LIGHT DARK MATTER

A NEW INTERACTION ?

Pierre FAYET

Workshop "Dark Side of the Universe"

Madrid, june 21st 2006

What is DARK MATTER ?

(Assuming it exists !)

- Assuming it is made of PARTICLES

presumably (even necessarily)

having some INTERACTIONS

$\longrightarrow$ NON-BARYONIC DARK MATTER

($\Omega_{dm} \simeq .23$)

DARK MATTER PARTICLES

- Normally: $\boxed{\text{WIMPS}}$

Weakly - Interacting Massive Particles

Best candidate:

$\boxed{\text{Spin-}\tfrac{1}{2}\ \ \text{NEUTRALINO}}$

of SUSY extensions of Standard Model

Stable from $\boxed{\text{R-PARITY}}$ conservation

with

$$R_p = (-1)^{2S}\,(-1)^{3B+L}$$

$\Rightarrow$ L.S.P. STable

$$\left\{\begin{array}{ll}\text{Ordinary particles:} & \oplus \\ \text{Superpartners} & : \ominus\end{array}\right. \quad \text{SUSY}$$

- BUT ....

NEUTRALINOS have not been seen

(yet)

LEP + ... results $\Rightarrow$

$m_{\text{Neutralino}} > \underline{\sim 30 \text{ GeV}}$

presumably also $\lesssim$ few hundred GeV

in most cases

if it is to be a

good Dark Matter candidate

- Compute relic abundance

$$\Omega_{dm} h^2 \sim \frac{1}{\sigma_{\text{annihilation}} v}$$

$\sim .1$

$$\Rightarrow \sigma_{ann} v \simeq 3\ 10^{-26} \text{ cm}^3/\text{s}$$

i.e. $\sim$ WEAK INTERACTION cr. sect.

Discuss possible

NEW CANDIDATES

for DARK MATTER

There is still room for

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

(thermic relics)

HOW COULD LIGHT DARK MATTER PARTICLES exist ?

should be :

- NEUTRAL
- STABLE

  ↓

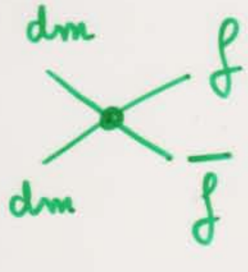
  new quantum number

- 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

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

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

$$\boxed{\Gamma \simeq H}$$ at freeze out $\left(T_F = \frac{m}{x_F}\right)$

$\downarrow$

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

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

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

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

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

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

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

depending on

$\rightarrow$ $dm = dm^*$ or $\neq dm^*$

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

$\rightarrow$ energy dep. of σ at threshold.

Recall:

"Lee-Weinberg" limit

on a heavy neutrino mass:

A weakly-interacting heavy neutrino

should be heavier than ≈ 2 GeV

$$\boxed{m_L \gtrsim 2 \text{ GeV}}$$

to have

$$\Omega_{dm}\, h^2 \lesssim 1$$

Now

$\Omega_{dm}\, h^2 \simeq .1$

given that

$$\Omega_{dm}\, h^2 \propto \frac{1}{< \sigma_{ann}\, v >}$$

with a <u>weak-interaction</u> annihilation cross section

$$\sigma_{ann}\, v \approx \frac{{G_F}^2}{(2\pi)}\ m_L^2\ \ldots$$

More precisely:

- $\rho_{dm} \;=\; (2)\; n_{\circ\, dm}\; m_{dm}$

$\Longrightarrow$ **Factor** 2 **present**

if Dark Matter particles differ from antiparticles

- $n_{\circ\, dm} \;=\; [\,\frac{4}{11}\,]\; \frac{T_{\circ\gamma}{}^3}{T_F^3}\; n_{dm}$

$\Longrightarrow$ $[\,\frac{4}{11}\,]$ **dilution factor present IF** $m_e \lesssim T_F \lesssim m_\mu$

This dilution factor is ABSENT, however, for

Lighter Dark Matter particles

($\lesssim$ **a few MeV)**

decoupling (at $T_F = m/x_F$**)**

after most electrons have annihilated.

- $n_{\circ\, dm}\; [\,\frac{11}{4}\,]\; \frac{T_F^3}{T_{\circ\gamma}^3}\; < \sigma_{ann}\, v_{rel} > \;\simeq\; 1.66\, \sqrt{g_*}\;\; \frac{T_F^2}{m_{Pl}}$

with $\quad g_*$ **depends on** T_F $\quad$ **and therefore on** m_{dm}

- **Further factor** ≈ 2 **of enhancement**

  of required annihilation cross section

  for P**-wave annihilation, for which**

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

(case of interest to us here)

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

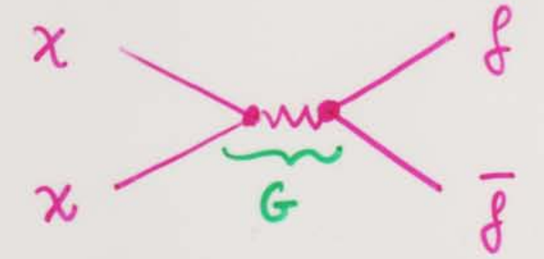
"relatively large" annihilation cross section !

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

LARGE ANNIHILATION CROSS. SECTIONS REQUIRED !

a few pb!

Usually :



- Interaction $\sim$ $G \;\; \bar{X} \dots X \;\; \bar{f} \dots f$

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

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

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

WEAK - INTERACTION
CROSS. SECTIONS
by far TOO SMALL
for correct relic abundance

$\Rightarrow$ TOO MUCH DARK MATTER !!

How can we have a

Sufficient ANNIHILATION RATE

for LIGHT DARK MATTER particles

?

$\oplus$ $\rightarrow$ [Large σ potentially troublesome!]

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

Discuss new situations, in particular

SCALAR DARK MATTER

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,
extra dimensions, strings .... !)

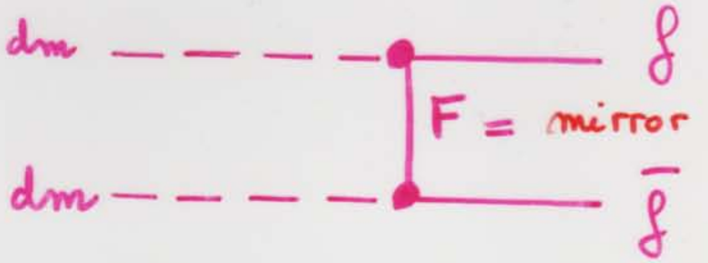
SCALAR DARK MATTER

[Spin $\frac{1}{2}$ light DM
also possible :
PF, Phys Rev D70 (2004) 023514]

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

2 possibilities:

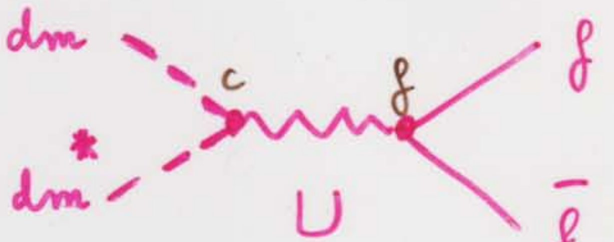
(I) Exchange of MIRROR FERMIONS



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

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

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



$$\sigma v \sim \frac{c^2 f^2}{(4E^2 - m_U^2)^2} E^2$$ can be large

But: if large σ's

Why have such new particles and processes not shown up in

- particle physics accelerators
- astrophysical processes

...

?

In particular, Large annihilation cross sections

$$dm\ dm \rightarrow f \bar{f}$$

dangerous, since could lead to

Excessive Gamma ray production

dangerous:

Seems to be EXCLUDED for

$m_{dm} \lesssim 100$ MeV

C. BOEHM. T. ENSSLIN J. SILK
(depending on how γ-ray production is evaluated)

UNLESS ....

CROSS-SECTIONS ARE ENERGY-DEPENDENT

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

(P-wave annihilation)

(at least at freeze-out)

Then

$(\sigma v)_{\text{residual annihilations}}$

$\sim 10^{-5} (\sigma v)_{\text{primordial annihilations at freeze out}}$

SMALL ENOUGH !

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

- 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

$\boxed{\begin{array}{c}\text{SPIN-1 U-BOSON} \\ \text{virtual production}\end{array}}$

(P-wave annihilation)

New GAUGE INTERACTION

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

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

Gluons , $W^{\pm}$, Z, γ , U

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

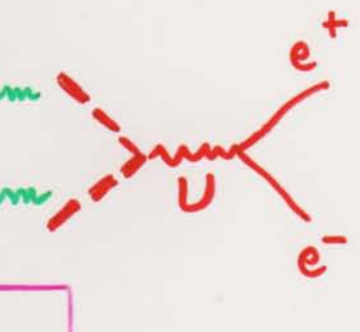
FROM GALACTIC CENTER

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

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 AT LOWER ENERGIES

when WEAK interactions are

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

But they are

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

AT HIGHER ENERGIES

when weak interactions are "strong"

as they are

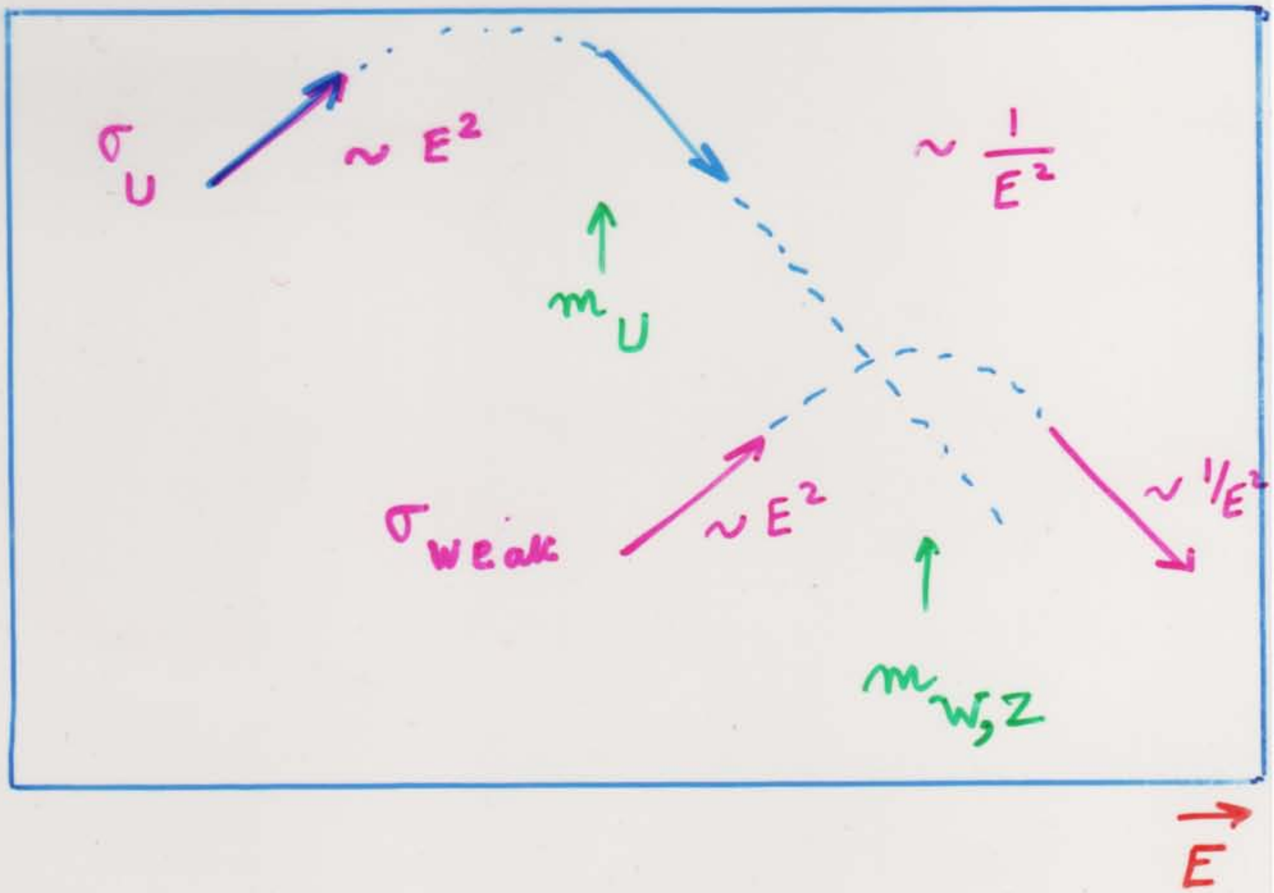
DAMPED BY U-PROPAGATOR effects

[Both for { spin-0, spin-1/2 } D.M. particles]

$$\boxed{\sigma v_{\text{ann rel}} \sim v^2 \underbrace{(c^2 f^2)}\,\frac{E^2}{(m_U^2 - 4E^2)^2}} \simeq \text{a few pb}$$

P wave annihilation

very small: typically $\underbrace{c\, f} \sim 10^{-6}$



U-interactions significantly

STRONGER than WEAK

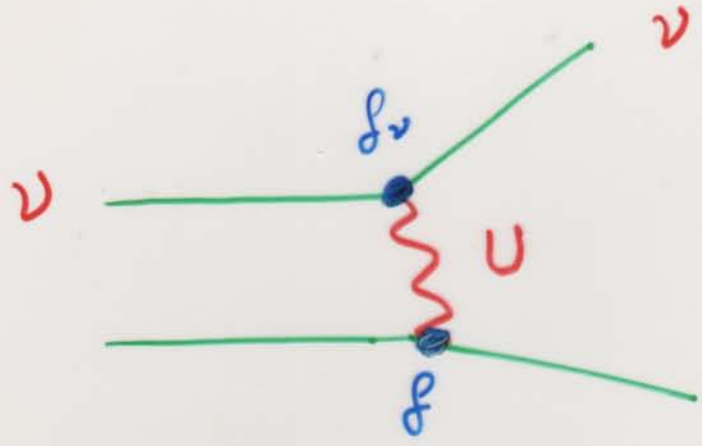
$\boxed{\text{but only at lower energies}}$

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



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

$$\downarrow$$

$$\ll 1$$

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

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

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

Direct production of U-boson ?

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

- Production cross-sections:

  $\sigma_{\text{prod.}} \gtrsim f^2$

Very small ?

Naïvely tend to vanish if $f \to 0$

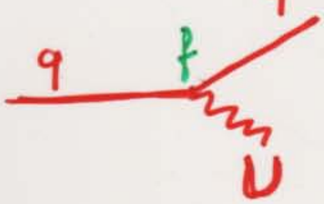
But:

THIS IS WRONG !!

For a U with longitudinal polarisation:

$$\varepsilon_L \sim \frac{k^\mu}{m_U}$$

$m_U \to$ small



Amplitudes:

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

~ small extra U(1) gauge coupling

independent of coupling g''

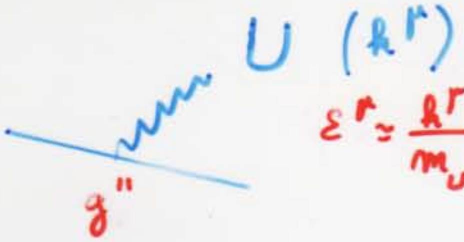
F = extra U(1) br. scale

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 !

AMPLITUDE



$\varepsilon^\mu \simeq \dfrac{k^\mu}{m_U}$

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

for longitudinally-polarized U-boson

very small × very large ⇝ finite

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

($\gtrsim$ electroweak scale)

⇒ "EQUIVALENCE THEOREM"

$\boxed{\text{A VERY-LIGHT SPIN-1 U-BOSON IS PRODUCED AND INTERACTS AS AN AXIONLIKE SPIN-0 PARTICLE}}$

(P.F. 1980)

(with axial part in the coupling)

• BUT PARTICLE PHYSICS EXPERIMENTS

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

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

Phys. Lett. 95B, 285; Nucl Phys B187, 184.

(you could make this longitudinal part almost "invisible", but you still want the U to interact significantly with ordinary matter) $\Longrightarrow$

$$\boxed{\text{Consider U- couplings to MATTER that are almost purely VECTORIAL}}$$

(OR: INVISIBLE U-BOSON MECHANISM

LARGE SYMMETRY BR. SCALE F

for EXTRA $U(1)$

through Large Higgs singlet v.e.v.)

limits

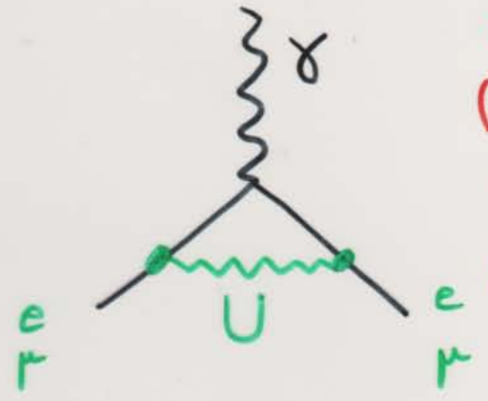
$\psi, \Upsilon \to \gamma\, U$:	$\dfrac{f_{A_q}^2}{m_U^2} < G_F/10$	hep-ph 04.08.357
$K^+ \to \pi^+ U$:	$\dfrac{f_{A_s}^2}{m_U^2} \lesssim G_F/300$	

OTHER CONSTRAINTS from

- $g-2$

for $m_e < m_U < m_\mu$

$$\begin{cases} f_{\nu e} \lesssim 2\ 10^{-4}\ m_U\,(\mathrm{MeV}) \\ f_{\nu \mu} \lesssim 6\ 10^{-4} \end{cases}$$



$\delta a_e =$
$(4 \pm 3)\ 10^{-11}$
$\delta a_\mu =$
$(2 \pm 2)\ 10^{-9}$

- Neutrino scatterings at lower energies

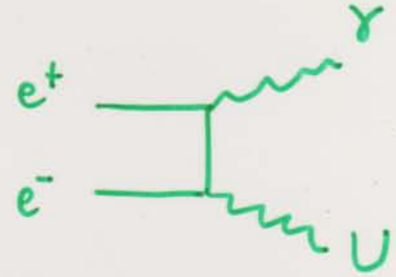
+ (W-Z terms)

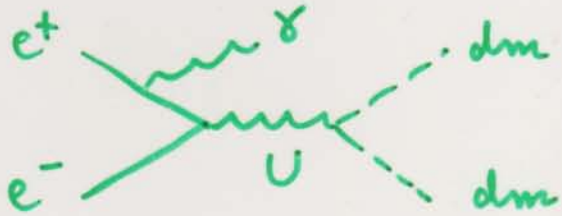
$$\frac{f_\nu f_e}{m_U^2} \lesssim G_F$$

- Nucleosynthesis

like 1 extra ν flavor?? but: ... !

- Searches in e^+e^-





- Funny effects in Nucleosynthesis etc:

Light Dark Matter particles

annihilating after Neutrino decoupling

would ultimately heat up photons relatively to Neutrinos.

$\rightarrow \quad T_\nu < T_{\nu \, \text{standard}} = T_\gamma \left(\frac{4}{11}\right)^{1/3}$

neutrinos contribute less to g^* !!

$g_{*\nu} < g_{*\nu \, \text{standard}}$

- Influence on Dark Matter residual abundance.
- Allows for less primordial helium than in Standard Model !

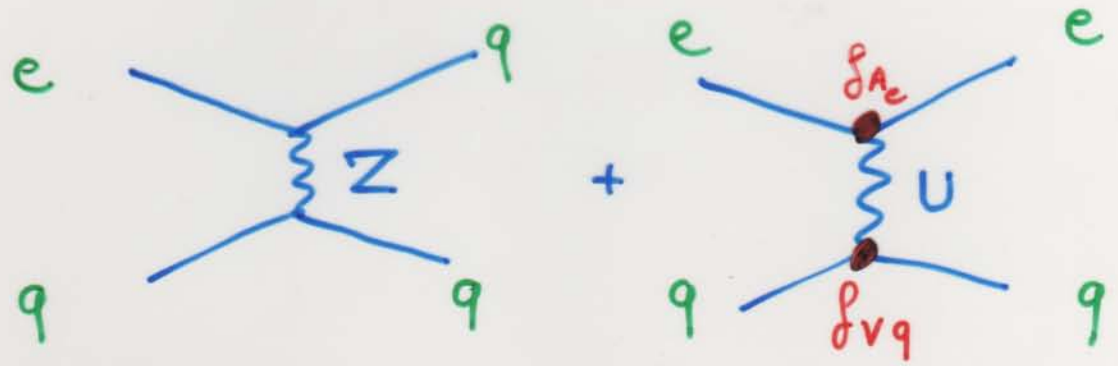
cf. Serpico. Raffelt - astro-ph. 0403417

BBN constraints $\rightsquigarrow$

$m_{dm} \gtrsim 2 \text{ MeV}$

PARITY-VIOLATION

in ATOMIC PHYSICS



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

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

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

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

(with no axion like particle)

$\Rightarrow$ favors VECTOR COUPLING

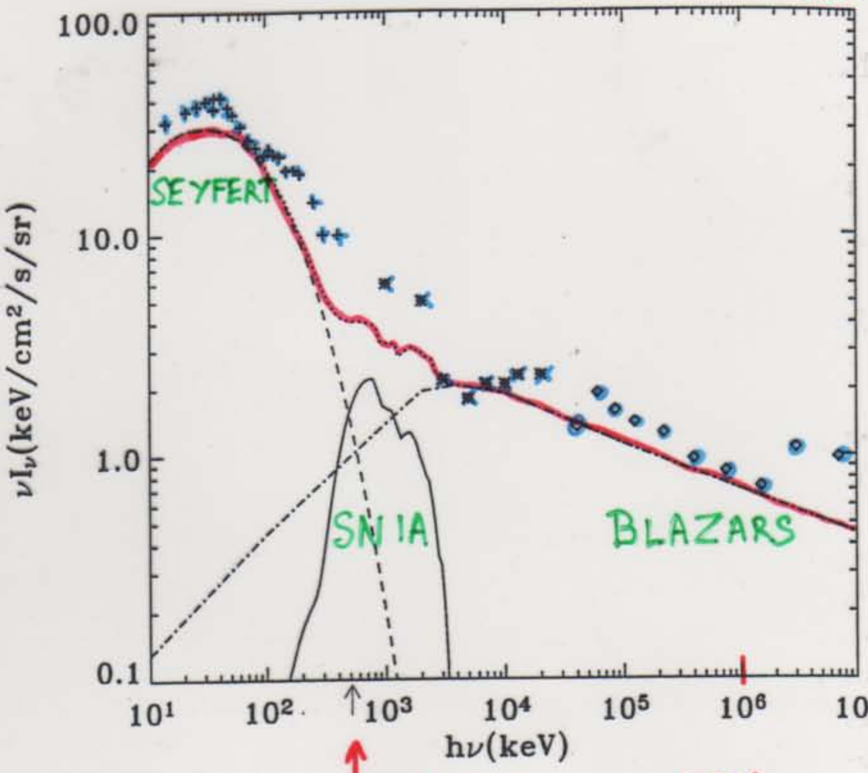
of U boson

DIFFUSE γ-RAY BACKGROUND

Y. Rasera et. al.

xxx : observations

——— : contribution from astrophysical sources



$\rightarrow h\nu$

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

⇒ Verify expected signal from all galaxies is indeed < this upper limit.

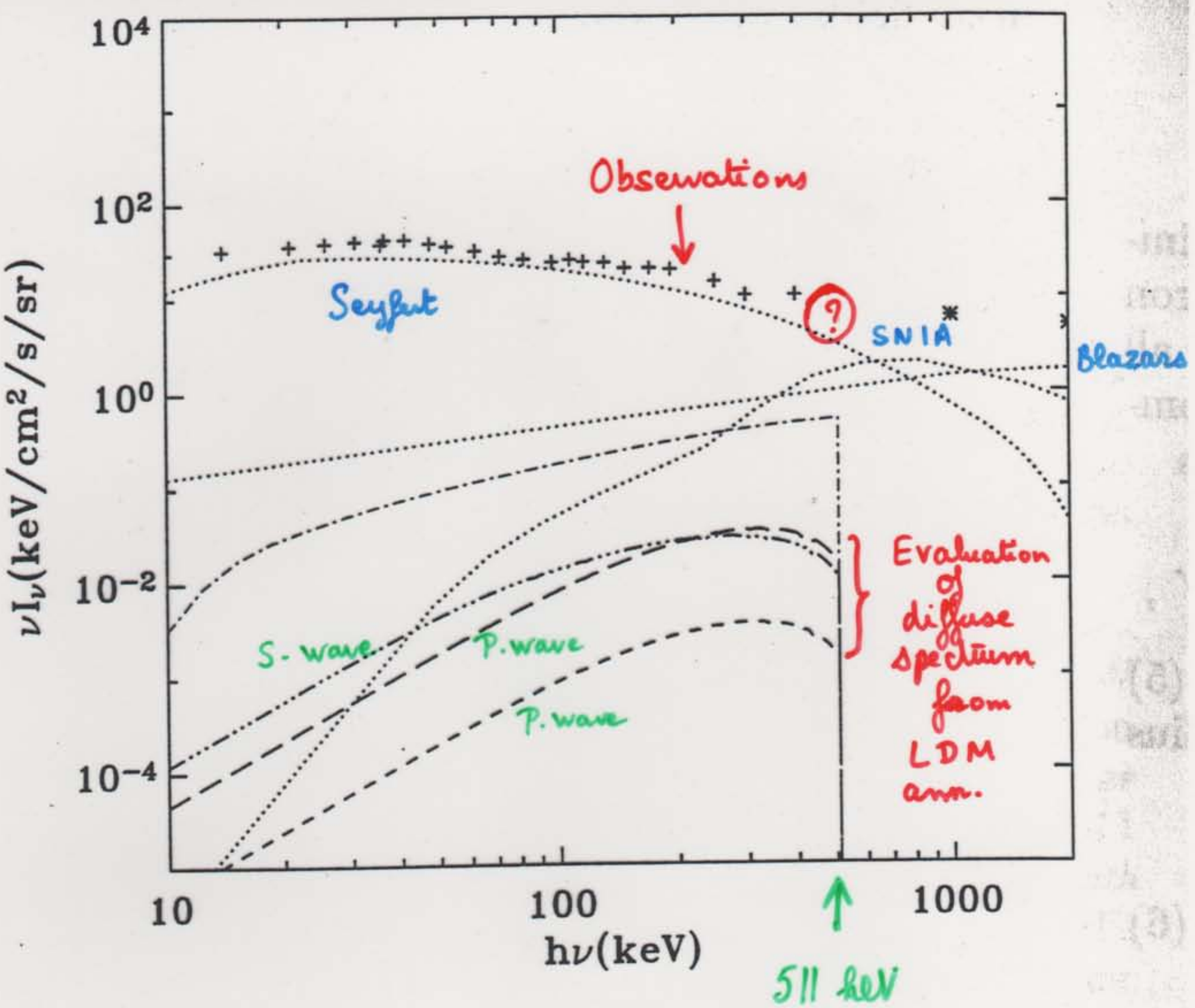
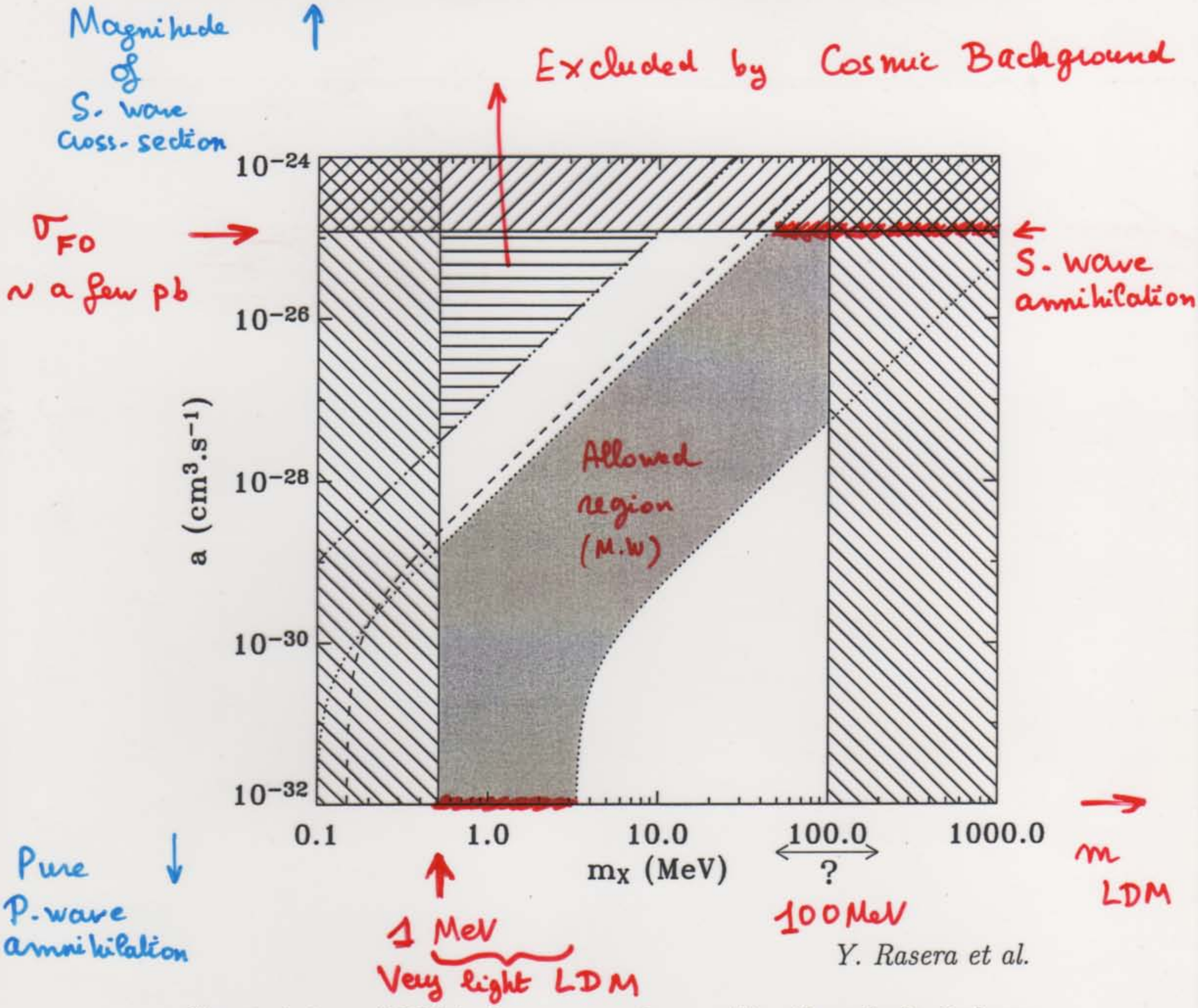


FIG. 4: Diffuse background spectrum. Crosses: HEAO data; stars: COMPTEL observations. The three dotted lines correspond to the contributions from Seyferts, SNIa and blazars. The dot-dot-dot-dashed line represents the new positron contribution to the cosmological gamma-ray background, for a S-wave cross-section. 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.)

Constraints on Light Dark Matter from SUPERNOVAE

with D. Hooper and G. Sigl

LDM particles can play a role in <u>core-collapse supernovae</u>

if relatively large

annihilation and scattering cross-sections

(compared to neutrinos)

- <u>Neutrinos stay in equilibrium</u> (through weak interactions) down to ≈ 8 MeV in supernovae explosion (ν_μ, ν_τ)

- <u>LDM particles annihilate</u>

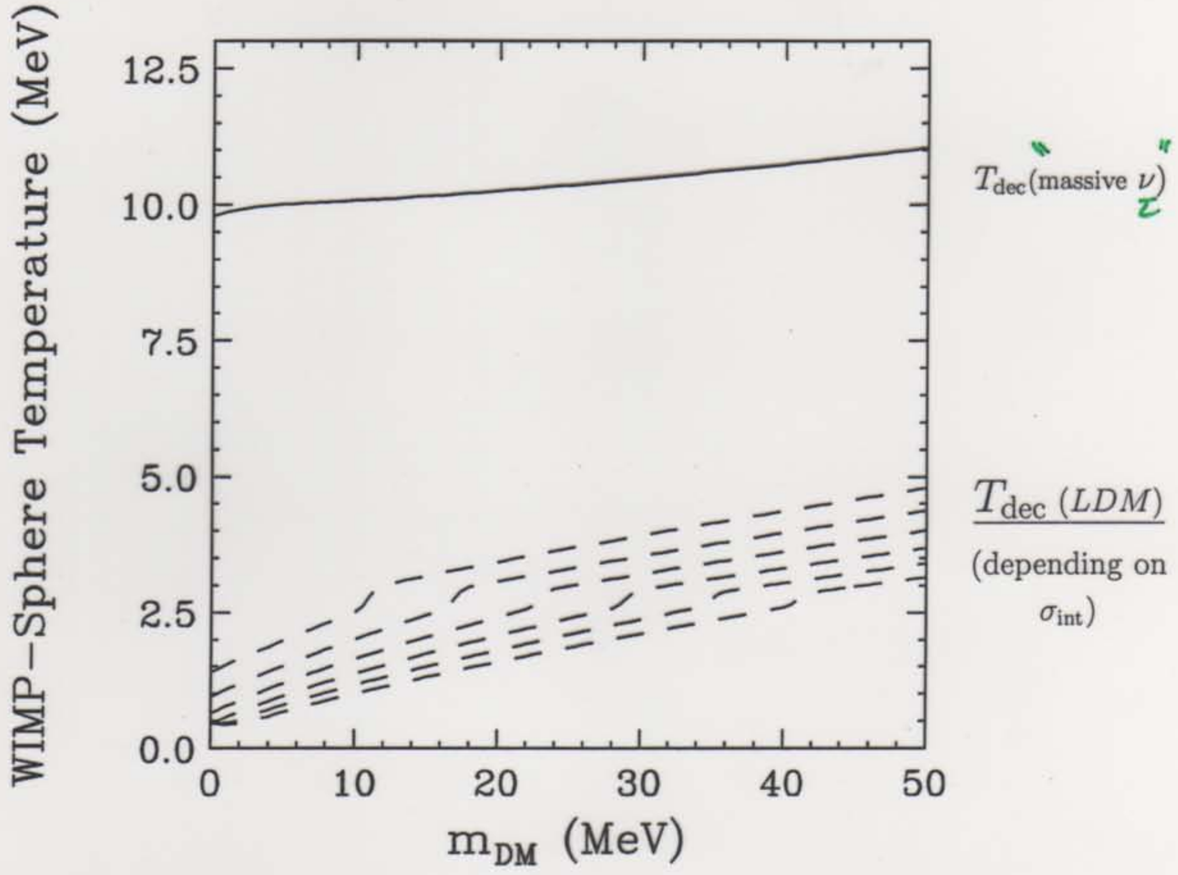
staying in equilibrium until they decouple

(occurs at $T_F \simeq m_X/17$, during expansion of Universe)

- **LDM particles can influence behavior of neutrinos in supernova by having relatively "large" interactions with them**

LDM decoupling temperature

(as a function of LDM-nucleon cross-sections):



$\Longrightarrow$ **Neutrinos** **may be kept**

longer in equilibrium

due to stronger-than-weak interactions with LDM particles

ν decoupling temperature in supernova

possibly lower than in Standard Model

if DM particles

1) are sufficiently light

2) interact sufficiently with neutrinos

Crucial ingredient: magnitude of

neutrino/LDM scattering cross-section

Lighter LDM masses $\lesssim$ 10 MeV

are practically excluded

UNLESS neutrino-LDM interactions

remain relatively small

compared to electron-LDM interactions

"small" neutrino-LDM cross-sections possible if:

- spin-0 LDM coupled through heavy fermions exchanges (due neutrino chirality)

and/or

- small (or 0) coupling of U boson to neutrinos

CONCLUSIONs

LIGHT DARK MATTER =

Viable possibility, to be confronted to

Standard WIMP (NEUTRALINO) SCENARIOS

Spin $\underline{\underline{0}}$ or Spin $\underline{\underline{1/2}}$

- LARGE $\sigma_{ann}\, v \approx v^2$
- New INTERACTIONS responsible for Dark Matter annihilations
- Annihilations due to a New light SPIN-1 BOSON U have the required characteristics: $\sigma v \sim v^2$

→ Stronger than weak at Low energy
Weaker than weak at High energy

- 511 KeV Line a poss. signature
- Consequences in Particle Physics / Astrophysics to be further Explored.