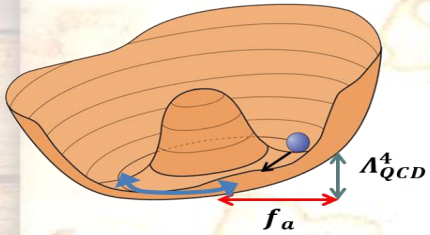
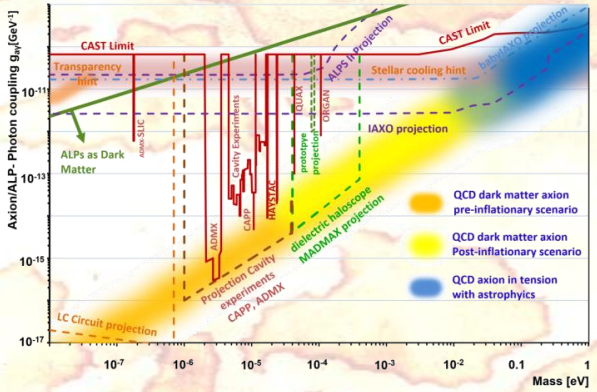
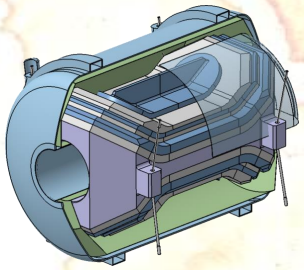
Axions and ALPs: Status, Challenges, Needs

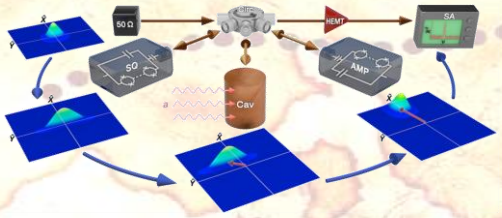
Béla Majorovits

MAX-PLANCK-INSTITUT FÜR PHYSIK









- Basic concepts
- Challenges & 'cross-talk' with other communities
- Current and future needs

A biased and incomplete view . . .

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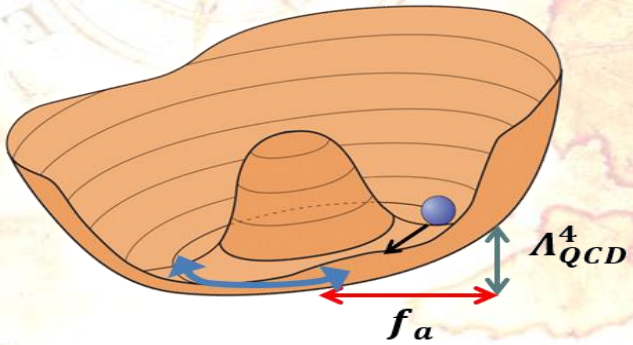
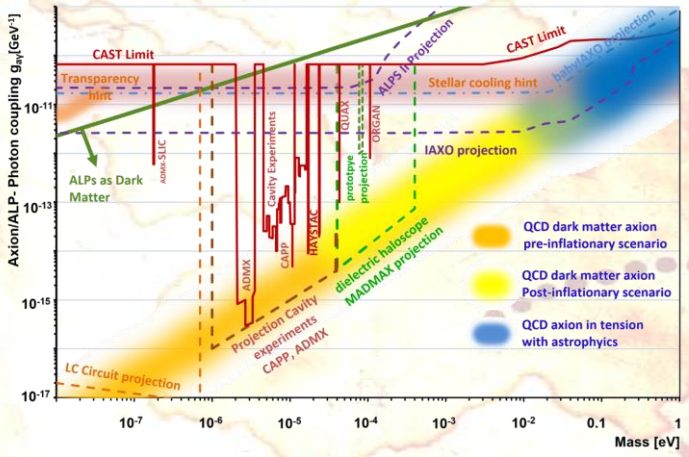
AGENDA:





- Basic concepts:
  - Status of research in the axion 'community'
- Challenges and 'cross-talk' with other communities
  - hardware: conversion/detection
  - comparability
  - software/tools
- Current and future needs
  - input from outside community?
  - what can axion community offer?
  - How can iDMEU help?

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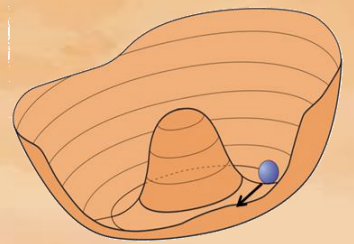
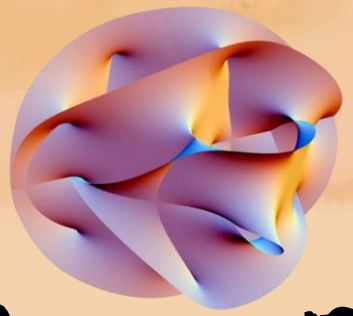
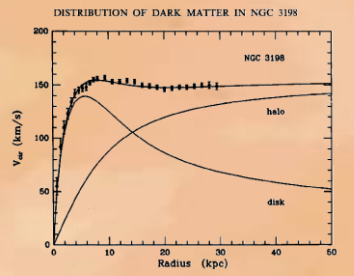
WANTED





the QCD Axion & family

Guilty for solving the strong CP problem! Prime suspect for cause of DM crisis!

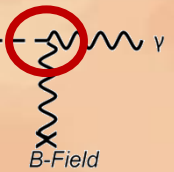


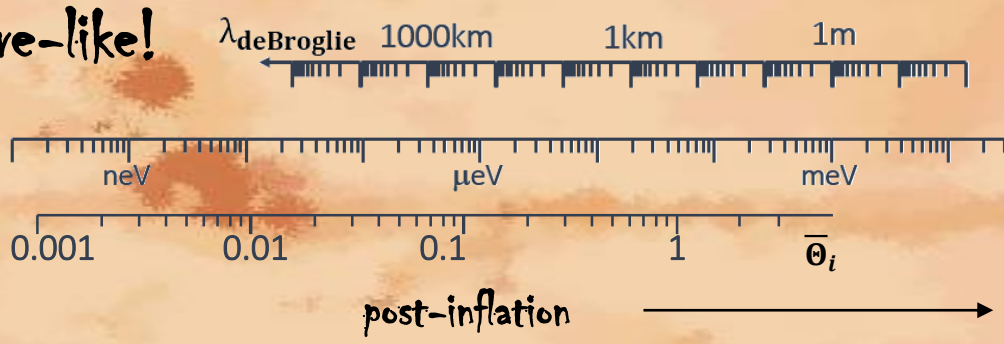
Members of the axion family: masters of disguise!

nearly invisible & wave-like!

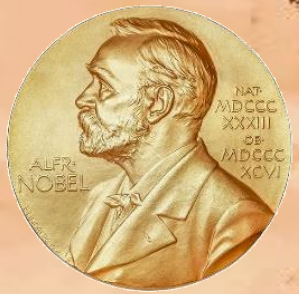
could hide anywhere

$g_{a\gamma} \propto 1/f_a$





Reward:



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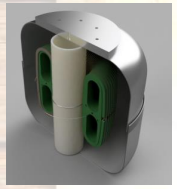
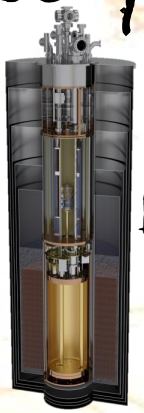
The bounty hunters:

Haloscope $g_{a\gamma}$



LC circuits
[arXiv:1901.10652]

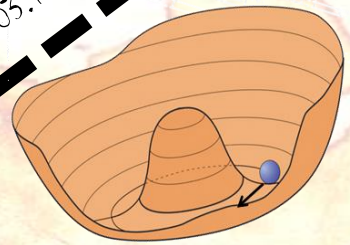


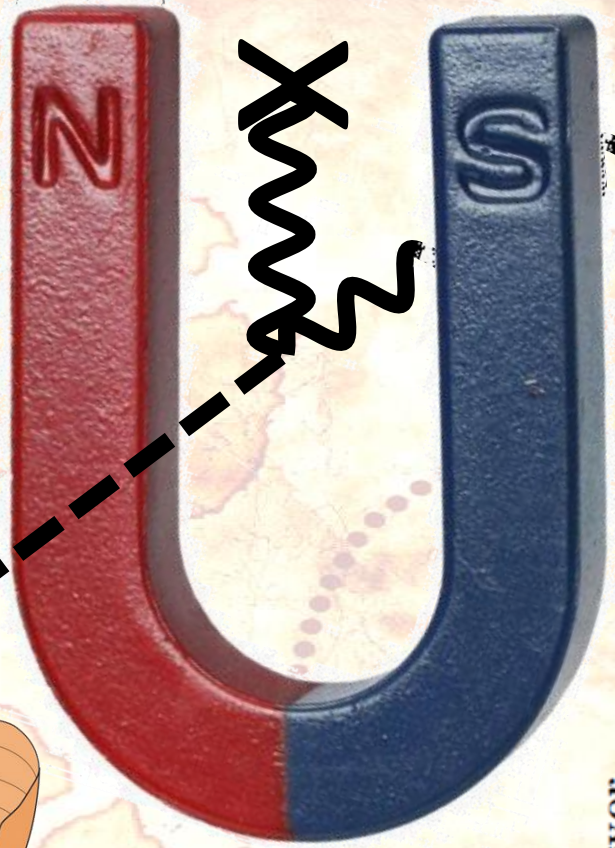
cavities
[arXiv:1804.05750]

[arXiv:2004.02754]

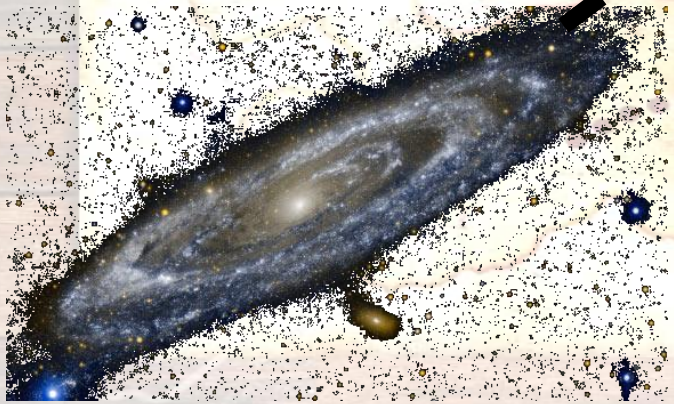
Meta materials
[1904.11872]
[1807.08810]

dielectric
[arXiv:2003.1089]





γ

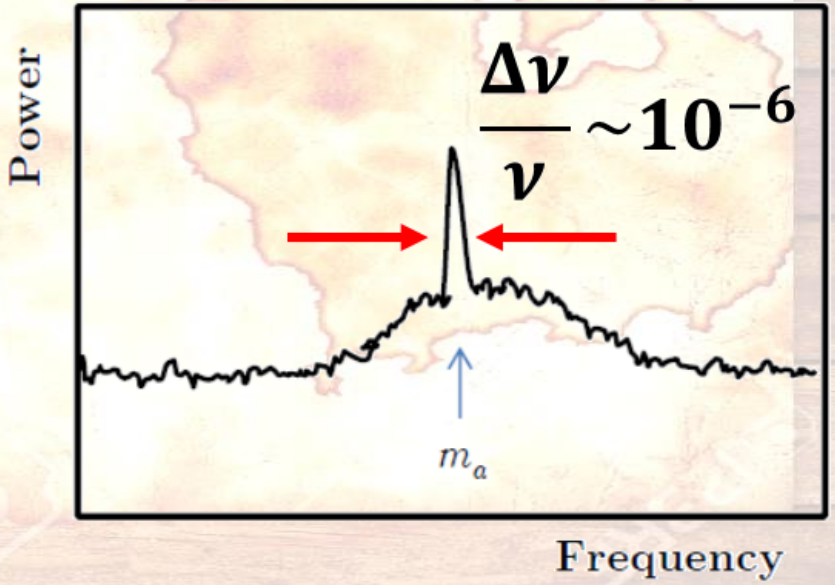


Galactic DM as source

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

$h\nu_a = m_a c^2$

RF detection



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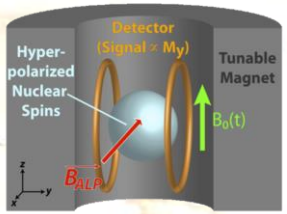
The bounty hunters:

Haloscope

g_{aEDM}

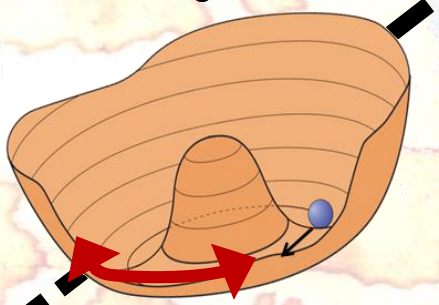
Axion field oscillation

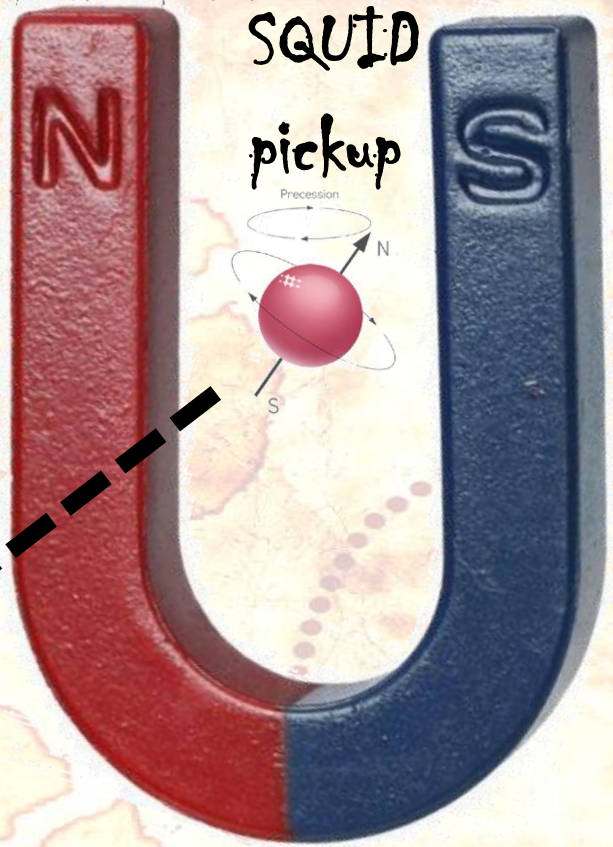
→ oscillating nEDM



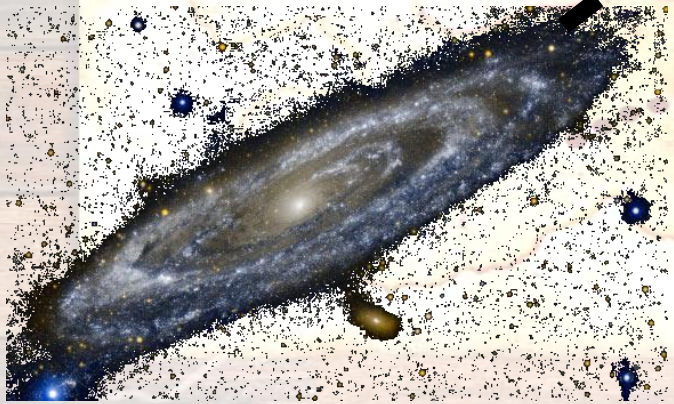
NMR techniques

[arXiv:1901.10843]





SQUID pickup



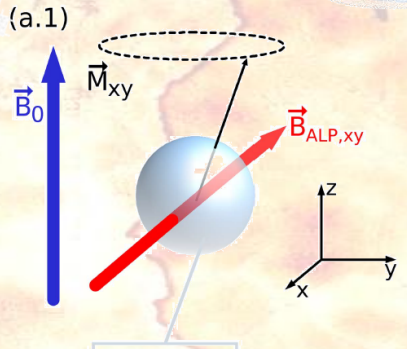
Galactic DM as source

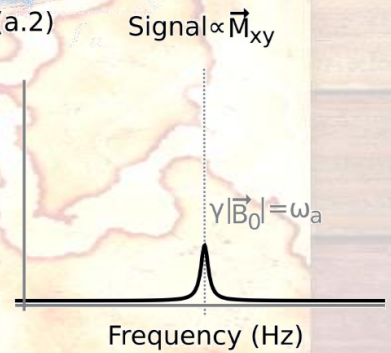
$\langle v_{DM} \rangle = 10^{-3} c$

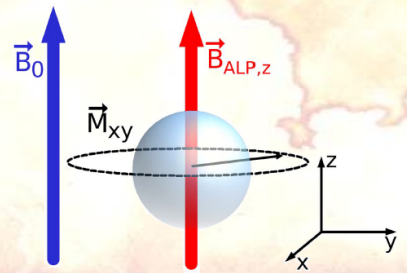
peV neV

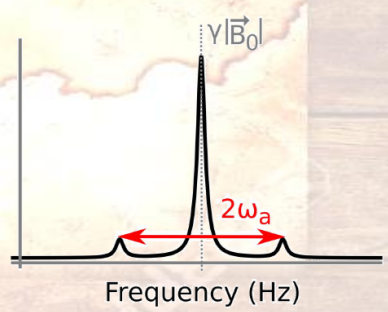
kHz MHz

Spin precession









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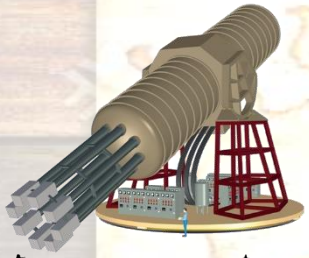
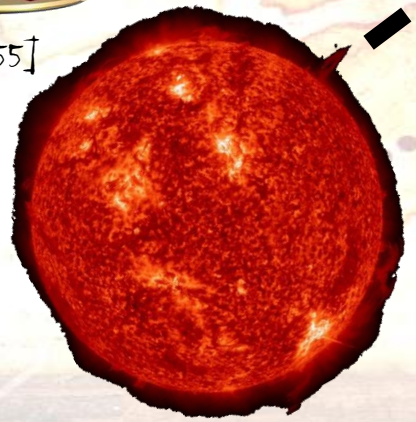
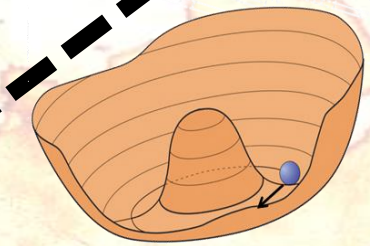
The bounty hunters:

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

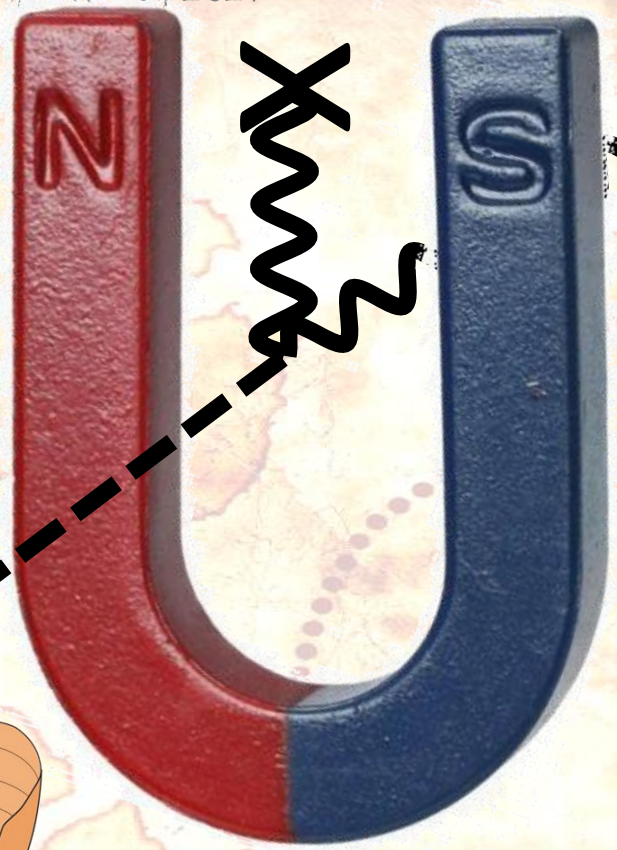


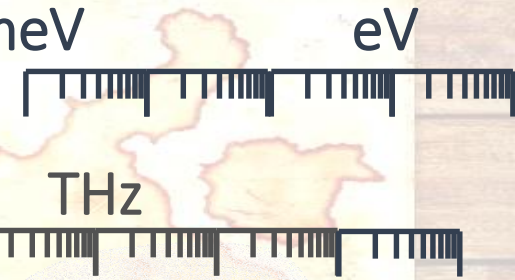
[arXiv:1904.09155]





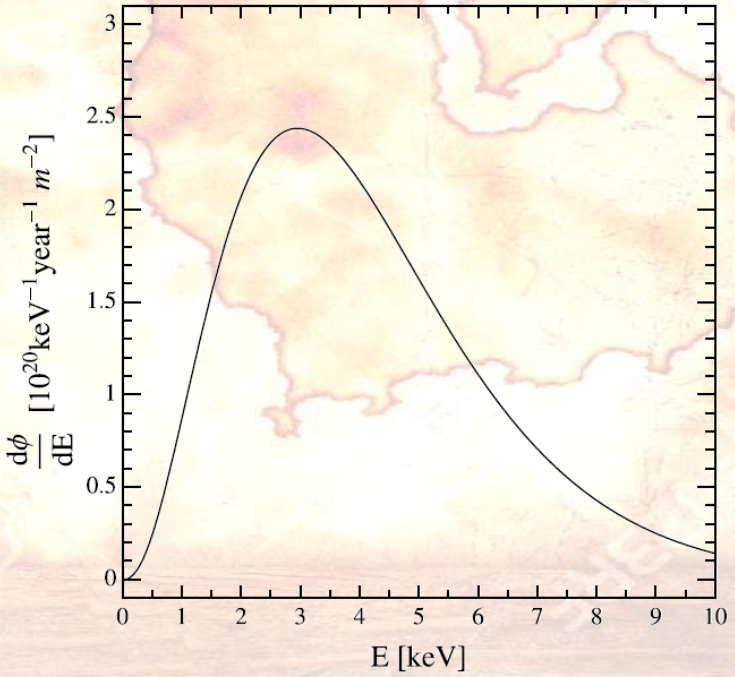
Solar axions





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

X-ray detection



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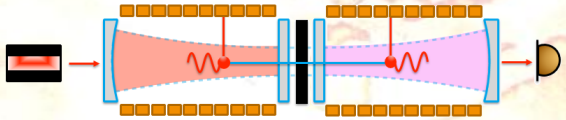
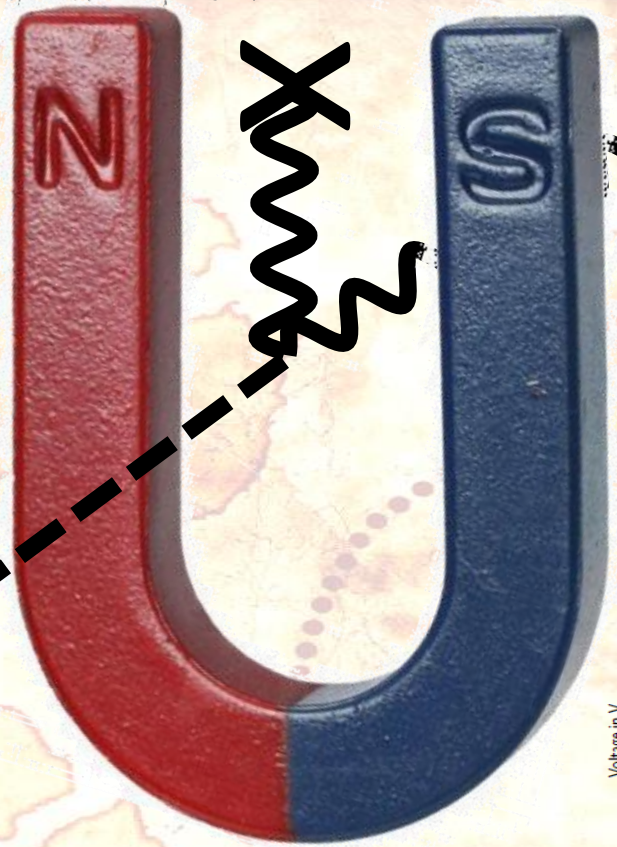
The bounty hunters:

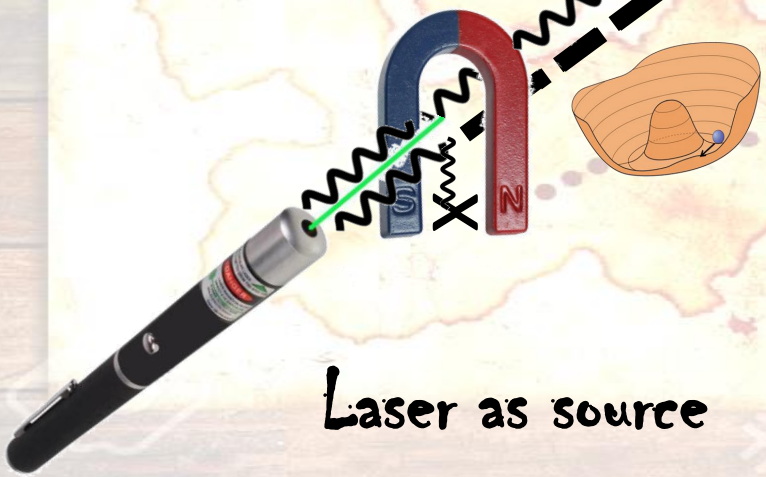
Lab experiment $g_{a\gamma}$



[arXiv:1302.5647]

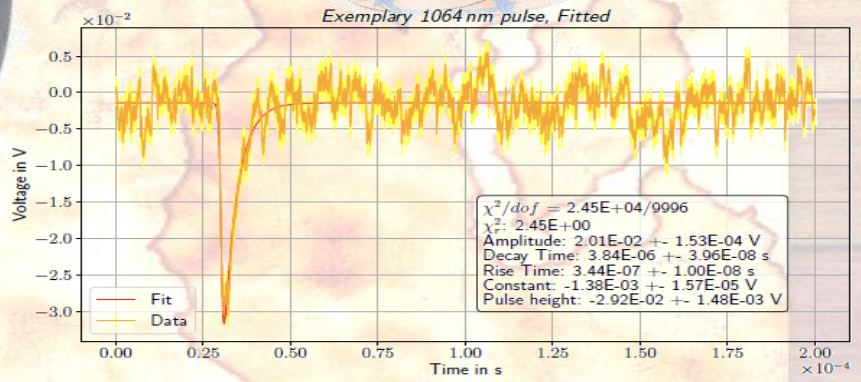
Light shining through the wall

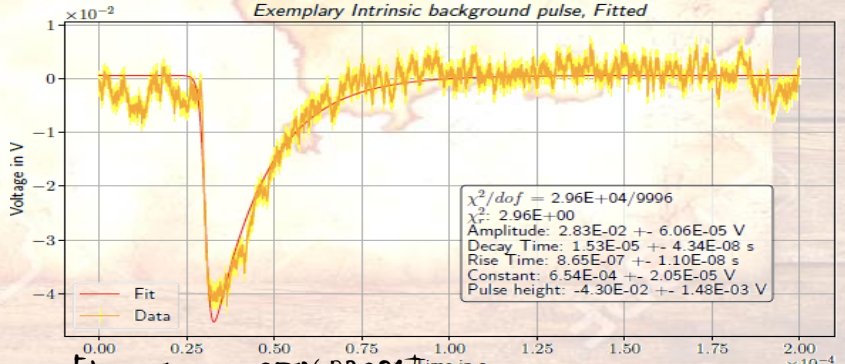




Laser as source

Single photon detection





[Aaron Spector, DESY PRC91]

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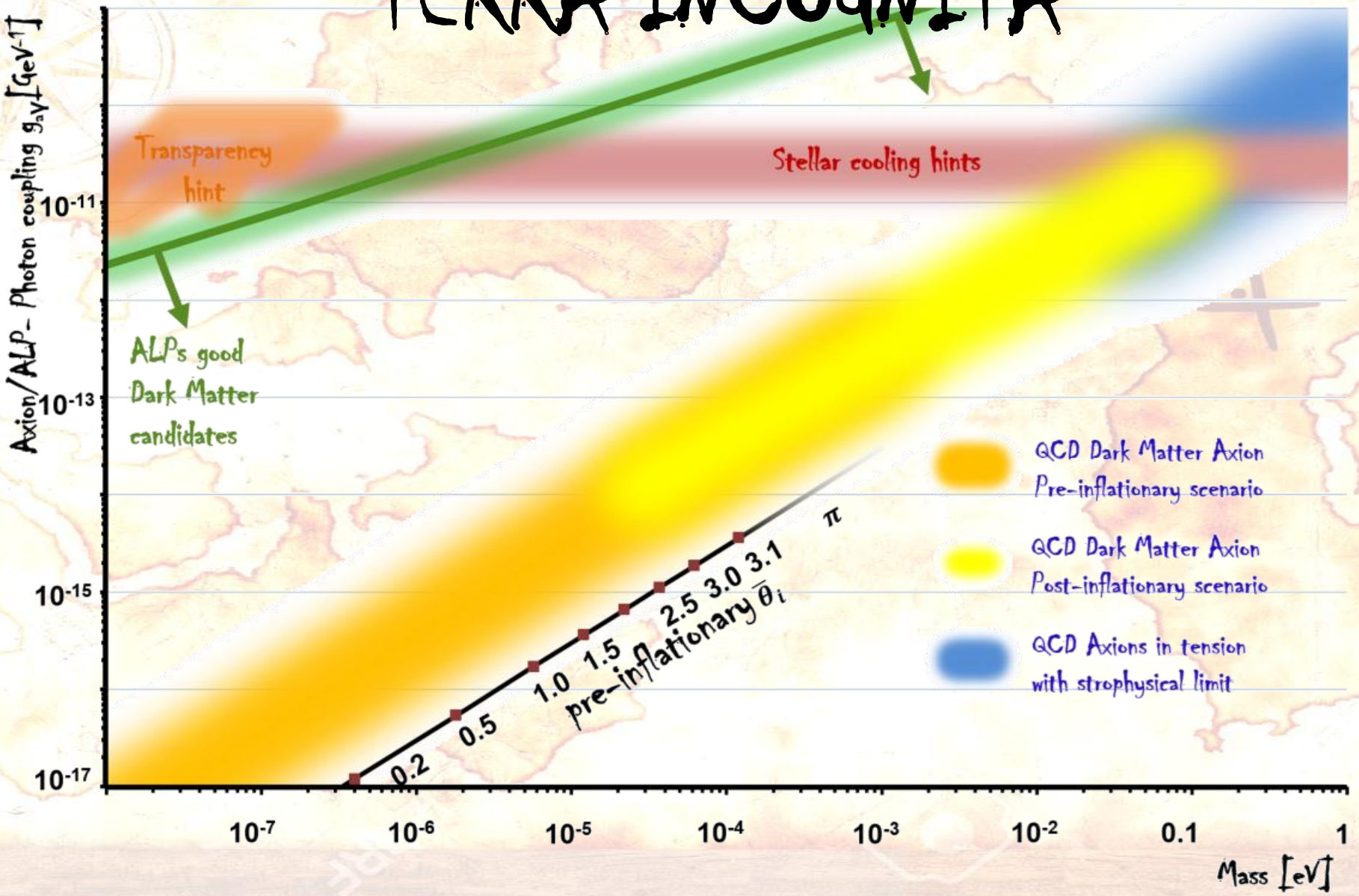
TERRA INCOGNITA



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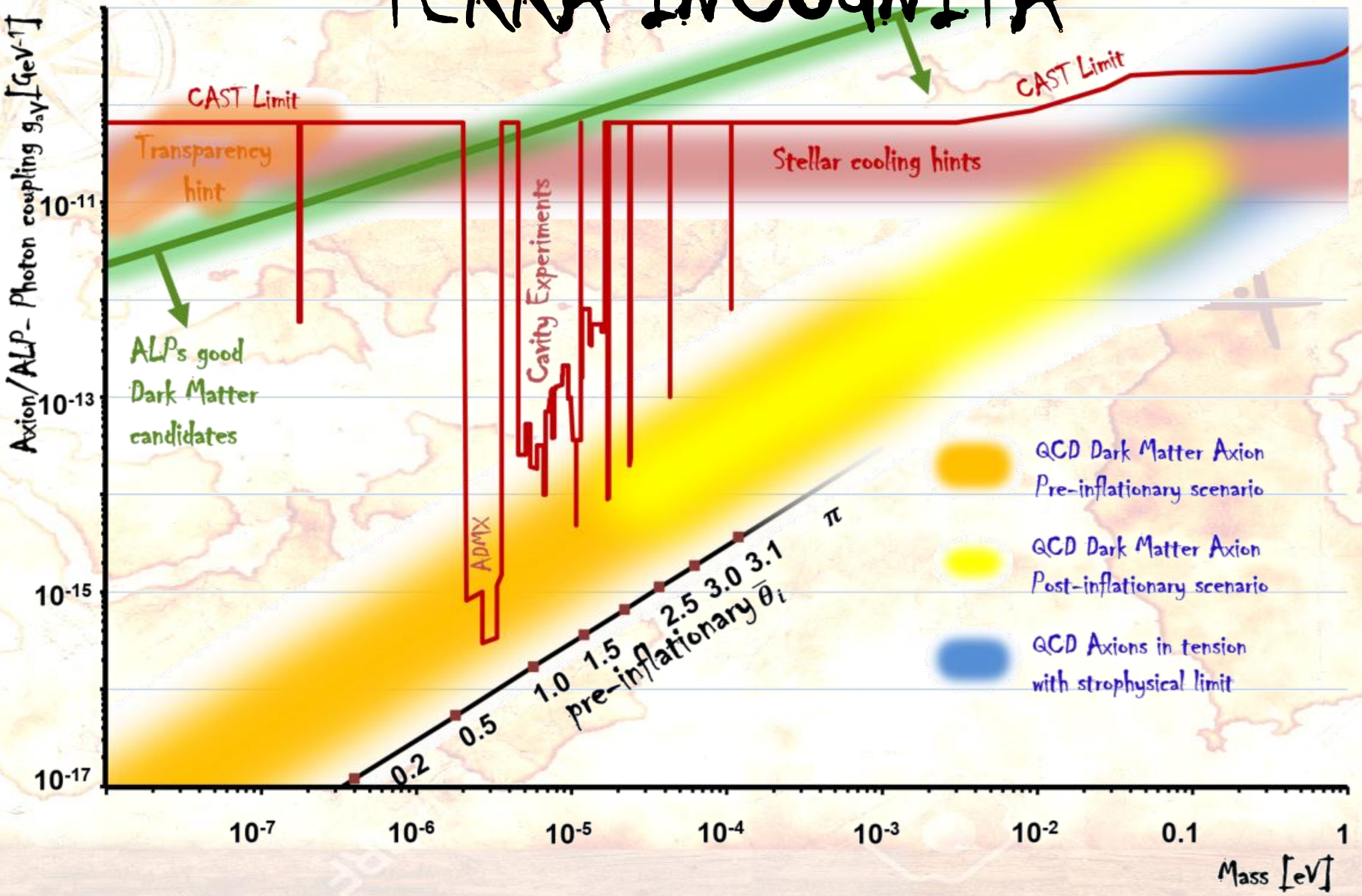

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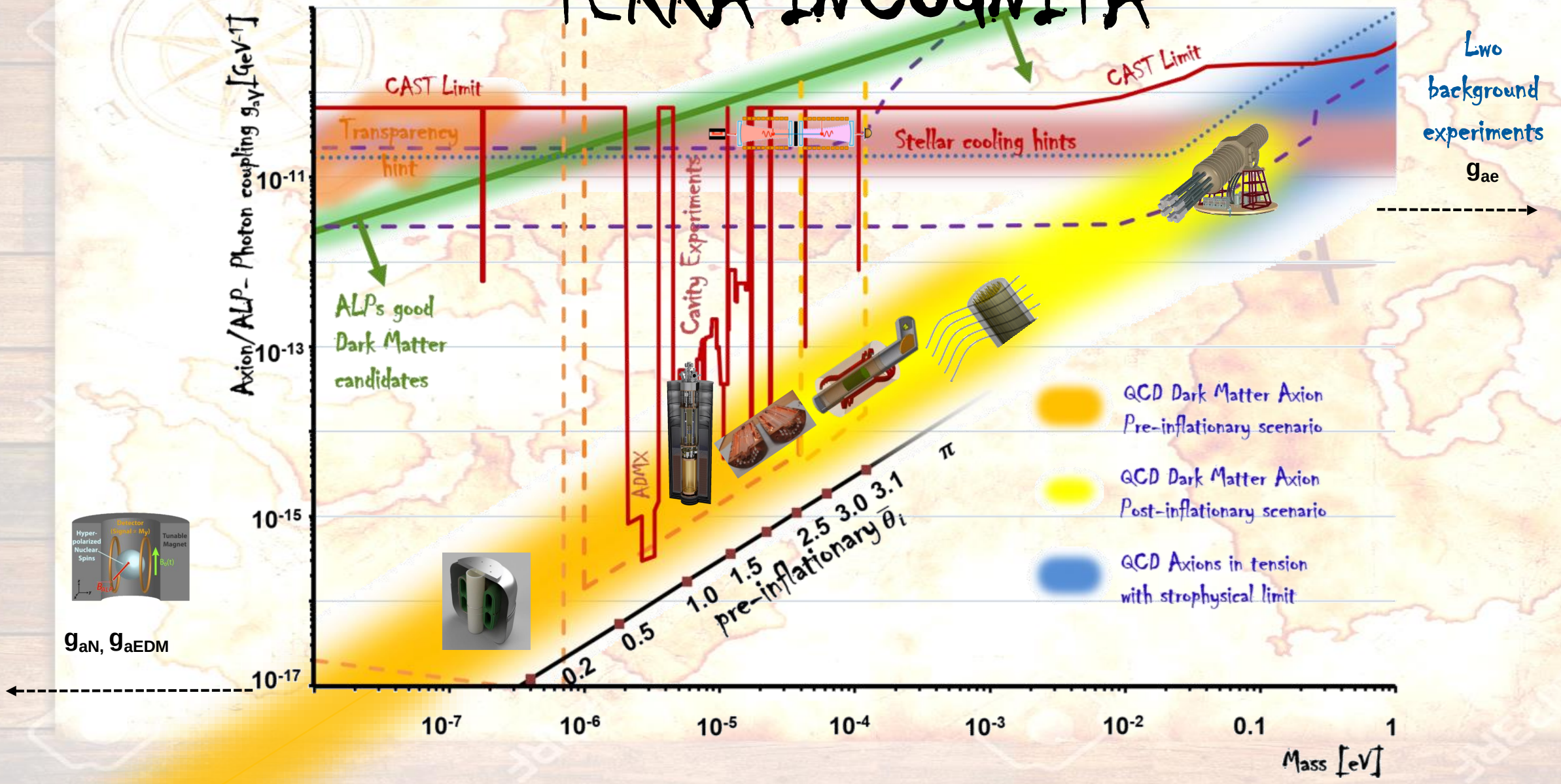

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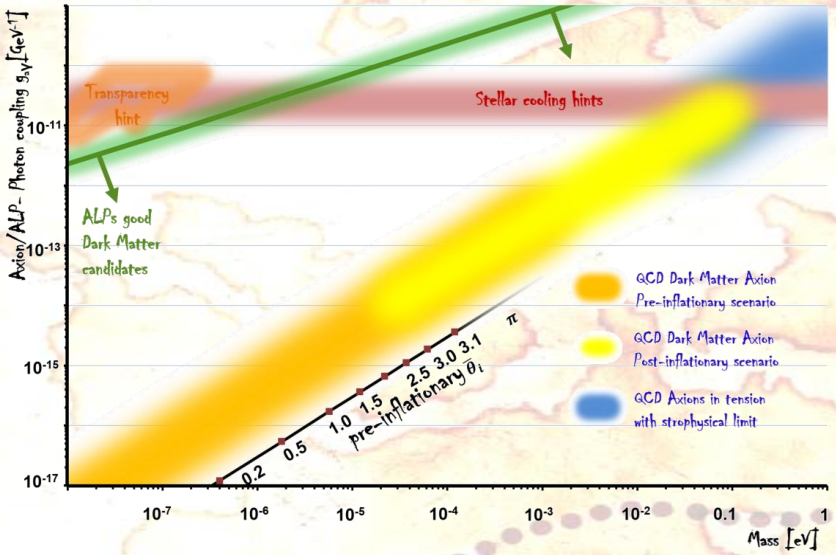
AGENDA:



- Basic concepts:
  - Status of research in the axion 'community'
- **Challenges and 'cross-talk' with other communities**
  - hardware
  - **comparability**
  - software/tools
- Current and future needs
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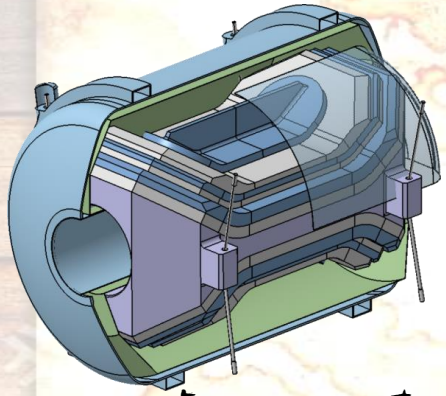
Instrumental Challenges

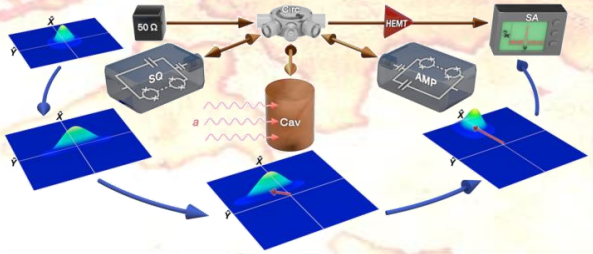
Magnets



[2003.10894]

Superconducting materials
Cryogenics

Photon detection
RF & single photons



[2008.01853]

Quantum detectors
Vacuum squeezing
TWPAs, SIS mixers
TES, Qbts, Graphene,

Low loss materials

[2004.02754]

Large scale dielectrics
tan delta < 10^{-4}
high ε material

Cryogenic engineering & infrastructure

[CERN courier 03/04 2021]

Instrumentation at cryogenics
cooling capacities
→ infrastructure!

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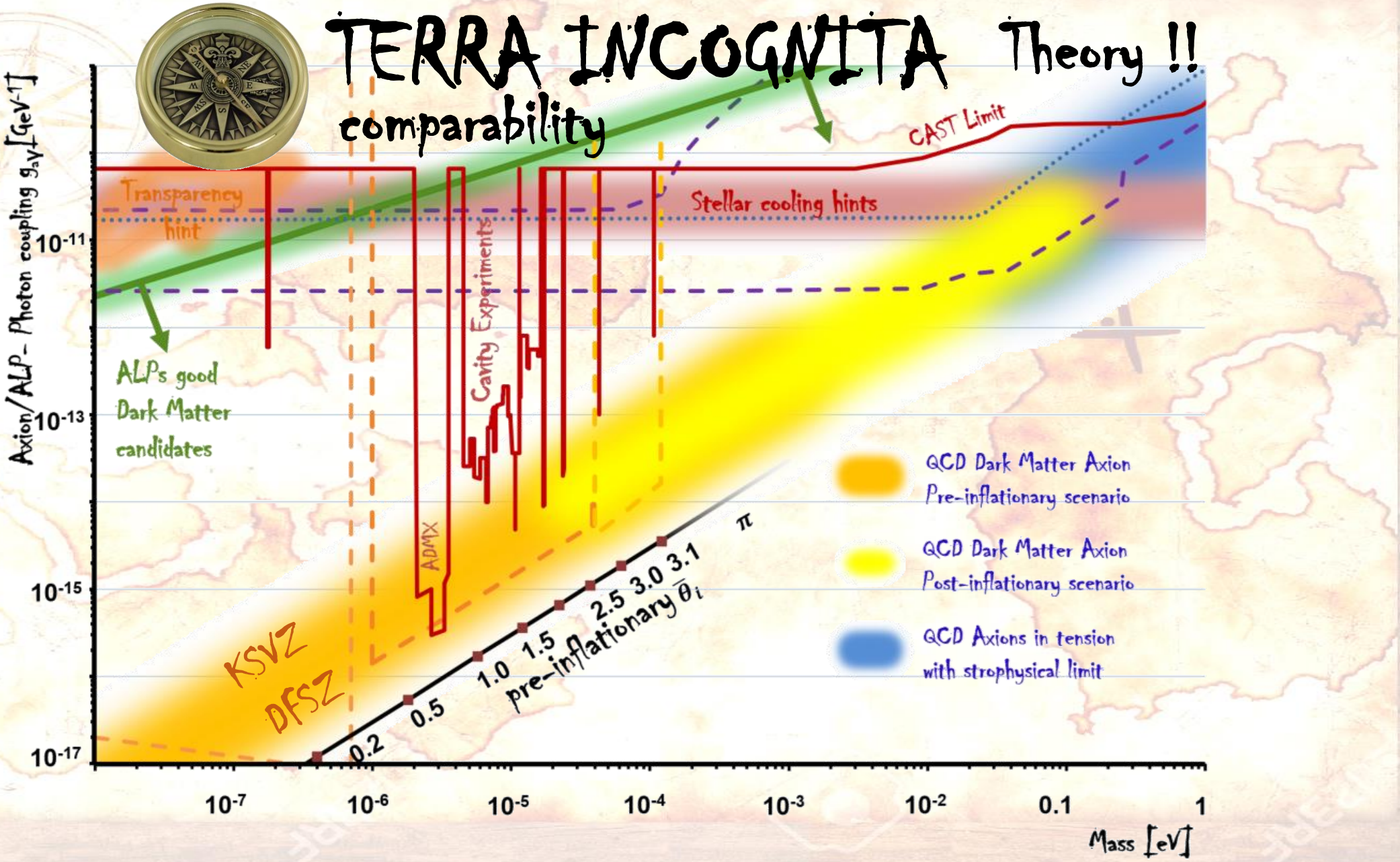

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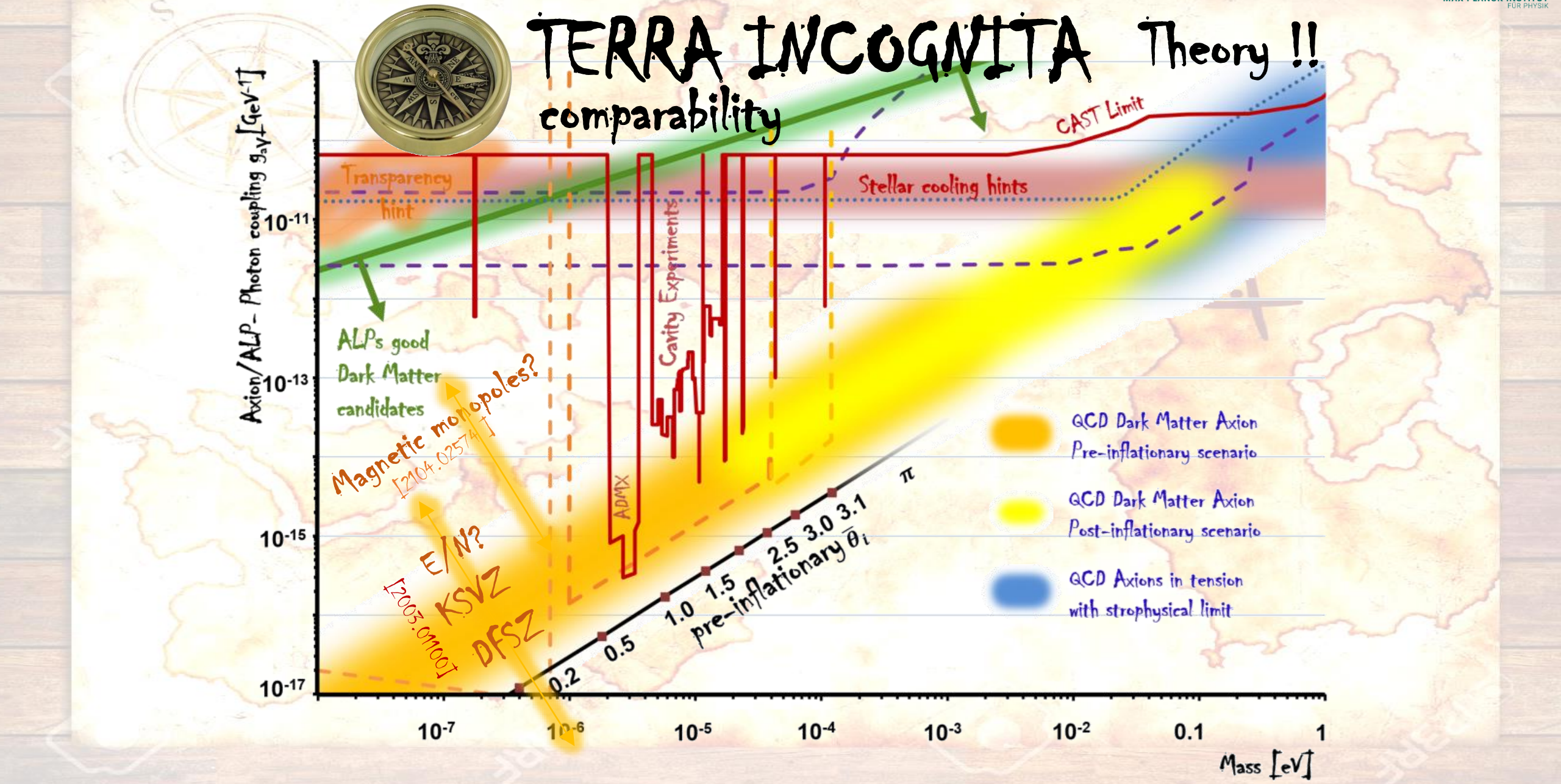

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TERRA INCOGNITA Theory !!

comparability

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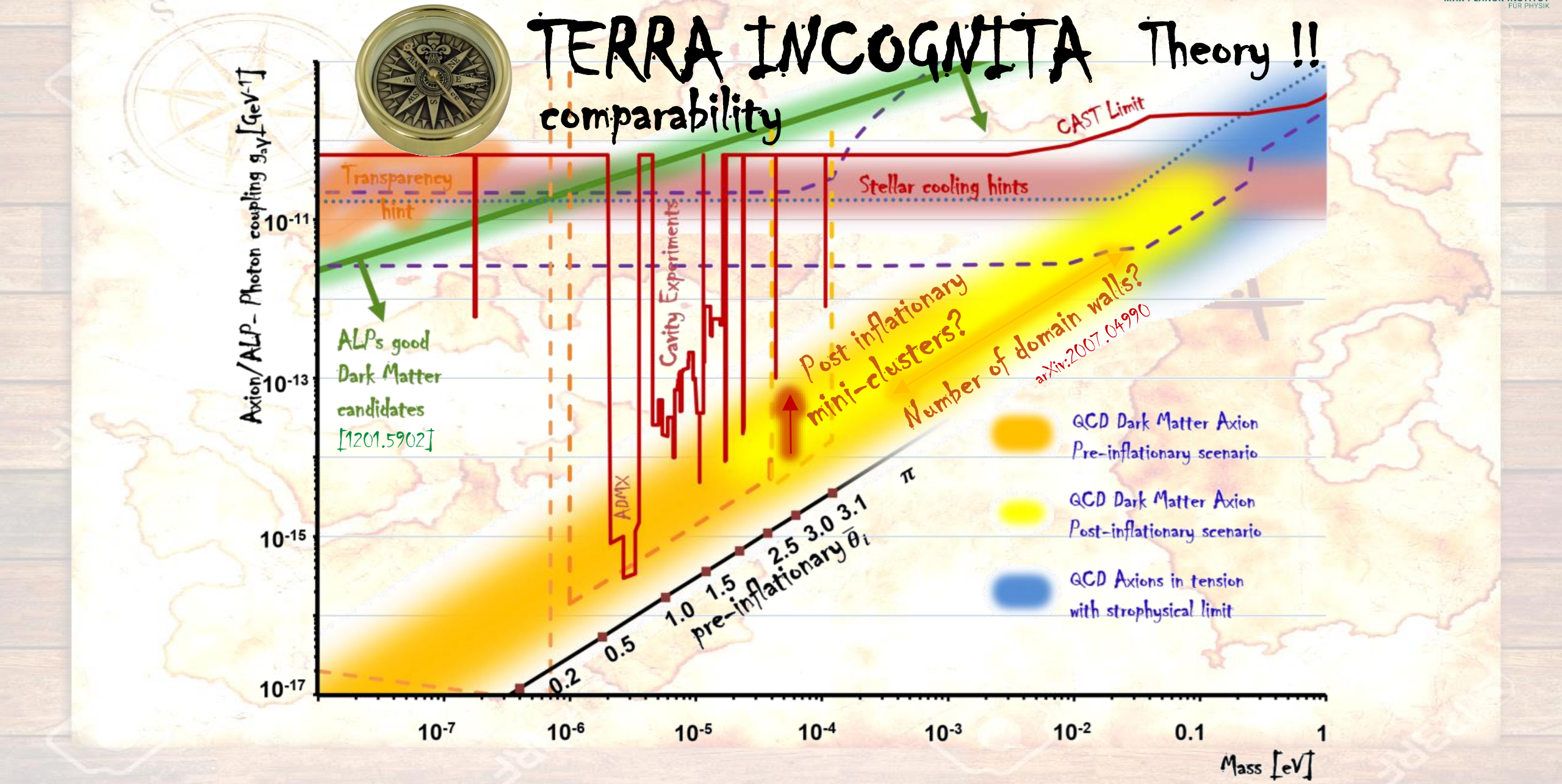

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TERRA INCOGNITA Theory !!

comparability

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TERRA INCOGNITA

comparability

Astrophysics

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TERRA INCOGNITA

comparability

Astrophysics

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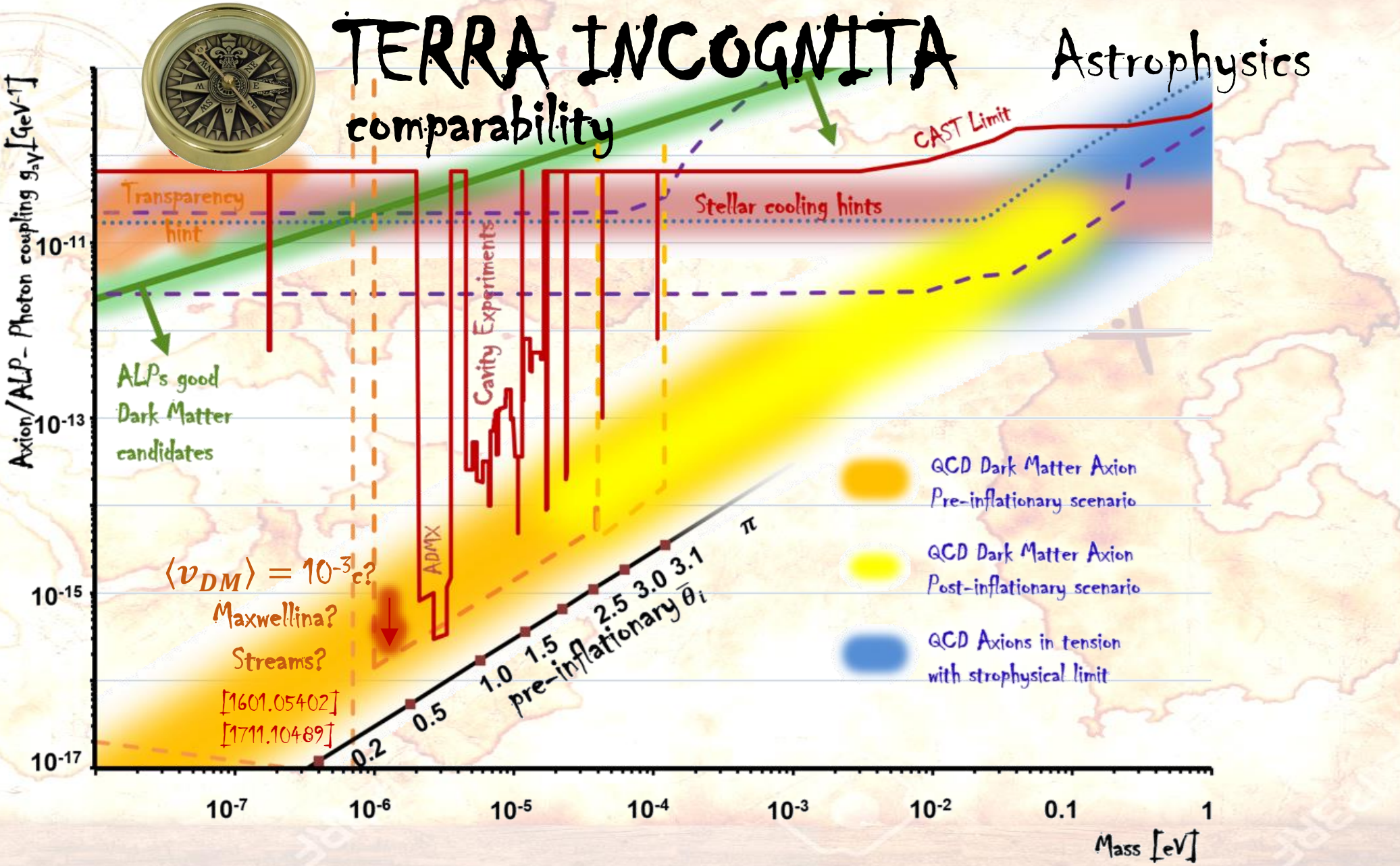

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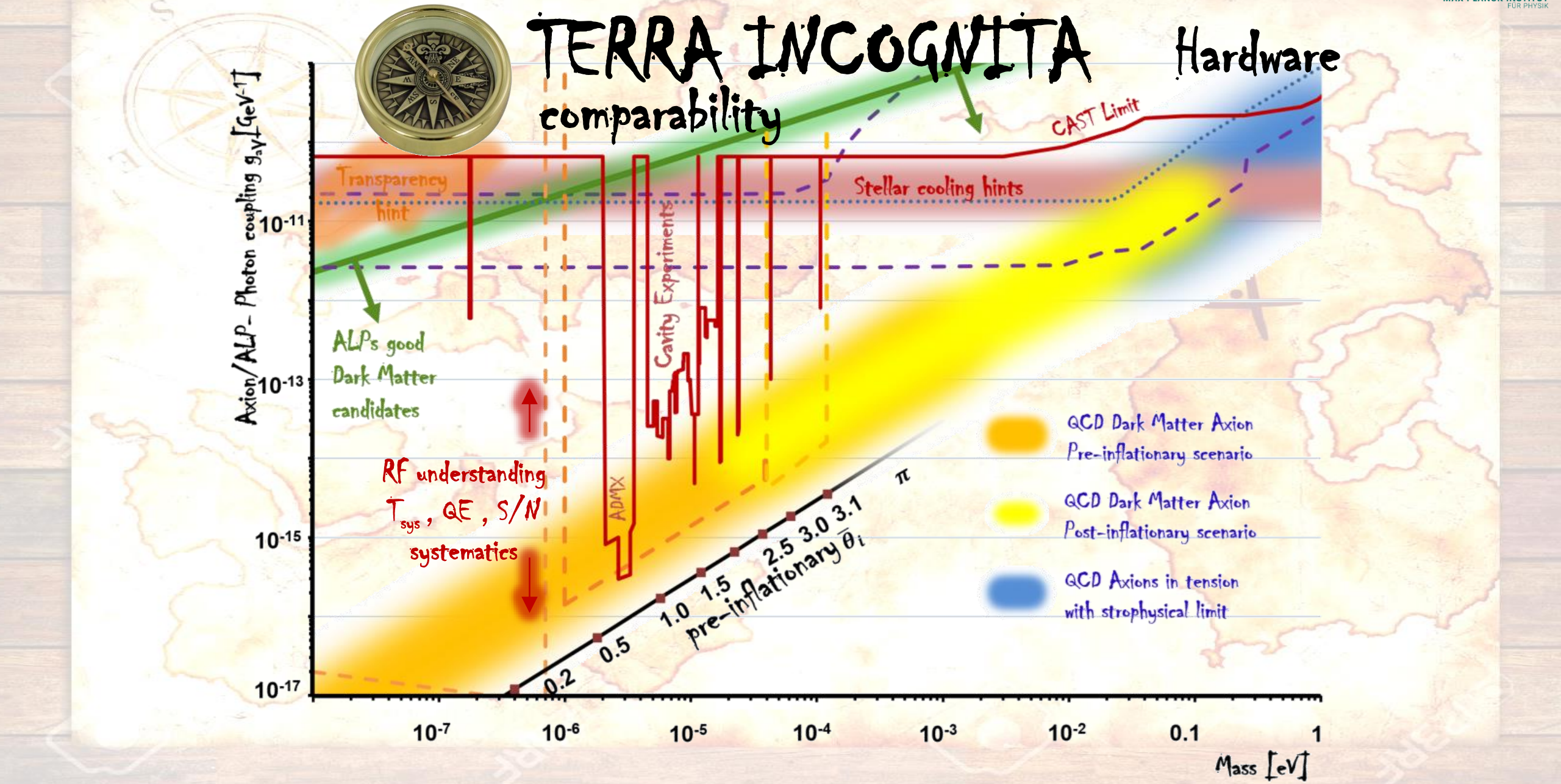

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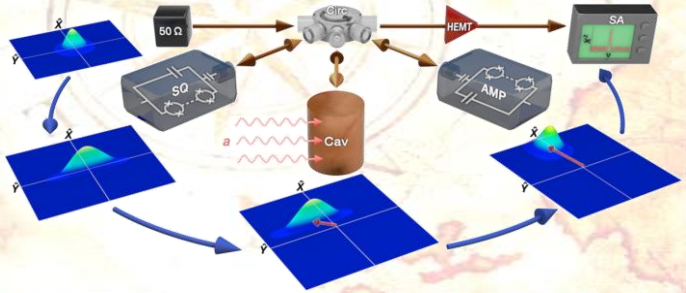

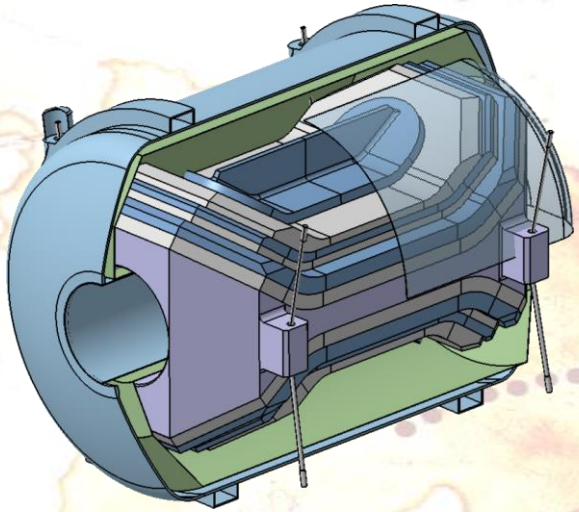

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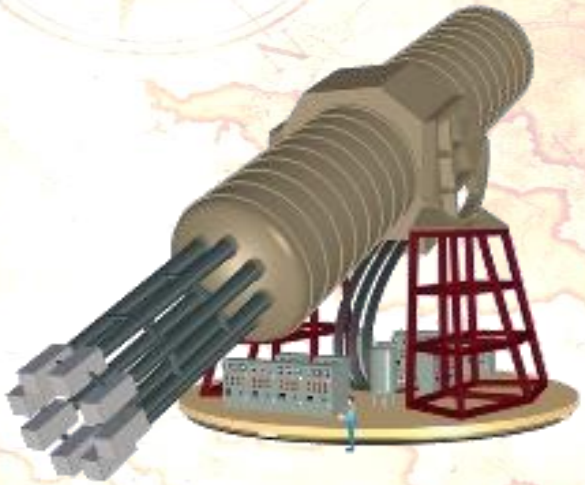
Needed arms:

Magnets

Strong (dipole) magnets !

Axion community R&D:

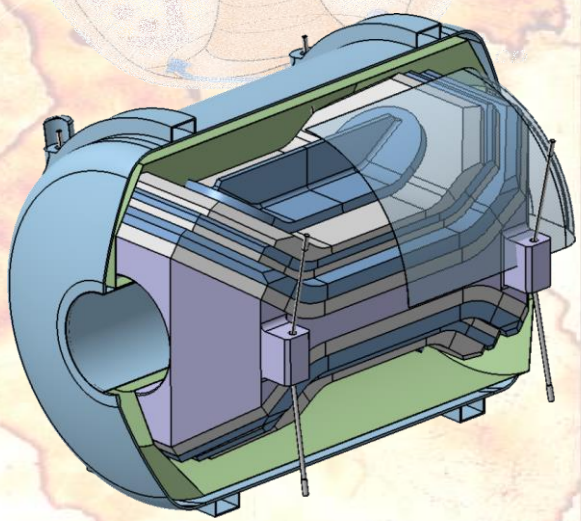
- Huge superconducting dipole magnets
  large stored energy
- Solenoids



magnet: based on existing
CERN technology from accelerator magnets

Input from other communities:

- accelerator physics,
- medical physics,
- fusion research,
- some aspects of solid state physics,
- ...



dipole magnet: being developed in terms of
EU-innovation partnership between MPP, Bilfinger-NOELL
and CEA-Irfu Saclay

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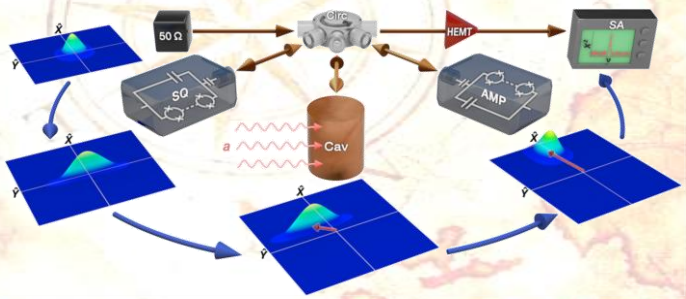
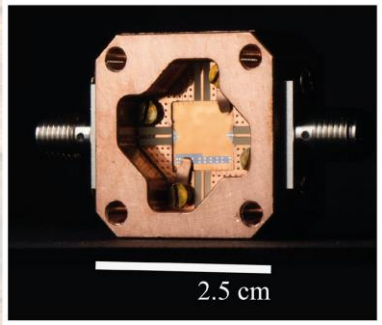
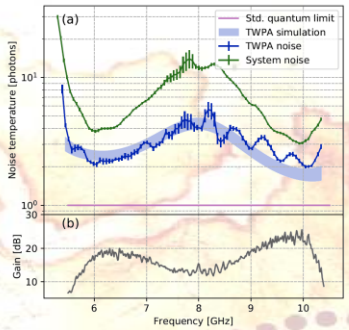
Needed arms:



squeezed states
[2008.01853]





Quantum limited TWPA
[2101.05815]

Photon detection

Improve detector sensitivity

→ increases mass range that can be covered in given time

Axion community R&D:

- quantum detectors (frequency < 100GHz):
  broad bandwidth (JPA, TWPA)
  beat quantum limit
- Single photon detectors (frequency > 10 GHz):
  extremely low threshold, low background: (QMONs, TES, MKIDs,...)

Input from other communities:

- Quantum computing
- Radio astronomy
- neutrino experiments & other light DM searches
- ...

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Needed arms:

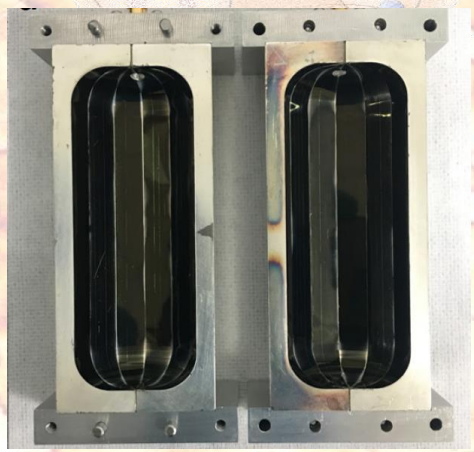
Low loss dielectrics and cavities

Low loss dielectrics
[1901.07401]

Minimize RF losses in cavities/booster, etc.

Axion community R&D:

- Large single crystals
- produce amorphous dielectrics
- Superconducting cavities,
- Meta-materials



Superconducting cavities
[2002.08769]

Photonic crystal
[2002.01816]

Input from other communities:

- Radio astronomy
- Quantum computing
- RF engineering – telecommunication
- ...

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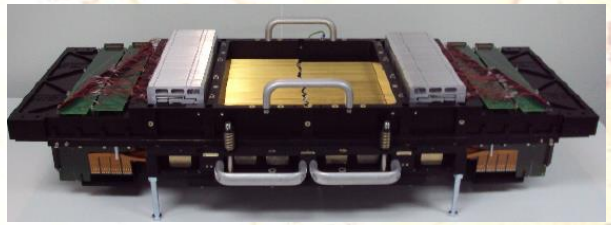
Needed arms:

Cryogenic precision engineering in B-field

Precision displacement at low temperature & strong B-field

tune frequency , minimizing noise, maximize signal

Cryogenic piezo linear stage
https://www.jpe-innovations.com/



Cryogenic configurable Slit Unit
For GTC telescope

[https://doi.org/10.1117/12.671793]

Axion community R&D:

- Precision machining of large objects
- Precision displacement at extreme conditions
- Macroscopic stroke at cryogenic temperature
- Reliability

Input from other communities:

- Cryo-electron microscopy
- Gravitational wave detectors
- Precision displacement technology in general
- Telescopes

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Fortify infrastructure

for experiments with axion sensitivity

Infrastructure for projects with QCD axion reach:

similar to particle physics – accelerator R&D:
well-equipped large (enough) experimental halls
cryogenic infrastructure

Necessary boundary conditions:

- operation of large aperture superconducting magnets,
- operating ultra-sensitive quantum detectors,
- minimize (thermal) RF noise & stable ground in detector surrounding.

MORPURGO magnet at CERN

Former HERA ring at DESY

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Many challenging R&D sites:

Theory:
map the ground!

Magnets:
Crank'em up!

Technologies:
be precise, stay cool!

Dielectrics:
Tolerate no loss!

Astrophysics:
per aspera ad astra!

RF understanding:
stay tuned!

Computing:
Not only simulating

Quantum detectors:
Dig deeper!

Many potential synergies with other communities:

Gravitational wave detectors

medical physics

Quantum computing

Cryo-electron microscopy

solid state physics

Radio astronomy

accelerator physics

fusion research

light DM searches

neutrino experiments

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How can iDMEU help?

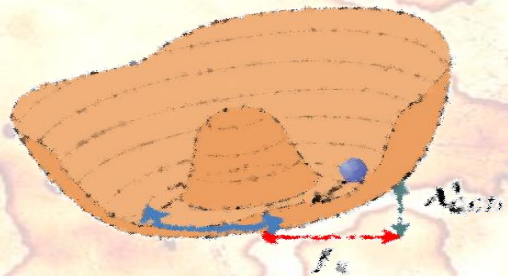
Many challenging R&D sites:

Where does the axion family hide?

How to get there?

How to hunt it down?

Lets exploit synergies



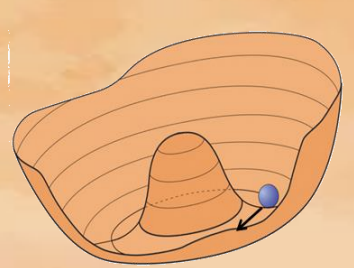
Raise interest with:

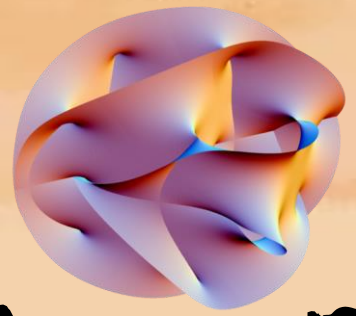
- Other communities
- Industry
- Last not least: Funding agencies!

Example:
technology forum

APPEC

WANTED





the QCD Axion & family

Guilty for solving the strong CP problem! Prime suspect for cause of DM crisis!

Many bounty hunters and helpers needed to earn an award:

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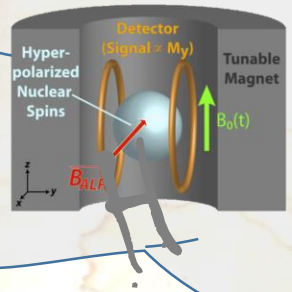
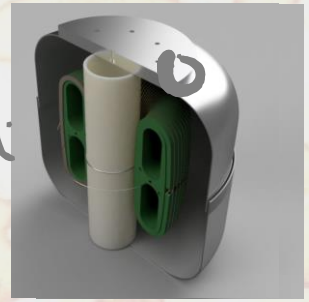
Projects with (expected) axion sensitivity

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

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

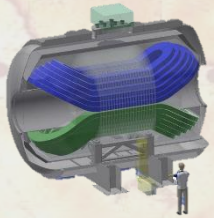


LC circuit g_{ay}

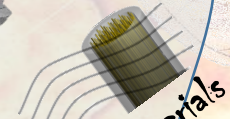


Cavity g_{ay}

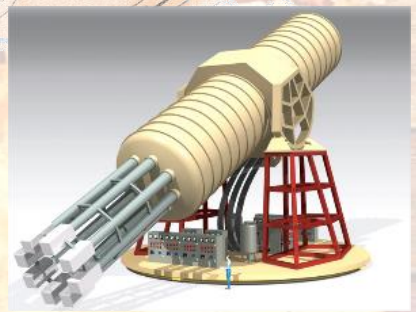
Di-electric haloscope

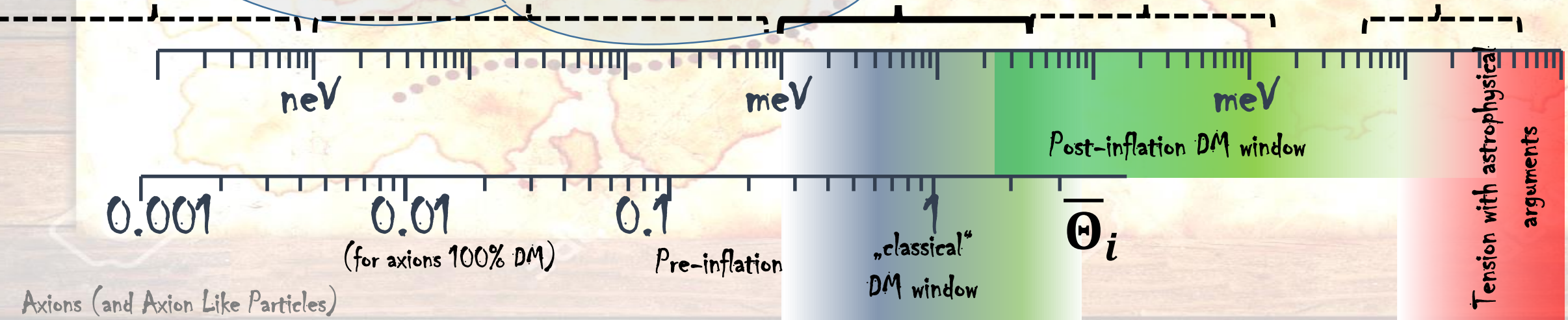


g_{ay} Meta materials



Helioscope
g_{ay} g_{ae}





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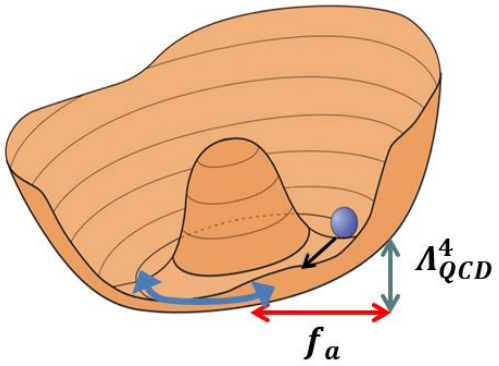
Axions and ALPs: basic concepts



f_a 10^{18} 10^{12} 10^{9} [GeV]

$m_a = 5.7\mu eV\left(\frac{10^{12}GeV}{f_a}\right)$

peV neV μeV meV → m_a

$h\nu_a = m_a c^2$

kHz MHz GHz THz → ν_a

Planck scale

Post-inflation

Pre-inflation

0.001 0.01 0.1 1 $\overline{\Theta}_i$ (for axions 100% DM)

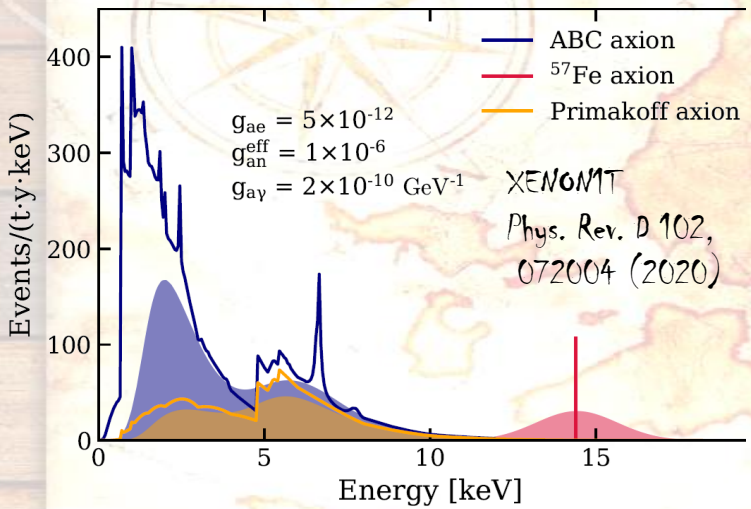
„Classical“ DM Window

$\lambda_{deBroglie}$ 1000km 1km 1m

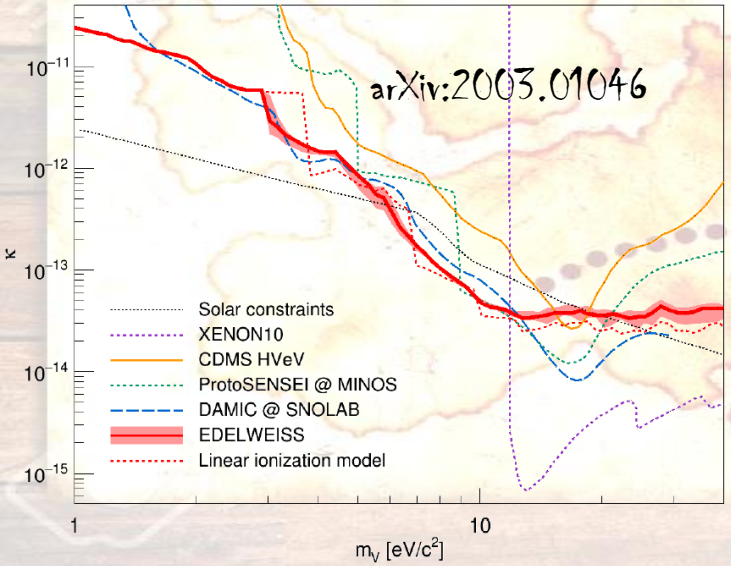
$\langle v_{DM} \rangle = 10^{-3}c$

Sensitivity of "low background" experiments

Solar axions – ALPs



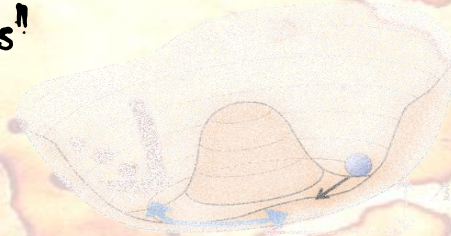
Hidden Photons



Sensitivity "for free" to

(solar) ALPs, Hidden Photon

or Vector Boson dark matter with "high masses"



No QCD axion sensitivity

compatible with astrophysical observations

But: Independent limits for axions from sun!

Some ALP sensitivity:

Some "fine tuning needed" for g_{ae} vs $g_{a\gamma}$

Hidden Photons/Vector bosons:

sensitive to parameter range not yet excluded

DM & neutrino experiments: sub eV thresholds!

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Experiment	Type	Techn.	$g_{\_}$	Mass range	Status	Limits	Location	Timescale
Experiments with expected sensitivity to DM axion benchmark models								
CASPEr-e[a]	∅	NMR	a_N	10^{-13} eV – 1 neV	R&D	ALP	BU	
DM Radio[b]	∅	LC	$a\gamma$	20 neV – 0.8 μeV	R&D	HP	Stanford	2025-30
ADMX[c]	∅	C	$a\gamma$	2 μeV – 40 μeV	running	**axion**[†]	UW	2017-30
HAYSTAC	∅	CS	$a\gamma$	15 μeV – 35 μeV	running	axion[‡]	Yale	2015-25
CULTASK	∅	SC/MC	$a\gamma$	3 μeV – 70 μeV	running	axion[⋆]	CAPP	2021-30
QUAX[d]	∅	SC/DC	$a\gamma$	30 μeV – 50 μeV	in prep.	ALP*	INFN	2021-25
MADMAX[e]	∅	DH	$a\gamma$	40 μeV – 400 μeV	prototype		DESY	2025-35[f]
ORGAN[d]	∅	DC/CS	$a\gamma$	60 μeV – 210 μeV	prototype	ALP	UWA	2025-35[f]
IAXO[g]	⊙	XR	$a\gamma$,ae	1 meV – 10 eV	in prep.		DESY	2023-35
ALP experiments								
CASPEr-w[a]	∅	NMR	ALP_N	10^{-22} eV – 1 μeV	running	ALP	HIM/UCB	
GNOME	∅	NMR	ALP_N	10^{-21} eV – 10^{-10} eV	running	ALP	global	2017-24
DANCE	∅	OC	ALP_γ	$\lesssim 10^{-10}$ eV	R&D	ALP	Tokyo	
Up/Download	∅	MO	ALP_γ	10^{-10} eV – 10^{-7} eV	prototype	ALP	UWA	
ABRA[b]	∅	LC	ALP_γ	1 neV – μeV	in prep.	ALP	MIT	
SHAFT	∅	LC	ALP_γ	$\lesssim$ 10 neV	R&D	ALP	BU	
ADMX-SLIC	∅	LC	ALP_γ	$\lesssim$ 0.2 μeV	R&D	ALP	UFL	
ALPS II	$\mathcal{L}$	LSW	ALP_γ	$\lesssim$ 0.1 meV	constr.		DESY	2021
RADES	∅	MC	ALP_γ	$\sim$30 – 50 μeV	R&D		CERN	
QUAX	∅	e^-S	ALP_e	30 μeV – 80 μeV	R&D	ALP	INFN	2021-25
BRASS	∅	DA	ALP_γ	1 μeV – 1000 μeV	in prep.		UH	2022-23
IAXO[g]	⊙	XR	ALP_γ	$\lesssim$ 1 eV	in prep.		DESY	2025-35
Hidden photon experiments (no axion or ALP coupling)								
SHUKET	∅	DA	ϵ	20 μeV – 30 μeV	in prep.	HP	CEA	2024
FUNK	∅	DA	ϵ	2 eV – 8 eV	upgrade	HP	KIT	

+ low background experiments