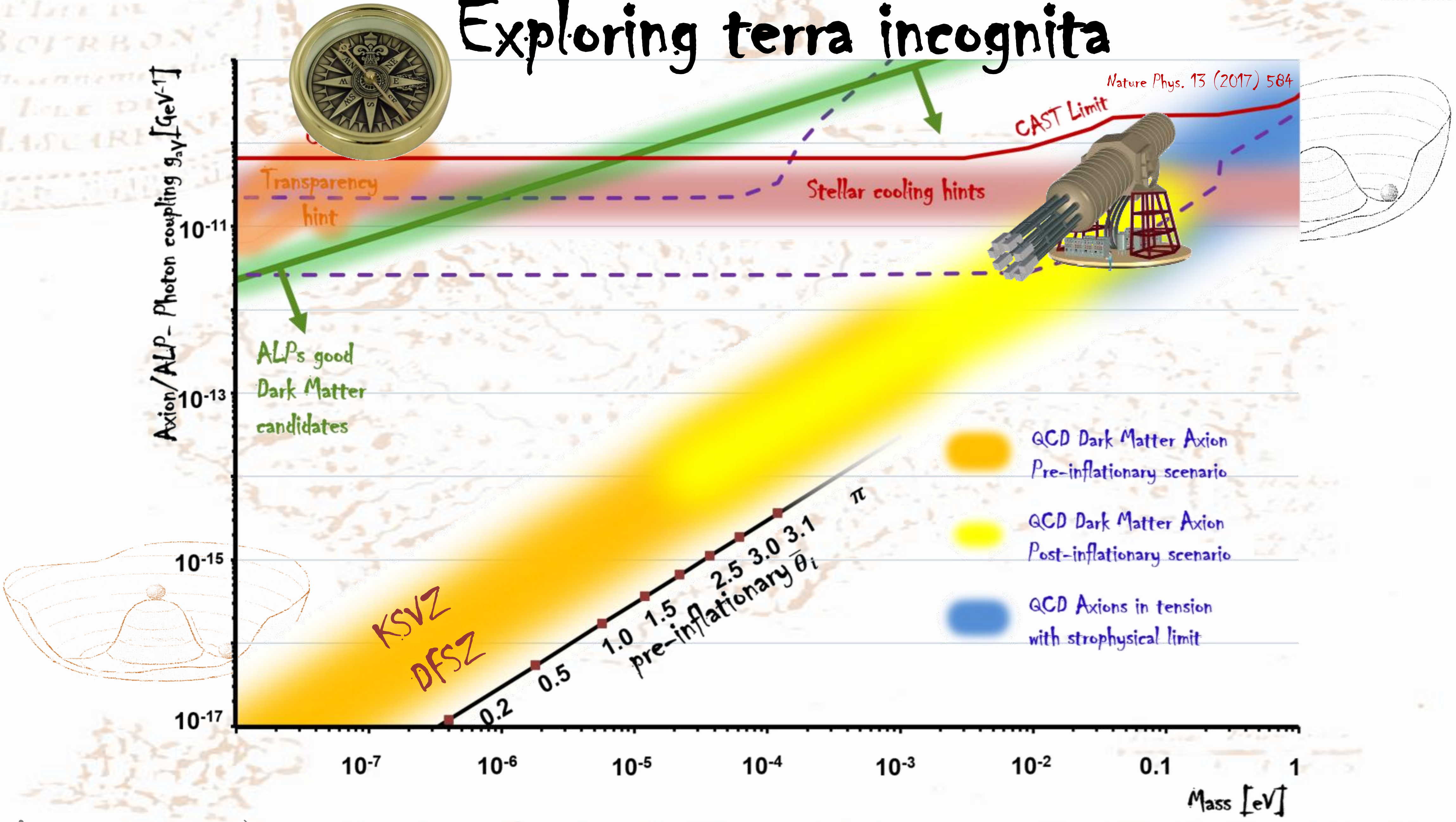


$h\nu_a = m_a c^2$

X-ray detection

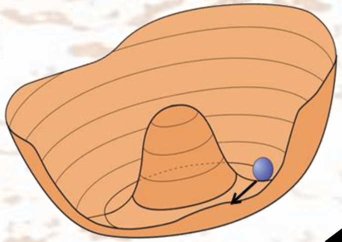
CAST@CERN {Nature Phys. 13 (2017) 584}

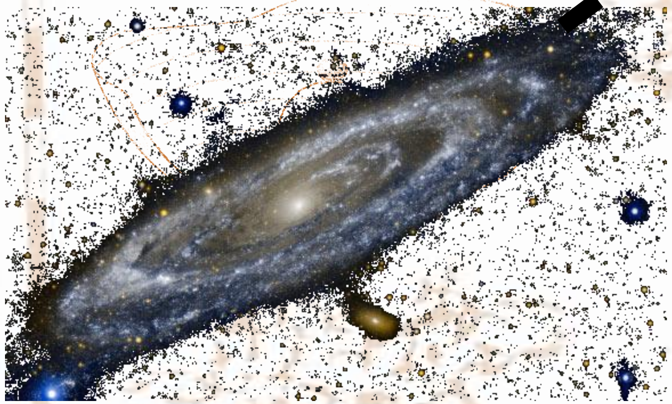
Exploring terra incognita

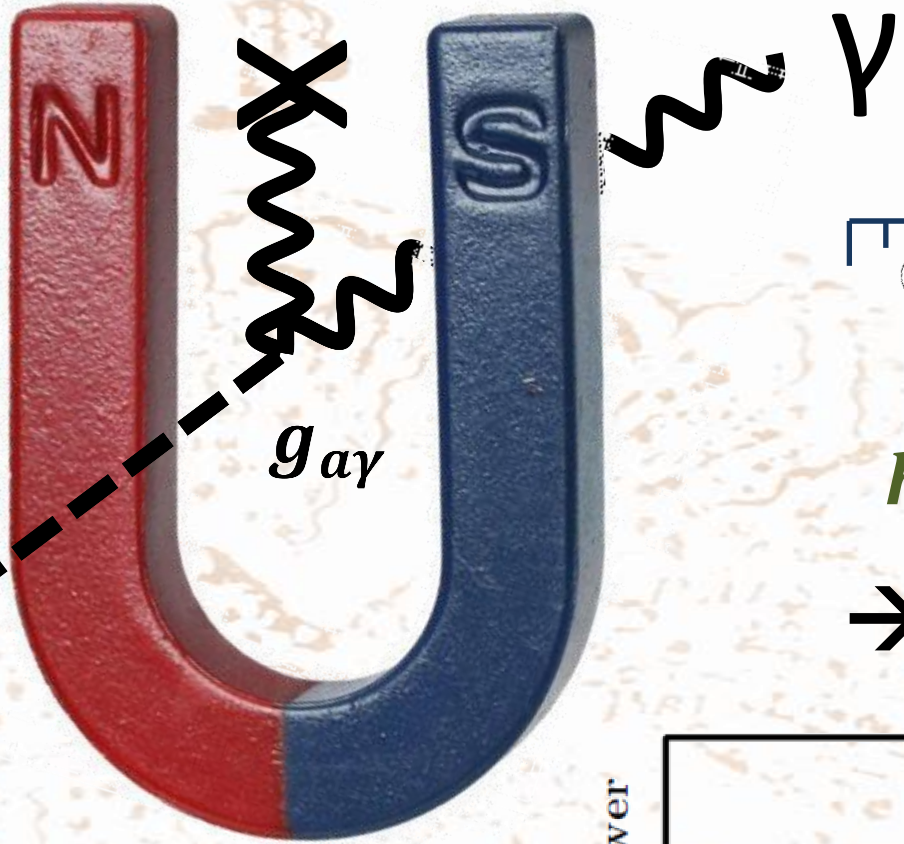


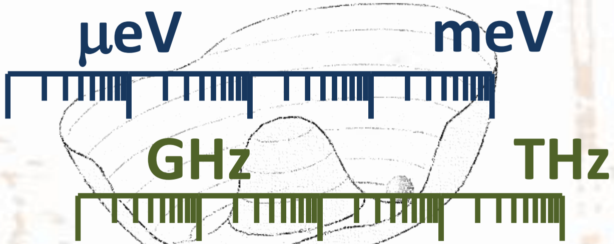
The bounty hunters:

Haloscope $g_{a\gamma}$



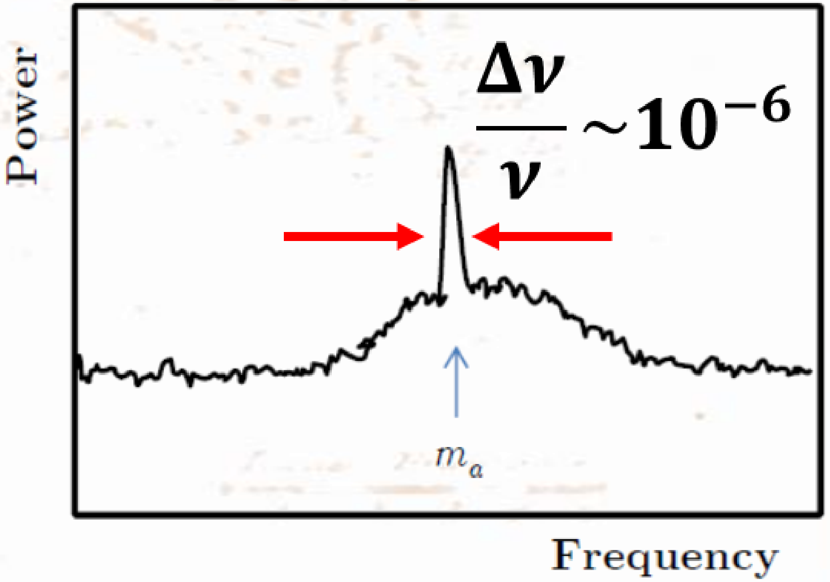






$$h\nu_a = m_a c^2$$

→ RF detection



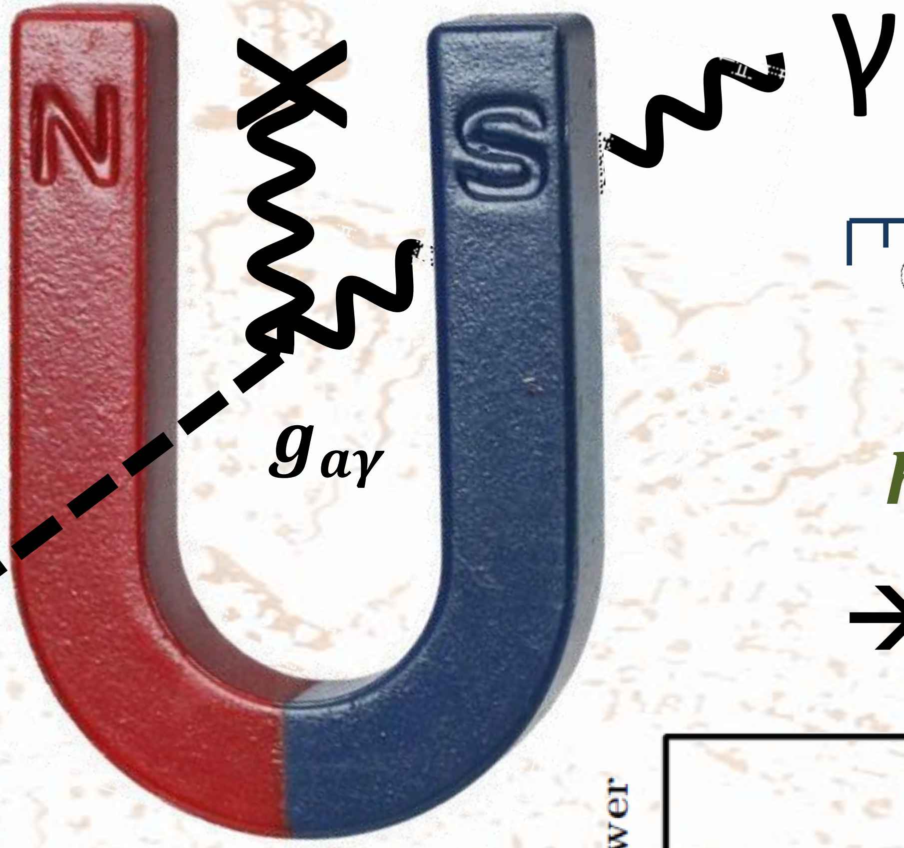
Galactic DM as source

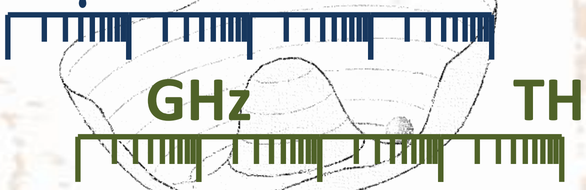
$$\langle v_{DM} \rangle = 10^{-3} c$$

The bounty hunters:

Haloscope $g_{a\gamma}$

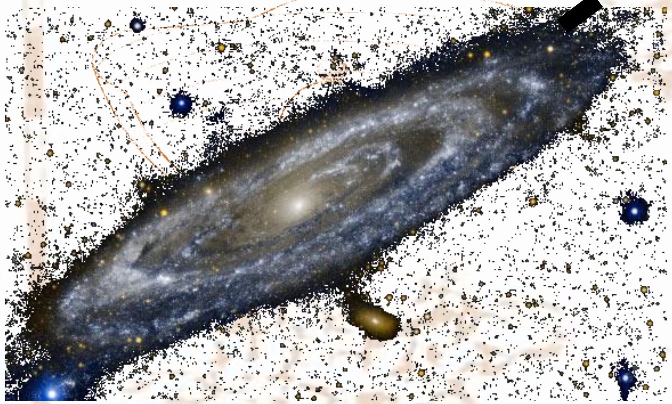
- Strong magnet
- Boosting E-field
- Ultra low noise amplifier
- Cryogenic temperatures





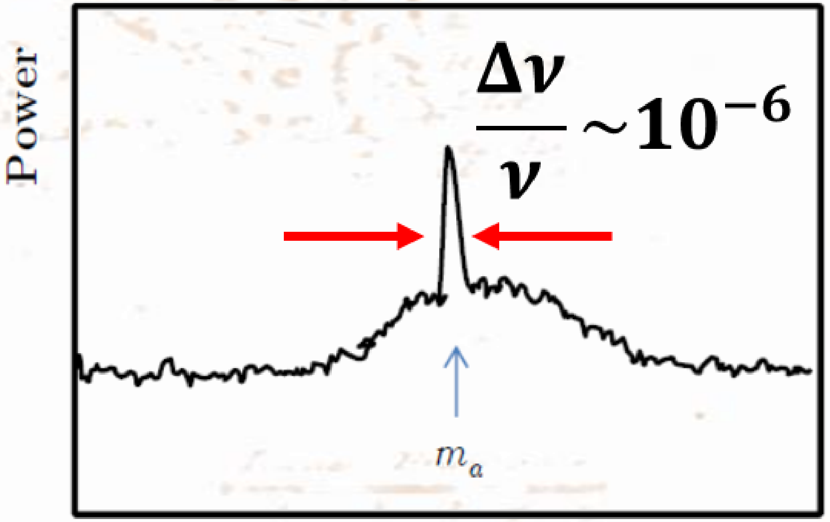
$h\nu_a = m_a c^2$

→ RF detection



Galactic DM as source

$\langle v_{DM} \rangle = 10^{-3} c$



Scanning at DFSZ sensitivity

ADMX@University of Washington, USA

UW Seattle, LLNL, Fermilab, PNNL, NRAO, Uni Sheffield, Uni Chicago, Uni Berkeley, Uni Florida, NIST, Uni Western Australia

Phys. Rev. Lett. 127, 261803 (2021)

Cavity & multistrip SQUID amplifier @ sub K

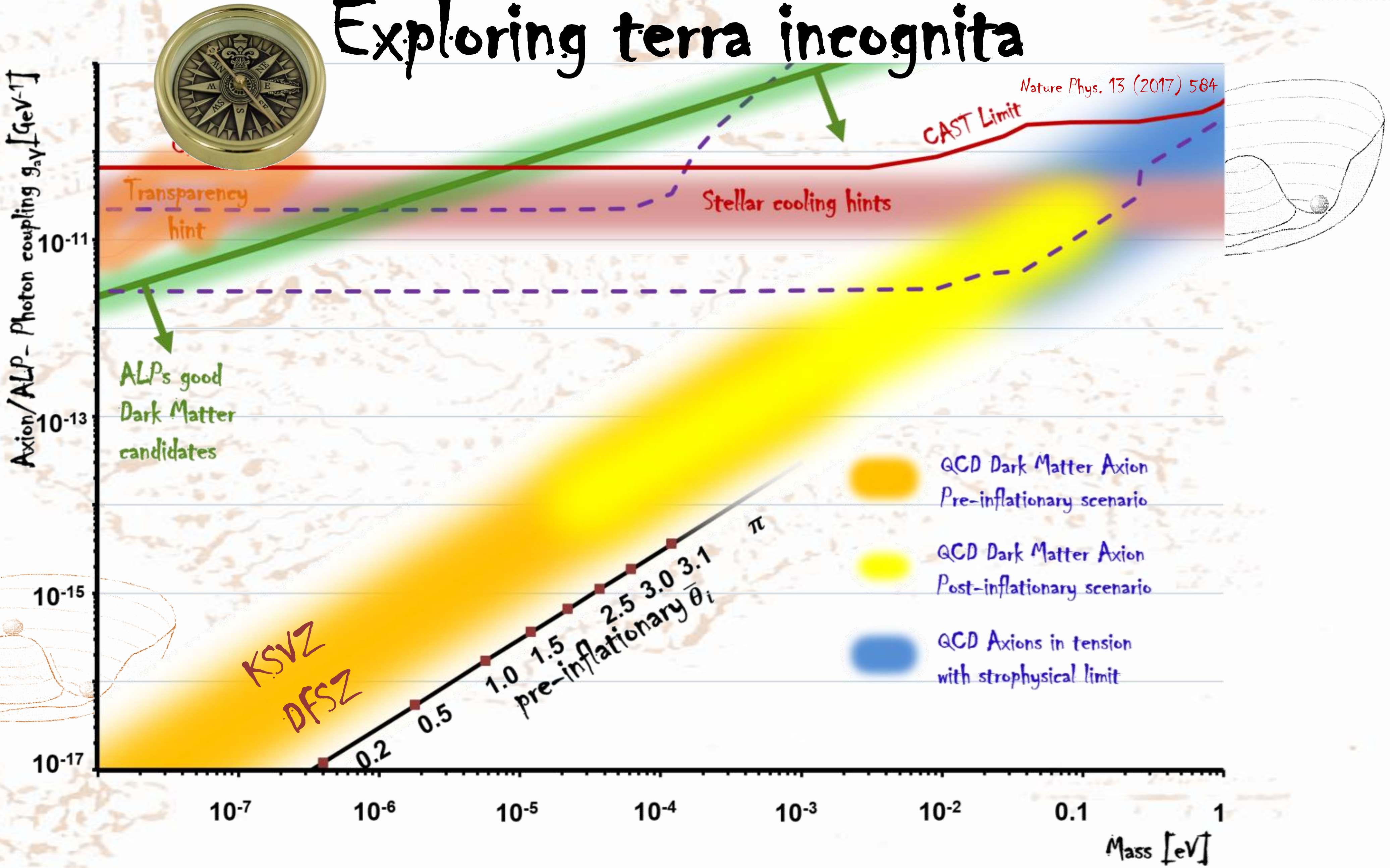
CULTASK@CAPP, South Korea

arXiv:2210.10961

Sensitivity at quantum limit

Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

Exploring terra incognita



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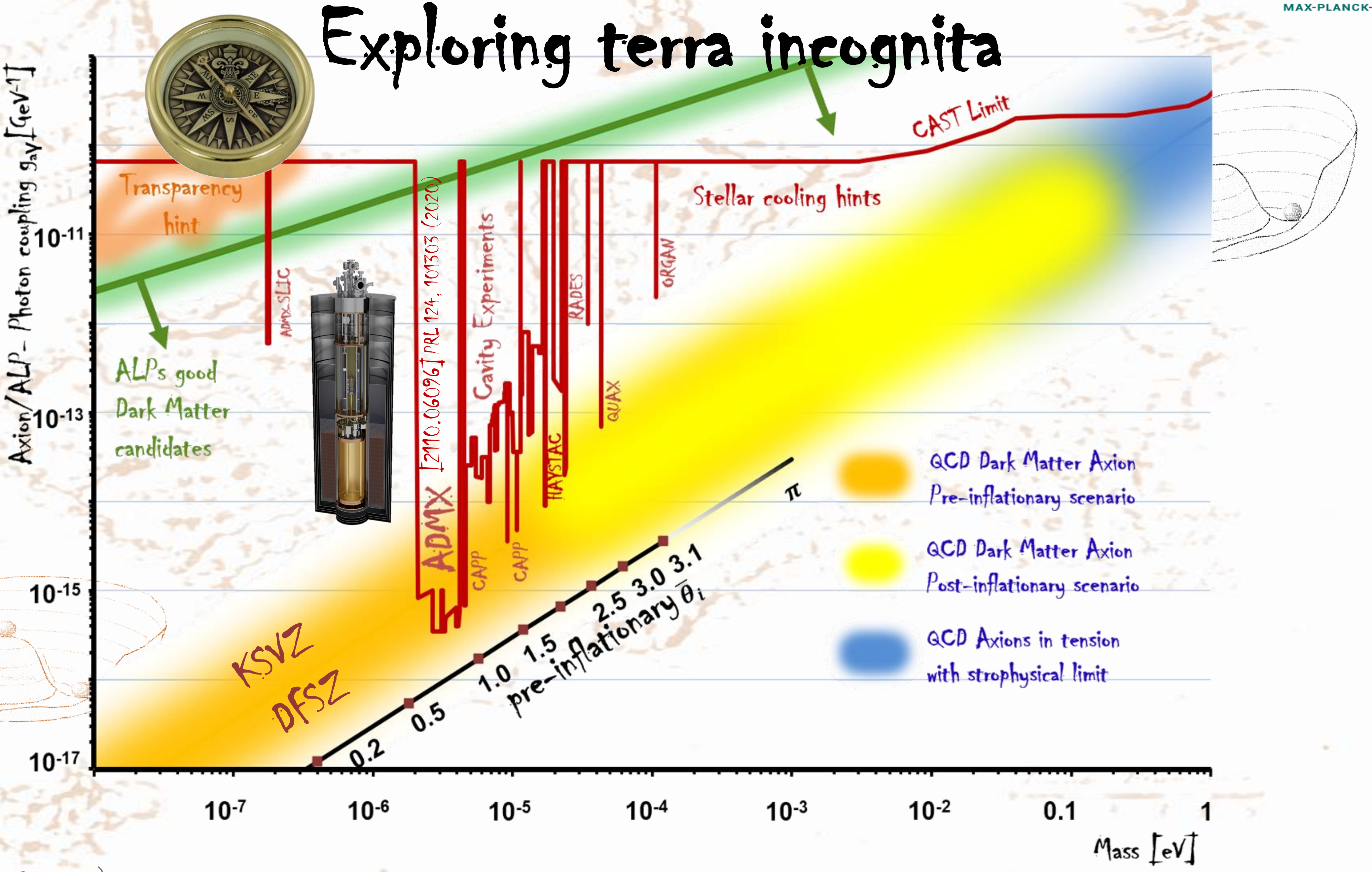
Exploring terra incognita



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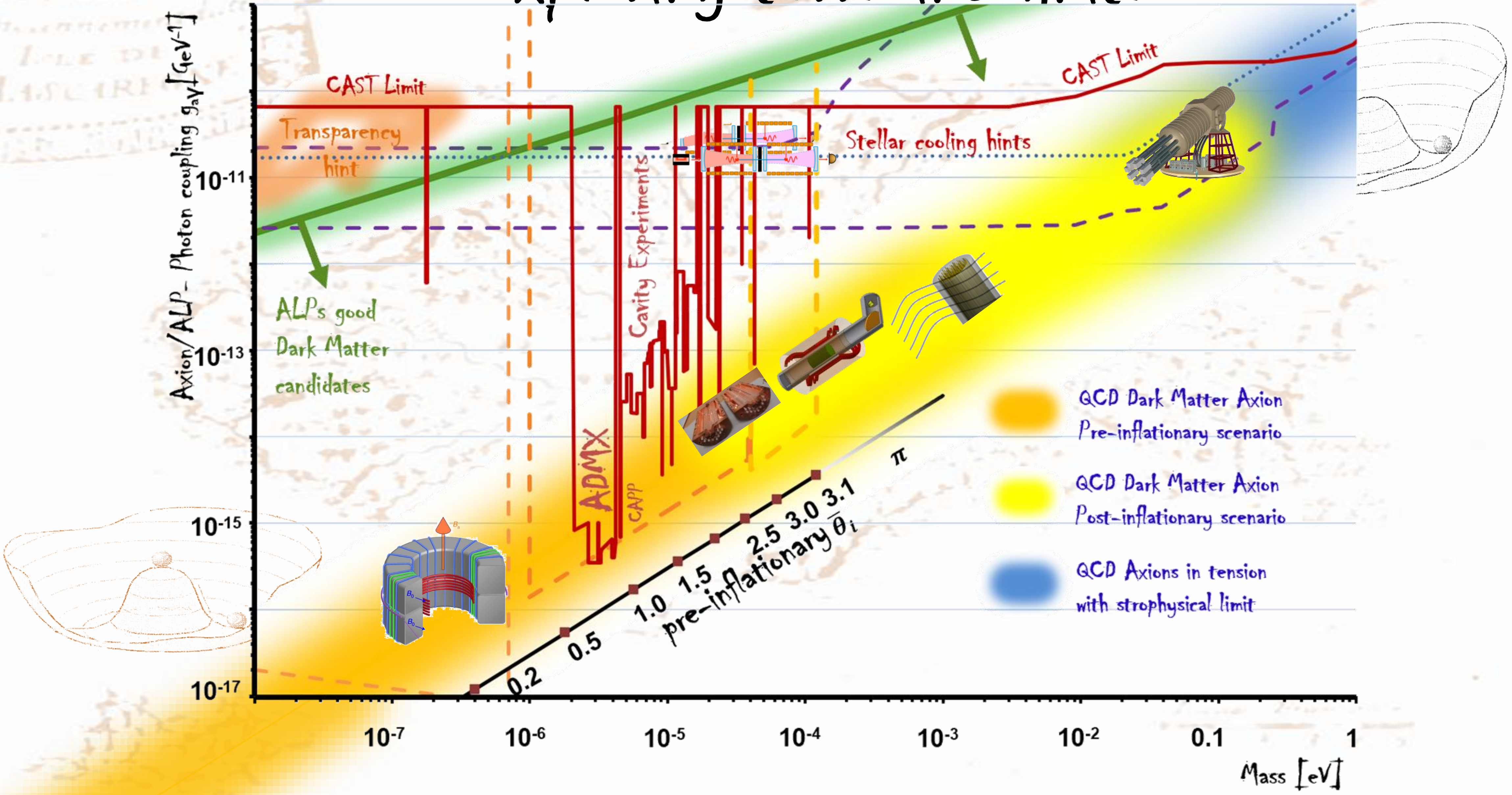
Exploring terra incognita



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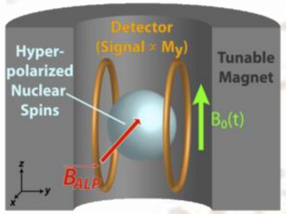
The bounty hunters:

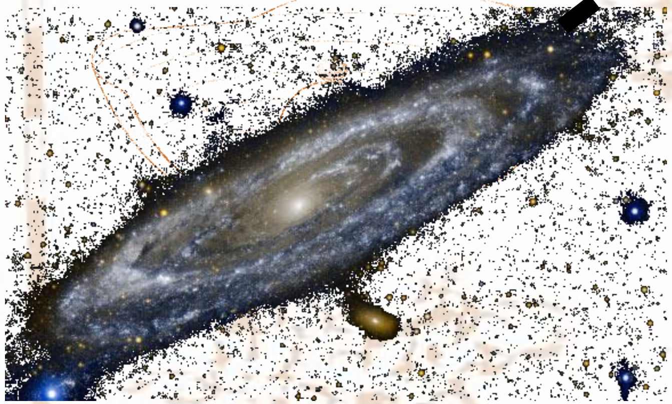
Haloscope

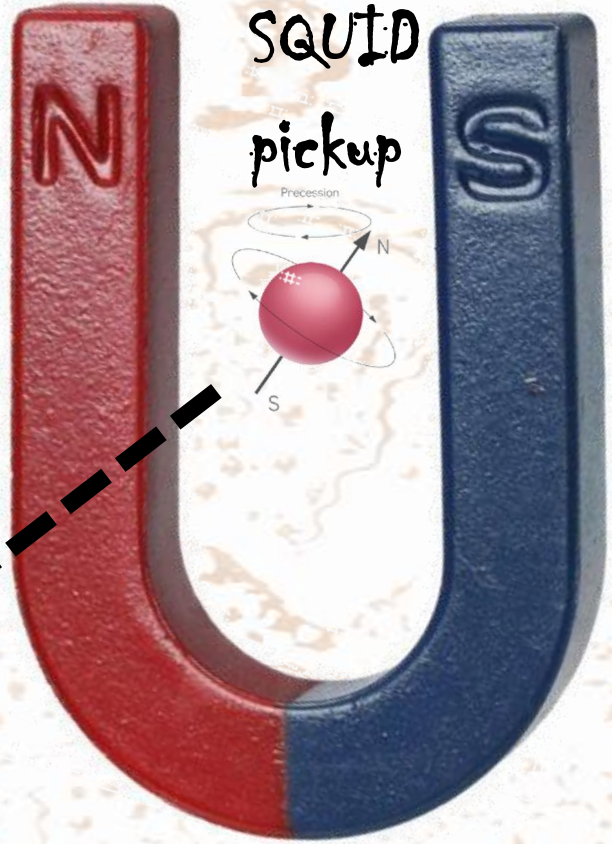
g_{aEDM} g_{aNN}

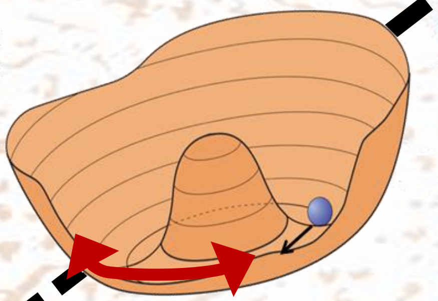
Axion field oscillation
→ oscillating nEDM

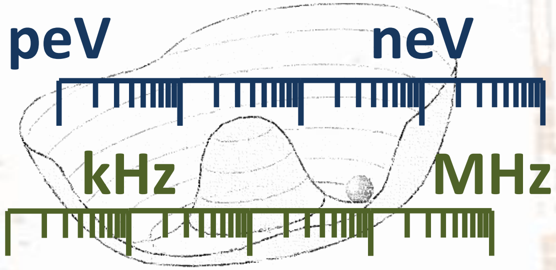


NMR techniques
PhysRevLett.122.191302

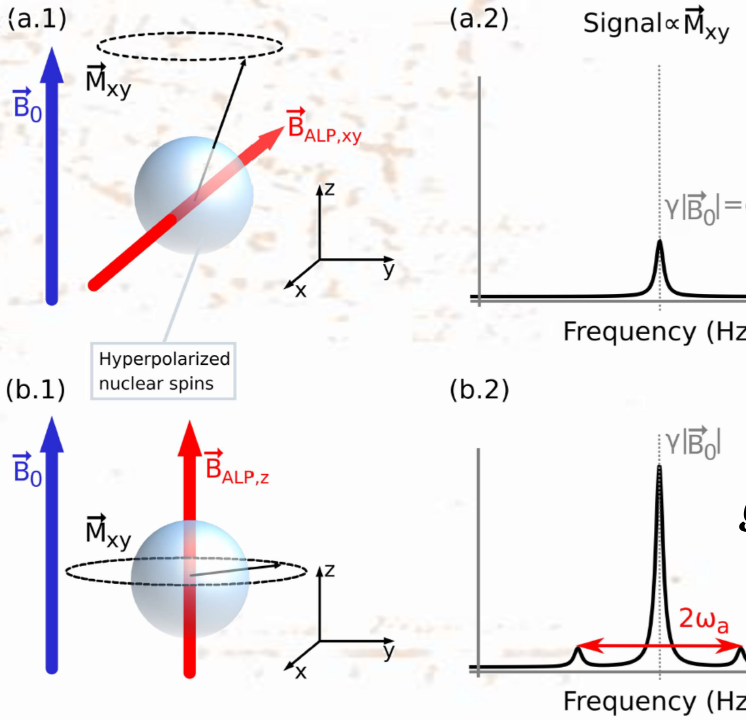








Spin precession



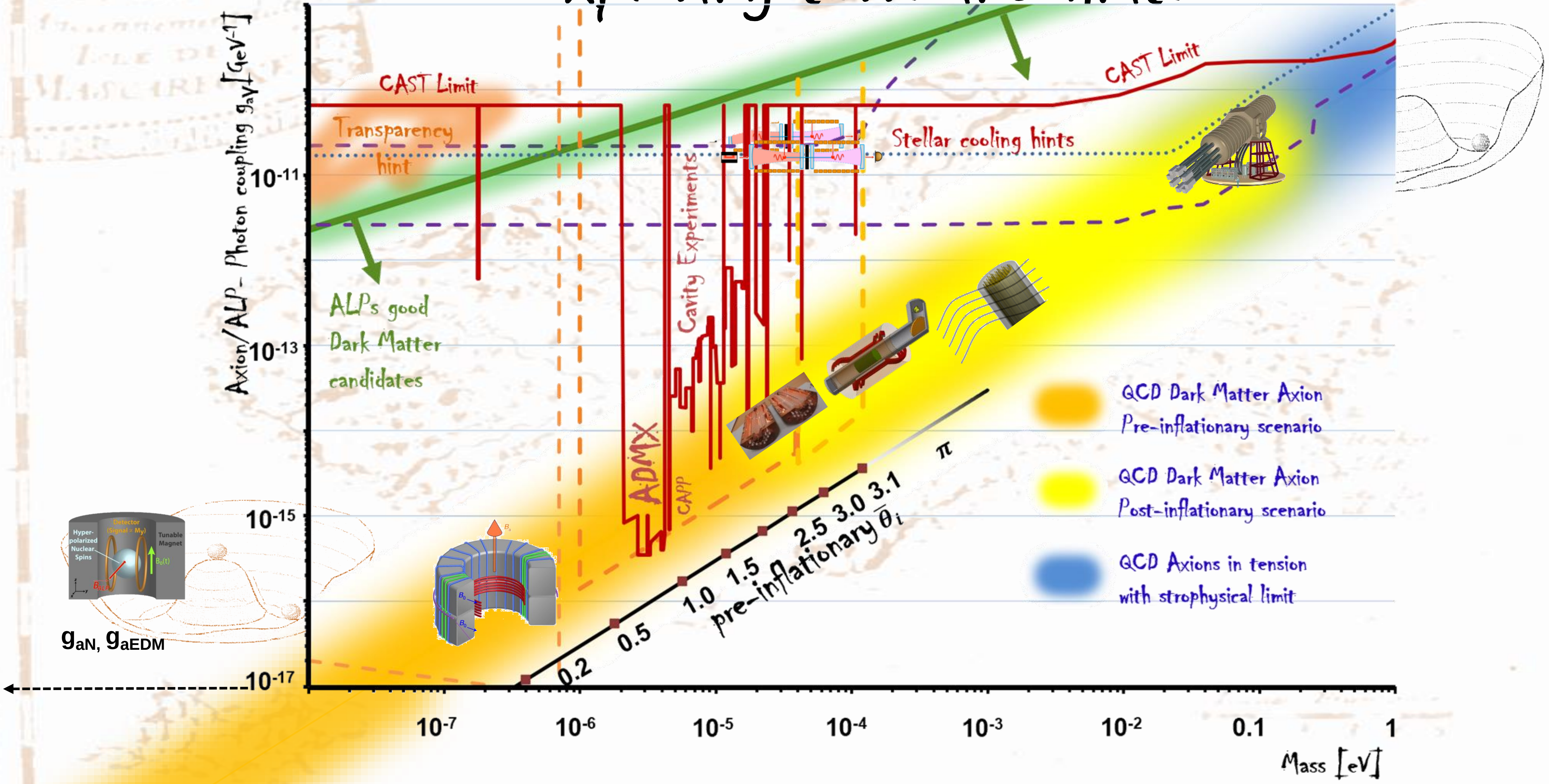
g_{aNN}

g_{aEDM}

Galactic DM as source

$\langle v_{DM} \rangle = 10^{-3} c$

Exploring terra incognita



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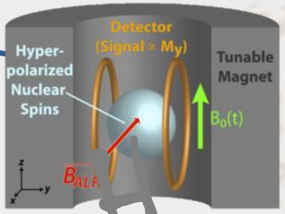
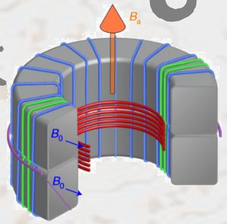
Status of axion mass survey

Exciting last ~5 – 10 years:
plethora of approaches emerging
VERY COMPLEMENTARY!

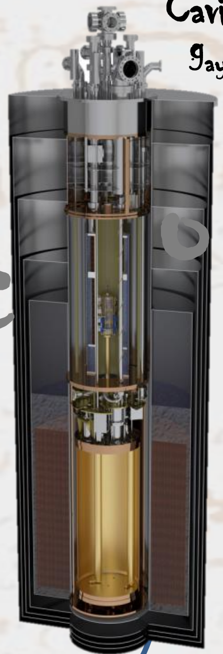
NMR / Spin-precession
g_{aN}, g_{aEDM}



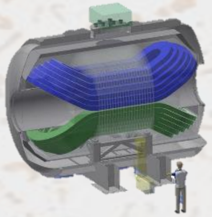
LC circuit
$g_{a\gamma}$



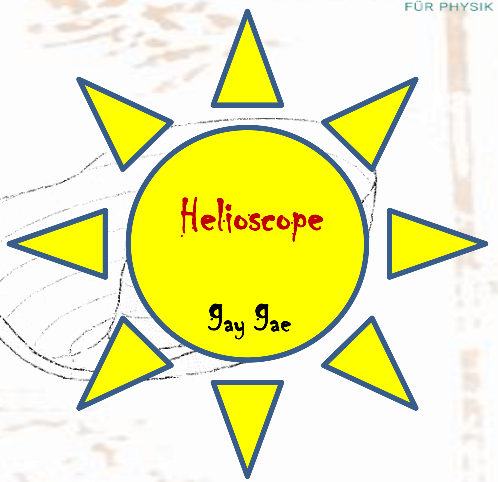
Cavity
$g_{a\gamma}$

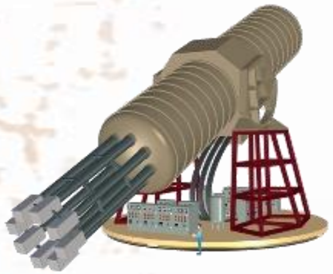


Di-electric haloscope
$g_{a\gamma}$



Meta materials





m_a

Planck limit

neV

meV

meV

Post-inflation DM window

0.001

0.01

(for axions 100% DM)

0.1

Pre-inflation

1

„classical" DM window

$\overline{\Theta}_i$

Tension with astrophysical arguments


BOURBON
ISLE DE
MASCAREGNE


BOURBON
ISLE DE
MASCAREIGNE

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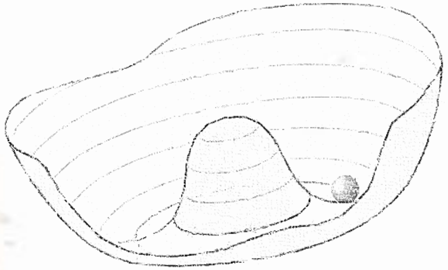
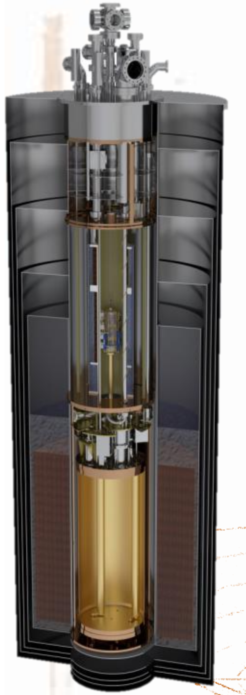
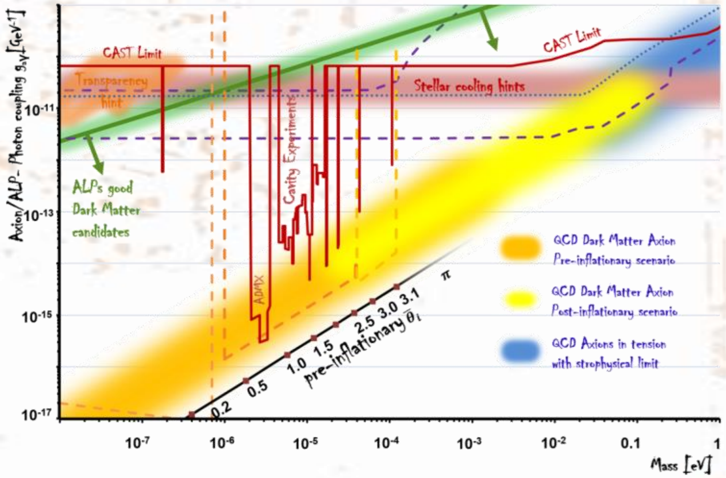
CONCLUSIONS:



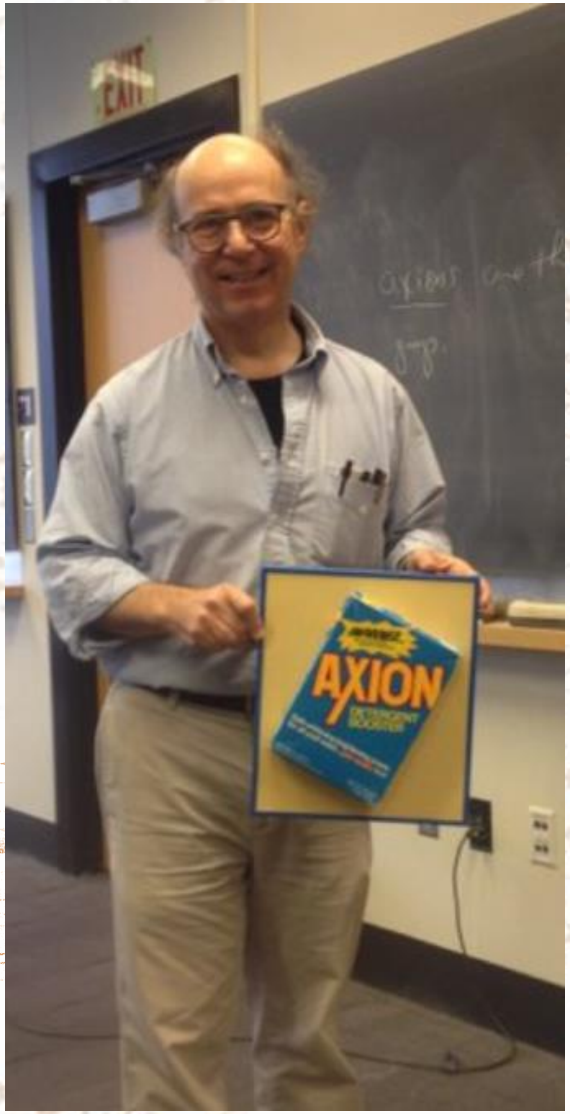


- axion (& ALPs) very well motivated particle candidates
- Theory models give guidance: vast range to explore
- ADMX sensitive to QCD dark matter axion
- Last years: promising new approaches
- Hopefully not too distant future:

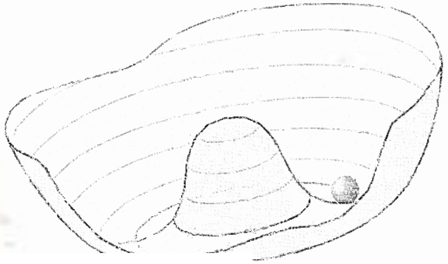


solve strong CP problem & find dark matter axion!

Thanks for your attention!



R. Peccei und *H. Quinn*,
Phys. Rev. Lett. **38**, 1440 (1977)
S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978);
F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978)



The Birth of Axions

Frank Wilczek
Institute for Advanced Study
Princeton, NJ 08540

usual, very light particle. I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving *axial* currents.

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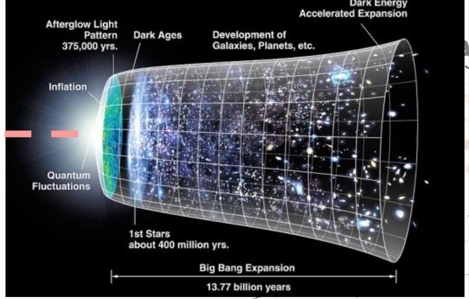
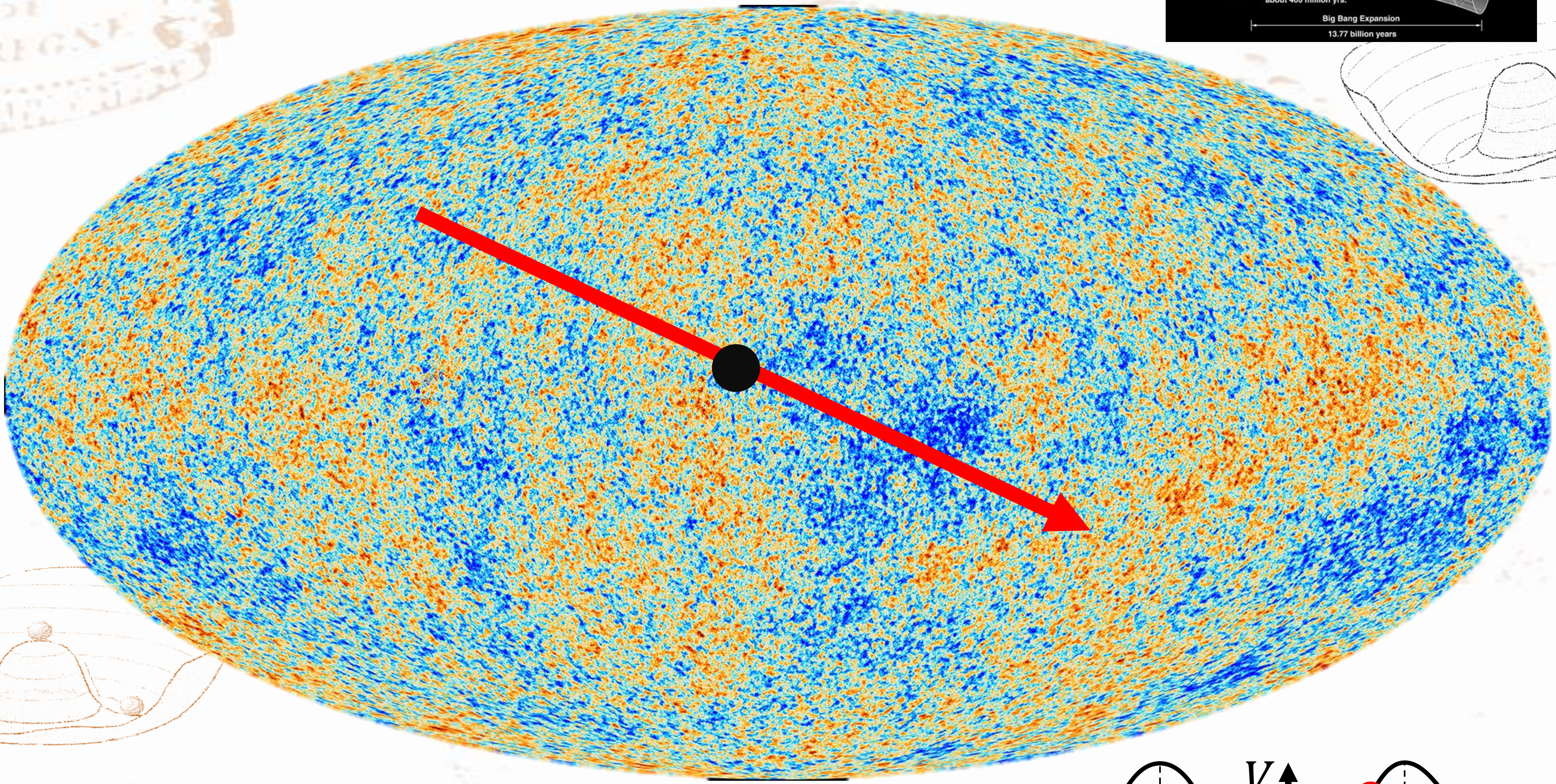
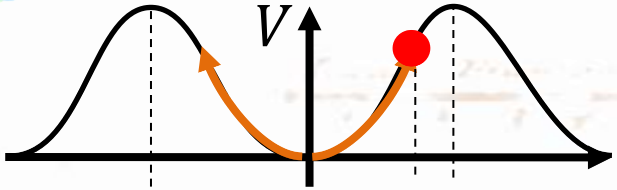
Pre-inflationary scenario

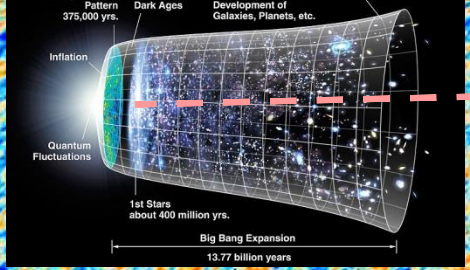




One value of $\bar{\Theta}_i$ in entire visible universe

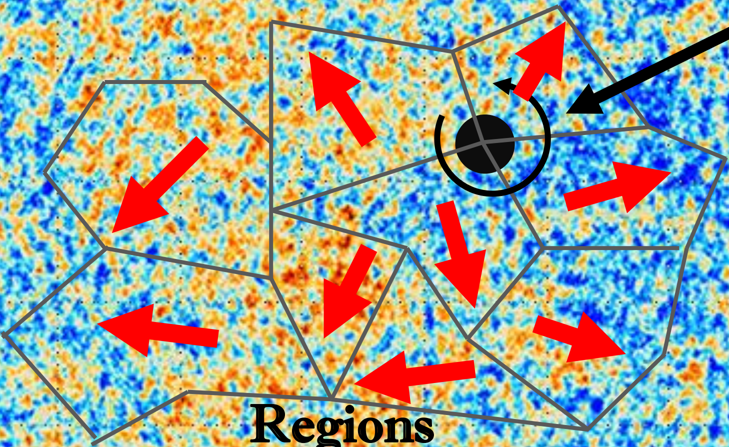
$$0 < |\bar{\Theta}_i| < \pi$$





Post-inflationary Scenario

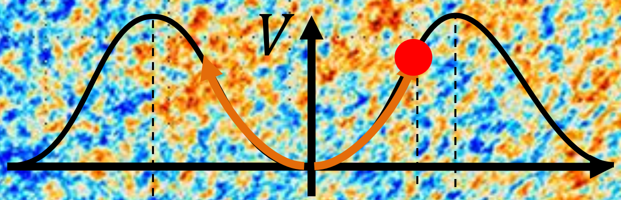
Complications by decay of topological defect



Regions
much smaller in reality

Average of all possible $\overline{\theta}_i$

→ Prediction for overall density



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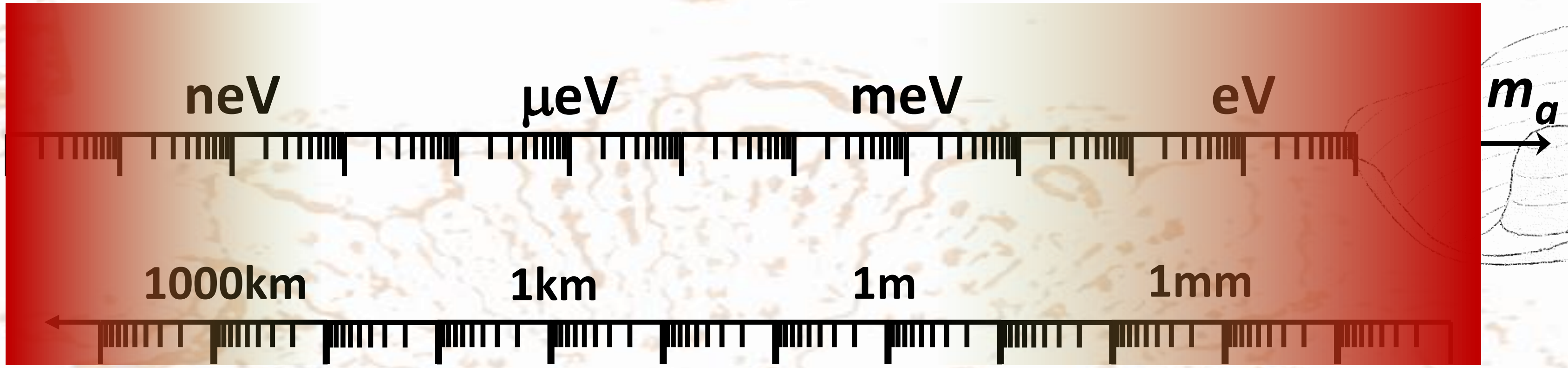
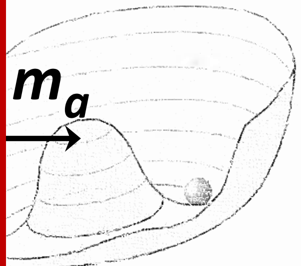
The size of DM Axions





$\lambda_{de\ Broglie}$
$\langle v_{DM} \rangle \sim 10^{-3} c$

Predictions:

$|\Theta_i|$ arbitrary $0 - \pi$

Pre-
inflationary scenario
Post-

$|\Theta_i|$ Ø of all possible values

DM axions fit into experiment!

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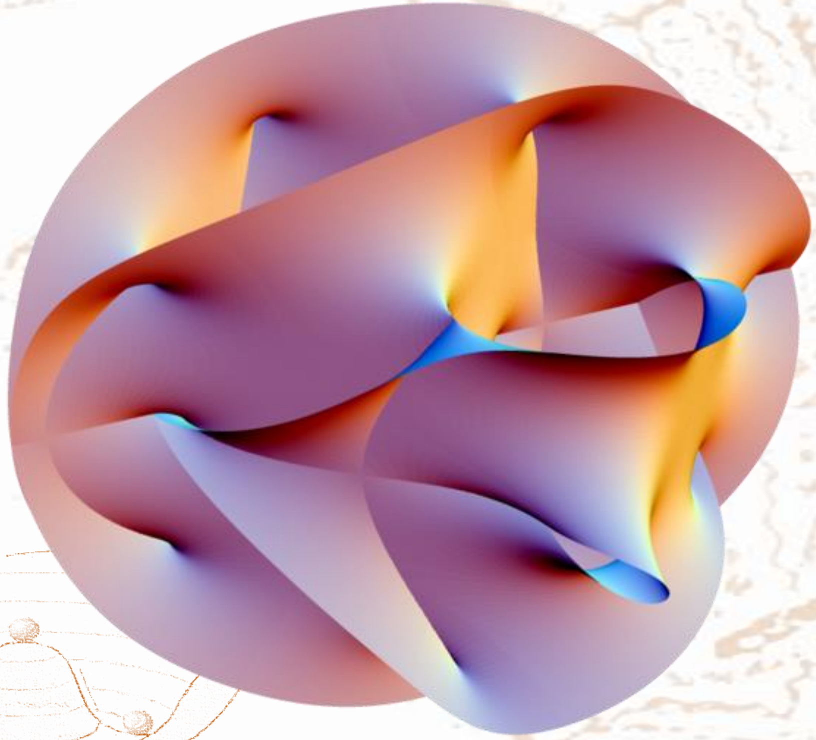
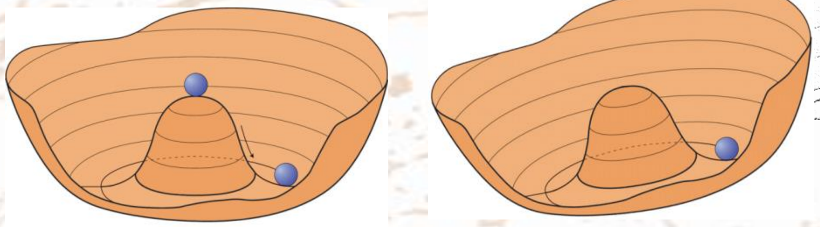
ALPs emerging from string compactification: the Axiverse





No directe relation btw. m_{ALP} and f_{ALP}

Some astrophysical inconsistencies:

- **Transparency hint**
- **Cooling anomalies**

Could be explained by ALPs

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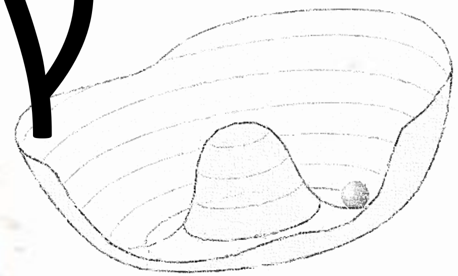
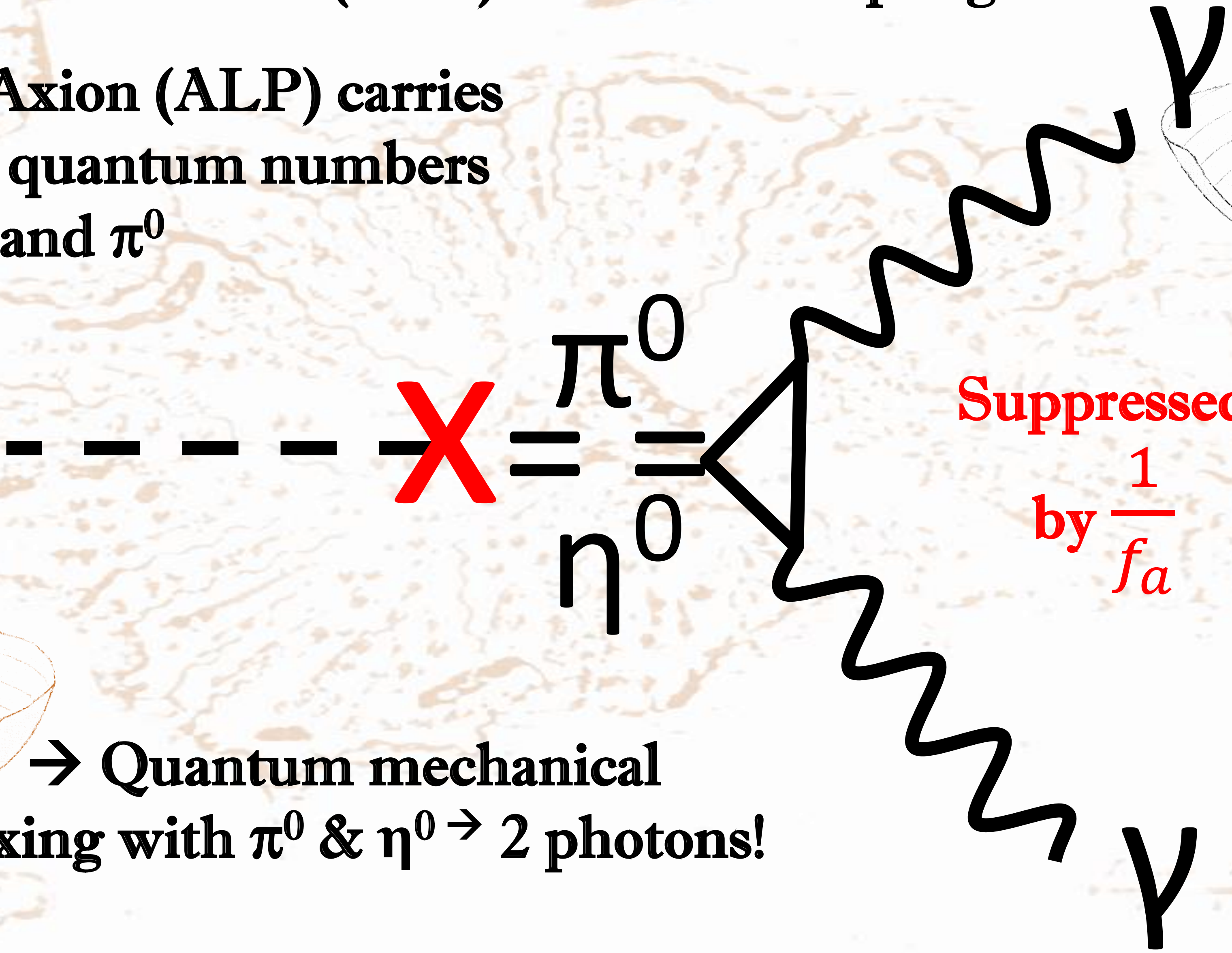
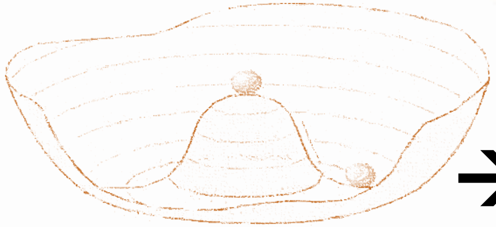
Axion (ALP) - Photon Coupling:



The Axion (ALP) carries same quantum numbers as η^0 and π^0



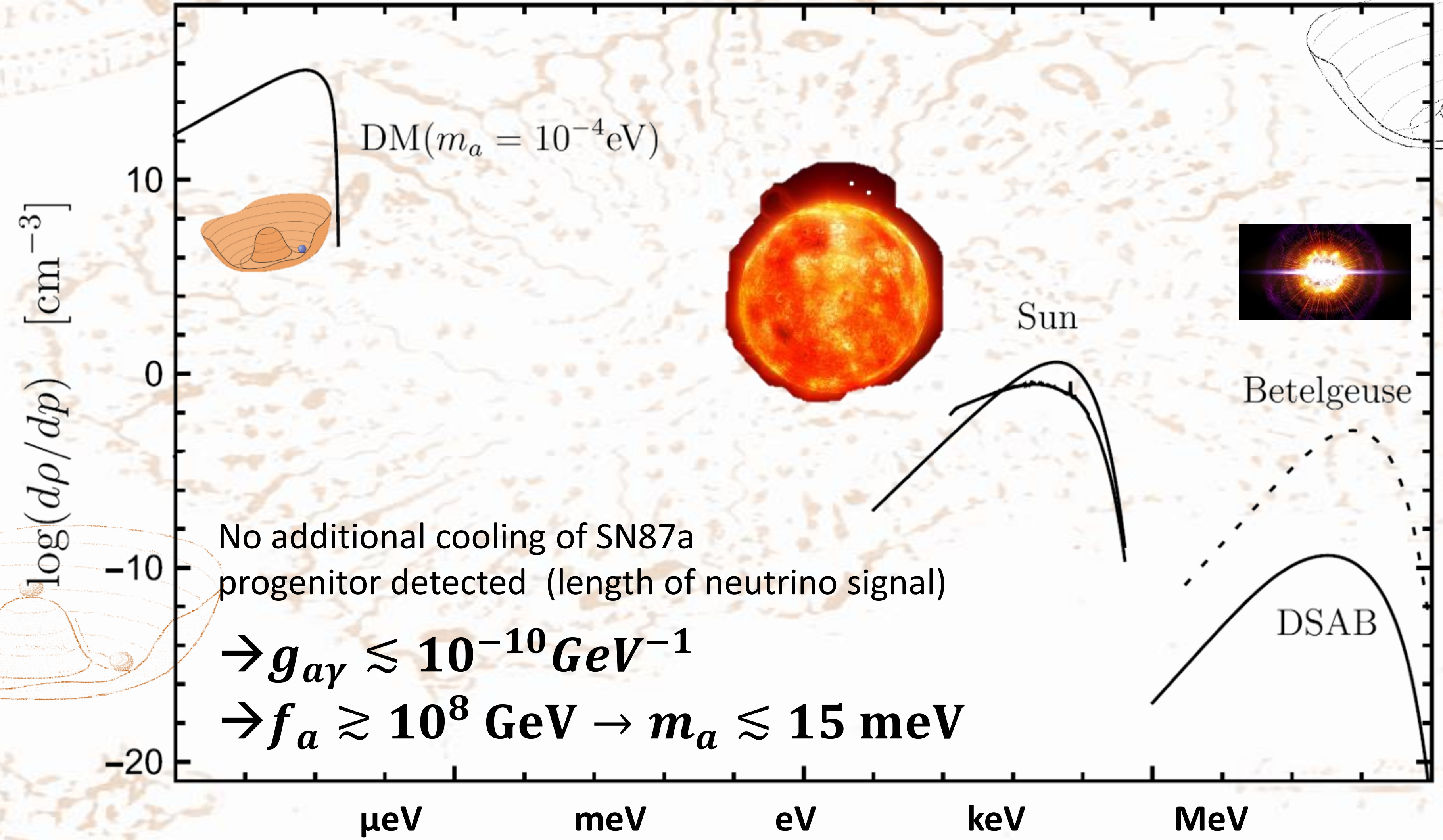
Suppressed by $\frac{1}{f_a}$



→ Quantum mechanical mixing with π^0 & η^0 → 2 photons!

Axion - Sources:

I.G. Irastorza, J. Redondo / Progress in Particle and Nuclear Physics 102 (2018) 89–159



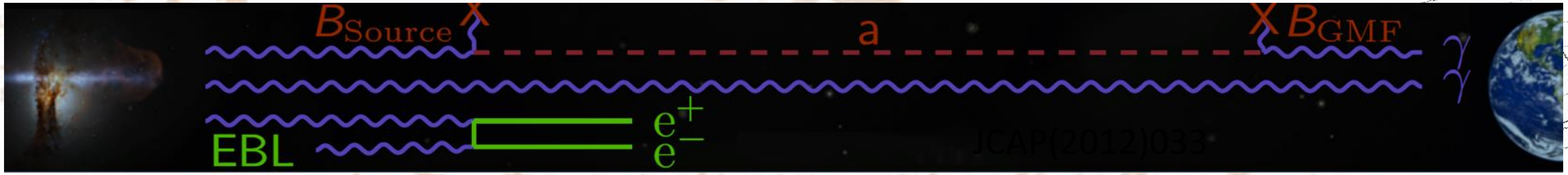
No additional cooling of SN87a progenitor detected (length of neutrino signal)

$\rightarrow g_{a\gamma} \lesssim 10^{-10} GeV^{-1}$

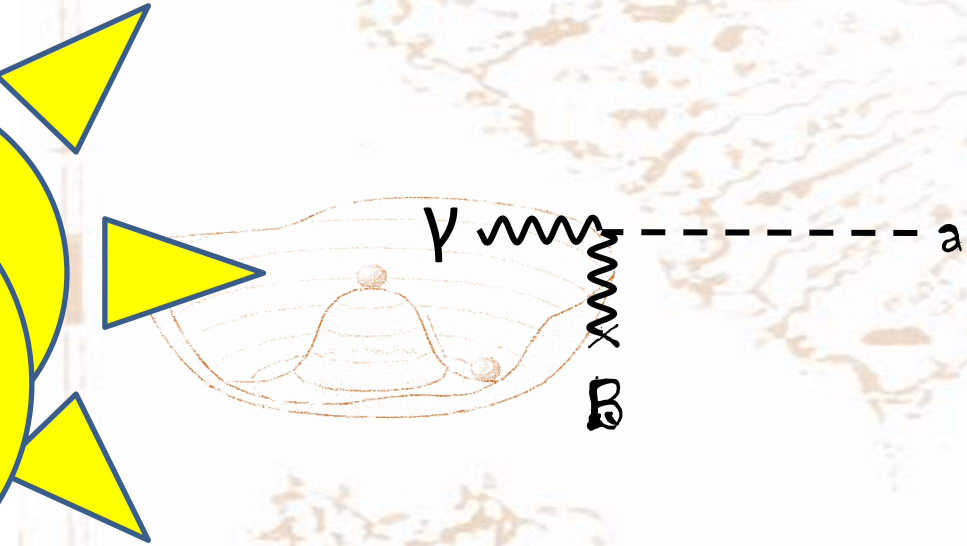
$\rightarrow f_a \gtrsim 10^8$ GeV $\rightarrow m_a \lesssim 15$ meV

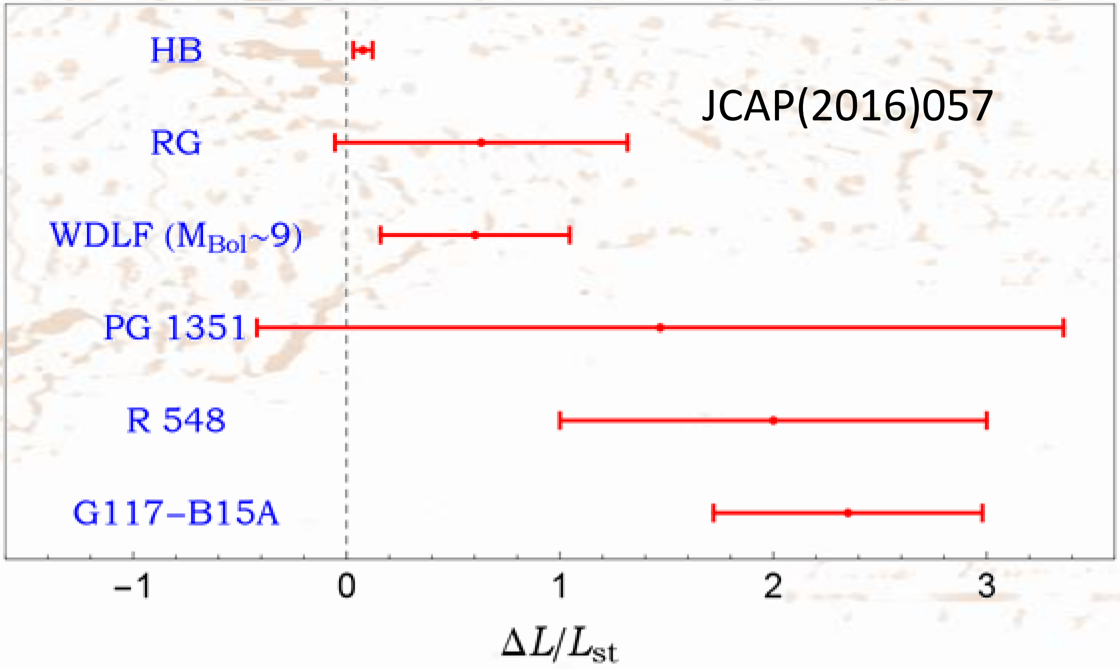
Evidence fo ALPs?

Transparency of intergalactic medium:



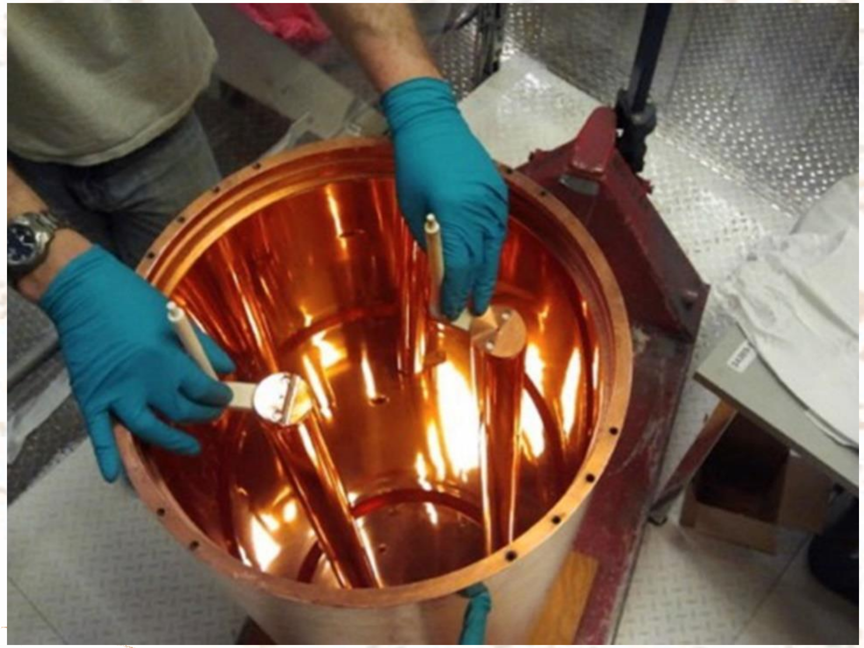
Anomalous cooling rate of white dwarfs and HB stars (?)





Cavities in B-Field:

Adjusting resonance frequency: "Tuning Rod"



ADMX
University of Washington, USA

HAYSTAC
Yale University, USA

$$P_{sig} \propto B^2 V\, Q_{cav}$$

$$P_{sig}(B{=}6.8\ T,\ V{=}136\ l,\ Q{=}10^5) \sim 2 \cdot 10^{-22}\ W$$

Béla Majorovits
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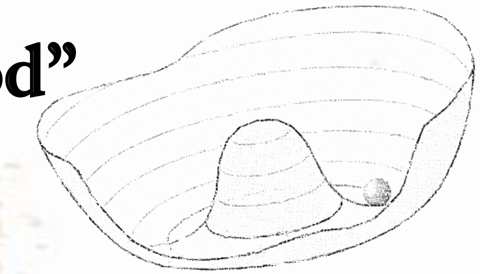
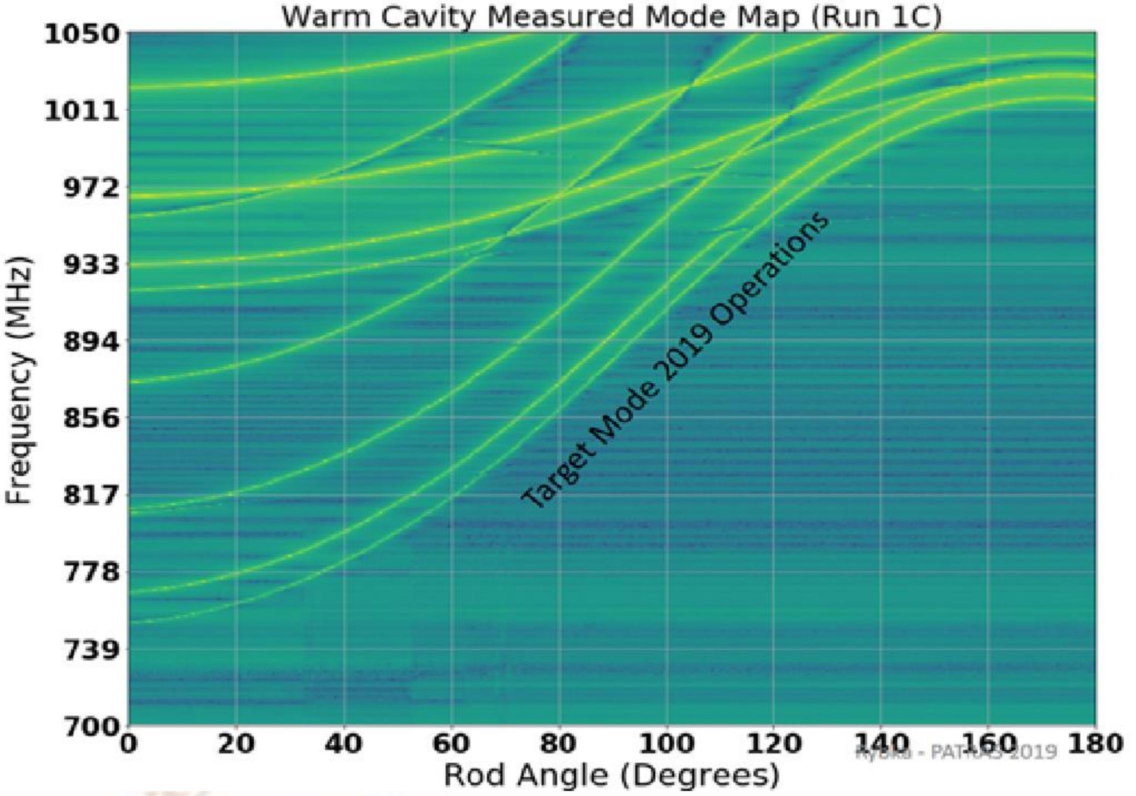
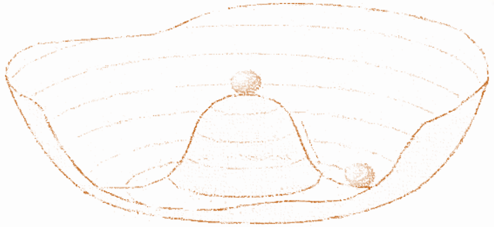
Cavities in B-Field:

Adjusting resonance frequency: “Tuning Rod”







$$P_{sig} \propto B^2 V\, Q_{cav}$$

$$P_{sig}(B{=}6.8\ T,\ V{=}136\ l,\ Q{=}10^5) \sim 2 \cdot 10^{-22}\ W$$

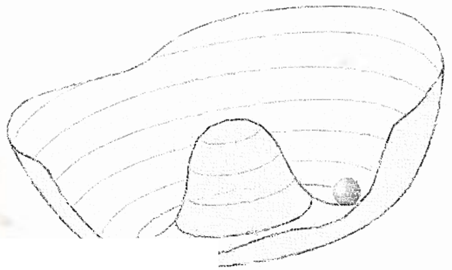
Béla Majorovits
MAX-PLANCK-INSTITUT FÜR PHYSIK

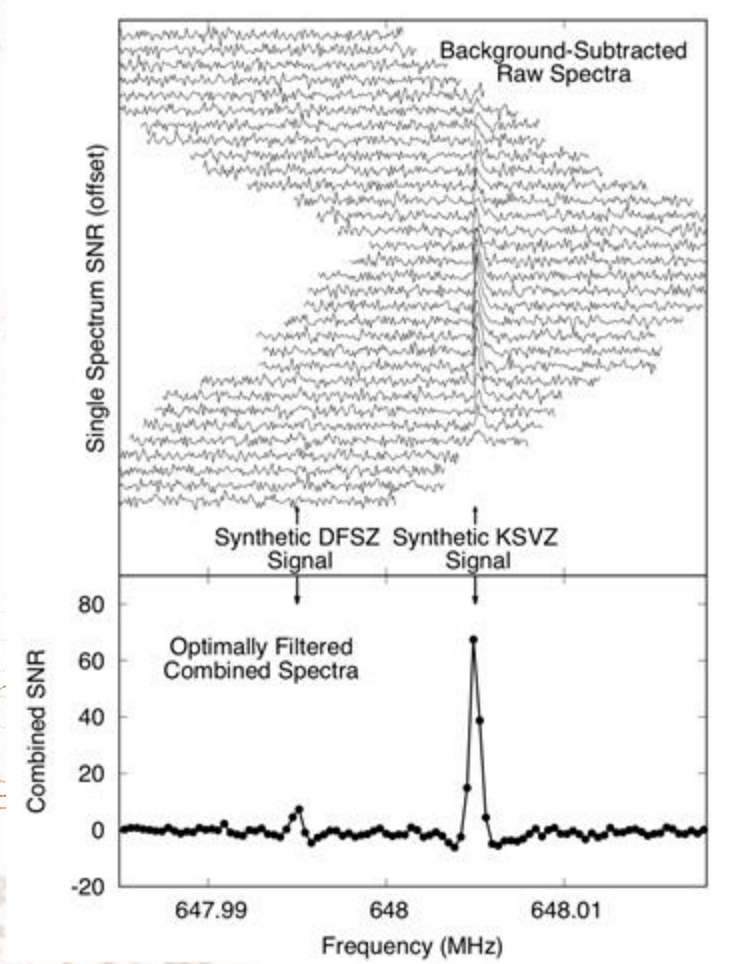
ADMX@University of Washington, USA

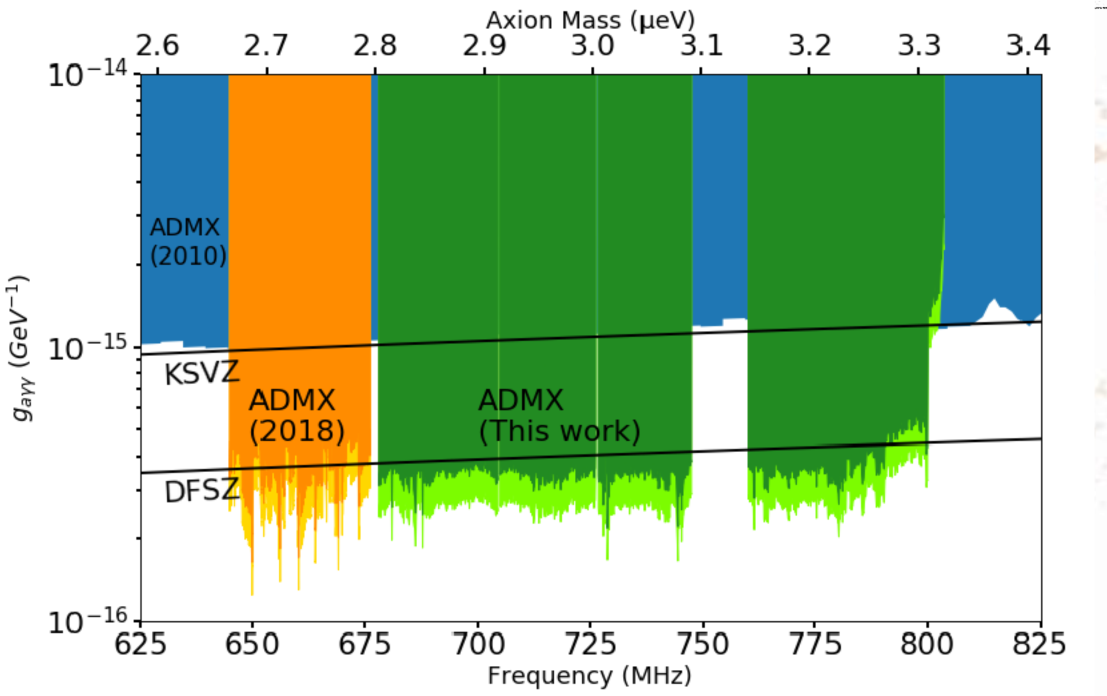
Measurements ongoin!

Sensitive to DM axion masses ~2-4μeV

Potential up to ~ 40μeV







ADMX: Phys. Rev. Lett. 124, 101303 (2020)

HAYSTAC: Phys. Rev. D 97, 092001 (2018)

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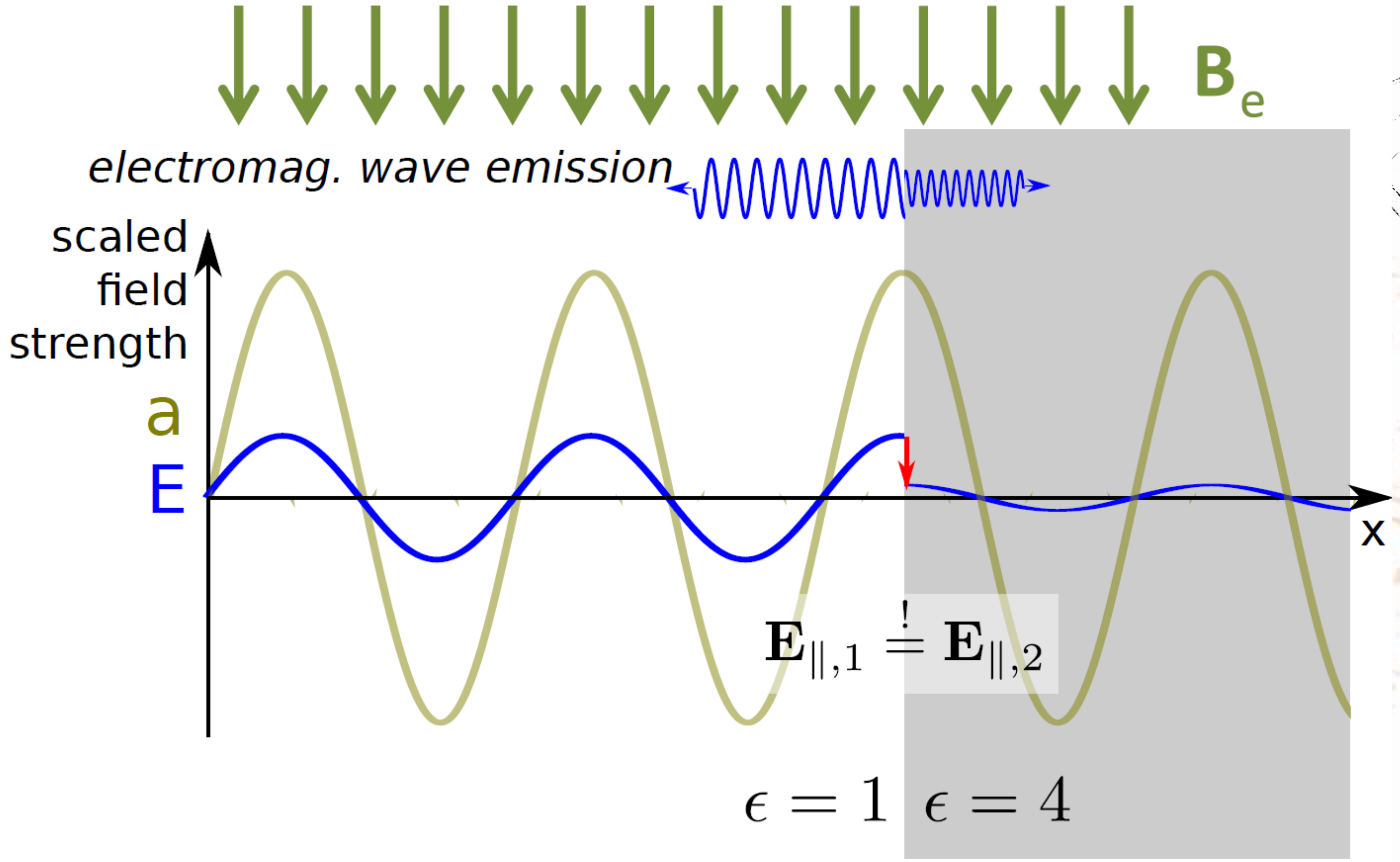
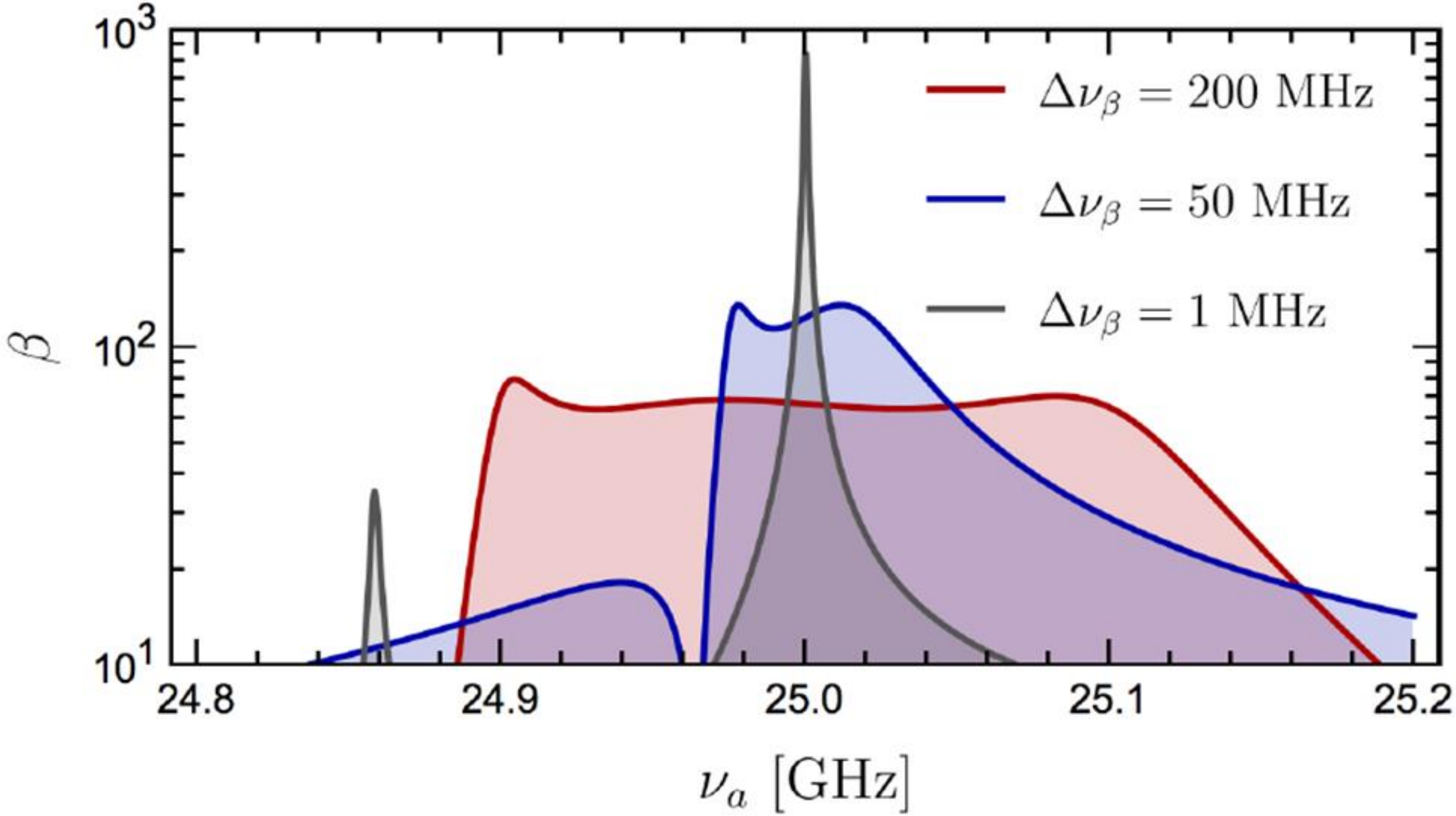
Dielectric Haloscope



$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{\|}}{10\ T}\right)^2 (g_{a\gamma\gamma} m_a)^2$$

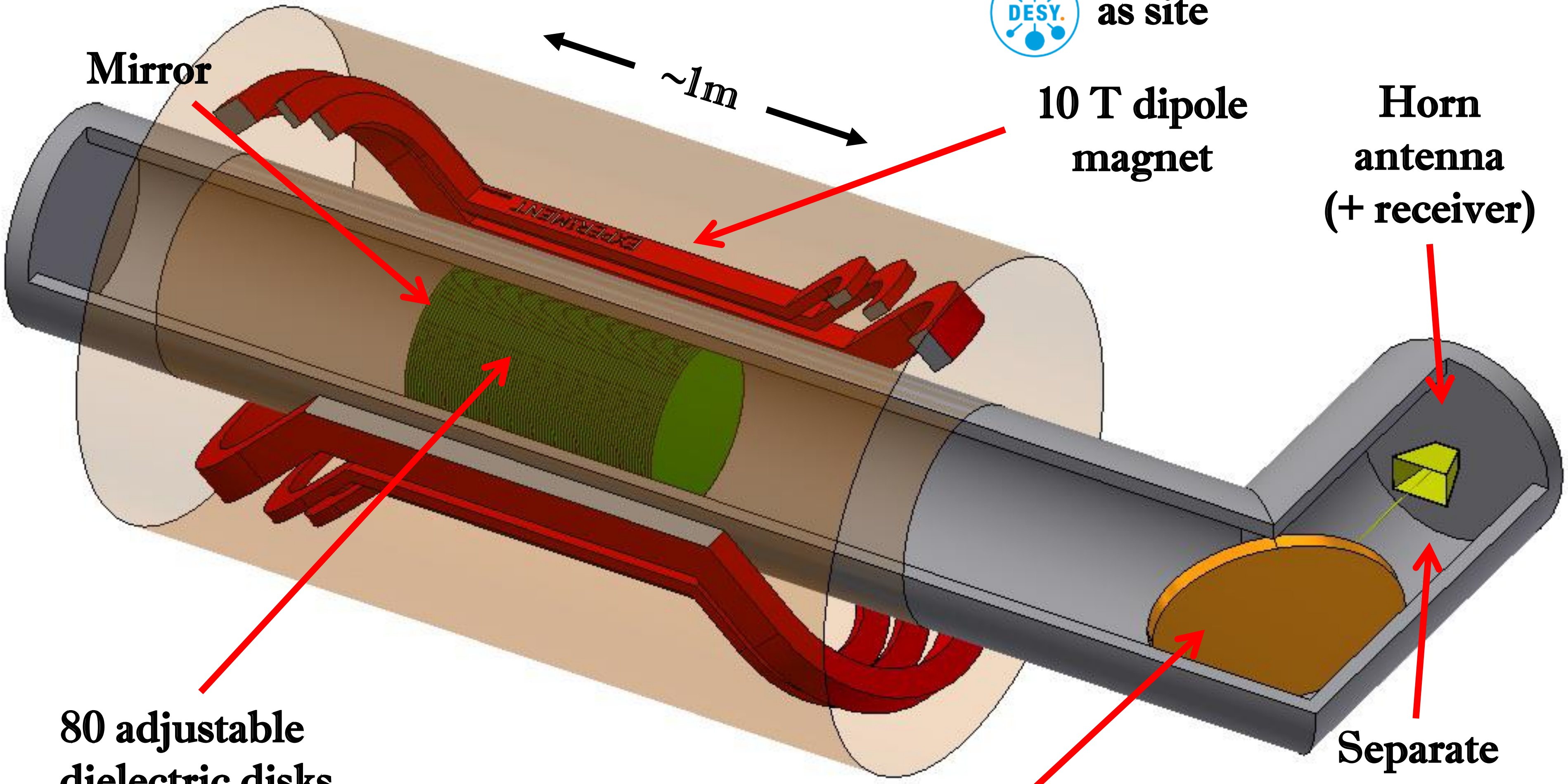
Dielectric Haloscope

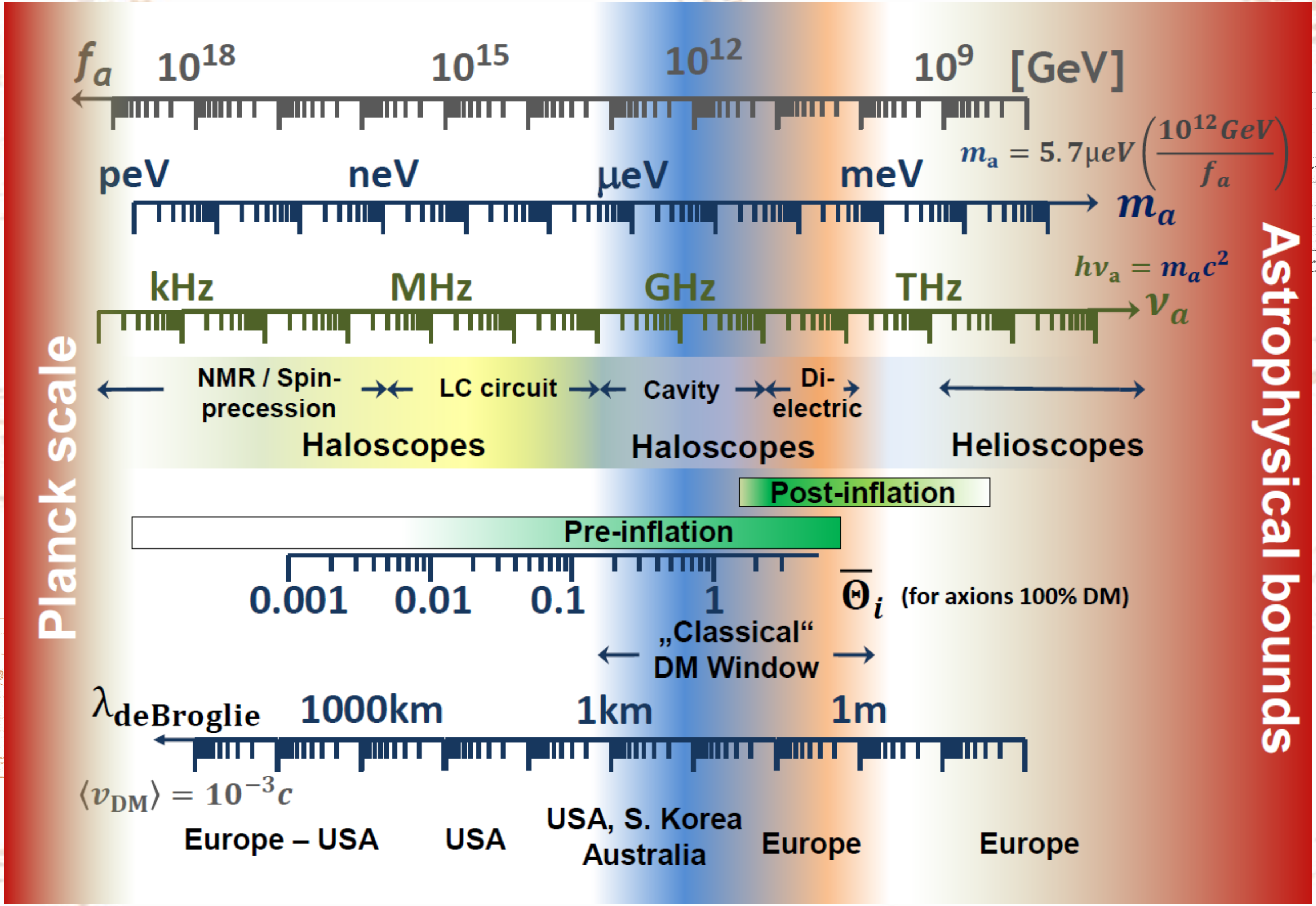


MADMAX

MAgnetized disk and Mirror Axion eXperiment

DESY. as site




f_a 10^{18} 10^{15} 10^{12} 10^{9} [GeV]
peV neV μeV meV
$m_a = 5.7\mu eV \left(\frac{10^{12} GeV}{f_a}\right)$
m_a
kHz MHz GHz THz
$h\nu_a = m_a c^2$
ν_a
NMR / Spin-precession
LC circuit
Cavity
Di-electric
Haloscopes
Haloscopes
Helioscopes
Post-inflation
Pre-inflation
0.001 0.01 0.1 1
$\overline{\Theta}_i$ (for axions 100% DM)
„Classical“ DM Window
$\lambda_{deBroglie}$ 1000km 1km 1m
$\langle v_{DM} \rangle = 10^{-3} c$
Europe – USA
USA
USA, S. Korea Australia
Europe
Europe
Planck scale
Astrophysical bounds