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Fondamental Physics at Low Energies

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Fundamental Physics
@
Low Energies

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For a review see, JJ and A. Ringwald 1002.0329

Where we want to go…

The Standard Model

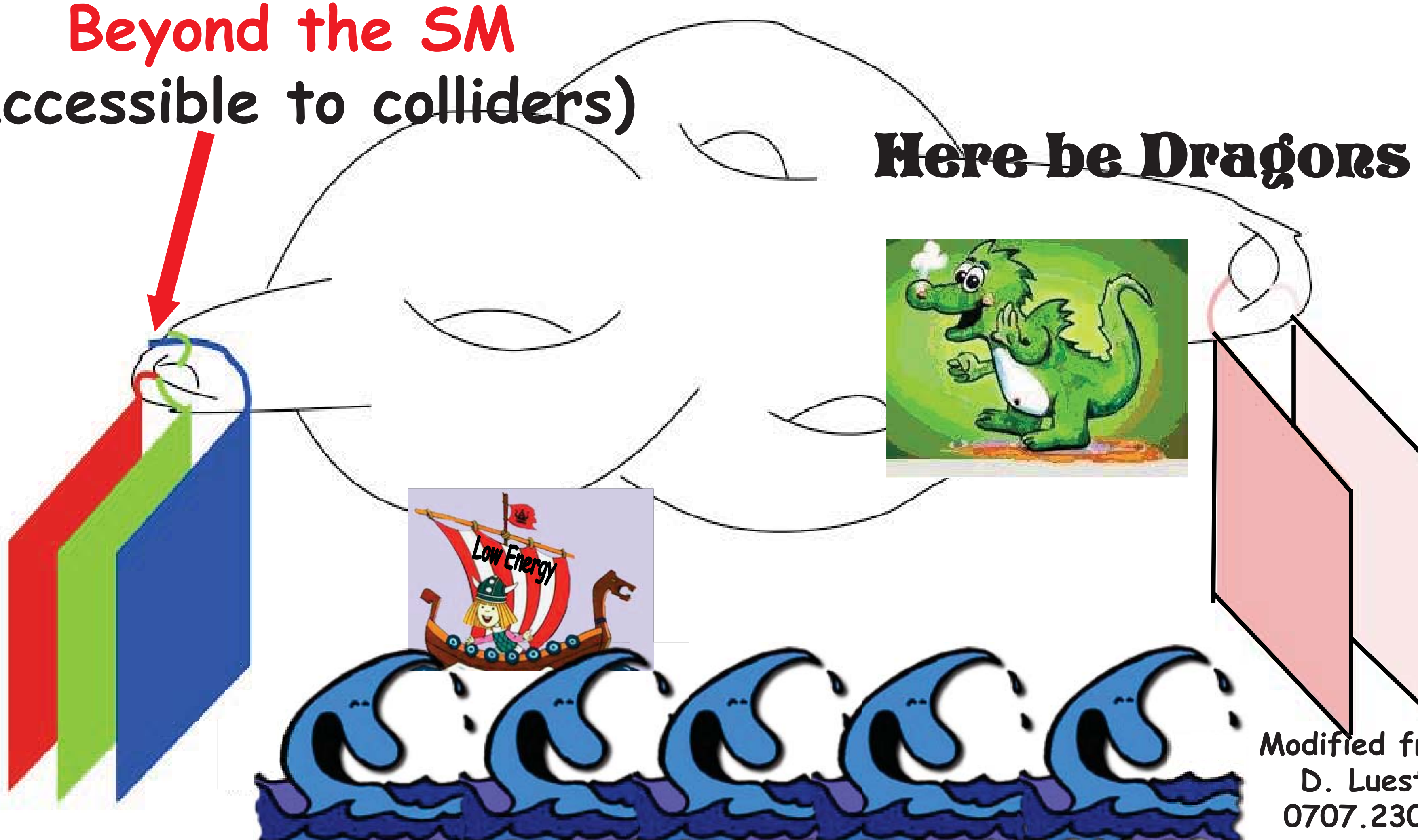
+

Beyond the SM

(accessible to colliders)

The Hidden Sector

Here be Dragons



Modified from
D. Luest
0707.2305

1.
The Physics Case
(for a low energy frontier
of particle physics)

The Standard Model

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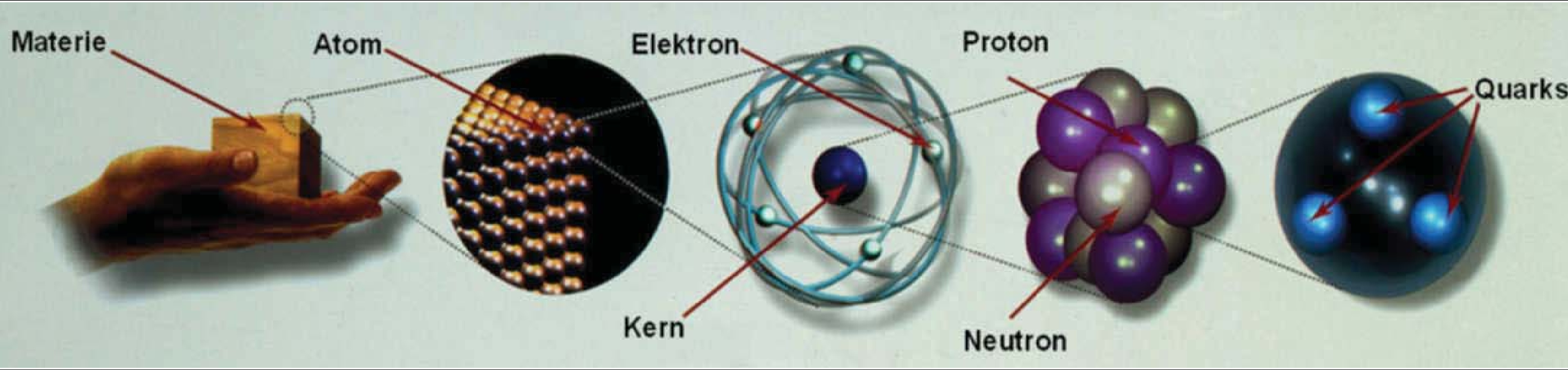


	Quarks		Leptons	
	Charge +2/3	Charge –1/3	Charge –1	Charge 0
1. Family	Up u	Down d	Electron e	e-Neutrino ν_e
2. Family	Charm c	Strange s	Myon μ	μ-Neutrino ν_μ
3. Family	Top t	Bottom b	Tau τ	τ-Neutrino ν_τ

Gravitation → graviton

Weak forces → W- und Z-bosons

Electromagnetism → photons (γ)

Strong forces → gluons

We need...

Physics beyond the Standard Model

Hints for new Physics

Uglyness of old models

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

- Naturalness problems. Finetuning.

  Examples:

  Higgs mass, θ-angle (strong CP-problem)

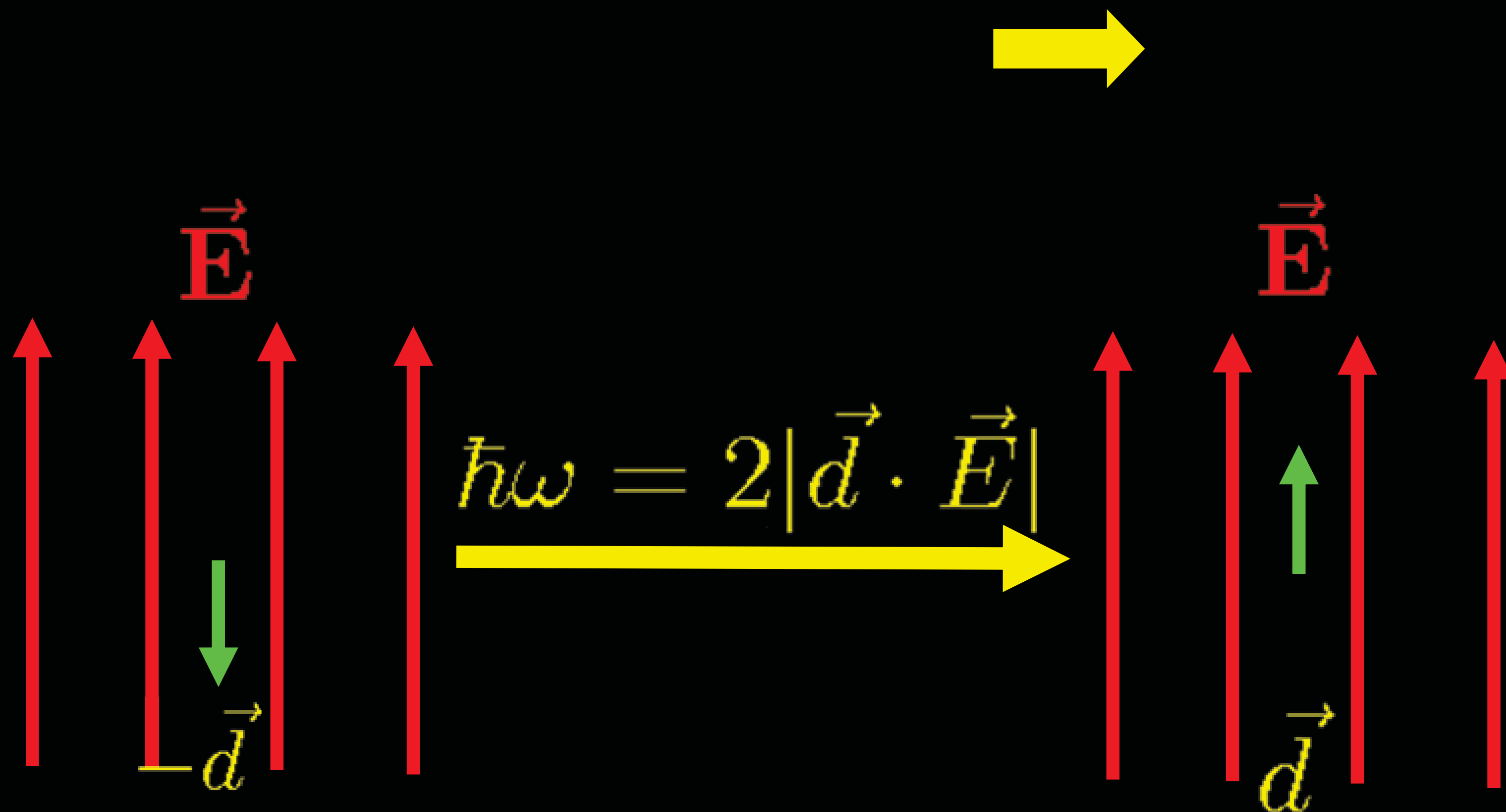
A dirty little secret...

$$S = \int d^4x \Big[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu}$$
$$+ i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \Big]$$

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

Measure electric dipole moment of the neutron!

Neutron electric dipole moment



Measure transition frequency.

No neutron electric dipole moment...

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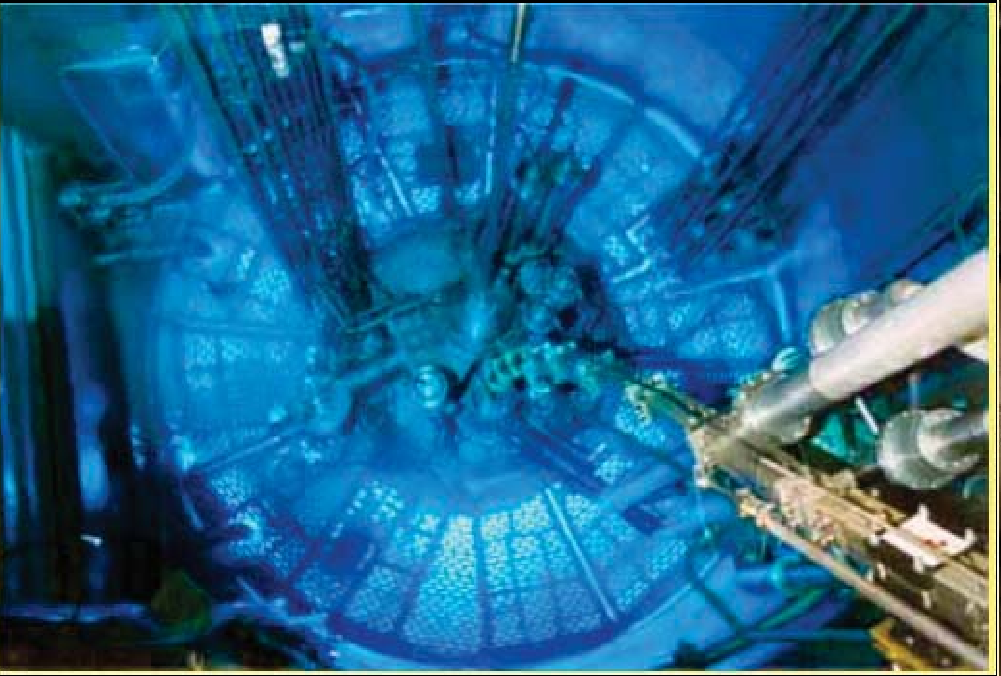
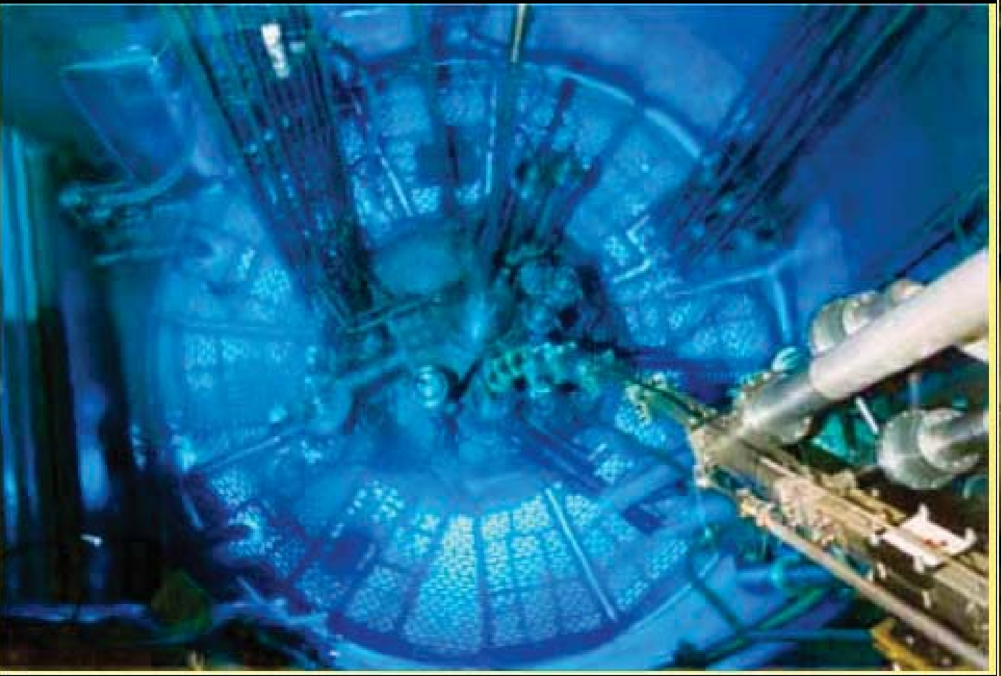


$$|\vec{d}| < 3\,10^{-26} e\,cm$$
$$= 3\,10^{-13} e\,fm$$

See also
https://neutronedm.org

No neutron electric dipole moment...



$$|\vec{d}| < 3\,10^{-26} e\,cm$$
$$= 3\,10^{-13} e\,fm \lll\lll \frac{1}{16\pi^2} e\,fm\,\theta$$

⇒ Very unnatural!

More precisely

- Detailed calculation gives

see e.g., J.E. Kim Phys.Rept. 150 1987

$$|\vec{d}| \sim 1 - 10 \times 10^{-16} e\, cm\, \theta$$

$$\Rightarrow \quad |\theta| < 3\, 10^{-10}$$

$\Rightarrow$ **Extremely unnatural!**

Strong CP Problem

Uglyness of old models

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

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

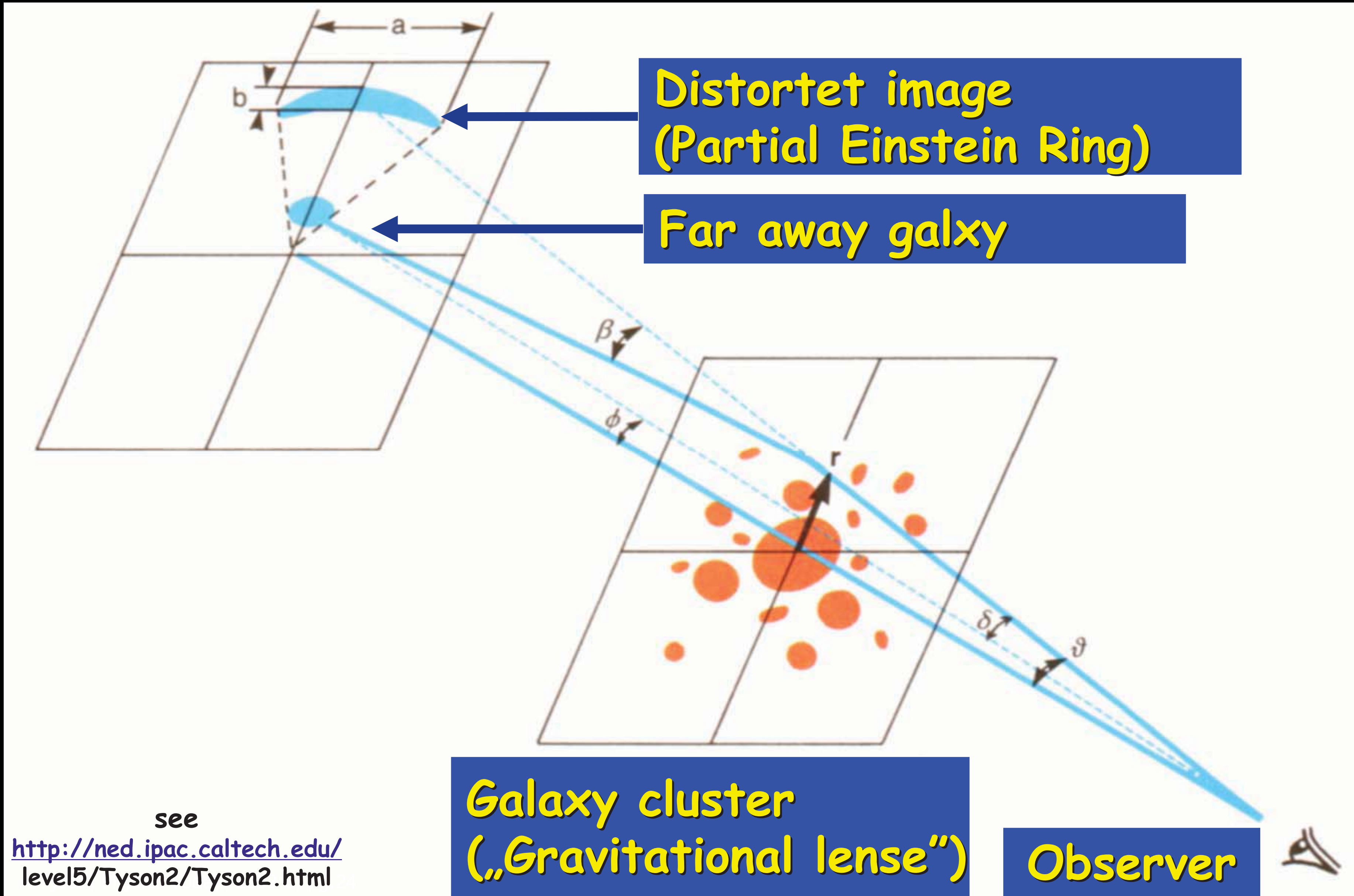
- Gravity separate, i.e. not unified.

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

Unexplained Stuff

- Dark Matter (25%)
  (astrophysical + cosmological observations)

Gravitational lenses



see
http://ned.ipac.caltech.edu/
level5/Tyson2/Tyson2.html

Gravitationslinsen Abell 2218

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)

Fix problem
`here and now'

Top-down (theory)

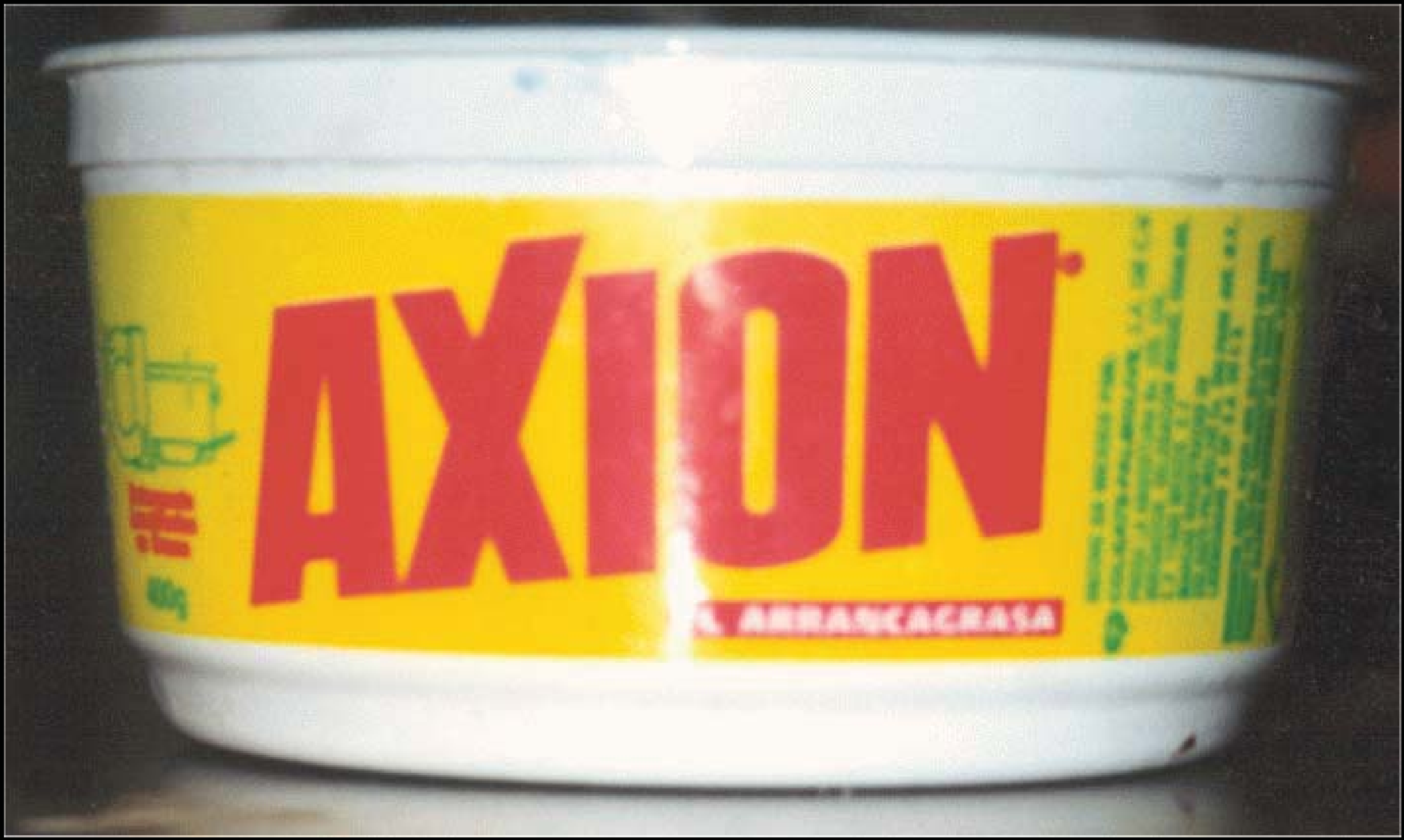
Go back to drawing board
`Start from scratch'

The Axion

Commercials

Your CP is violated too strongly?

Use Axion!



New! With special cleaning particles and extra strong photon coupling.

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

- **Idea:** see e.g., J.E. Kim Phys.Rept. 150 1987 and references therein
  - Make θ a dynamical degree of freedom a.
  - Let a have no tree level potential
  - Let a have only derivative couplings
- **Then:**

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

$\Rightarrow$ a will evolve to a=θ=0

$\Rightarrow$ CP is conserved

What is a?

- Properties:
  - Let a be a dynamical degree of freedom.
  - Let a have no tree level potential
  - Let a have only derivative couplings
  - $a/f_a \in [0,2\pi]$ 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 $\sim f_X$
  - Coupling to $G\tilde{G}$: $\sim \frac{a}{f_X} G^{\mu\nu}\tilde{G}_{\mu\nu}$
  - Scale of explicit breaking $\sim \frac{1}{f_X} m_\pi^2 f_\pi^2$

⇒ Goldstone mass $m_a^2 \sim \frac{\Lambda^4}{f_X^2}$

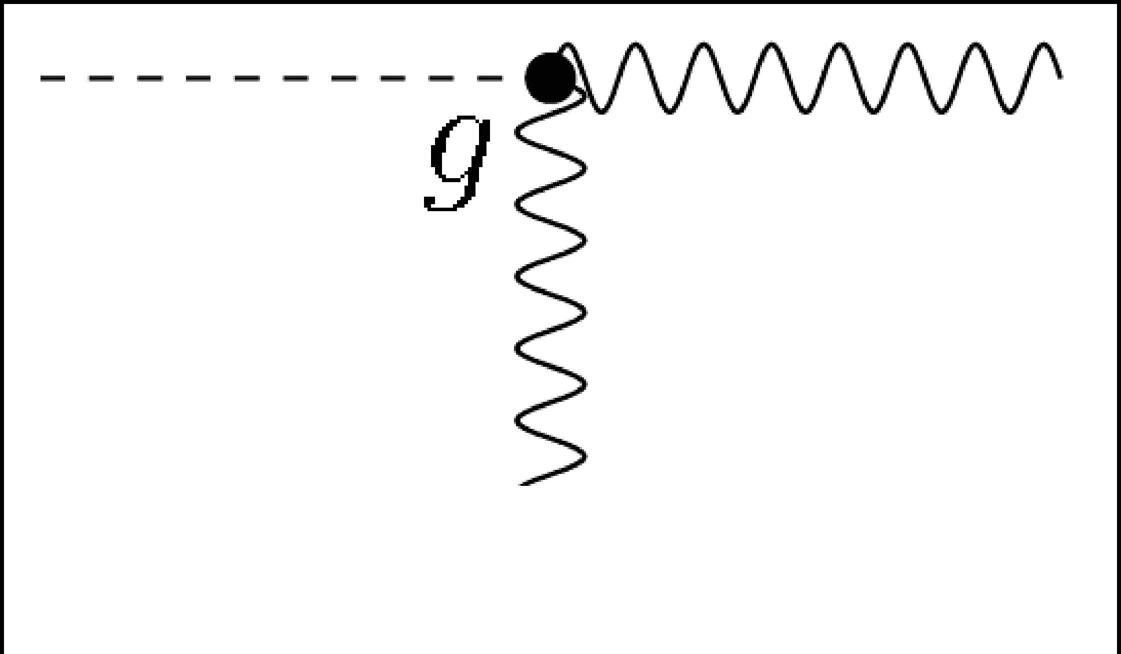
Large scale

↓

Small coupling

The axion couples to two photons

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



Axion coupling to two photons

- Effective higher dimensional coupling

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

Coupling to two photons!

- Small coupling for large axion scale:

Small

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

Large

Large scale

Small mass

Axion See-Saw

- The axion mass is small, too!

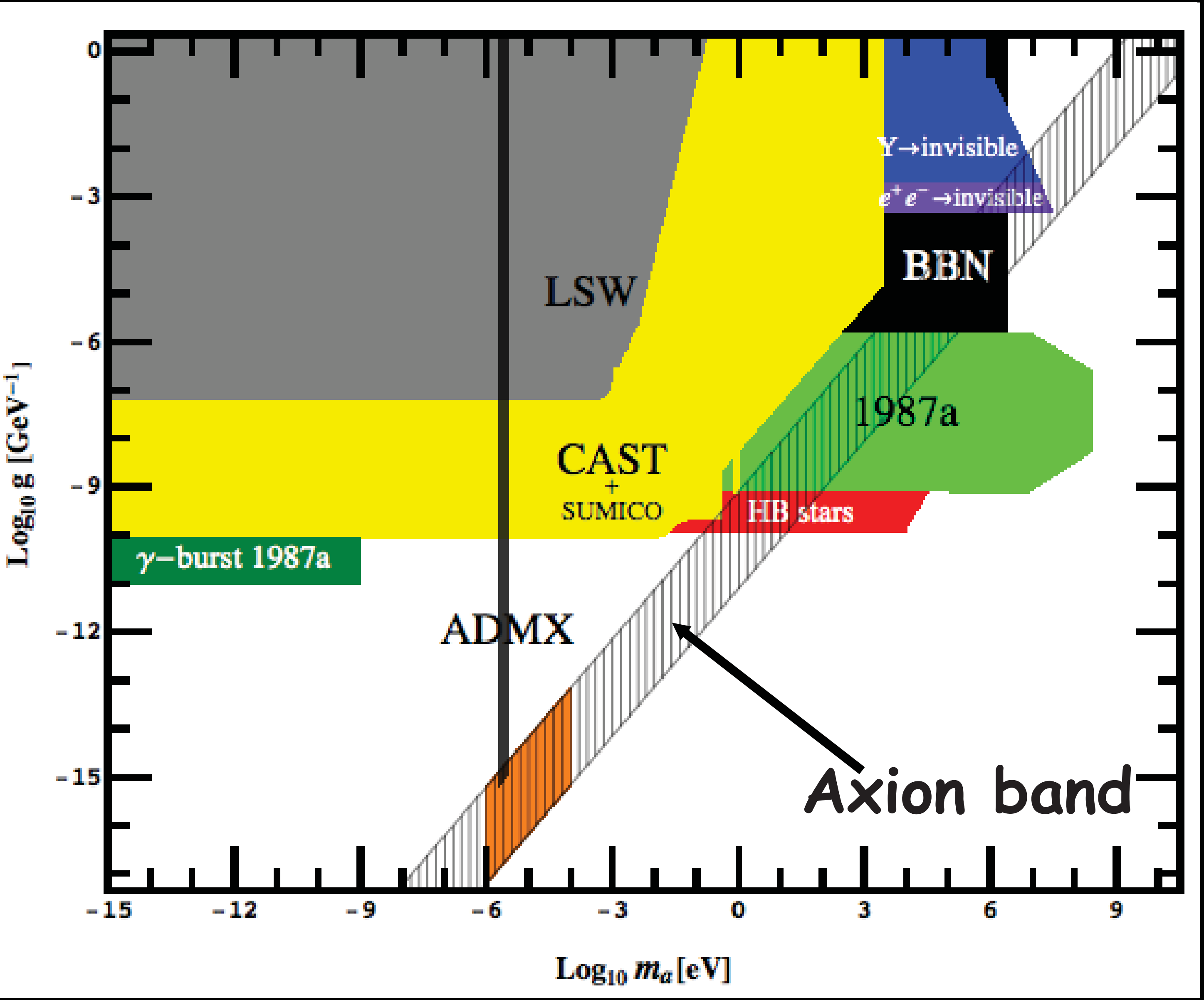
$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

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

Sub-eV mass

Large scale

Axions live at small mass and coupling



The strong CP problem: Axions

- Introduce new Peccei-Quinn symmetry to solve naturalness problem

- Predict as a consequence a new particle: The Axion

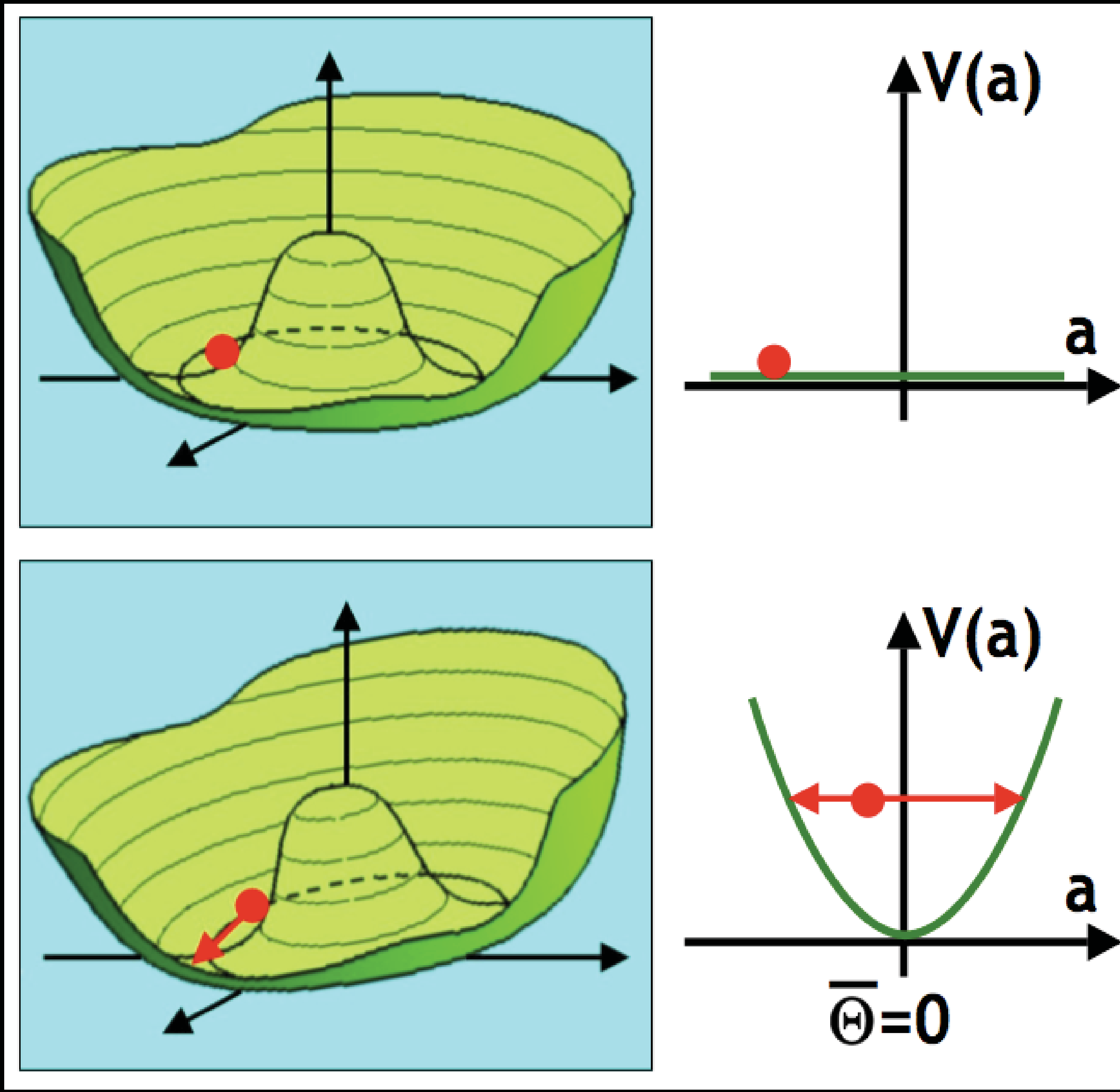
  (it's a Weakly Interacting Sub-eV Particle)

Good motivation for axion/WISP experiments

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



see S. Hannestad at Patras 2009

Oscillations behave like dark matter

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- 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**

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

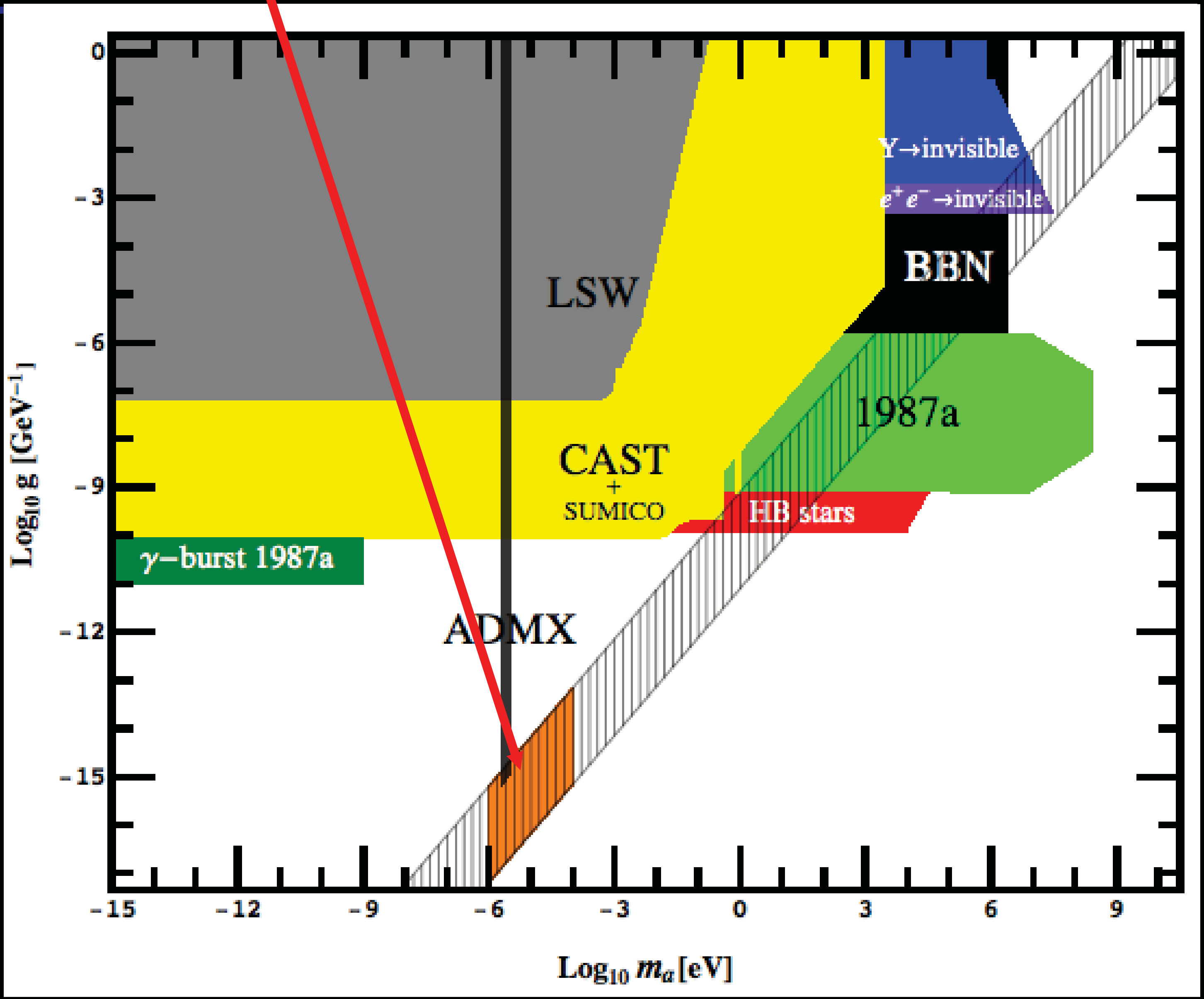
Too much?

- 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



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!

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

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

The strong CP problem: Axions

- Introduce new Peccei-Quinn symmetry to solve naturalness problem

- Predict as a consequence a new particle: The Axion

  (it's a Weakly Interacting Sub-eV Particle)

Dark matter candidate

Good motivation for axion/WISP experiments

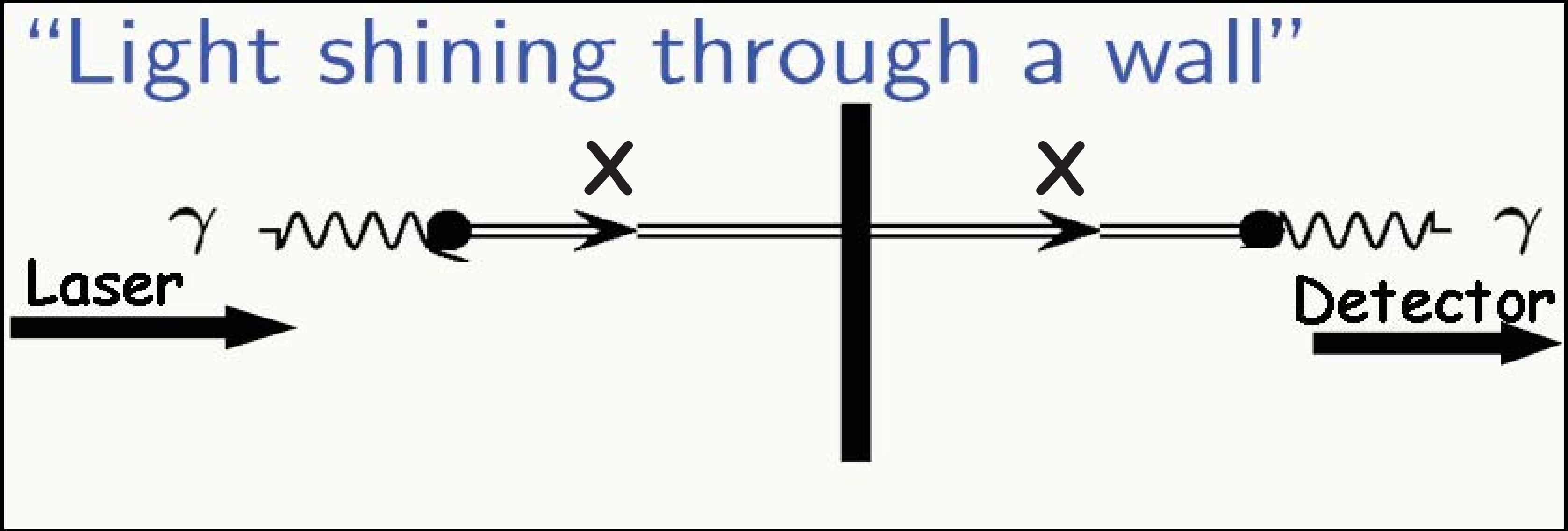
A reason for Experimentalists!!!

Very cool experiments:

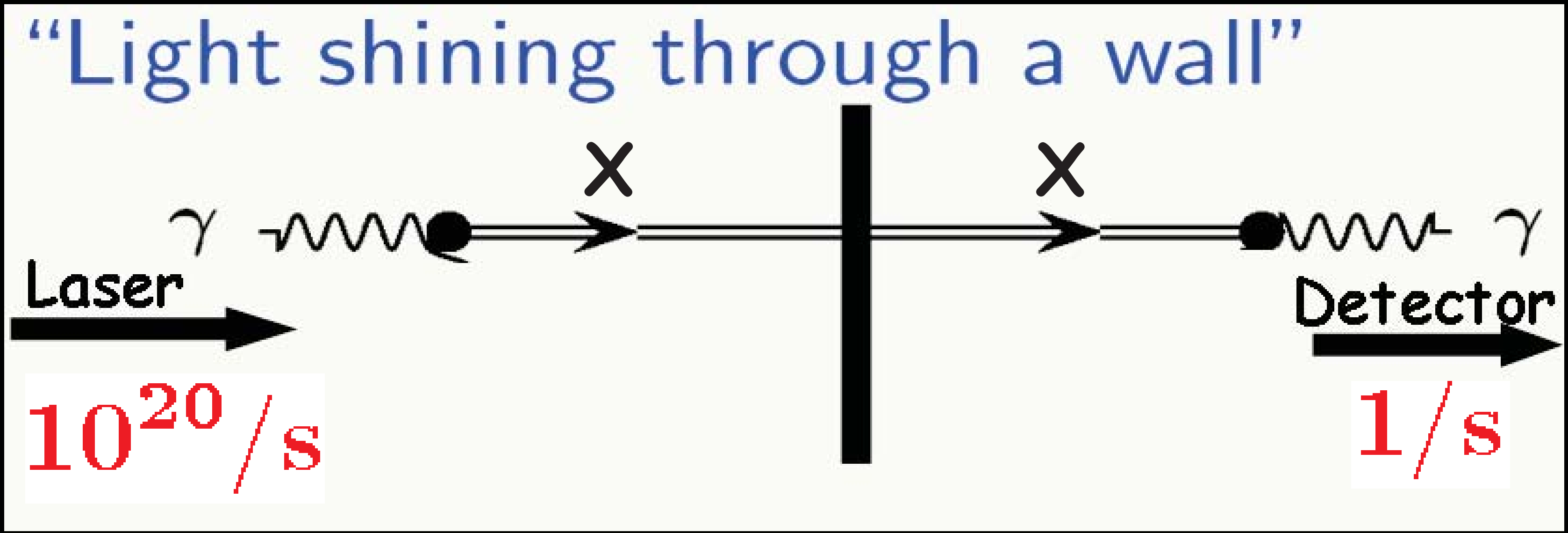
Light shining through walls

(preview for Saturday)

Light shining through walls



Light shining through walls

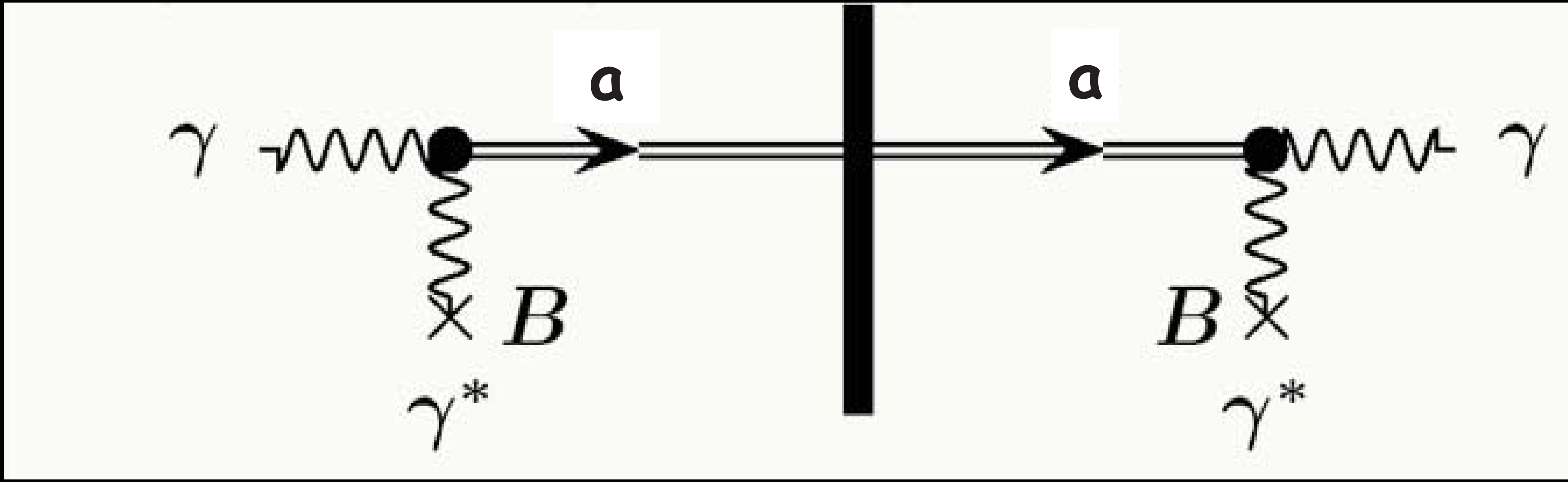


- Test $P_{\gamma \to X \to \gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

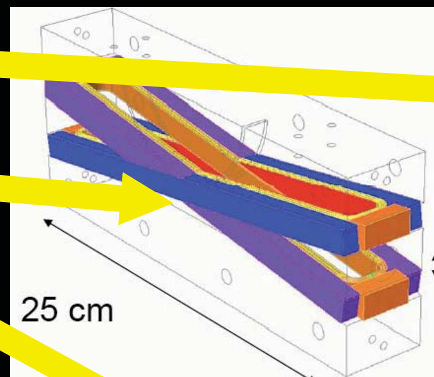
- It could be Axion(-like particle)s!
- Coupling to two photons: $\frac{1}{M} a\tilde{F}F \sim \frac{1}{M} a\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$

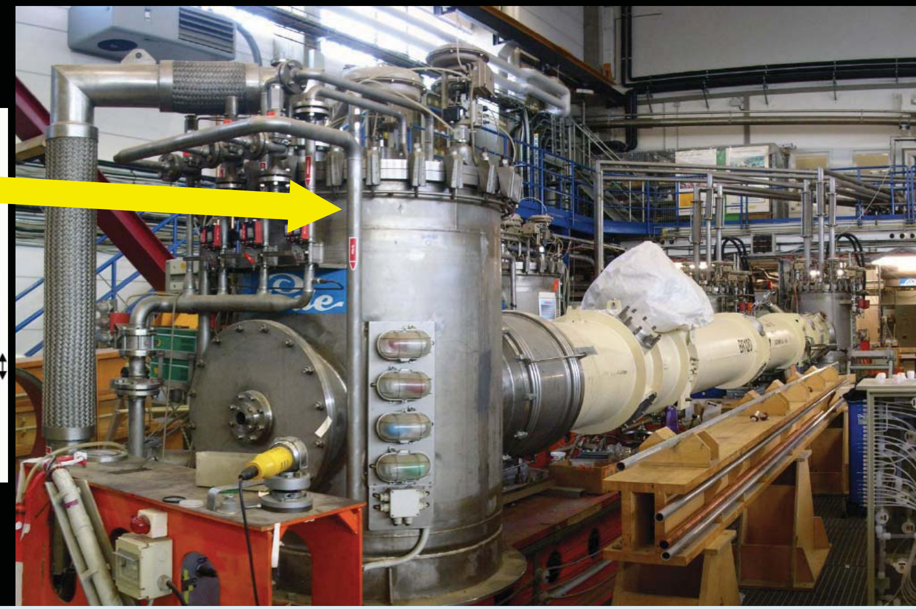


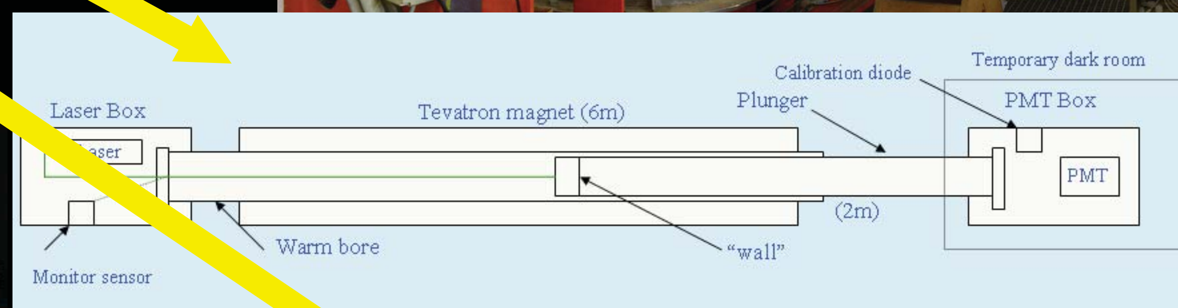
$$P_{\gamma\to a\to\gamma} \sim N_{\text{pass}} \left(\frac{BL}{M}\right)^4$$

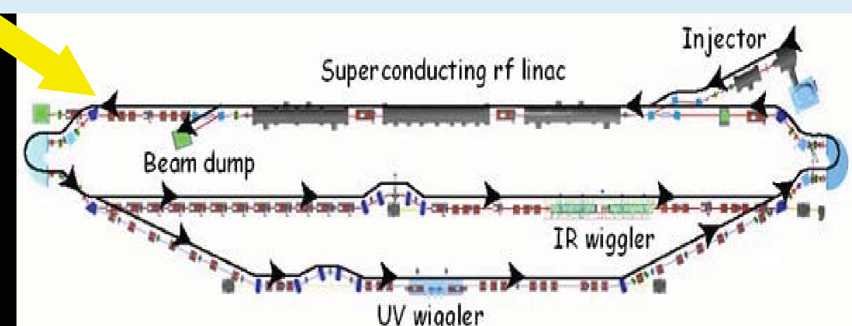
Light Shining Through Walls

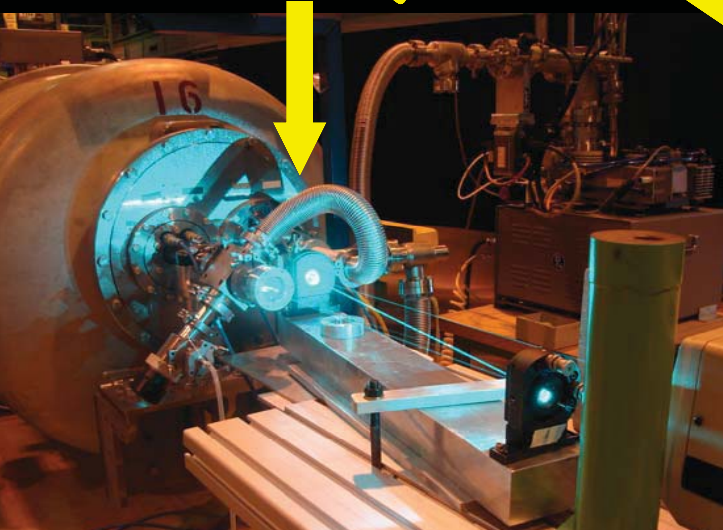
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR



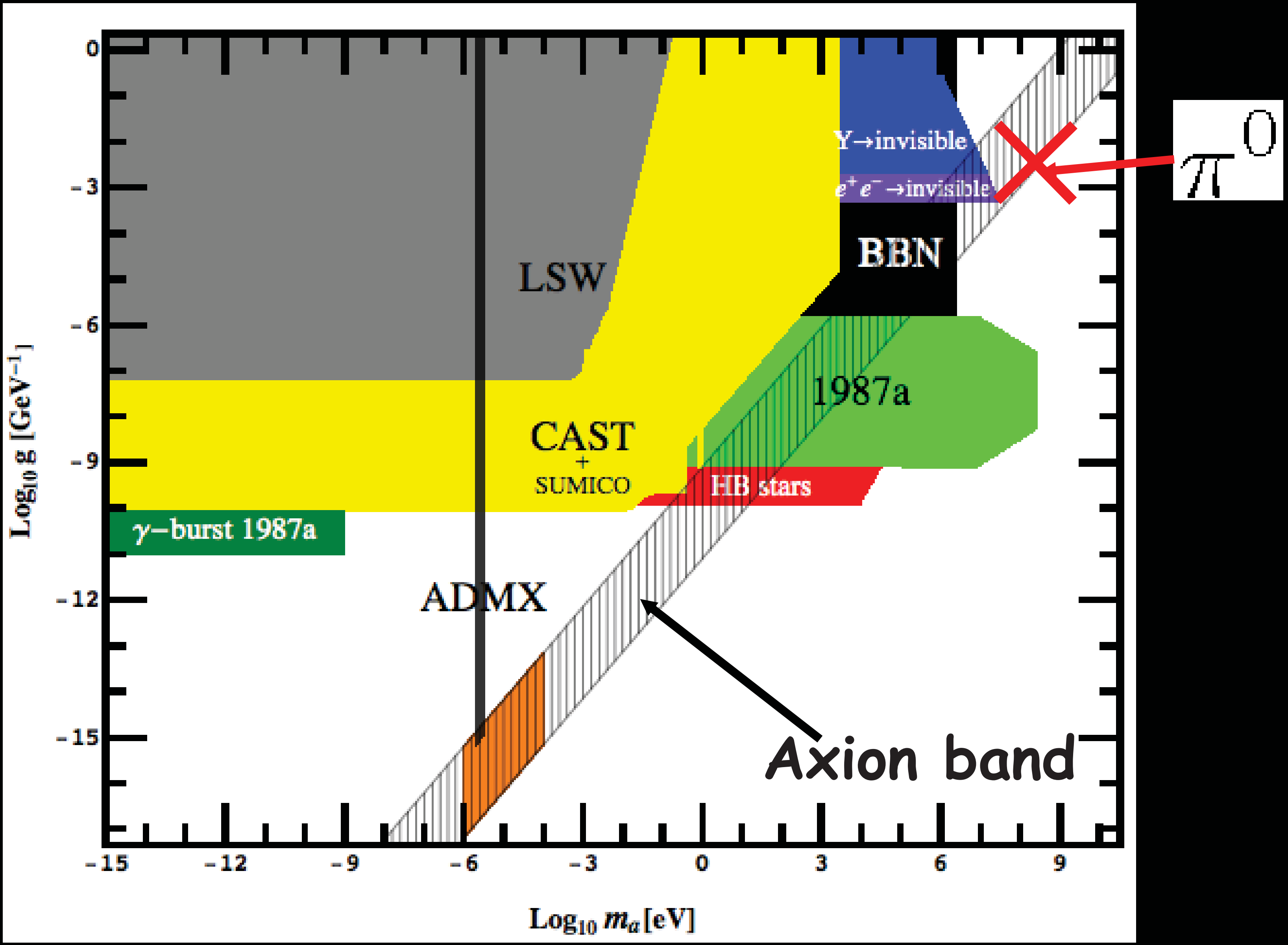








Small coupling, small mass



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

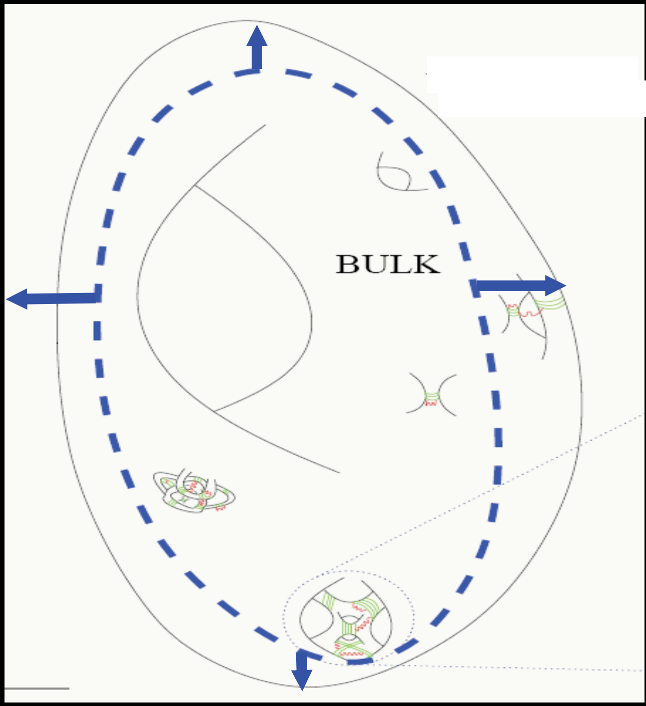
Axion(-like particles)

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

Axions and Moduli

- Gauge field terms

$$\mathcal{L} = \frac{1}{g^2} F^2 + i\theta F\tilde{F}$$

+ Supersymmetry/supergravity

$$\mathcal{L} = \mathrm{Re}[f(\Phi)]F^2 + \mathrm{Im}[f(\Phi)]F\tilde{F}$$

Scalar ALP/moduli coupling + pseudoscalar ALP coupling

see J. Conlon at Patras 2009

Axions and Moduli

- Gauge couplings always field dependent (no free coupling constants)
- Axions + Moduli always present in String theory

Masses and Couplings

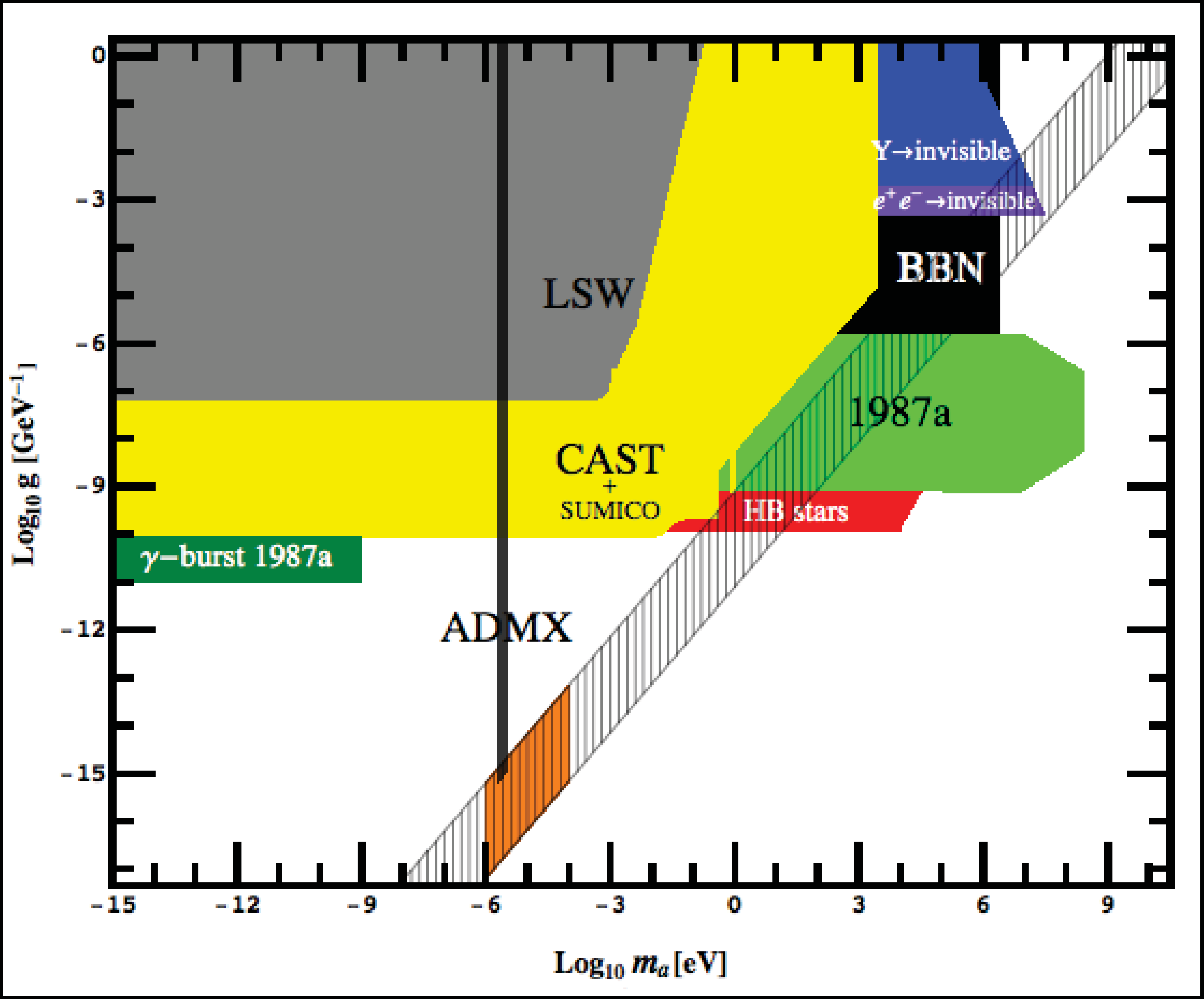
- "Axion scale" related to fundamental scale

$$f_a \sim \frac{M_P}{\mathrm{Volume}^x} \sim M_s \left(\frac{M_s}{M_P} \right)^y$$

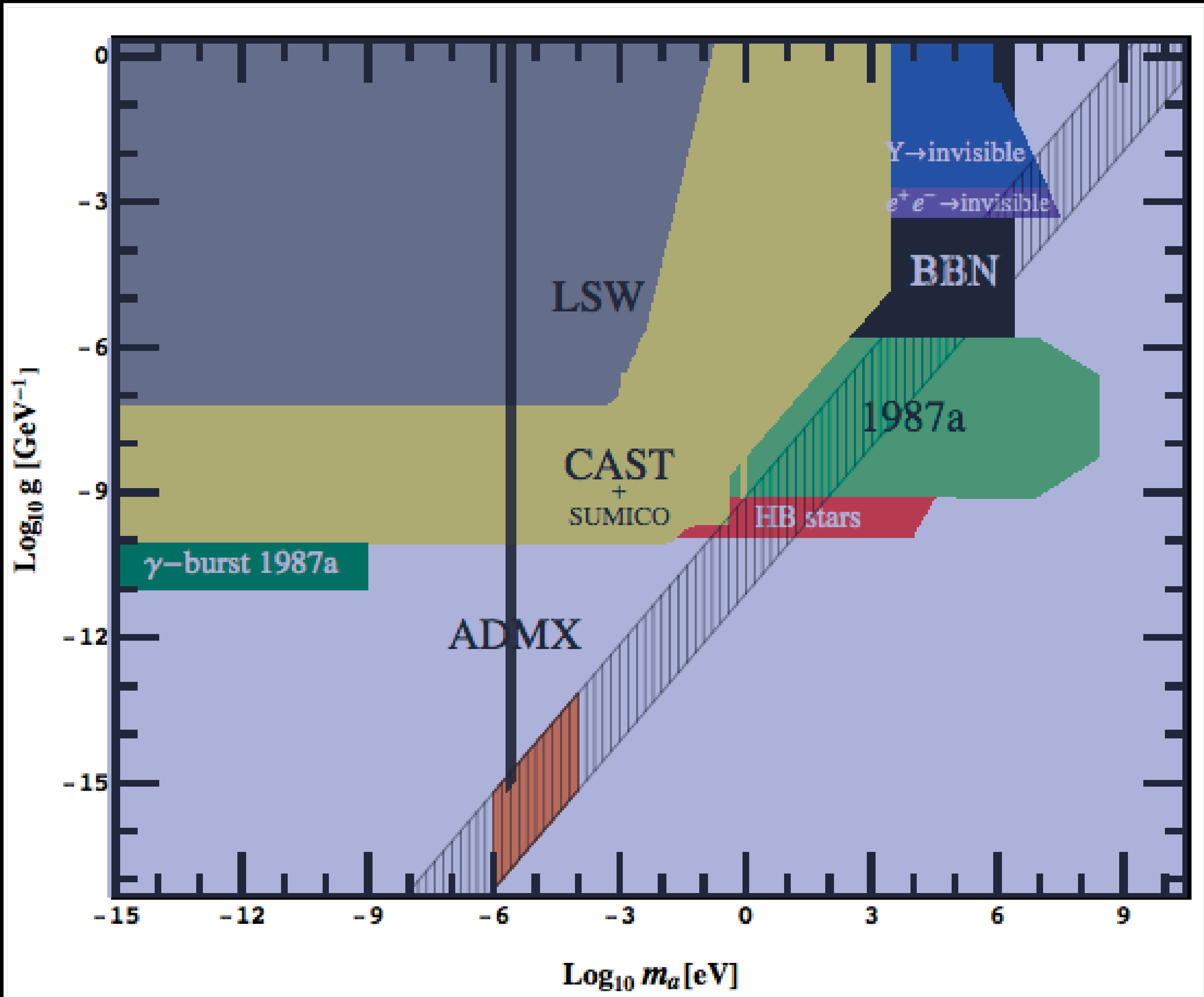
- If QCD axion: m_a fixed
- However, if not QCD axion

$$m_{\mathrm{ALP}} \sim \frac{\Lambda^2}{f_a}$$ (nearly) arbitrary

Axion (like particles): Where are we?

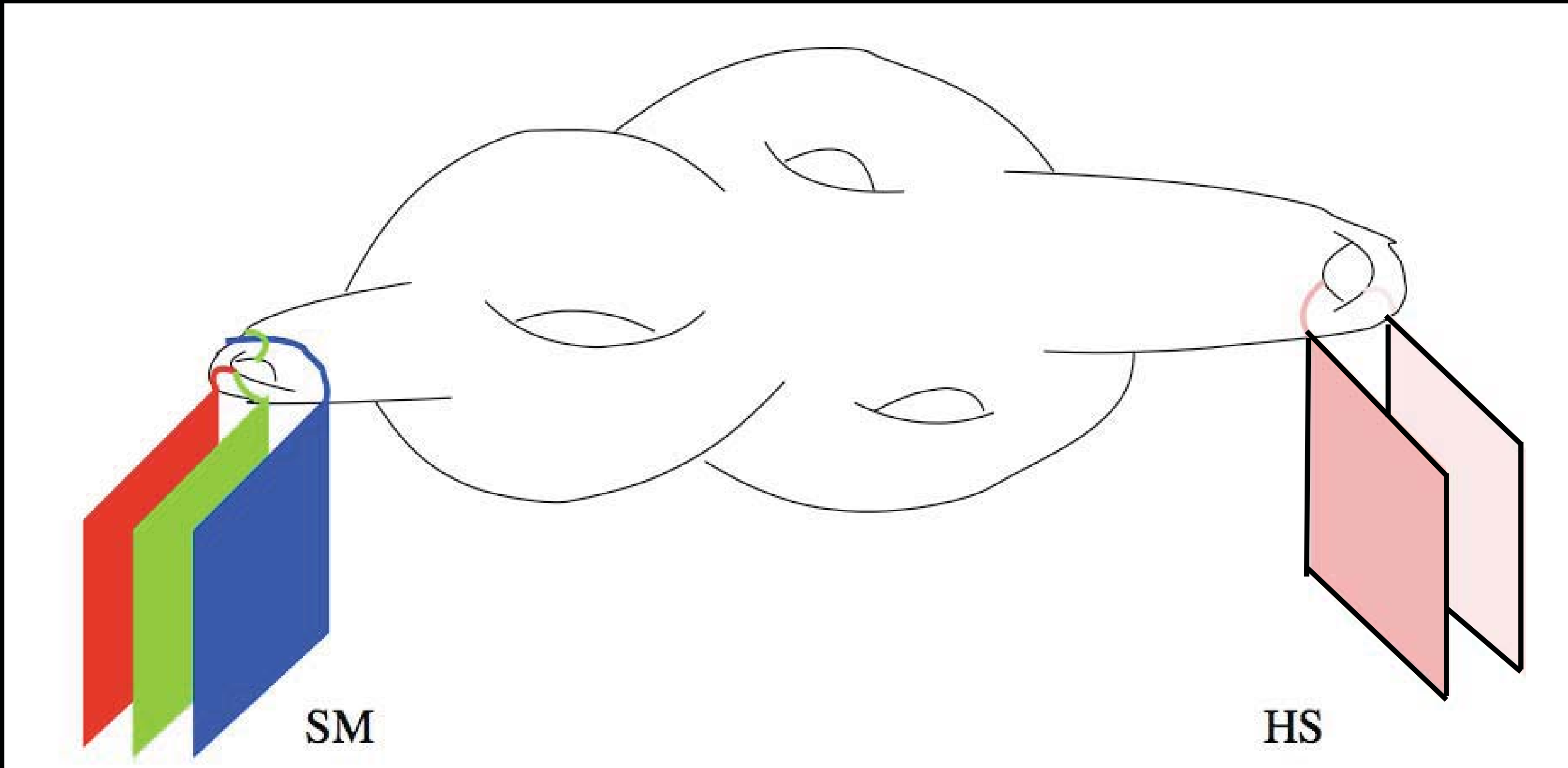


Axion (like particles): Where are we?



Hidden Photons

String theory likes extra gauge groups



D. Luest 0707.2305

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

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

Many extra U(1)s!

Candidates for WISPs

S. Abel, JJ, V. Khoze, A. Ringwald hep-ph/0608248

S. Abel, M. Goodsell, JJ, V. Khoze, A. Ringwald 0803.1449

How coupled?

- Kinetic mixing

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F^{\mu\nu}_{(\rm A)}F_{(\rm A)\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\rm B)}F_{(\rm B)\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\rm A)}F_{(\rm B)\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

+ Mass

$$\mathcal{L}_{\rm mass} = \frac{1}{2}m^2_{\gamma'}X^{\mu}X_{\mu}$$

photon – hidden photon oscillations
Light shining through walls
Fixed target signatures

If you don't like string theory…

- Another simple motivation:

  Question: Are there extra gauge groups?

  Testcase: U(1) is the simplest example we can think of!

How to get Kinetic Mixing ...

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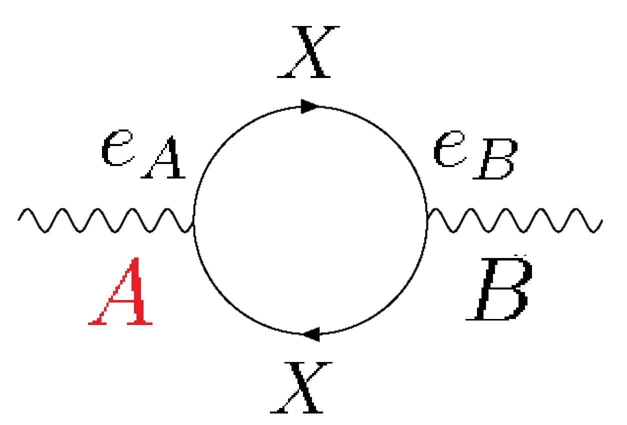
- Field Theory:



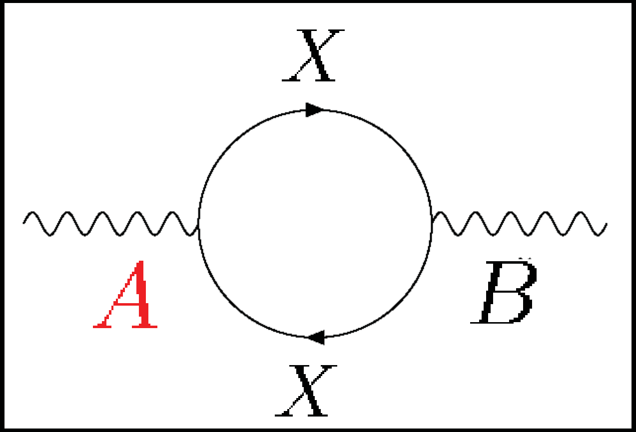
$$\Rightarrow \quad \chi \sim \frac{e_A e_B}{16\pi^2} \log\left(\frac{m_X^2}{\Lambda^2}\right)$$

UV sensitive since dimension 4 operator.

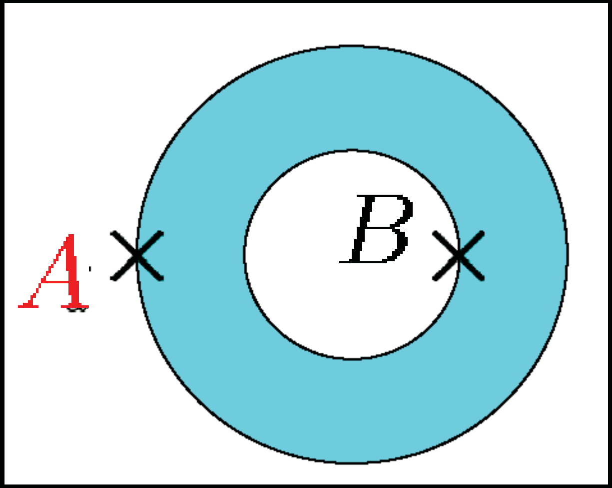
$\Rightarrow$ Tests underlying high scale physics!

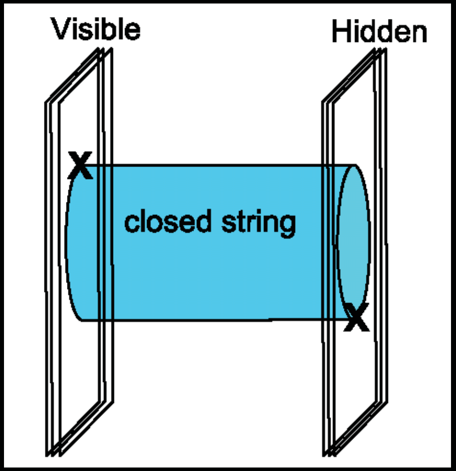
How to get Kinetic Mixing ...

- **Field Theory:**

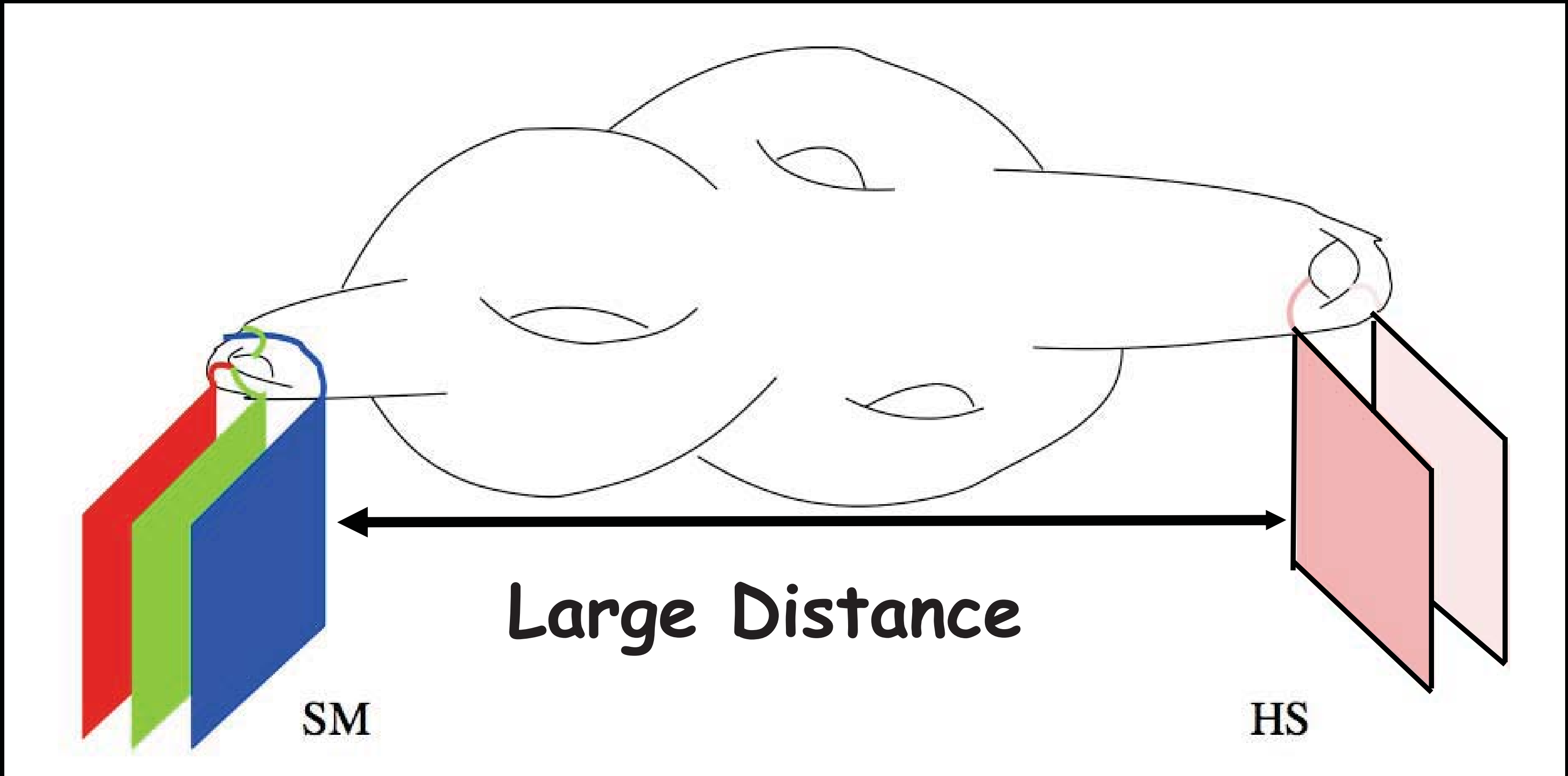


- **String Theory:**





Hidden by distance

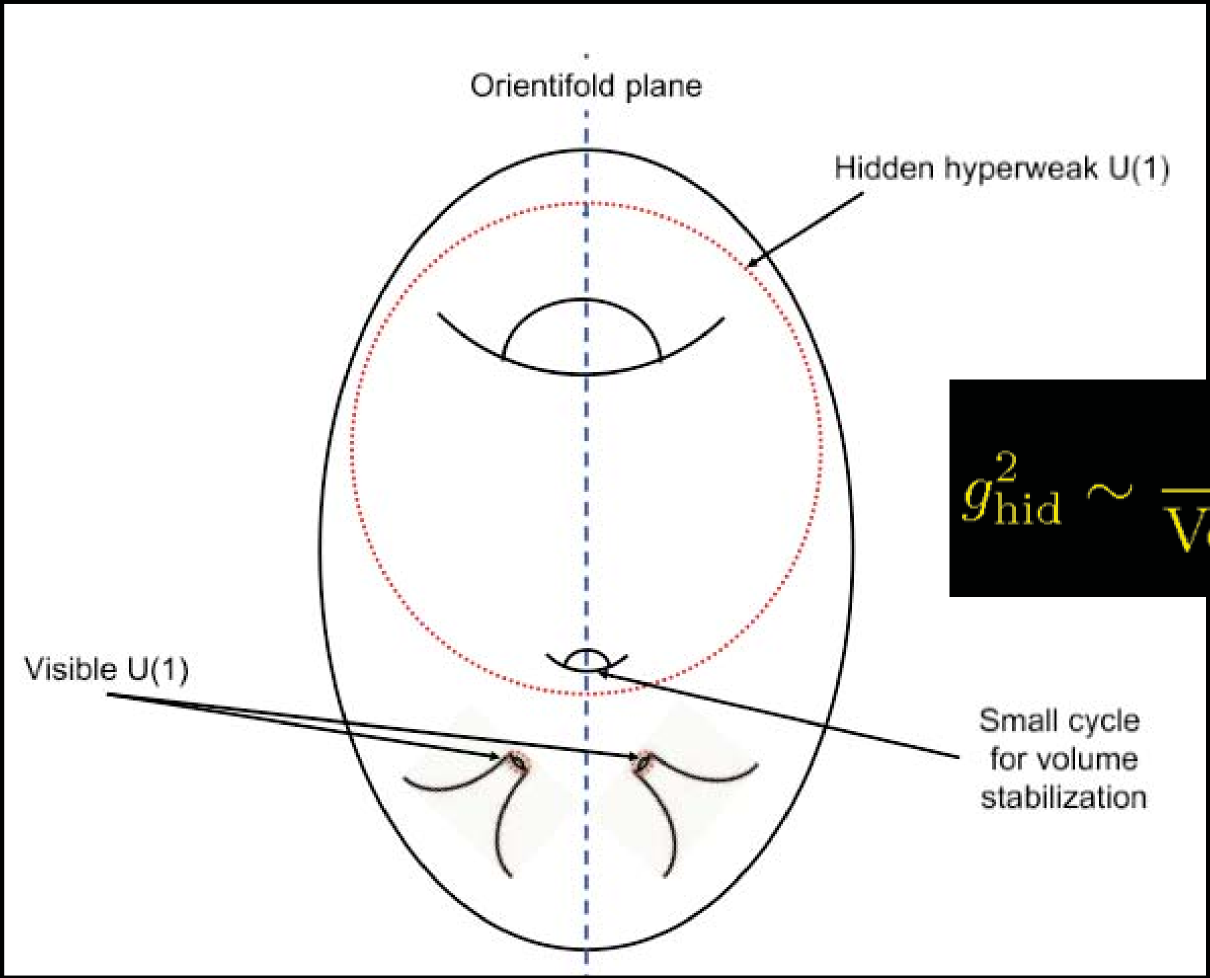


$U(A) \times U(B) \times U(C)$

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

$$\chi \sim \frac{g_s}{8\pi} \frac{1}{Volume^x} \qquad g_{\rm hid} \sim 1$$

Hidden by weakness

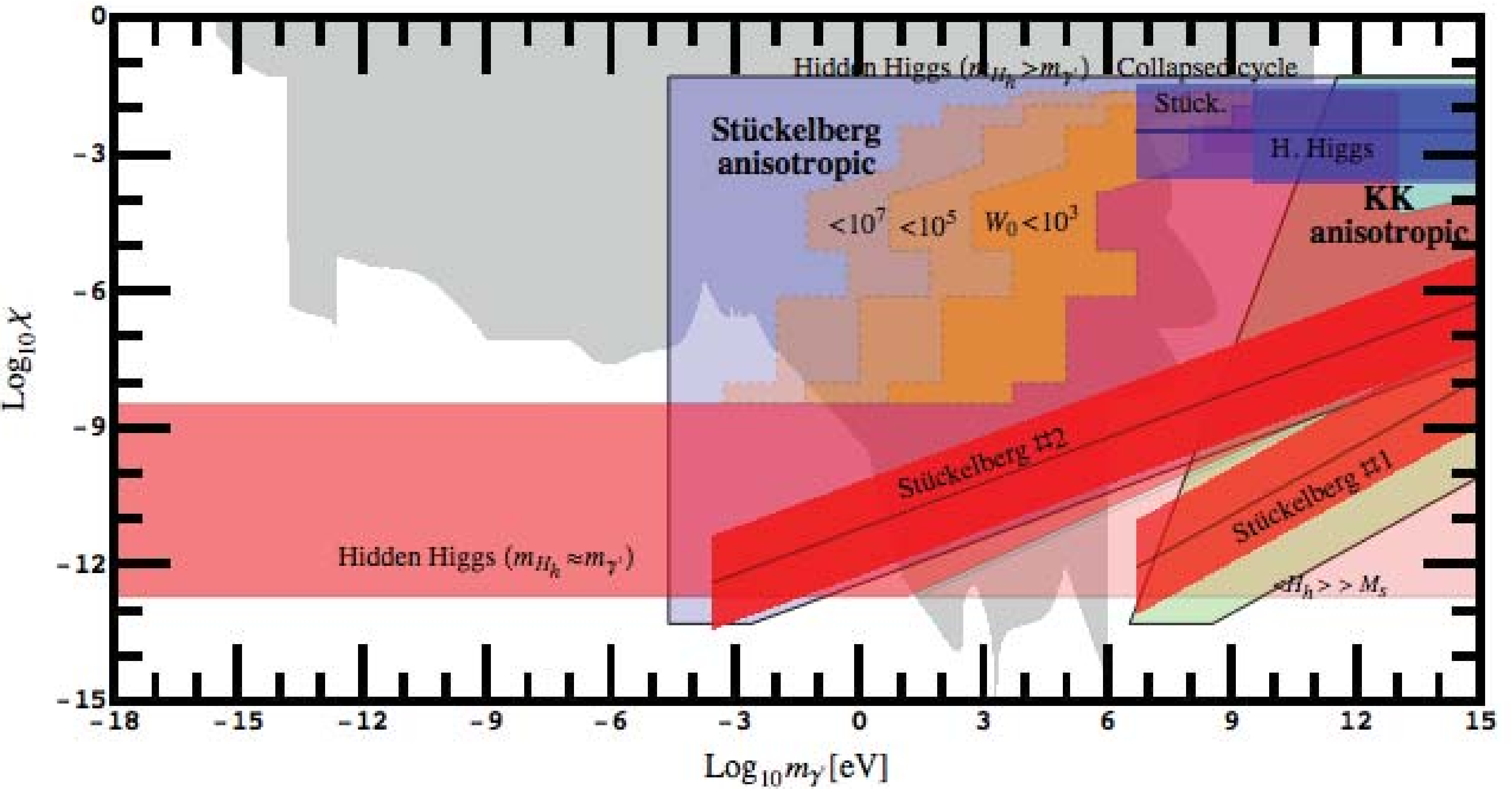


M. Goodsell, JJ,
J. Redondo, A. Ringwald
0909.0515
M. Cicoli,
M. Goodsell, JJ,
J. Redondo, A. Ringwald
1103.3705

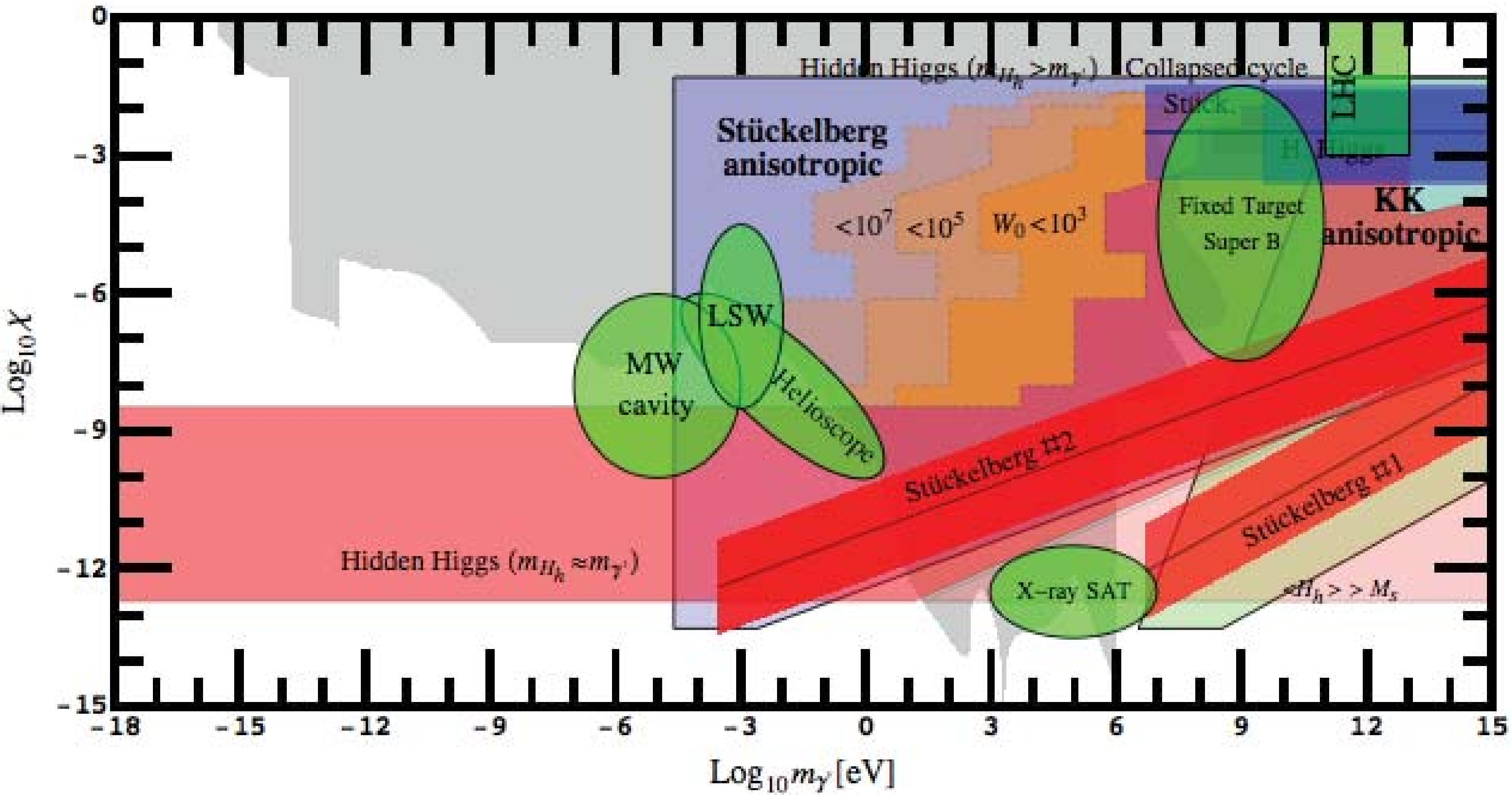
$$g^2_{\rm hid} \sim \frac{2\pi g_s}{\rm Volume^x} \sim \left(\frac{M_s^2}{M_P^2}\right)^x \ll 1$$

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

Hidden Photons, all over the place



Hidden Photons: Preview for Wednesday…



Time warp

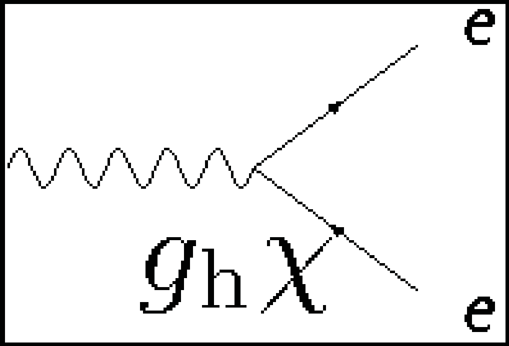
Hidden Matter

-

Minicharged Particles

Minicharged particles

- Extra U(1) gauge boson, i.e. extra photon
- Normal matter not charged under it
- Main interaction:
  - Small coupling to photons, related to kinetic mixing



$$\chi \sim dimensionless \ll 1$$

$$g_{\mathrm{h}} \sim dimensionless \sim 1 \quad or \quad \ll 1$$

How coupled?

- Kinetic mixing

$$\mathcal{L}_{\mathrm{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\mathrm{B})}F_{(\mathrm{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{B})\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

+ Matter $\mathcal{L}_{\mathrm{int}} = g_{\mathrm{hid}}\bar{h}\gamma_{\mu}X^{\mu}h$

⇒ Particles with small electric charges

LSW + other experiments

Kinetic Mixing - How to get Minicharges

- Two U(1)'s

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\text{A})}F_{(\text{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\text{B})}F_{(\text{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\text{A})}F_{(\text{B})\mu\nu},$$

„Our" U(1) „Hidden" U(1) Mixing

$$\text{"} = \text{"}\, A^2 + B^2 - 2\chi AB,$$

$$= A^2 + (B + \chi A)^2 + \mathcal{O}(\chi^2)$$

Diagonalization: $B^\mu \rightarrow B^\mu + \chi A^\mu$

Kinetic Mixing - How to get Minicharges

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- Two U(1)'s

$$\mathcal{L}_{\mathrm{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\mathrm{B})}F_{(\mathrm{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{B})\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

⇒ Diagonalization: $B^\mu \rightarrow B^\mu + \chi A^\mu$

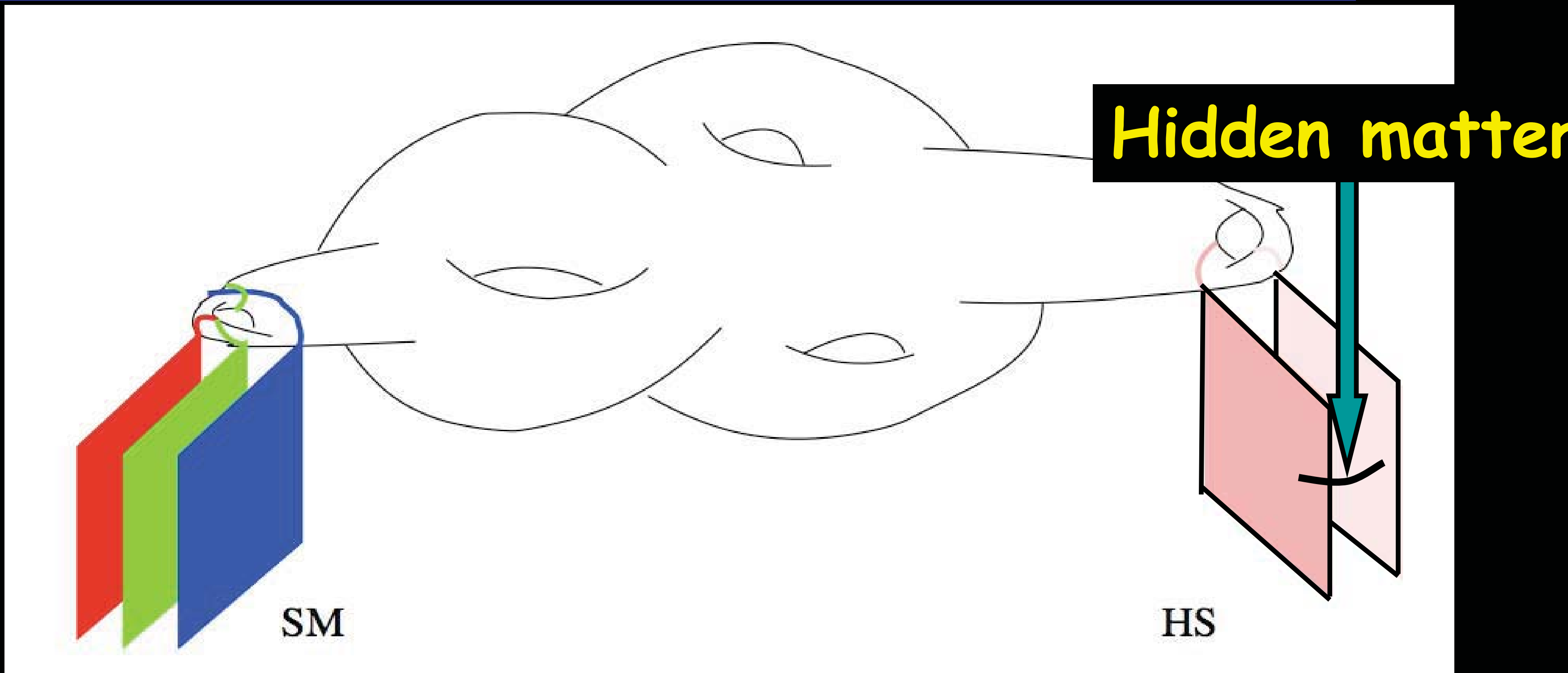
⇒ $g_h \bar{\mathrm{h}} B^\mu \mathrm{h} \rightarrow g_h \bar{\mathrm{h}} B^\mu \mathrm{h} + \chi g_h \bar{\mathrm{h}} A^\mu$

⇒ h carries $\epsilon = \chi g_h$ electric charge!

Necessary ingredients:

- Extra `hidden' U(1) gauge groups! ✓
- Kinetic mixing term! ✓
- Matter charged under hidden U(1)

String theory likes extra matter



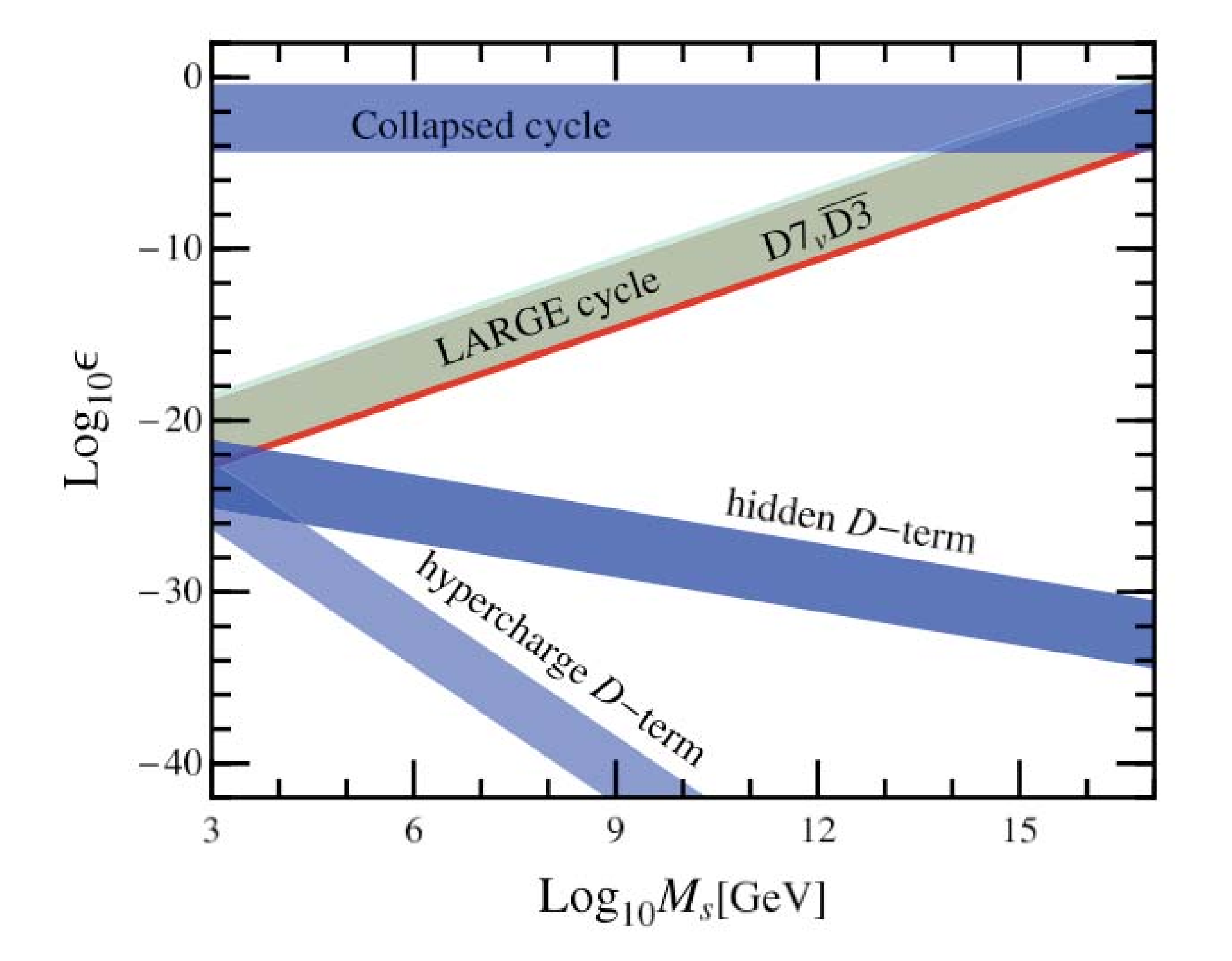
$U(A) \times U(B) \times U(C)$

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

➡ Hidden sector matter

➡ Appears to be minicharged

Minicharged particles…



Crazy stuff

Summary

Summary

- Good motivation for:

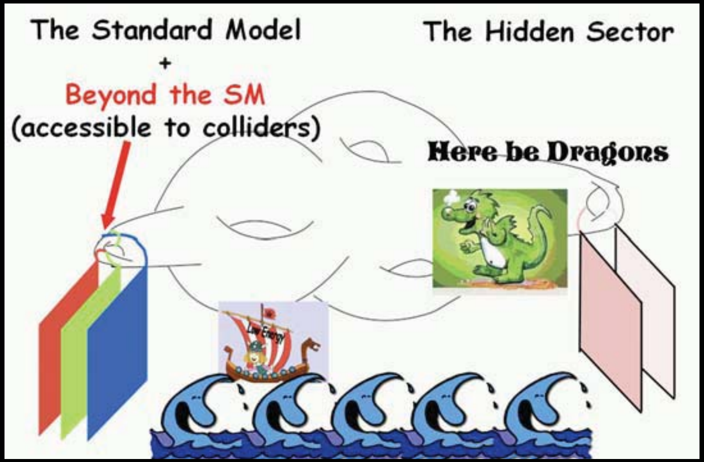
  Axions and other light very weakly coupled

  From Bottom-Up (Strong CP problem, DM)

  Top-down (String theory)

  +++ Cool experiments

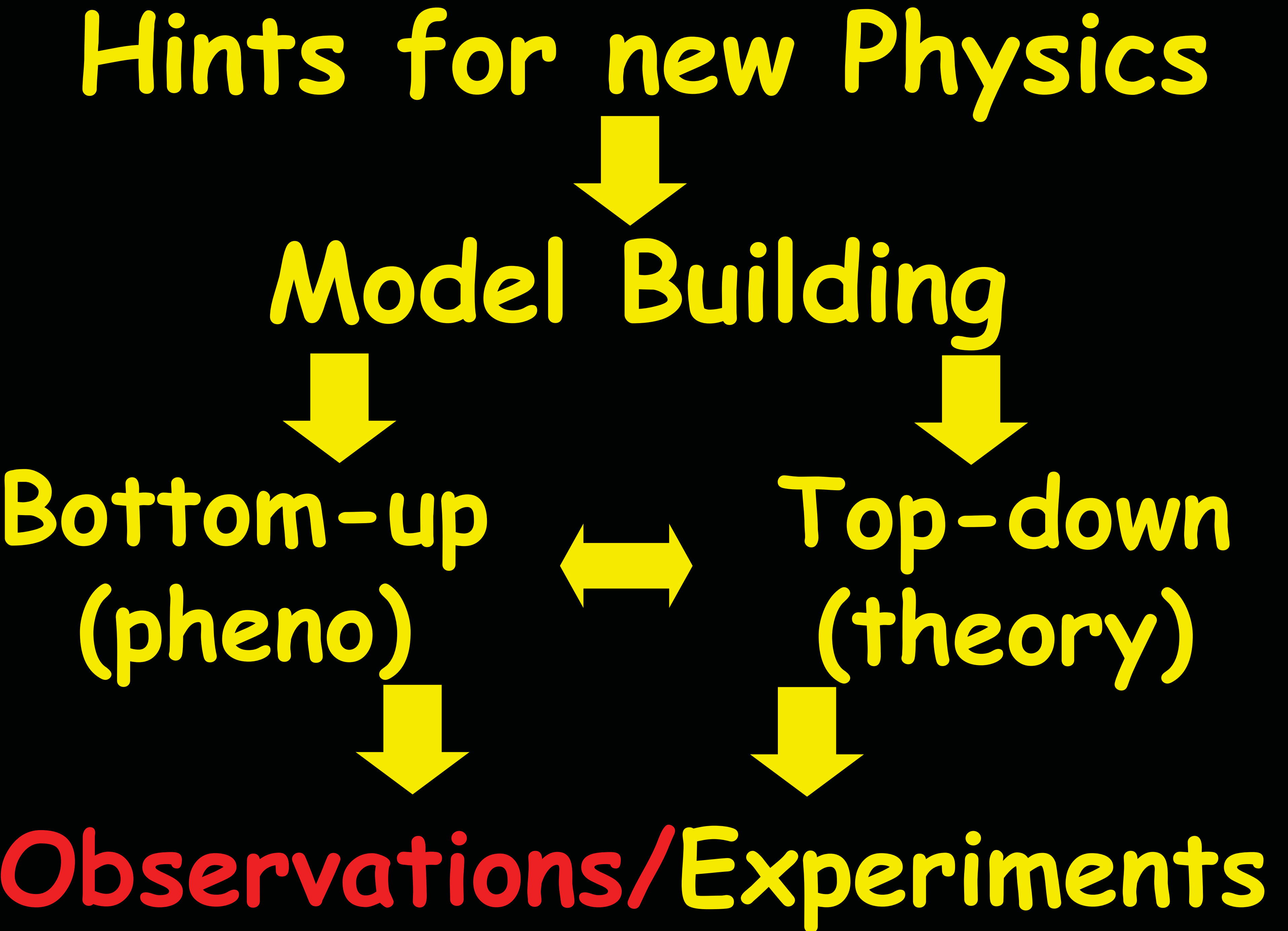
- Insight into light particles may provide information on hidden sectors and thereby into the underlying fundamental theory



- Surprises like Lorentz symmetry violation possible!

→ explore `The Low Energy Frontier'

2.
Light particles in astrophysics and cosmology



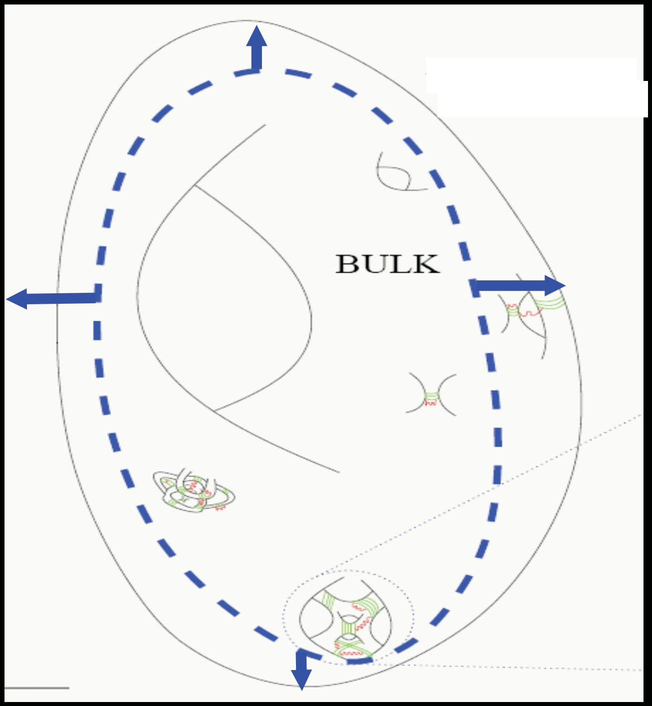
Hints for new Physics
Model Building
Bottom-up
(pheno)
Top-down
(theory)
Observations/Experiments

Warmup

More particles +

Photon-WISP interactions

Axion(-like particles)

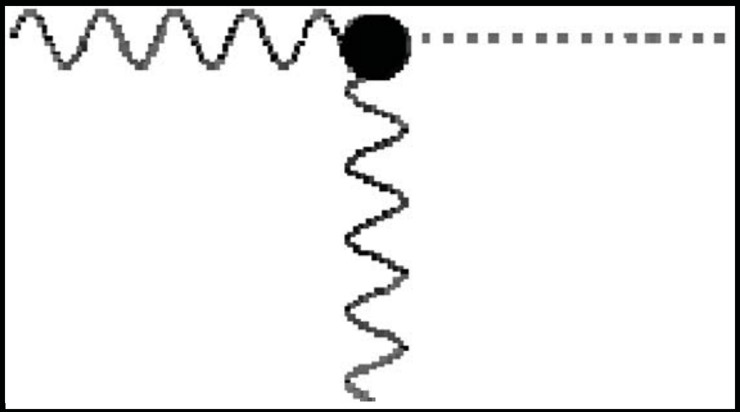


How can we see light particles?

- Example: Axions

$$\mathcal{L}_a = \partial_\mu a \partial^\mu a - m_a^2 a^2 - \frac{1}{4} g a F^{\mu\nu} \tilde{F}_{\mu\nu} + \ldots$$

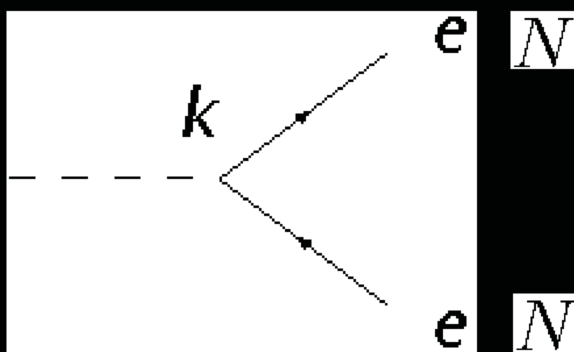
Two-photon interaction!



Axion interactions

- Light scalars or pseudoscalars

  Can also have Yukawa couplings



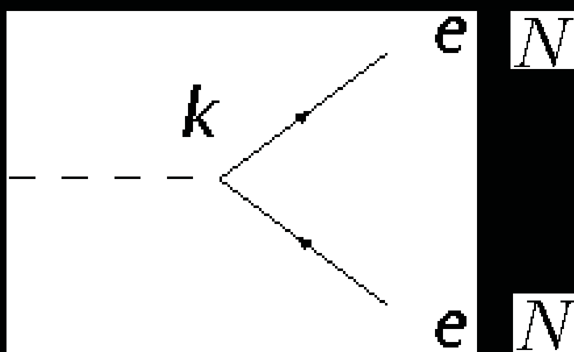
$$k \sim dimensionless \ll 1$$

  - Electrons, e
  - Nucleons, N

Axion(-like particle) interactions

- Light scalars or pseudoscalars

Can also have Yukawa couplings



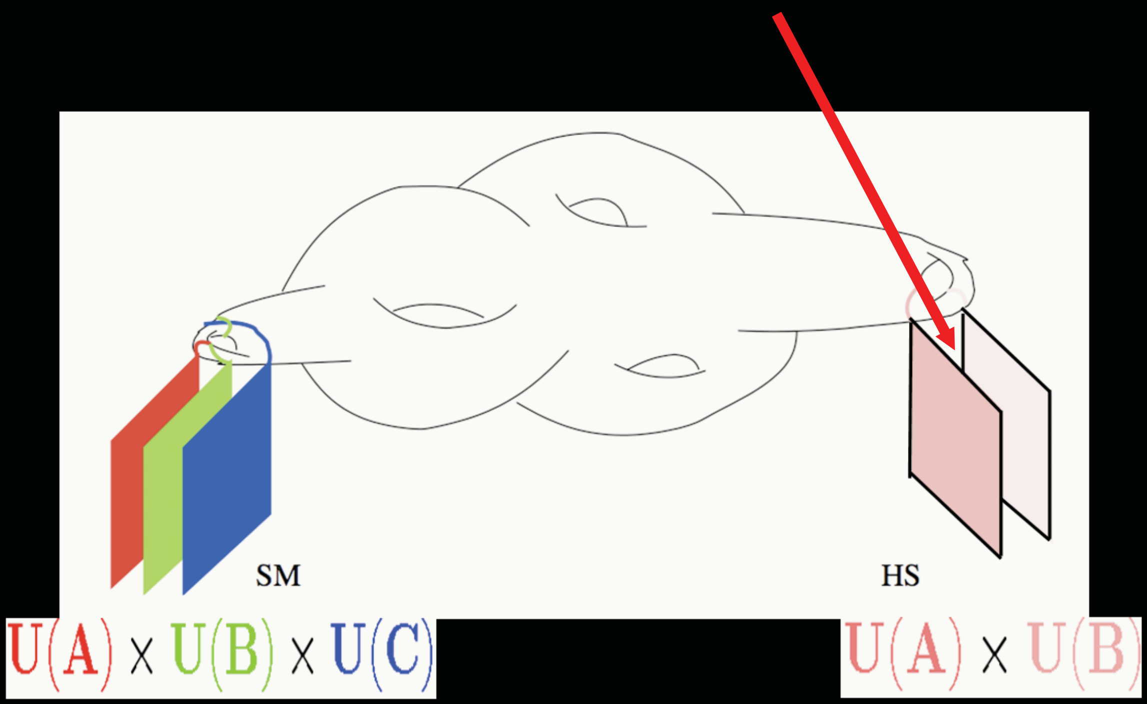
$$k \sim dimensionless \ll 1$$

- Electrons, e
- Nucleons, N

For QCD axion:

$$k_{e,N} \sim \frac{m_{e,N}}{f_a} \ll 1$$

Hidden Photons



Hidden Photon interactions

- **Kinetic mixing**

$$\mathcal{L}_{\mathrm{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\mathrm{B})}F_{(\mathrm{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{B})\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

+ **Mass** $$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2}m^2_{\gamma'}X^{\mu}X_{\mu}$$

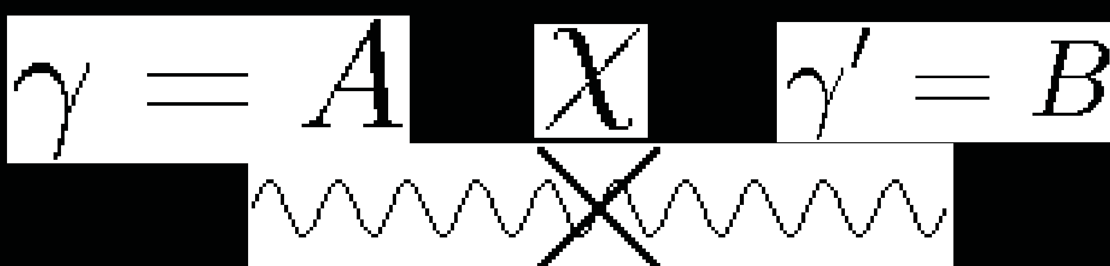
Hidden Photons

- Extra U(1) gauge boson, i.e. extra photon
- Normal matter not charged under it

- Main interaction: Kinetic mixing

$$+\frac{\chi}{2} F^{\mu\nu}_{(A)} F_{(B)\mu\nu},$$

$$\chi \sim dimensionless \ll 1$$



Hidden Photon: Different basis

- Kinetic mixing

$$\mathcal{L}_{\mathrm{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\mathrm{B})}F_{(\mathrm{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\mathrm{A})}F_{(\mathrm{B})\mu\nu},$$

\+ Mass

$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2}m^2_{\gamma'}X^\mu X_\mu$$

\+ Interactions with electrons

$$\mathcal{L}_{\mathrm{int}} = j^\mu A_\mu$$

Removing kinetic mixing

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F^{\mu\nu}_{(\rm A)}F_{(\rm A)\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\rm B)}F_{(\rm B)\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\rm A)}F_{(\rm B)\mu\nu},$$

$+$

$$\mathcal{L}_{\rm mass} = \frac{1}{2}m^2_{\gamma'}B^{\mu}B_{\mu}$$

$$\begin{aligned} \text{''} \quad &= \text{''}\, A^2 + B^2 - 2\chi AB, \\ &= A^2 + (B + \chi A)^2 + \mathcal{O}(\epsilon^2) \\ &= (A + \chi B)^2 + B^2 + \mathcal{O}(\epsilon^2) \end{aligned}$$

Diagonalization: $A^{\mu} \longrightarrow \hat{A}^{\mu} - \chi B^{\mu}$

Hidden Photon: Different basis

- No Kinetic mixing for $\hat{A}$

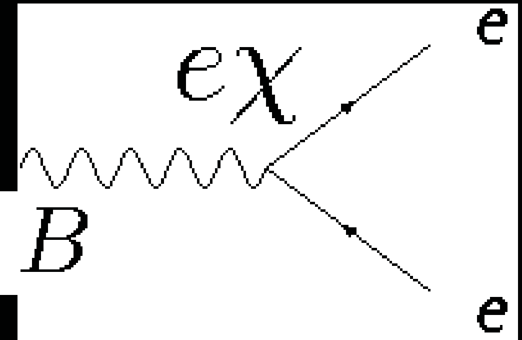
$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}\hat{F}^{\mu\nu}_{(\rm A)}\hat{F}_{(\rm A)\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\rm B)}F_{(\rm B)\mu\nu}$$

+ Mass

$$\mathcal{L}_{\rm mass} = \frac{1}{2}m^2_{\gamma'}B^\mu B_\mu$$

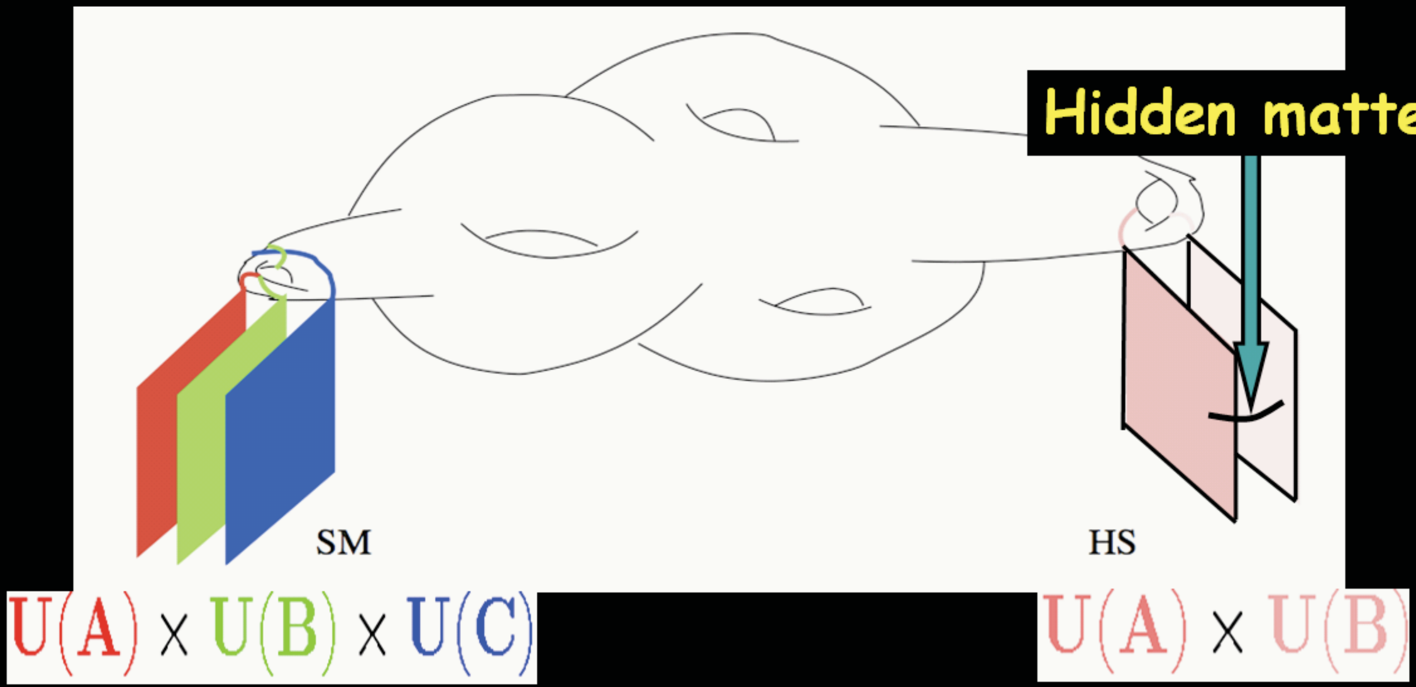
+ Interactions with electrons (and other charges)

$$\mathcal{L}_{\rm int} = j^\mu(\hat{A}_\mu - \chi B_\mu)$$



$$\gamma' = B$$

Minicharged Particles



How coupled?

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- **Kinetic mixing**

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F^{\mu\nu}_{\rm (A)}F_{{\rm (A)}\mu\nu} - \frac{1}{4}F^{\mu\nu}_{\rm (B)}F_{{\rm (B)}\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{\rm (A)}F_{{\rm (B)}\mu\nu},$$

„Our“ U(1)

„Hidden“ U(1)

Mixing

+ Matter $\mathcal{L}_{\rm int} = g_{\rm hid}\bar{h}\gamma_\mu X^\mu h$

Particles with small electric charges
LSW + other experiments

Kinetic Mixing - How to get Minicharges

- Two U(1)'s

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\text{A})}F_{(\text{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\text{B})}F_{(\text{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\text{A})}F_{(\text{B})\mu\nu},$$

„Our" U(1)

„Hidden" U(1)

Mixing

$$\begin{aligned} \text{''} &= \text{''}\, A^2 + B^2 - 2\chi AB, \\ &= A^2 + (B+\chi A)^2 + \mathcal{O}(\chi^2) \end{aligned}$$

Diagonalization: $B^\mu \rightarrow B^\mu + \chi A^\mu$

Kinetic Mixing - How to get Minicharges

- Two U(1)'s

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4} F^{\mu\nu}_{(A)} F_{(A)\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(B)} F_{(B)\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(A)} F_{(B)\mu\nu},$$

„Our" U(1) „Hidden" U(1) Mixing

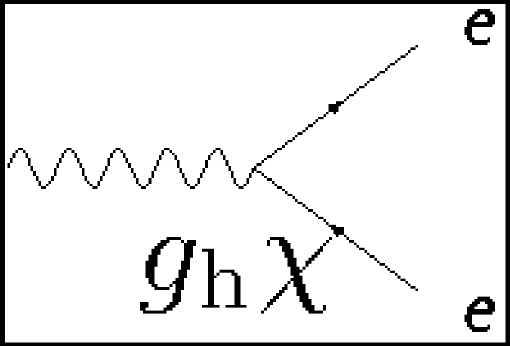
Diagonalization: $B^\mu \to B^\mu + \chi A^\mu$

$$g_h \bar{\rm h} B^\mu {\rm h} \to g_h \bar{\rm h} B^\mu {\rm h} + \chi g_h \bar{\rm h} A^\mu {\rm h}$$

h carries $\epsilon = \chi g_h$ electric charge!

Minicharged particles

- Extra U(1) gauge boson, i.e. extra photon
- Normal matter not charged under it
- Main interaction:
  - Small coupling to photons, related to kinetic mixing



$$\chi \sim dimensionless \ll 1$$

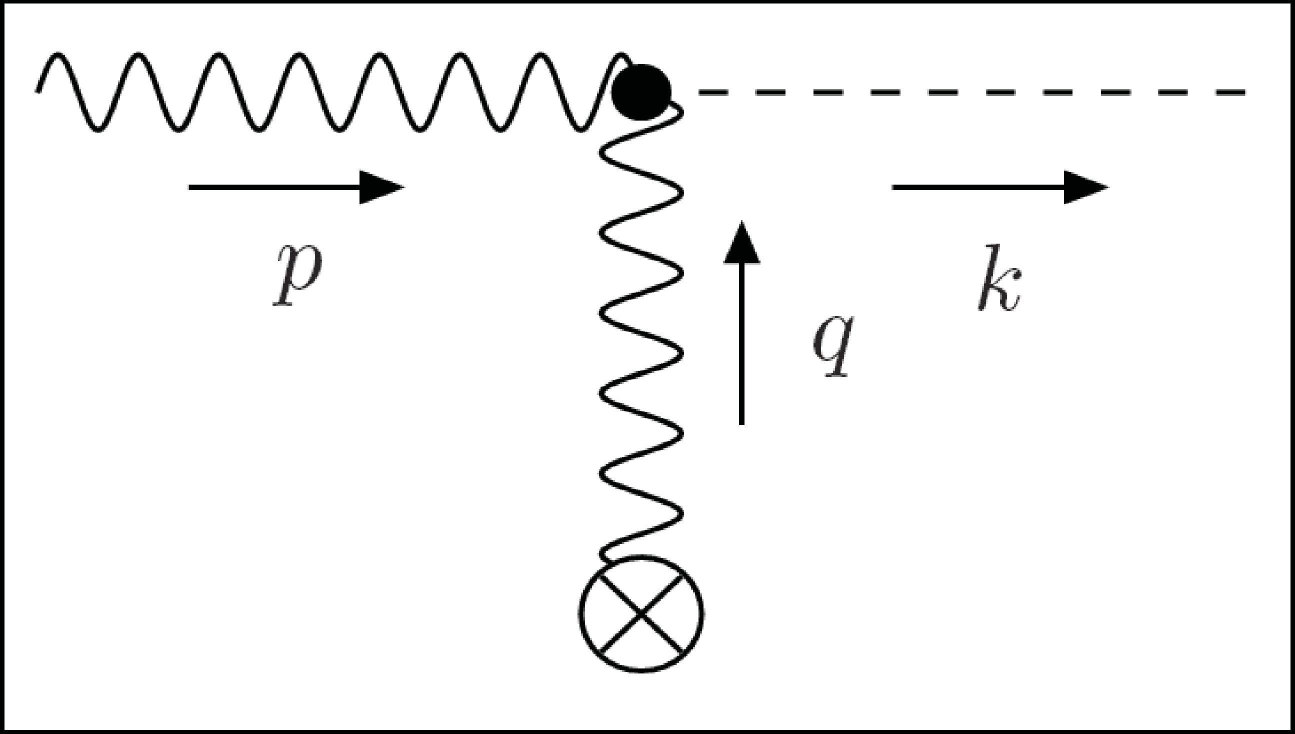
$$g_{\mathrm{h}} \sim dimensionless \sim 1 \quad or \quad \ll 1$$

Energy loss in
Stars

See
G. Raffelt
"Stars as Laboratories
for Fundamental Physics"

Axions

- Primakoff proces

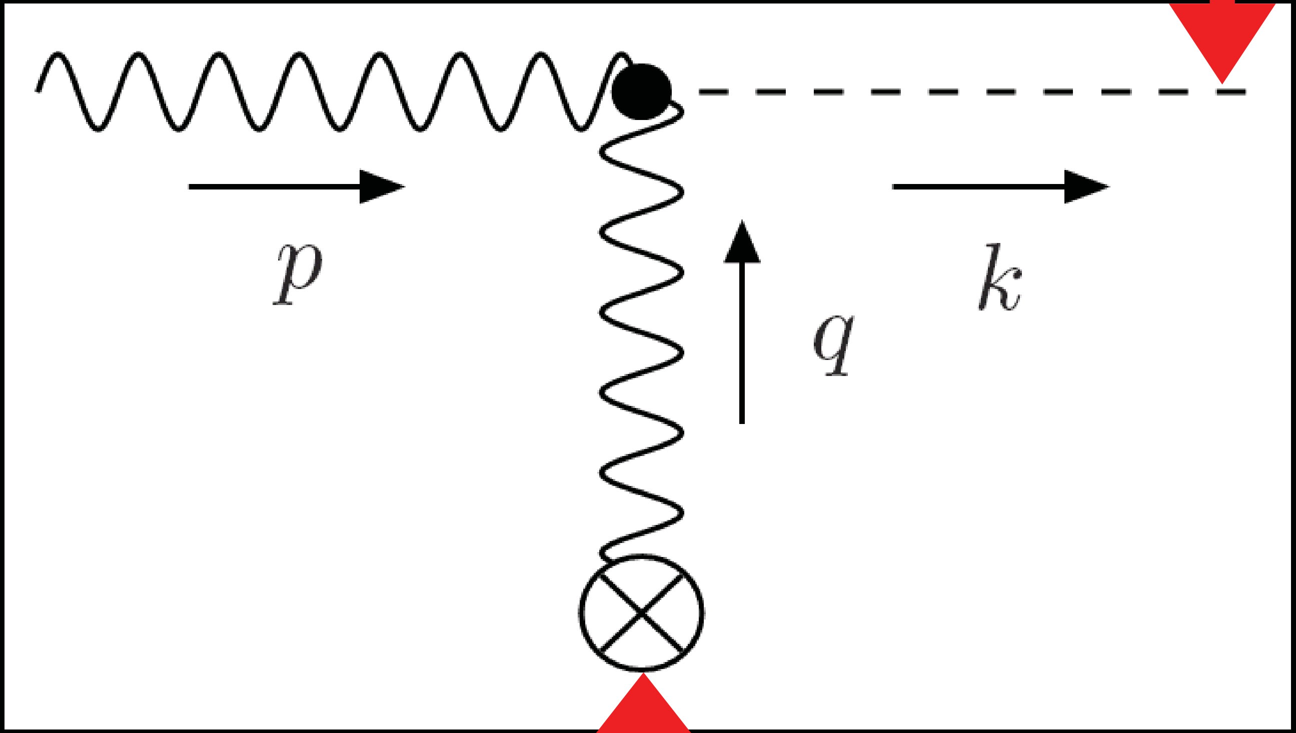


Axions

- Primakoff process (in the sun)

ALP (leaving the sun)

Photon (plasma)



Ion or electron

We would freeze...

- If the coupling g is too large the sun would have died long ago.
- Why?

Axions can leave the sun without further interaction (in contrast to photons)

⇒ Large energy loss from axion emission

⇒ Sun burns fuel faster

⇒ Sun would have died long ago

A (Very) Moderate Bound

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- Without ALPs sun has fuel for about 10^{10} years
- Energy loss via ALPs:

$$L_a \approx 1.7\,10^9 (g\,10^4\mathrm{GeV})^2\,L_\gamma$$

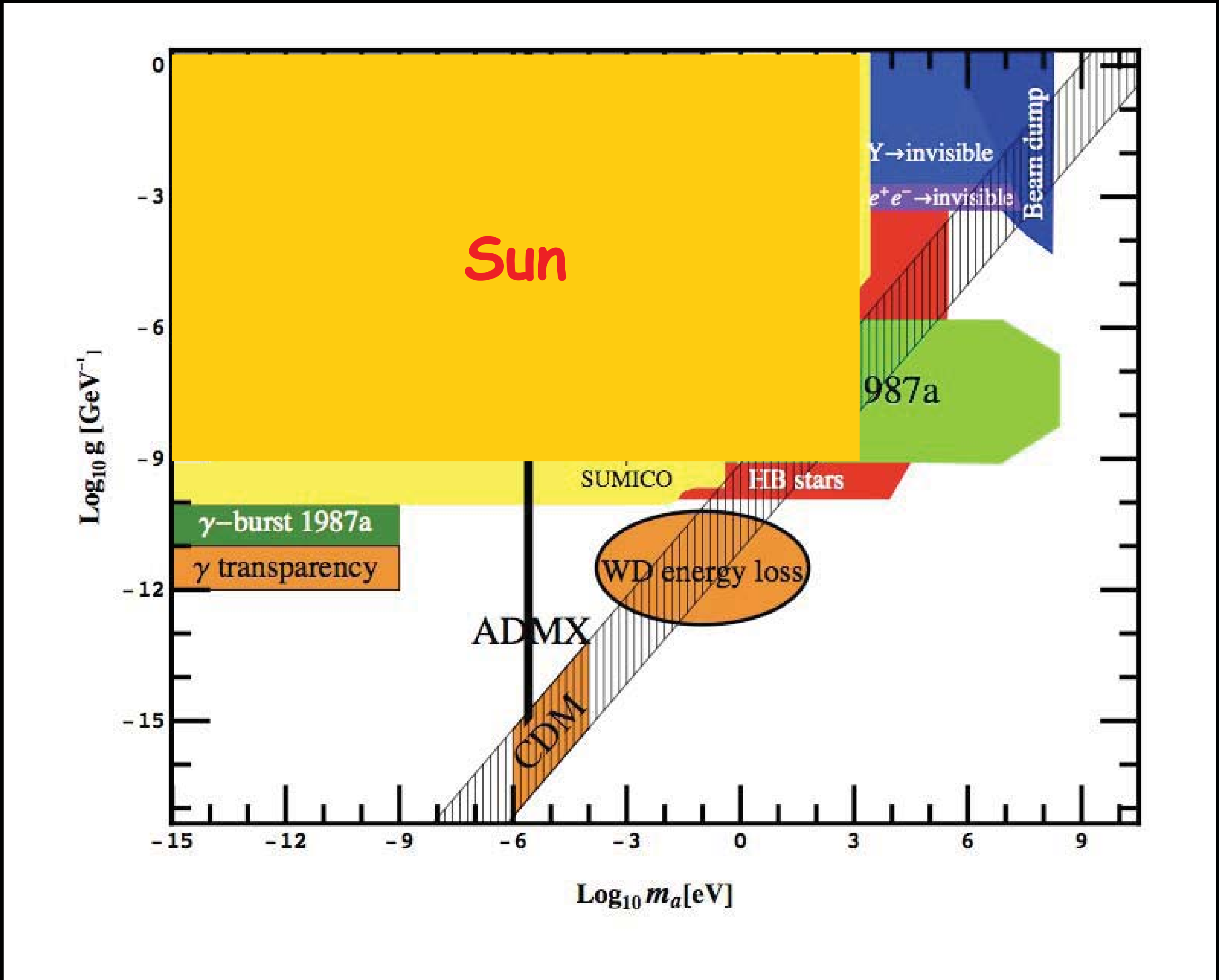
- Sun Lifetime with ALPs

$$t_{sun} \sim 10\,years \times \left(g\,10^4\mathrm{GeV}\right)^{-2}$$

- Pretty sure sun has been around for more than 10 years

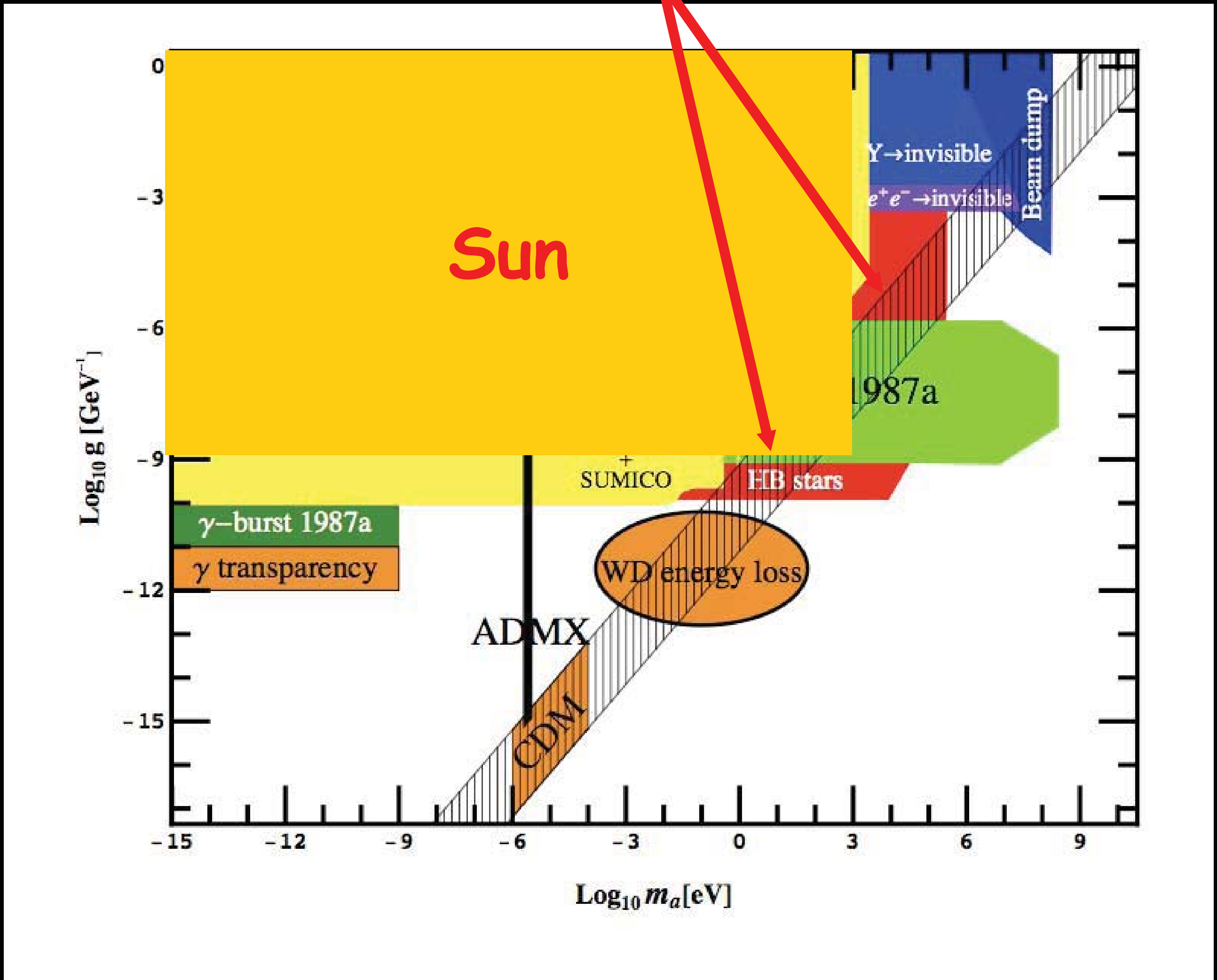
$$\Rightarrow \quad g \leq \frac{1}{10^4 GeV}$$

Axion-like particles

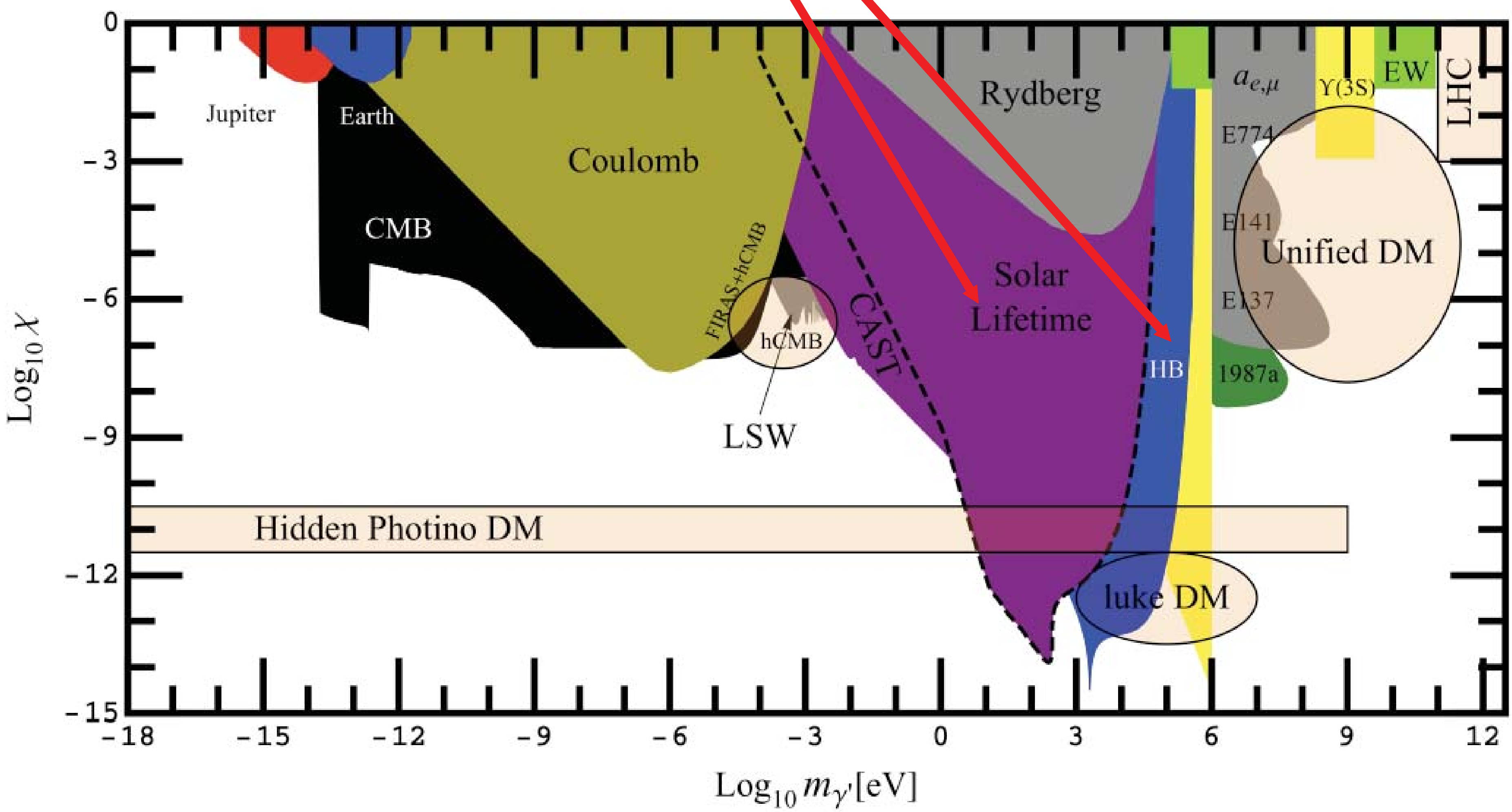


Can do better…

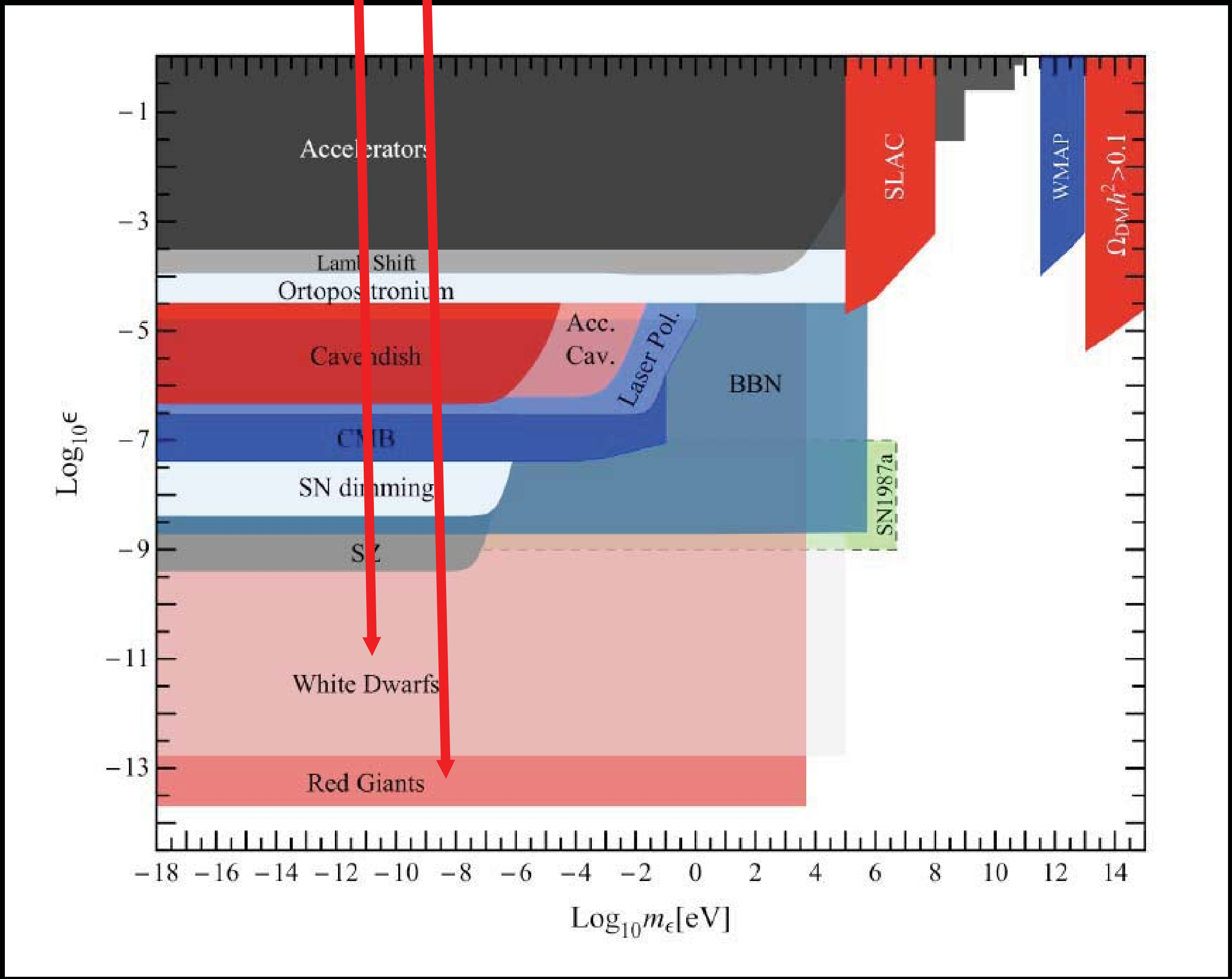
- Look at variety of stars
- Best are horizontal branch stars.



Works also for hidden photons…



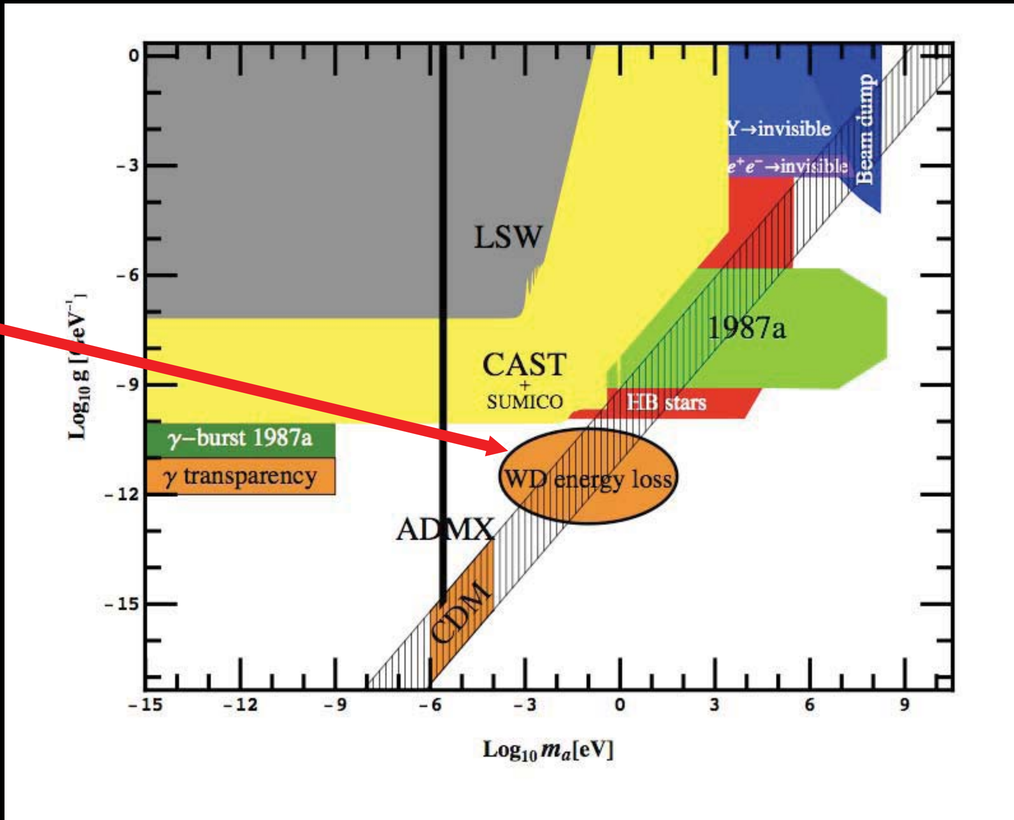
…and minicharged particles



Not only bounds but also a new hint!!!

- White Dwarfs seem to loose a bit more energy than expected.
- This could be explained by an Axion(-like particle) coupled to electrons

- The corresponding two-photon coupling



Extra degrees of freedom at

BBN

See, e.g.
E. Kolb and M. Turner
"The Early Universe"
Also S. Hannestad 2010

Basic facts of Big Bang Nucleosynthesis

- After the quark-hadron transition
  - T~few 100 MeV, t~10^{-6} s
  - Most hadrons are Pions.

Basic facts of Big Bang Nucleosynthesis

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- Later when $T << 100$ MeV$\sim m_\pi$
  - pions decay away
  - Mostly neutrons and protons (+ electrons)

In equilibrium:

$$\frac{n_n}{n_p} = \exp\left(-\frac{\delta m}{k_B T}\right)$$

$$\delta m = m_n - m_p = 1.293\mathrm{MeV}$$

Are we in eqilibrium?

- n-p changing interactions

$$\nu_e + n \leftrightarrow e^- + p$$
$$e^+ + n \leftrightarrow \bar{\nu}_e + p$$
$$n \leftrightarrow e^- + p + \bar{\nu}_e$$

- Rate

$$\Gamma_{n-p} = n\langle \sigma v \rangle \sim T^3 G_F^2 T^2$$

- Hubble

$$H = \sqrt{\frac{8\pi}{3}\frac{\rho}{m_{Pl}^2}} \sim 1.66\sqrt{g_\star}\frac{T^2}{m_{Pl}}$$

- Freeze out:

$$\Gamma_{n-p} < H \Rightarrow T_{freeze} \sim 1\,\mathrm{MeV}.$$

Are we in eqilibrium?

- Freeze out:

$$\Gamma_{n-p} < H \Rightarrow T_{freeze} \sim 1\,\mathrm{MeV}.$$

- At this point in time $\frac{n_n}{n_p} \sim \exp\left(-\frac{m_n - m_p}{T_{freeze}}\right) \frac{1}{6}$

- From then on: Neutrons decay with τ_n=886 s

Nucleosynthesis...

- The first process is

$$p + n \leftrightarrow D + \gamma$$

- Naively it should start when

$T < m_D - m_p - m_n \sim 2.2$ MeV

- However much much more γ than p, n!!!

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

Need: $\Gamma_{production}(D) = \Gamma_{destruction}(D)$

Nucleosynthesis...

$$\left.\begin{aligned}\Gamma_{production} &\approx n_B \langle \sigma v \rangle \\ \Gamma_{destruction} &\approx n_\gamma \langle \sigma v \rangle e^{-E_b/T}\end{aligned}\right\} \Rightarrow T_{BBN} \approx -\frac{E_b}{\ln(\eta)} \approx 0.2\,\mathrm{MeV}$$

$$\Rightarrow t_{BBN} \sim 50s$$

- At this point in time $\frac{n_n}{n_p} \sim \frac{1}{7}$

Nucleosynthesis…

- After formation of deuterium everything goes quickly

- Nearly all neutrons end in helium.

$$Y_{He} = \frac{4n_{He}}{n_{nucleon}} = \frac{4}{16} = 0.25$$

- This is roughly what is observed!

Extra species…

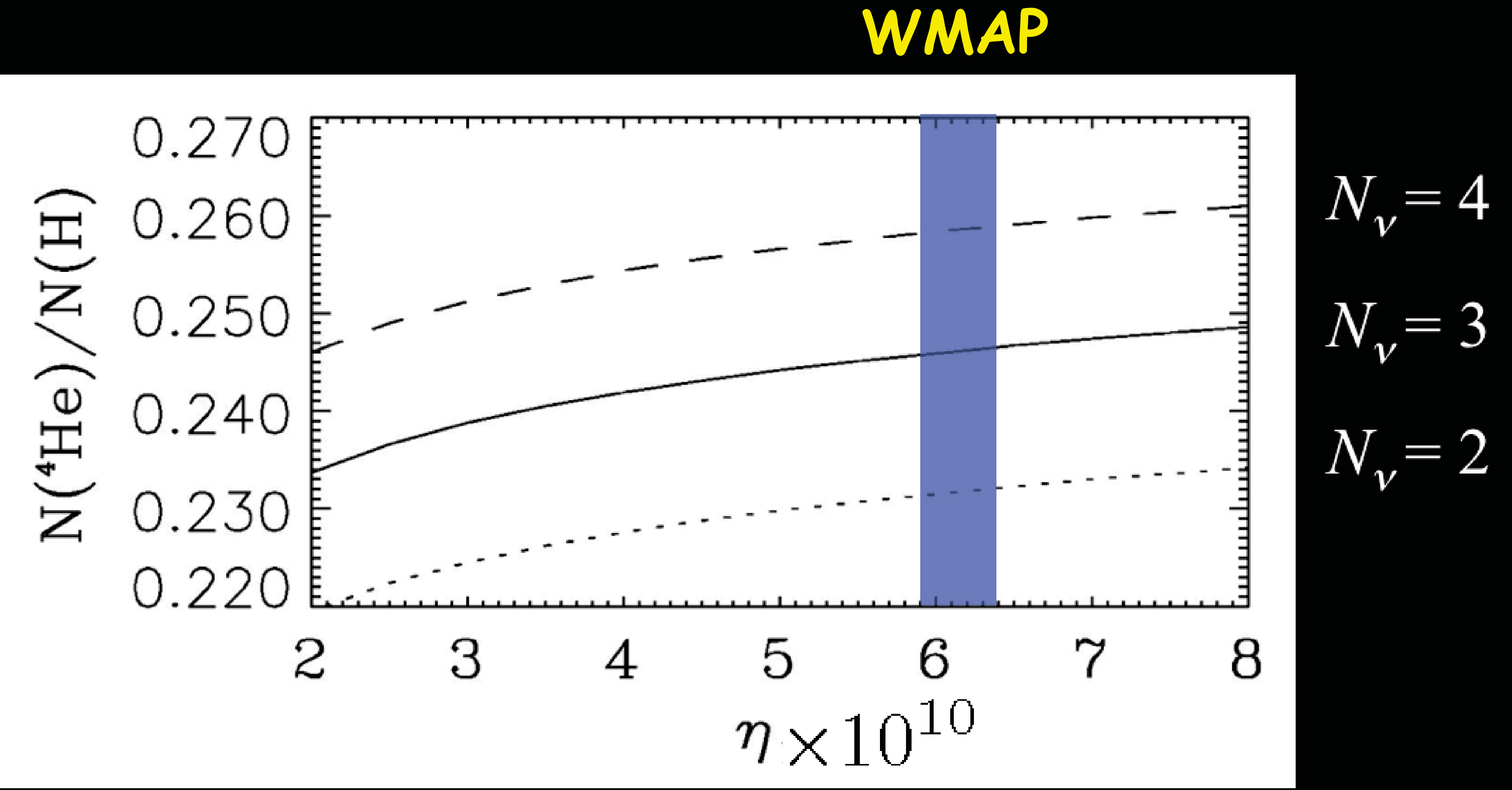
- Extra light particles in equilibrium increase the Hubble constant

→(Smallish) changes in

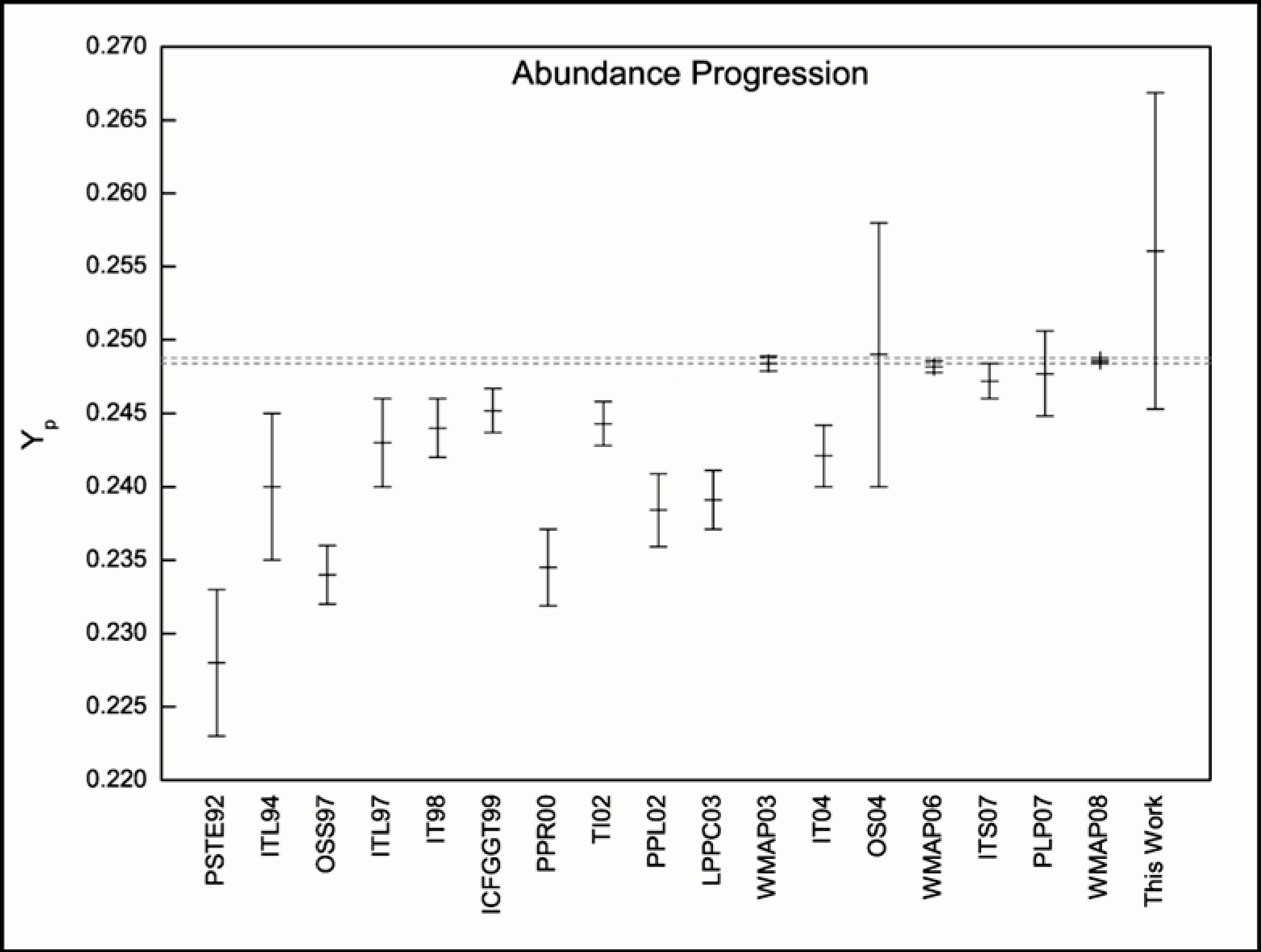
$$t_{freeze}, t_{BBN}$$

→Changes Y_{He} (and other element abundances)

Extra species…



Measured abundancies…



Extra species…

- Extra light particles in equilibrium increase the Hubble constant

→(Smallish) changes in

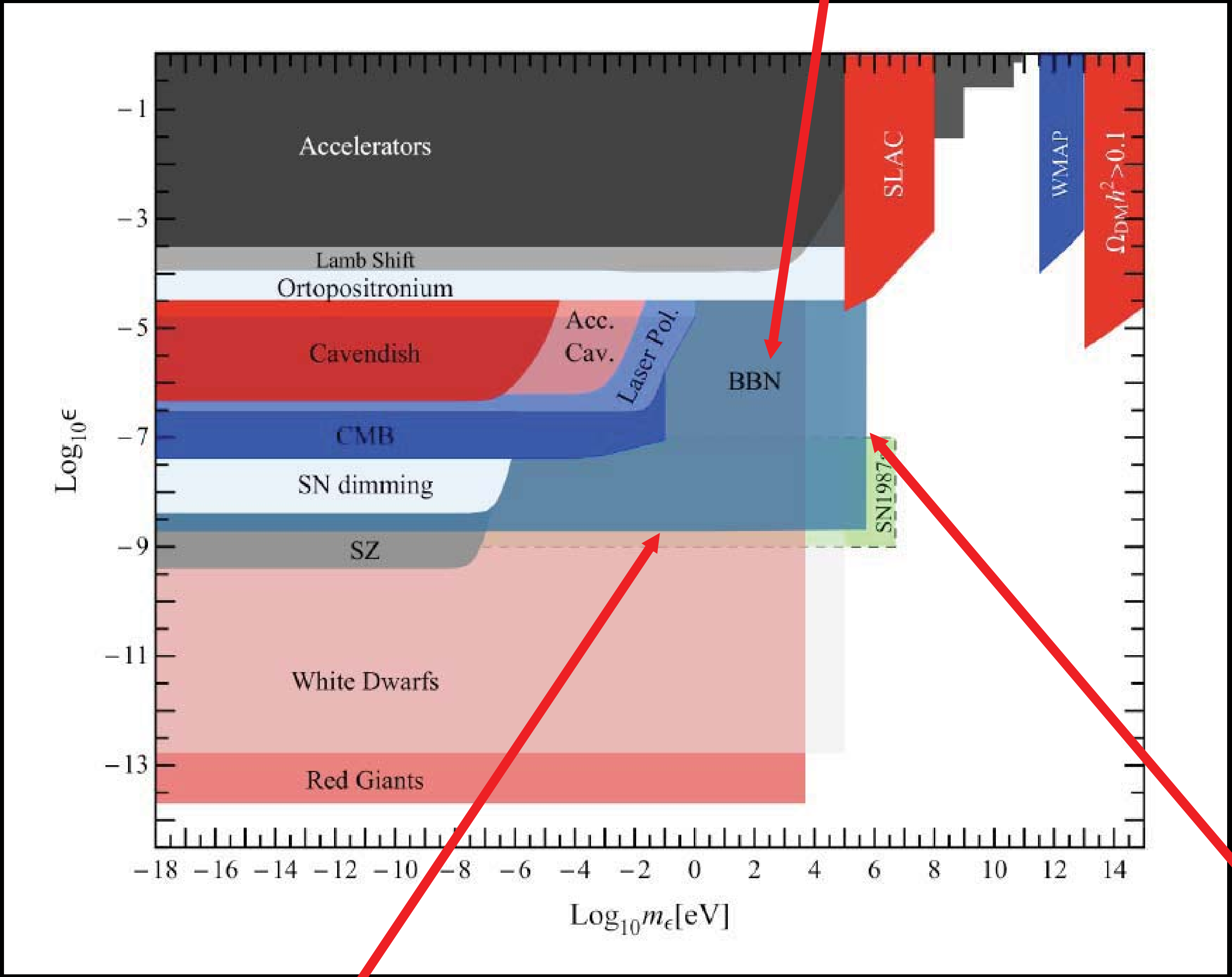
$$t_{freeze}, t_{BBN}$$

→Changes Y_{He} (and other element abundances)

⇒ We can constrain (or have a hint ;-)):

$$n_{\rm light\ species} \sim 1 \pm 2$$

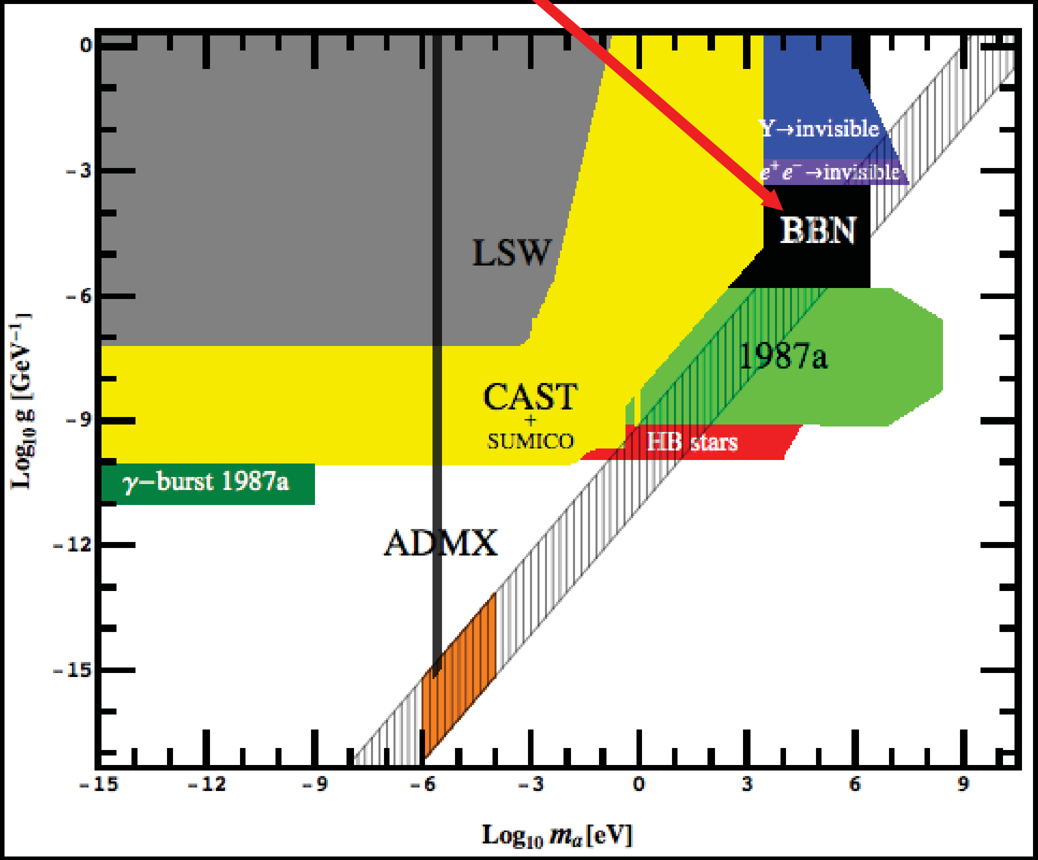
Example of constraint: Minicharges



Not in equilibrium

Not enough energy

Axion-like particles



- Not my favourite bound: only 1 extra degree of freedom.
- Need to use one of the optimistic error estimate

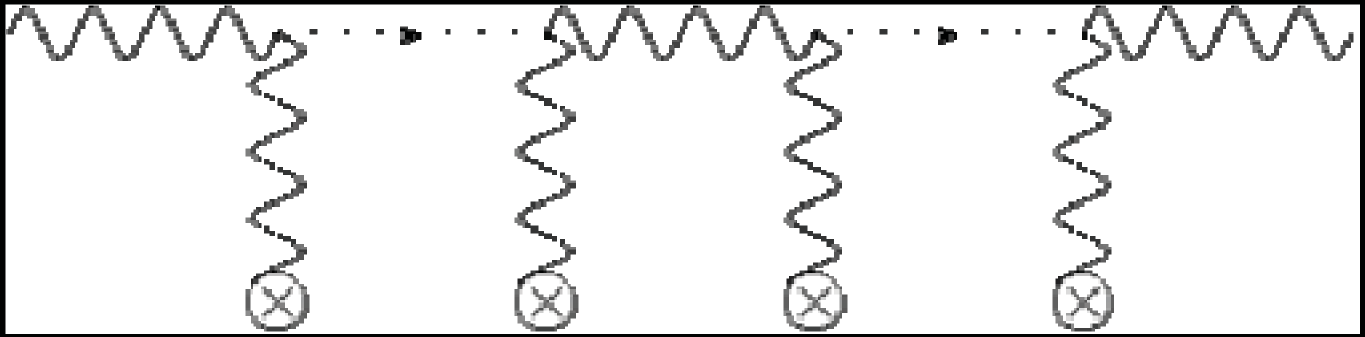
Intermezzo

Photon-WISP oscillations

Coherent evolution…

- In many situations we have coherent interactions over long distances.

- Multiple interactions…



- All tree-level

⇒ Use classical equations of motion!

Equations of motion…

$$[\omega^2 \mathbf{1} + \partial_z^2 \mathbf{1} - \mathcal{M}^X] \begin{pmatrix} A \\ X \end{pmatrix} = 0,$$

- **Axion-like particles**

$$\mathcal{M}_{\parallel}^{a^-} = \begin{pmatrix} 0 & -gB\omega \\ -gB\omega & m_a^2 \end{pmatrix}$$

Equations of motion…

$$\left[\omega^2 \mathbf{1} + \partial_z^2 \mathbf{1} - \mathcal{M}^X\right] \begin{pmatrix} A \\ X \end{pmatrix} = 0,$$

- Hidden photons

$$\mathcal{M}^{\gamma'} = m_{\gamma'}^2 \begin{pmatrix} \chi^2 & -\chi \\ -\chi & 1 \end{pmatrix}$$

Solutions…

$$v_1 = \exp(-\mathbf{i}(\omega t - k_1 z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-\mathbf{i}(\omega t - k_2 z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix}$$

- Propagation eigenstates
  $\neq$ interaction eigenstates
- Photons mix with new particles!!
- Analog of neutrino oscillations!

Solutions... Details

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$$v_1 = \exp(-\mathbf{i}(\omega t - k_1 z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-\mathbf{i}(\omega t - k_2 z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix}$$

In general:

$$\tan(2\,\delta) = 2\frac{\mathcal{M}^X_{12}}{\mathcal{M}^X_{11} - \mathcal{M}^X_{22}},$$

$$k_1^2 = \omega^2 - \mathcal{M}^X_{11}, \quad k_2^2 = \omega^2 - \mathcal{M}^X_{22}.$$

Solutions… Details

$$v_1 = \exp(-\mathbf{i}(\omega t - k_1 z)) \begin{pmatrix} 1 \\ \delta \end{pmatrix}, \quad v_2 = \exp(-\mathbf{i}(\omega t - k_2 z)) \begin{pmatrix} -\delta \\ 1 \end{pmatrix}$$

For hidden photons:

$$\delta \approx \chi$$

$$k_1 = \omega, \qquad k_2 \approx \omega - \frac{m_{\gamma'}^2}{2\omega}$$

And finally oscillations

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$$A(\gamma \rightarrow \gamma') = \chi\left[\exp(ik_1 x) - \exp(ik_2 x)\right]$$

$$= \chi \exp(i\omega x)\left[1 - \exp\left(\frac{m_{\gamma'}^2}{2\omega}x\right)\right]$$

$$P(\gamma \rightarrow \gamma') = 4\chi^2 \sin^2\left(\frac{m_{\gamma'}^2}{4\omega}x\right)$$

Exactly the same structure as neutrino oscillations!!!

Modifications of the

CMB

In the early Universe…

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- We can have photon – hidden photon (WISP) oscillations!

- Small complication: Plasma ➡ photon plasma mass!

$$\tan(2\,\delta) = 2\frac{\mathcal{M}^X_{12}}{\mathcal{M}^X_{11} - \mathcal{M}^X_{22}},$$

In the early Universe…

- We can have photon – hidden photon (WISP) oscillations!

- Small complication: Plasma ⇒ photon plasma mass!

$$\tan(2\,\delta) = 2\frac{\mathcal{M}_{12}^{X}}{\mathcal{M}_{11}^{X} - \mathcal{M}_{22}^{X}},$$

Hidden photon mass

In the early Universe…

- We can have photon – hidden photon (WISP) oscillations!
- Small complication: Plasma ➡ photon plasma mass!

$$\tan(2\,\delta) = 2\frac{\mathcal{M}^X_{12}}{\mathcal{M}^X_{11} - \mathcal{M}^X_{22}},$$

Hidden photon mass

Can be equal ➡ Resonance!

➡ Big effect!

Is observable…

- It transfers energy from Photons to hidden photons

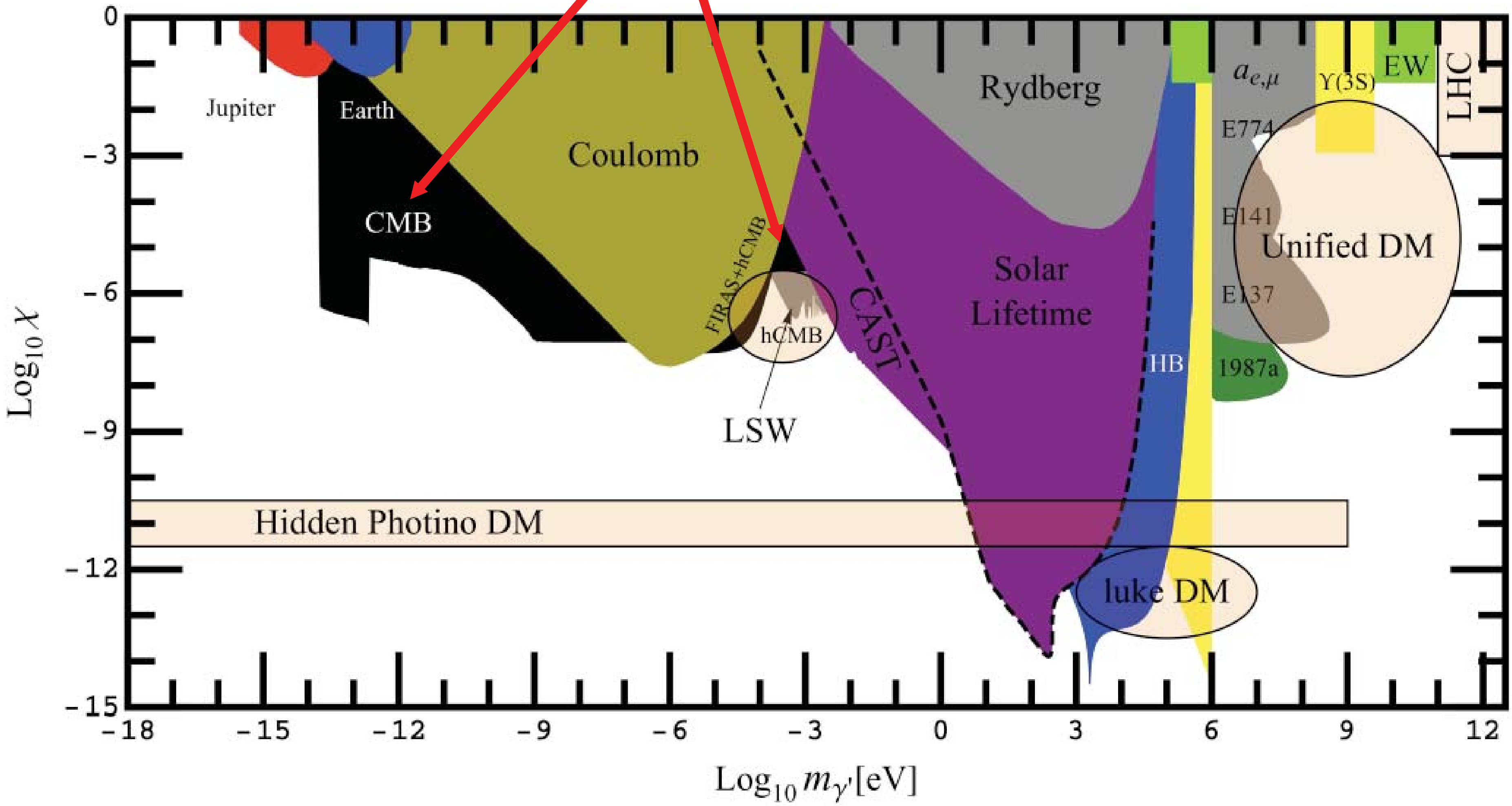
$$\Rightarrow \quad \Delta n_{\text{light species}}$$

- It is energy dependent!

$$P(\gamma \rightarrow \gamma') = 4\chi^2 \sin^2\left(\frac{m_{\gamma'}^2}{4\omega}\right)$$

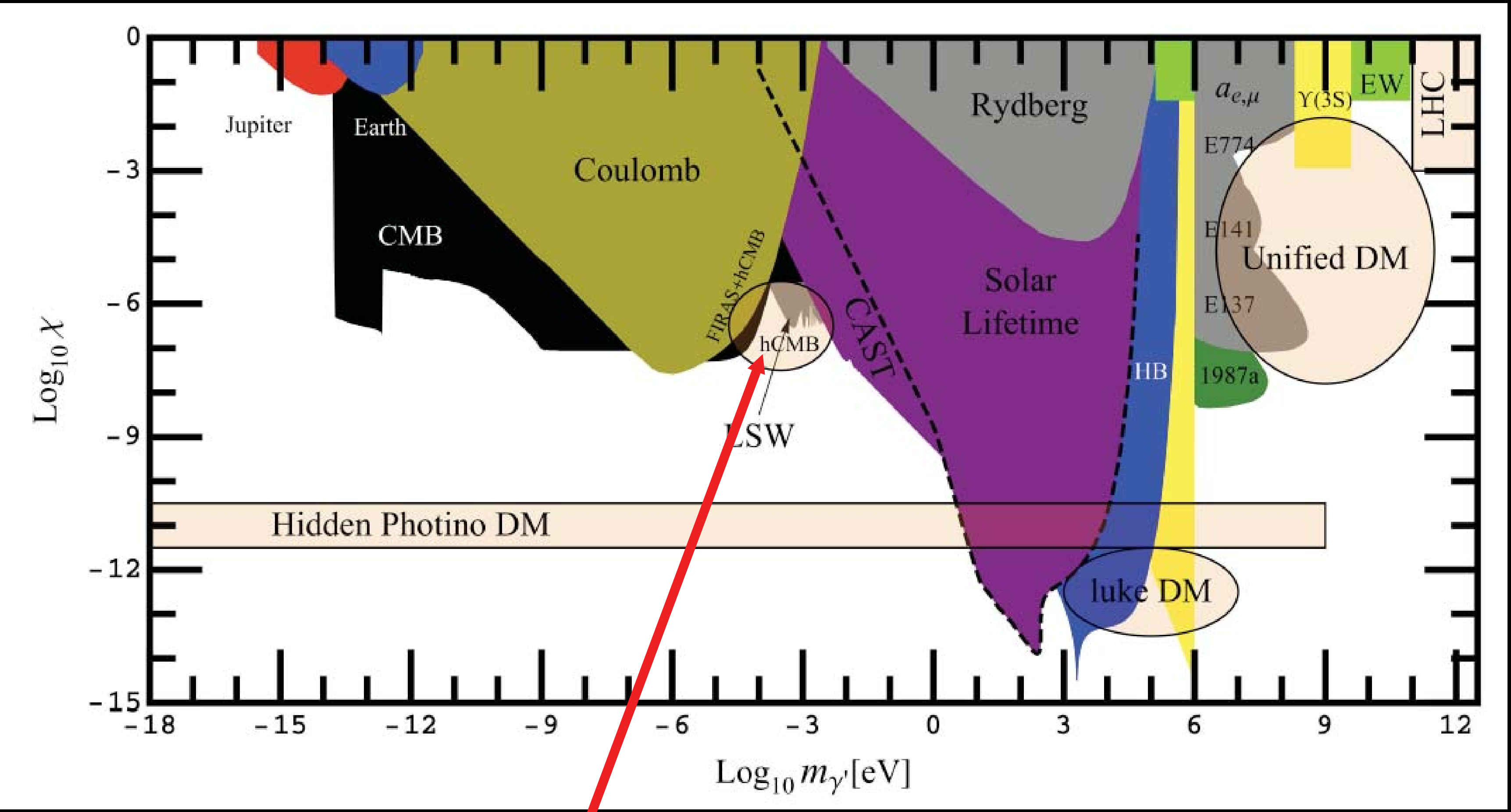
$\Rightarrow$ Can distort the CMB blackbody spectrum!!!

Powerful bounds...



JJ, J. Redondo and A. Ringwald 0804.4157
A. Mirizzi, J. Redondo and G. Sigl 0901.0014

Powerful bounds… and a hint!



WMAP observes $\Delta n_{\text{light species}} \sim 2$

More Hints...

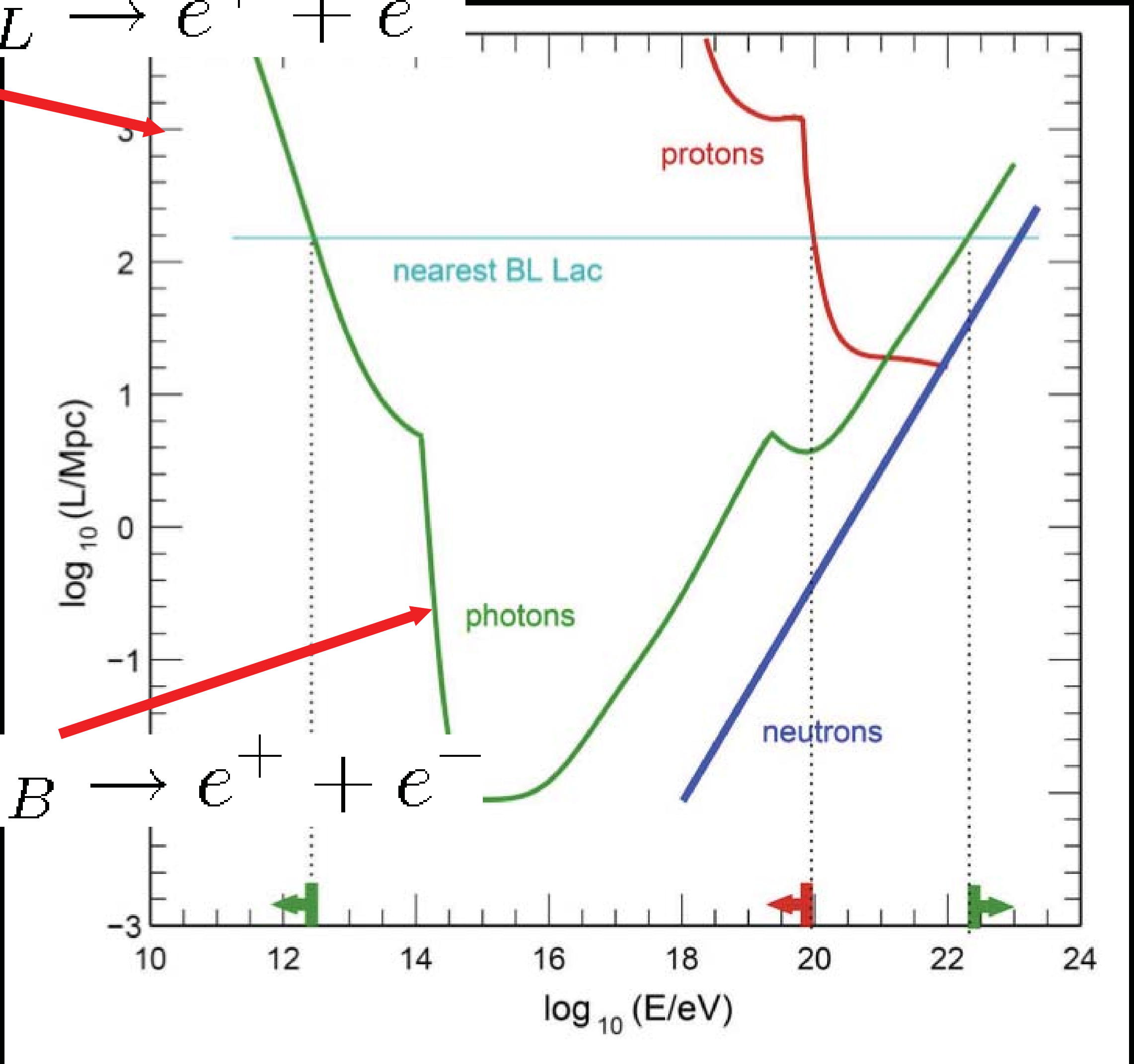
Transparency of the Universe

See M. Fairbairn at Patras 2009

The Universe should be quite opaque…

- … for high energy photons

$$\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$$

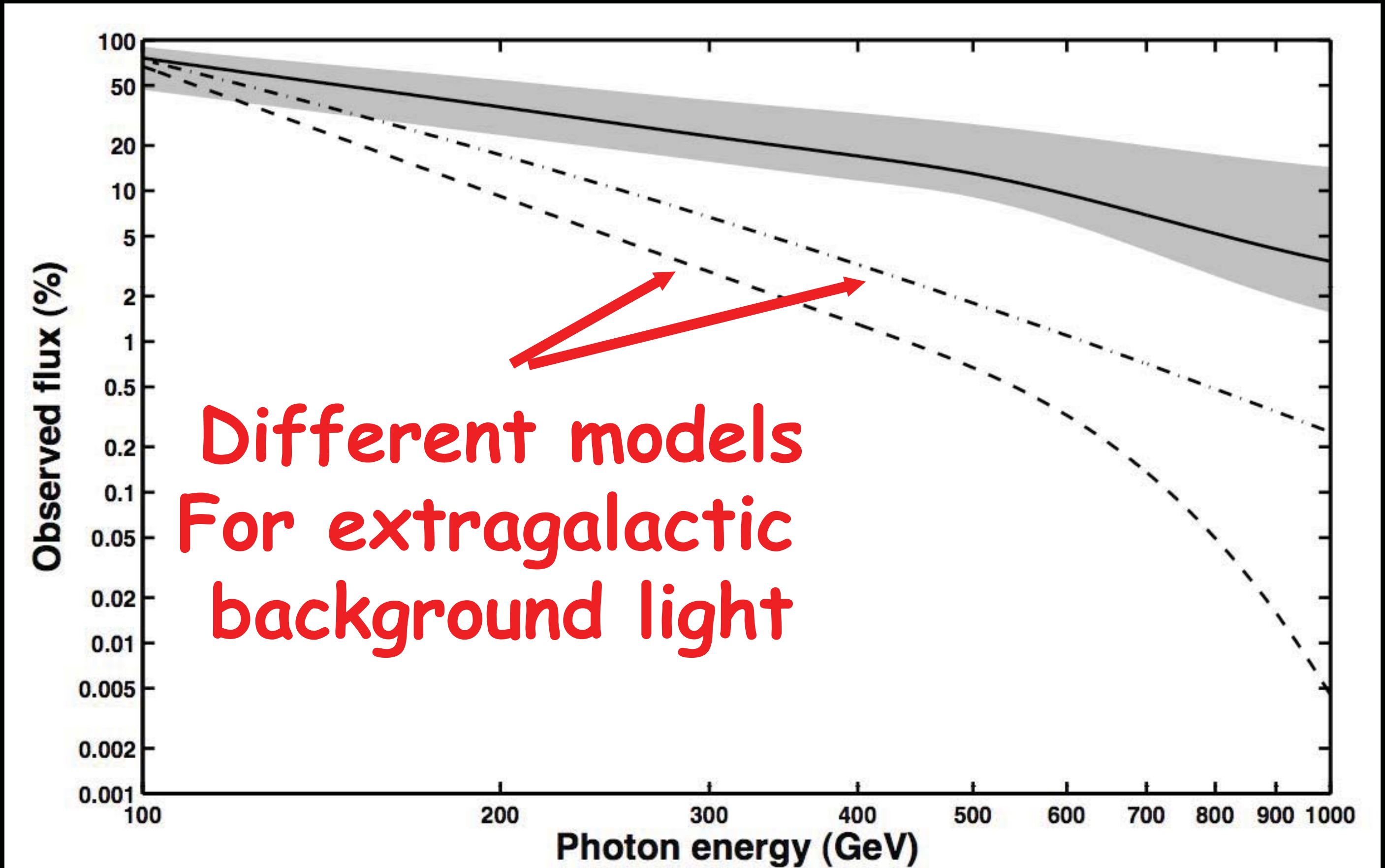


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

From far away γ-ray source

- Expect fewer high energy events!!

- Example 3C279

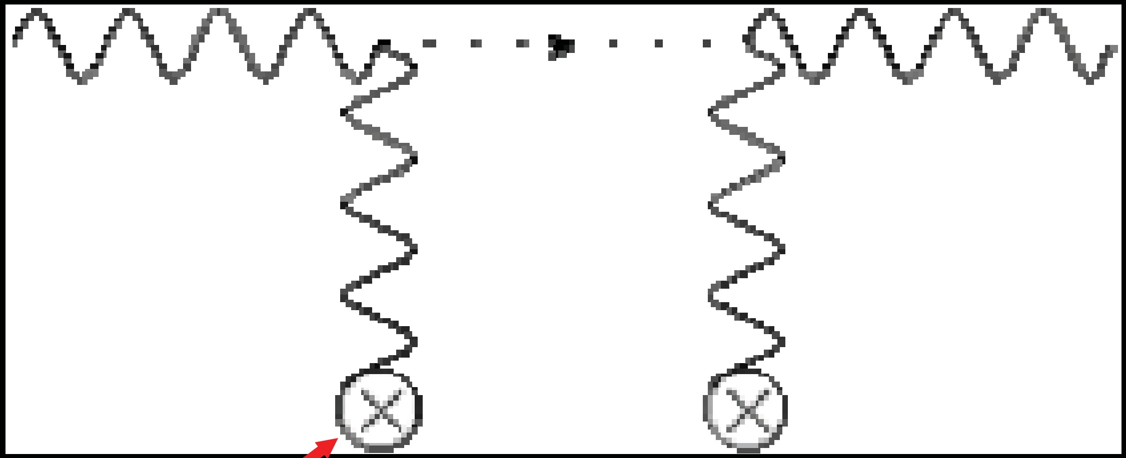


Observed…

- No such strong energy dependence!

Axion-like particles can help!

- Photon oscillates into ALP



Intergalactig magnetic field~10^{-13} T

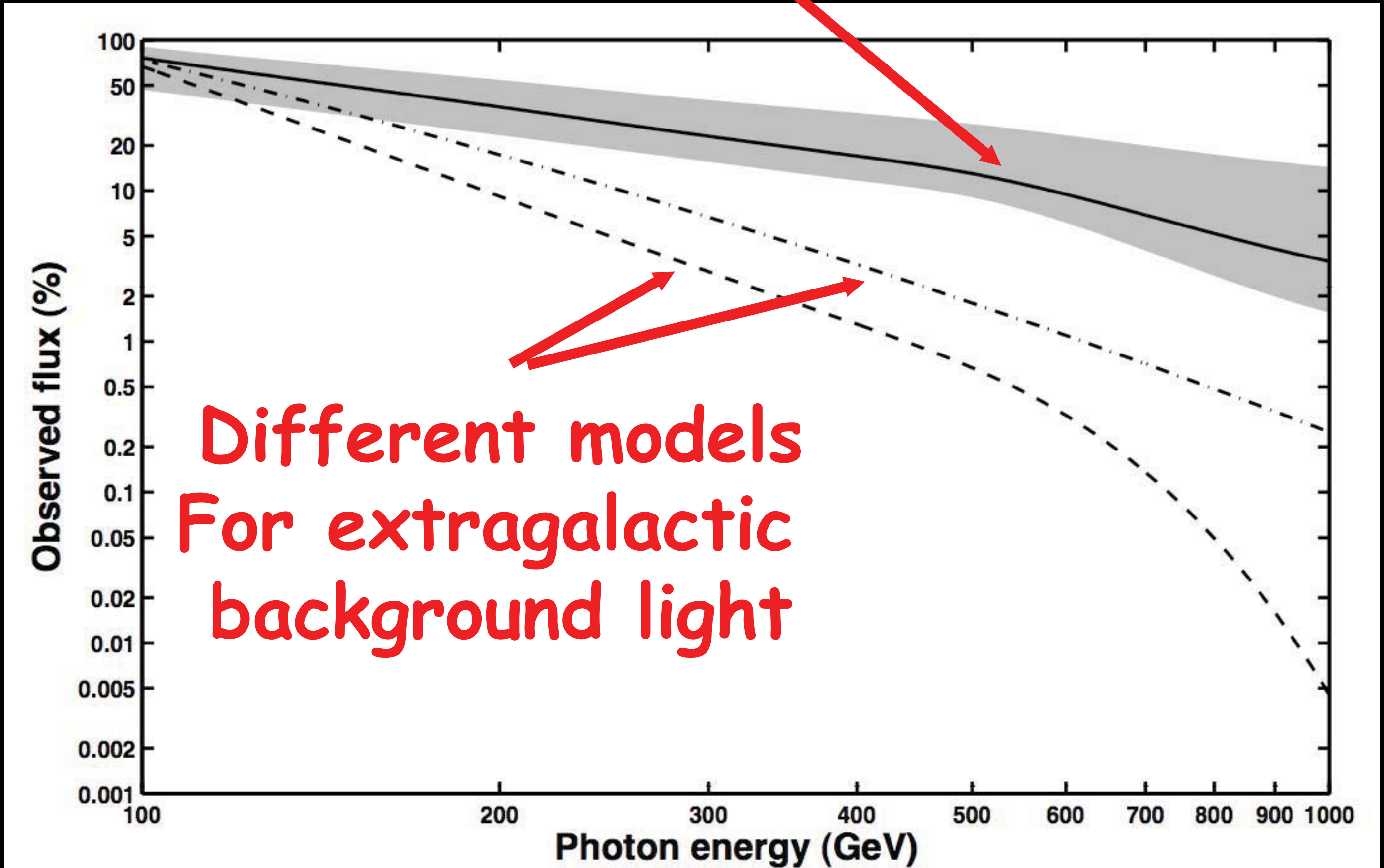
- ALP doesn't see other photons

⇒ Not absorbed

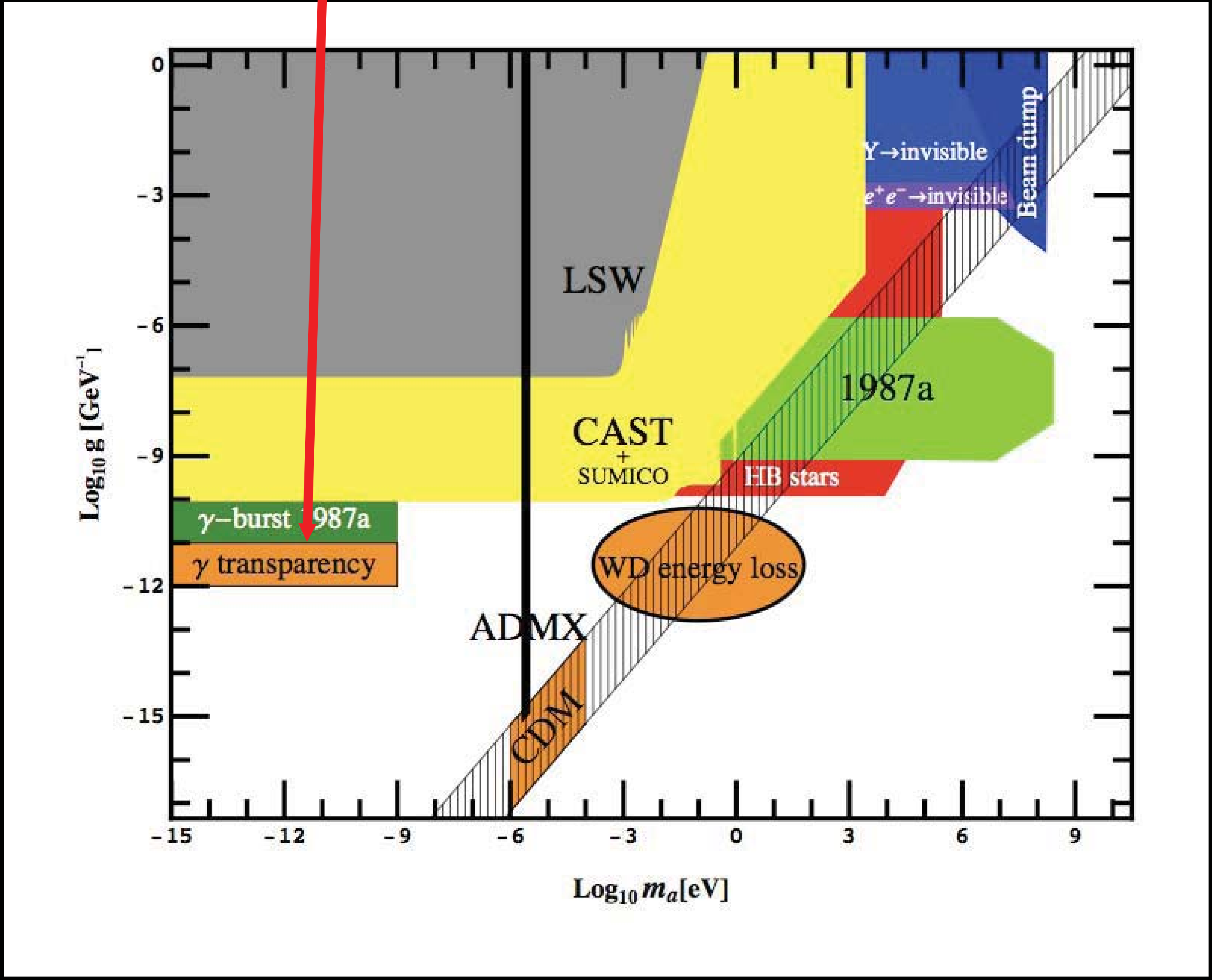
⇒ Greater Transparency!!

ALPs help!

- Example 3C279



Where are they???



Summary

Summary

- Astrophysics and Cosmology are a powerful probe of new light particles.

- Can test incredibly tiny interactions!!!

$$\chi \sim 10^{-8} - 10^{-14}, \quad , \epsilon \sim 10^{-14}, \quad g \sim \frac{1}{10^{10}\,\mathrm{GeV}}$$

- Interesting hints for new particles!

- Not always perfectly understood!

  ➡ Beware of uncertainties!

3.
Searching light particles in the Lab

Hints for new Physics

Model Building

Bottom-up (pheno)

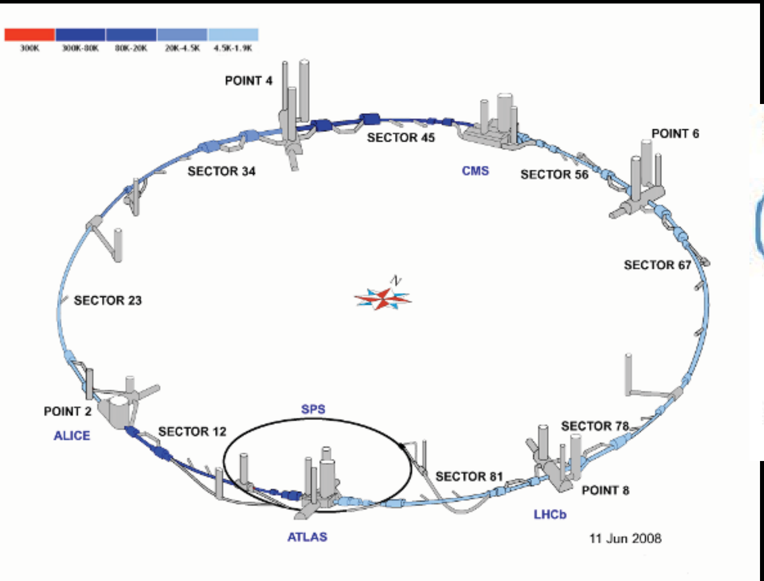
Top-down (theory)

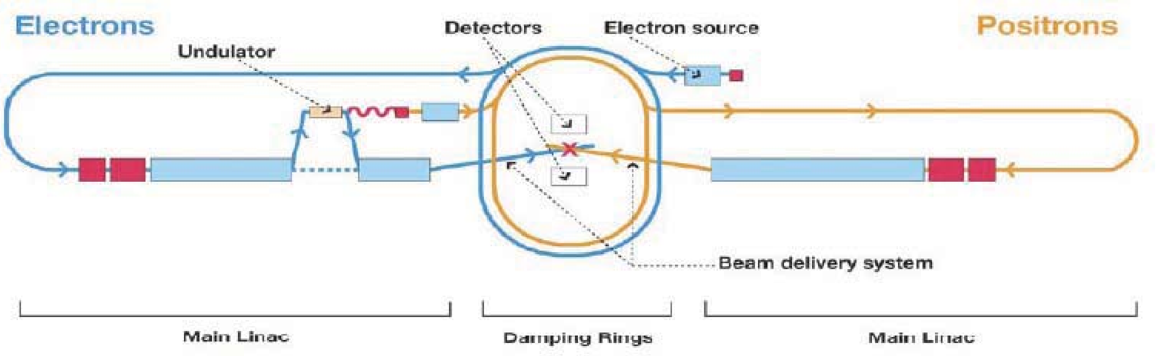
Observations/Experiments

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…

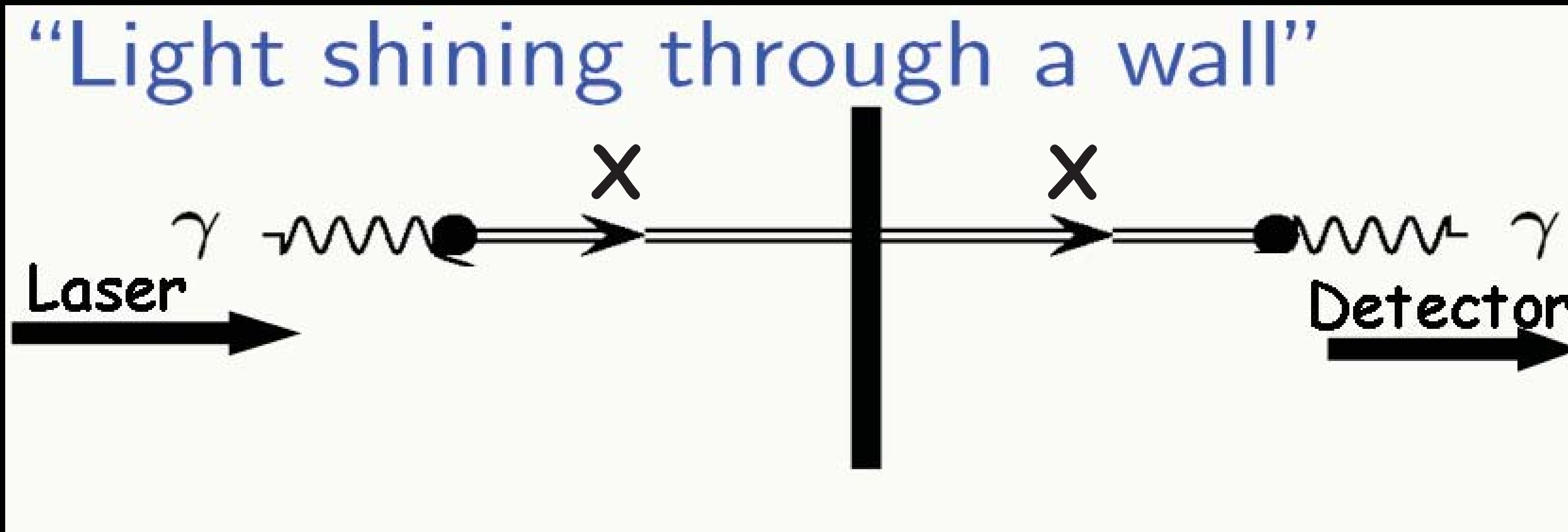
- May miss very weakly interacting matter (Axions, WIMPs, WISPs…)
- Current maximal energy few TeV

Recycling...

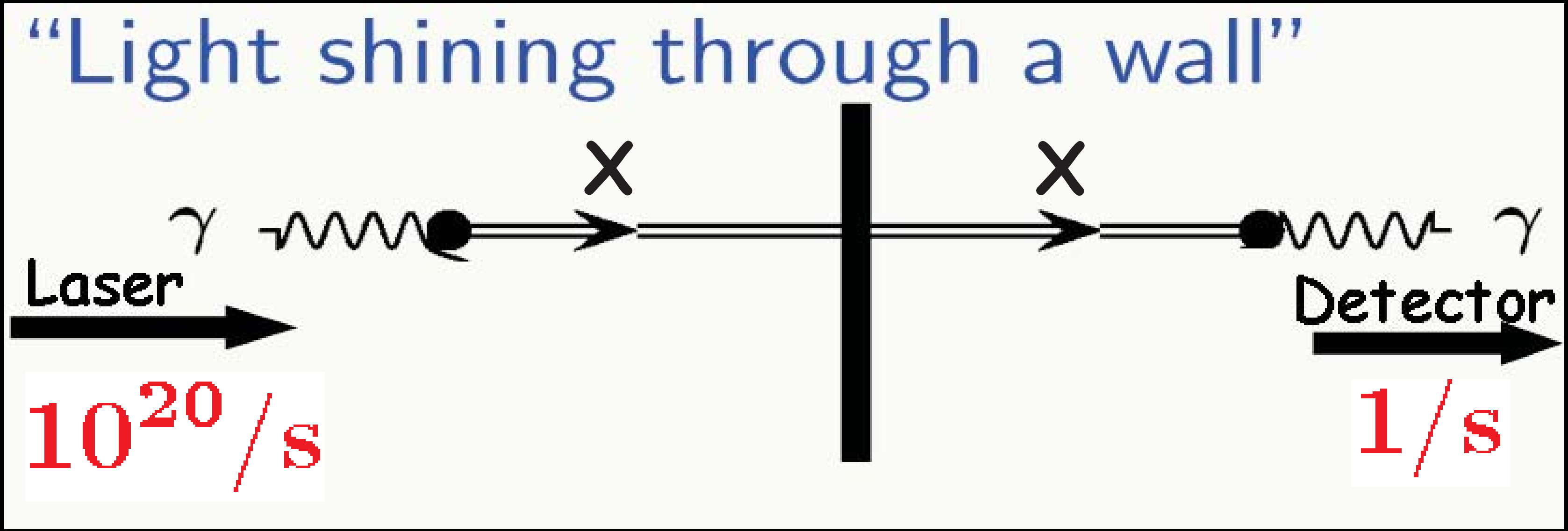
Complementary approaches

Light shining through walls

Light shining through walls



Light shining through walls

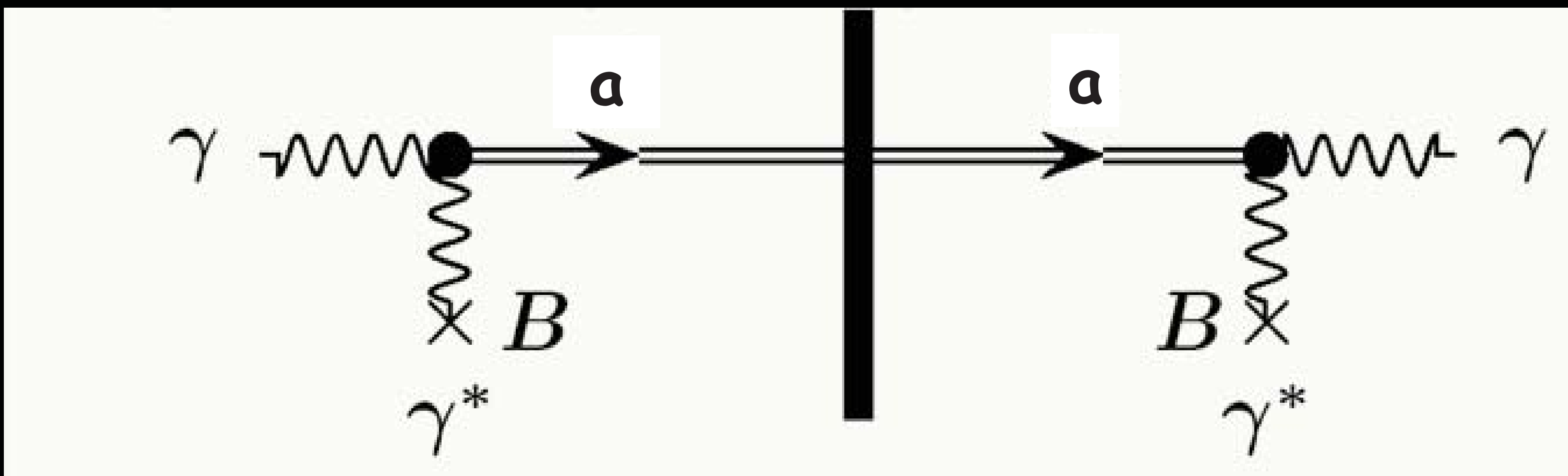


- Test $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$

- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

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

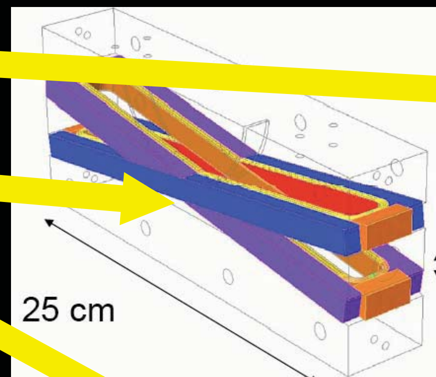


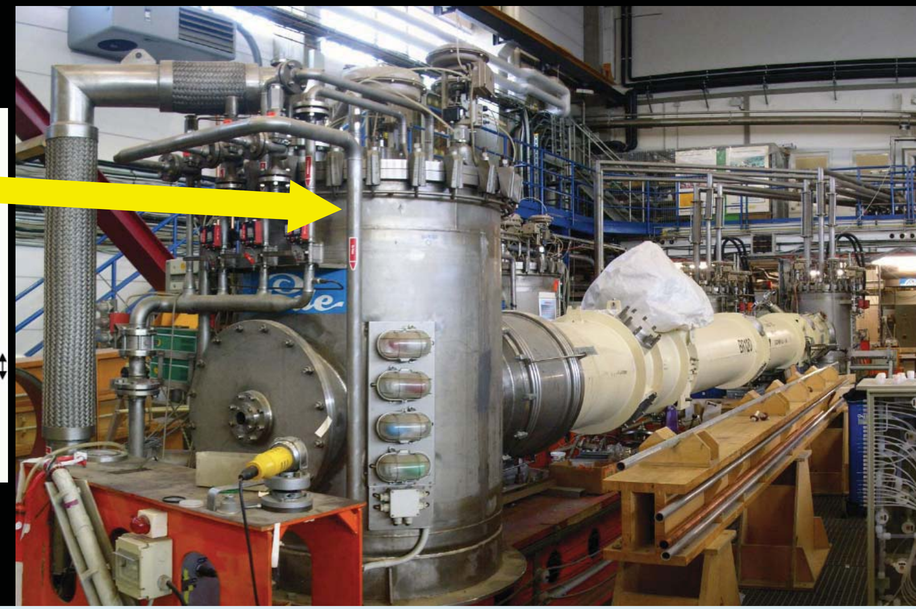
$$P_{\gamma\to a\to\gamma} \sim N_{\rm pass}\left(\frac{BL}{M}\right)^4$$

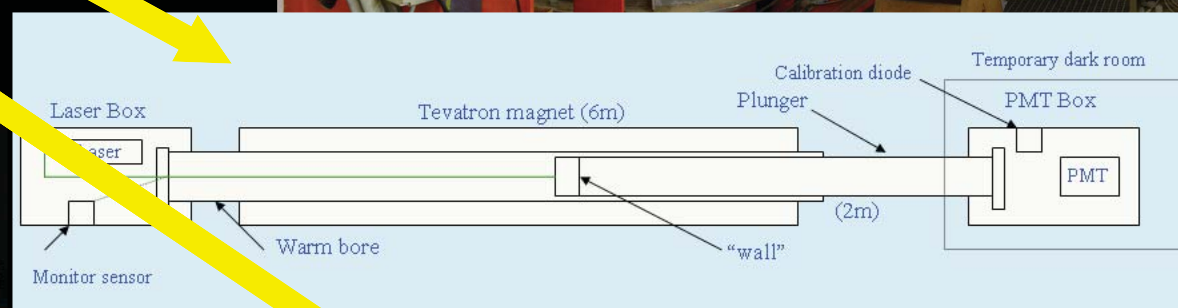
Light Shining Through Walls

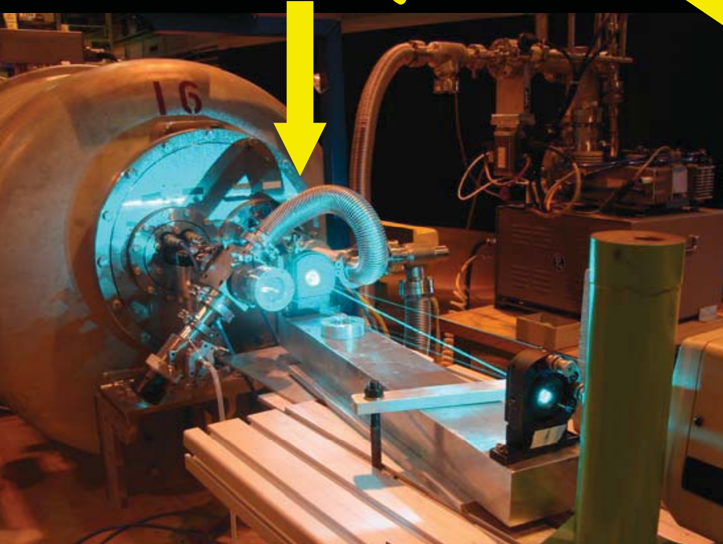
University of Durham

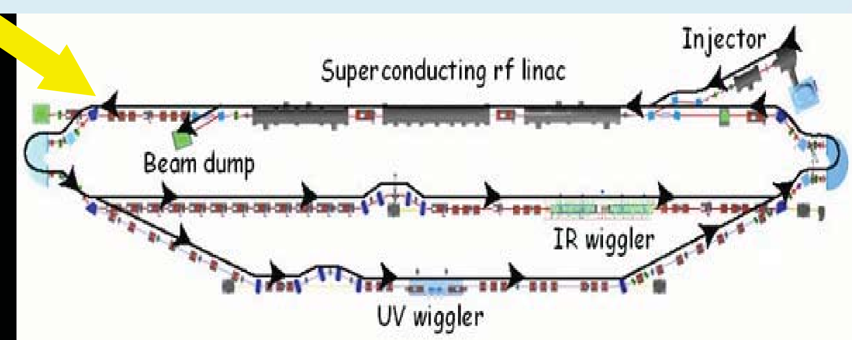
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR



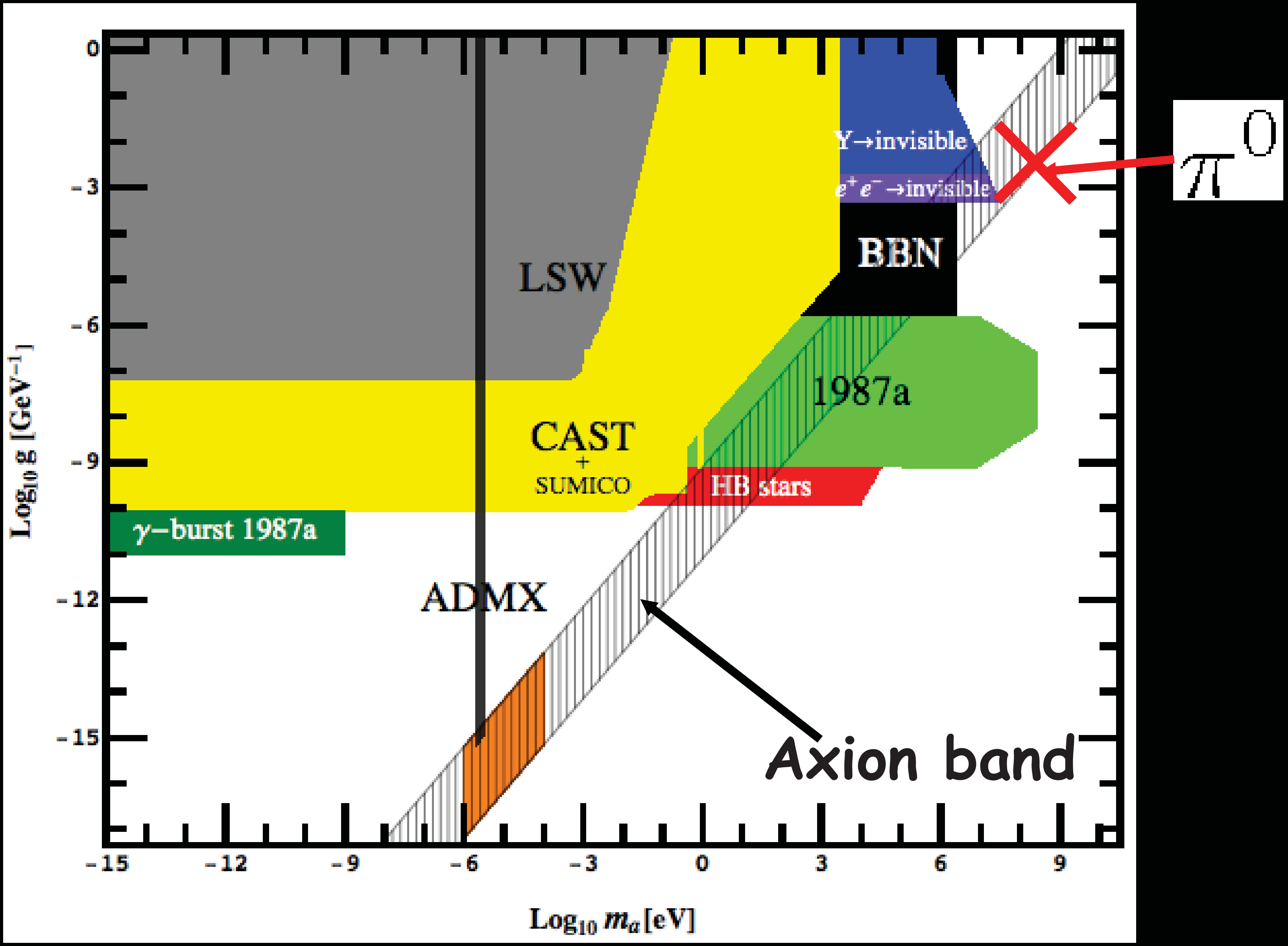






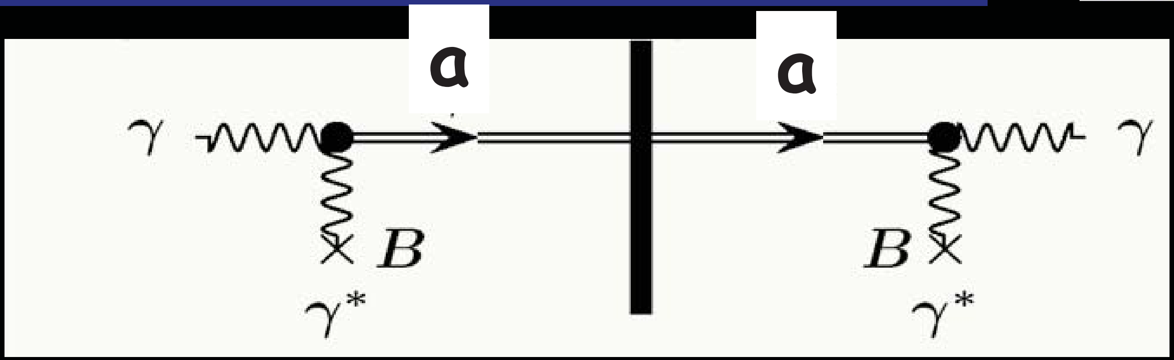


Small coupling, small mass

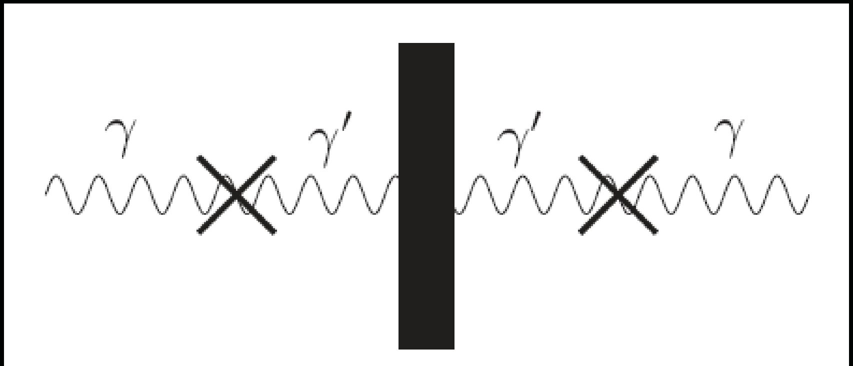


WISPS=Weakly interacting sub-eV particles

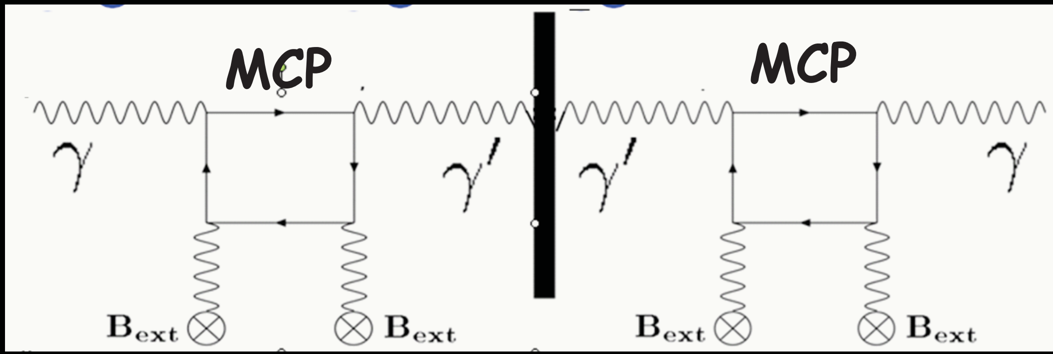
- Axions



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

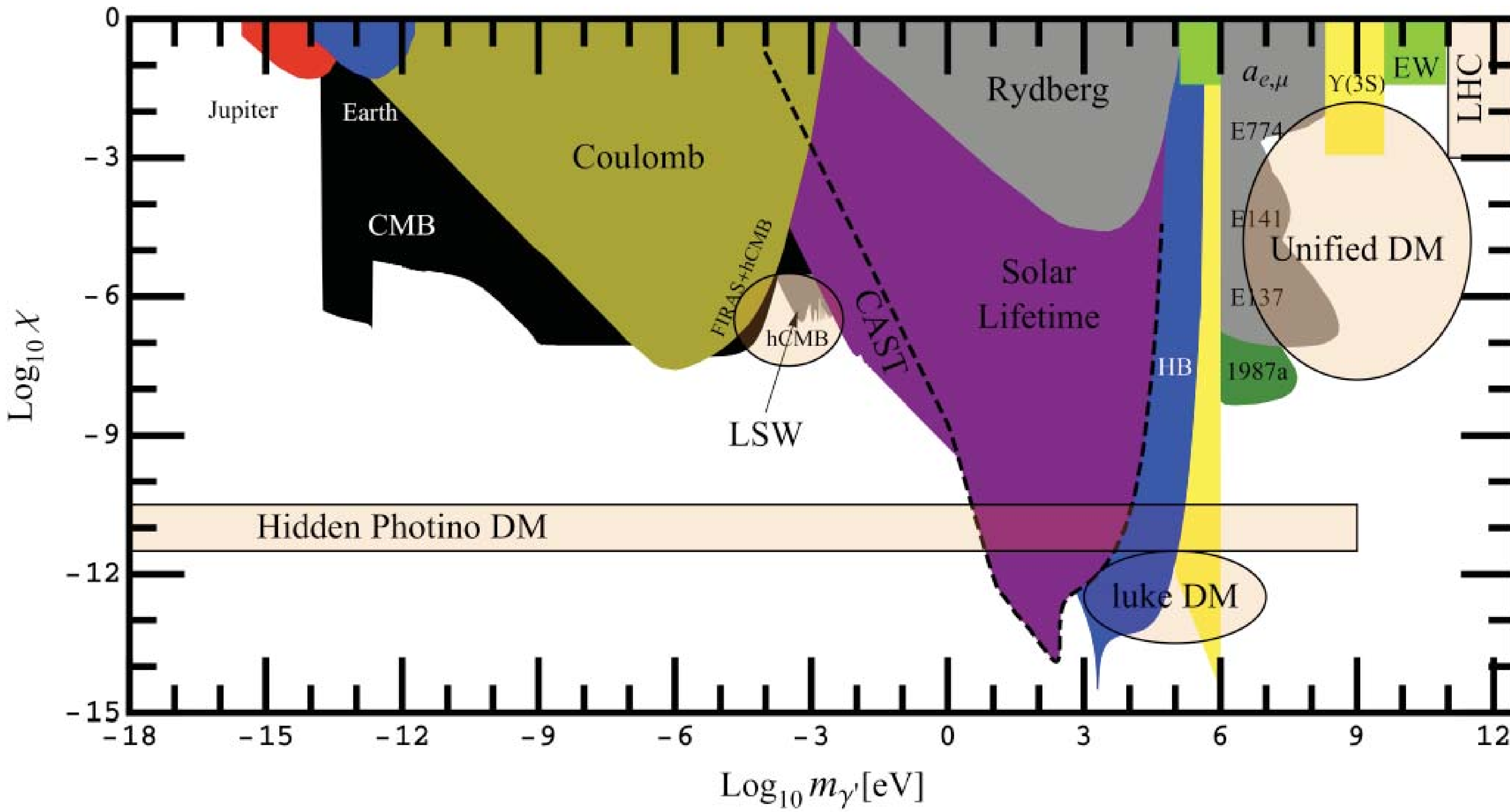


- Hidden photon + minicharged particle (MCP)



Hidden Photons

LSW already competitive + testing interesting area



Coincidences?

- Neutrino masses:

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

- Scale of dark energy:

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

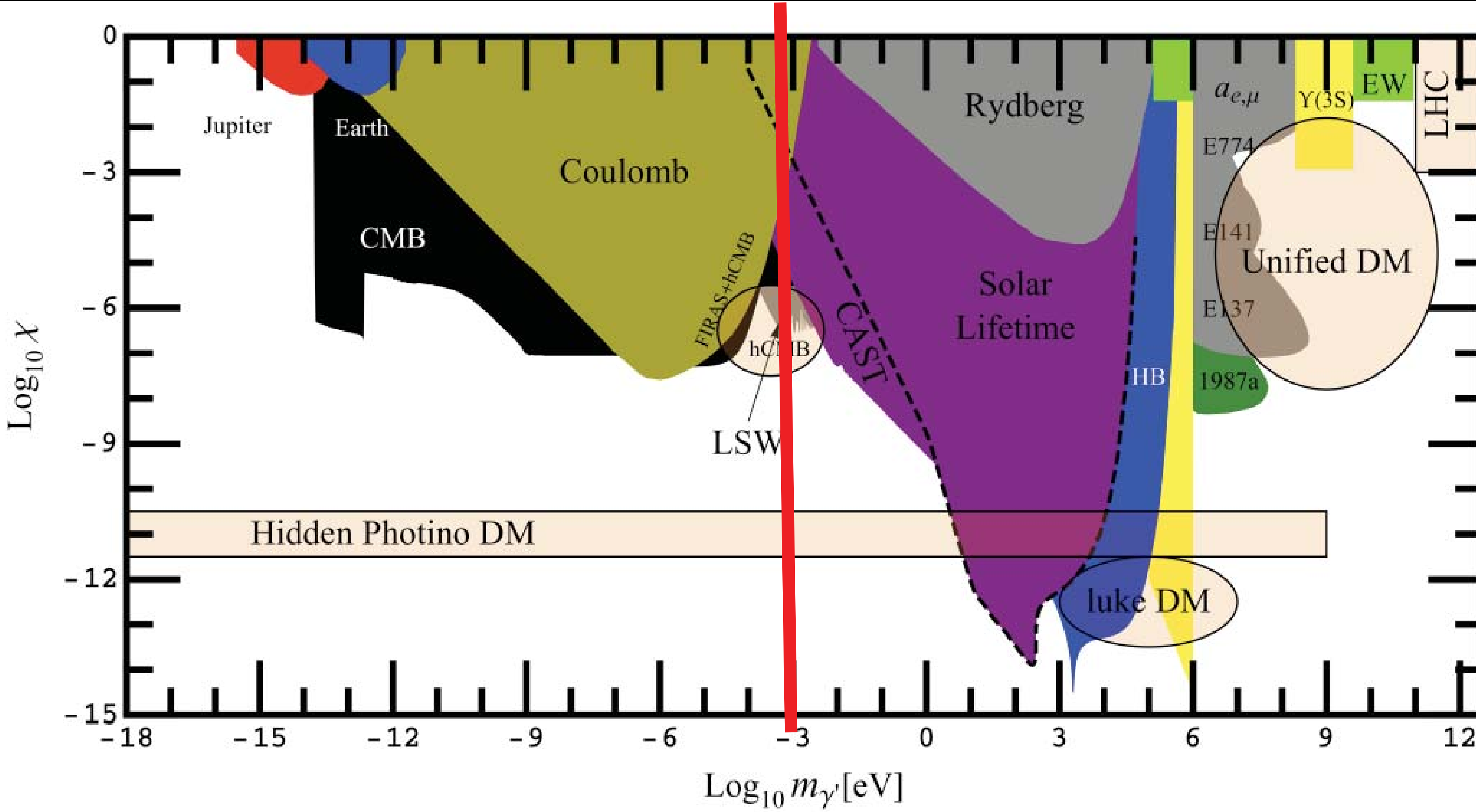
- Energy density of the Universe:

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

Hidden Photons

LSW already competitive + testing interesting area

Dark energy scale



Something to hide?

Something
to hide?

Use Hidden Photons©

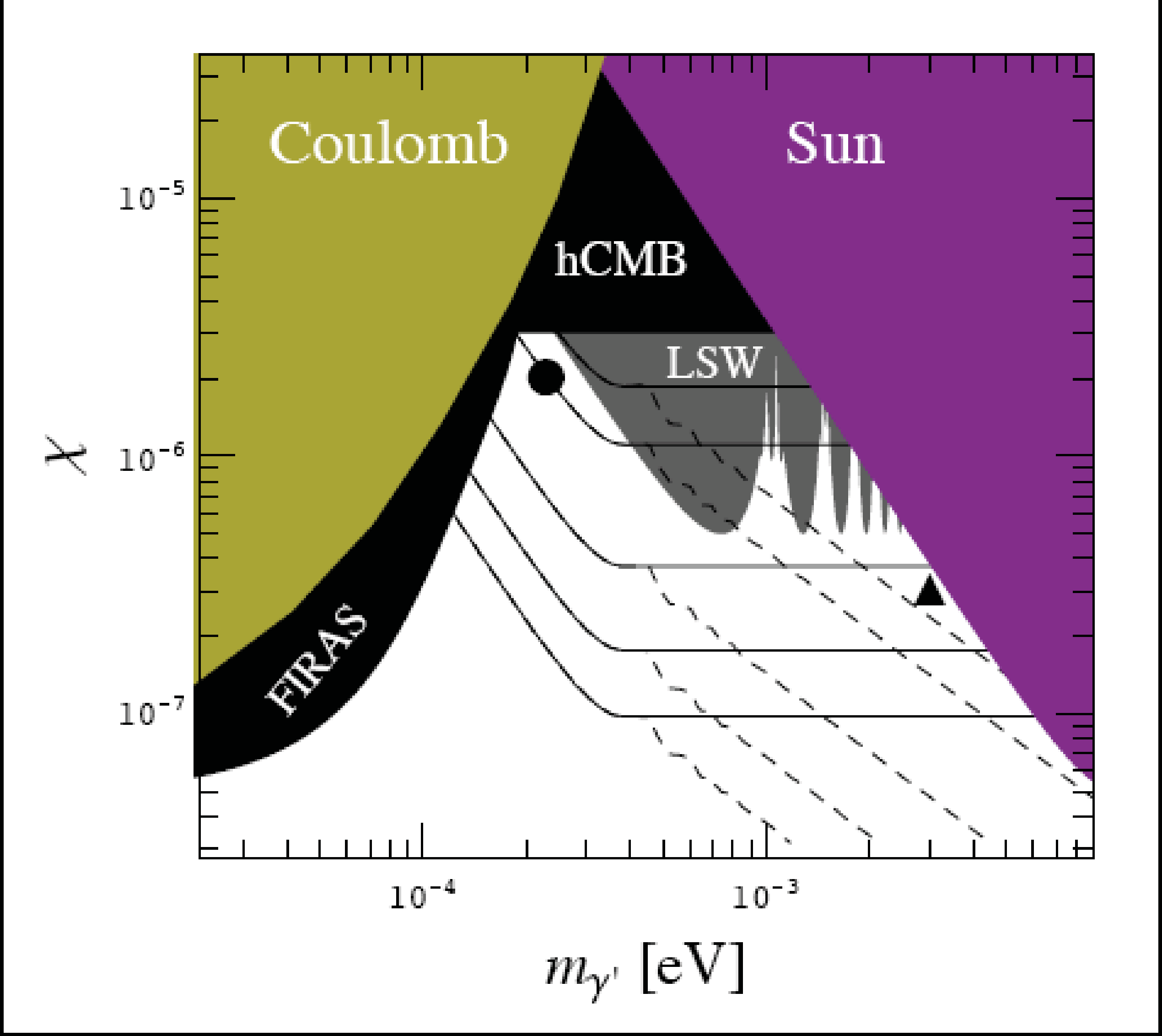
to communicate!

Practical applications ;-)

- Communicating through the Earth

JJ, J. Redondo and A. Ringwald 0903.5300

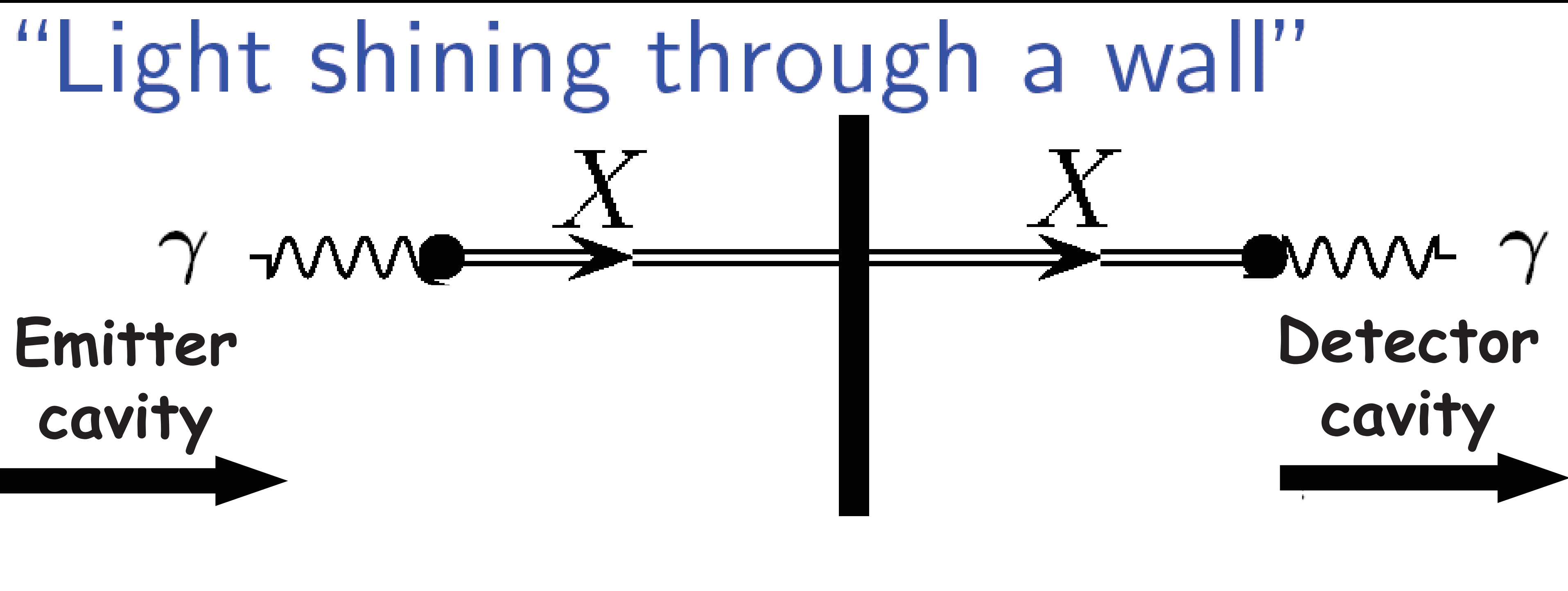
Practical applications ;-)



A cavity experiment

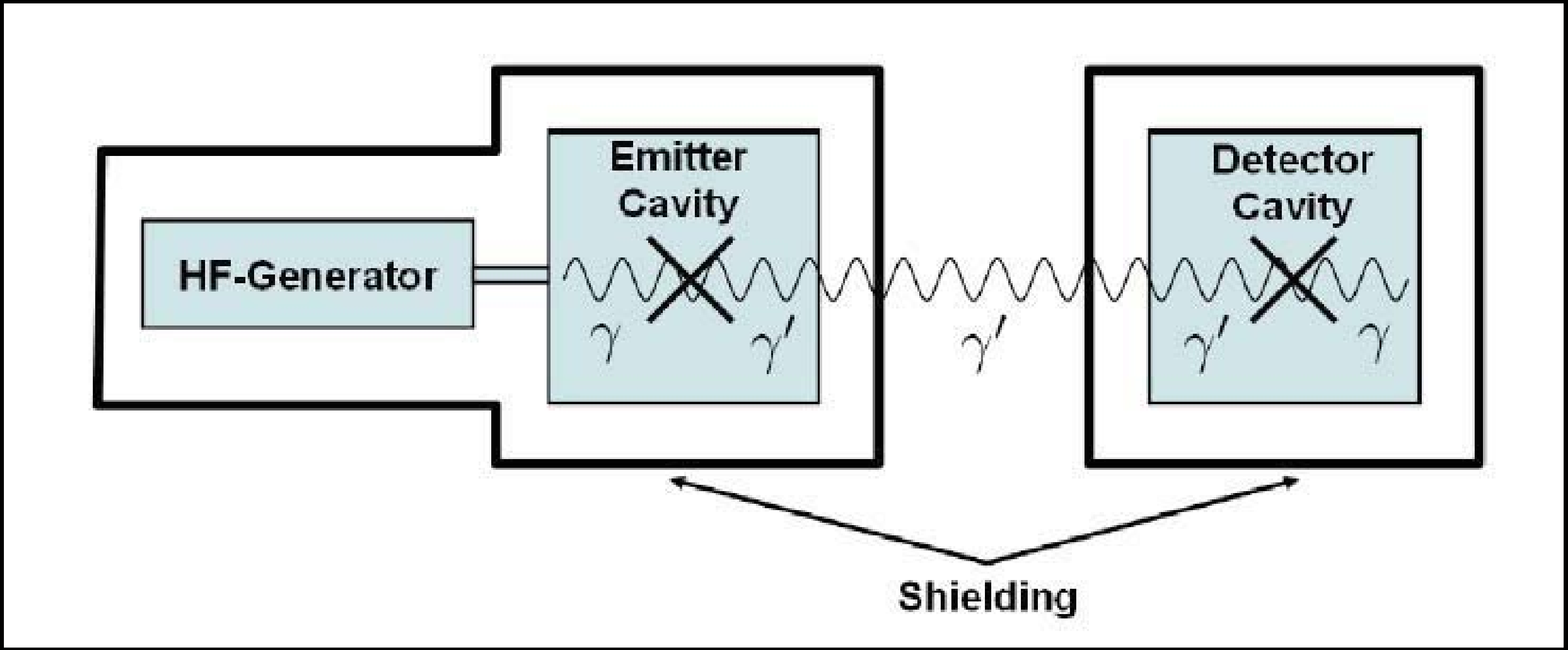
JJ and A. Ringwald 0707.2063

It's a Light shining through walls clone



- Microwaves instead of laser

Setup



Emitter Cavity
Detector Cavity
HF-Generator
γ
γ'
γ'
γ'
γ
Shielding

Advantages

- Resonant cavity setup: Cavity in production and regeneration region

$$\mathrm{signal} \sim Q_1 \times Q_2$$

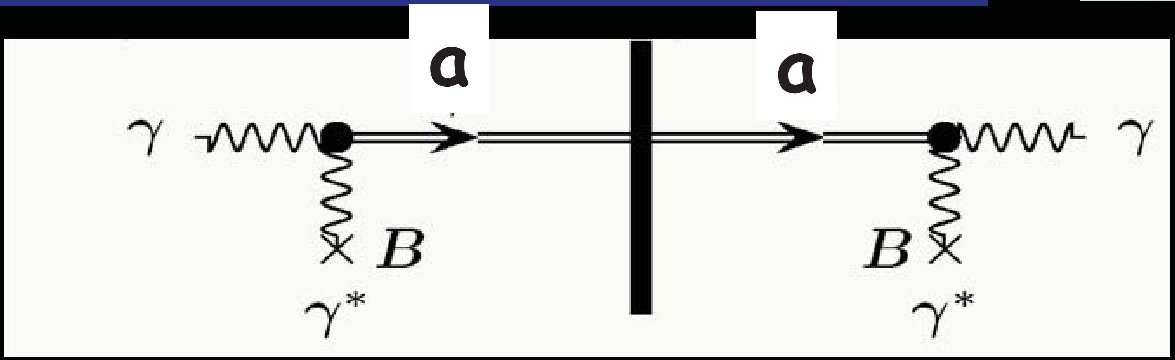
- Microwave cavities can have very high Q-factors~10^{11}!

- Sensitive to masses in the interesting μeV-meV range

Sensitive to variety of WISPs

- Axions

$$\frac{1}{M} a \tilde{F} F$$



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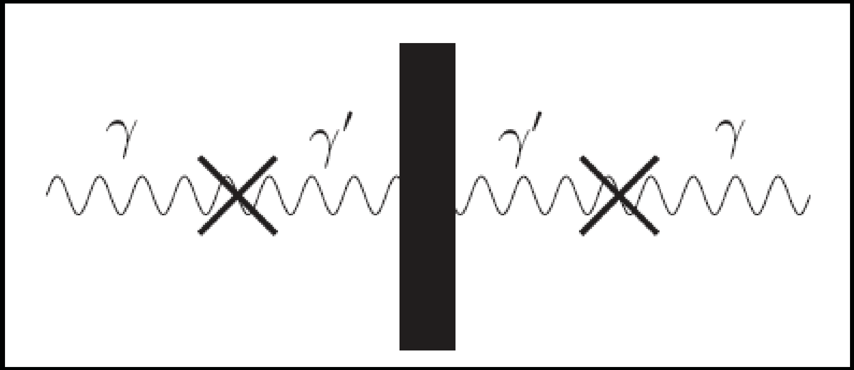
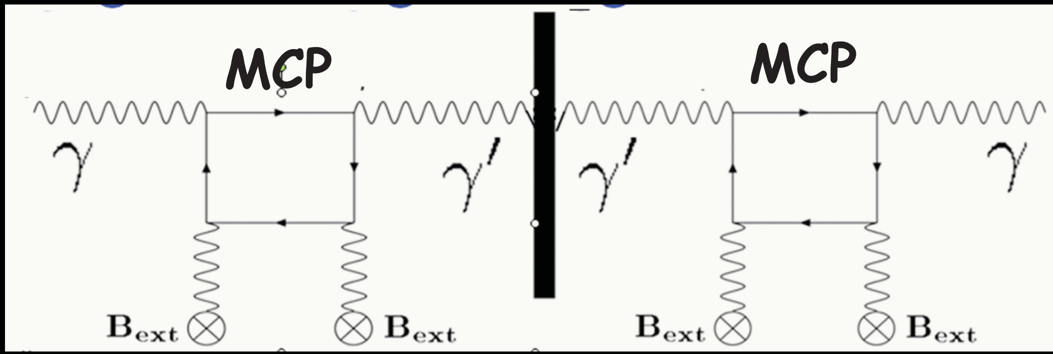
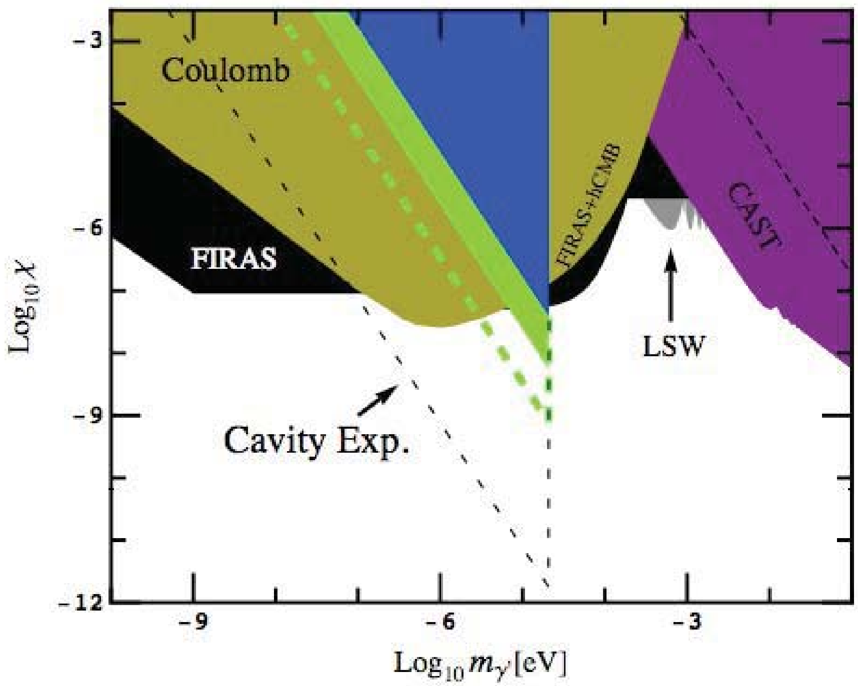


- Hidden photon + minicharged particle (MCP)

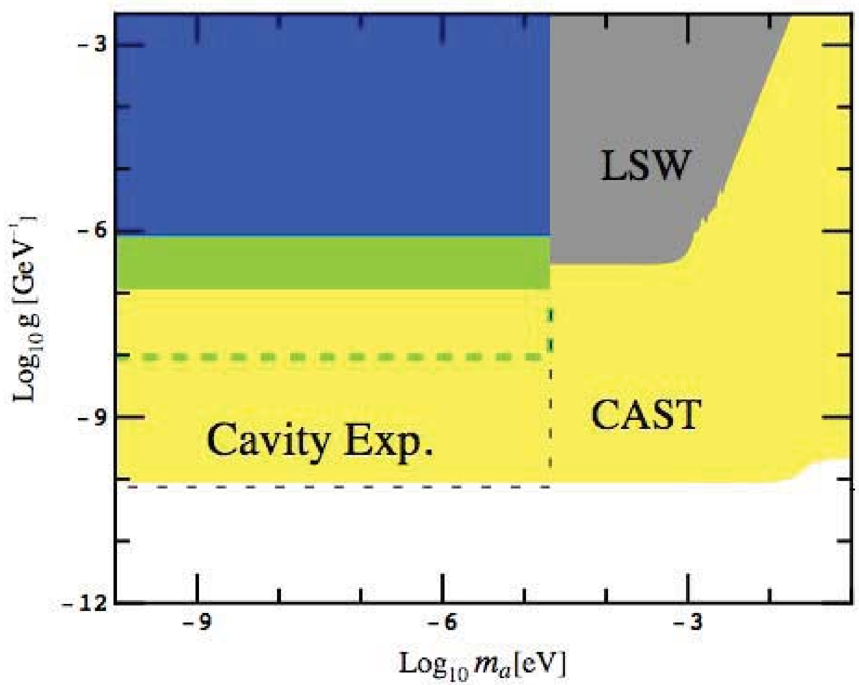


Impressive sensitivity/discovery potential

Hidden photons



Axion (-like particle)s



Impressive sensitivity/discovery potential

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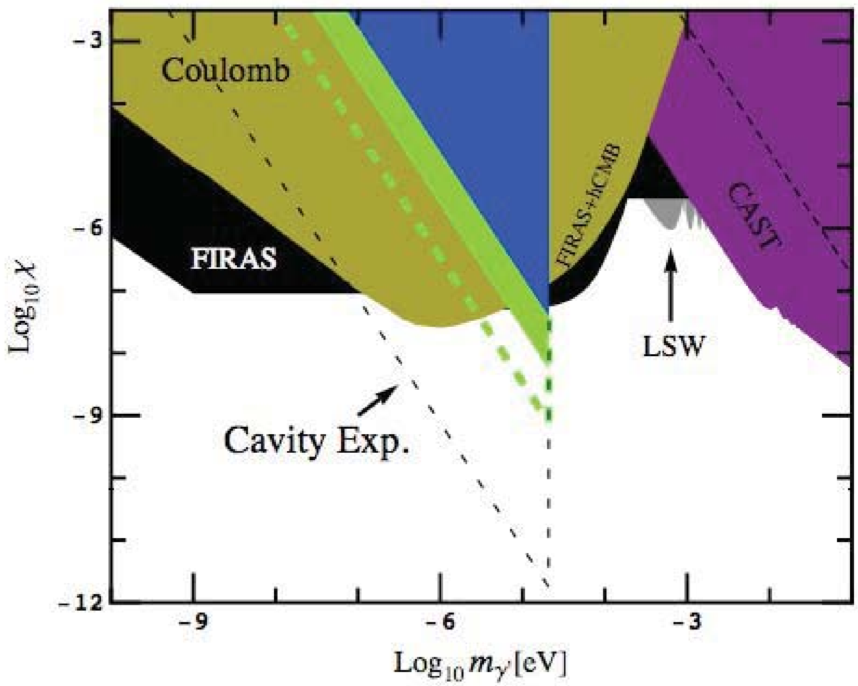
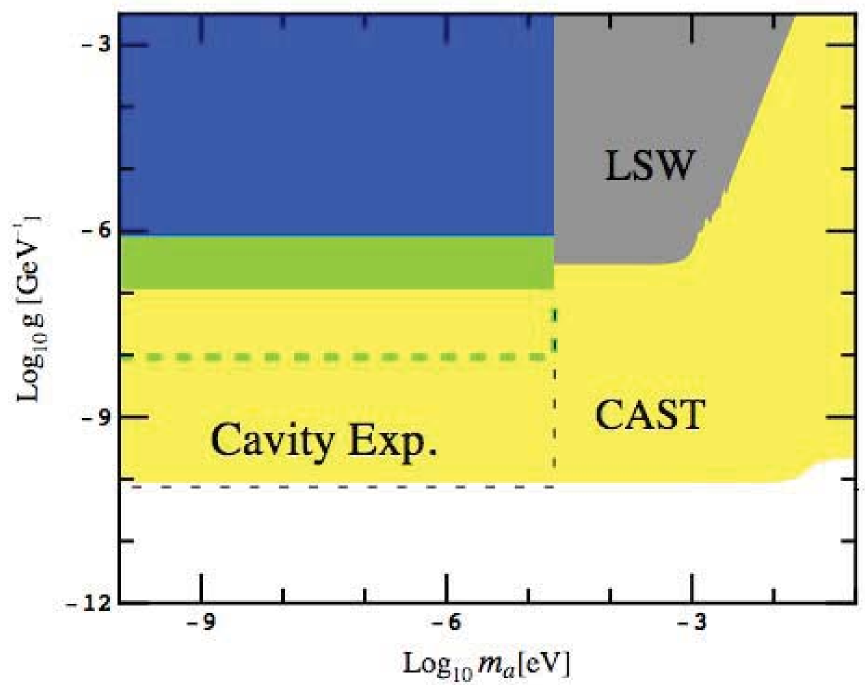


Axion (-like particle)s



Experiments are underway:

@ UWA Perth

@ Yale

An aside:
Sub-Quantum interference

J. Hartnett, JJ, R. Povey and M. Tobar
1101.4089

Resonant regeneration

$$\text{signal} \sim Q_1 \times Q_2$$

detector cavity

- The detector acts as high quality oscillator driven by (small) external force (ALPs, HPs…)

- Amplification because
  the photon amplitude adds up in each pass

Less than one photon inside cavity...

- Already at relevant power levels

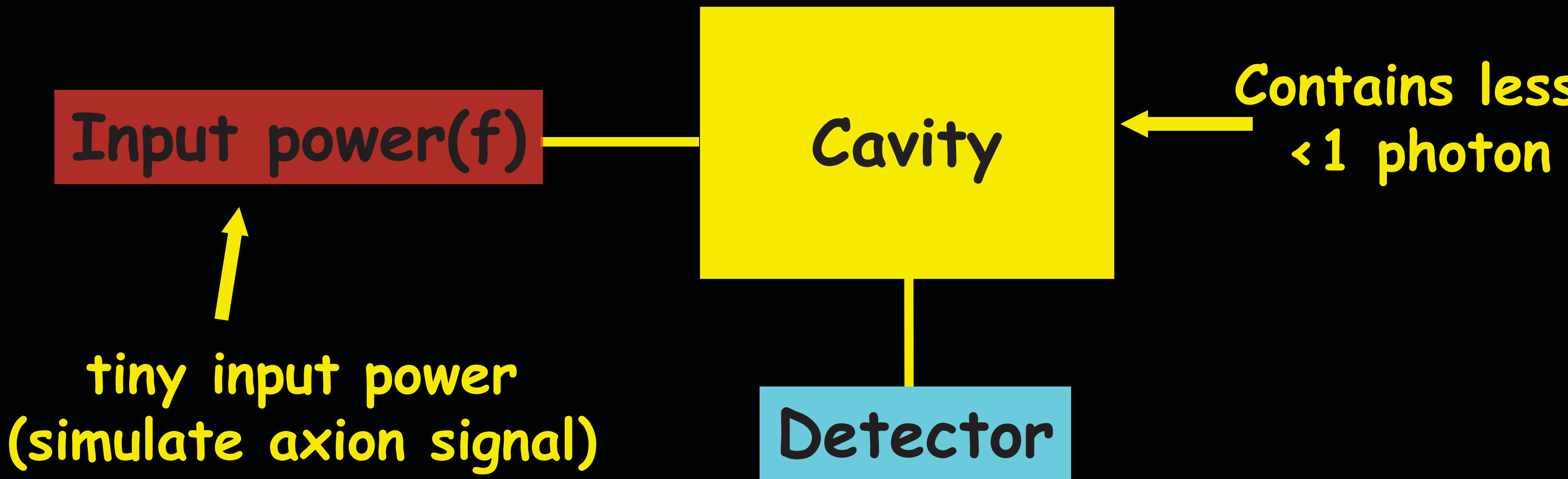
$$P_{\rm out} \sim P_{\rm loss} \;=\; \omega \frac{E_{\rm stored}}{Q} = \omega \frac{\hbar\omega}{Q}$$

$$\sim \; 2.6 \times 10^{-19}\,{\rm W} \left(\frac{f}{\rm GHz}\right)^2 \left(\frac{10^5}{Q}\right) \gg 10^{-23}\,{\rm W}$$

- Even more relevant for optical experiments (higher frequency)

Is there amplification in this "sub-quantum" regime?

A test/demonstration setup…

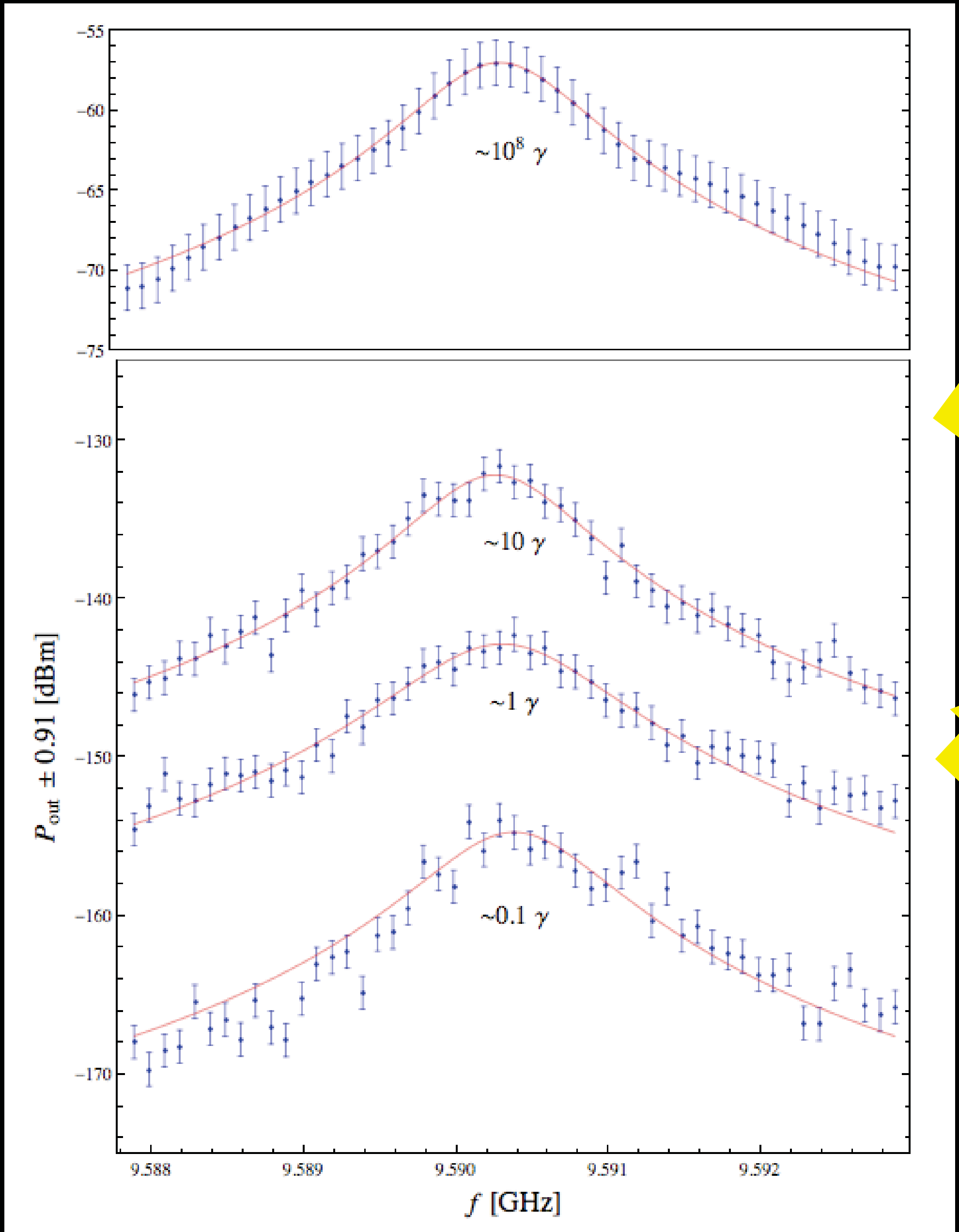


- Do we see the (fractional) photon interfering with itself?

  (i.e. amplitudes adding up)

➡ Look at resonance curve

A true measurement...(preliminary!!)



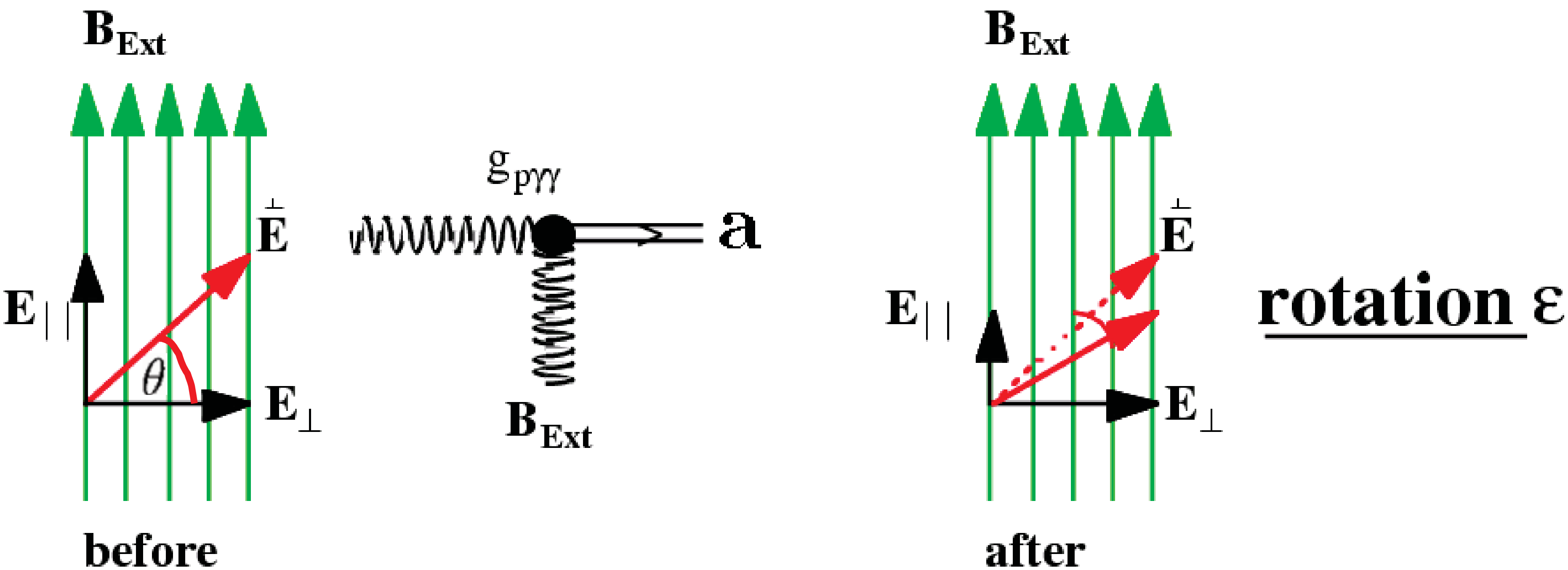
Interference works!

Laser Polarization Experiments

Dichroism (Rotation)

University of Durham

- Coupling $\mathcal{L} \sim ga\, F^{\mu\nu}\, \tilde{F}_{\mu\nu} \sim ga\vec{E}\cdot\vec{B}$

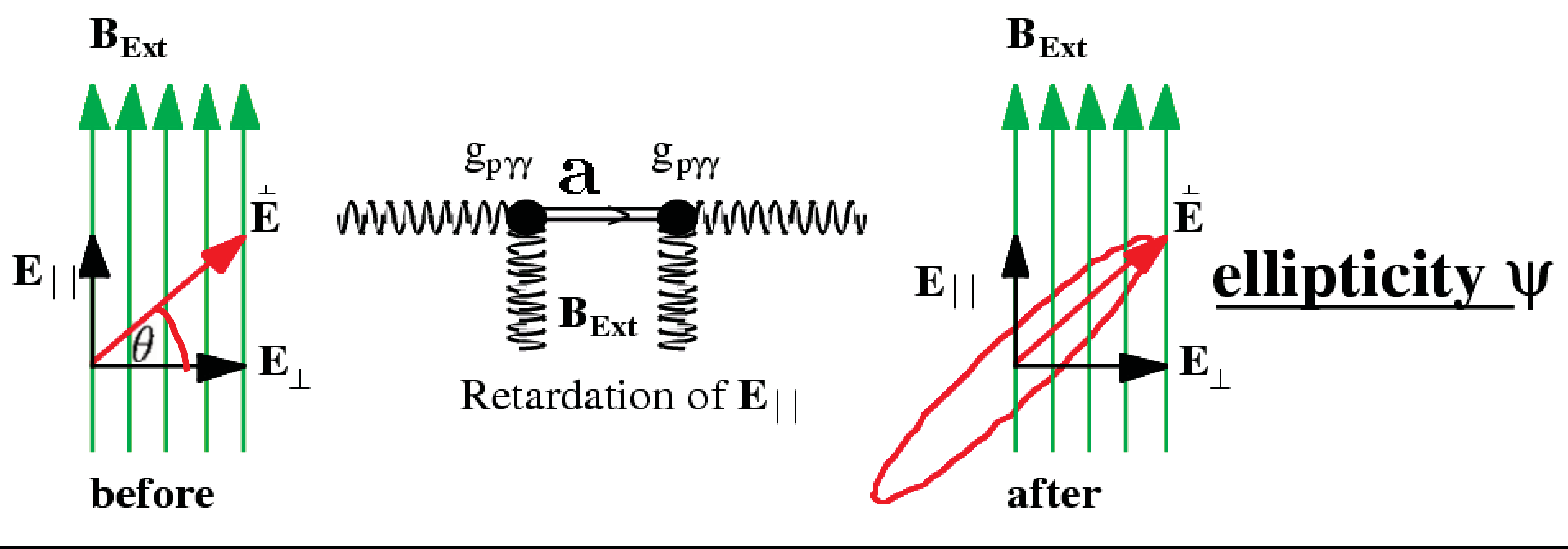


F. Brandi et al. hep-ex/0006015

$$\epsilon \approx -N\left(\frac{gBL}{4}\right)^2 \sin(2\theta)$$

Ellipticity

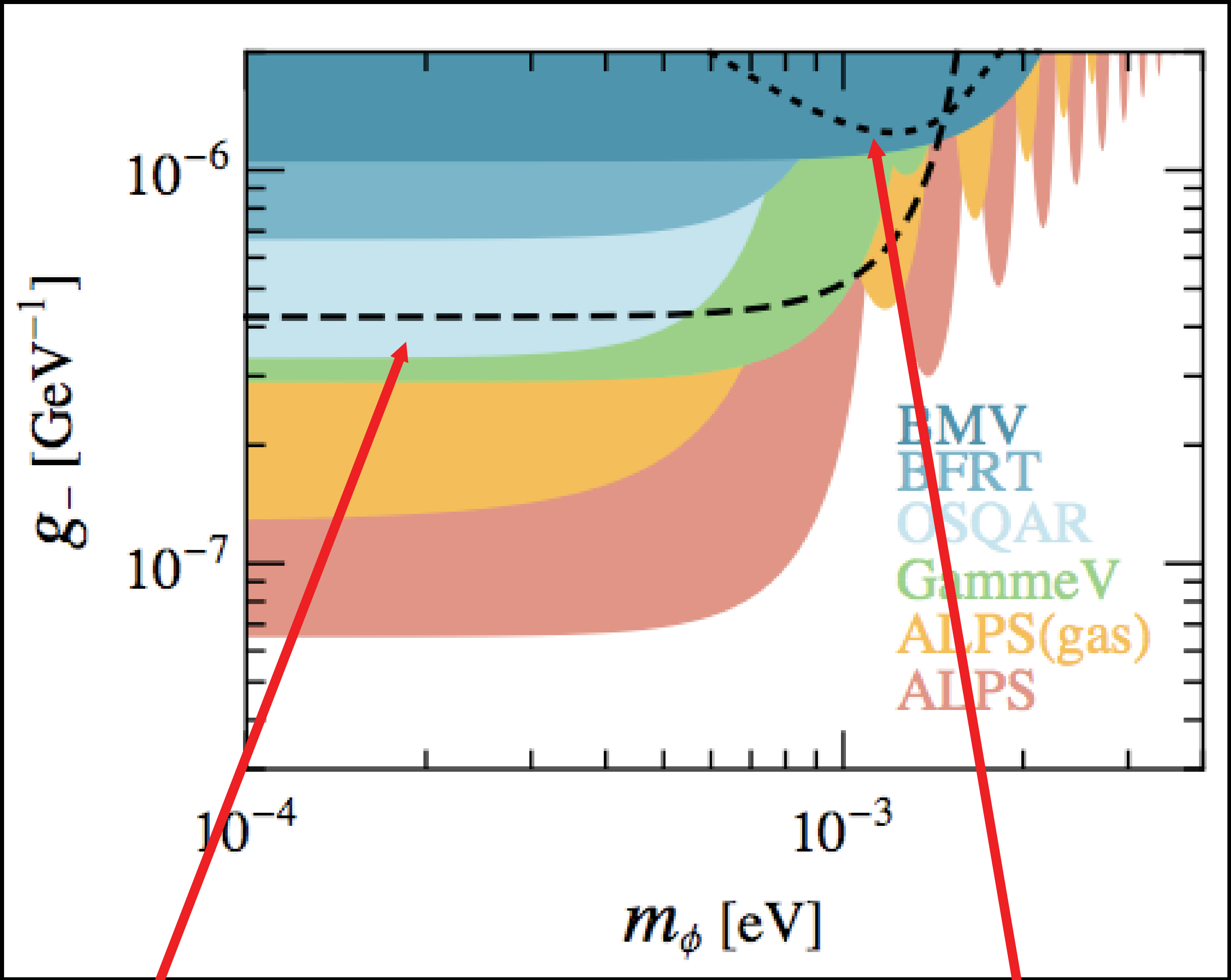
Virtual ALP production leads to Birefringence



$$\psi \approx \frac{N}{6}\left(\frac{gBL}{4}\right)^2 \frac{m_a^2 L}{\omega} \sin(2\theta)$$

Bounds on ALPs

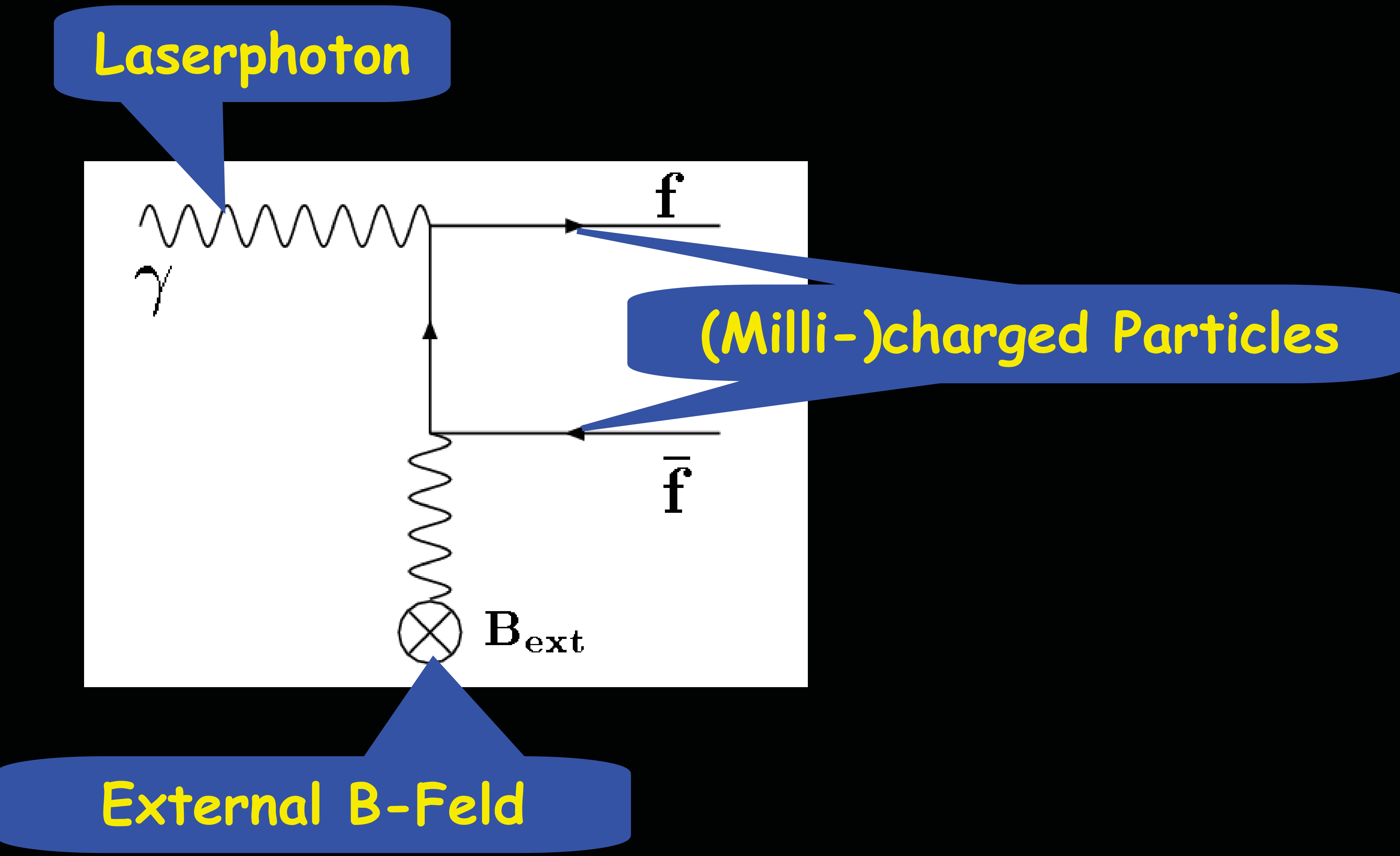
K. Ehret et al. 1004.1313



PVLAS rotation

PVLAS ellipticity

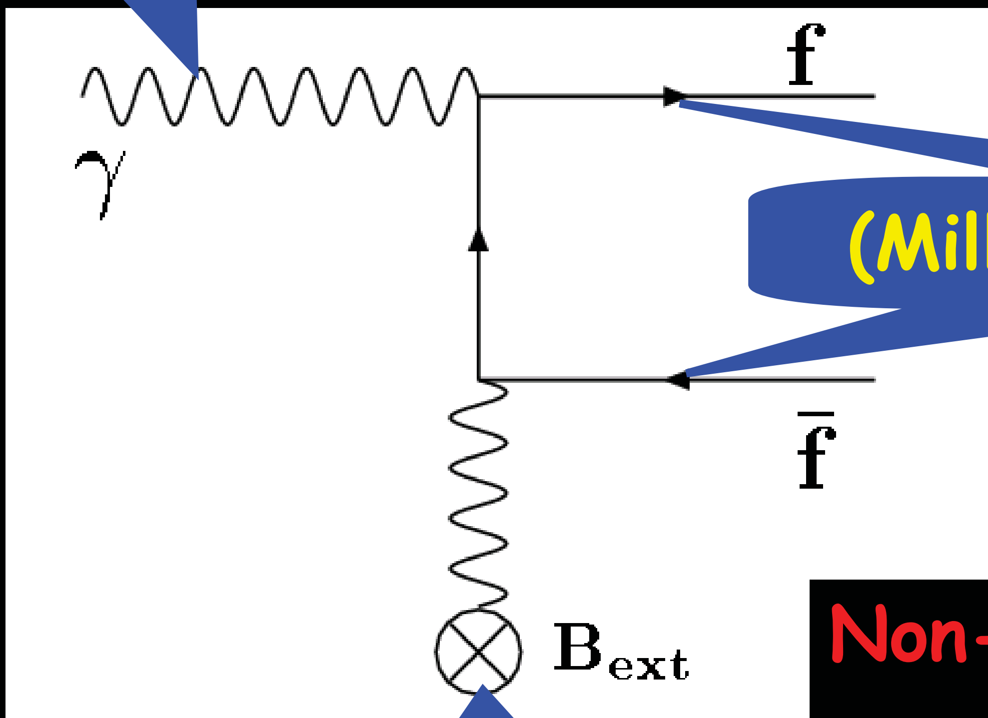
Pairproduction with a Laser



Pairproduction with a Laser

University of Durham

Laserphoton



(Milli-)charged Particles

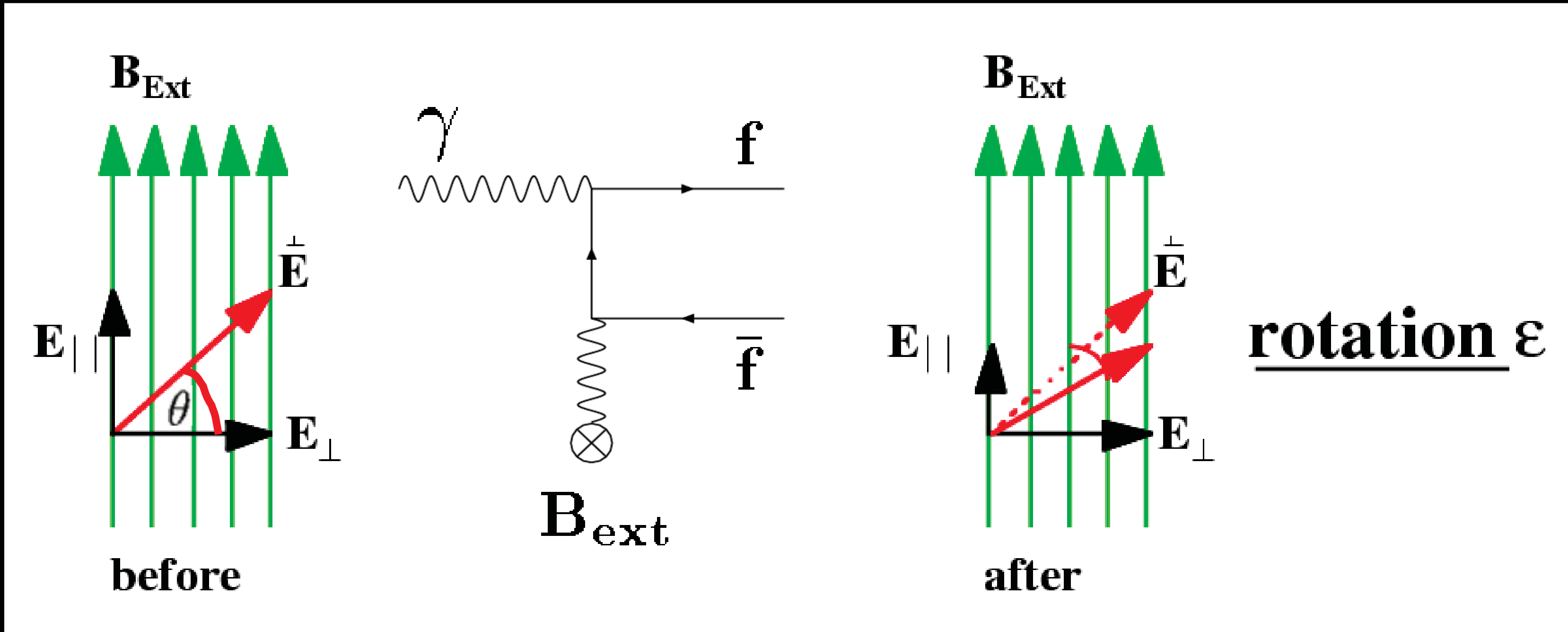
Non-perturbative: Why?
➔ Homework

External B-Feld

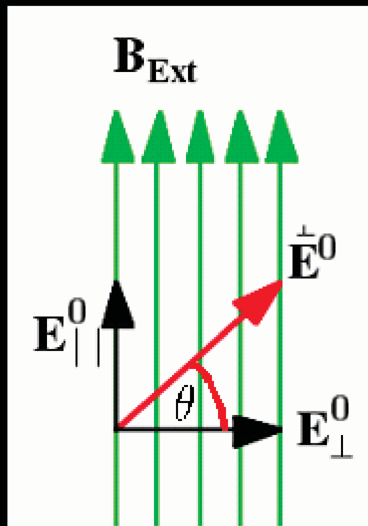
Dichroism (Rotation)

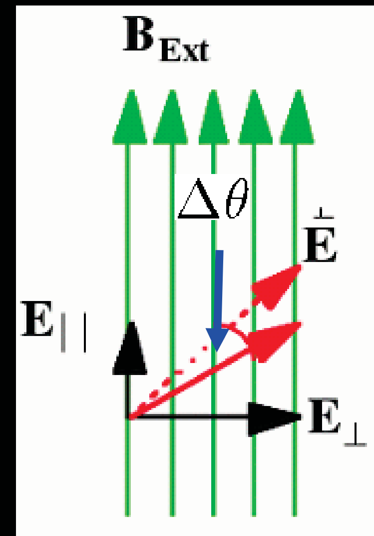
- Pairproduction leads to an „absorption“ of Laser light
- Pairproduction depends on relative orientation of Laser polarization and B-field

H. Gies, JJ and A. Ringwald
hep-ph/0607118



Geometry

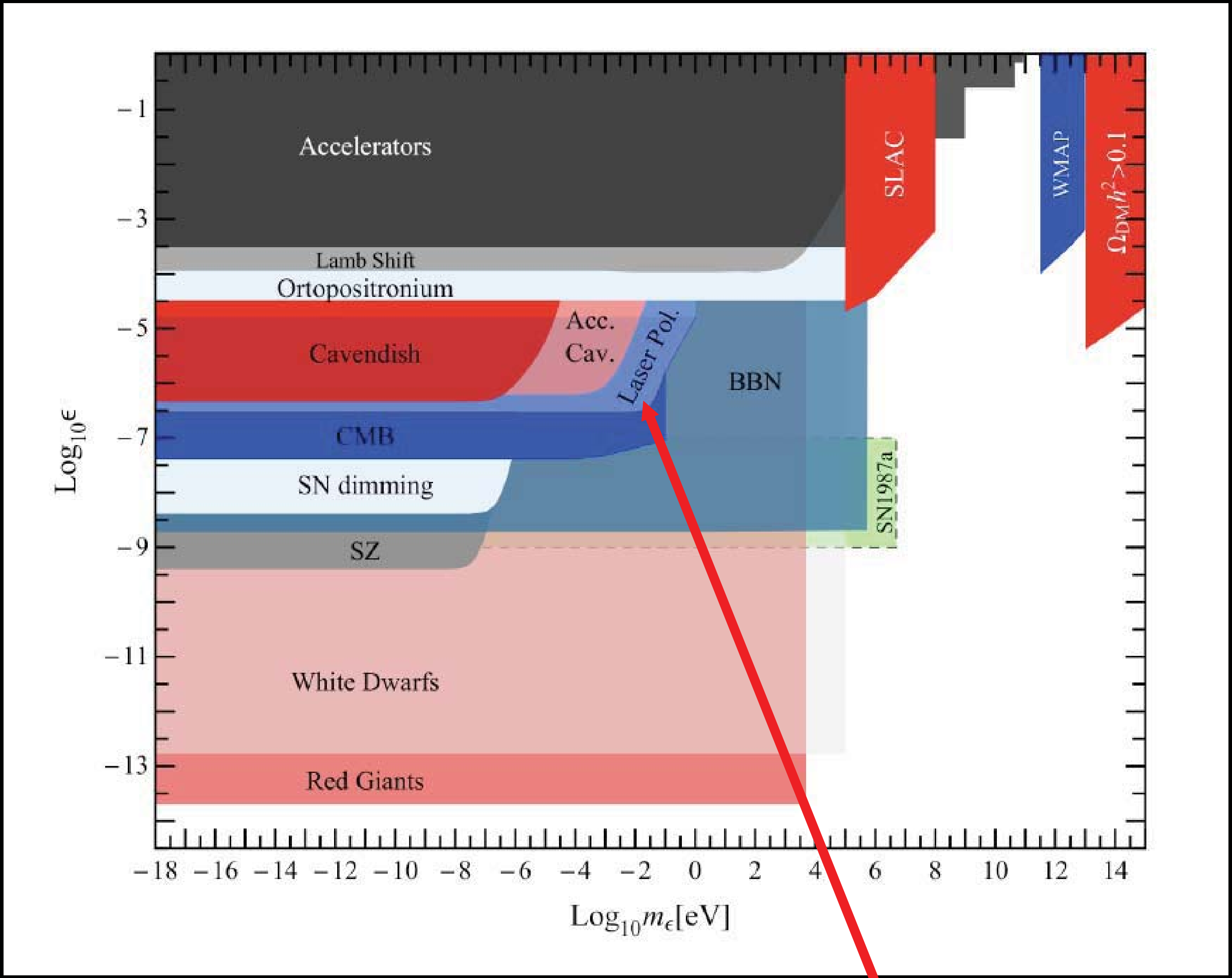




$$\tan(\theta - \Delta\theta) = \frac{E_{||}}{E_{\perp}} = \frac{E^0_{||}}{E^0_{\perp}} \exp\left(-\frac{1}{2}(\kappa_{||} - \kappa_{\perp})\ell\right)$$

$$\Delta\theta \simeq \frac{1}{4}(\kappa_{||} - \kappa_{\perp})\ell \sin(2\theta)$$

Minicharges



One of the best laboratory bounds!

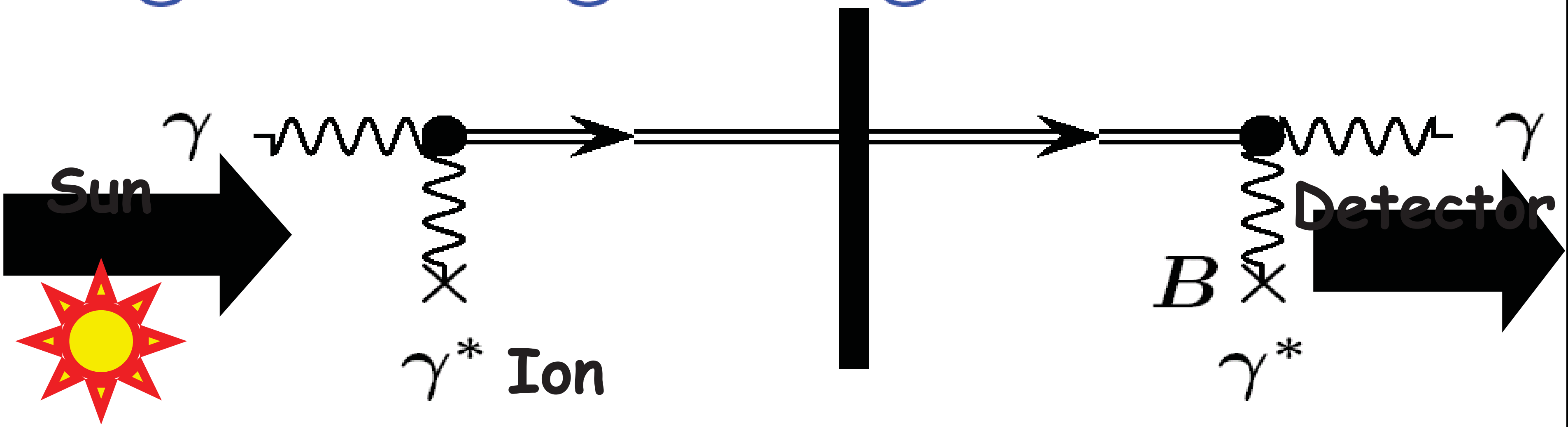
Helioscopes

Helioscopes

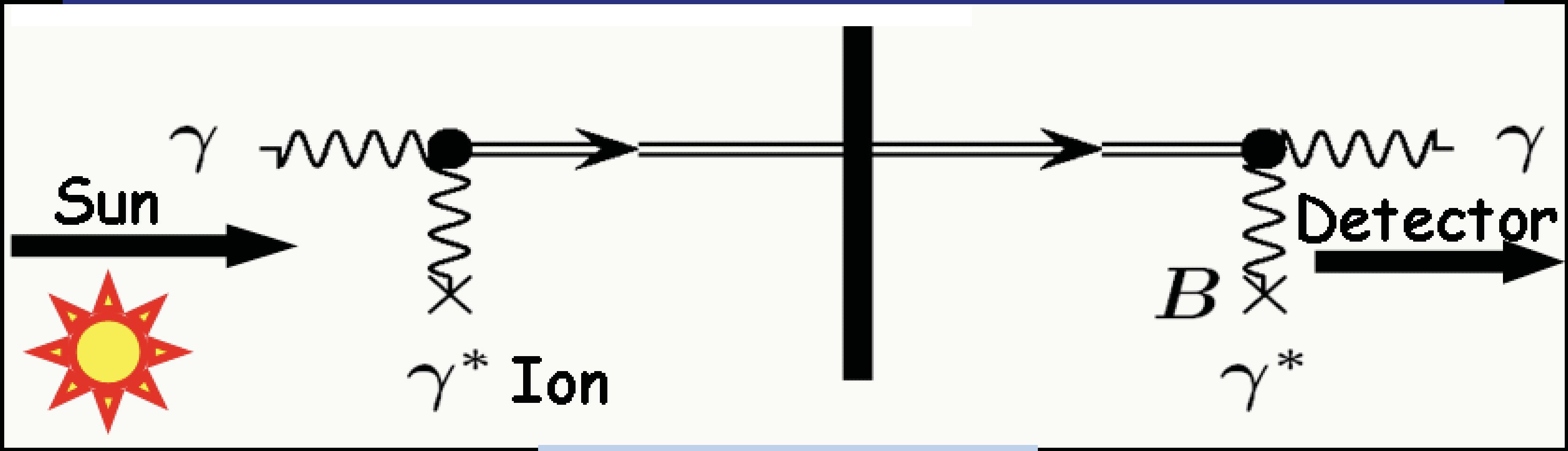
CAST@CERN

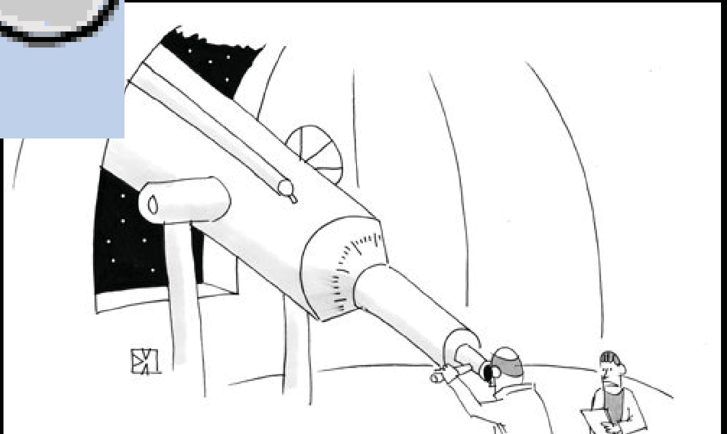
SUMICO@Tokyo

“Light shining through a wall”



Perfect for astronomy in Durham ;-)

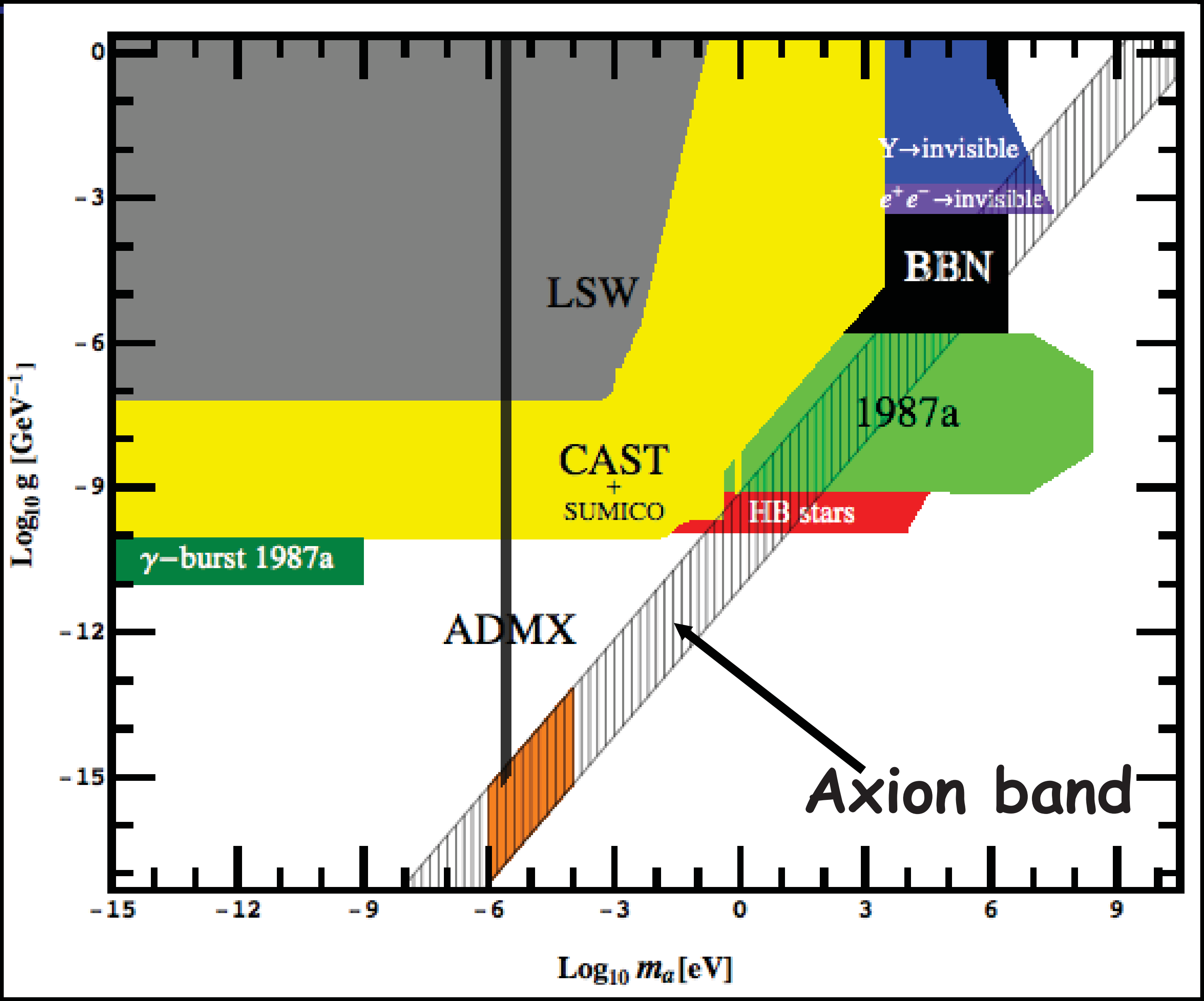




Ion

This isn't Dark matter,
I just forgot to take off the lens cap

Sensitivity



Searching light Dark Matter

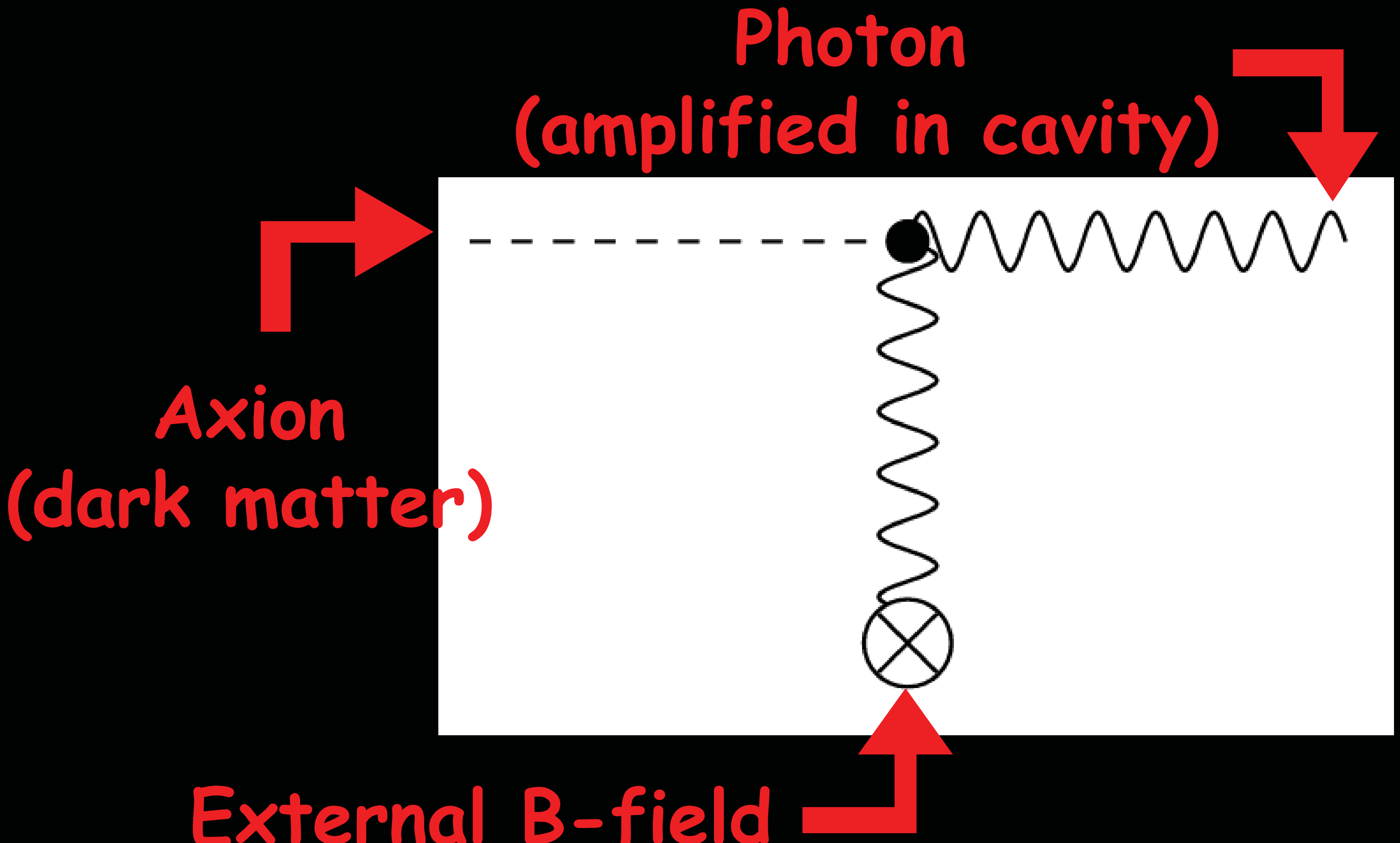
-

Haloscopes

See, e.g.
G. Rybka at Patras 2009

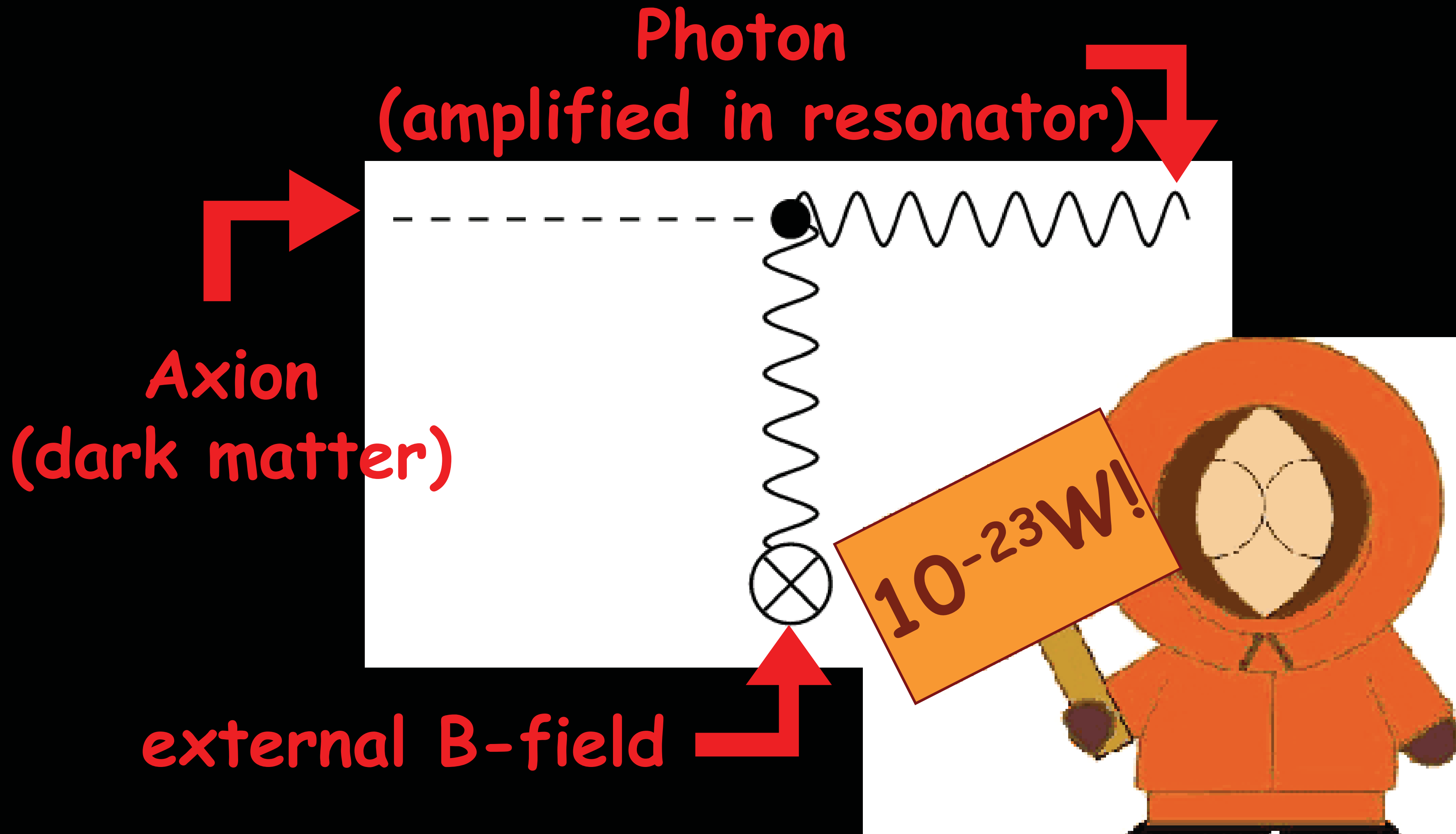
Axions: Two photon coupling

- Photon generation from axions!

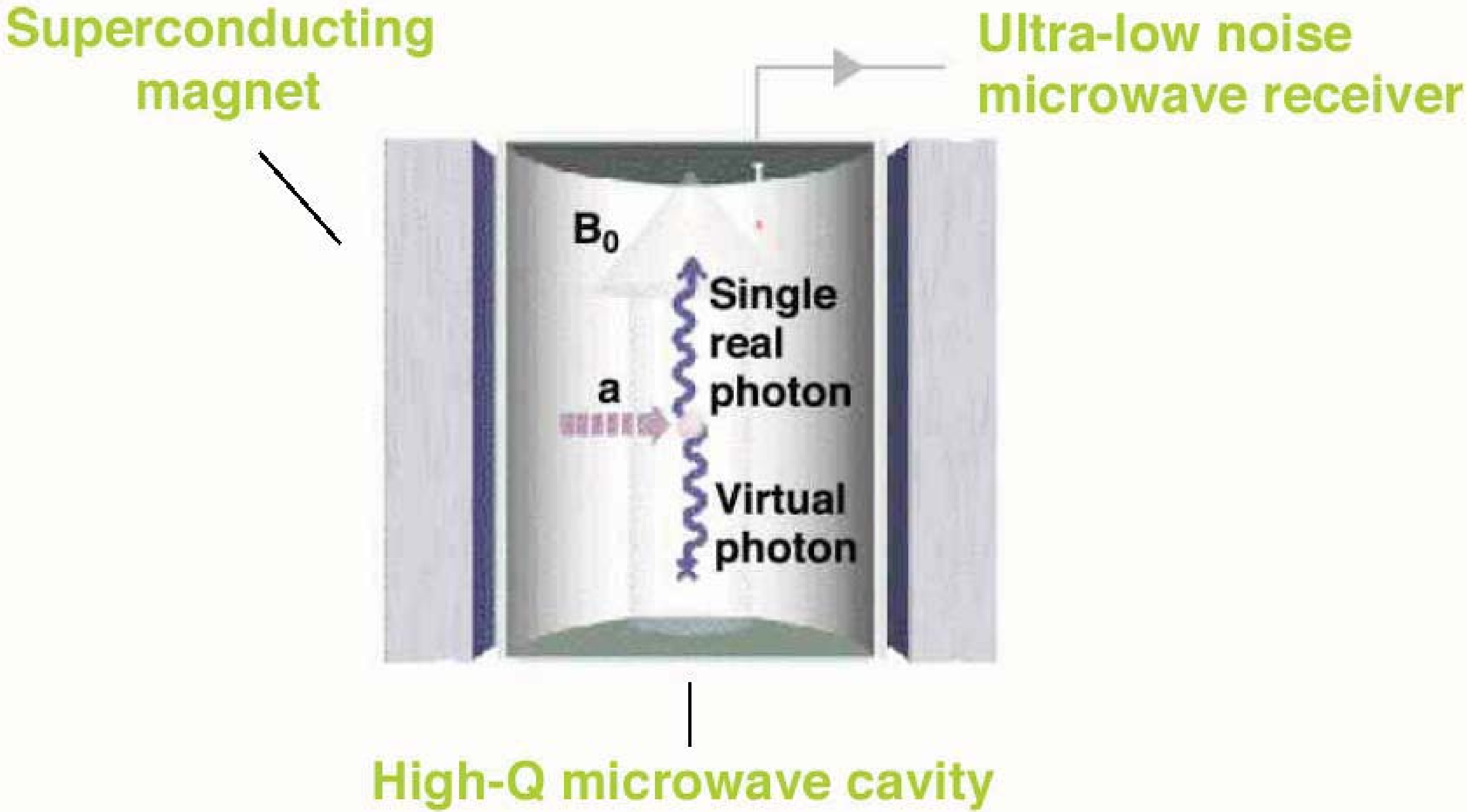


Electricity from Dark Matter ;-).

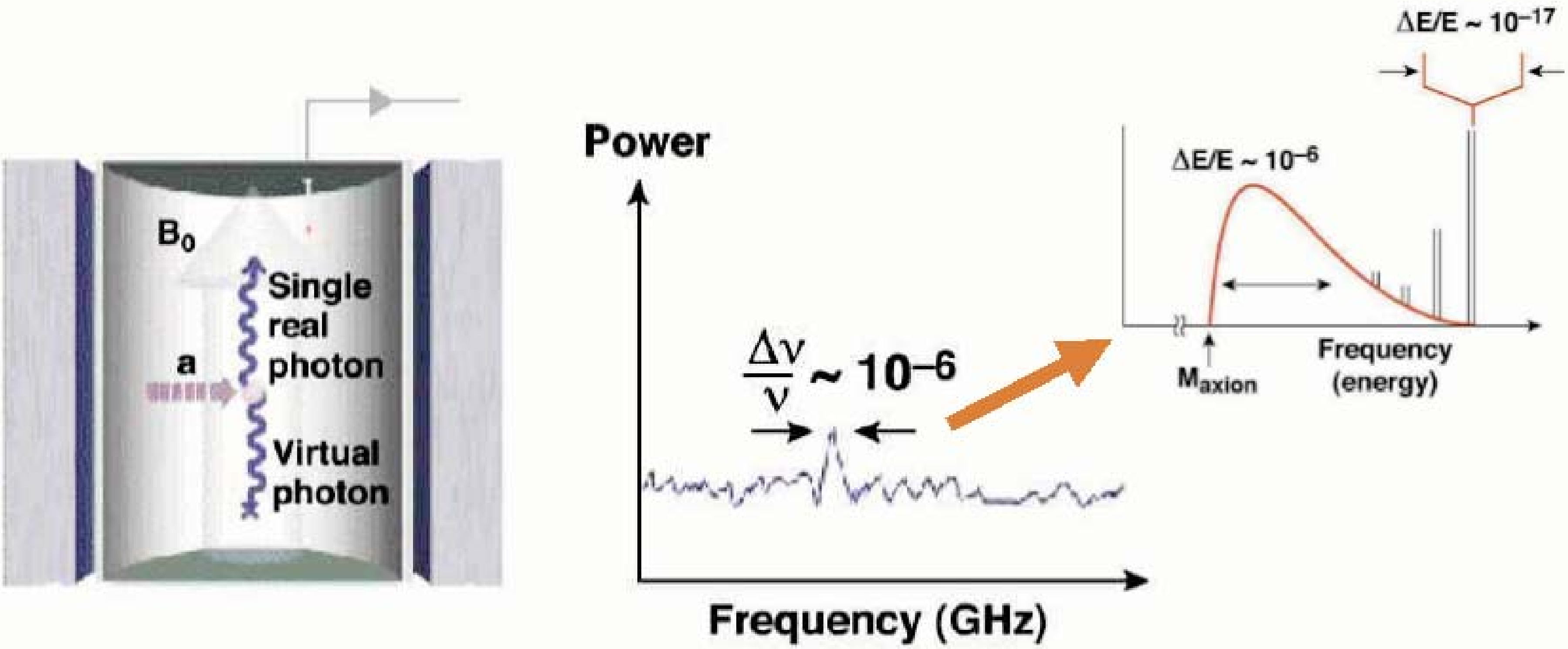
- Photon Regeneration



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!

Optimizing

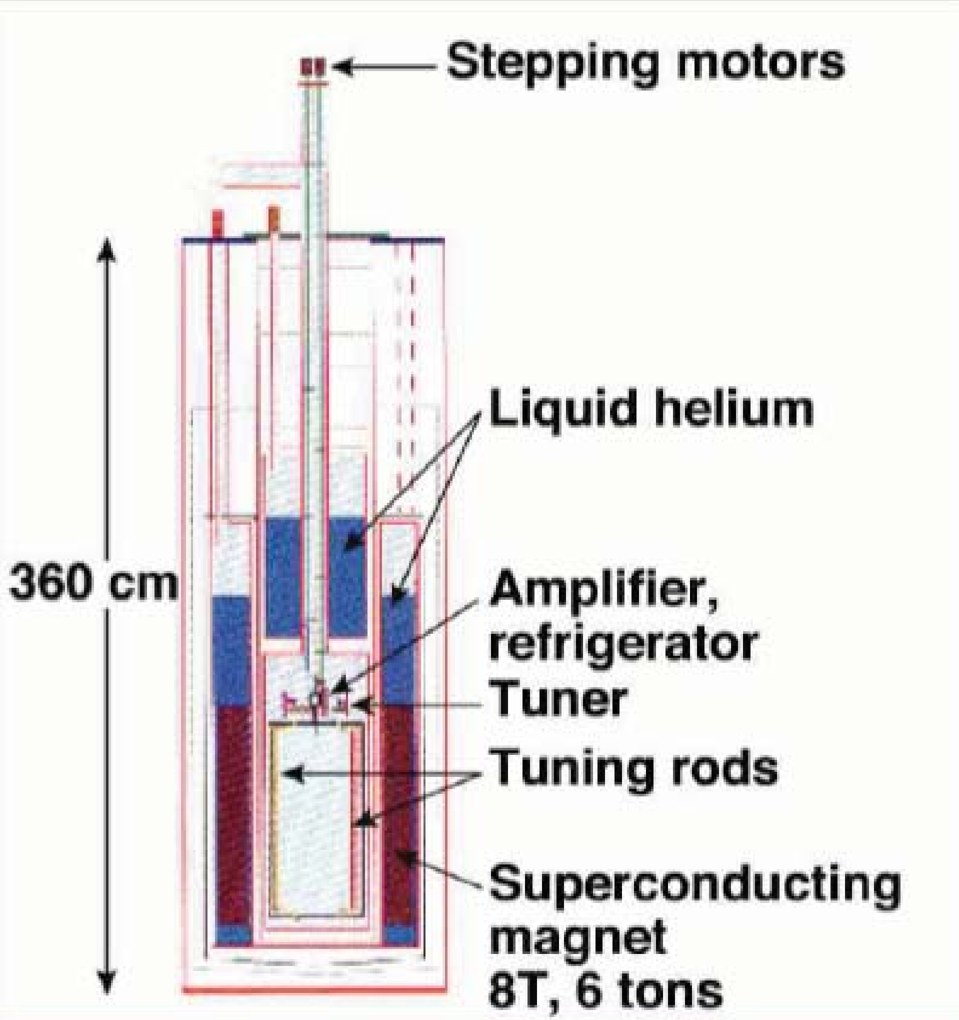
$$P \sim 10^{-22}\,W \frac{\mathrm{Vol}}{10l}\left(\frac{B}{6T}\right)^2 \min\left(1, Q\frac{\Delta\nu}{\nu}\right)$$

$$s/n = \frac{signal}{noise} \sim \frac{P}{kT}\sqrt{\frac{t}{\Delta\nu}}$$

How it looks I

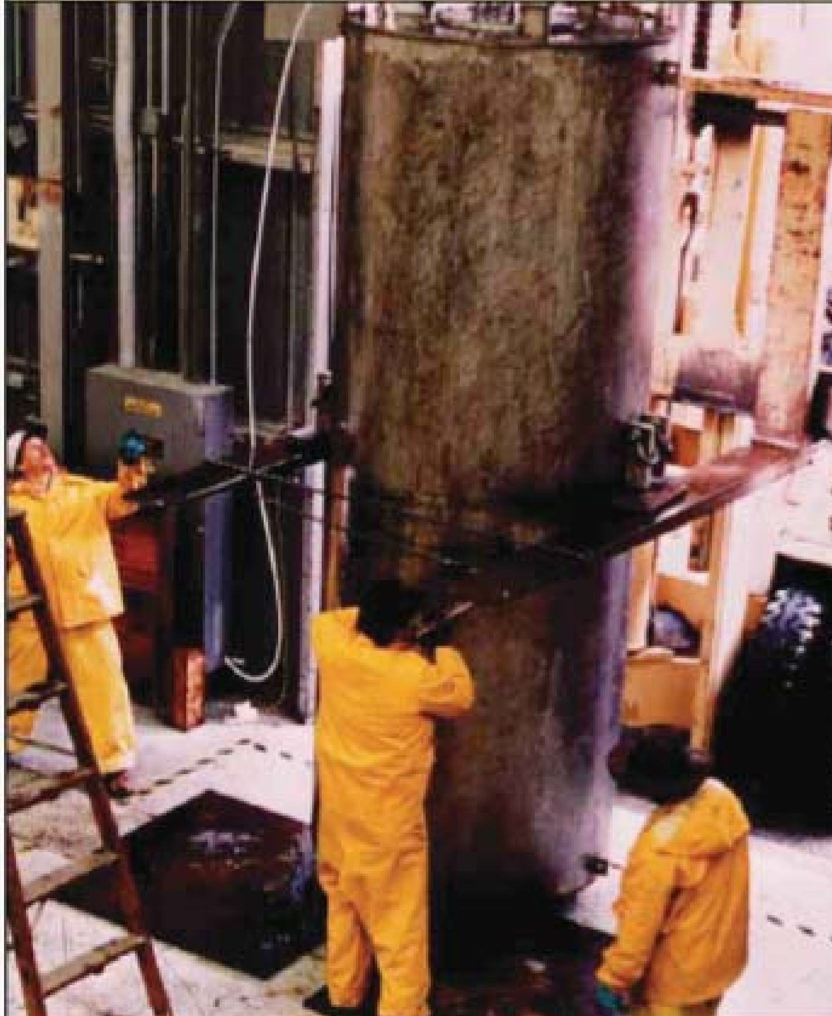
IP3 University of Durham

Magnet with Insert (side view)



Pumped LHe → T ~ 1.5 k

Magnet (Wang NMR Inc.)

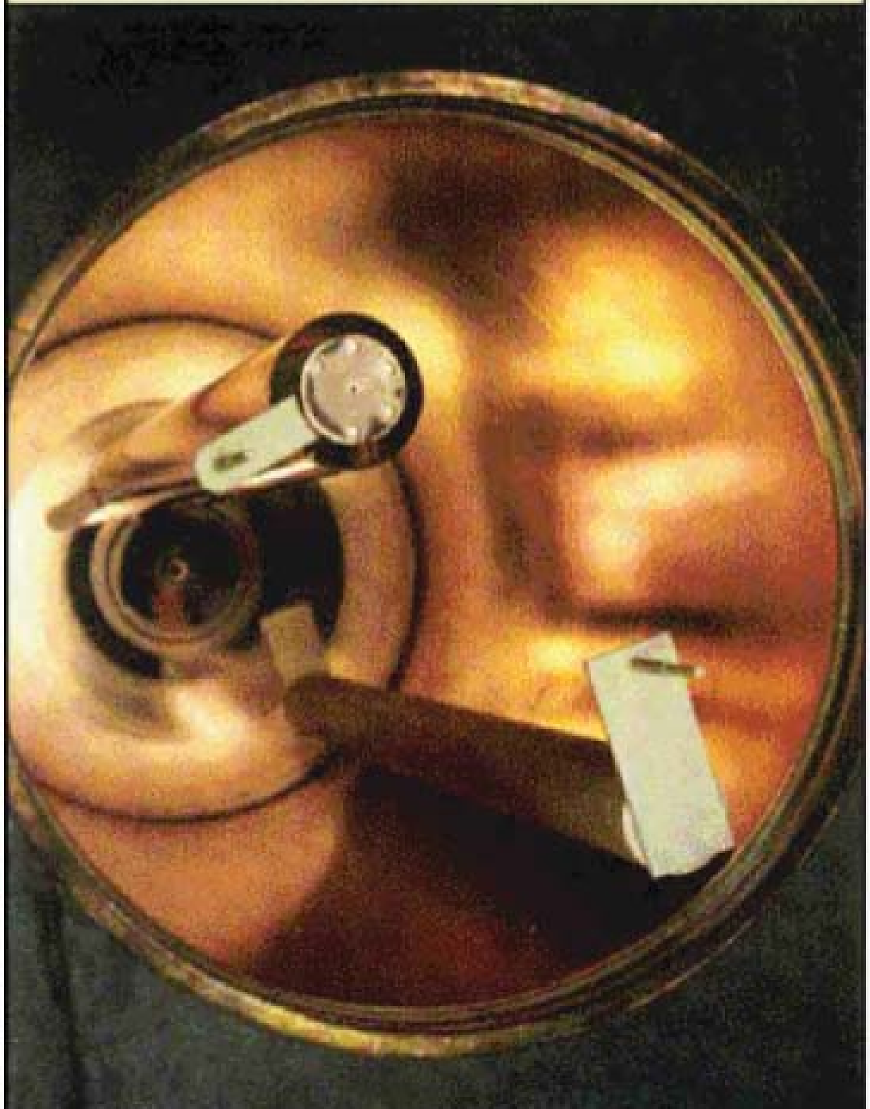


8 T, 1 m × 60 cm ∅

How it looks II

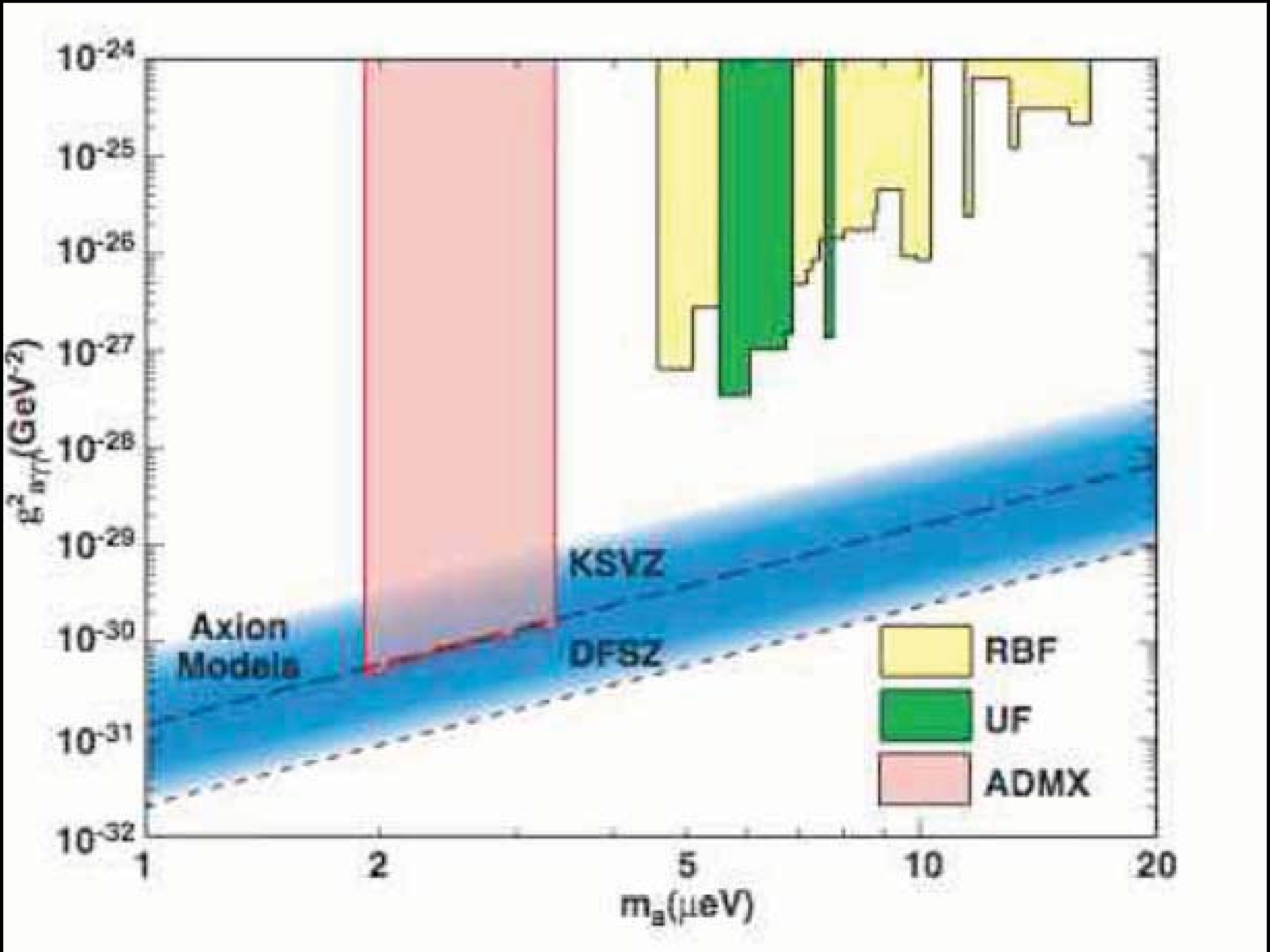
University of Durham

High-Q Cavity (~200,000)



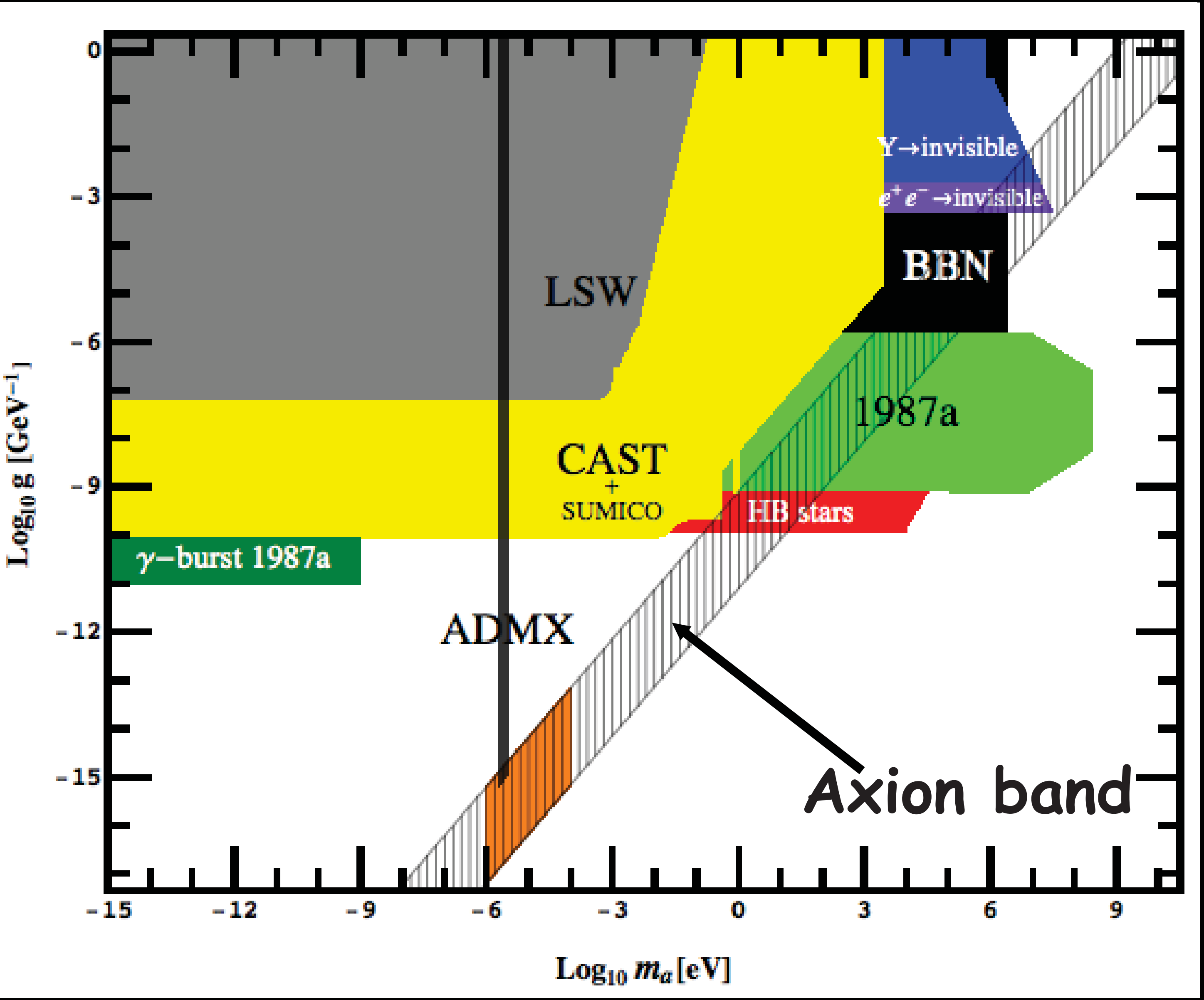
Experimental Insert

Results



10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
$g^2_{a\gamma\gamma}$ (GeV^{-2})
1
2
5
10
20
m_a (μeV)
KSVZ
DFSZ
Axion Models
RBF
UF
ADMX

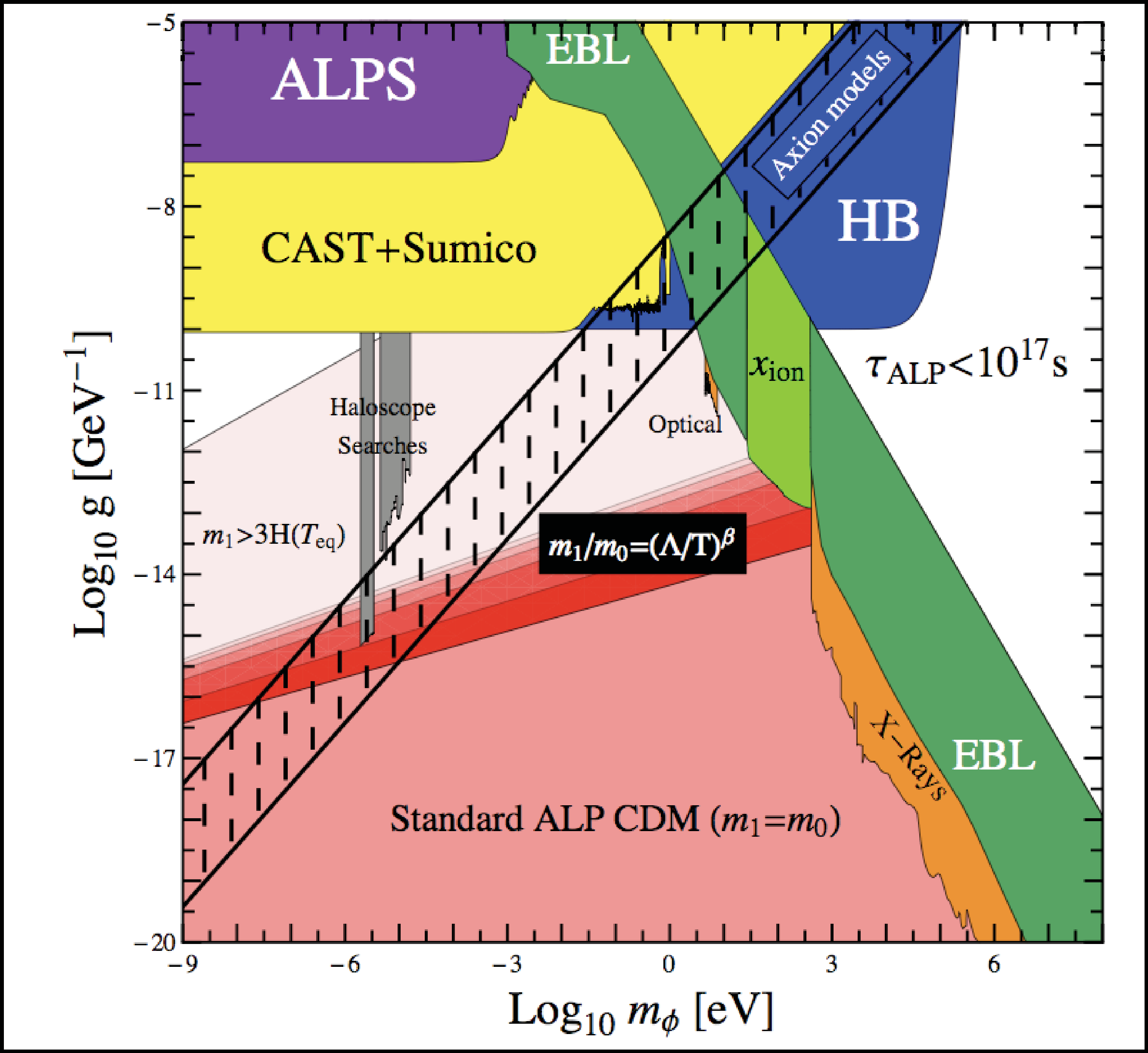
Exciting times!!!



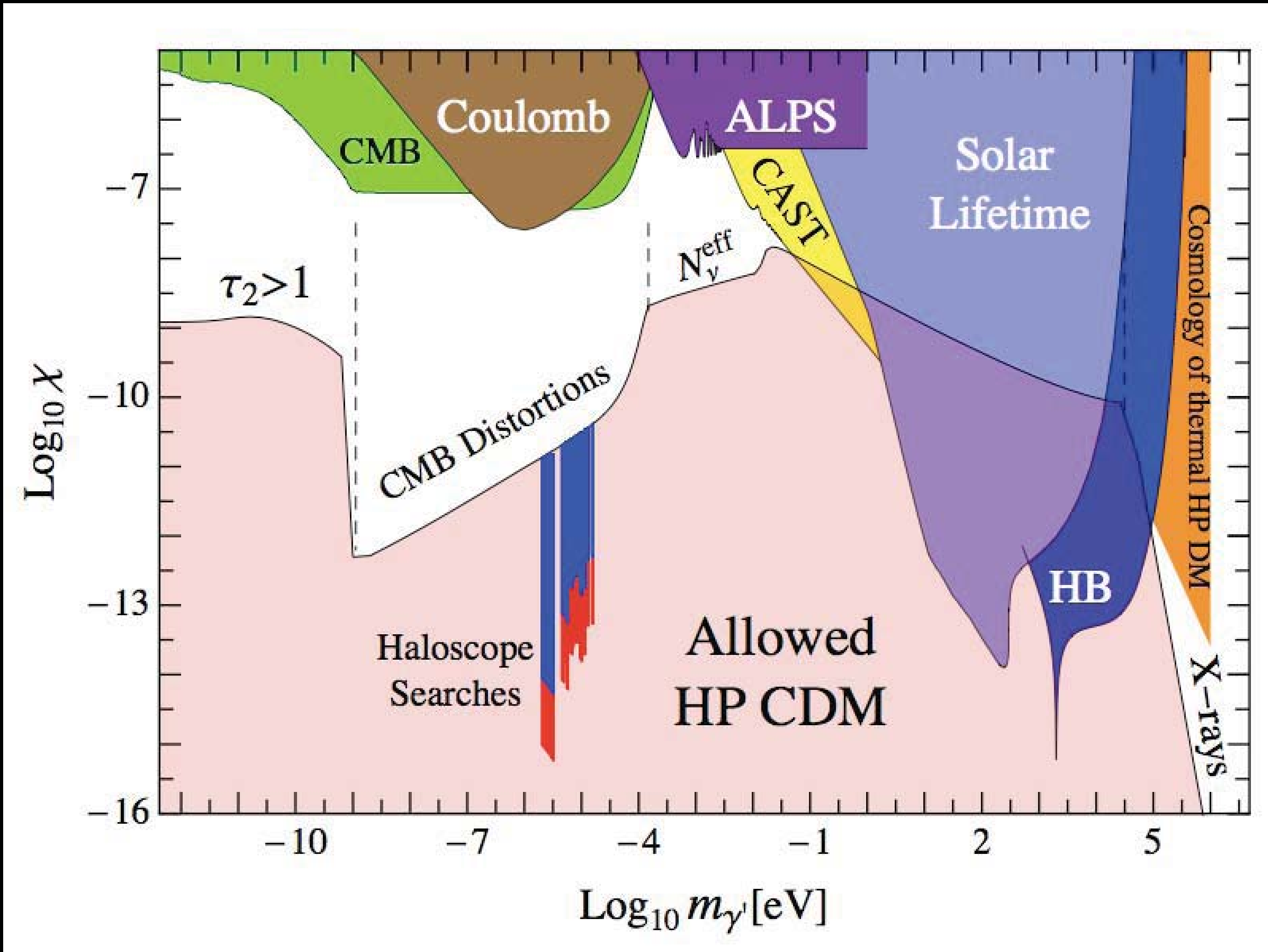
Works for general WISP Dark Matter

Nelson and J. Scholtz 1105.2812
P. Arias, D. Cadamuro, M.Goodsell, JJ, J. Redondo A. Ringwald 1201.5902

ALPs


ALPS
EBL
Axion models
CAST+Sumico
HB
$\tau_{ALP}<10^{17}$s
x_{ion}
Haloscope
Searches
Optical
$m_1>3H(T_{eq})$
$m_1/m_0=(\Lambda/T)^\beta$
X-Rays
EBL
Standard ALP CDM ($m_1=m_0$)
$\mathrm{Log}_{10}\, g\ [\mathrm{GeV}^{-1}]$
$\mathrm{Log}_{10}\, m_\phi$ [eV]
−5
−8
−11
−14
−17
−20
−9
−6
−3
0
3
6

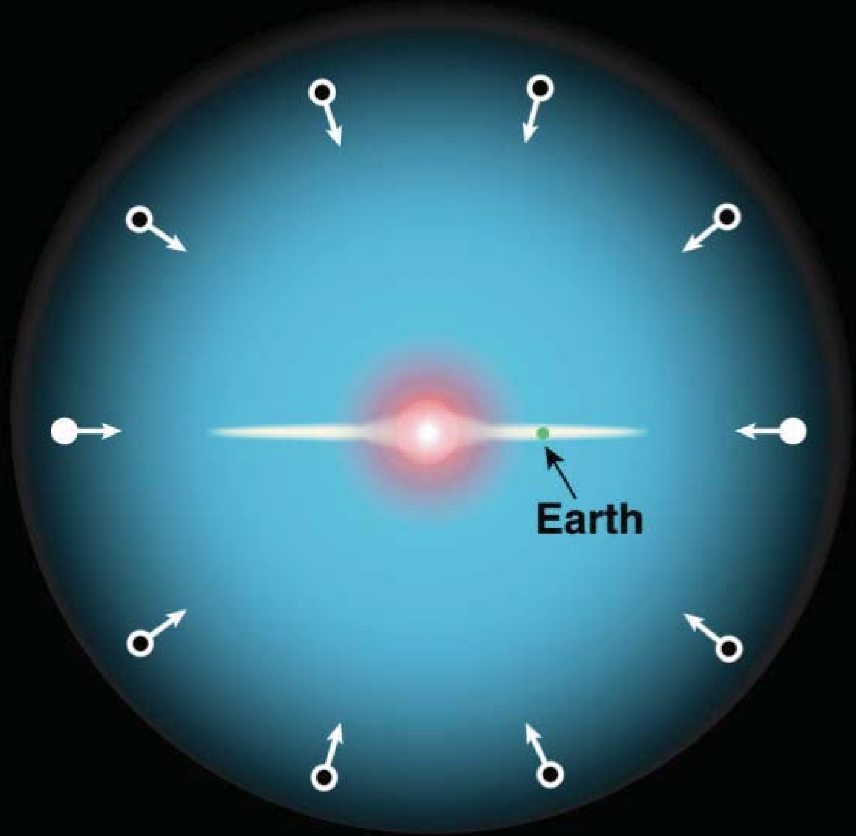
Hidden Photons

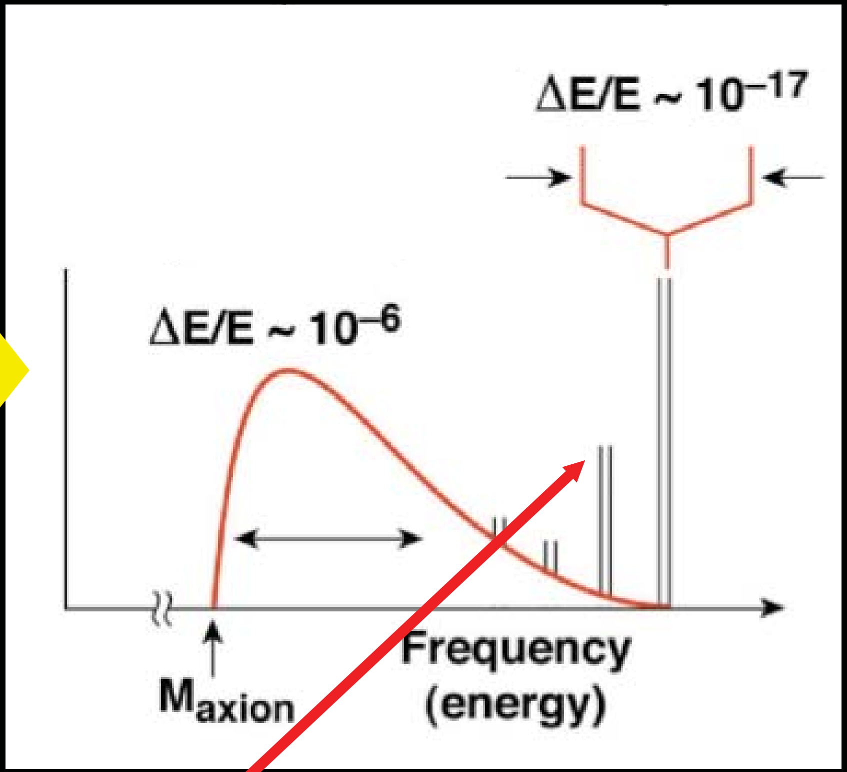


Measuring structure (formation)

See, e.g.
S. Asztalos at Patras 2007

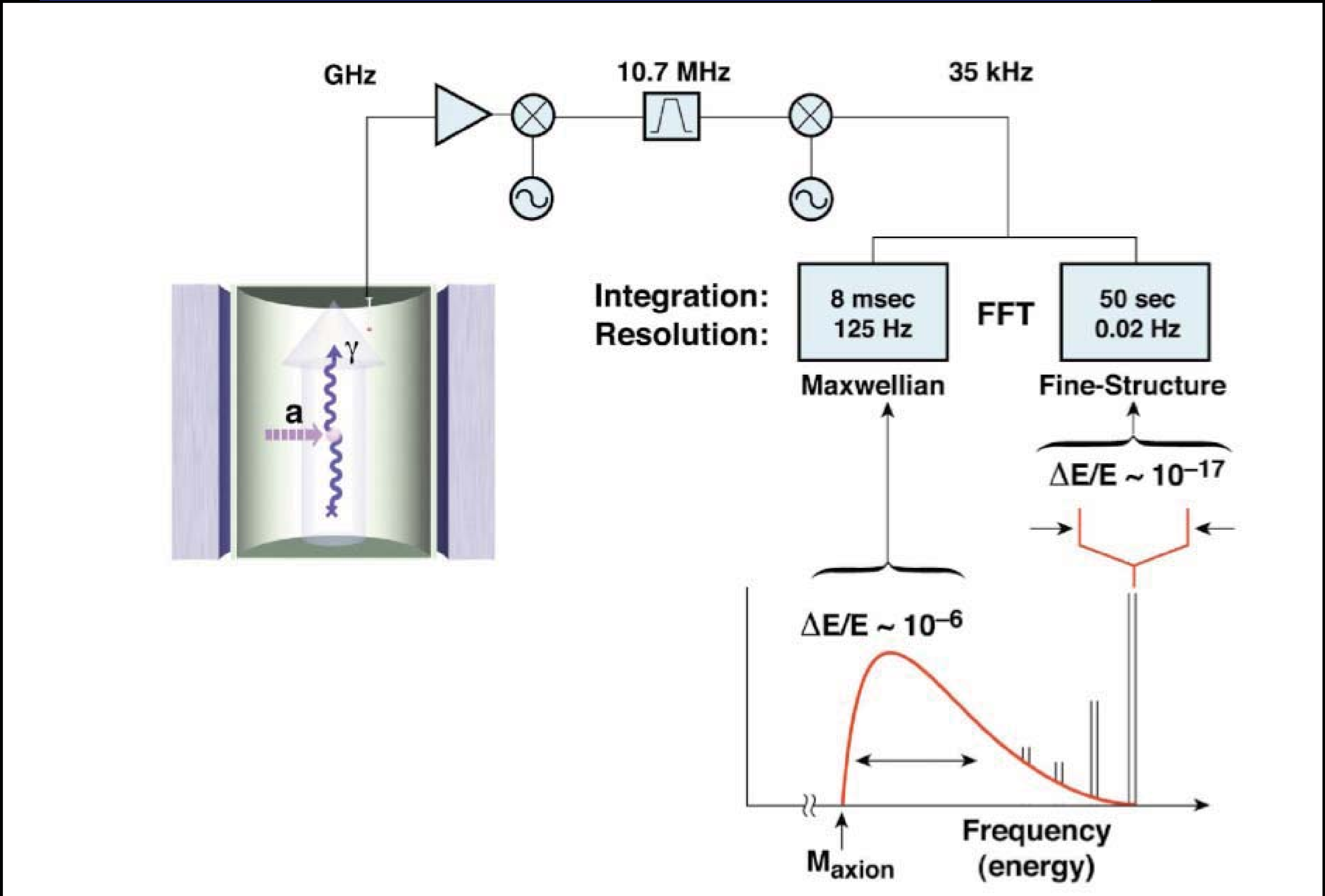
Example: infall of matter





Features in the velocity/energy spectrum of dark matter

Detect these features in ADMX

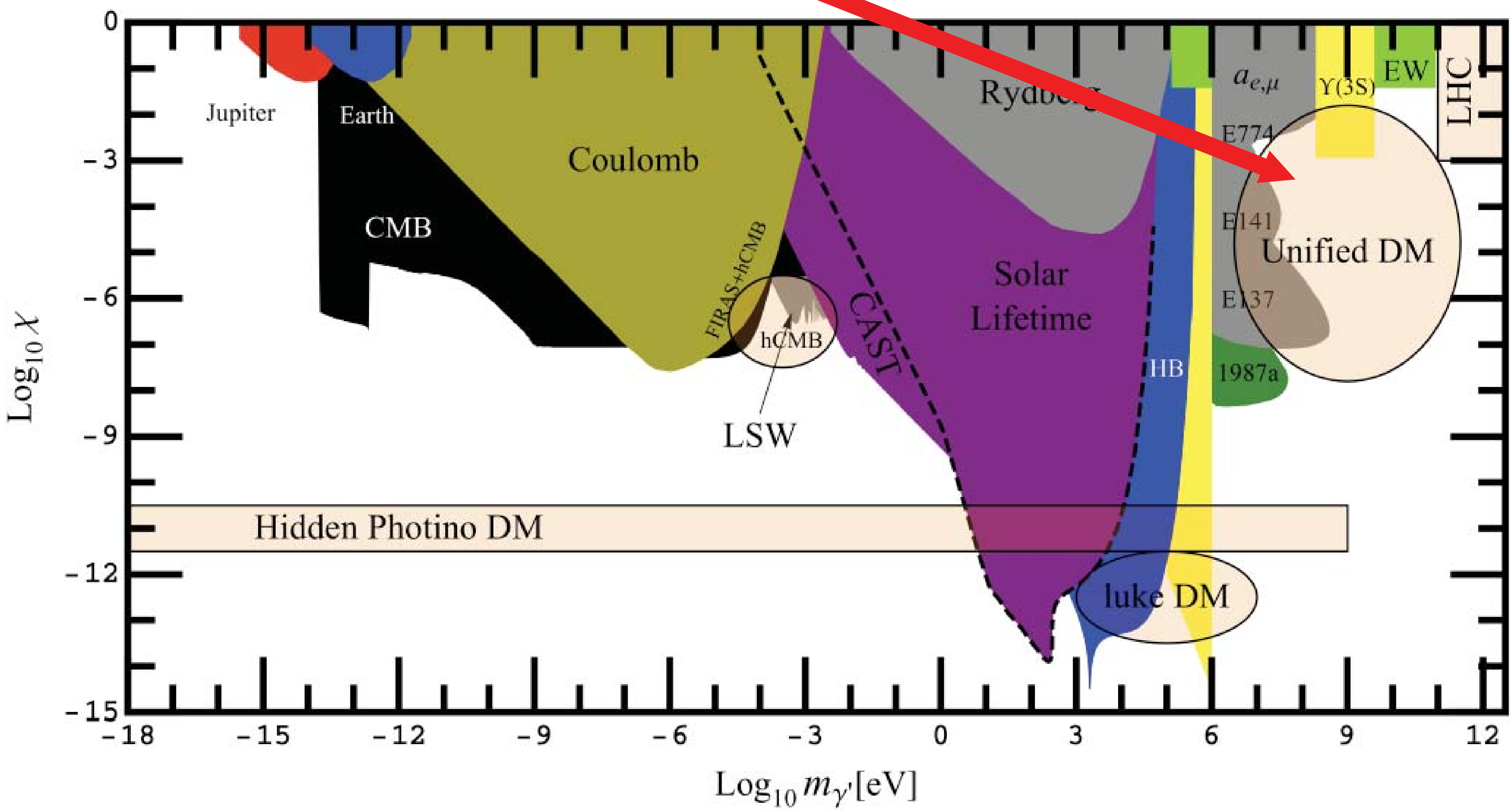


Searching WISPishs*

*Weakly interacting sub-TeV particles

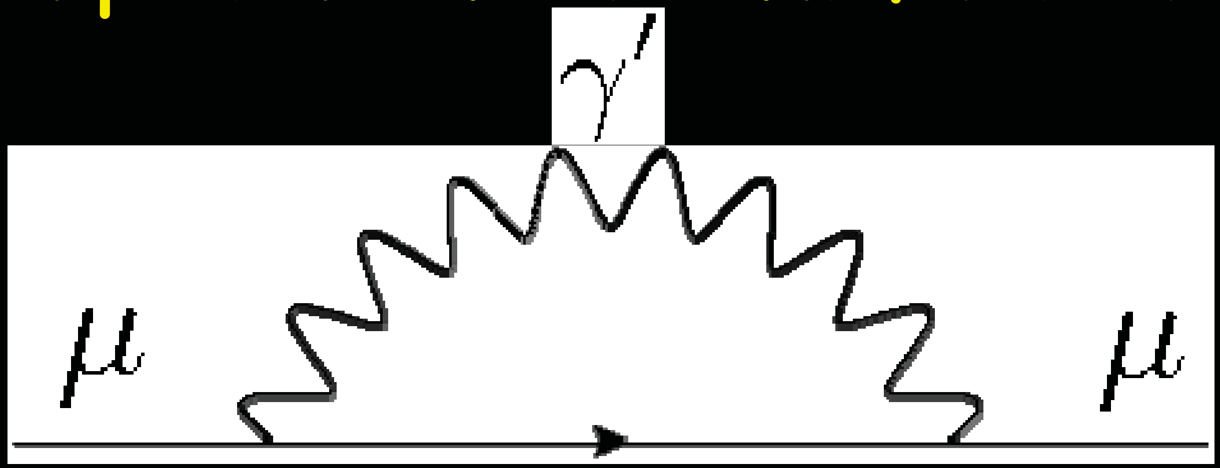
Why?

- Lots of interest from astrophysics
- Pamela, DAMA, CoGent…



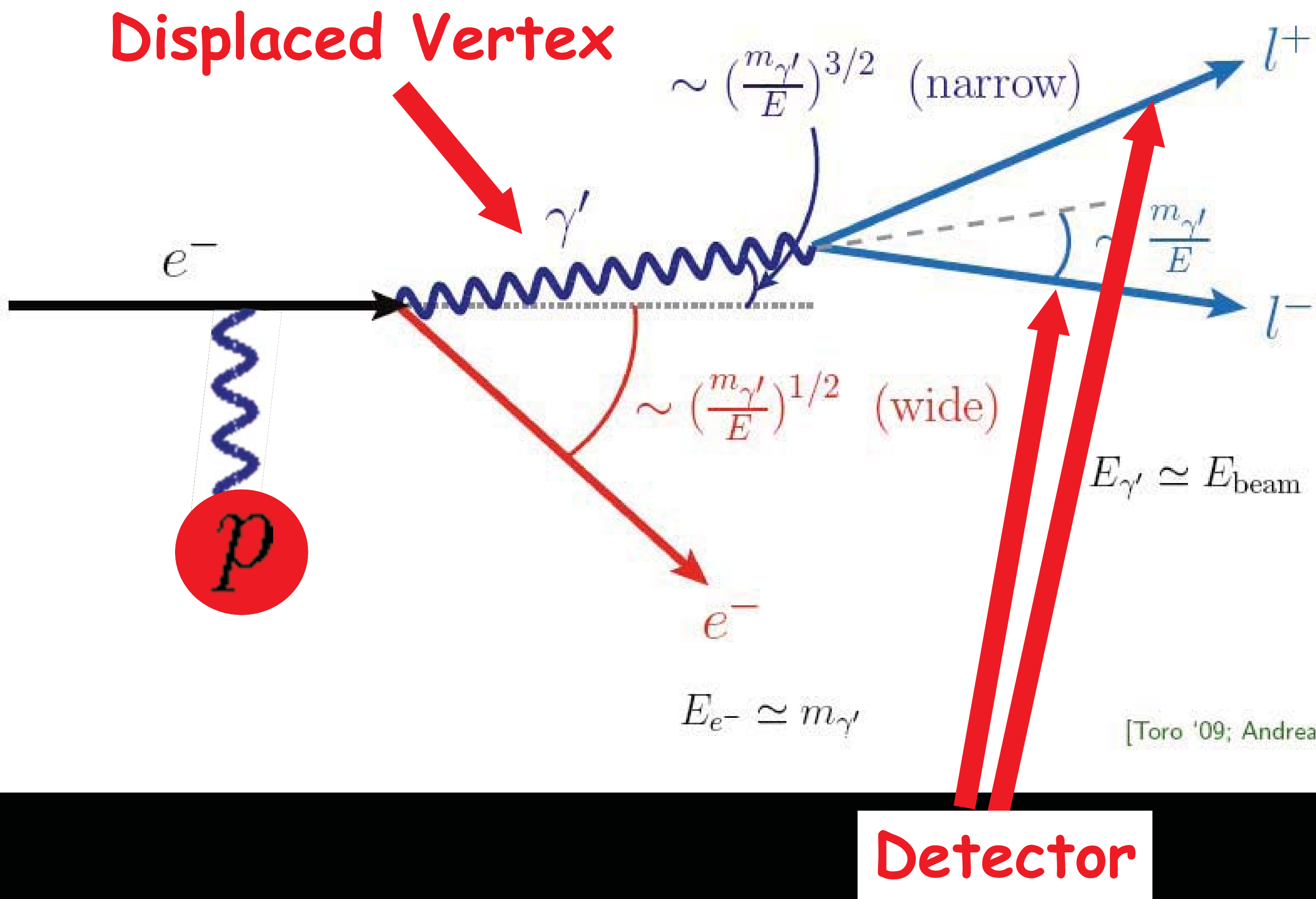
and $(g-2)_\mu$

- $2.x\ \sigma$ deviation from SM observed
- Hidden photon could account for this!



$$\Delta(g-2)_\mu = \frac{\alpha}{4\pi} f\left(\frac{m_{\gamma'}}{m_\mu}\right)$$

Fixed targets



Medium energy, high current

- Medium energies of beam 100 MeV-50 GeV

- BUT: High current $\sim mA \sim 10^{16} e^{-}/s$

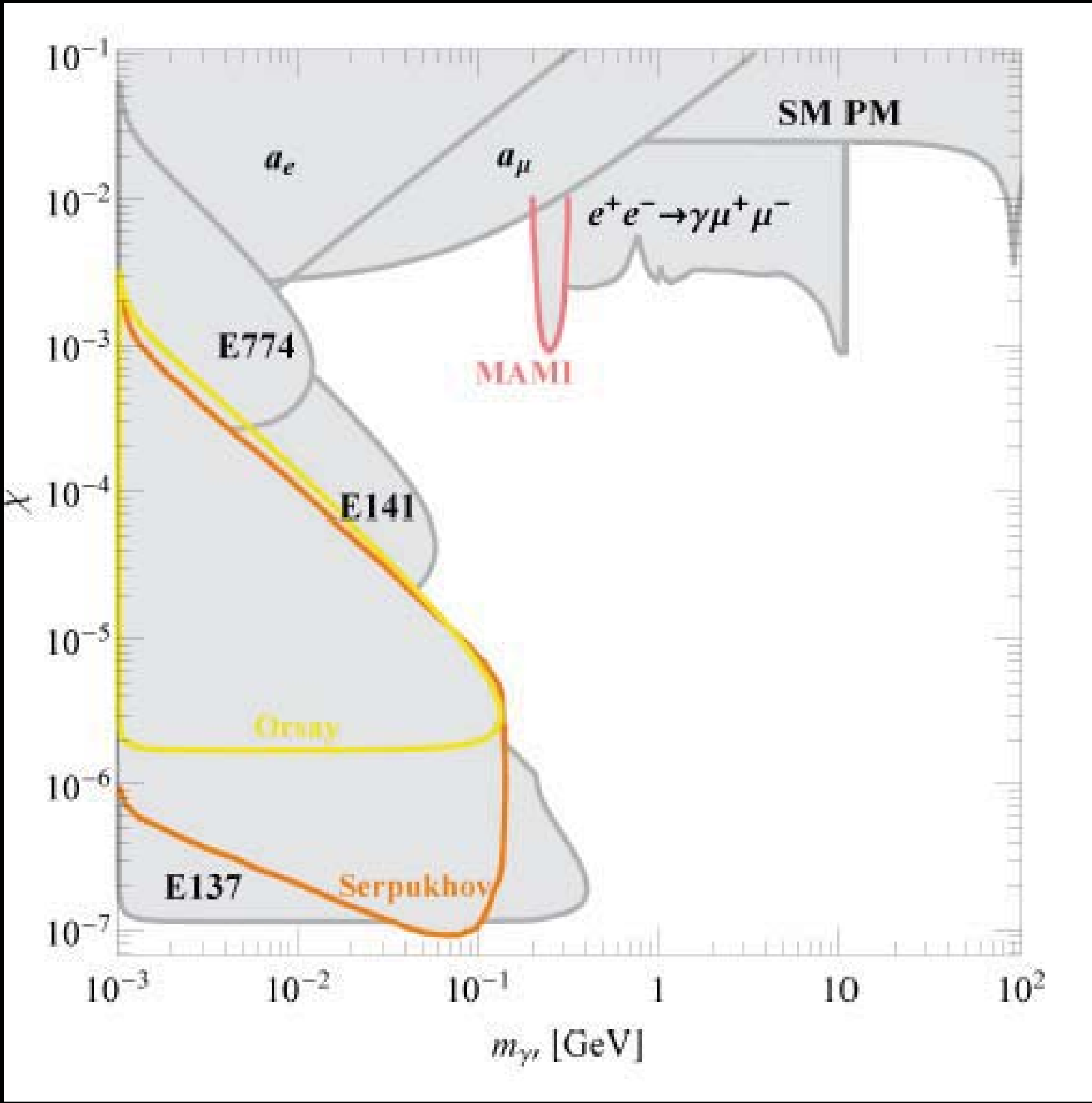
$\Downarrow$

Test weak interactions!!

Many beams, many chances…

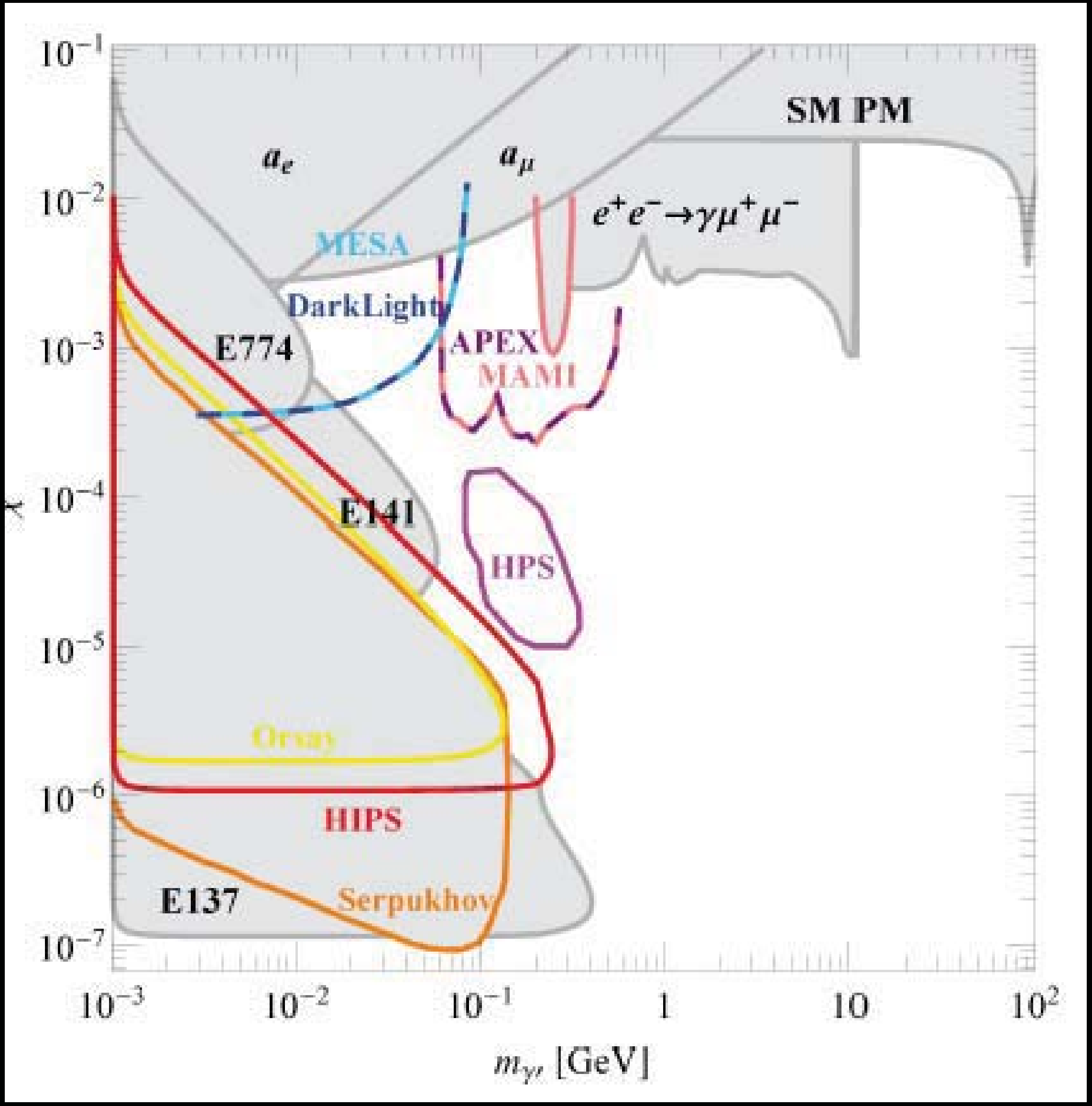
- DESY
- Jefferson Lab
- Mainz Microtron (MaMi)
- …

Current state



Cf. S. Andreas, M. Goodsell, A. Ringwald 1109.2869

Near future



SM PM
a_e
a_μ
$e^+e^- \to \gamma\mu^+\mu^-$
MESA
DarkLight
E774
APEX
MAMI
E141
HPS
Orsay
HIPS
E137
Serpukhov
κ
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-3} 10^{-2} 10^{-1} 1 10 10^2
$m_{\gamma'}$ [GeV]

Even More Hints...

Muonic Hydrogen

R. Pohl et al. Nature 466, 213, 2010
JJ and S. Roy 1008.3536

The Lamb shift a test of new and old physics

University of Durham

- In ordinary QM $2s_{1/2}$ and $2p_{1/2}$ level degenerate

- This is a very peculiar feature of Coulomb's law,

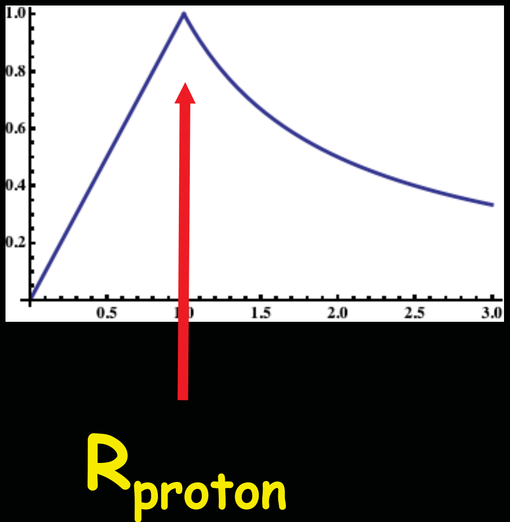
$$F(r) \sim \frac{1}{r^2}$$

⇒ Deviations from Coulomb's law split $2s_{1/2}$ and $2p_{1/2}$

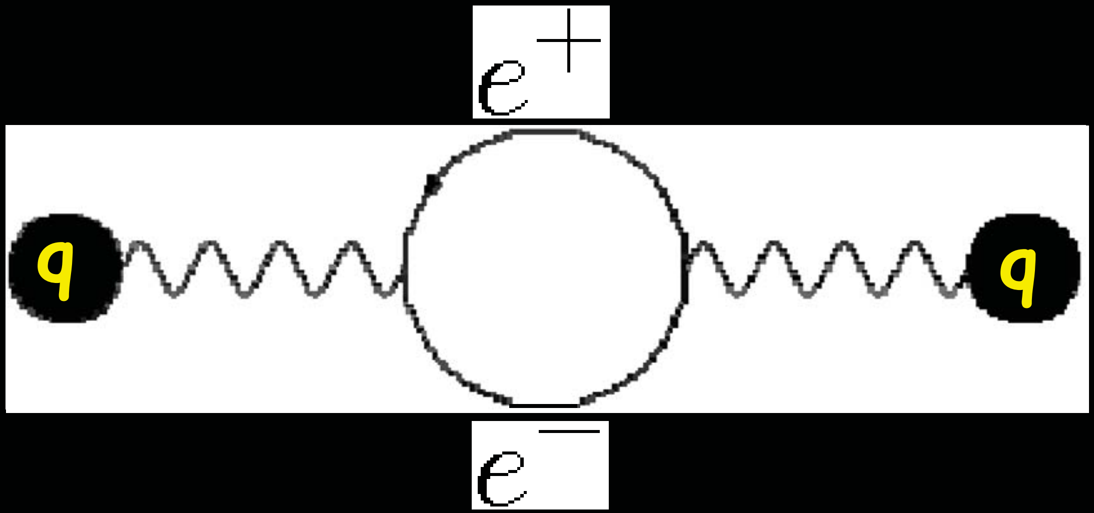
⇒ Measuring the Lamb shift is a precise test of Coulomb's law!

Known contributions…

- Finite size of proton:



- QED effects:

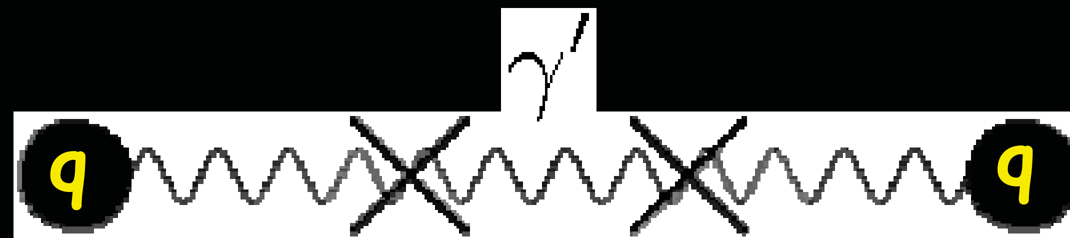


$$\delta V(r) \sim \delta(r)$$

Test for hidden photons and MCPs

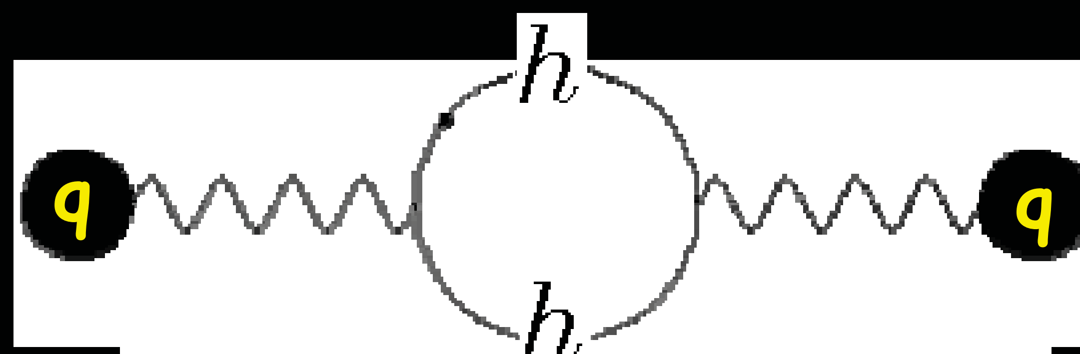
- WISPs modify Coulomb's law

- Hidden photons:



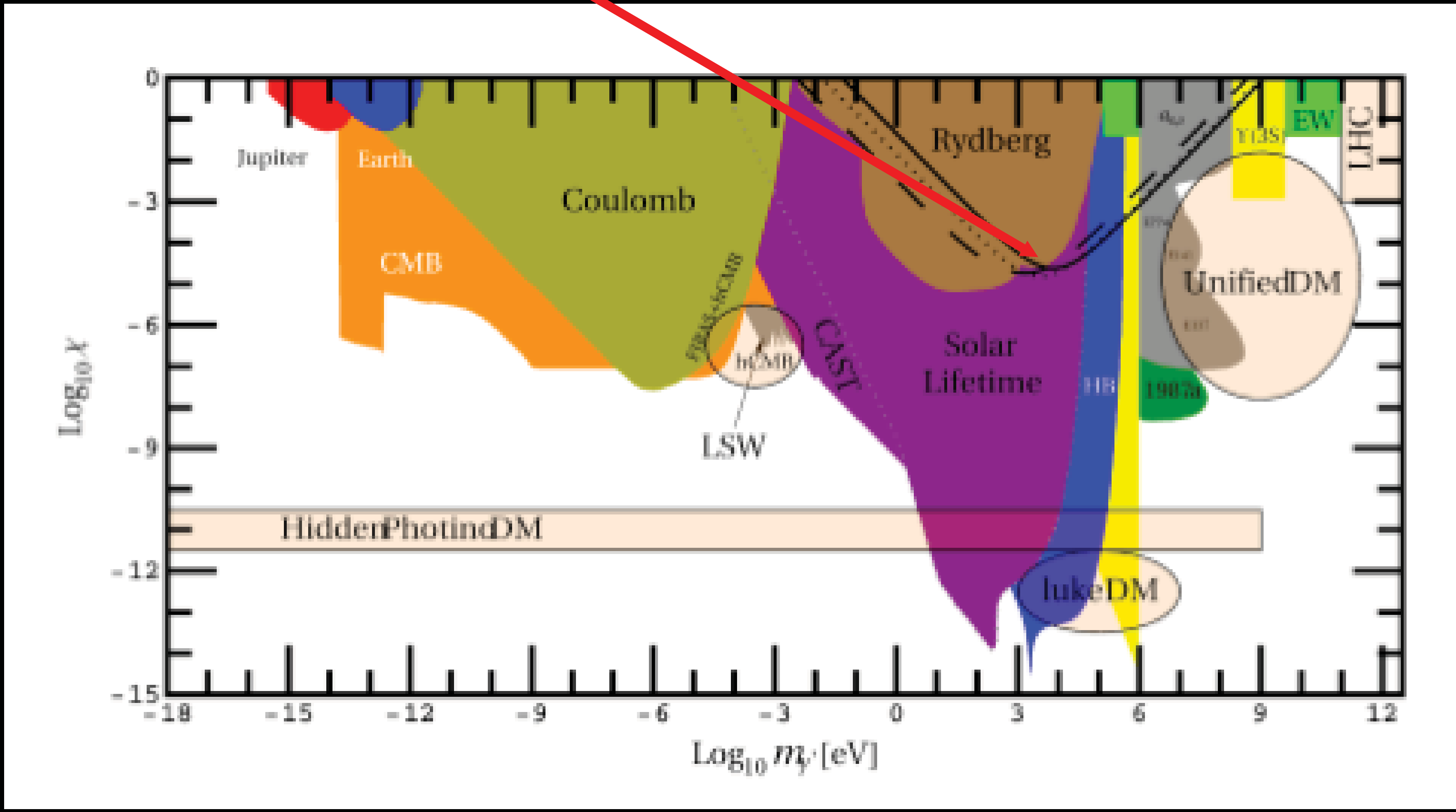
$$\delta V \sim \alpha q^2 \chi^2 \frac{\exp(-m_{\gamma'} r)}{r}$$

- Minicharged particles



$$\delta V(r) \approx \frac{Q\alpha}{r}\left[\frac{\alpha\epsilon^2}{4\sqrt{\pi}}\frac{\exp(-2mr)}{(mr)^{\frac{3}{2}}}\right]$$

New bounds...



Jupiter
Earth
CMB
Coulomb
LSW
CAST
Rydberg
Solar Lifetime
HB
UnifiedDM
EW
LHC
HiddenPhotinoDM
lukeDM
$\mathrm{Log}_{10}\,\chi$
$\mathrm{Log}_{10}\,m_{\gamma'}\,[\mathrm{eV}]$
0
-3
-6
-9
-12
-15
-18
-15
-12
-9
-6
-3
0
3
6
9
12

A puzzling measurement

- Use muonic hydrogen, i.e. $e^- \rightarrow \mu^-$
- Recently measured

$$\Delta E_{s_{1/2}^{F=1} - p_{3/2}^{F=2}} = -206.295000(3)\mathrm{meV}$$

- Compared to expected

$$\Delta E_{s_{1/2}^{F=1} - p_{3/2}^{F=2}} = -205.984(062)\mathrm{meV}$$

$\Rightarrow$ 5 σ deviation!!!

Can it be hidden photons???

- No! $e^- \longrightarrow \mu^-$
- Wrong sign; hydrogen would be more strongly affected!

⇒ Need more creative solution!

Can it be hidden photons???

University of Durham

- No!
- Wrong sign; hydrogen would be more strongly affected!

$$e^- \longrightarrow \mu^-$$

⇒ Need more creative solution!

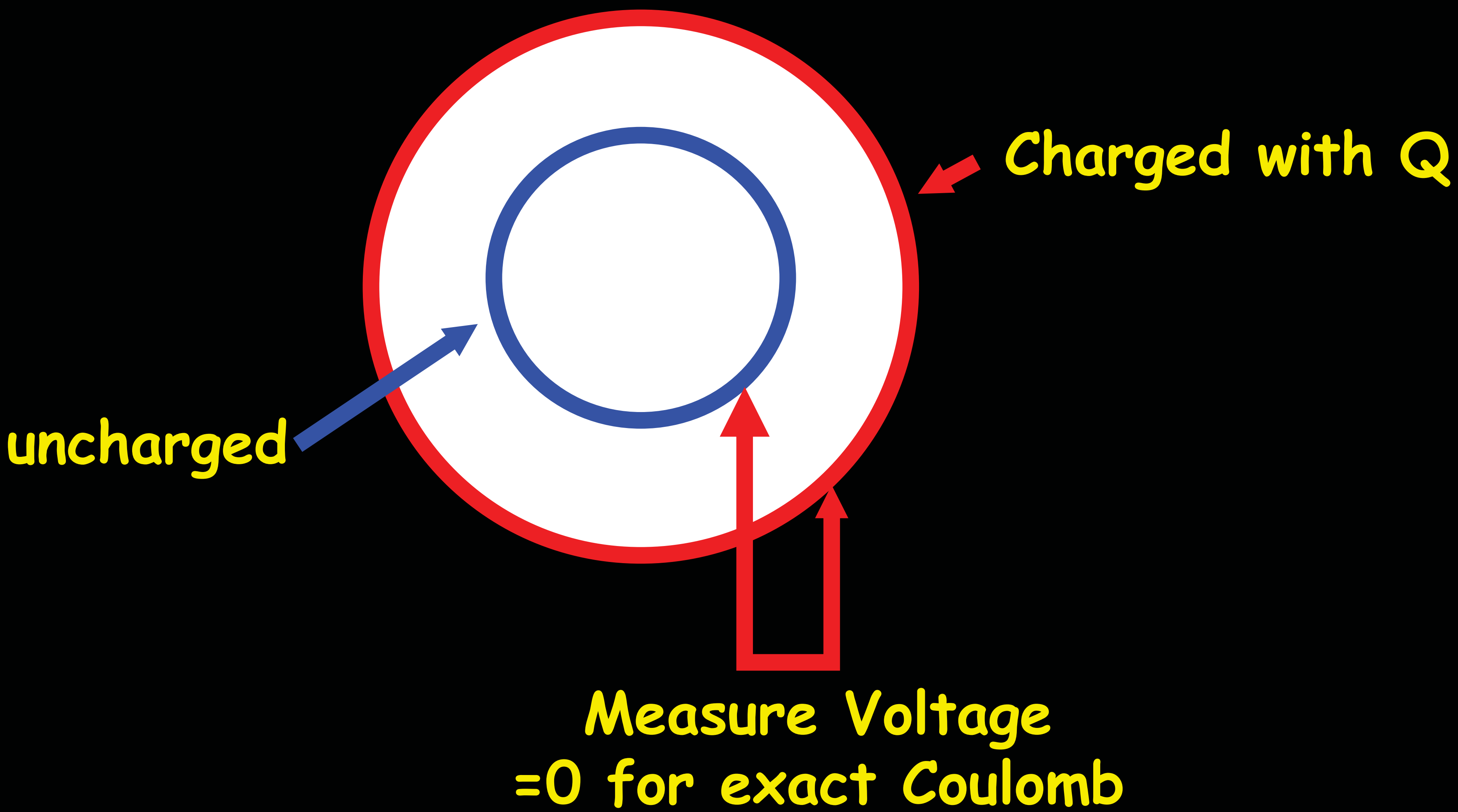
⇒ Homework ;-)

Experimental Homework.

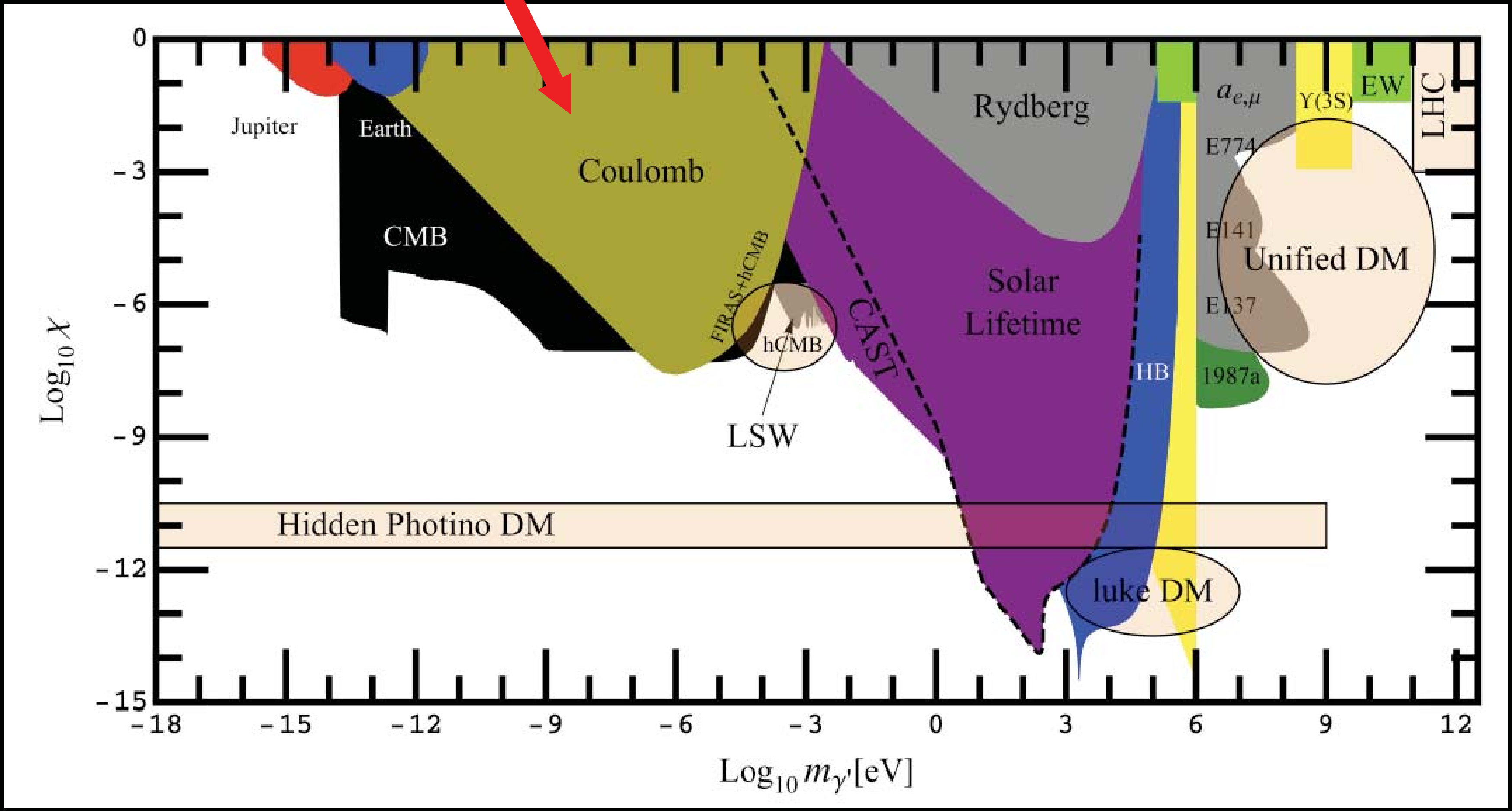
- WISPs may be visible in deviations of Coulomb's law

Something to Revive?
Tests of Coulomb's law

Cavendish Experiments



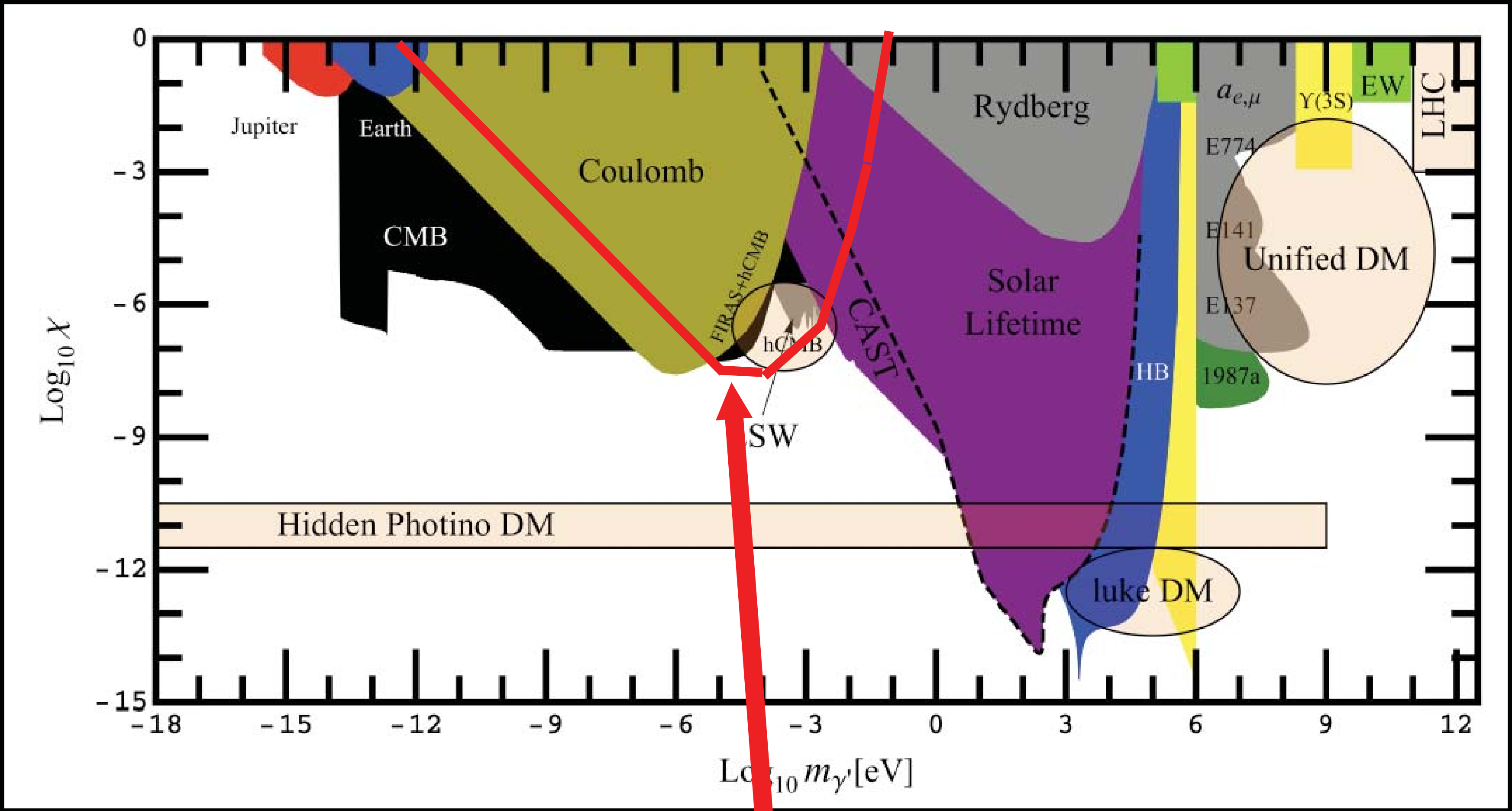
Quite sensitive



- **Best experiment 40 years old!!!!**

E. Williams, J. Faller and H. Hill PRL 26, 721, 1971

Experimental Homework



cm-scale Cavendish test with precision ~ few 10^{-15}

Conclusions

Conclusions

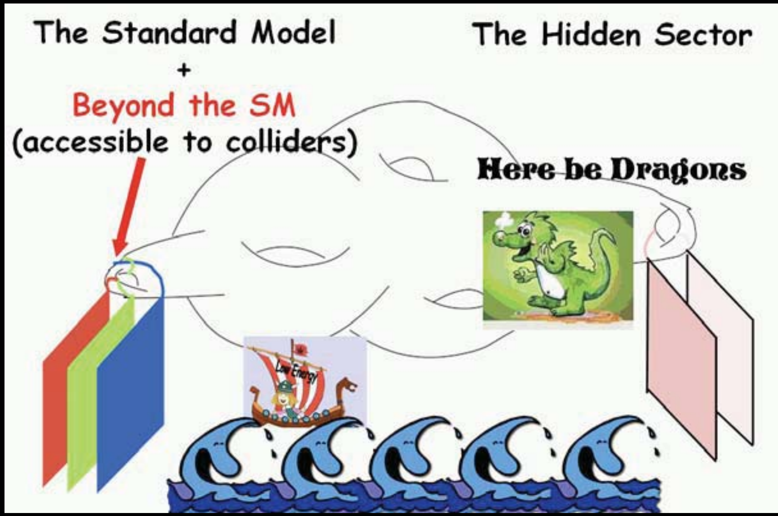
- Good Physics Case for Axions, WIMPs and WISPs

  ➡ explore `The Low Energy Frontier'

- Low energy experiments/observations test energy scales much higher than accelerators

  ➡ Complementary!

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



- Surprises (like Lorentz symmetry violation) possible!