Ultralight dark matter

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Outline

- mass < eV, ~~Fermions~~, bosons

- Theoretical motivation

- Relic abundance

- Ultralight is different

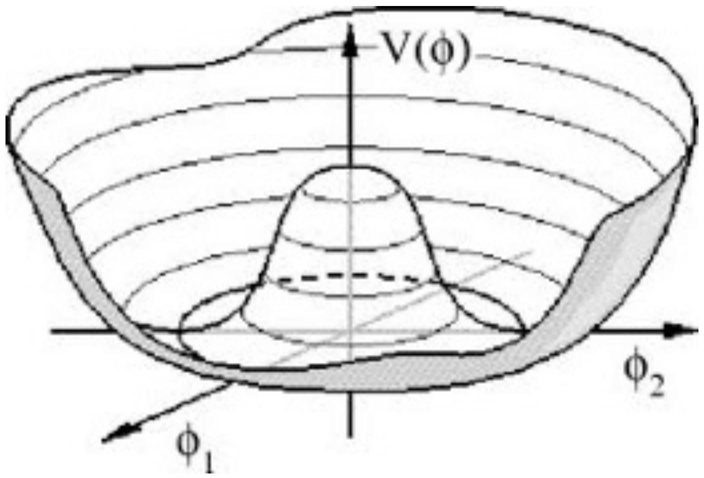
- Direct Detection

- Laboratory searches

- Indirect Detection ... not much

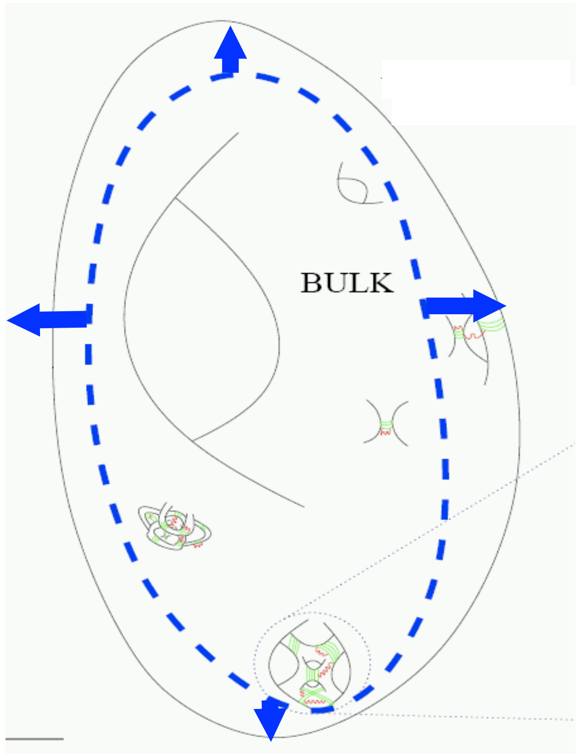
Low mass bosons (technically natural)

- Pseudo-Goldstone bosons
  Very generic BSM
  Axions motivated by the strong CP problem
  Majorons, familons, etc...

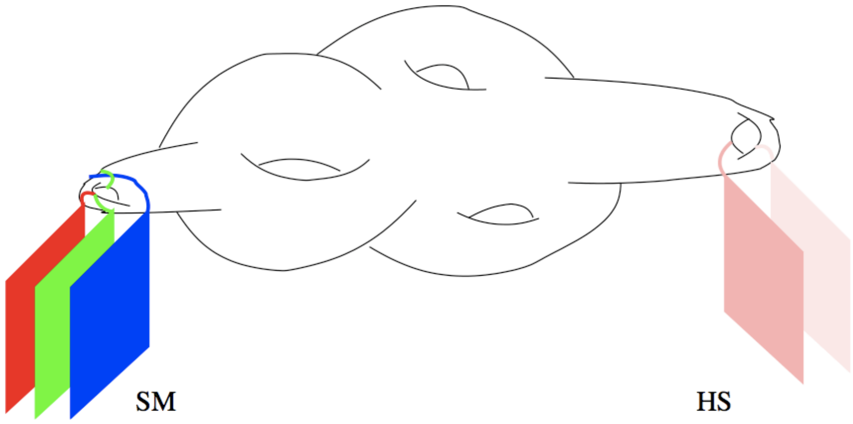


- Axion-like particles in string theories
  Non-perturbative masses

  O(100) ALPs in compactifications ... an Axiverse!



- Gauge U(1) vector bosons
  Stuckelberg mass
  Hidden sectors of string theory?



Axions and strong CP (bottom up)

- The value of θ controls matter-antimatter differences in QCD

$$\theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

↓

P, T (CP) violating

Axions and strong CP (bottom up)

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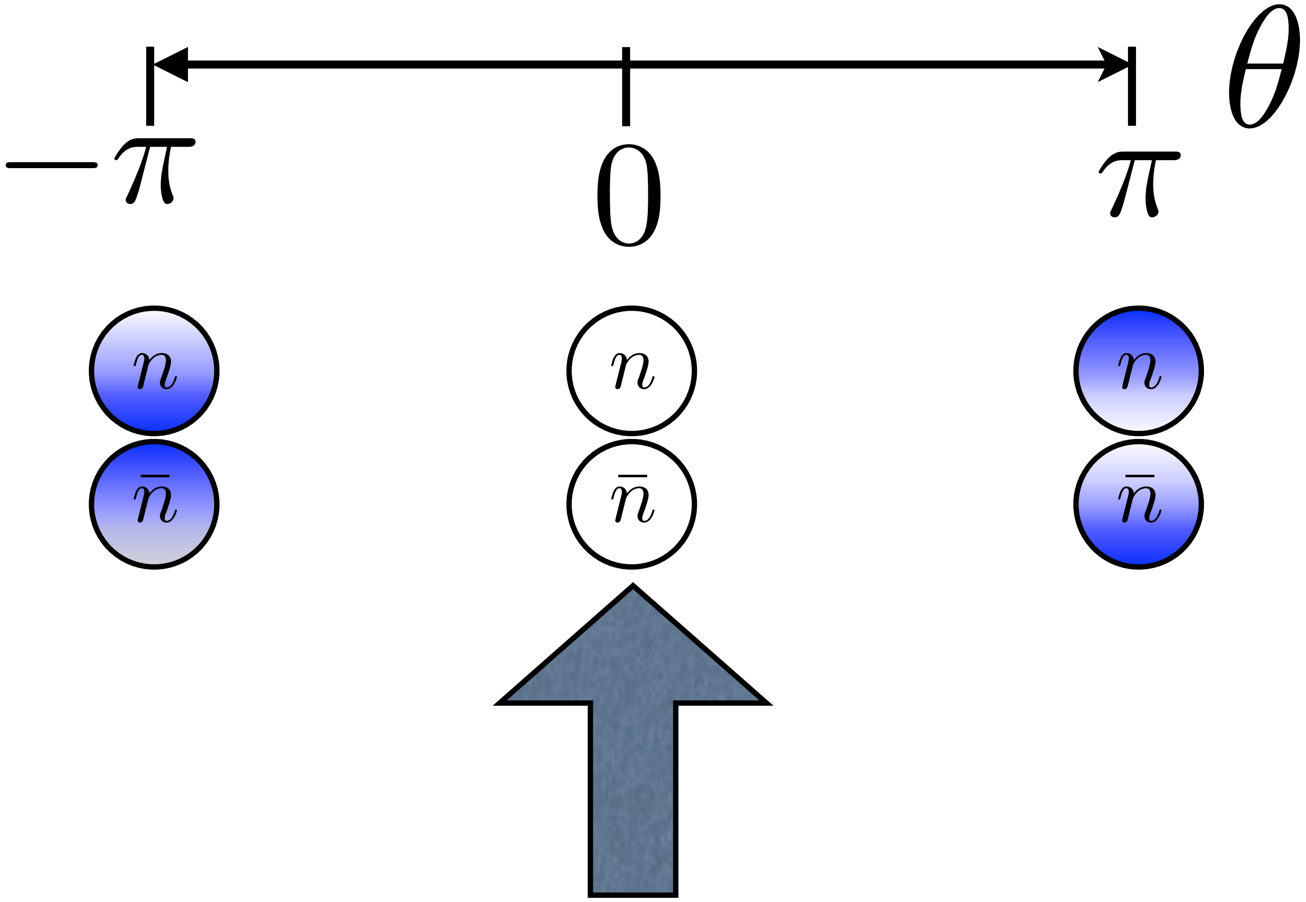
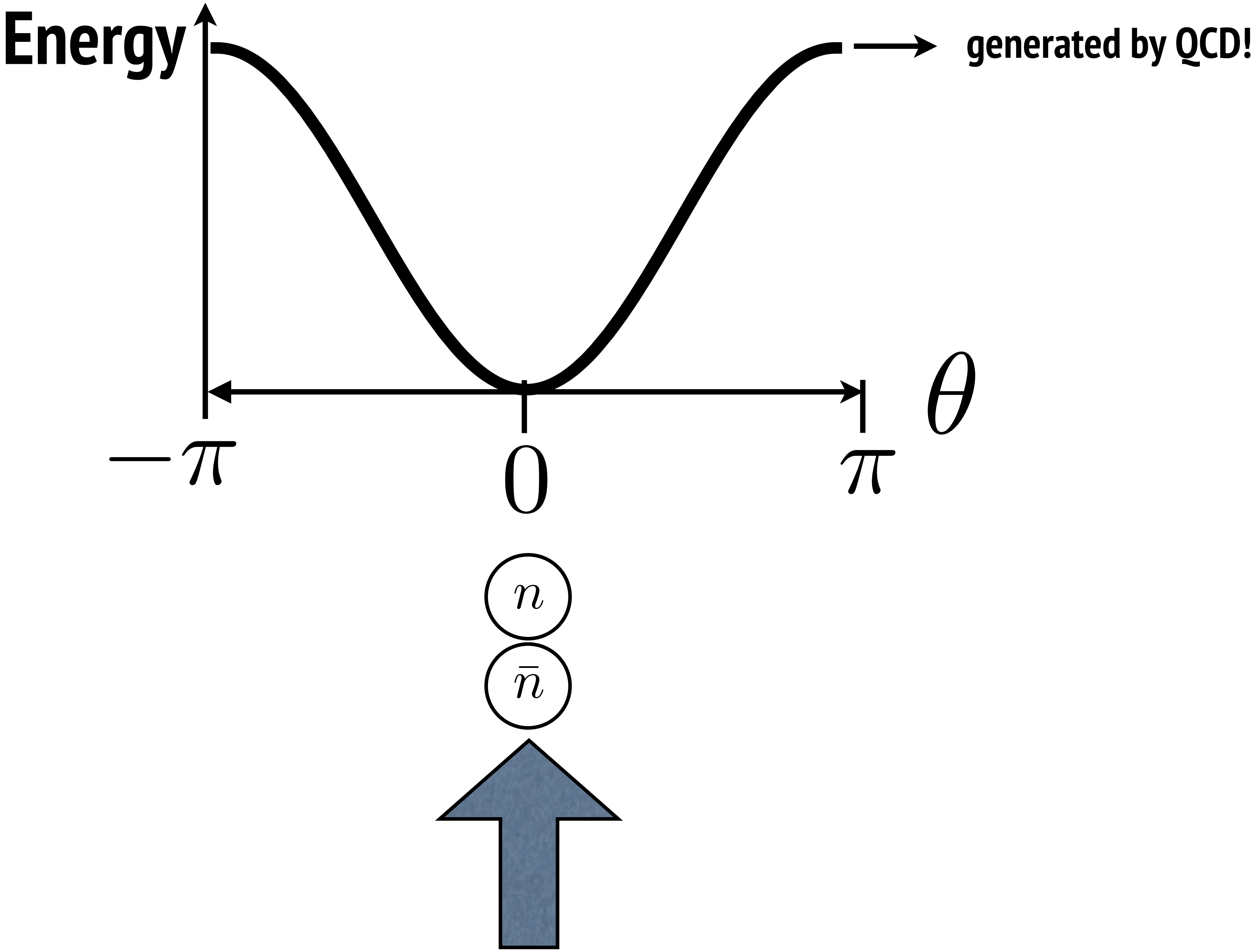


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Axions and strong CP (bottom up)

- **is it a dynamical field?** $\theta(t, \mathbf{x})$



generated by QCD!

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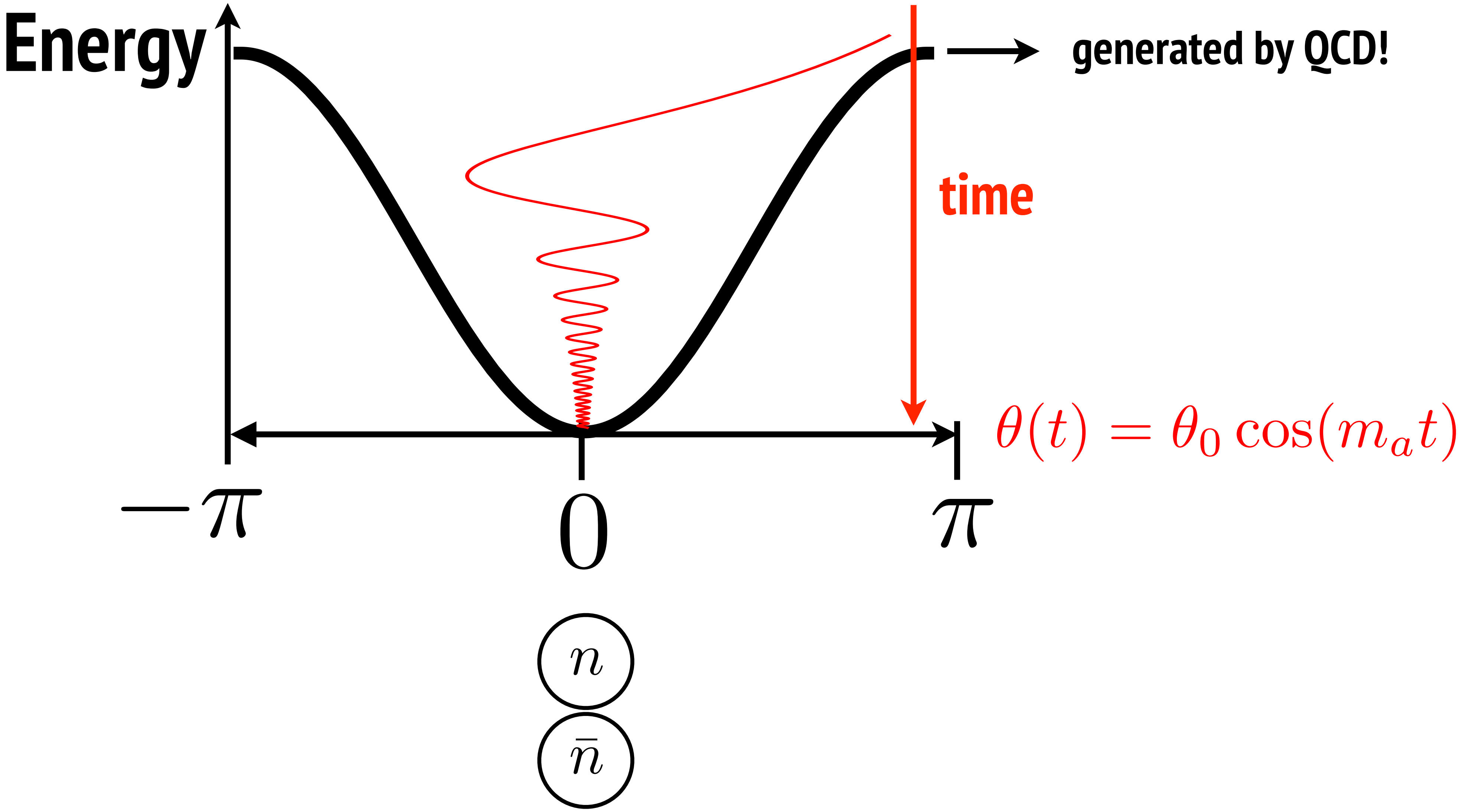

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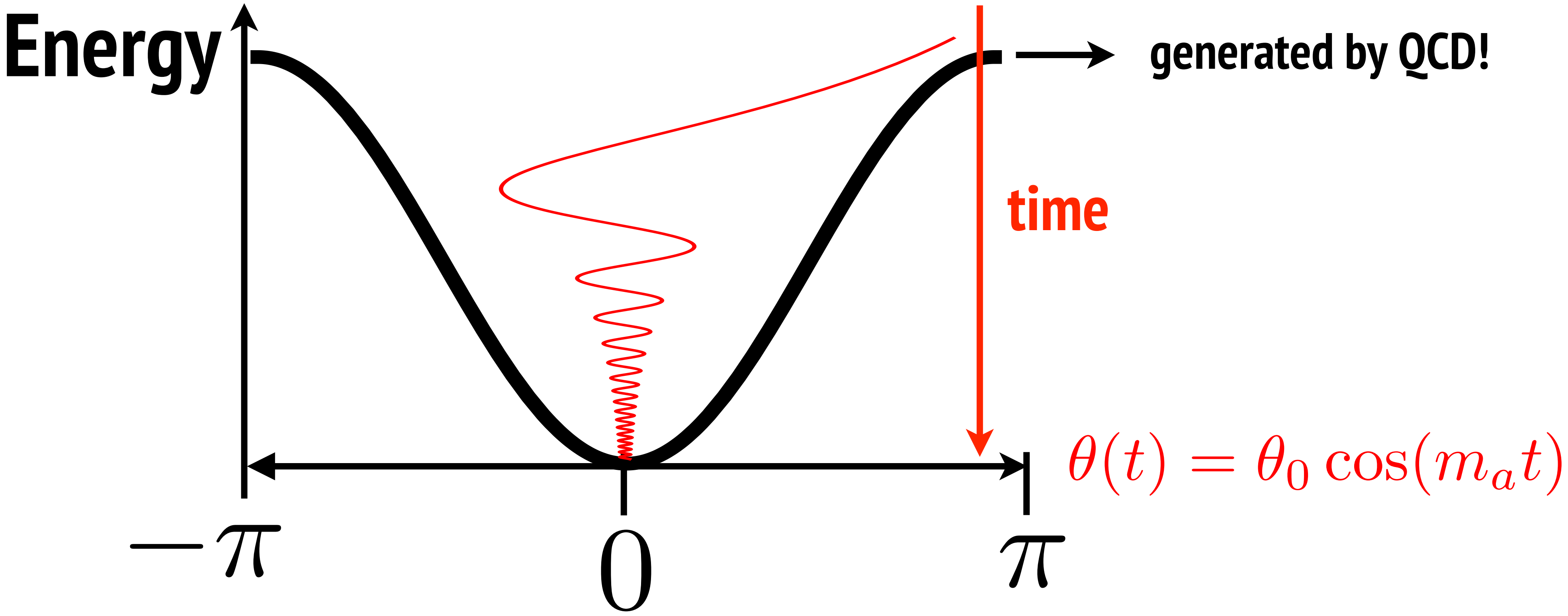

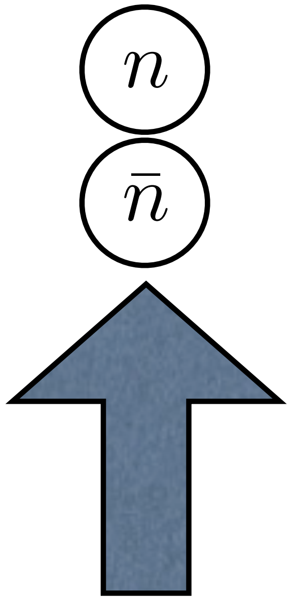

~ One parameter theory

$$\theta(t,x) = a(t,x)/f_a$$

axion mass

$$m_a = 6\,\mathrm{meV}\frac{10^9\,\mathrm{GeV}}{f_a}$$

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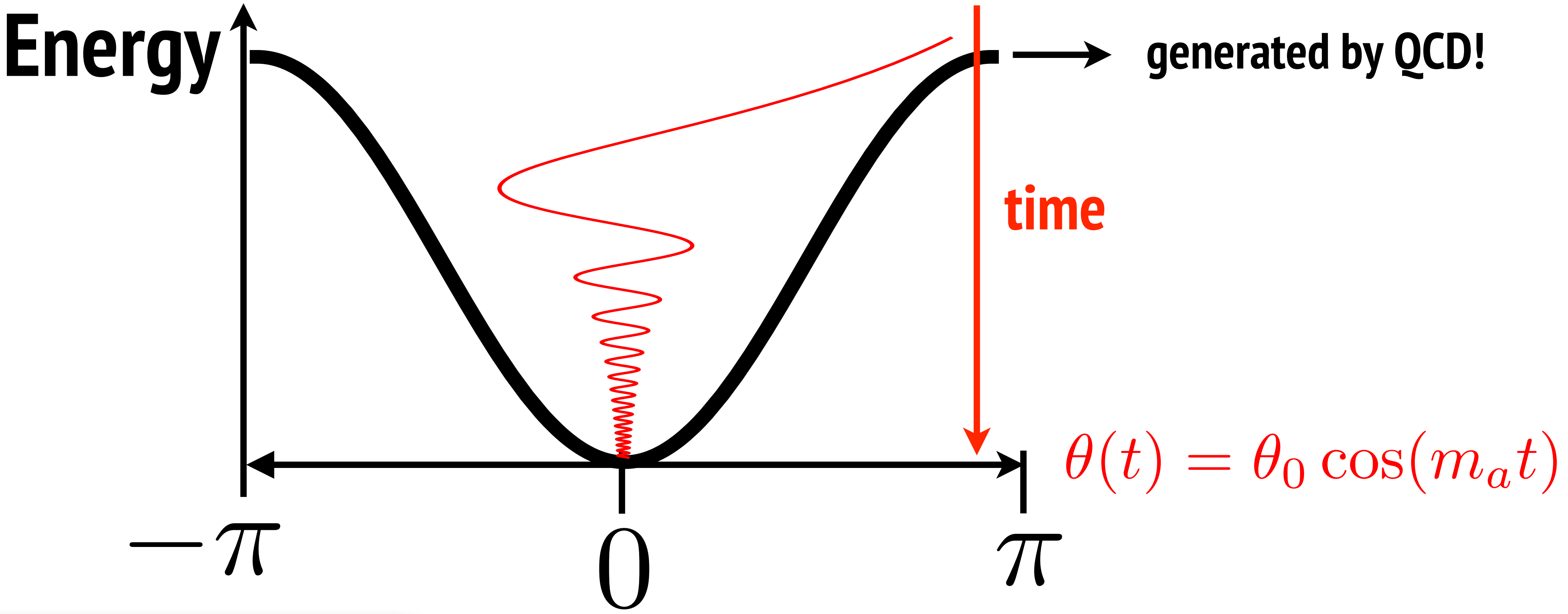
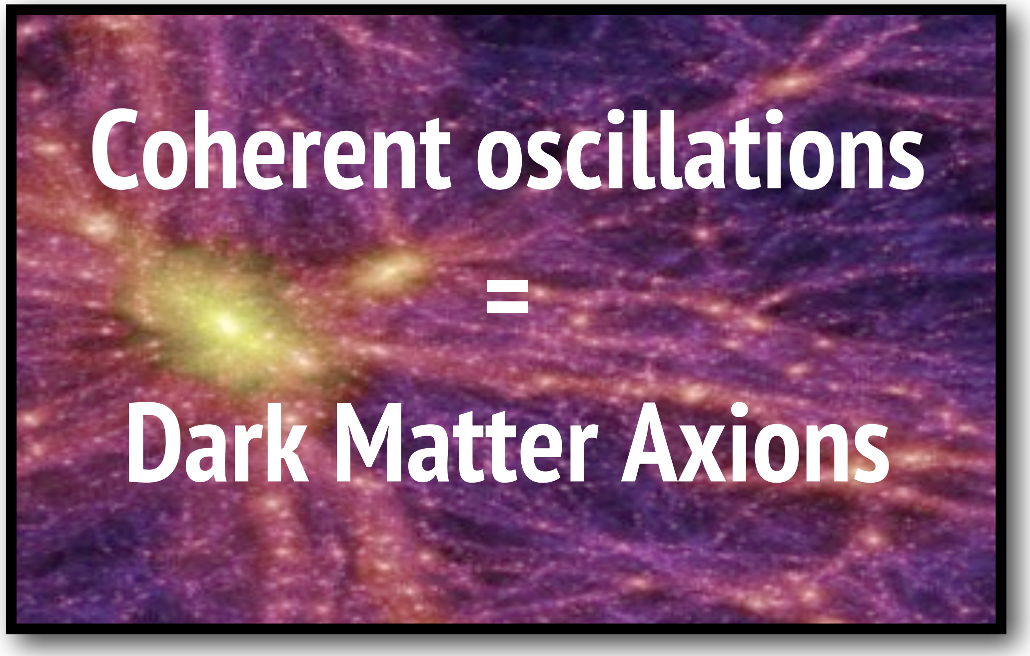
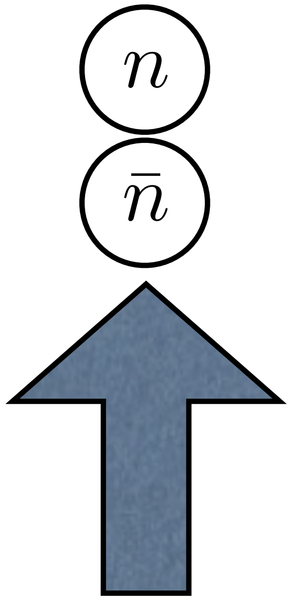




Coherent oscillations

=

Dark Matter Axions



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Axion Mass/couplings

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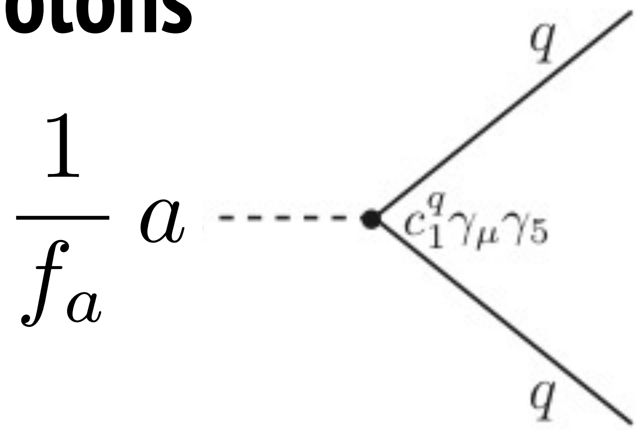
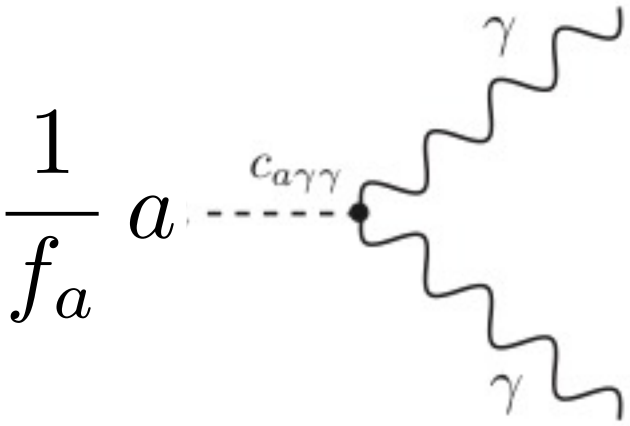
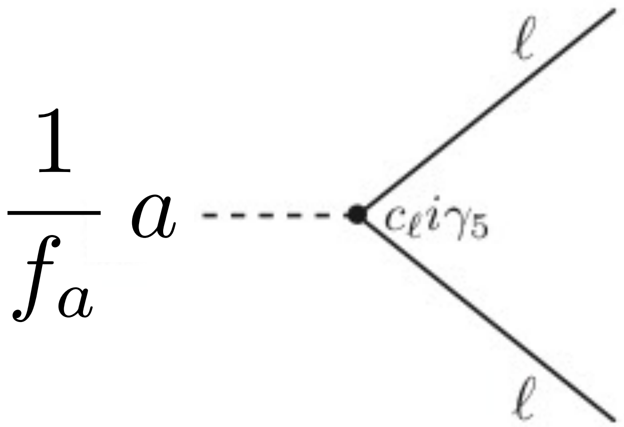
Quarks, Photons





Leptons



- Generic interactions for Pseudo-Goldstone bosons
- Stringy ALPs, f scale ~ string scale, mass unrelated

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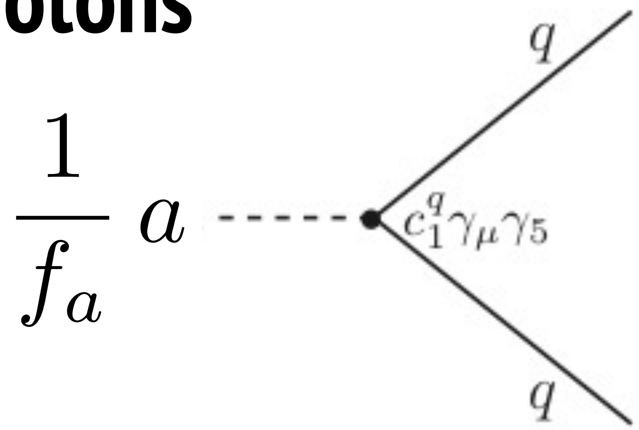

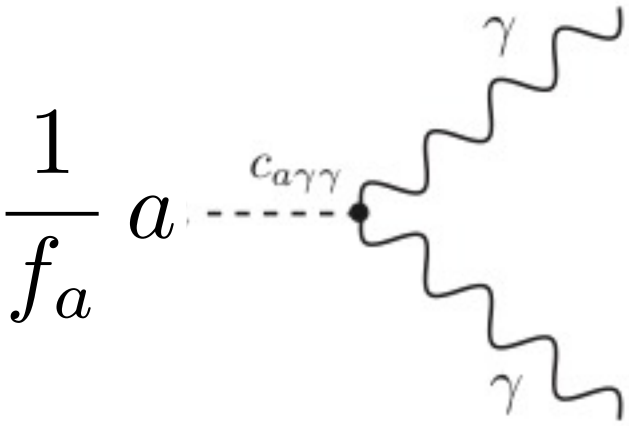

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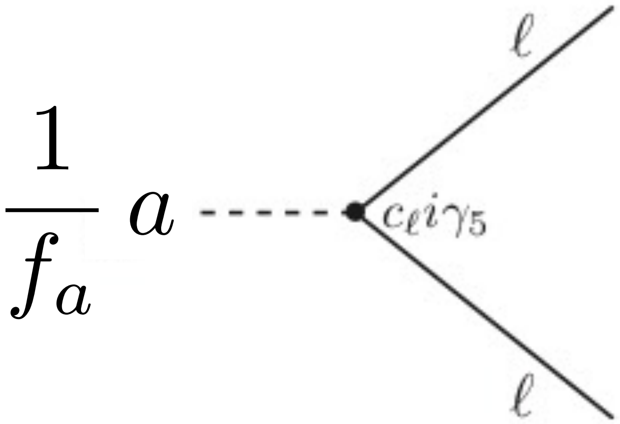

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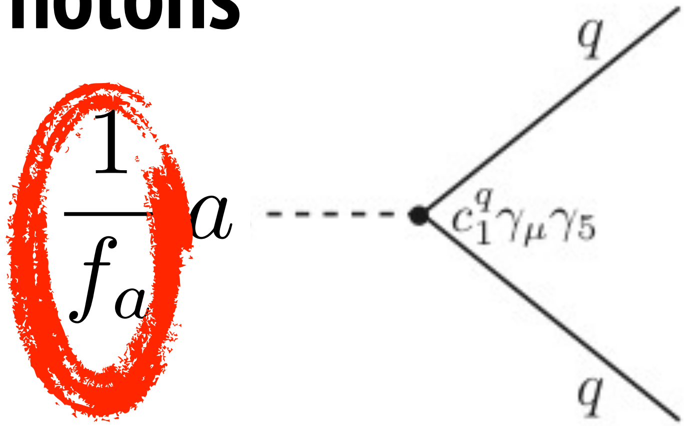

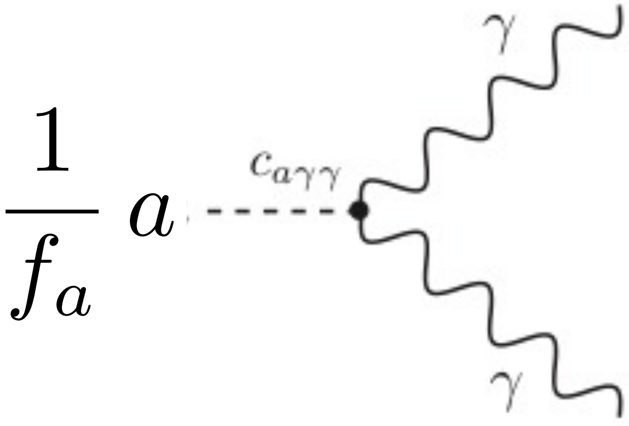

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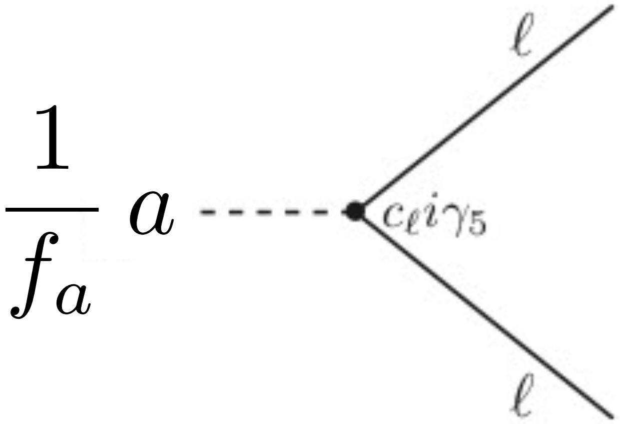

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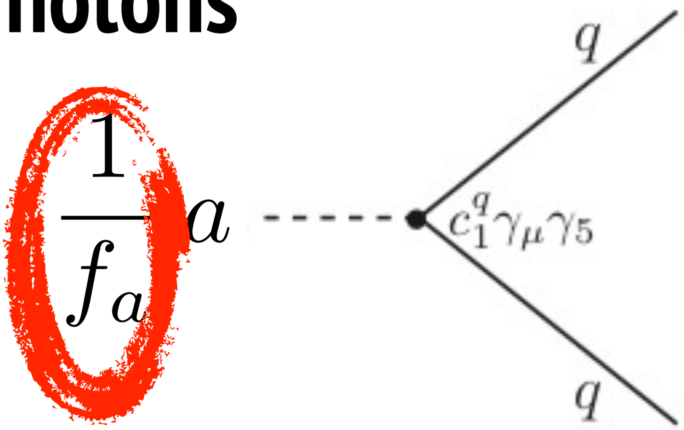

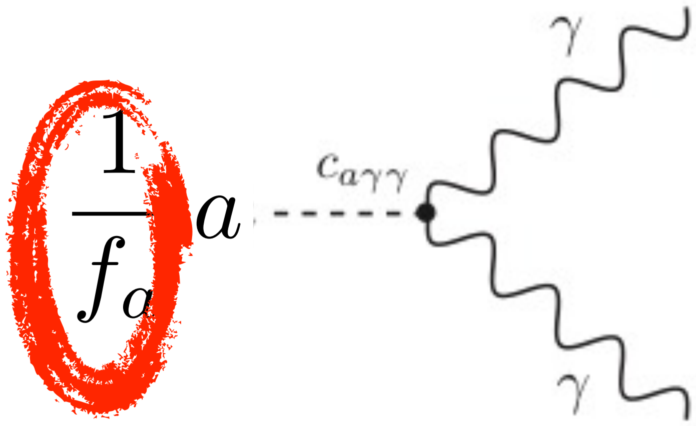

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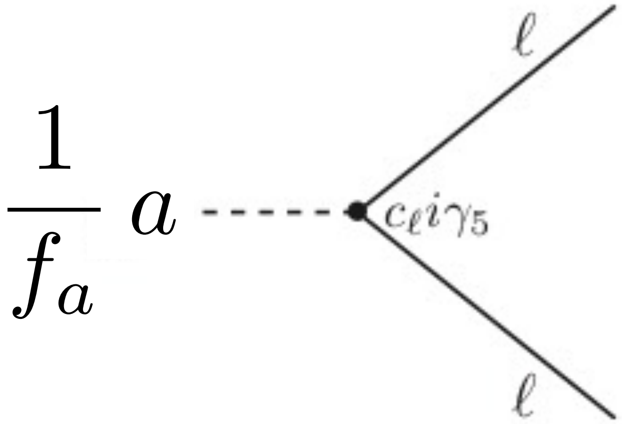

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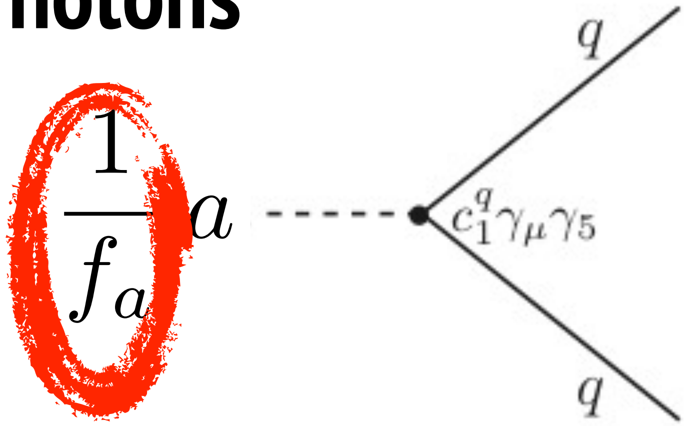

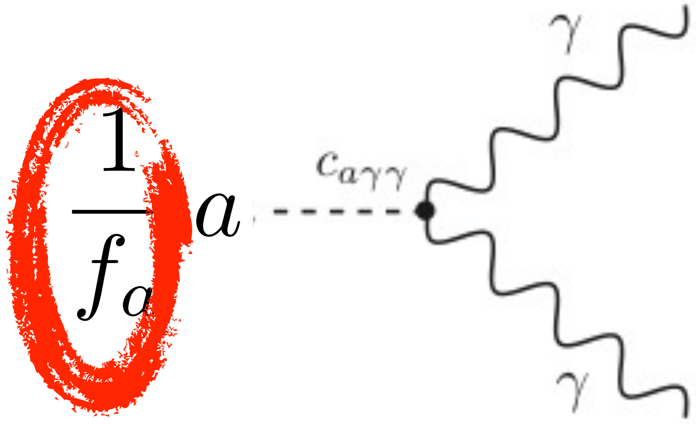

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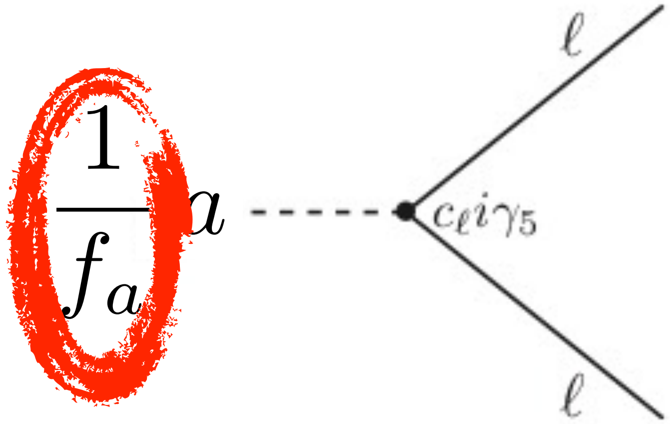

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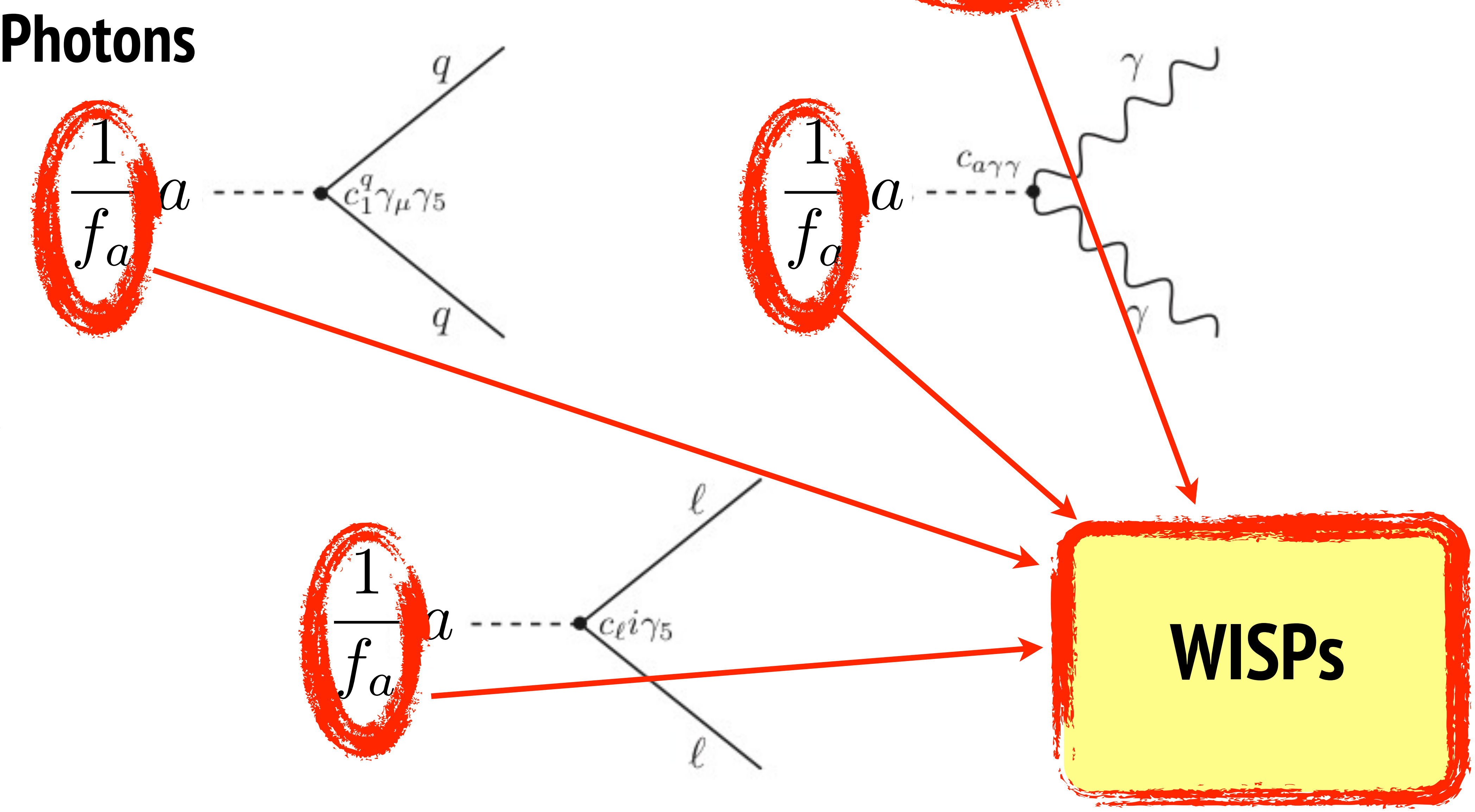

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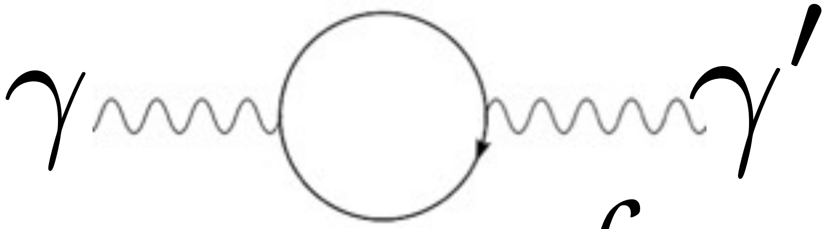
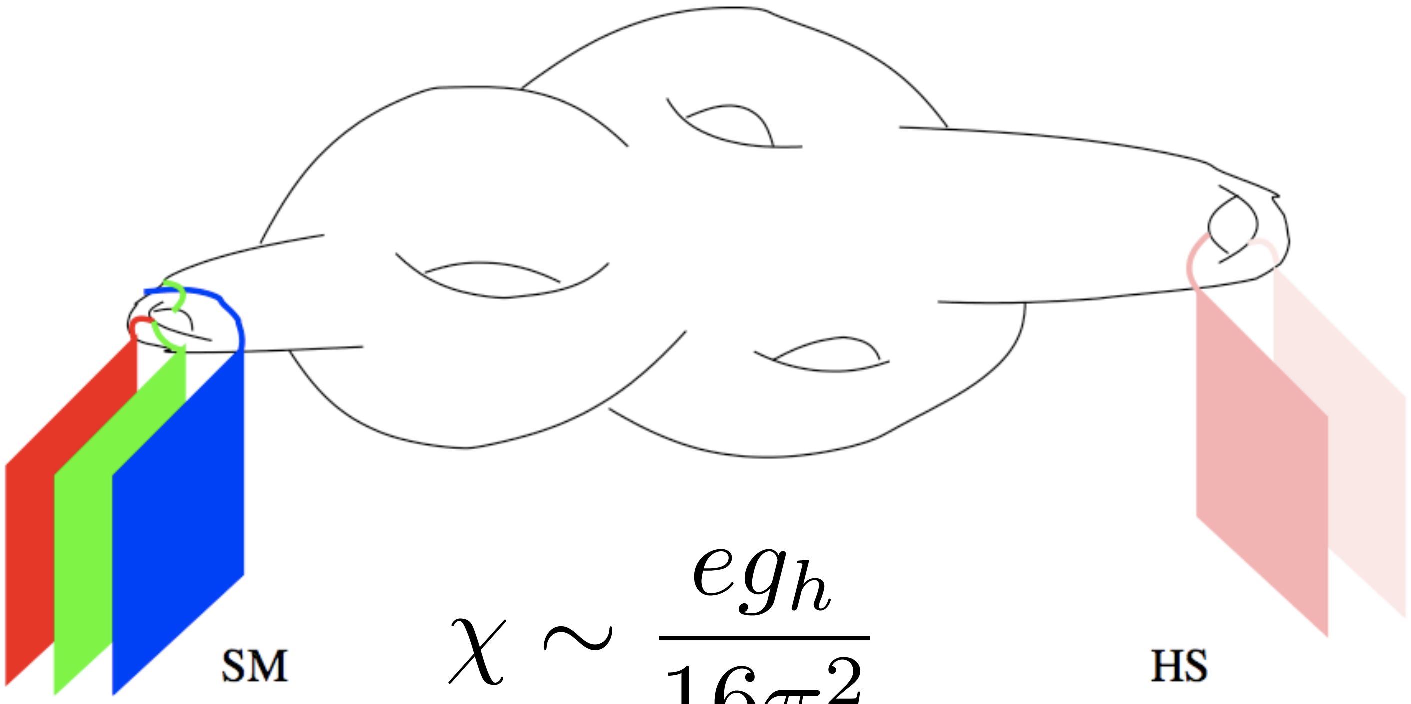
New gauge forces : light hidden photons

- **Extra hidden U(1)'s (Stückelberg mass)**
- **Kinetic mixing with photon**



$$\mathcal{L}_I = -\frac{1}{2}\chi F_{\mu\nu}B^{\mu\nu}$$

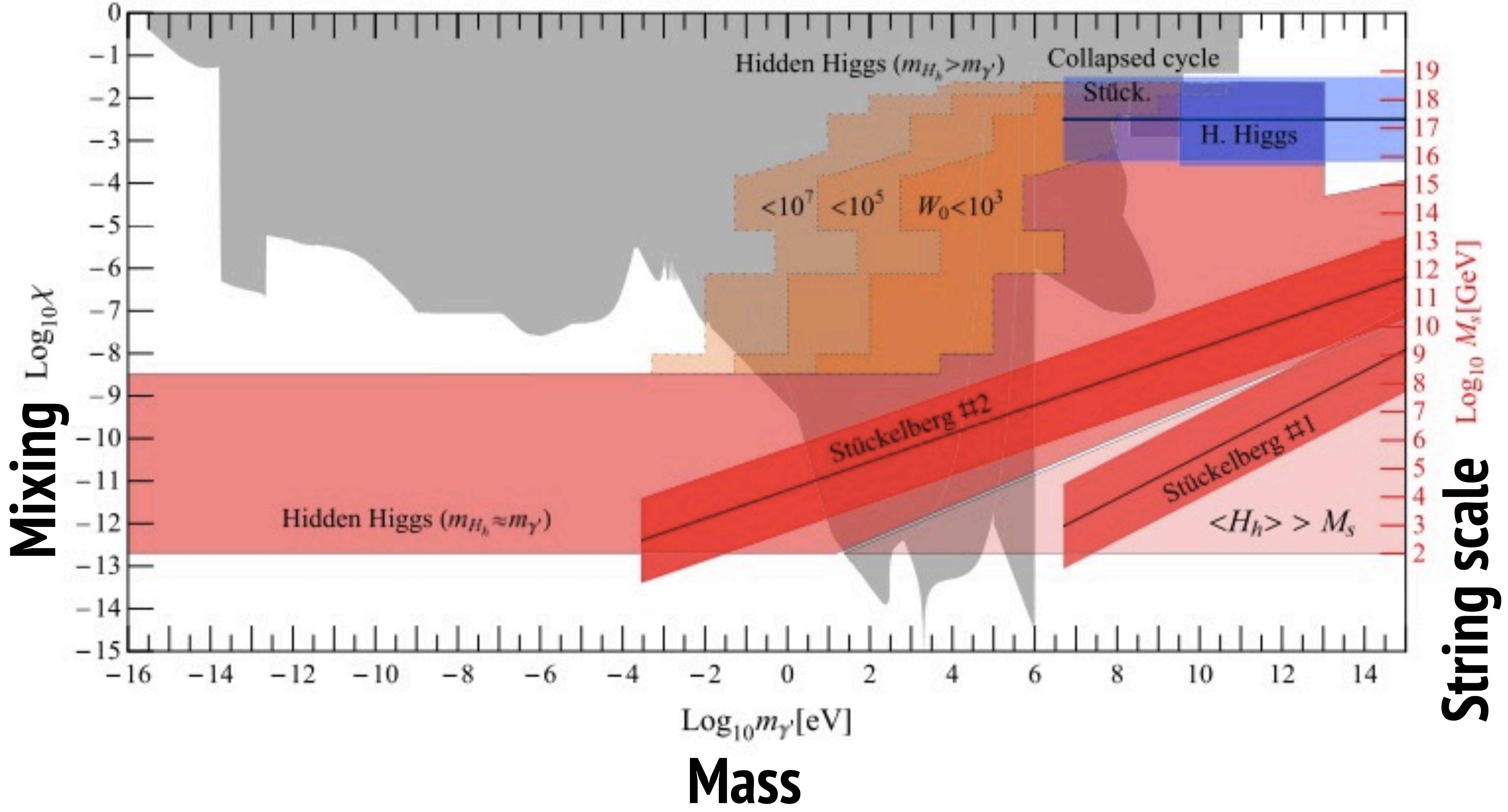
- **Building blocks in type IIb string theory**



$$\chi \sim \frac{e g_h}{16\pi^2}$$

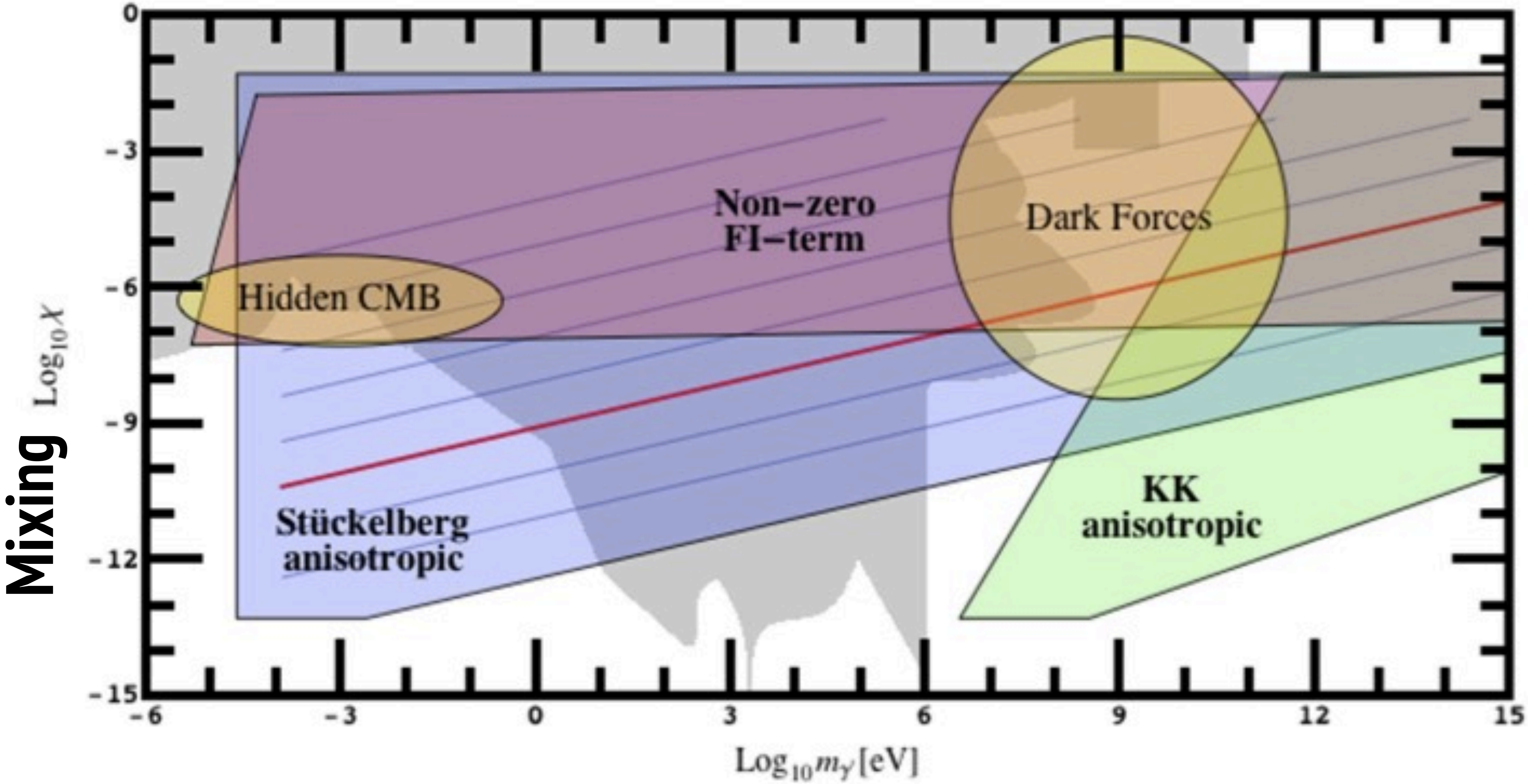
Predictions ...

Goodsell 2011



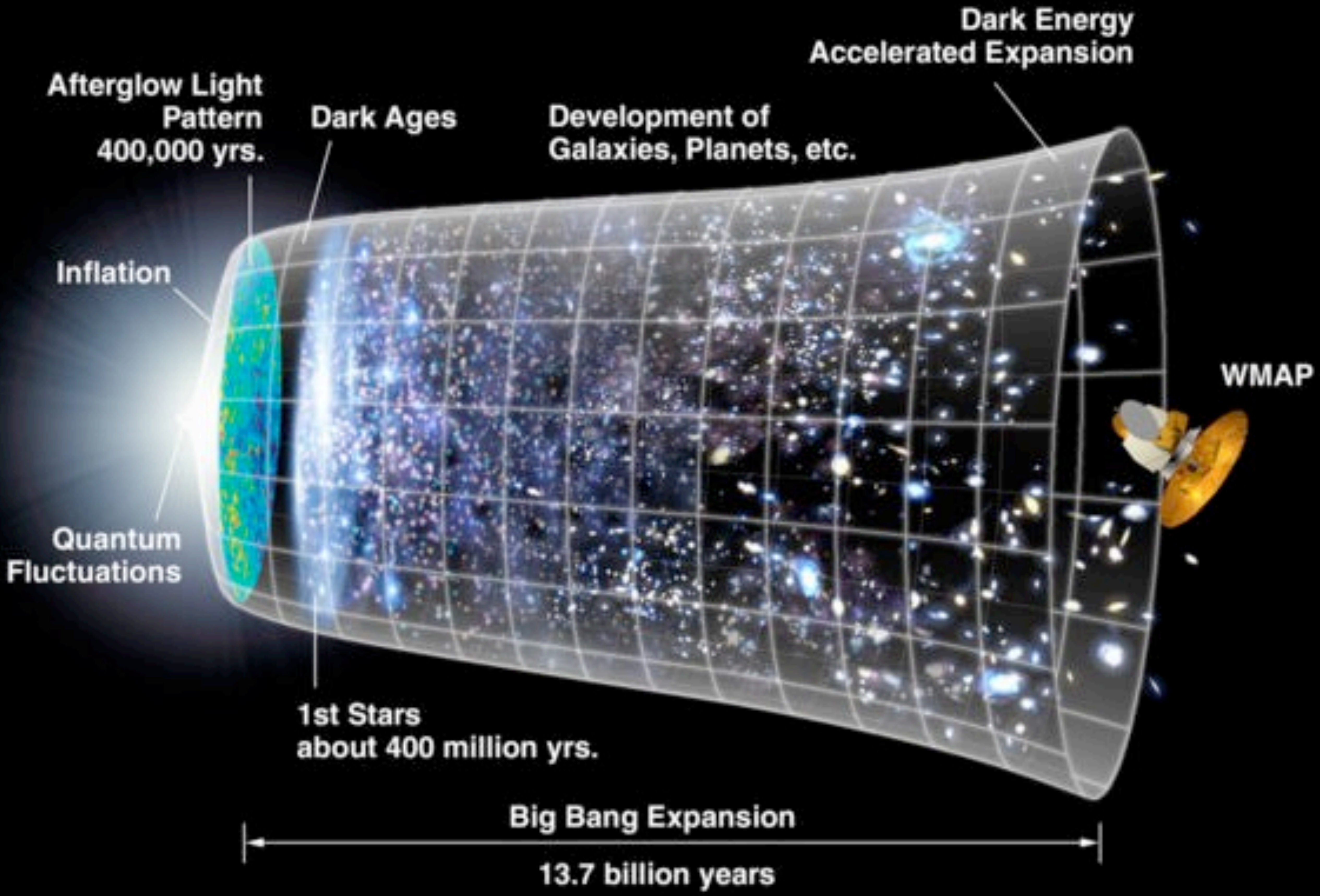
Anisotropic predictions ...

Cicoli 2011



Mass

Relic production



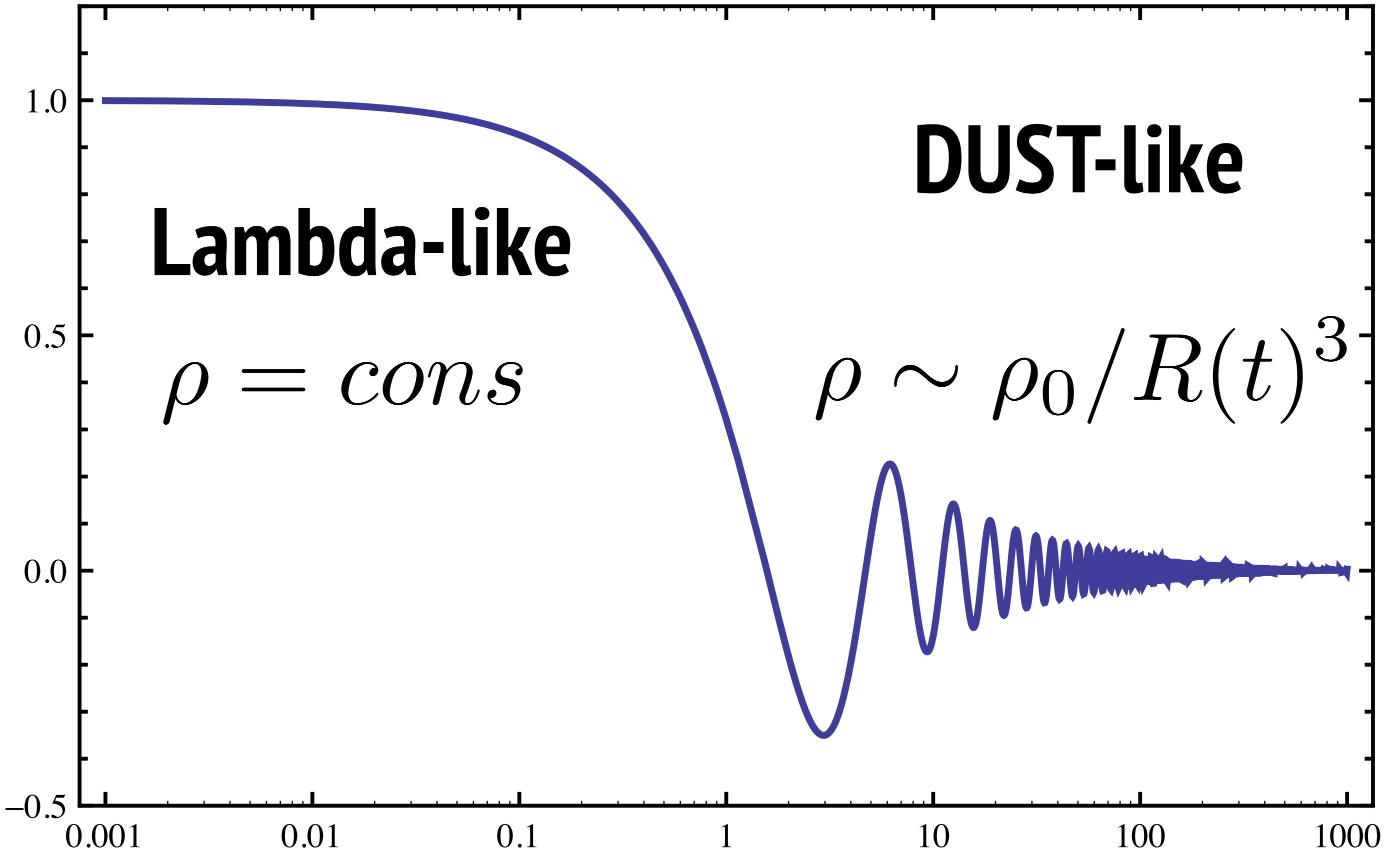
Relic production: realignment

- Thermal relics would be hot DM but never enough (recall m<eV)

- Non-thermal mechanisms: realignment from initial conditions

Evolution of decoupled field (zero mode) $\ddot{a}_k + 3H\dot{a}_k + m_a^2 a_k \simeq 0$

$$\theta(t) = \frac{a(t)}{a_I}$$



$$t \sim \frac{1}{m_a}$$

Relic production: realignment

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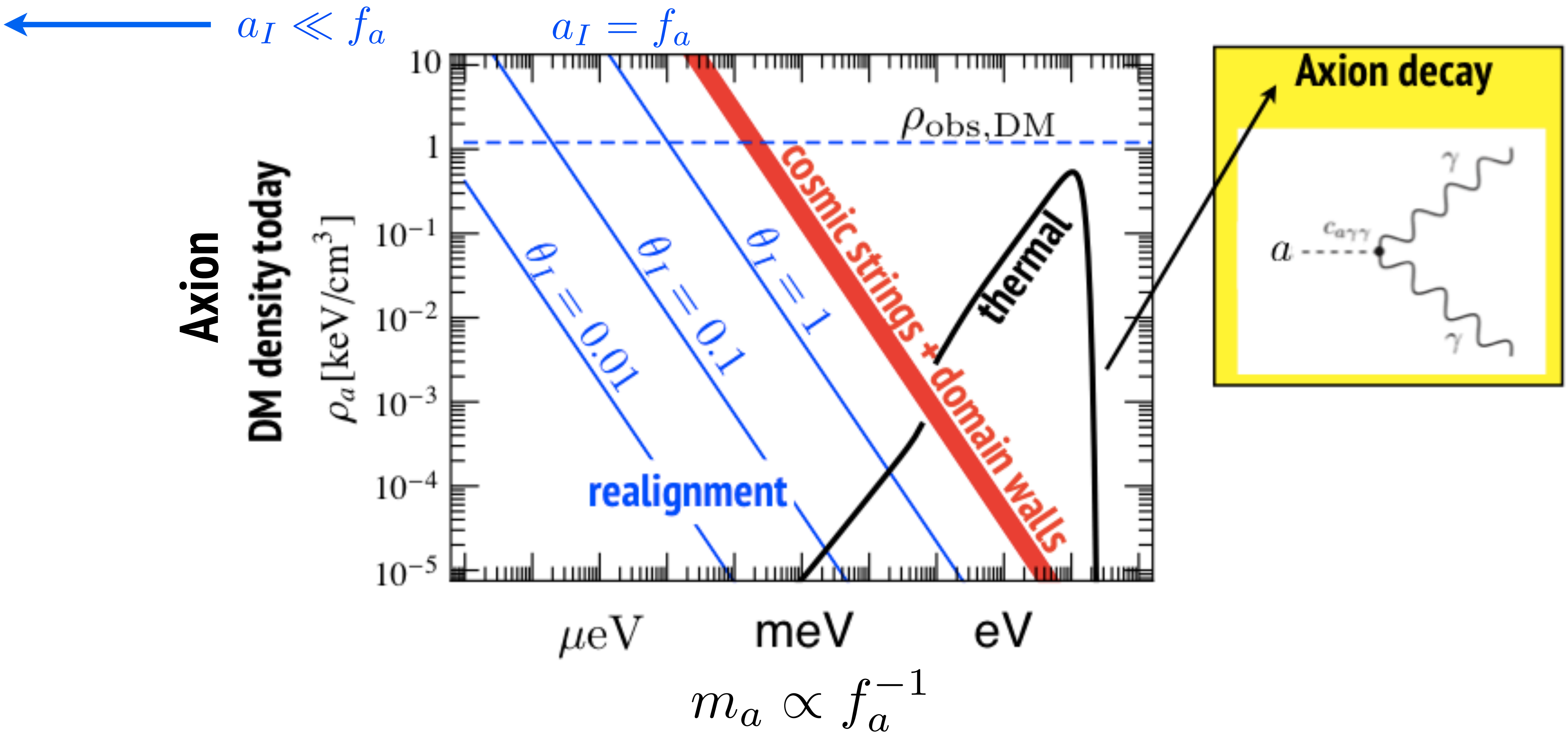
$$\rho_{\rm CDM} \simeq \rho_{\rm DM} \times \sqrt{\frac{m_a}{\rm eV}} \left(\frac{a_I}{4.8\times 10^{11}\,{\rm GeV}} \right)^2$$

Is Predictivity lost? not completely



Relic production: topological defects

- After phase transition
- random initial conditions
- average is predictive

- but topological defects!

- decay into axions uncertain!
  - Sikivie, Shellard,...
  - Kawasaki & al 2014
  - Fleury & Moore 2015

π

θ

$-\pi$

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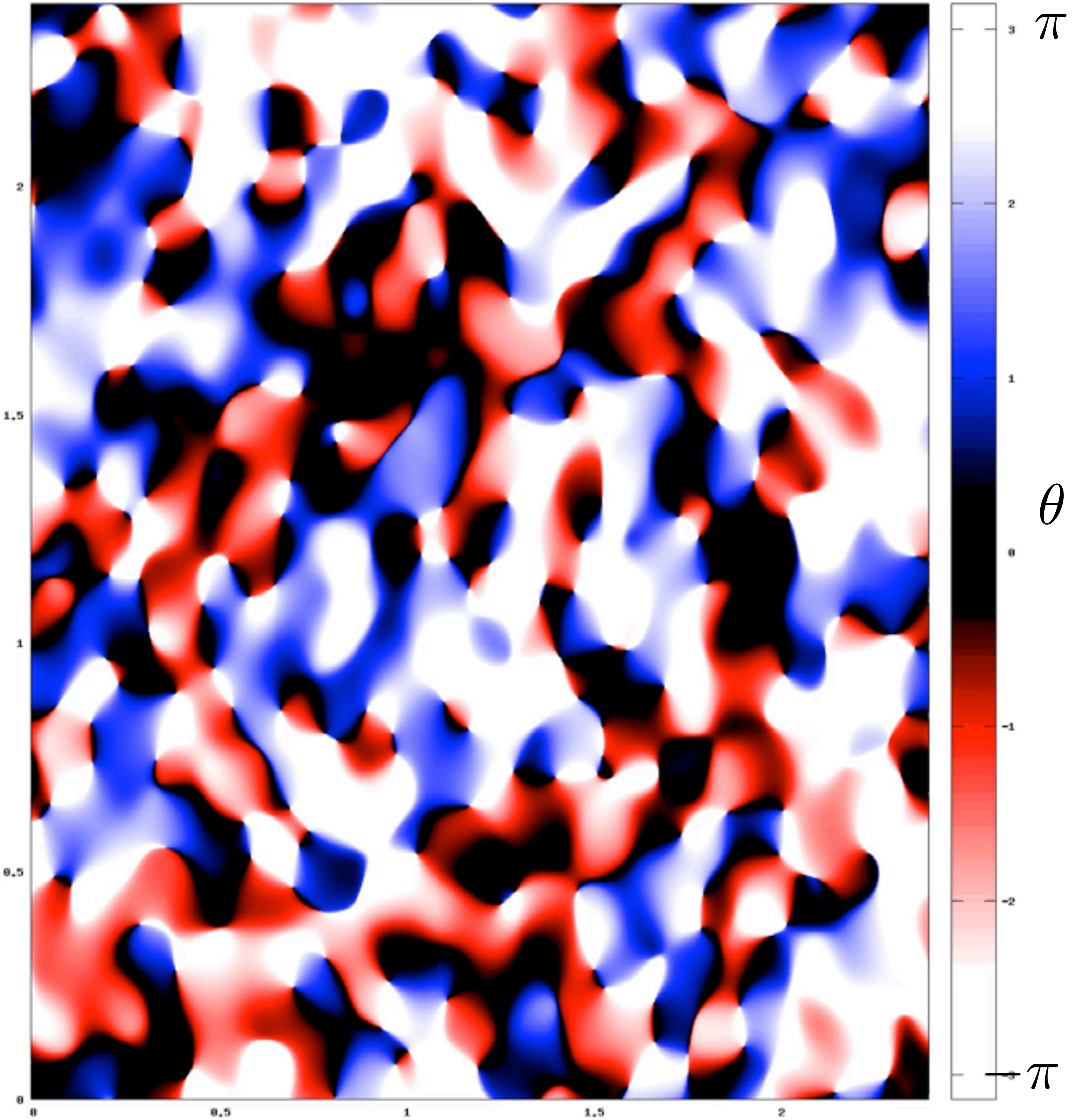

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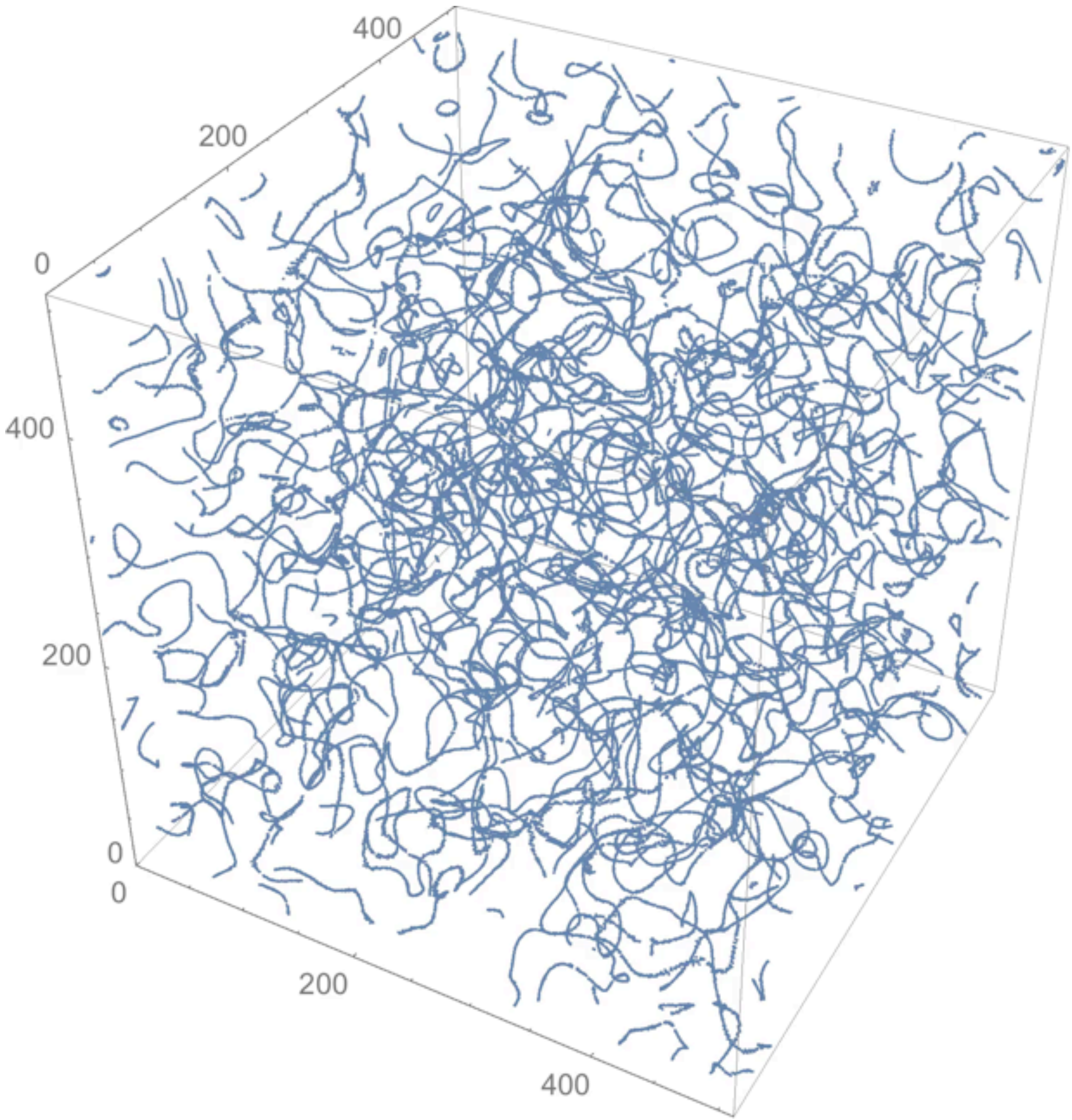
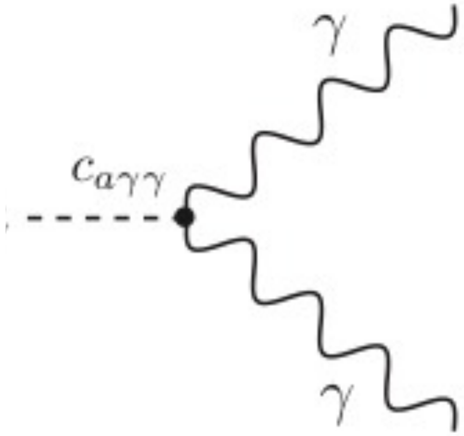
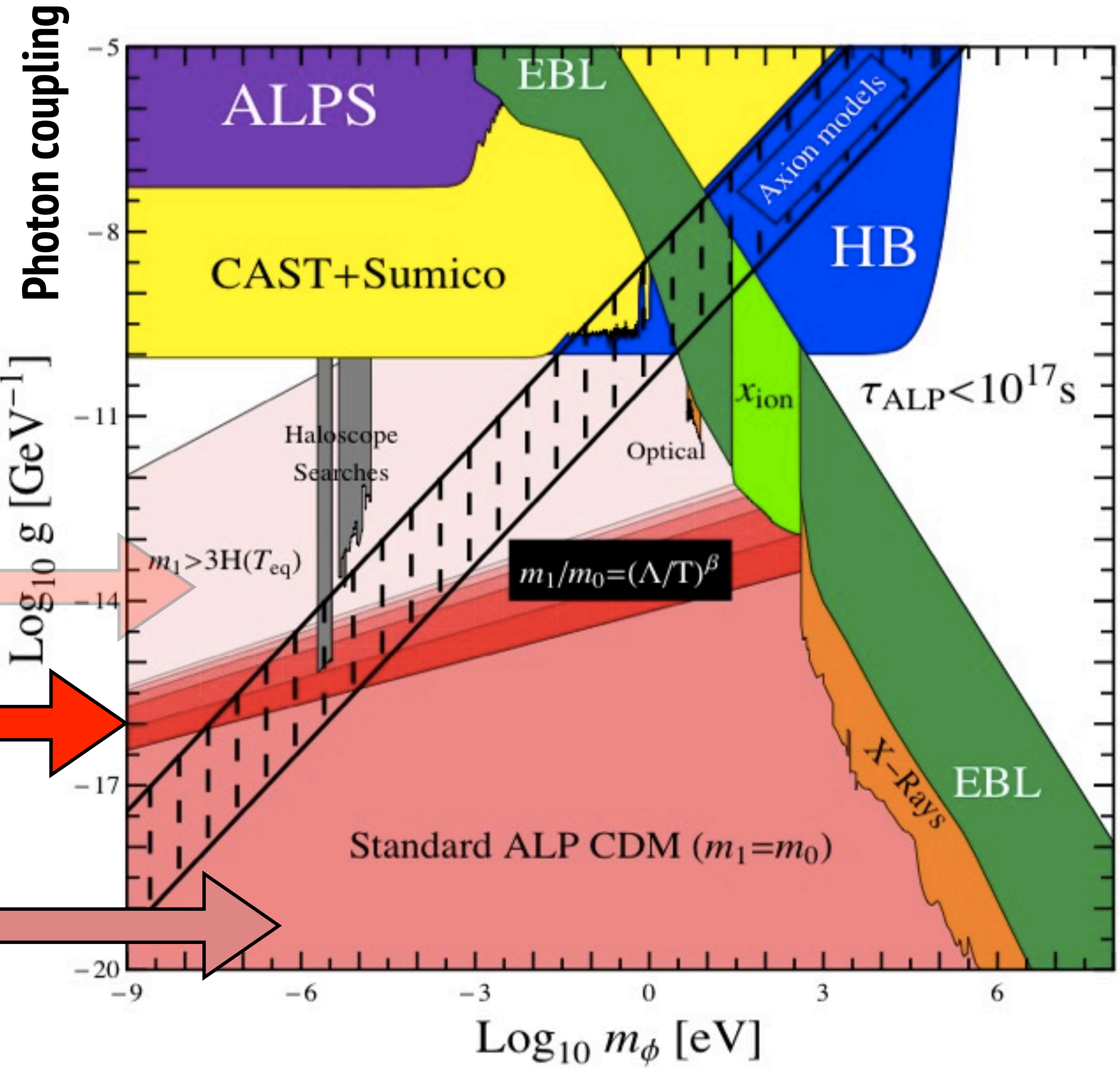


Generalisation for ALPs coupled to photons

Arias et al 2012

$$g \sim \frac{\alpha}{2\pi a_I}$$





why-not models

Average models

$a_I \ll f_a$ **models**

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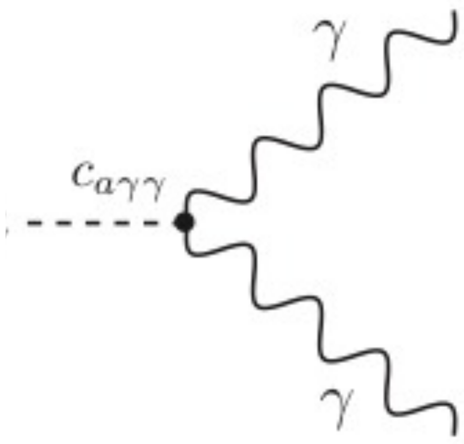

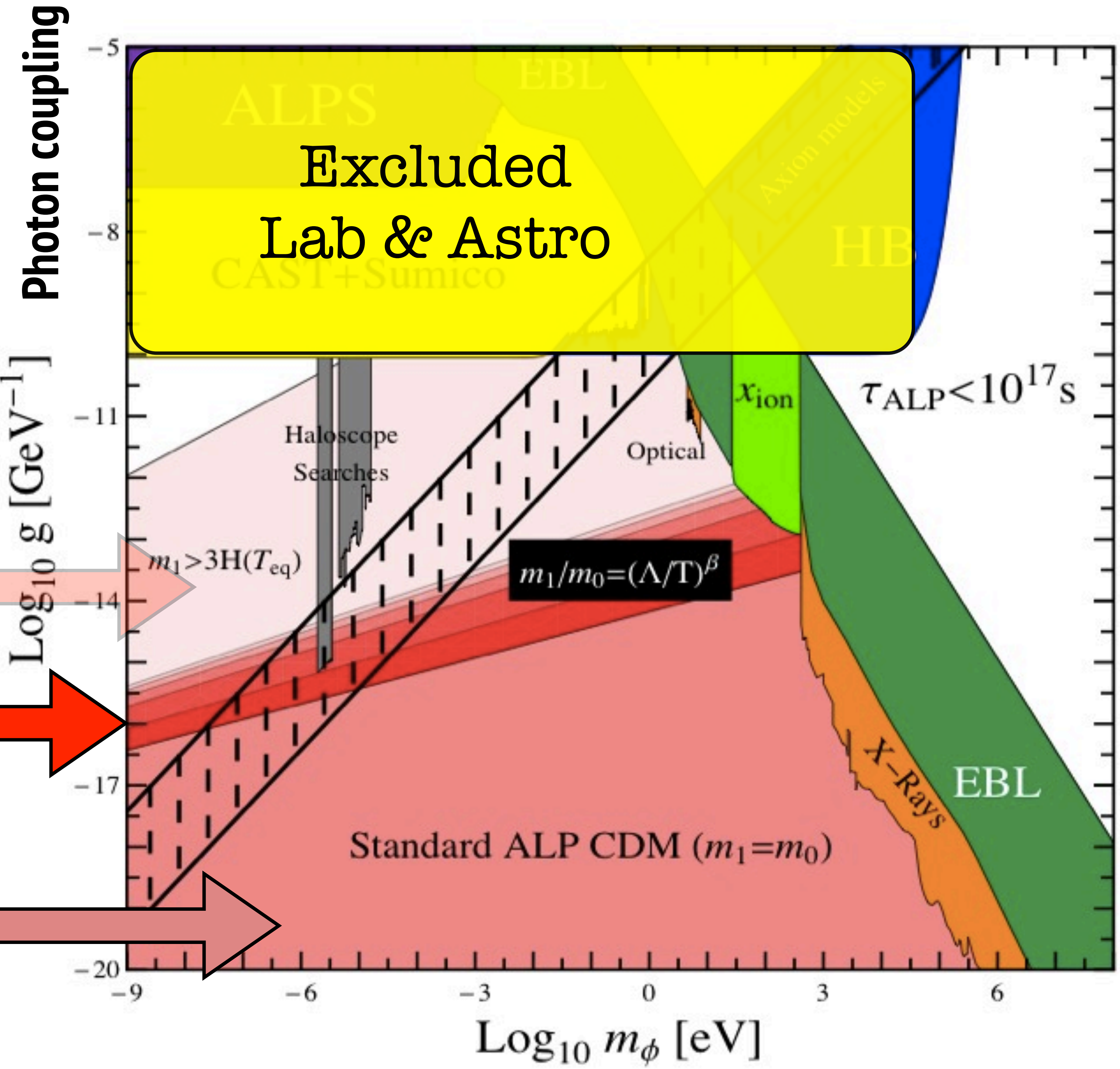

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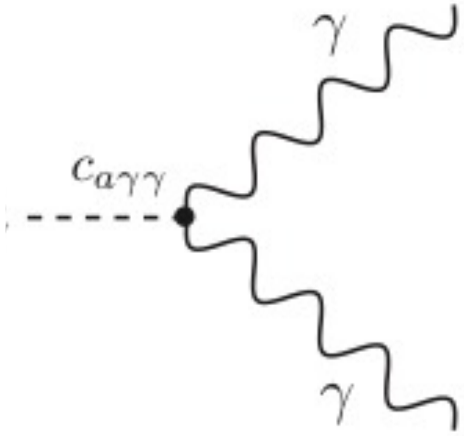

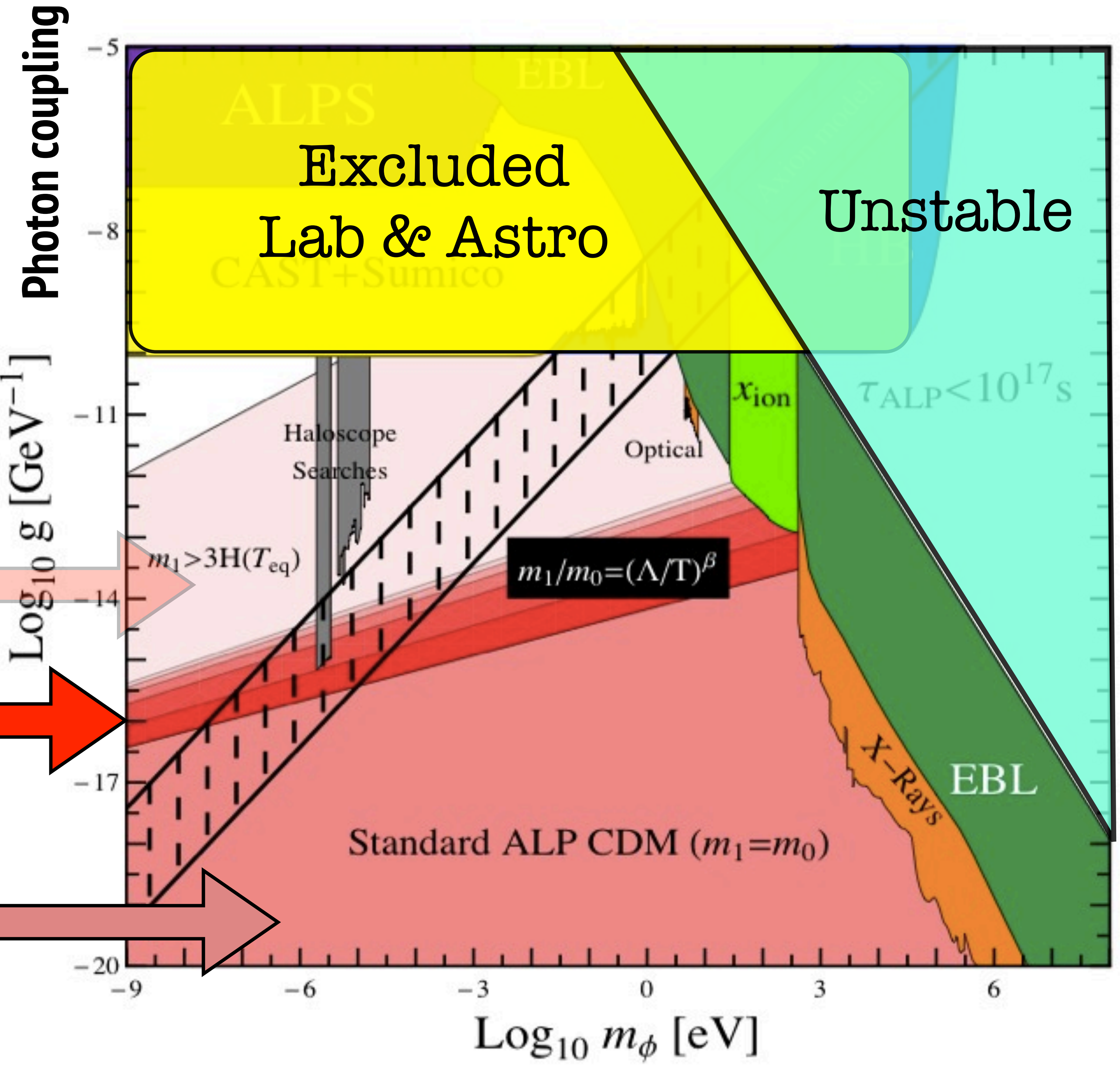

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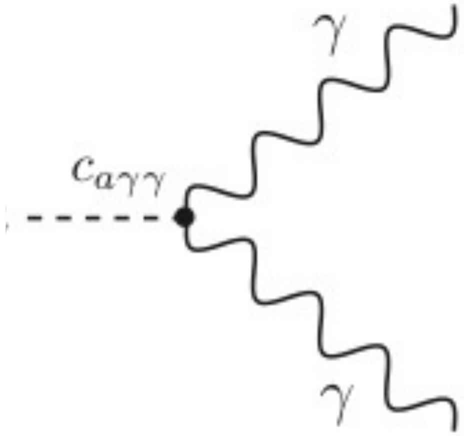
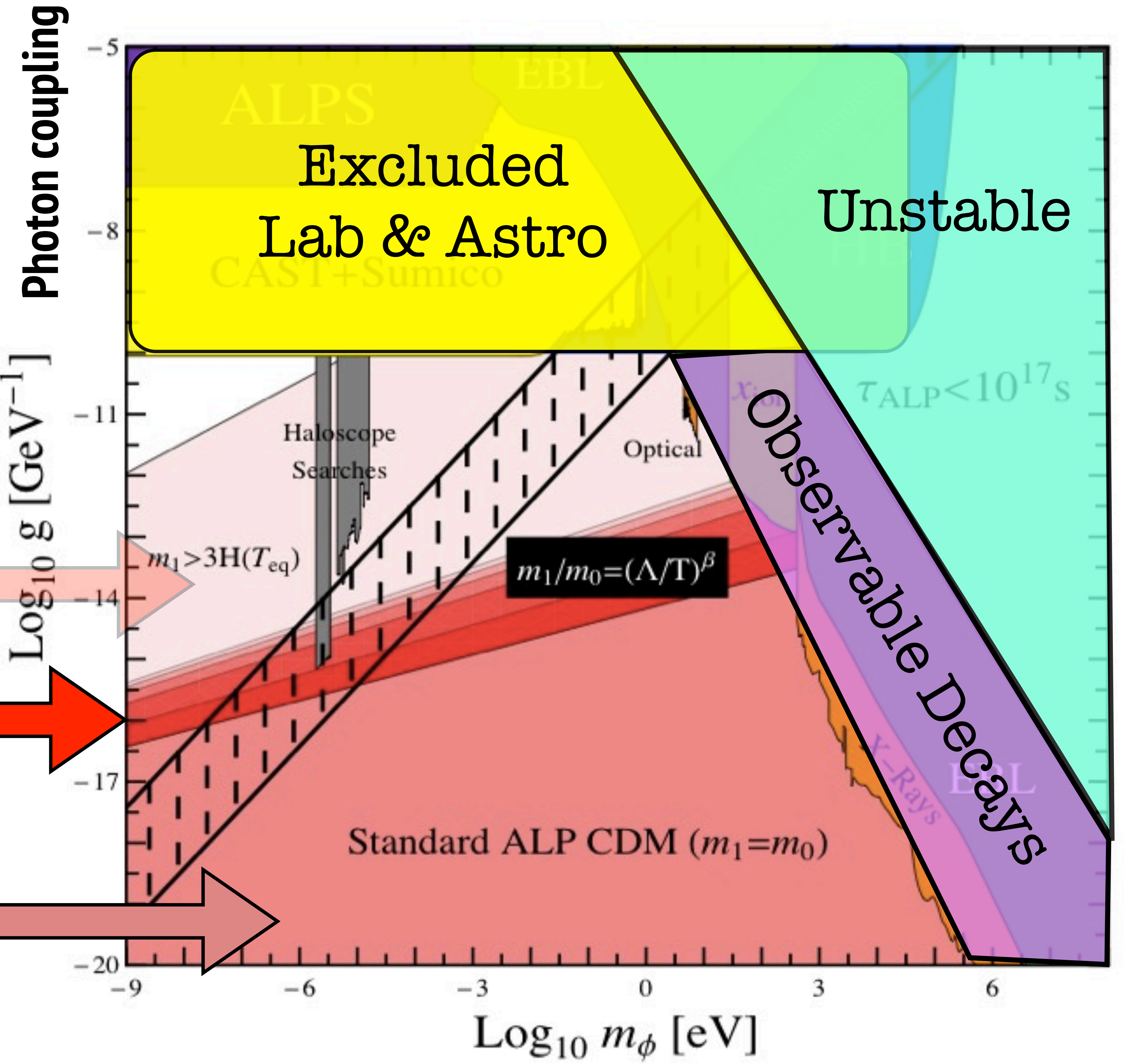




why-not models

Average models

$a_I \ll f_a$ **models**

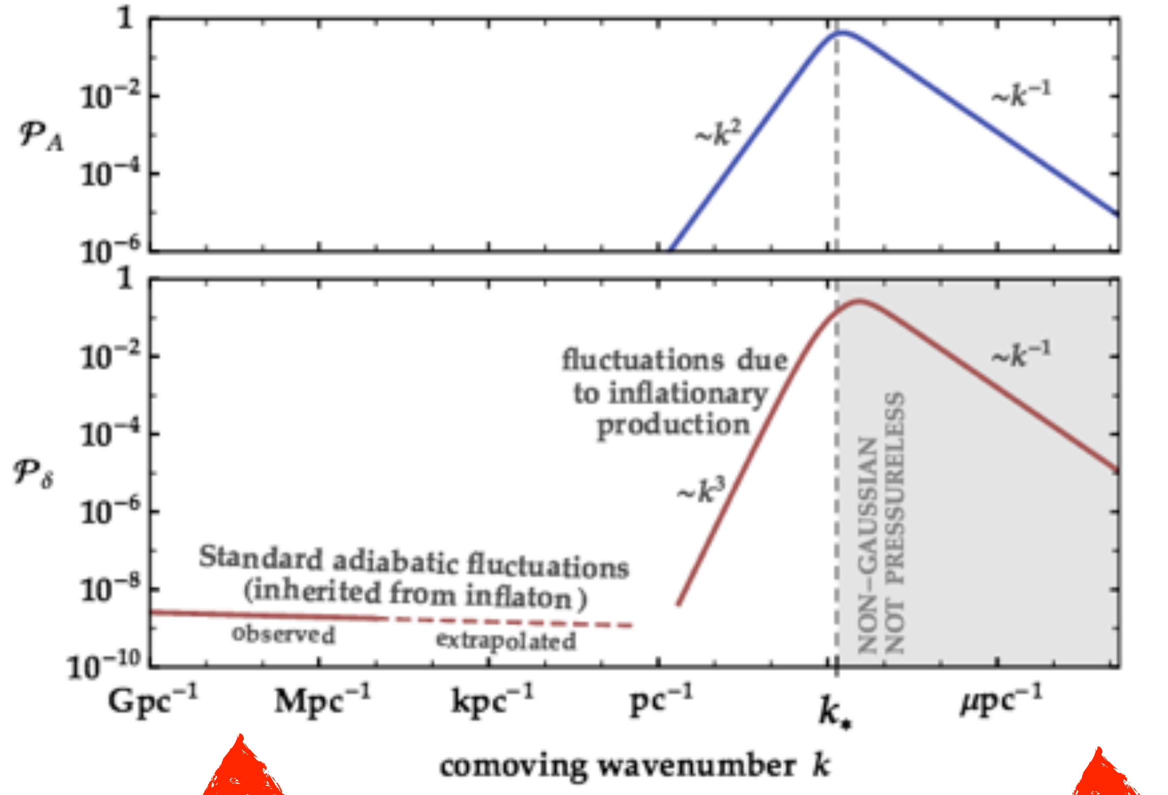
Hidden photons : isocurvature dark matter

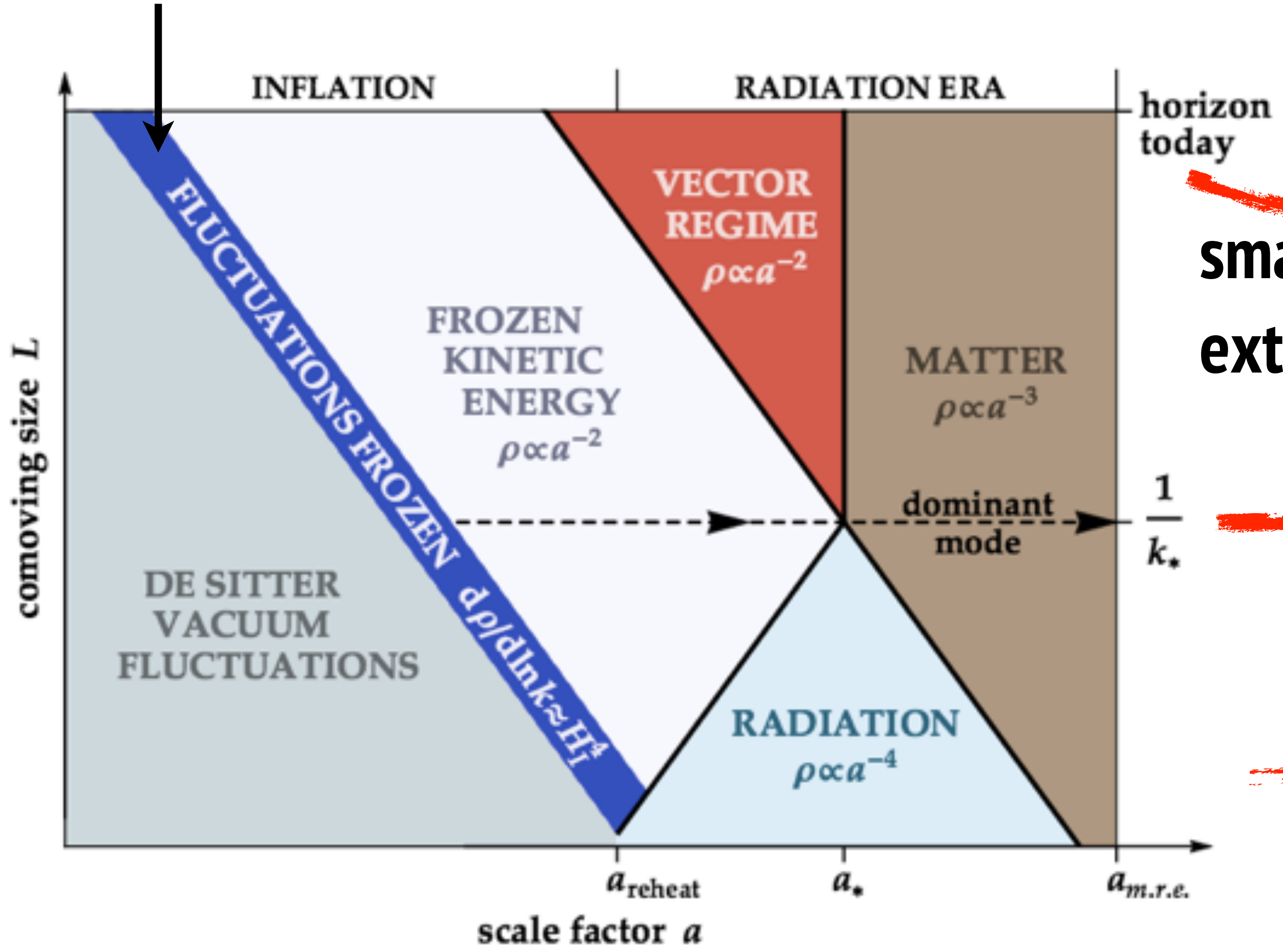
Graham 2015

- Misalignment sourced by Inflation itself

$$\langle |A_l| \rangle \sim \frac{H_I}{2\pi}$$

- Longitudinal mode ~ scalar
- Except for extra suppression low modes
- Compatible with CMB isocurvature constraints
- Not possible for axions & ALPs





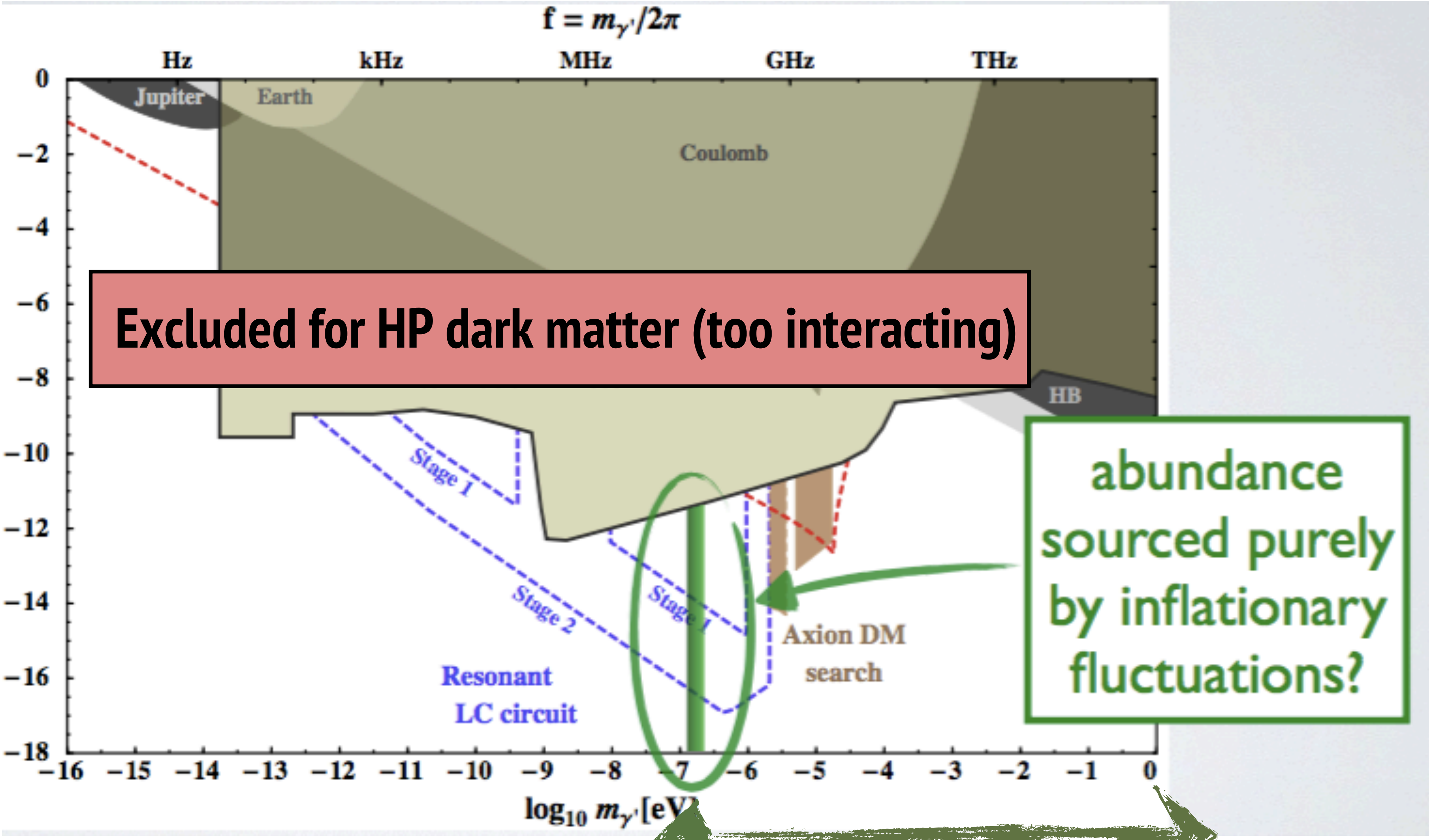
small scale

extra suppression

Hidden photons : isocurvature dark matter

Graham 2015

- Prediction?, connection of DM abundance with H-Inflation (measurable from B-modes)



Excluded for HP dark matter (too interacting)

abundance sourced purely by inflationary fluctuations?

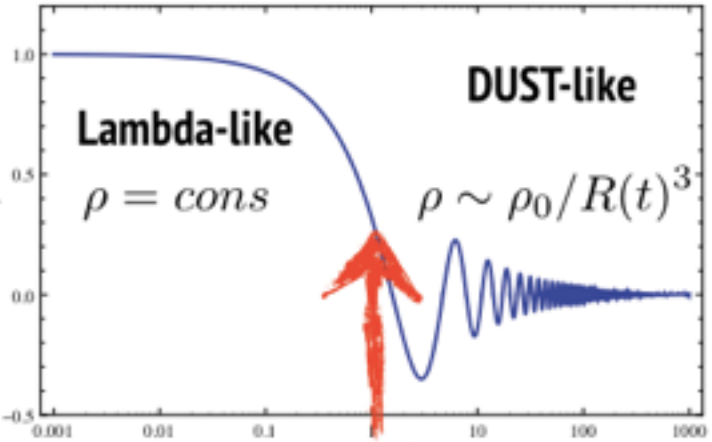
$H_I \sim 10^{14}\mathrm{GeV}$

$H_I < 10^{14}\mathrm{GeV}$

Ultralight is different

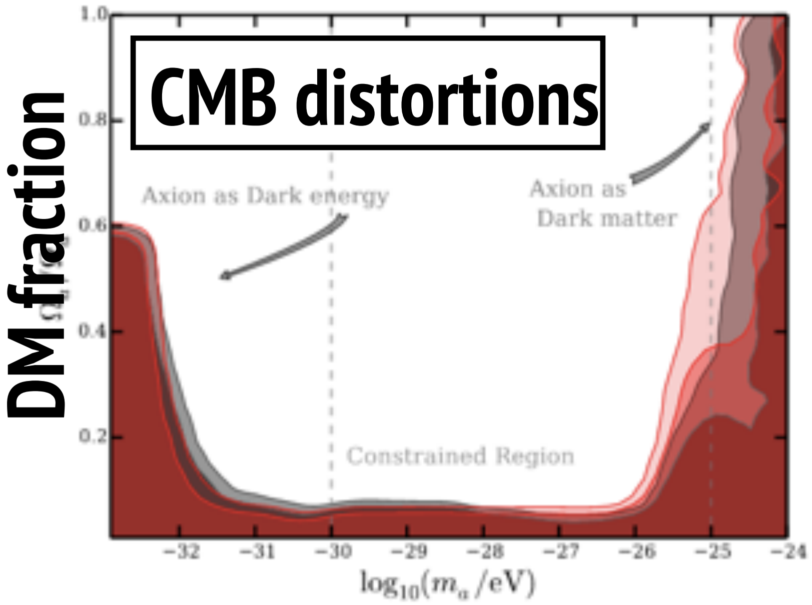
- DUST-like period before matter-radiation!
- Lower limit to the mass

$$\theta(t) = \frac{a(t)}{a_I}$$

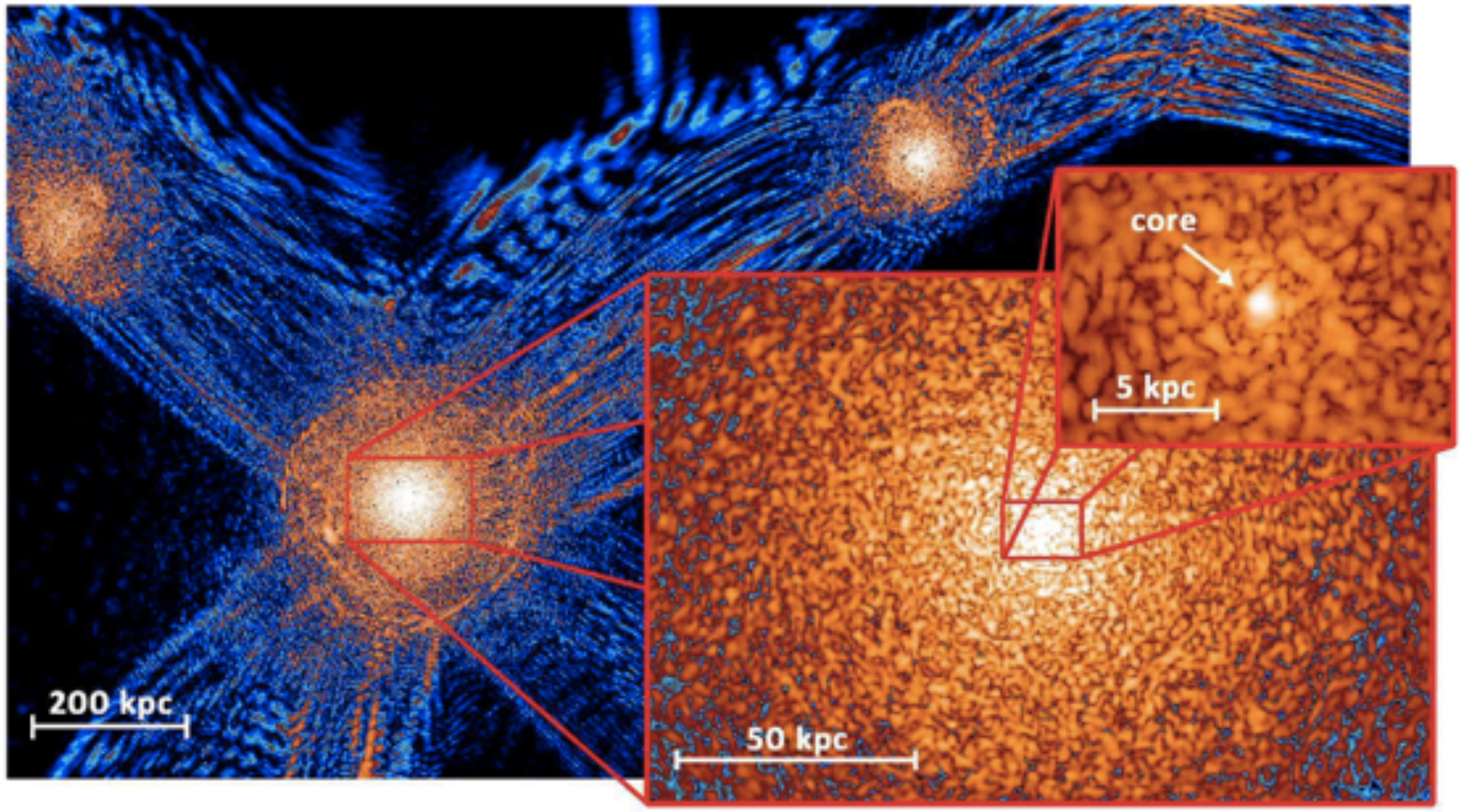


$$t \sim m_a^{-1} \lesssim t_{\rm eq}$$

Hlozek 2015



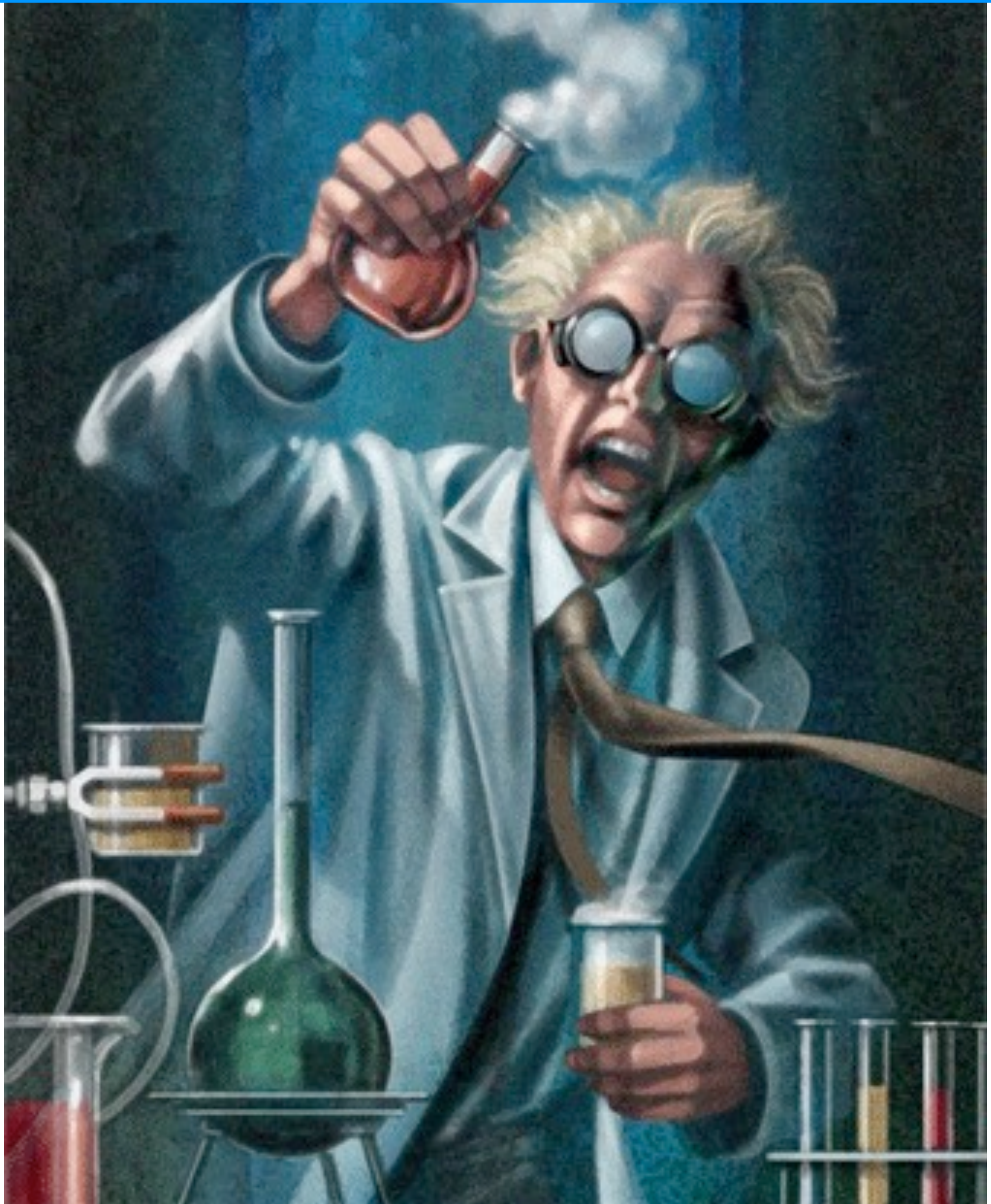
- Ultralight axions (~10^-22 eV) differences in Structure formation (wave interference)



Schive 2014

- Lengths ~ 1/m
- softer cores
- low mass halos suppressed
- Sikivie's condensate...

DM Direct detection



Cavity experiments

- Dark matter, classical field $\theta(t), \phi(t), \vec{A}'(t) \propto \cos(mt)$
- Axions, ALPs HPs couple to photons
- Modified Electrodynamics (example axions)

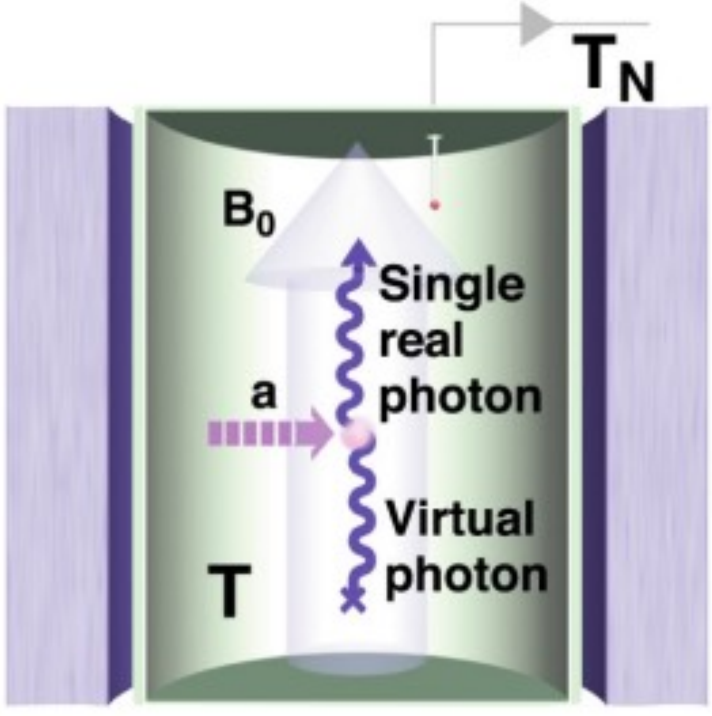
$$\begin{aligned}
\nabla \cdot \mathbf{D} &= \rho_f \\
\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J}_f - c_\gamma \frac{\alpha}{2\pi} \mathbf{B} \frac{\partial \theta}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0
\end{aligned}$$

In a magnetised medium

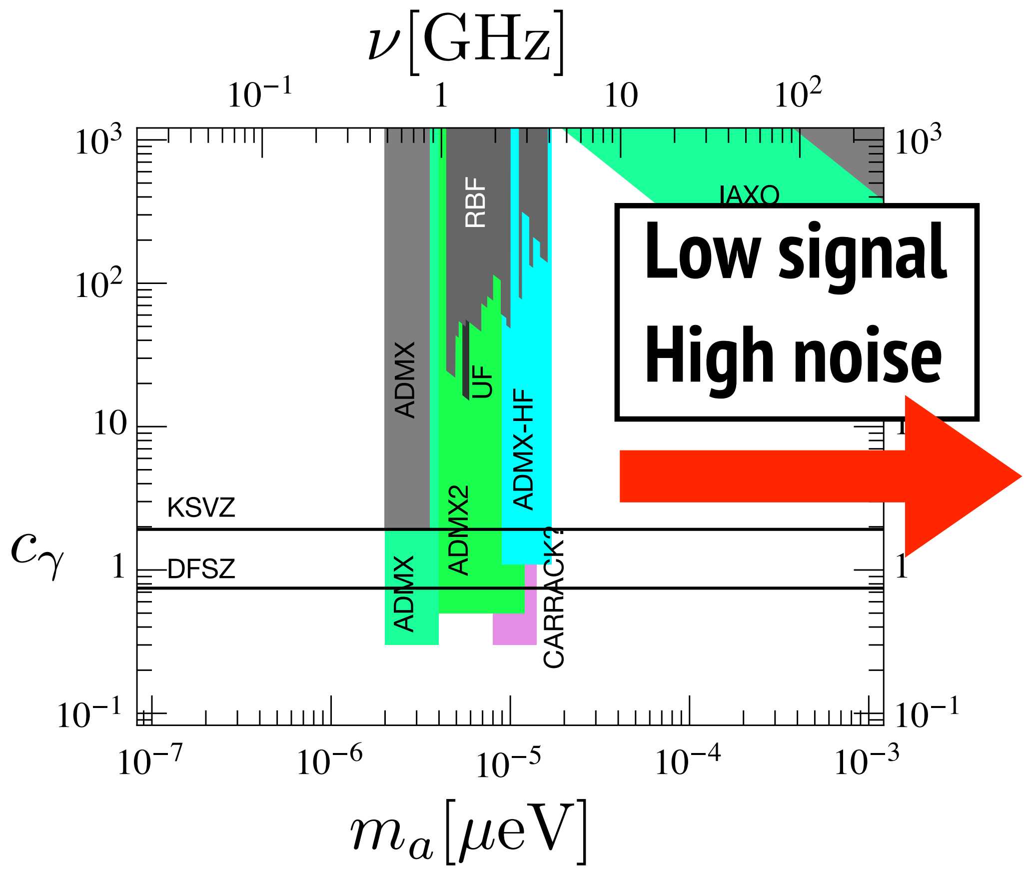
$$\mathbf{E}_a(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

$$|\mathbf{E}_a| \sim 0.6 c_\gamma \times 10^{-30} \frac{V}{m}$$

- Amplify signal in a MW resonant cavity (Sikivie ‘83)



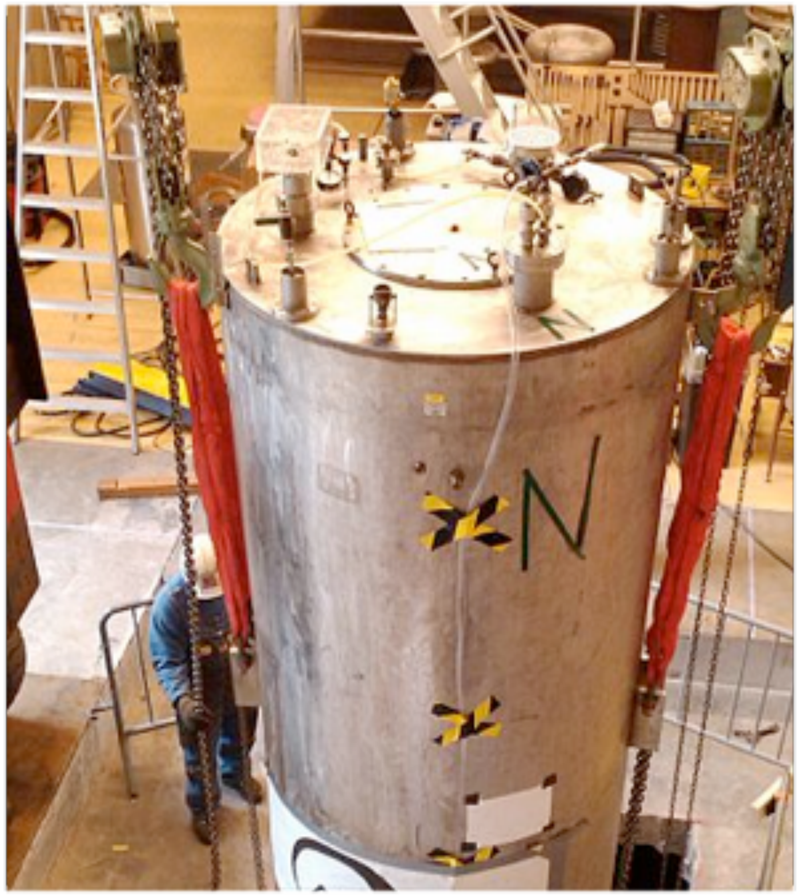
- Tunable cavity
- High B field
- Low Temperature (<K)
- Low noise pre-amp (<K)



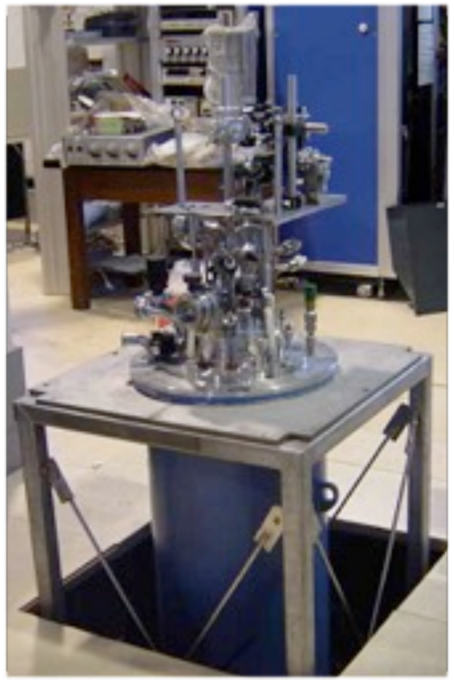
Low signal
High noise

Cavity experiments

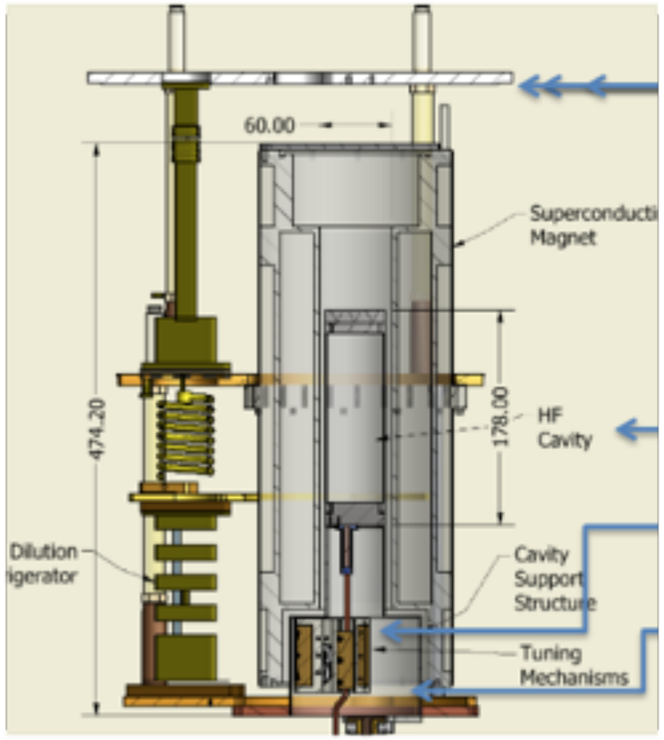
ADMX



CARRACK (discontinued)

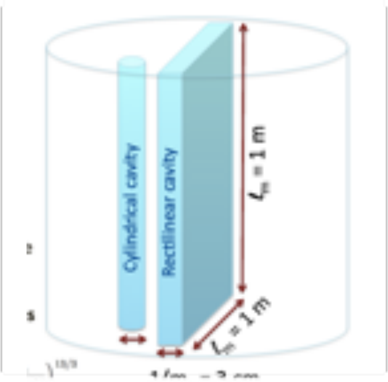


CULTASK - CAPP -Korea

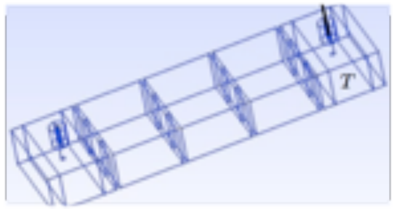


ADMX-HF

ADMX-Fermilab

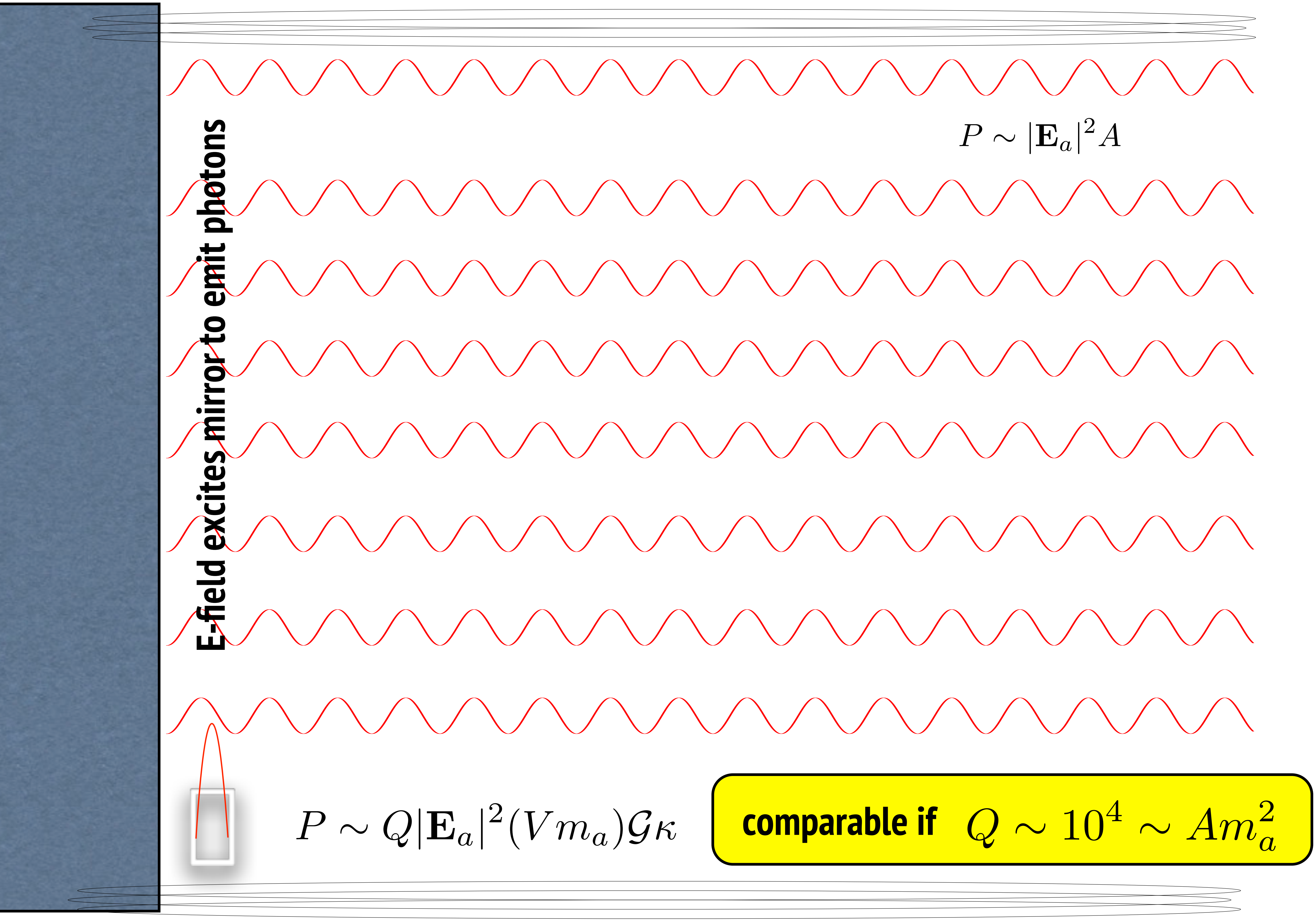


RADES



CAST-CAPP

Dish antenna



E-field excites mirror to emit photons

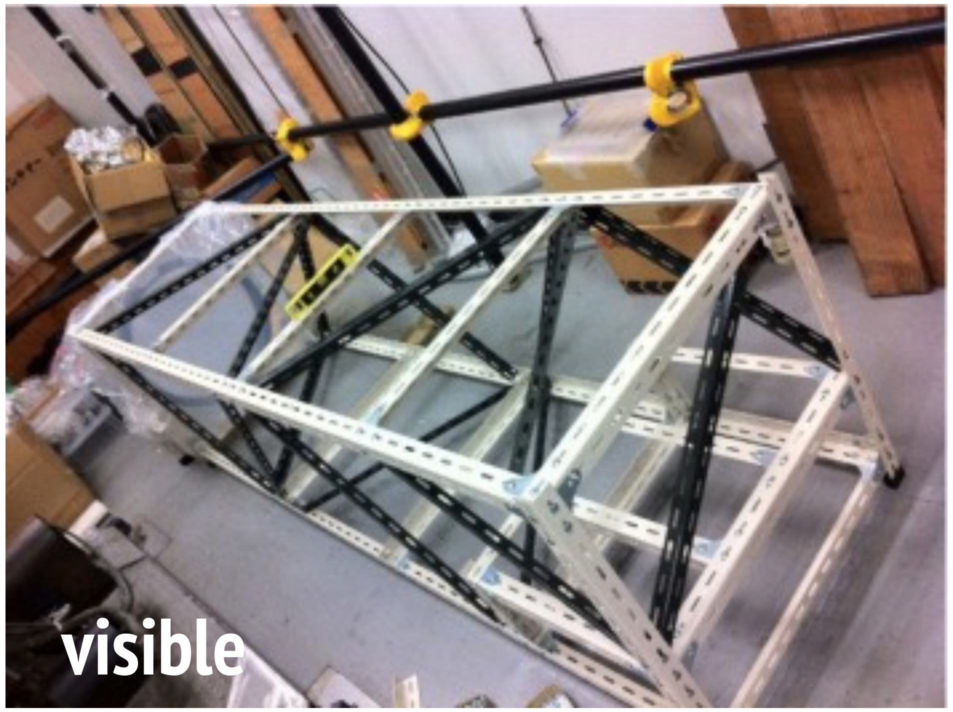
$$P \sim |\mathbf{E}_a|^2 A$$

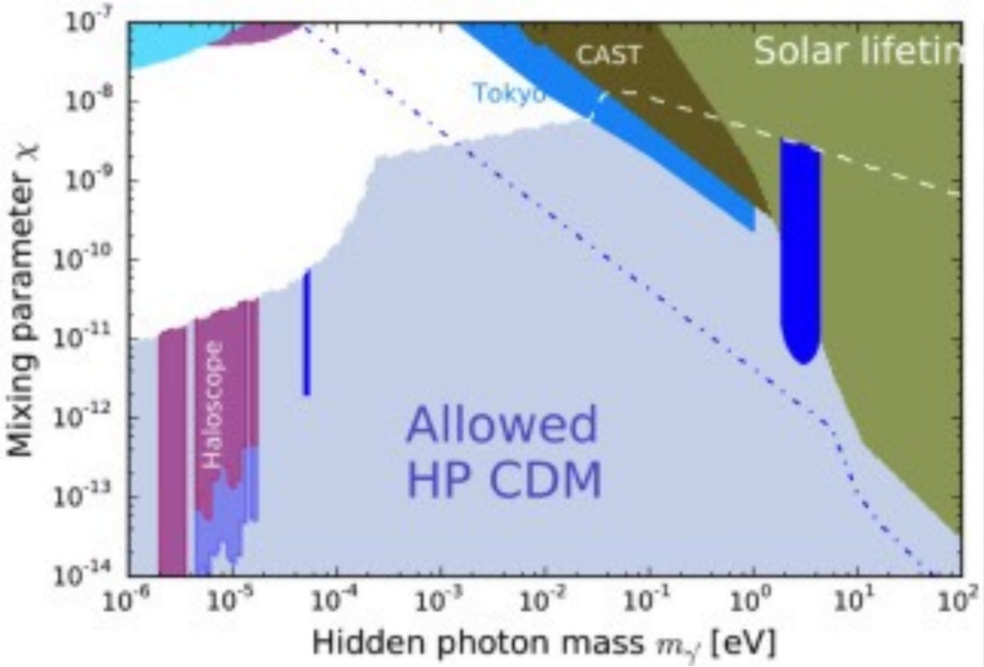
$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$$

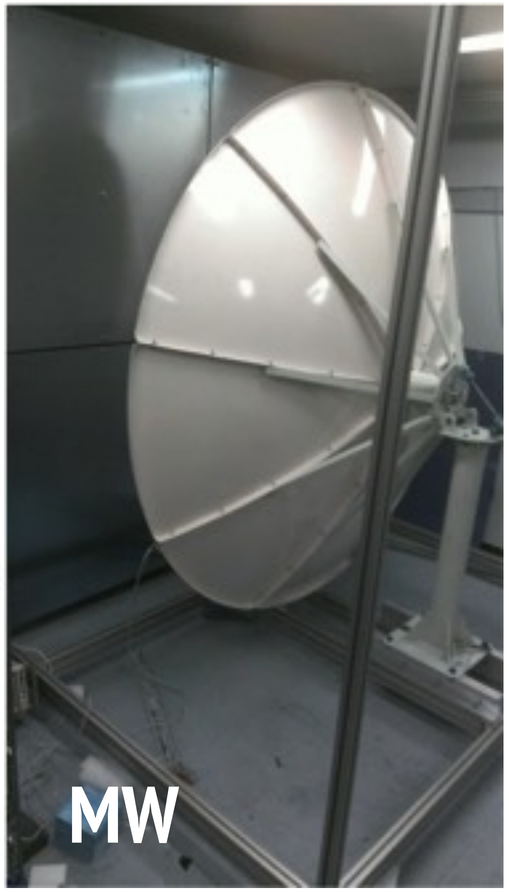
comparable if $Q \sim 10^4 \sim A m_a^2$

Dish antenna for Hidden Photons

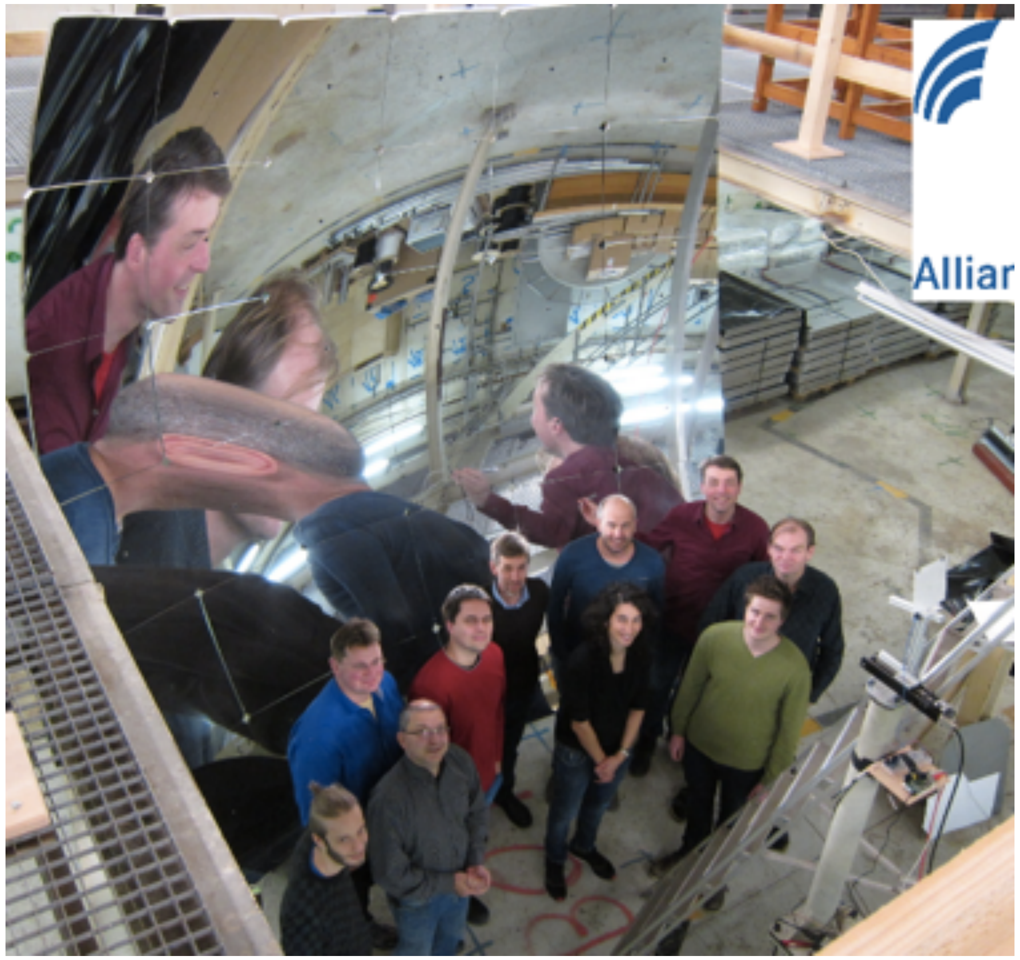
Tokyo Experiments







Karsruhe FUNK



Enhanced mirror with dielectric layers

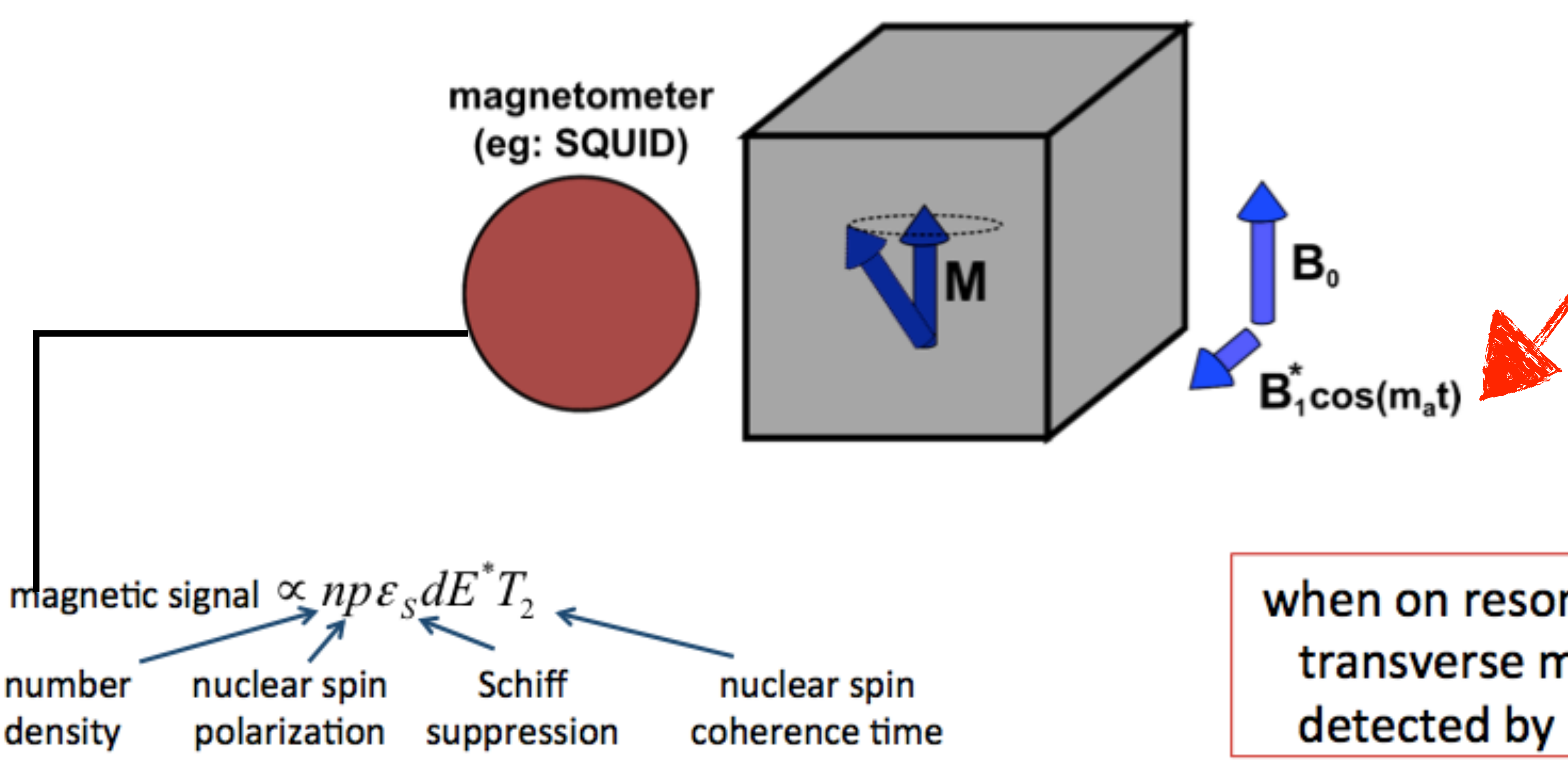
- Just a mirror is not good enough for axions ...
- Use many (mirror configuration, cavity configuration)

$P \sim |\mathbf{E}_a|^2 A \times \beta$ **boost**

Oscillating electric dipole moment (axion DM)

$$d_n \sim 10^{-35} \cos(m_a t) \mathrm{e\,cm}$$

EDM + Large E-fields in PbTiO3



magnetic signal $\propto n p \varepsilon_S d E^* T_2$

number density

nuclear spin polarization

Schiff suppression

nuclear spin coherence time

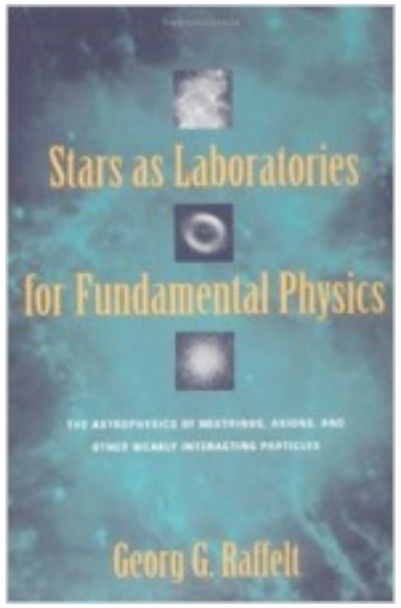
resonance condition:

$$\mu B_0 = m_a$$

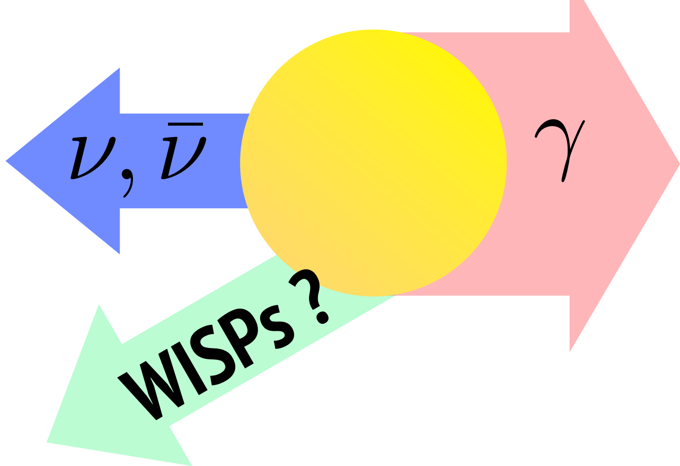
when on resonance, oscillating transverse magnetization is detected by magnetometer

- Mainz (D. Budker’s group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Phase I starts in 2016, Phase II physics results

Stars as Laboratories



Stellar cooling

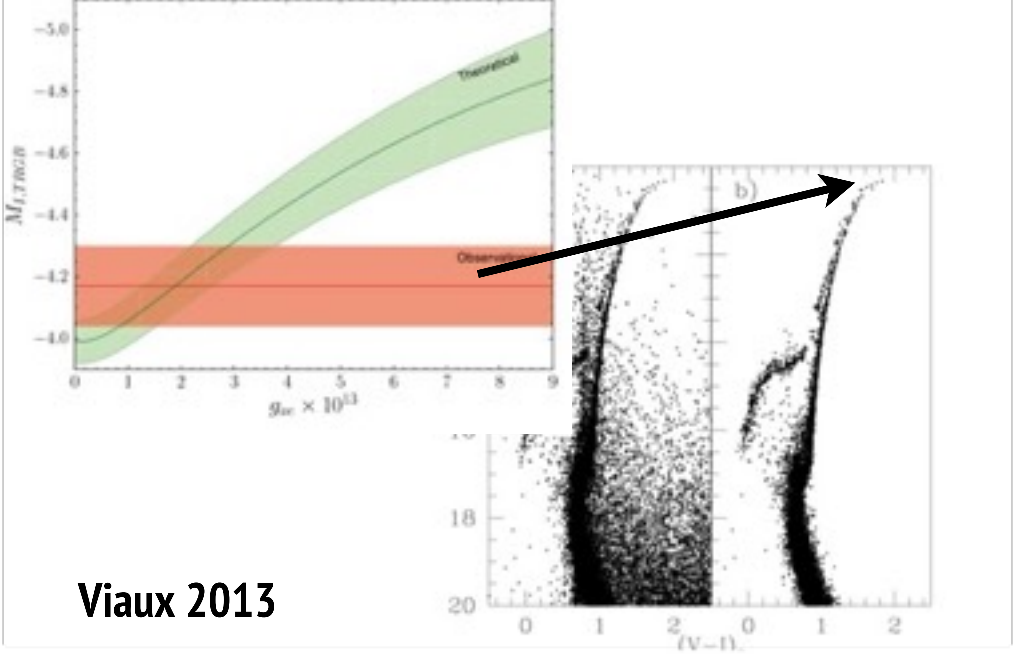


Numerical simulations

vs. Observations

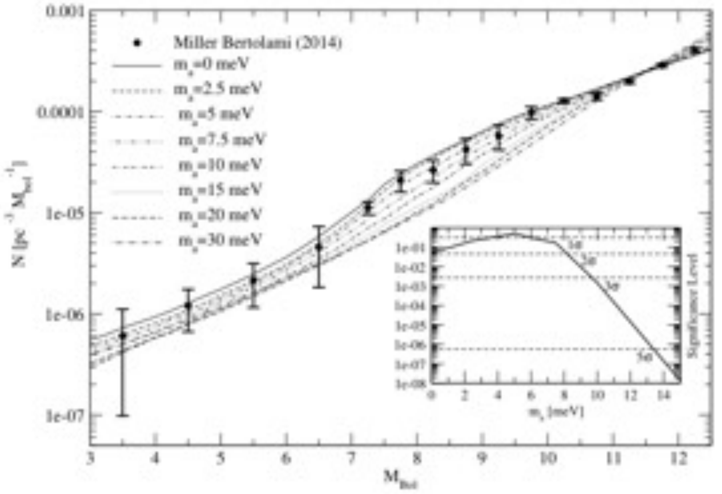
- Strong constraints (Sun, SN1987A, WDs, RG, HB ...)
- But slight preferences for meV-mass axions (electron/neutron coupling)

Luminosity of brightest Red Giant



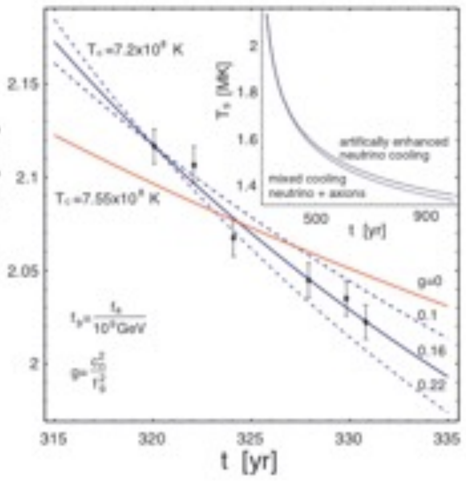
Viaux 2013

White dwarf luminosity F



Bertolami 2014

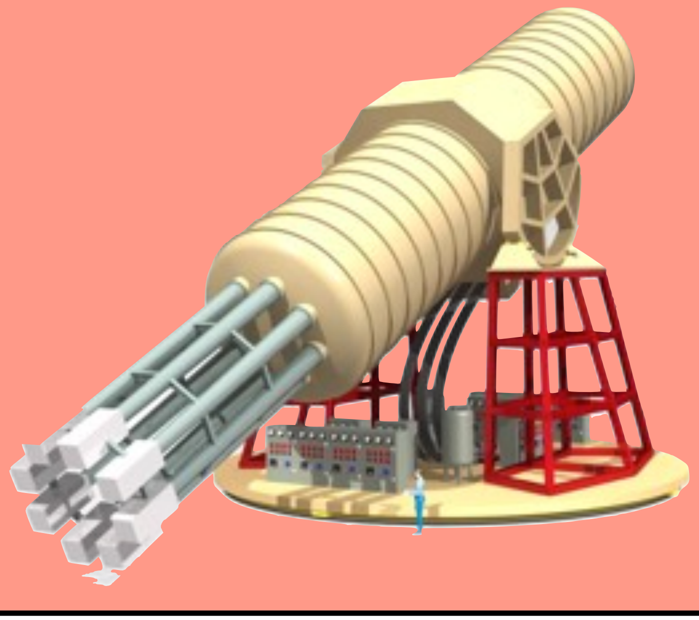
CAS A cooling



Stetson 2014

Laboratory searches : Axions

Solar Axions

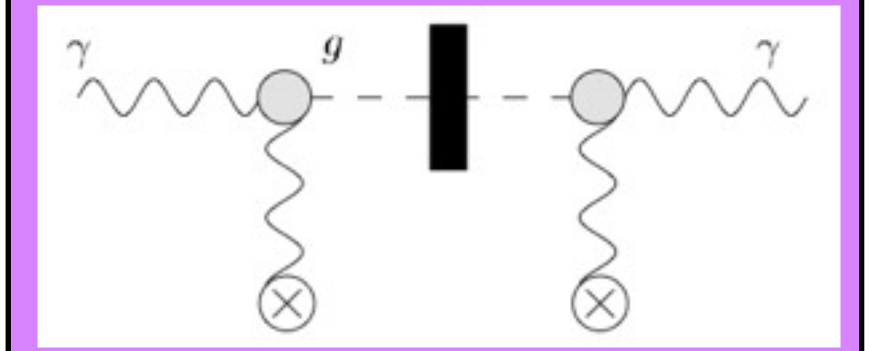


IAXO CDR 2014

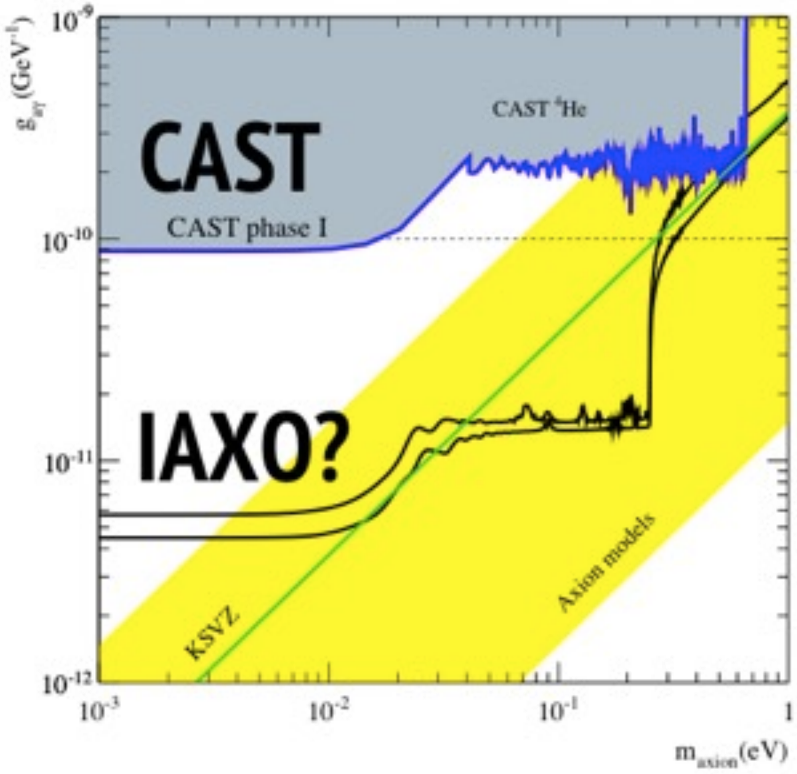
5th forces

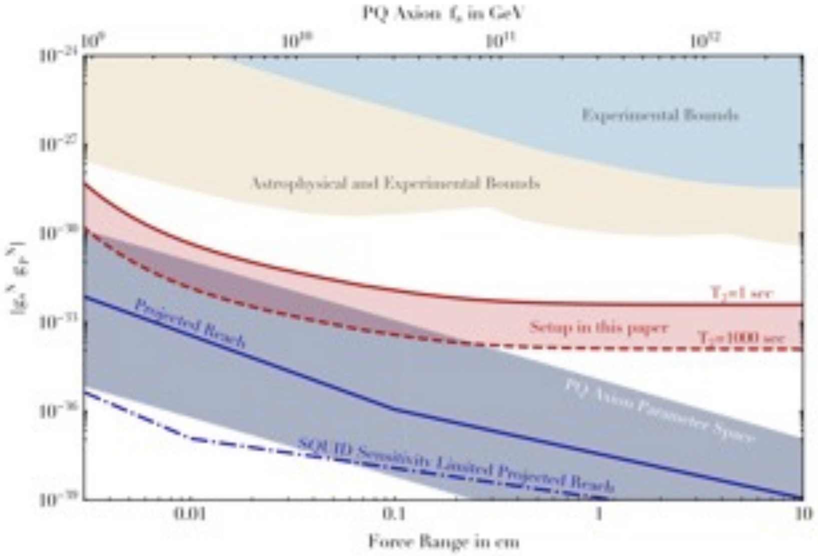
Arvanitaki Geraci PRL 2014

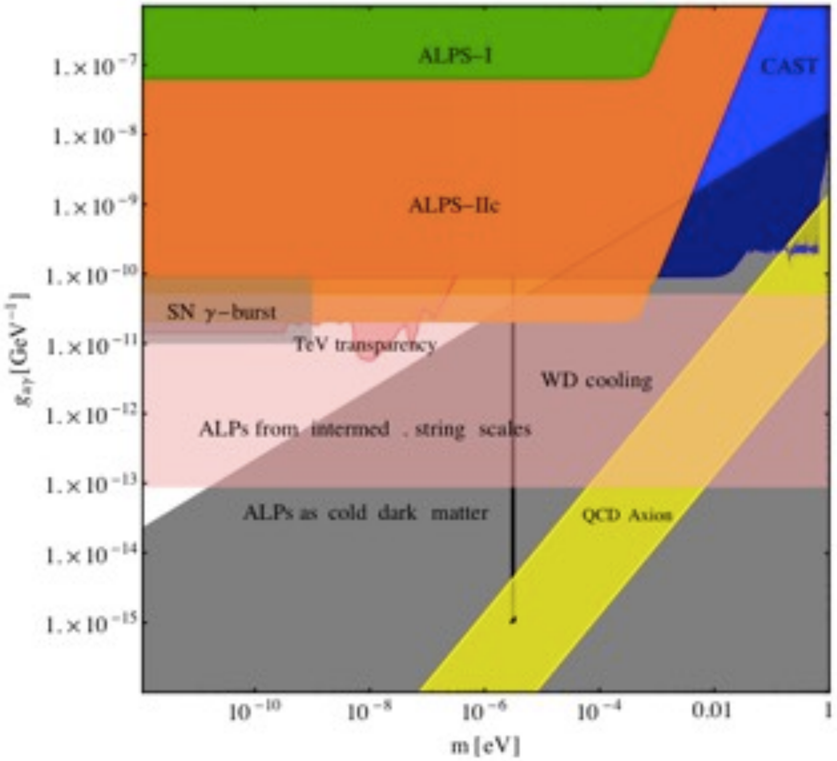
Photon regeneration



ALPS-II TDR 2013





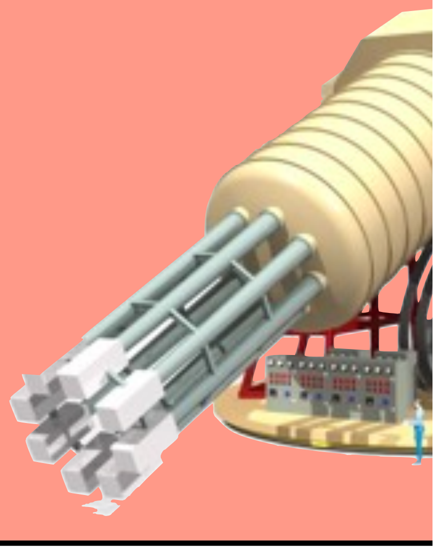


Laboratory searches : Axions

Solar Axions

5th forces

Photon regeneration



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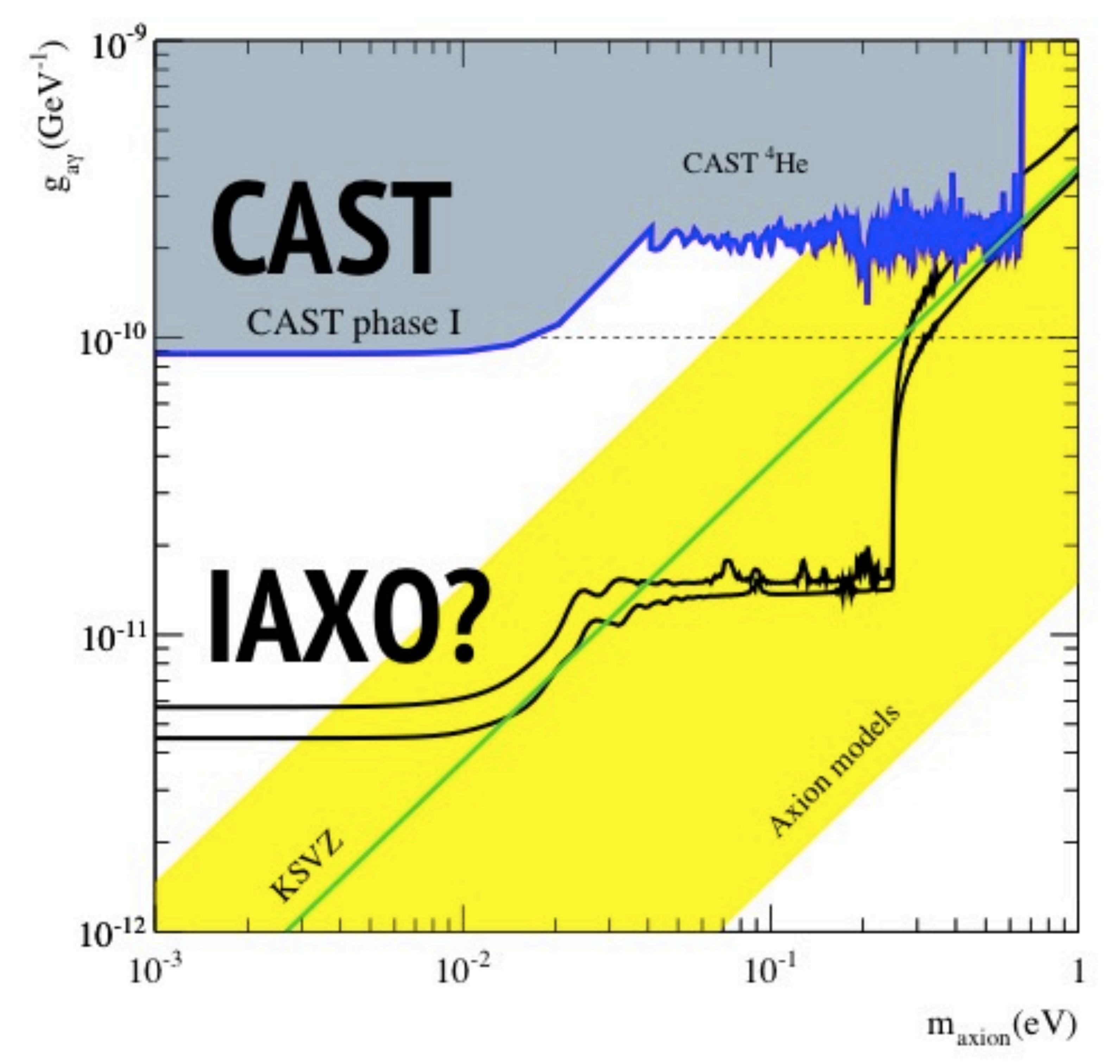
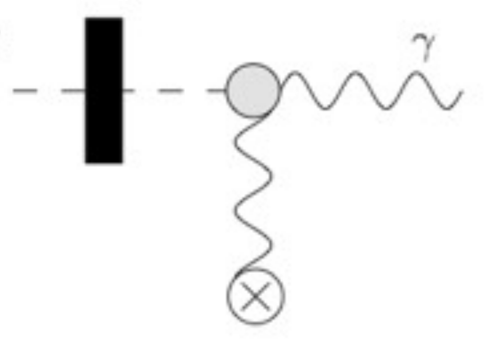
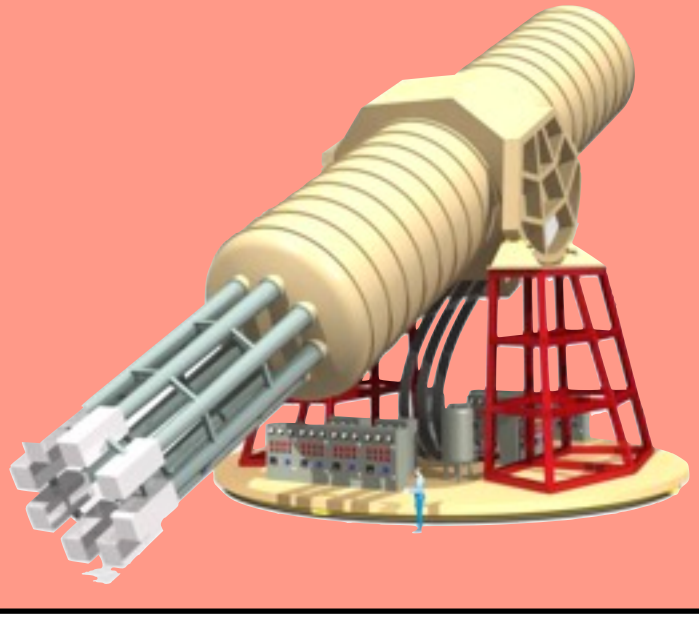




ALPS-II TDR 2013

Laboratory searches : Axions

Solar Axions

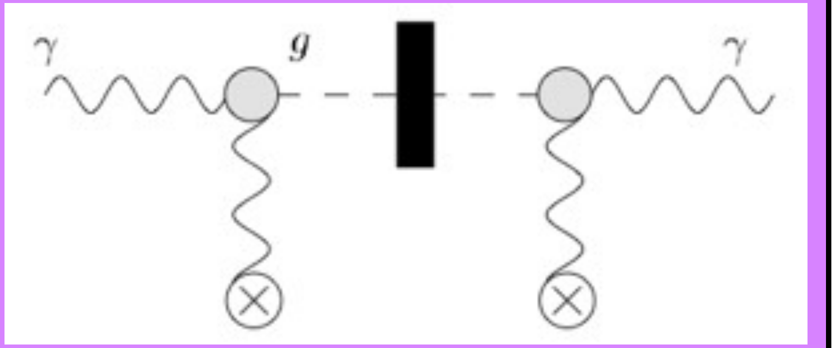


IAXO CDR 2014

5th forces

Arvanitaki Geraci PRL 2014

Photon regeneration



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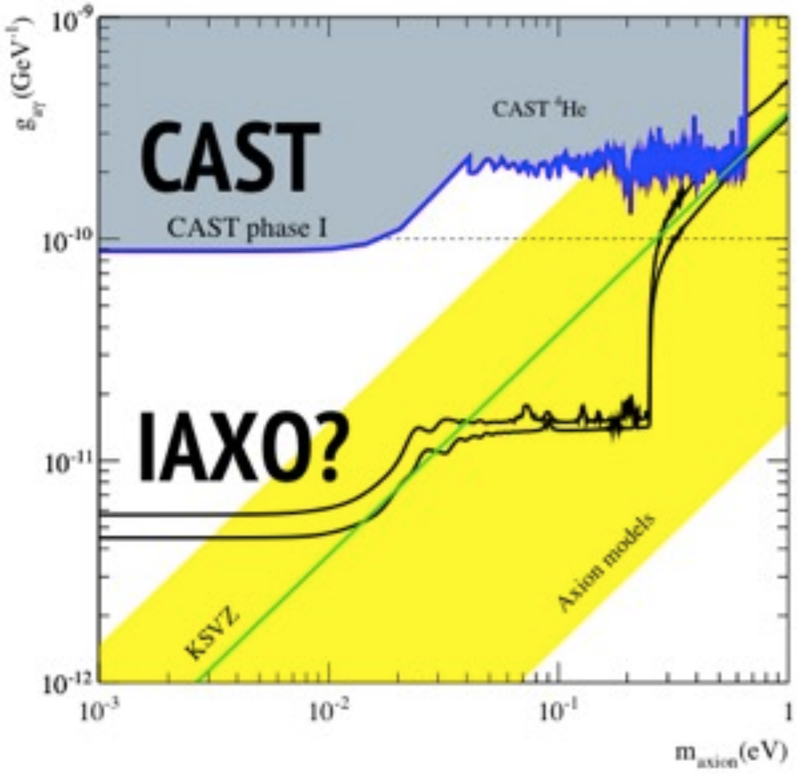
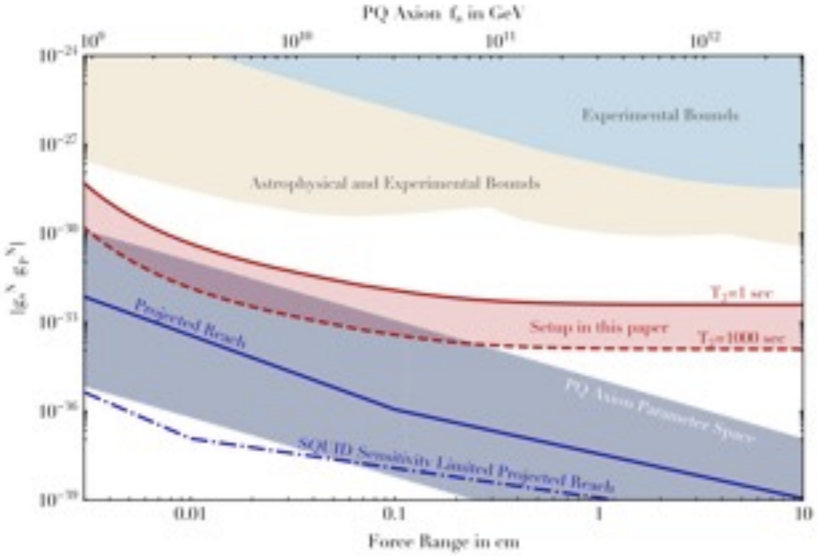
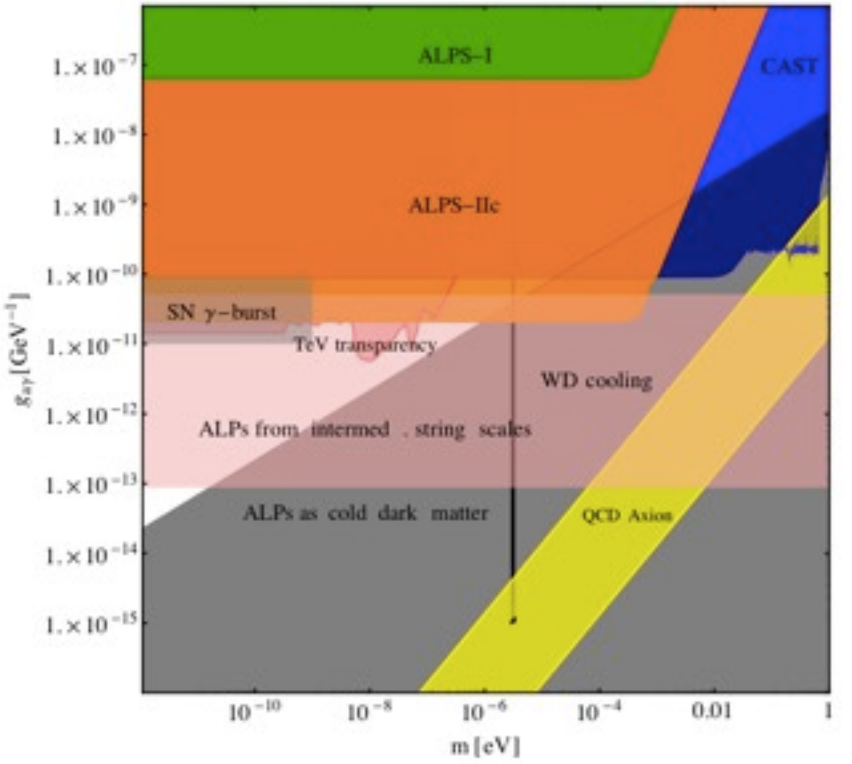
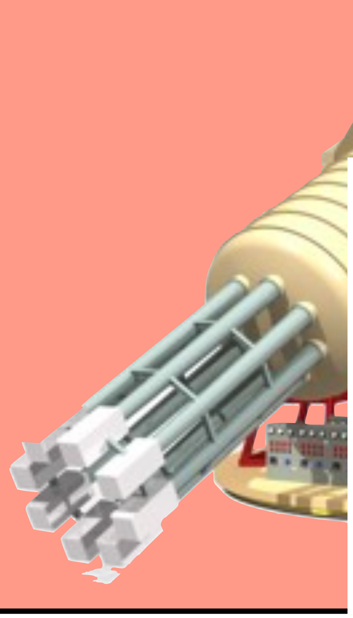






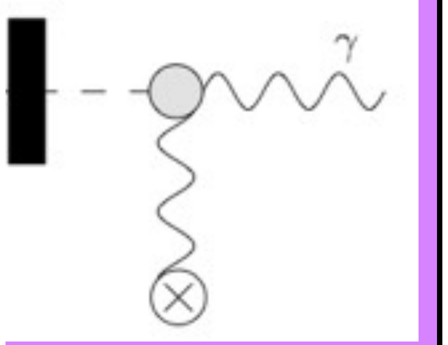
Laboratory searches : Axions

Solar Axions

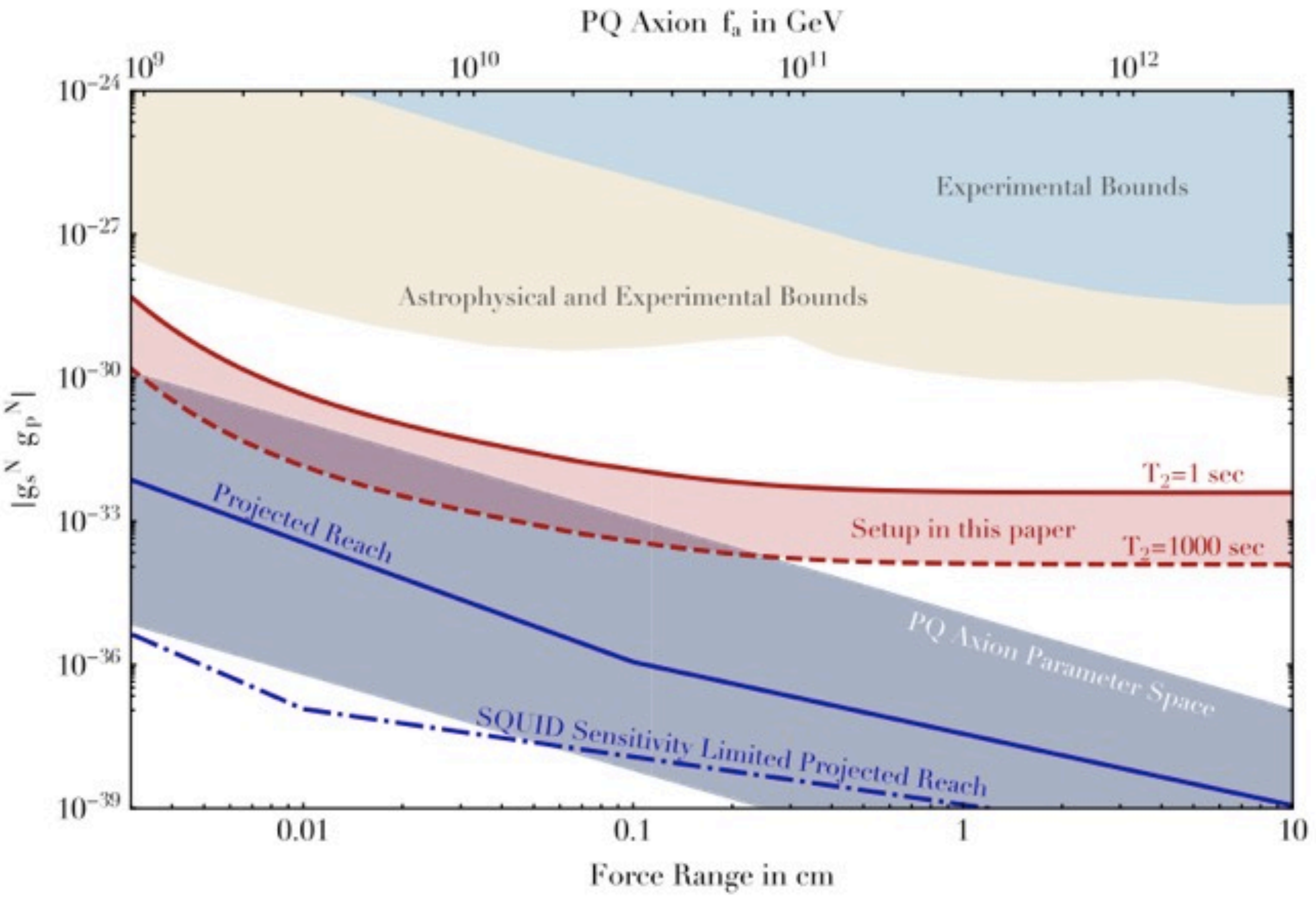


5th forces

Photon regeneration

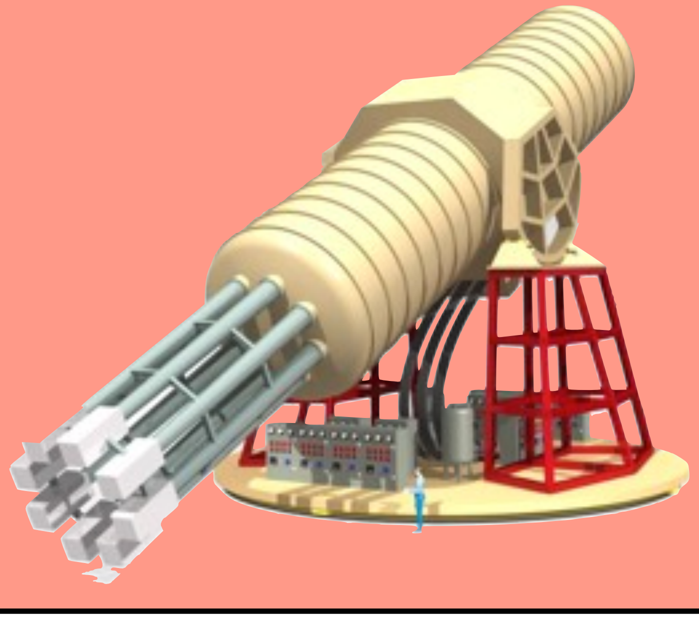


ALPS-II TDR 2013



Laboratory searches : Axions

Solar Axions

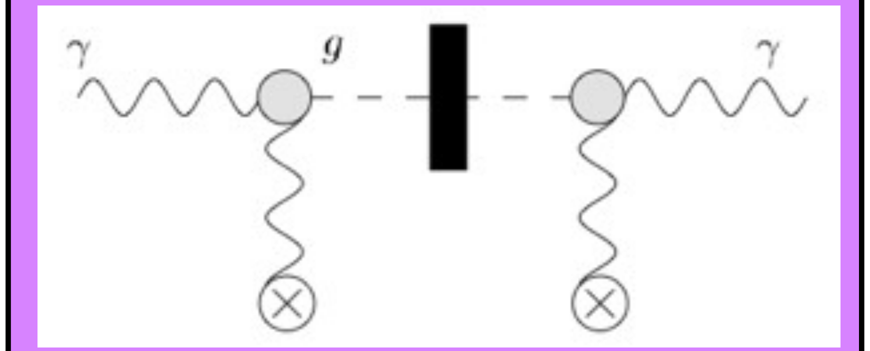


IAXO CDR 2014

5th forces

Arvanitaki Geraci PRL 2014

Photon regeneration



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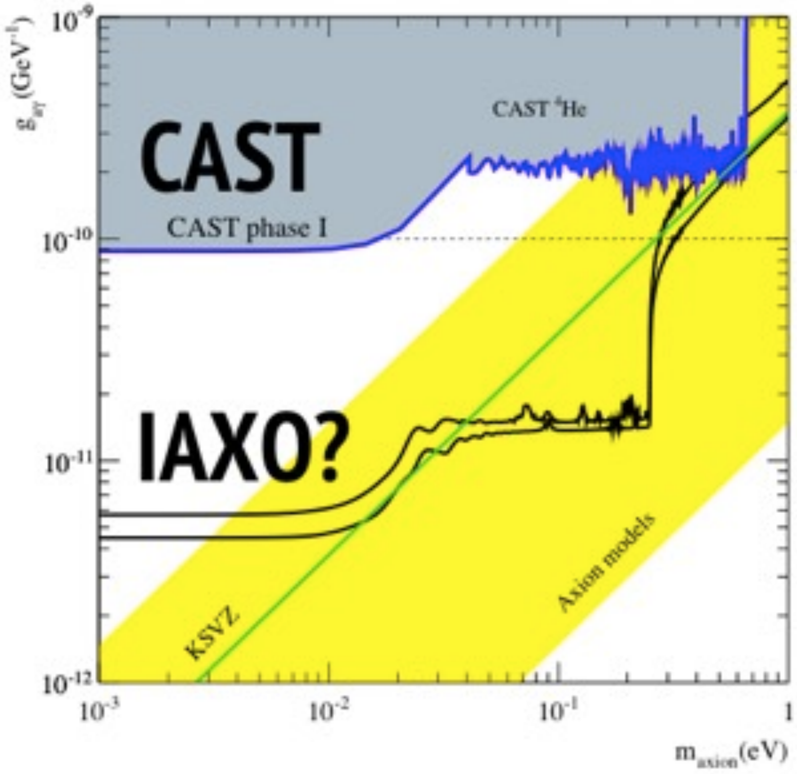
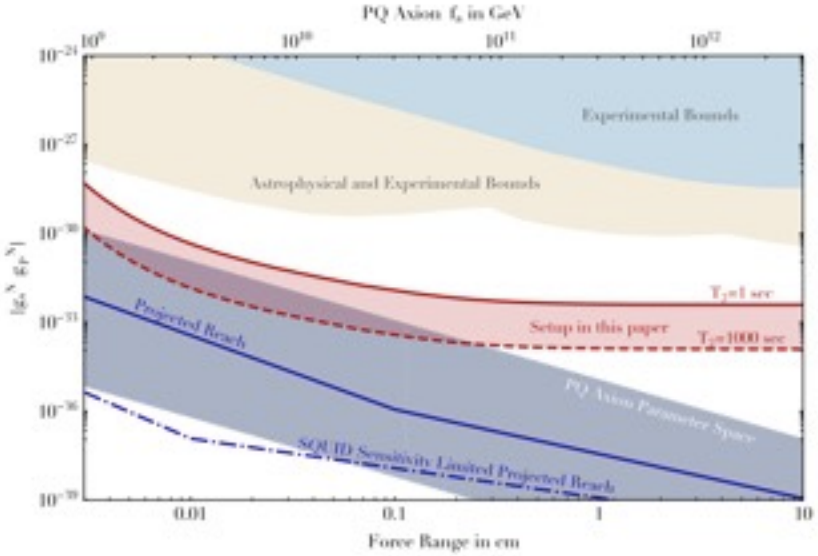
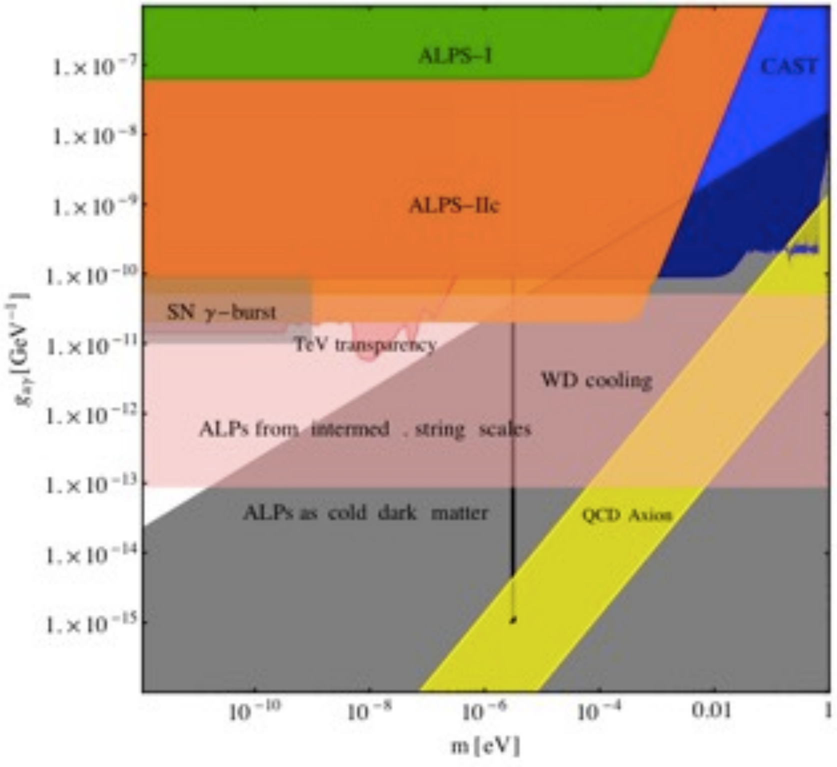
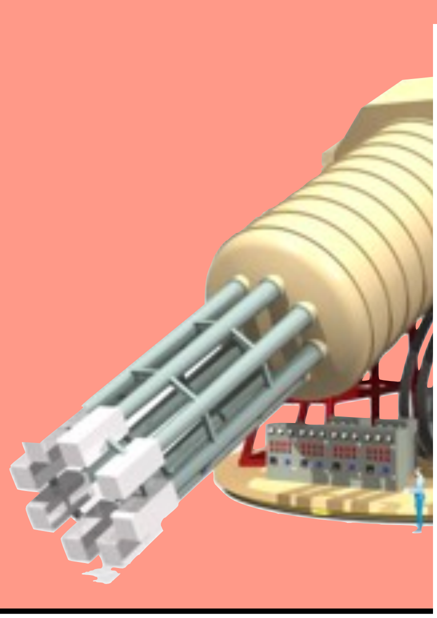






Laboratory searches : Axions

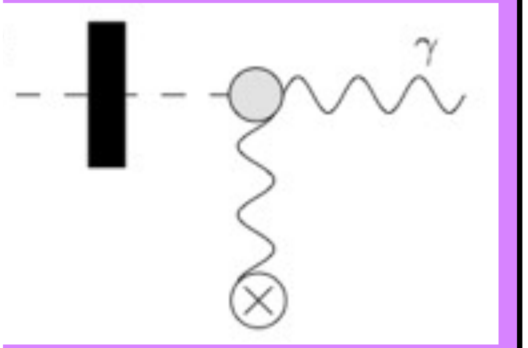
Solar Axions



IA

5th forces

Photon regeneration



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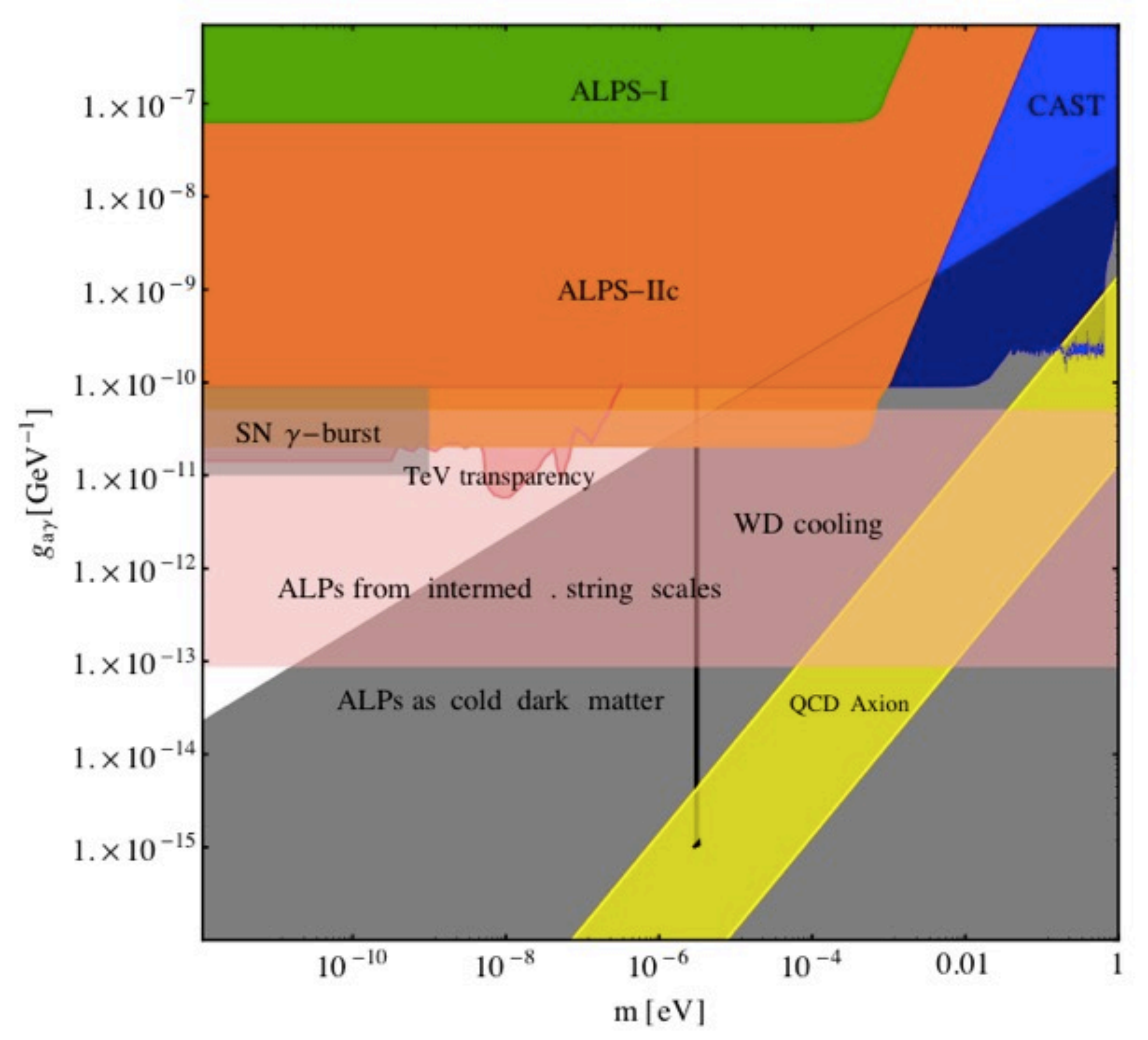
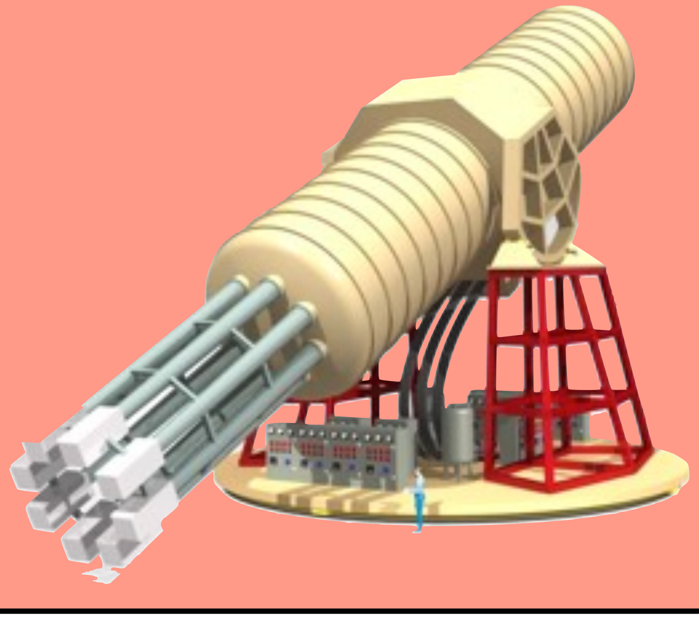
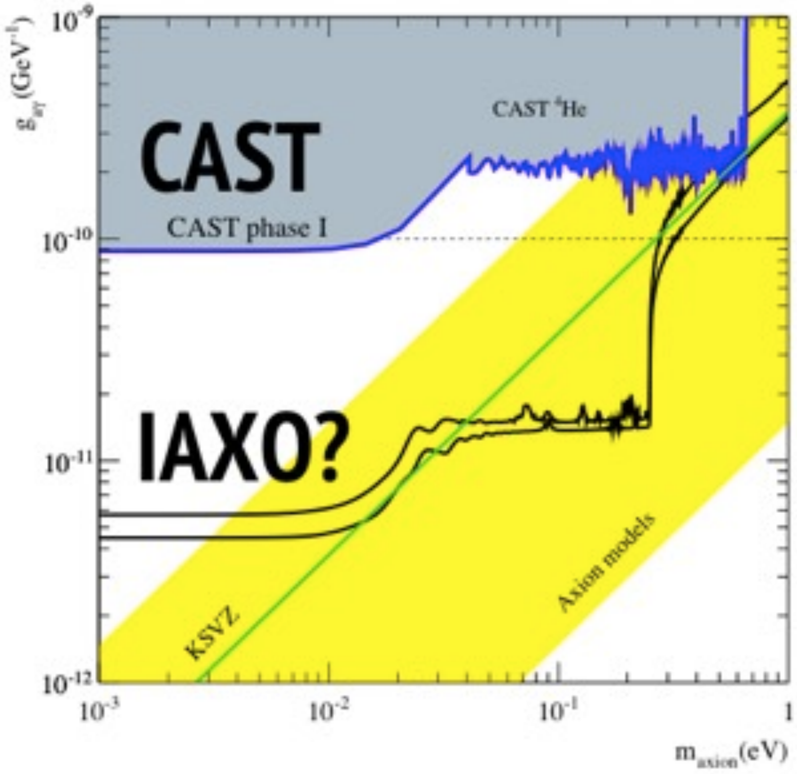


Laboratory searches : Axions

Solar Axions

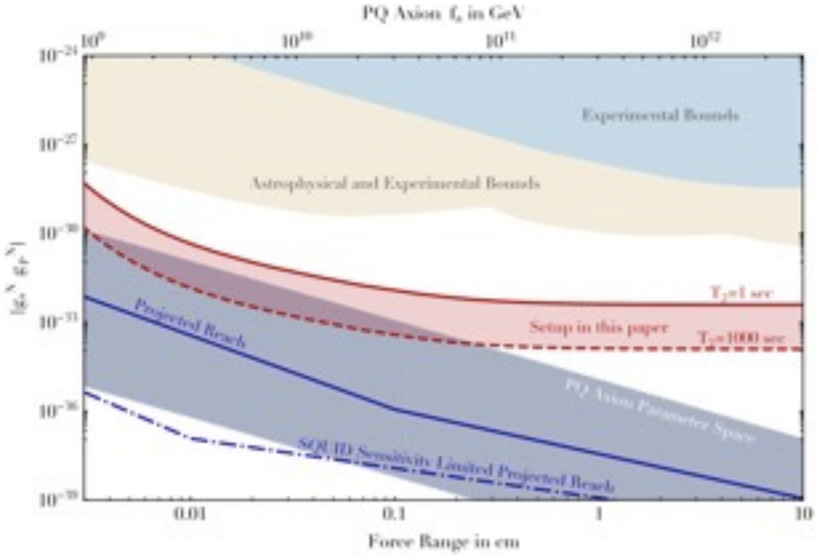


IAXO CDR 2014

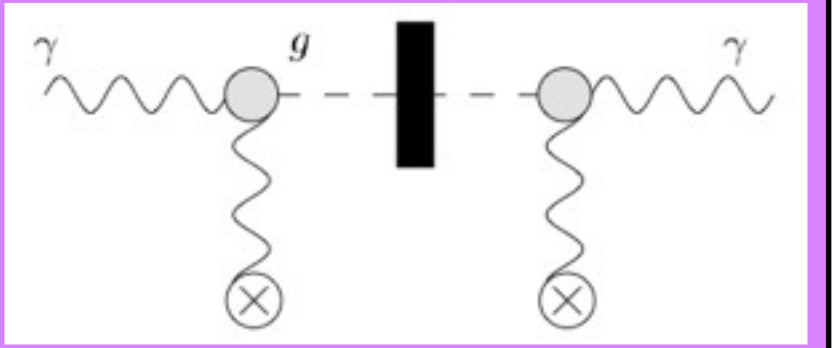


5th forces

Arvanitaki Geraci PRL 2014



Photon regeneration



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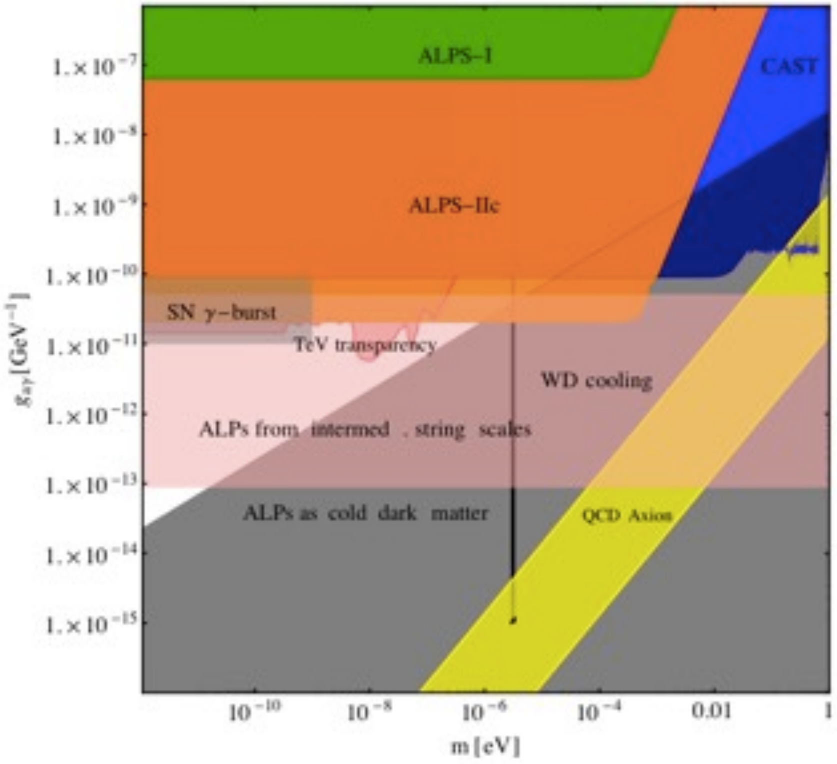
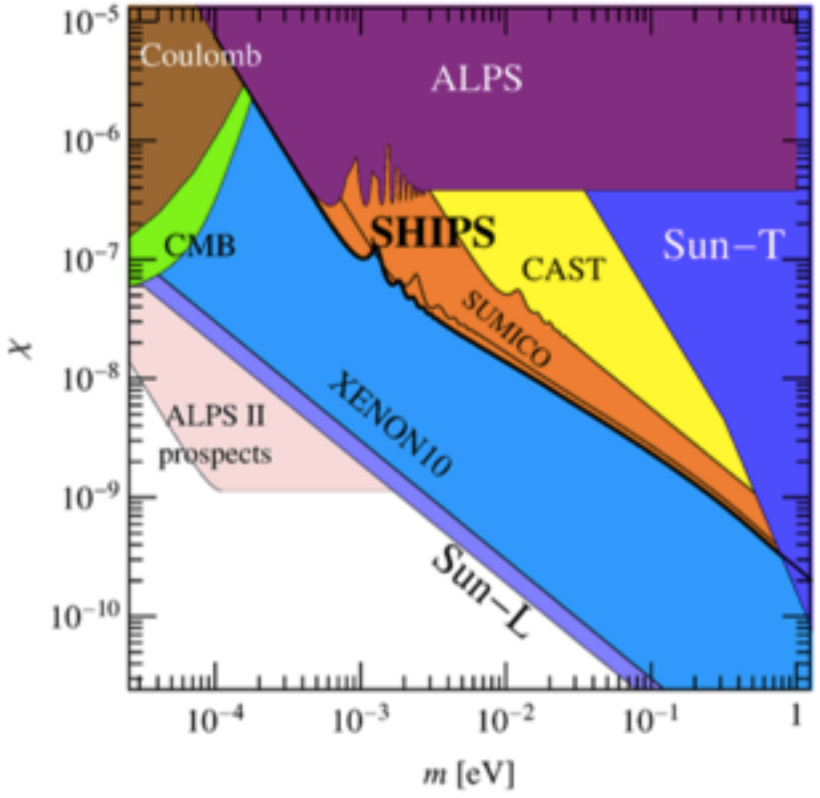


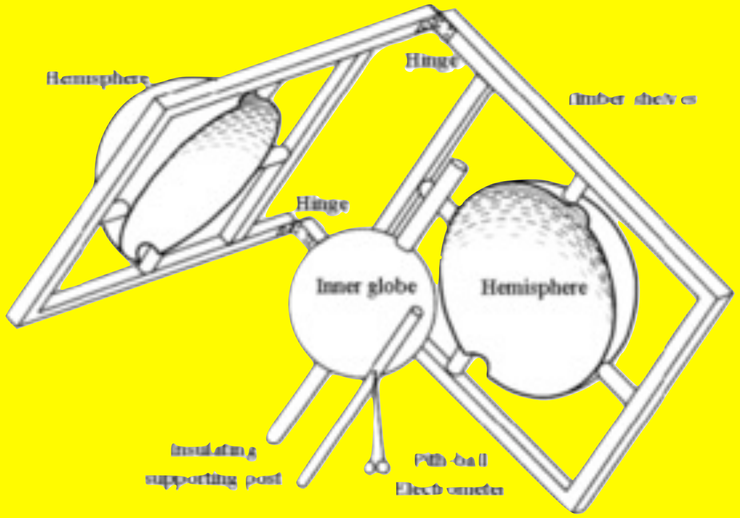
Laboratory searches : HPs

Solar HPs

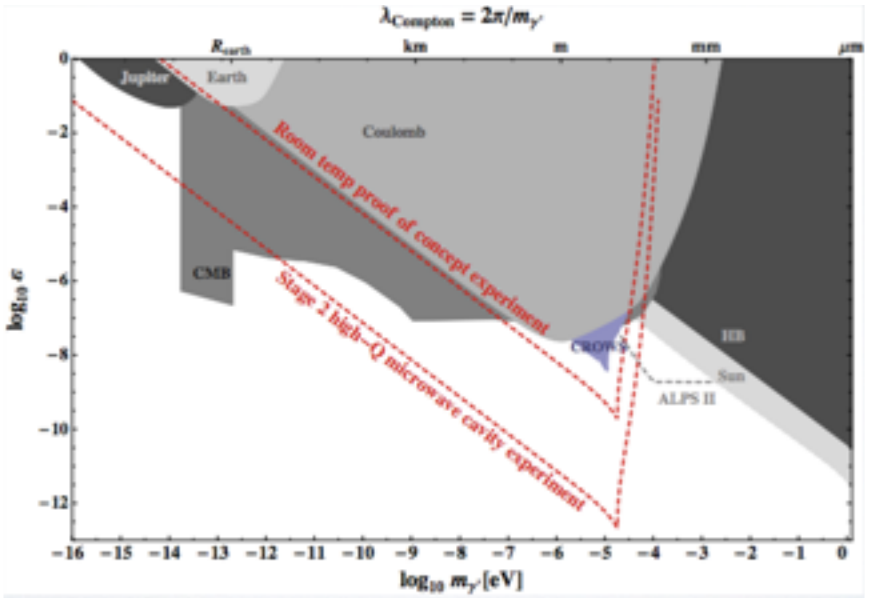
SHIPS, DM detectors XENON10



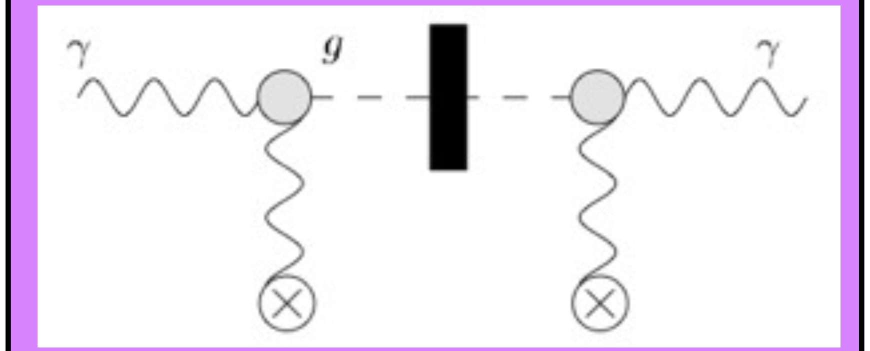
Coulomb's law



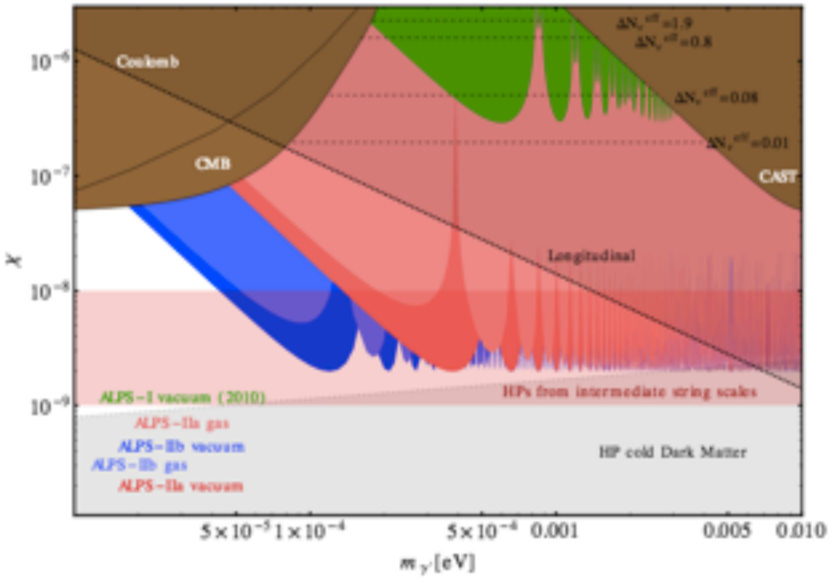
Williams ... 1971



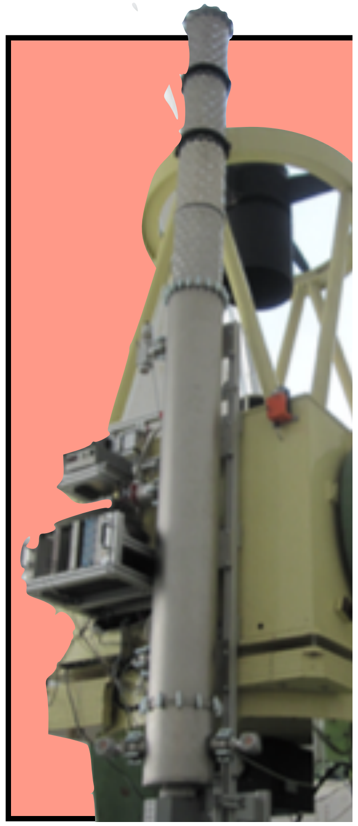
Photon regeneration



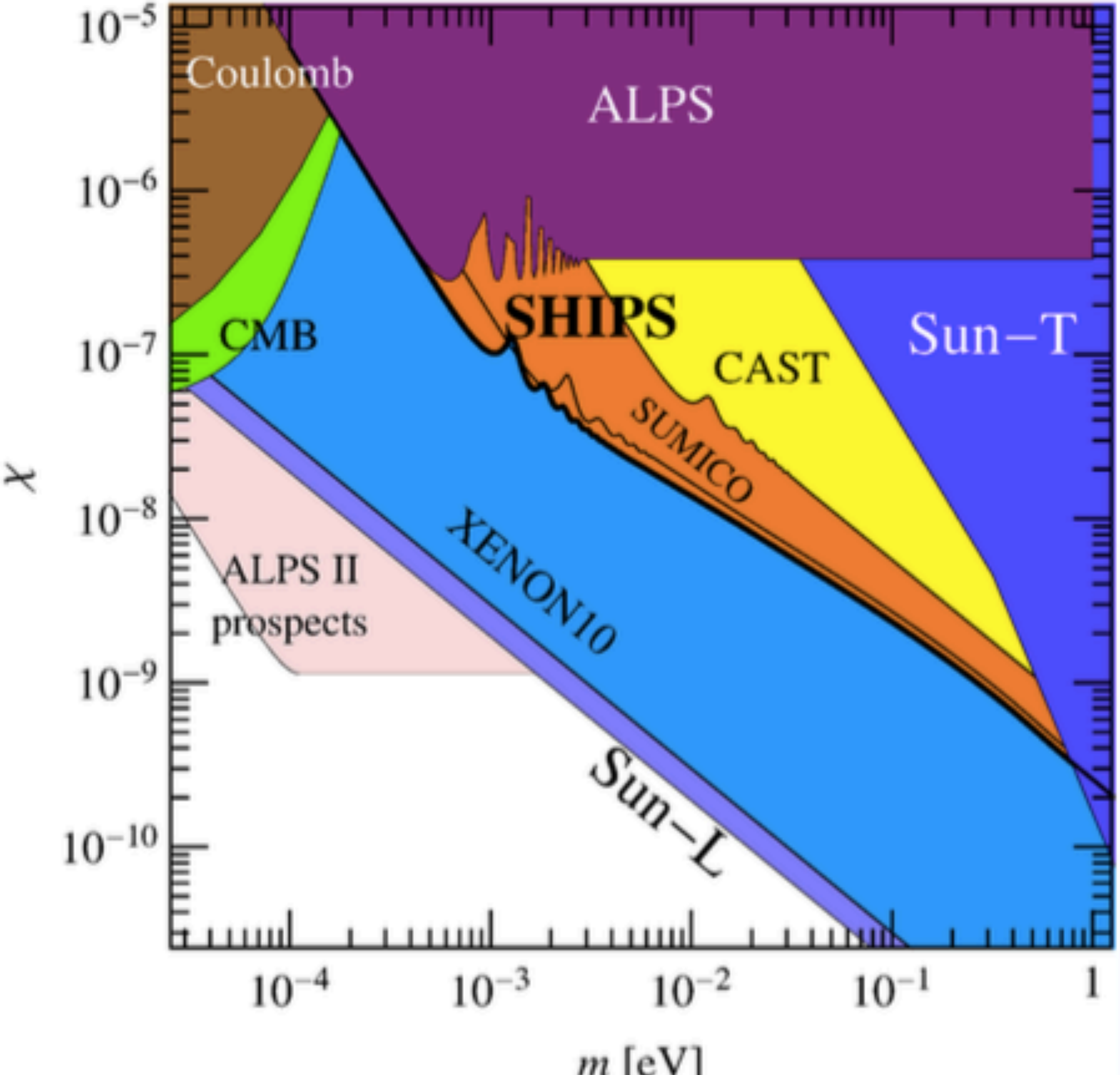
ALPS-II, MW cavities

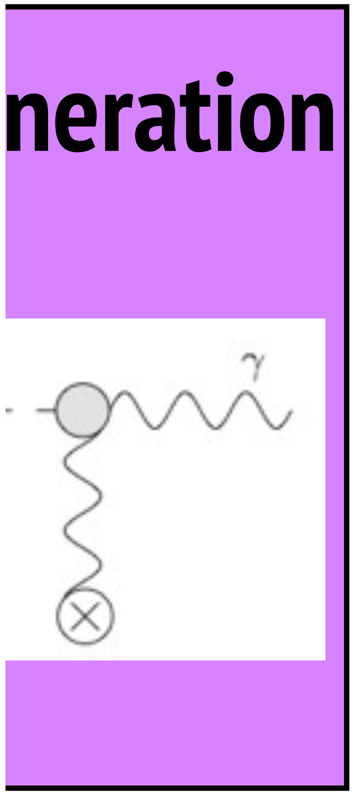


Laboratory searches : HPs



SHIPS, DN





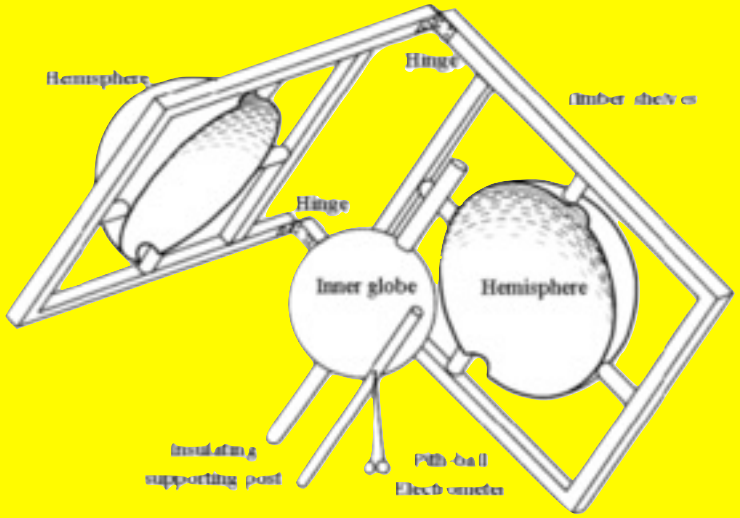
II, MW cavities

Laboratory searches : HPs

Solar HPs

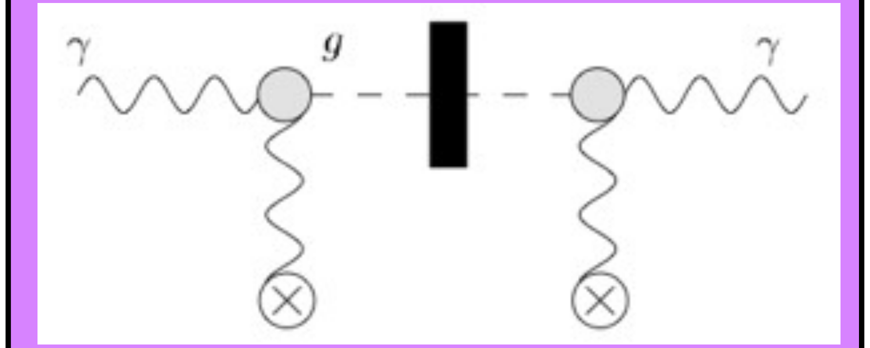
SHIPS, DM detectors XENON10

Coulomb's law

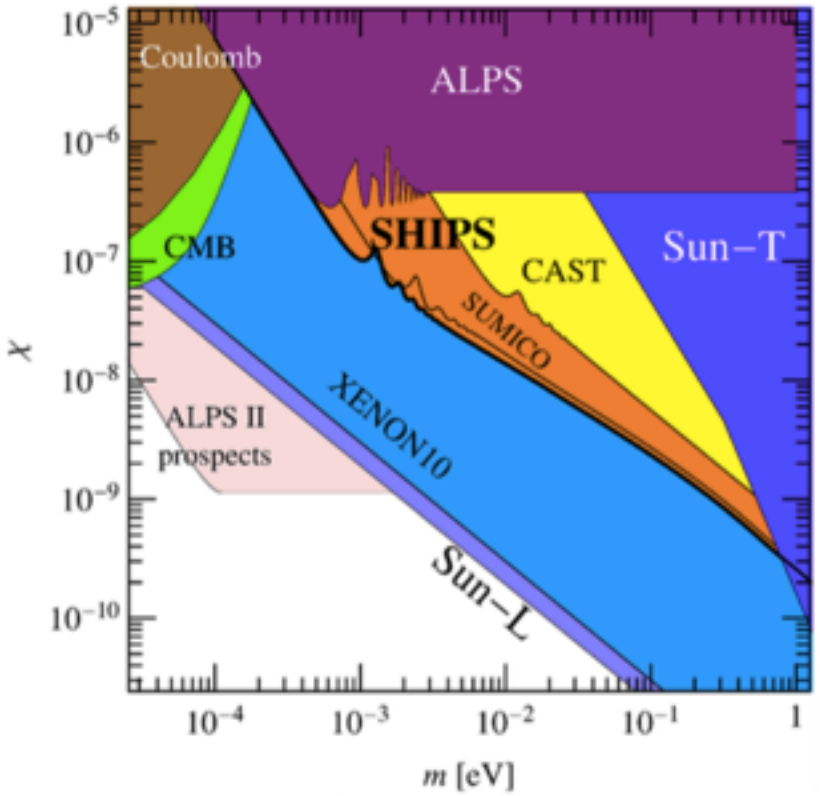


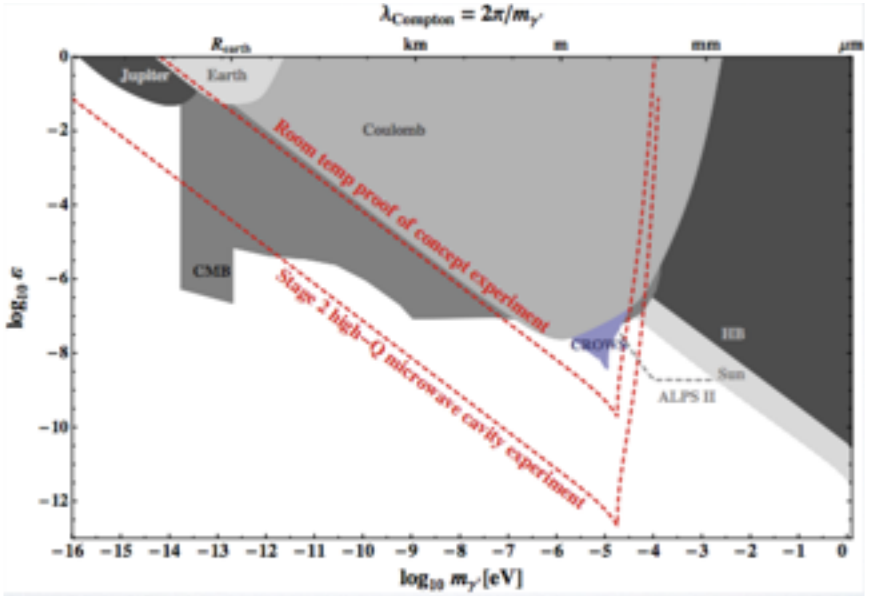
Williams ... 1971

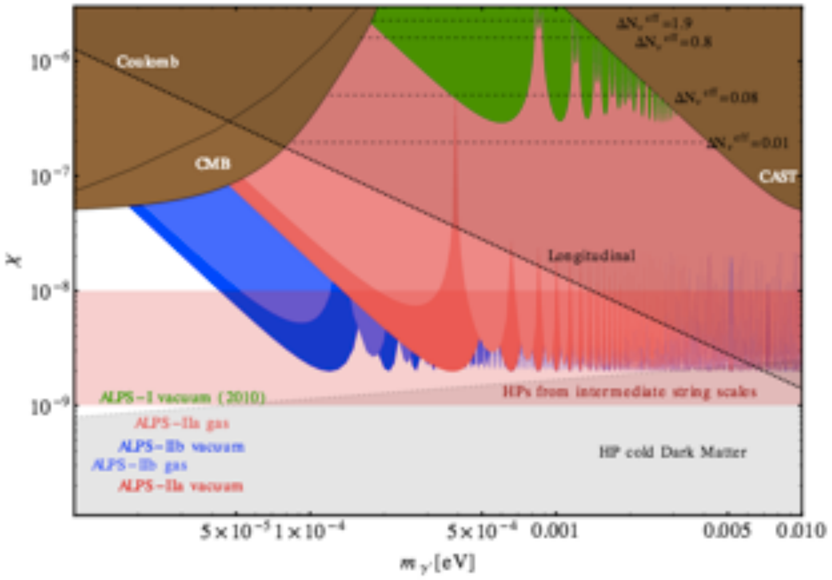
Photon regeneration



ALPS-II, MW cavities





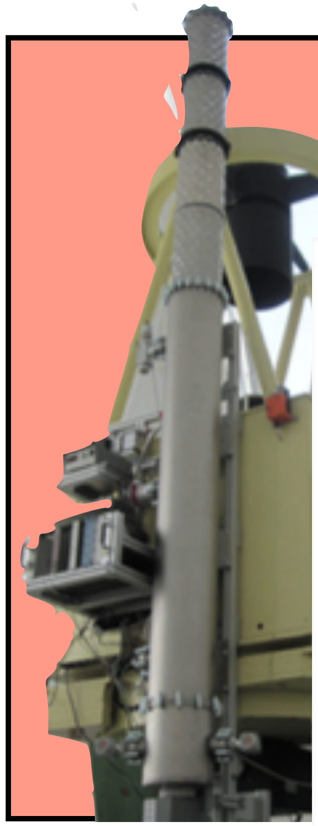


Laboratory searches : HPs

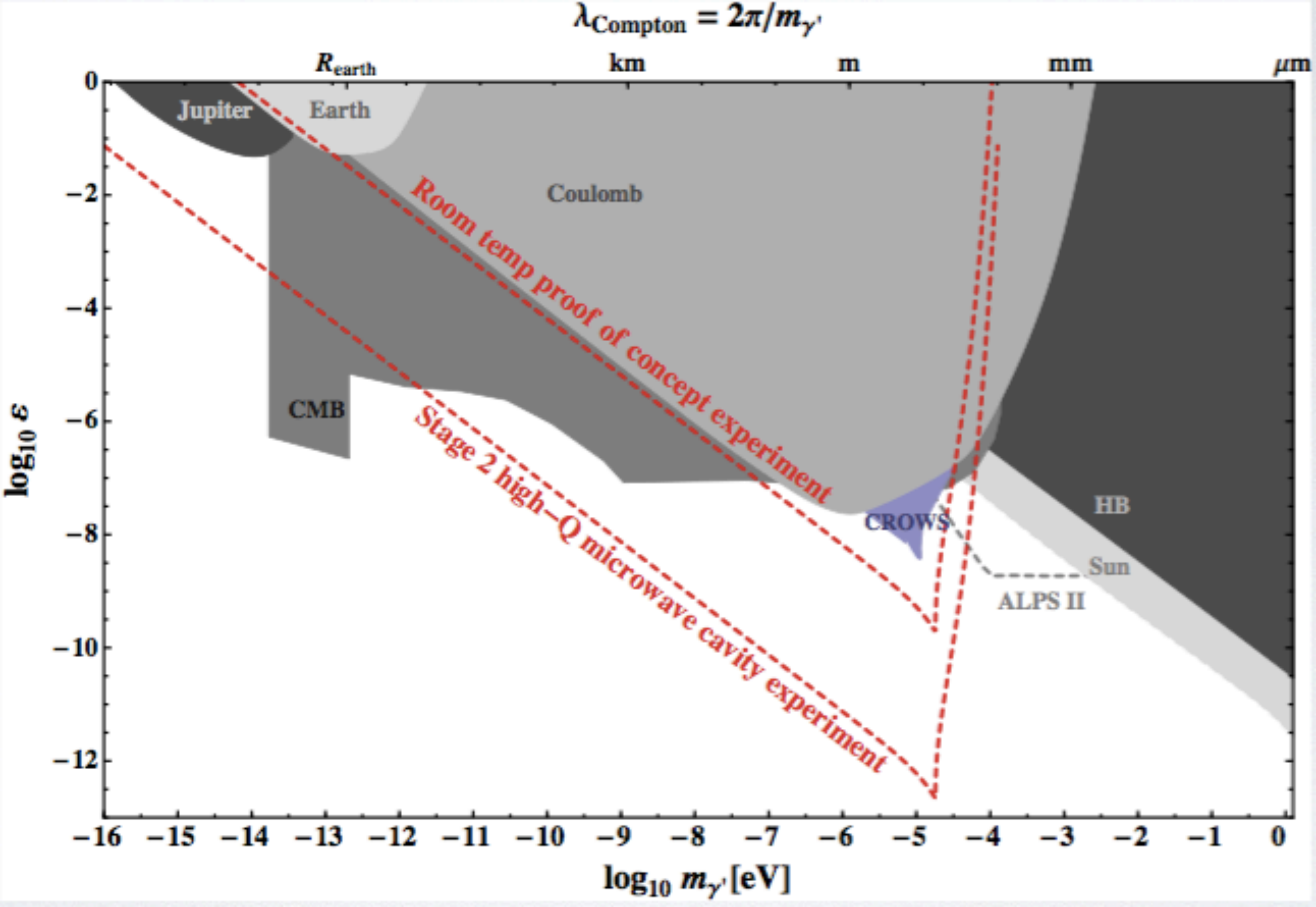
Solar HPs

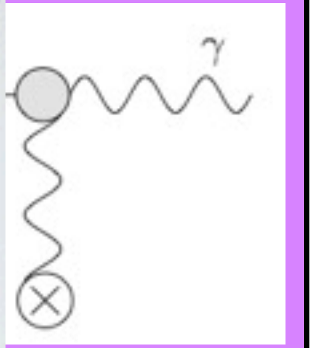
Coulomb's law

Photon regeneration



SHIPS,



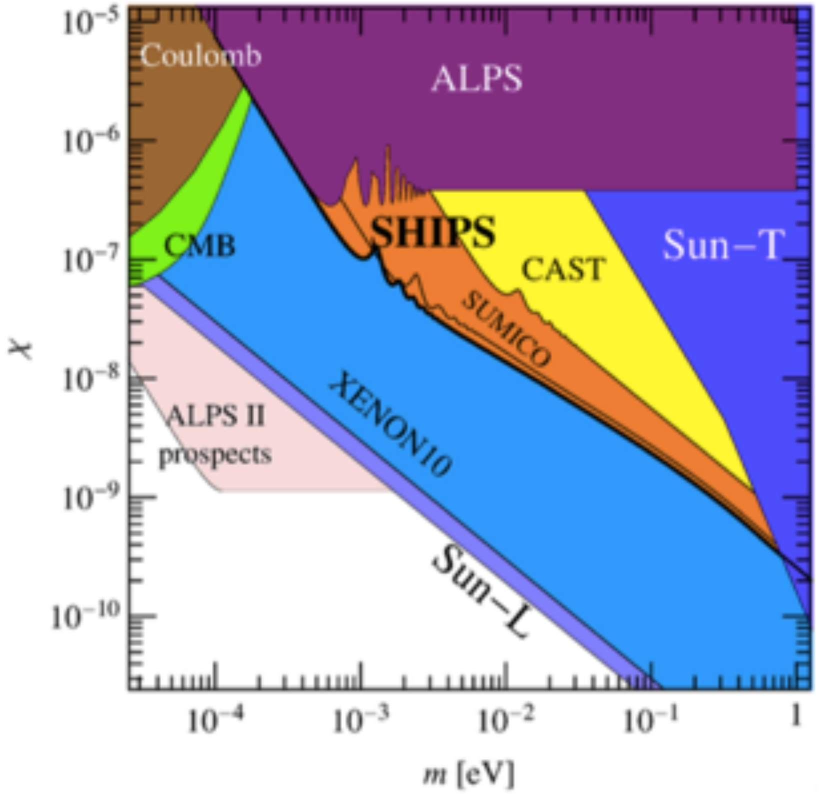


MW cavities

Laboratory searches : HPs

Solar HPs

SHIPS, DM detectors XENON10



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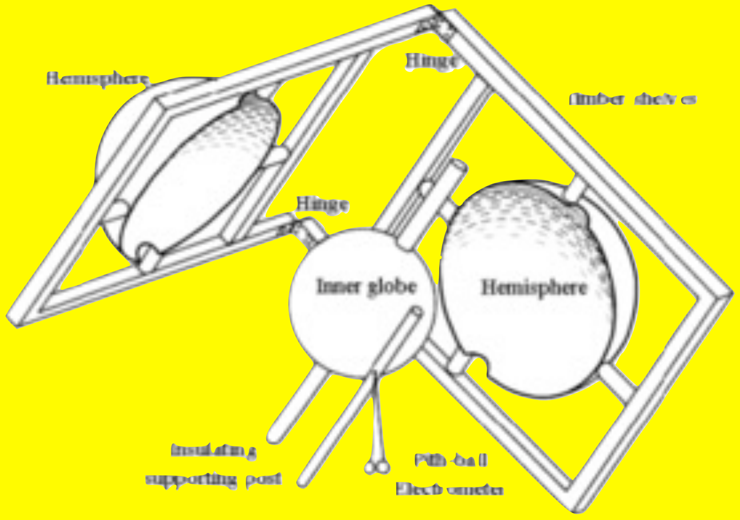
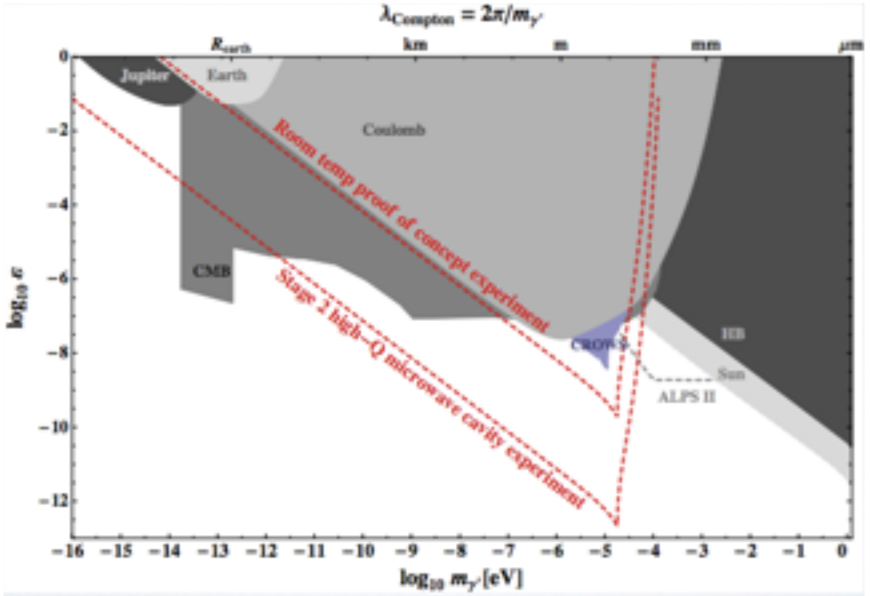
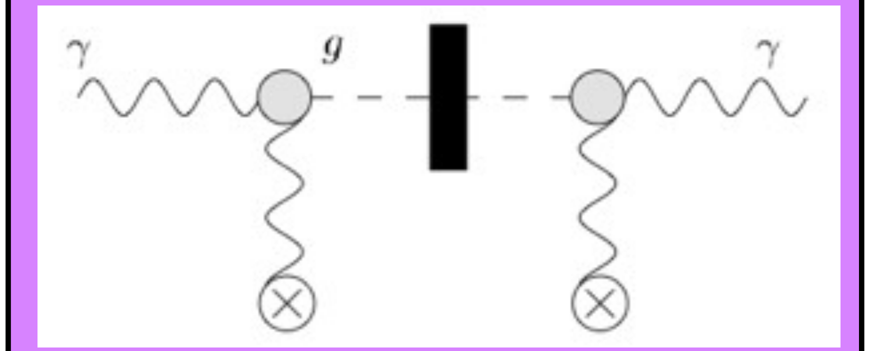


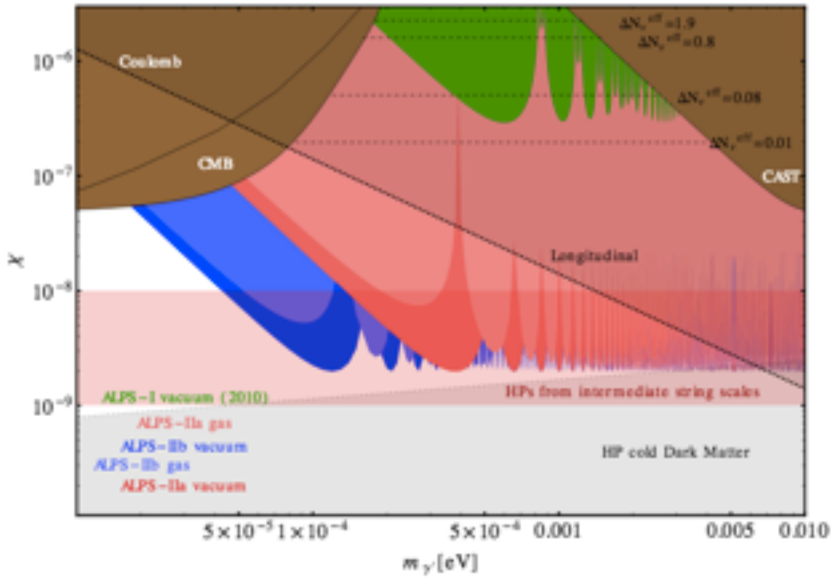
Williams ... 1971



Photon regeneration



ALPS-II, MW cavities



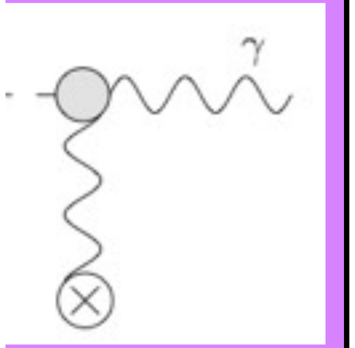
Laboratory searches : HPs

Solar HPs

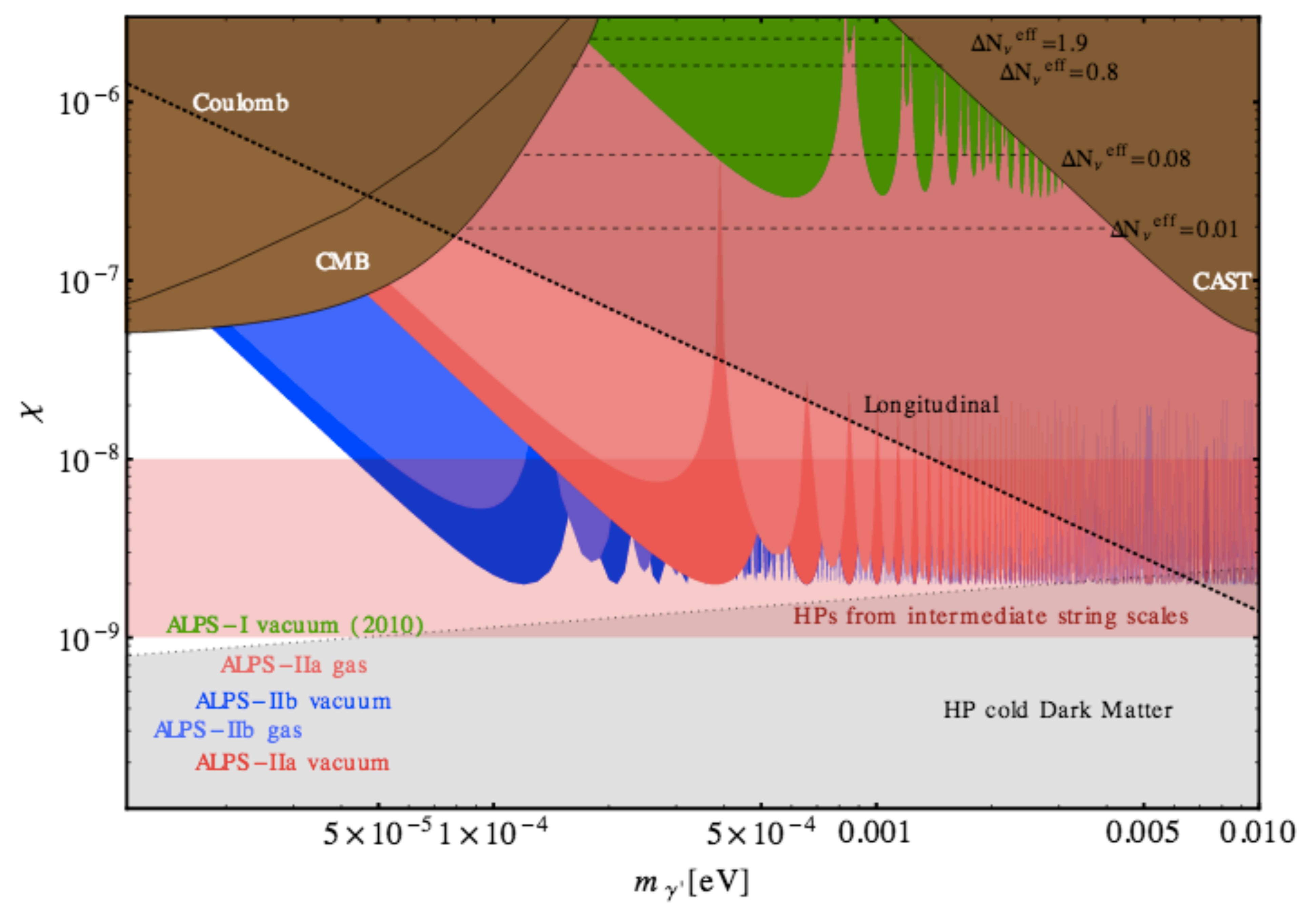
SHIPS, DN

Coulomb's law

Photon regeneration



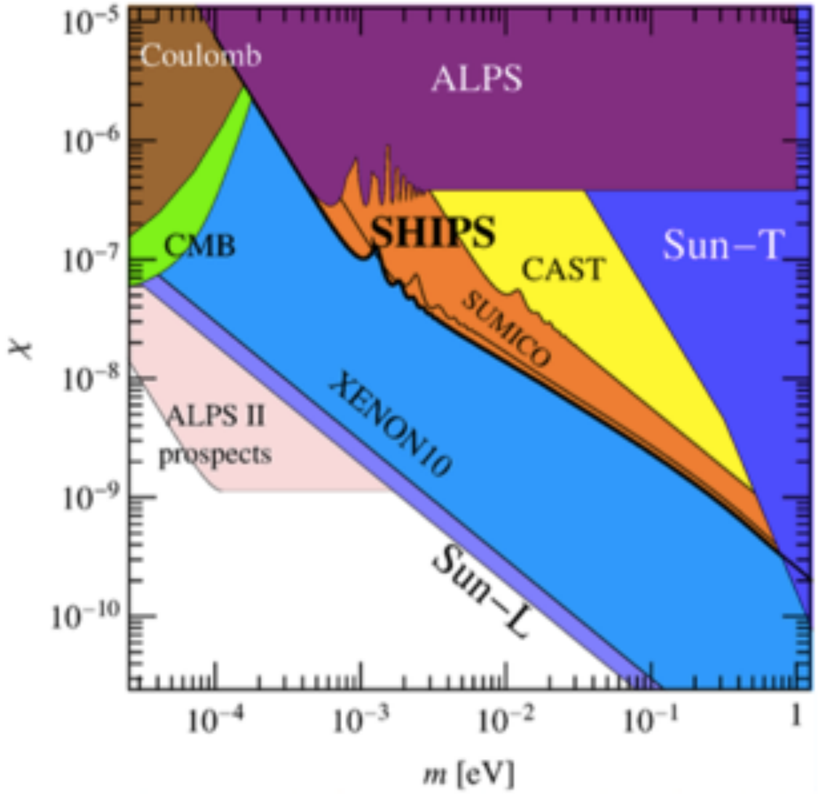
II, MW cavities



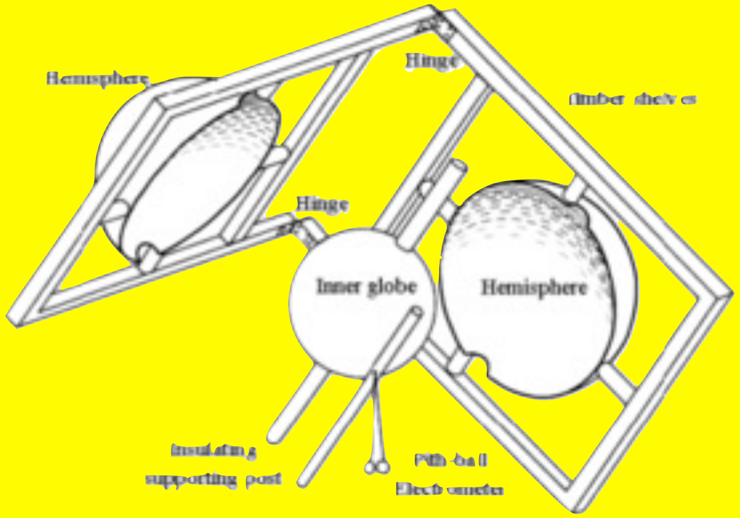
Laboratory searches : HPs

Solar HPs

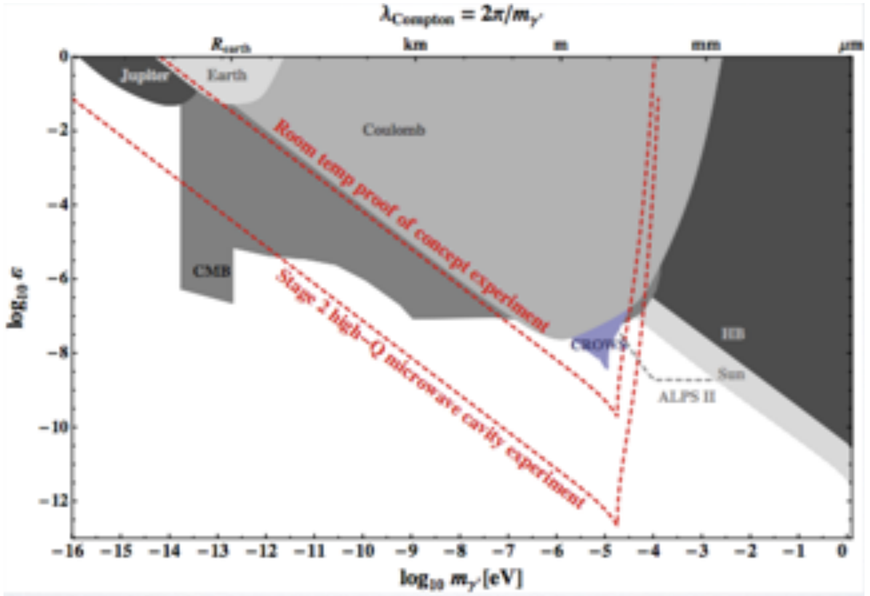
SHIPS, DM detectors XENON10



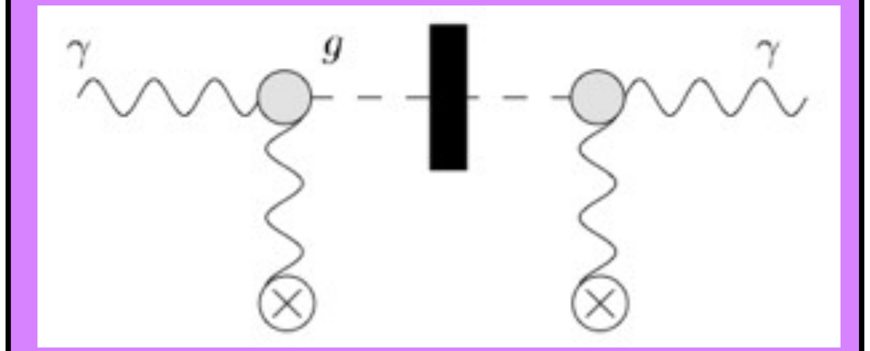
Coulomb's law



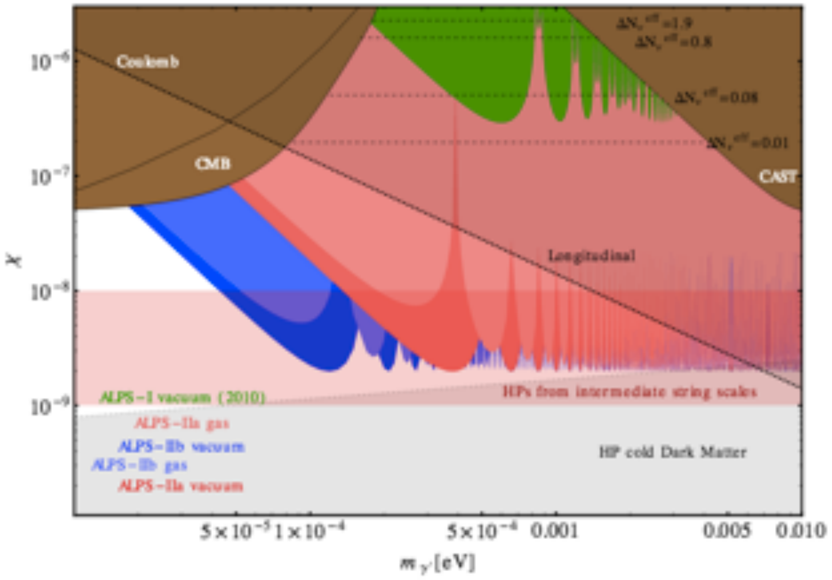
Williams ... 1971



Photon regeneration



ALPS-II, MW cavities



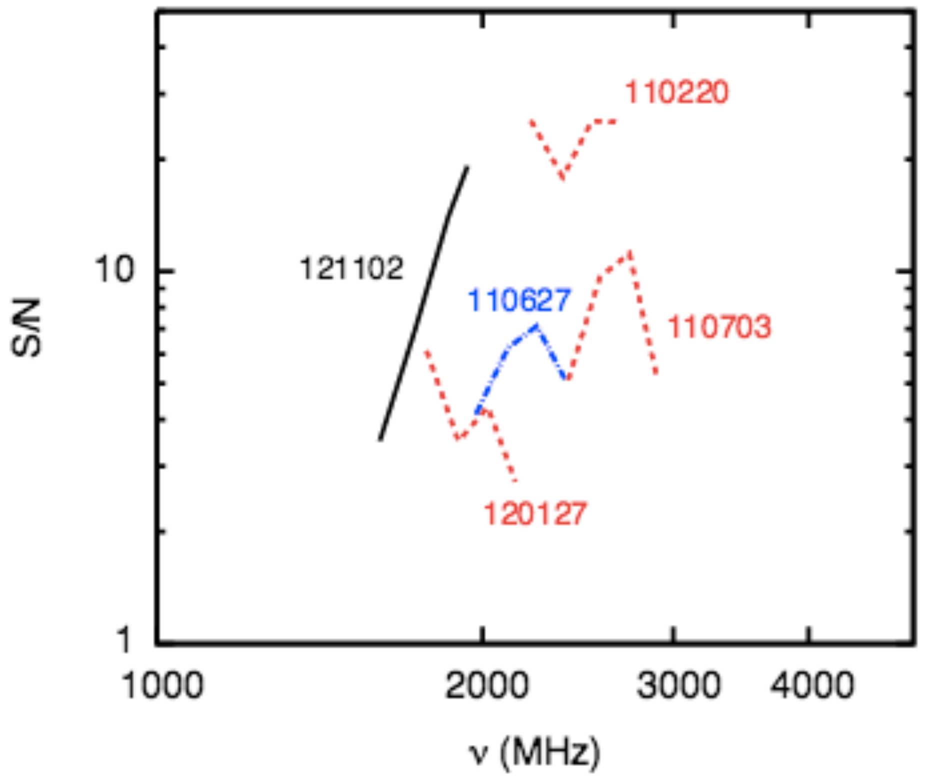
Indirect detection

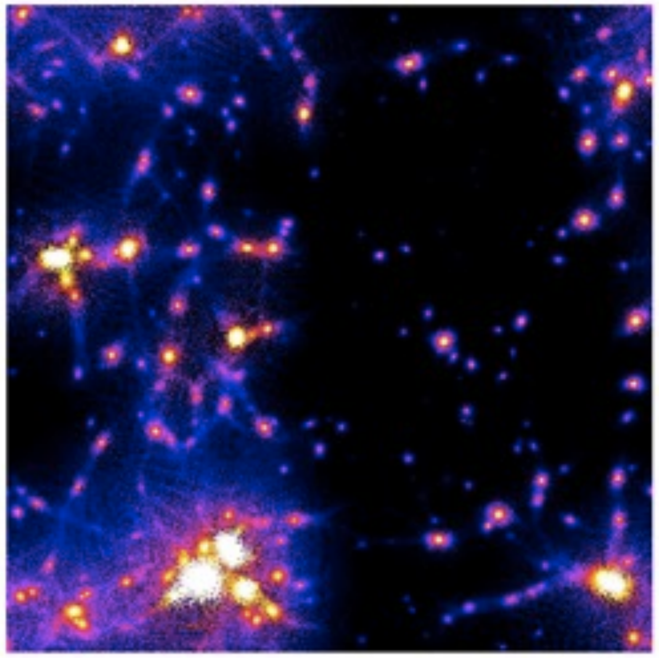
- Axions, ALPs, HPs are not stable $a \to \gamma\gamma \quad , \quad \gamma' \to \gamma\gamma\gamma$

- Decay lifetime very long (sub-eV)
- Annihilation negligible

- But inhomogeneous DM, axion miniclusters, HP clumps
- Annihilation in a neutron star ... Fast Radio Bursts?

Iwazaki; Tkachev , 2014





Zurek et al 07, See also Kolb & Tkachev 94

Conclusions

- Axions, Axion-likes, Hidden Photons make good dark matter

- Bottom-up and Top-bottom motivation

- Relic abundance : realignment and topological defects

- Ultralight is different : hyperlow mass effects in structure formation

- Direct Detection: key target areas not completely covered

- Laboratory searches,

- Indirect Detection ... not much

Axion DM : A developing picture