LIGHT DARK MATTER

A NEW INTERACTION ?

+ A NEW LIGHT GAUGE BOSON

U

Pierre FAYET

Workshop "Dark Side of the Universe"

Minneapolis, june 7$^{\text{th}}$ 2007

Discuss possible

NEW CANDIDATES

for DARK MATTER

There is still room for

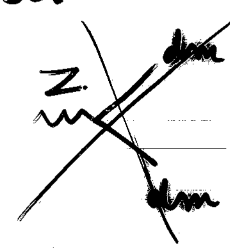
$$\boxed{\text{UNCONVENTIONAL POSSIBILITIES}}$$

relics)

HOW COULD LIGHT DARK MATTER PARTICLES exist !

should be :

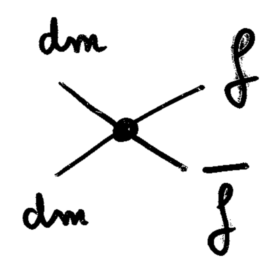
- NEUTRAL
- STABLE
  ↓
  new quantum number



- No direct coupling to the **Z**

  (otherwise, would have been "seen" in Z decays at LEP)

- Annihilation cross-sections



$$dm + dm \to f \bar{f}$$

should lead to

CORRECT RELIC DENSITY

knowing that

$$\Omega_{dm} h^2 \sim \frac{1}{\sigma_{ann} \, v_{rel}}$$

$\Omega_{LDM} \simeq 22\%$

Evaluate required ANNIHILATION CROSS-SECT. for LIGHT D.M.

$\boxed{\Gamma \simeq H}$ at freeze out

$(T_F = \frac{m}{x_F})$

$\downarrow$

$$n_{dm} \langle \sigma_{ann} v_{rel} \rangle \approx \sqrt{g_*} \, \frac{T_F^2}{m_{Pl}}$$

Now: $N_{odm} = (2)\, n_{odm} = (2) \left[\frac{4}{11}\right] \left(\frac{T_{o\gamma}}{T_F}\right)^3 n_{dm}$

if $\underset{\sim\sim\sim}{dm \neq dm^*}$ if $\underset{\sim\sim\sim}{\sim m_e < T_F < \sim m_\mu}$

$\rightarrow \quad \rho_{dm} = (2)\; n_{odm}\, m_{dm}$

$\rightarrow$

$$\underset{\sim\sim\sim}{\Omega_{dm} h^2} \approx (2) \left[\frac{4}{11}\right] \ldots x_F \sqrt{g_*} \; \frac{\cdots\cdot}{\underset{\sim\sim\sim}{\langle \sigma_{ann} v_{rel} \rangle}}$$

$\uparrow \quad \uparrow \qquad \uparrow \quad \uparrow$

$\Omega_{dm} h^2 \simeq .11 \quad \longleftrightarrow$

$\boxed{\langle \sigma_{ann} v_{rel} \rangle \sim 2 \text{ to } 10 \text{ pb}}$ here

depending on

$\rightarrow \underline{dm = dm^*}$ or $\underline{\neq dm^*}$

m_{dm} : $\rightarrow T_F < \sim m_e$ or $T_F > \sim m_e$ $\qquad x_F \qquad g^*$

Altogether – in the case of

$$\sigma_{ann}\, v_{rel} \;\propto\; v^2$$

(*P*-**wave annihilation** cross **section**)

we get:

- for self-conjugate spin-1/2 **Majorana** particles:

$$< \sigma_{ann}\, v_{rel}/c > \;\simeq\; \underline{\mathbf{4\text{ - }5\ \ pb}}$$

- for non-self-conjugate **spin-0 scalars**:

$$< \sigma_{ann}\, v_{rel}/c > \;\simeq\; \underline{\mathbf{8\text{ - }10\ \ pb}}$$

[self-conjugate scalars cannot have a P-wave pair annihilation cross section !]

Remember that:

$$1 \text{ pb} \;=\; 10^{-36}\ \text{cm}^2$$

$$1 \text{ pb} \times c \;\simeq\; 3\ 10^{-26}\ \text{cm}^3/\text{s}$$

These are in fact

"relatively large" annihilation cross section !

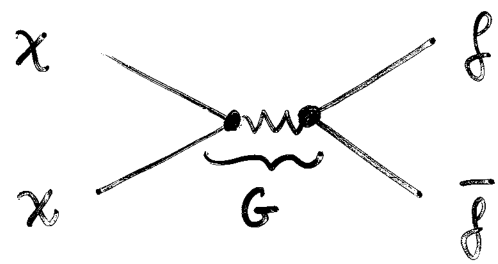
... yes, but as compared to **what ??**

LARGE ANNIHILATION

CROSS. SECTIONS REQUIRED !

a few pb !

Usually :



- Interaction $\sim$ $G \quad \bar{\chi} \ldots \chi \quad \bar{f} \ldots f$

$$\sigma v \sim \frac{G^2}{2\pi} \, m_\chi^2$$

- Weak interactions: $G = G_F = 10^{-5} \; GeV^{-2}$

$$\frac{G_F^2}{2\pi} \, (1 \; GeV)^2 \simeq 10^{-38} \; cm^2 = \frac{1}{100} \; pb$$

$$\boxed{\begin{array}{l} \text{WEAK. INTERACTION} \\ \quad \text{CROSS. SECTIONS} \\ \text{by far TOO SMALL} \\ \text{for correct relic abundance.} \end{array}}$$

⇒ TOO MUCH DARK MATTER !!

How can we have a

sufficient ANNIHILATION RATE

for LIGHT DARK MATTER particles

? ⊕ ↳ [Large σ potentially troublesome!]

$$\boxed{\text{NEW ANNIHILATION MECHANISMS needed}}$$

Discuss new situations, in particular

SCALAR DARK MATTER

$$\boxed{\text{New PARTICLES + possibly NEW INTERACTIONS required}}$$

[spin-$\frac{1}{2}$ D.M. also possible]

... as in all extensions

of the STANDARD MODEL

(supersymmetric theories, axions, GUTs,

LIGHT DARK MATTER MODEL

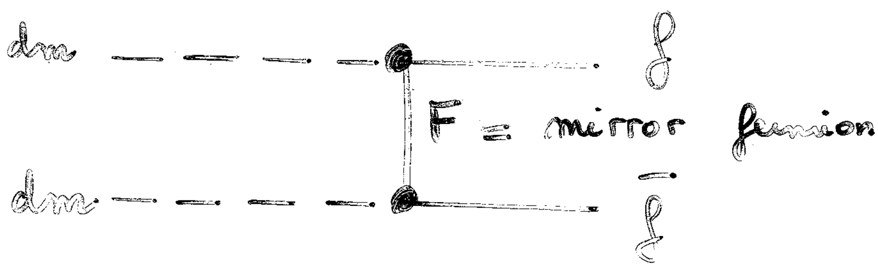
LIGHT SCALAR DARK MATTER

LIGHT SPIN 1/2 DM

with C. BOEHM
(may 2003)
Nucl. Phys B 683 (2004) 219

3 possibilities:

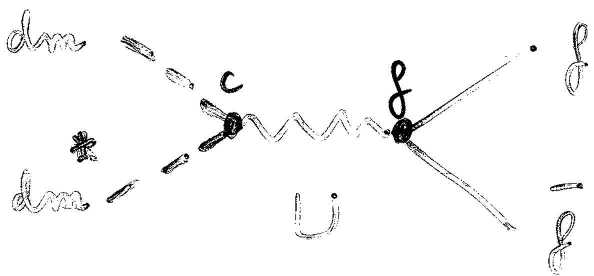
(I) Exchange of MIRROR FERMIONS



(reminiscent of N=2 SUSY or extra dim. theor.)

$$\sigma v \sim \frac{\cdots\cdot}{m_F^{2}} \qquad \text{can be large}$$

(II) Virtual production of LIGHT NEUTRAL NEW GAUGE BOSON **U**

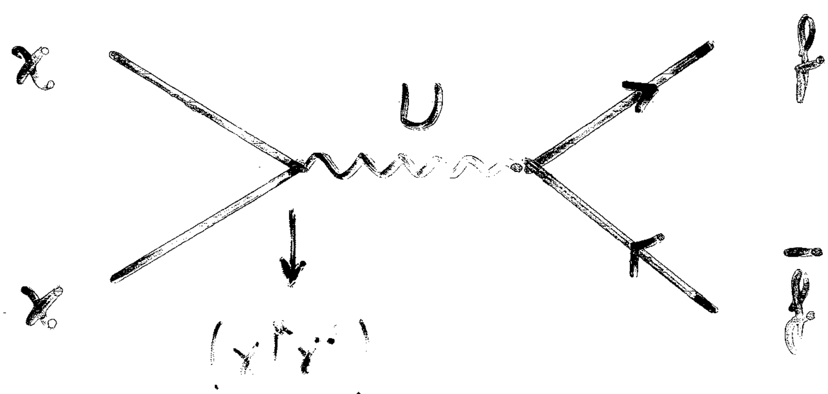


III

SPIN - 1/2 LIGHT DARK MATTER

annihilating through

U - BOSON EXCHANGE



Phys. Rev. D 70 (2004)
[illegible]

BUT: If large σ

Why have such new particles and processes not shown up in

– particle physics accelerators

Potential difficulty with, maybe, excessive γ-ray production: avoided if

CROSS-SECTIONS ARE ENERGY-DEPENDENT

$$\boxed{\sigma_{ann}\, v_{rel} \sim v^2}$$

Boehm-Ensslin-Silk

P-WAVE ANNIHILATION

(at least at freeze-out)

$\Rightarrow$ $(\sigma_{ann} V)_{\text{residual annihilations}}$

$\sim 10^{-5} \, (\sigma_{ann} V)_{\text{primordial ann. at freeze out}}$

small enough.

$\rightarrow$ USE $\boxed{\langle \sigma_{ann} v_{rel} \rangle \approx v^2}$

at least at freeze-out

- This is not the case for annihilation through MIRROR ~~EXCHANGES~~

(S-wave annihilation)

(↳ could still contribute to halo annihilations)

- This is the case for annihilations through

$$\boxed{\text{SPIN-1 U-BOSON}\quad \text{virtual production}}$$

(P-wave annihilation)

New GAUGE INTERACTION

cf. P.F. Phys. Lett. B 95 (1980) 285, Nucl. Phys. B 187 (1981) 184 ...

$$SU(3) \times \underbrace{SU(2) \times U(1)} \times \text{Extra } U(1)$$

$\downarrow \qquad\qquad\qquad\qquad \downarrow$

A GAMMA RAY SIGNATURE

from the GALACTIC CENTER

at low energy

could be due to a

LIGHT NEW GAUGE BOSON

C. Boehm - P.F

(May 2003)

→ Nucl. Phys. B, 2004

(Sept. 2003)

INTEGRAL Observes

BRIGHT 511 KeV γ RAY LINE

FROM GALACTIC CENTER

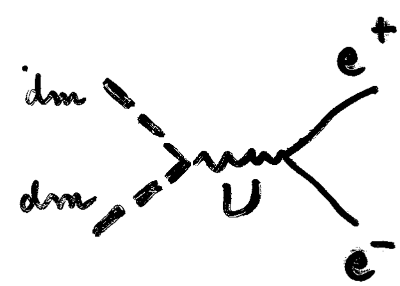
Signals decays of

POSITRONIUM $\rightarrow \gamma\gamma$

Where are the e^+ coming from ?

- Apparently not so easy to get them from Astrophysical processes.

- Could be a sign of



$\boxed{\text{LIGHT DARK MATTER ANNIHILATIONS}}$ into e^+e^-

(C. BOEHM, M. CASSE PRL 2004
D. HOOPER, J. SILK, J. PAUL

Origin of a LIGHT GAUGE BOSON

U in SUSY THEORIES

SUSY EXTENSIONS OF S. M.

with

electroweak breaking : 2 HIGGS DOUBLETS + 1 SINGLET

$$\begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \qquad N \tag{74}$$

and trilinear $\lambda\, H_1 H_2 N$ superpot.

$\cancel{\mu\, H_1 H_2}$

[cf. "nMSSM" superpot.

$$\lambda\, H_1 H_2 N + \sigma N$$

generates electroweak breaking

even before SUSY breaking

[Nucl. Phys. B90, 104

- Consider <u>extra-$U(1)$-symmetry</u>

which rotates "differently" the 2 doublets:

$$H_1 \to e^{i\alpha} H_1 \qquad H_2 \to e^{i\alpha} H_2$$

$$N \to e^{-2i\alpha} N \tag{74}$$

$$\underbrace{\lambda \cdot H_1 H_2 N + \cancel{\sigma N}}_{\sim \text{ MSSM}} \qquad \cancel{\mu H_1 H_2} \quad \cancel{N^2} \quad \cancel{N^3}$$

Naturally small $\to$ even 0

- Acts axially on quarks and leptons

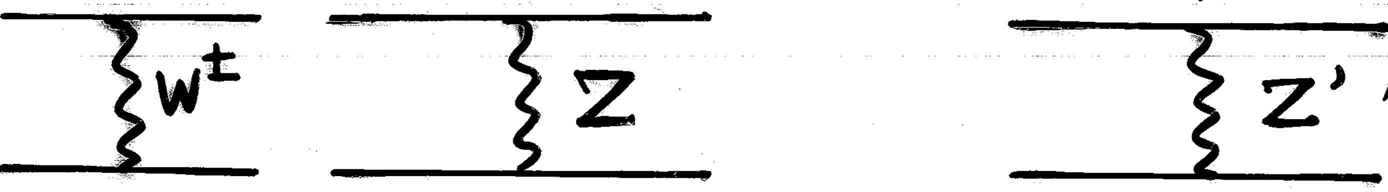
$U(1)_A$

- Gauge it $\Rightarrow$ "UMSSM" PL 69B (1977) 489

(with mirror fermions or exotic fermions to cancel anomalies)

→ Additional neutral current:

new gauge coupling



S.M. $\sim G_F$ S.M. $\sim G_F$ $\sim G_F$? $\rightsquigarrow$ U

would spoil N.C. Phenomenology

($\gtrsim G_F$?)

— unless very heavy ($\to \gtrsim$ TeV)

as usual

(using extra singlet v.e.v.)

— or

$\boxed{\text{light and very weakly coupled} \quad \text{U BOSON}}$

(1980)

(not safe yet ....)

Coming back to LDM annihilations:

WHY has such a NEW PARTICLE

and corresponding NEW INTERACTION

not been observed

?

especially if NEW INTERACTIONS

are $\boxed{\text{STRONGER than WEAK INT.}}$

as necessary to provide for

sufficient ANNIHILATIONS of

LIGHT DARK MATTER particles

?

yes, U-Interactions are

$\boxed{\text{stronger than weak interactions}}$

but ONLY <u>AT LOWER ENERGIES</u>

when WEAK interactions are

REALLY WEAK ($\sim G_F^2 E^2$)

But they are

$\boxed{\text{WEAKER than WEAK}}$

<u>AT HIGHER ENERGIES</u>

when weak interactions are "strong"

as they are

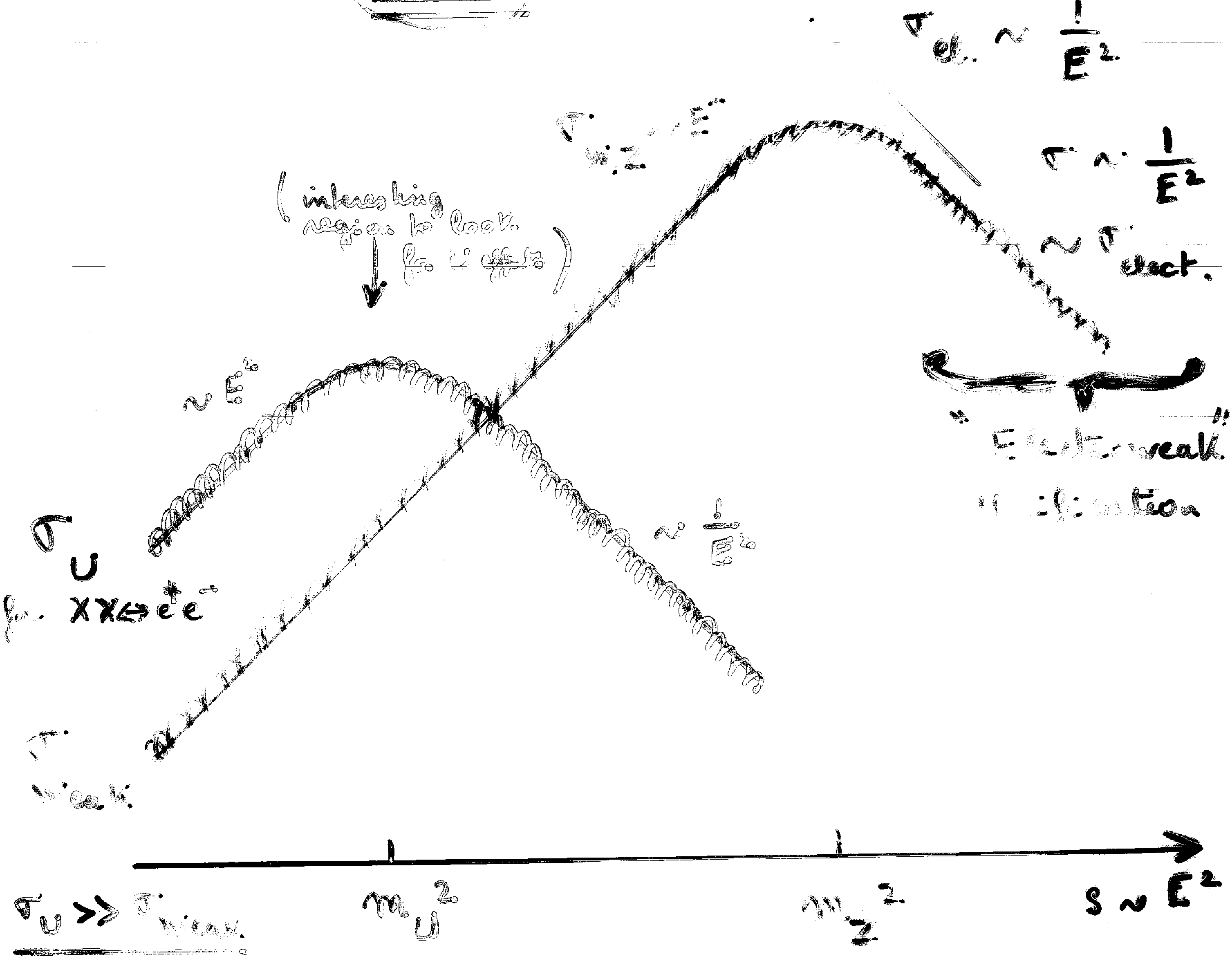
DAMPED BY U-PROPAGATOR effects

Both Spin 0 or Spin $\frac{1}{2}$

$$\boxed{\sigma_{ann}\, v_{rel} \sim v^2 \underbrace{(c^2 f^2)}_{\text{Very small: typically of} \sim 10^{-6}} \frac{E^2}{(m_U^2 - 4E^2)^2} \approx \text{a few pb}}$$

v^2: P. wave ann

Why a new LIGHT GAUGE BOSON U:



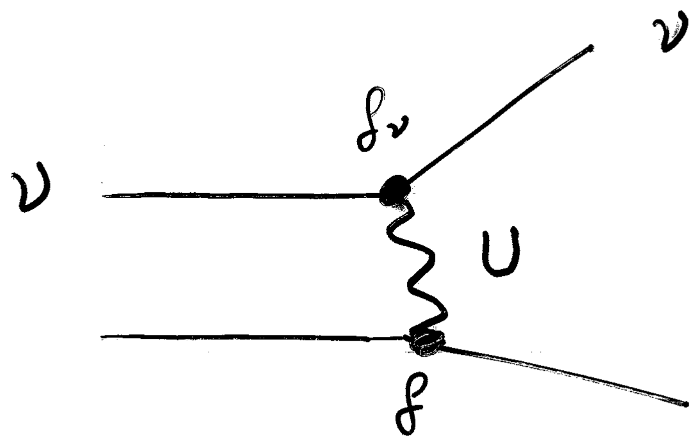
U-Interactions significantly STRONGER THAN WEAK

POSSIBLE EFFECTS ON :

- NEUTRINO
  scattering CROSS-SECTIONS
- Direct PRODUCTION
  of U-BOSONS
- Anomalous MAGNETIC MOMENTS
  of e^-, μ^-.
- PARITY-VIOLATION
  in Atomic physics
- NUCLEOSYNTHESIS

etc.

NEUTRINO SCATTERING



$$\mathcal{A} \sim \frac{f_\nu f}{m_U^2 - q^2} = \frac{f_\nu f}{m_U^2} \, \frac{m_U^2}{m_U^2 - q^2}$$

$$\downarrow$$

$$\ll 1$$

$$\text{if } m_U < \sqrt{|q^2|}$$

- No constraints at high-energy
- Constraint from $\nu + e$ at low. q^2

$$\boxed{\frac{f_\nu f_e}{m_U^2} \lesssim G_F}$$

If $f_\nu \sim f_e$

Direct production of U-boson ?

- Couplings to matter $f \ll e$ (by several orders of magnitude)
- Production cross-sections:

$$\underline{\sigma_{prod.} \approx f^2}$$

Very small ?

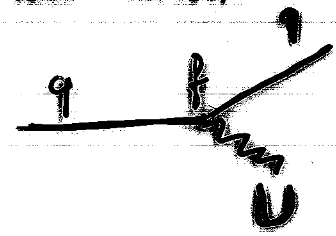
Naïvely tend to vanish if $f \to 0$

But:

THIS IS WRONG !!

For a U with longitudinal polarisation:

$$\varepsilon_L \sim \frac{k^\mu}{m_U} \quad m_U \to \text{small}$$



Amplitudes:

$$\mathcal{A} \sim f \, \frac{k^\mu}{m_U = g'' F} \sim \frac{k^\mu}{F}$$

f, g'': ~ small extra U(1) gauge coupling

$\frac{k^\mu}{F}$: independent of coupling g''

F = extra U(1) br. scale

If the <u>U-CURRENT</u> has a (non-conserved) <u>AXIAL PART</u>

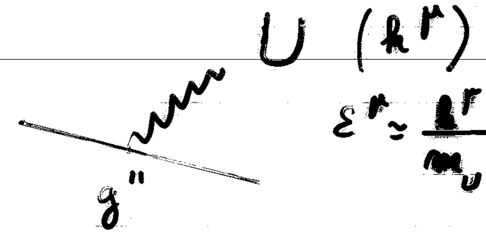
the U-boson would behave much like a <u>spin-0 AXION</u>

↓

unobserved !

[$f_{\text{pseudoscalar}}$ with the $=$ $2\, m_f$ f_{Axial}]

AMPLITUDE



$$\sim \quad g'' \quad \left(\sim \frac{k^\mu}{m_U} \right) \quad \times \quad \text{current}$$

for longitudinally polarized U boson

very small × very large $\rightsquigarrow$ finite

$$\frac{g''}{m_U} = \frac{1}{\text{extra } U(1) \text{ breaking scale}}$$

($\gtrsim$ electroweak scale)

$\Rightarrow$ "EQUIVALENCE THEOREM"

in low mass and low coupling limit

A VERY-LIGHT SPIN-1 U-BOSON IS PRODUCED AND INTERACTS AS AN AXIONLIKE SPIN-0 PARTICLE

(with axial part in the coupling)

(P.F. 1980)

- BUT PARTICLE PHYSICS EXPERIMENTS

$$\begin{cases} \psi \longrightarrow \gamma + \text{axion} < 1.4 \; 10^{-5} \\ \Upsilon \longrightarrow \gamma + \text{axion} < \underset{1.5}{\cancel{4}} \; 10^{-5} \end{cases}$$

EXCLUDED THE STANDARD AXION !

- WHAT ABOUT A SPIN-1 U-BOSON ?

Is it excluded ?

Not necessarily, as for the axion.

(Use large scale symmetry-breaking F)

THE AXION CAN BE MADE "INVISIBLE" — THE U-BOSON ALSO CAN BE MADE "INVISIBLE"

(using large Higgs singlet v.e.v.)

P.F. 1980

Owing to

① "EQUIVALENCE THEOREM"

for spin-1 U

in low mass / low coupling limit

U behaves as

spin-0 Goldstone boson a

of extra U(1)

"axion like"

② Large Higgs singlet v.e.v.

Extra U(1) broken "at a high scale"

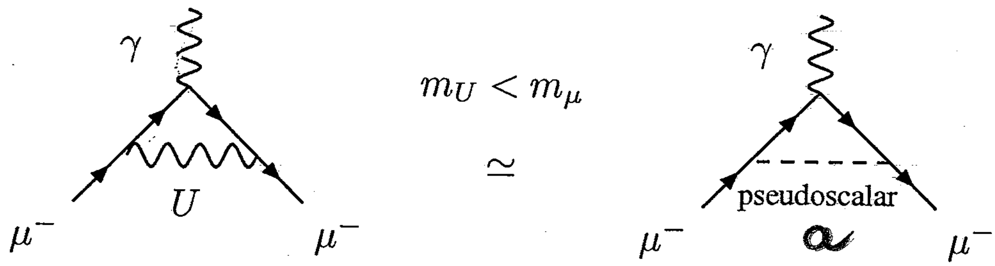
$$\boxed{U \to a = \overset{r}{\cos\zeta}\; \underset{\text{doublet}}{A} + \sin\zeta \;\text{singlet}}$$

amplitudes are multiplied par r (or r^2) < 1

"Equivalence theorem"

for light-weakly coupled gauge bosons

Contribution of <u>axial</u> coupling to $g_\mu - 2$:



For $m_U < m_\mu$, axial contribution roughly equivalent to that of very light pseudoscalar a, with axionlike couplings.

$$f_{\mu\,p} \;=\; \underbrace{2^{1/4}\, G_F^{1/2}\, m_\mu\, \frac{1}{x}}_{\text{as for standard axion}} \quad \underbrace{r}_{= \cos\zeta}$$

or very light A of MSSM

as for "invisible" axion

$$\text{with} \quad \frac{1}{x} = \tan\beta$$

$$A = \sqrt{2}\ \mathrm{Im}\,(\sin\beta\ h_1^\circ + \cos\beta\ h_2^\circ)$$

$$a = \cos\zeta\ A + \sin\zeta\ .\ \text{singlet}$$

"invisible U boson mechanism

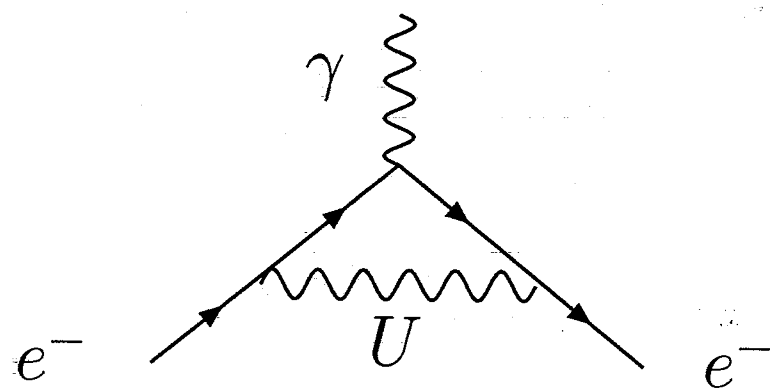
$r = \cos\zeta =$ "invisibility parameter" of the U boson, or of the corresponding axionlike pseudoscalar a

as

$$\delta a_\mu^A \approx - \underbrace{\frac{G_F\, m_\mu^2}{8\,\pi^2\,\sqrt{2}}}_{\simeq\, 1.2\, 10^{-9}} \frac{r^2}{x^2}$$

with $r^2/x^2 = \cos^2\zeta\ \tan^2\beta$,

CONSTRAINTS from $g-2$



- U-contribution to $g_e - 2$

$$\delta a_e \approx \frac{f_{eV}^2 - 5\, f_{eA}^2}{12\, \pi^2}\, \frac{m_e^2}{m_U^2} \quad \text{if } m_e \ll m_U$$

- U-contribution to to $g_\mu - 2$

Contribution of vector coupling:

$$\delta a_{\mu V} \approx \frac{f_{\mu V}^2}{8\, \pi^2} \quad \text{if } m_U < m_\mu$$

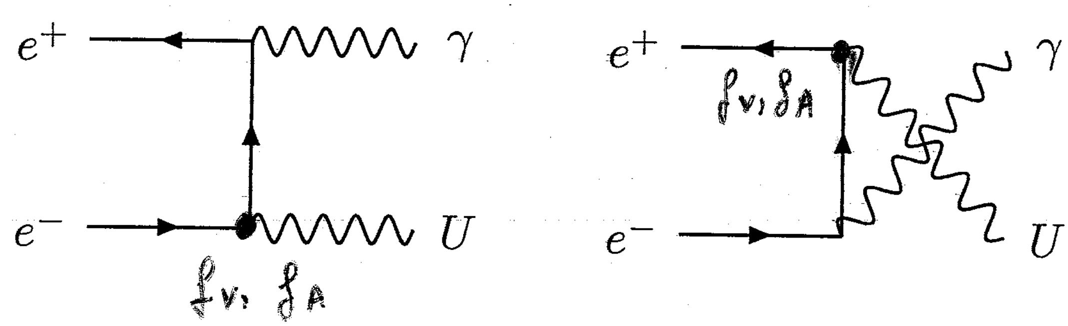
$\longrightarrow$ Could be responsible for

$$\delta a_\mu = a_\mu^{exp} - a_\mu^{th} \simeq (28 \pm 8)\ 10^{-10}$$

3 σ effect ?

$$\boxed{e^+ e^- \rightarrow \gamma U}$$

Boehm + F. Borodatchenkova, Choudhury and Drees



Production of U in e^+e^- annihilation:

$U \rightarrow$ preferentially LDM particles if $m_U > 2\,m_\chi$,
(or $\rightarrow$ e^+e^- or $\nu\bar{\nu}$)

light U:

$$d\sigma\,(e^+e^- \rightarrow \gamma\, U) \;\simeq\; 2\;\frac{f_{eV}^2 + f_{eA}^2}{e^2}\;d\sigma(e^+e^- \rightarrow \gamma\gamma)$$

Look for single monochromatic γ + missing energy-mom.

(Discussed in 1981 for positronium annihil., if $m_U < 1$ MeV)

Size of cross section depends on magnitude of f_{eV}, f_{eA}

?

severely limited

Also: from gauge invariance:

$$\boxed{f_{eA} = f_{\mu A} = f_{bA}}$$

(e, μ ! get mass from $\langle h_i^0 \rangle$)

Axial couplings to electrons f_{eA}

get constrained by

$\Upsilon \to \gamma + U/a$ decays

and

Parity-violation effects

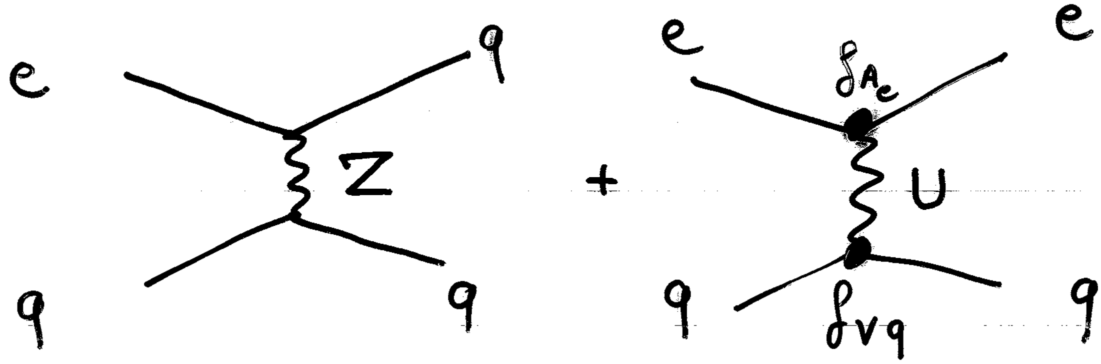
in atomic physics

S[illegible]

PRD [illegible] ([illegible]) CERN [illegible]

PARITY VIOLATION in ATOMIC PHYSICS

with Bouchiat



$$Q_W = \begin{cases} -72.74\ (29)\ (36) & \text{exp.} \\ -73.19 \pm .13 & \text{SM} \end{cases}$$

$$\Delta Q_W = .45 \pm .48$$

$$\boxed{-10^{-3}\, G_F < \frac{-\delta_{A_e}\,\delta_{V_q}}{m_U^2} < 3\ 10^{-3}\, G_F}$$

C. Bouchiat. P.F. ($m_U \gtrsim$ few MeV's)

(with no axion like particle)

$\Rightarrow$ favors VECTOR COUPLING

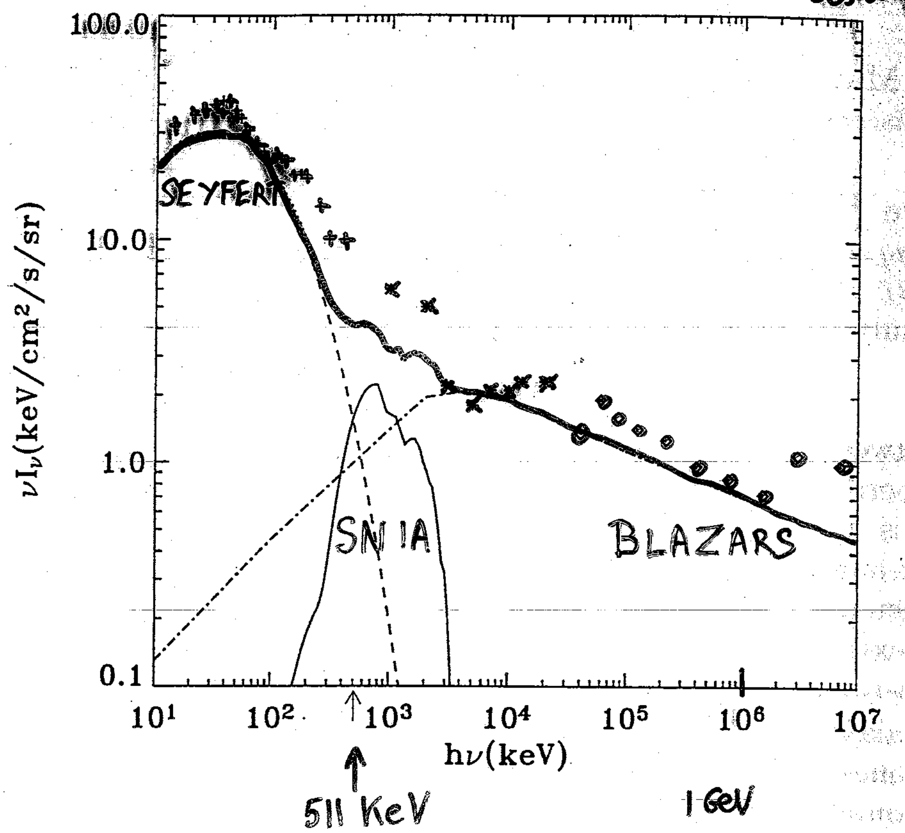
of U boson

DIFFUSE γ-RAY BACKGROUND

Y. Rasera et. al.

××× : observations

—— : contribution from astrophysical sources



→ $h\nu$

FIG. 1: Diffuse background spectrum as a function of photon energy. The crosses (HEAO), stars (COMPTEL) and diamonds (EGRET) correspond to the observations [1, 2]. At low energy, Seyfert galaxies (dashed line) are the main contributors [1]. At intermediate energy, SNIa (continuous line), as calculated in this article, dominates. At high energy blazars (dot-dashed line) explain the observed cosmological gamma-ray background [4]. Altogether the sum of the three contributions (dotted line) reproduces it rather well. However, an additional contribution from light Dark Matter particles, of up to about 4 keV cm^{-2} s^{-1} sr^{-1}, is not excluded near 511 keV (indicated by an arrow).

⇒ MAXIMUM POSSIBLE NEW CONTRIBUTION

$\lesssim$ 4 KeV / cm^2 / s / sr ↘ around 511 KeV

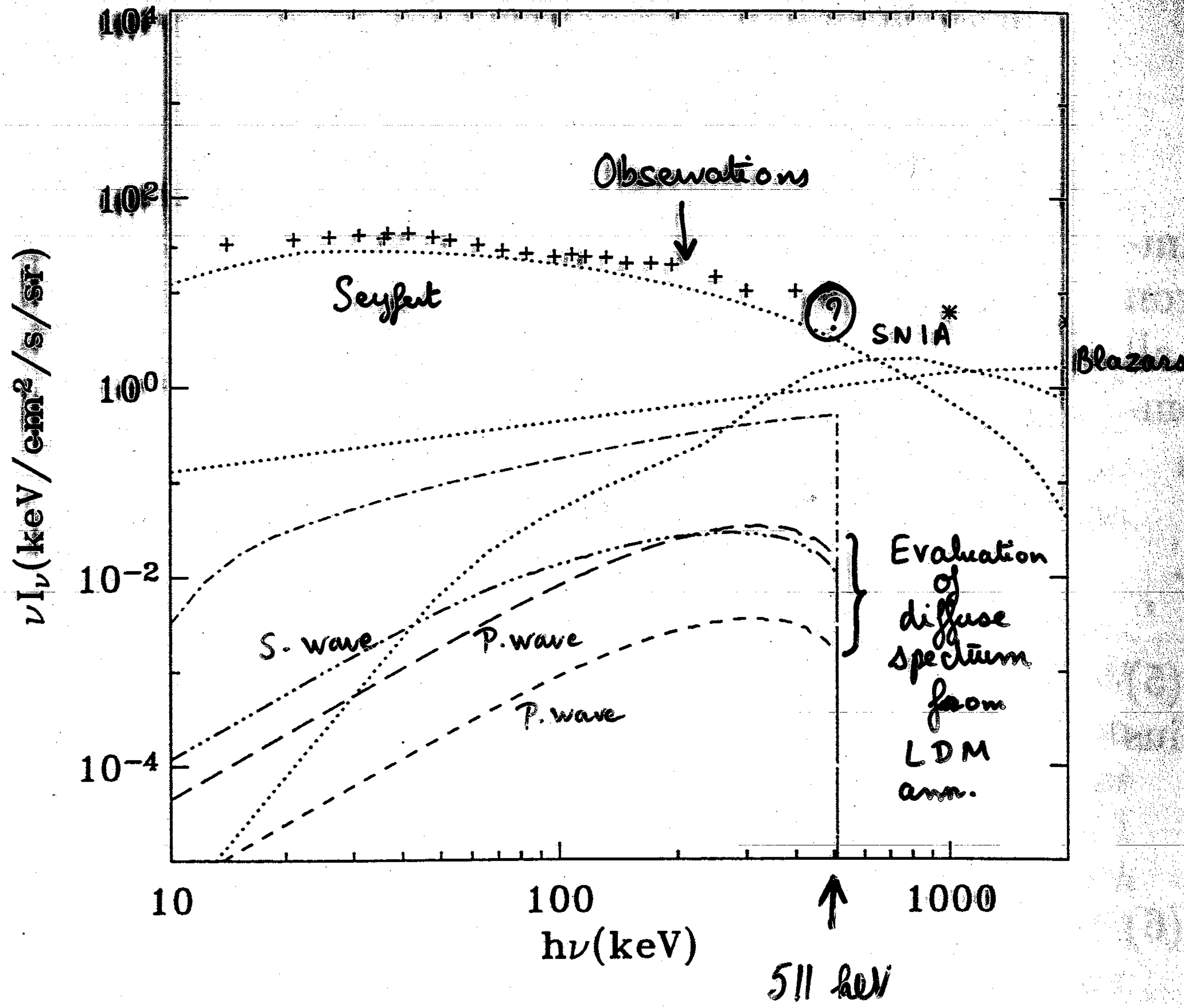
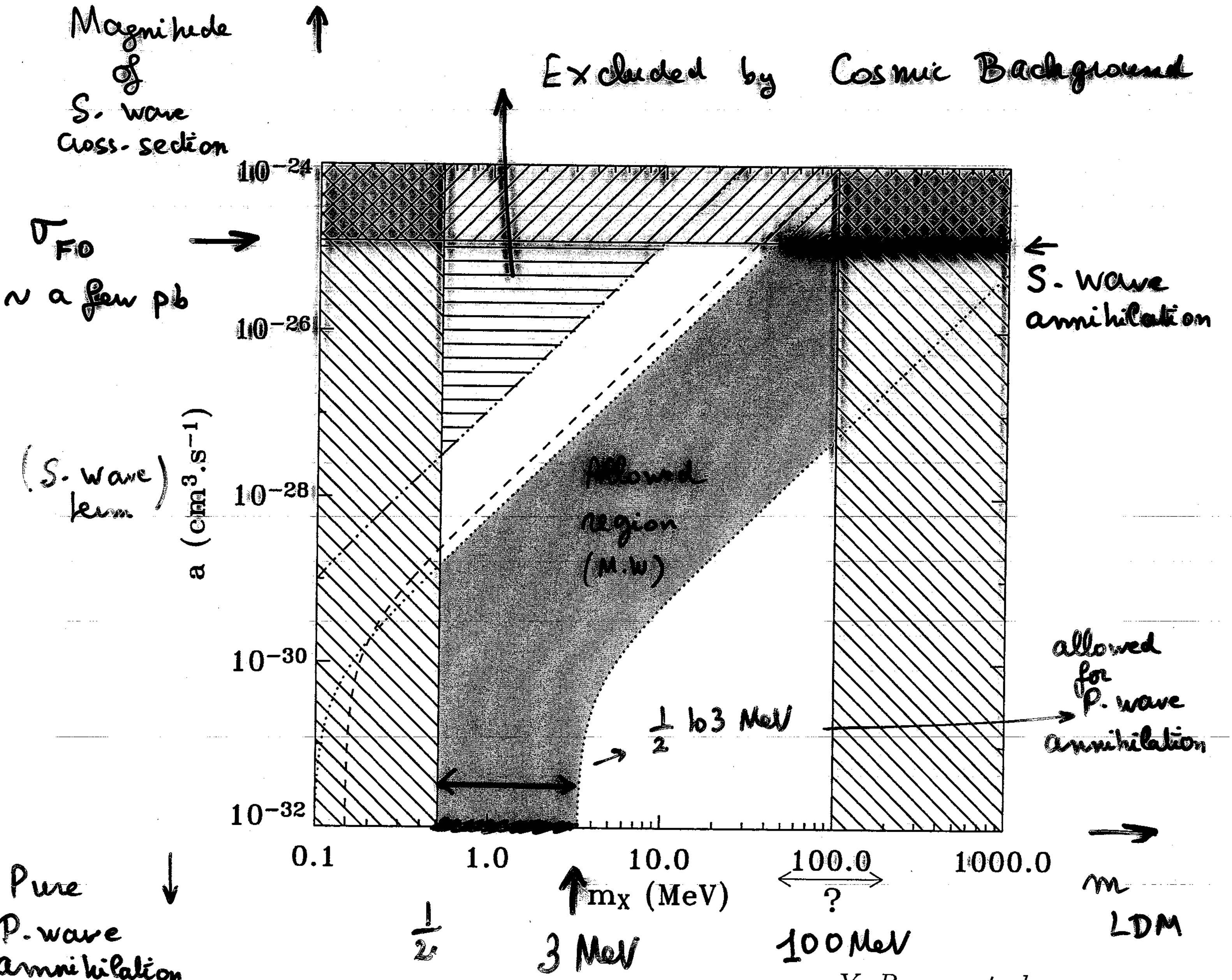


FIG. 4: Diffuse background spectrum. Crosses: HEAO data; stars: COMPTEL observations. The three dotted lines correspond to the contributions from Seyferts, SNIa and blazars. The dot-dot-dot-dashed line represents the new positron contribution to the cosmological gamma-ray background, for a S-wave cross-section. This contribution for a P-wave cross-section is also given for a NFW (dashed line) or Moore profile (long dashed line). (The background as computed in [13], significantly higher, is also shown for comparison, as a dot-dashed line.)



Y. Rasera et al.

Constraints on LDM in the $a - m_X$ plane, with a the velocity-independent part in $\sigma_{\rm ann}\, v_{\rm rel}$. b is fixed by the relic density, so that $\langle \sigma\, v_{\rm rel}\rangle_F \simeq < a + b\, v^2 >_F \approx 10^{-25}$ cm^3 s^{-1} at freeze-out. The upper line $a \simeq 10^{-25}$ cm^3 s^{-1} corresponds to a purely S-wave cross-section, and the lower part of the diagram to a P-wave dominated one. We limit ourselves to the mass interval $\frac{1}{2}$ to 100 MeV.

The grey region is the one compatible with the galactic constraint, based on the total level of emission, using the (Moore or NFW) dark-matter distributions of Table I (its upper part corresponds to a Milky-Way emission S-wave-dominated, with a behaving like $1/m_X^2$).

The dot-dashed line is associated with a LDM-induced background (for a NFW profile) that would correspond to the missing 4 keV cm^{-2} s^{-1} sr^{-1}, the top left-hand corner above this line being excluded on the basis of the cosmic background data. (Same for the dashed line with Moore profiles.)

CONCLUSIONs

* **LIGHT U-BOSON** (80)

hypothesis originated from

GAUGING of EXTRA-U(1)

in UMSSM (77)

with trilinear $\lambda H_1 H_2 N$ coupling

* Provided new interaction

with required characterics to make

LIGHT DARK MATTER possible

(before INTEGRAL results)

(03)

Spin-0 L.D.M

Spin-$\frac{1}{2}$ L.D.M

* $\sigma_{ann} v \propto v^2$

* New interaction:

  - stronger than weak at Low energy
  - weaker than weak at High energy

* LDM ann $\rightarrow e^+e^-$

  $\rightarrow$ POSITRONS

possibly at origin of 511 KeV Line

* $\boxed{\text{L.D.M + U - BOSON explain both RELIC DENSITY of D.M. + 511 KeV line}}$

* New Interesting effects in

  Particle Physics / Astrophysics

  to be further explored