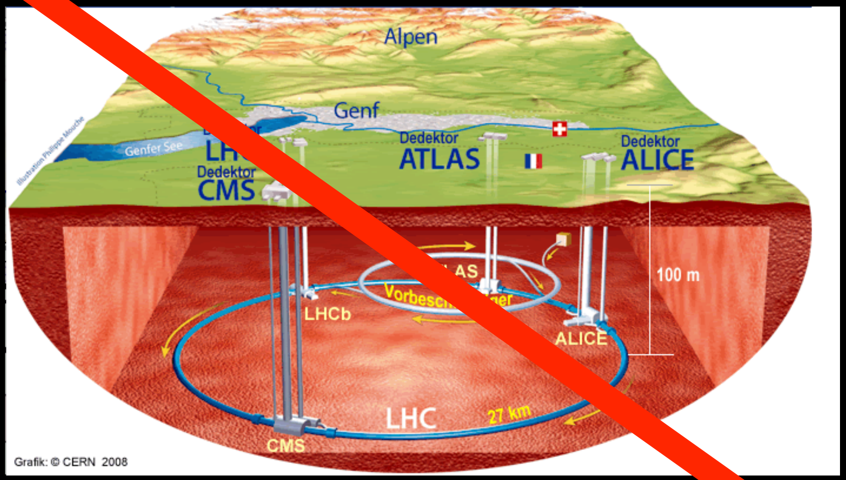
Light Particles Not @ the LHC

Heavy particle



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Where we want to go…

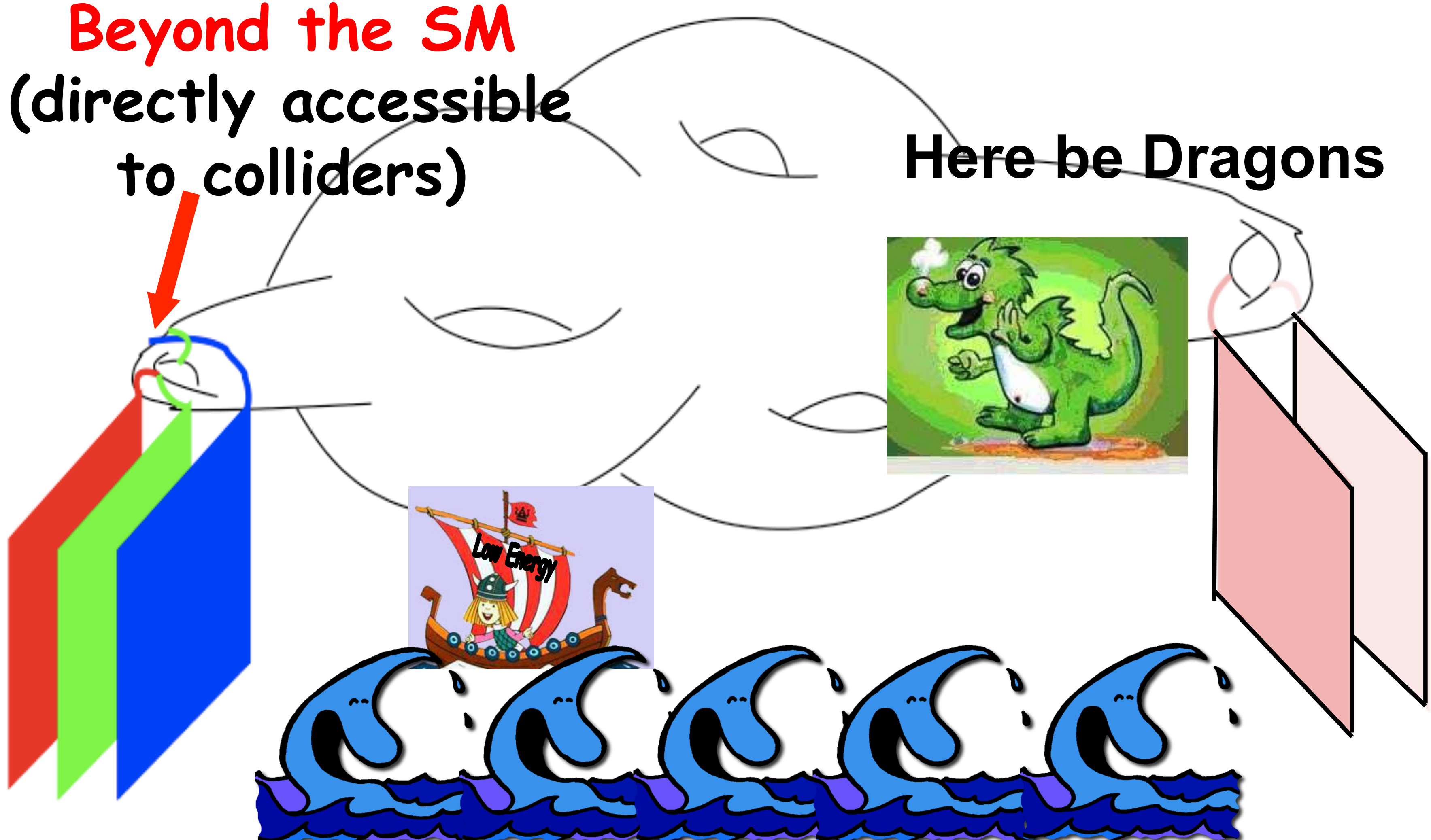
The Standard Model

+

Beyond the SM

(directly accessible to colliders)

The Hidden Sector



We need...

Physics beyond the Standard Model

Hints for new Physics

Uglyness of old models

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- The Standard Model has many free parameters: O(30)

- Naturalness problems. Finetuning.
  Examples:
  Higgs mass, θ-angle (strong CP-problem)

A dirty little secret...

$$S = \int d^4x \Big[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$+ \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \Big]$$

- The θ-term is CP violating!
- Connected to strong interactions!

➡ **Measure electric dipole moment of the neutron!**

Neutron electric dipole moment

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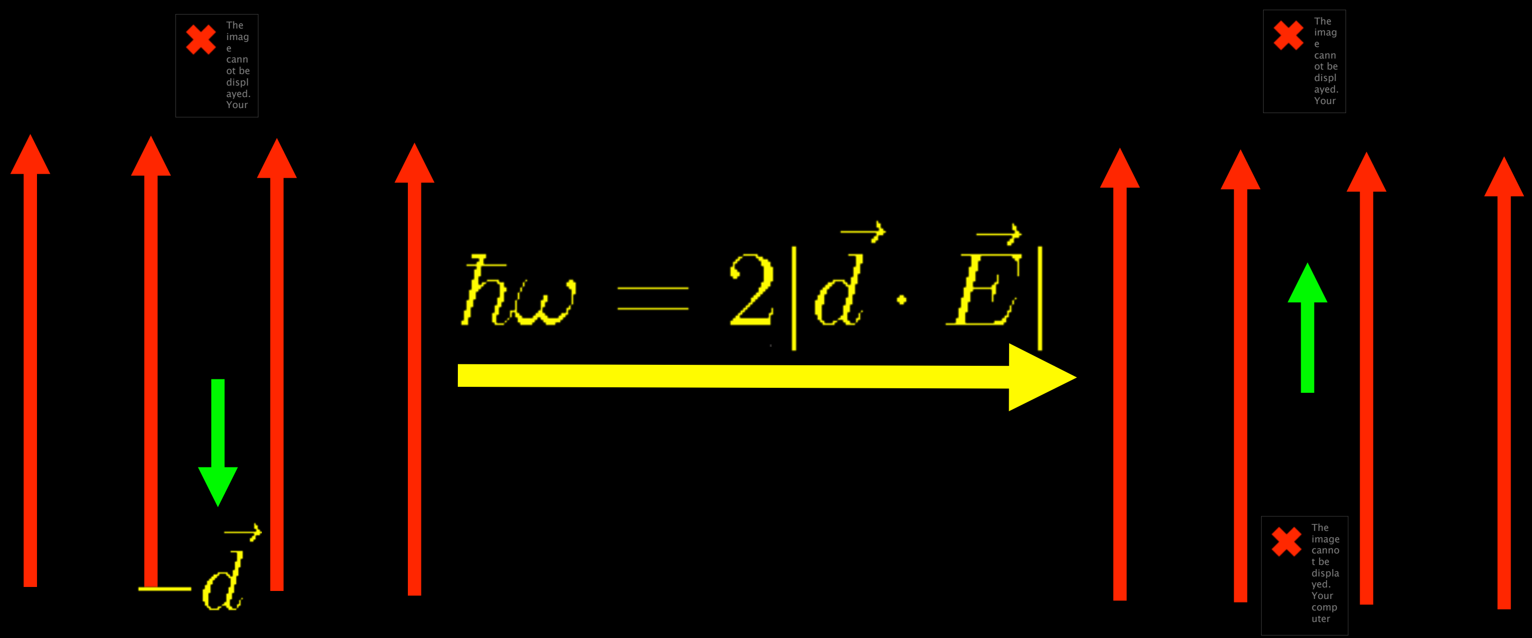
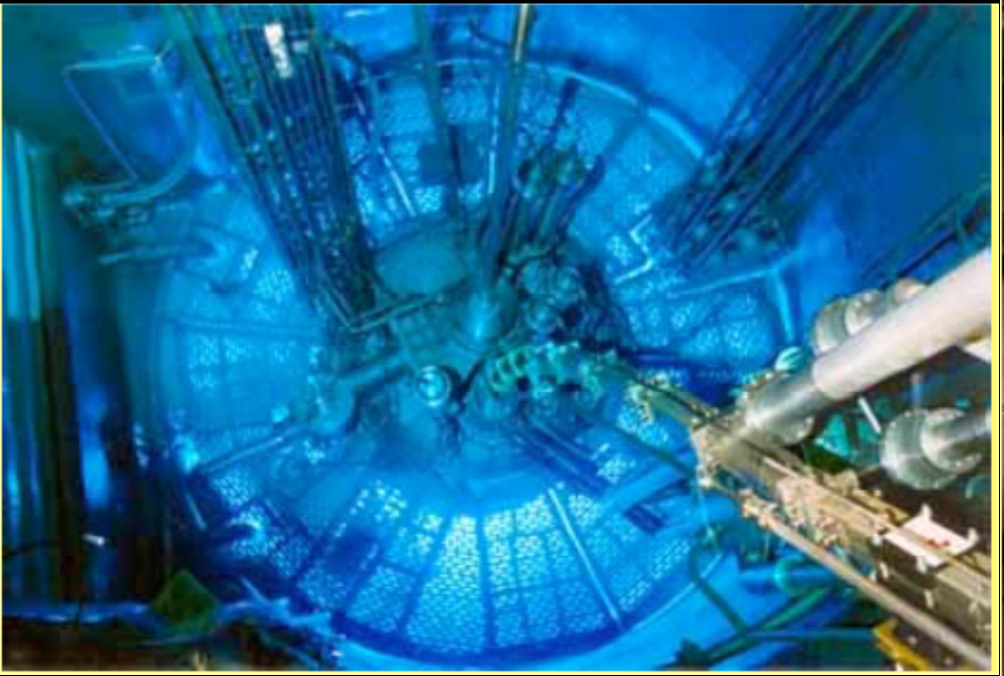
- θ would cause neutron EDM ⟶ Experiment

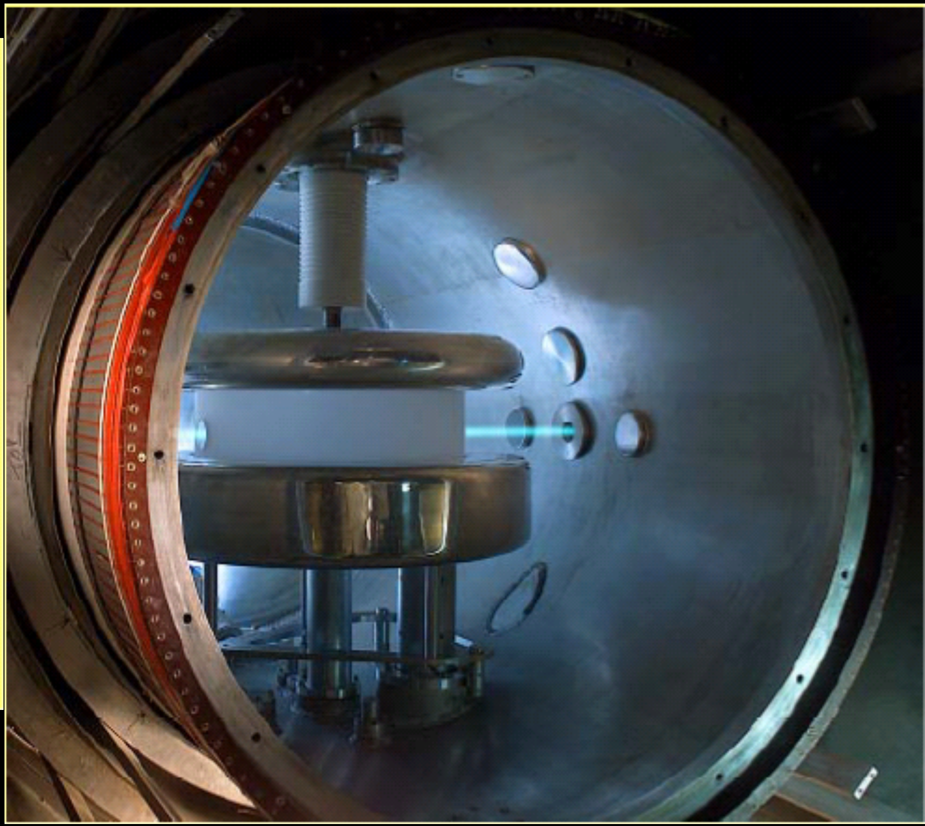


$$\hbar\omega = 2|\vec{d}\cdot\vec{E}|$$

⟶ Measure transition frequency.

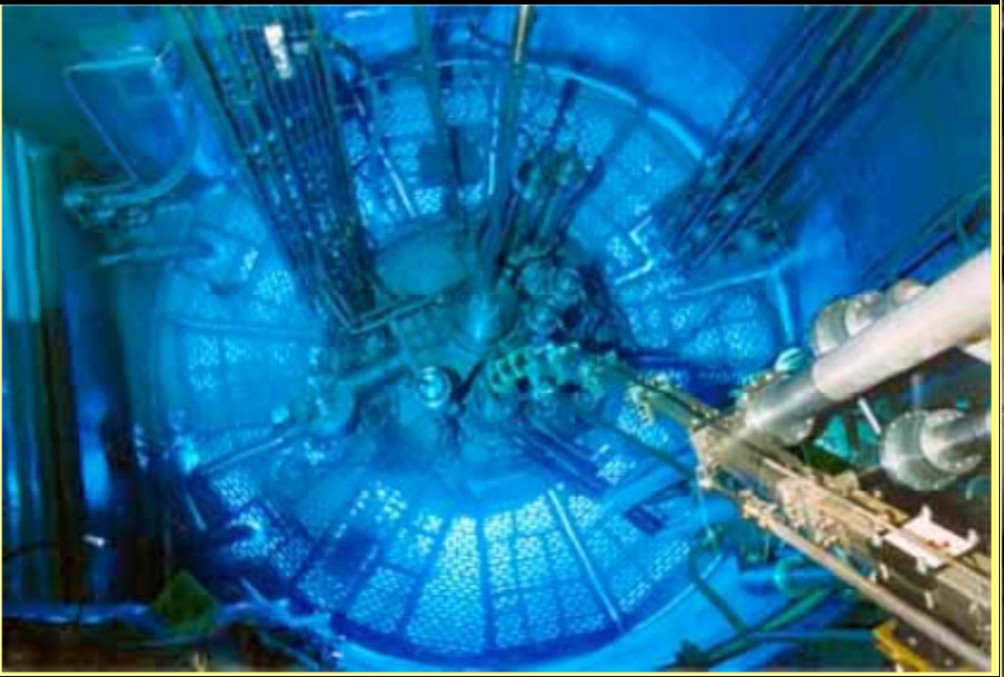
No neutron electric dipole moment...

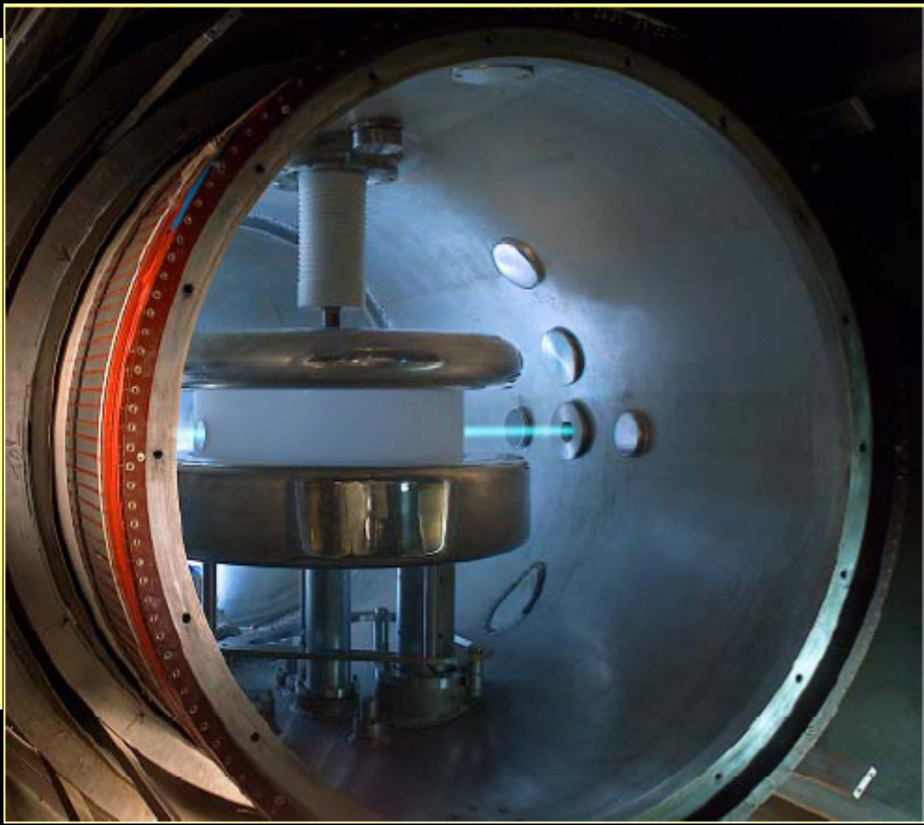




$$|\vec{d}| < 3\,10^{-26} e\,cm$$
$$= 3\,10^{-13} e\,fm$$

No neutron electric dipole moment...





$$|\vec{d}| < 3\,10^{-26} e\, cm$$

$$= 3\,10^{-13} e\, fm \lll \frac{\theta}{16\pi^2}\, e\, fm$$

Very unnatural!

Uglyness of old models

- The Standard Model has many free parameters: O(30)

- Naturalness problems. Finetuning.
  Examples:
  Higgs mass, θ-angle (strong CP-problem)

- Gravity separate, i.e. not unified.

- (Probably) Breaks down at a finite energy scale
  Landau poles etc.

Unexplained Stuff

- Dark Matter (25%)
  (astrophysical + cosmological observations)
- Dark Energy (70%)
  (astrophysical + cosmological observations)
- Mass Hierarchies
  (colliders, neutrino exp, etc)
- Small parameters (θ-angle, again)
  (neutron electric dipole measurements)

BSM physics @ Work

- $(g-2)_\mu$ deviations from SM prediction
- DAMA anomaly
- CoGeNT etc.
- PAMELA+Fermi observation
- WMAP observes extra “neutrinos”
- Proton radius in muonic hydrogen

Hints for new Physics

Model Building

Bottom-up (pheno) ⟷ **Top-down (theory)**

Fix problem
`here and now'

Go back to drawing board
`Start from scratch'

As we have seen...

$$S = \int d^4x \Big[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$+ \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \Big]$$

No electric dipole moment of the neutron!

➡ $|\theta| < 3\, 10^{-10}$

➡ **Need an explanation!**

A Dynamical θ

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- Idea:
  - Make θ dynamical degree of freedom: a/f_a
  - Let a have no tree level potential
  - Let a have only derivative couplings
- Then:

$$\Rightarrow V[0] \leq V[a] \ \forall a$$

⇒ a will evolve to a=θ=0

⇒ CP is conserved

What is a?

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- Properties:
  - Let a be a dynamical degree of freedom.
  - Let a have no tree level potential
  - Let a have only derivative couplings
  - $a/f_a 2[0,2\pi]$ since $$\int d^4x \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{32\pi^2} = n \in \mathbb{Z}$$

→ a is Goldstone boson of a U(1) symmetry

→ Axion!

→ Peccei-Quinn Symmetry

The mass of the Axion

- $U(1)_{PQ}$ is not exact

⇒ Goldstone → Pseudogoldstone

- Dimensional considerations
  - SSB scale $\sim f_a$
  - Coupling to $G\tilde{G}$: $\sim \frac{a}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$
  - Scale of explicit breaking $\sim \frac{1}{f_a} m_\pi^2 f_\pi^2$

⇒ Goldstone **mass** $m_a^2 \sim \frac{m_\pi^2 f_\pi^2}{f_a^2}$

The strong CP problem: Axions

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- Introduce new Peccei-Quinn symmetry to solve naturalness problem

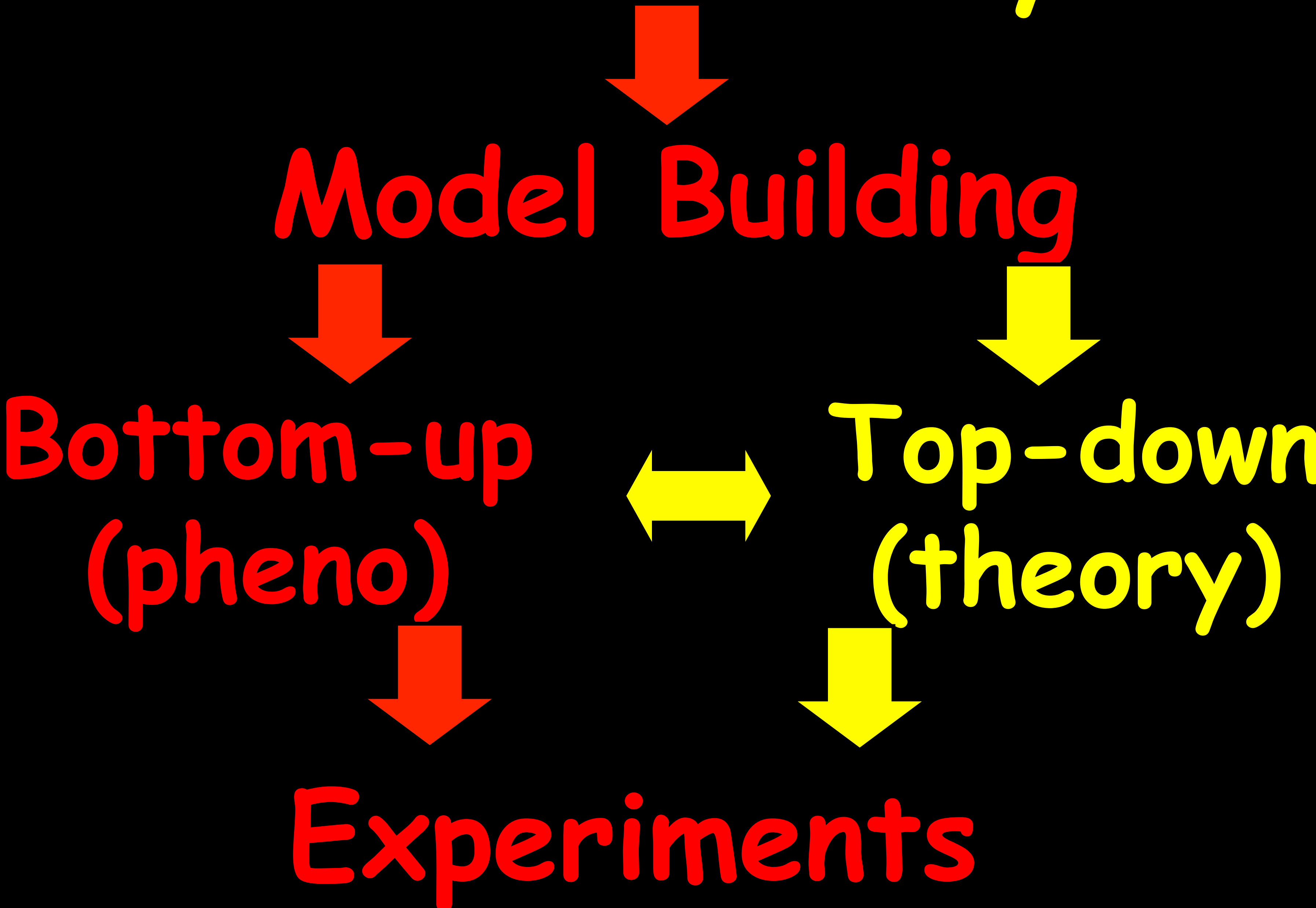
- Predict as a consequence a new particle: **The Axion**

  (it's a **W**eakly **I**nteracting **S**ub-eV **P**article)

Dark matter candidate

Good motivation for axion/WISP experiments

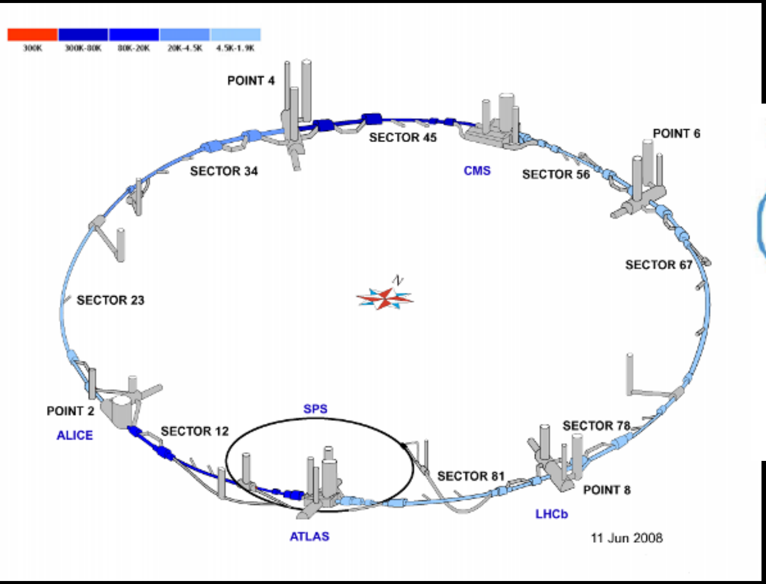
Hints for new Physics

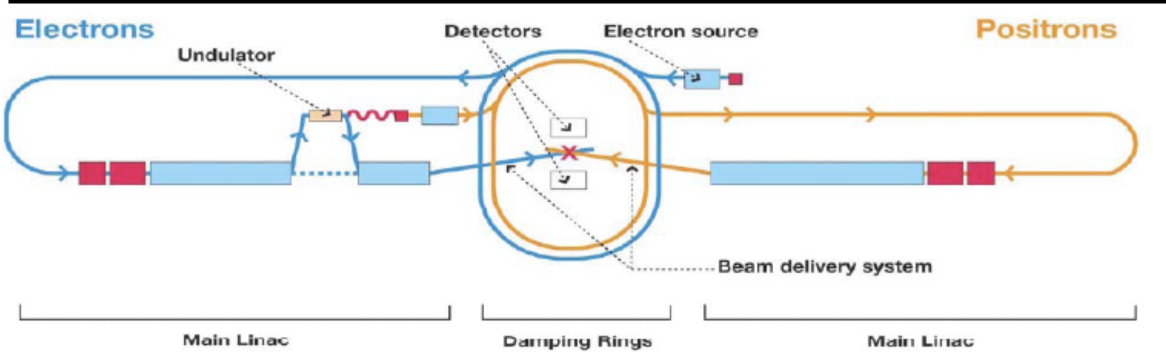


Exploring fundamental high energy physics…

- The direct approach: MORE POWER

LHC, Tevatron + ILC,CLIC





- Detects most things within energy range
- E.g. may find SUSY particles, WIMPs etc.

But…

- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV
- Man its DANGEROUS…

But…

- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV

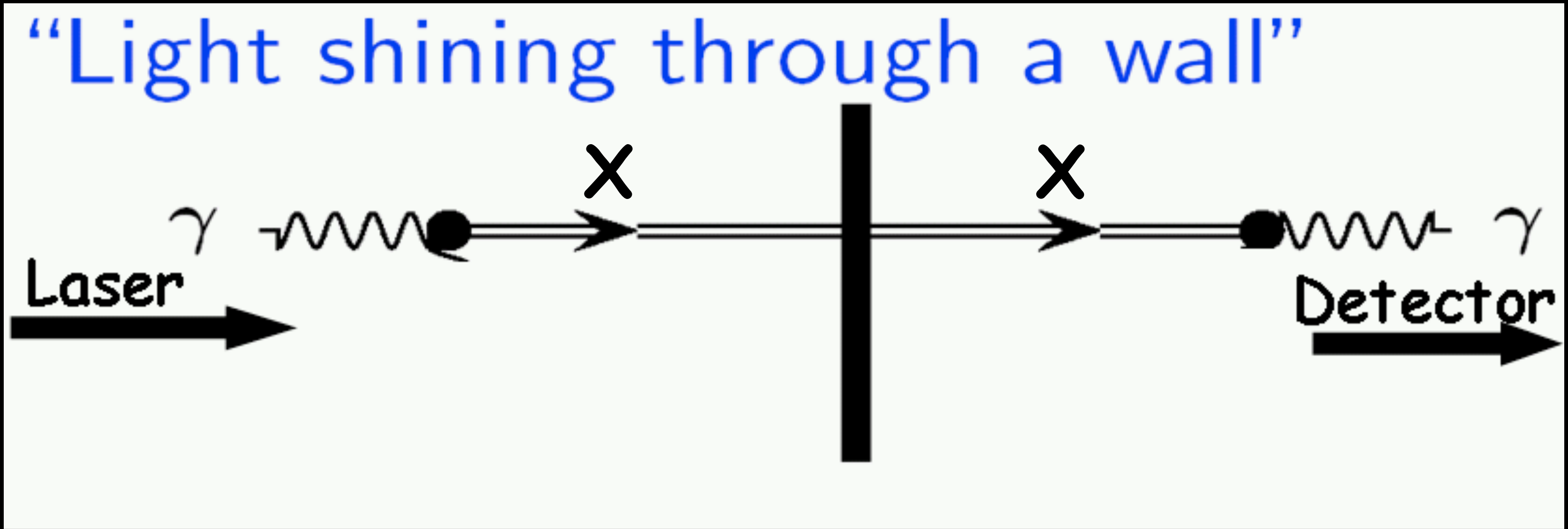
- Or much much more horrifying:

No signal above background!

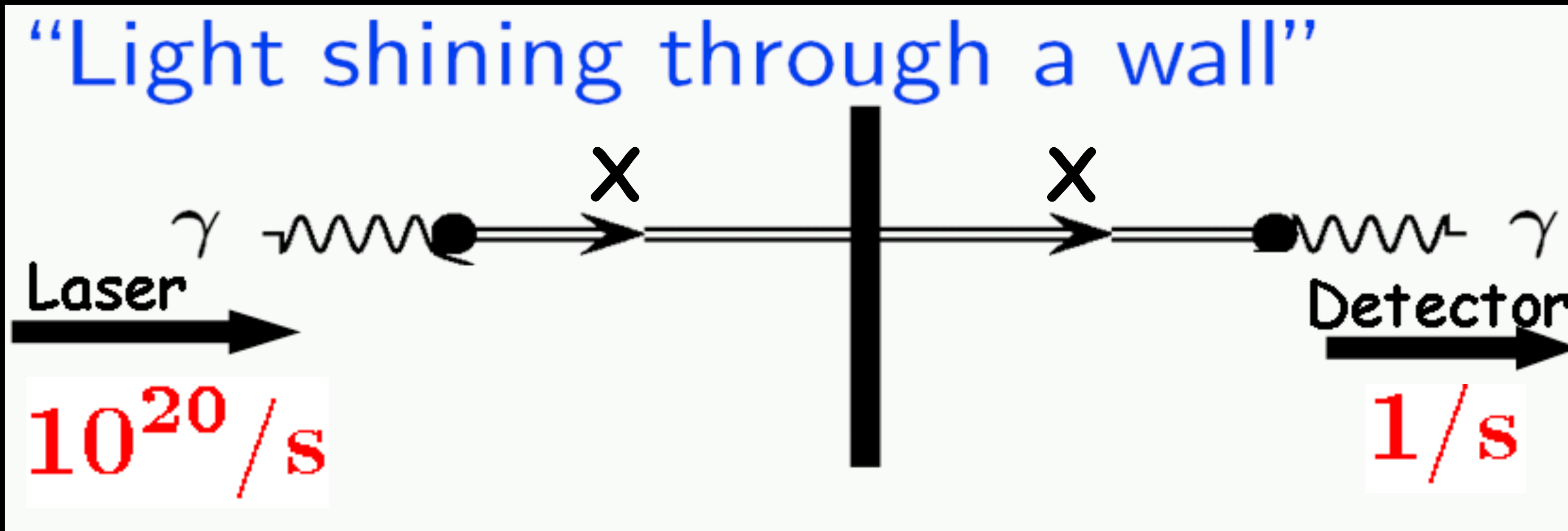
Recycling…

Complementary approaches

Light shining through walls



Light shining through walls

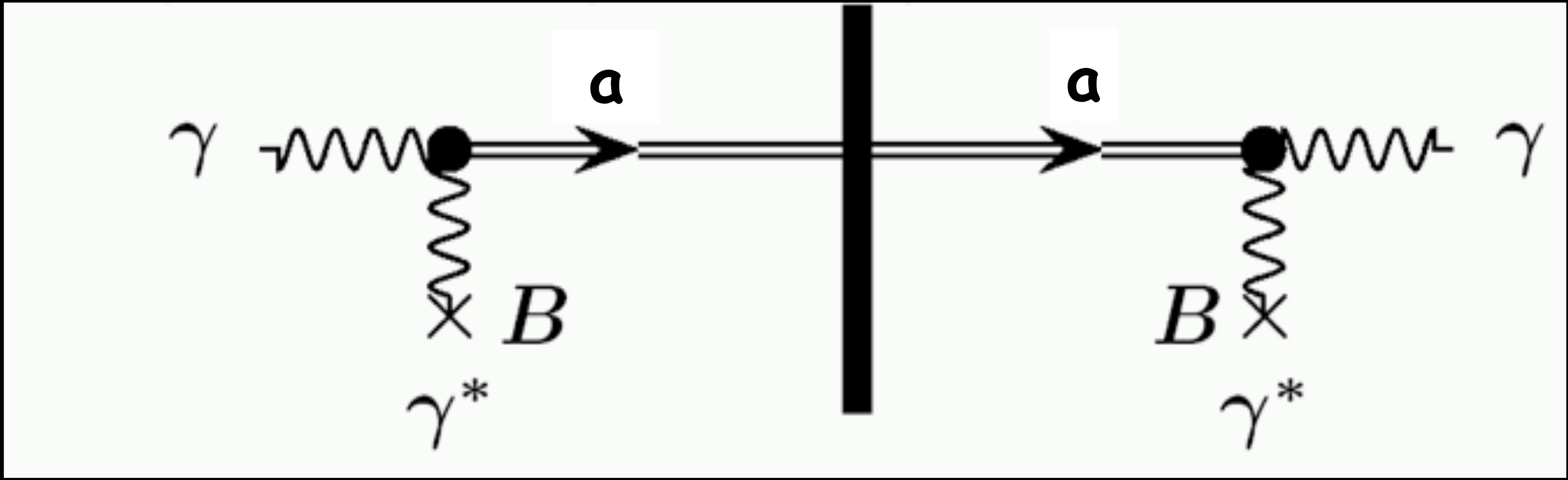


- **Test** $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

- It could be Axion(-like particle)s!
- Coupling to two photons: $\frac{1}{M} a\tilde{F}F \sim \frac{1}{M} a\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$



$$P_{\gamma\to a\to\gamma} \sim N_{\text{pass}} \left(\frac{BL}{M}\right)^4$$

Light Shining Through Walls

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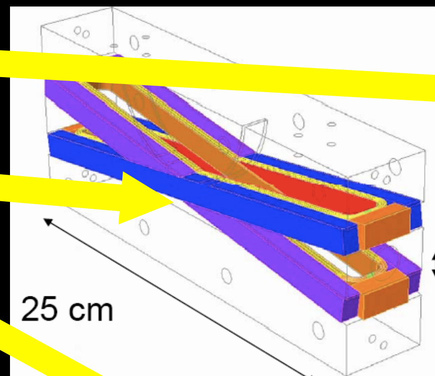
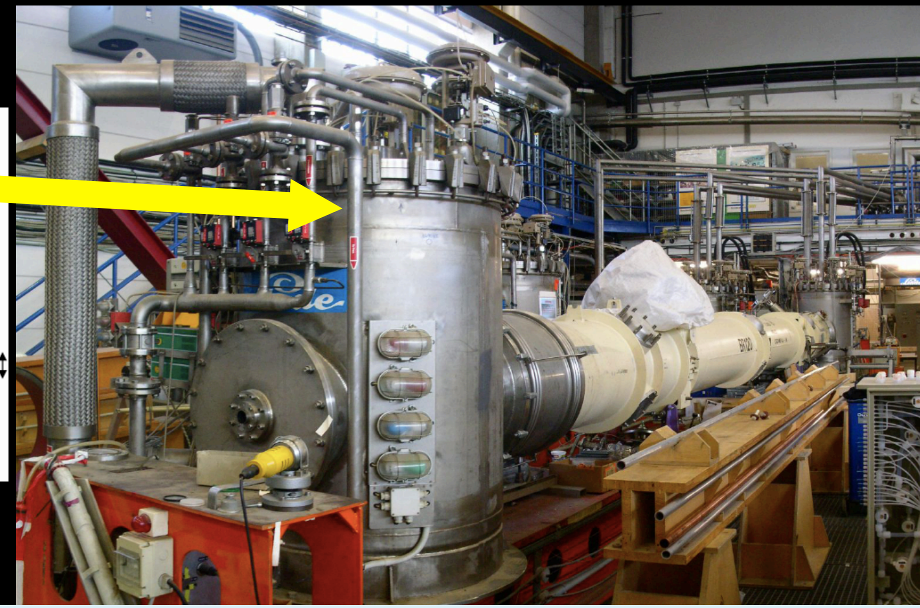
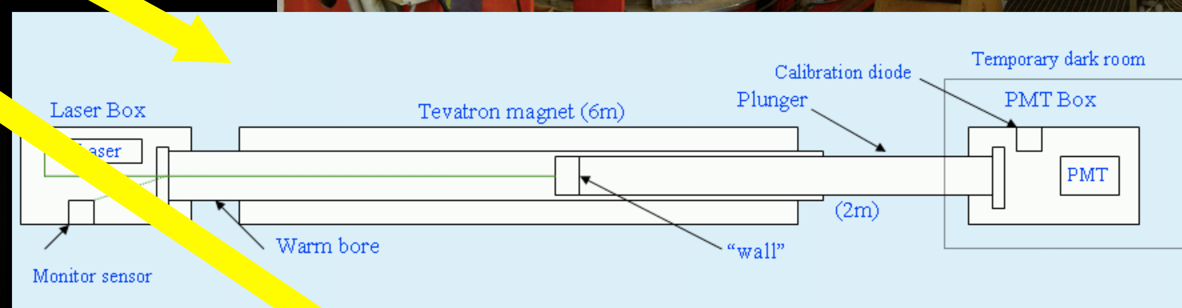
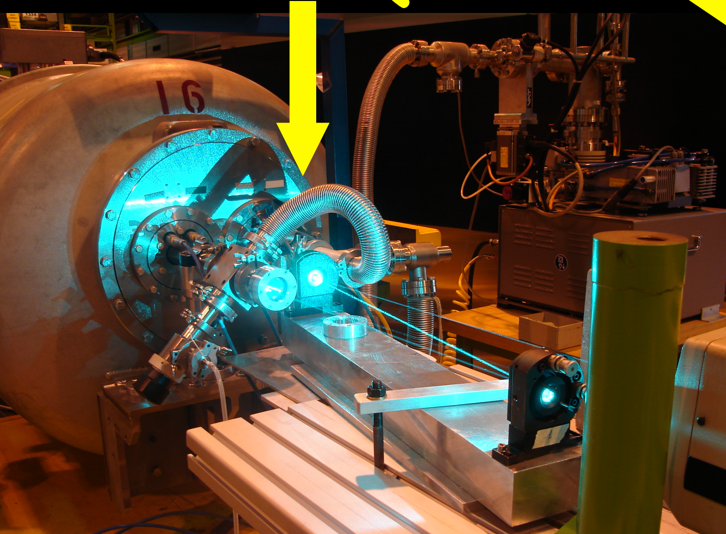
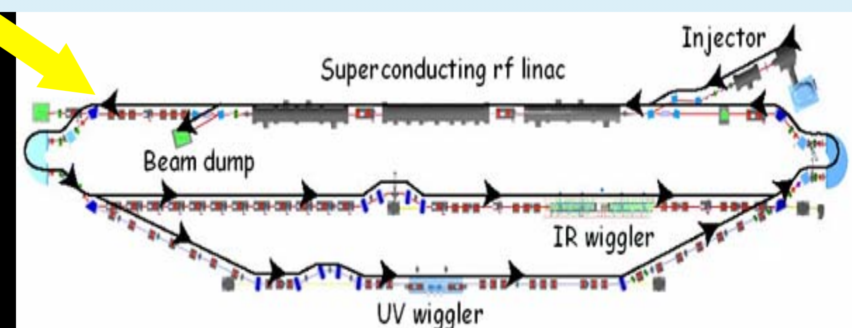
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR











Small coupling, small mass

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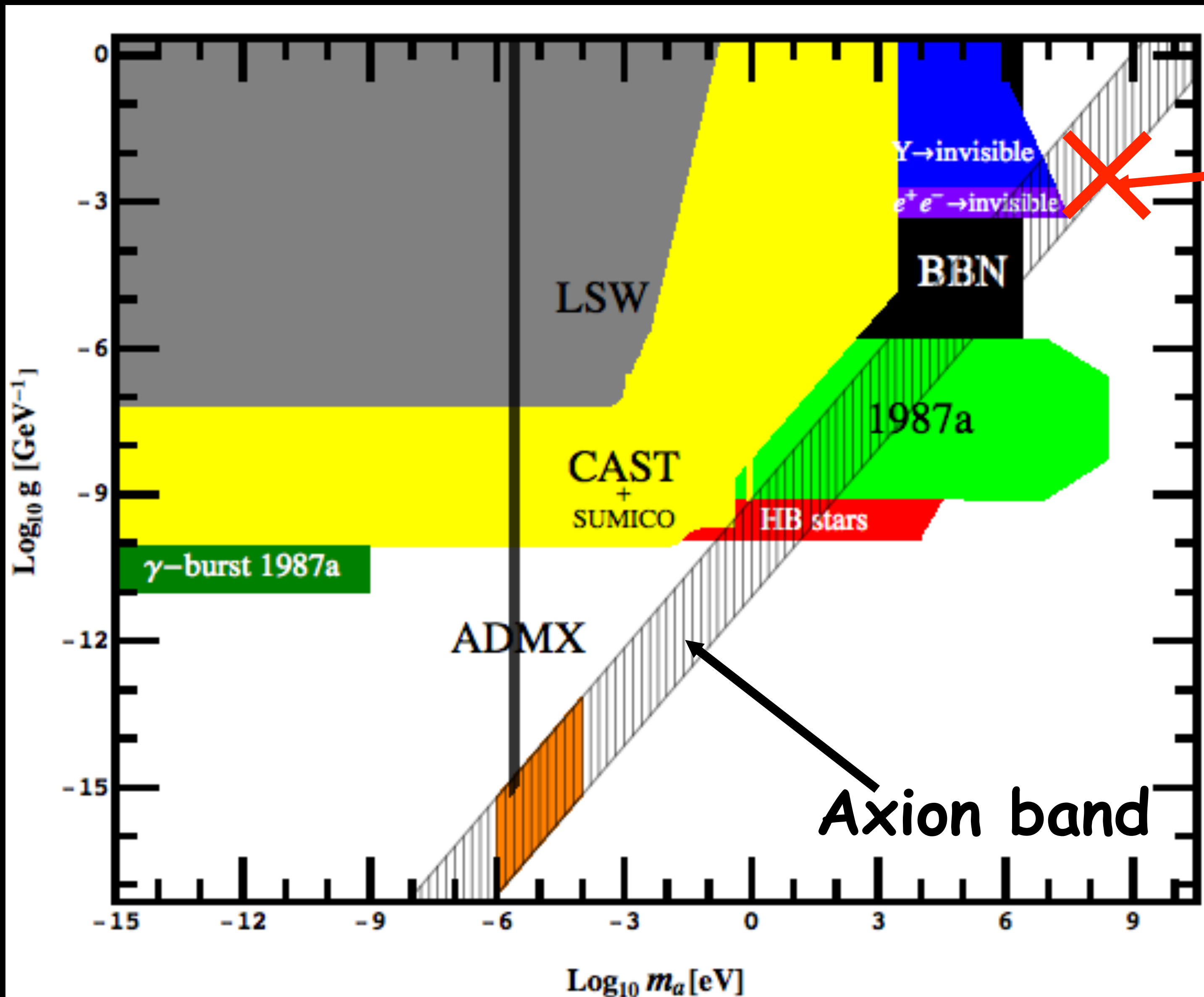

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Helioscopes

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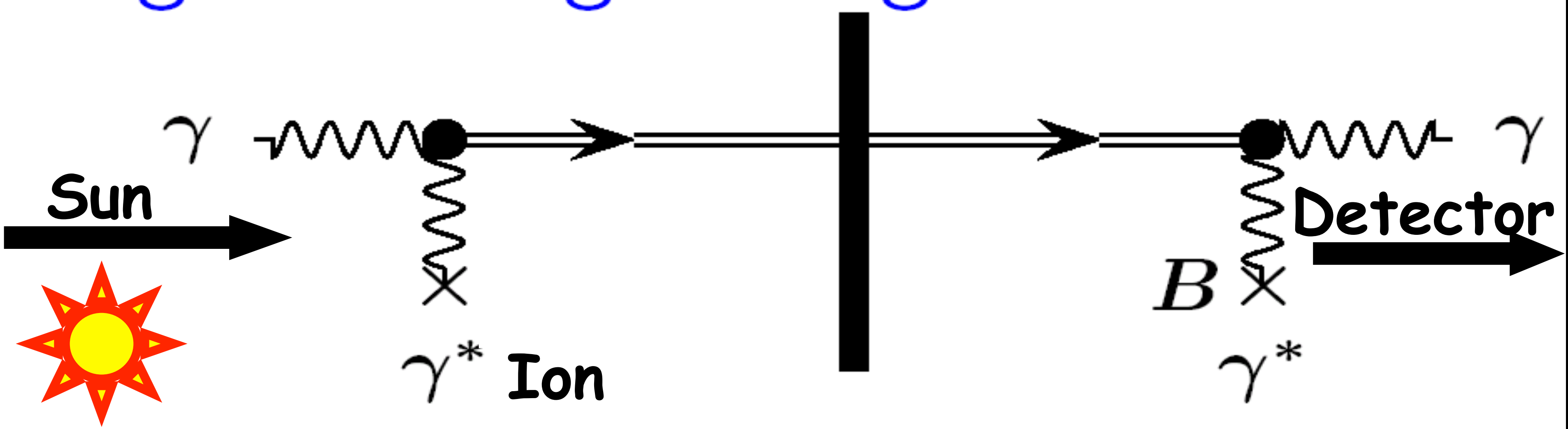
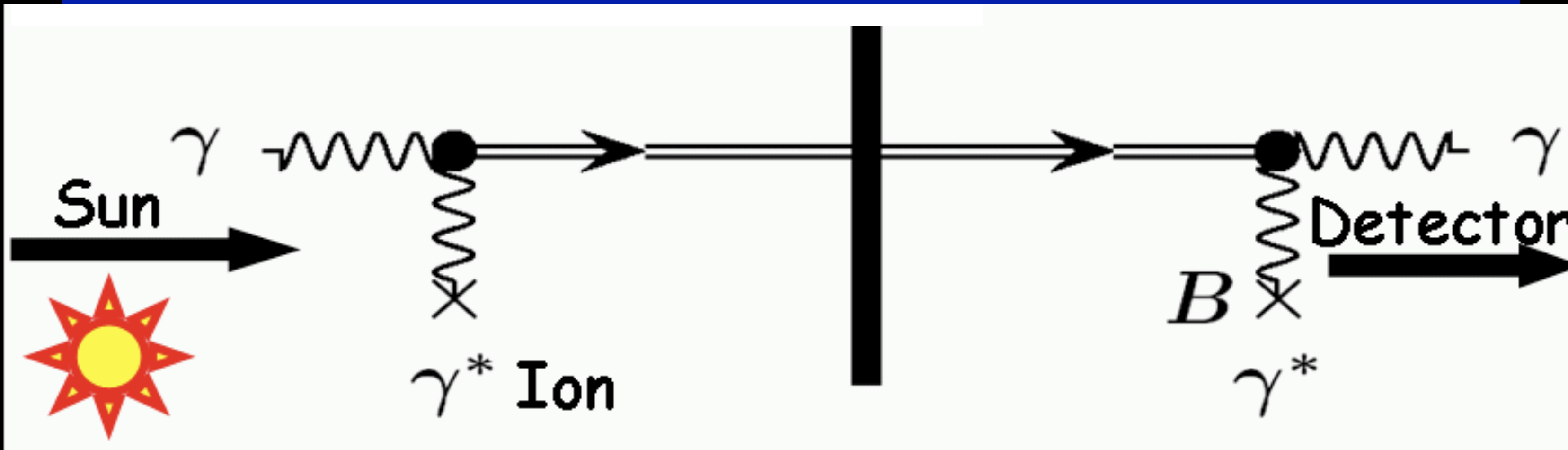
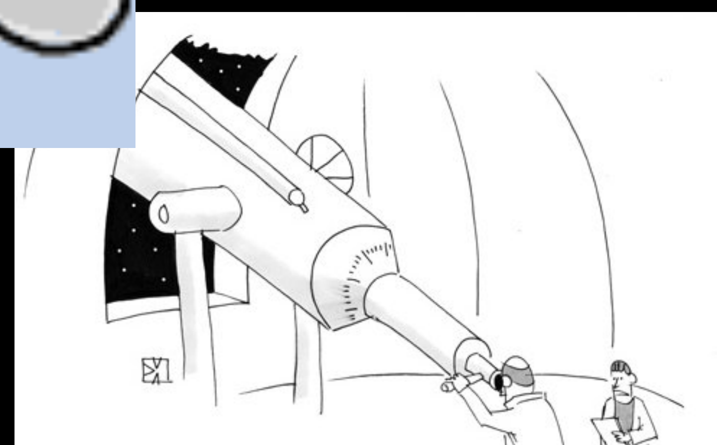
CAST@CERN
SUMICO@Tokyo
SHIPS@Hamburg

“Light shining through a wall”



Perfect for astronomy in Durham ;-)

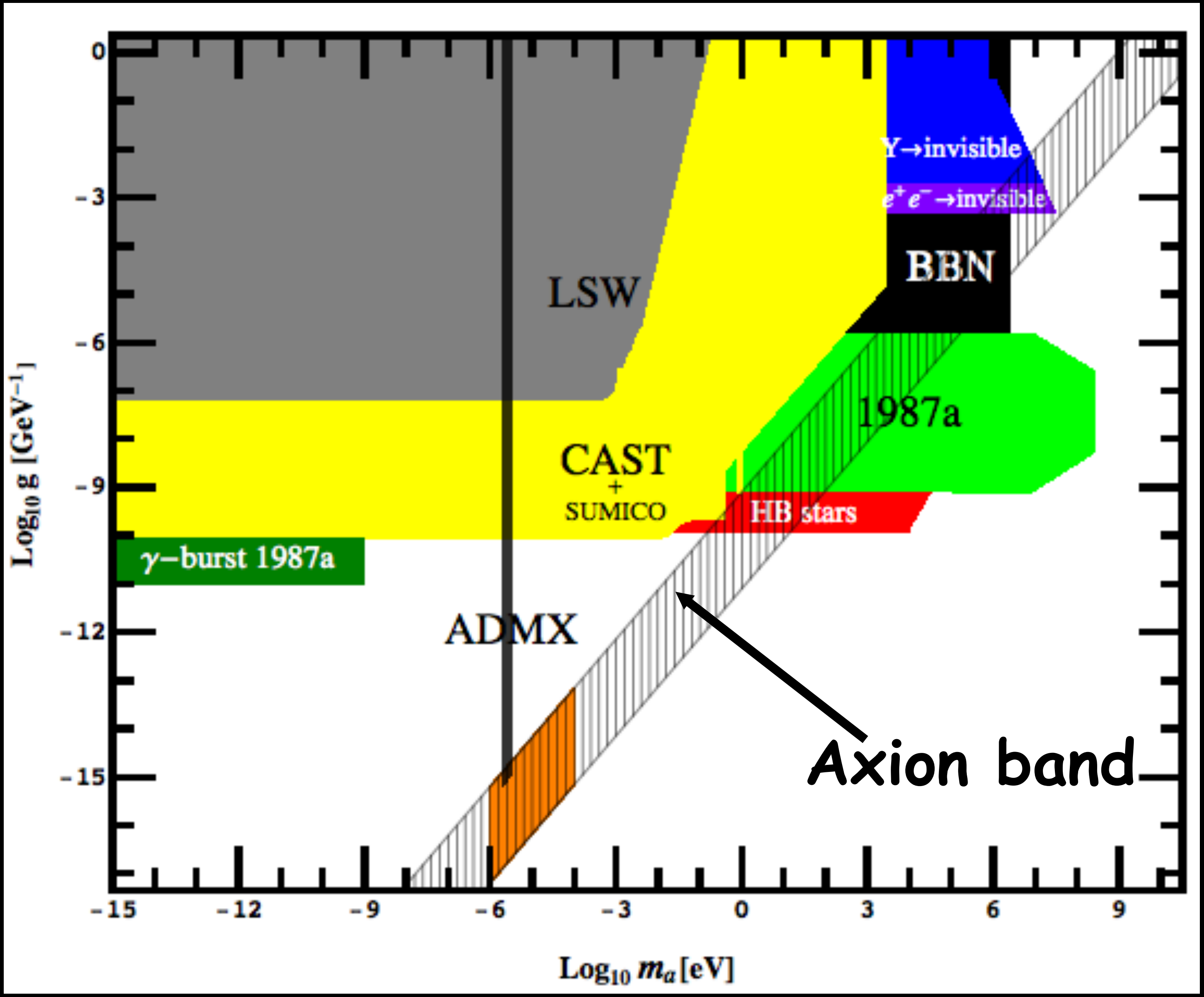




This isn't Dark matter,

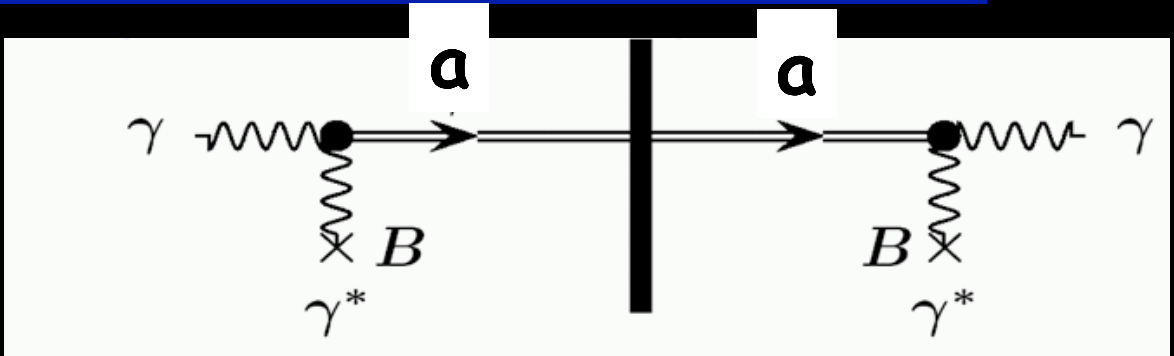
I just forgot to take off the lens cap

Sensitivity

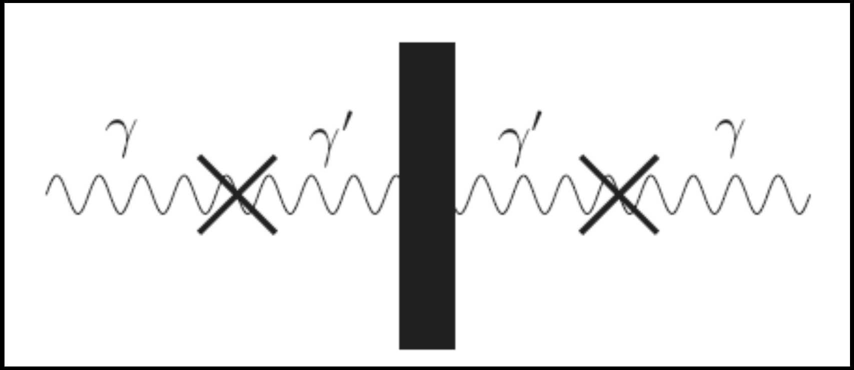


WISPS=Weakly interacting sub-eV particles

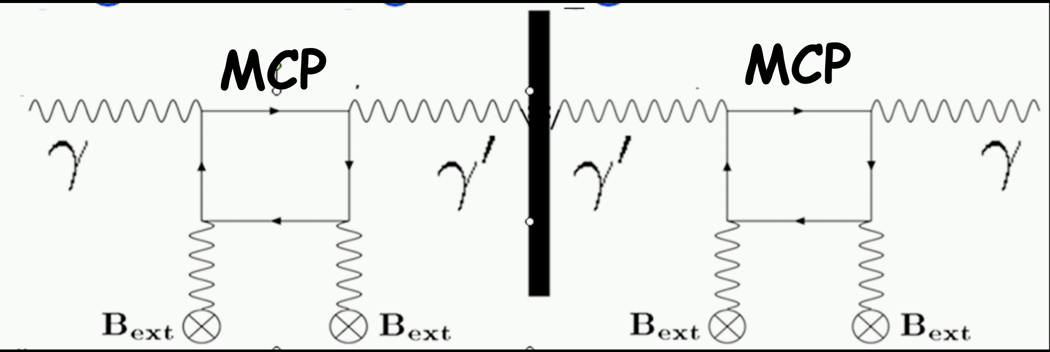
- Axions



- Massive hidden photons (without B-field) =analog ν-oscillations

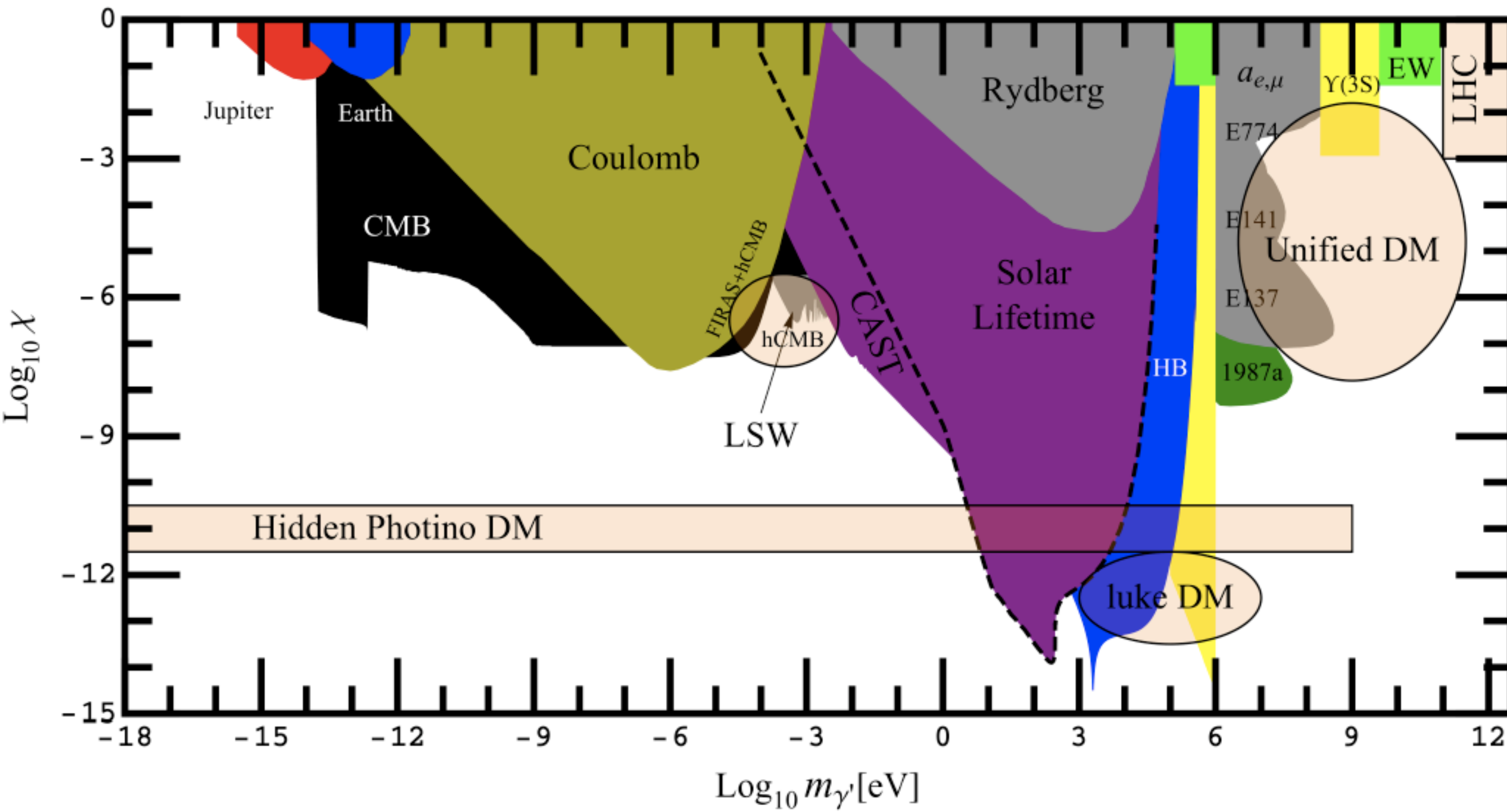


- Hidden photon + minicharged particle (MCP)



Hidden Photons

LSW already competitive + testing interesting area



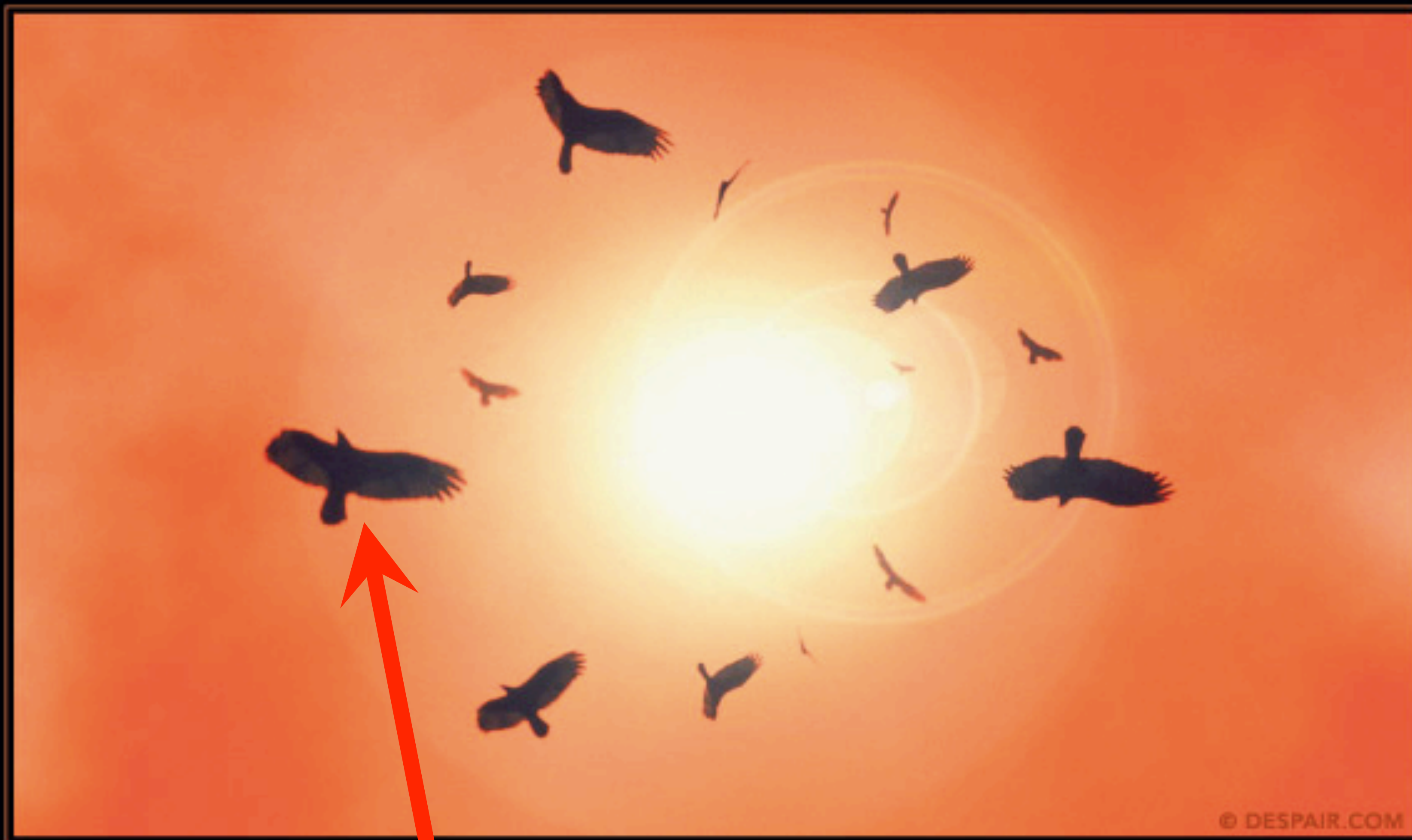
Hints for new Physics

⬇

Model Building

HOPE for light particles?

May Not Be Warranted at this Point.



HOPE for light particles?

Needs the high (scale) point of view

Coincidences?

- Neutrino masses:

$$m_\nu \sim \mathrm{meV}$$

- Scale of dark energy:

$$\rho_\Lambda \sim (\mathrm{meV})^4$$

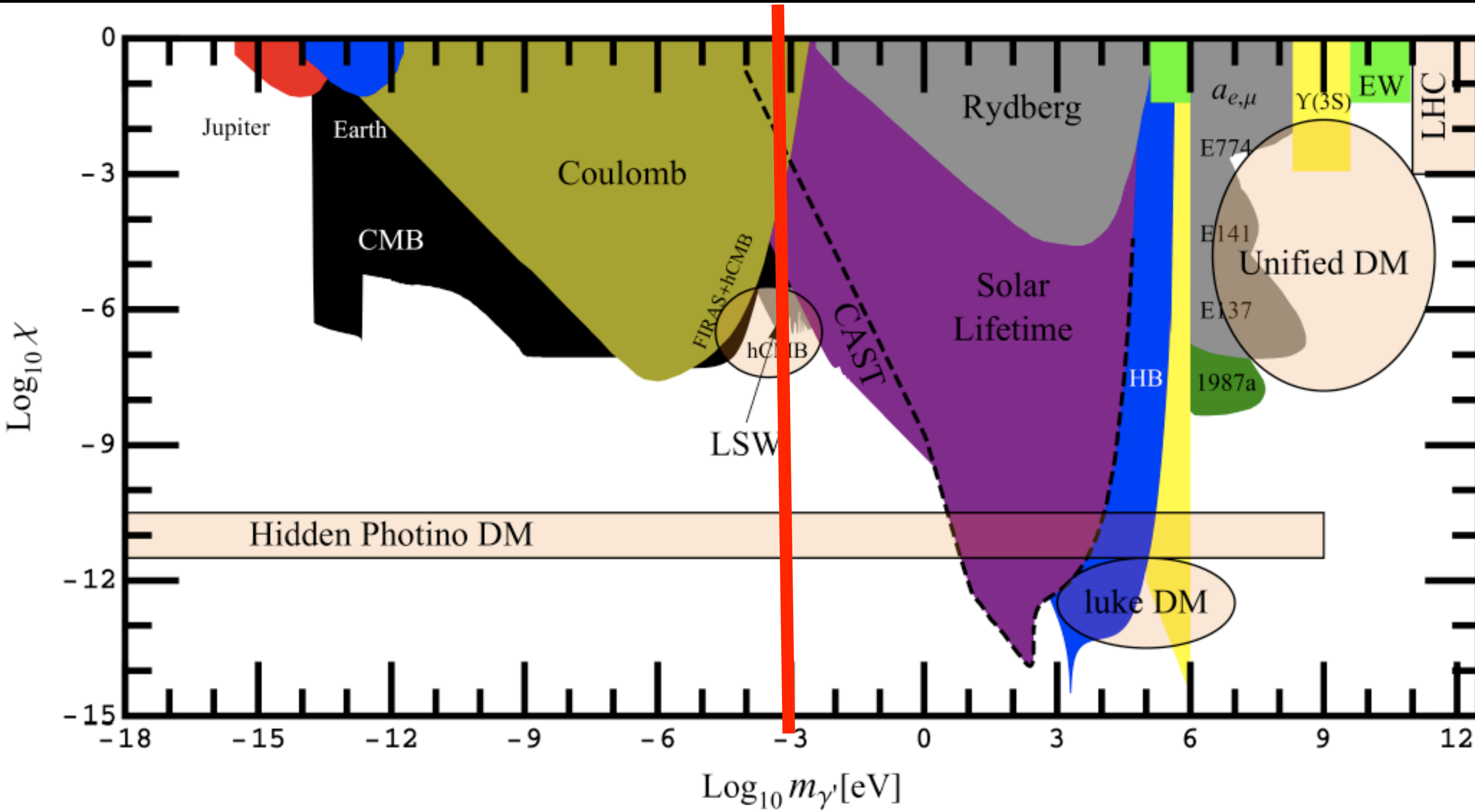
- Energy density of the Universe:

$$\rho_{\mathrm{today}} \sim (\mathrm{meV})^4$$

Hidden Photons

LSW already competitive + testing interesting area

Dark energy scale



High Scale

↓

Small Coupling

Example: Axion coupling

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- Effective higher dimensional coupling

$$\mathcal{L}_{Int} = -\frac{1}{4} g a F^{\mu\nu} \tilde{F}_{\mu\nu} = -g a \mathbf{E} \cdot \mathbf{B}$$

- Small coupling for large axion scale:

small → $g \sim \dfrac{\alpha}{2\pi f_a}$ ← large

Huge Scale>> LHC Energy!

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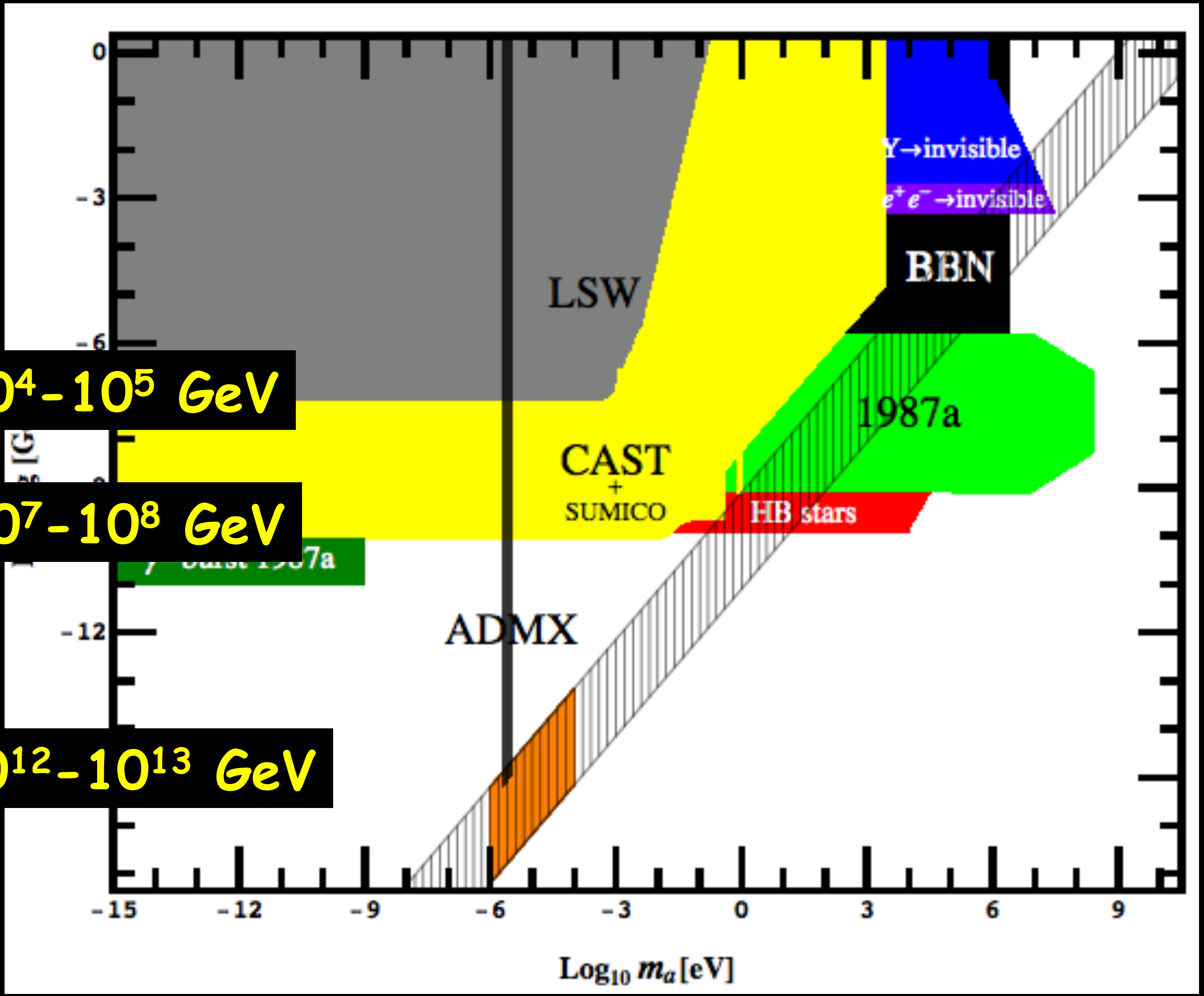


ca 10^4-10^5 GeV

ca 10^7-10^8 GeV

ca 10^{12}-10^{13} GeV

High Scale

↓

Small Mass

Example: Axion See-Saw

- The axion mass is small, too!

Small → $$m_a \sim \frac{m_\pi f_\pi}{f_a}$$ ← Large

Example: Axion See-Saw

- The axion mass is small, too!

Small → $$m_a \sim \frac{m_\pi f_\pi}{f_a}$$ ← Large

Pseudo-Goldstone Boson!

Example: Axion See-Saw

- The axion mass is small, too!

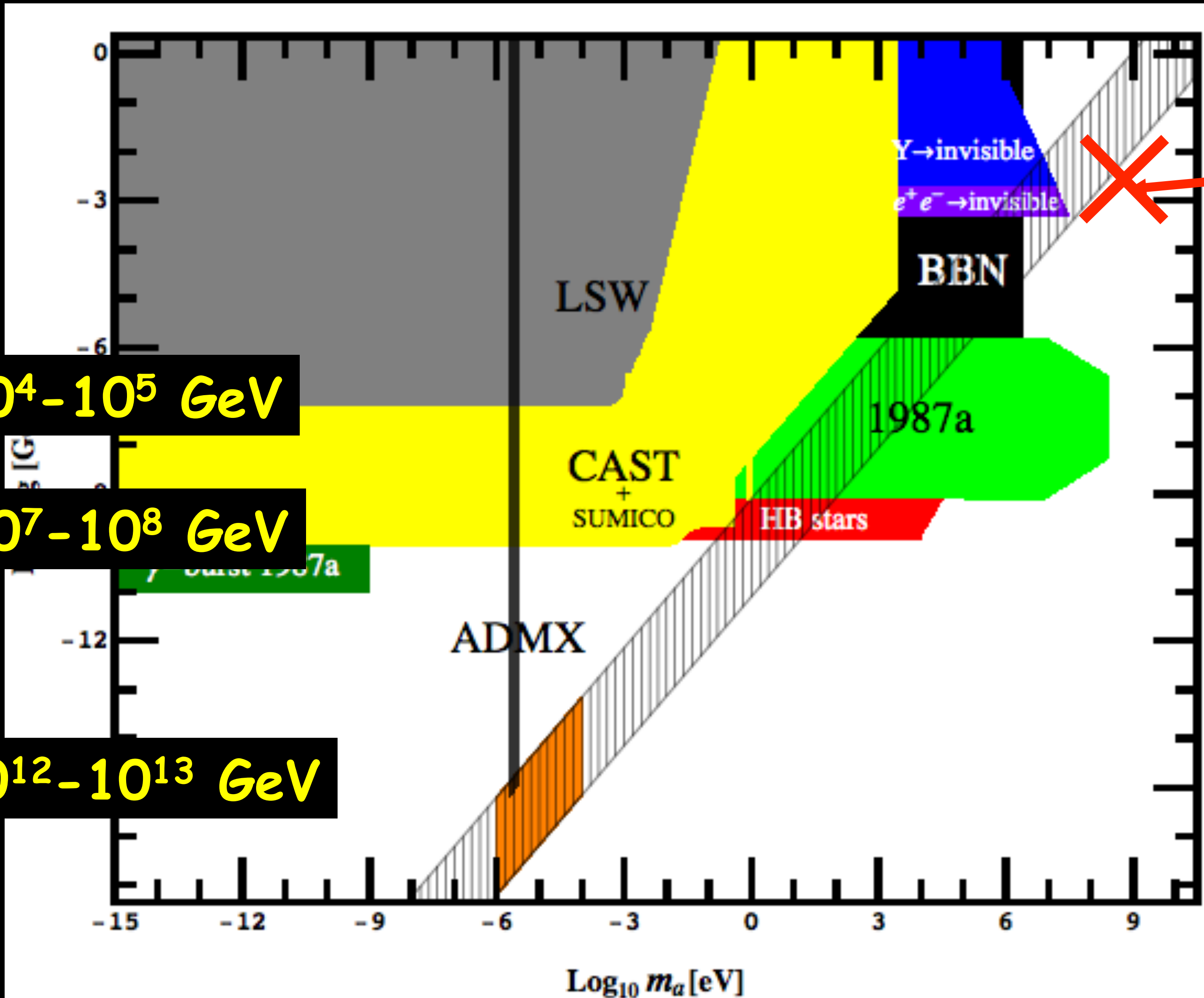
$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

$$\sim 0.6\,\mathrm{meV}\left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)$$

Sub-eV mass

Large scale

Large Scale but light!



ca 10^4-10^5 GeV

ca 10^7-10^8 GeV

ca 10^{12}-10^{13} GeV

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Hints for new Physics

Model Building

Bottom-up (pheno) ↔ **Top-down (theory)**

Go back to drawing board
`Start from scratch'

WISPs
from
String Theory

String theory

- Attempt to unify SM with gravity
- New concept: strings instead of point particles

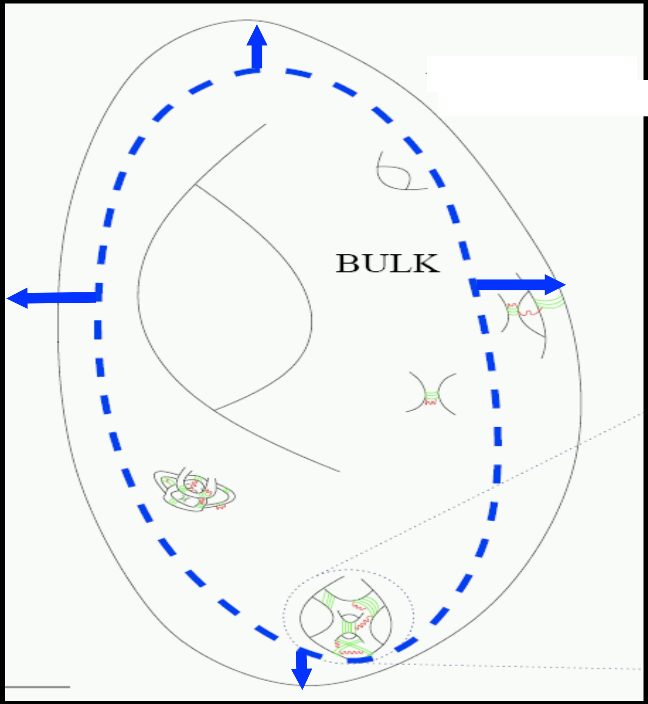
Axion(-like particles)

String theory: Moduli and Axions

- String theory needs Extra Dimensions

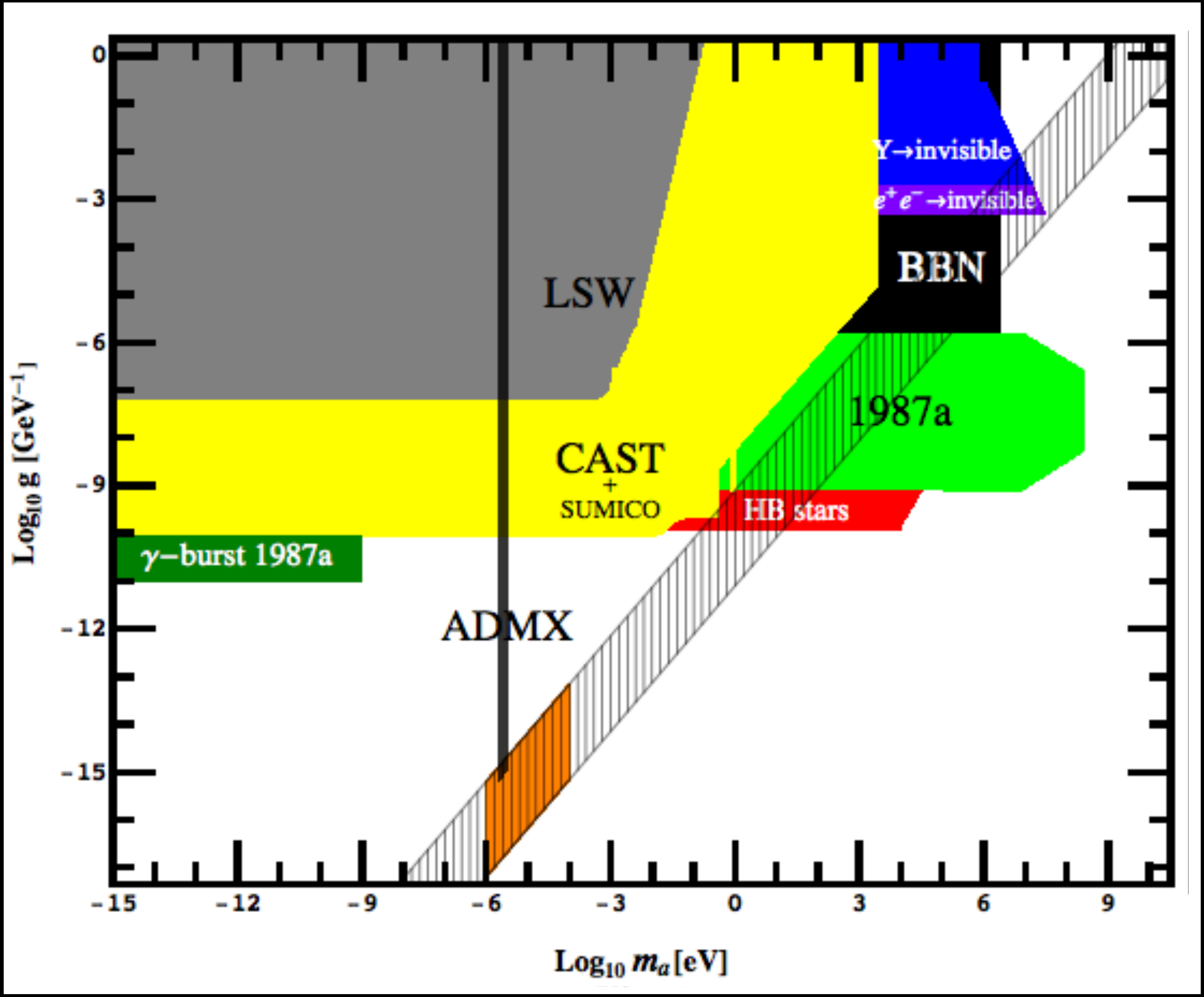
Must compactify

- Shape and size deformations correspond to fields:
  Moduli (WISPs) and Axions
  Connected to the fundamental scale, here string scale

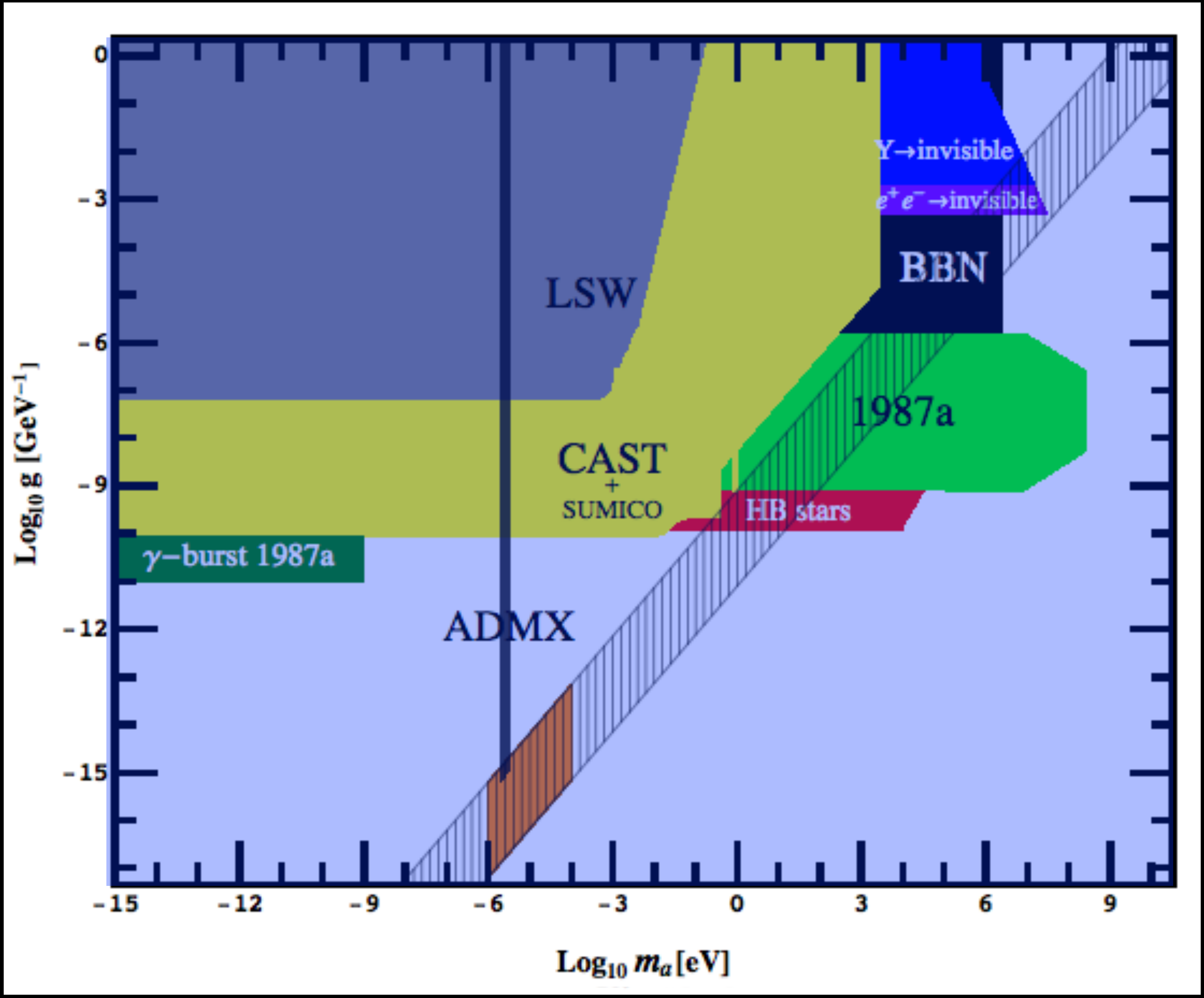


WISP candidates

Axion (like particles): Where are we?

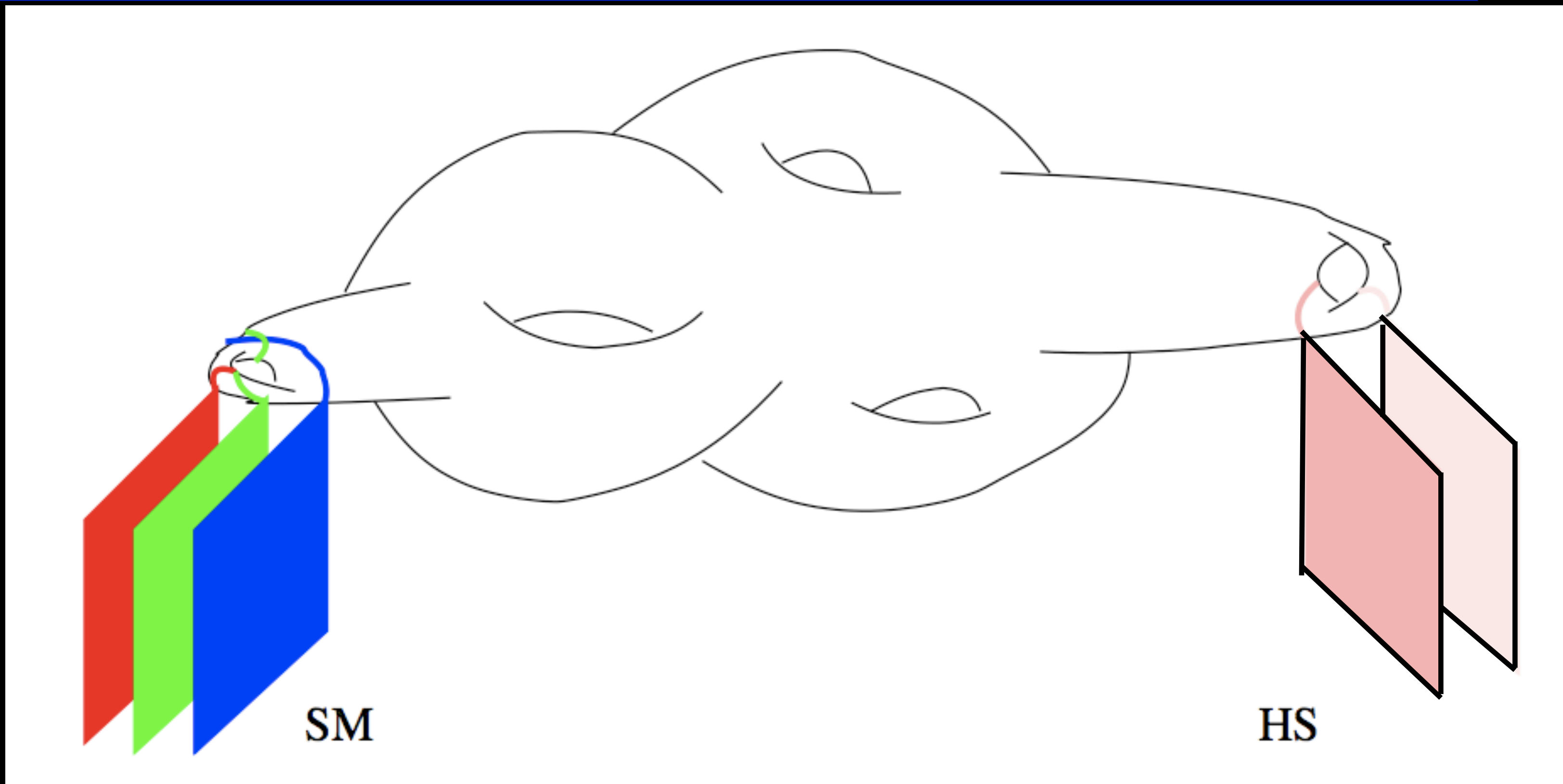


Axion (like particles): Where are we?



Hidden Photons

String theory likes extra gauge groups



$U(A) \times U(B) \times U(C)$ $\quad$ $U(A) \times U(B)$

Many extra U(1)s!

Candidates for WISPs

Hidden by distance

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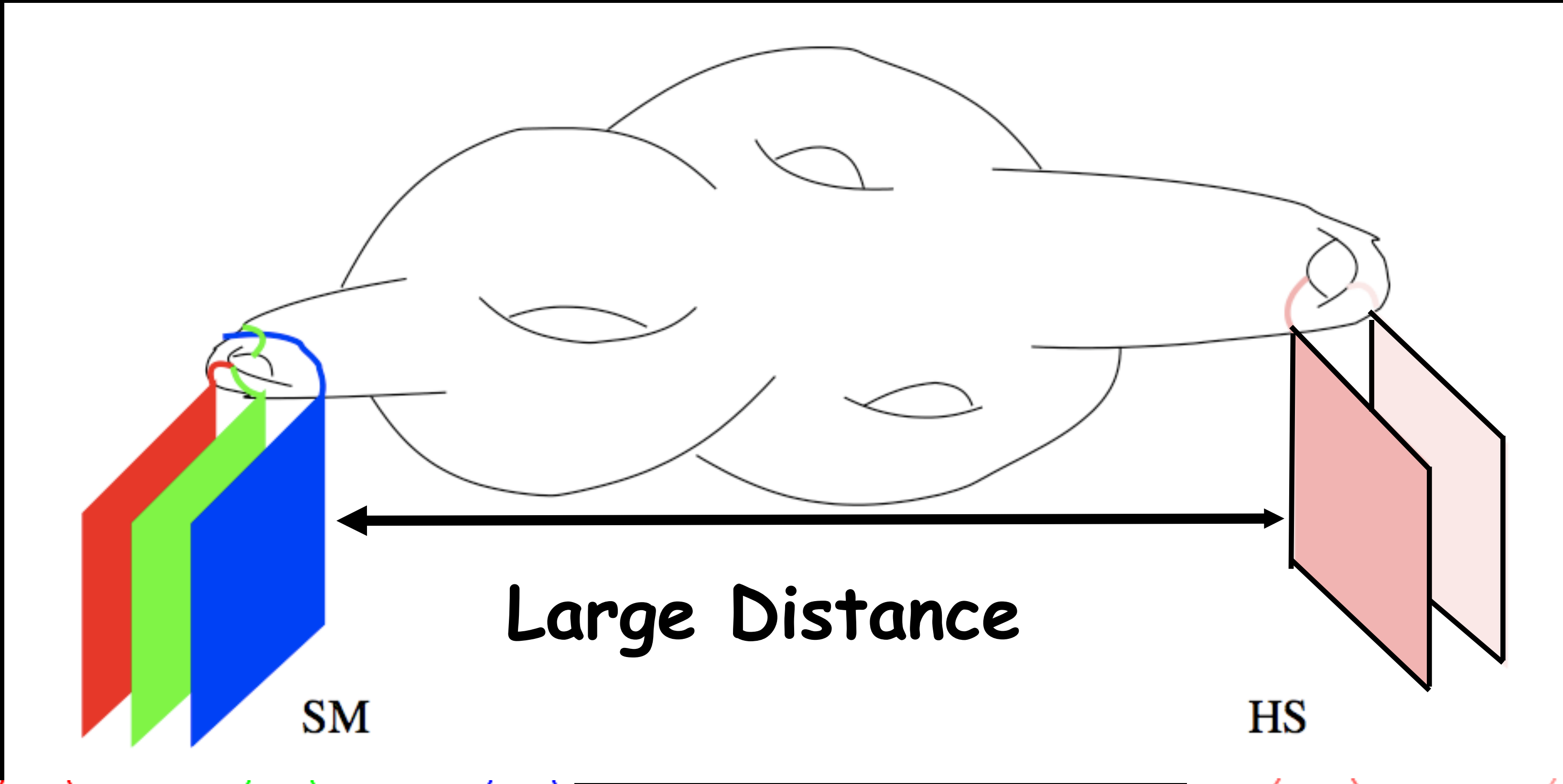


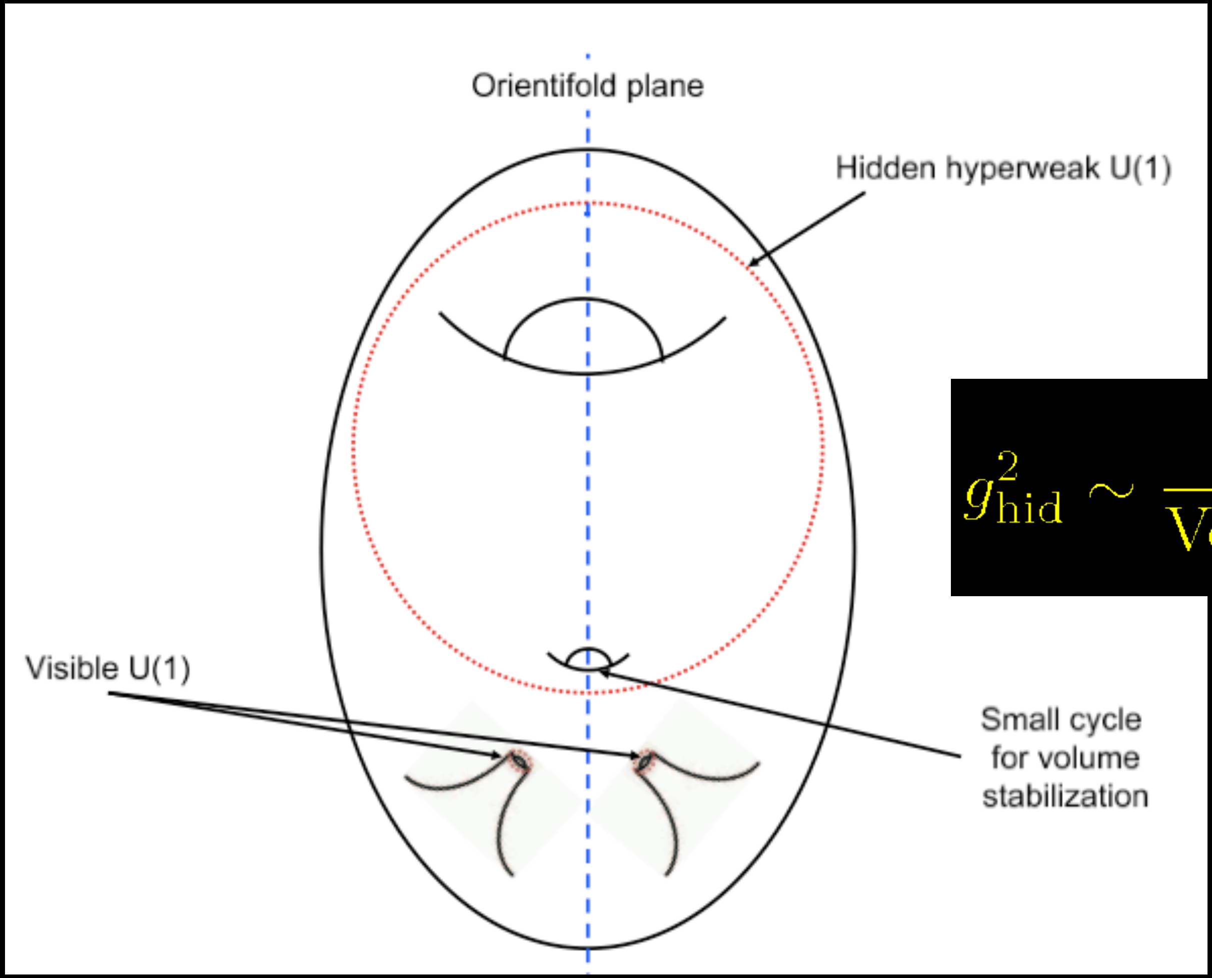
$U(A) \times U(B) \times U(C)$

$U(A) \times U(B)$

$$\chi \sim \frac{g_s}{8\pi} \frac{1}{Volume^x}$$

$$g_{\rm hid} \sim 1$$

Hidden by weakness



$$g_{\rm hid}^2 \sim \frac{2\pi g_s}{\text{Volume}^x} \sim \left(\frac{M_s^2}{M_P^2}\right)^x \ll 1$$

$$\chi \sim \frac{g_{\rm vis} g_{\rm hid}}{16\pi^2} \sim \frac{2\pi g_s}{\text{Volume}^{x/2}} \sim \left(\frac{M_s^2}{M_P^2}\right)^{x/2} \ll 1$$

Hidden Photons, all over the place

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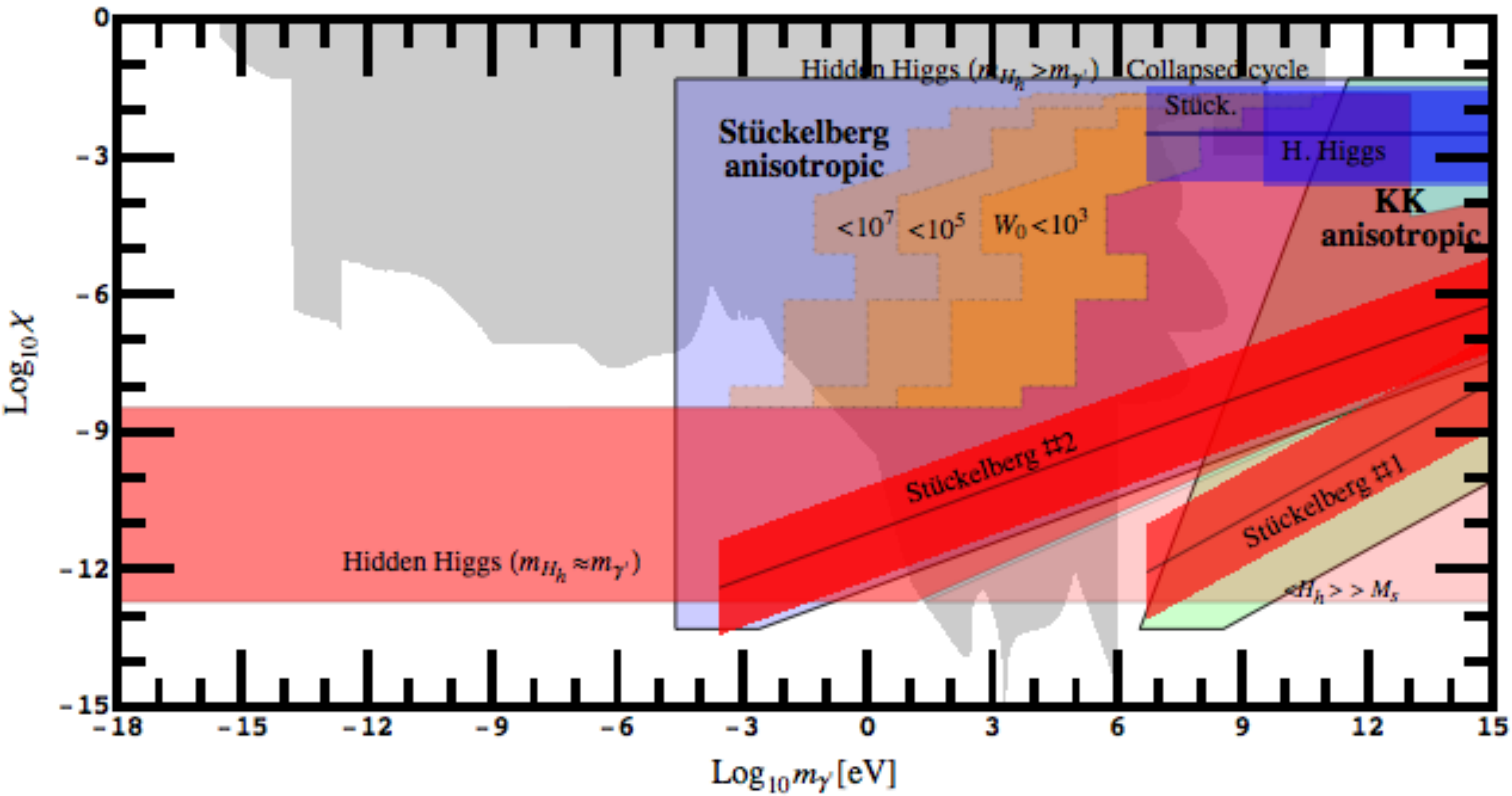


Hints for new Physics

↓

Model Building

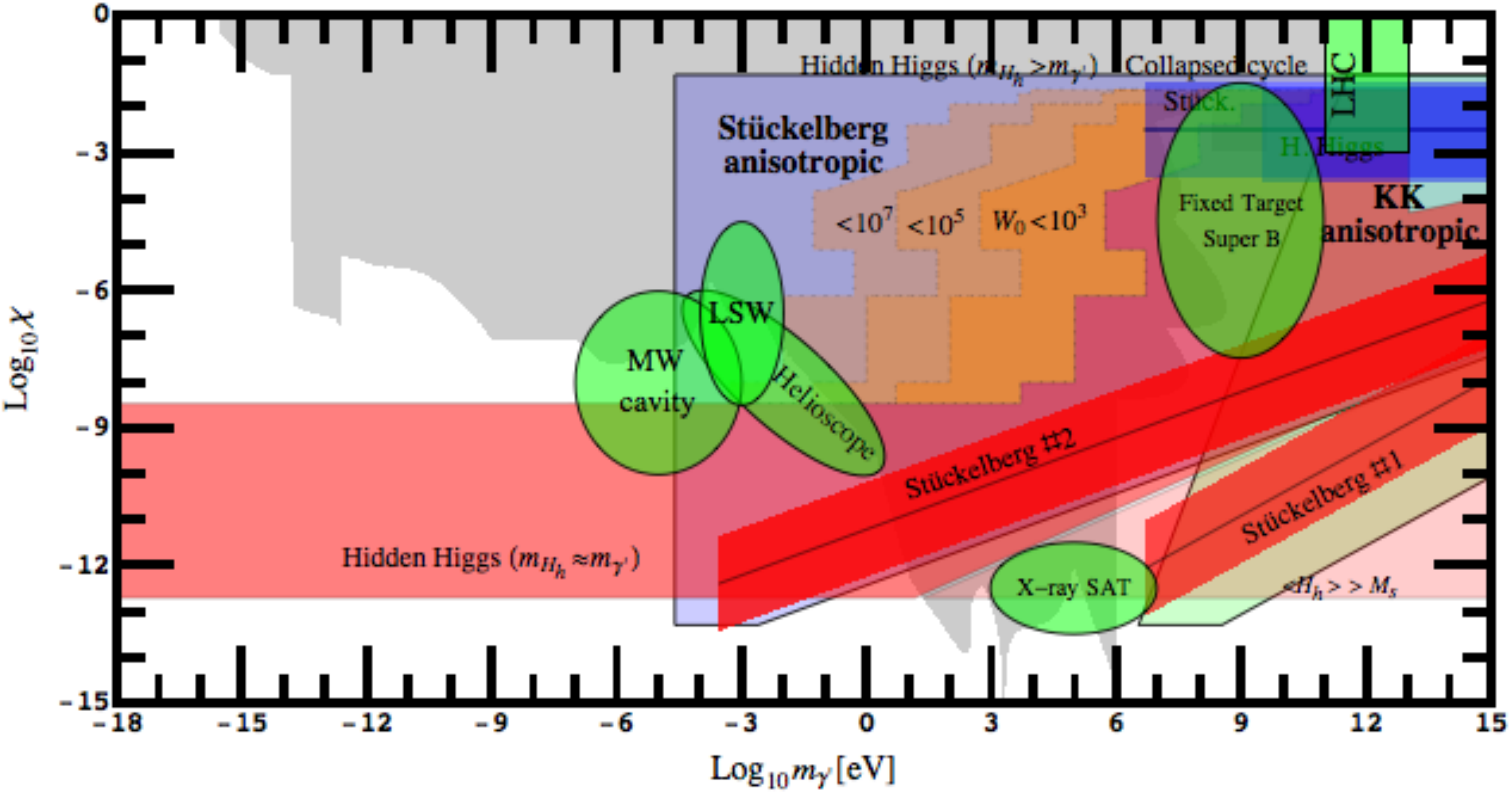
↓ ↓

Bottom-up (pheno) ⟷ **Top-down (theory)**

↓ ↓

New, cool **Experiments**

Hidden Photons: Back to Experiment



Hints for new Physics

Model Building

Bottom-up (pheno) ⟷ Top-down (theory)

Happy Convergences

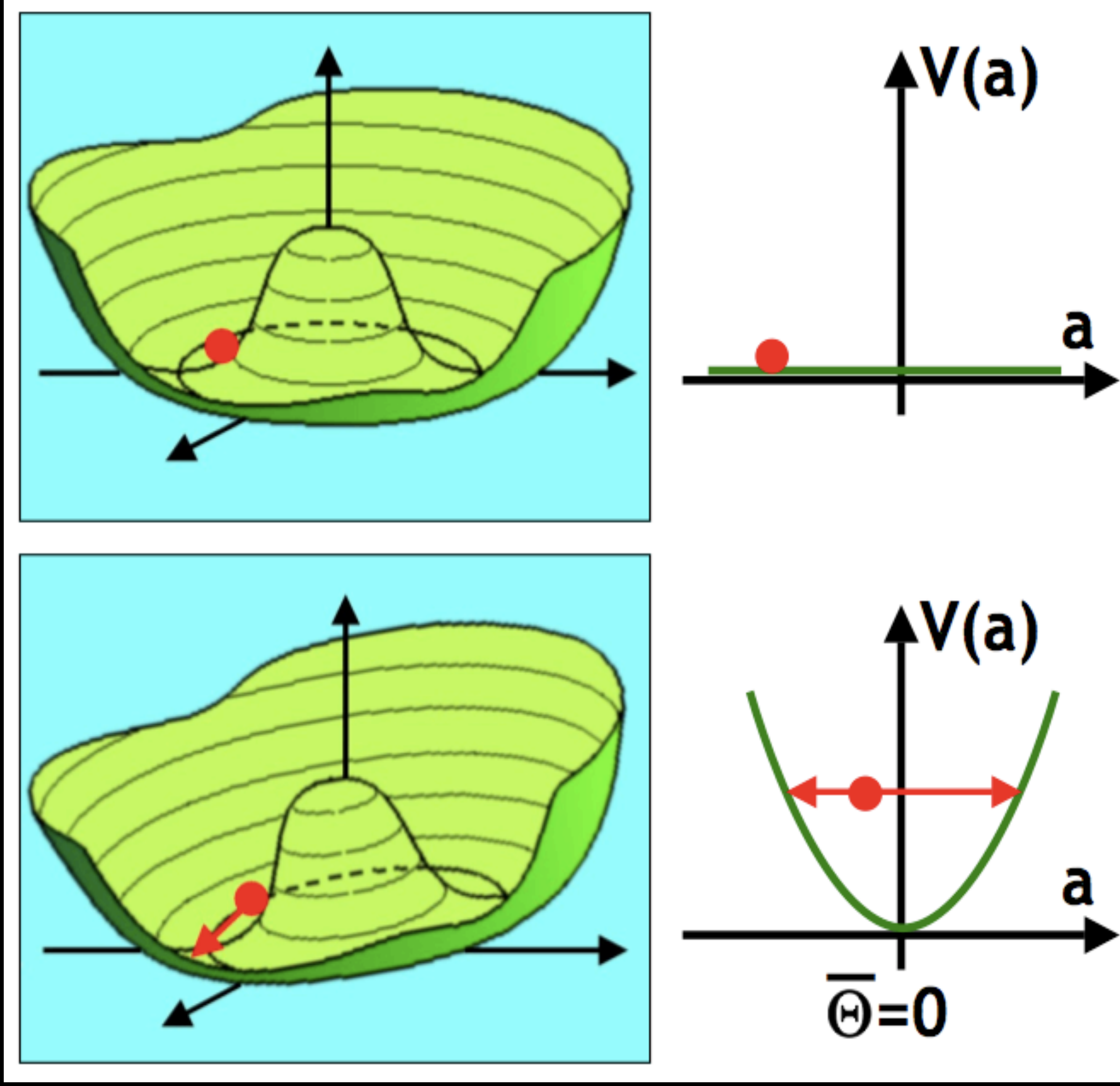
Dark Matter(s)

Axion Dark Matter

Axion production

- $T < f_a$
- Axion potential is flat
- Axion can sit anywhere

- $T < T_{QCD}$
- Potential arises
- $H < m_a$
- Axion starts to oscillate



Oscillations behave like dark matter

- Initial energy density $$\rho_{\rm ini} = \frac{1}{2} m_a^2 f_a^2 \theta_{\rm ini}^2$$

+ damped Oscillations $$\ddot{\theta} + 3H\dot{\theta} + m_a^2 \theta = 0$$

↓

Scales like matter

$$\rho_a(t) \sim \frac{\rho_{\rm ini}}{a^3(t)}$$

How much?

- Energy density

$$\Omega_a h^2 = \kappa_a \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{1.175} \theta_{\mathrm{ini}}^2$$

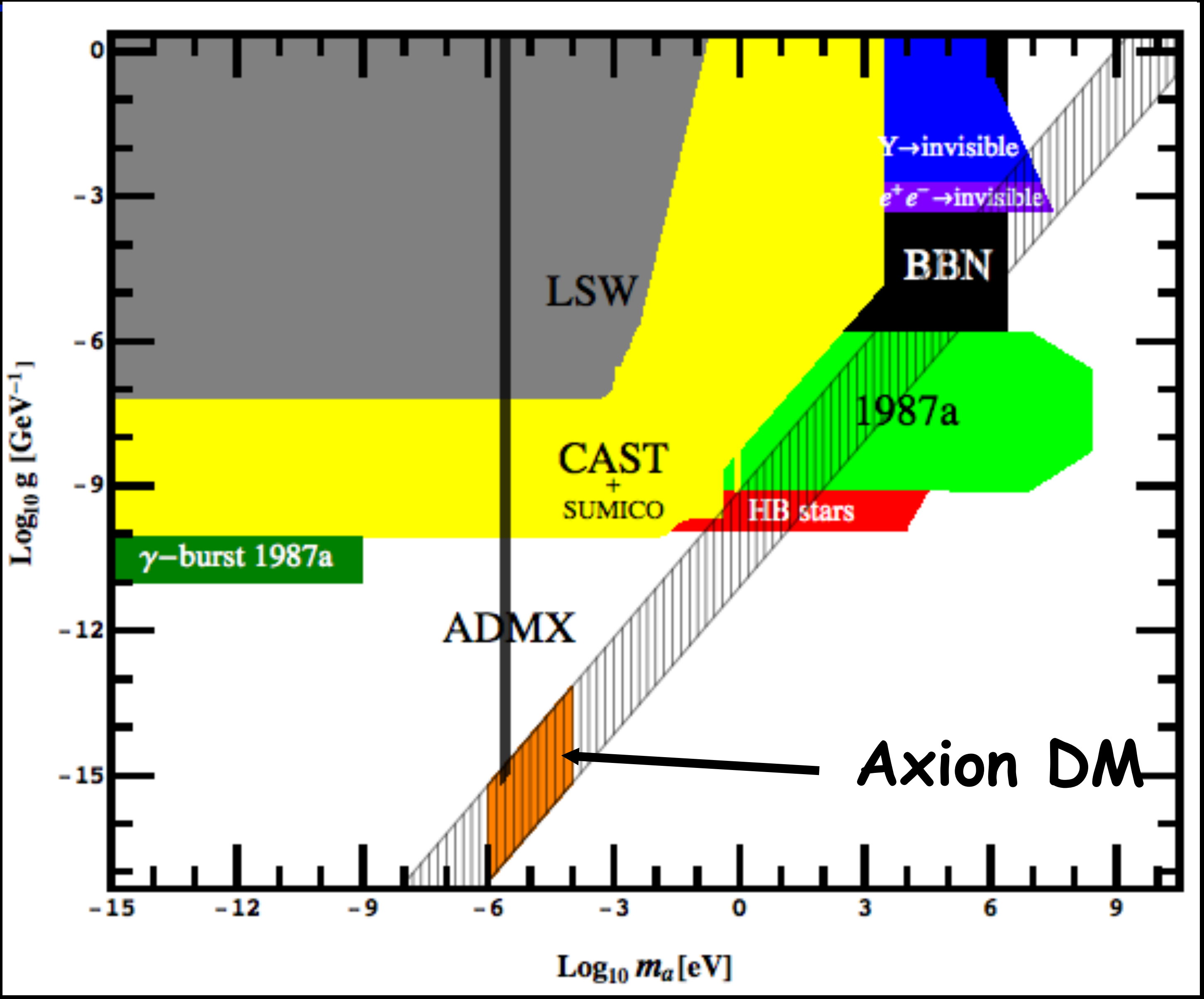
Too much?

- Energy density

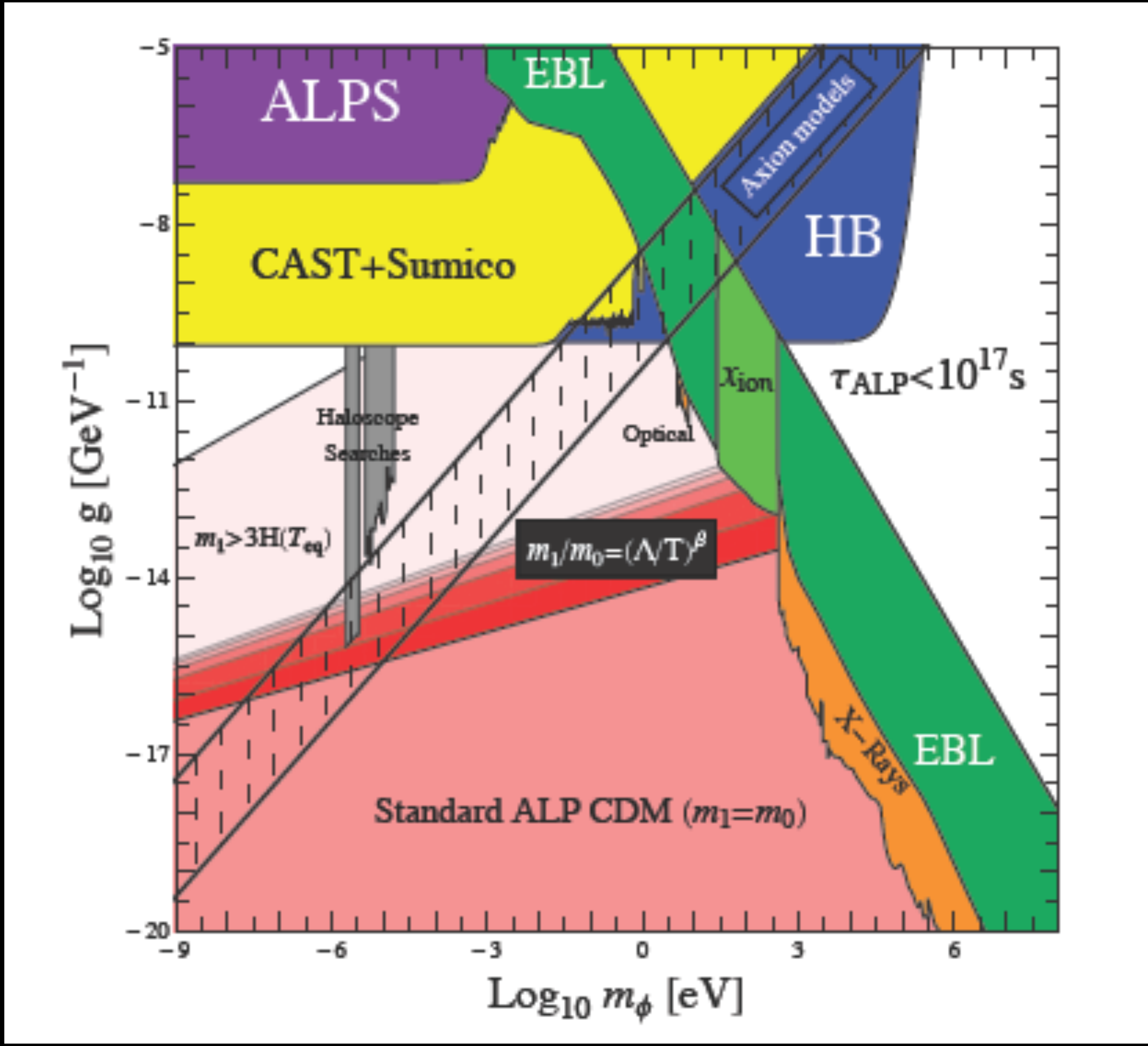
$$\Omega_a h^2 = \kappa_a \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{1.175} \theta_{\mathrm{ini}}^2$$

For $f_a >> 10^{12}$ GeV too much DM!

Axion dark matter



Axion-like particle dark matter



→ Plenty of space to explore!!!

How can it be?

- Axions are very light:
- How can they be COLD dark matter?

⇒ **Non-thermal production!**

Supercold?

- **At the beginning axion value everywhere the same**
- **Coherent Oscillations => Supercold!**

$$p_{\mathrm{today}} = p_{\mathrm{ini}} \frac{T_{\mathrm{today}}}{T_{\mathrm{ini}}}$$

$$\sim H_{\mathrm{ini}} \frac{T_{\mathrm{today}}}{T_{\mathrm{ini}}} \sim 10^{-22}\,\mathrm{eV} \ll m_a$$

Hidden Photon Dark Matter

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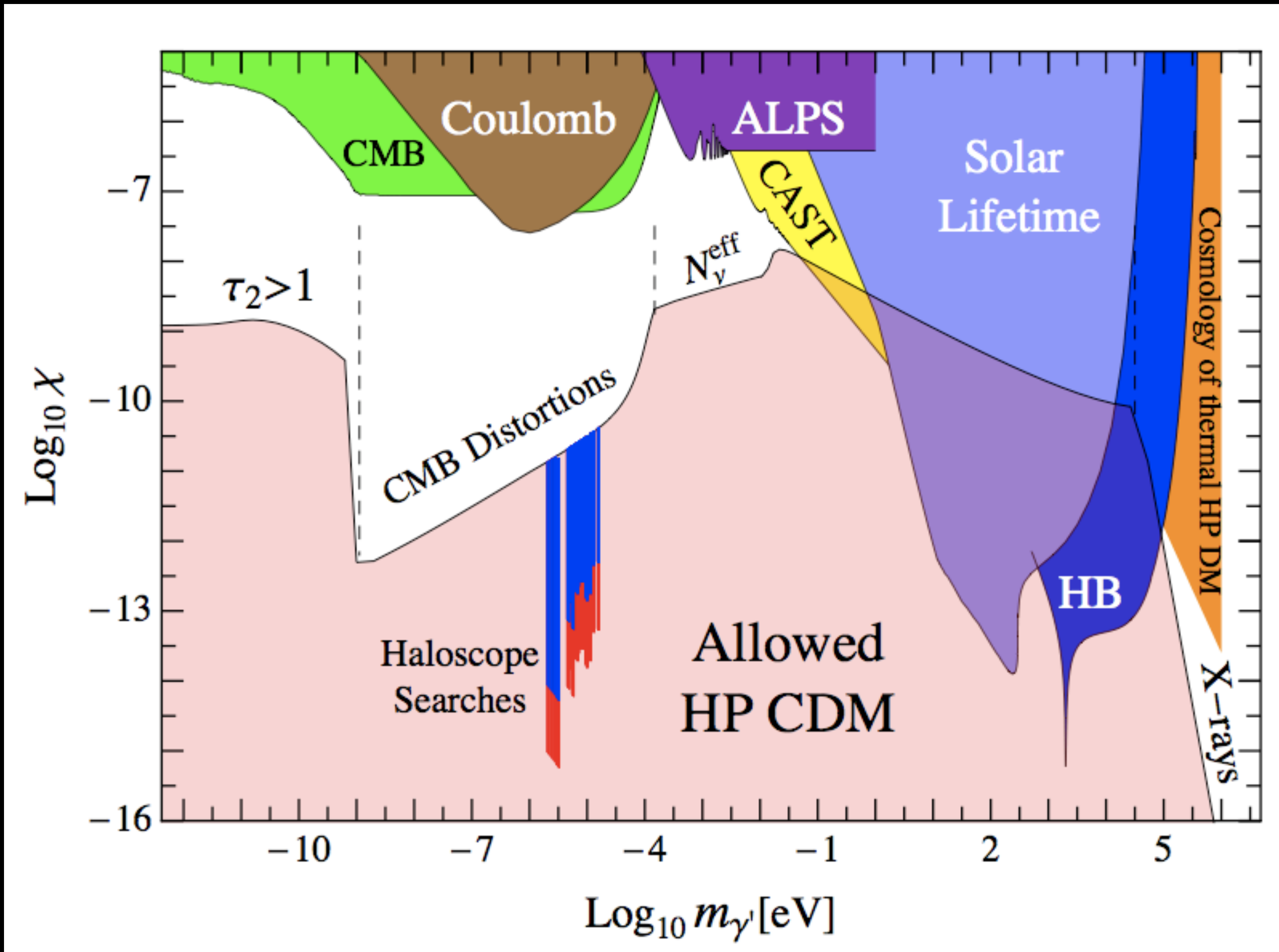

In the year 1 AH* ...

...we think we understand EW symmetry breaking

* After Higgs discovery

Understanding the origin of mass

We are still trying to understand most of the mass in the Universe: The Dark Matter Mass

SUSY WIMPs

$$m_{WIMP} \sim M_{SUSY} - const.\ \frac{m_z^2}{M_{SUSY}}$$

0% - ε% understood

Understanding the origin of mass

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We are still trying to understand most of the mass in the Universe: The Dark Matter Mass

SUSY WIMPs

$$m_{WIMP} \sim M_{SUSY} - const.\,\frac{m_z^2}{M_{SUSY}}$$

0% - ε% understood

Axions

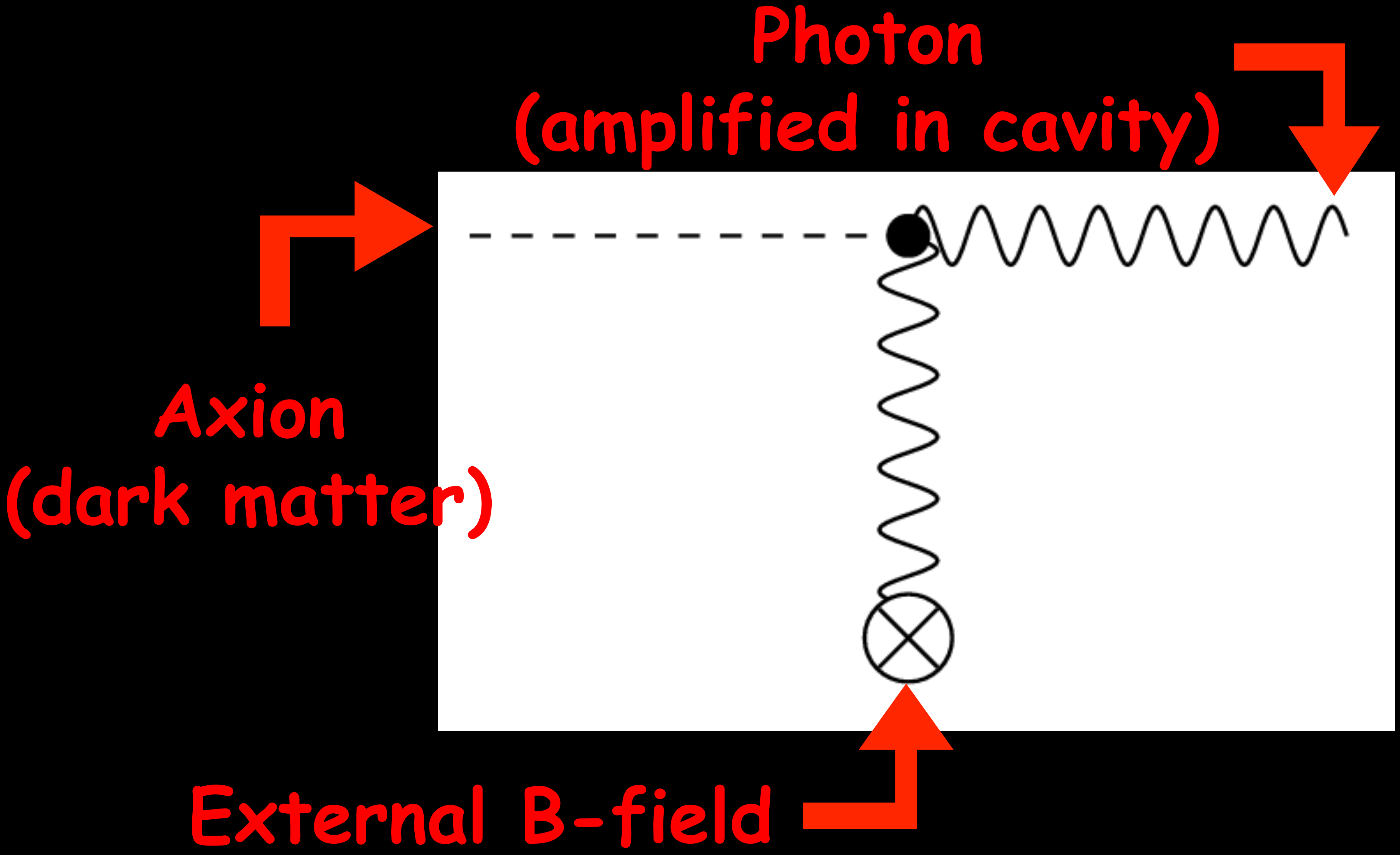
$$m_{axion} \sim \frac{\sqrt{m_{quark}\Lambda_{QCD}}\,\Lambda_{QCD}}{f_a}$$

>75% understood ☺

Searching WISPy Dark Matter

Use a plentiful source of WISPs

- Photon generation from axions!



Electricity from Dark Matter ;-).

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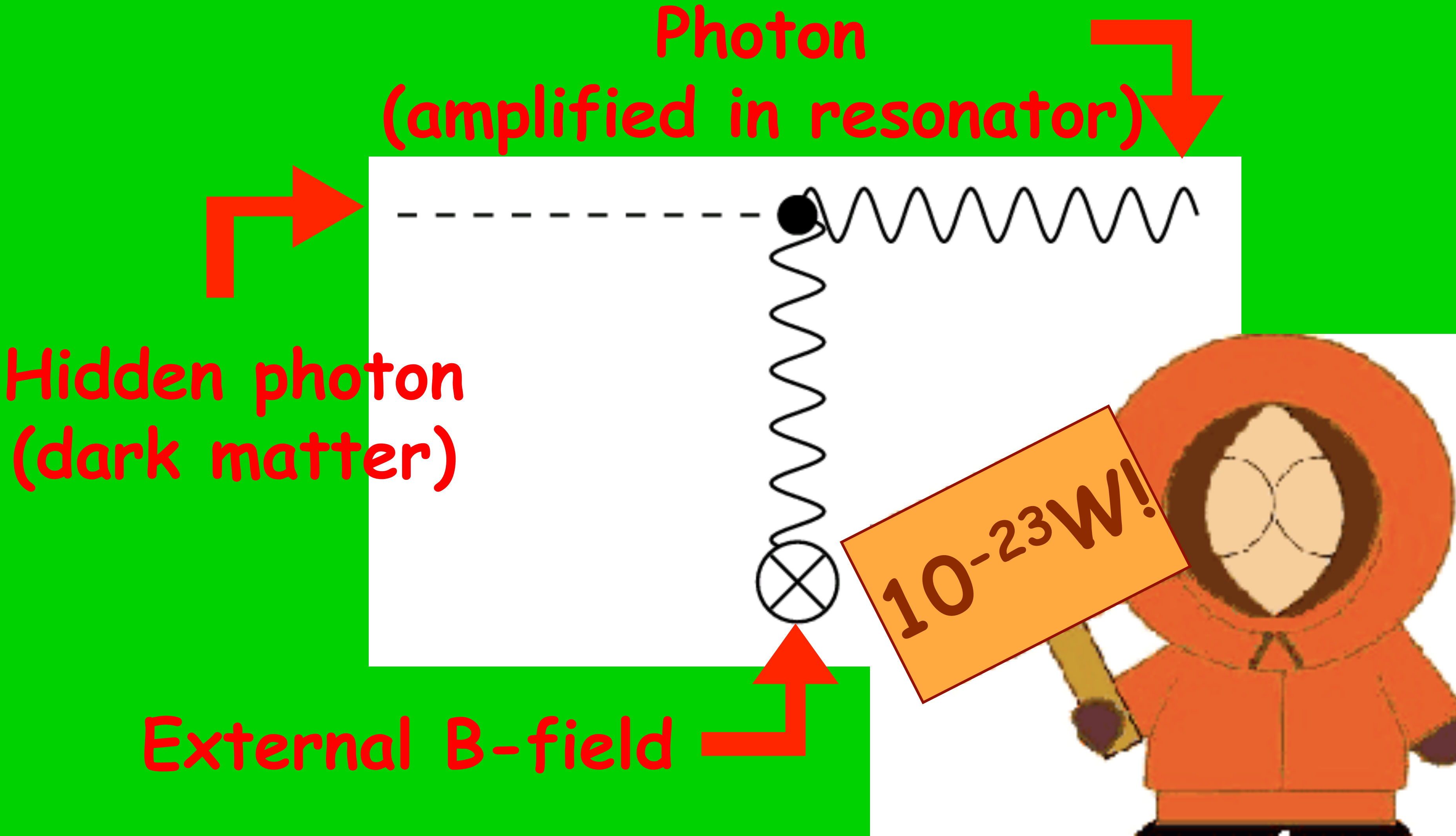
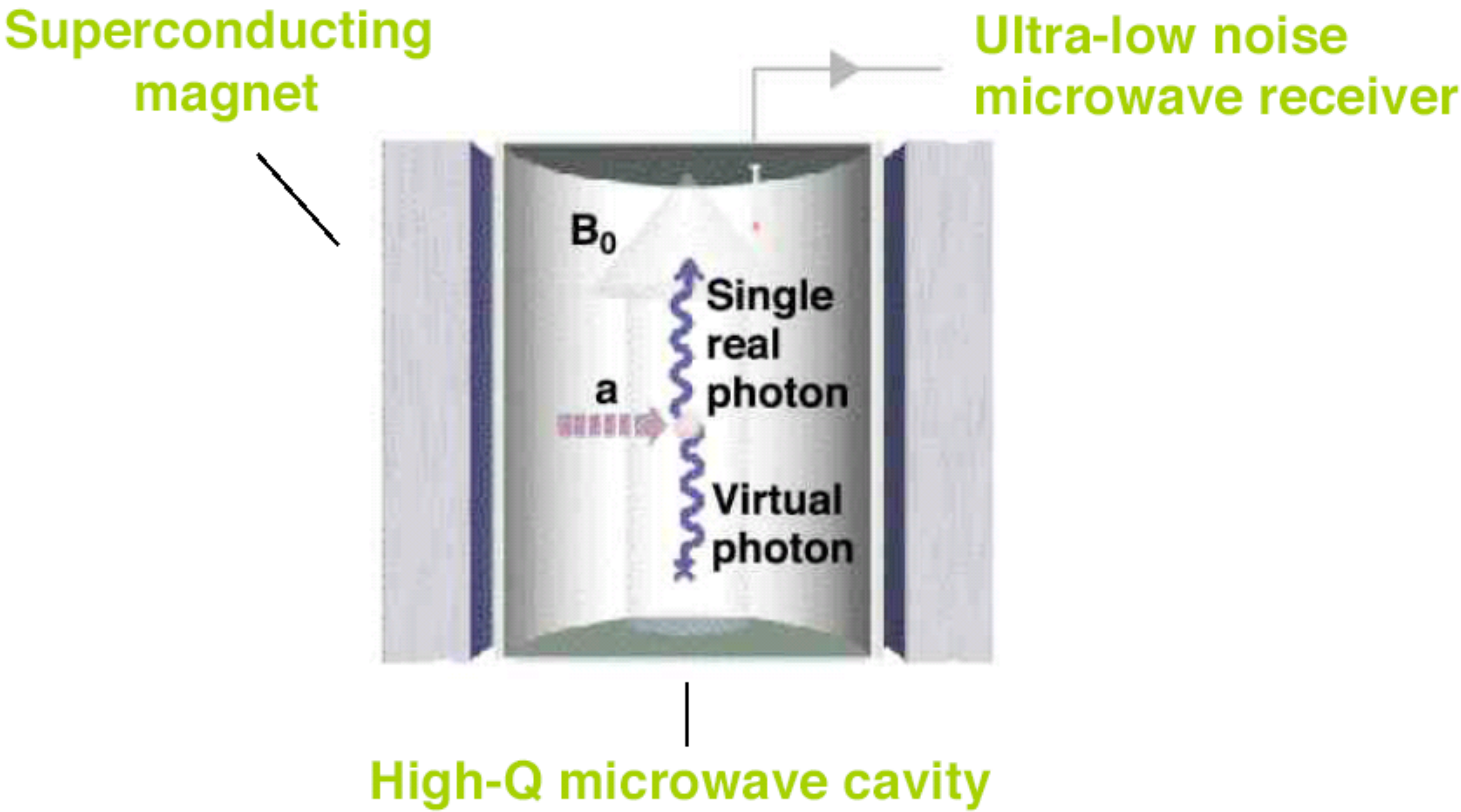
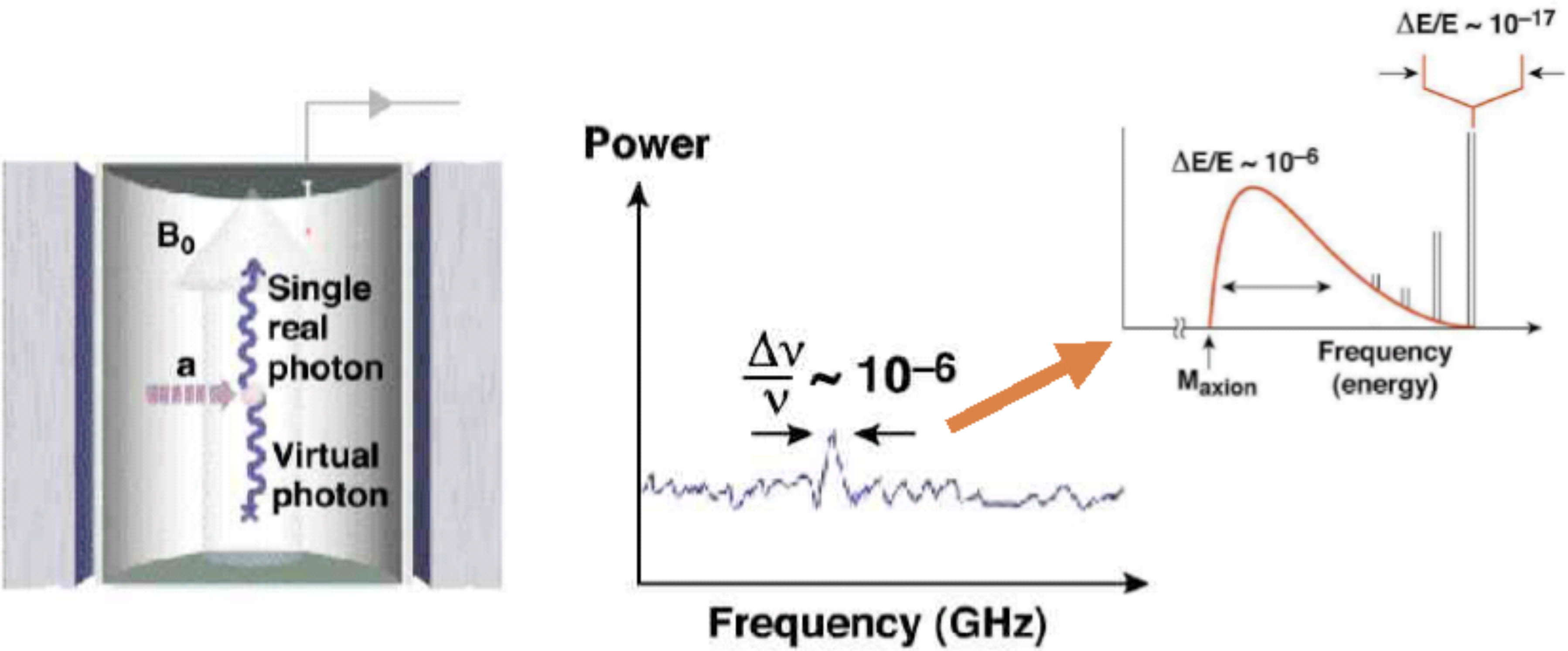
- Photon Regeneration



Axions in Cavity



Signal: Total energy of Axion

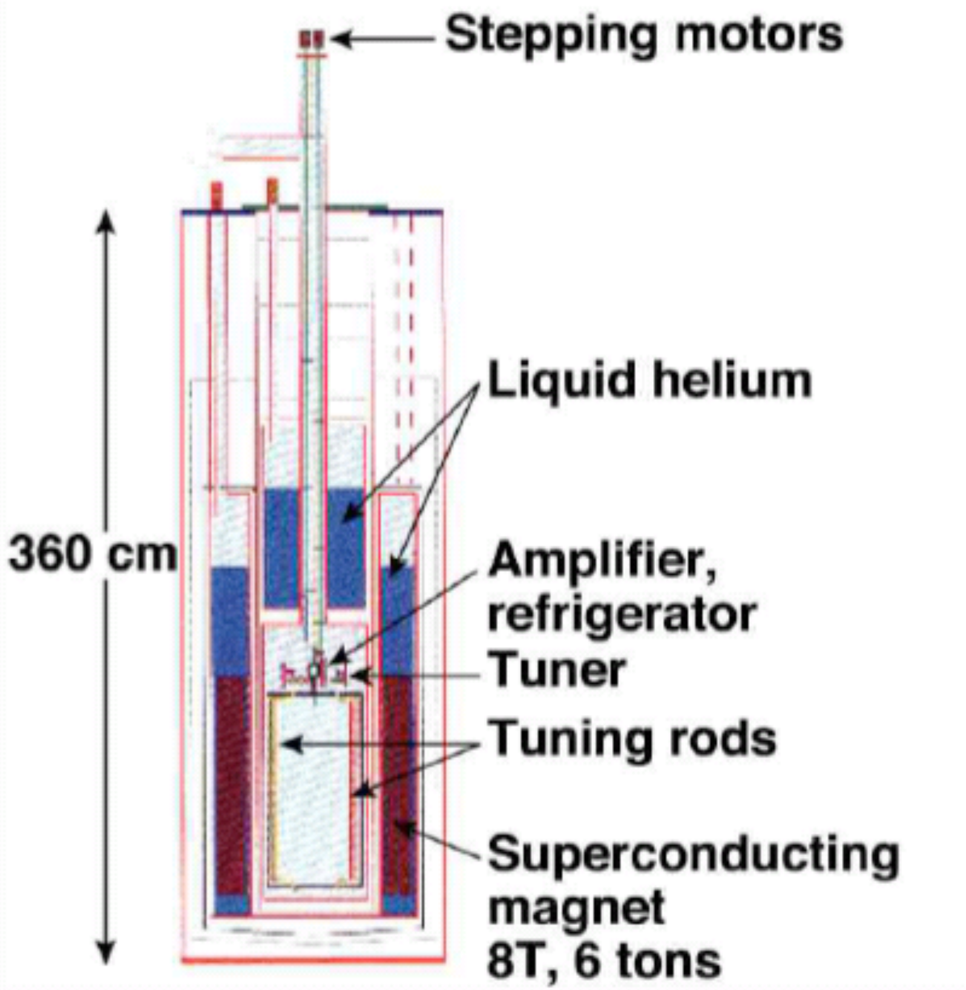


$$h\nu = m_a c^2 [1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

How it looks I

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

8 T, 1 m × 60 cm ∅

How it looks II

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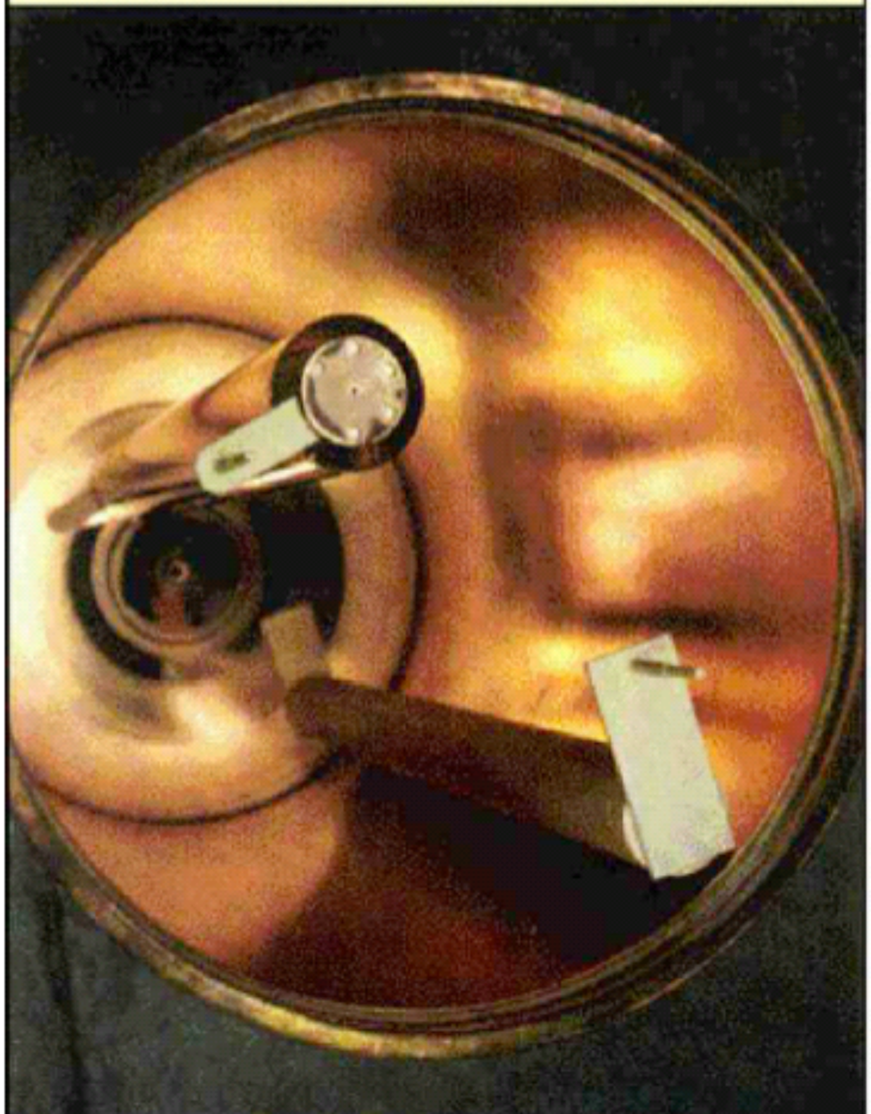
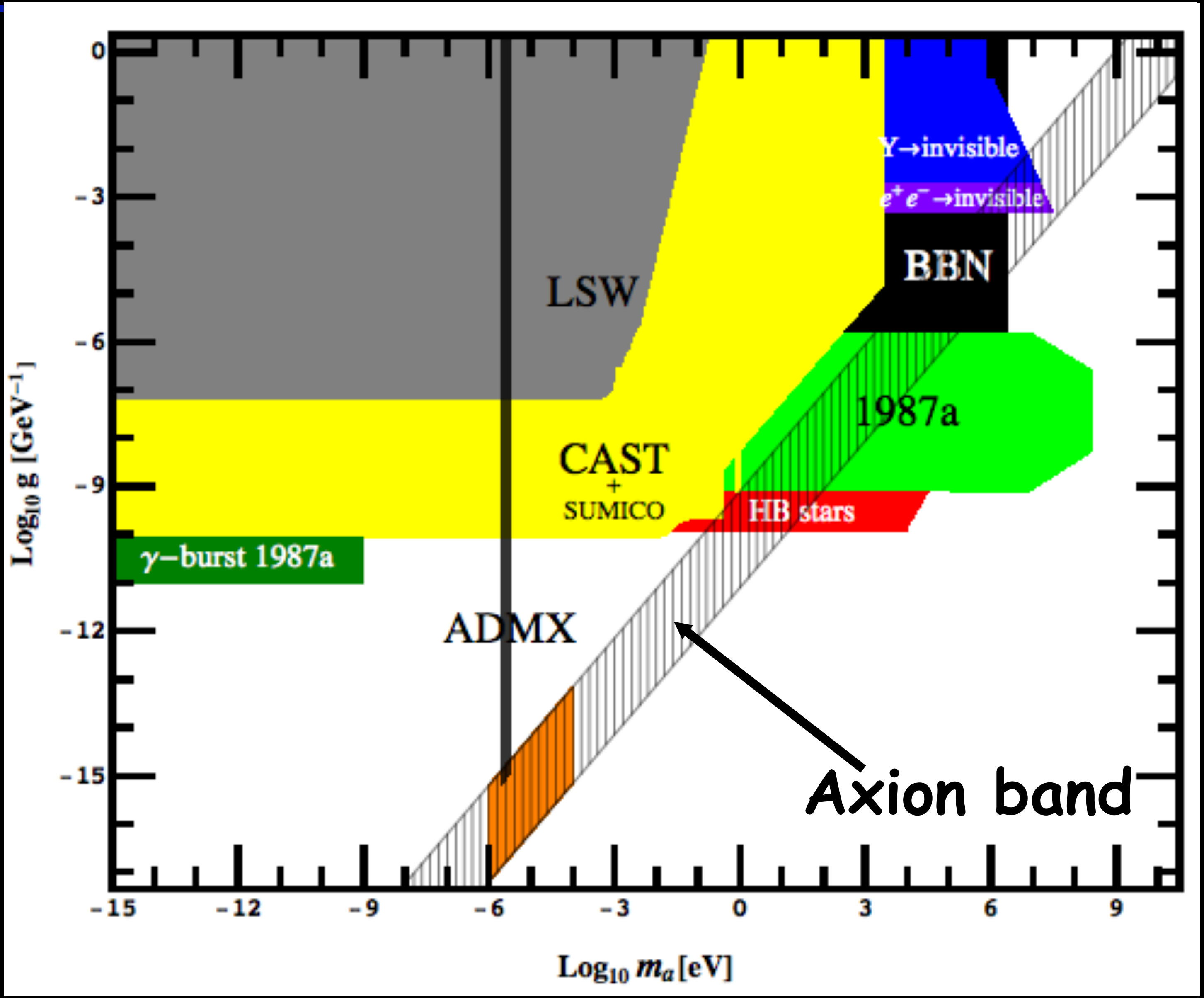
High-Q Cavity (~200,000)



Experimental Insert

Exciting times!!!



Hidden Photon Dark Matter

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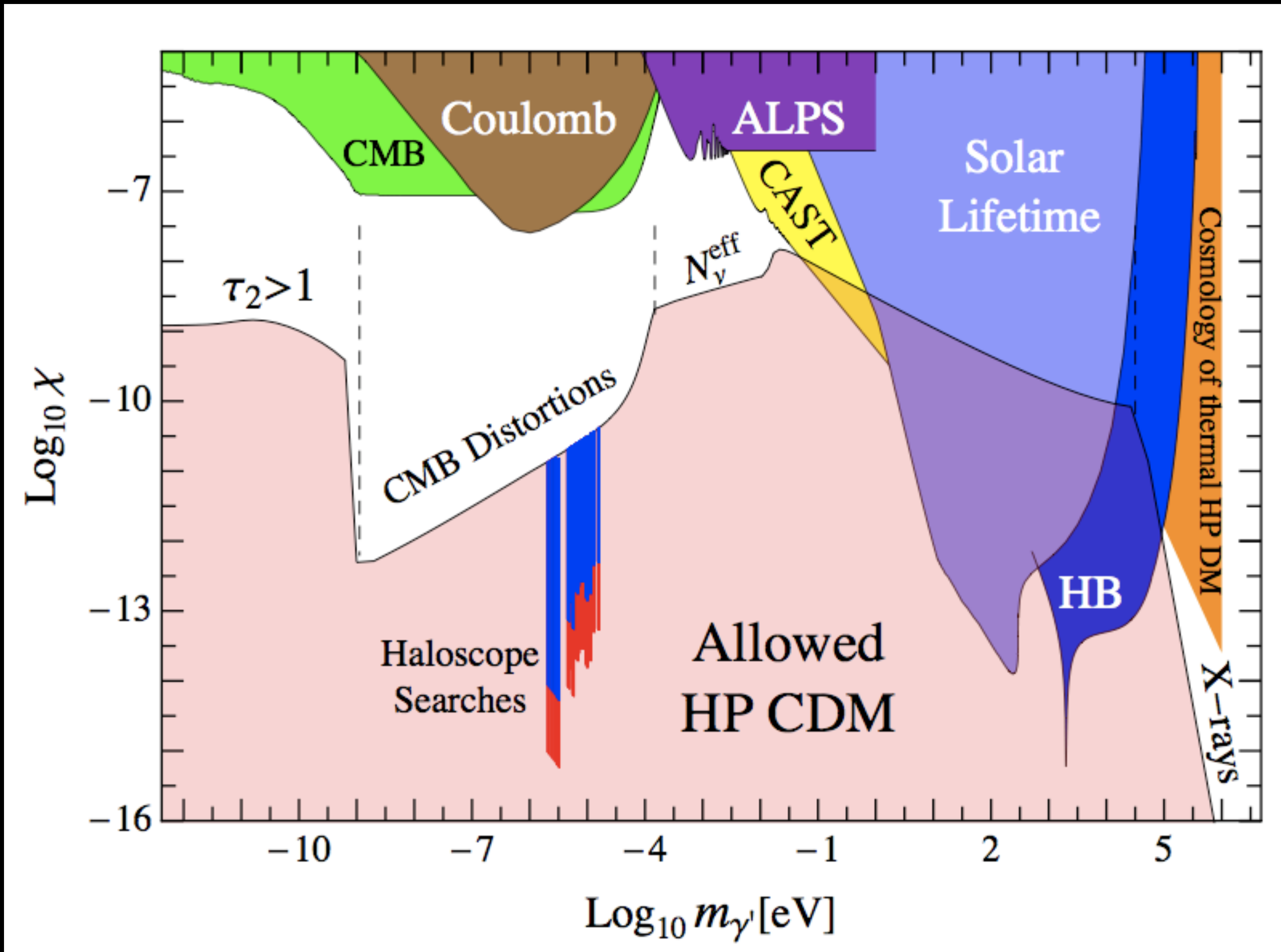
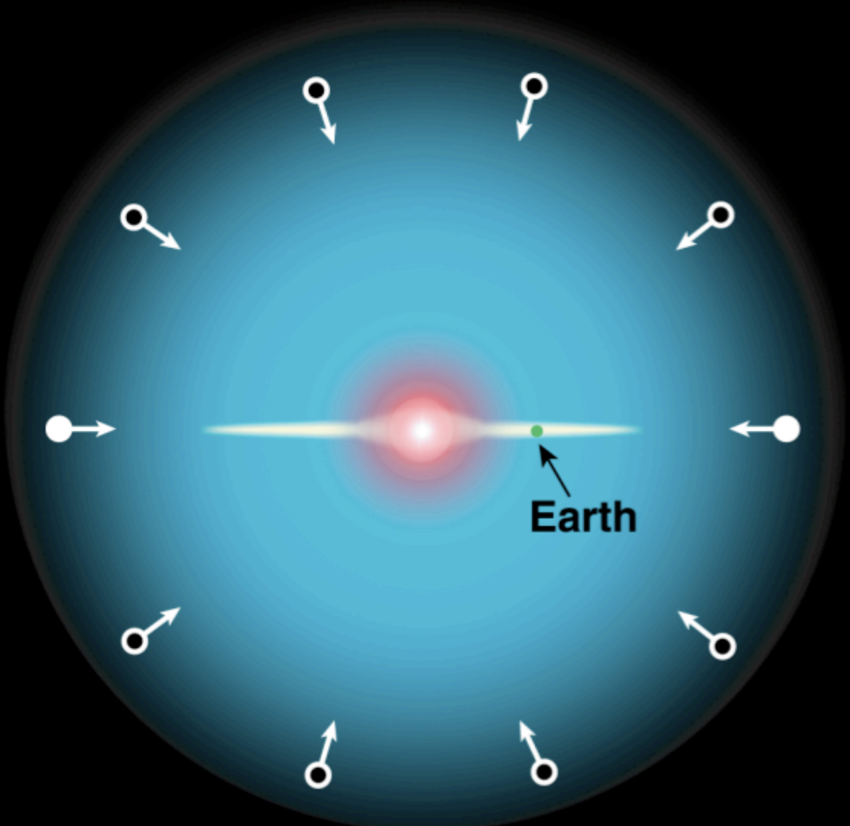
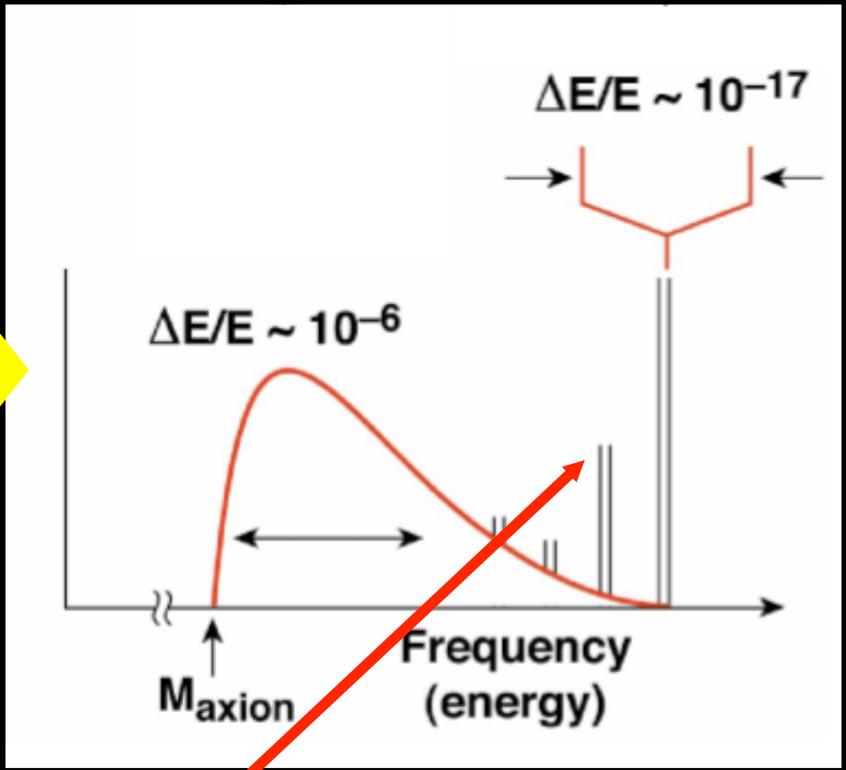


Measuring structure (formation)

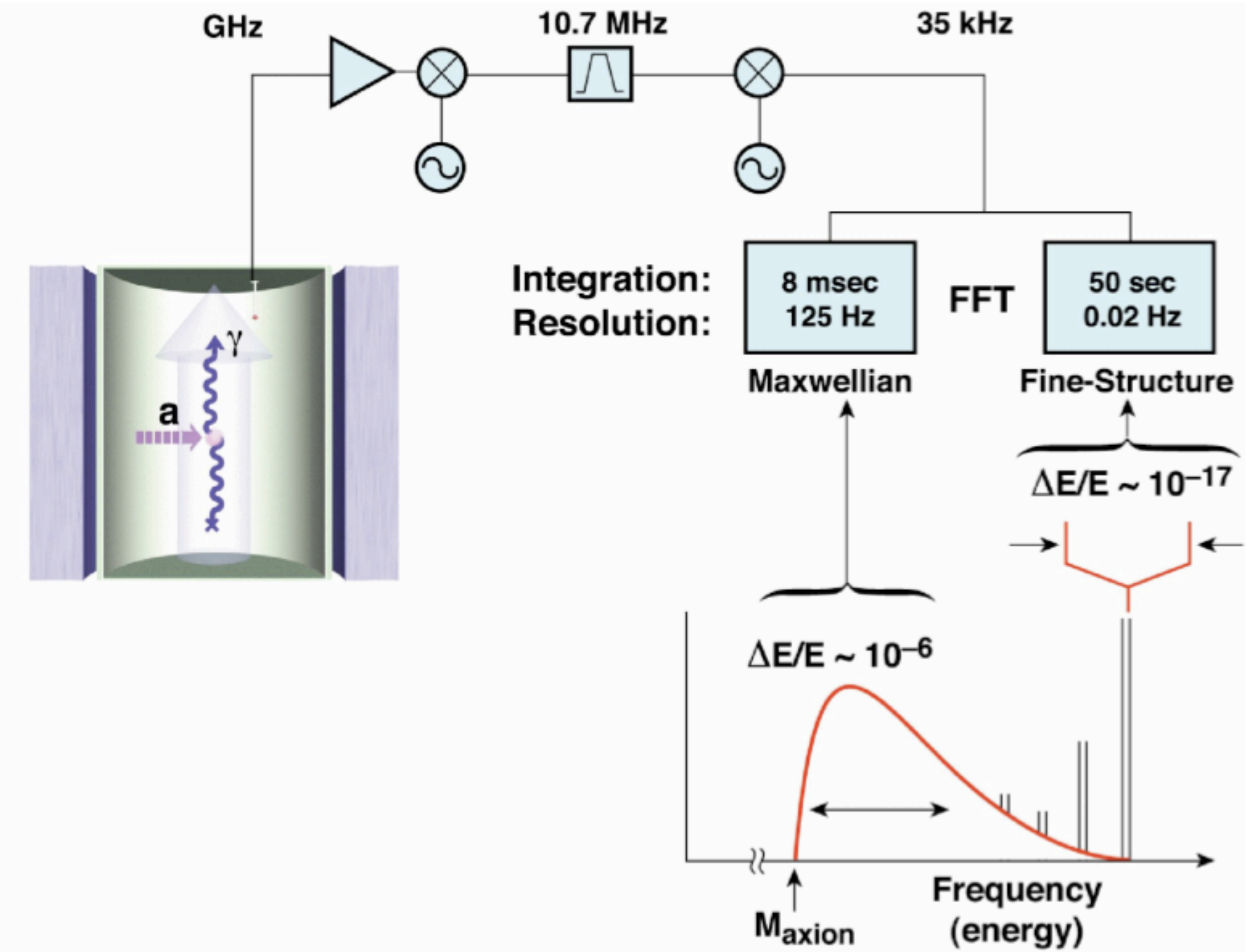
Example: infall of matter





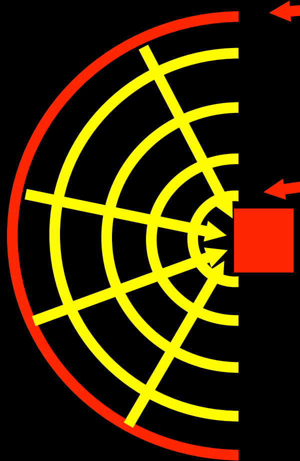
Features in the velocity/energy spectrum of dark matter

Detect these features in ADMX



Broadband Search Strategy

Dark Matter Antenna

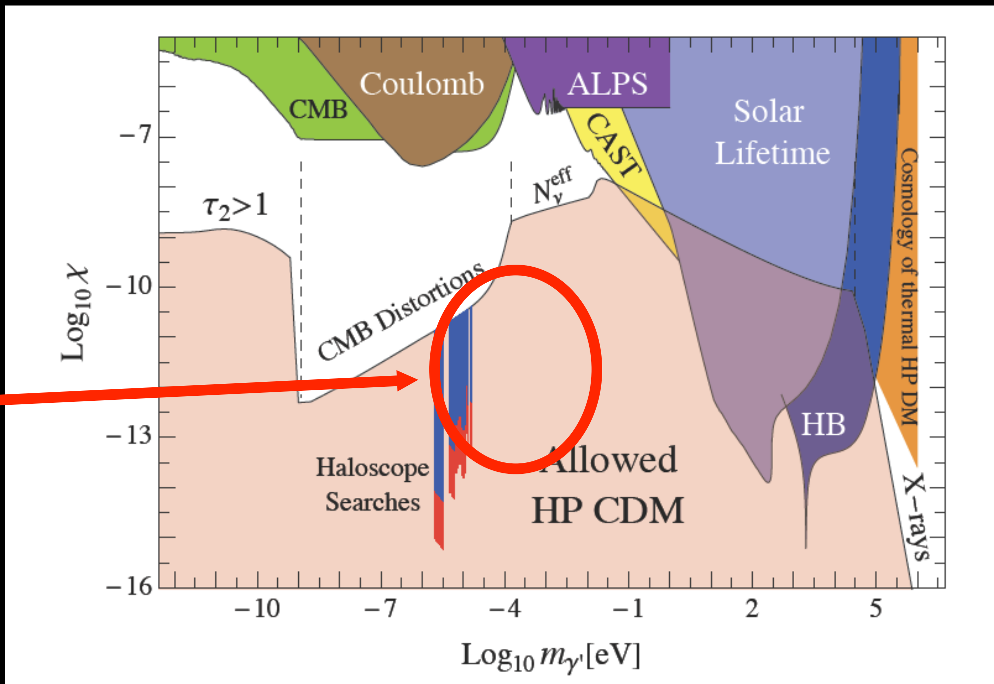


Antenna converts HP->photon

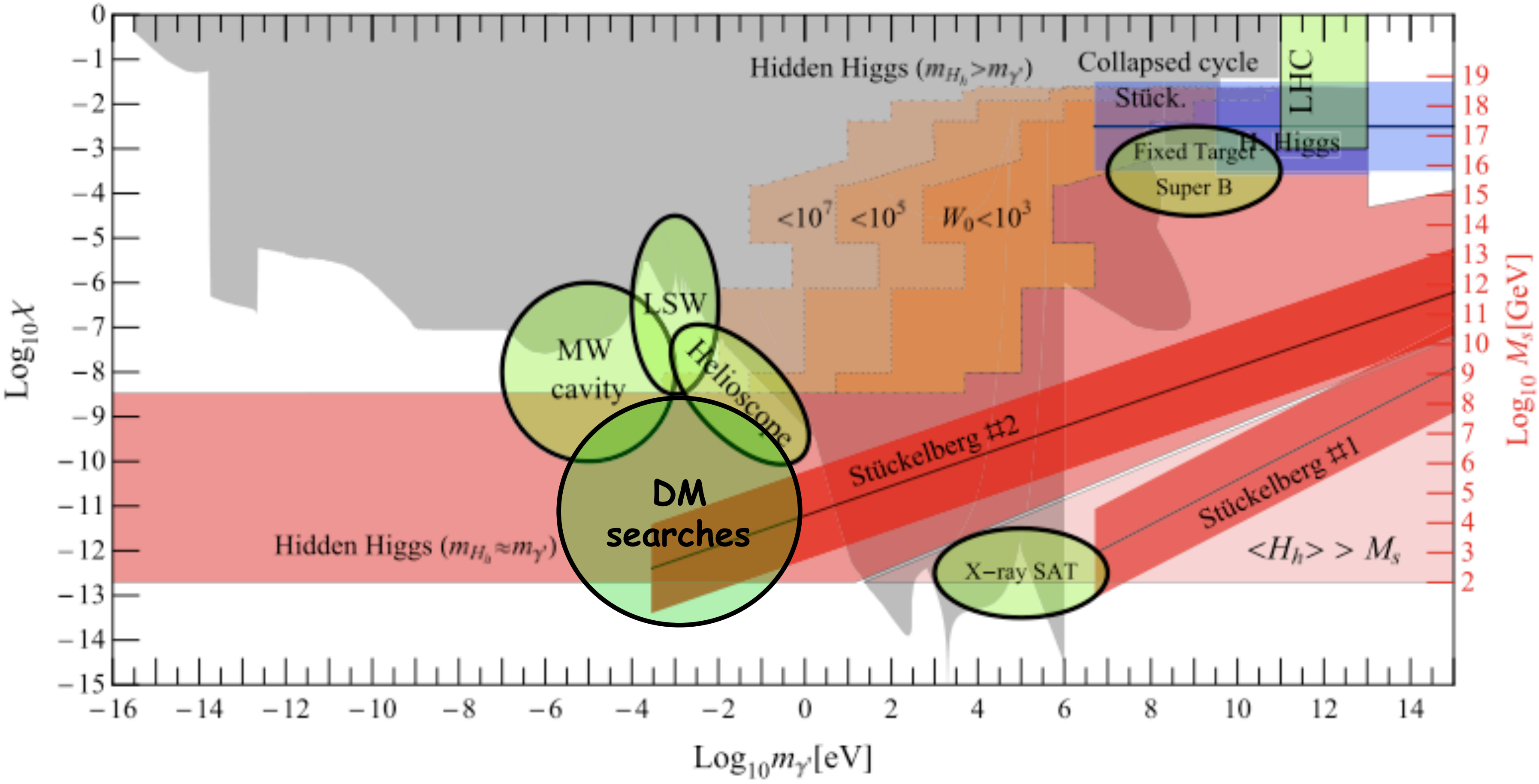
Radiation concentrated in center

Detector

Probes here;
very sensitive!!



Many more tests...



Exciting things go on NOW!!!

Conclusions

Conclusions

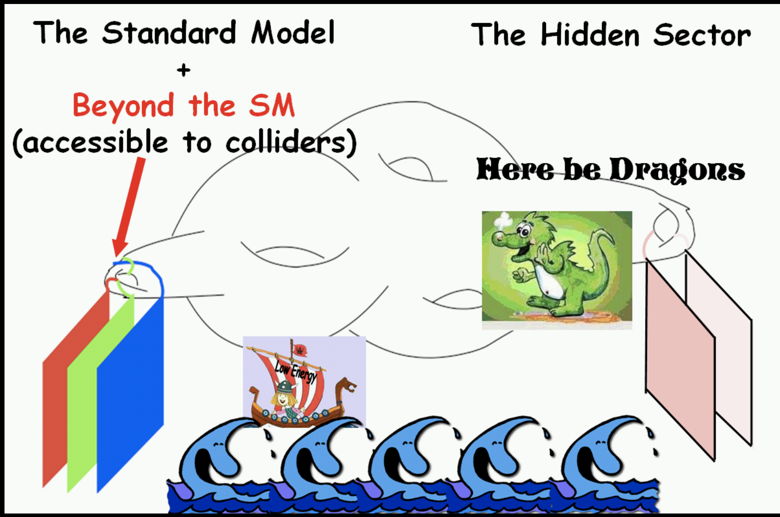
- Good Physics Case for Axions and WISPs

  ➡ explore `The Low Energy Frontier'

- Low energy experiments test energy scales much higher than accelerators

  ➡ Complementary!

- May provide information on hidden sectors and thereby into the underlying fundamental theory



- Dark Matter may be light ☺


Discover the Hidden Islands