A map of the low energy frontier:

WISP opportunities beyond QCD axions

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1st Axion strategy meeting (27th January 2009)

Hidden Sectors

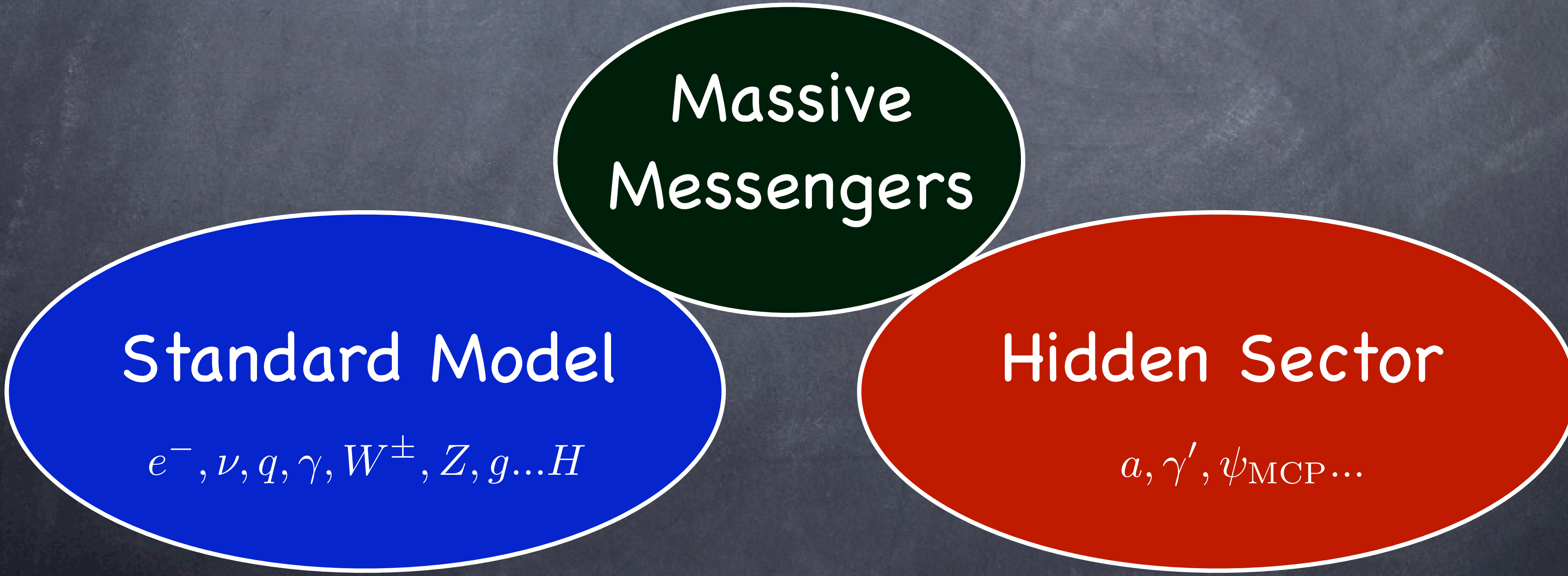
Extensions of SM often include Hidden Sectors

Fields coupled to SM only through gravity or high energy "messenger" fields...

This is the case in string theory (compactifications produce many particles, new gauge symmetries, and KKs)

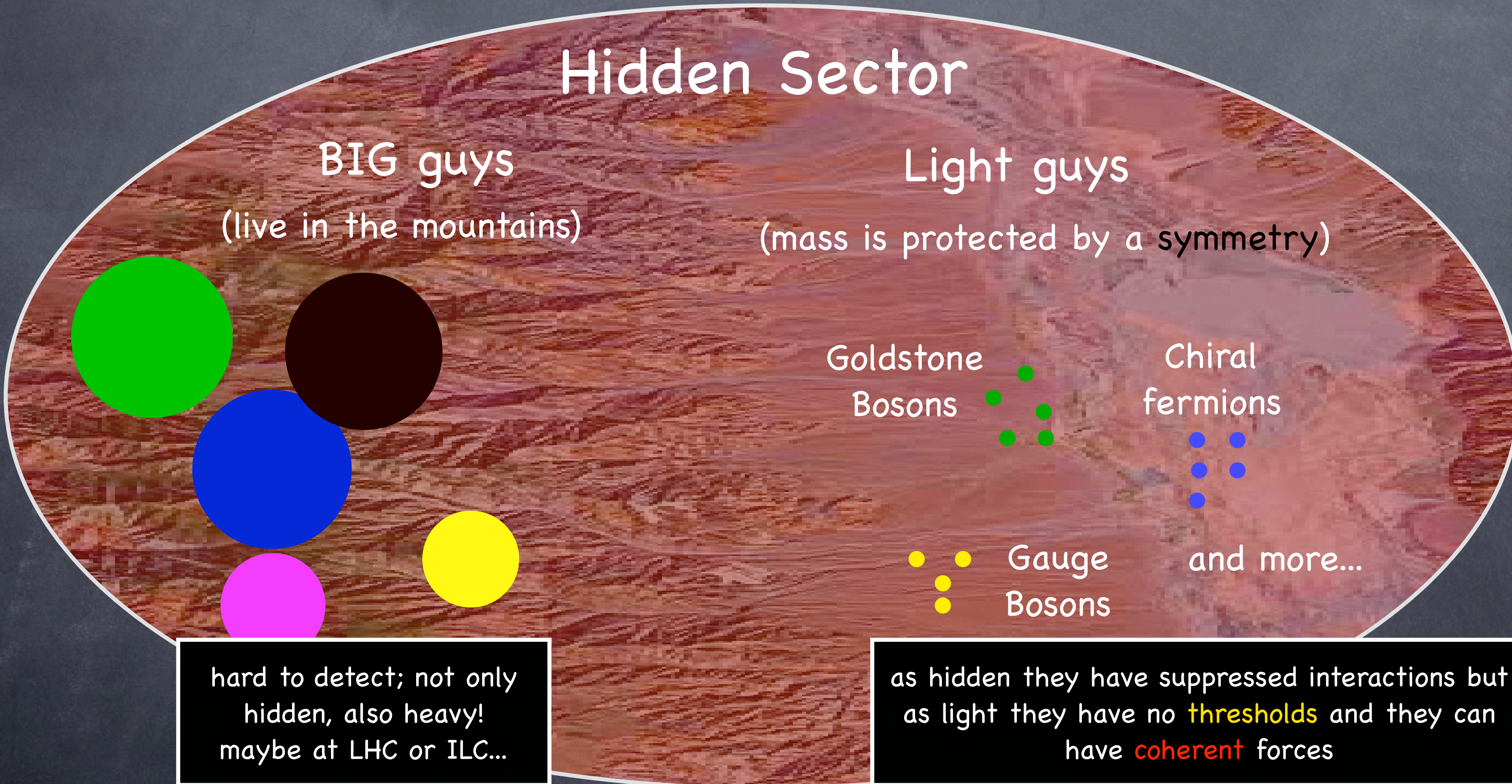
Desirable for ~~SUSY~~

Also in GUT theories...



Hidden Sectors can be quite complicated

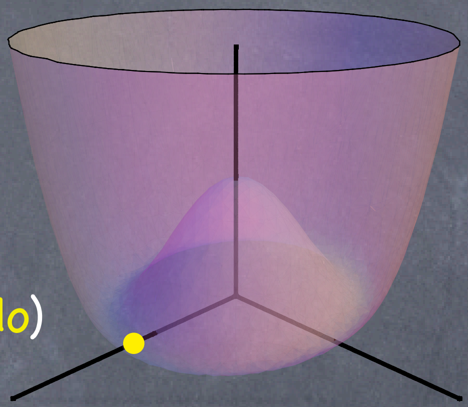
we certainly don't know!



Let symmetry be our guide !

Symmetries and weakly interacting sub eV particles WISPs

1- Global U(1)s and (pseudo) Goldstone Bosons



When a global symmetry is spontaneously broken in the vacuum
(i.e. respected by the interactions but not by the vacuum)
there appears a massless particle in the spectrum: a Goldstone boson
(if it is slightly explicitly broken... then it acquires a little mass-> pseudo)

2- Local U(1)s : Hidden Photons

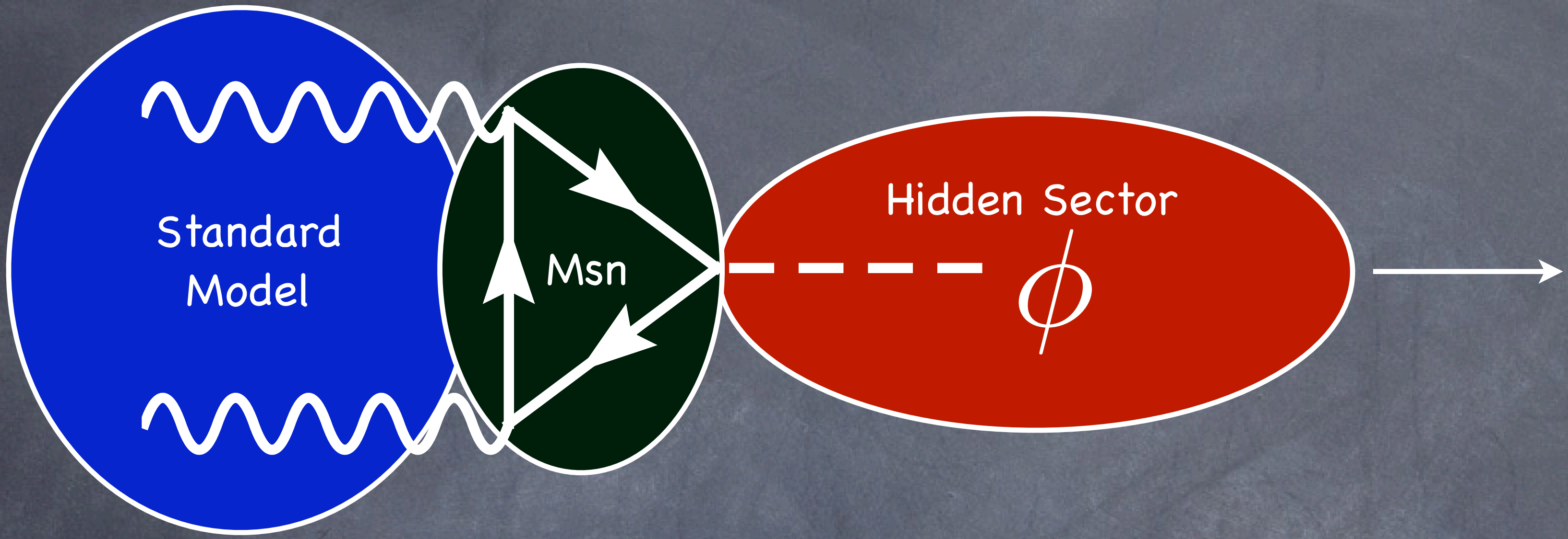
Gauge invariance protects masses of gauge bosons (m=0 for non-abelian group, not for U(1))
Masses can be given by the Stückelberg mechanism
Kinetic mixing with the photon is the stronger of all mediator mechanisms (discussed here)
(Additional U(1)'s are ubiquitous in PBSM)

3- Chiral sym : Mini-charged Particles

Chiral symmetries may forbid a mass term for fermions; or protect it.
When these particles have interactions with a hidden U(1) that mixes with Photon
they appear as mini-charged particles

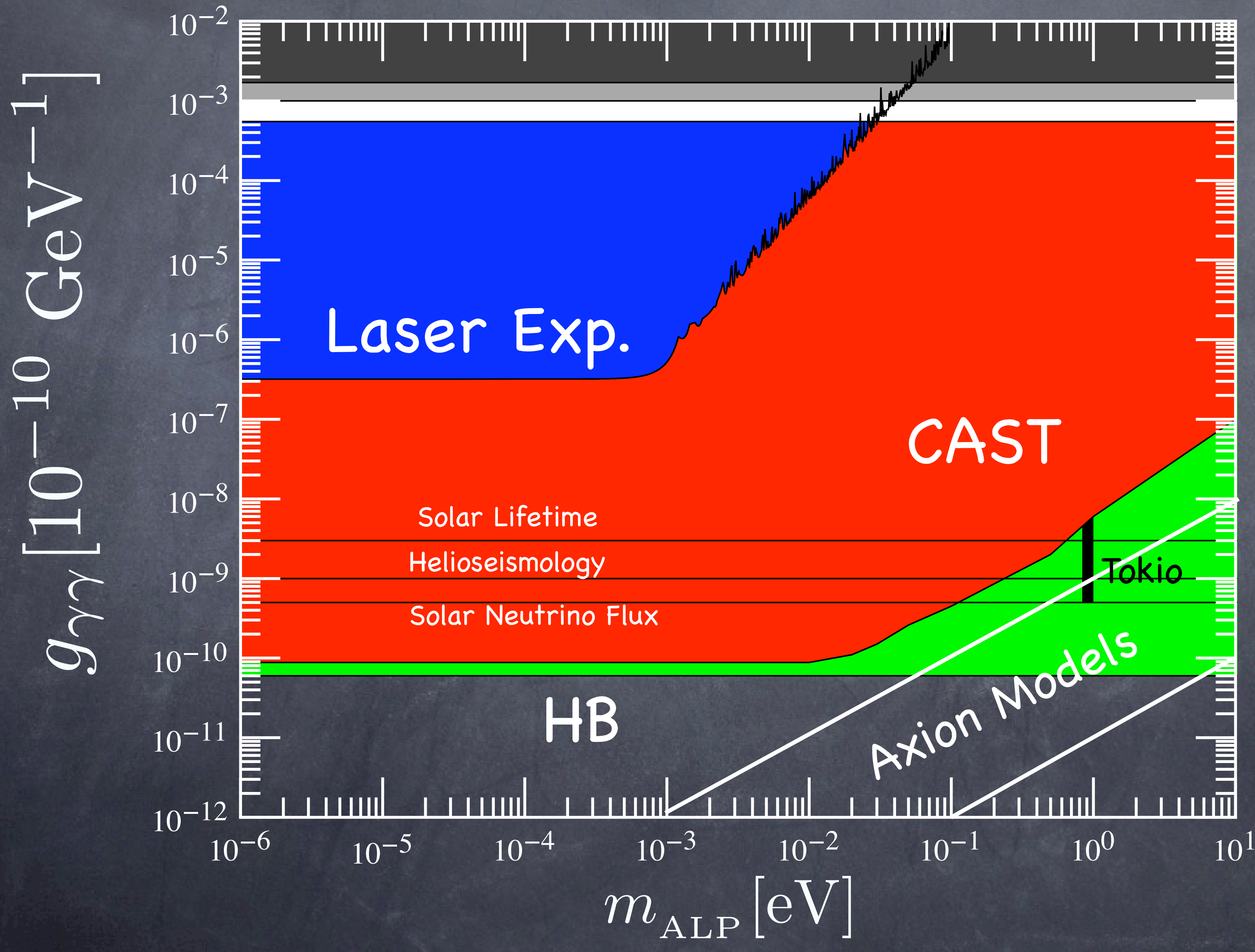
Axions and PGBs

Our favorites!



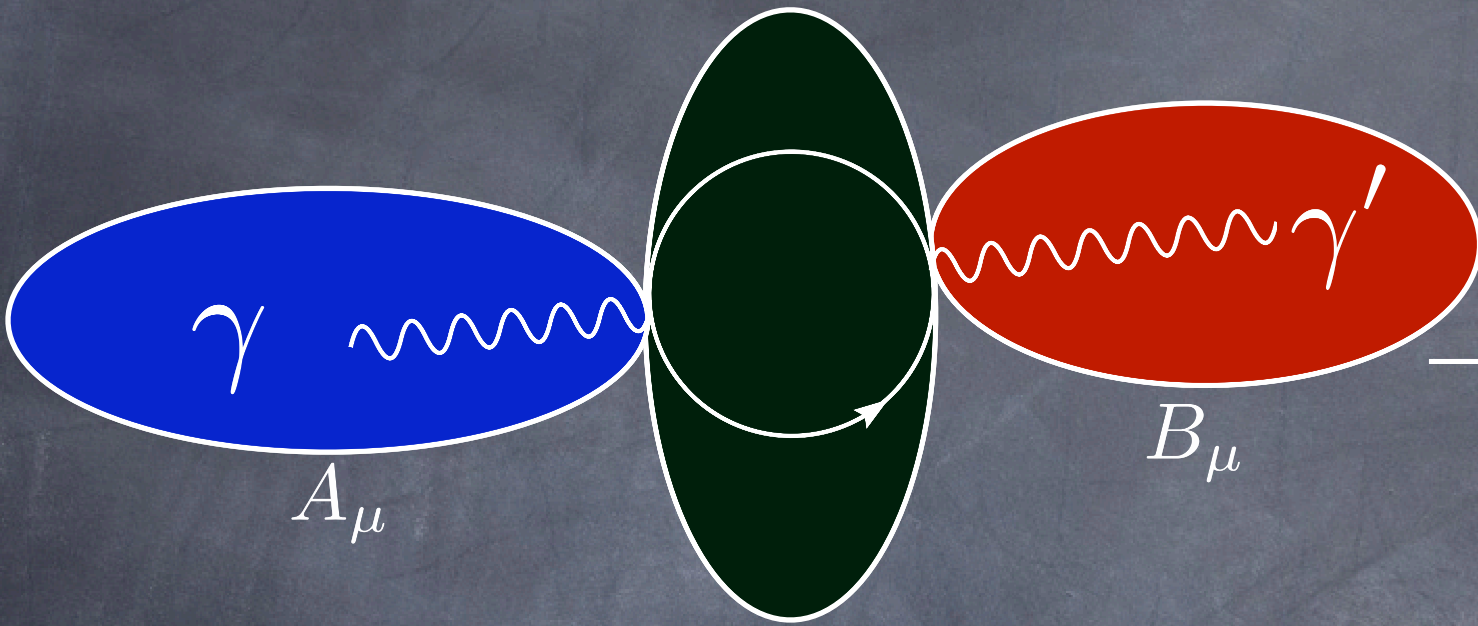
$$F\tilde{F}\frac{1}{M}\phi$$

A summary: general ALPS (pseudoscalars coupled to 2 photons)



Hidden Photons

$U(1)_{\mathrm{EM}} \times U(1)_{\mathrm{hidden}}$



$$\longrightarrow \frac{\sin\chi}{2} A_{\mu\nu} B^{\mu\nu}$$

kinetic mixing with photon

$$\sin\chi = \frac{e g_B}{6\pi^2} \sum_i Q_{{}_A} Q_{{}_B} \, \mathrm{Log}\frac{M_i}{\mu}$$

Loop suppression but NO mass suppression, just a log

SUSY, String theory ...

$$\sin\chi = 10^{-4,-16}$$

small values can come from mass degeneracy of particles with opposite charges

K. R. Dienes, C. F. Kolda, and J. March-Russell. Nucl. Phys., B492:104–118, 1997.

Massless Hidden Photons are invisible

$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + ej_\mu A^\mu$$

$$-\frac{\sin\chi}{2}A_{\mu\nu}B^{\mu\nu}$$

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

change of variables $B^\mu \to \tilde{B}^\mu - \sin\chi A^\mu$ gets rid of the kin. mix.

$$-\frac{1-\sin^2\chi}{4}A_{\mu\nu}A^{\mu\nu} + ej_\mu A^\mu$$

$$-\frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu}$$

$\sin\chi \longrightarrow$ harmless renormalization of electric charge

$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + \frac{e}{\cos\chi}j_\mu A^\mu$$

Massless Hidden Photons produce χ-charges

B. Holdom. PLB166 196 (1986)

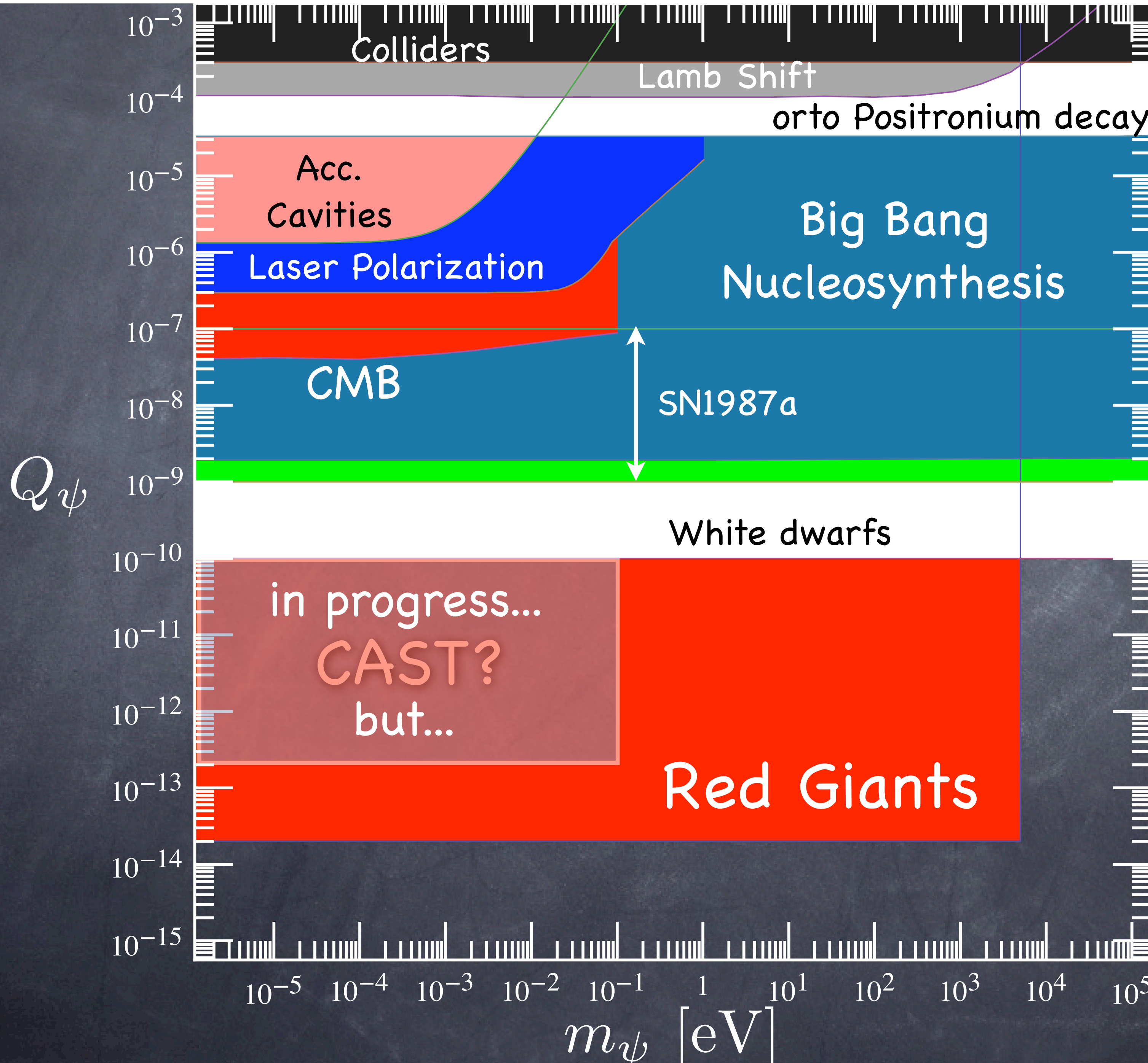
suppose there are particles charged under U(1), i.e. a hidden current

$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + ej_\mu A^\mu \qquad -\frac{\sin\chi}{2}A_{\mu\nu}B^{\mu\nu} \qquad -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + e_{\rm h}B_\mu j^\mu_{\rm h}$$

change of variables $B^\mu \to \tilde{B}^\mu - \sin\chi A^\mu$

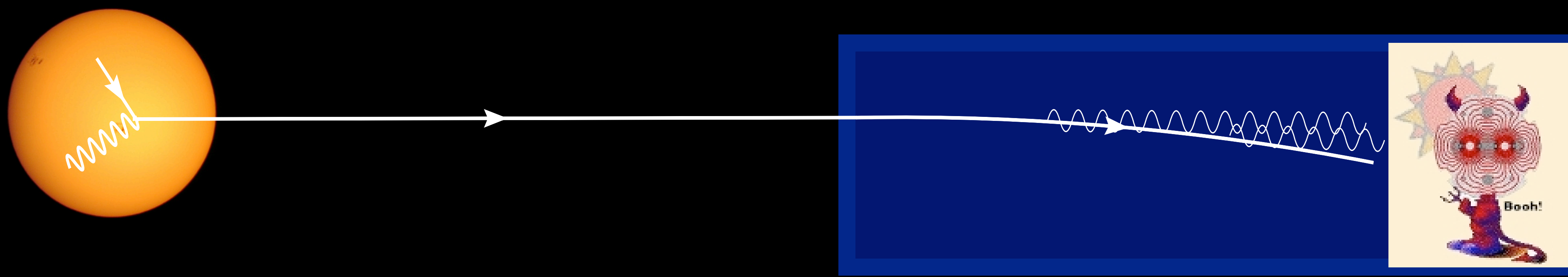
$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + ej_\mu A^\mu \qquad -e_{\rm h}\sin\chi A_\mu j^\mu_{\rm h} \qquad -\frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} + e_{\rm h}\tilde{B}_\mu j^\mu_{\rm h}$$

MiniCharged Particles (MCPs)



CAST & MCPs

Detect Solar MCPs at earth by their synchrotron radiation inside the magnet



Astrophysical MCPs

We know nothing but crude upper bounds
on the magnetic fields of the interior of stars,
it might well be that the MCPs could be trapped in
toroidal fields, or delayed in dipoles
in their way out of the star

CAST might produce sounder results than HB or SN,
but some knowledge of the Sun magnetic
fields has to be collected

Massive Hidden Photons and photon oscillations

L. B. Okun. Sov. Phys. JETP, 56:502, 1982.

$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + ej_\mu A^\mu \quad - \frac{\sin\chi}{2}A_{\mu\nu}B^{\mu\nu} \quad -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}B_\mu B^\mu$$

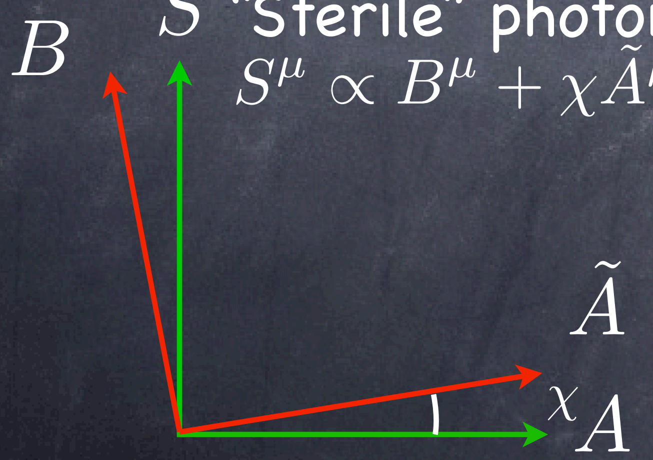
$$A^\mu \to \tilde{A}^\mu - \sin\chi B^\mu \sim \tilde{A}^\mu - \chi B^\mu$$

$$-\frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} \quad ej_\mu(\tilde{A}^\mu - \chi B^\mu) \quad -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}B_\mu B^\mu$$

"Flavor" eigenstate — "mass" eigenstates

S "Sterile" photon

$S^\mu \propto B^\mu + \chi\tilde{A}^\mu$



photon-sterile oscillation prob.

$$P_{A-S} = \sin^2 2\chi \times \sin^2 \frac{m^2_{\gamma'}L}{4\omega}$$

why I came up working on them?

2005 PVLAS claim: rotation of polarization plane of laser light traveling through a magnet

$\propto g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ $g \sim 10^{-6}\mathrm{GeV}^{-1}$ ⟺ $g_{\mathrm{astro}} < 10^{-10}\mathrm{GeV}^{-1}$

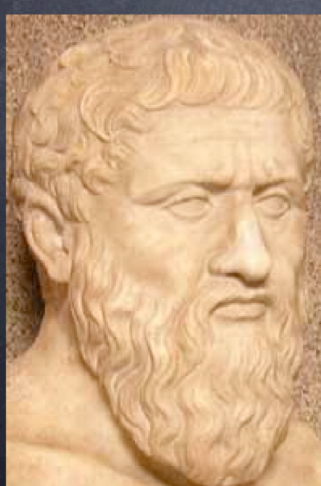
``Axion-Like Particle?" ??

strong impact on stellar evolution !!

Model in which this coupling arises from two Hidden photon exchange was able to relax this tension

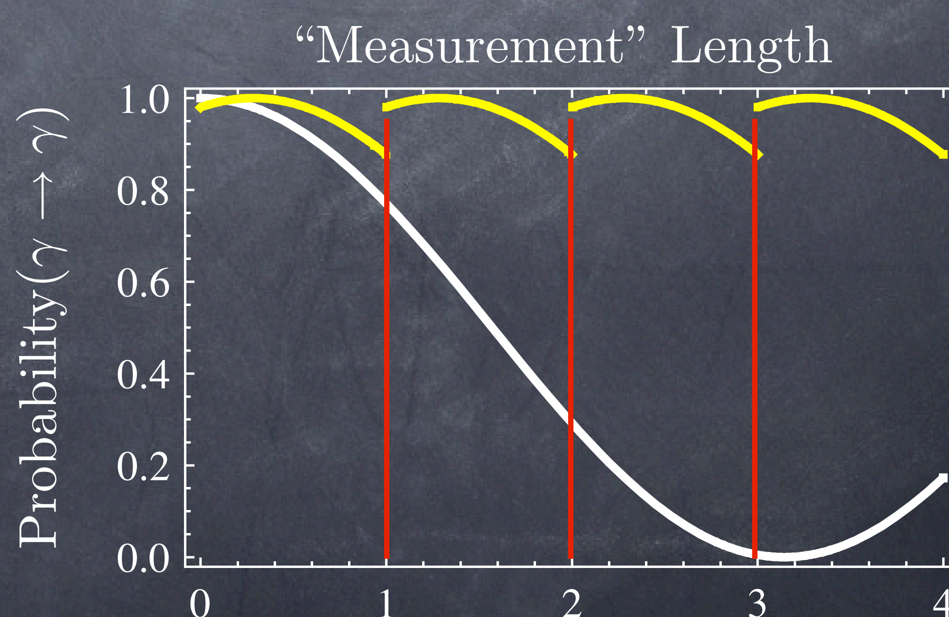
Massó & Redondo, Phys. Rev. Lett. **97**, 151802 (2006).

Very Basic Idea: Hidden photons need distance to oscillate:
in stellar plasmas they have little paths compared to m scales in experiments



Not so Basic Idea:
-Quantum Zeno effect-

charged particles measure "photonic" state reducing amplitude of A-S oscillations



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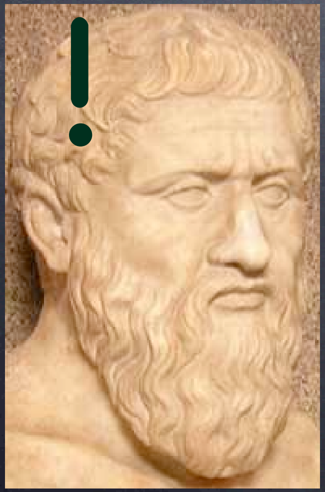


They naturally evade astrophysical limits allowing detection in macroscopic experiments !!

Hidden sector photons: flavor oscillations in a medium

$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu} + A_\nu \Pi^{\mu\nu} A_\mu \qquad -\frac{\chi}{2}A_{\mu\nu}B^{\mu\nu} \qquad -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B_\mu B^\mu$$

$$A^\mu \longrightarrow \tilde{A}^\mu - \chi_{\rm eff}\tilde{S}^\mu$$

(small mixing. It means basically $\chi_{\rm eff} \ll 1$)

$$-\frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} + \frac{1}{2}\pi\tilde{A}_\mu\tilde{A}^\mu \qquad j_\mu(\tilde{A}^\mu - \chi_{\rm eff}\tilde{S}^\mu) \qquad -\frac{1}{4}\tilde{S}_{\mu\nu}\tilde{S}^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2\tilde{S}_\mu\tilde{S}^\mu$$

The mixing angle depends on $\pi(\omega_{\rm P})$

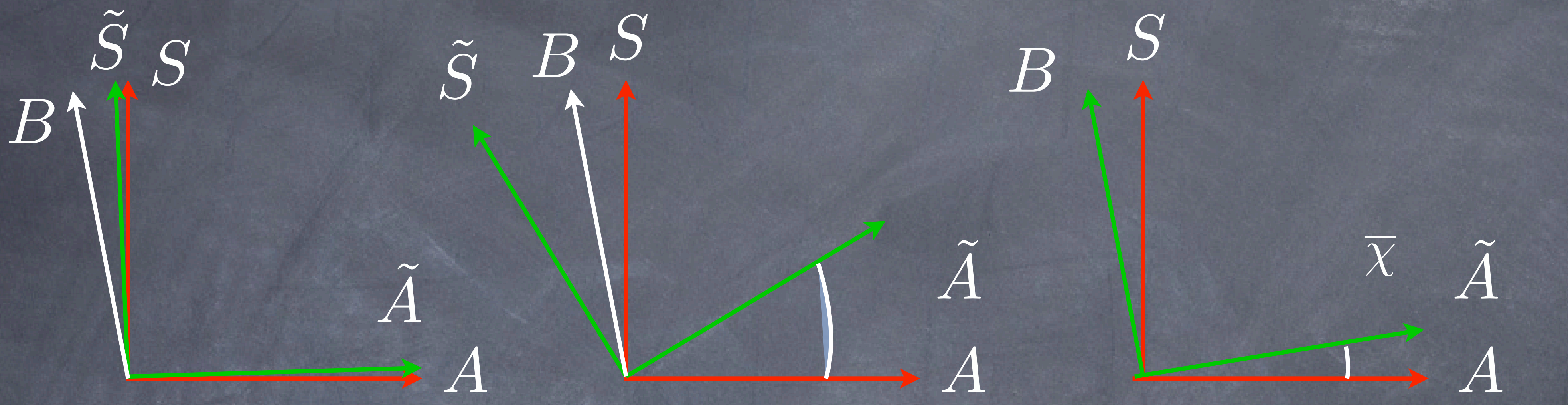
(usefull small mixing approximation)

$$\chi_{\rm eff} = \chi\frac{m_{\gamma'}^2}{\pi - m_{\gamma'}^2}$$

In a plasma : $$\chi\frac{m_{\gamma'}^2}{\omega_{\rm P}^2 - m_{\gamma'}^2 - i\omega\Gamma_{\rm T}}$$

refraction: plasma mass absorption

Hidden sector photons: ``flavor" oscillations in a plasma: regimes



$\chi_{\rm eff}(m_{\gamma'} \ll \omega_P, \Gamma) \ll \chi$ $\chi_{\rm eff}(m_{\gamma'} \simeq {\rm Re}\{\pi\}) > \chi$ $\chi_{\rm eff}(m_{\gamma'} \gg \omega_P, \Gamma) \simeq \chi$

Suppression **Resonance** **Vacuum**

$$\chi_{\rm eff} = \chi \frac{m_{\gamma'}^2}{\pi - m_{\gamma'}^2}$$

Not necessarily suppressed, resonance is also possible!

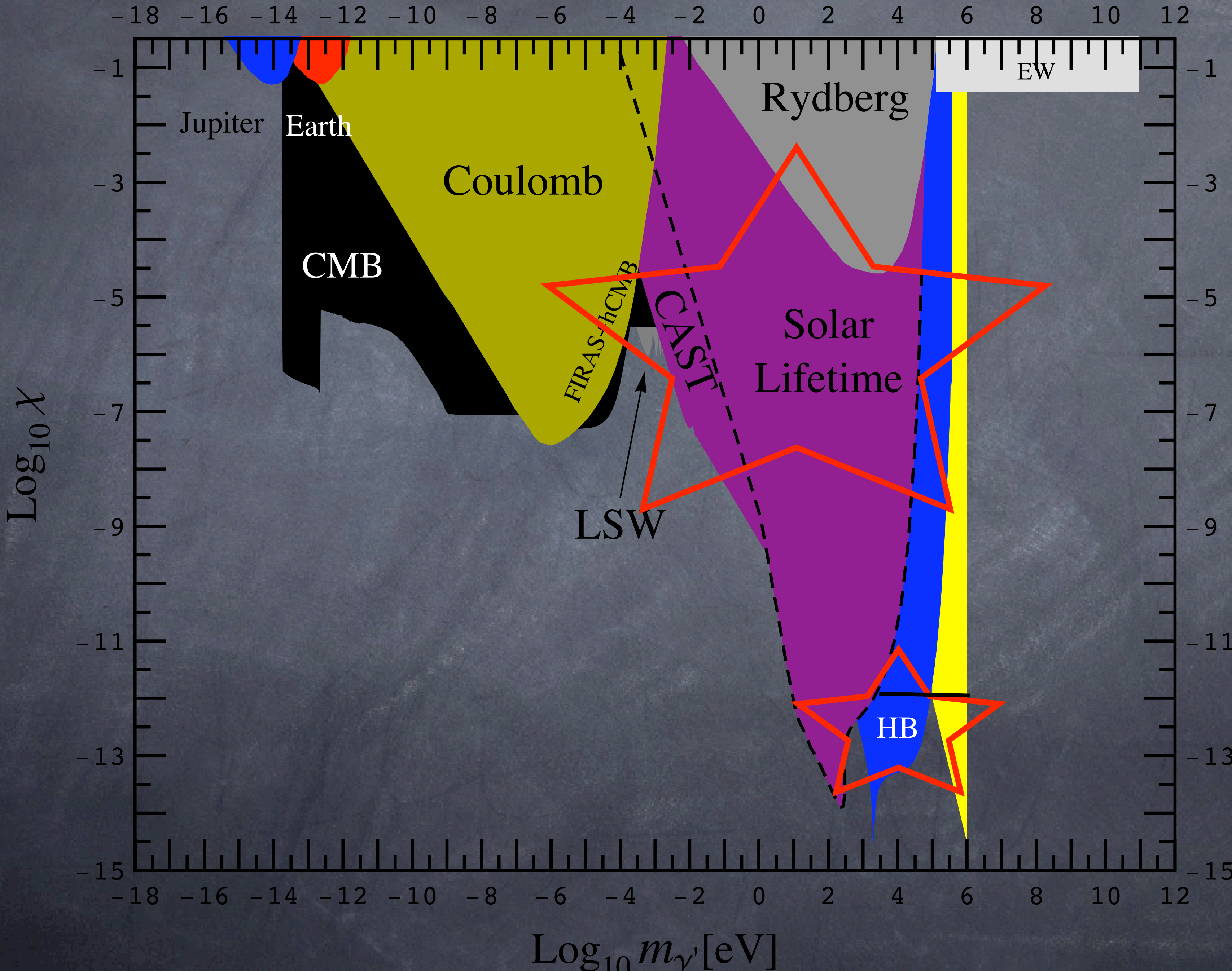
$\pi \propto n_e$

free electron density

We have looked for resonantly produced HPs in cosmology and astrophysics

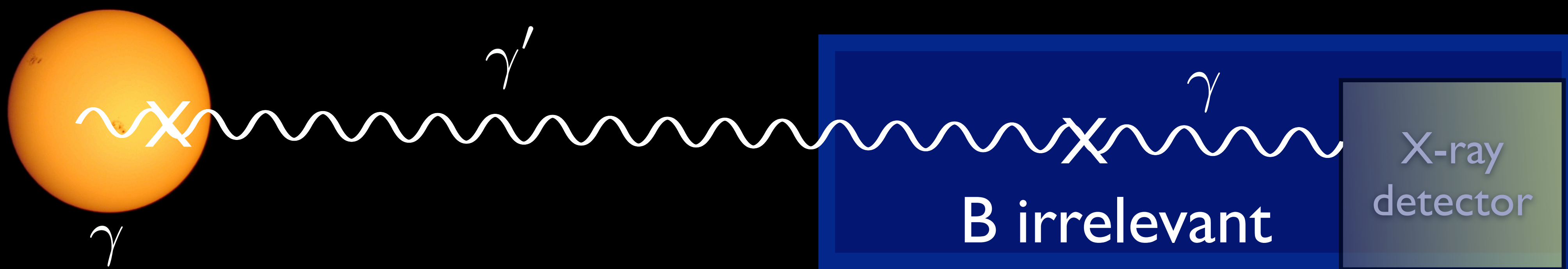
smooth $n_e(t), n_e(r)$

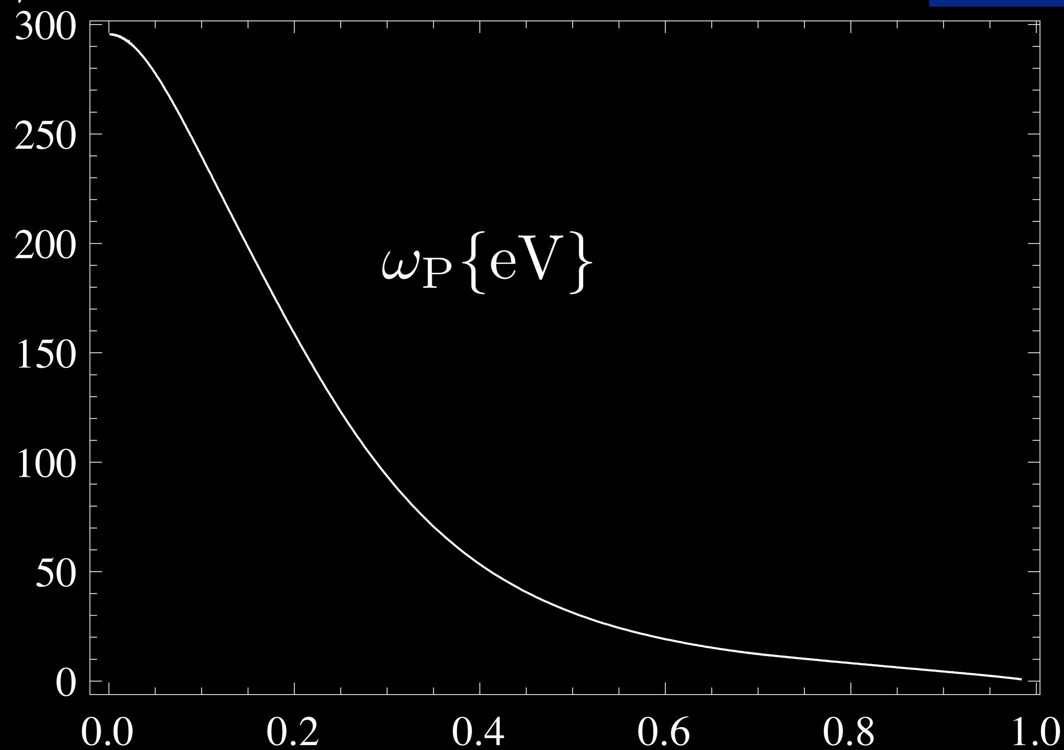
Hidden sector photons: Astrophysics



CAST Helioscope: Hidden Photons

Detect Solar Paraphotons at earth by oscillations inside a closed cavity





Plasma frequency typically much larger than eV (Suppressed mixing)

CAST beats energy loss in suppressed-FLUX scenarios !

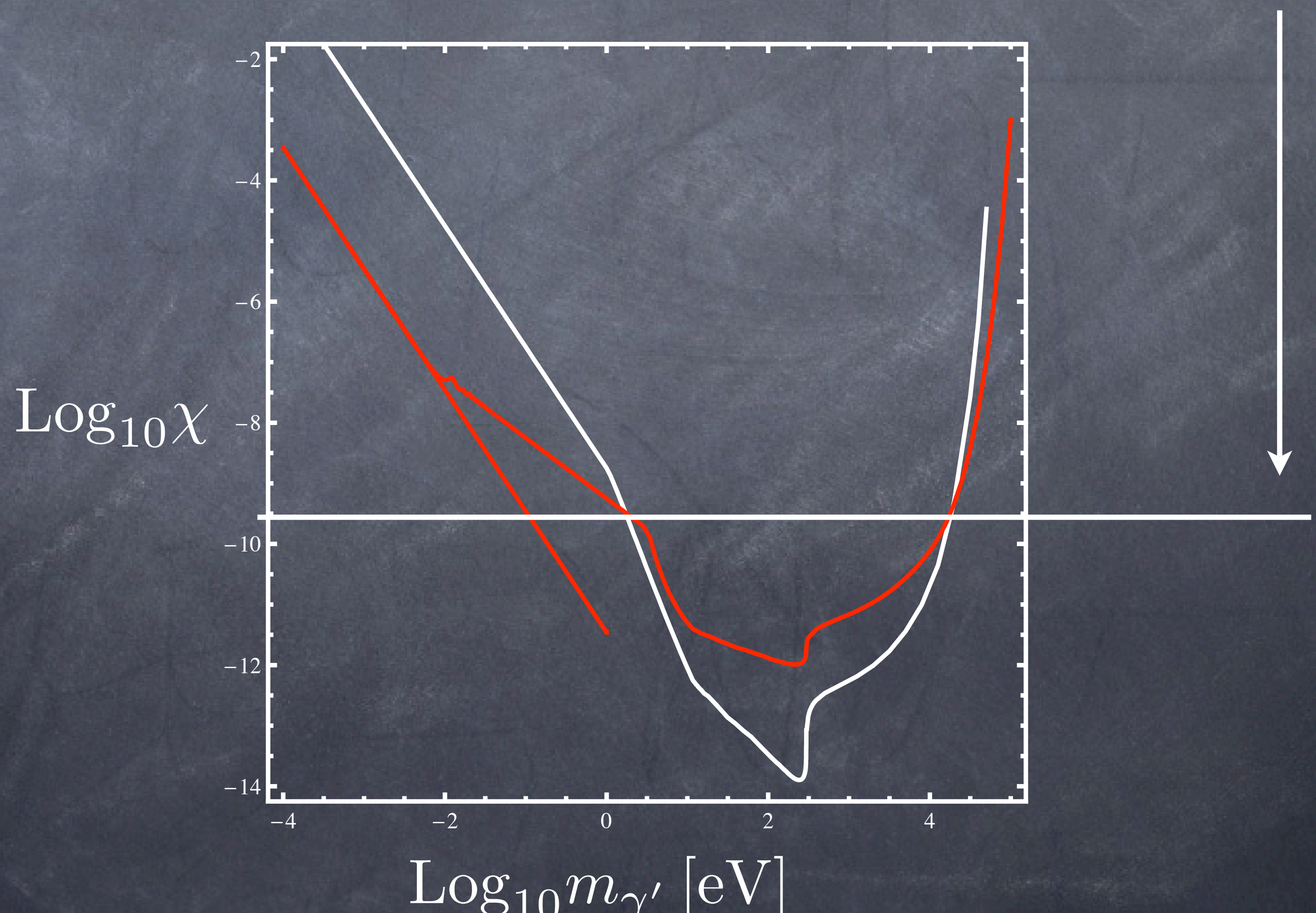
Energy Loss $\chi^4_{\rm CAST}\Phi P < B$

CAST $\chi^2_{\rm Eloss} 4\pi R^2_\oplus \Phi\langle\omega\rangle < L_\odot$

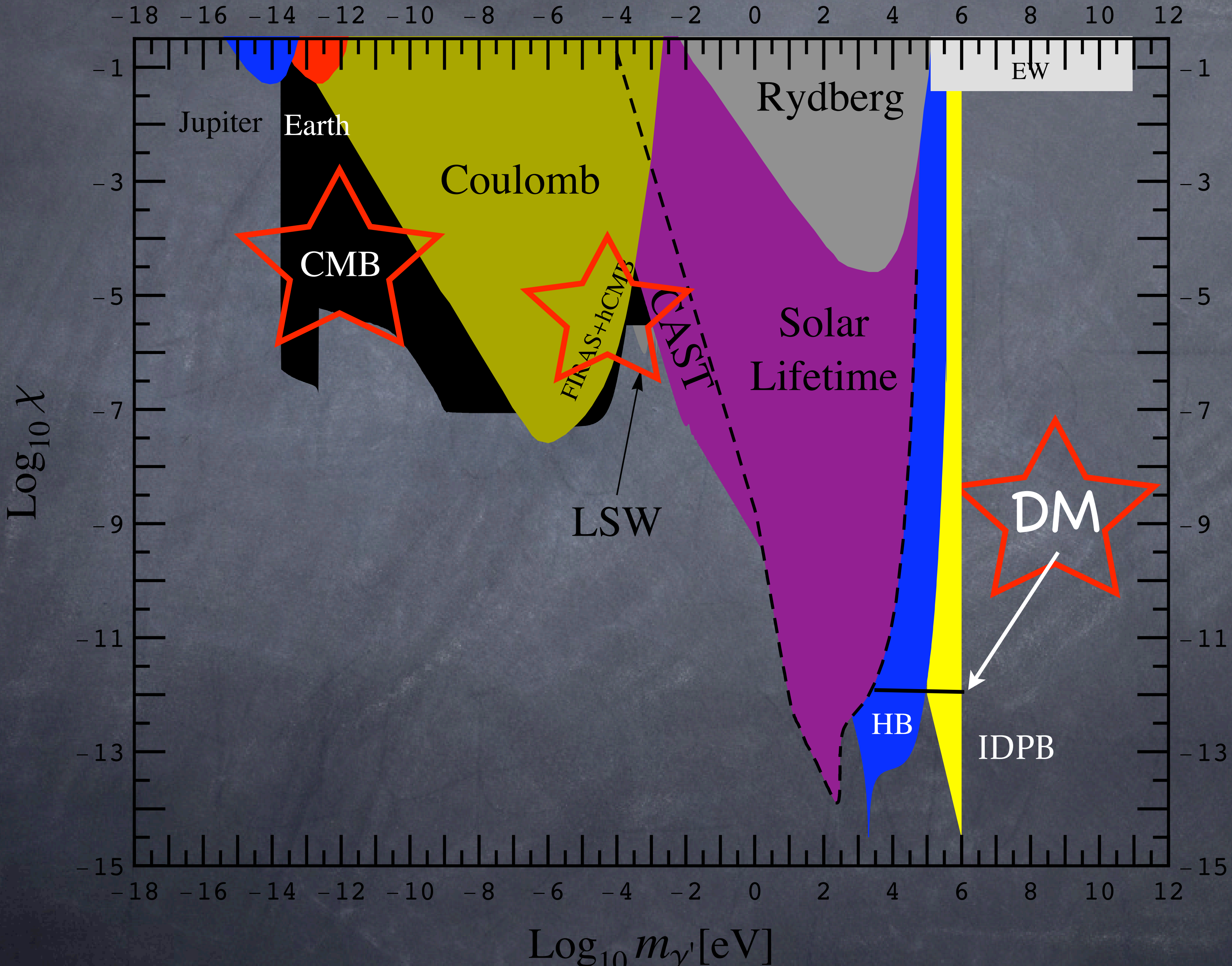
$$\chi_{\rm CAST} = \sqrt{\chi_{\rm Eloss}}\sqrt[4]{\frac{4\pi R^2_\oplus B\langle\omega\rangle}{L_\odot}}$$

$$\mathrm{Log}_{10}\chi_{\rm CAST} = \frac{1}{2}\mathrm{Log}_{10}\chi_{\rm CAST} - 4.8$$

$$\mathrm{Log}_{10}\chi_{\rm CAST} \sim \mathrm{Log}_{10}\chi_{\rm CAST} \ \text{ at } \ -9.6$$



Hidden sector photons: Cosmology



Late cosmology the meV Valley: Hidden CMB !

For low χ only resonance is relevant

Oscillations transfer energy from photons to hidden photons

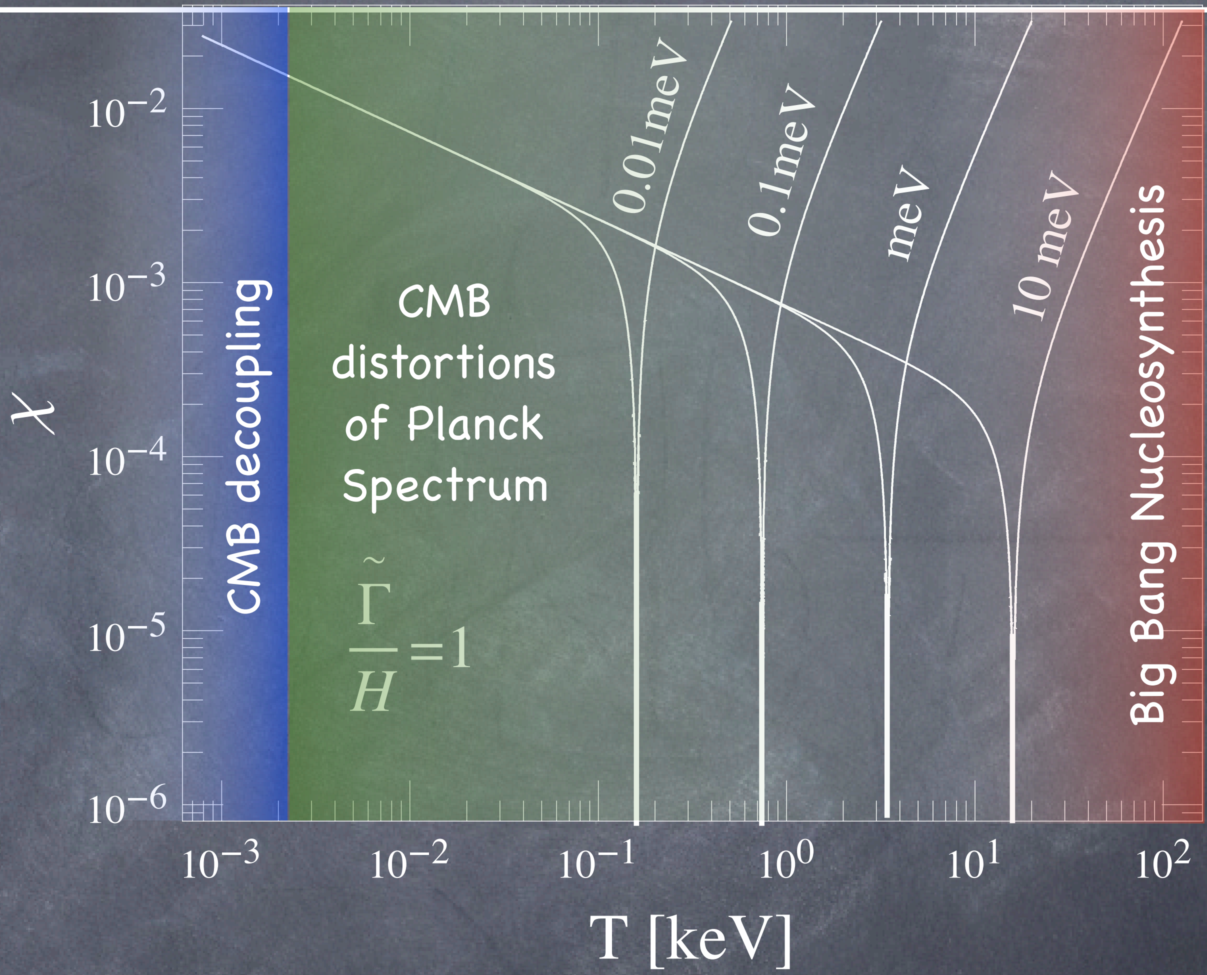
$$x \equiv \frac{\rho_{\gamma'}}{\rho_\gamma}$$

Photon temperature readjusted after

$$T^{after} = (1-x)^{1/4} T^{before}$$

but standard neutrinos untouched so its temperature relative to photons is increased!

$$N_\nu^{eff}(x) = \frac{N_\nu}{1-x} + \frac{8}{7}\frac{x}{1-x}\left(\frac{11}{4}\right)^{4/3}$$



Conversion of photons into hidden photons

Enlarges baryon to photon ratio

hidden photons decouple before CMB effectively act as neutrino species

Both quantities are measured at BBN and CMB!

BBN results (PDG)

Assume $N_\nu = 3.046$

$$\eta^{\mathrm{BBN}} = 5.7^{+0.8}_{-0.9} \times 10^{-10}$$

CMB results (Steigman)

(WMAP5+otherCMB+LSS+SN+HST)

$$\eta^{\mathrm{CMB}} = 6.14^{+0.3}_{-0.25} \times 10^{-10}$$

$$N_\nu^{\mathrm{eff}} = 2.9^{+2.0}_{-1.4}6$$

CMB results (Hamann)

(WMAP3+...+SDSS+Ly-alpha)

$$N_\nu^{\mathrm{eff}} = 3.8^{+2.0}_{-1.6}$$

$$N_\nu^{\mathrm{eff}} < 4.8$$

$$\frac{\eta^{\mathrm{BBN}}}{\eta^{\mathrm{CMB}}} > 0.75$$

⇓

$$x < 0.2$$

$$x < 0.32$$

BBN results (PDG)

Assume $N_\nu = 3.046$

$$\eta^{\rm BBN} = 5.7^{+0.8}_{-0.9} \times 10^{-10}$$

~~CMB results (Steigman)~~

~~(WMAP5+otherCMB+LSS+SN+HST)~~

~~$\eta^{\rm CMB} = 6.14^{+0.3}_{-0.25} \times 10^{-10}$~~

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CMB results (Hamann)

(WMAP3+...+SDSS+Ly-alpha)

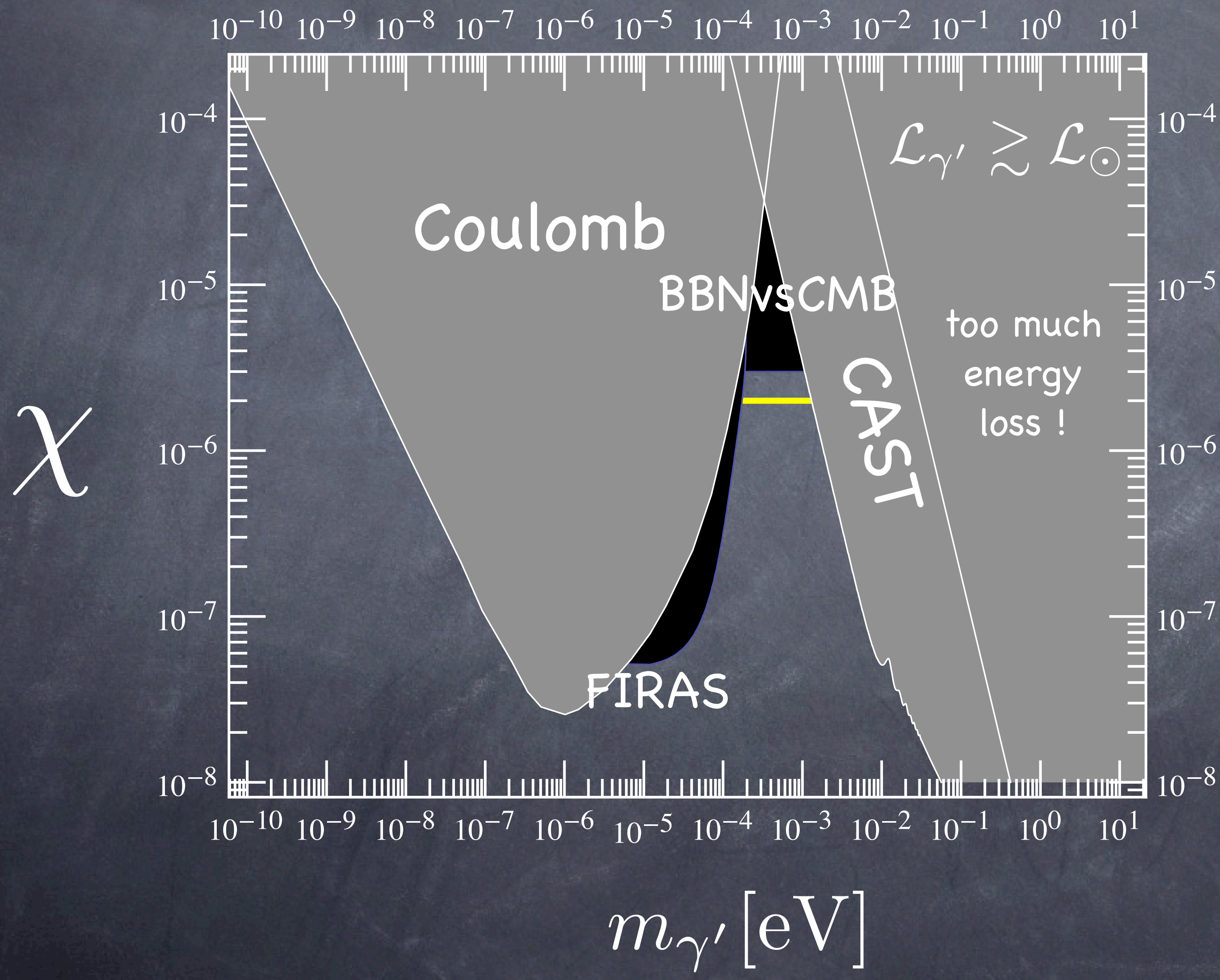
$$N_\nu^{\rm eff} = 3.8^{+2.0}_{-1.6}$$

Both suggest

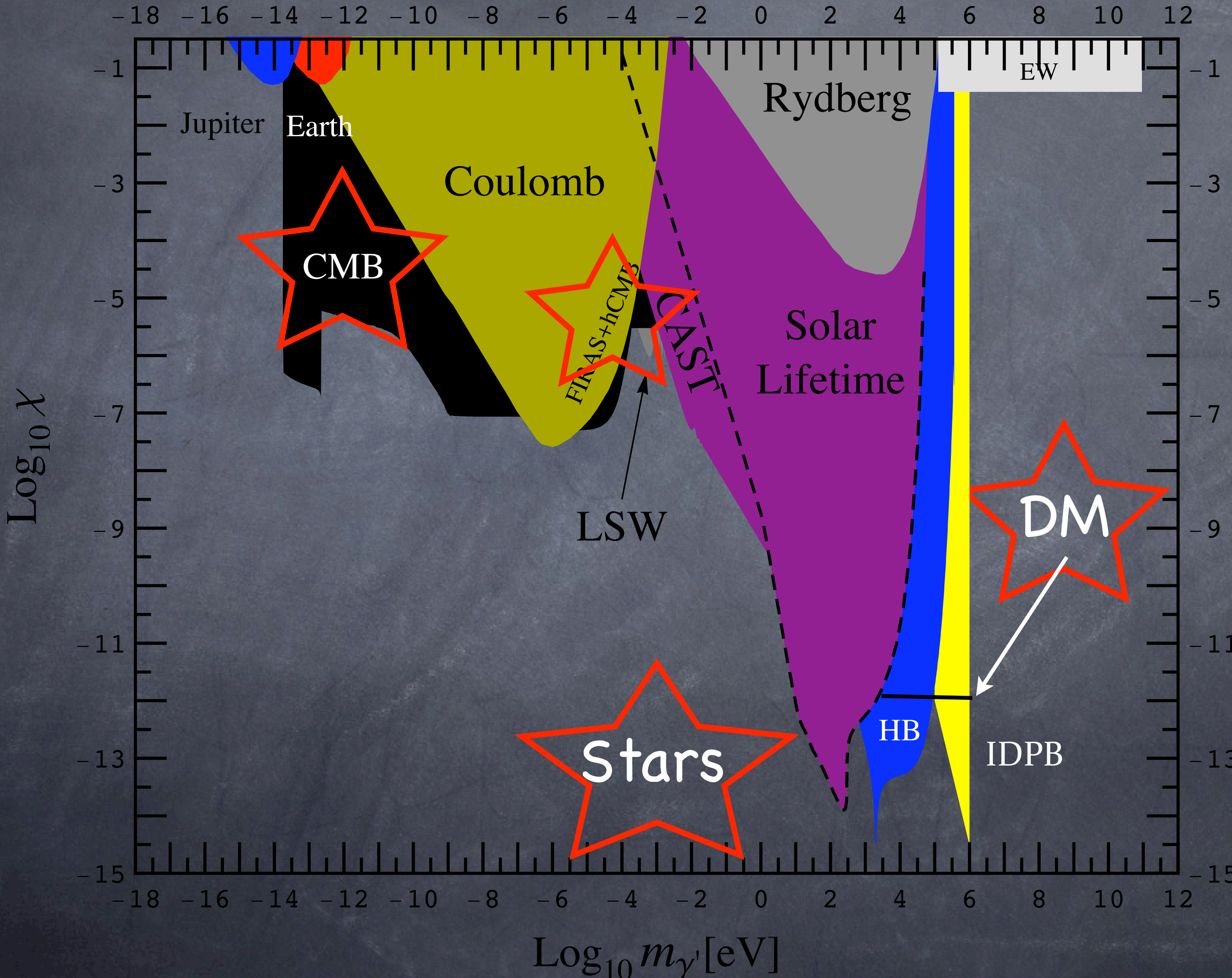
$$x \simeq 0.1$$

Take it as the biggest surprise one can face!

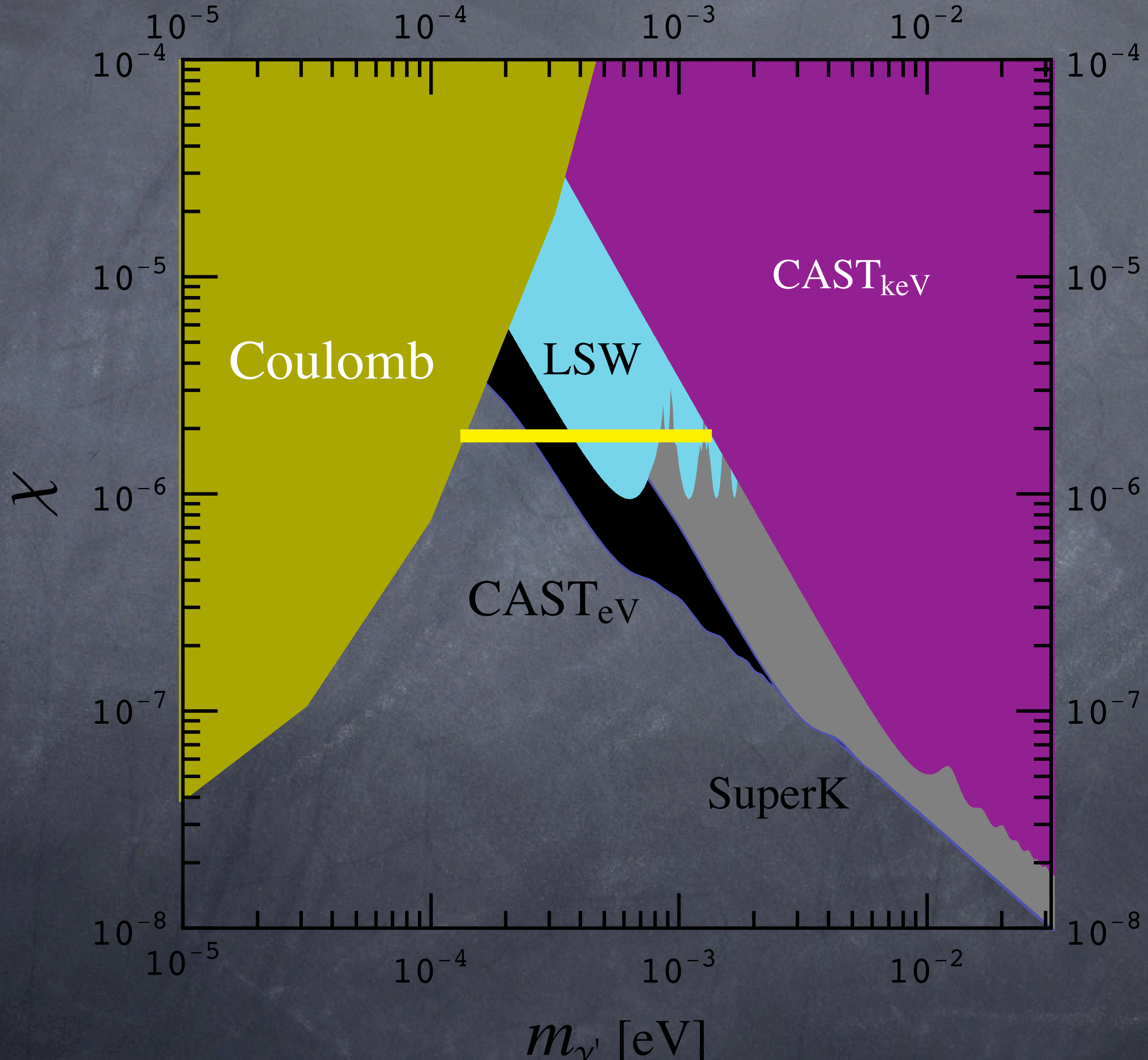
massive Hidden photons and the meV Valley



Hidden sector photons: oscillations in a plasma



The meV Valley and CAST in the visible



Conclusions :

1 - Hidden Sectors arise in PBSM

2 - Weakly Interacting sub eV Particles WISPs might be there

3 - Symmetries keep masses small; GBs, hidden photons, MCPs

4 - kinetic mixing can be relatively big, despite massive messengers

5 - Not clear the impact on MCPs in stellar cooling (Magnetic fields?)
CAST can have something to say

6 - hidden photon oscillations: suppression and resonance

7 - HPs can have a minor role in cosmology (dark radiation)
(testable with CAST in the eV)

8 - HPs can be a fraction of the dark matter (also testable)

Summary:

There are exciting opportunities beyond axions (and the like)

Expect the unexpected!

Motivation

- Extensions of SM often include Hidden Sectors

Fields coupled to SM only through gravity or high energy "messenger" fields...

- Very high mass particles unreachable (LHC ?)

- what about low mass particles???

Low mass particles can be easily accommodated if have masses protected by symmetries, but they should have feeble interactions to have escaped detection

- Organize WISPs by the symmetry that protects their mass