# $\theta$ -term and strong CP problem

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}(i\not{D} - M)q + \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \cdots$$

$\theta$-term is CP-violating

Physical effects depend on the combination

$\bar{\theta} = \theta + \text{Arg Det } M$

$$d_n \sim \frac{e}{m_n} \bar{\theta} \frac{m_u m_d}{m_u + m_d} \frac{1}{\Lambda_{\text{QCD}}}$$

$$d_n < 0.63 \times 10^{-25} \; e\,\text{cm} \quad \Rightarrow \quad \bar{\theta} < 10^{-9}$$

The CP problem:

why $\bar{\theta}$ so small ?

$\theta_{\text{QCD}}$

Arg Det $M$

unrelated

makes the problem worse !

# Peccei-Quinn solution and axions

Peccei, Quinn

Chiral symmetry $U(1)_{PQ}$ allows to rotate $\bar{\theta}$ away

Spontaneous breaking of anomalous global symmetry → Pseudo Goldstone Boson (PGB)

(QCD)- Axion model has large breaking scale $f_a$

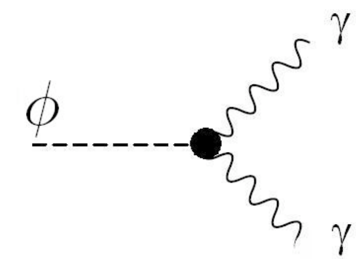
- Interactions are weak $\propto f_a^{-1}$ — Invisible axion
- Mass is small $m_a \propto f_a^{-1}$

Experiments looking for axions use coupling to two photons

$$c_\gamma \, \frac{\alpha}{\pi} \, \frac{1}{f_a} \, \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \, a$$

# Light bosons coupled to $\gamma\gamma$

**Consider $\phi$ light PS or S coupled to $\gamma\gamma$**




$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8}\, g_{\phi\gamma\gamma}\ \phi\ \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = g_{\phi\gamma\gamma}\ \phi\ \vec{E}\vec{B}$$

two (independent) properties : $m$ (mass) $\quad g_{\phi\gamma\gamma} \equiv \frac{1}{M}$ (coupling)

- (Current) axion experiments sensitive to $\gamma\gamma$ coupling
- Other GB or PGB
  - Family, Lepton num. sym. ⇒ familons, majorons
  - MetaSM theories ⇒ $0^-,\ 0^+$
- Even for the axion, there might be extra contributions to mass, altering relation $m_a \sim f_a^{-1}$
- Interesting imlications, cf. SN dimming, ...

# Axions and their relatives

Eduard Massó
(UAB/IFAE)

with: Carla Biggio
Javier Redondo
Francesc Rota
Gabriel Zsembinszki

and: Tony Grifols
Ramon Toldrà

and: Andreas Ringwald
Jörg Jäckel
Fuminobu Takahashi

# OUTLINE OF THE TALK

- ★ Strong CP, PQ, axions, light bosons with $\phi\gamma\gamma$

- ★ $\phi\gamma\gamma$ coupling: consequences / constraints
- ★ Recent results: CAST & PVLAS; the conflict
- ★ Ideas to evade astrophysical constraints

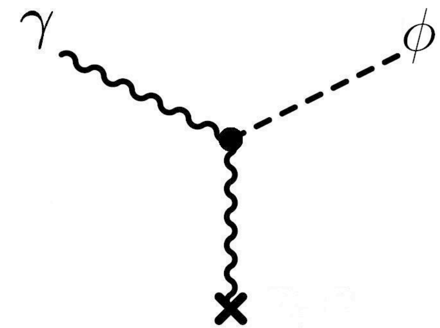
- ★ Light bosons as Dark Matter
- ★ Planck-induced symmetry breaking and PGB DM

- ★ Bounds on forces mediated by light bosons

# Consequences of $\phi\gamma\gamma$

- Primakov-like processes

  allows $\gamma \rightarrow \phi$ and $\phi \rightarrow \gamma$




  (cf. Primakov process for $\pi^0\gamma\gamma$ )

- $\phi\gamma$ mixing in external B-field

$$\mathcal{L}_{\text{int}} = \mathcal{L}_{\phi\gamma\gamma} \Rightarrow g_{\phi\gamma\gamma}\ \phi\ \vec{\epsilon}\cdot\vec{B}$$

strength of interaction

photon polarization

# Consequences of $\phi\gamma\gamma$

Interaction states $\neq$ Propagation states

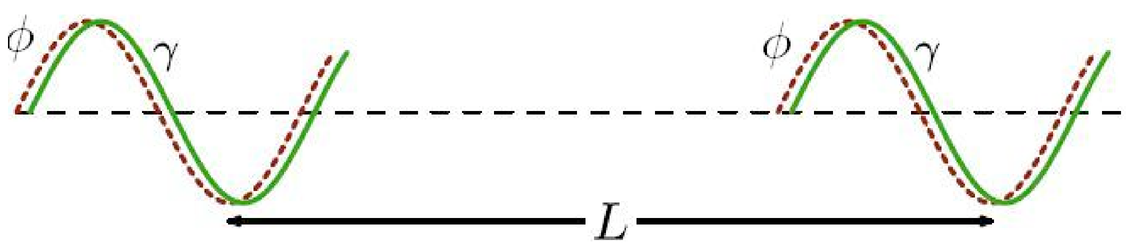
Sikivie
Raffelt, Stodolsky

$$|\phi'\rangle = \cos\theta\,|\phi\rangle - \sin\theta\,|\gamma\rangle$$
$$|\gamma'\rangle = \sin\theta\,|\phi\rangle + \cos\theta\,|\gamma\rangle$$

transition probability
after traveling a distance L

$$P(\gamma \to \phi) = \frac{1}{4}\, g_{a\gamma}^2\, B_T^2\, L^2$$

Coherent effect




Condition *

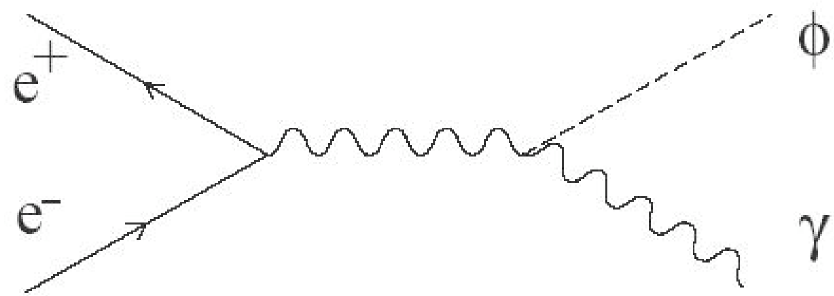
$$|k_\gamma - k_\phi|\, L \ll 2\pi \quad \Rightarrow \quad \frac{Lm^2}{E} < 1$$

$E =$ energy
(in vacuum)

* (Valid when $g_{\phi\gamma\gamma} B \ll L$ and $m_\phi^2/2E \ll E$ )

## Constraints on $\phi\gamma\gamma$

1. Particle physics




$$M = g_{\phi\gamma\gamma}^{-1} > 10^5 \text{ GeV}$$

EM, Toldrà

Klebart, Rabadan

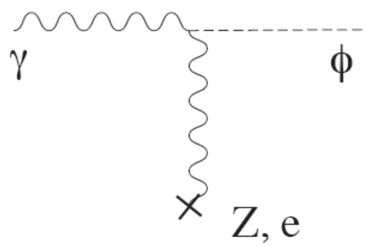
2. Astrophysical

3. Cosmological

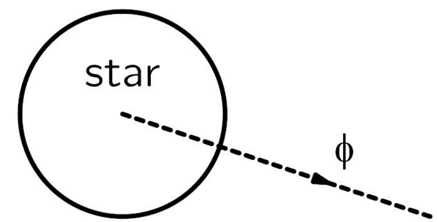
They push (very much) terrestrial limits

# Astrophysical (Energy Loss Arguments)

**Production** Primakov in the stellar plasma




**Emission** Weakly interacting particles leave the star




New energy loss channel accelerates star evolution

Time-scale observation constrains exotic energy drain from the star :

$$M > 2 \times 10^{10}\ \text{GeV}\ (m < 10\ \text{keV})$$

Raffelt

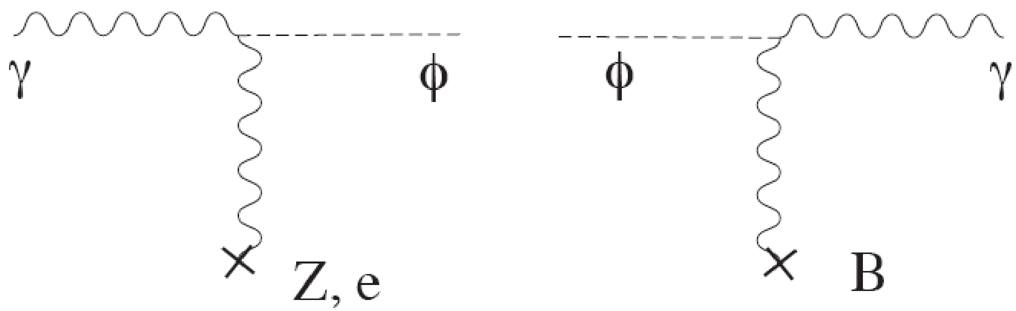
Horizontal Branch Stars

Also SN87 A $M > 10^{9}\ \text{GeV}\ (m < 50\ \text{MeV})$

# Gamma-rays from SN

Grifols, EM, Toldrà
Brockway, Carlson, Raffelt

Part of the $\phi$-flux produced in the SN core can be (partially) converted back to photons in galactic B

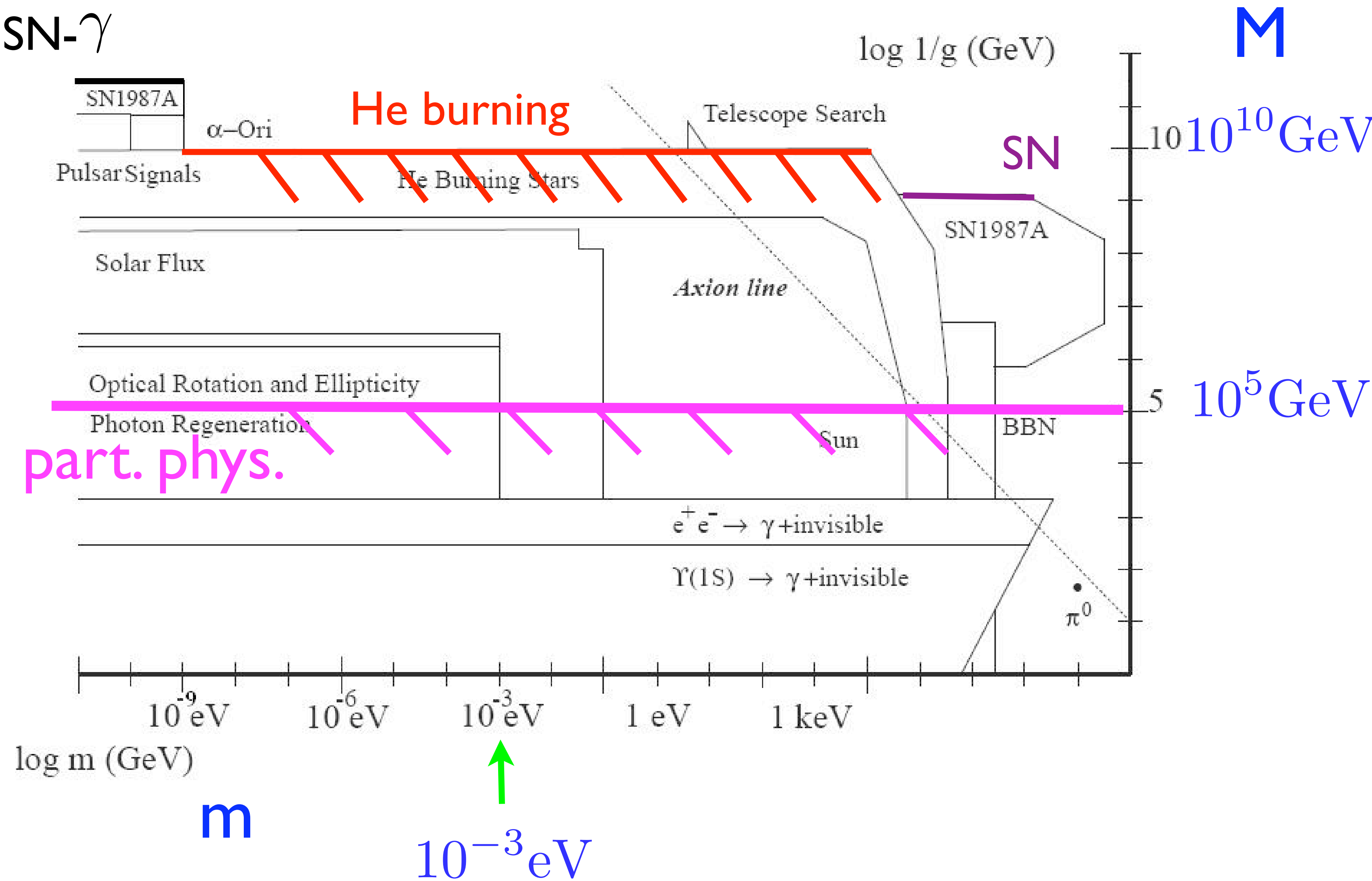



Limits on $\gamma$-flux by GRS at the time of observation of $\nu$-flux in 02.1987

$$M > 10^{12}\ \text{GeV}$$

$$(m < 10^{-9}\ \text{eV})$$

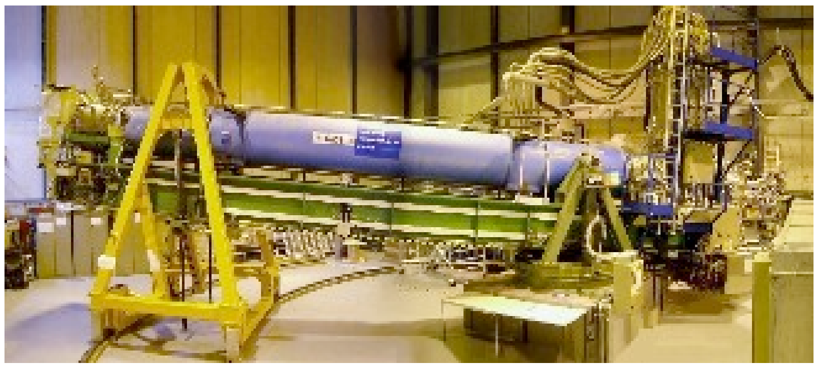
In future galactic SN, we might get a signal since we have now more sensitive gamma-rays detectors in satellites



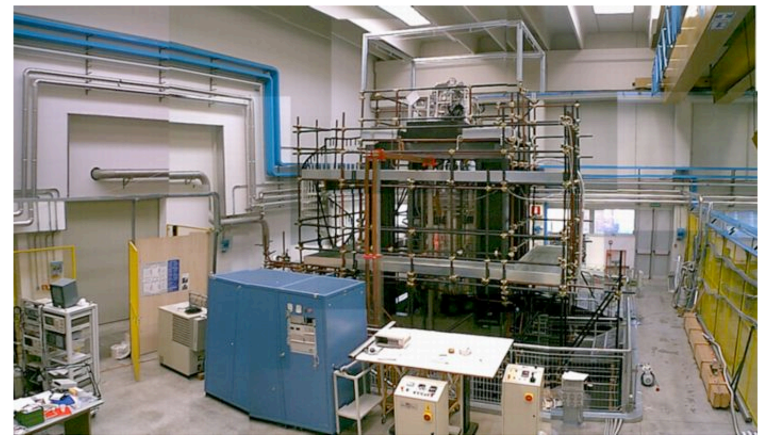

EM, Toldrà
Klebart, Rabadan

# Recent experimental results (small masses)

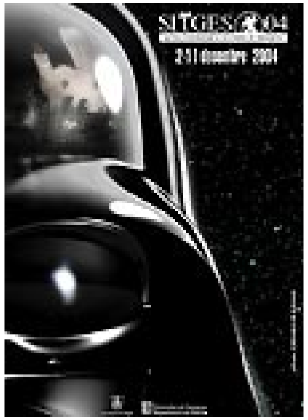
## CAST (CERN)



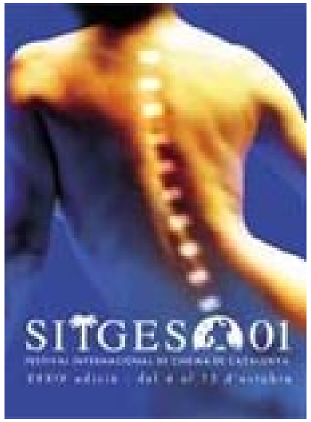

## PVLAS (INFN)



# Sitges Cine Festival (Horror and Fantastic)





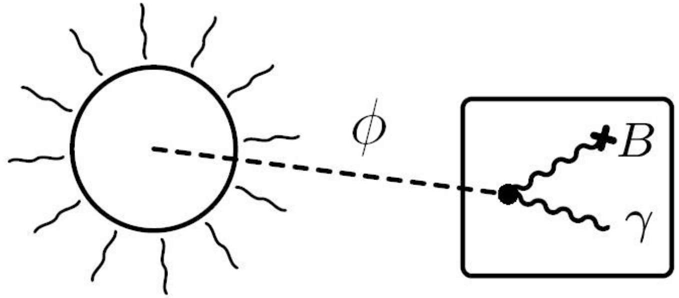


Get inspiration
for next experiments !

# CAST search

## Helioscope

Sikivie




Idea: Sun is source of axion-like particles.
Use B to convert them back to photons
(of few keV , X-rays)

Comparable to stellar bounds

<u>NO</u> signal
(at the moment)

$$M > 0.9 \times 10^{10} \ \text{GeV}$$
$$(m < 0.02 \ \text{eV})$$

K. Zioutas et al. PRL 94 (2005)

Comments: Past helioscopes; Crystal search (Bragg-Primakov)

PVLAS search

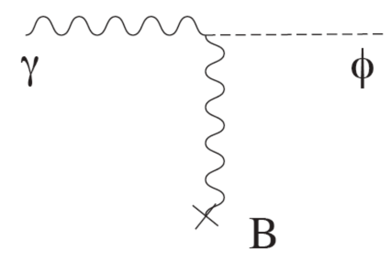
E. Zavattini et al.
hep-ex/0507107, sub. PRL

# ROTATION of polarization plane of laser in B field

$B \simeq 5T, \;\; L \simeq 1m, N \simeq 4.4 \;\; 10^5$

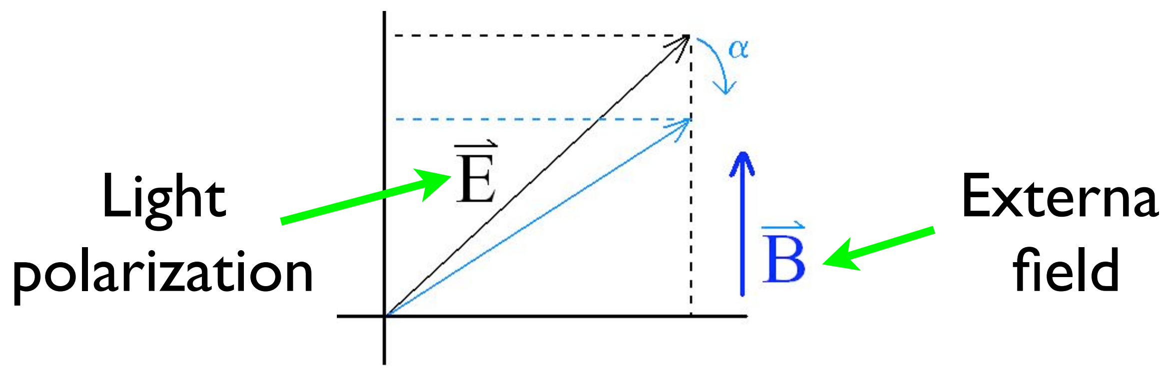
$$\alpha = (3.9 \pm 0.5) \;\; 10^{-12} \;\; \text{rad/pass}$$

A possible interpretation :




$$\vec{\epsilon} \cdot \vec{B} = \epsilon_{\parallel} \, B$$

Selective absorption
(dichroism)




**Scale:** $1 \;\; 10^5 < M < 6 \;\; 10^5 \;\; \text{GeV}$ $\quad M = g_{\phi\gamma\gamma}^{-1}$

**Mass:** $0.7 < m < 2 \;\; \text{meV}$

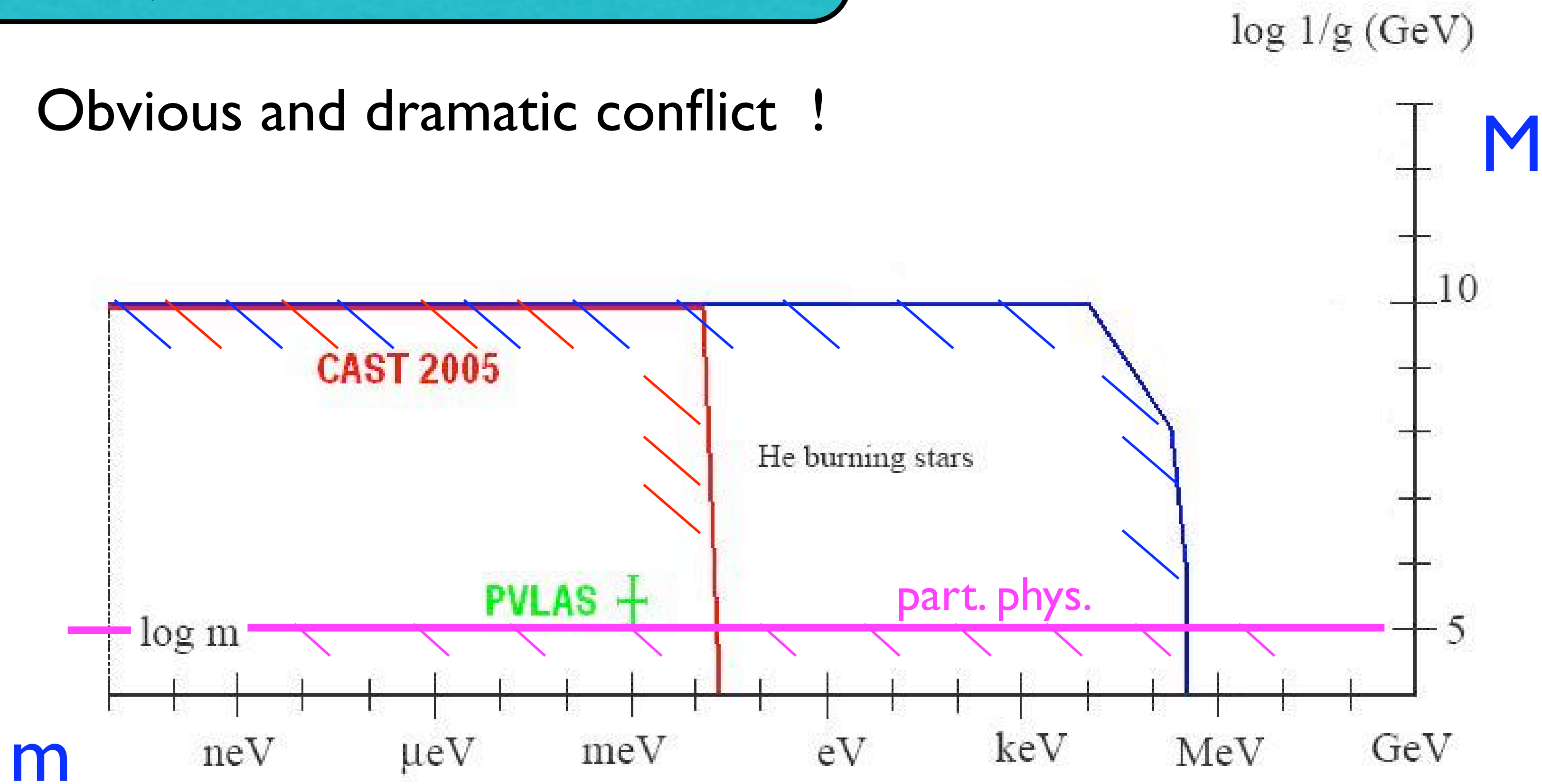
Even if particle interpretation is correct,

this particle

would NOT be the standard axion

# PVLAS, CAST & the STARS

Obvious and dramatic conflict !




PVLAS strength of interaction leads to $\mathcal{L}_{exotic} \sim 10^6\ \mathcal{L}_{\odot}$

Difficult problem;
not easy to circumvent

# Future (experimental)

- CAST
  - → higher m (gas)
  - → Lower photon energy

- PVLAS
  - → higher m (gas)
  - → Search induced ellipticity

Should be present if rotation signal is due to $\phi\gamma\gamma$

- New experiments welcome

For example post-HERA Ringwald

CERN-SPSC-2005-034
SPSC--001
17 October 2005

Letter of Intent

# QED Test and Axion Search by means of Optical Techniques

To the CERN SPSC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***Abstract***

The re-use of recently decommissioned 15-meter long twin aperture LHC superconducting magnet prototypes, providing a transverse magnetic field $B \approx 9.5$ T offers a unique opportunity for the construction of a new powerful two-in-one experiment to investigate the properties of the vacuum by means of optical techniques. Linearly polarised laser light beams will be used as probes inside vacuum chambers housed inside superconducting magnet apertures. One of the apertures will be dedicated to the measurements of the Vacuum Magnetic Birefringence (VMB) and optical absorption anisotropy whereas the other one will be used to detect the photon regeneration from axions using "a shining light through the wall". The VMB predicted by the QED theory is expected to be measured for the first time and the CPT symmetry precisely tested. The values or the limiting values of mass and coupling constant to two photons of weakly interacting scalar or pseudo-scalar particles like axions are also aimed to be deduced from a sizeable deviation of the QED prediction. In case of null result for axion search and with the most conservative view concerning the detection technique, the limits of both parameters, i.e. mass and di-photon coupling constant, can be improved by at least 2 orders of magnitude with respect to present reference results obtained with a purely laboratory experiment. The interest in axion search, providing an answer to the strong-CP problem, lies beyond particle physics since such hypothetical neutral light spin zero particle is considered as one of the good dark matter candidates, and the only non-supersymmetric one.


[*] Contactperson



# Photon Regeneration from Pseudoscalars at X-ray Laser Facilities


Raul Rabadan,[1,*] Andreas Ringwald,[2,†] and Kris Sigurdson[1,‡]

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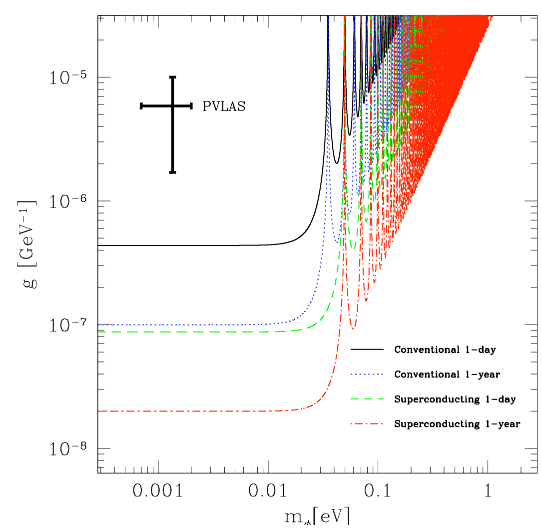
[2] *Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*



Recently, the PVLAS collaboration has reported an anomalously large rotation of the polarization of light in the presence of a magnetic field. As a possible explanation they consider the existence of a light pseudoscalar particle coupled to two photons. In this note, we propose a method of independently testing this result by using a high-energy photon regeneration experiment (the X-ray analogue of "invisible light shining through walls") using the synchrotron X-rays from a free-electron laser (FEL). With such an experiment the region of parameter space implied by PVLAS could be probed in a matter of minutes.

# PVLAS, CAST & the STARS

EM, Redondo

A way out of the puzzle is to have a model where
the Sun emits much less axion-like particles
than expected

⇒ There would be less energy loss
and thus stellar limit are avoided

⇒ CAST limit not valid because
it assumes "solar- standard" $\phi$ - flux

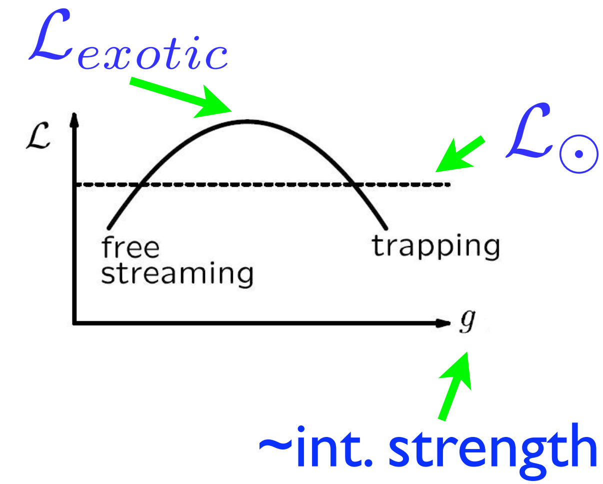
I discuss
two possibilities

I) Trapping

II) Suppression of production

# PVLAS & the STARS

EM, Redondo




- 1) Trapping

Strongly interacting $\phi$

$\phi$ would follow a random walk
on its way out of the Sun (like photons).
When emitted would have much less energy
than when produced in the core.

Problem: a strong interaction
should have been seen elsewhere

Interact through mediators ?

MODEL
WANTED

# PVLAS & the STARS

## II) Suppression of production

Required suppression
to make compatible PVLAS
with stellar limits
(and a fortiori with CAST)

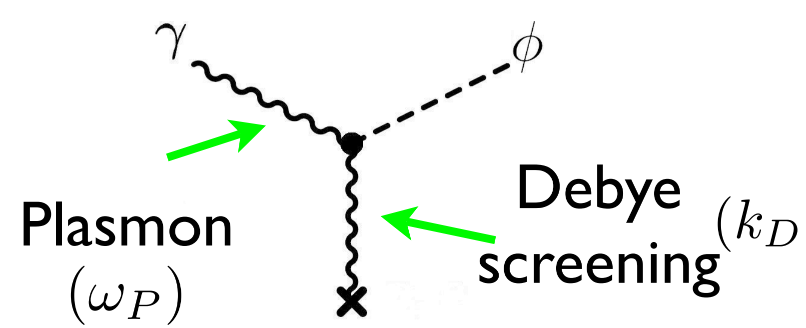
$$\left[|F|^2 \frac{1}{M^2_{\rm pvlas}}\right] \frac{1}{M^2_{\rm pvlas}} < \left[\frac{1}{M^2_{\rm cast}}\right] \frac{1}{M^2_{\rm cast}}$$

$$\Rightarrow \quad |F| < 2 \times 10^{-9}$$

A difference between

the lab & the solar plasma

$$|q^2| \sim 0 \longrightarrow |q^2| \sim {\rm keV}^2$$




$$k_D, \omega_P \sim {\rm keV}$$

Suppression F due to a (low scale) form-factor effect

# Form factor for $0^-$ mesons

Form factor F in $\pi^0\gamma\gamma$ or $\eta\gamma\gamma$ when $\gamma$ virtual ?

## THEORETICAL EXPECTATIONS

effective interaction

$$\mathcal{L} = \frac{1}{\Lambda}\,\pi\;\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$$

scale

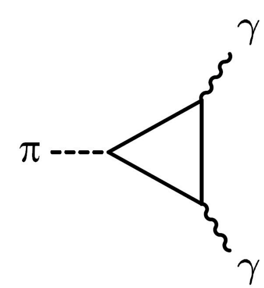
dim. 5 operator

Not expected to be valid at arbitrarily high energies

➡ Variation with energy

VMD model $\Lambda \sim M_\rho$

Quark triangle $\Lambda \sim M_{u,d}$




pQCD, chiral theories $\Lambda \sim M_{had}$

AND ...

# Measured Form-factor

... IT IS OBSERVED !!

$$|Q^2| < M_{had} \sim M_\rho$$

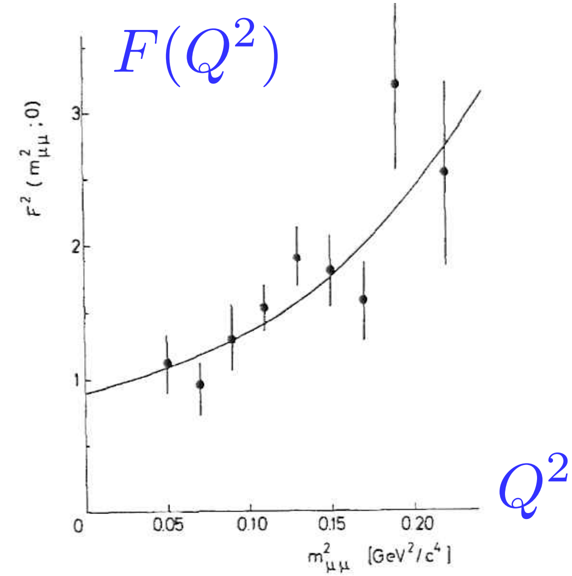


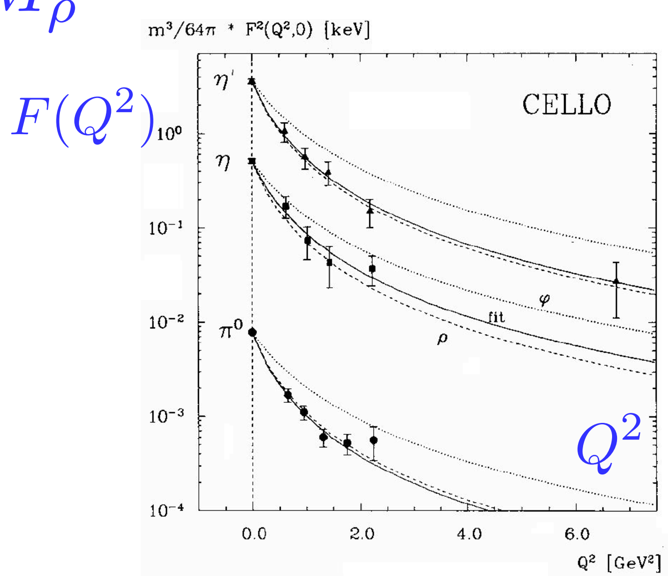

Fig. 2. Data on the electromagnetic form factor of the $\eta$ meson. The points are the experimental values for $F^2(m^2_{\mu\mu};0)$. The curve is the result of fitting with the dependence $K \cdot (1 - m^2_{\mu\mu}/\Lambda^2)^{-2}$, where $\Lambda = (0.72 \pm 0.09)$ GeV/$c^2$ and the coefficient $K$ takes into account the experimental normalization uncertainty.

IHEP

$$\eta \to \mu^+\mu^-\gamma$$

$$|Q^2| >> M_{had} \sim M_\rho$$

Transition form factors




CELLO

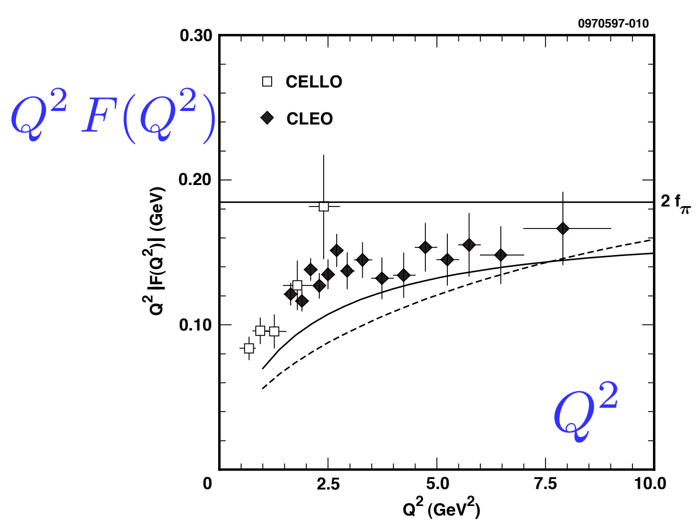



FIG. 19. Comparison of the results (points) for $Q^2|\mathcal{F}_{\gamma^*\gamma\pi^0}(Q^2)|$ with the theoretical predictions made by Cao *et al.* [16] with the asymptotic wave function (solid curve) and the CZ wave function (dashed curve).

CLEO II

# Axion-like particle may be composite

EM, Redondo

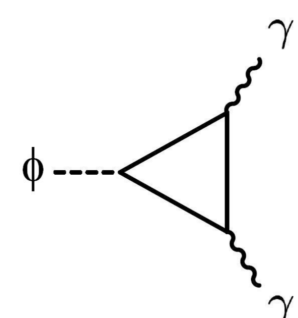

<u>Key point:</u> Composite particle has a form factor

Postulate that

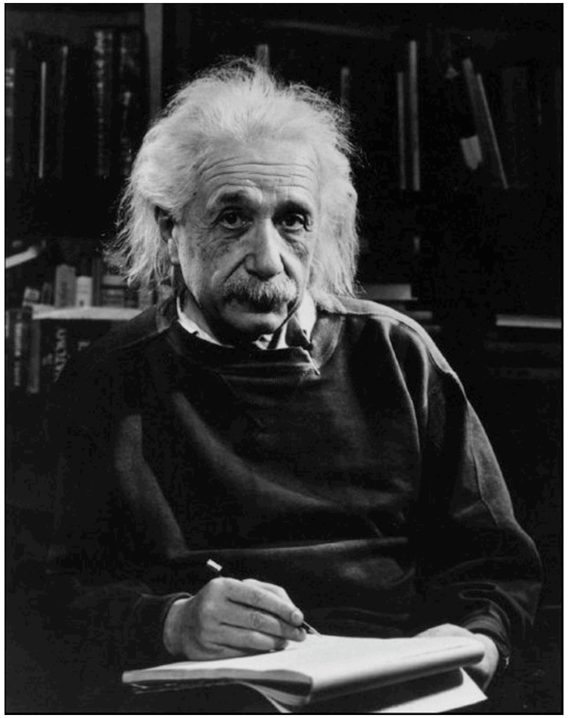
$\phi$ <u>IS A COMPOSITE PARTICLE</u>

NEED
- New constituents
- New confining forces

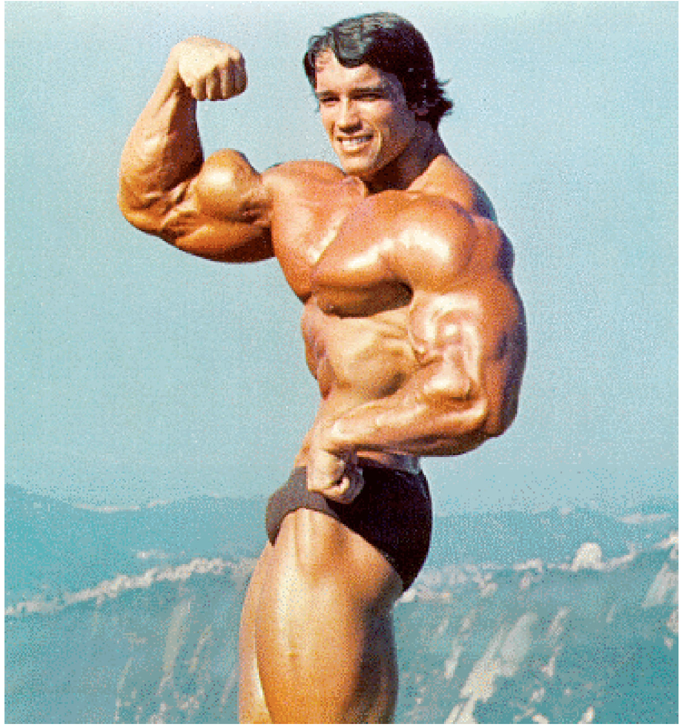
there will be form-factor effects with a new low-energy scale




Difference between being composite or being elementary



COMPOSITE



ELEMENTARY

# Evaluate new scale

Assume only one constituent $f$ (fermion, SM singlet)

& SU(N) for new forces (nothing to do with color)

To evaluate new scale : calculate triangle diagram with internal fermion for off-shell photons

detail

needed suppression

MAIN RESULT:

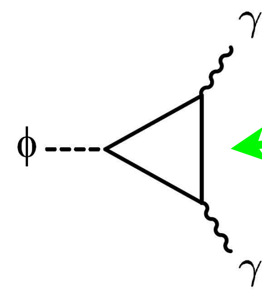
$$|F| < 2 \times 10^{-9} \quad \Rightarrow \quad \Lambda \sim M_f < 2 \times 10^{-2}\mathrm{eV}$$

new scale

Notice: same order than mass m of $\phi$

(Not necessary a priori, perhaps a clue)

# Evaluate new scale




$M_f$

$$f_{\gamma\gamma} = -\frac{gM}{\pi^2 m_\pi^2} arcsin^2(m_\pi/2M)$$

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$$

$$F(s_1, s_2; s_0) = \frac{gM}{2\pi^2 f_{\gamma\gamma}} \frac{1}{\lambda^{\frac{1}{2}}(s_0, s_1, s_2)} \times$$
$$\sum_{i=0,1,2} \left[ Li_2\left(\frac{Y_i}{Y_i - Y_{+i}}\right) + Li_2\left(\frac{Y_i}{Y_i - Y_{-i}}\right) - Li_2\left(\frac{Y_i - 1}{Y_i - Y_{+i}}\right) - Li_2\left(\frac{Y_i - 1}{Y_i - Y_{+i}}\right)\right]$$

$$Li_2(x) = -\int_0^x \frac{ln(1-t)}{t} dt$$

$$Y_i = \frac{1}{2}\left[1 + \frac{s_j + s_k - s_i}{\lambda^{\frac{1}{2}}(s_0, s_1, s_2)}\right] \quad , \quad i \neq j \neq k \;\; ; \;\; i \neq k$$

$$Y_{\pm i} = \frac{1}{2}\left[1 \pm \sqrt{1 - \frac{4M^2 - i\varepsilon}{s_i}}\right]$$

$$s_1 > s_2 >> s_0 = m_\pi^2$$

$$F(s_1, s_2; s_0) \rightarrow \frac{1}{2|s_1 - s_2|} ln^2 \frac{|s_1 - s_2|}{s_0^2}$$

## Remarks/Next

- To QCD or not to QCD

  We have been inspired by QCD, $\pi's$ & $q$
  But we dont know if QCD is the reference model
  until last consequences (like it was inTechnicolor)

- Need low energy scale << keV, in any case

  For example $F \sim (\Lambda^2/Q^2)^n$ $\Lambda$ a few eV for n=2

- If similar to QCD... $\eta$ vs. $\eta'$

- $q_f \neq 0$ but very small

  not to have undesirable consequences

  cosmological
  astrophysical
  laboratory

  (paraphoton models give arbitrarly epsilon-charges)

  Okun
  Holdom

- Future: Model building and look for signatures

# OUTLINE OF THE TALK

- Light bosons as Dark Matter
- Planck-induced symmetry breaking and PGB DM

- Bounds on forces mediated by light bosons

# Relic density of particles coupled to photons

Work out $\phi$ decoupling in the early universe

Processes
$$e^-\phi \leftrightarrow e^-\gamma$$
$$\gamma\phi \leftrightarrow e^-e^+$$

(and any other charged particle in equilibrium)

Freeze-out
$$H(T_f) = \Gamma(T_f)$$

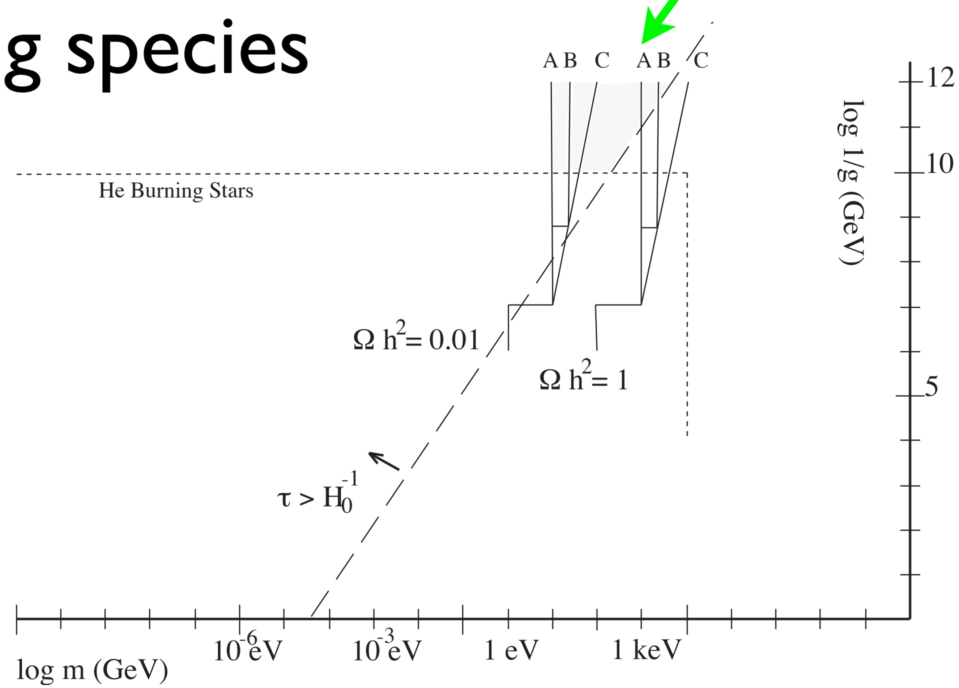
Interaction rate

Hubble parameter

$$\Omega = \frac{\rho}{\rho_c}$$

Entropy release of annihilating species

Finally Find parameters leading to DM $\phi$



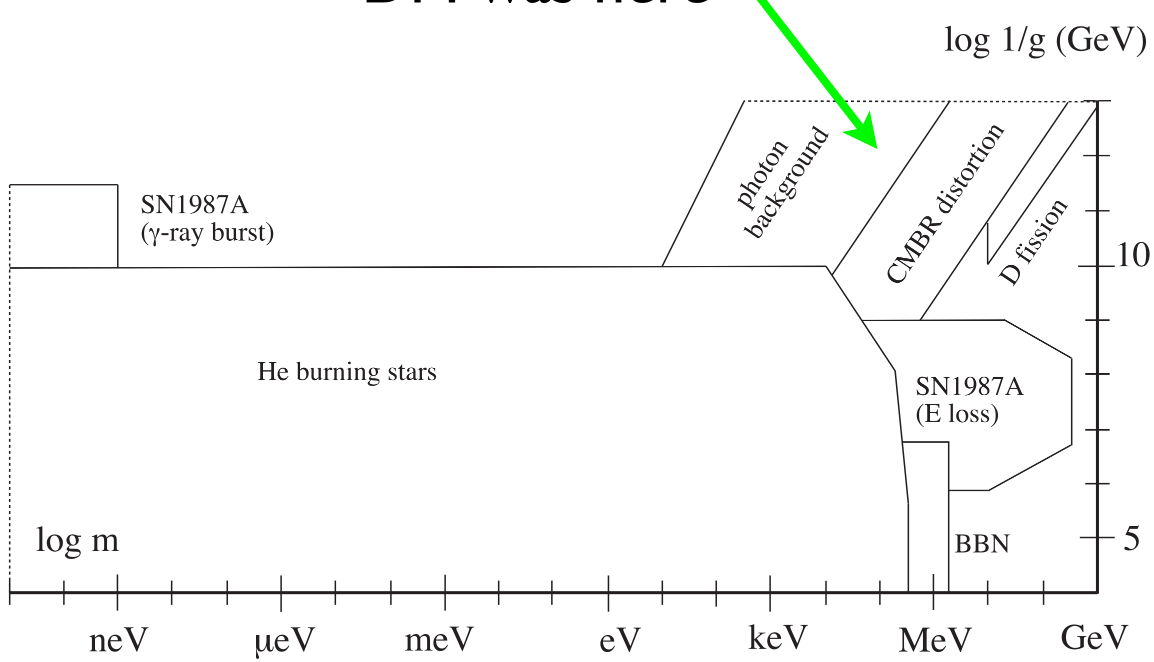
# Cosmological constraints (Other than BBN)

For larger m, necessary to consider effects of unstable $\phi$

➡ Injection of energy m at a finite lifetime $\tau_\phi$

Depending on $\tau_\phi$ there might be cosmological effects on:
Photon Background, CMBR distortion or D-fission

DM was here




NO DM

# Dark matter

We have assumed thermal production
due to the coupling to photons

In realistic models : Other couplings

Other production mechanisms

DM candidates

Most famous example:
QCD-axions is a DM candidate

# A model with PGB

Global symmetries are expected to be (explicitly) broken by quantum gravity effects

$$V = V_{sym} + V_{non-sym}$$

Consider one scalar field, U(1) symmetry

EM, Rota, Zsembinszki

$$V_{sym} = \frac{1}{4}\lambda[|\Psi|^2 - v^2]^2$$

$$V_{non-sym} = -g\frac{1}{M_P^{n-3}}|\Psi|^n\left(\Psi e^{-i\delta} + \Psi^\star e^{i\delta}\right)$$

$g$ could be exponentially small

Planck-mass suppressed

$n \geq 4$

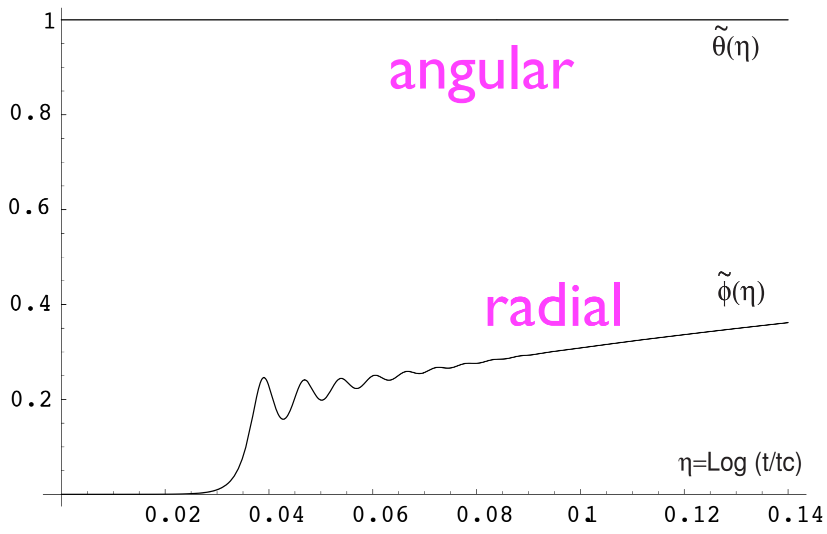
(most simple) not invariant piece

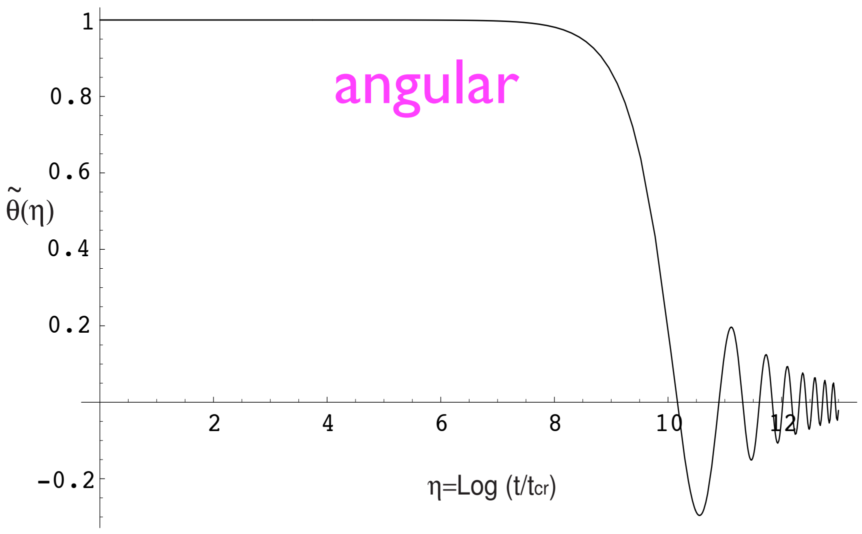
# A model with PGB

Spontaneous breaking
in presence
of a small explicit breaking

$$\Psi = \phi\, e^{i\theta/v},$$

$$m_\theta^2 = 2g \left(\frac{v}{M_P}\right)^{n-1} M_P^2$$

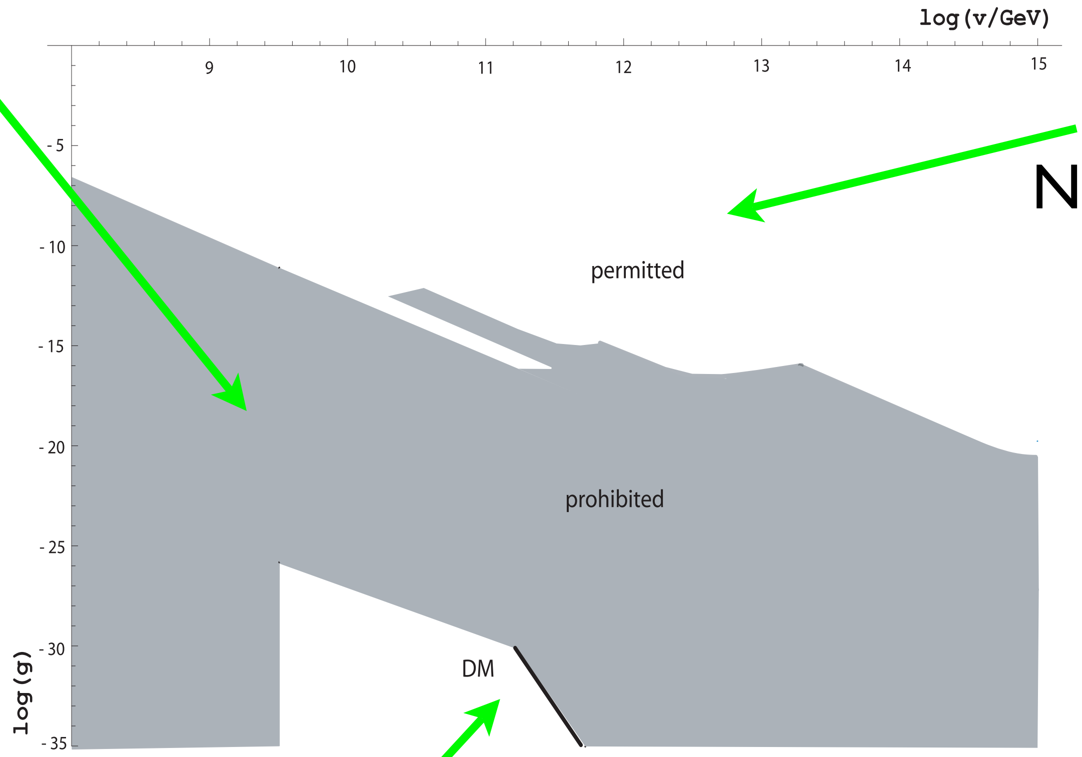



(Numerical integration of eqs.)

# PGB dark matter

Astrophysics + cosmology
constrain
the parameter space of the model




Very short lived
Not cosmo-interesting

DM

$$m_\theta \lesssim 20\,\mathrm{eV}$$

$$g < 10^{-30}$$

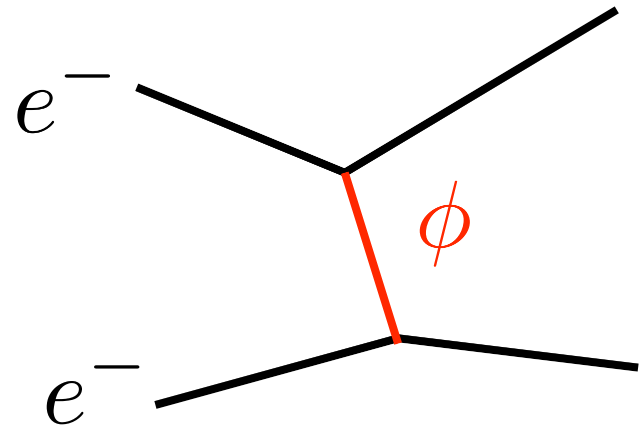
## Long-range forces

Realistic models have couplings
of axion-like particles to matter

Other effects:
Violation of the equivalence principle

# Long-range forces

$m_\phi$ small




<u>Interest</u> in new (non-gravitational) forces

Experiments: were motivated by (false alarm) 5th force claim

Theory: x-dimensions, models with light scalars, etc

Axion and other PS lead to spin-dependent forces

I restrict here to forces mediated by scalar or vector coupled to lepton number

# Long-range leptonic forces

$\alpha_L < 10^{-48} - 10^{-49}$ from Eotvos-type experiments

Lee, Yang
Okun

$$\left(\frac{m_p}{M_P}\right)^2 \sim 10^{-38} \qquad \left(\frac{m_e}{M_P}\right)^2 \sim 10^{-45}$$

Limit improved by considering the effect on solar $\nu$ oscillations

Grifols, EM

Solution to $\nu_\odot$-problem : LMA resonant MSW matter oscillations

$$\Delta m^2 = 5.5 \times 10^{-5} \mathrm{eV}^2$$

$$\sin^2 2\theta = 0.83$$

# Long-range leptonic forces

New contribution

$$\langle \nu_e | H_{int} | \nu_e \rangle = \sqrt{2} G_F N_e + V_L \qquad V_L(r) = \frac{\alpha_L}{r} \int_0^r d^3 r N_e$$

Demand not to spoil $\nu_\odot$ solution

$$\Rightarrow \quad \alpha_L \leq 6.4 \times 10^{-54}$$

$10^5$ improvement

free from screening effects
valid for ranges > solar radius

# CONCLUSIONS

If PVLAS signal confirmed, and it is due a new particle coupled to photons, we need a model to explain why astrophysical bound are not valid.

We have presented a model where the new particle is composite and there is a low energy scale. The model allows to evade astrophysical constraints.

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