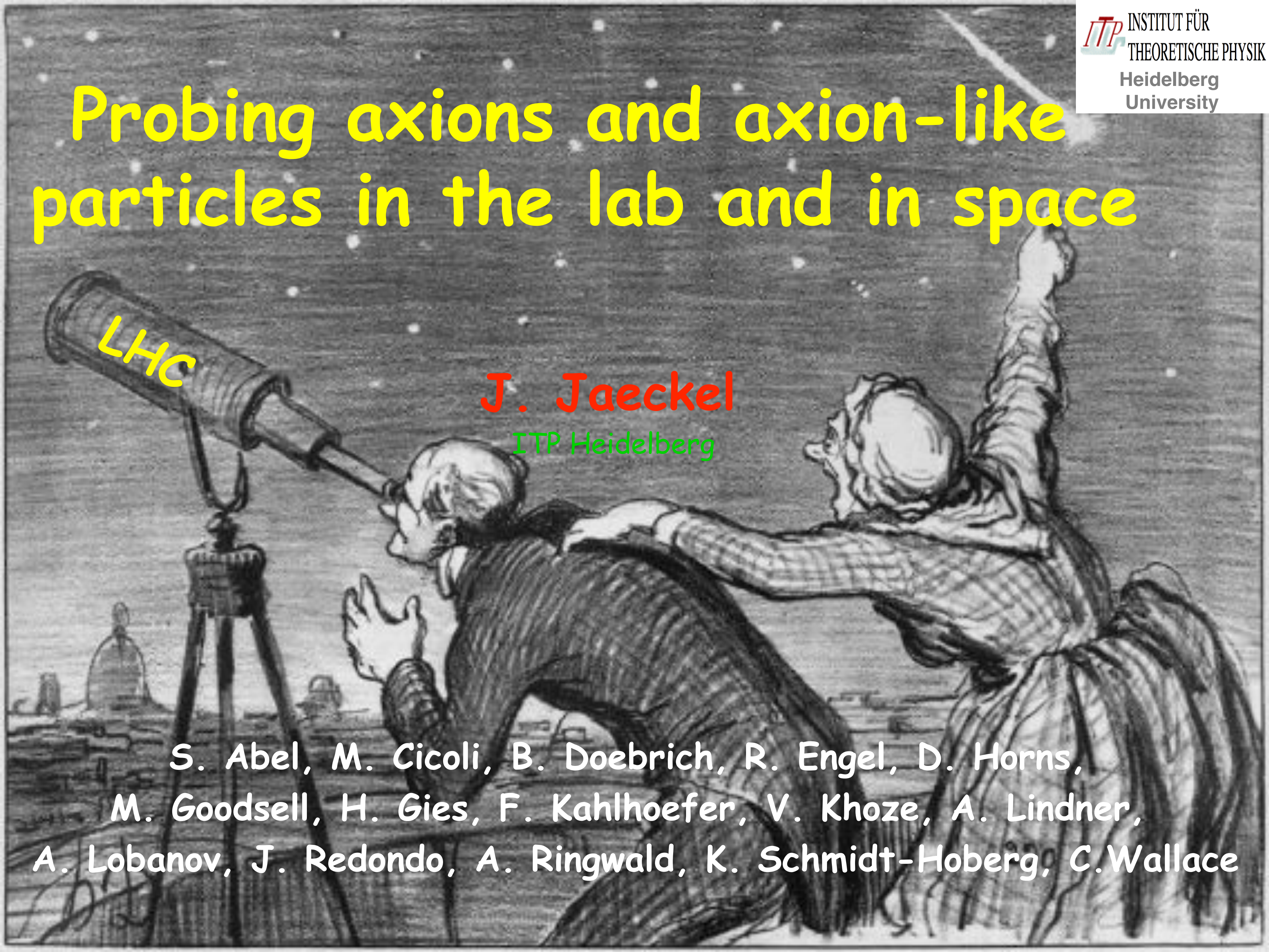
INSTITUT FÜR
THEORETISCHE PHYSIK
Heidelberg
University

Probing axions and axion-like particles in the lab and in space



J. Jaeckel
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S. Abel, M. Cicoli, B. Doebrich, R. Engel, D. Horns,
M. Goodsell, H. Gies, F. Kahlhoefer, V. Khoze, A. Lindner,
A. Lobanov, J. Redondo, A. Ringwald, K. Schmidt-Hoberg, C.Wallace

Where we want to go…

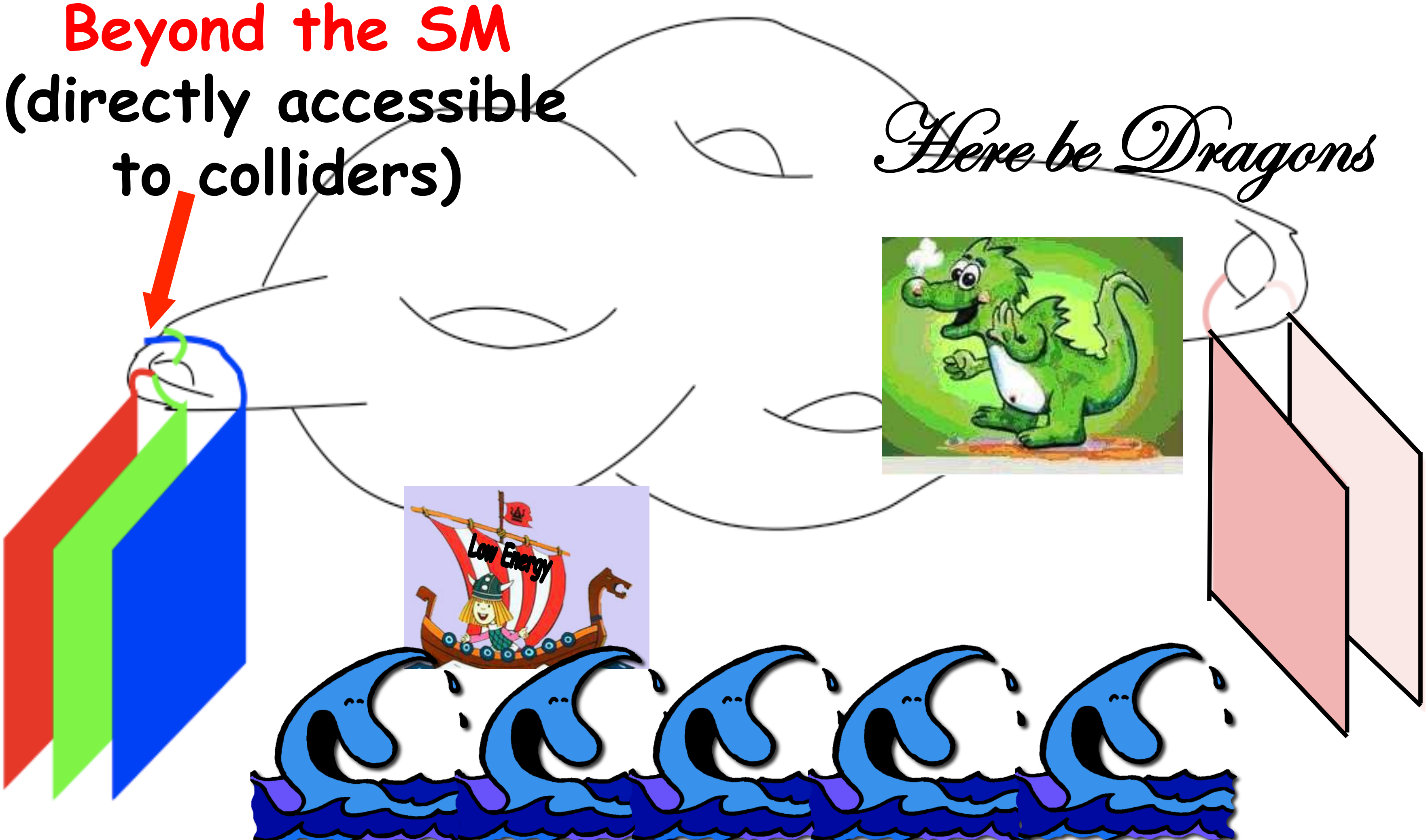
The Standard Model

+

Beyond the SM

(directly accessible to colliders)

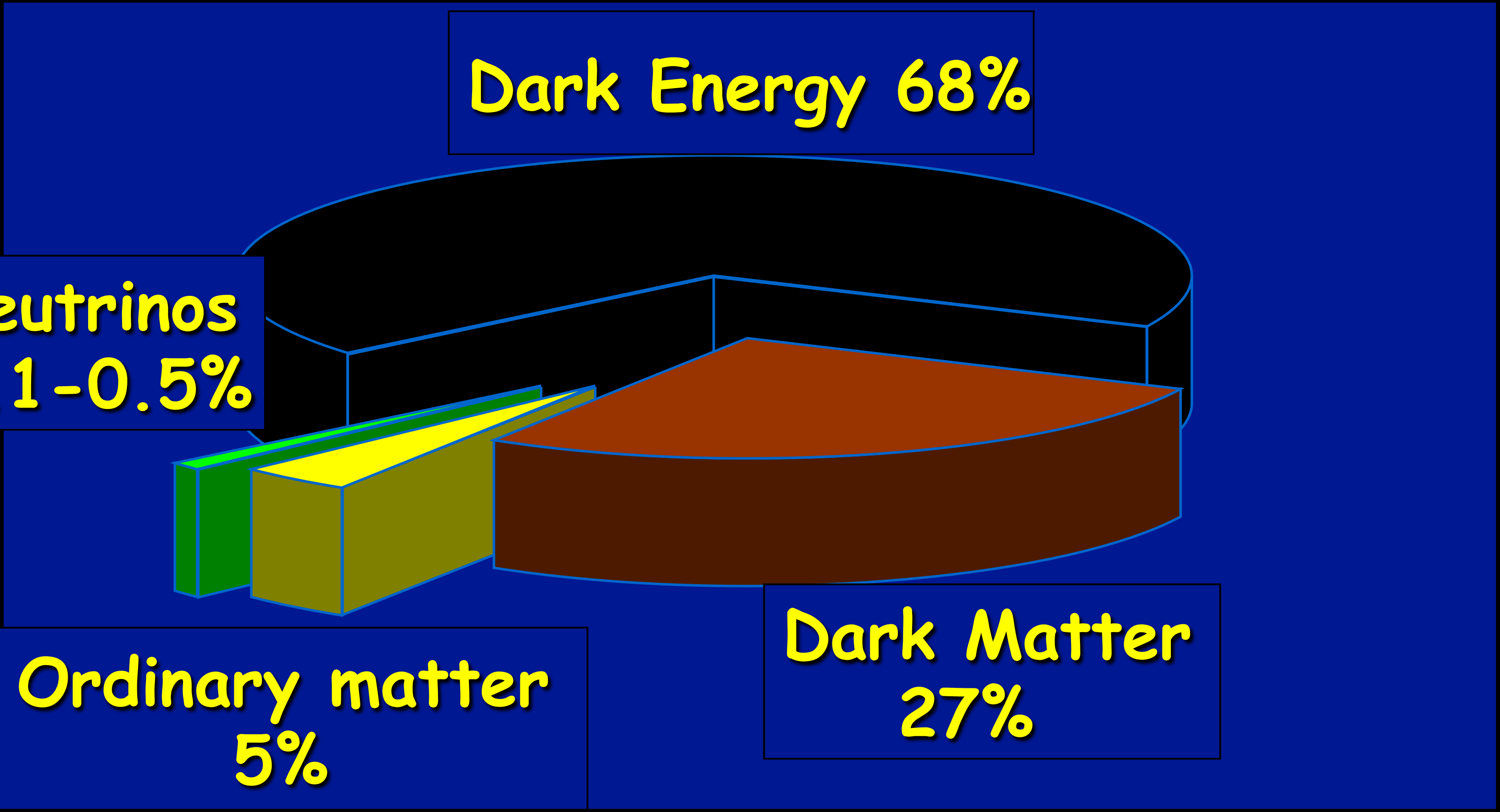
The Hidden Sector



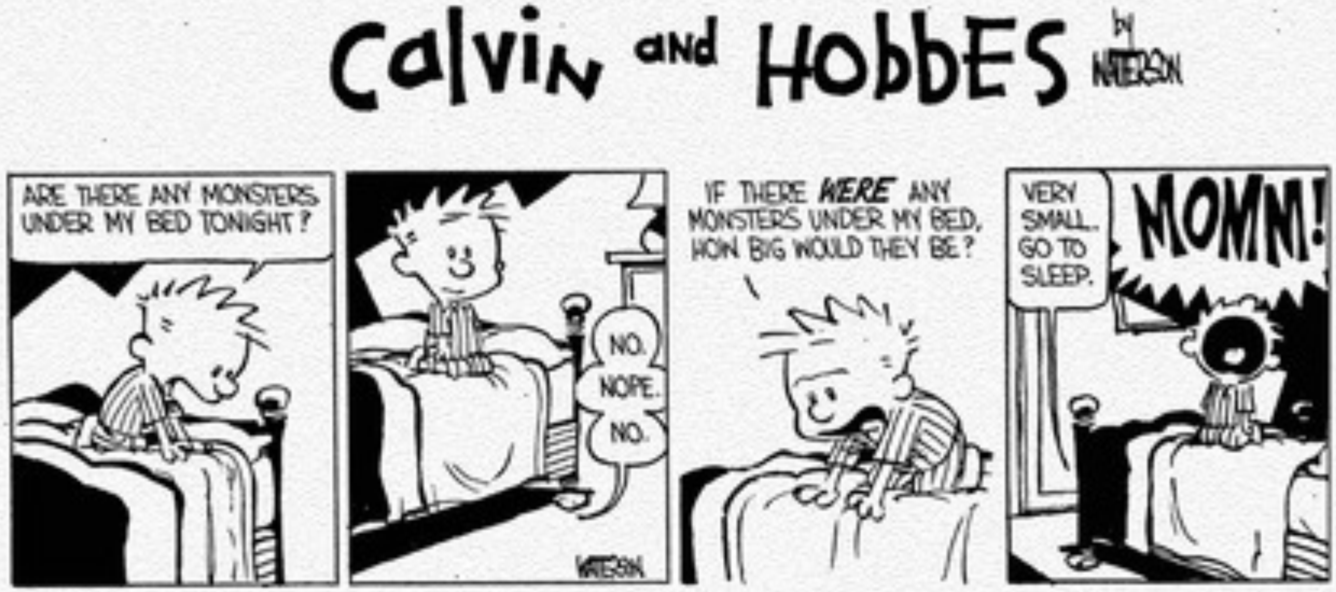
We need...

Physics beyond the Standard Model

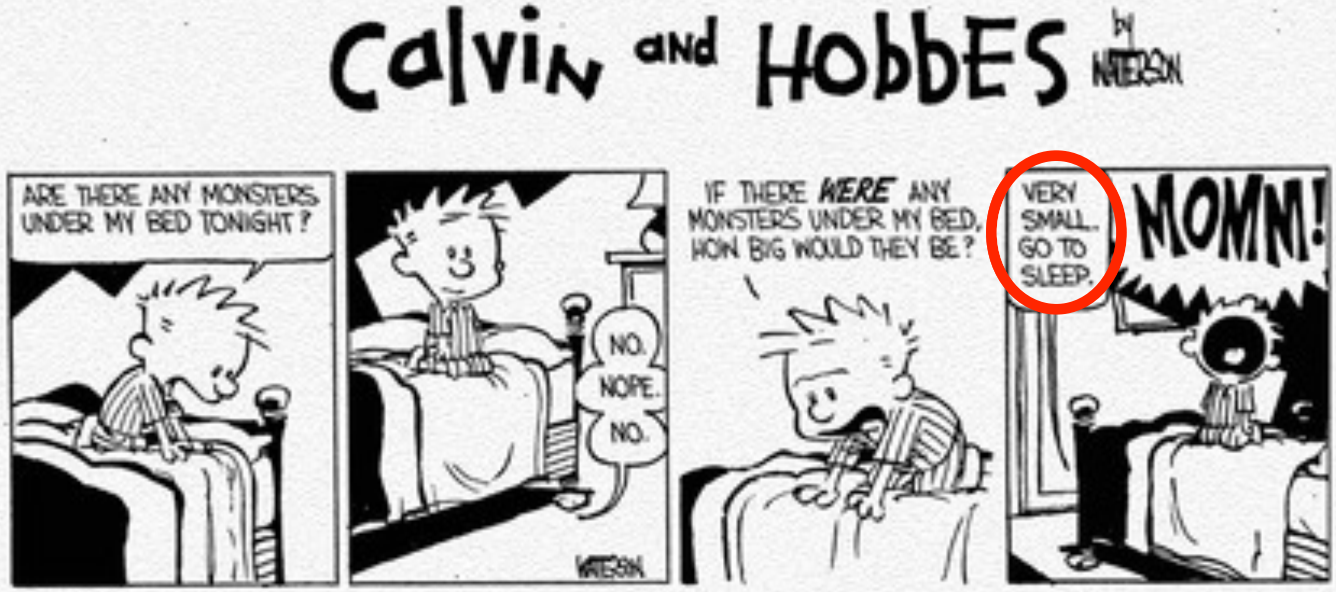
Inventory of the Universe



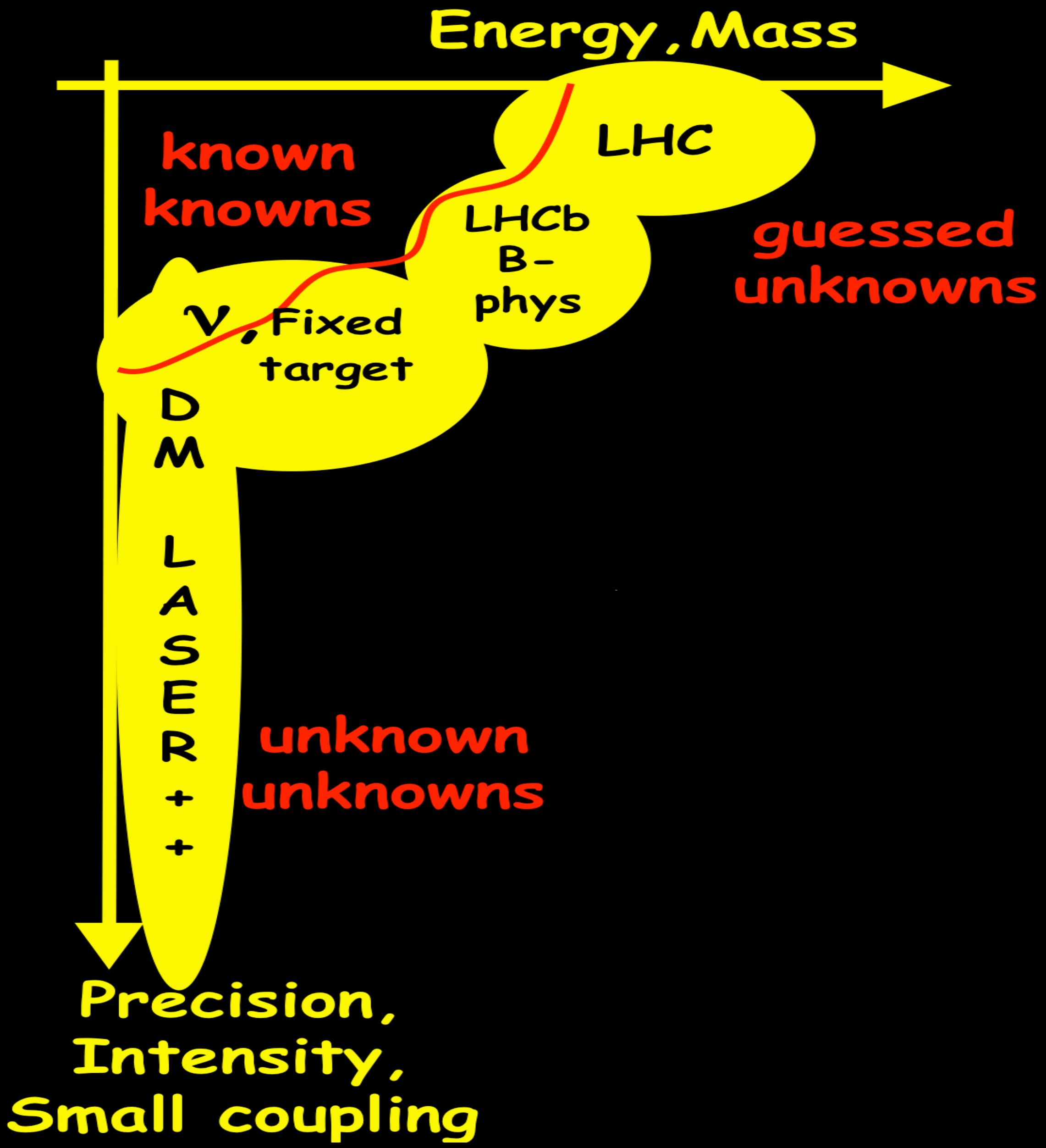
Where does it hide?



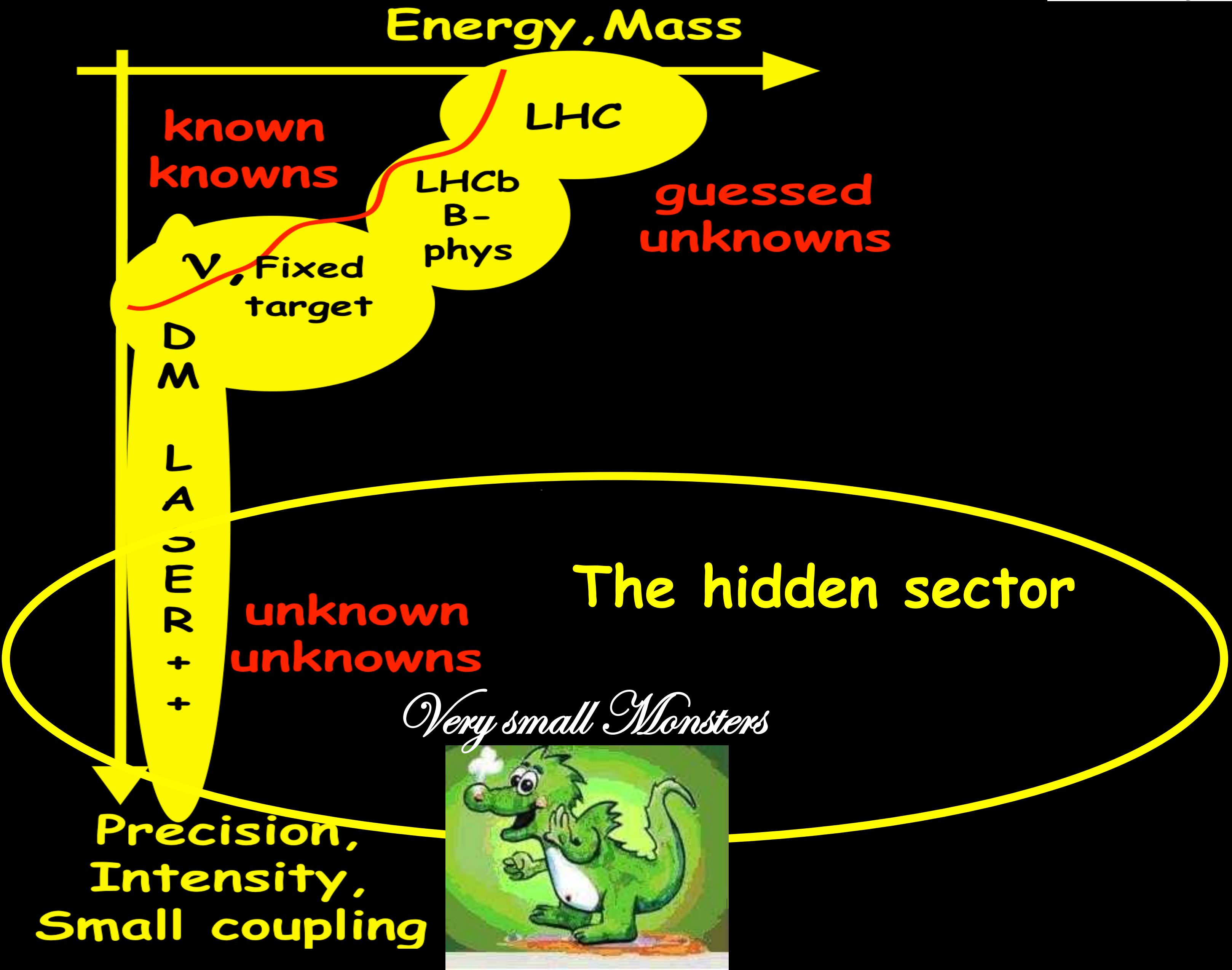
Where does it hide?



Exploring is (at least) 2 dimensional



Exploring is (at least) 2 dimensional



The axion example

High Scale

↓

Small Coupling

Example: Axion coupling

- Effective higher dimensional coupling

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

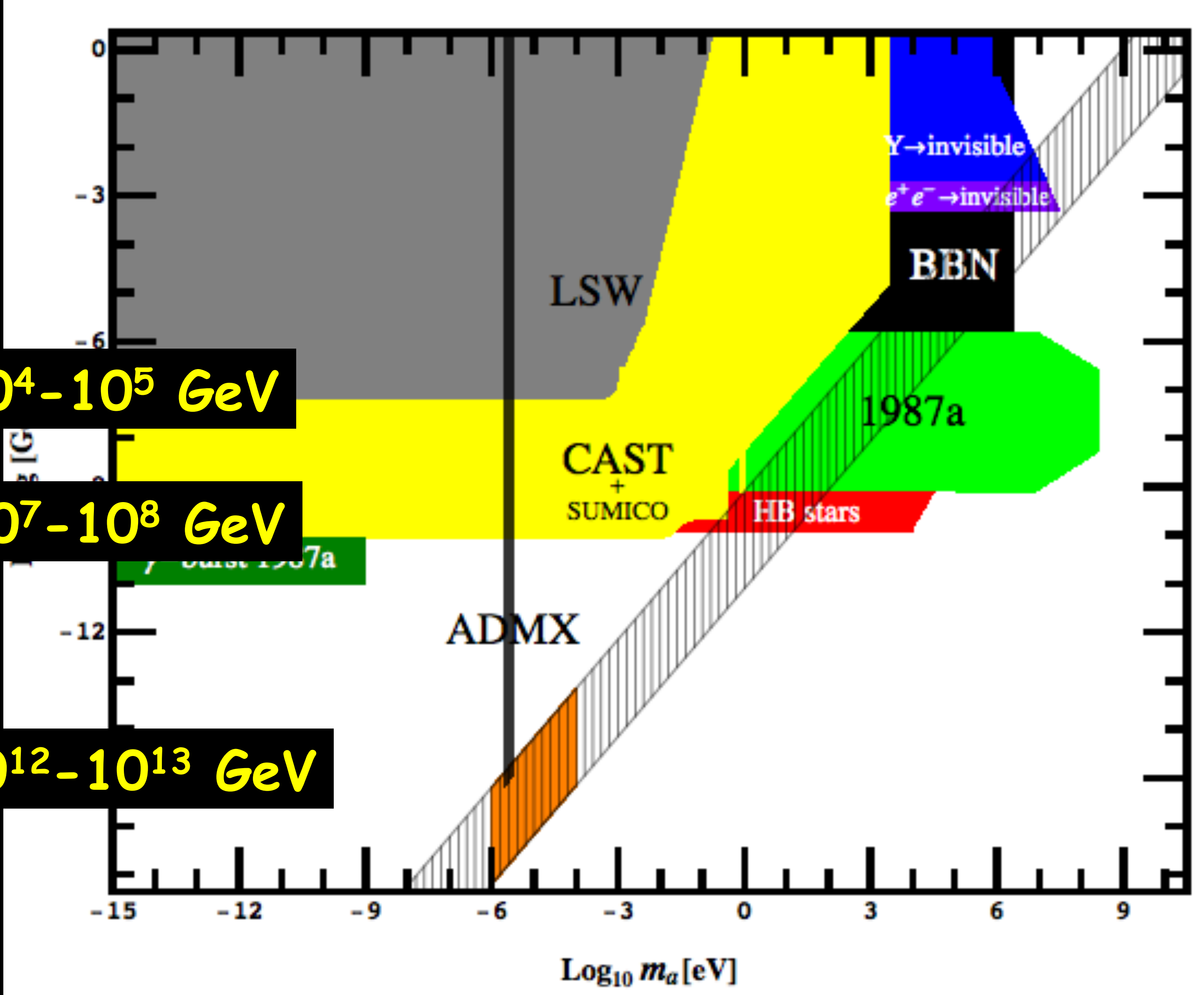
- Small coupling for large axion scale:

small

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

large

Huge Scale>> LHC Energy!



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!

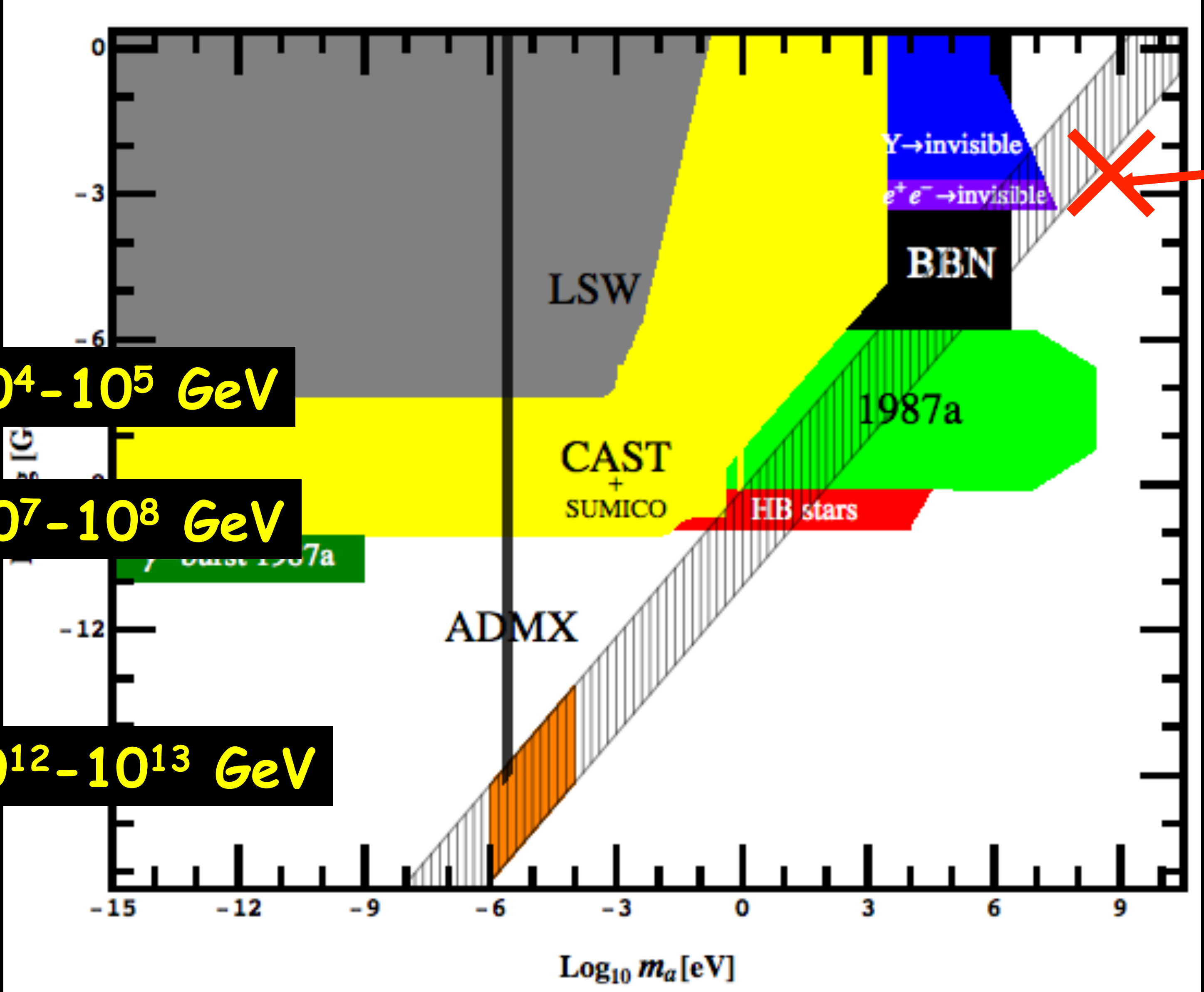
$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

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

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

π^0

Typical
Pseudo-Goldstones

Goldstones

- Goldstone bosons arise when a global symmetry is broken.
- They are essentially the phase of the Higgs field (e.g. U(1) symm)

$$\phi = \left(\langle\phi\rangle + \varphi\right)\exp\left(i\frac{a}{F}\right)$$

Goldstone

Derivative interactions

- Phase of ϕ can be removed by LOCAL transformation $\exp\left(-i\frac{a(x)}{F}\right)$

- Local transformation is not symmetry
  ➔ New term in Lagrangian

$$\mathcal{L} \to \mathcal{L} + \frac{1}{F}(\partial_\mu a)J^\mu$$

Goldstone

Noether current

Derivative interactions

- Explicit example

$$\mathcal{L}_{ferm} = i\bar{\psi}\gamma^\mu\partial_\mu\psi$$

- Symm: $\psi \to \exp(-i\gamma^5\alpha)\psi$

- Do LOCAL with $\alpha = -\frac{a(x)}{F}$

- Result:

$$\mathcal{L}_{ferm} \to \mathcal{L}_{ferm} + \frac{\partial_\mu a(x)}{F}\bar{\psi}\gamma^\mu\gamma^5\psi = \frac{\partial_\mu a(x)}{F} j^\mu_{axial}$$

At tree level

- Can use partial integration and Dirac equation to obtain

$$\frac{\partial_\mu a(x)}{F}\bar{\psi}\gamma^\mu\gamma^5\psi \rightarrow a(x)\frac{2m_\psi}{F}\bar{\psi}\gamma^5\psi$$

Small Yukawa interaction

$$Y = \frac{2m_\psi}{F} \ll 1$$

At tree level

- Can use partial integration and Dirac equation to obtain

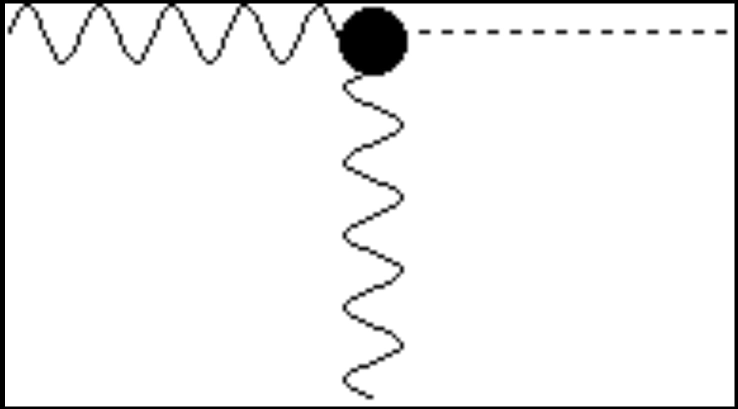
$$\frac{\partial_\mu a(x)}{F}\bar{\psi}\gamma^\mu\gamma^5\psi \to a(x)\frac{2m_\psi}{F}\bar{\psi}\gamma^5\psi$$

Small Yukawa interaction

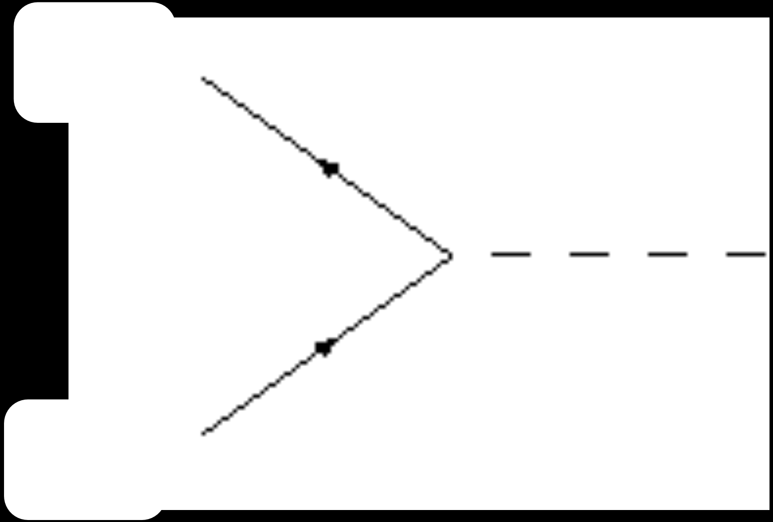
$$Y = \frac{2m_\psi}{F} \ll 1$$

Careful: if one does not have the γ^5 RHS=0!!!

Summary typical interactions



$$\sim a(x)\frac{\alpha_i}{2\pi F}F^{i,\mu\nu}\tilde{F}^i_{\mu\nu}$$



$$\sim \frac{m_\psi}{F}\bar{\psi}\gamma^5\psi$$

All interactions suppressed by $\sim \frac{1}{F}$

Anomalous symmetries

- If the symmetry is anomalous (e.g. axial symmetries)

Extra term appears from the local symmetry transformation

$$\mathcal{L} \to \mathcal{L} + \frac{1}{F}(\partial_\mu a) J^\mu + a(x)\frac{C_i \alpha_i}{2\pi F} F^{i,\mu\nu} \tilde{F}^i_{\mu\nu}$$

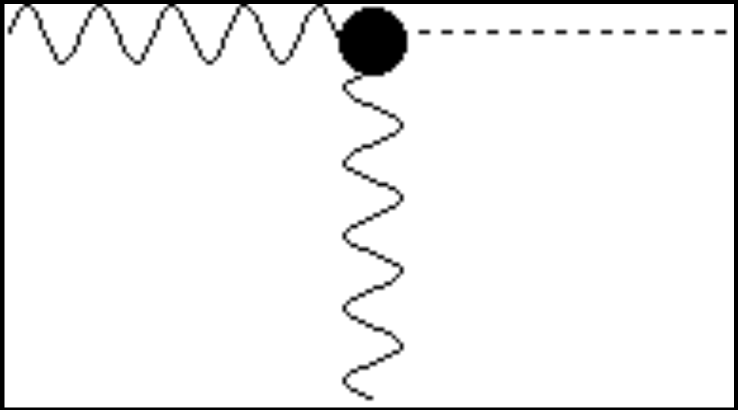
Coupling to two gauge bosons

How can we see light particles?

- Example: Axions

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

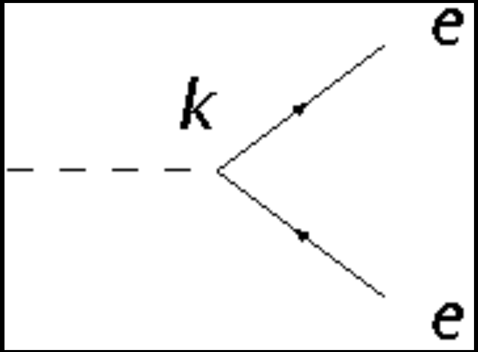
Two-photon interaction!



Axion(-like particle) interactions

- Light scalars or pseudoscalars

Can also have Yukawa couplings



$$k \sim dimensionless \ll 1$$

For QCD axion:

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

- Electrons, e
- Nucleons, N

ALPs

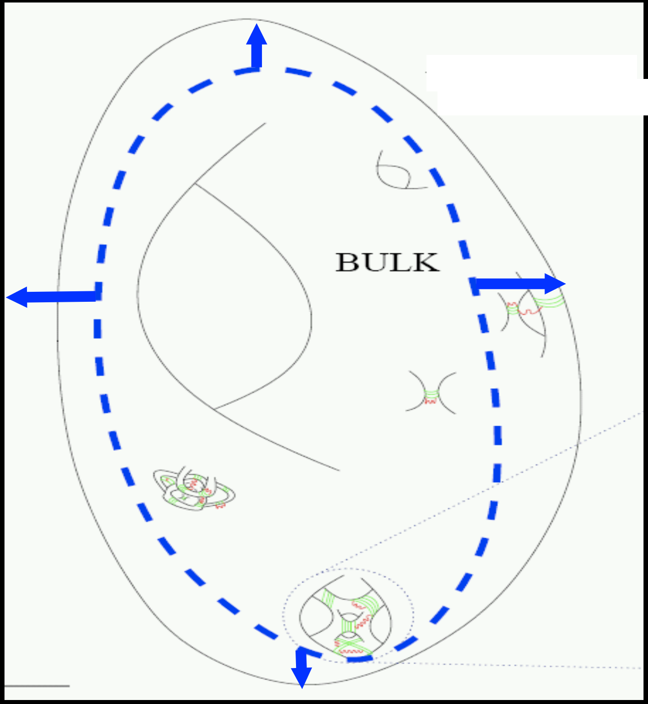
from

String Theory

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

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

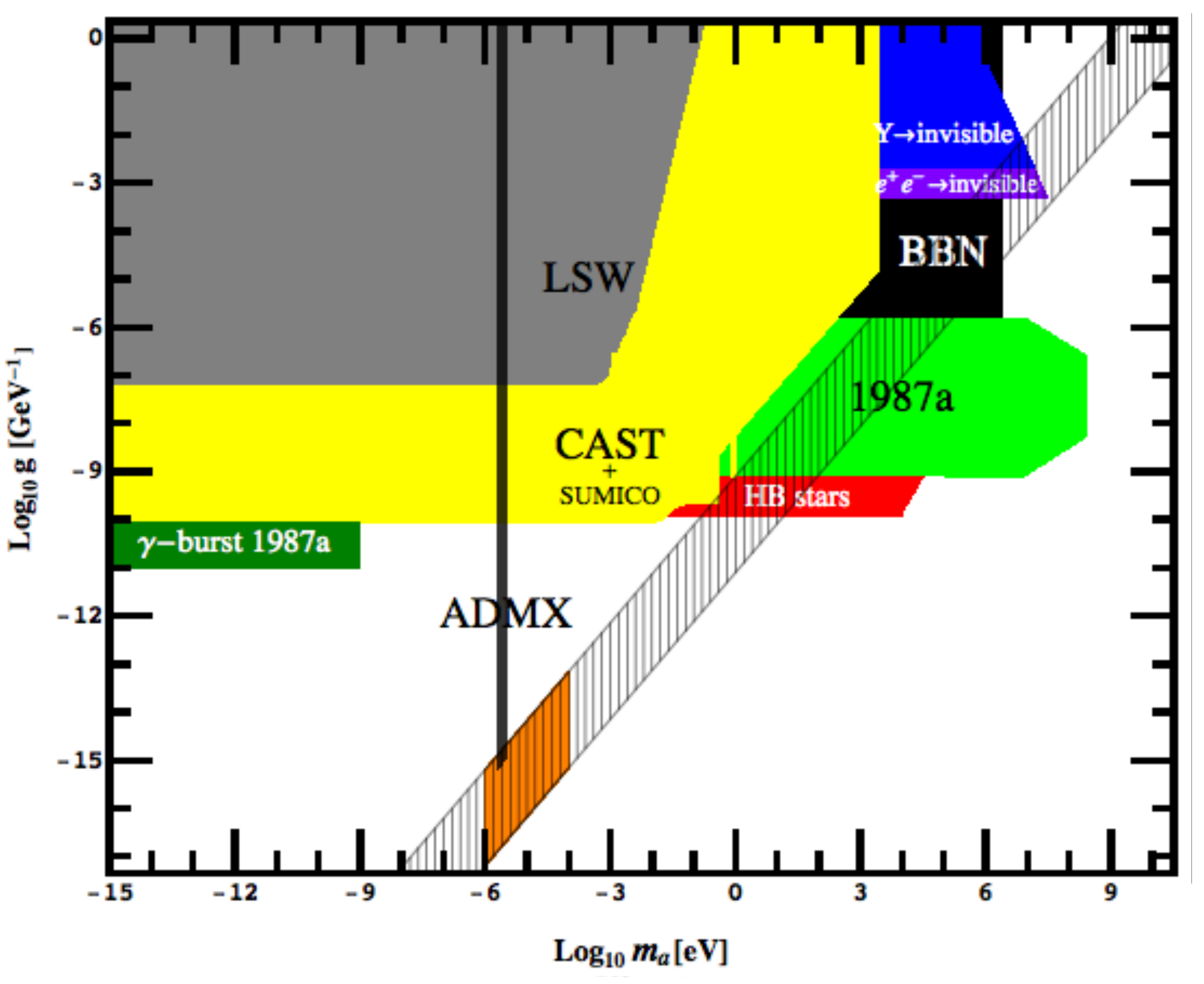
$$f_a \sim \frac{M_P}{\mathrm{Volume}^x} \sim M_s \left(\frac{M_s}{M_P}\right)^y$$

- If QCD axion: m_a fixed

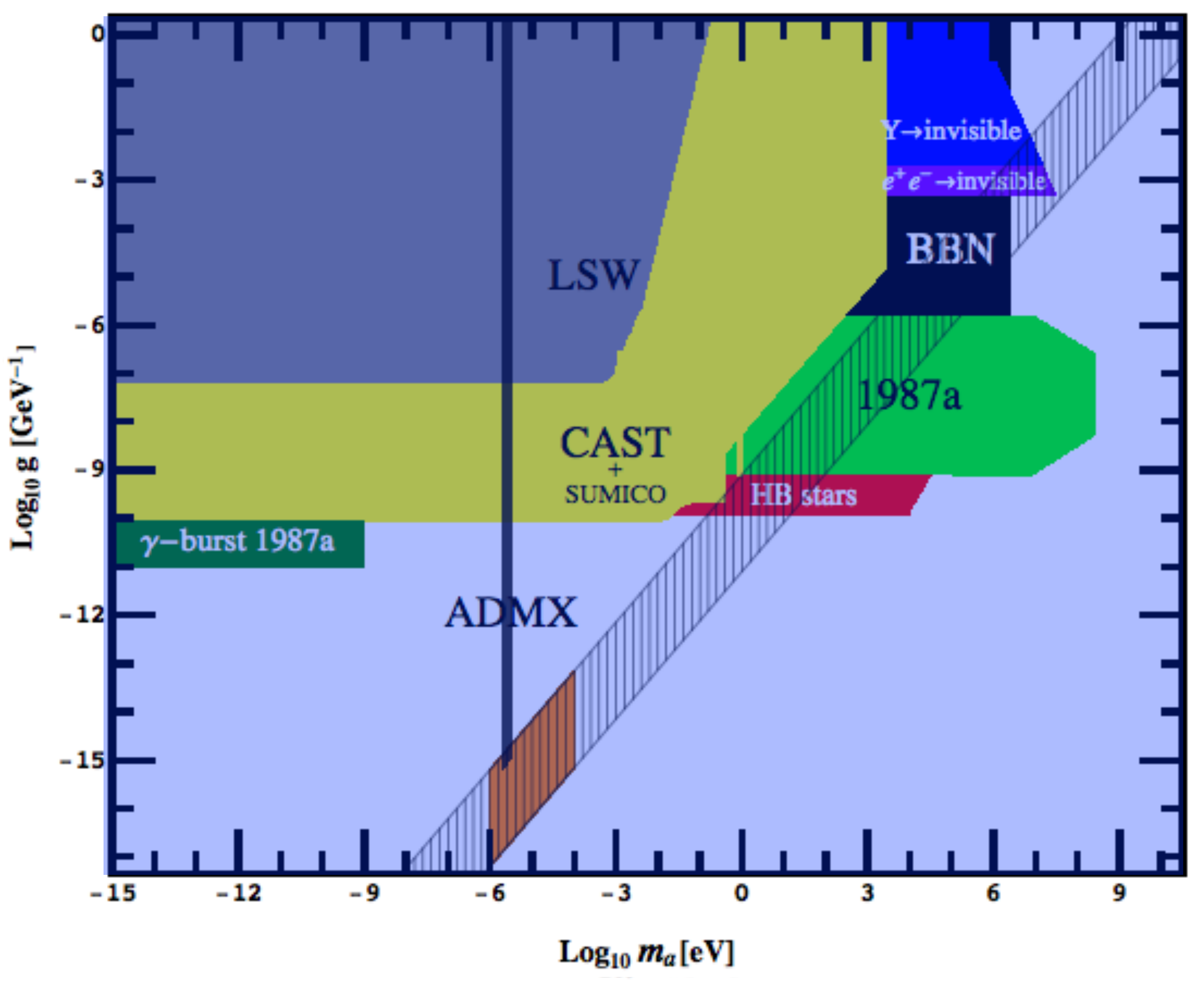
- However, if not QCD axion

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

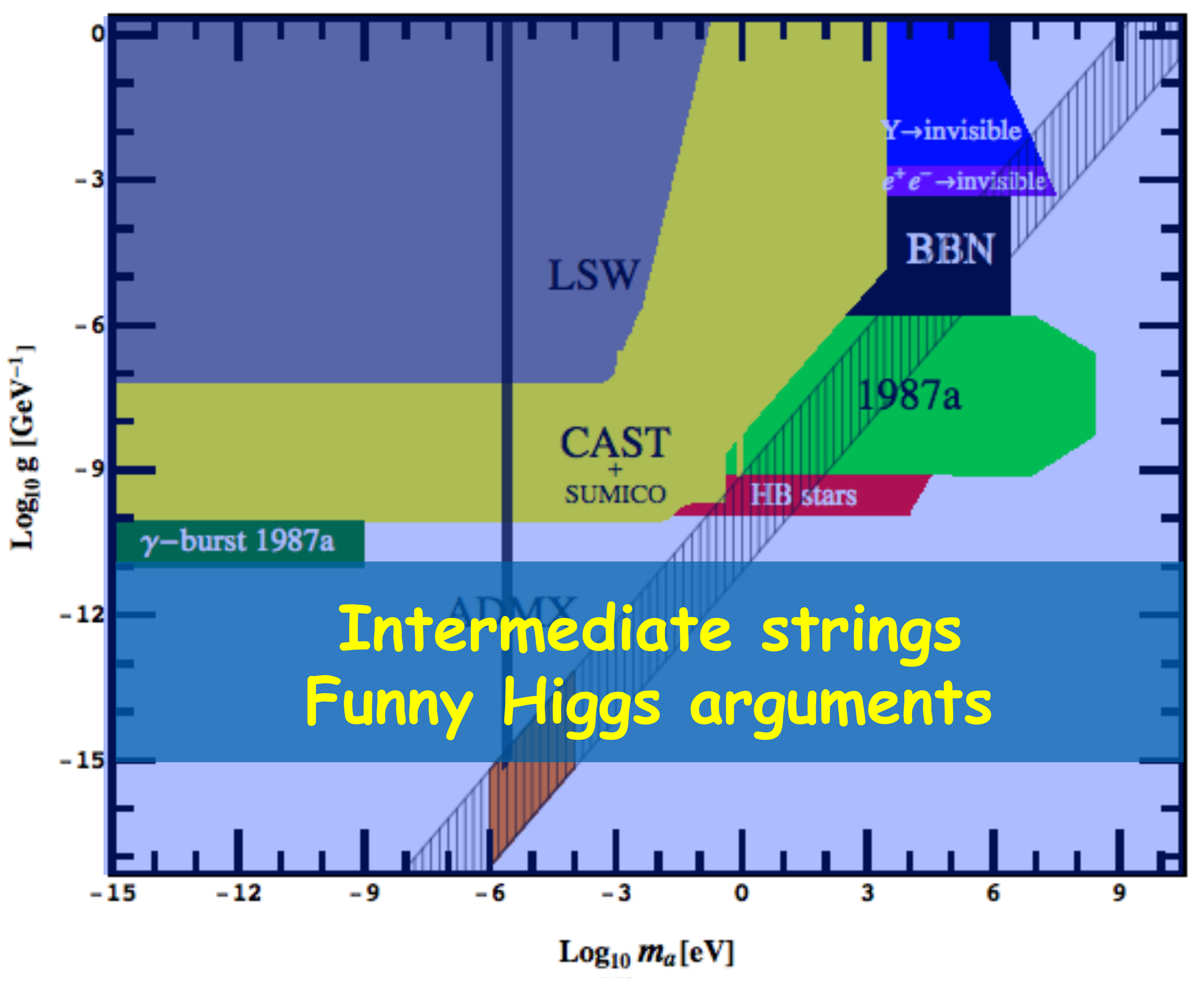
Axion (like particles): Where are we?



Axion (like particles): Where are we?



Axion (like particles): Where are we?



Intermediate strings
Funny Higgs arguments

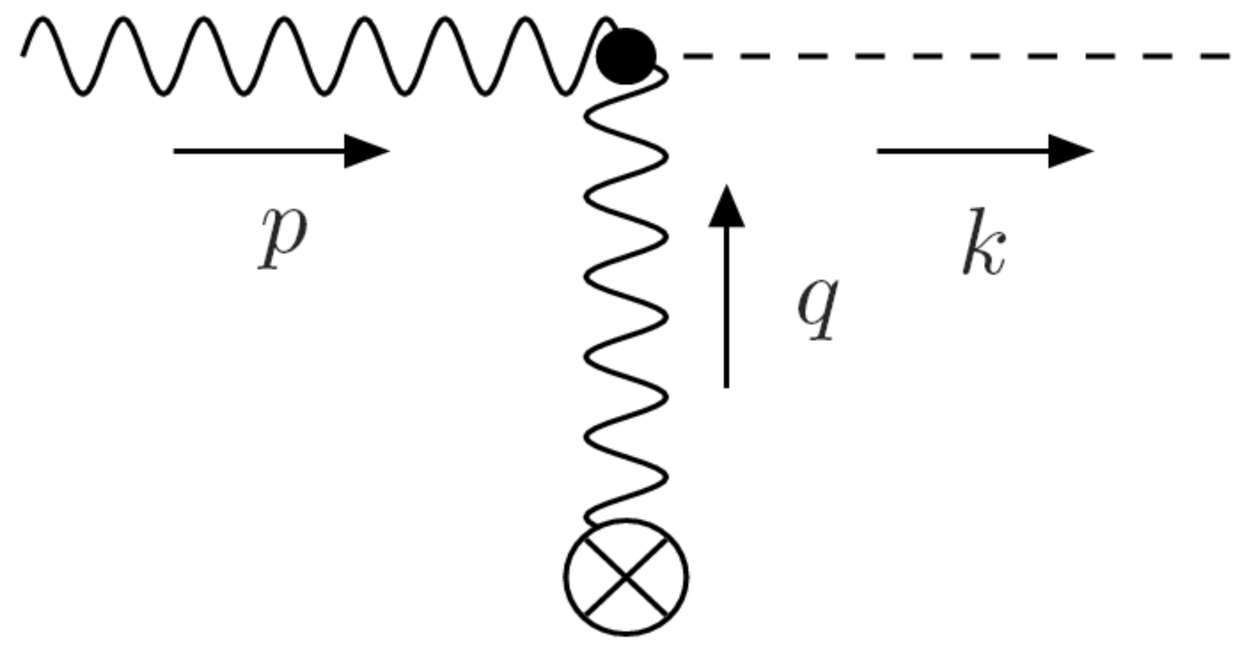
Light particles in astrophysics and cosmology

Energy loss in

Stars

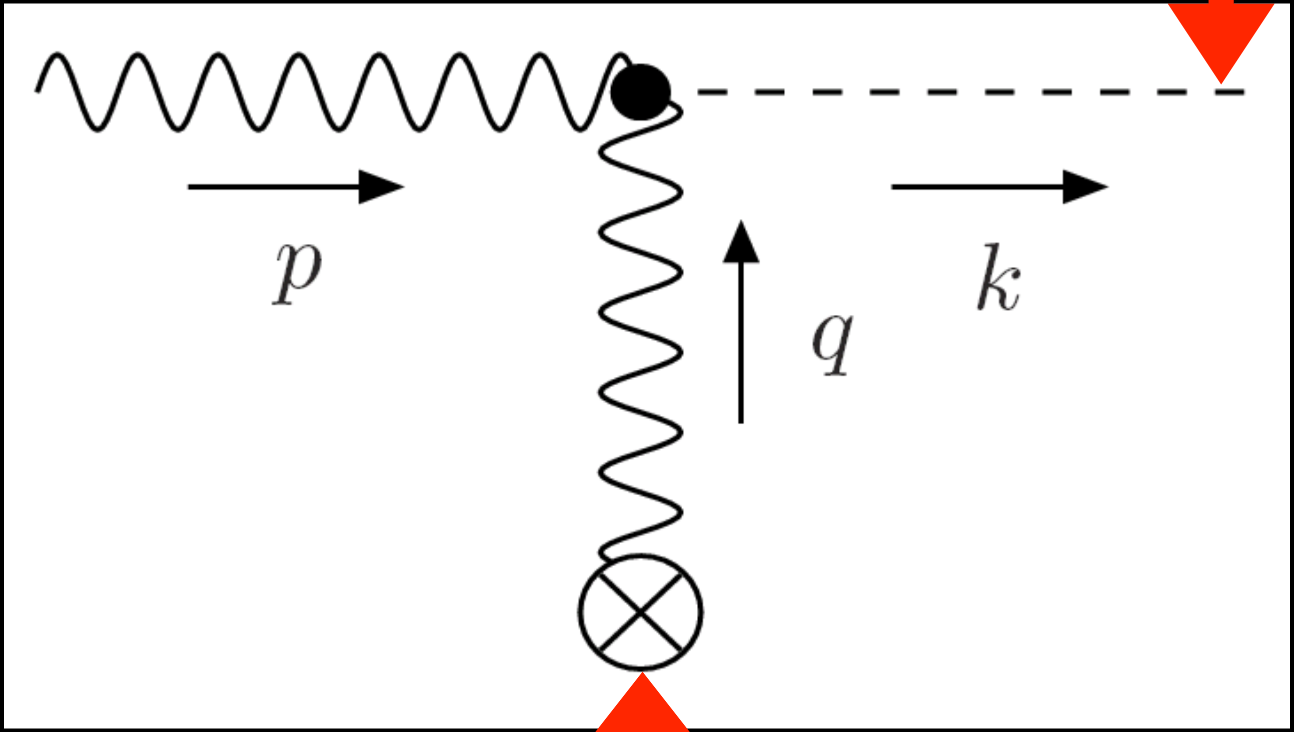
Axions

- 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

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

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

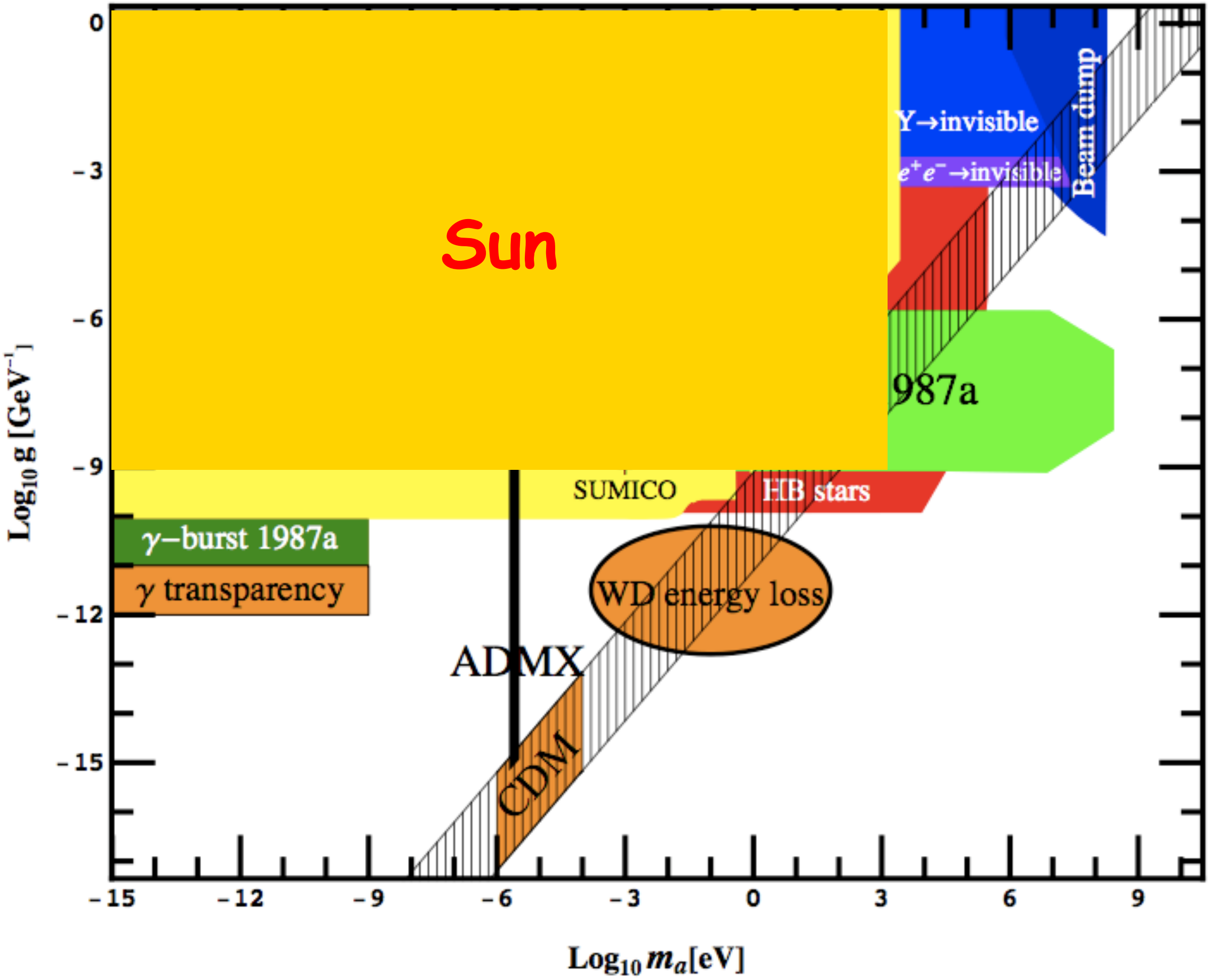
- Sun Lifetime with ALPs

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

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

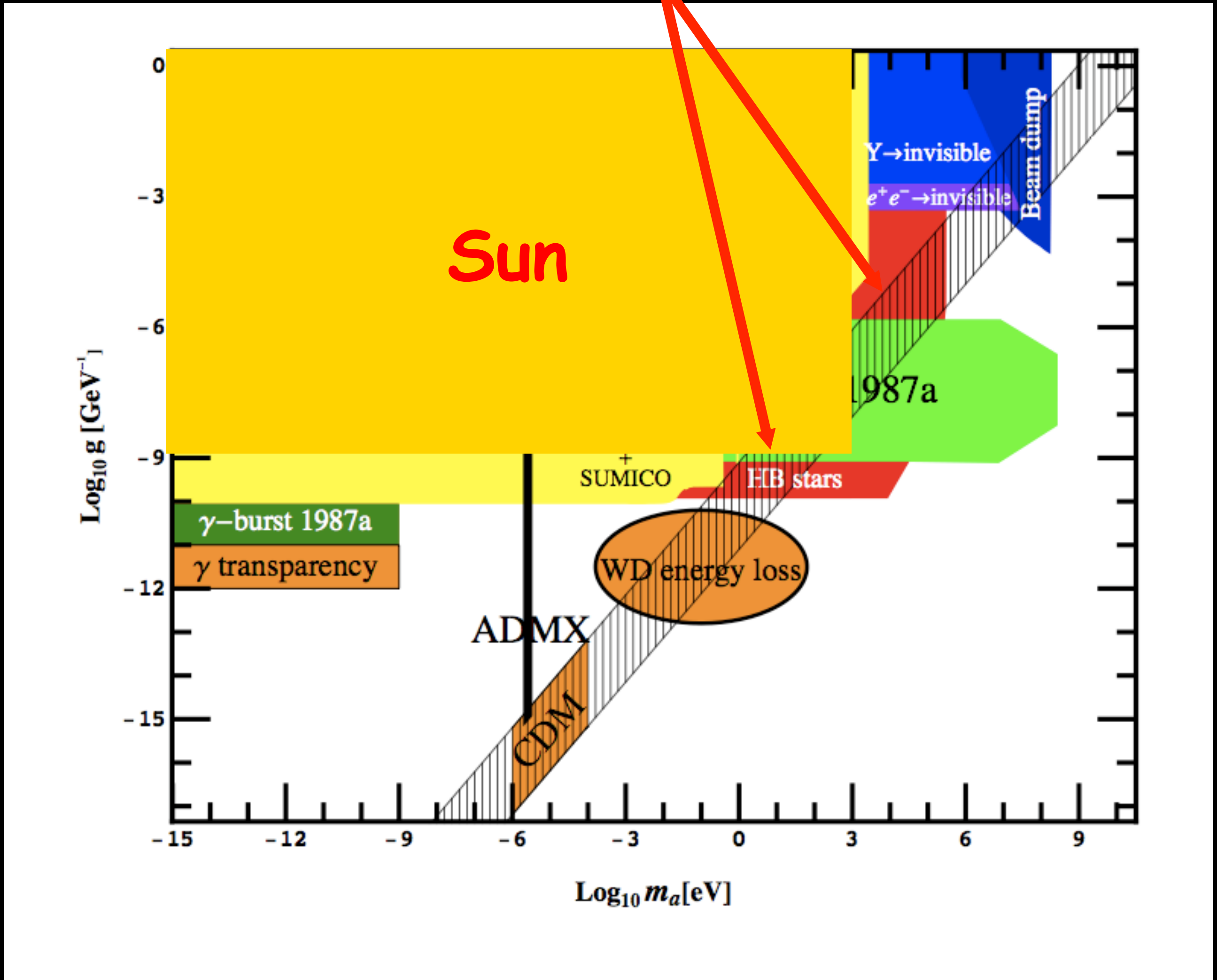
$$\Rightarrow \quad g \leq \frac{1}{10^4 GeV}$$

Axion-like particles



Can do better…

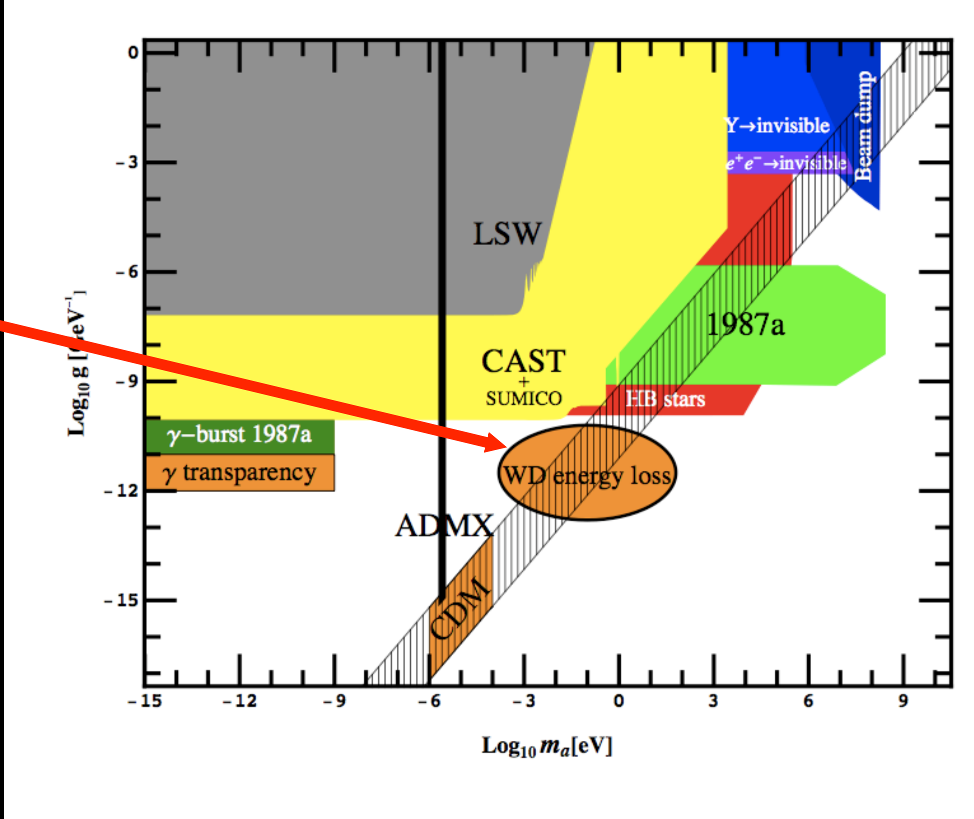
- Look at variety of stars
- Best are horizontal branch stars.



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

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

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

In equlibrium:

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

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

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:

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

➡ Decay: Neutrons decay with τ_n=886 s

Are we in eqilibrium?

- Freeze out:

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

- At this point in time $\frac{n_n}{n_p} \sim \frac{1}{6}$

- 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...

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

➡ $t_{BBN}\sim 50s$

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

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…

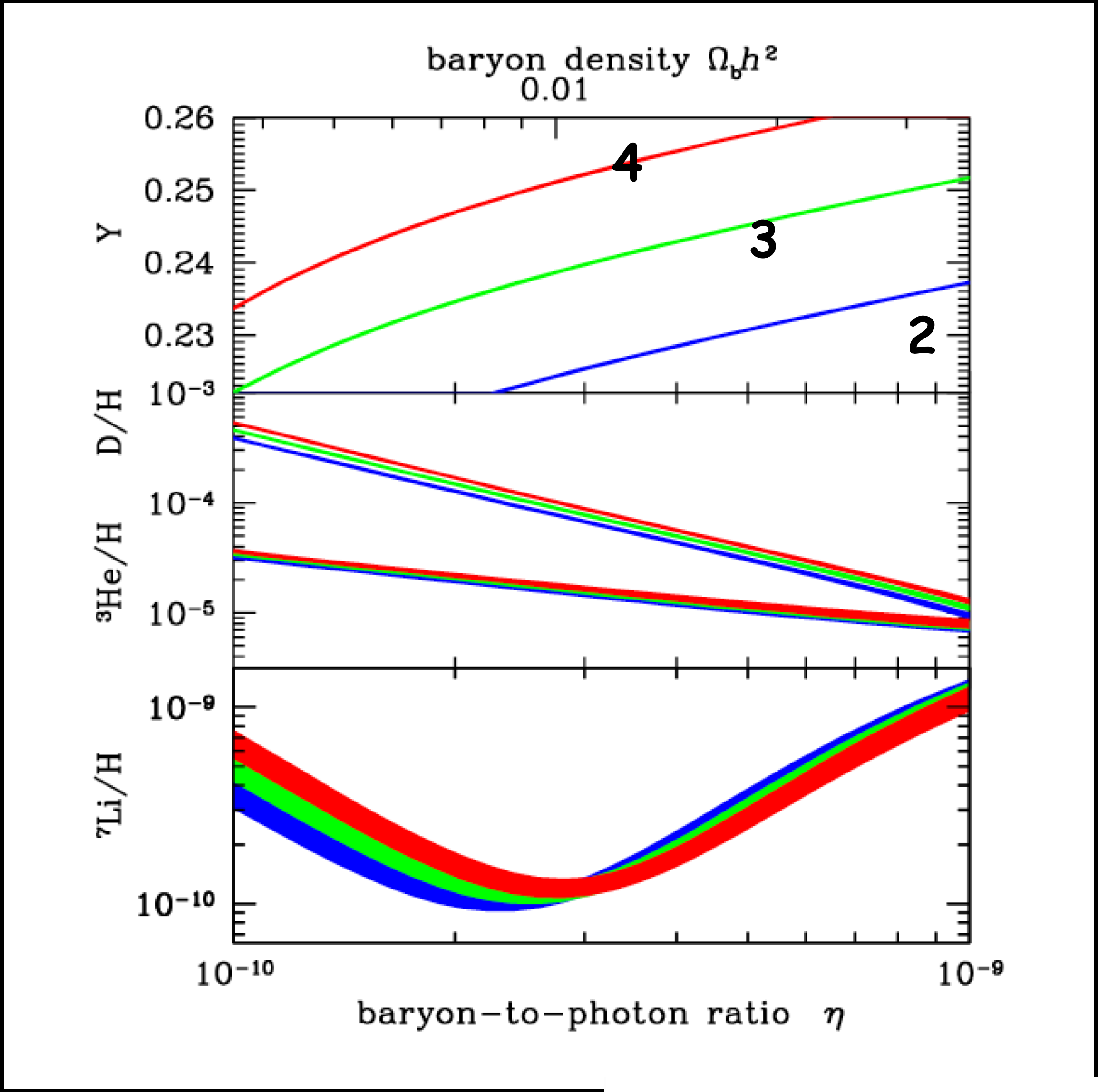
- Extra light particles in equilibrium increase the Hubble constant

→(Smallish) changes in

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

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

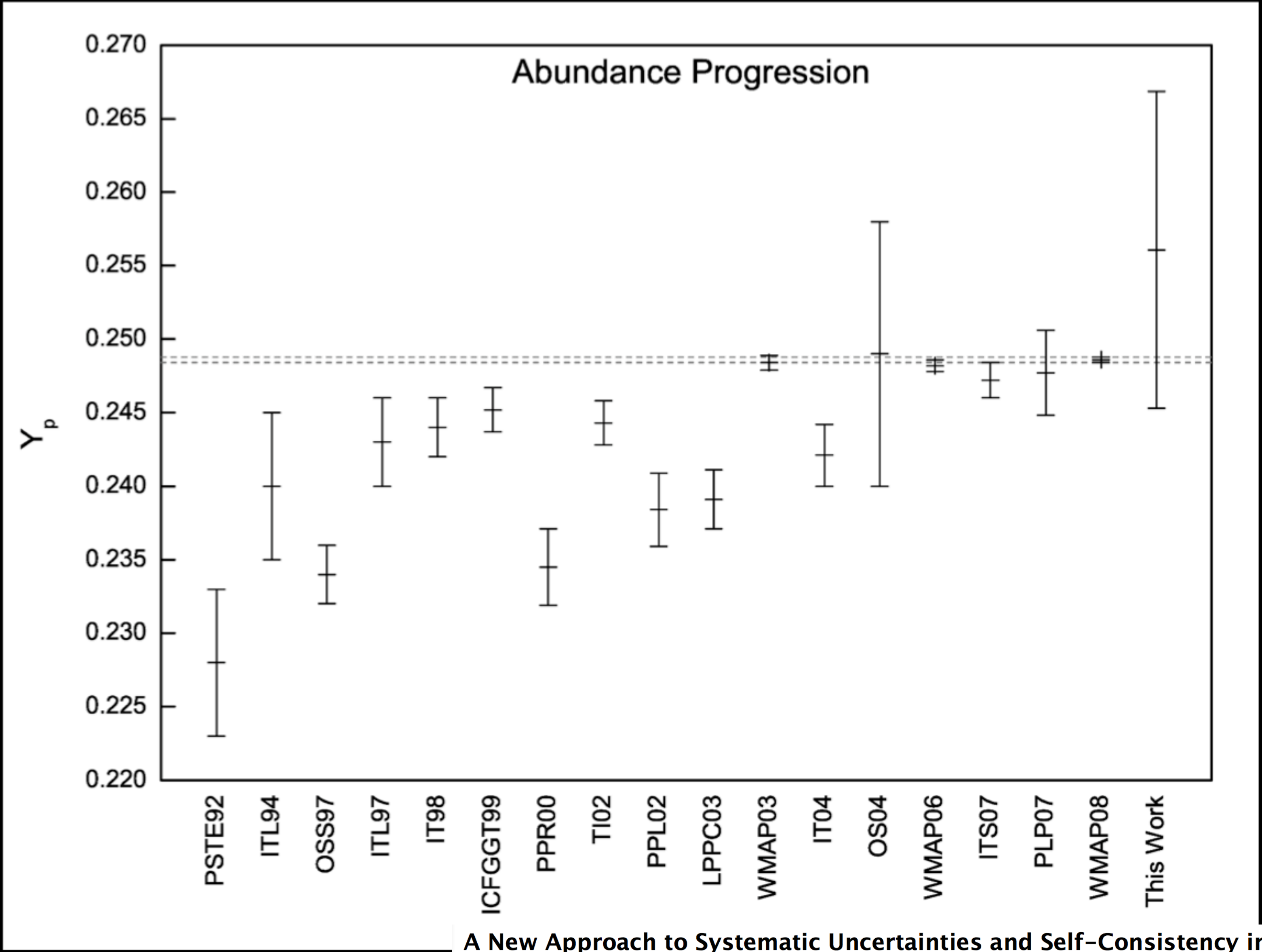
Extra species…



Big Bang Nucleosynthesis: 2015

Richard H. Cyburt, Brian D. Fields, Keith A. Olive, Tsung-Han Yeh

Measured abundancies…



A New Approach to Systematic Uncertainties and Self-Consistency in Helium Abundance Determinations

Erik Aver, Keith A. Olive, Evan D. Skillman

Extra species…

- Extra light particles in equilibrium increase the Hubble constant

→(Smallish) changes in

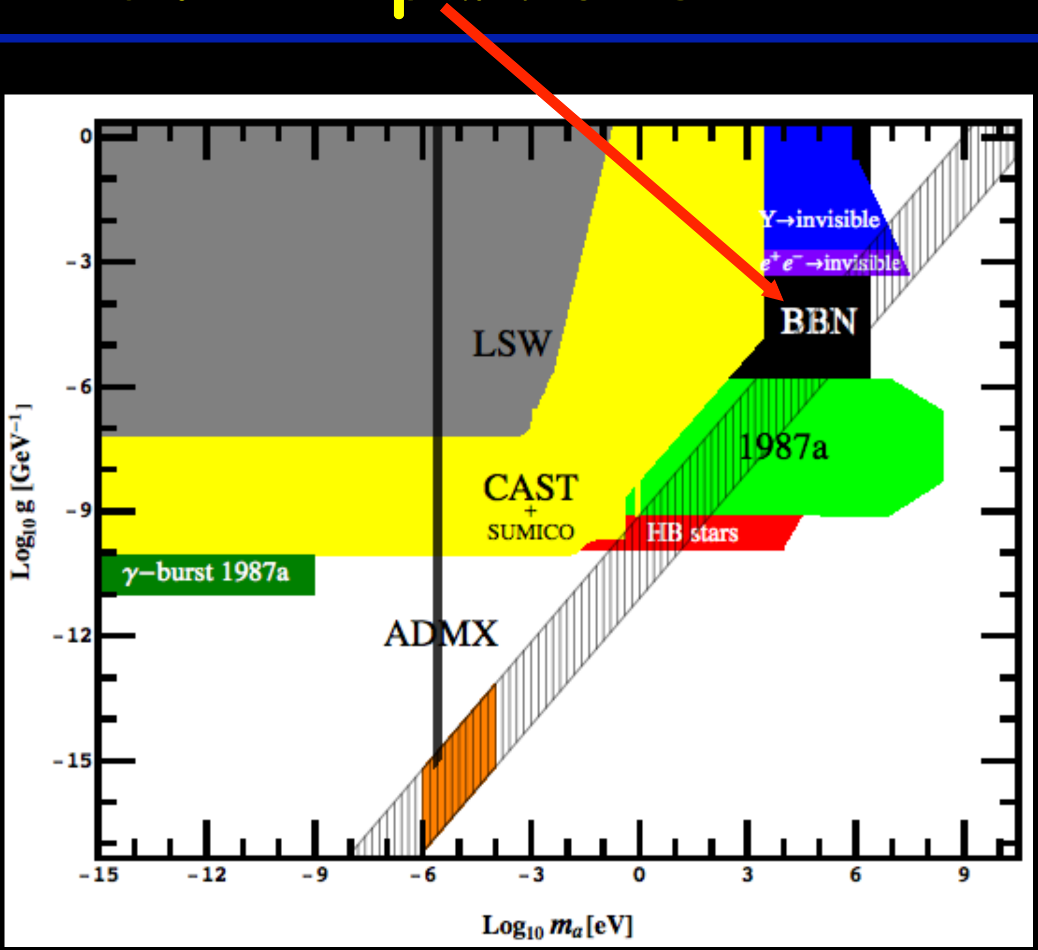
$$t_{freeze}, t_{BBN}$$

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

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

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

Axion-like particles



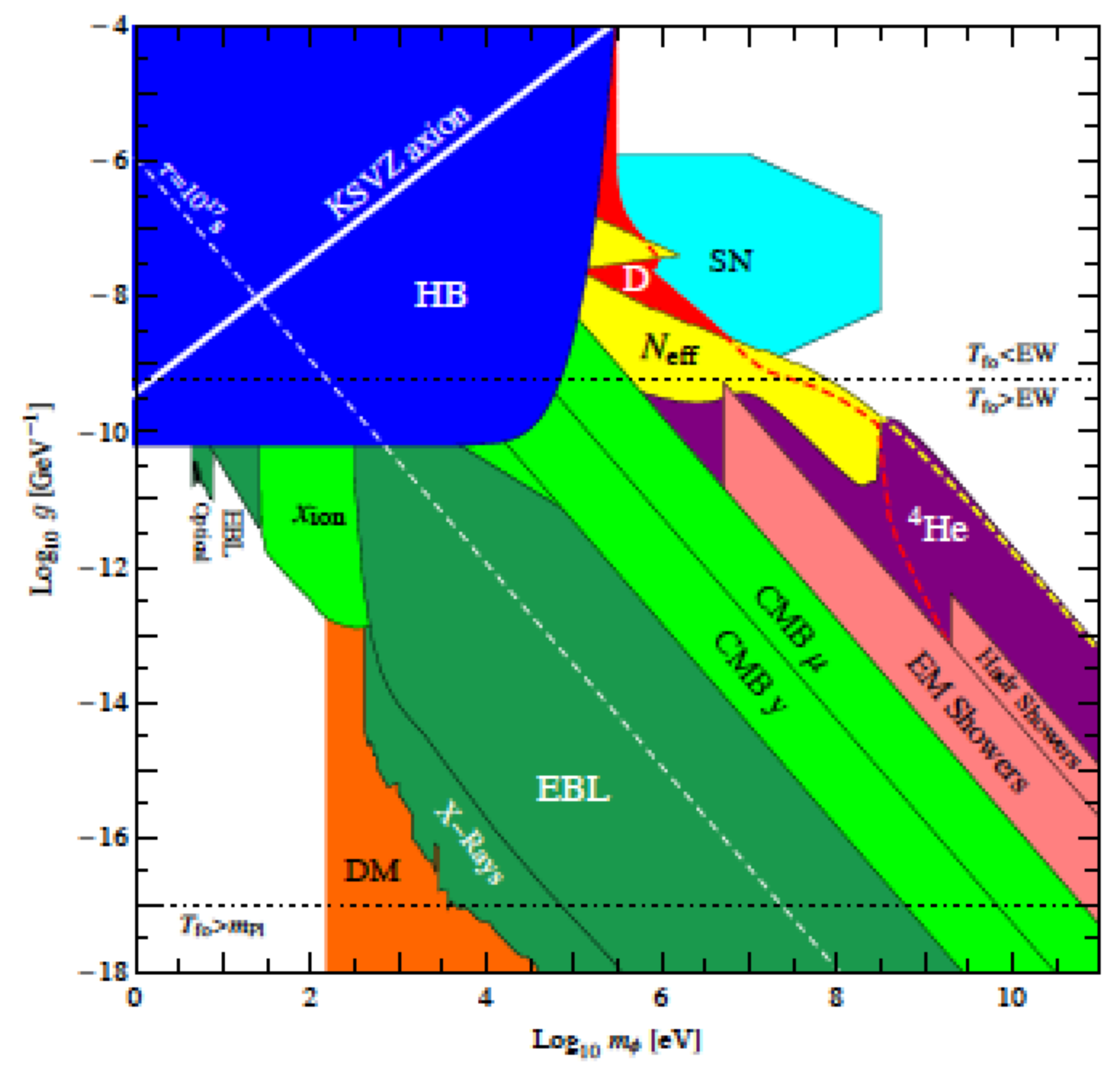
- Not my favourite bound: only 1 extra degree of freedom.
- Need to use one of the optimistic error estimate

Decaying ALPs

Decaying ALPs

- Thermal processes establish thermal ALP population
- Too much, and long lived ➔ Hot Dark matter
- Decay during BBN ➔ BBN changed
- Later decays would appear in CMB and EBL measurements

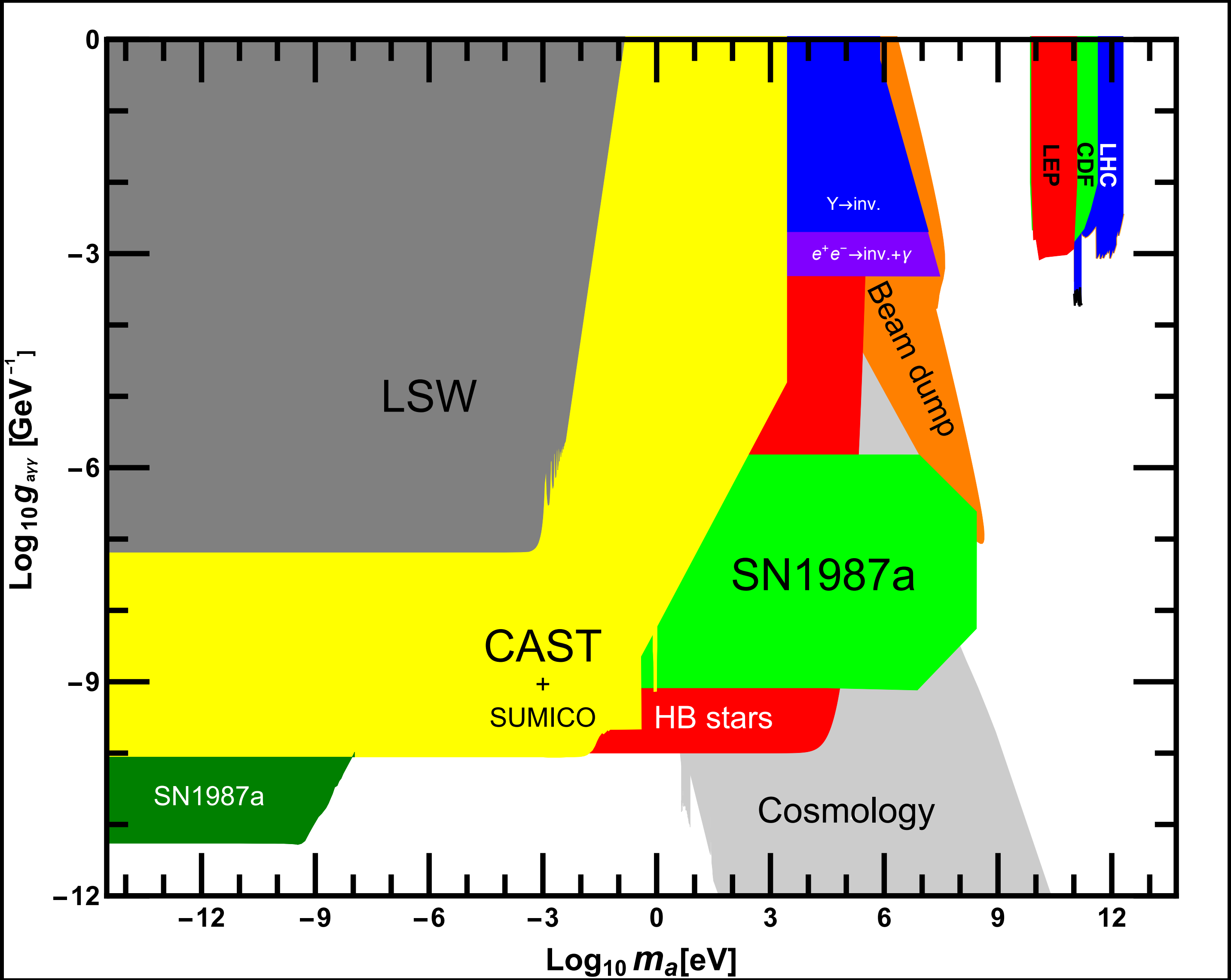
Thermal ALP limits



Cosmological bounds on pseudo Nambu-Goldstone bosons

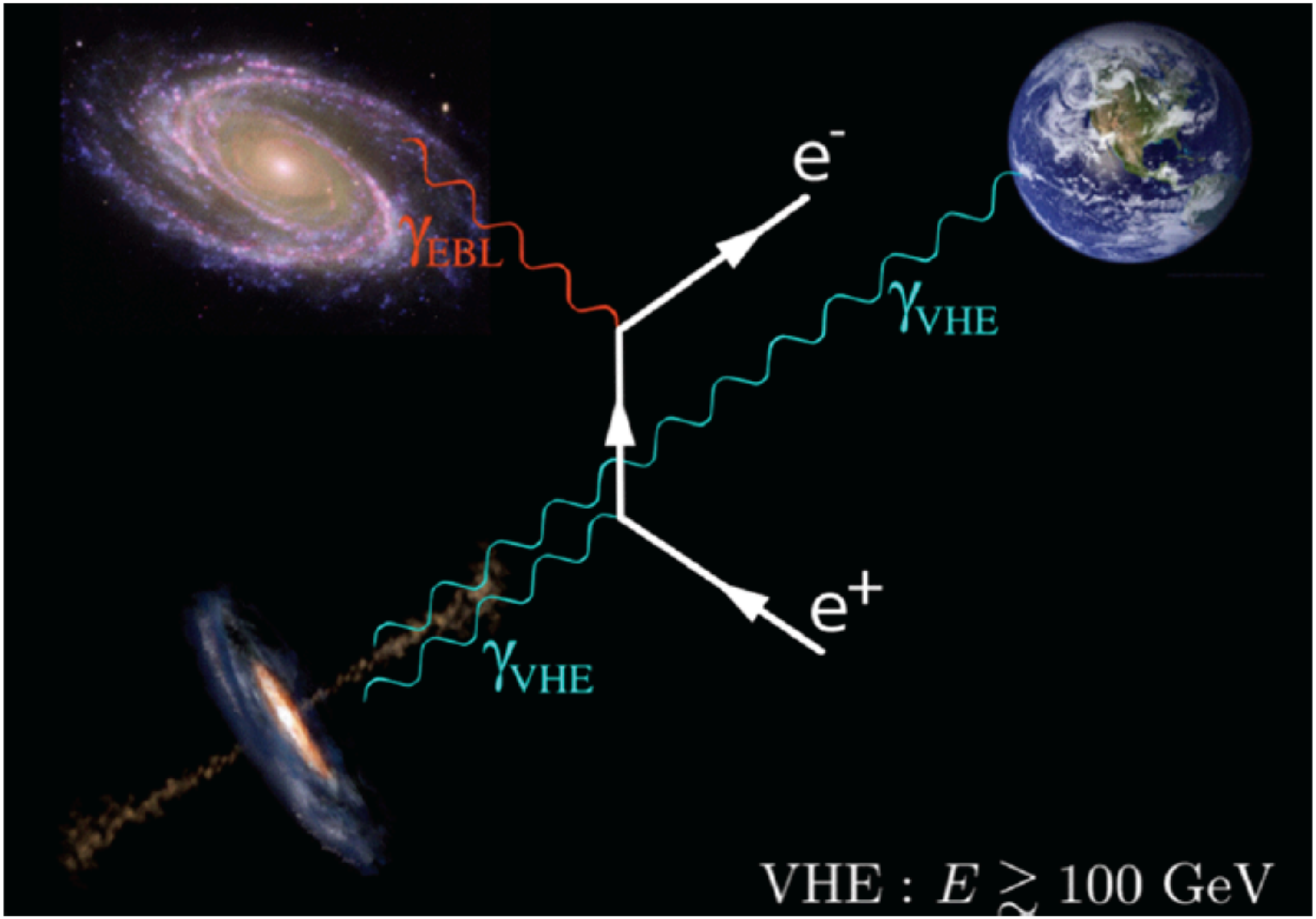
Davide Cadamuro, Javier Redondo

All together



A cosmic hint for ALPs

High energy cosmic rays get absorbed

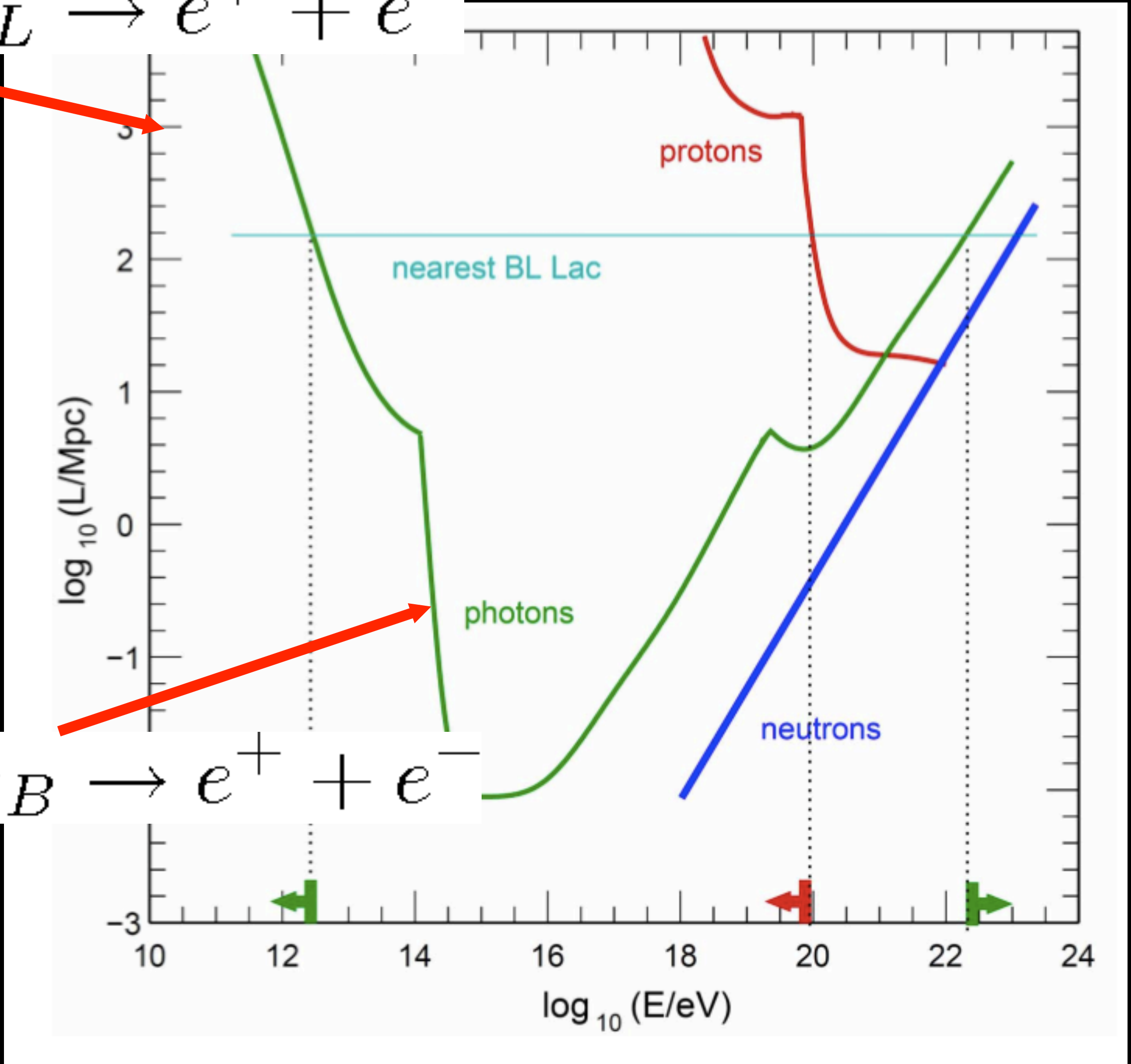


[Manuel Meyer 12]

The Universe should be quite opaque…

- … for high energy photons

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

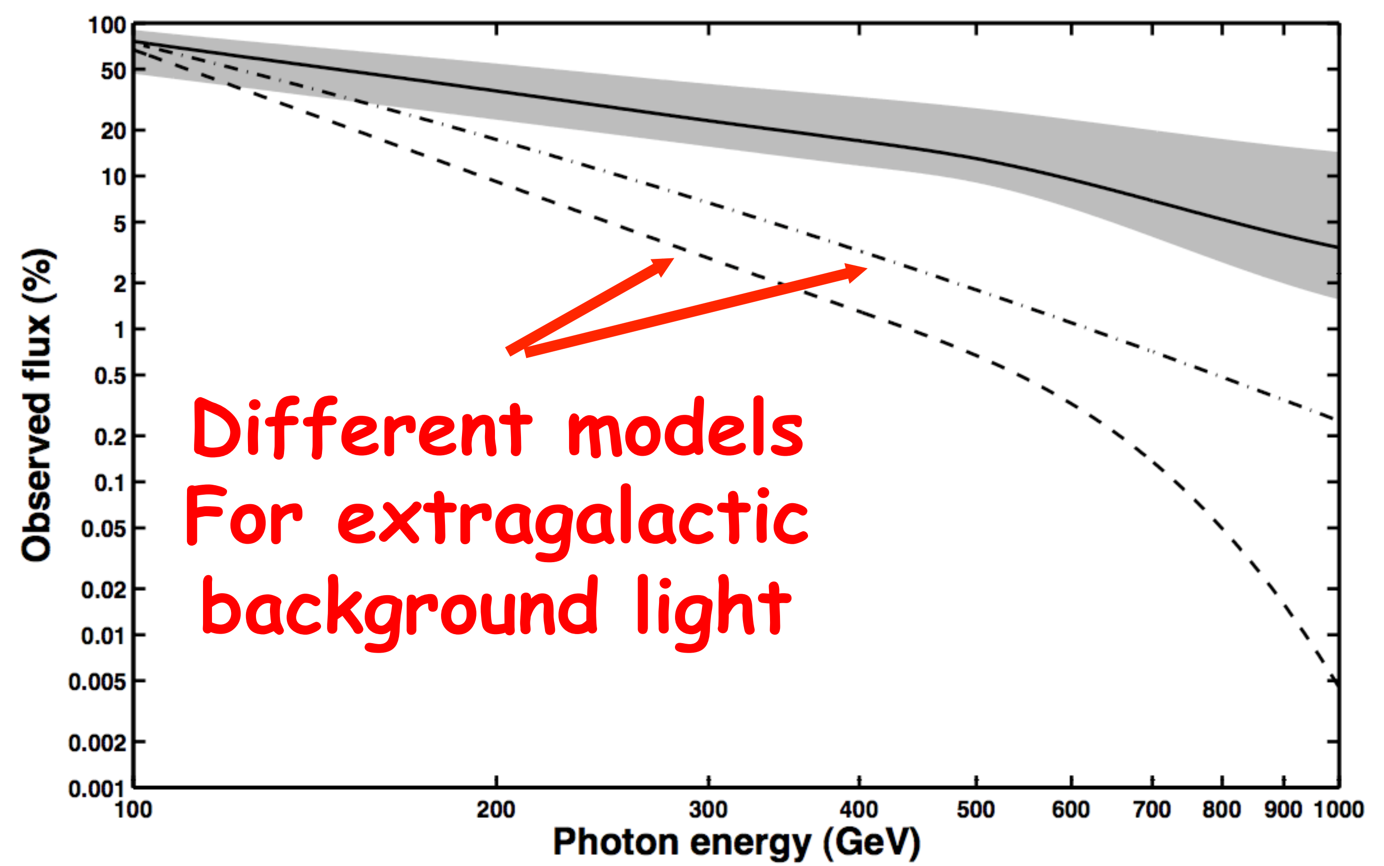


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

From far away γ-ray source

- Expect fewer high energy events!!

- Example 3C279



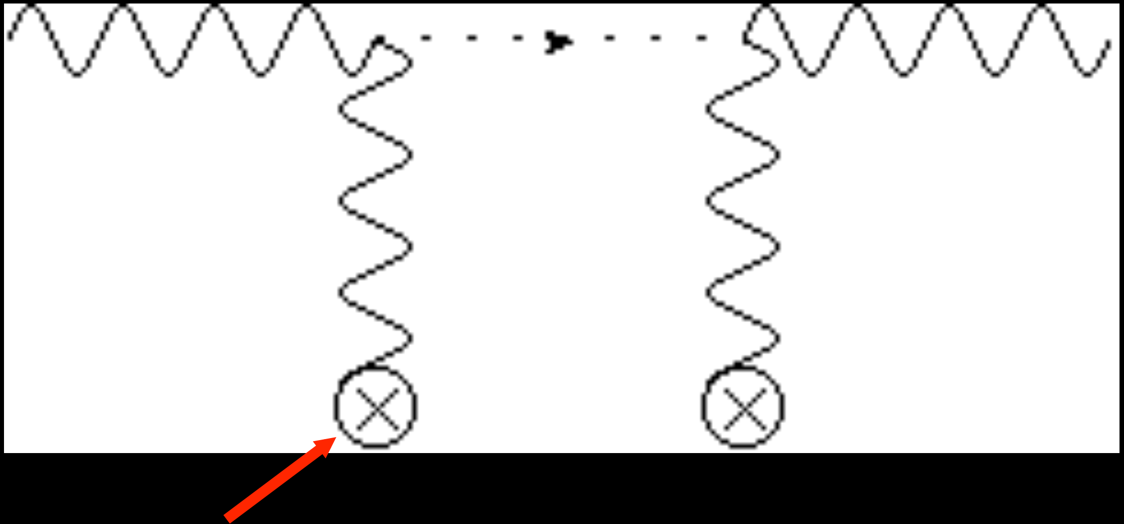
Different models
For extragalactic
background light

Observed…

- **No such strong energy dependence!**

Axion-like particles can help!

- Photon oscillates into ALP



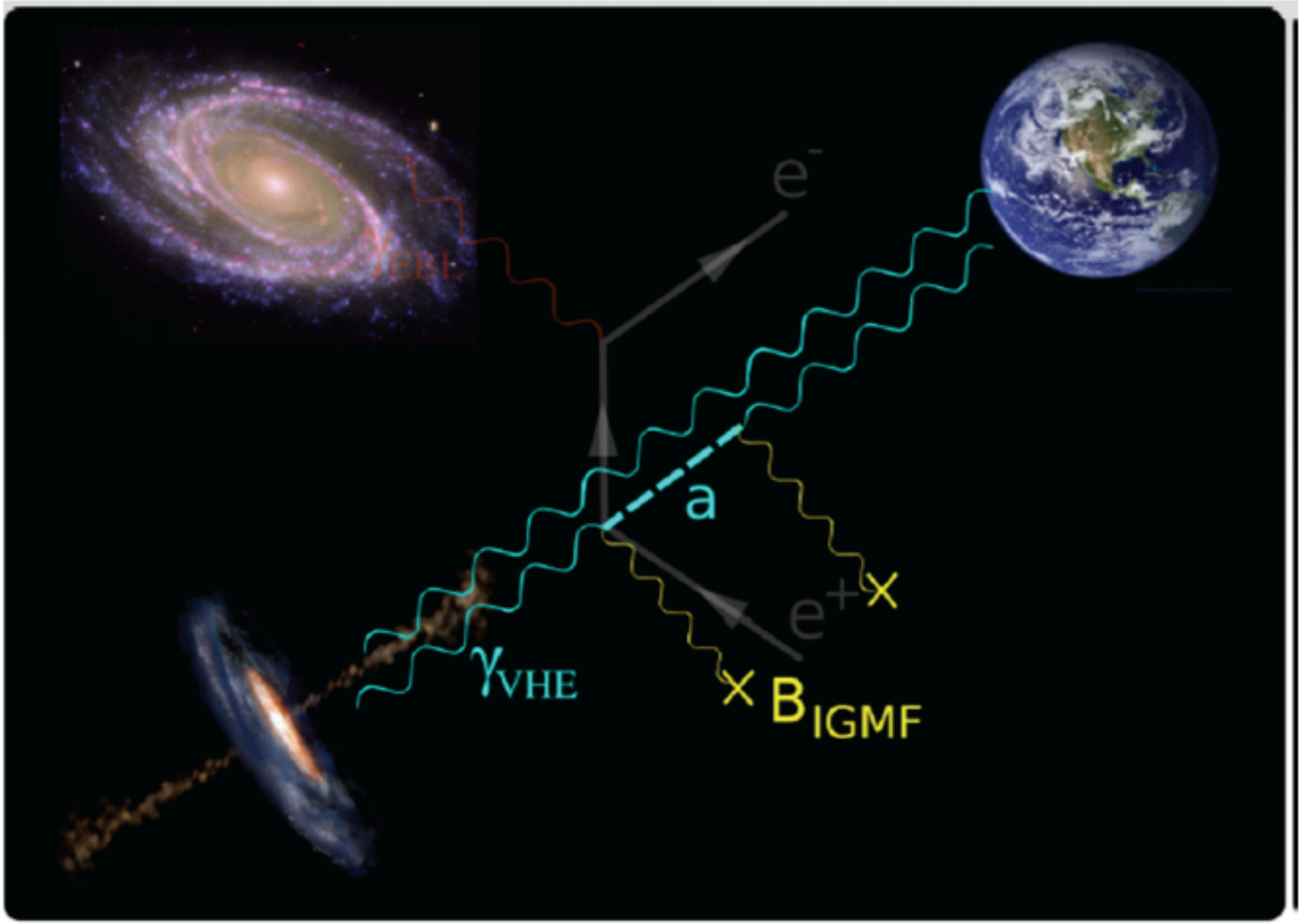
Intergalactig magnetic field~10^{-13} T

- ALP doesn't see other photons

⇒ Not absorbed

⇒ Greater Transparency!!

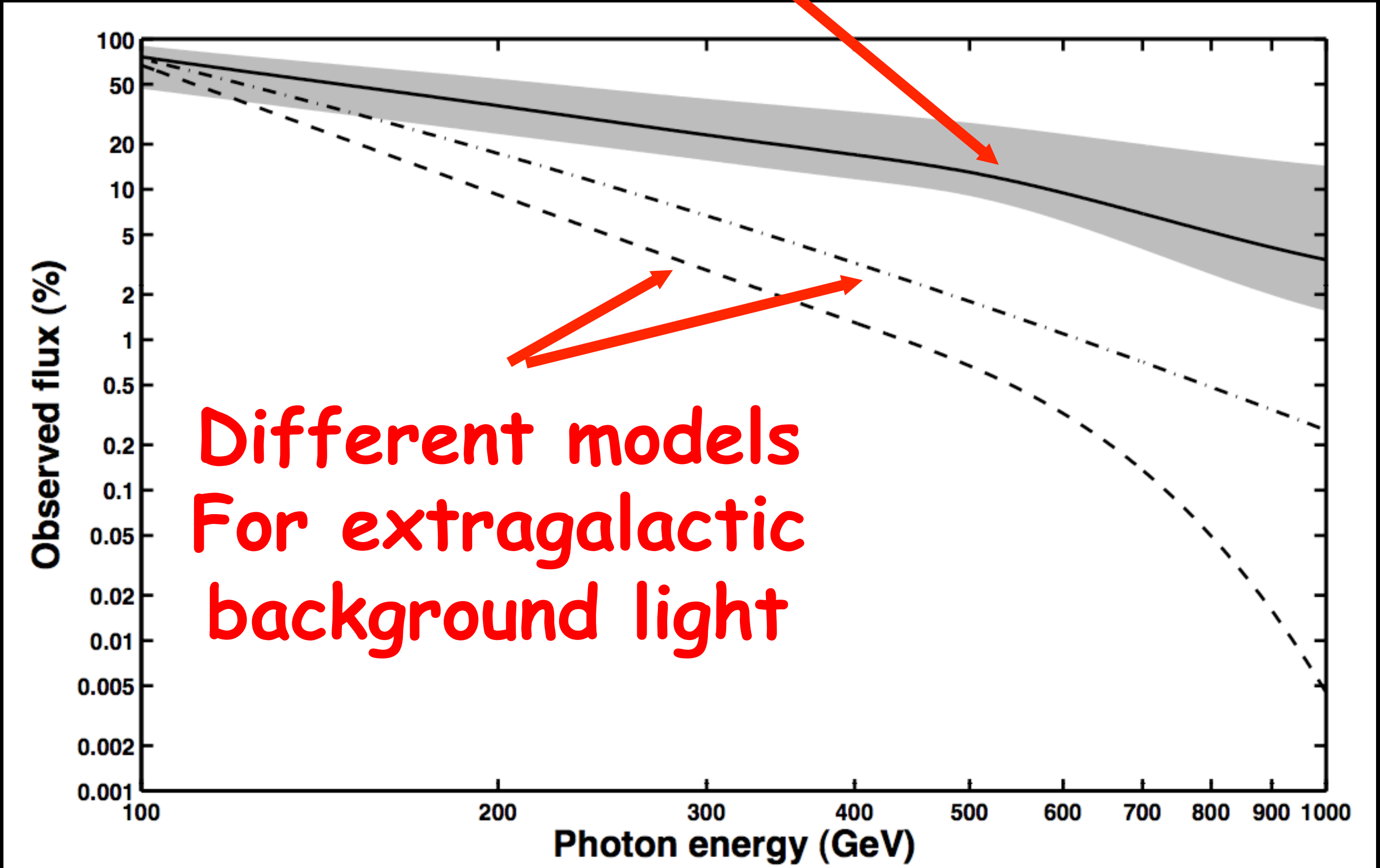
Cosmic Light-shining-through-walls



[Manuel Meyer 12]

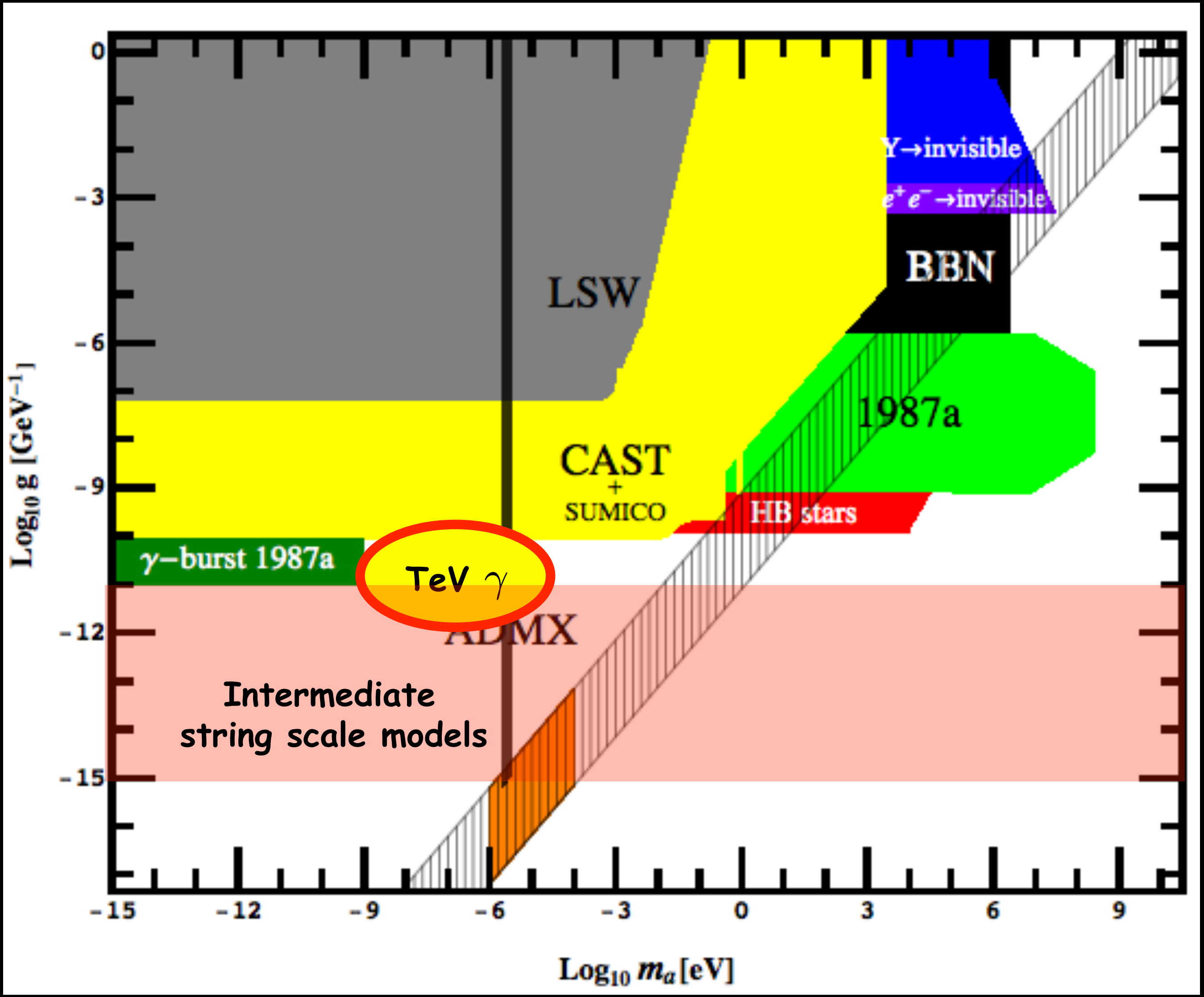
ALPs help!

- Example 3C279



Different models
For extragalactic
background light

An interesting area…

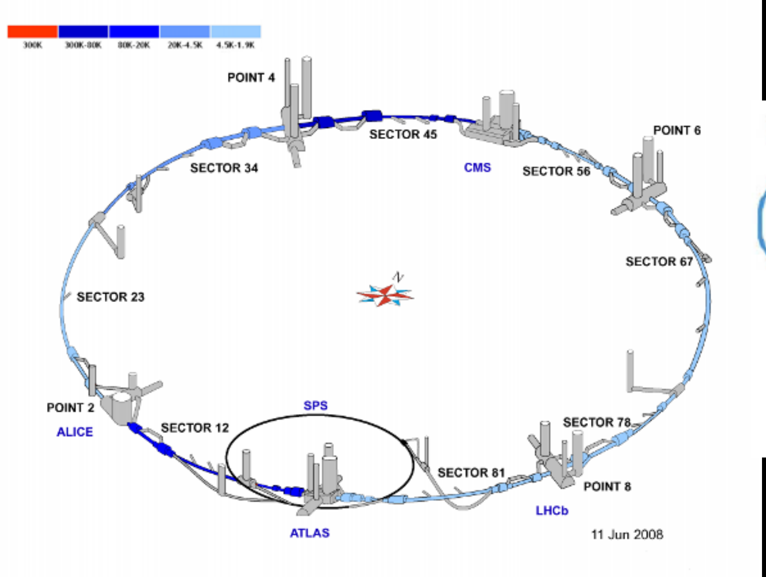


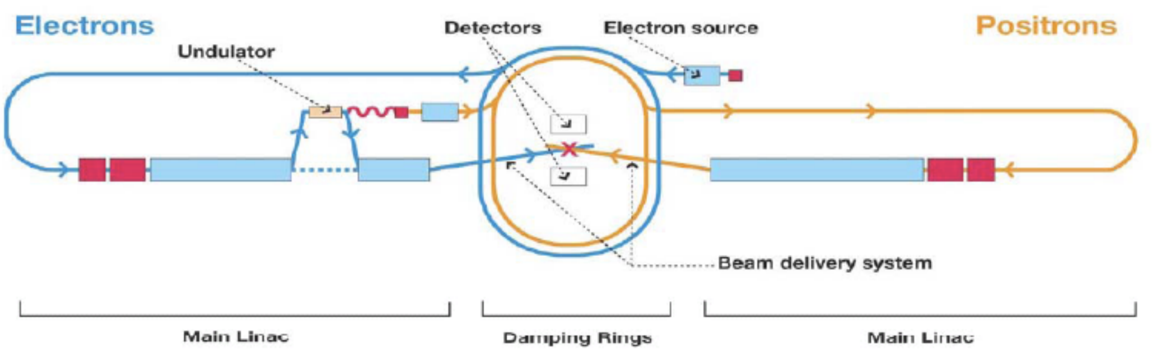
Searching light particles in the Lab

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…

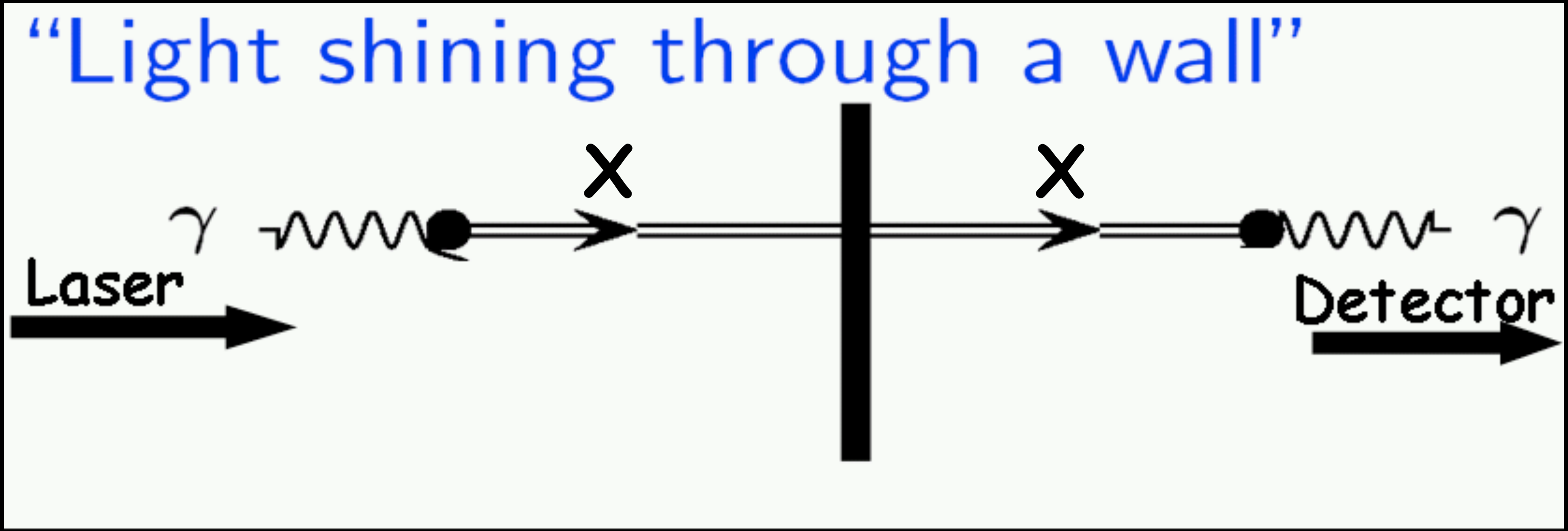
☺

Recycling…

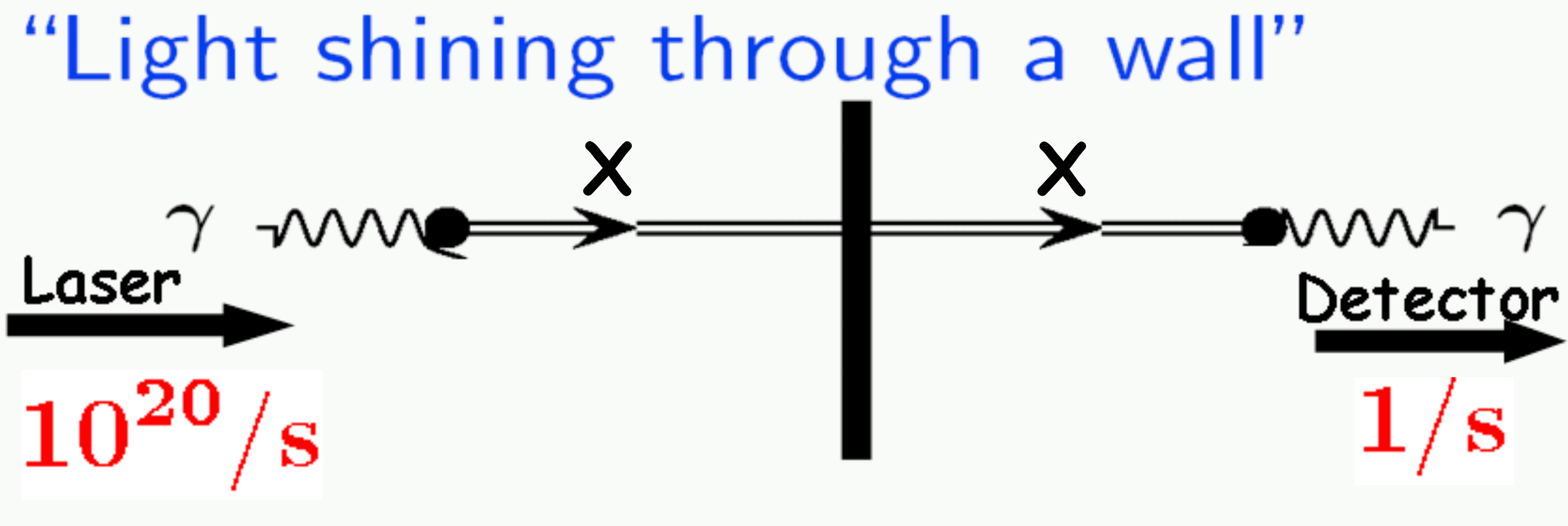
Complementary approaches

Light shining through walls

Light shining through walls



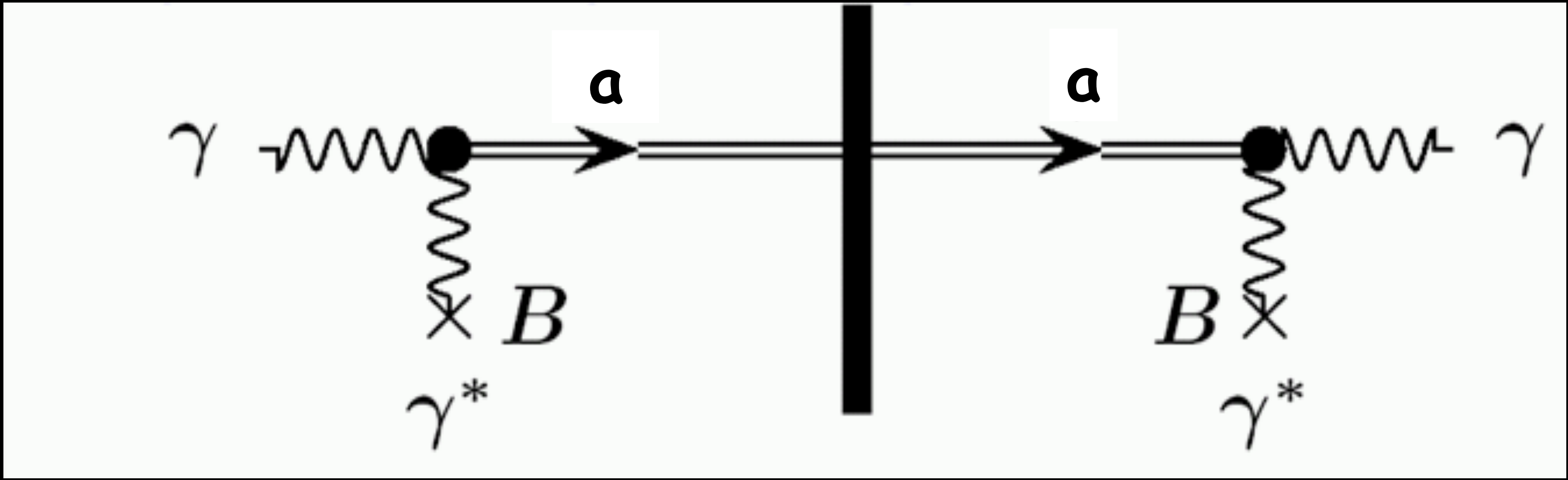
Light shining through walls



- **Test** $P_{\gamma\to X\to\gamma} \lesssim 10^{-20}$
- Enormous precision!
- Study extremely weak couplings!

Photons coming through the wall!

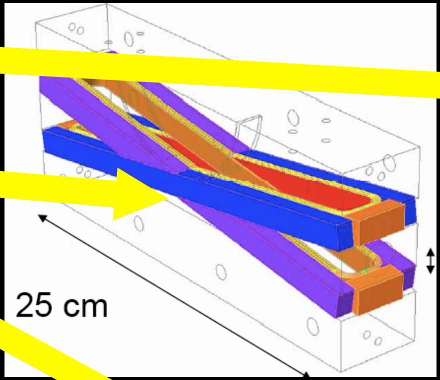
- It could be Axion(-like particle)s!
- Coupling to two photons: $\frac{1}{M} a\tilde{F}F \sim \frac{1}{M} a\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}$

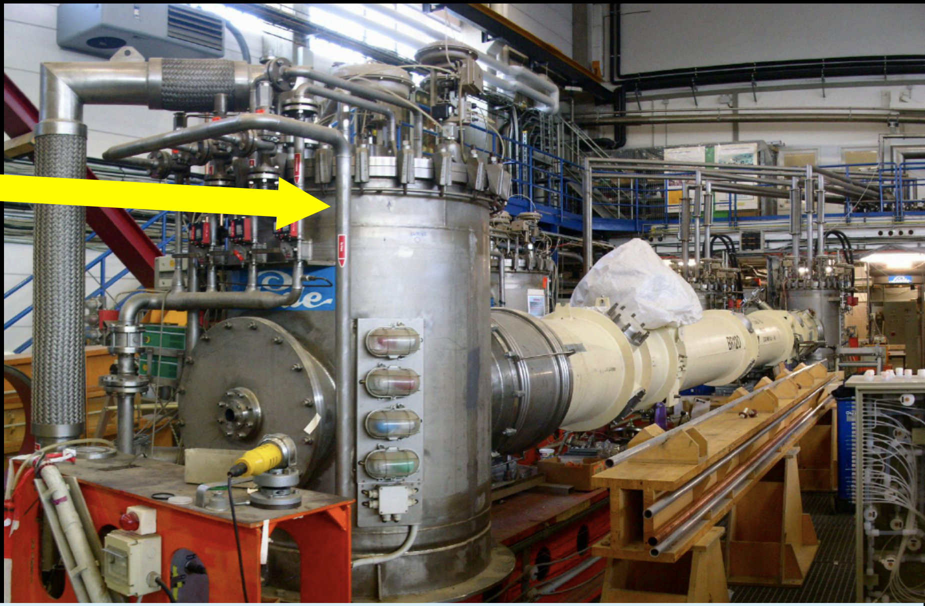


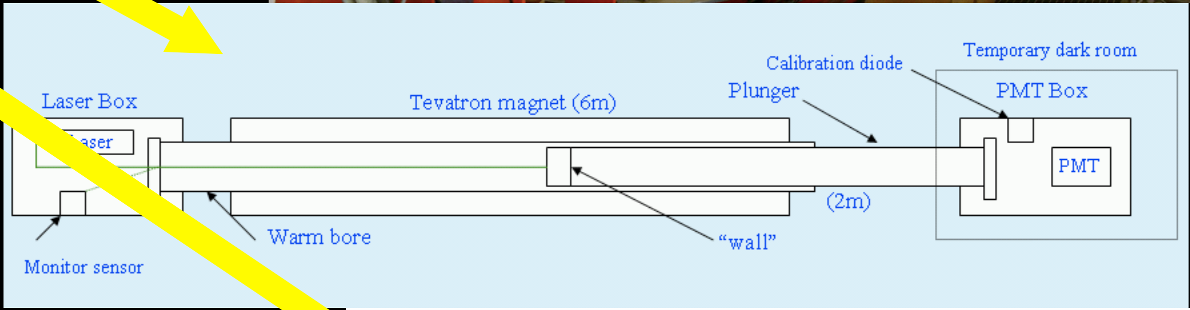
$$P_{\gamma\to a\to\gamma} \sim N_{\text{pass}}\left(\frac{BL}{M}\right)^4$$

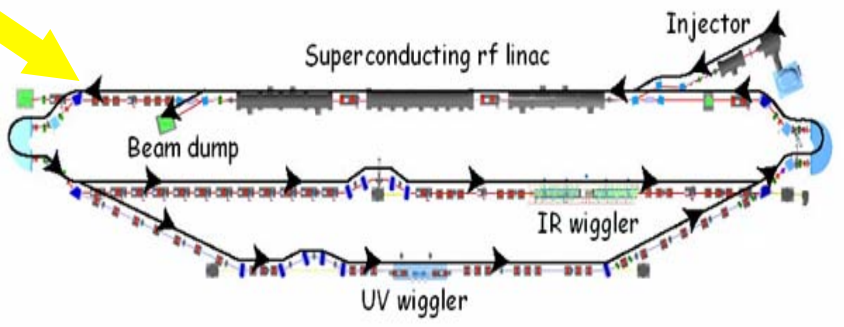
Light Shining Through Walls

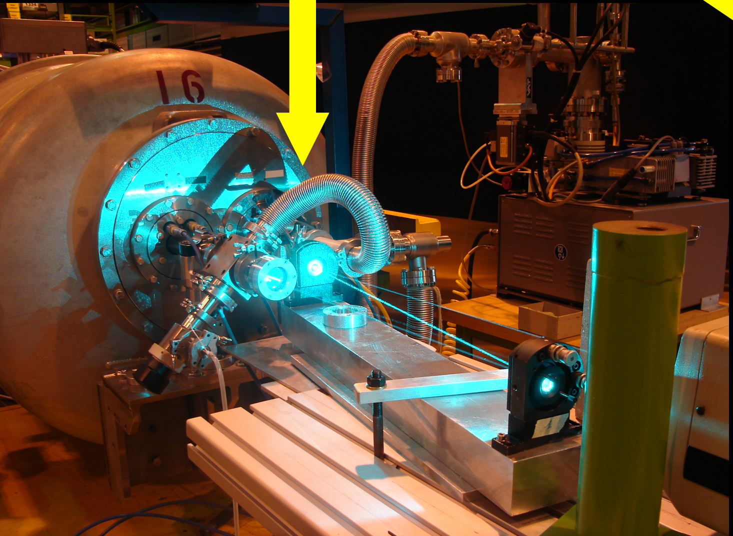
- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR



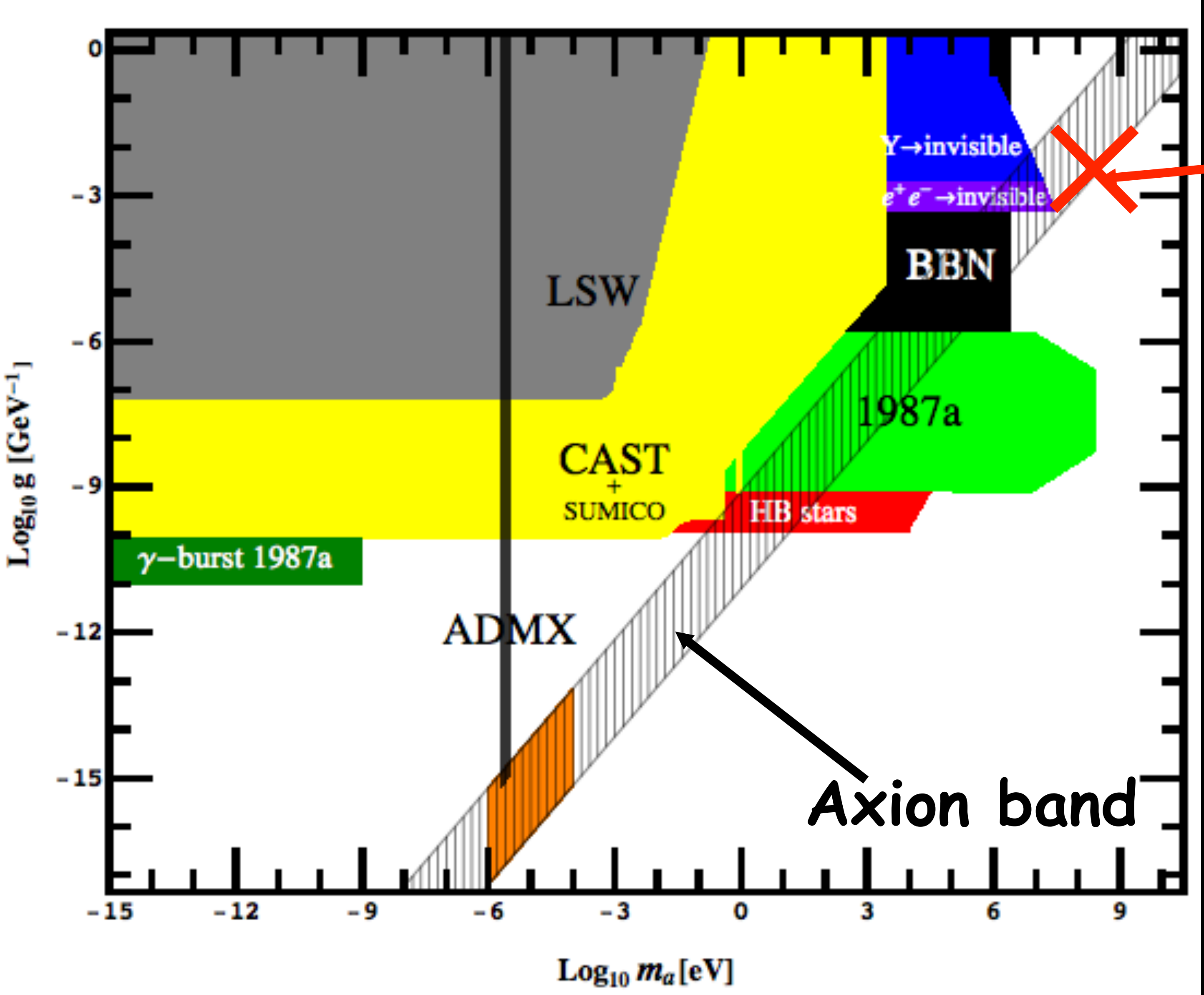






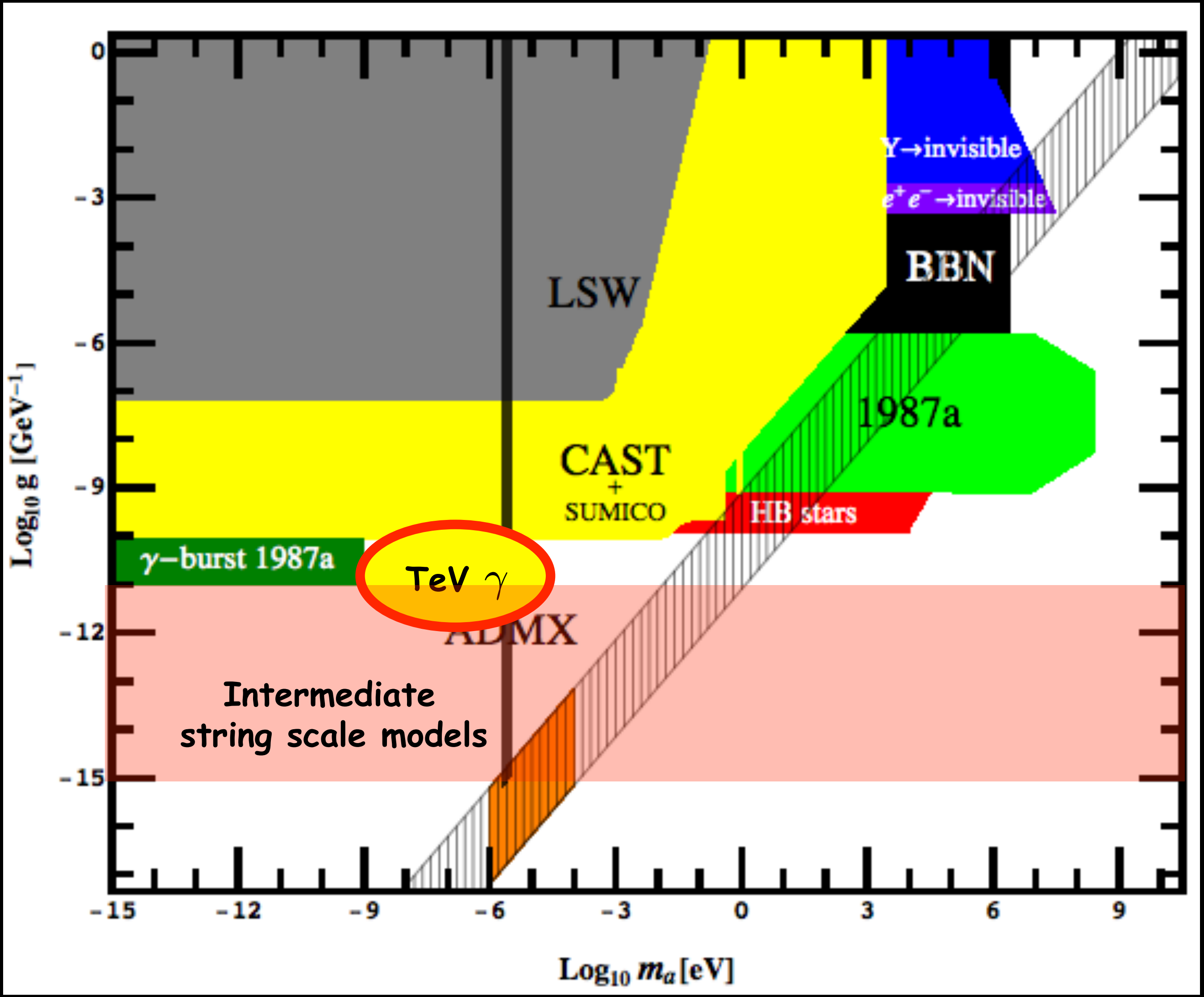


Small coupling, small mass

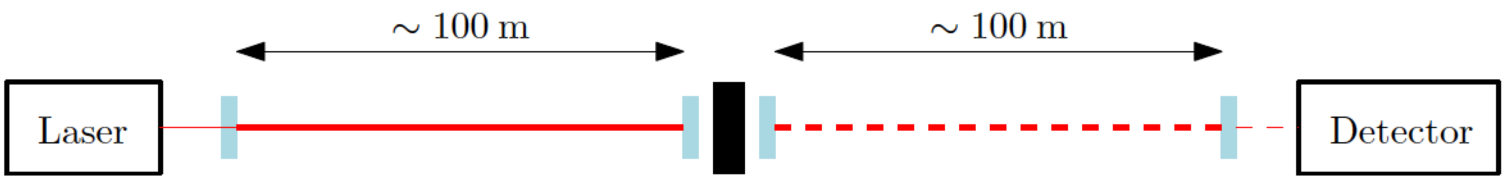


Axion band

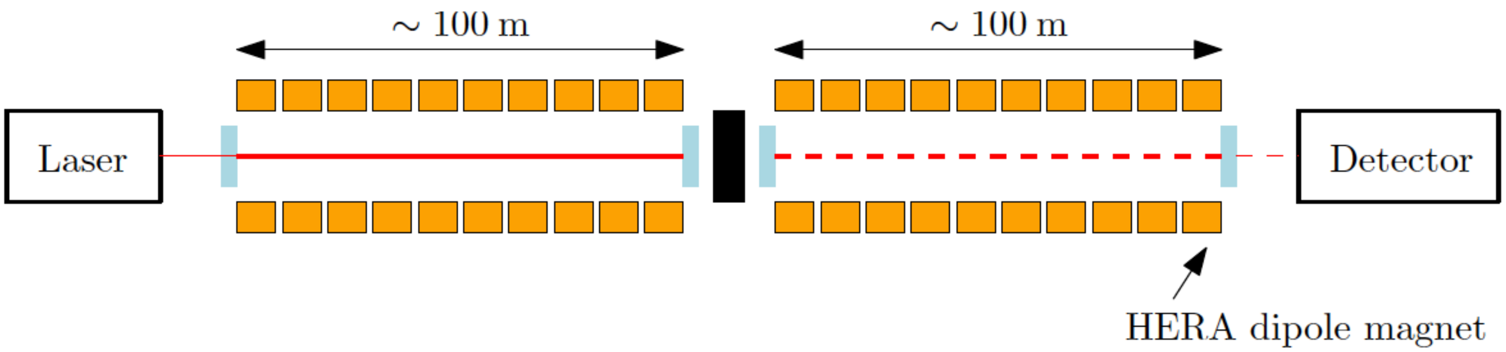
An interesting area...



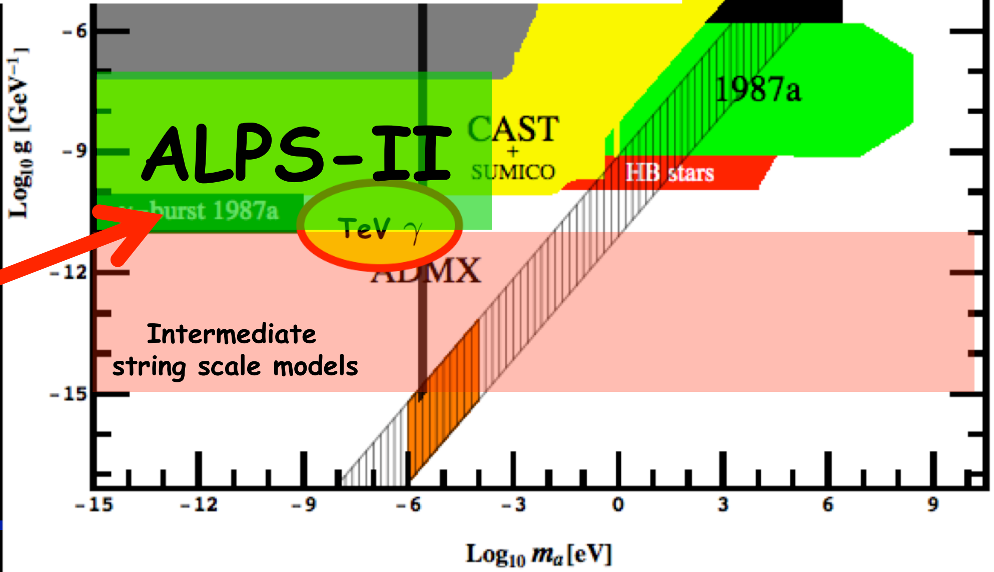
The future ALPS-II @ DESY



(c) ALPS-IIb



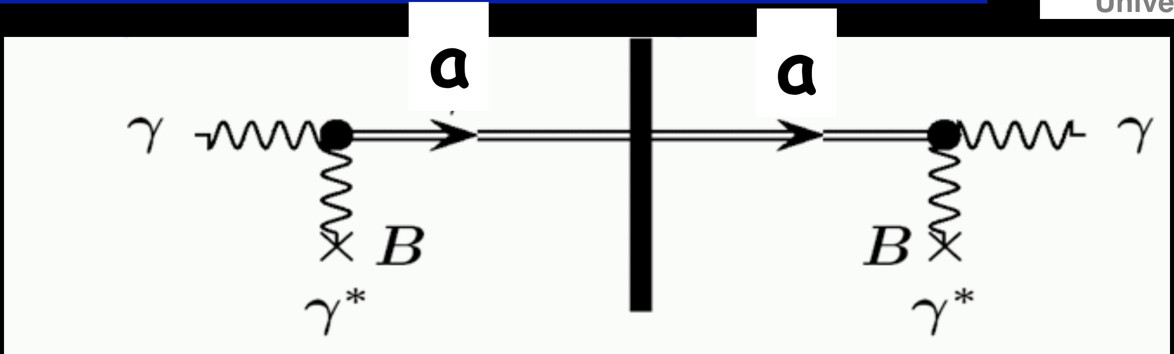
(d) ALPS-IIc



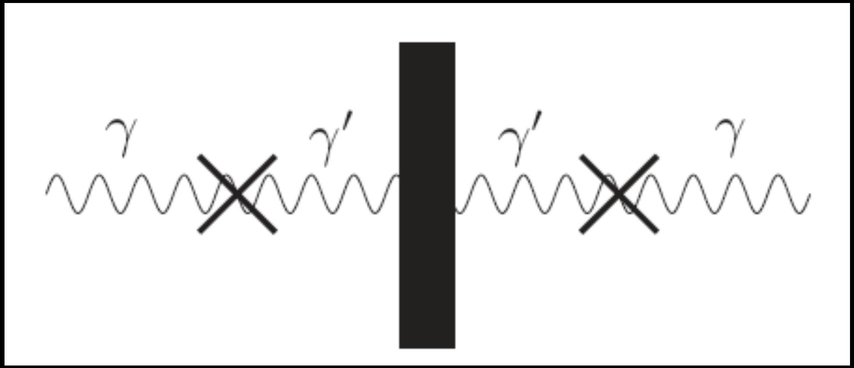
Test of
TeV transparency

WISPS=Weakly interacting sub-eV particles

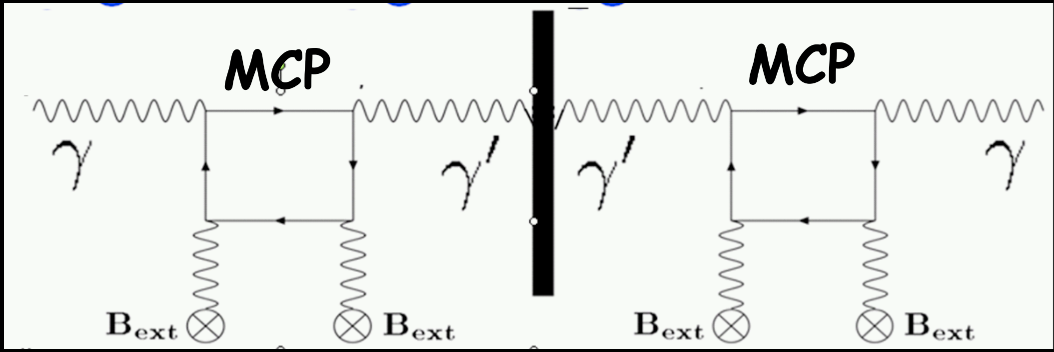
- Axions



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



- Hidden photon + minicharged particle (MCP)



Something to hide?

Something
to hide?

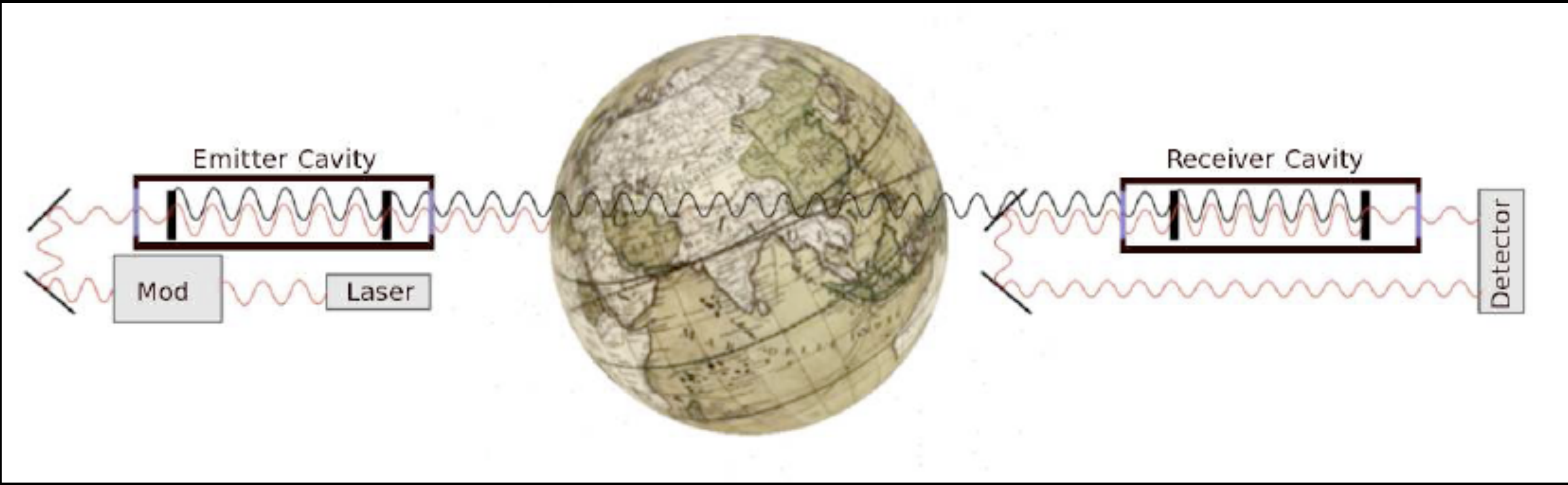
TOP
SECRET

Use Hidden Photons©

to communicate!

Practical applications ;-)

- Communicating through the Earth



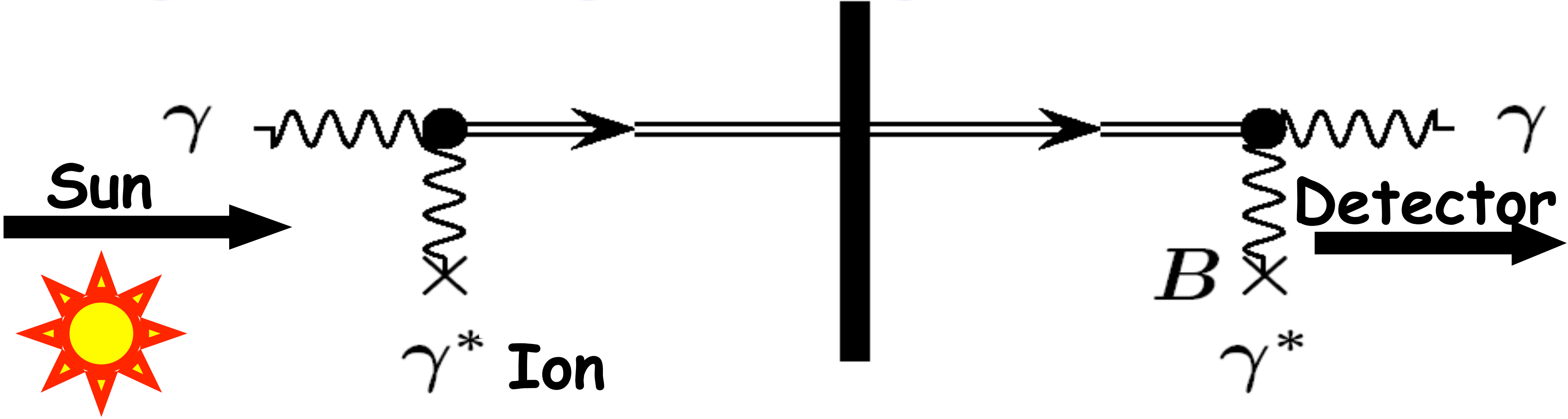
Helioscopes

Helioscopes

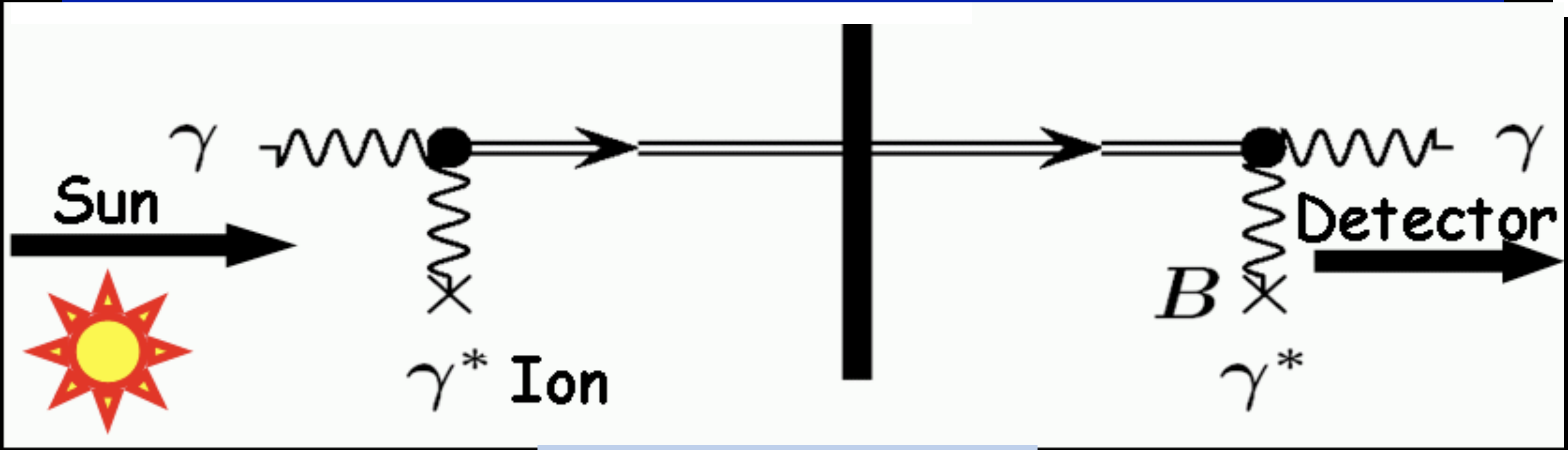
CAST@CERN

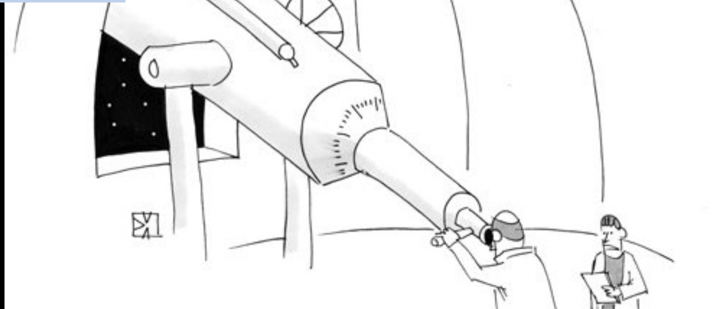
SUMICO@Tokyo

"Light shining through a wall"



Perfect for astronomy in Paris ;-)

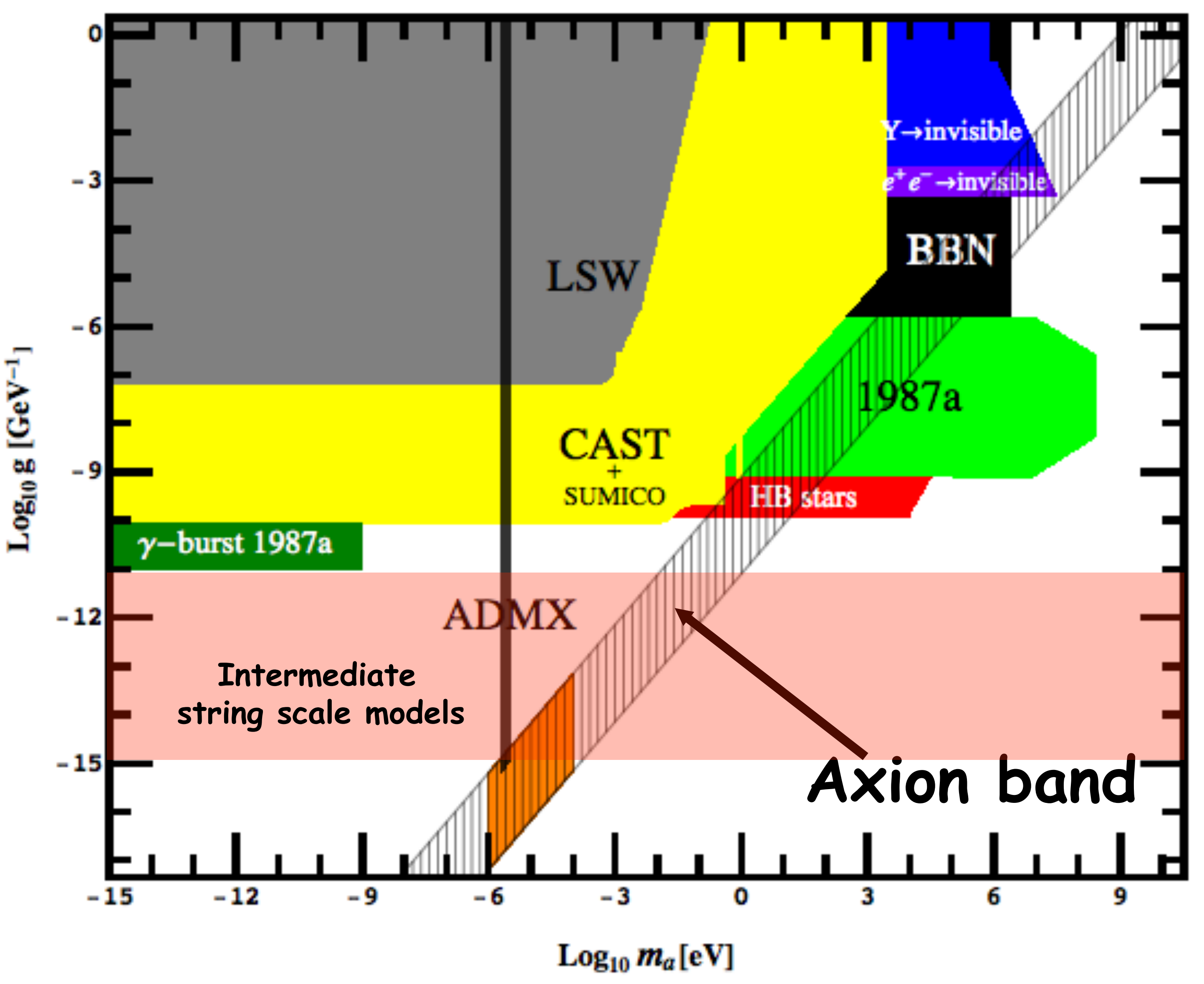




This isn't Dark matter,

I just forgot to take off the lens ca

Sensitivity

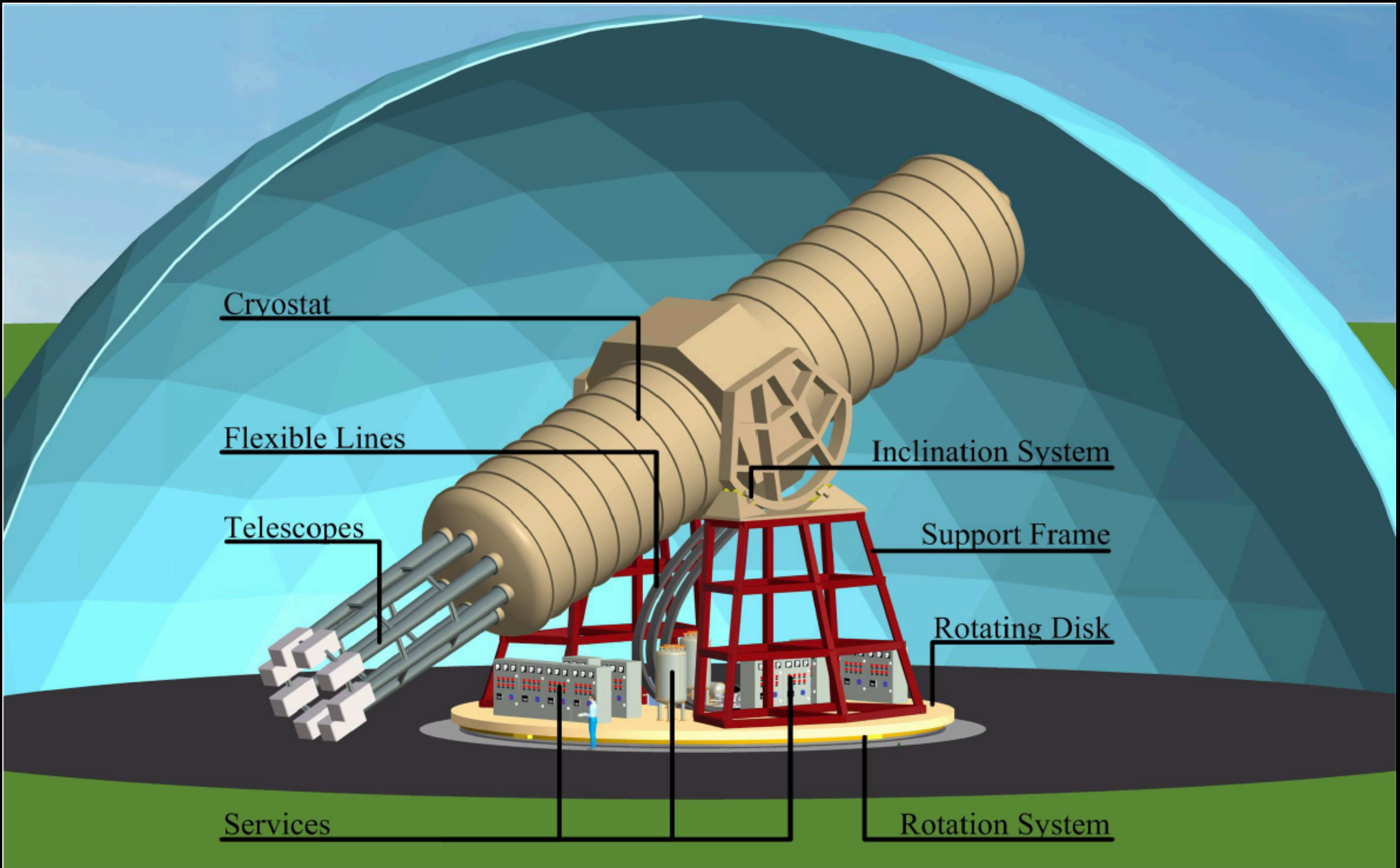


Intermediate string scale models

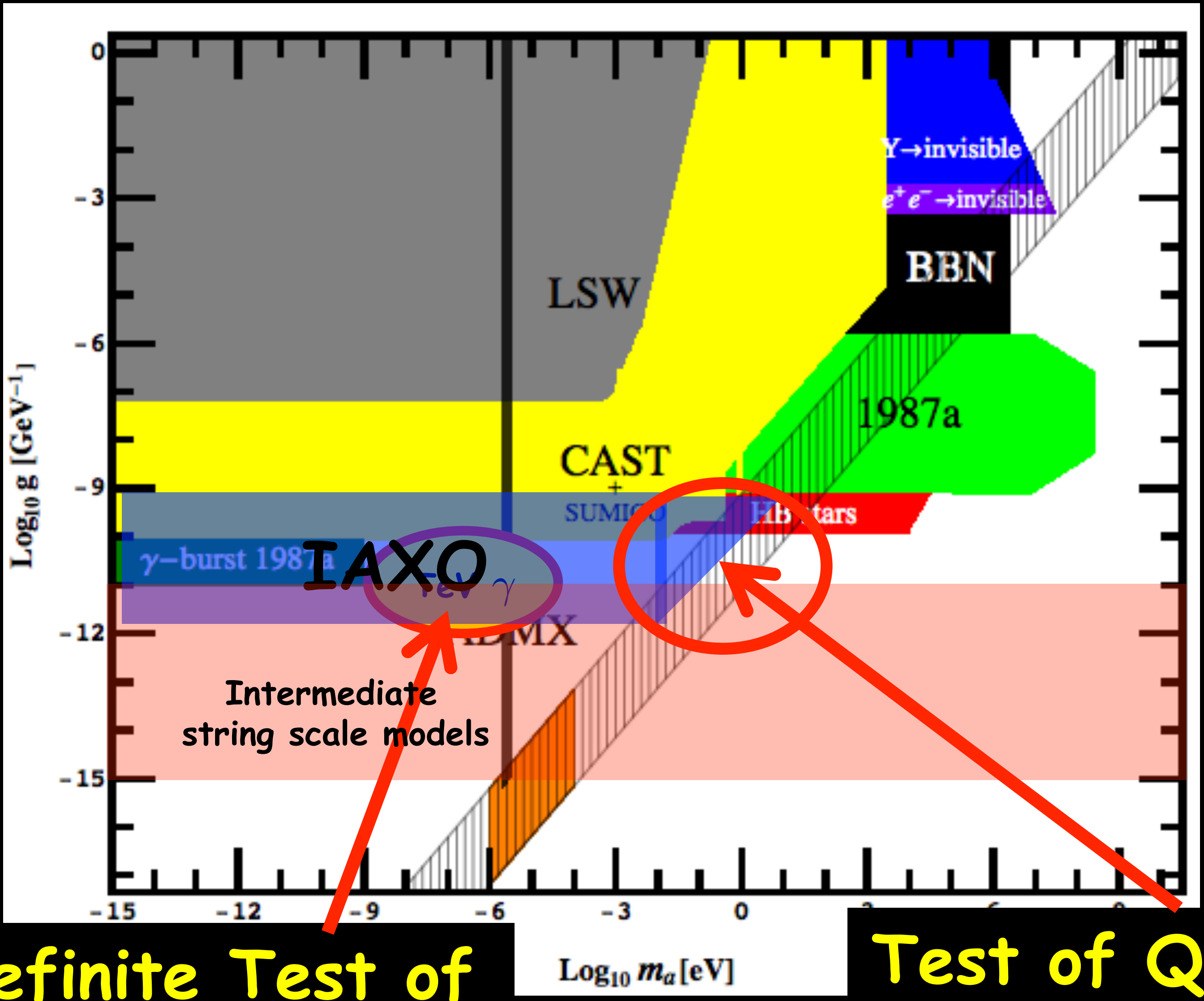
Axion band

Going to the future: IAXO

The International Axion Observatory



An interesting area...



Definite Test of TeV transparency

Test of QCD axion + white dwarf anomaly

Conclusions

Summary … astro

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

- Can test incredibly tiny interactions!!!

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

- Interesting hints for new particles!

- Not always perfectly understood!

  → Beware of uncertainties!

Summary… lab

- Light-shining through walls
- Helioscopes
- Much cleaner and controlled than astro-tests
- On the verge of exceeding astro tests

➡ Stay tuned for exciting years!!!