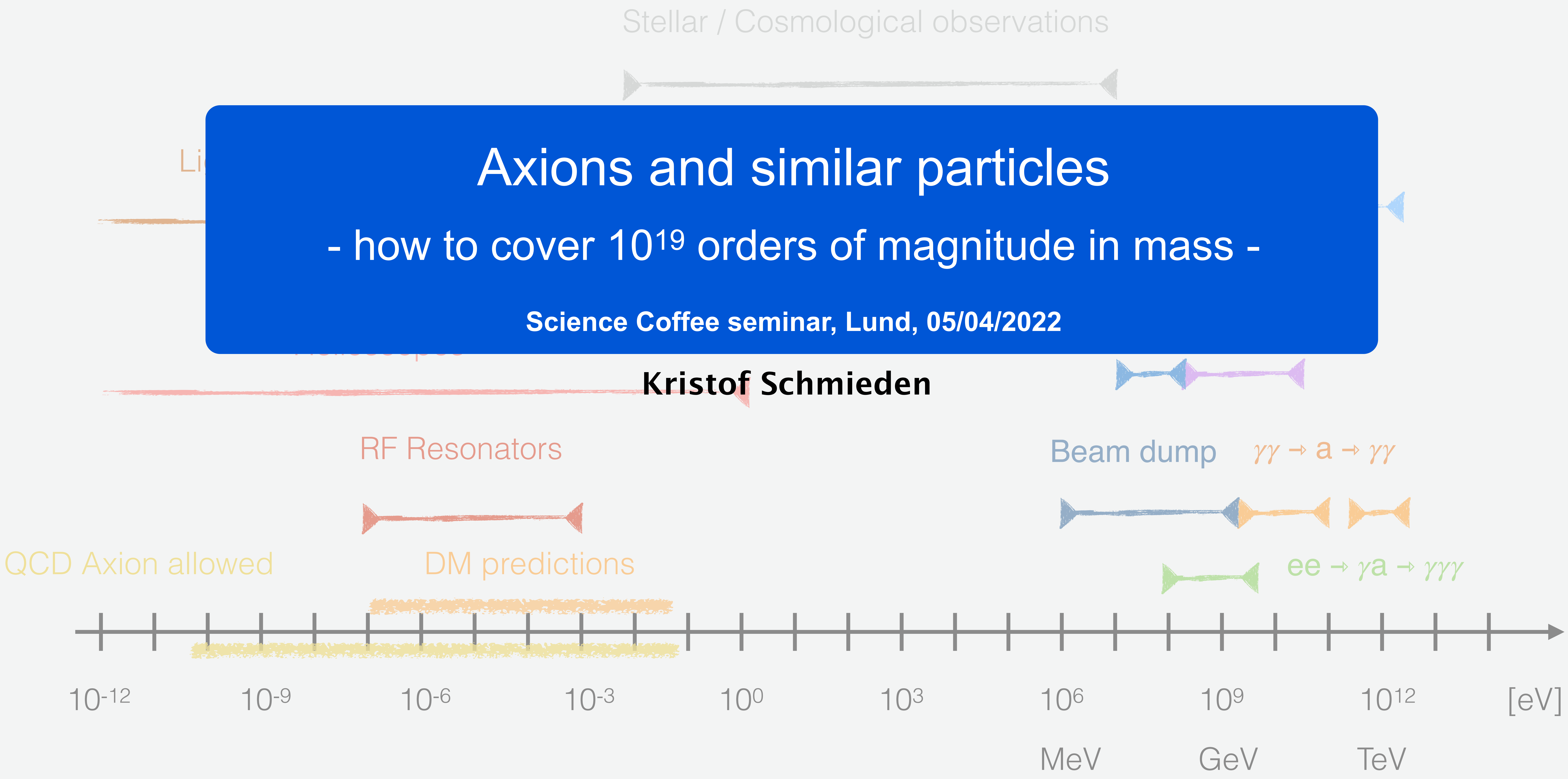
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Axions and similar particles

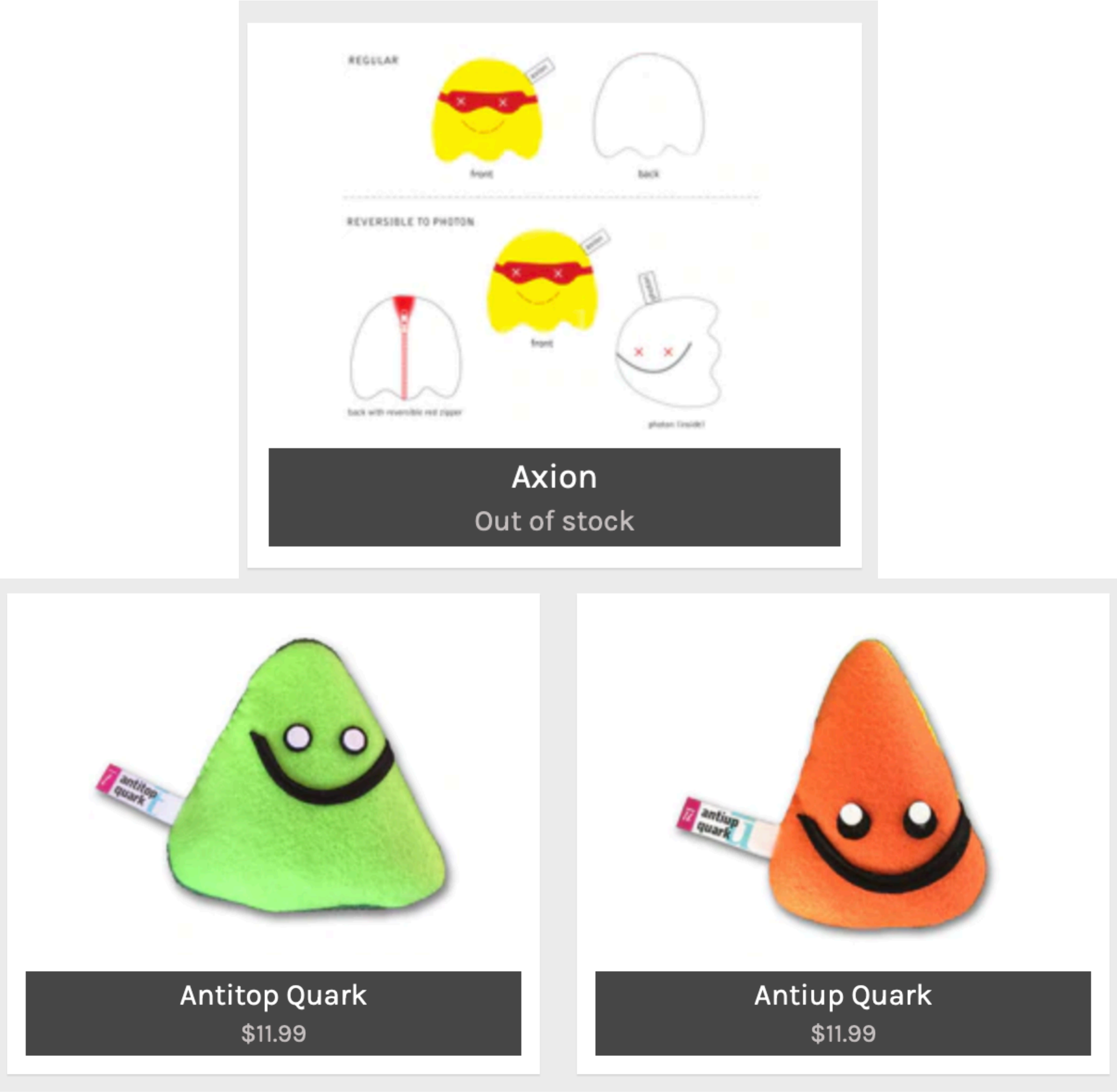
- how to cover 10^{19} orders of magnitude in mass -

Science Coffee seminar, Lund, 05/04/2022

Kristof Schmieden



What are Axions?



Axion
Out of stock

Antitop Quark
$11.99

Antiup Quark
$11.99

Axions are:

Very likeable

Very popular
(none available at present)

[https://www.particlezoo.net/collections/all]

What are Axions?

- The QCD Axion was postulated by Peccei and Quinn (1977) in their theory to solve the *strong CP* problem

- Strong CP problem:
  - CP violating term in QCD Lagrangian

$$\mathscr{L}_\theta = \bar{\theta}\frac{g_s^2}{32\pi^2}G_a^{\mu\nu}\tilde{G}^a_{\alpha\beta}$$

  - $\theta \in [0, 2\pi]$, free parameter
  - From electric dipole moment of neutron (EDM):
    - $\theta < 10^{-10}$
    - => fine tuning

- Solution (PQ theory)
  - Adding global U1 symmetry
    - Spontaneously broken at scale f_a

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{SM,axion}} + \bar{\theta}\frac{g_s^2}{32\pi^2}G_a^{\mu\nu}\tilde{G}^a_{\alpha\beta} + \xi\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G_b^{\mu\nu}\tilde{G}^b_{\alpha\beta}$$

  - CP-breaking terms cancel due to structure of the QCD vacuum:

➡ Pseudo Goldstone boson: Axion

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➡ Pseudo Goldstone boson: Axion

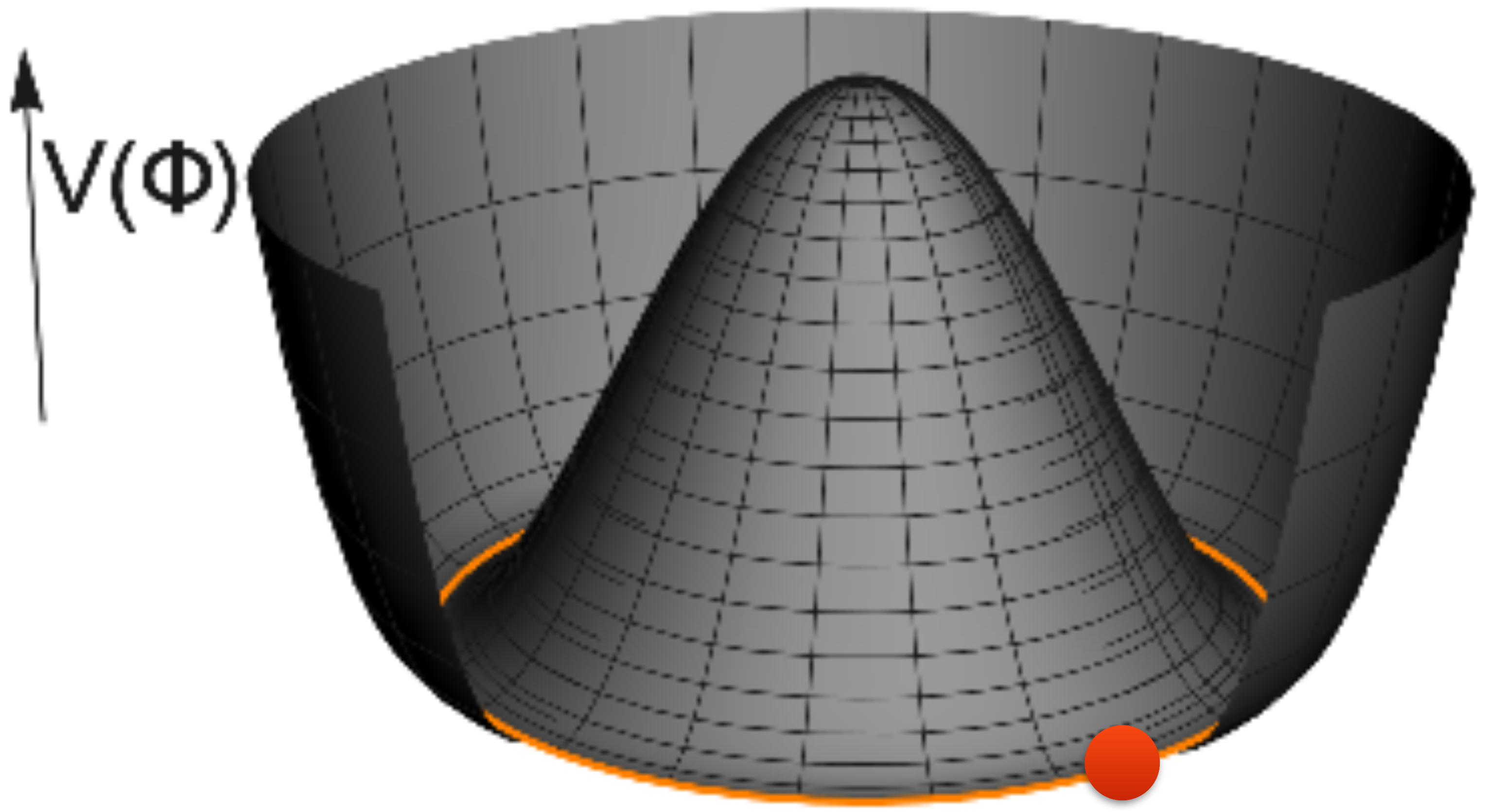
Coupling: $g_i \propto \frac{1}{f_a}$ $g_i \propto m_a$

Axion:
Massive, pseudo-scalar particle

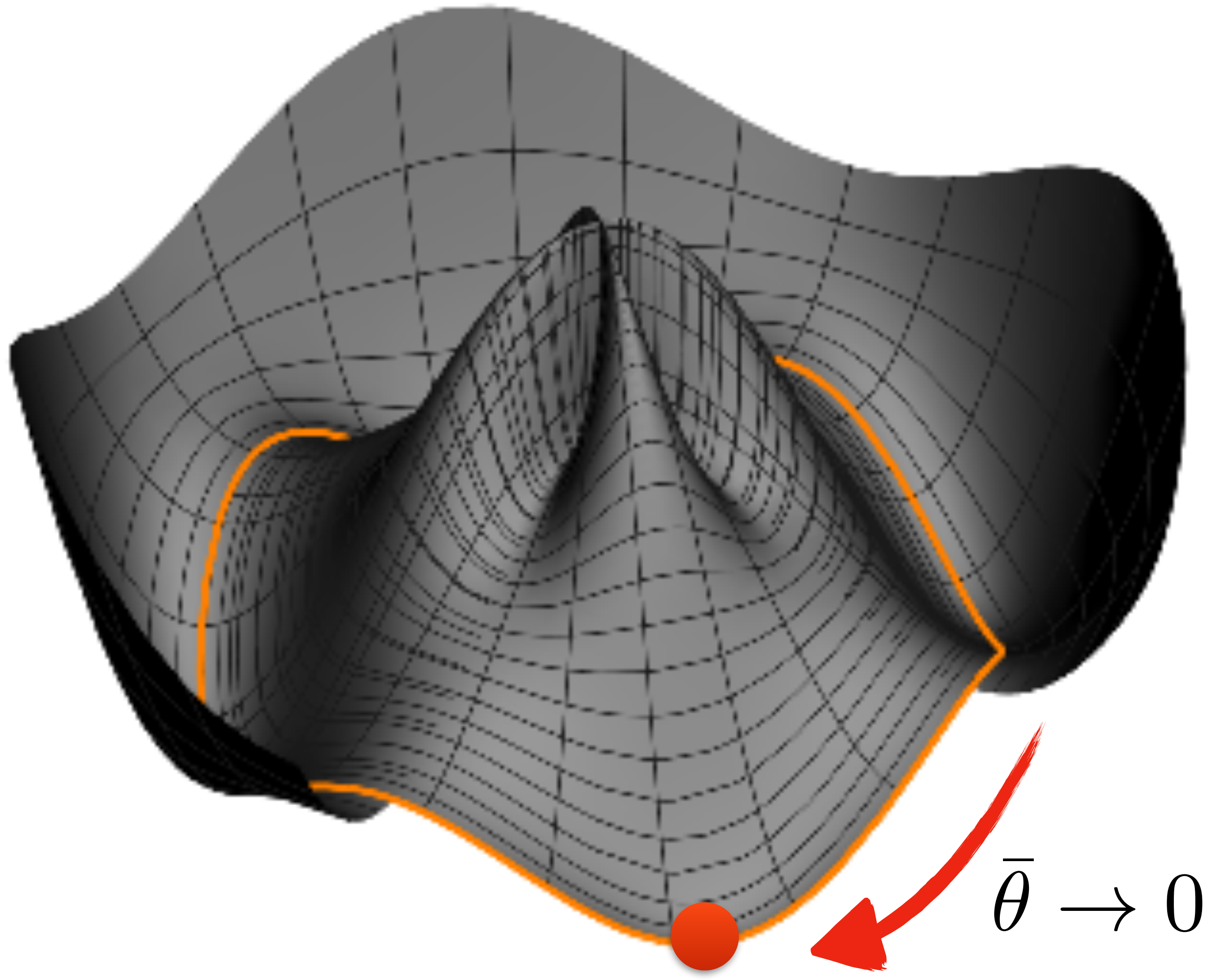
PQ potential

[J. Ellis et al.: arXiv.org:2105.01406]

- Before QCD phase transition



- After QCD phase transition
  (Color anomaly N=4)

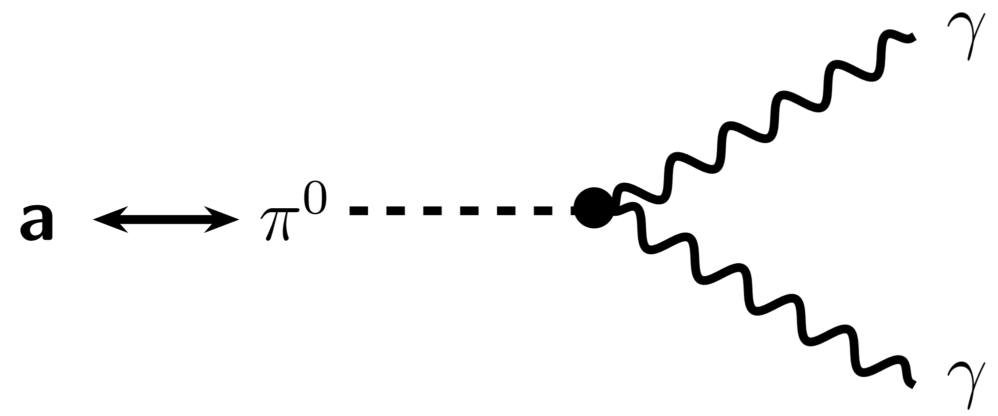


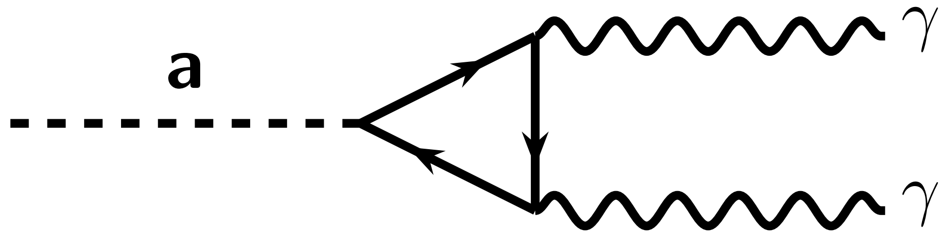
- Exact symmetry
  - Spontaneously broken
  - Massless goldstone boson

- Approximate symmetry
  - U(1) symmetry explicitly broken by color anomalies.
  - Restores CP symmetry
  - Axion gains mass

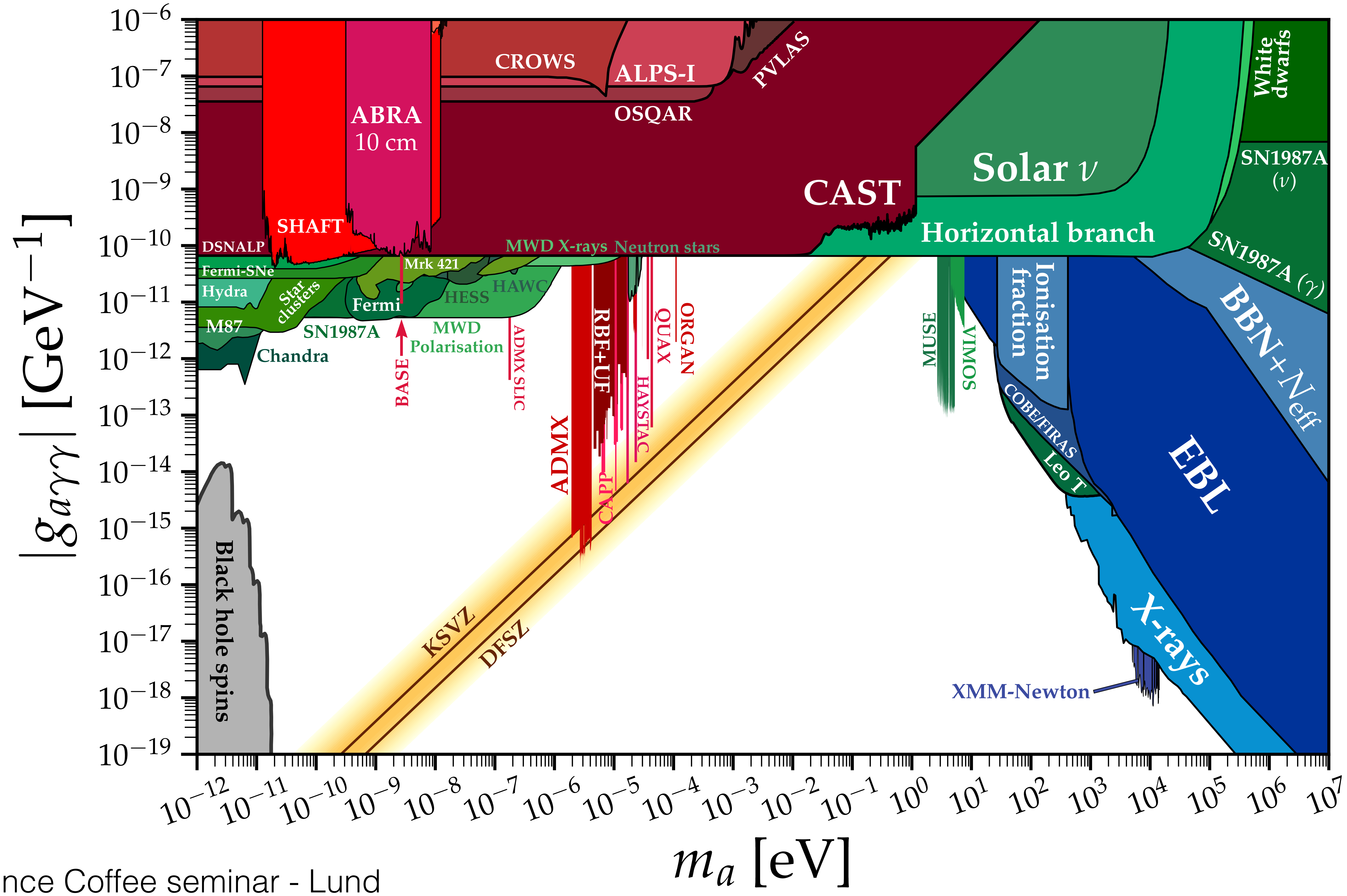
Couplings of the QCD Axion

- Axions couple to quarks by definition
- Axions also couple to **photons**
  - Can mix with pi0
- May couple to other SM particle





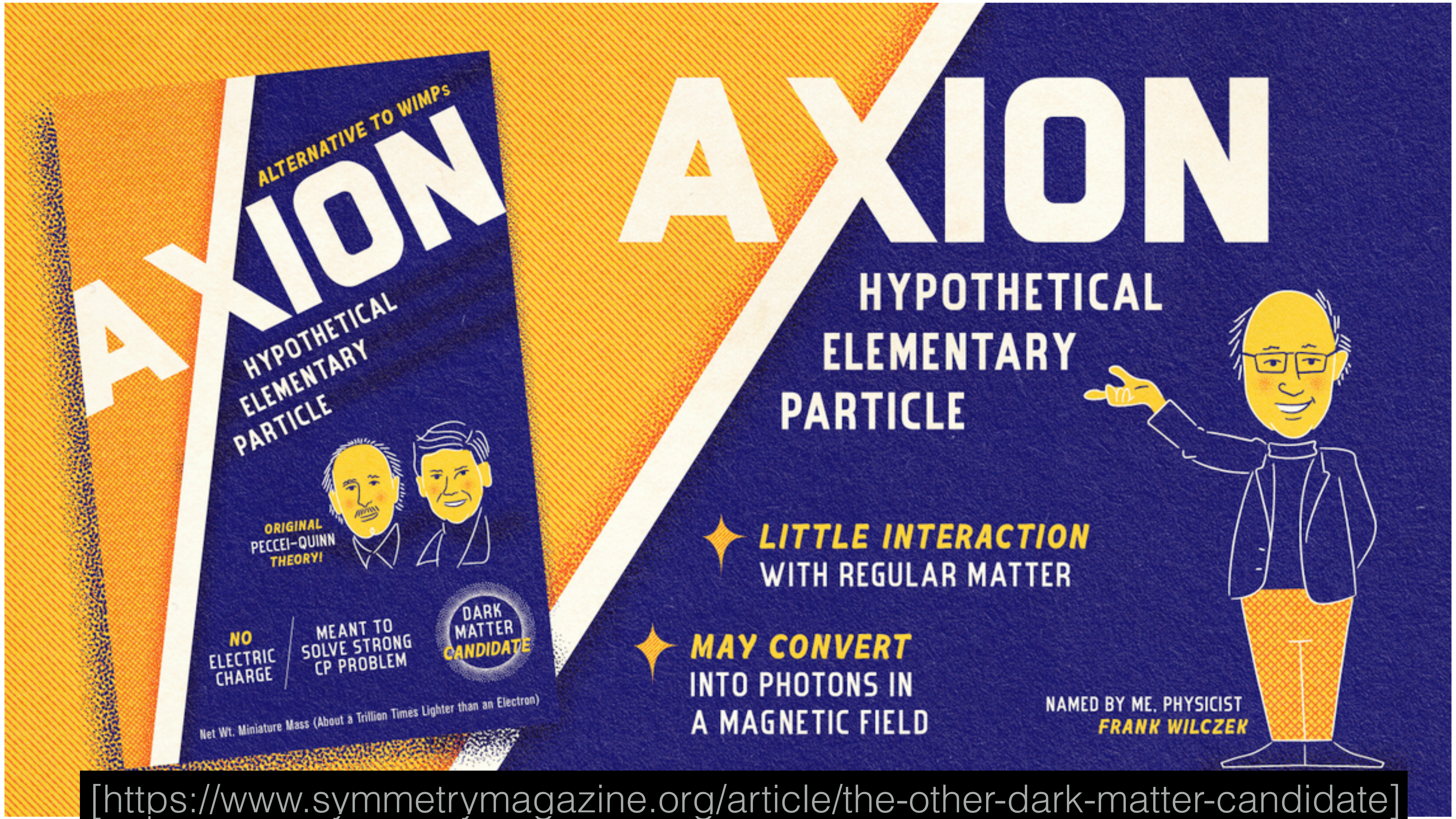
- Two benchmark models:
  - **KSVZ**: Heavy, electrically neutral, quarks carrying PQ charge
  - **DFSZ**: Quarks carry PQ charge, additional Higgs doublet needed



[source: https://github.com/cajohare/AxionLimits]

Axion Like Particles

- Dropping requirement to solve strong CP problem:
  - No strict mass - coupling strength relation
  - Vast parameter space opens up
- Any new pseudo-scalar particle:
  - Qualitatively similar properties to QCD Axion
    ➡ Axion Like Particle (ALP)



[https://www.symmetrymagazine.org/article/the-other-dark-matter-candidate]

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  - Any new symmetry breaking ‘Higgs’-like field requires additional (pseudo)-scalar particles
  - e.g. **SUSY, GUT**
  - **String theories**:
    - Any theory predictions extra dimensions leads to the existence of ALPs

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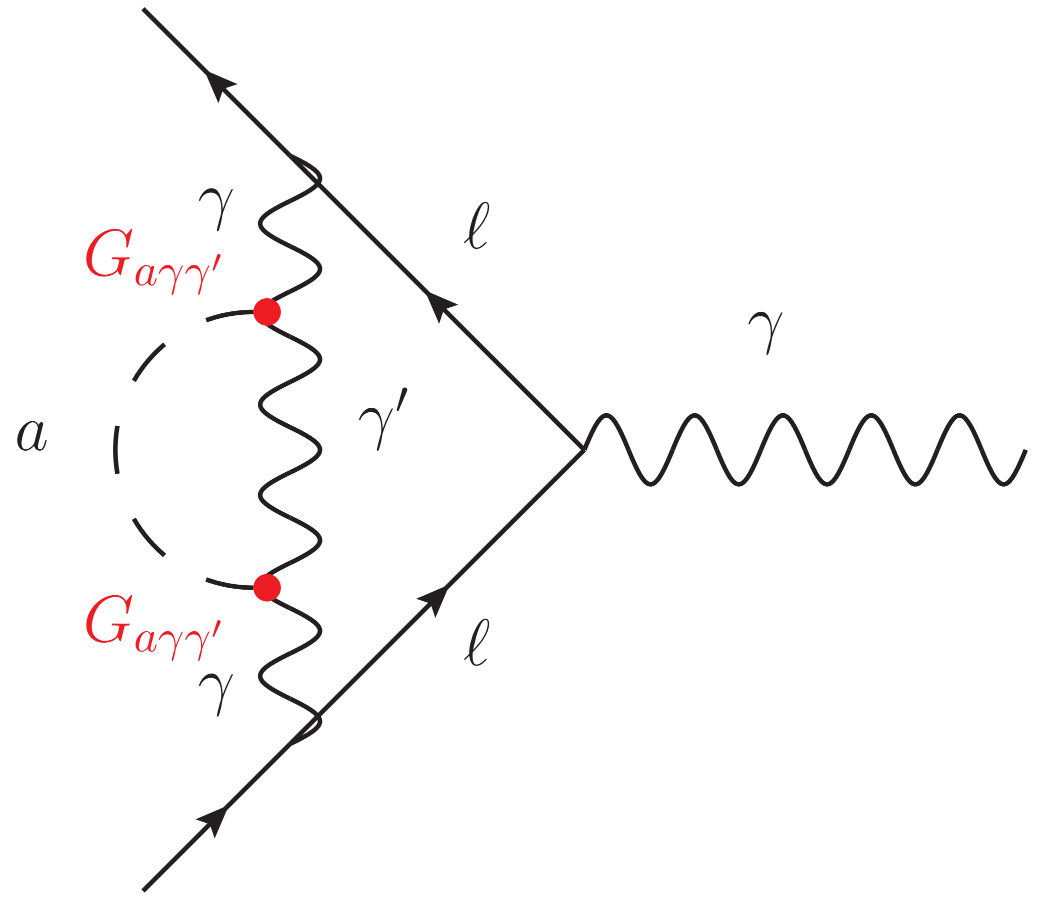
- Contributes to $(g-2)_\mu$
  - Debated in literature if it helps to solve the $(g-2)_\mu$ discrepancy



- **Axions could be Dark Matter!**

ALPs as Dark Matter

- Axions follow Bose-Einstein statistics

- Ensemble of light axions:
  macroscopic, wave-like behaviour
  - **Acts as cold dark matter**

- $m_a > 10^{-22}$ eV, otherwise no structure formation possible

- QCD axions:
  - $m_a < 2 \cdot 10^{-2}$ eV from neutrino flux of SN1987A

- No upper bound on mass of ALPs

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- Assuming all of DM is QCD Axions: Predict it's mass

  - Depends on production mechanism

  - Generation in strings and domain walls
    - Computationally difficult:

  - no ab initio calculation possible
    ➡ **model dependent results**

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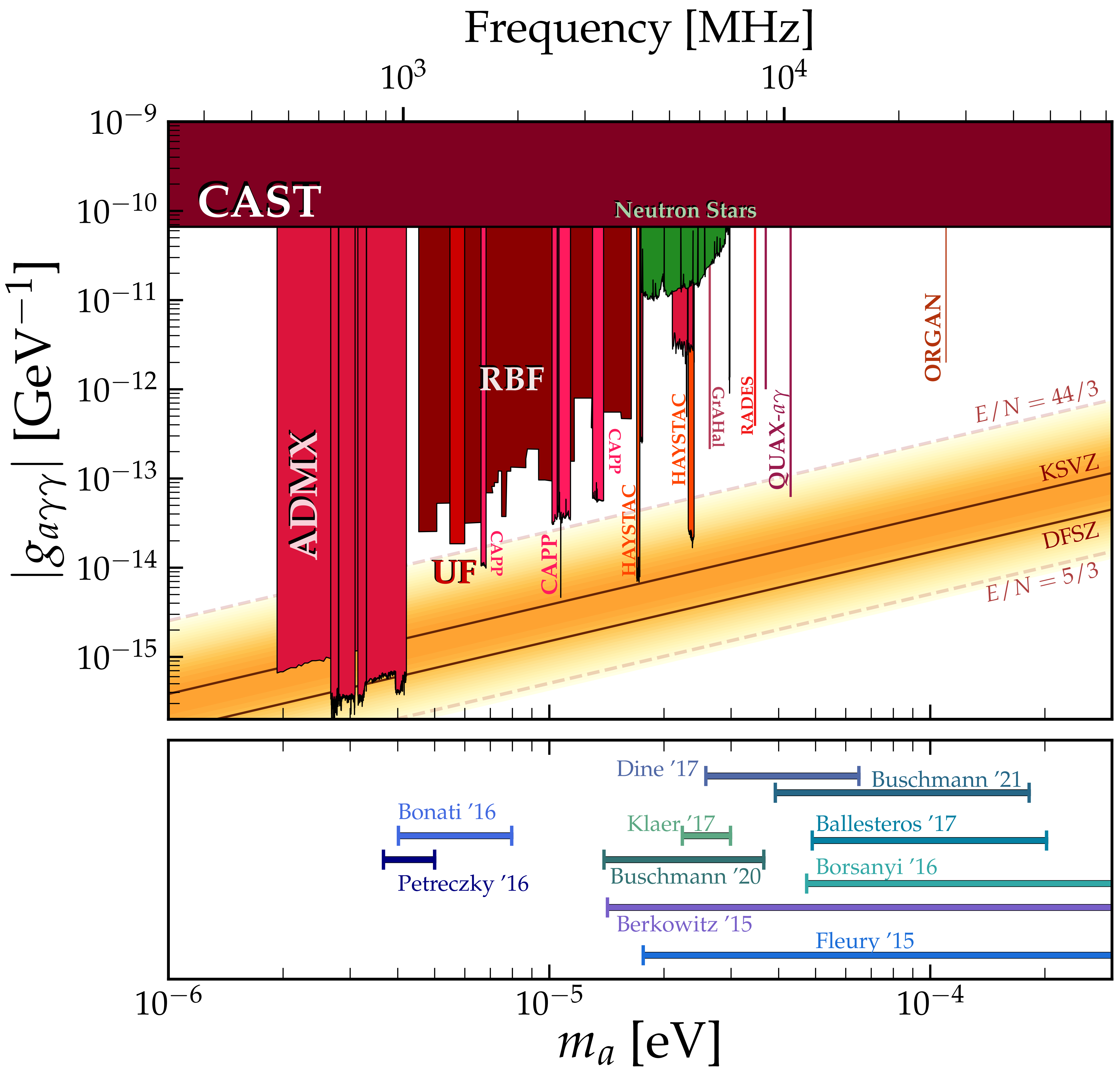

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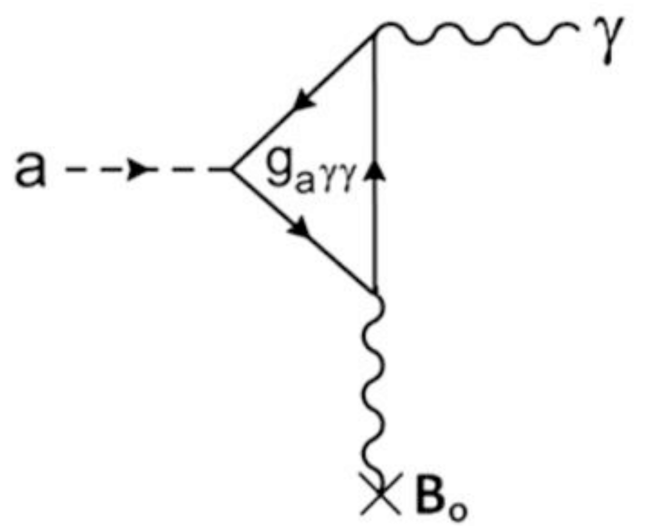
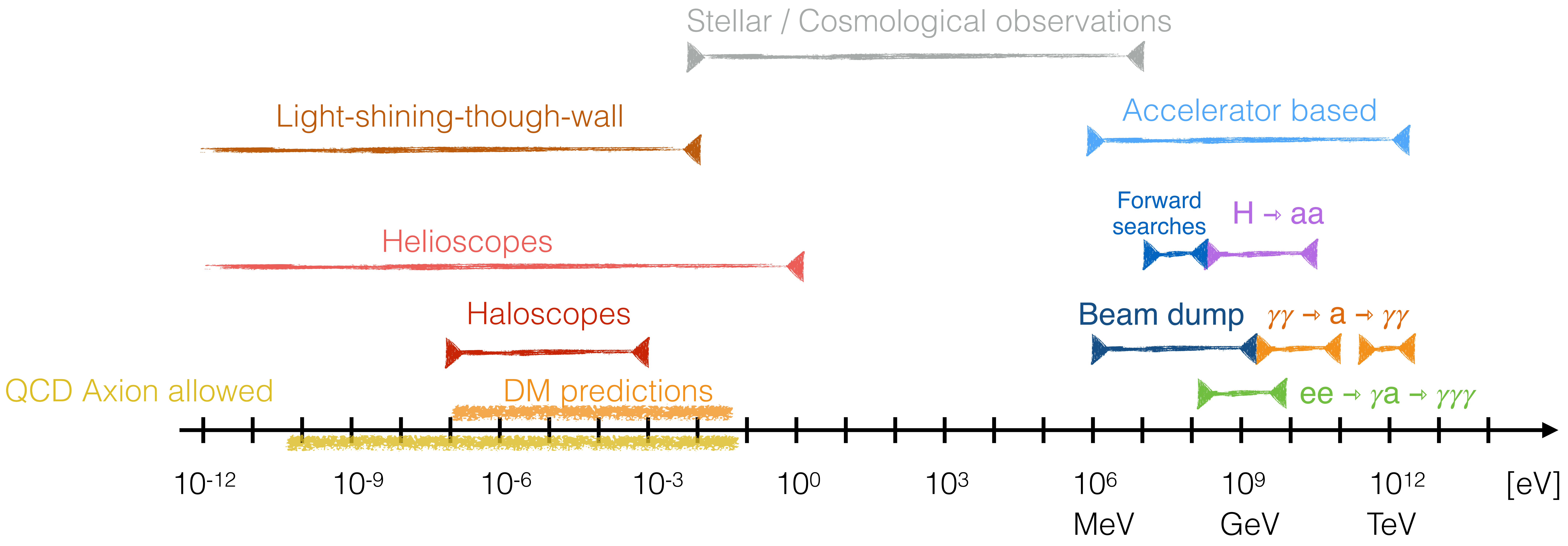
Parameter Space for ALPs

- Light axions:
- Conversion to photon in magnetic field
  (Primakoff effect)



- Heavy axions:
  - All couplings studied at collider experiments


Stellar / Cosmological observations

Light-shining-though-wall

Accelerator based

Forward searches

H → aa

Helioscopes

Haloscopes

Beam dump

$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$

QCD Axion allowed

DM predictions

ee → $\gamma a \rightarrow \gamma\gamma\gamma$

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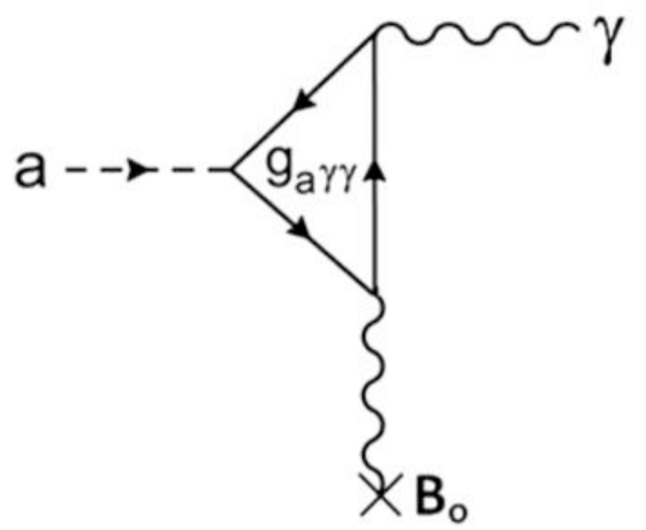

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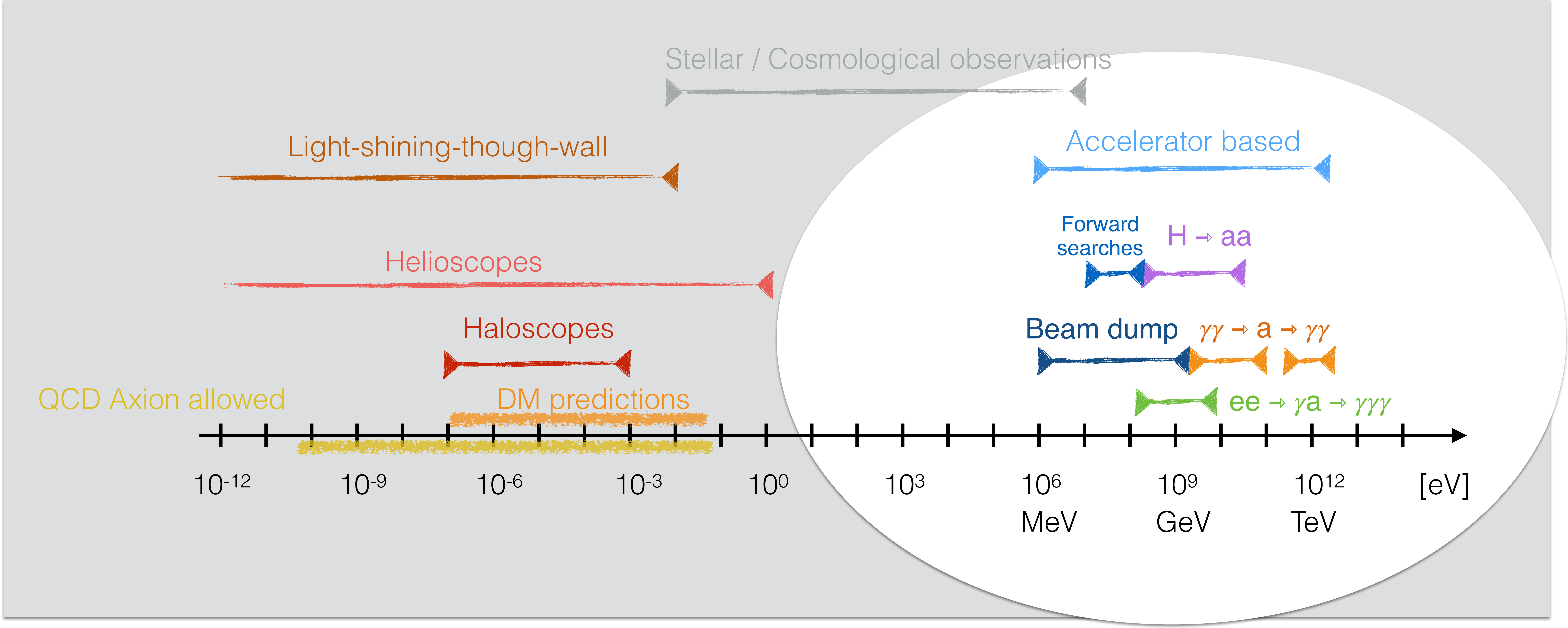
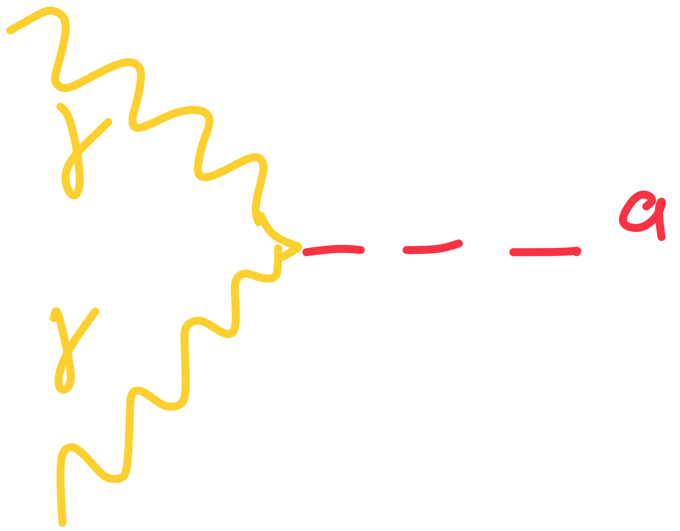


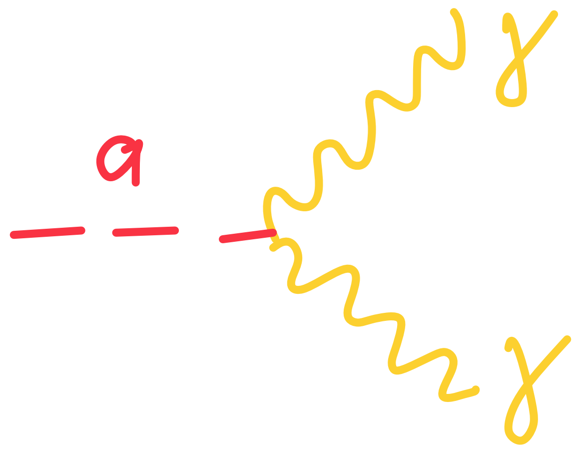
Heavy axions - Collider Based Searches - Photons

- **Production modes (at the LHC):**

Photon fusion



- **Decay channels considered**



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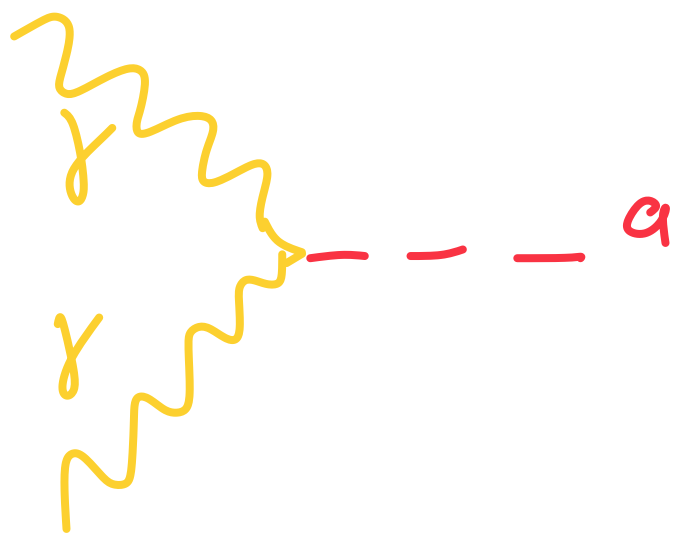

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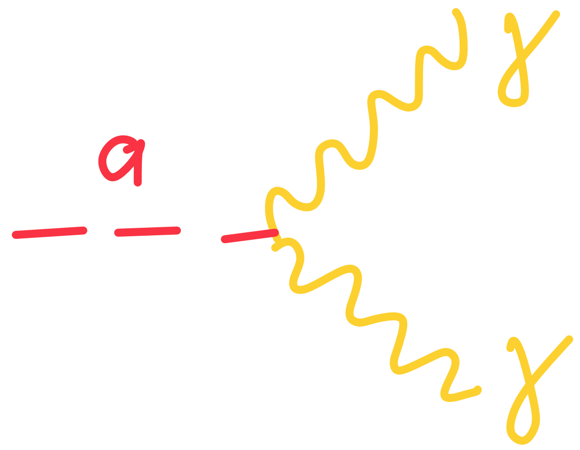

Photons

- Relativistic nuclei are an intense source of (quasi-real) photons
- Equivalent photon flux scales with Z^4
  - Pb beams at LHC are a superb source of high energy photons!

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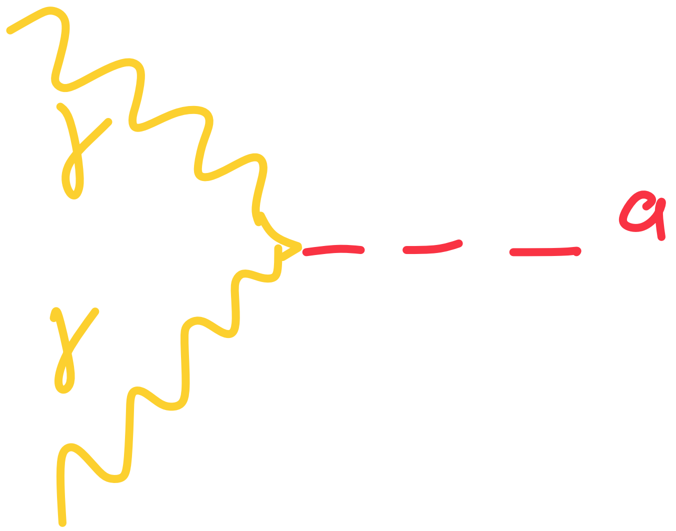

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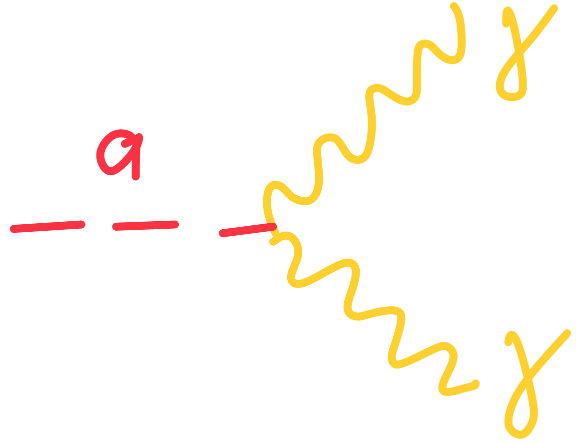

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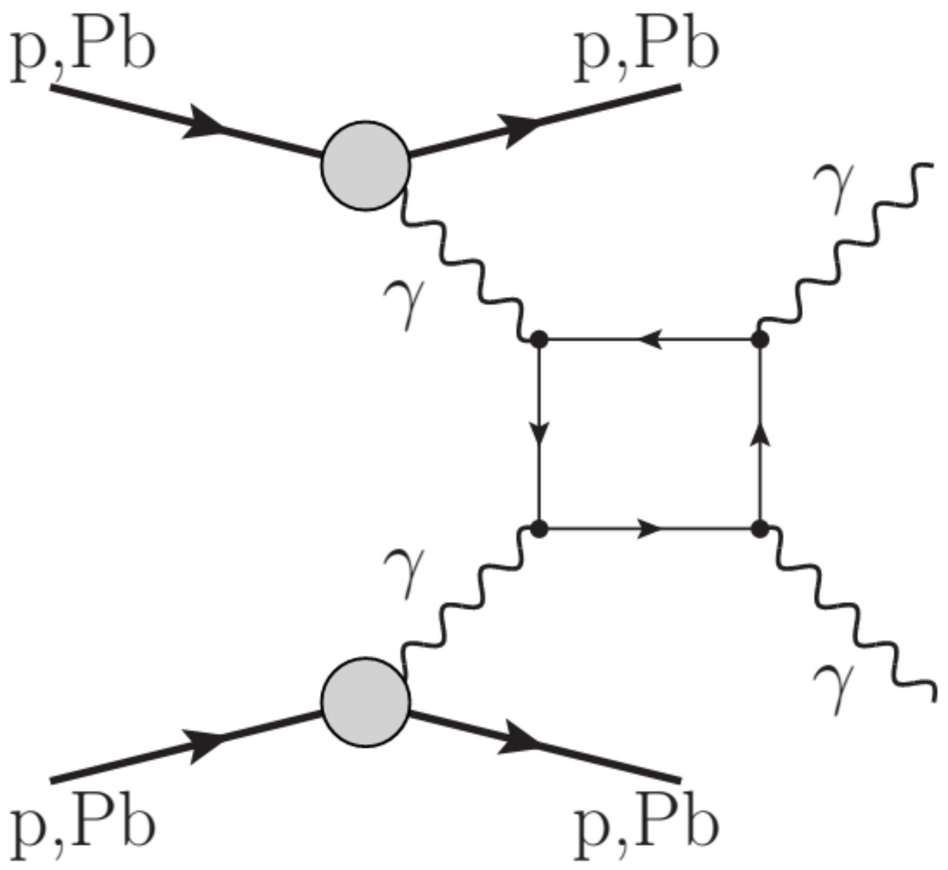
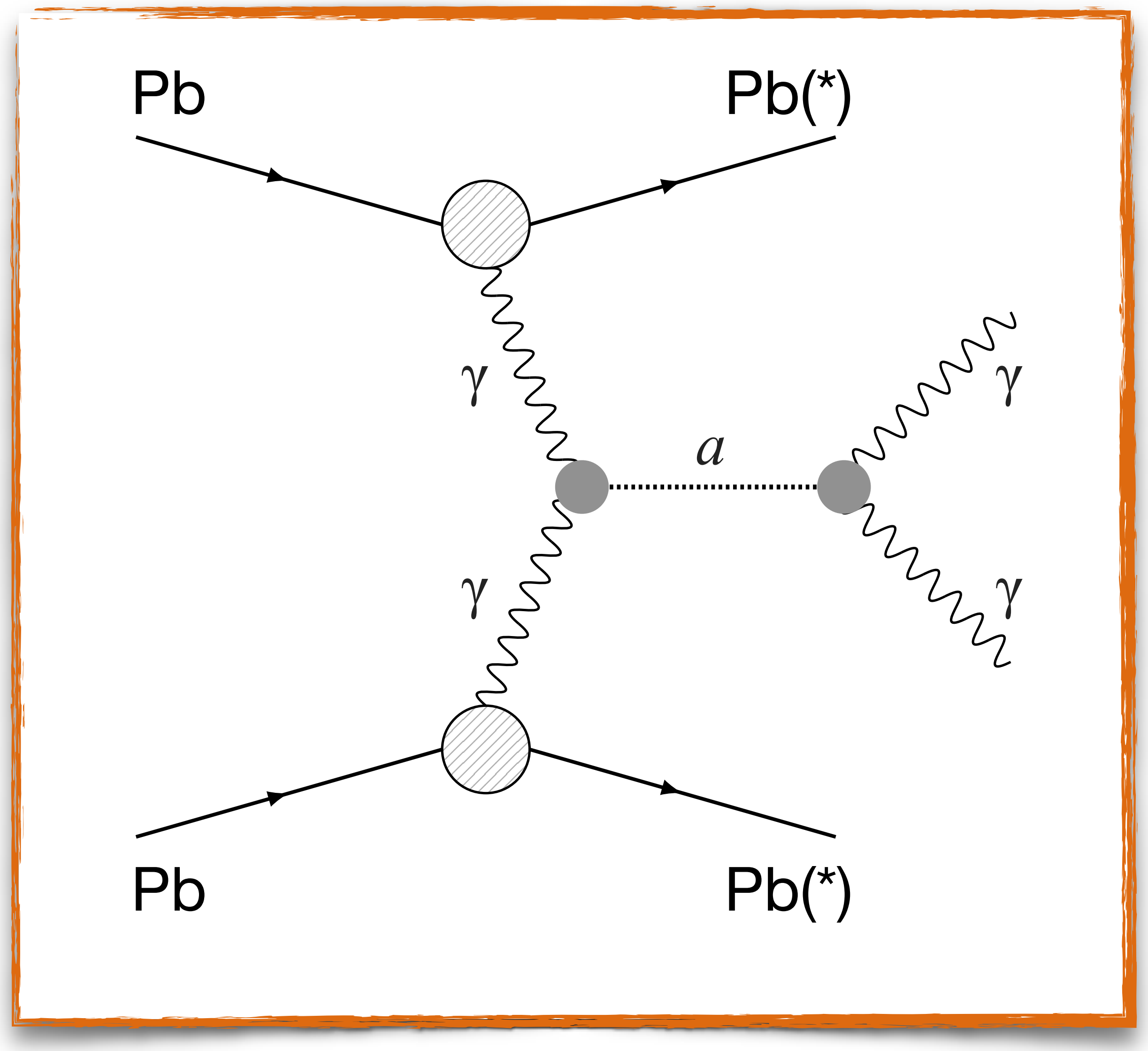
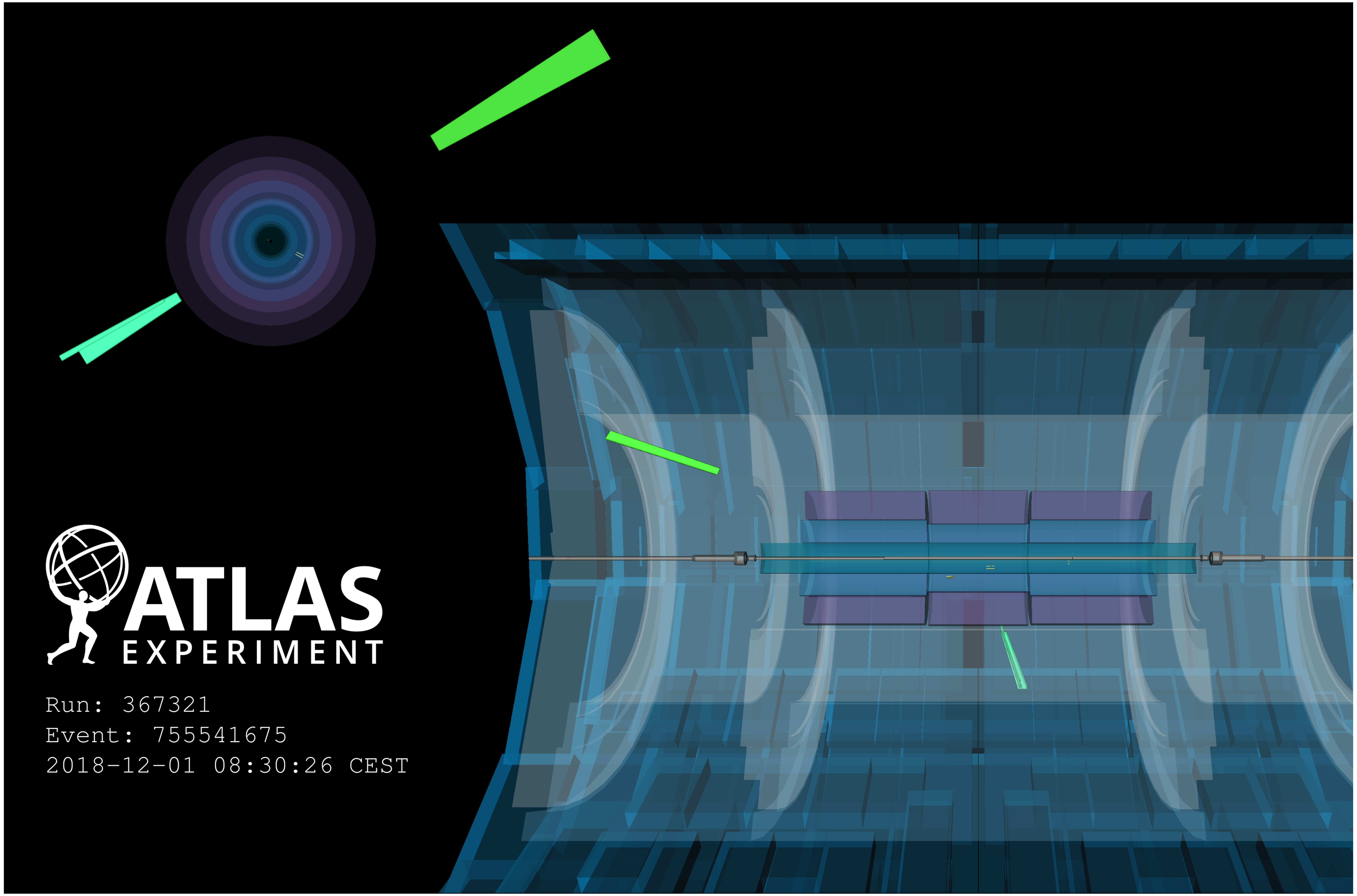




- **Beam particles stay intact**

- First proposal to measure LbyL scattering at LHC in 2013:
  [D. d'Enterria, G. G. da Silveira Phys. Rev. Lett. 111, 080405]

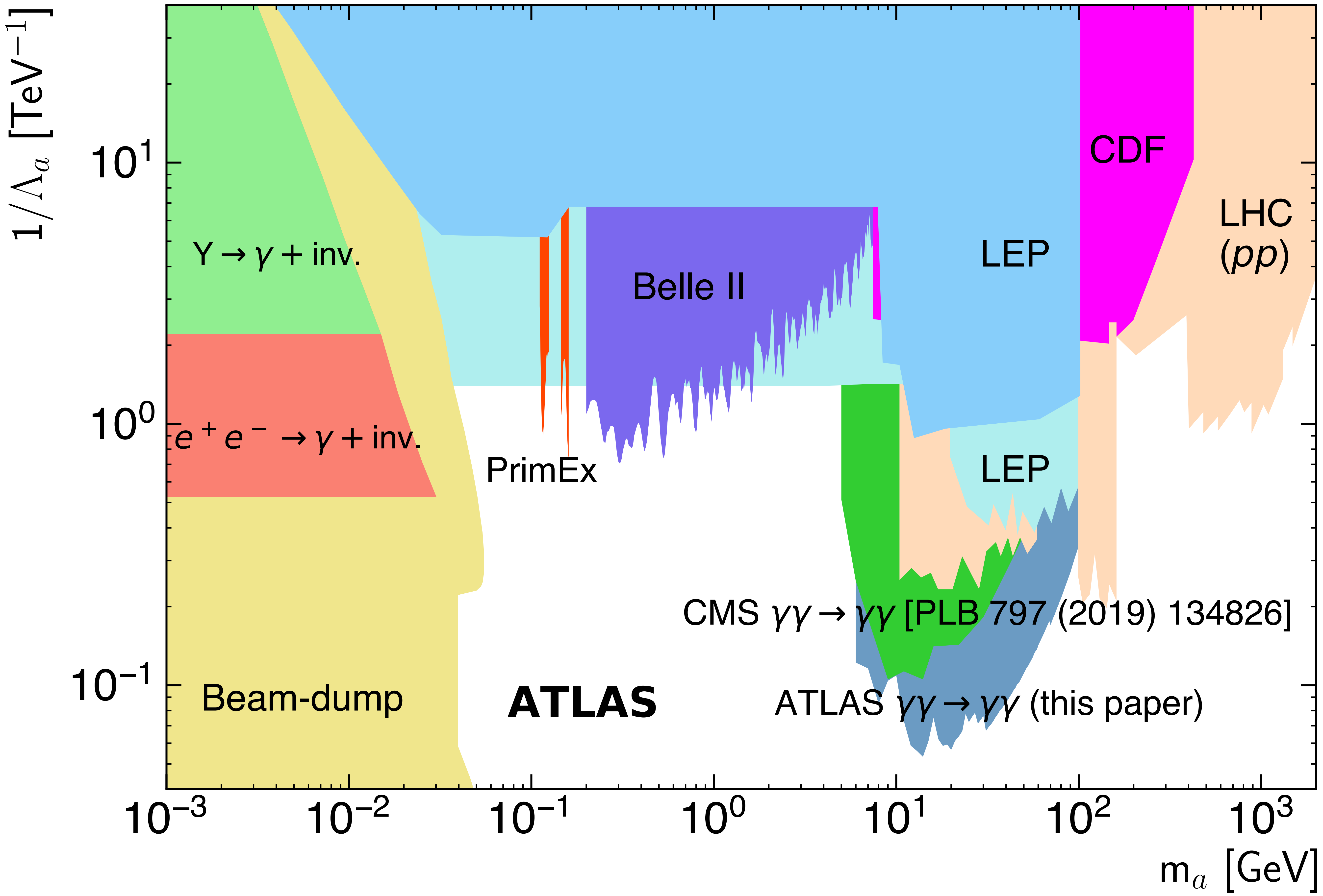
Heavy axions - Collider Based Searches - Photons

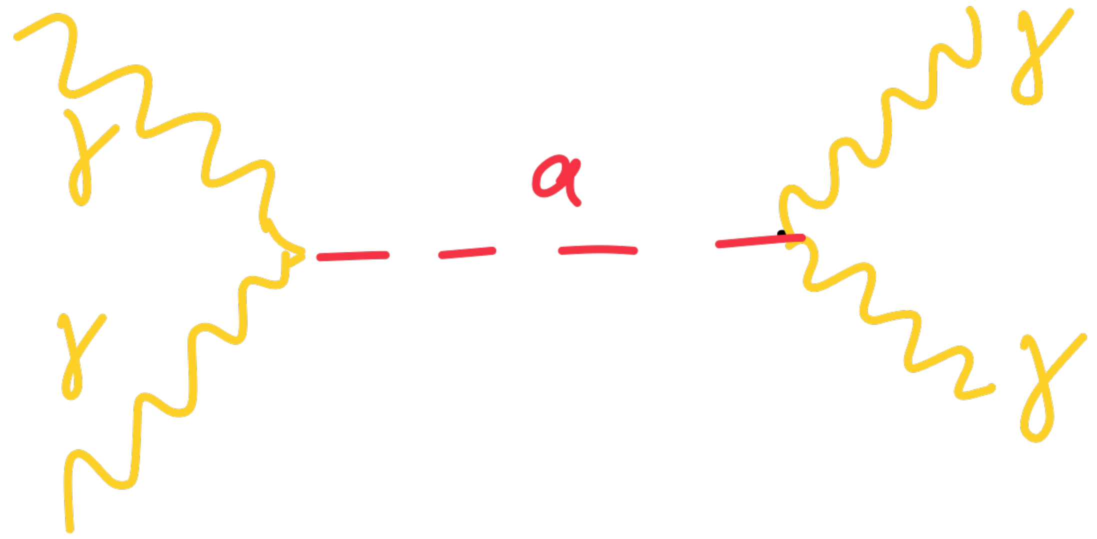


ATLAS HION-2018-19

Heavy axions - Collider Based Searches - Photons

Existing constraints from JHEP 12 (2017) 044





ATLAS: JHEP 03 (2021) 243

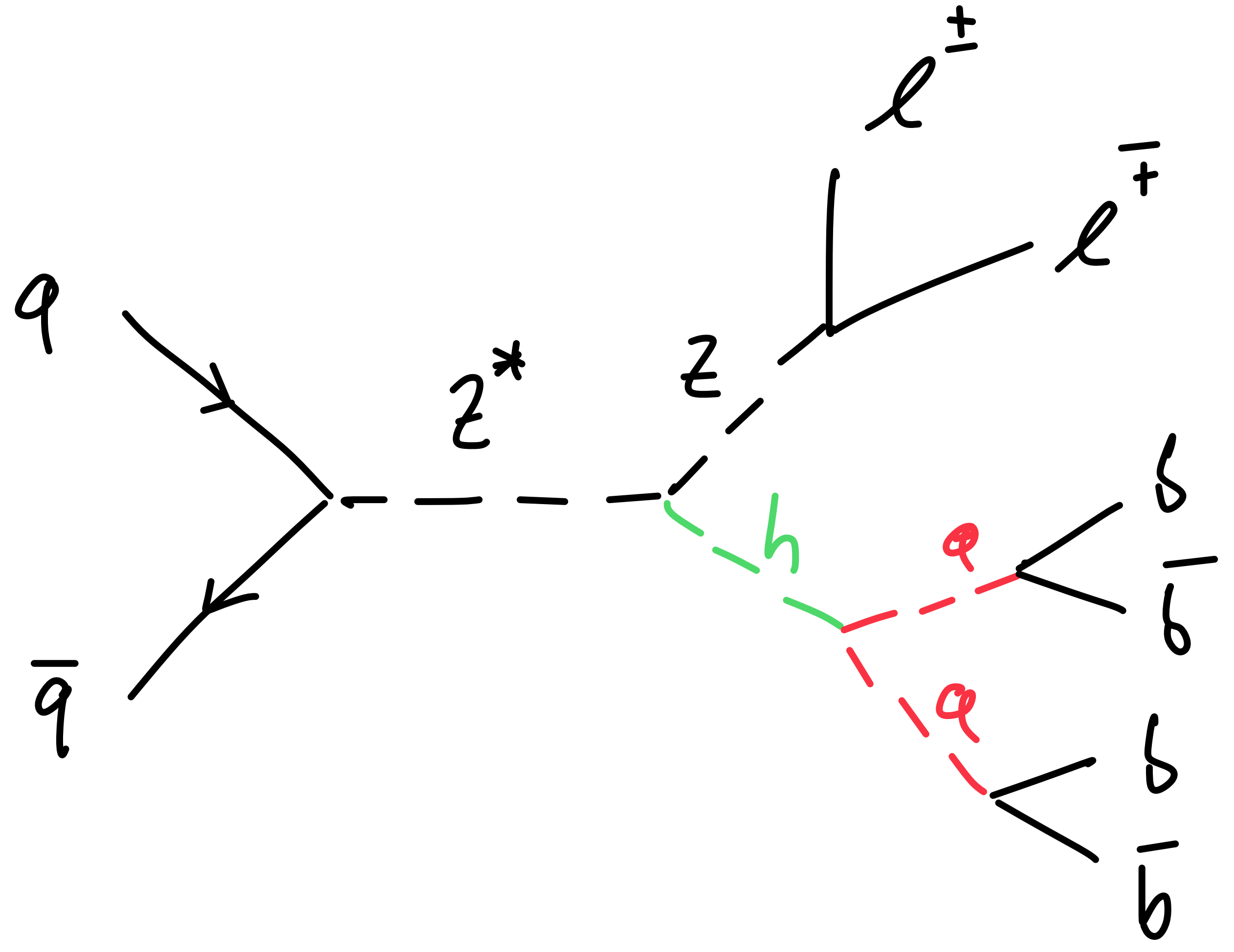
CMS Phys.Lett.B 797 (2019) 134826

ee → γa → γγγ

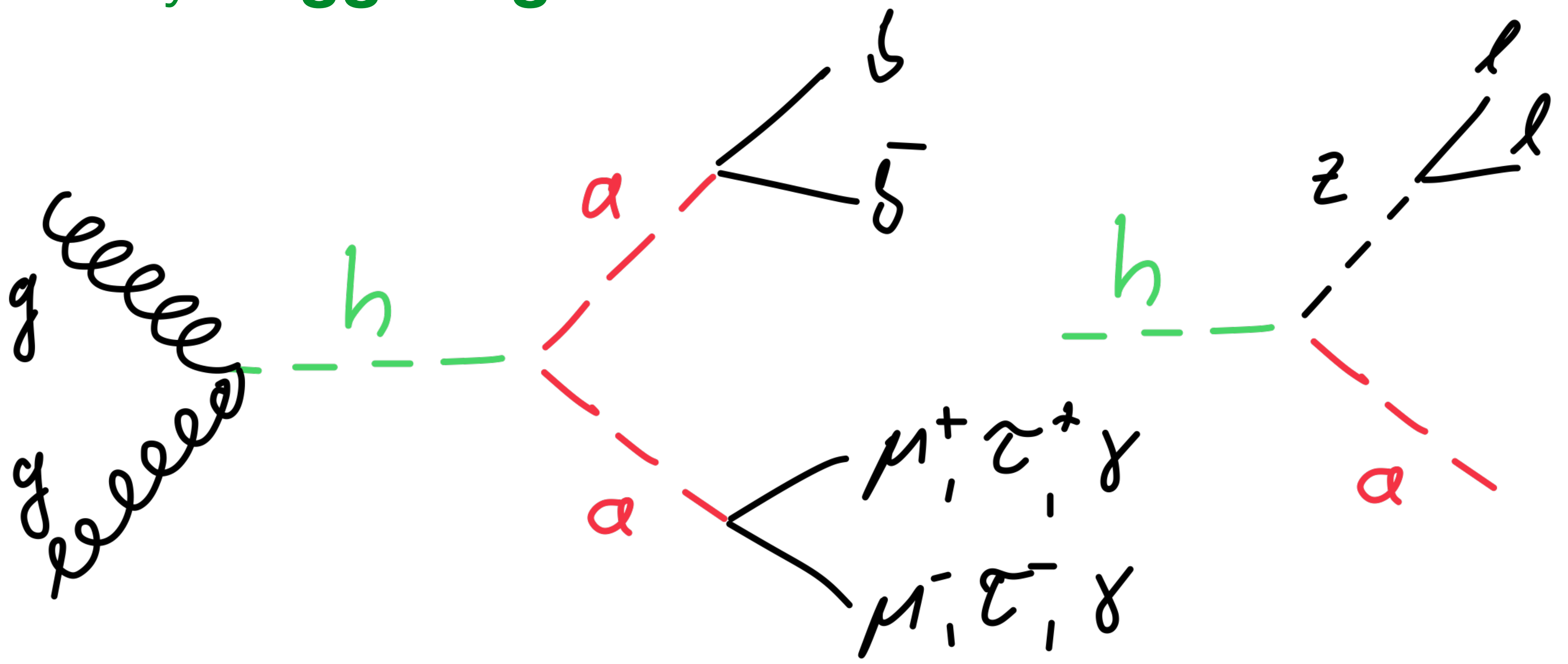
Belle II Phys. Rev. Lett. 125, (2020) 161806

- Prospects for run 3 + run 4:
  - 10 times more Lumi: 20 nb^{-1}
  - Slight increase in CME: 5.02 TeV -> 5.52 TeV
  - Limits on coupling would improve by factor 3
    - From $6 \cdot 10^{-2}$ to $2 \cdot 10^{-3}$

Heavy axions - Collider Based Searches - Higgs decays



- Associated Z boson:
  - Lepton final states considered
  - Easy **Triggering**



- pp → H vs. pp → ZH
  - 65 times larger cross section

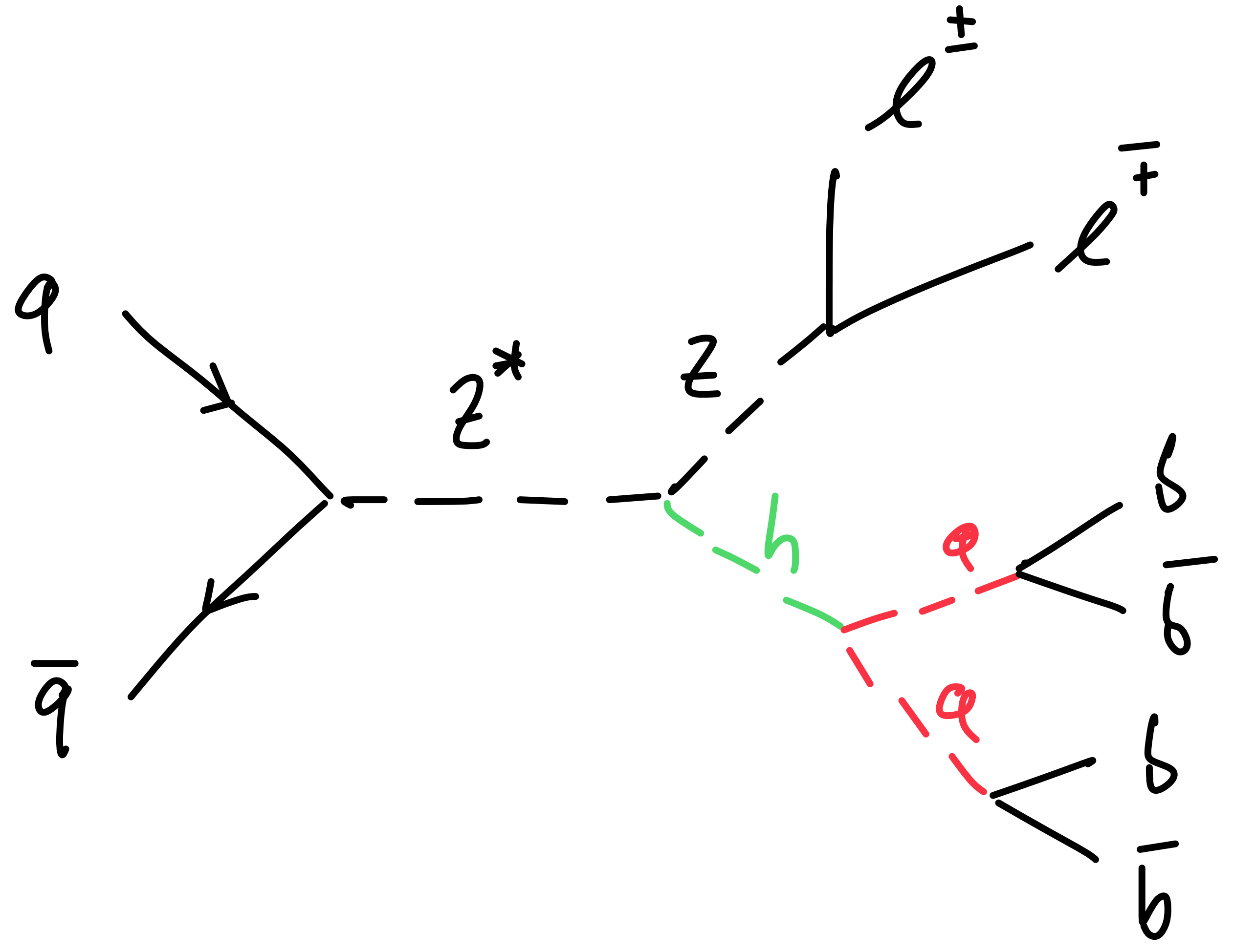
- If ALP is a pseudo scalar:
  - Yukawa interaction expected
  - B-quark / tau final states interesting
    - Large branching fraction
  - μ final states experimentally clean

a → bb

a → μμ

10x better mass resolution

Heavy axions - Collider Based Searches - Higgs decays



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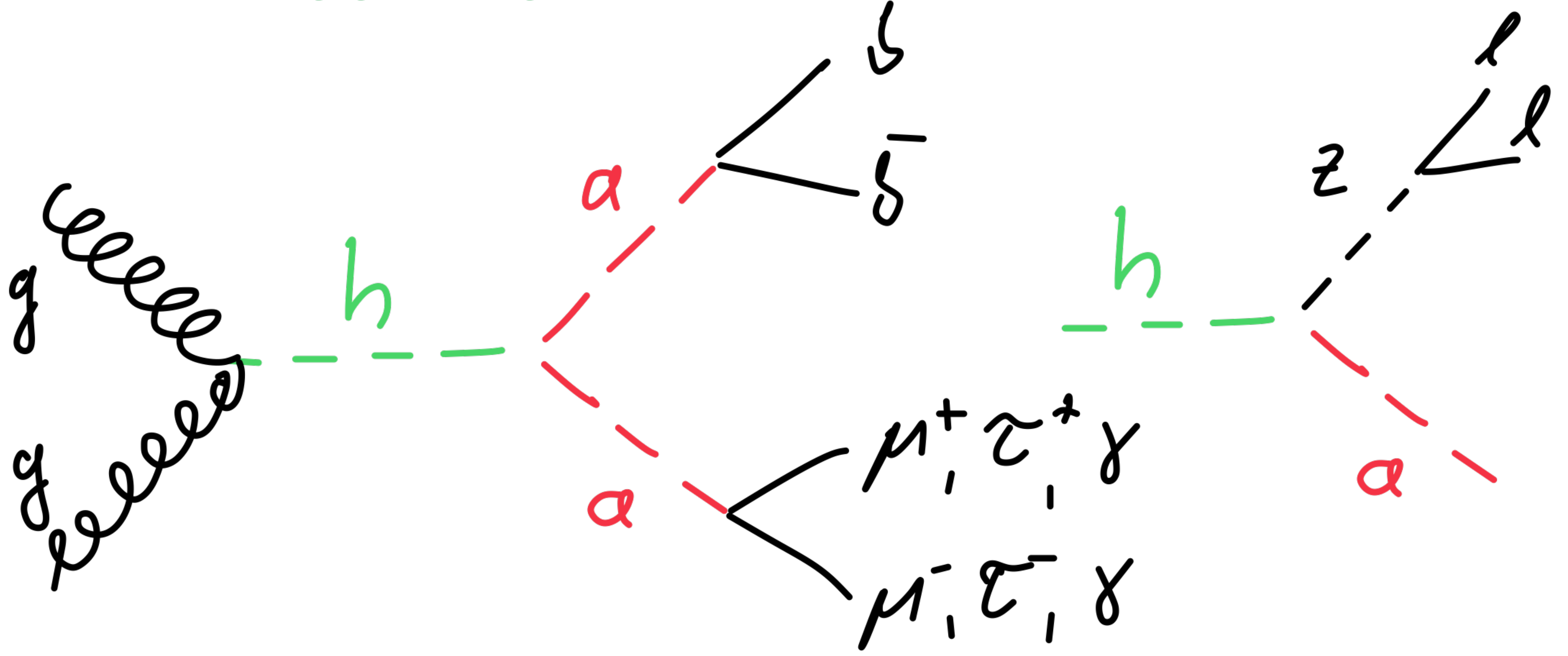

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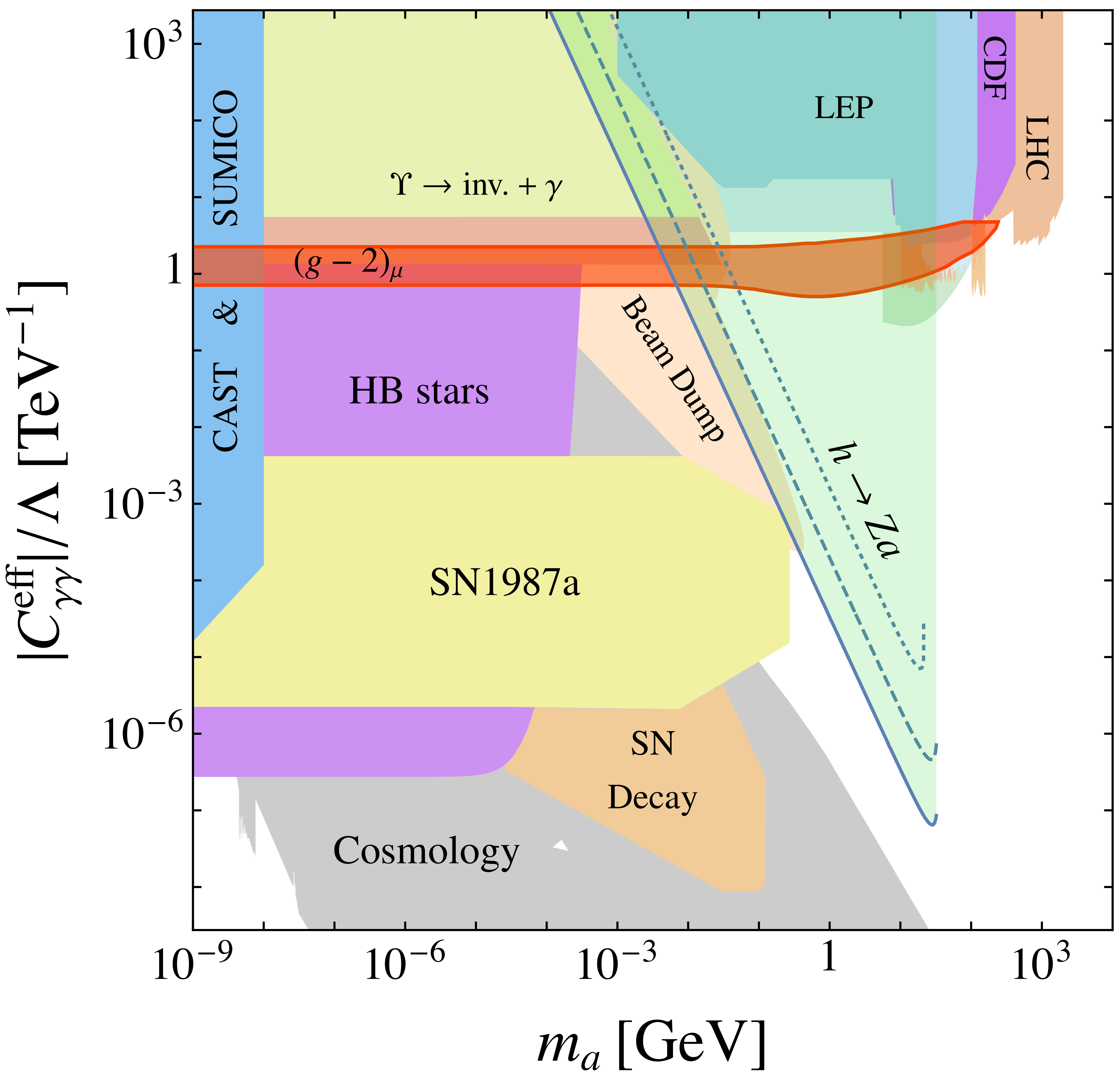
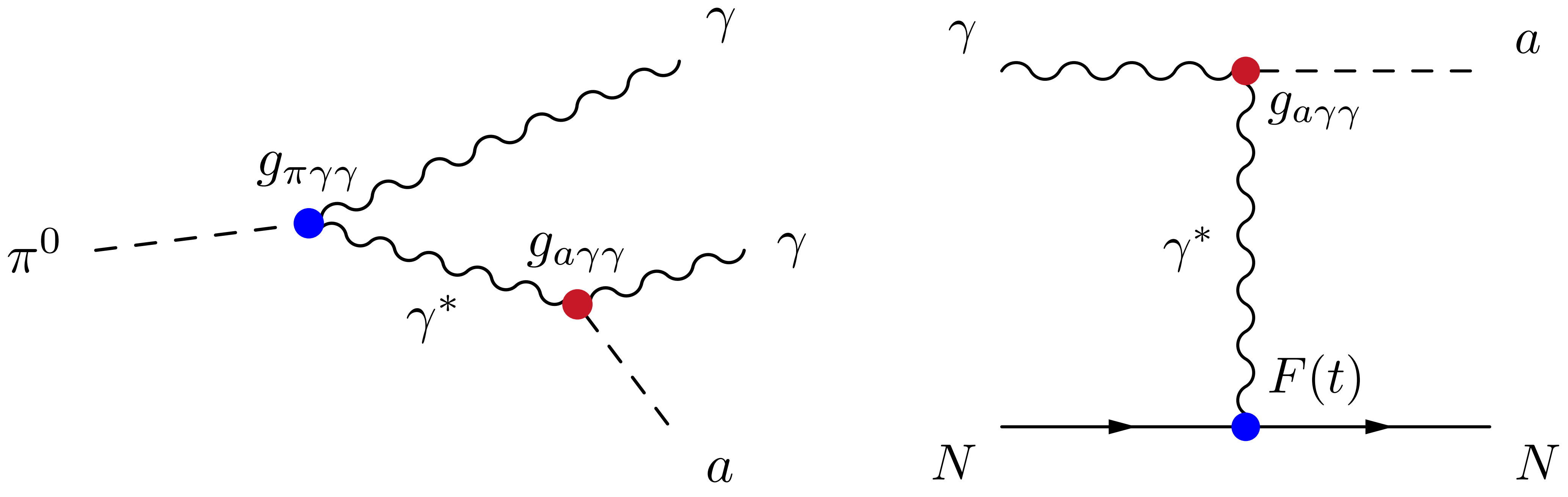


[M. Bauer et. al: arXiv:1708.00443]

Forward searches / beam dump experiments

ALP production
(Proton beams -> pions -> photons ->ALPs)



Instrumented beam dump:
Detection of missing energy / momentum

Absorber

ALP
Detection

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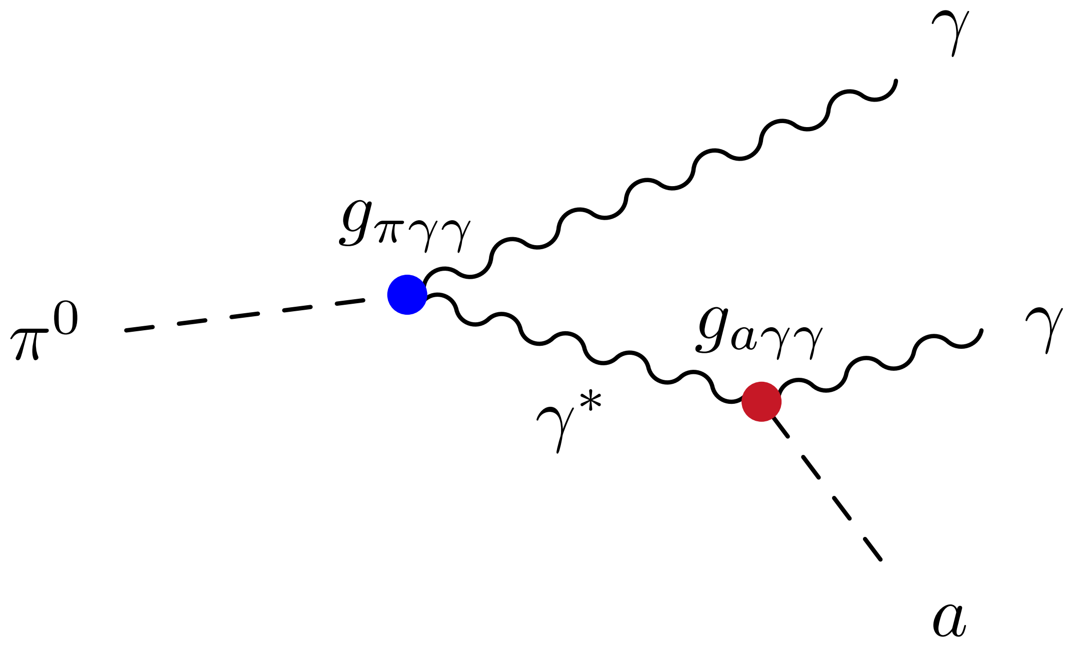
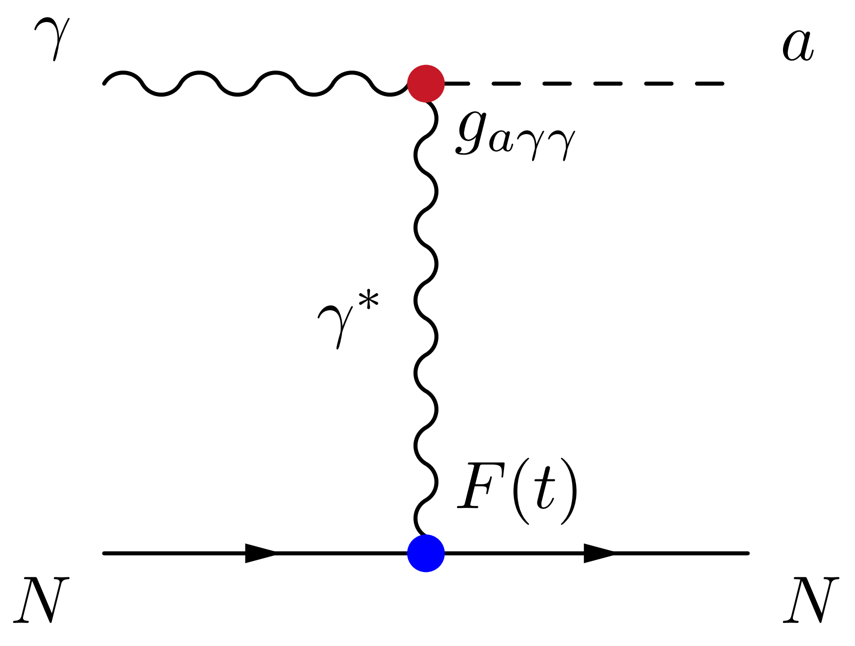
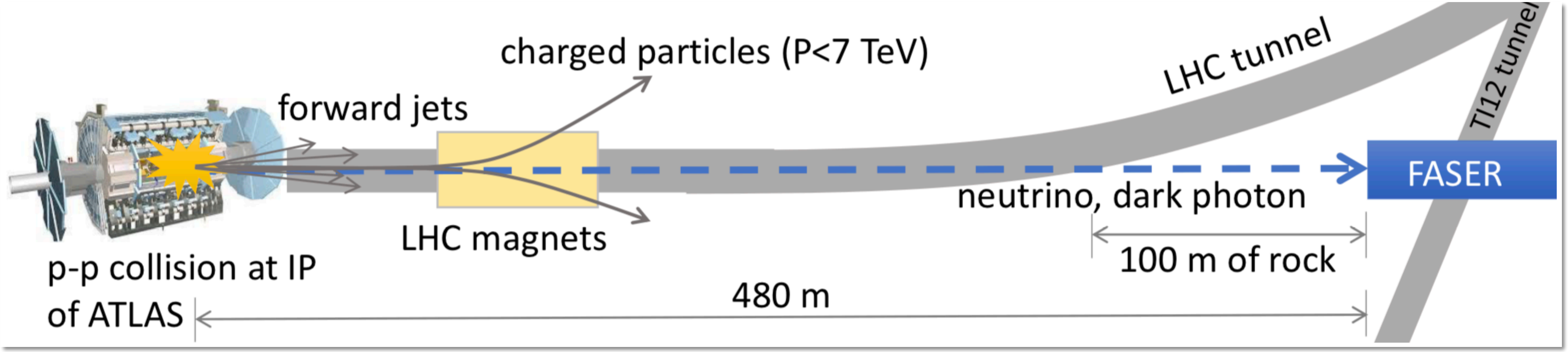




Absorber

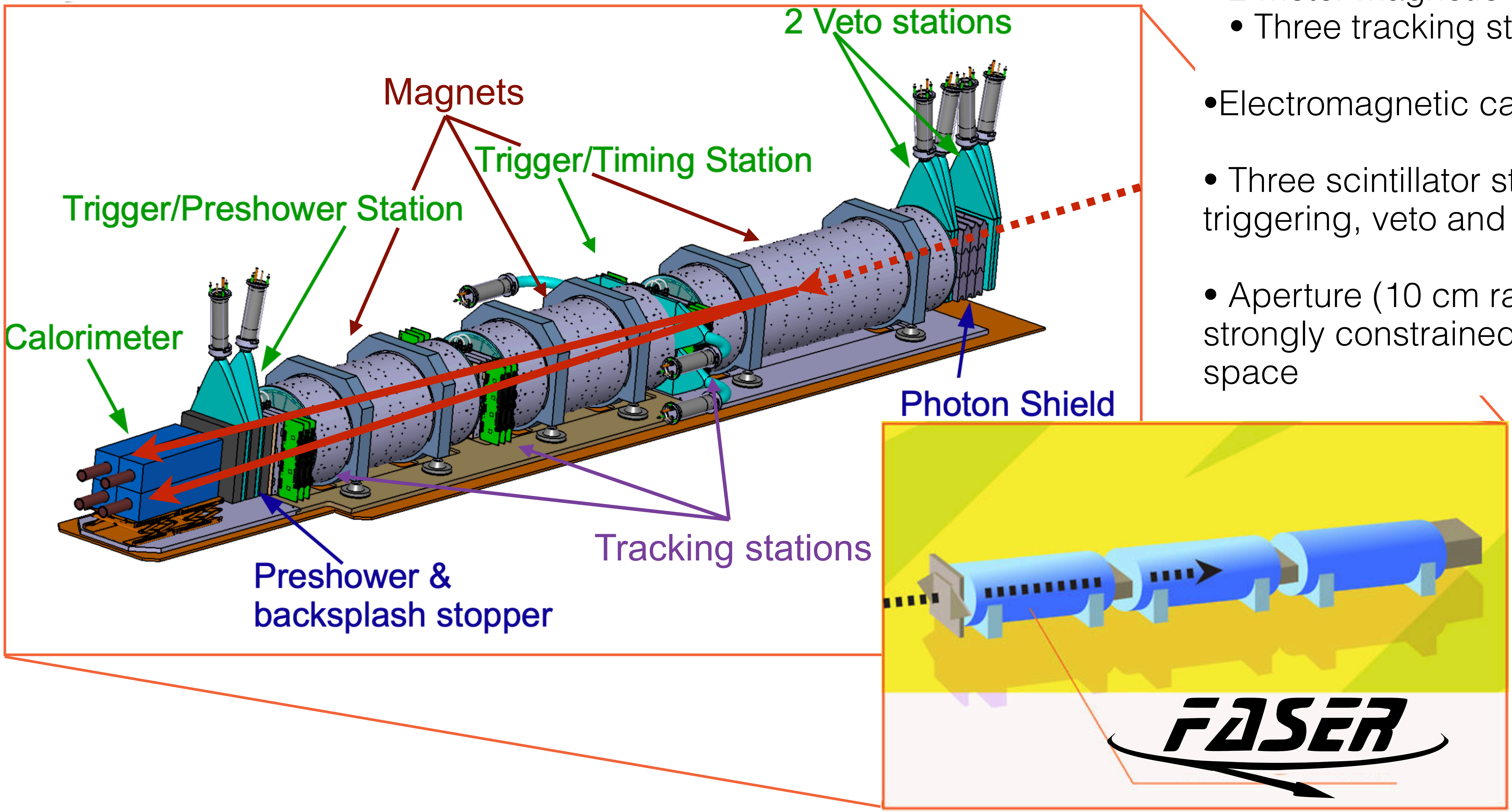
ALP Detection

- **FASER**: installation completed, data taking during LHC run-3



FASER detector

- 1.5-meter magnetized decay volume
- 2-meter magnetic spectrometer
  - Three tracking stations
- Electromagnetic calorimeter
- Three scintillator stations for triggering, veto and precise timing
- Aperture (10 cm radius) and length strongly constrained by available space



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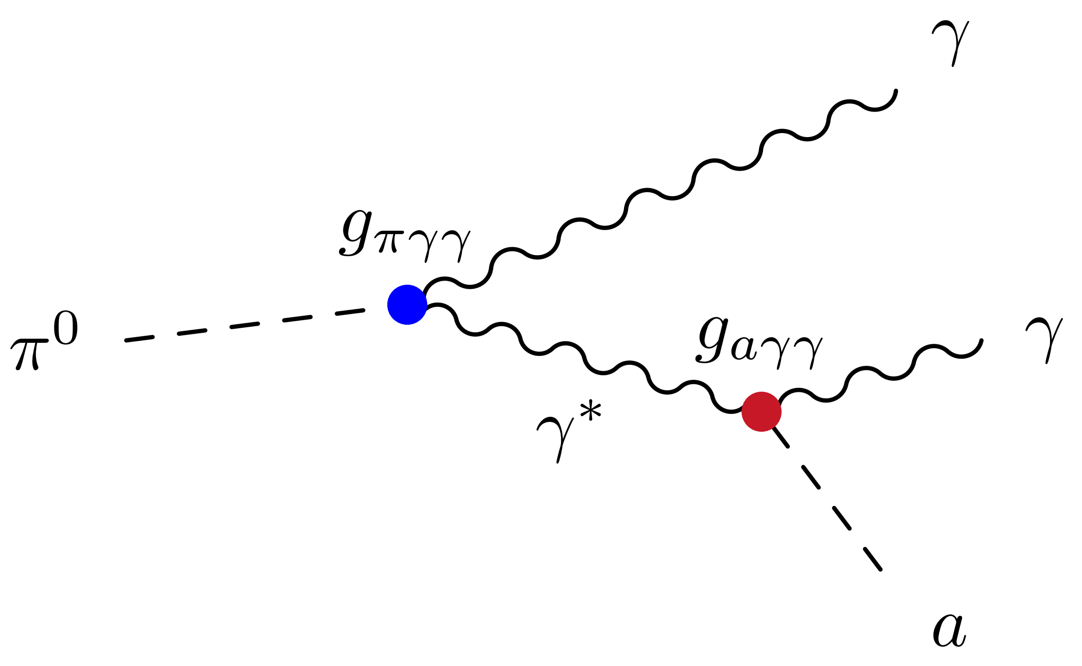
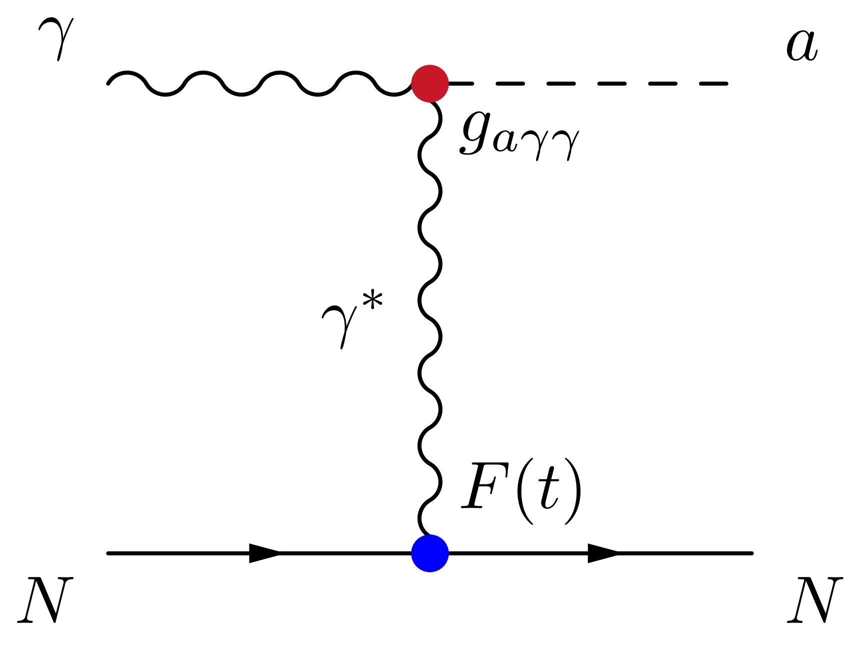
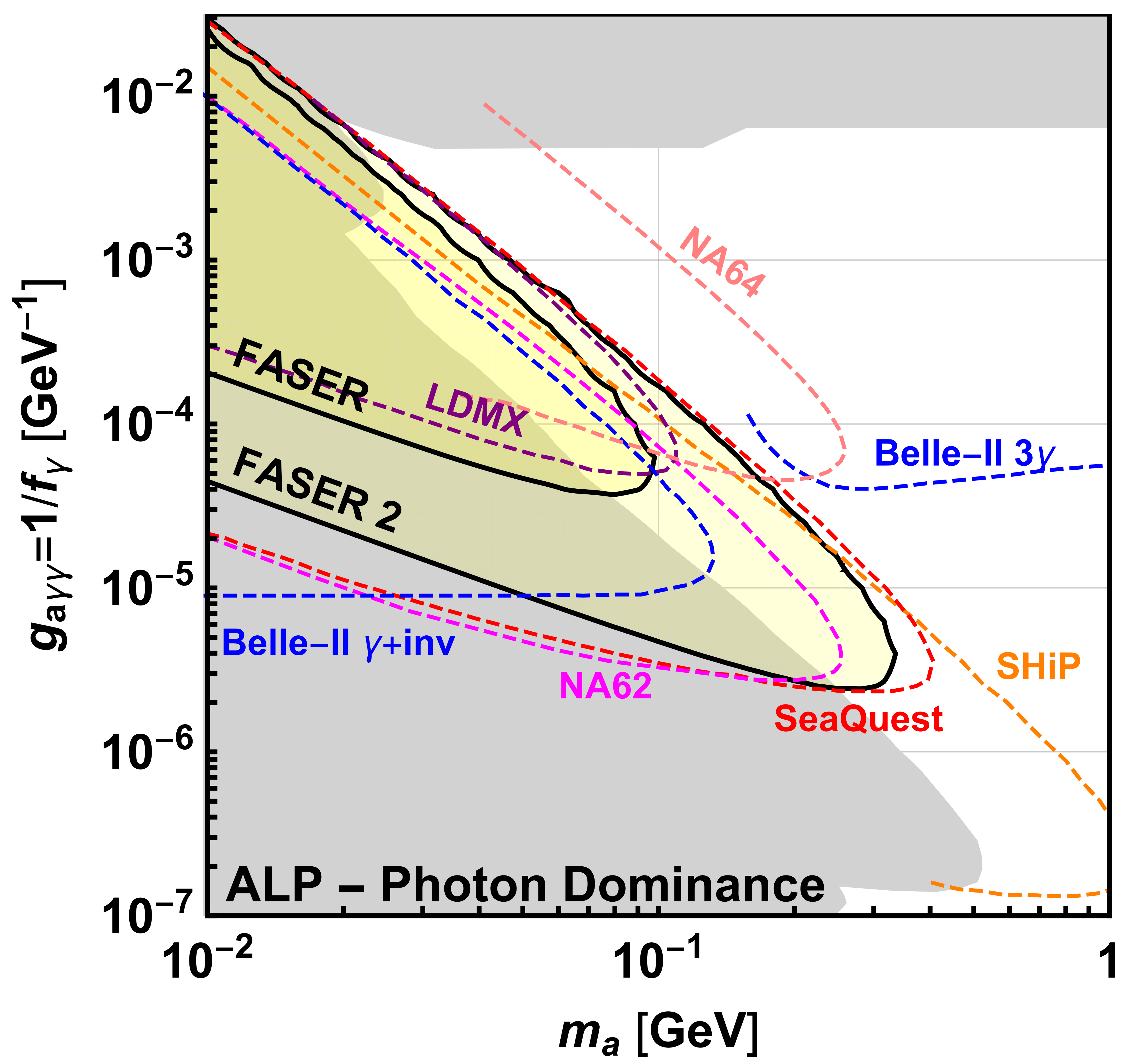


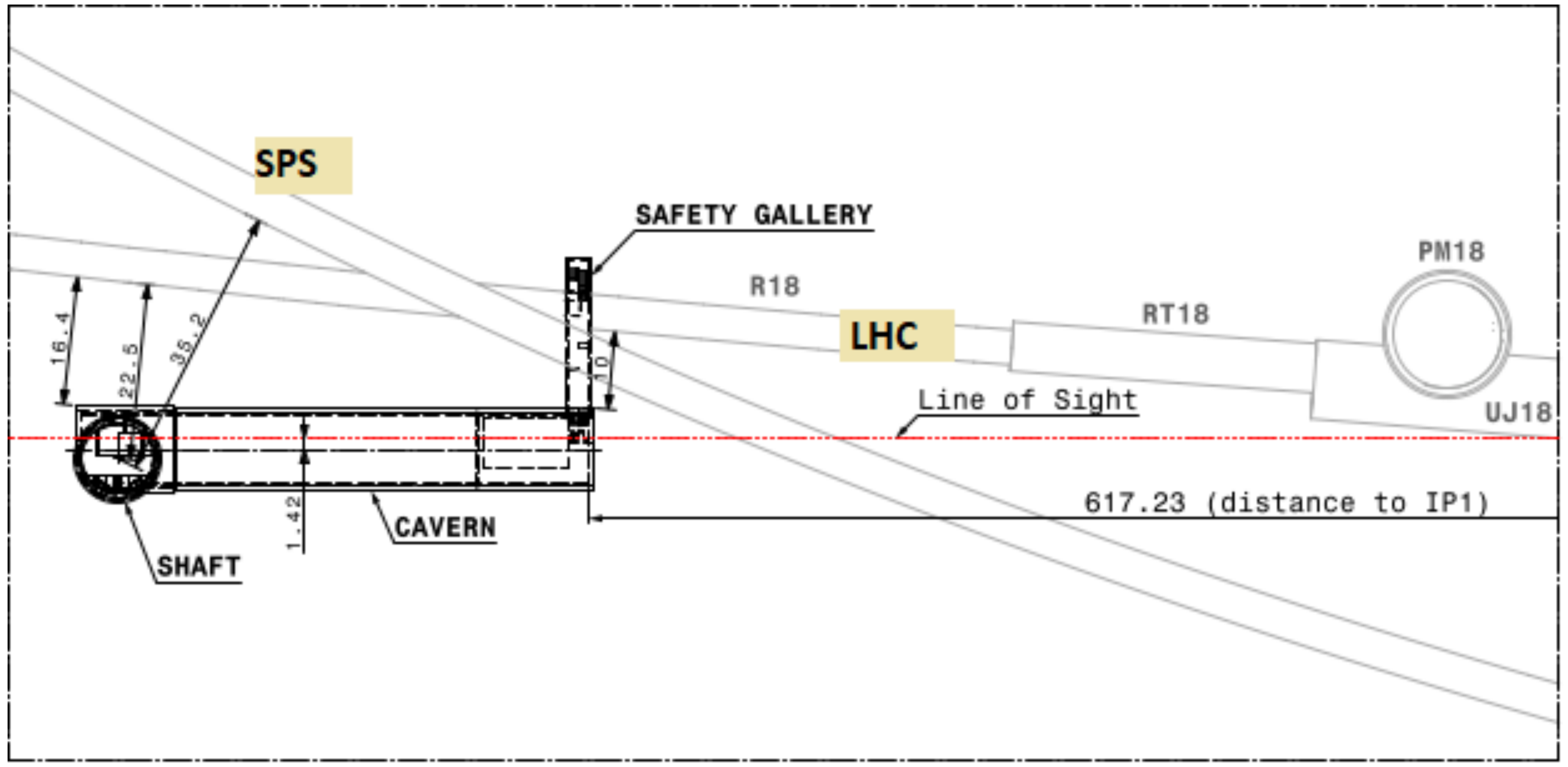


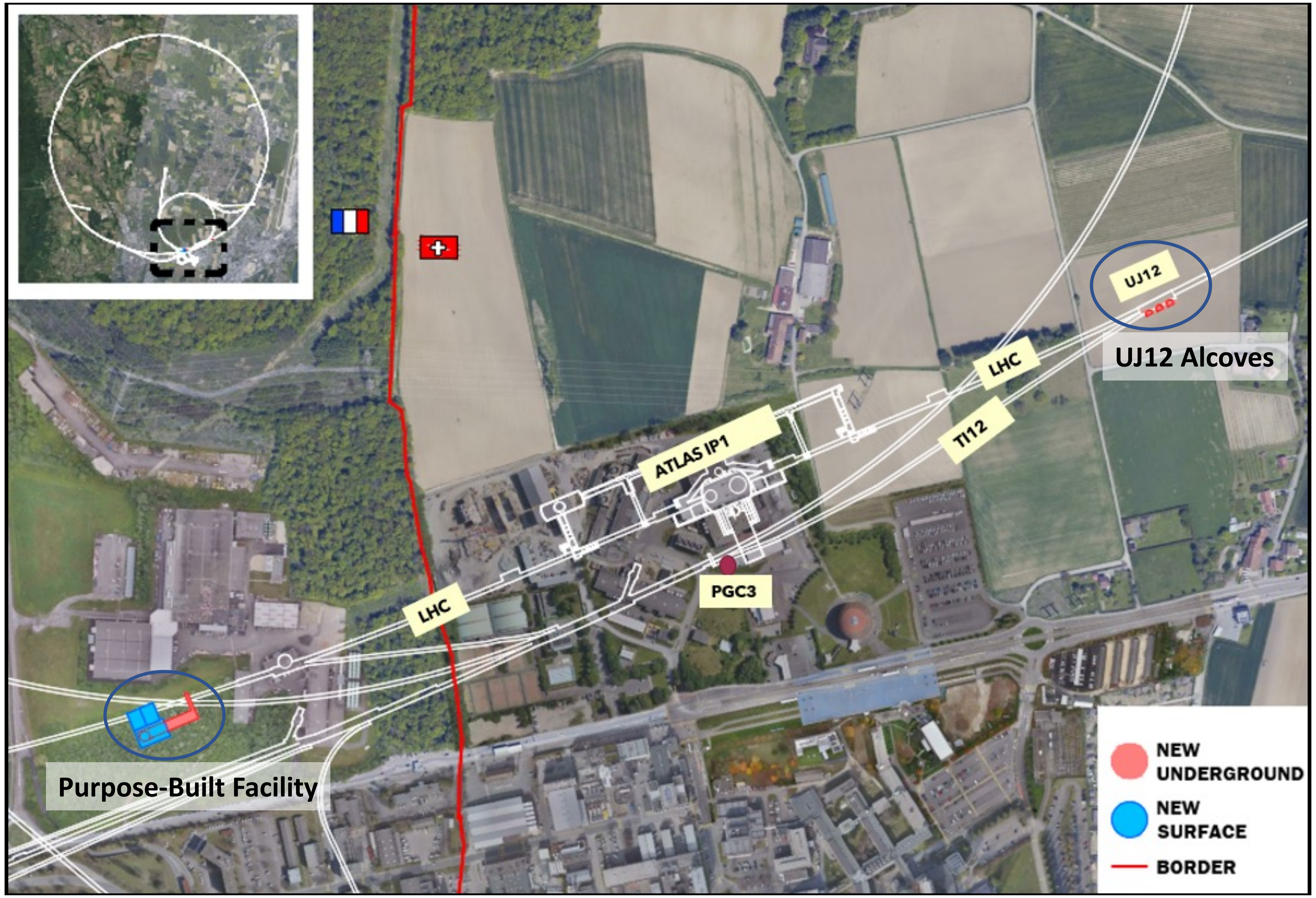
- Sensitivity: ~10 MeV < ma < ~100 MeV
- Several proposals for new experiments
- Similar physics reach to ALPs

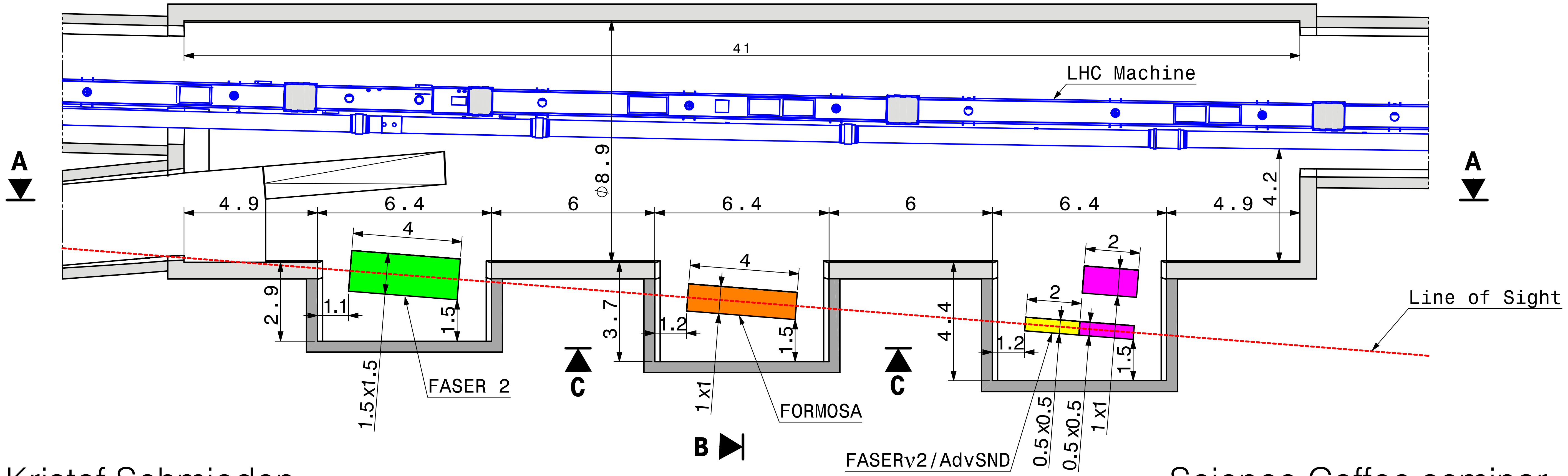


Phys. Rev. D 99, 095011

Forward physics Facility proposal

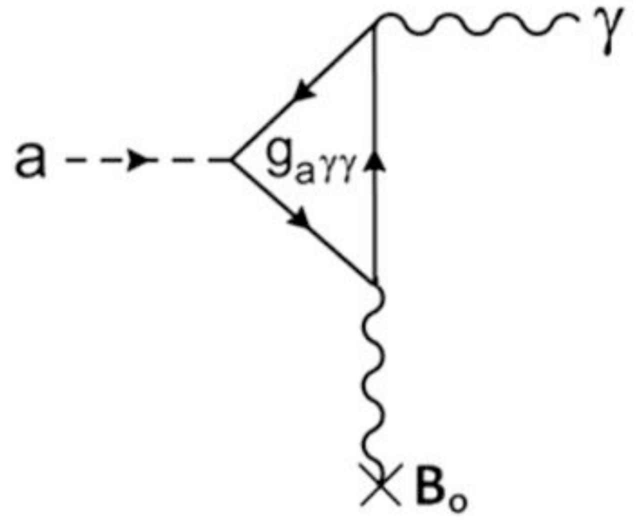


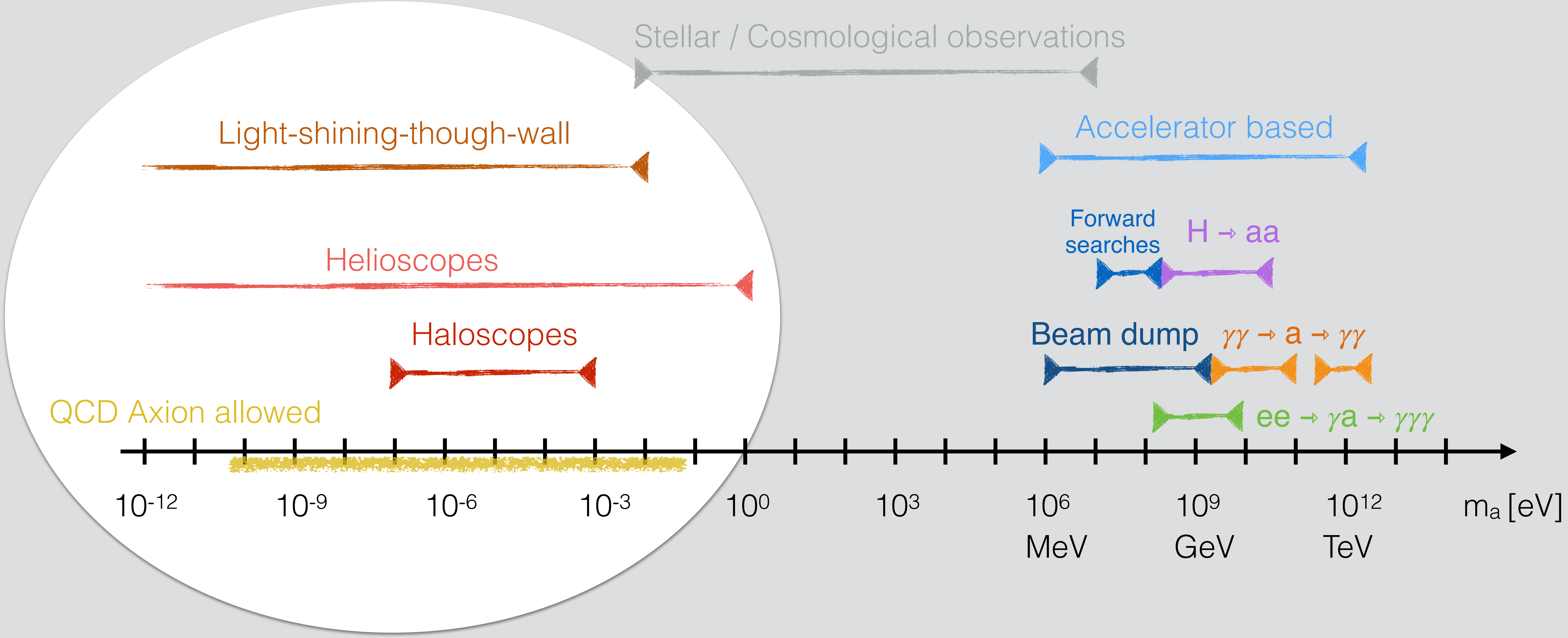




Light Axions

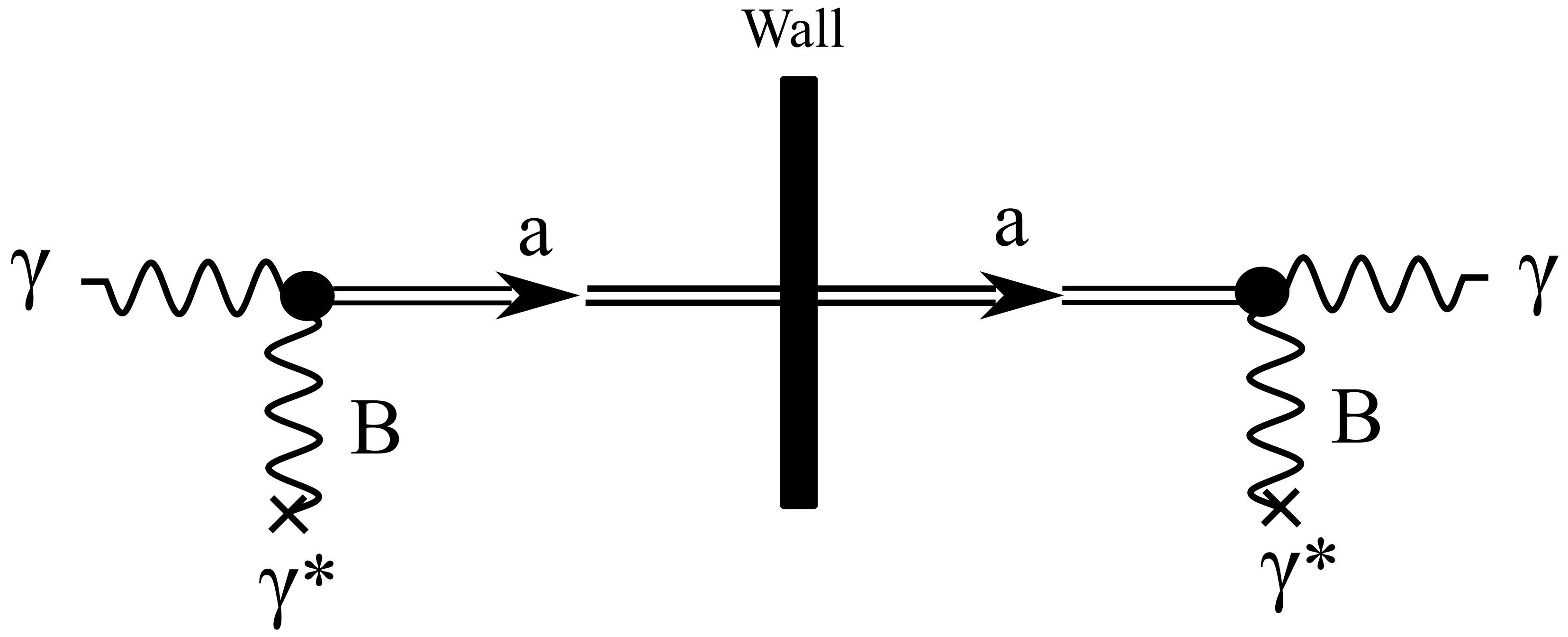
- Light axions:
- Conversion to photon in magnetic field
  (Primakoff effect)



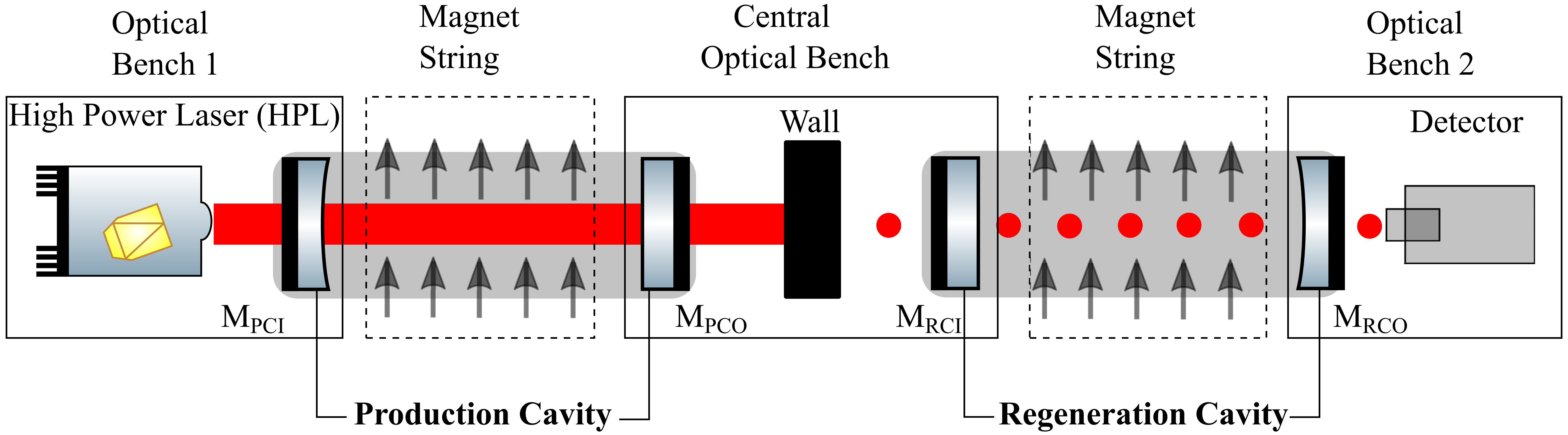


Light shining through wall experiments

- Idea:
  - Produce axions from laser photons
    - After optically tight wall:
  - Detect photons from axion conversion
  - Sensitivity: m_a < meV



- Challenges:
  - High power laser resonator with large dimensions
  - Large B-field
  - Very sensitive, noise free optical detectors



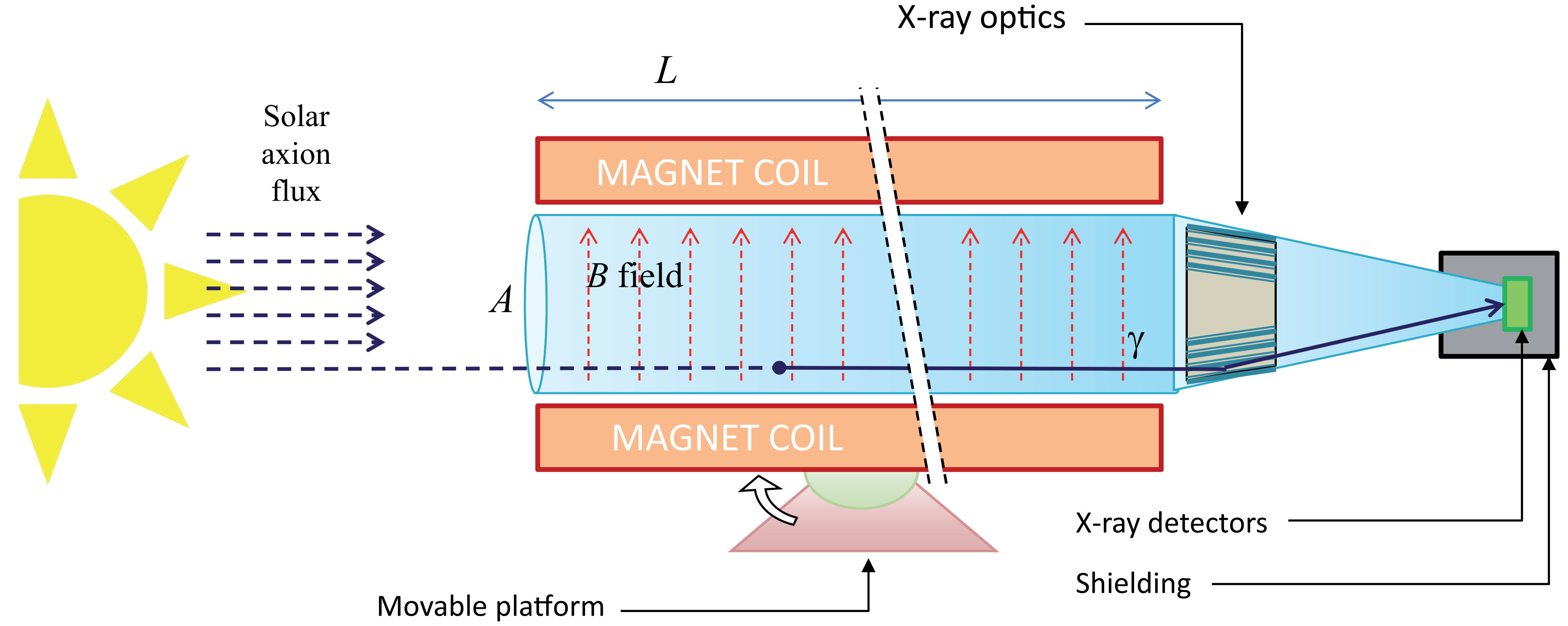
https://doi.org/10.15488/11022

- ALPS-II (Any Light Particle Search):
  - 70W laser @ 1064nm -> 150kW stored in resonator
  - 122m long optical cavity: BL = 560 Tm
  - 12 x 5.3T SC dipole magnets
  - Detection: Transition Edge Sensors & Heterodyne receiver

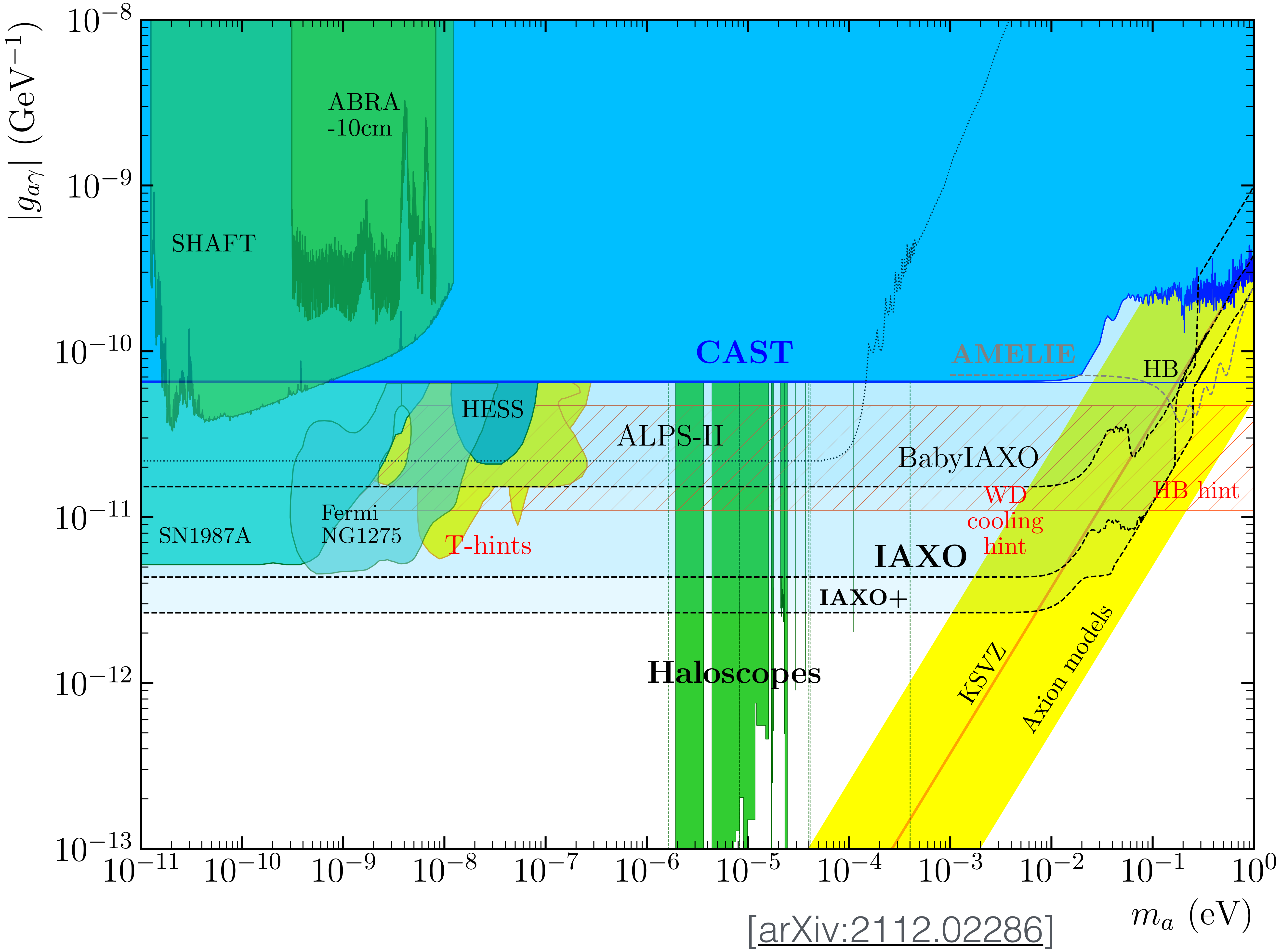
Light Axions - Helioscopes

- Using the sun as axion source
- Detection of axions in magnetic field, tracking sun
    - Conversion photons in x-ray regime
    - Sensitivity: $m_a < \sim 1$ eV
    - Current result: CAST
      (CERN Axion Solar Telescope)
    - New developments: IAXO
      (International AXion Observatory)

Helioscopes

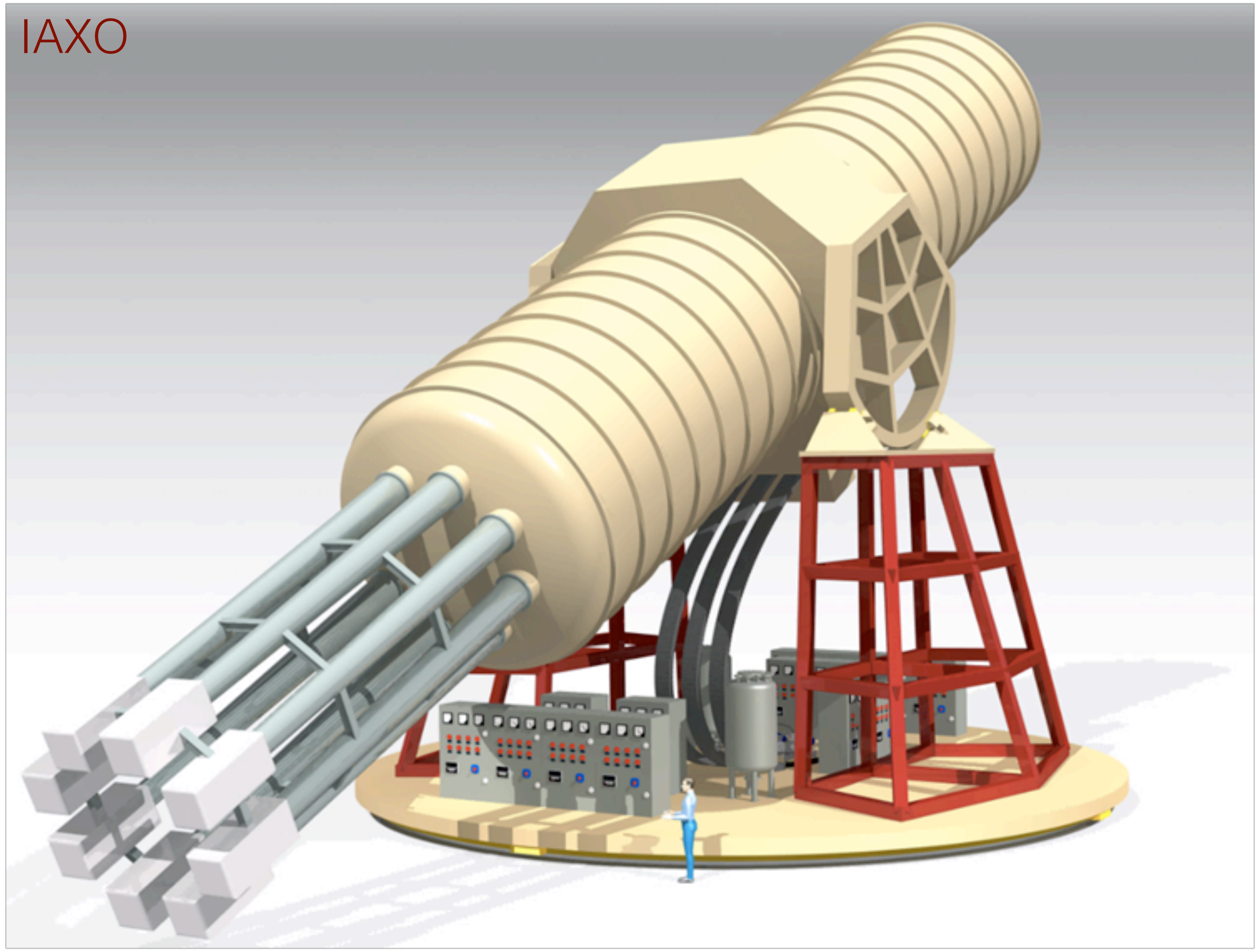


[arXiv:1401.3233]



[arXiv:2112.02286]

Light Axions - Helioscopes



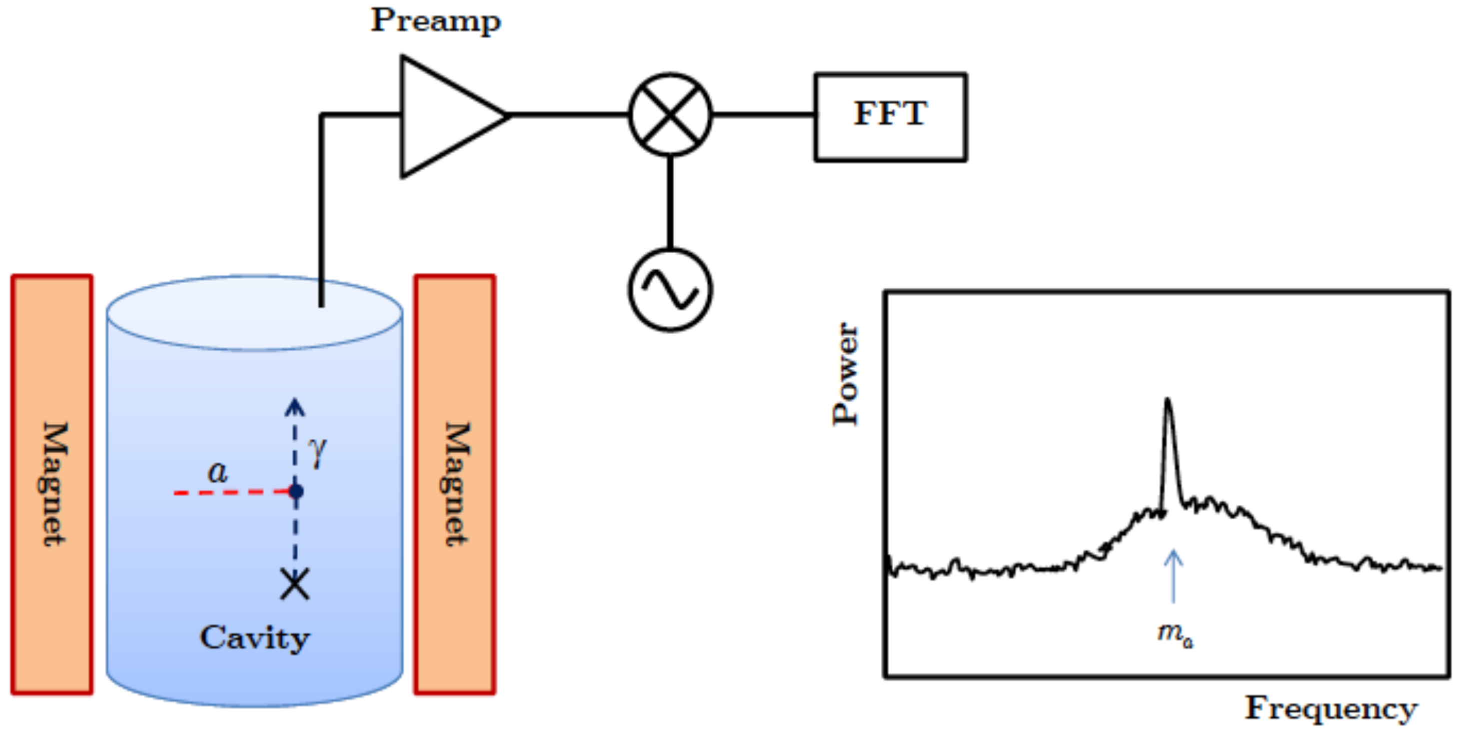
- 20m long toroid magnet
- 8 x 60cm bores for instrumentation
- Readout using x-ray telescopes and micro mega detectors

- 15m long dipole magnet
- 1 x 5cm bores for instrumentation
- Readout using various x-ray detectors

Light Axions - Haloscopes - RF cavity based searches

- Axion conversion to photons in B-field
- Using RF resonators to enhance the signal
- Sensitivity: ~μeV - meV

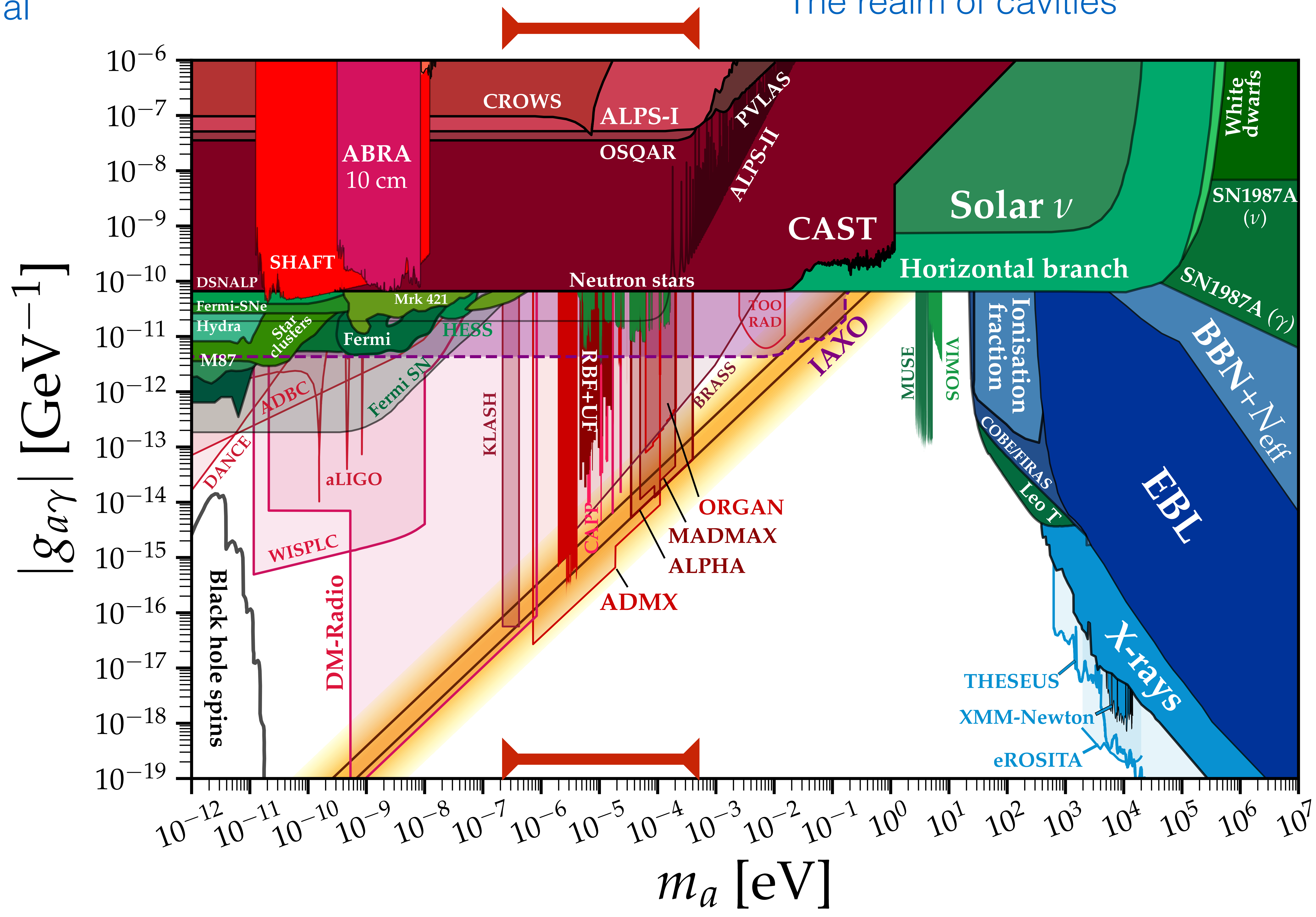
- 3 orders of magnitude in frequency:
  - Various designs of resonators & DAQ
  - Many experiments!



- Typ signal power: 10^{-24}W

65 MHz - 50 GHz

The realm of cavities



[source: https://github.com/cajohare/AxionLimits]

Light Axions - RF cavity based searches - New developments

- Up to 14T magnets in use
  - Up to 20T envisioned
- Larger fields - smaller volume

- Depends on cavity material:
  - High purity copper: ~$5 \cdot 10^4$
  - Superconducting: difficult in high magnetic field!
    - Target: 10^6
    - Achieved: $3 \cdot 10^5$ (CAPP, non tunable)
      - Materials under study: Nb_3Sn, HTS materials (YBCO)
  - Dielectric resonators (saphir):
    - Achieved: $9 \cdot 10^6$ @ 8 T B-field (QUAX, non tunable)

$$P_{sig} \propto B^2 Q_0 V g_\gamma^2$$

- Volume limited by
  - Magnet aperture
  - Resonance frequency
  - Tuning elements

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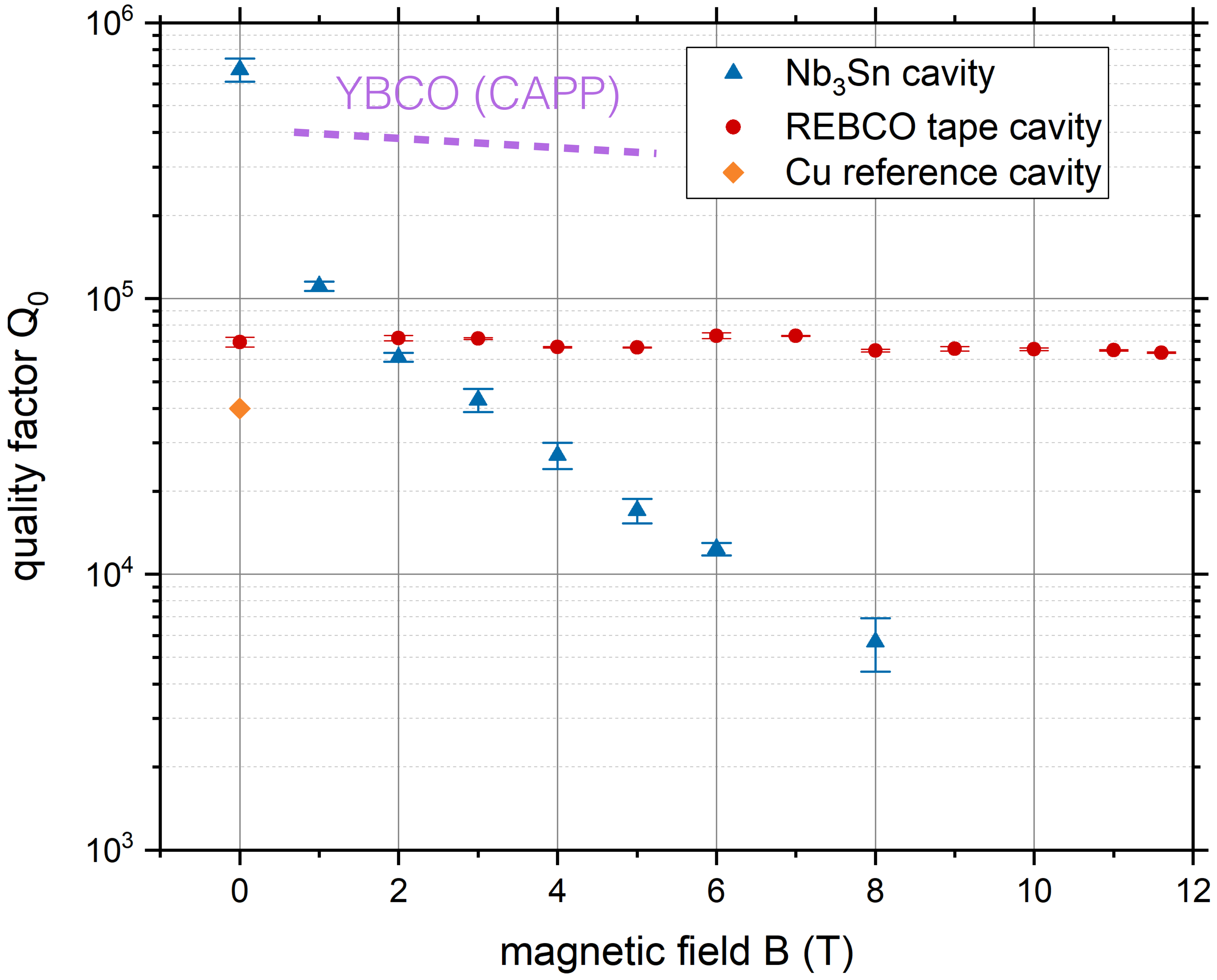
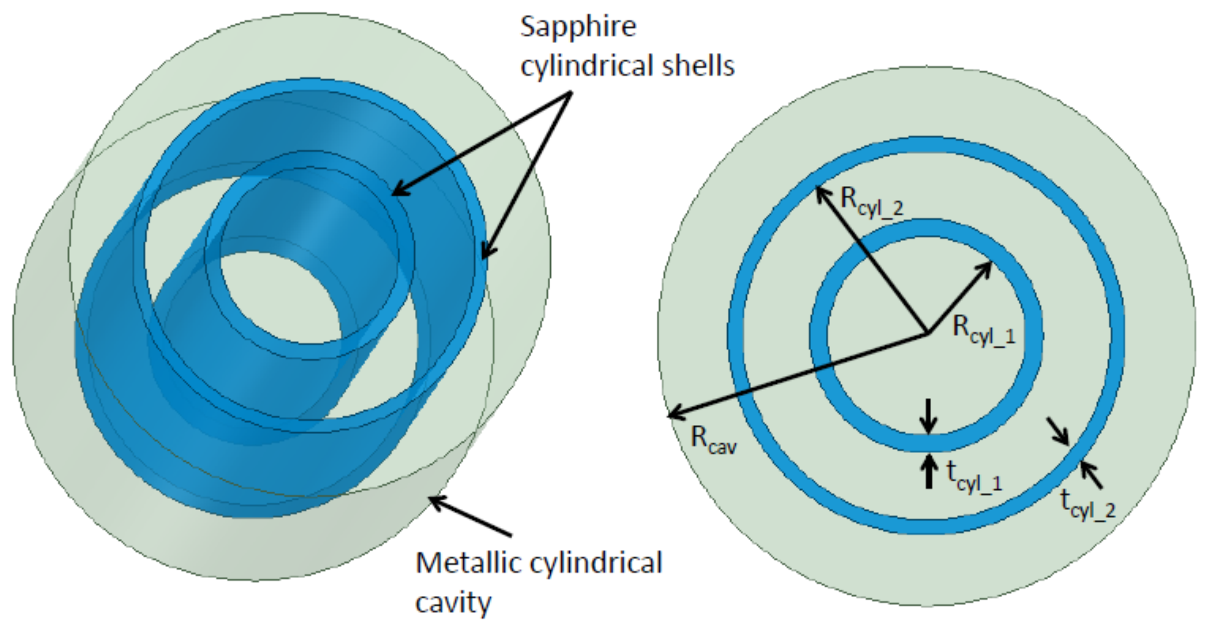


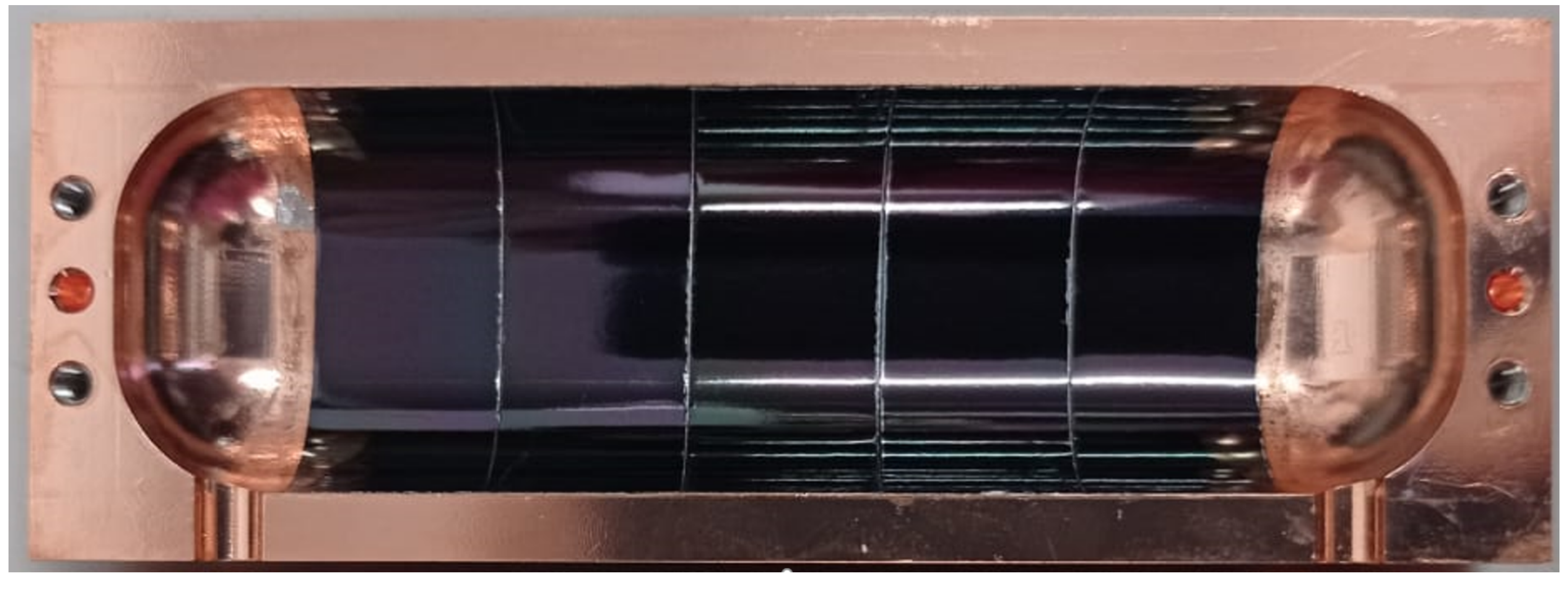
- D. Ahn et. al (CAPP), ~7 GHz https://arxiv.org/abs/2002.08769
- J. Golm et. al (RADES), ~8 GHz https://arxiv.org/abs/2110.01296

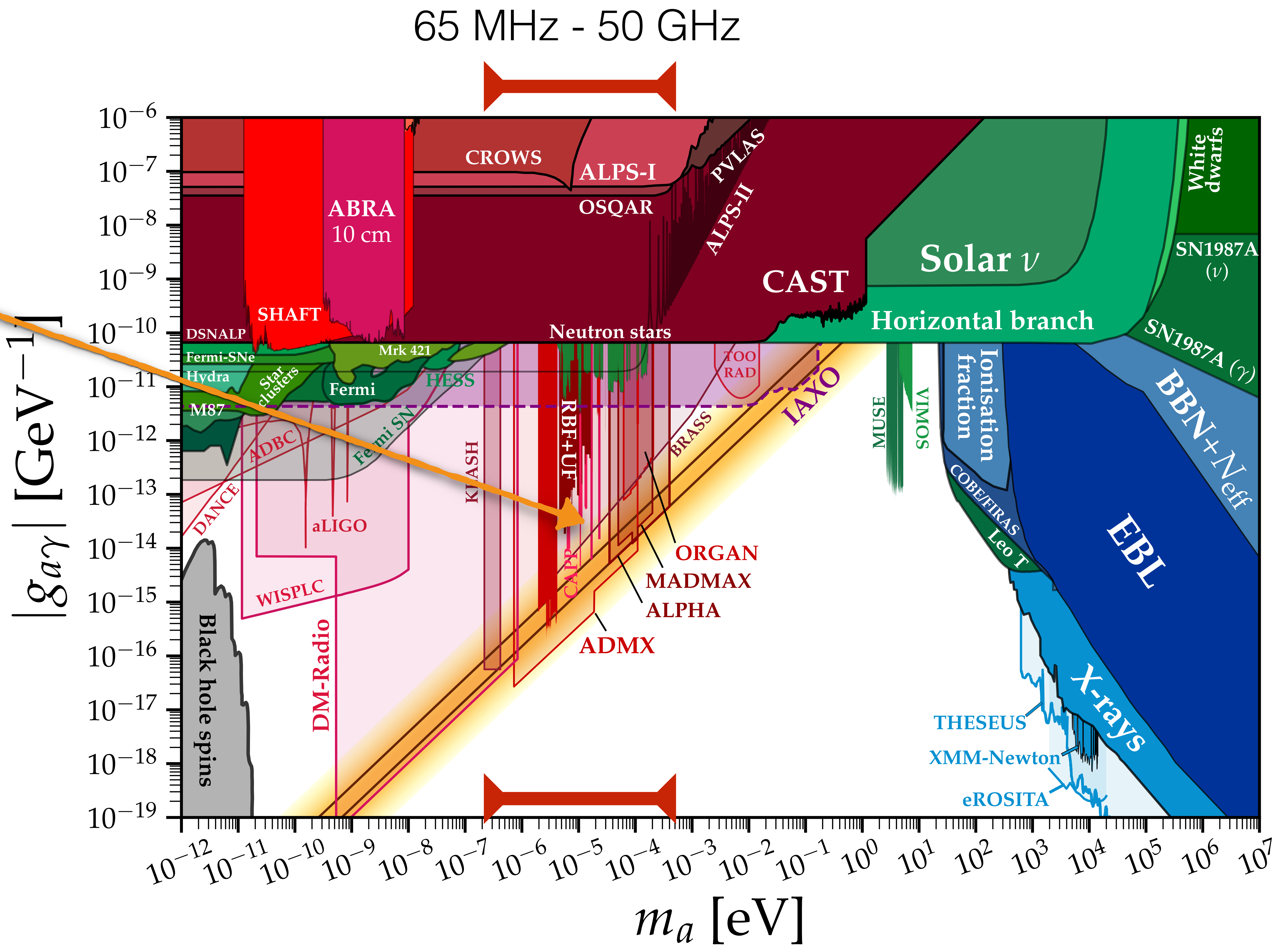
- QUAX, ~10 GHz arXiv:2201.04223



Light Axions - RF cavity based searches - Proposed experiments

- Increasing the cavities Q-factor:





[source: https://github.com/cajohare/AxionLimits]

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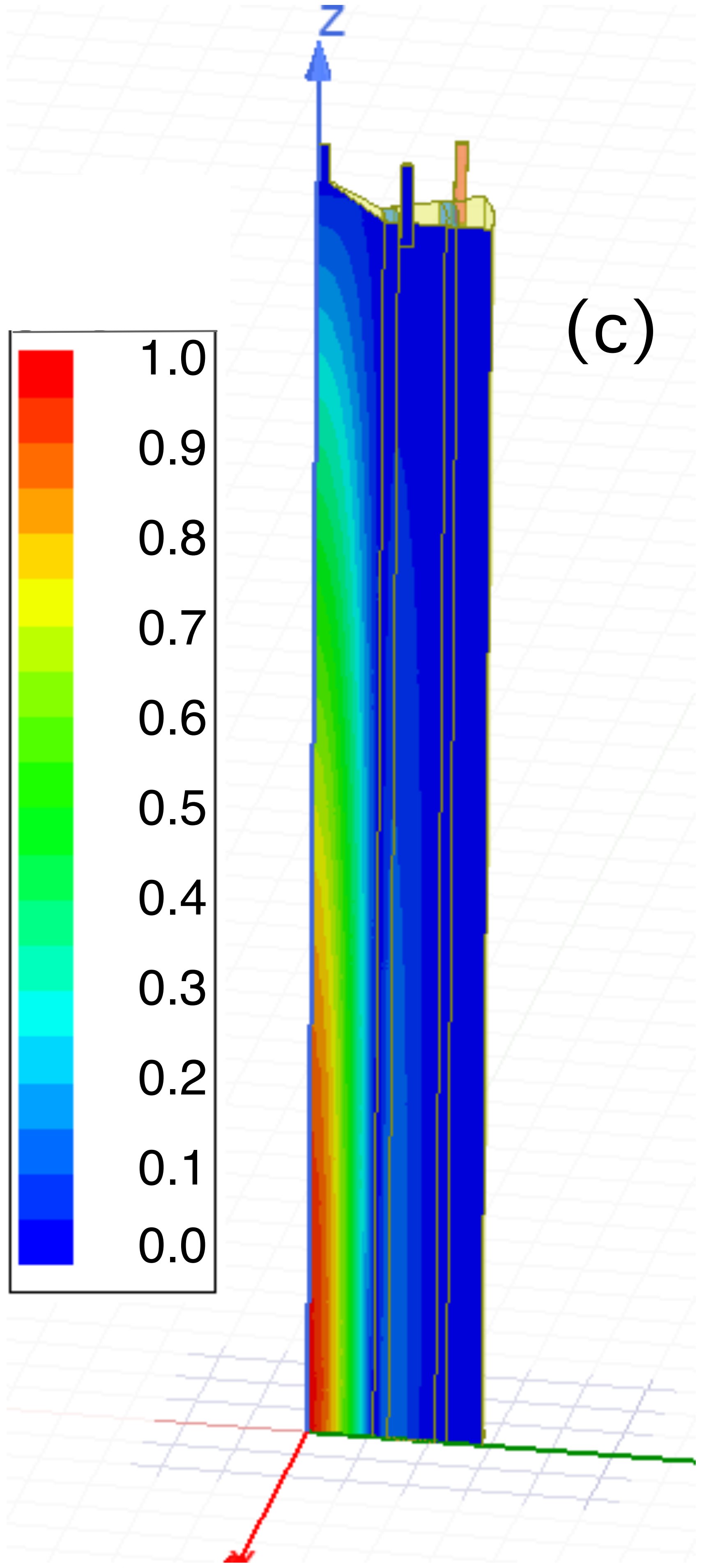
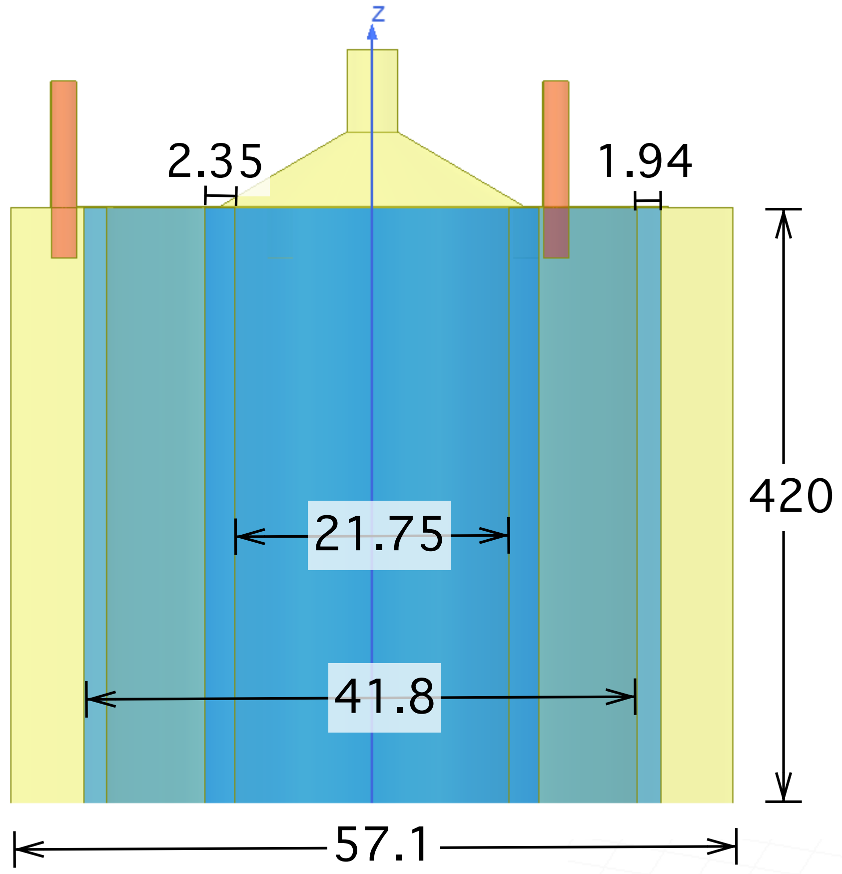
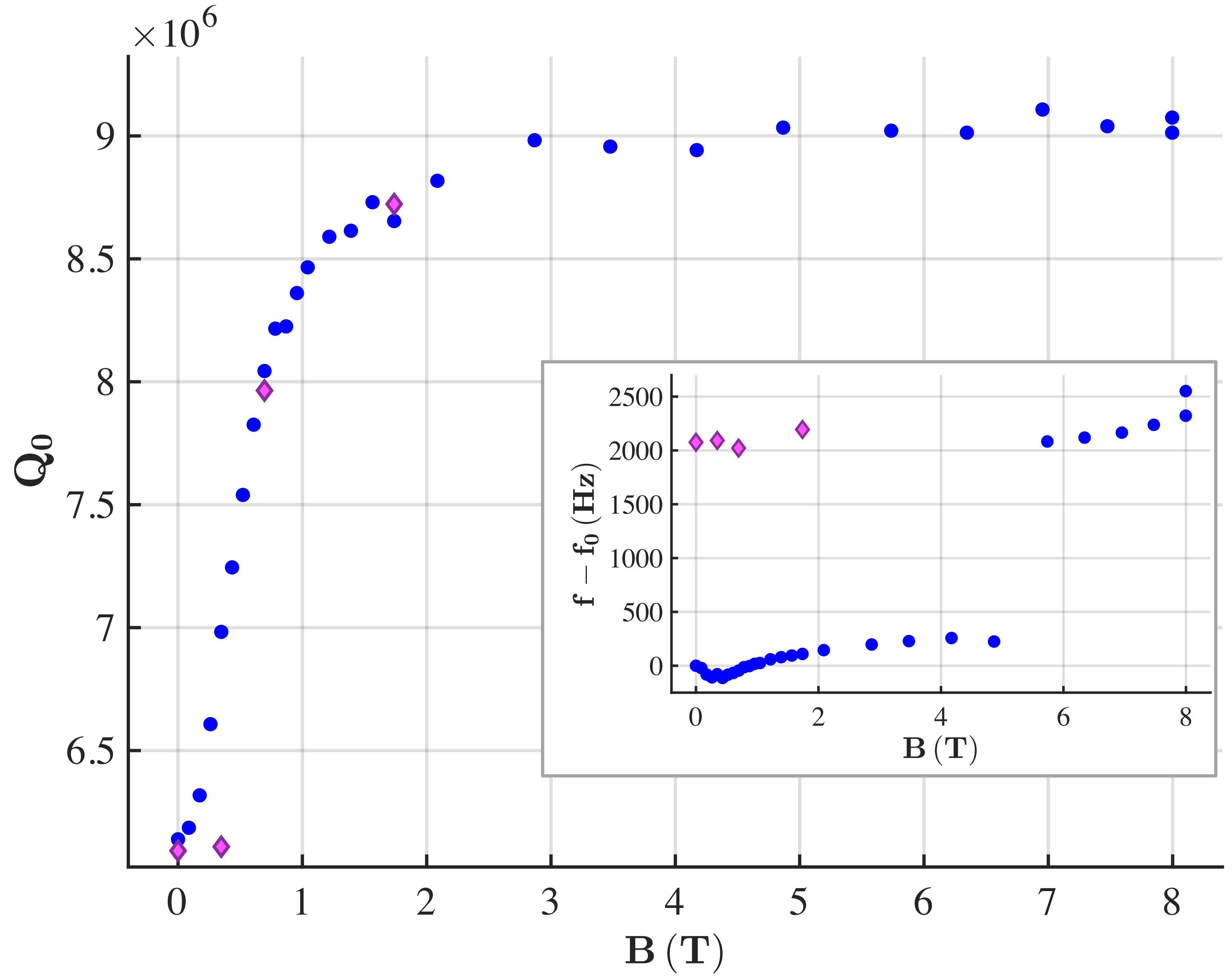
Light Axions - RF cavity based searches - Proposed experiments

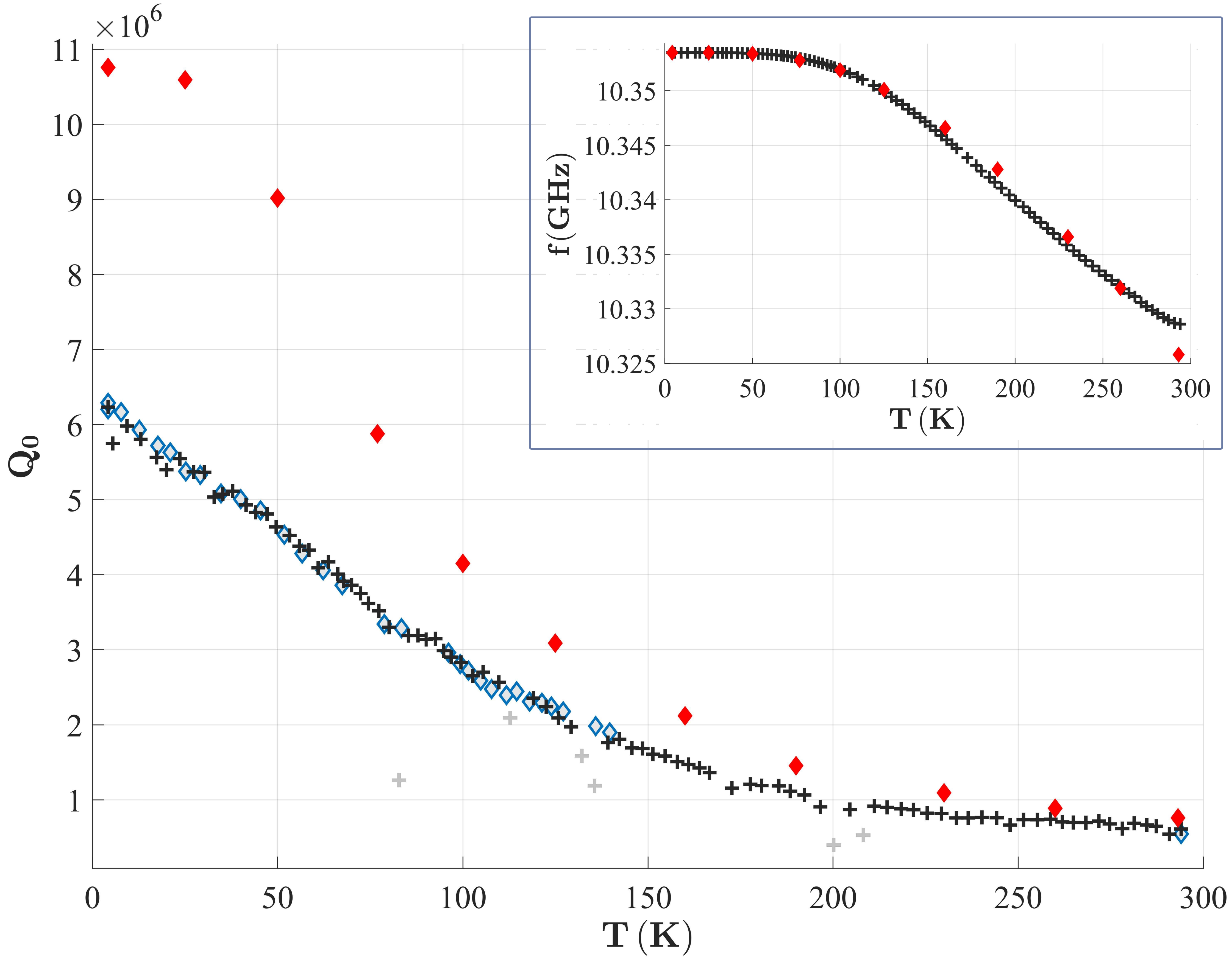
Quax: arXiv:2201.04223

- Increasing the cavities Q-factor:
  - Dielectric cylinders - Quax's approach:
  - Shaping EM field to minimize losses in copper







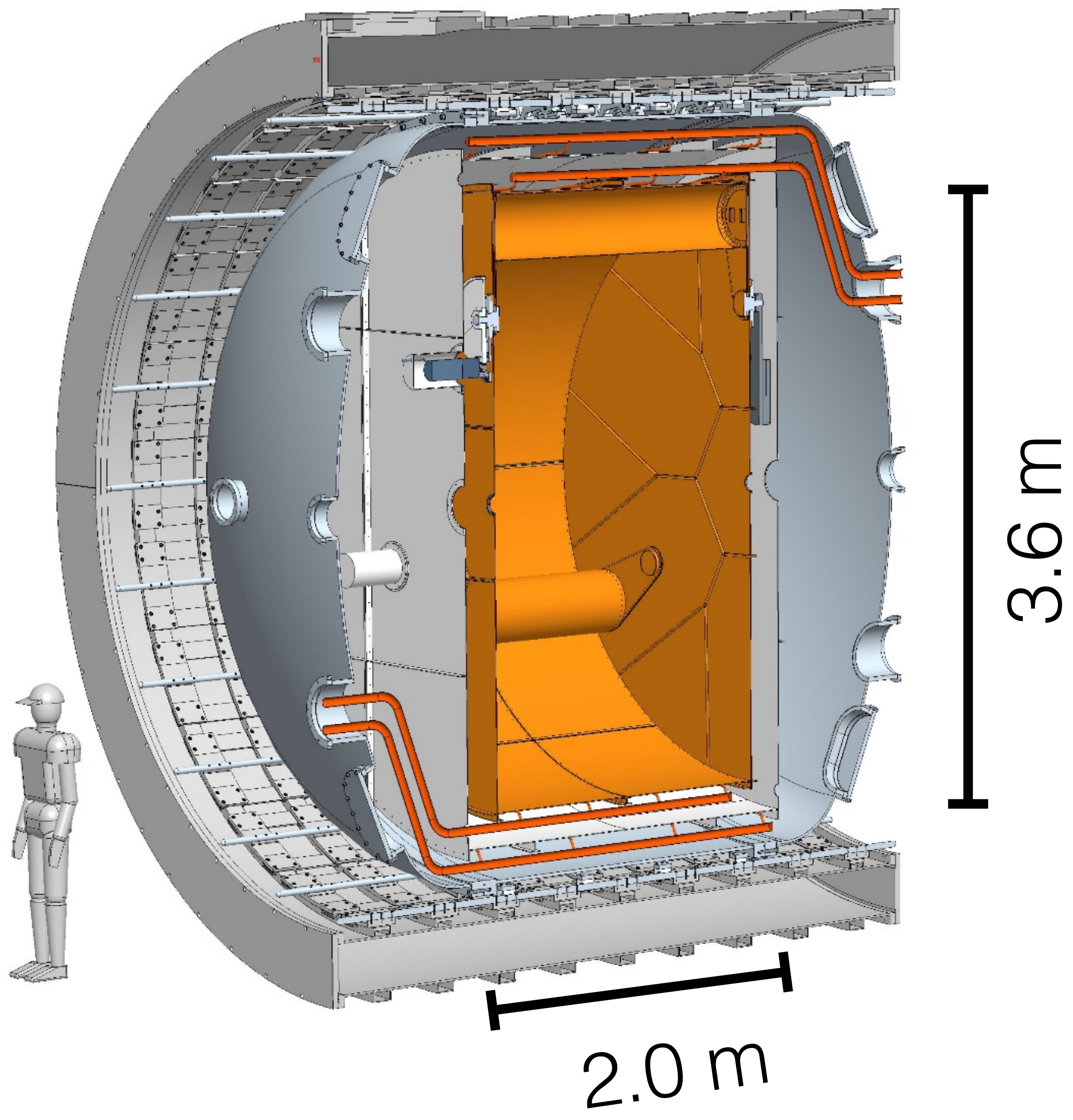


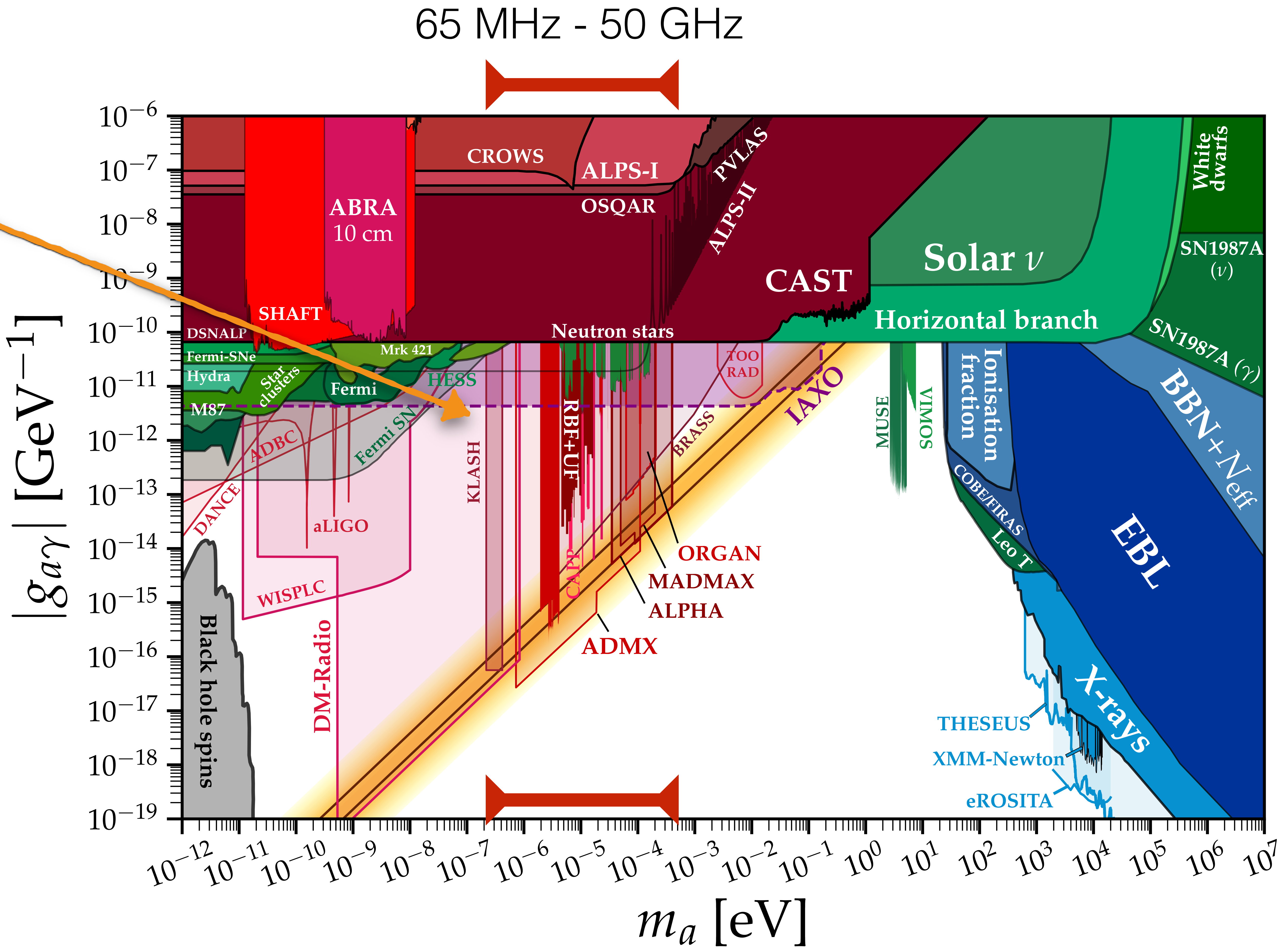
- Paramagnetic clusters from impurities
- Electron spin resonance frequency tuned away by B-field

Light Axions - RF cavity based searches - New developments

- Increasing the Volume of the cavity

  - Low frequency -> large size cavities:
    - KLASH: Cavity inside the KLOE magnet (0.6T)
      65 - 150 MHz https://arxiv.org/abs/1911.02427





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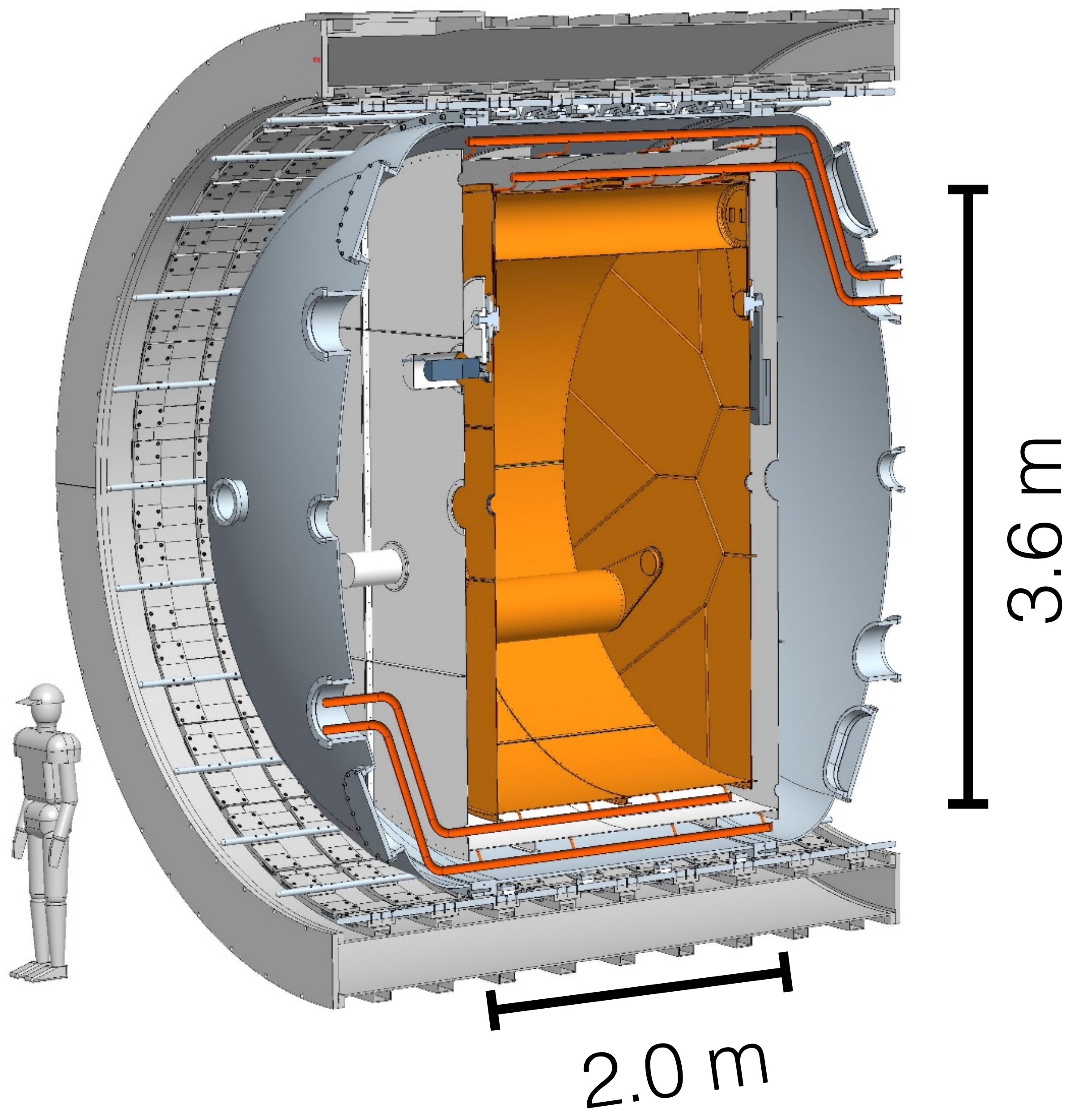

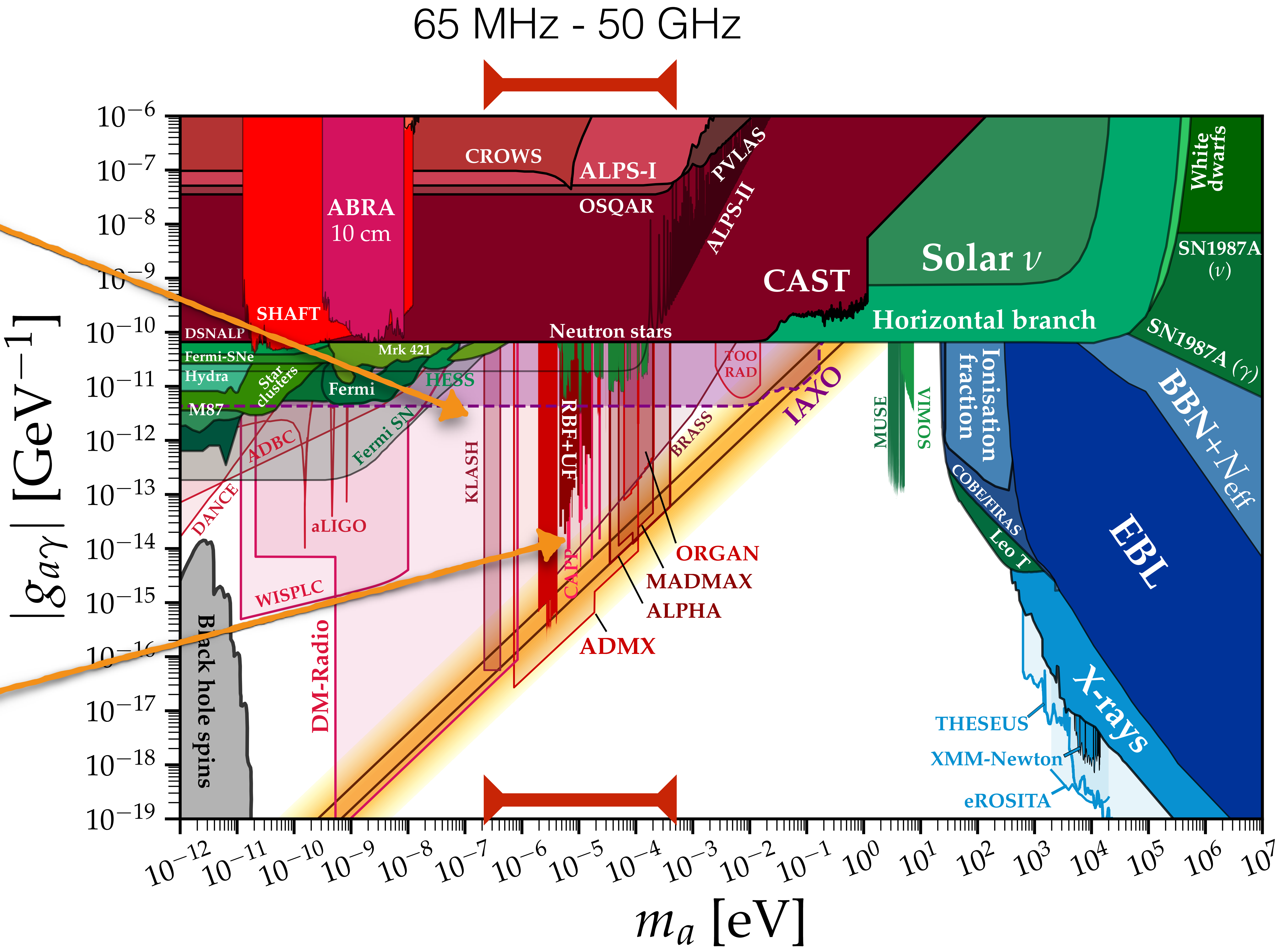

- Medium frequencies:
  - Coupled cavities: CAPP-9T (3 GHz) https://doi.org/10.1103/PhysRevLett.125.221302

[source: https://github.com/cajohare/AxionLimits]

Light Axions - RF cavity based searches - New developments

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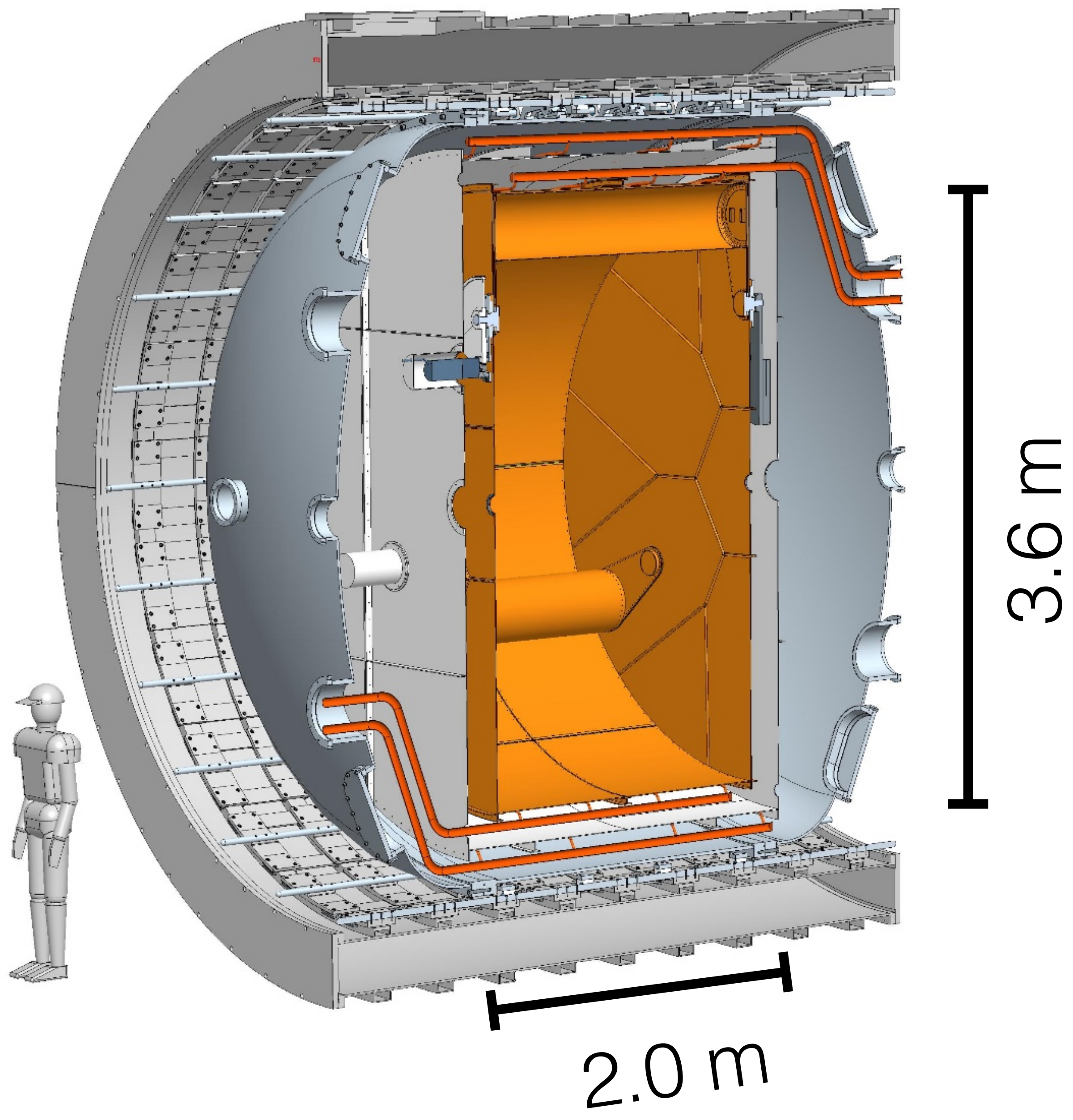
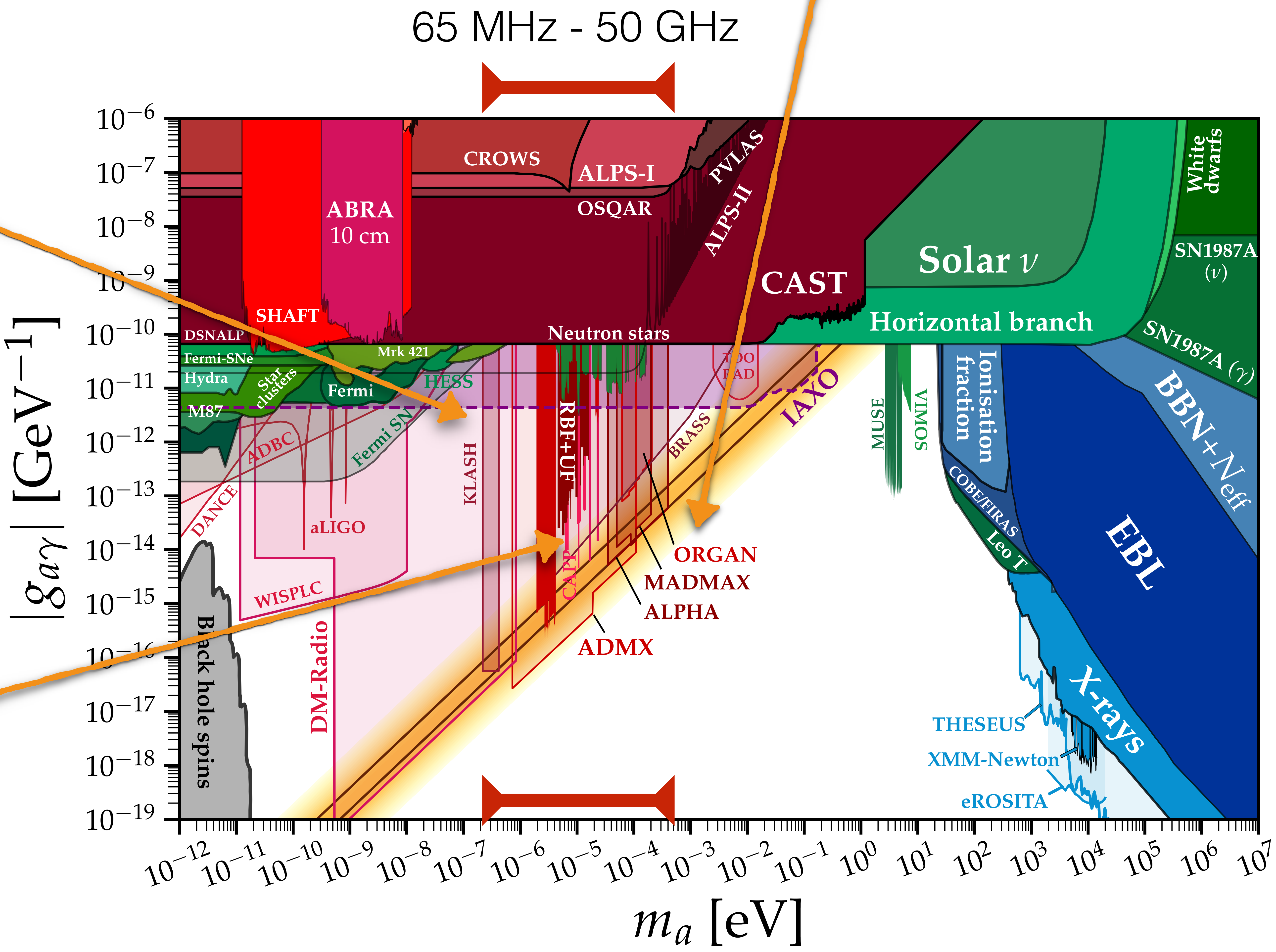


- High frequencies:
  - Use **higher order modes** in large R cavity
    - (ORGAN) TM_{030} 26-27 GHz

    https://doi.org/10.1007/978-3-319-92726-8_14



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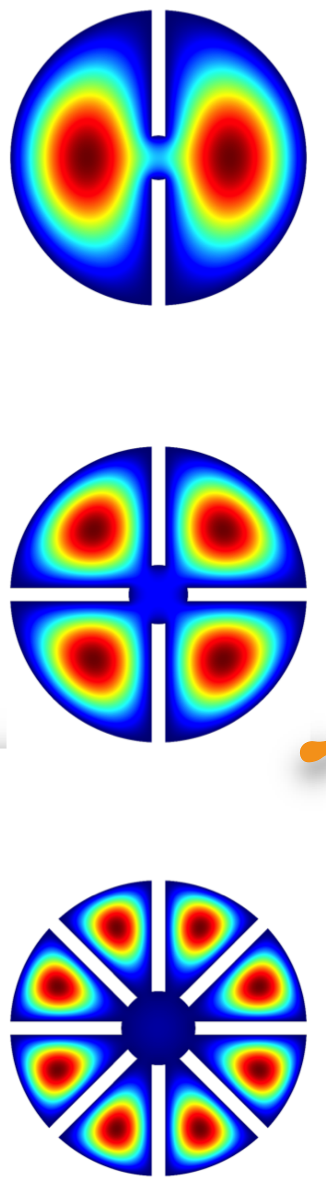


- Medium frequencies:
  - Coupled cavities: CAPP-9T (3 GHz)

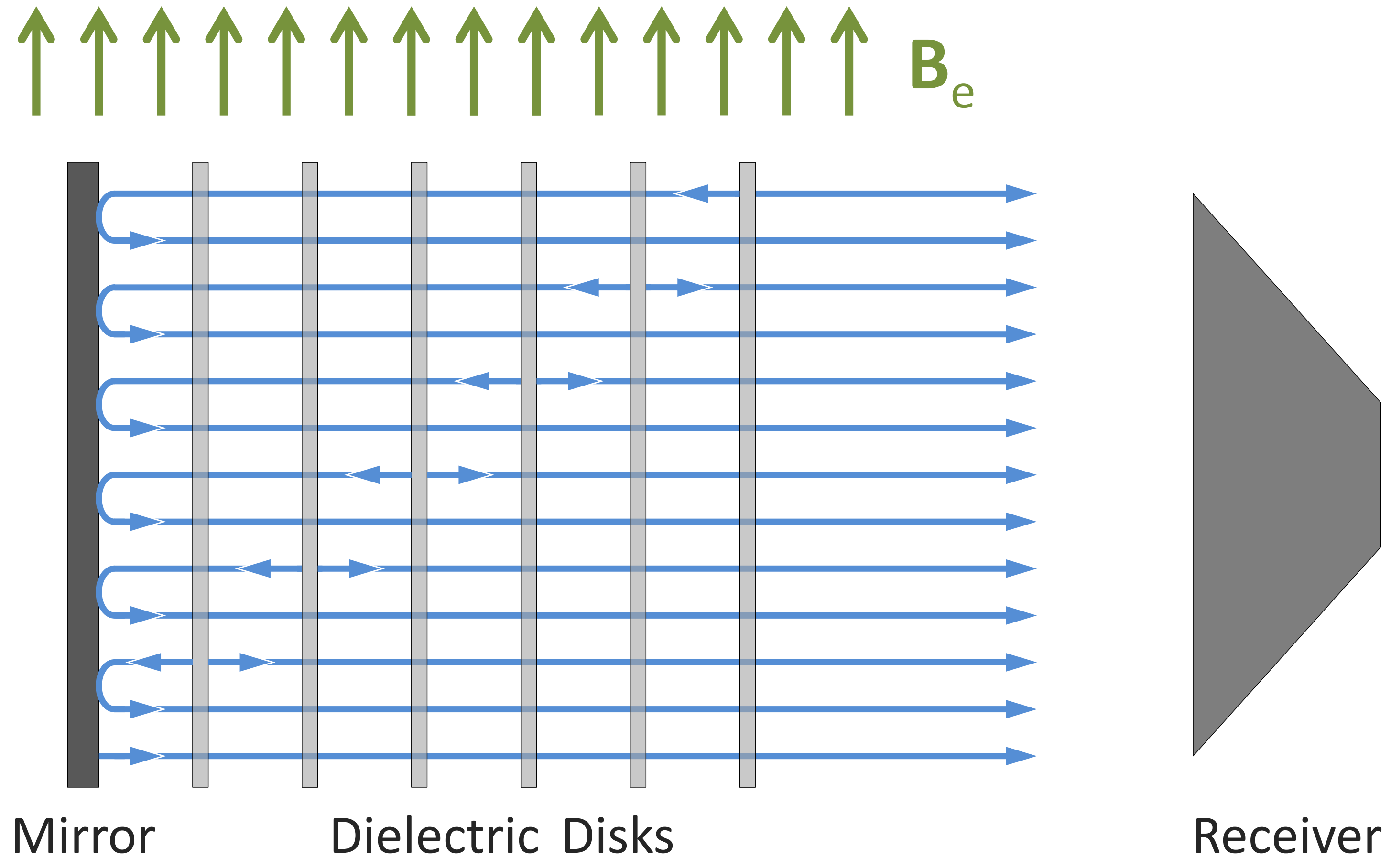
  https://doi.org/10.1103/PhysRevLett.125.221302

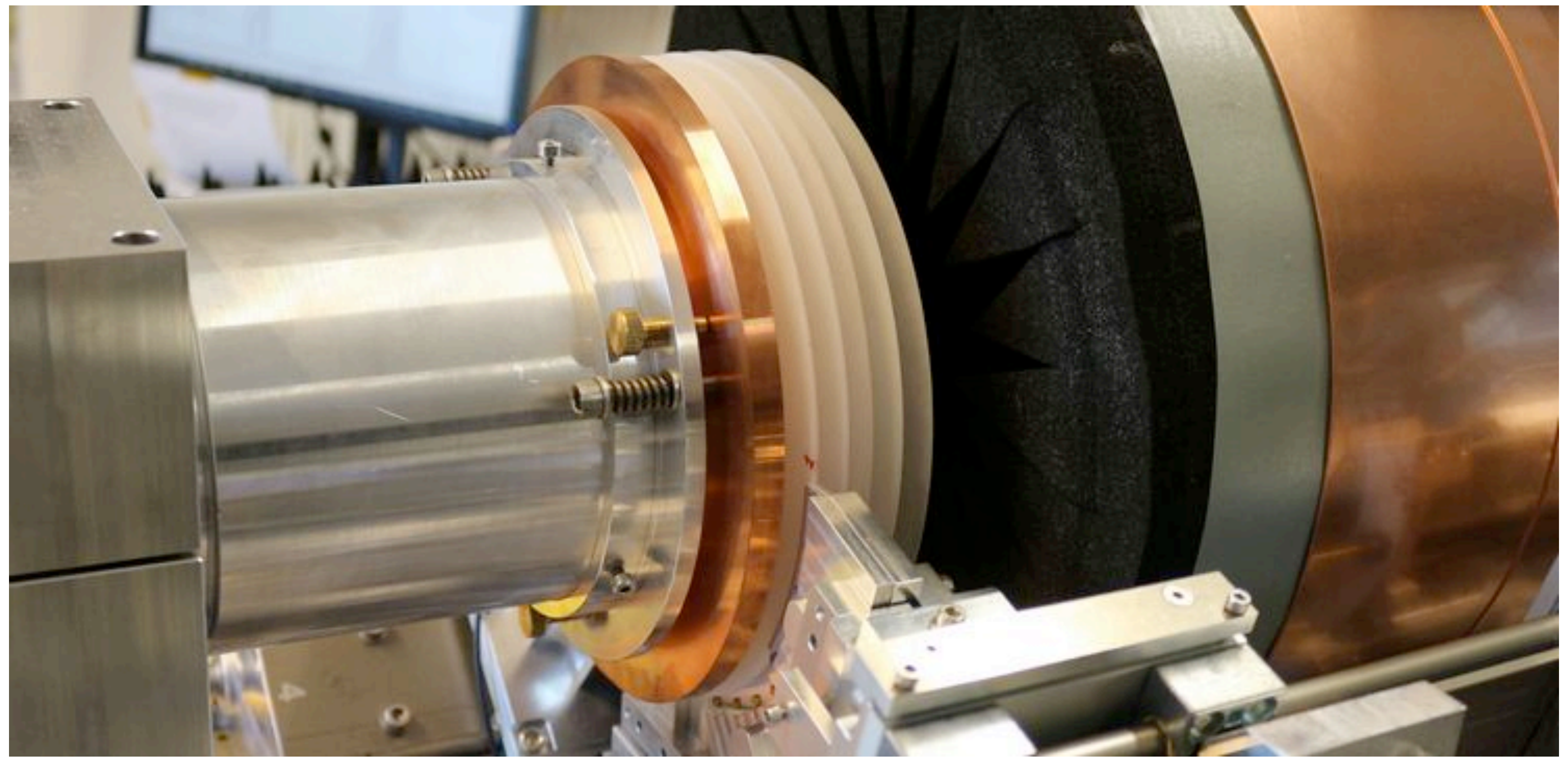
Light Axions - RF cavity based searches - High frequencies

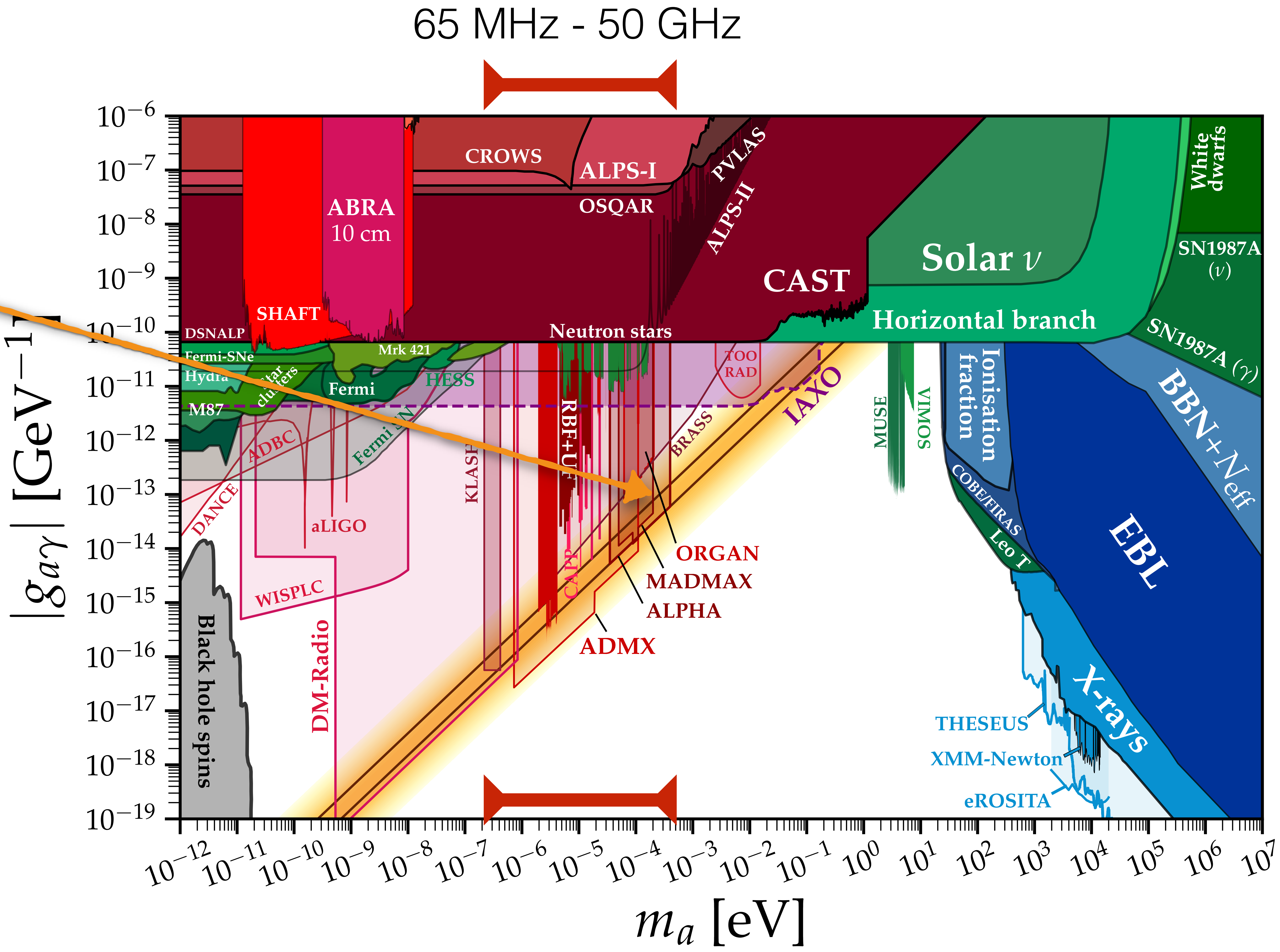
- Creating a linear cavity using dielectric discs: MADMAX

Eur. Phys. J. C 79 (2019) no.3, 186

- Exploiting interference effects
- Frequency range: 10-100 GHz







[source: https://github.com/cajohare/AxionLimits]

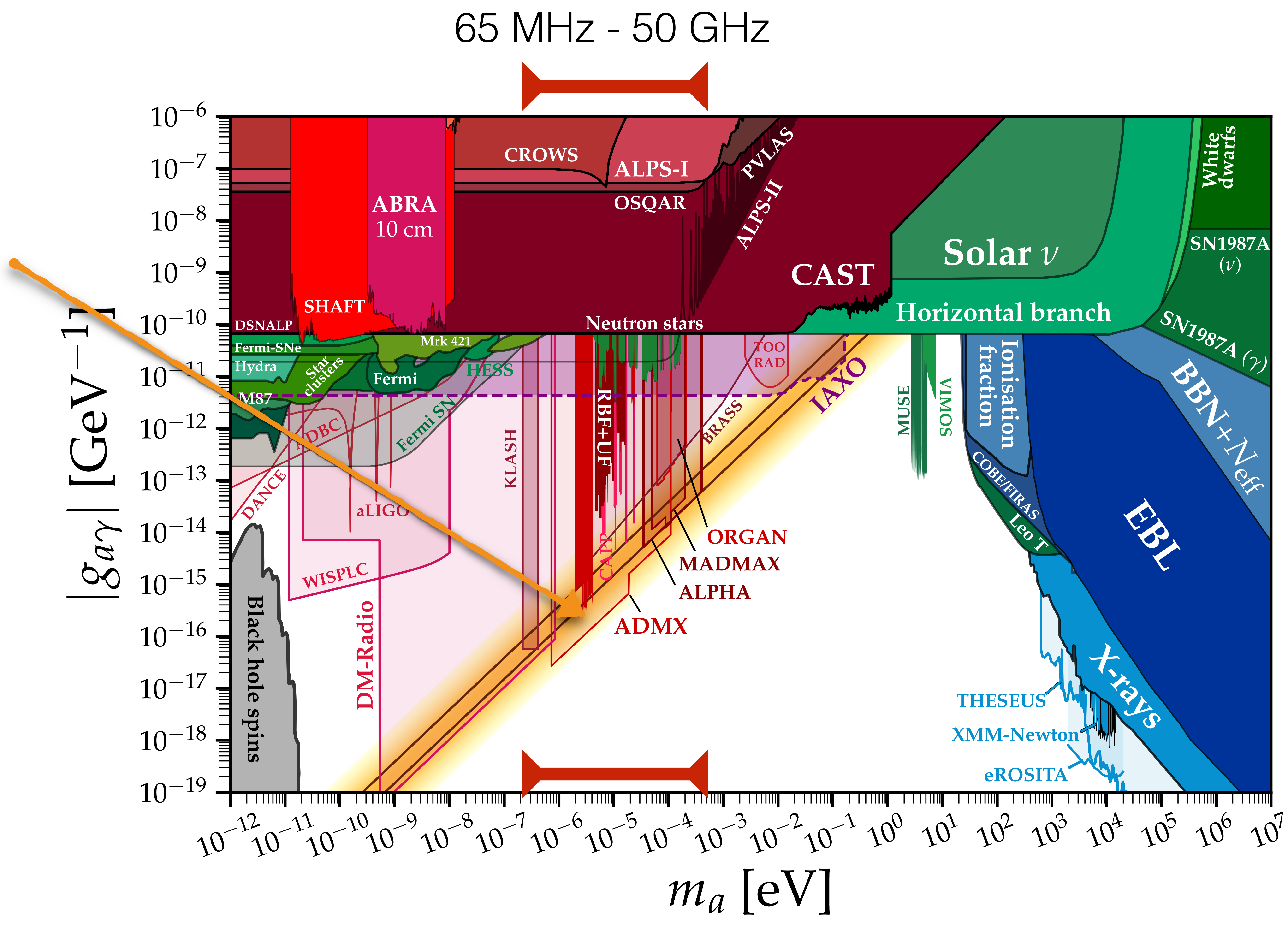
Light Axions - RF cavity based searches - New developments

- Lower Readout noise
  - Lower temperature: <100mK in dilution refrigerators
  - Low noise amplifiers (ADMX):
    - Transistor based amplifiers: T_{noise} ~ 2-4 K
    - SQUID based readout: T_{noise} ~ 100 mK
      - Typical gain: 10 dB

    http://arxiv.org/abs/1105.4203v1

- Overcoming quantum limit of linear amplifiers
  - Using squeezed states in cavity
  - Using **q-bits** for single RF photon readout

  https://doi.org/10.1103/PhysRevLett.126.141302



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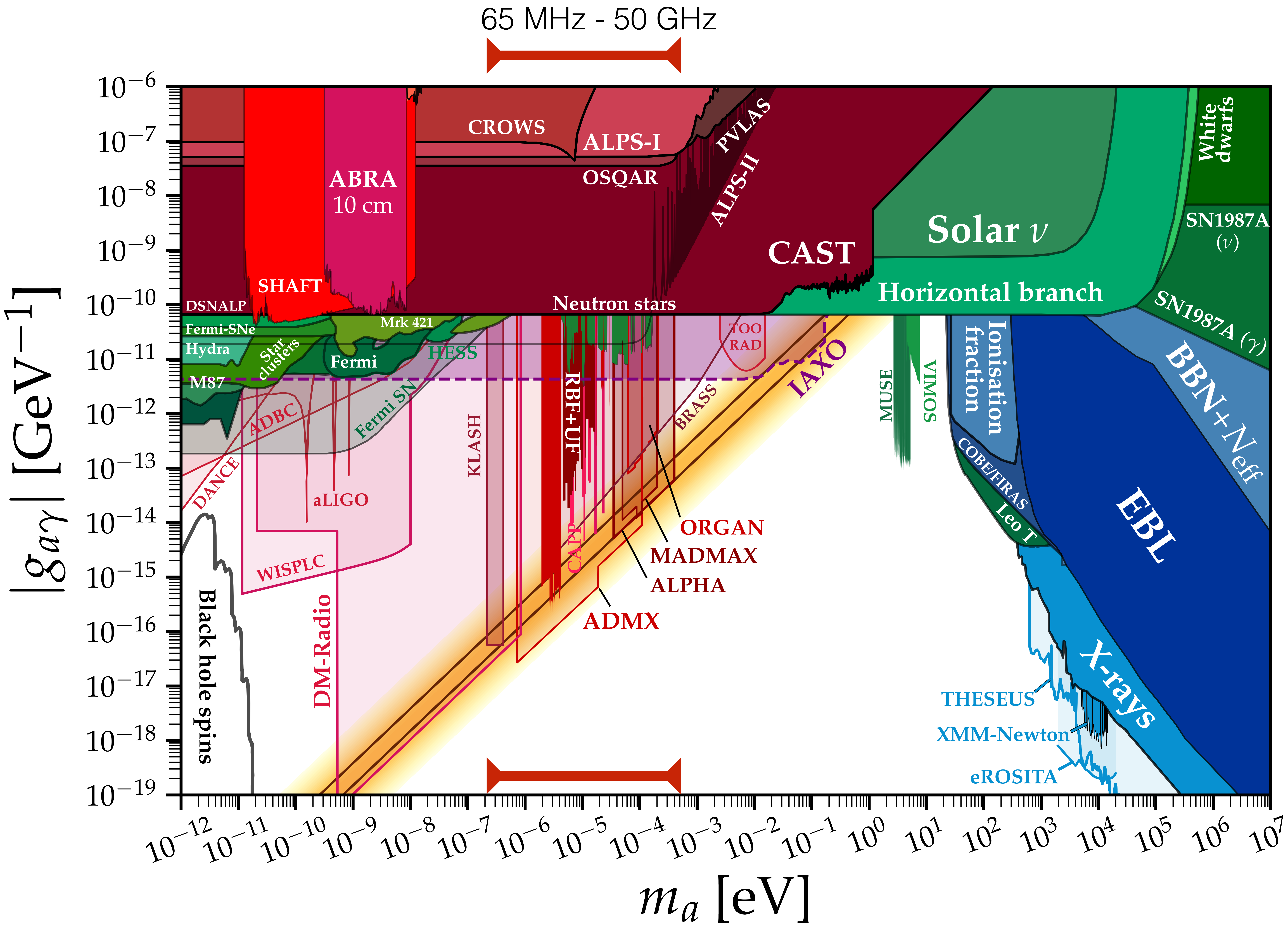
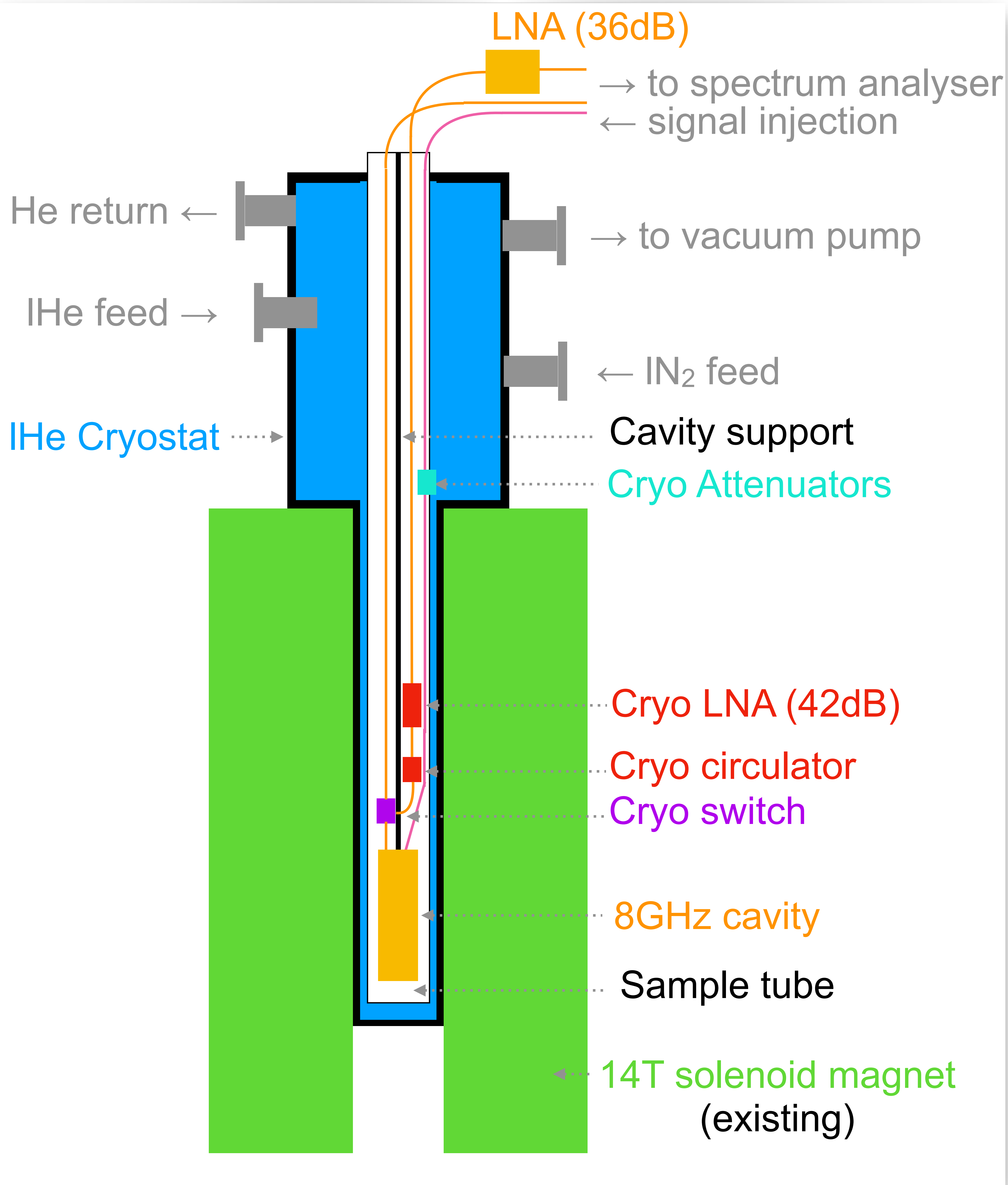
Expectations on sensitivity for future experiments



Efforts in Mainz - SupAx setup



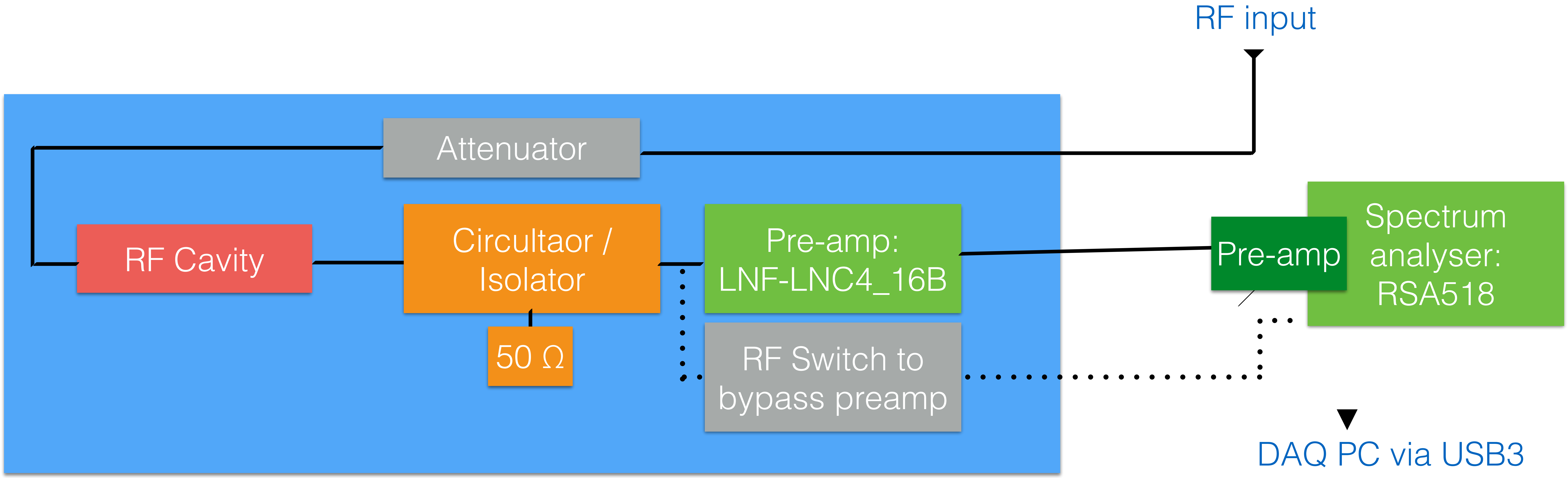
- Magnet bore: 89mm
  - Inner cryostat diameter: 50 mm

- Suppression of 300K noise from outside:
  - Attenuators on input lines @ 4K

- Isolator (Circulator) before Preamp
  - Reduction of residual RF reflection

- Cryo Preamp @ 4K, 10GHz:
  - Gain: 36 dB
  - Noise: 3.8K (0.06dB)

DAQ & Data analysis



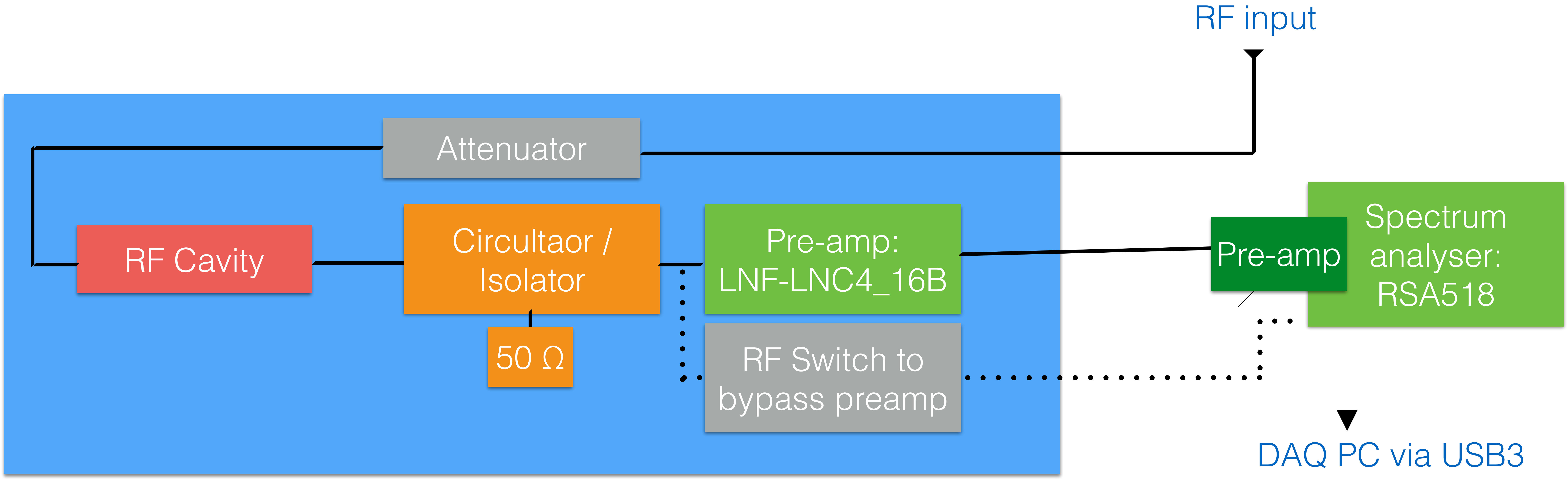
- Tec details:
  - Pre-amp @ 10 GHz, 4K:
    - T_{noise} = 3.8K (0.06dB)
    - Gain = 36 dB
  - Pre-amp @ 10 GHz, 296K:
    - T_{noise} = 58K
    - Gain = 38 dB

- Signal Power (in 1kHz bin):
  - 10^{-23} W = -200 dBm
- Thermal Power (in 1kHz bin):
  - 4K: 10^{-19} W = -160 dBm
  - 0.1K: 10^{-21} W = -176 dBm

- Signal Power:
  - $4 \cdot 10^{-20}$ W = -164 dBm

- Signal Power:
  - $3 \cdot 10^{-16}$ W = -126 dBm

DAQ & Data analysis



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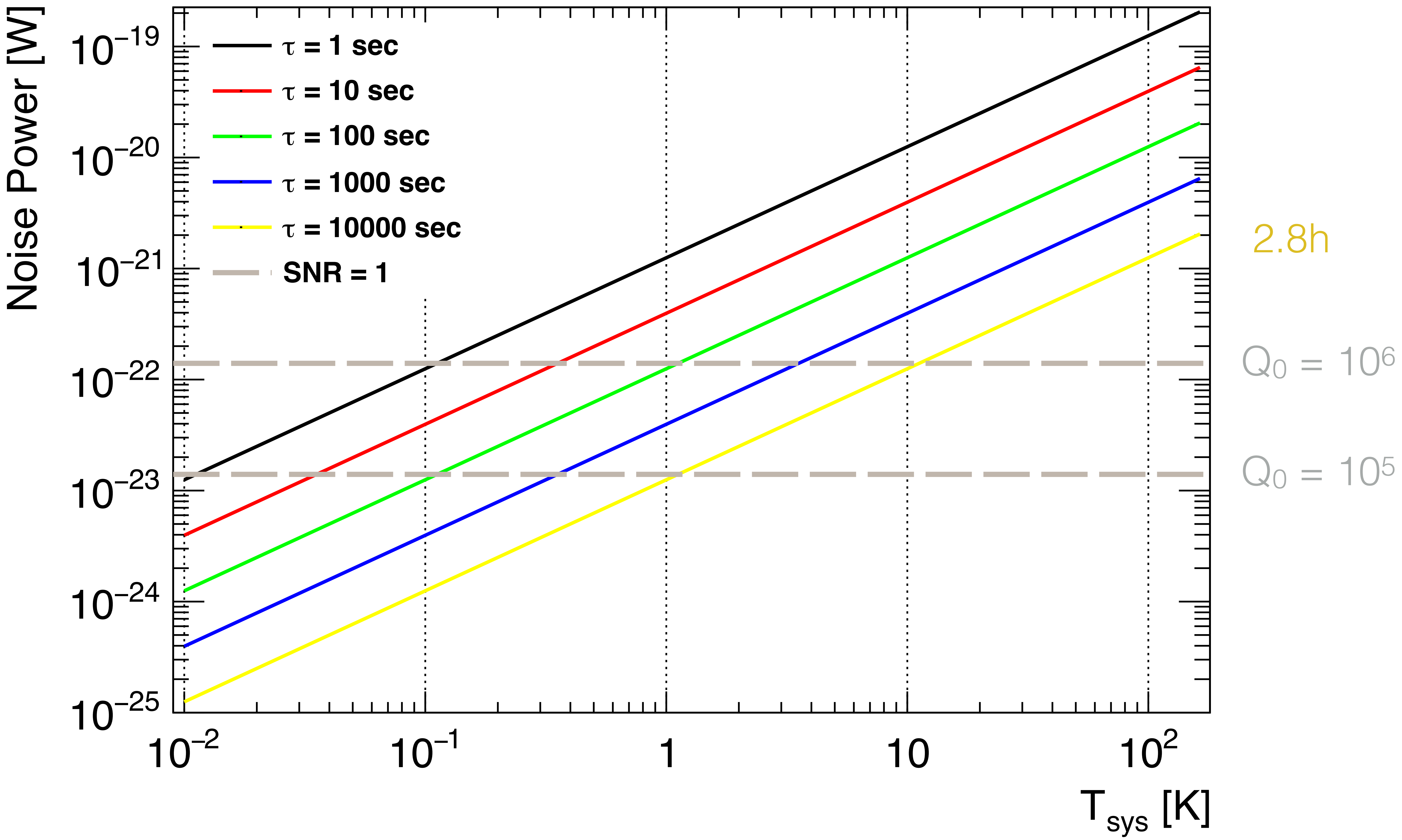
Statistical Noise -> reduce by **averaging**

DAQ & Data analysis



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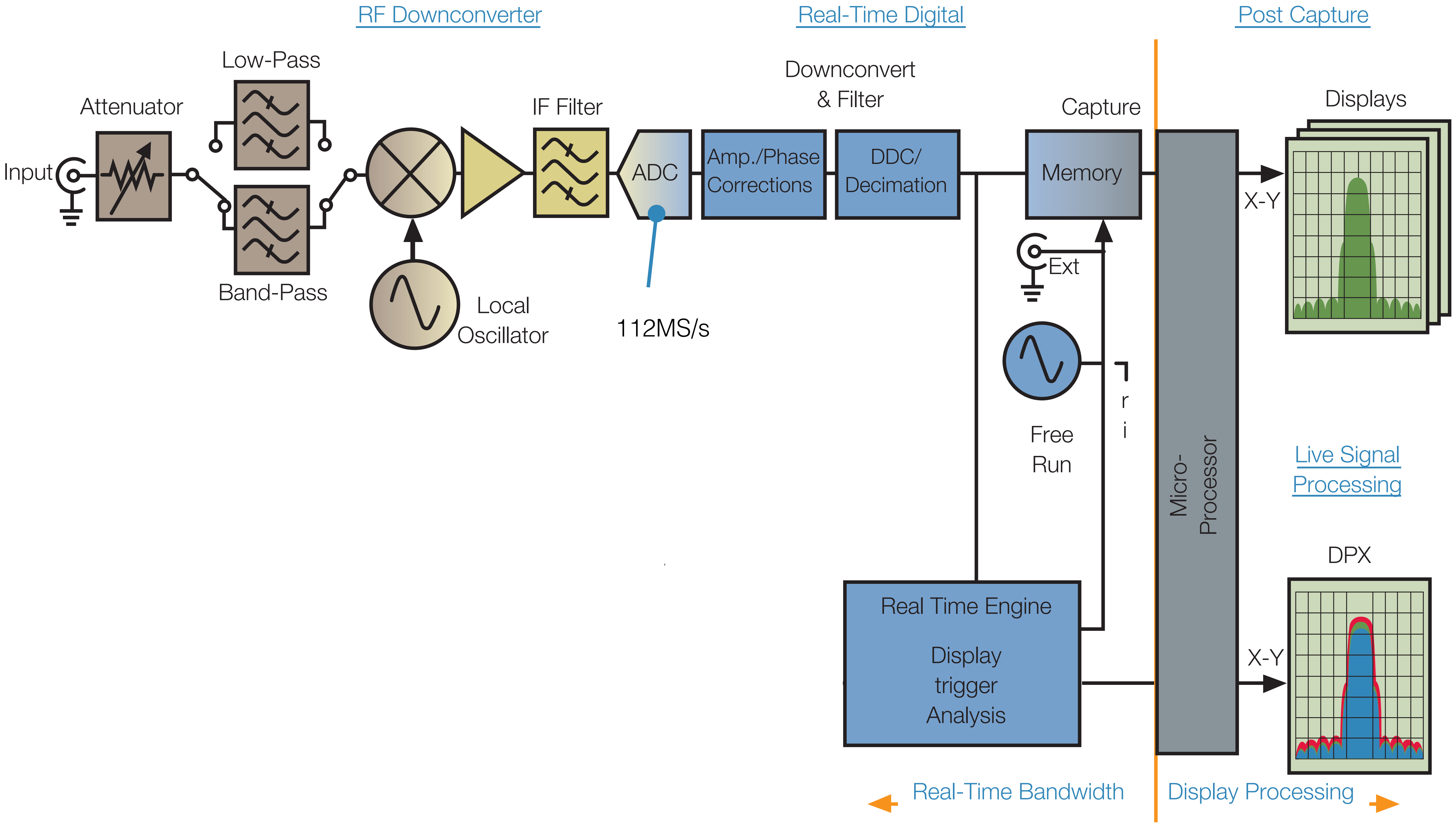
DAQ & Data analysis

- Real time acquisition:
  - 112 MS/s (= 56MS/s of IQ values)
  - Max. 40MHz bandwidth
- IQ time series to app or file
  - Conversion from IF -> IQ in software



From Tektronix:
Fundamentals of Real-Time Spectrum Analysis

DAQ & Data analysis

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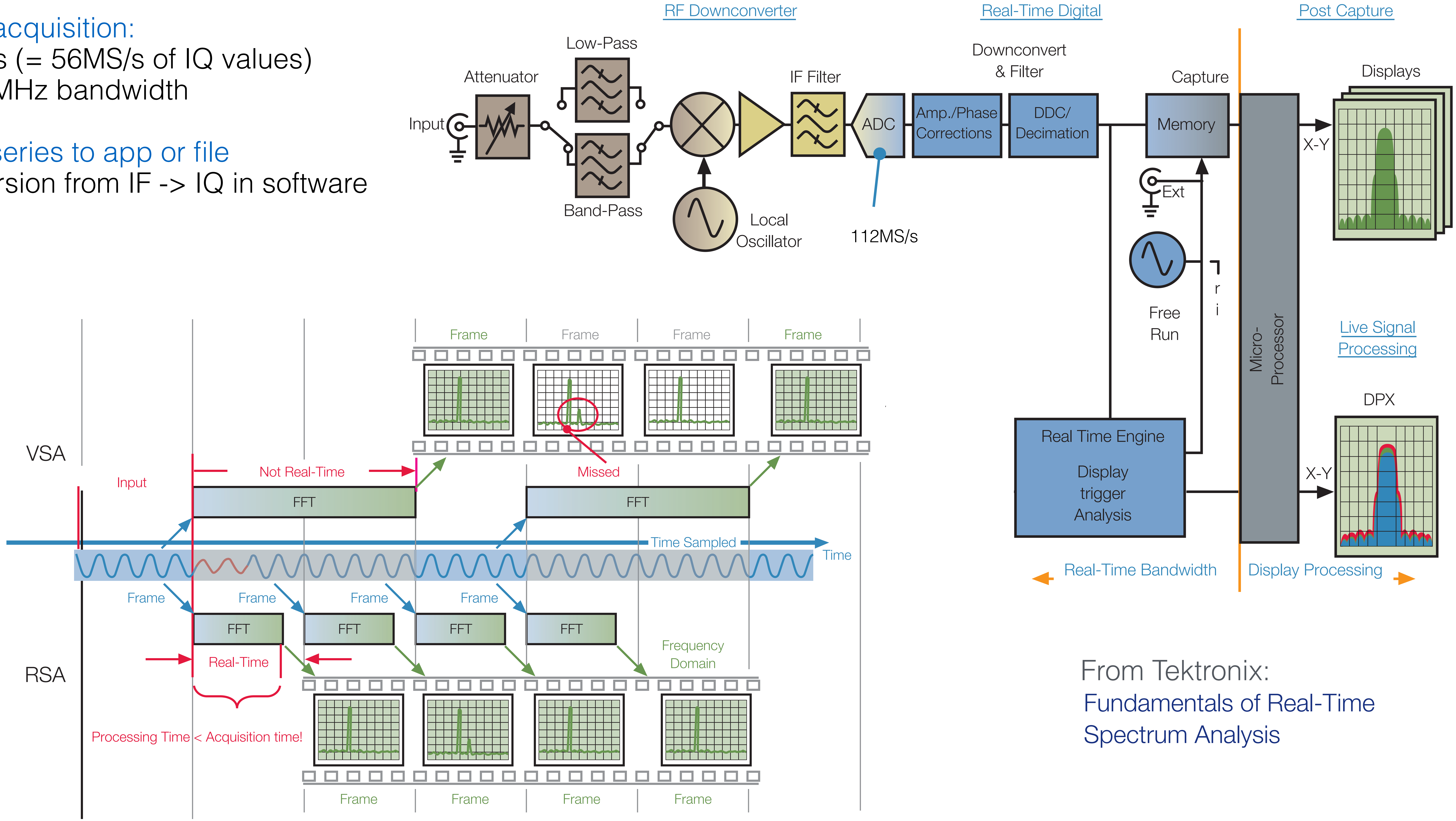
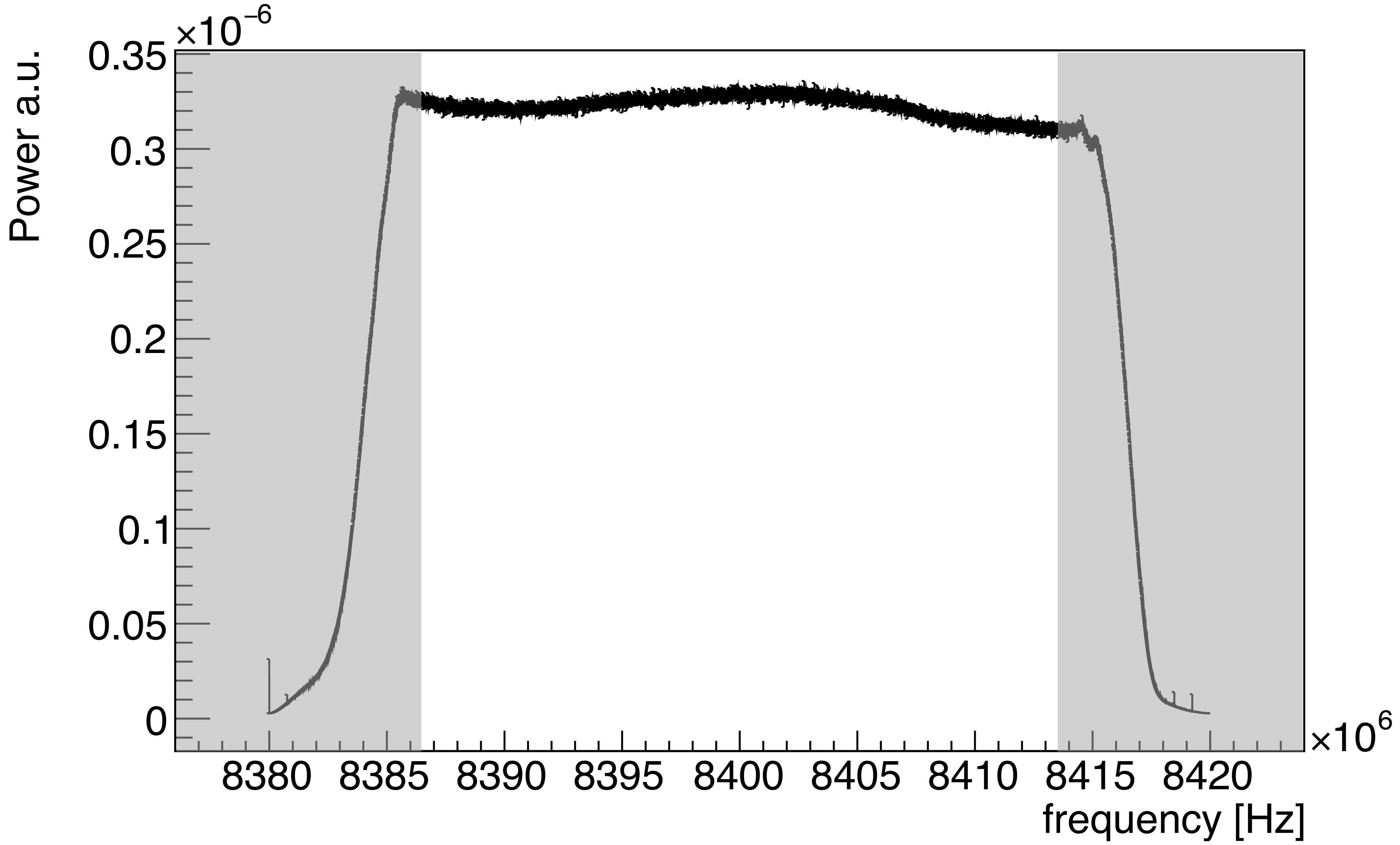


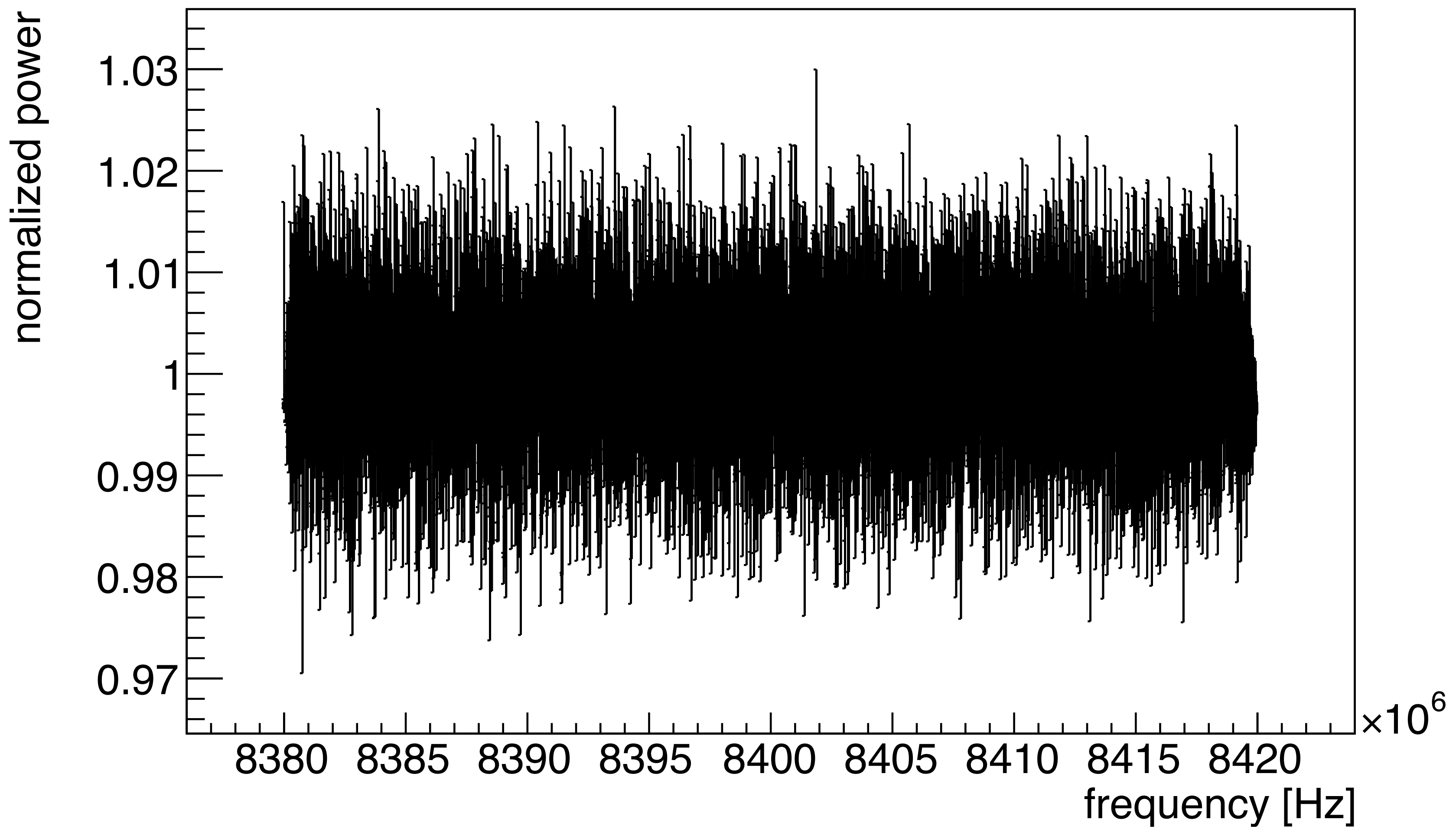
From Tektronix:
Fundamentals of Real-Time Spectrum Analysis

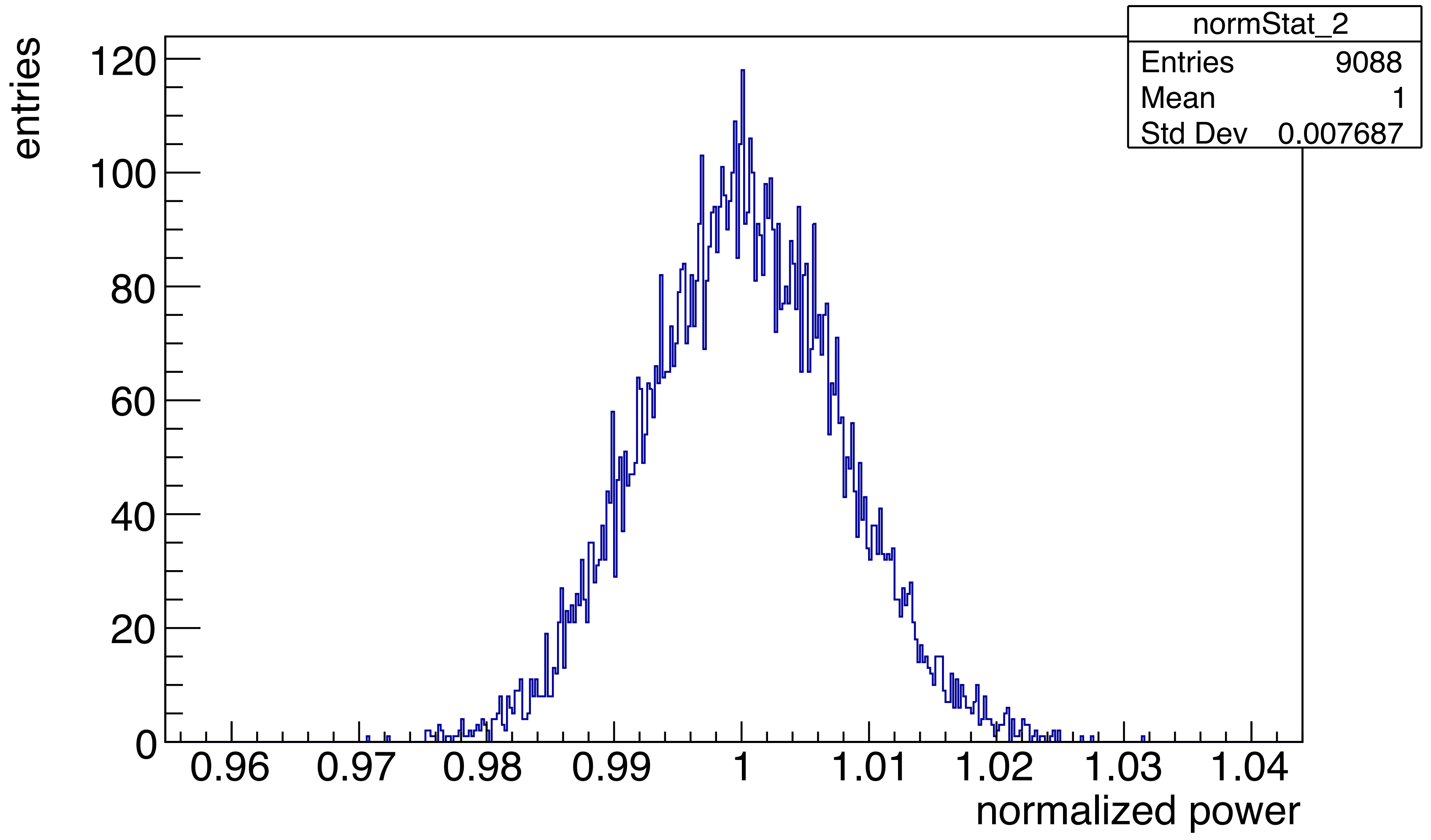
DAQ & Data analysis

- Example spectrum: **open RSA input**
  - 40MHz bandwidth
  - 2 second averaging
  - 4kHz RBW



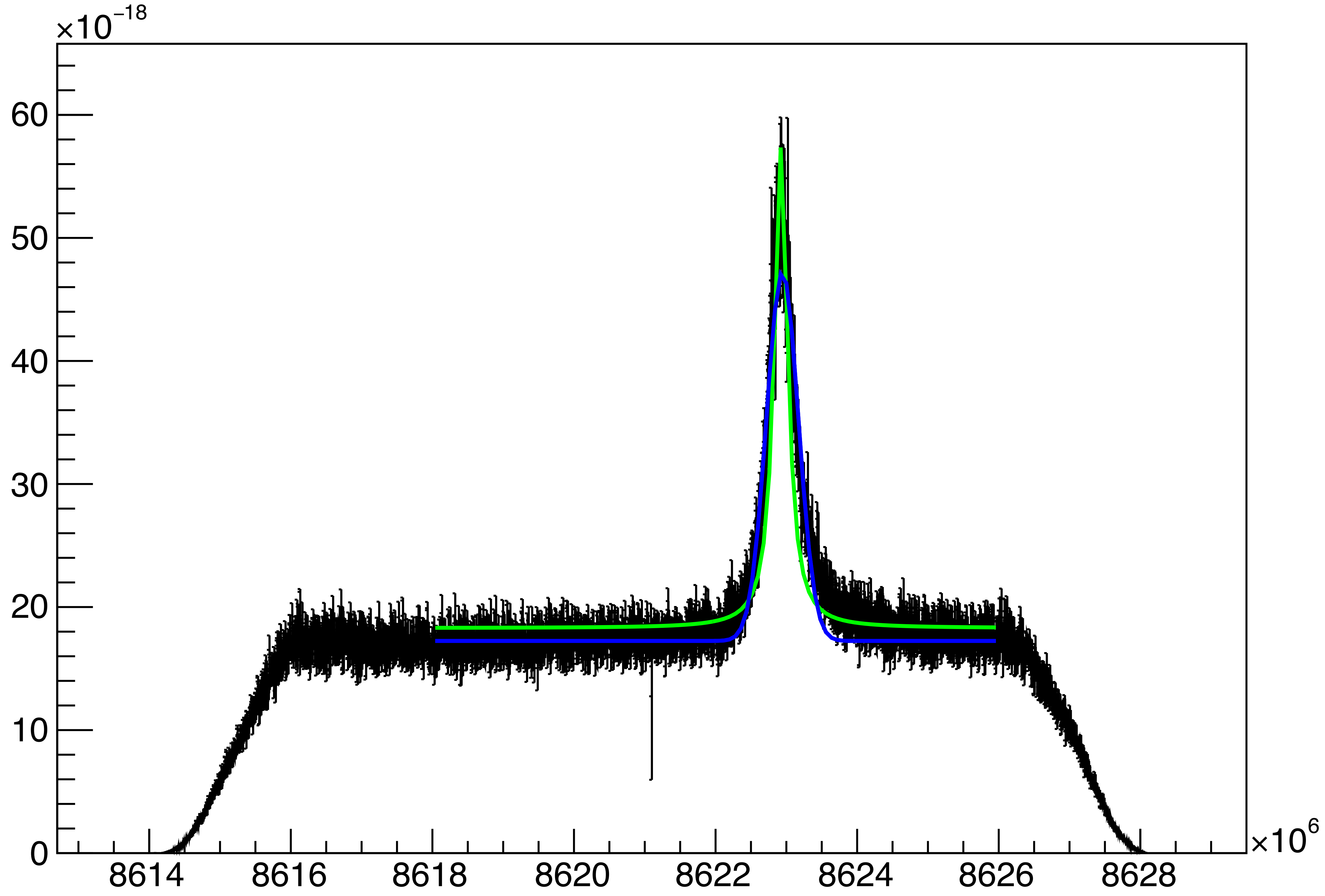
- Test of Noise shape:
  - Divide adjecent 2sec intervals





DAQ & Data analysis

- Example spectrum: test cavity at 4K
  - All preamps ON
  - Cavity resonance shape clearly visible



~20ms of data

- Averaging over several hours requires **stability**:
  - **Freq**.
  - **Gain**
  - **Noise**

- Environmental condition:
  - **Cavity**: Pressure, Temperature
  - **Readout**: Temperature, ageing

- Reflections:
  - Cause interference / beat frequencies
  - Noise scaling behaviour changed
    - Non-gaussian noise components

DAQ & Data analysis

- Two approaches for data calibration:

  - Calibration measurement with B-field OFF
    - Physics run with B-field ON normalized with calibration run
    - Offline averaging
    - Narrow band bump hunt for signal

  - Requires long term stability of setup (~days)
    - Most likely not achievable

DAQ & Data analysis

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- Calibration measurement with B-field OFF
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↓ Baseline

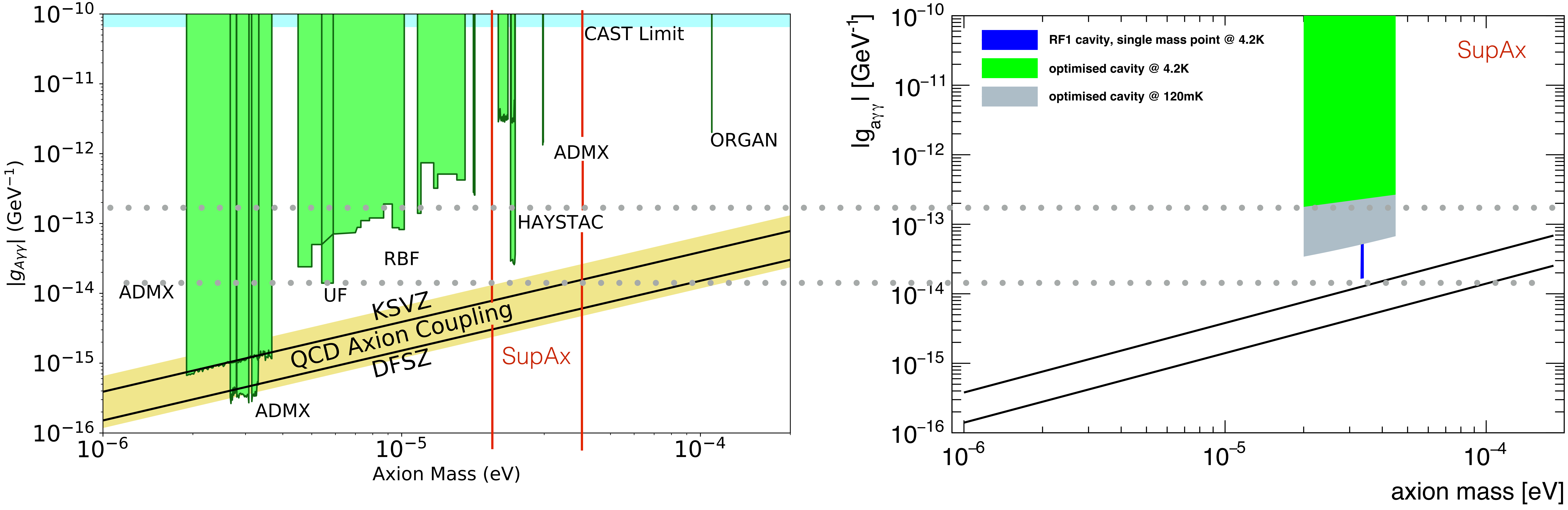
- Physics run with B-field ON
  - Fit of cavity resonance curve
    + Polynomial description of electronic gain variations
    - Repeat fit in regular chunks of data
    - Normalise data by fitted calibration
    - Offline averaging
    - Narrow band bump hunt for signal

- Requires stability over ~min
- Monitoring of drifts in DAQ for free

- Non-trivial modelling of signal path

Expected sensitivity

Scan rate: 1MHz/h

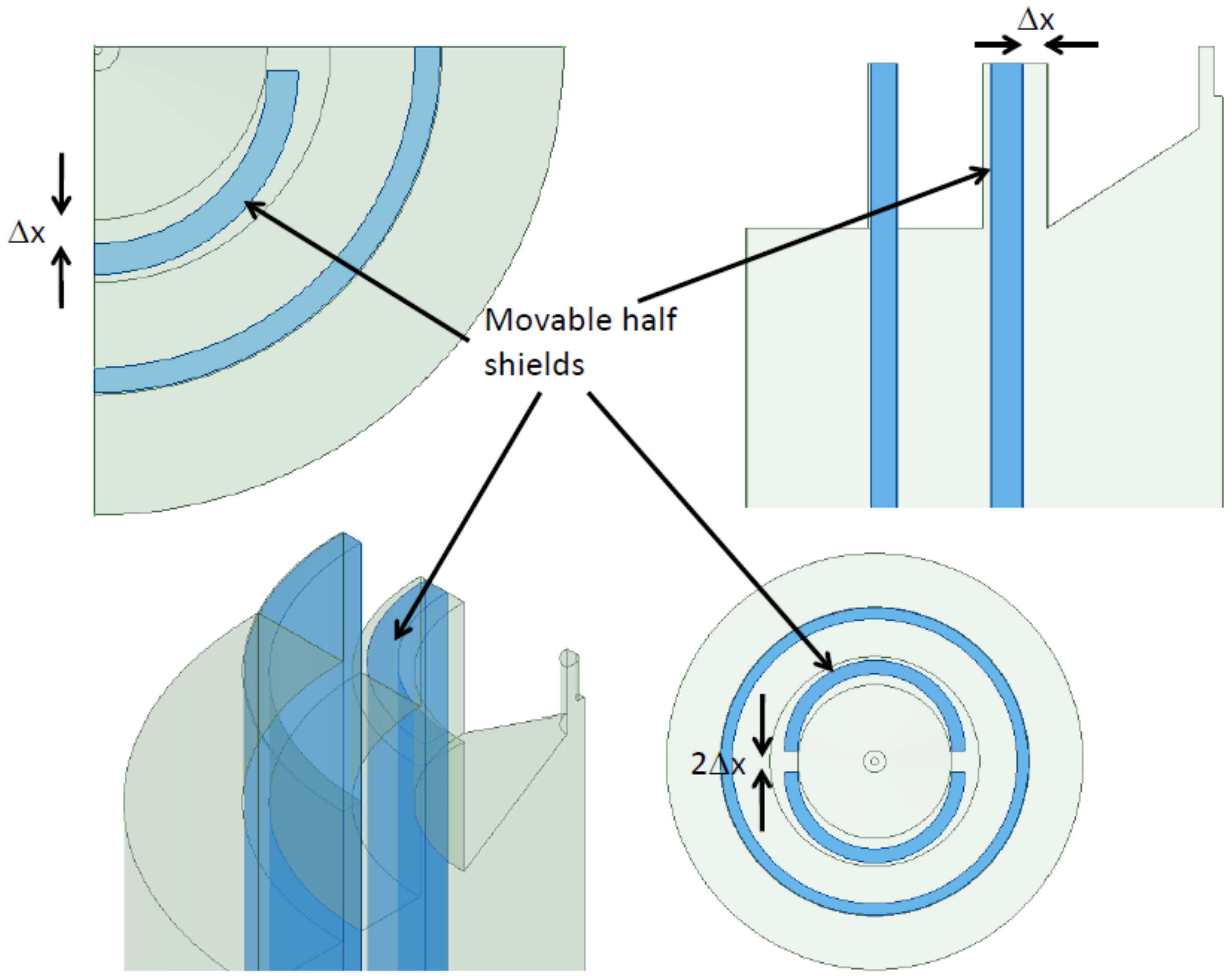


Tuning of cavities

- Aim: scan a large frequency range
  - Requires **frequency tuning**

Deformation of cavity

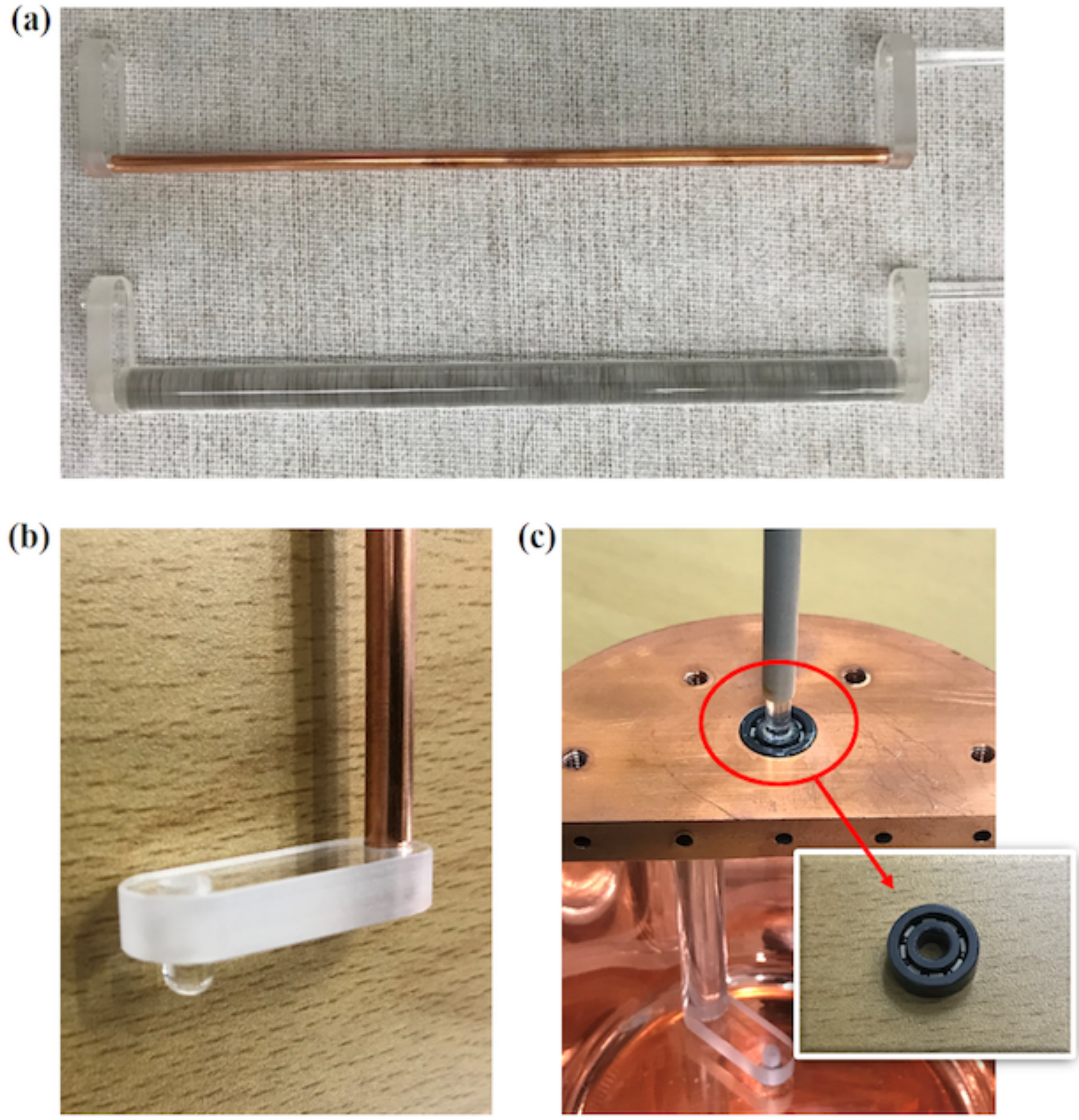
10.38 - 10.92 GHz - 5%



QUAX: arXiv:2004.02754

Movement of dielectric rods

2.45 - 2.65 GHz - 8%



CAPP: arXiv:1910.11591

Pressure change / gas chance

8.1 - 8.2 GHz - 1%

- Cavity within heat exchange gas
- Gas acts as dielectric
- Change in Pressure changes resonance frequency
- Few % tuning possible

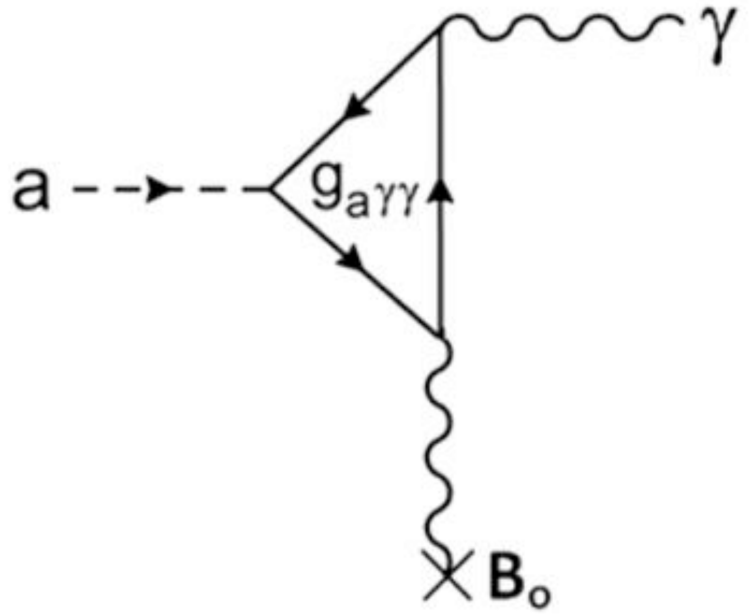
Could RF cavities be used for something else?

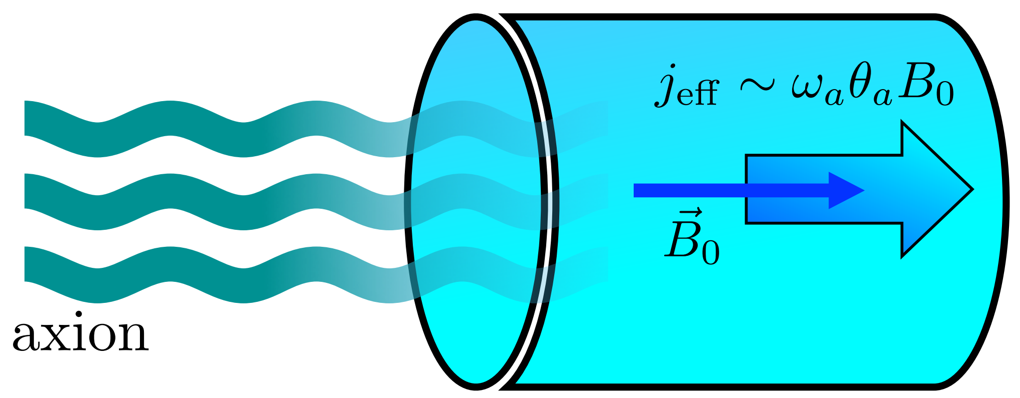
Interaction with magnetic field

- Axions:
  - CDM: non relativistic
  - Resulting E-field direction given by static B-field

$$\mathcal{L} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\ \mathbf{E}\cdot\mathbf{B}$$

$$\boldsymbol{j}_{\text{eff}} \supset g_{a\gamma\gamma}\,\partial_t a\,\mathbf{B}_0 \simeq \omega_a\,\theta_a\,\mathbf{B}_0$$





- Preferred mode: TE_{010}

- Effective signal current enters Maxwell equations:

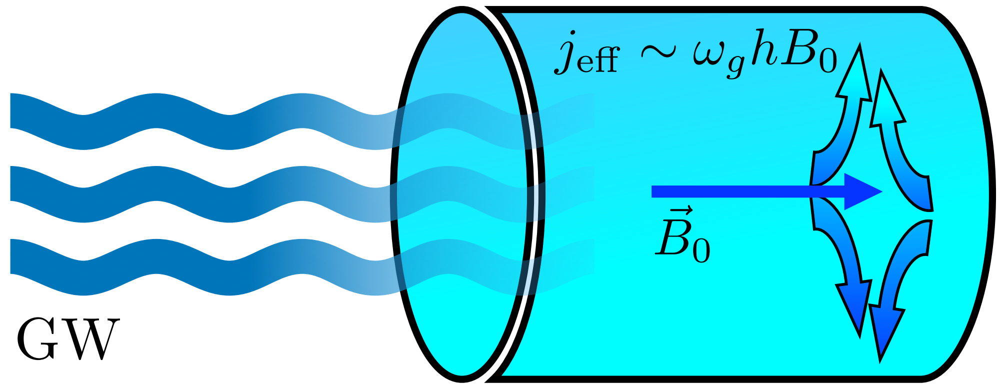
$$\nabla\cdot\mathbf{E} = \rho_{\text{eff}} + \rho,$$

$$\nabla\times\mathbf{B} - \partial_t\mathbf{E} = \boldsymbol{j}_{\text{eff}} + \boldsymbol{j}$$

- GW excites different mode compared to axion!

- Gravitational Waves:
  - Always relativistic
  - Resulting E-field direction given by GW direction

$$j_{\text{eff}} \sim \underset{\text{freq. of GW}}{\omega_g}\ \underset{\text{strain of GW}}{h}\ B_0$$



- Preferred mode: TE_{212}

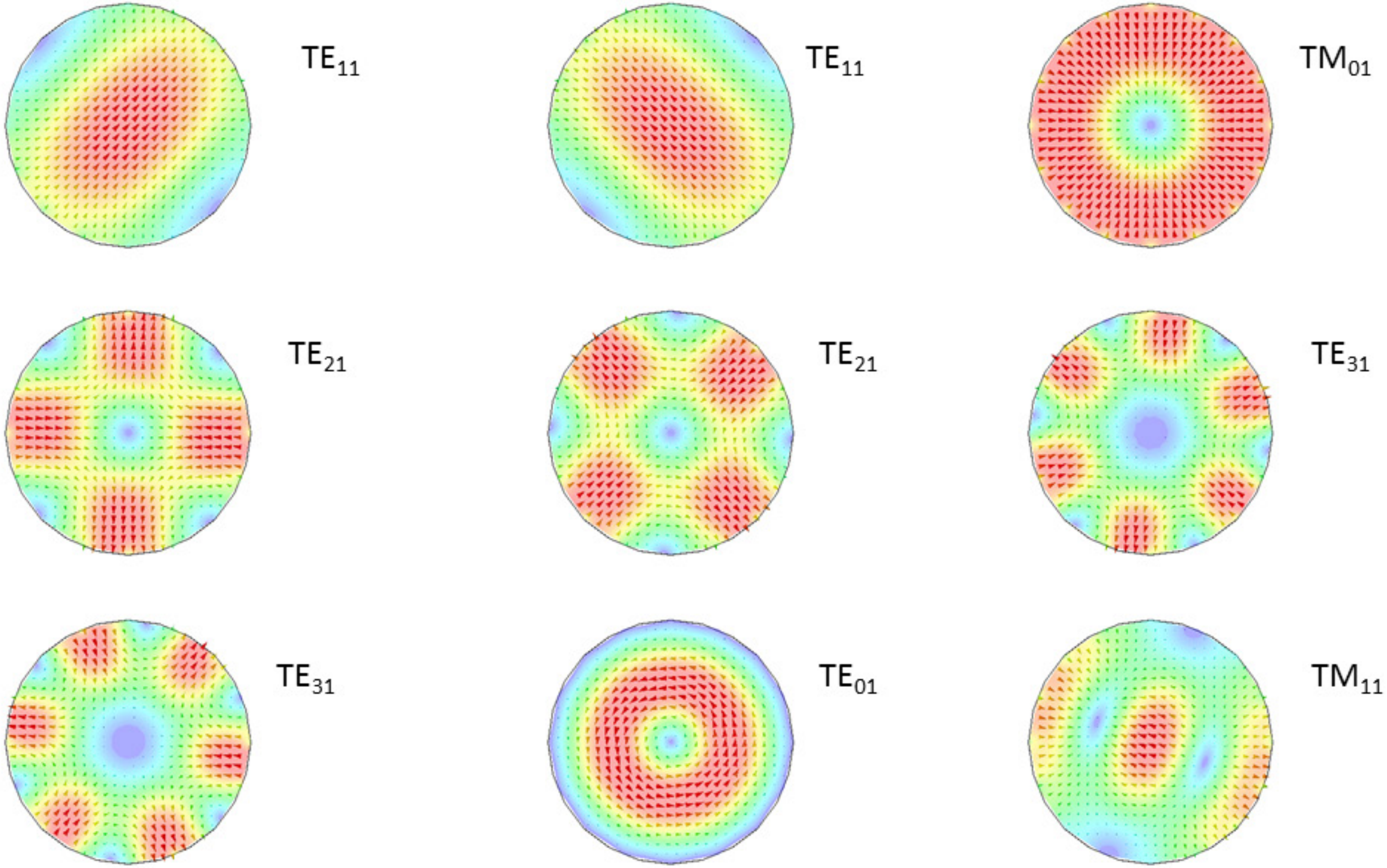
GW waves exited higher order mode(s) in cavity

- Signal Power

$$P_{\text{sig}} = \frac{1}{2}\, Q\, \omega_g^3\, V_{\text{cav}}^{5/3}\, (\eta_n\, h_0\, B_0)^2$$

Effective coupling to EM field, dependent on selected cavity mode

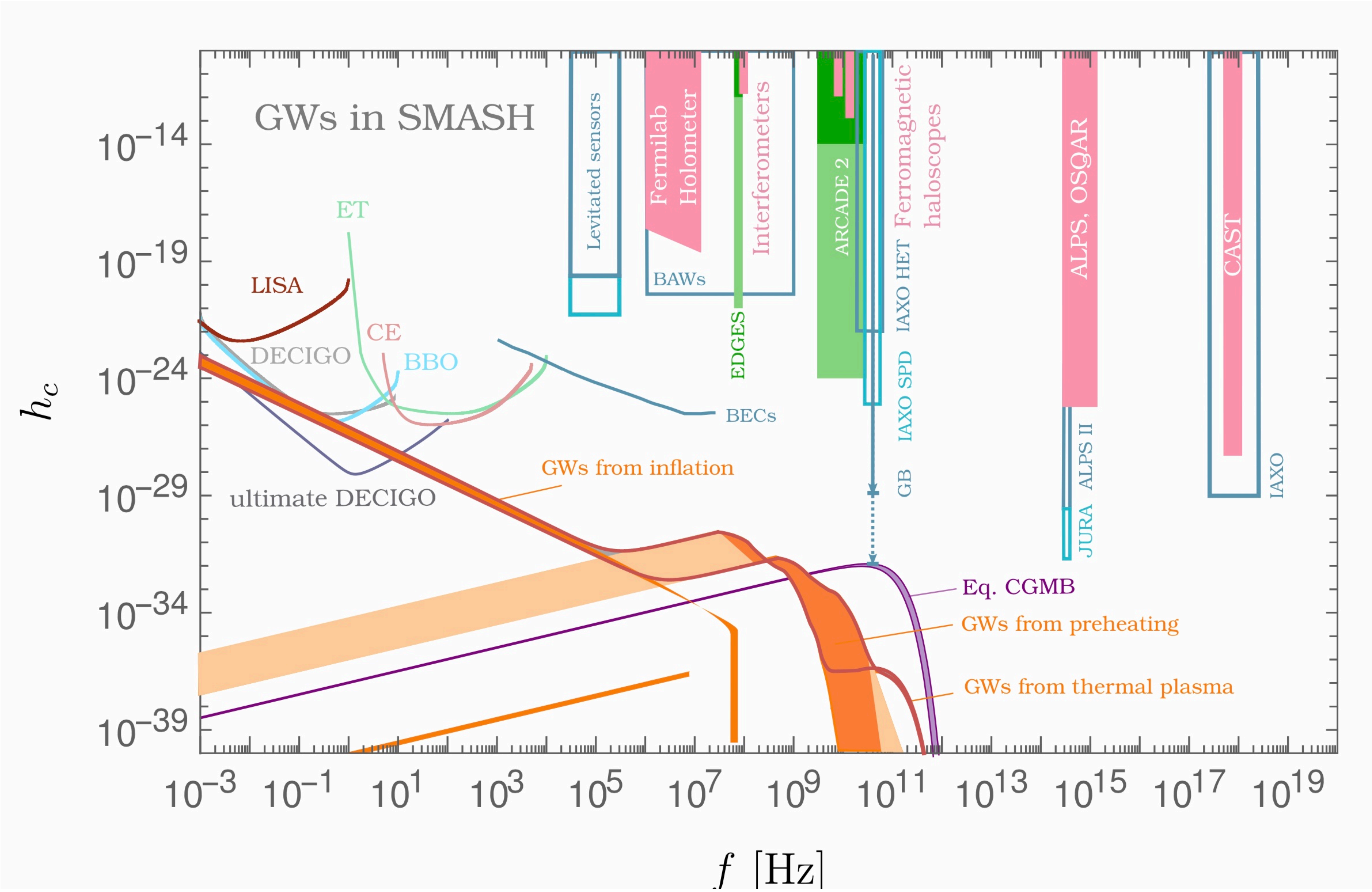
$$\eta_n \equiv \frac{\left| \int_{V_{\text{cav}}} d^3\mathbf{x}\ \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times} \right|}{V_{\text{cav}}^{1/2} \left(\int_{V_{\text{cav}}} d^3\mathbf{x}\ |\mathbf{E}_n|^2 \right)^{1/2}}\ ,$$

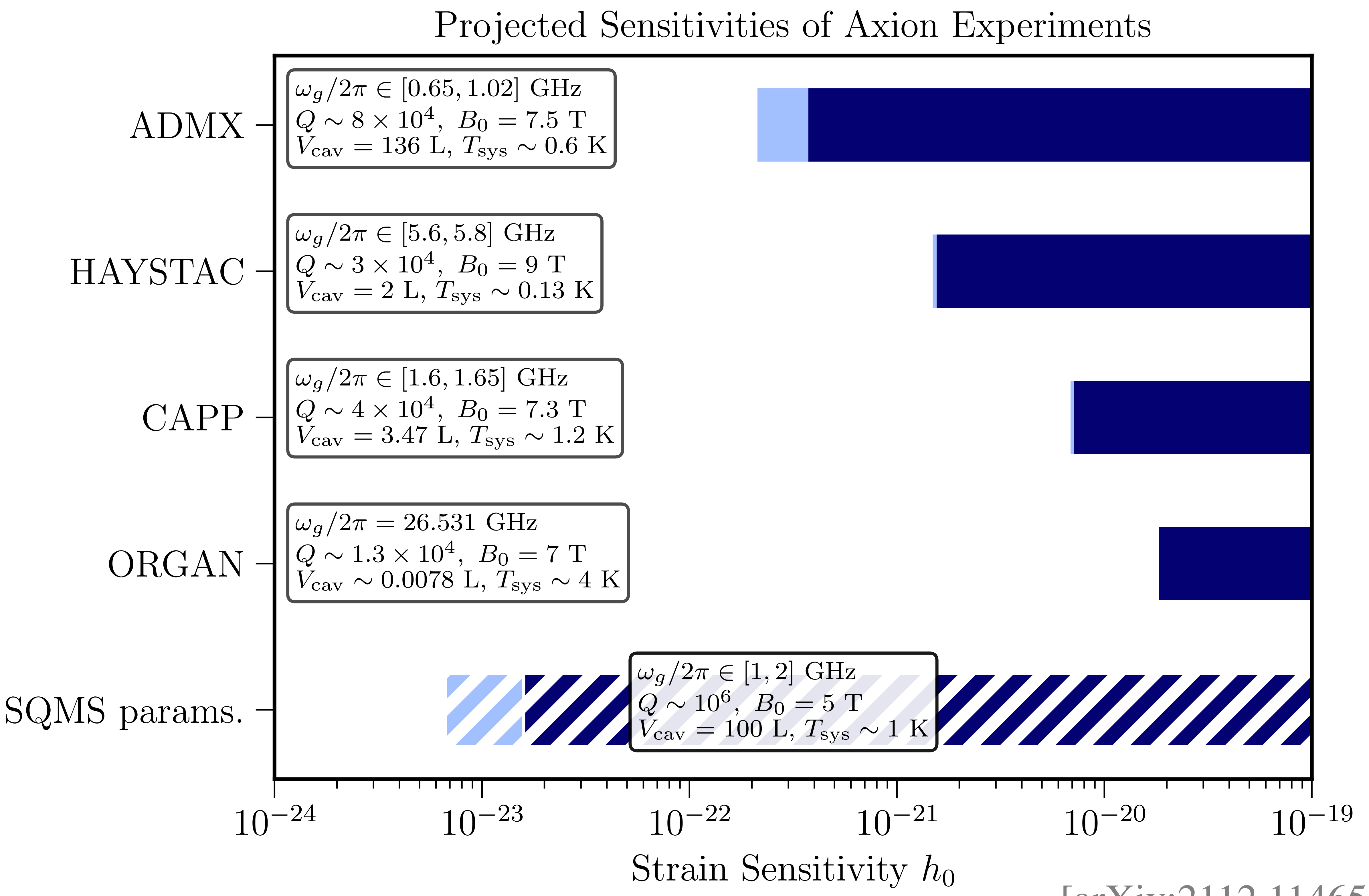


[arXiv:1601.05230]

Recasting axion experiments into GW searches

- Expecting competitive measurements w.r.t. Haystack



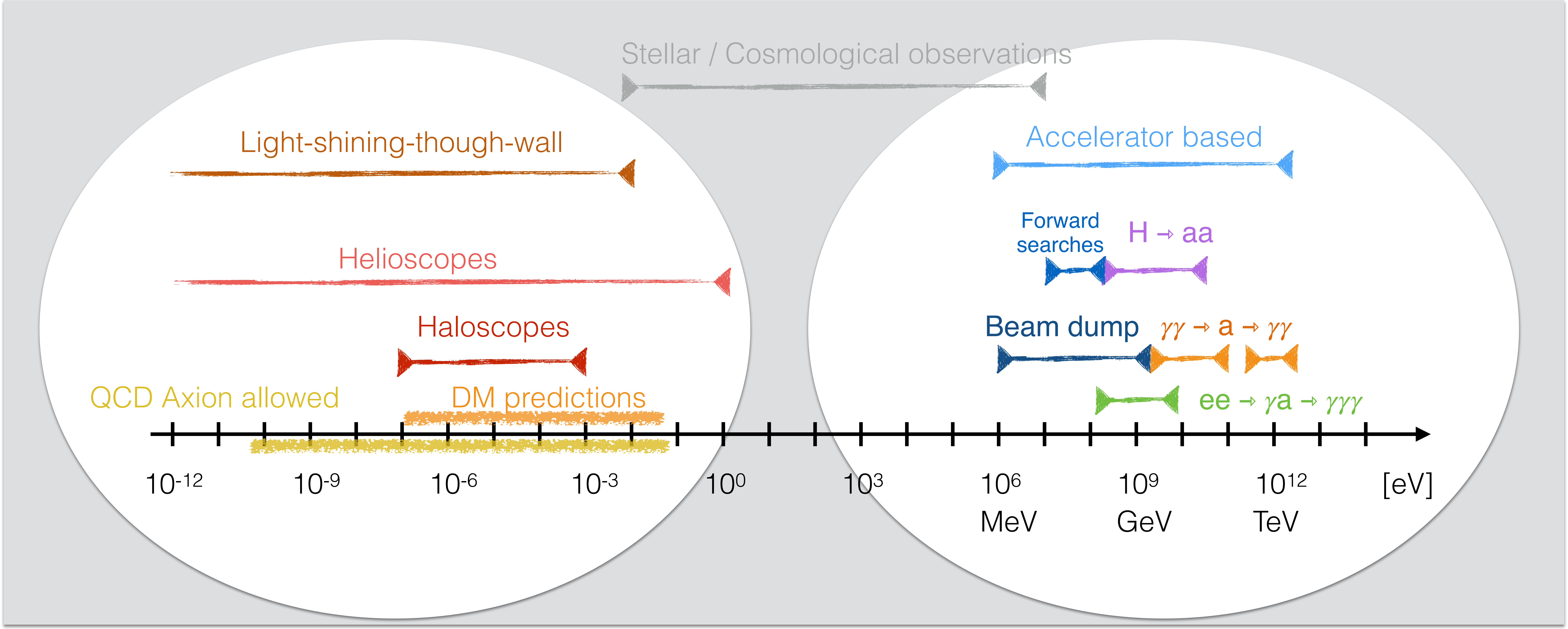


[arXiv:2112.11465]

Summary

ALPs & Axions:

Theoretically well motivated — Intriguing candidate for Dark Matter — Huge parameter range
Diverse array of experimental approaches



NB.: Only a personal selection of experimental approaches was shown

Advertisement: **Wavy Dark Matter summer in Mainz**

https://wavydarkmatter.org/

17TH PATRAS WORKSHOP ON AXIONS, WIMPS AND WISPS

08 - 12 August 2022

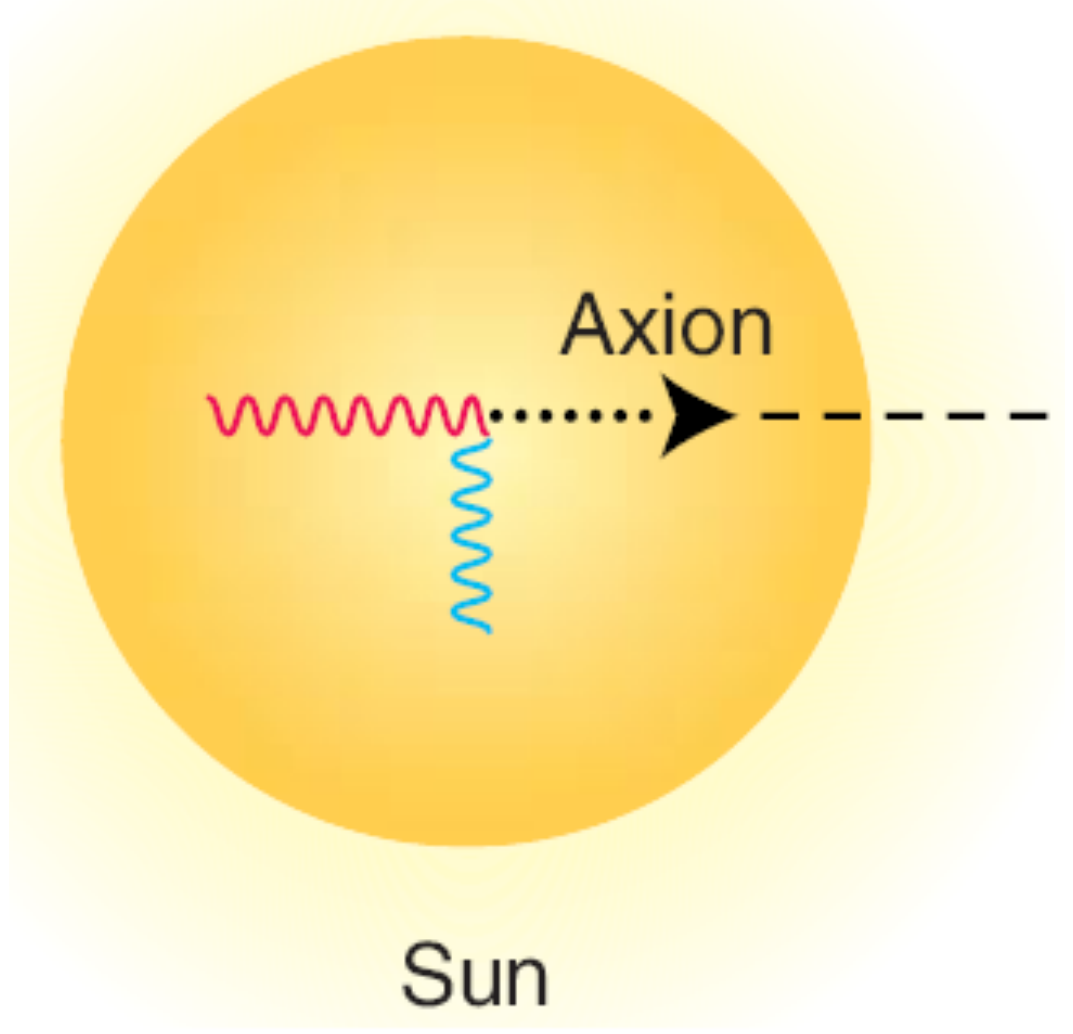
31.07.-05.08.2022	Ultralight Dark Matter - Scientific foundations and experimental searches Summer School (Physics Center Bad Honnef, Germany) Scientific program
08.08.-12.08.2022	17th Patras Workshop on Axions, WIMPs and WISPs (Johannes Gutenberg University in Mainz (JGU), Germany)
15.08.-19.08.2022	Wavy Dark Matter Detection with Quantum Networks Workshop (Mainz Institute for Theoretical Physics (MITP), Germany)

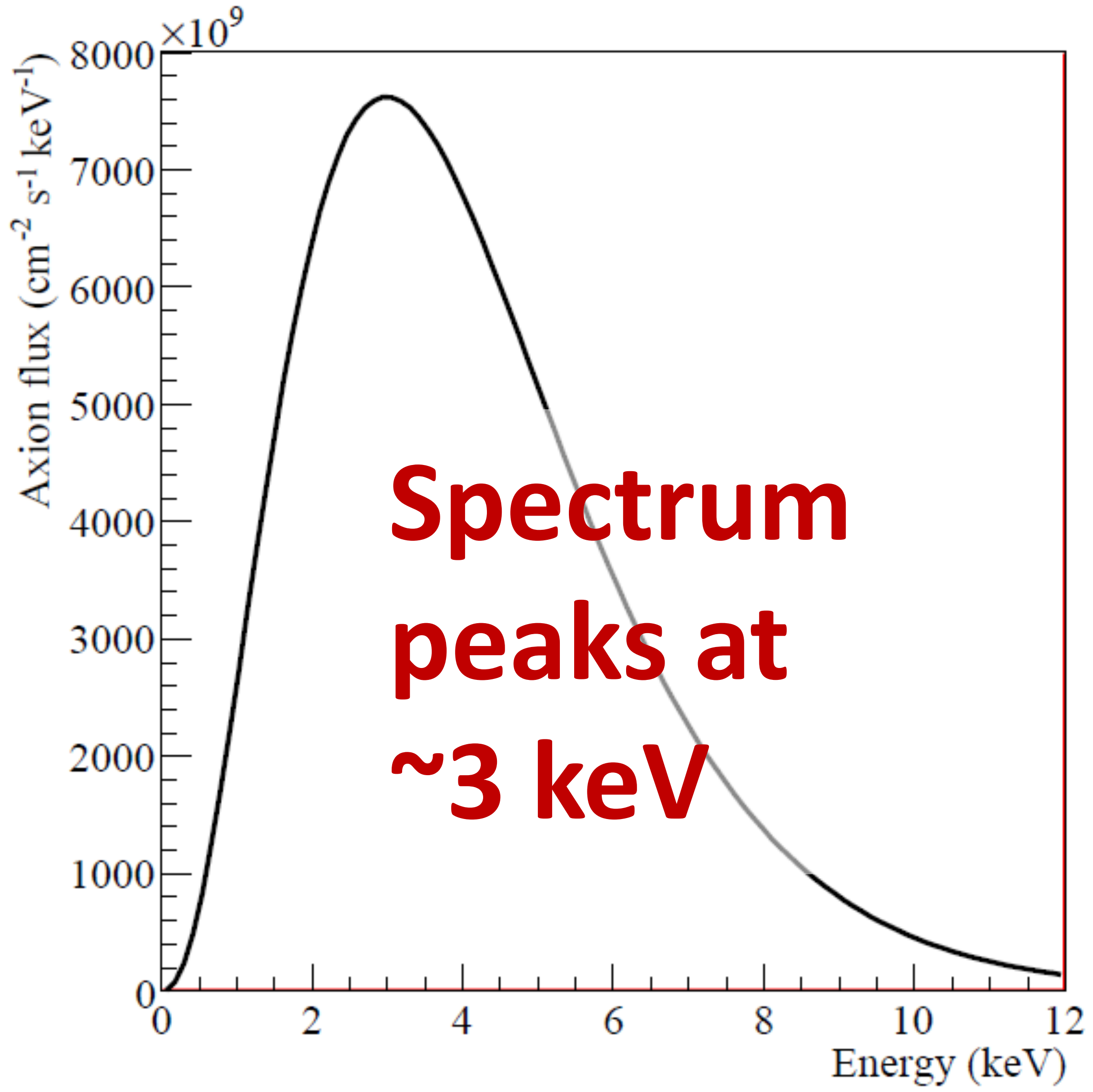
BACKUP

Axion Spektrum from the sun

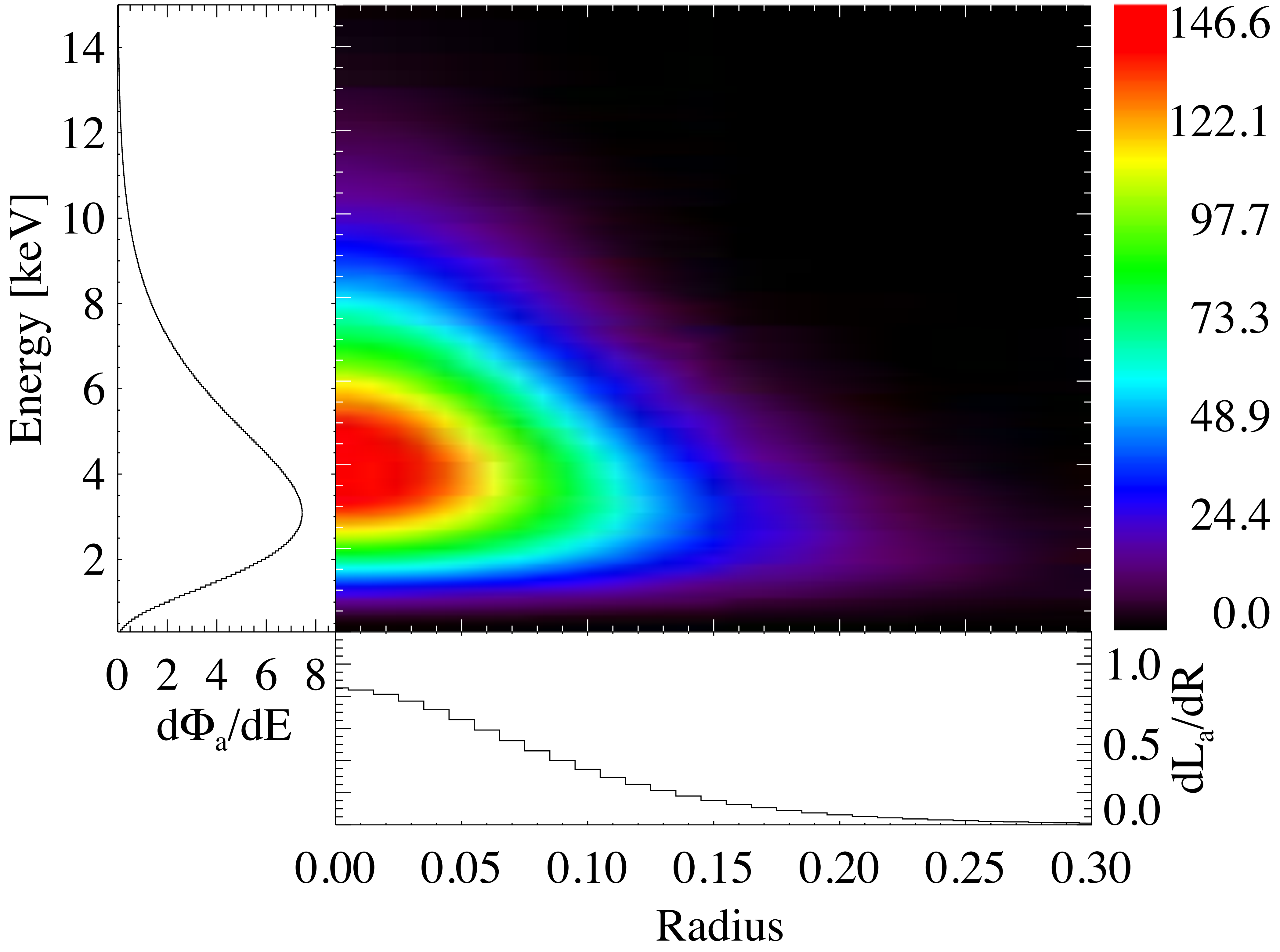
- Blackbody radiation in solar core in keV regime
  - Convert to axions in sun’s magnetic field

Primakoff effect





Spectrum peaks at ~3 keV



- Axions mainly produced in core of sun

Light Axions - RF cavity based searches

- Integration time is defined by targeted SNR
- Null measurement with expected SNR 5.1 <=> 95% CL upper limit on $g_{a\gamma\gamma}$

Integration time

$$SNR = \frac{P_{\text{sig}}}{k_B T_{\text{sys}}} \sqrt{\frac{\tau}{\Delta \nu_a}}$$

- Combination of
  - Cavity temperature
  - Readout noise

- Bandwidth of the readout
  - Axion line width = 1kHz,
  - Cavity bandwidth depending on Q, typ: ~25kHz

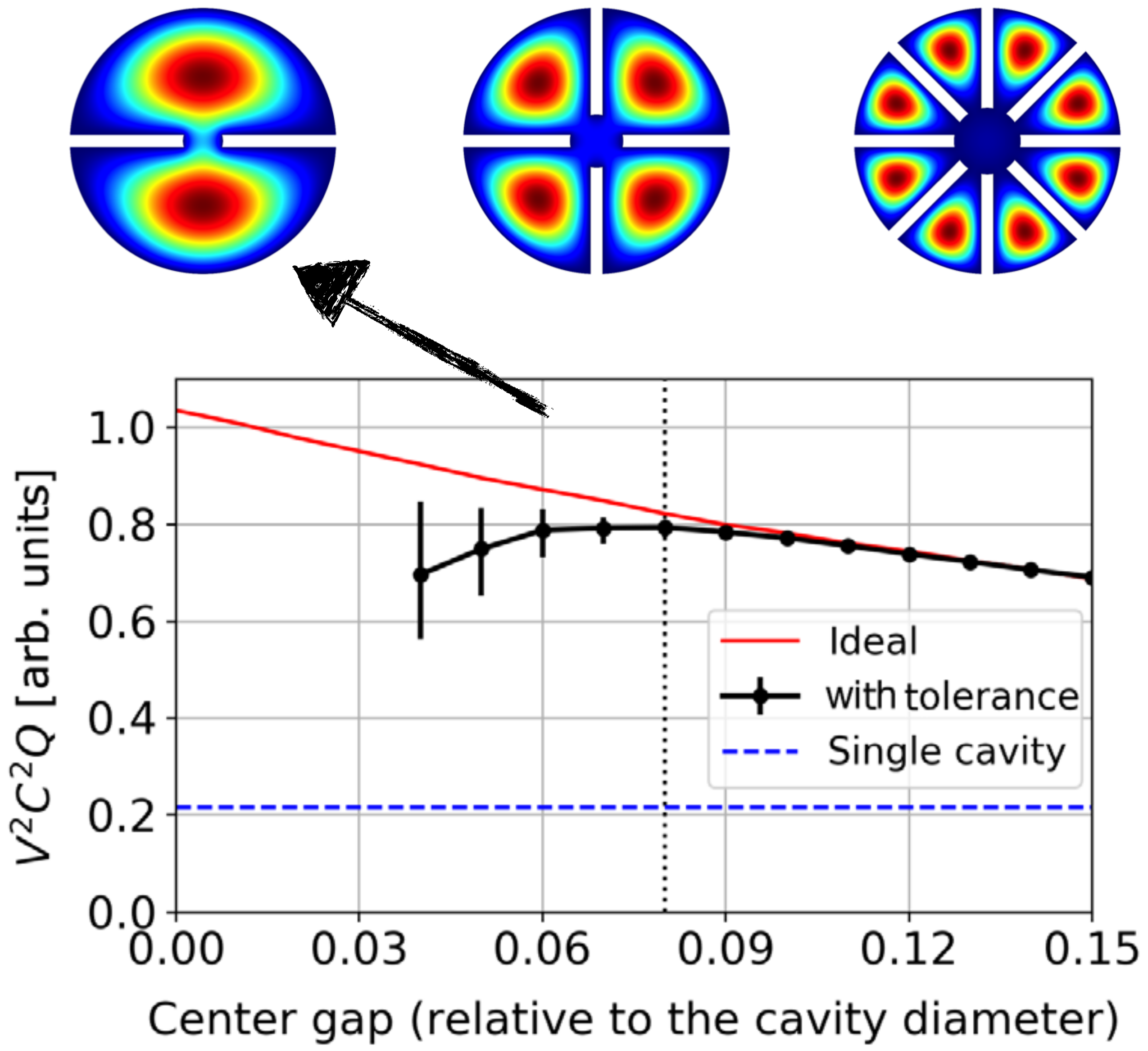
- Main figure of merit: scanning speed

$$\frac{\partial \nu}{\partial t} \propto \frac{g^4_{a\gamma\gamma}}{m_a^2} \left(\frac{1}{SNR}\right)^2 \left(\frac{1}{k_b T_{sys}}\right)^2 \boxed{B^4 V^2 Q_L}$$

Light Axions - RF cavity based searches - Proposed experiments

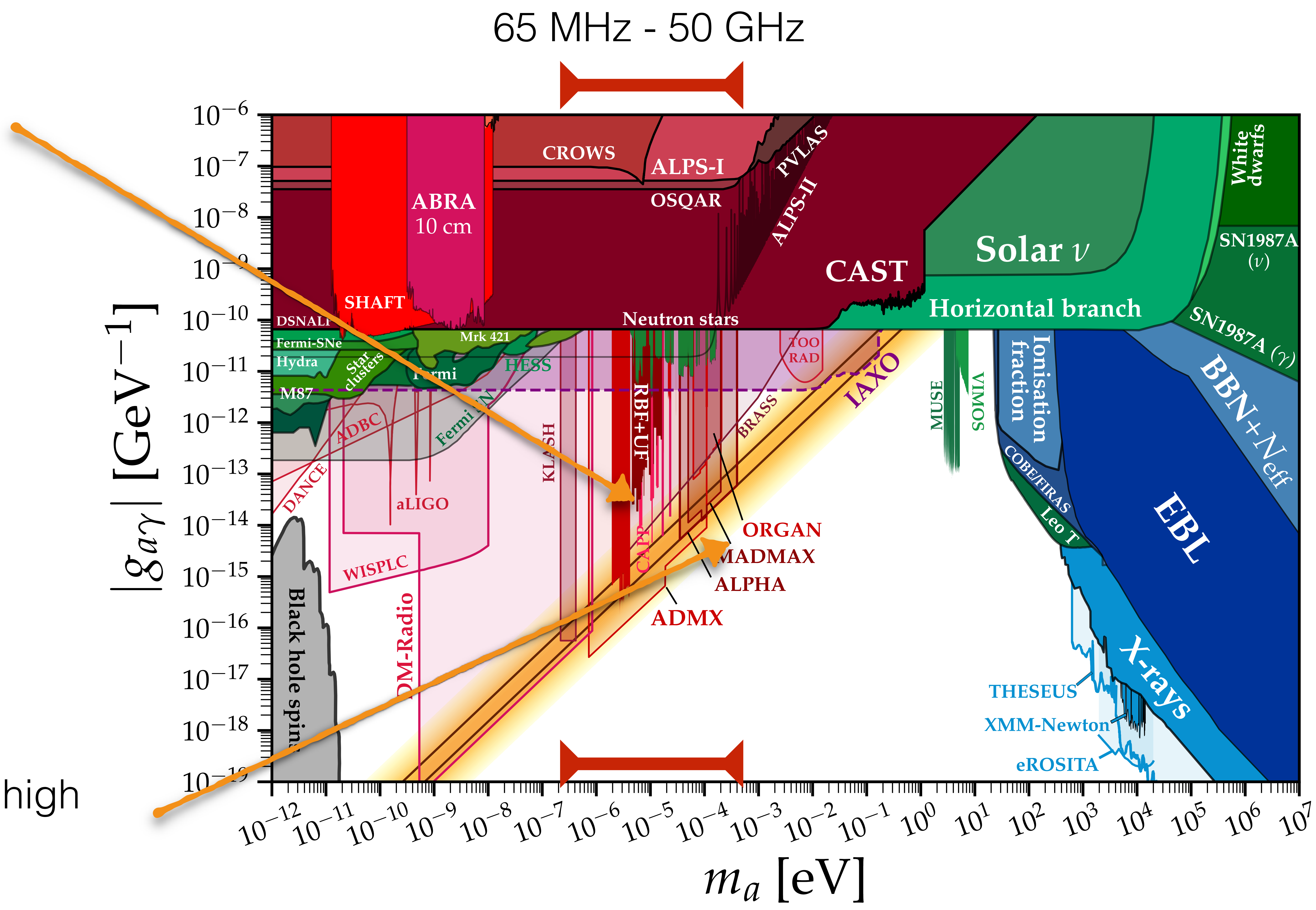
- Medium frequencies:
  - Coupled cavities: CAPP-9T (3 GHz)

    https://doi.org/10.1103/PhysRevLett.125.221302



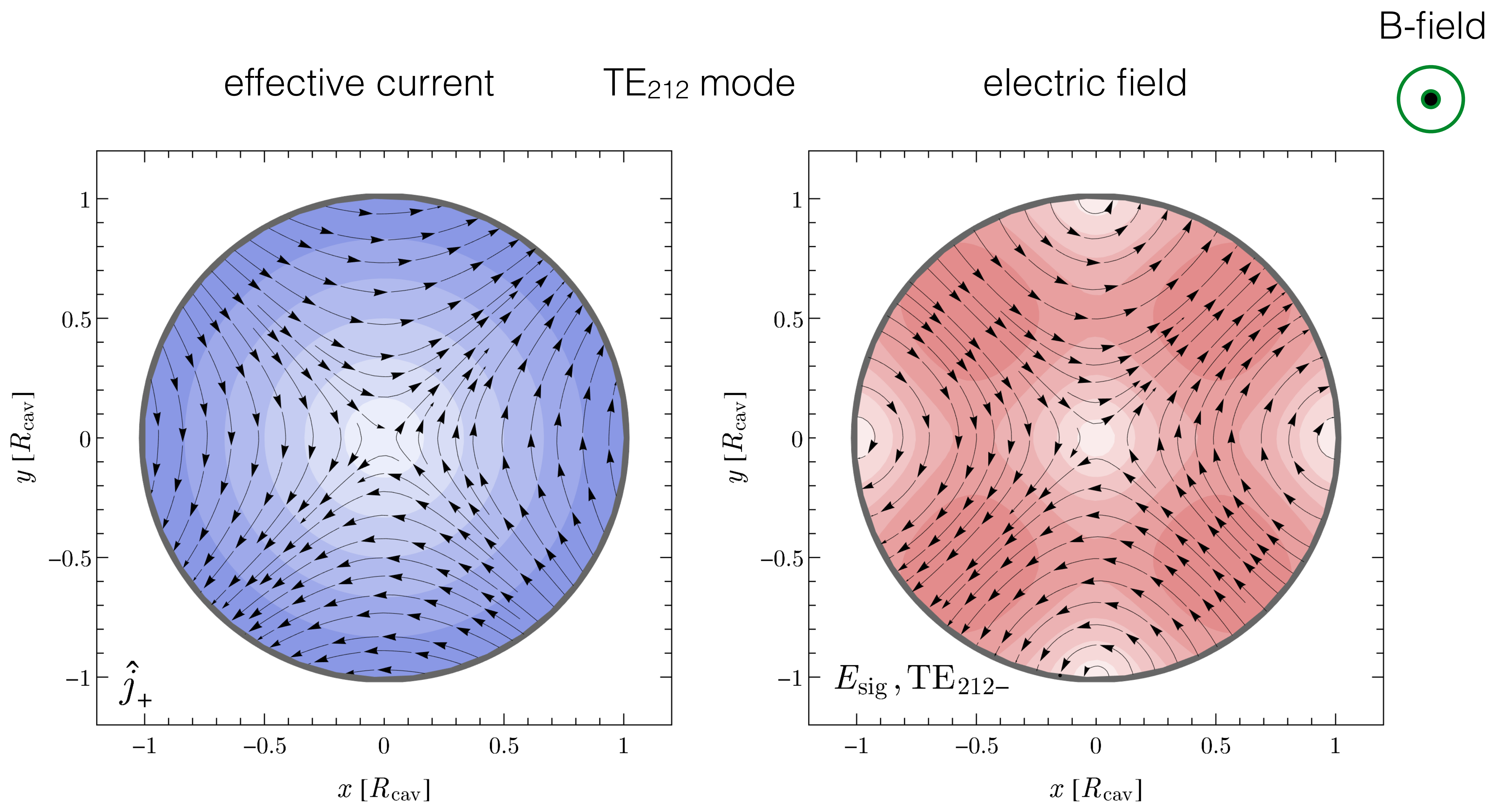
- High frequencies:
  - Use **higher order modes** in large R cavity
    - (ORGAN) TM$_{030}$ 26-27 GHz
    - Need to introduce dielectric rings to keep coupling high

  https://doi.org/10.1007/978-3-319-92726-8_14



[source: https://github.com/cajohare/AxionLimits]

GW waves exited higher order mode(s) in cavity



[arXiv:2112.11465]

- Signal Power

$$P_{\rm sig} = \frac{1}{2}\, Q\, \omega_g^3\, V_{\rm cav}^{5/3}\, (\eta_n\, h_0\, B_0)^2$$

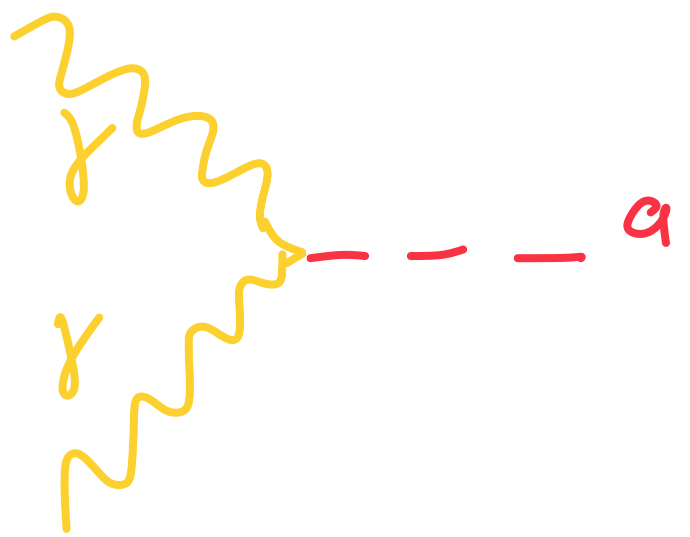
Effective coupling to EM field,
dependent on selected cavity mode

$$\eta_n \equiv \frac{\left|\int_{V_{\rm cav}} d^3\mathbf{x}\ \mathbf{E}_n^* \cdot \hat{\boldsymbol{j}}_{+,\times}\right|}{V_{\rm cav}^{1/2}\left(\int_{V_{\rm cav}} d^3\mathbf{x}\ |\mathbf{E}_n|^2\right)^{1/2}}\ ,$$

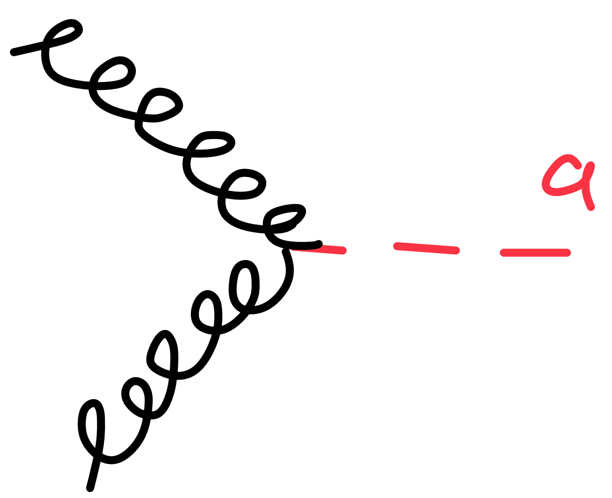
Heavy axions - Collider Based Searches

- **Production modes (at the LHC):**

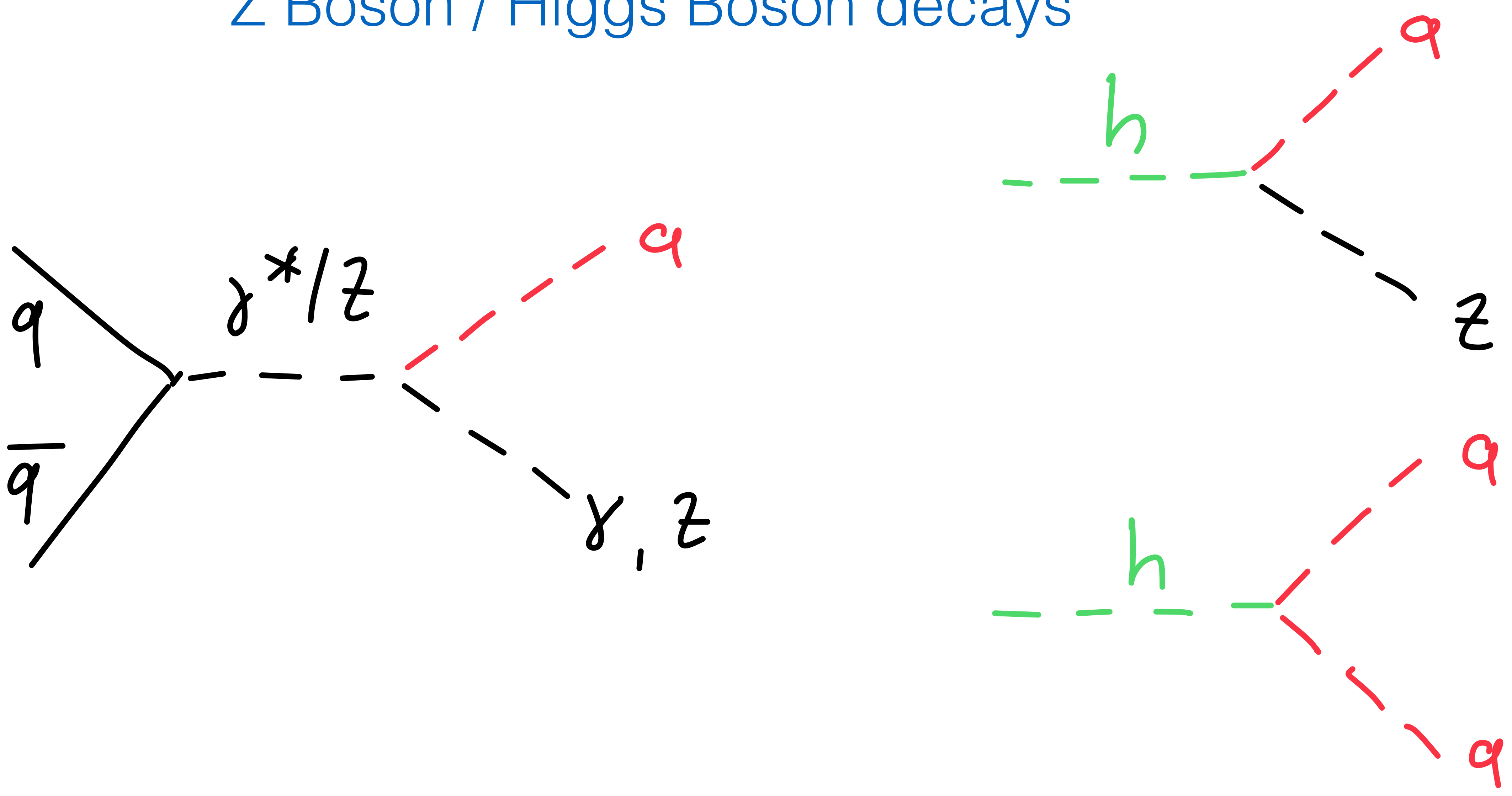
Photon fusion



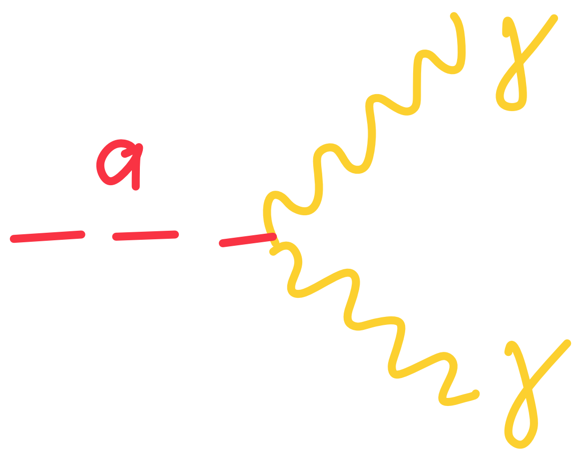
Gluon fusion



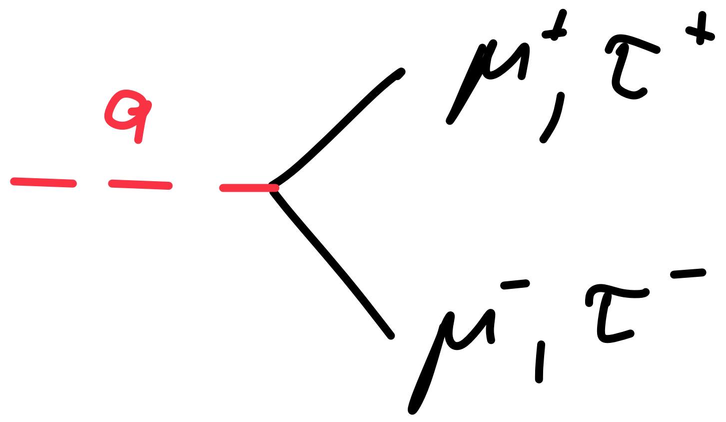
Z Boson / Higgs Boson decays



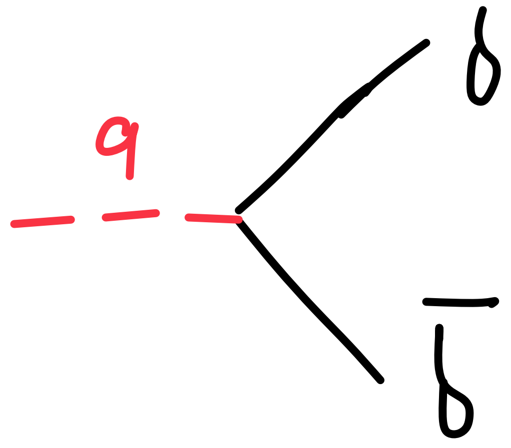
- **Decay channels considered**



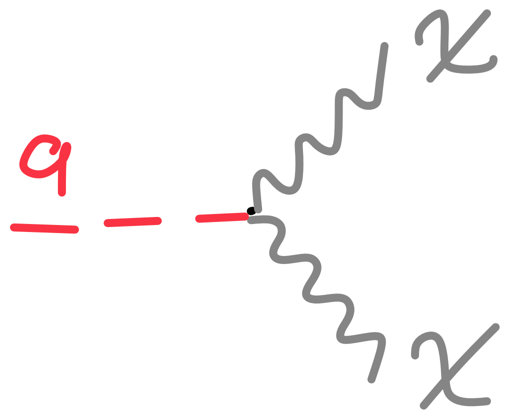
Photons



Leptons

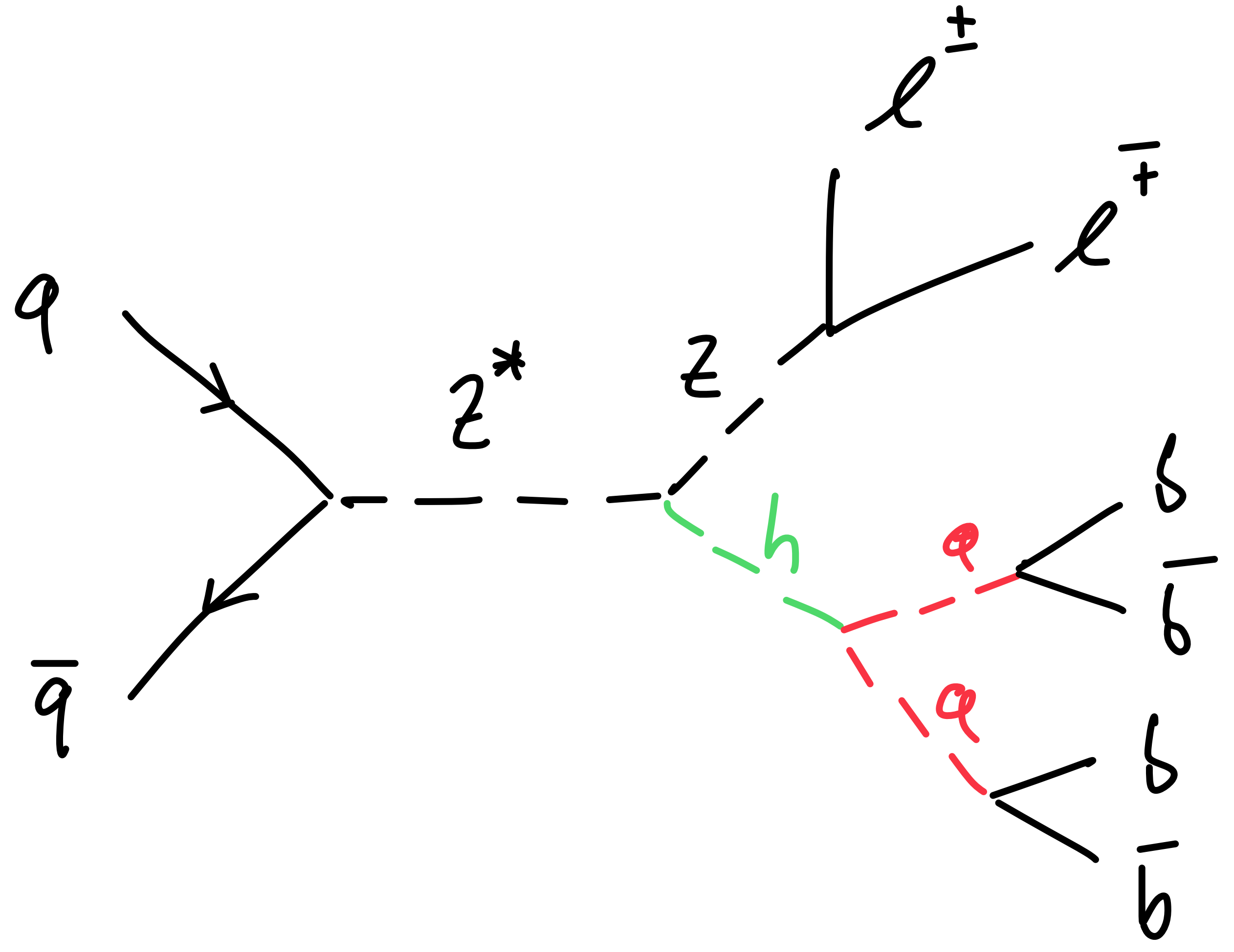


Quarks

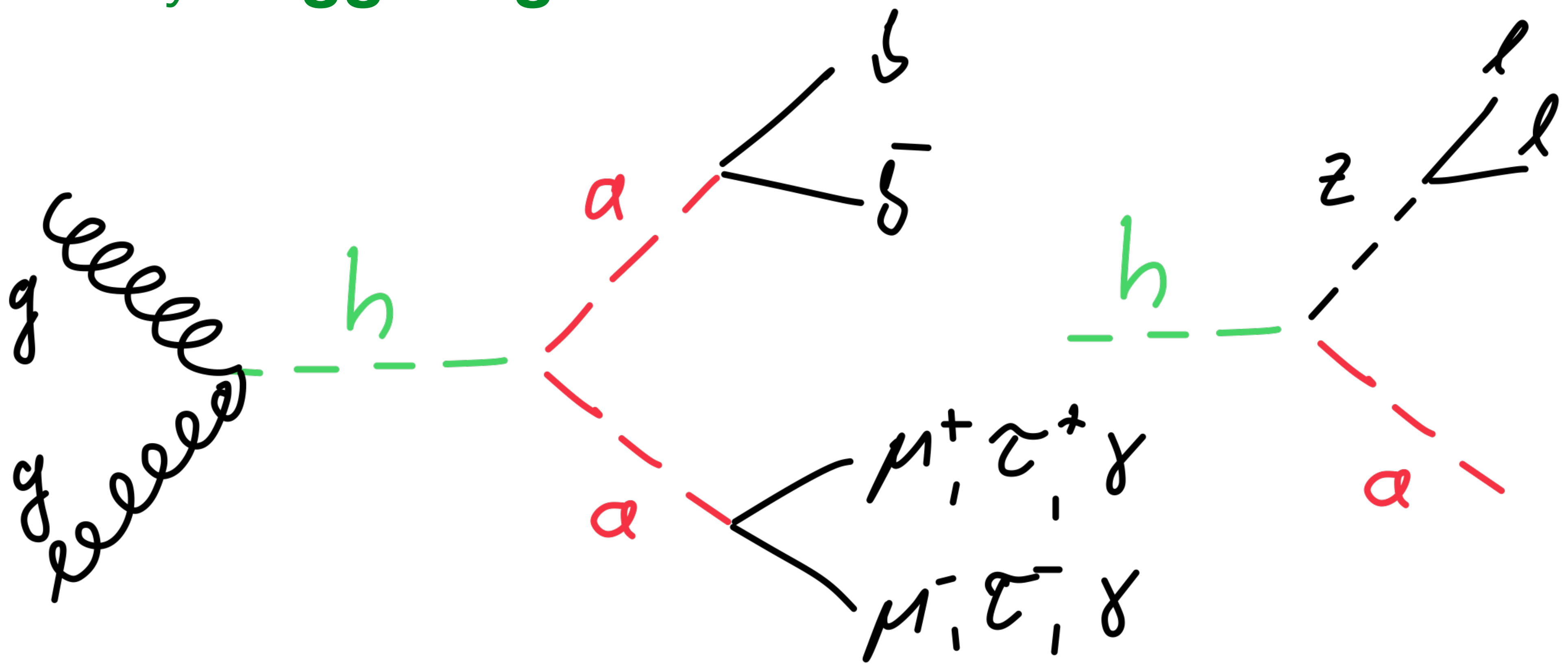


Invisible

Heavy axions - Collider Based Searches - Higgs decays



- Associated Z boson:
  - Lepton final states considered
  - Easy **Triggering**



- pp → H vs. pp → ZH
  - 65 times larger cross section

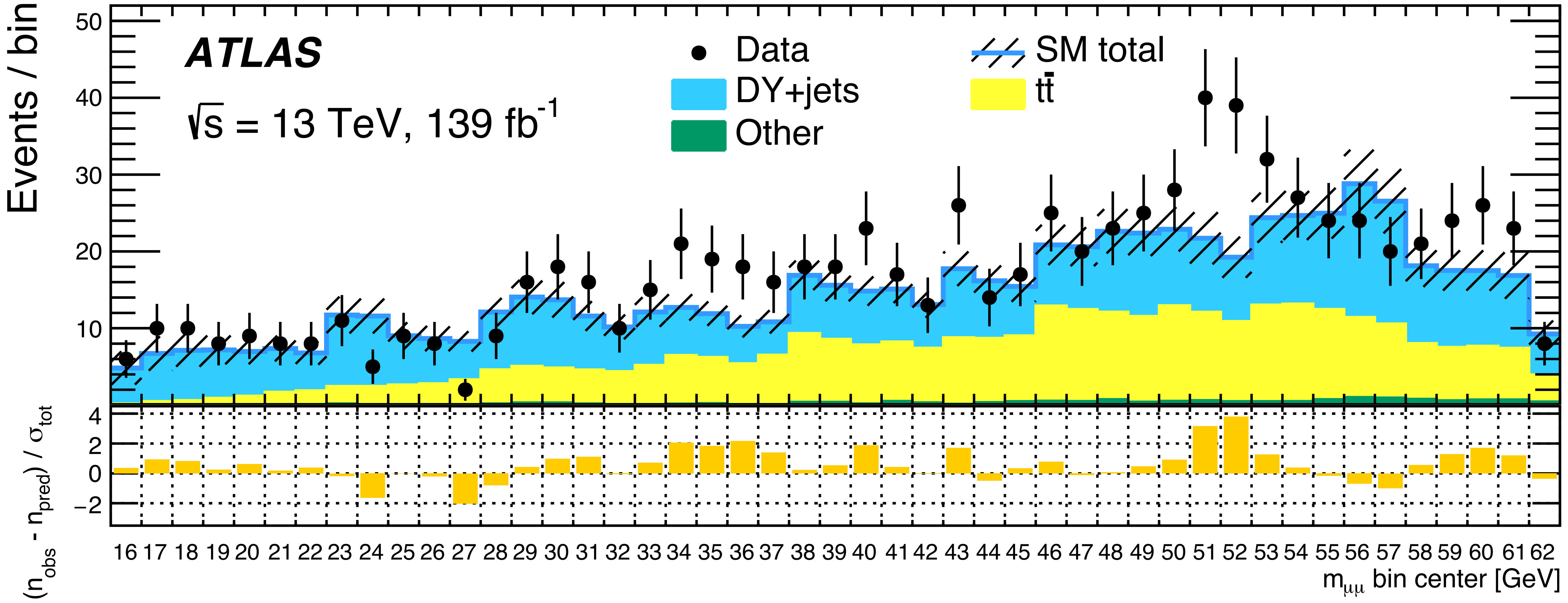
- Event selection exploiting:
  - 4 particle invariant mass
  - relation between reconstructed axions
  - Usually MVA methods utilised to reduce background
- Axion mass reconstruction:
  - Easy with leptons in final state
  - Hadronic final states:
    - Worse mass resolution
    - Attempts to reconstruct mass using NN

Example: H → aa → 2b2μ

Phys. Rev. D 105 (2022) 012006

CMS: Phys. Lett. B 795 (2019) 398

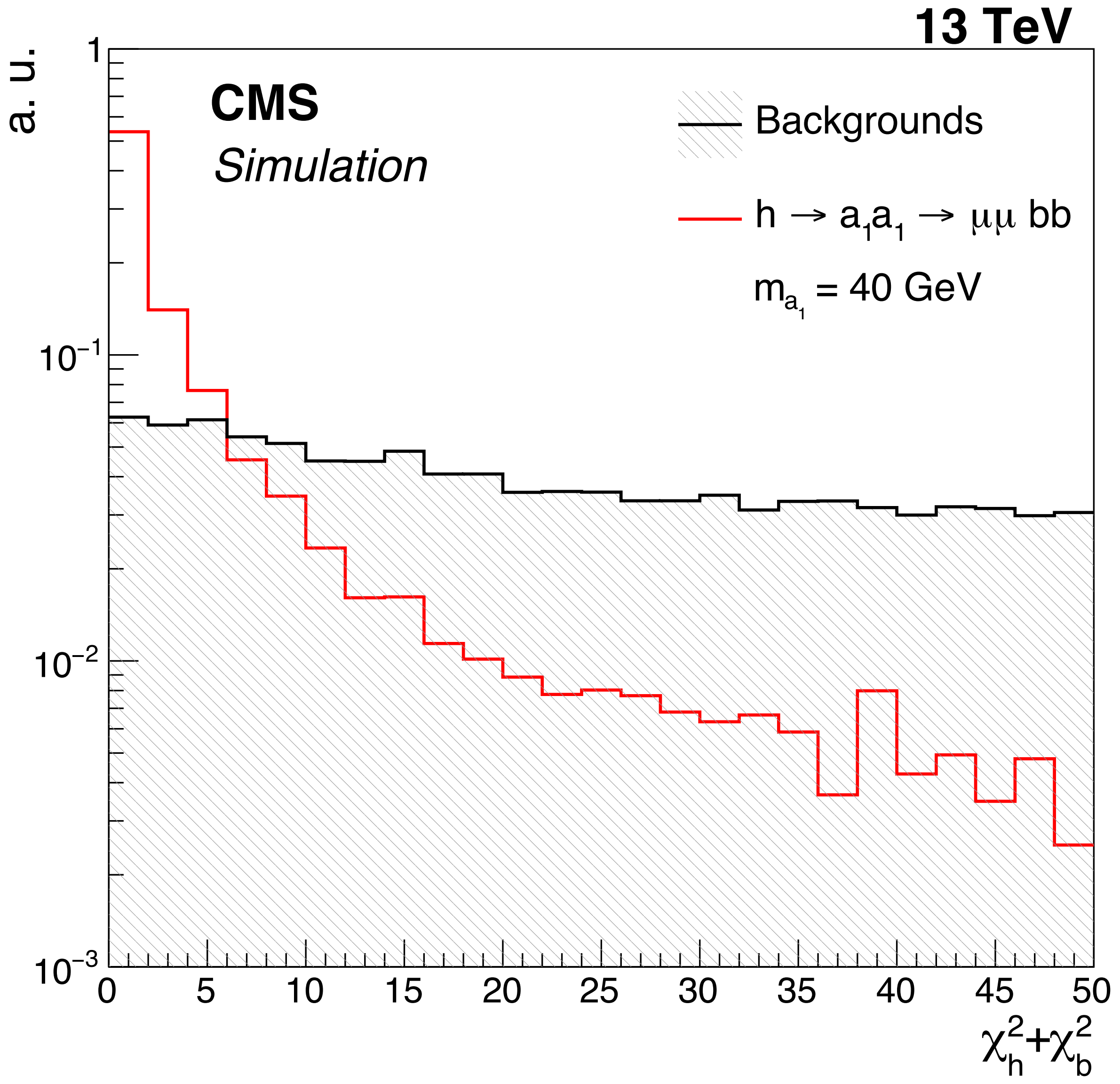
- Background: Drell-Yan + jets, top
- Event selection (ATLAS):
  - using kinematic fit to optimise 4-object invariant mass
  - MVA method exploiting dijet and dimuon kinematics



- Event selection (CMS):
  - Defining chi2 variable based on relative mass differences

$$\chi_{\mathrm{bb}} = \frac{(m_{\mathrm{bb}} - m_{\mu\mu})}{\sigma_{\mathrm{bb}}}$$

$$\chi_{\mathrm{h}} = \frac{(m_{\mu\mu\mathrm{bb}} - m_{\mathrm{h}})}{\sigma_{\mathrm{h}}}$$



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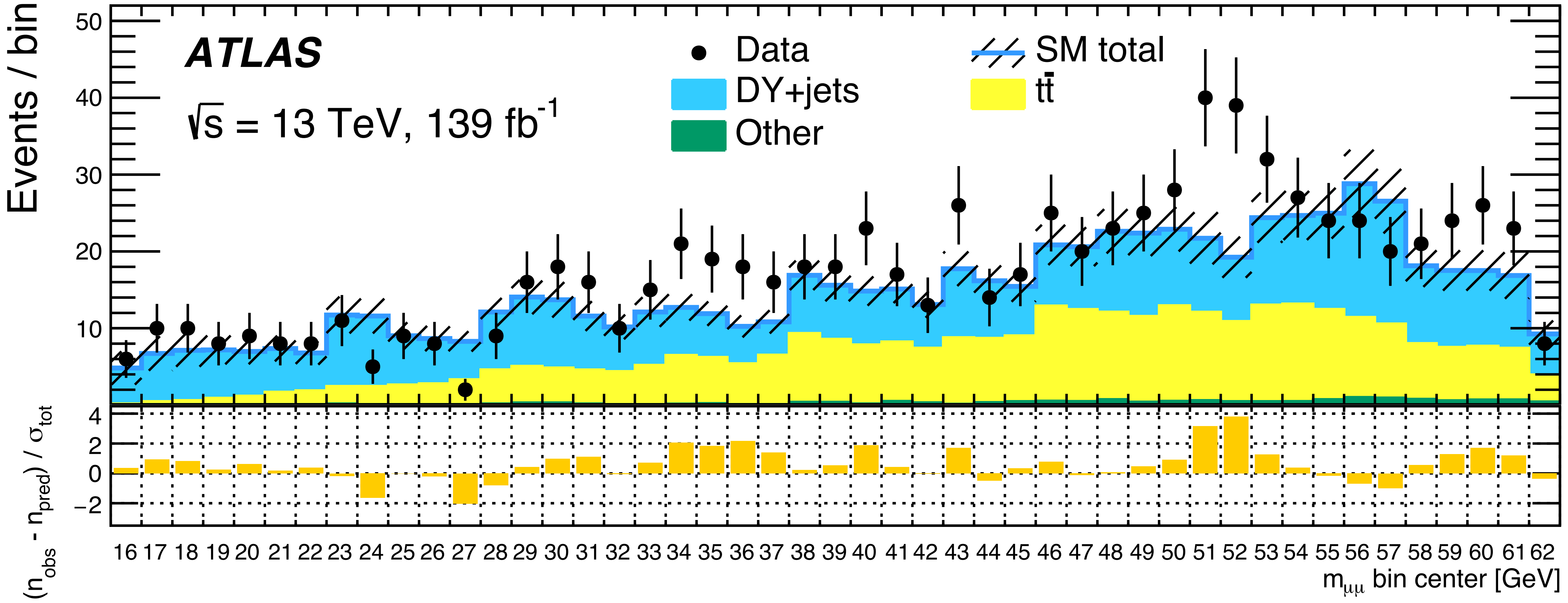
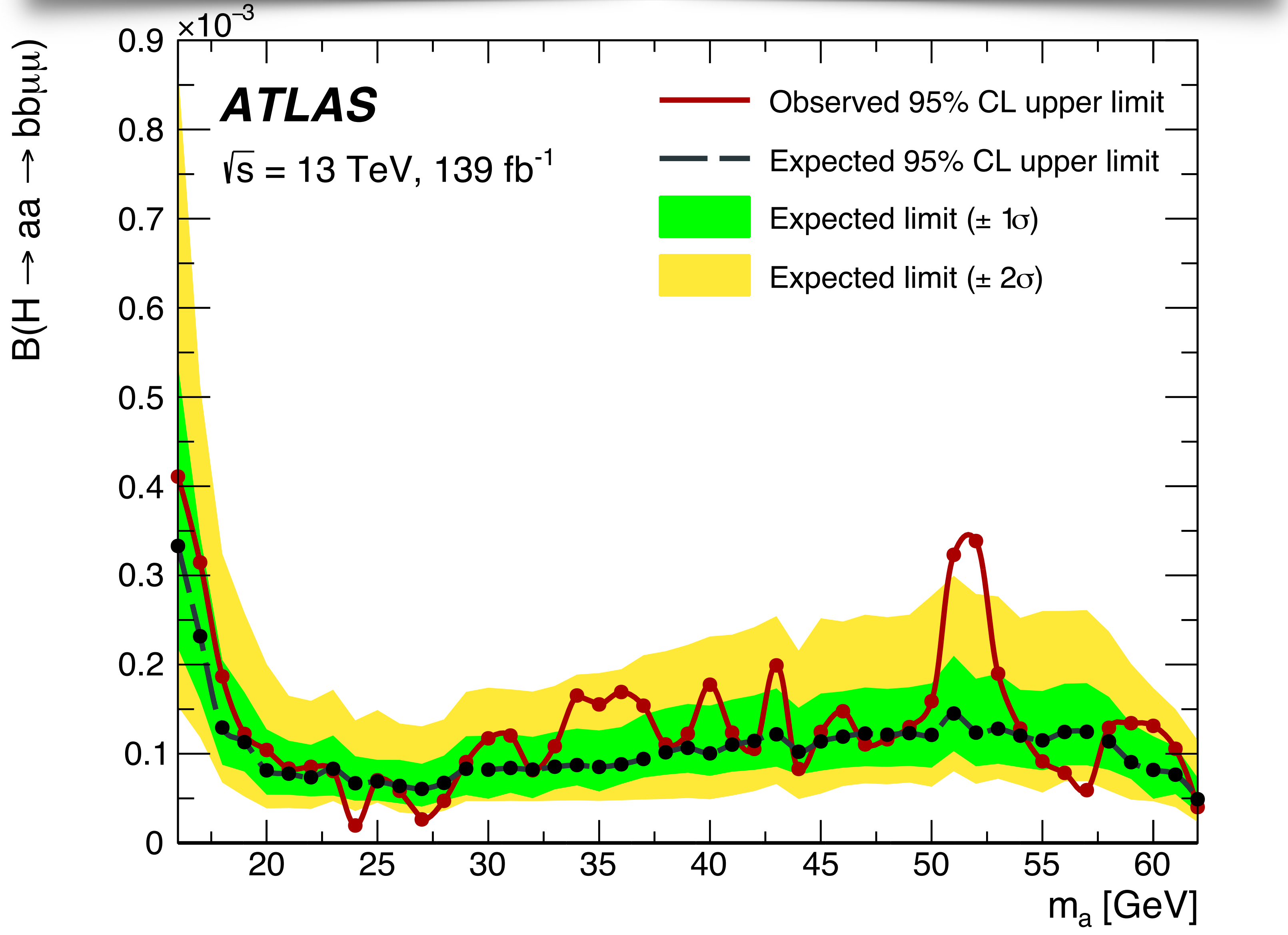
Local: 3.3σ, Global: 1.7σ @ m = 52 GeV





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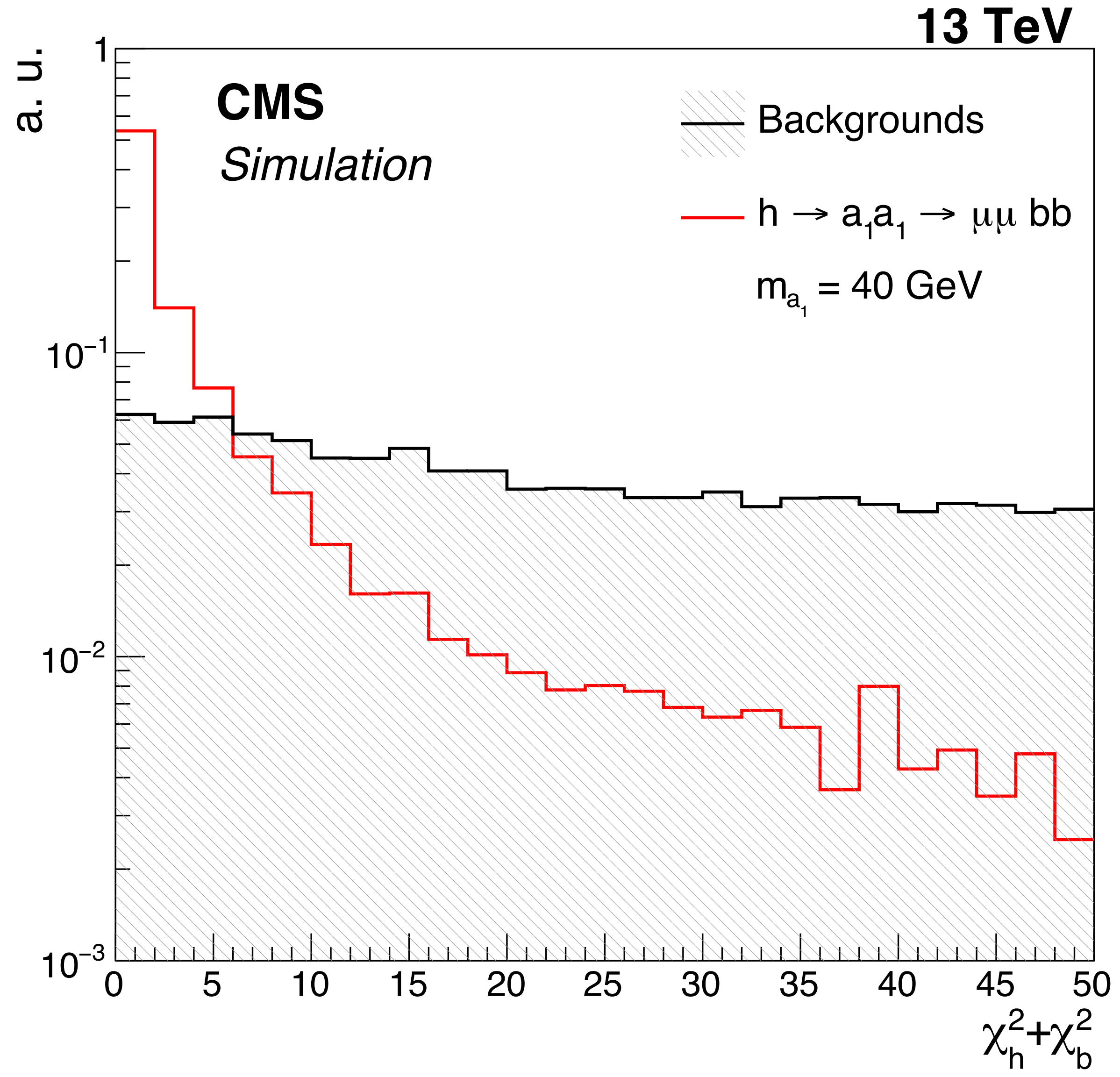
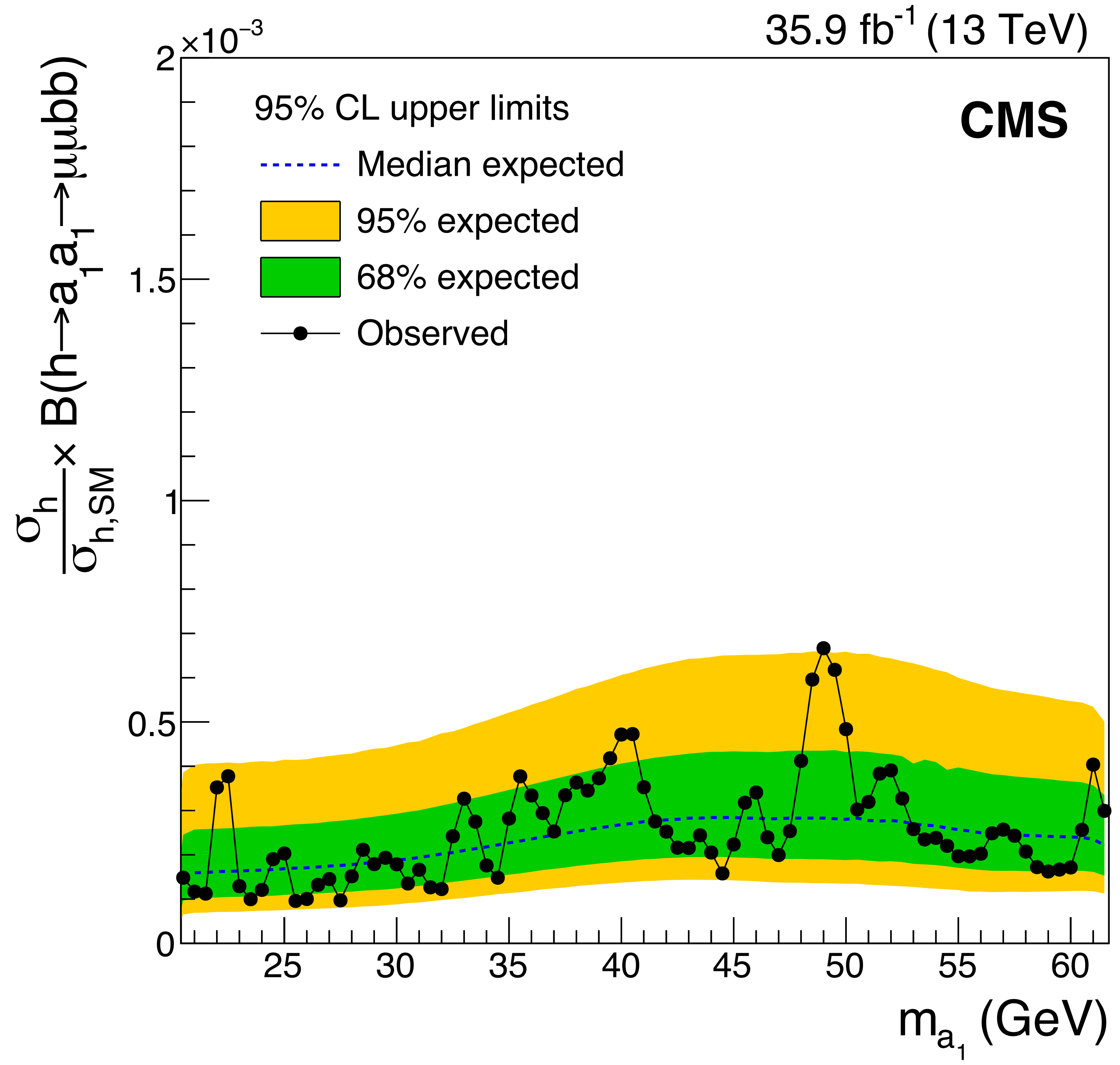


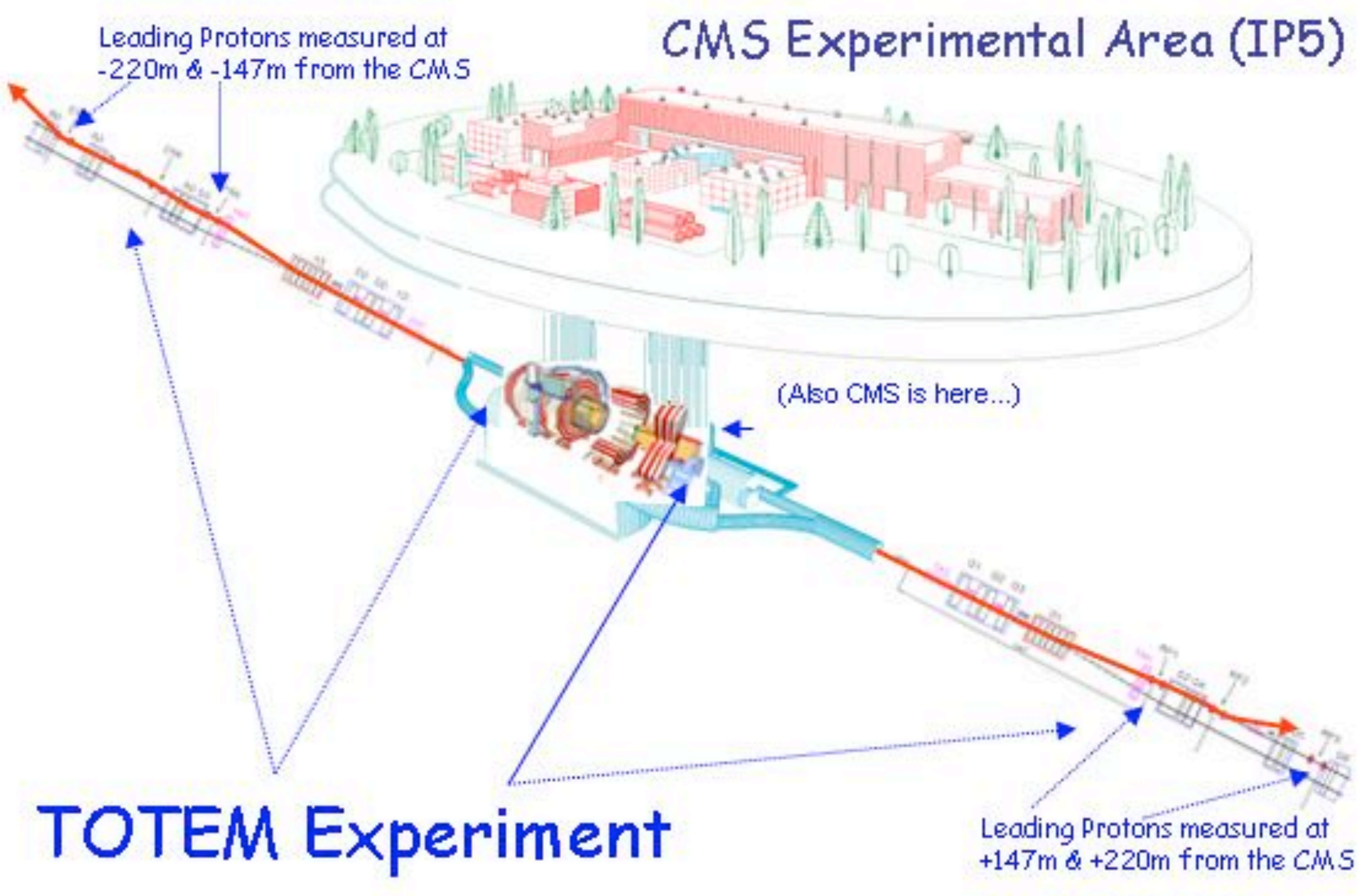


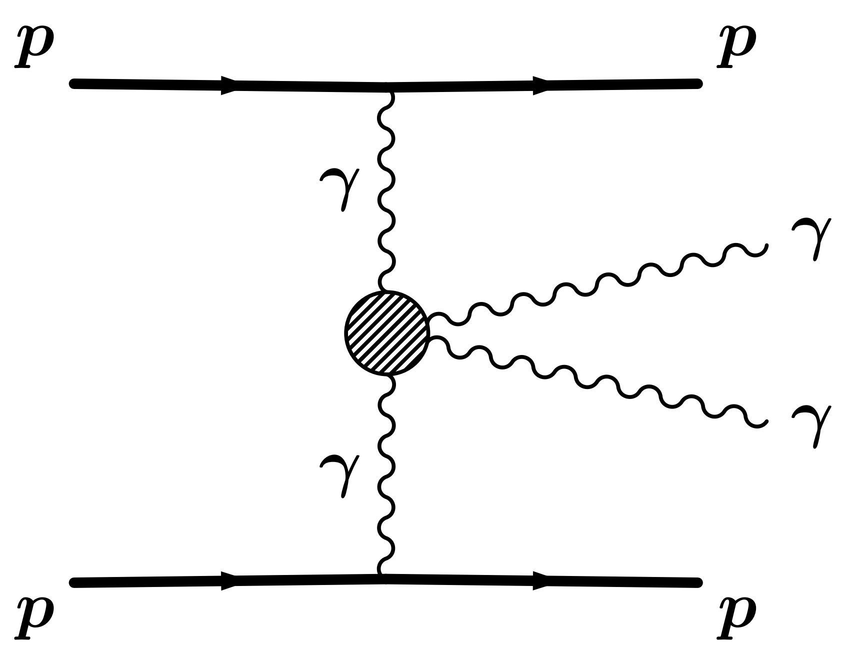
Photon collisions using proton - proton beams

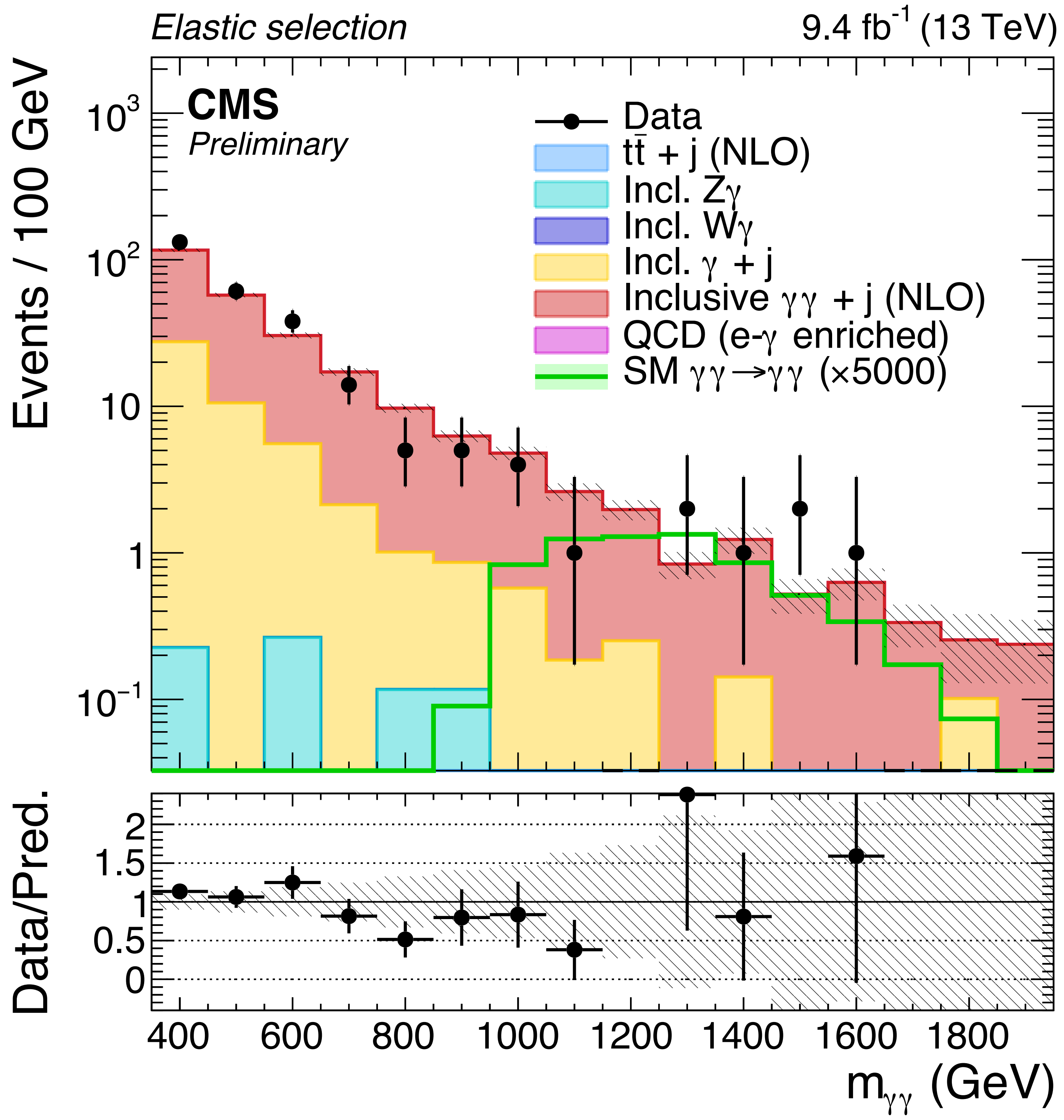
CMS PAS EXO-18-014

- Scattered protons need to be tagged
  - Invariant di-photon mass depends on proton tagger position & LHC optics

- CMS & TOTEM:

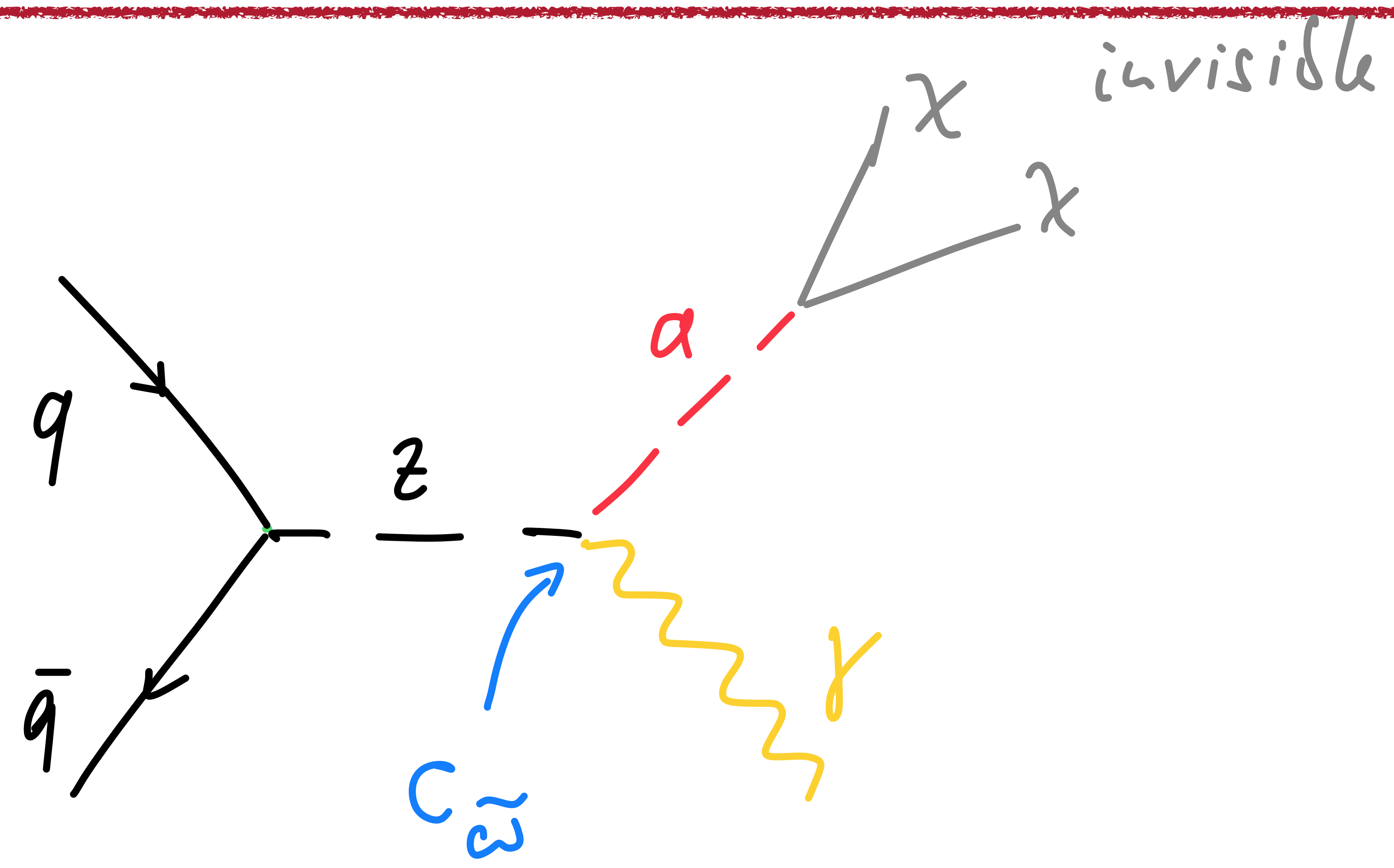


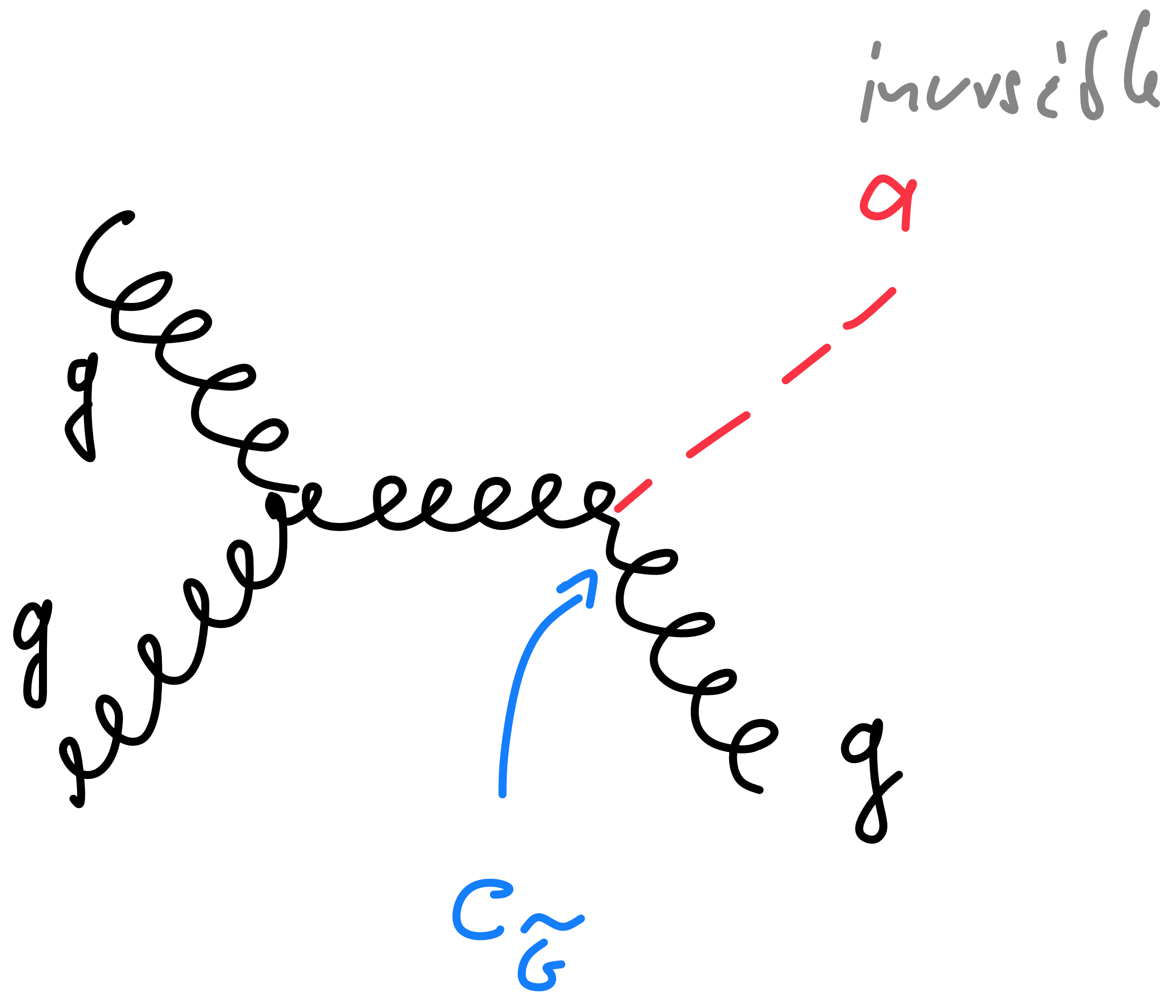




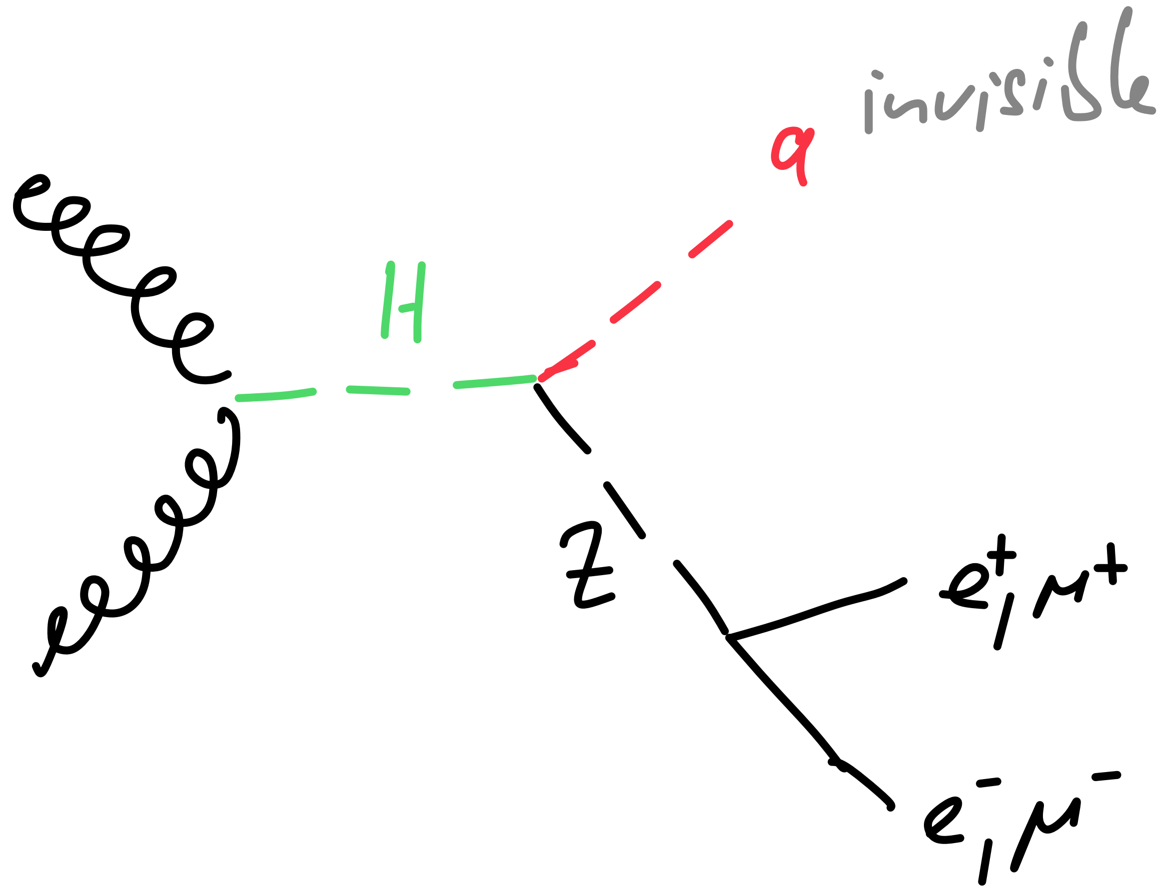
- Measurement can be interpreted as ALP search
  - In progress

ALPs @ LHC: Mono - X signatures





- ALP **invisible**
  - Decay to invisible particles
  - Long lived
- Missing transverse energy typ. > 200 GeV
- No reconstruction of ALP mass
- Final state particles:
  - Triggering



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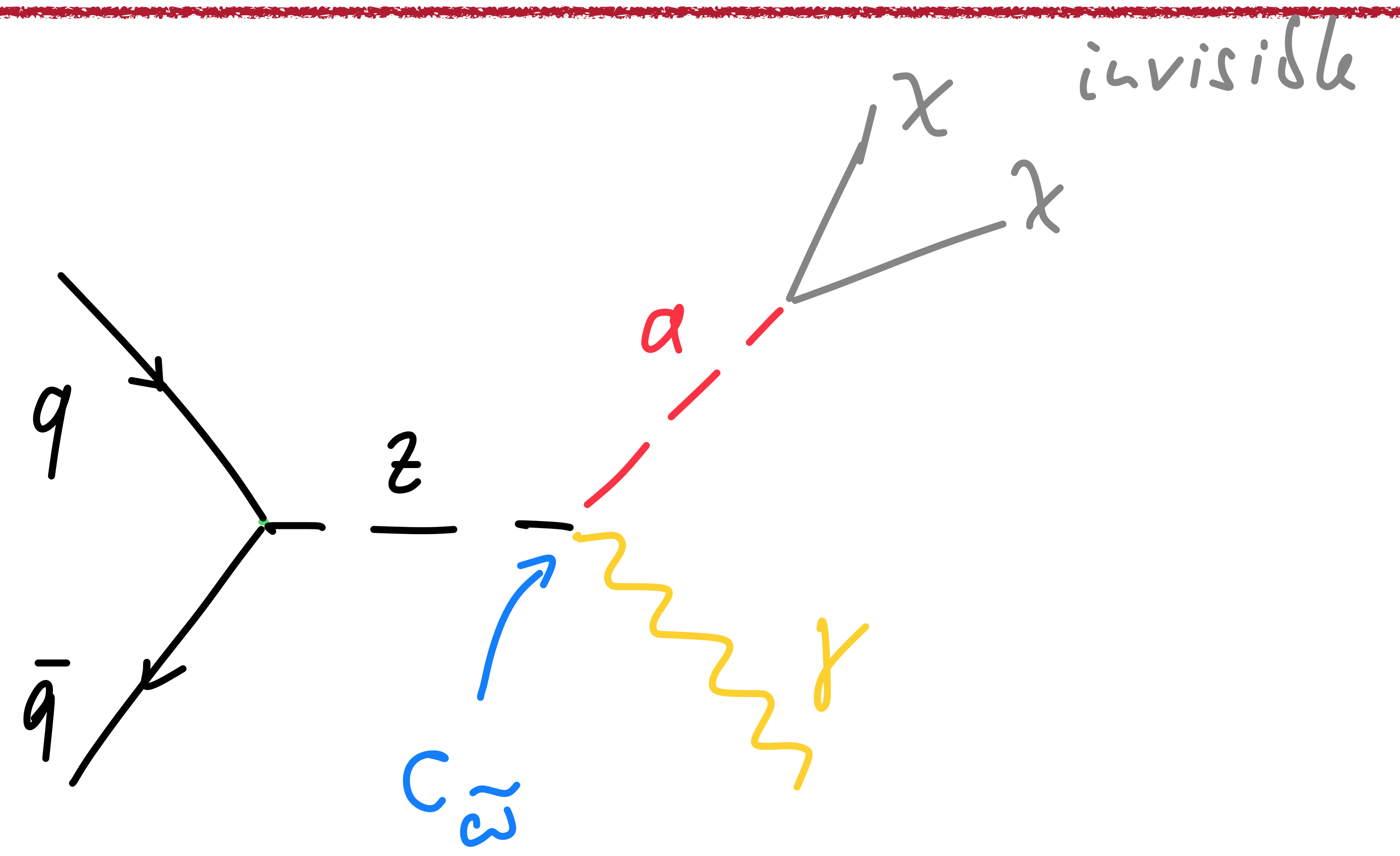
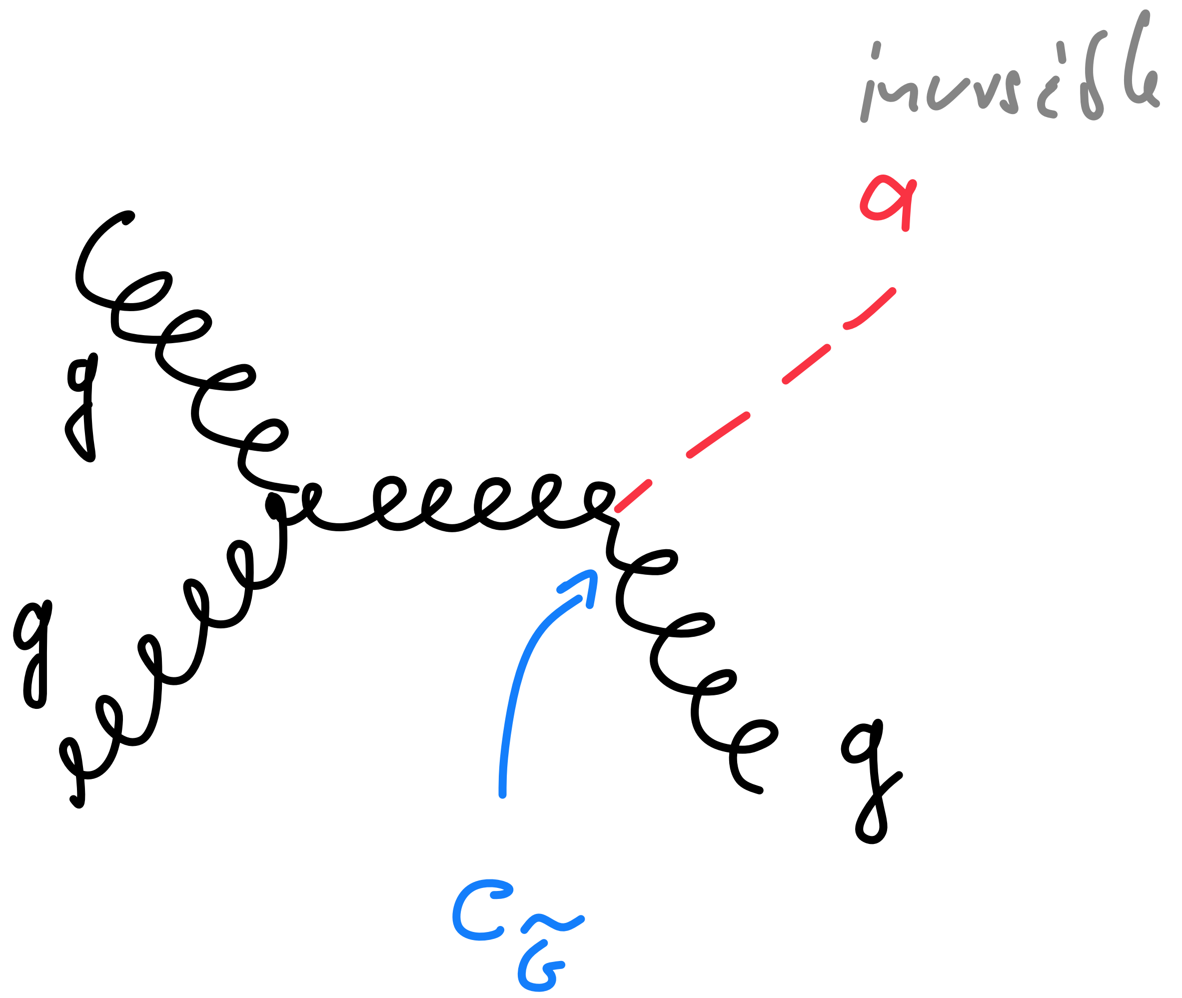


- Largest backgrounds
  - Electron / Jet **mis-identified** as photon
  - Z/W + photon processes



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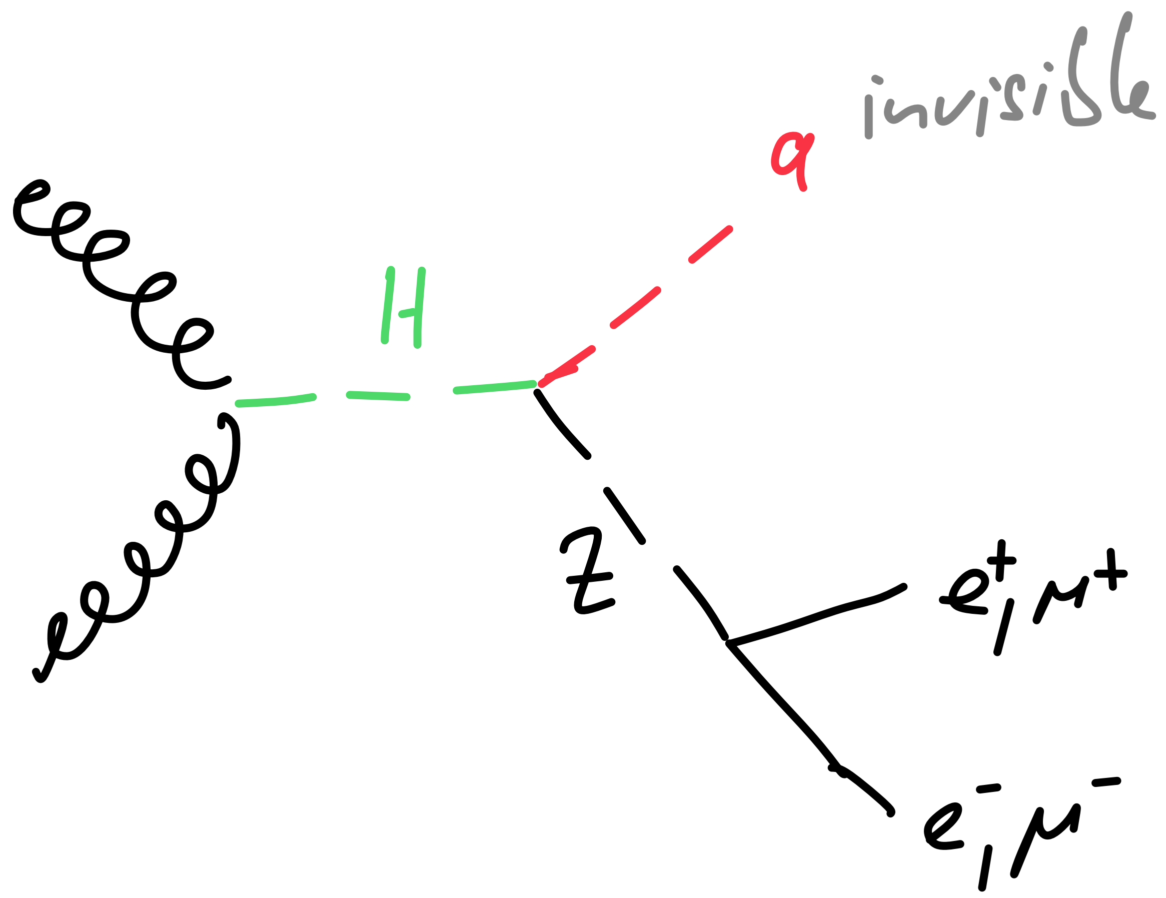

- Largest backgrounds
  - ZZ, WZ