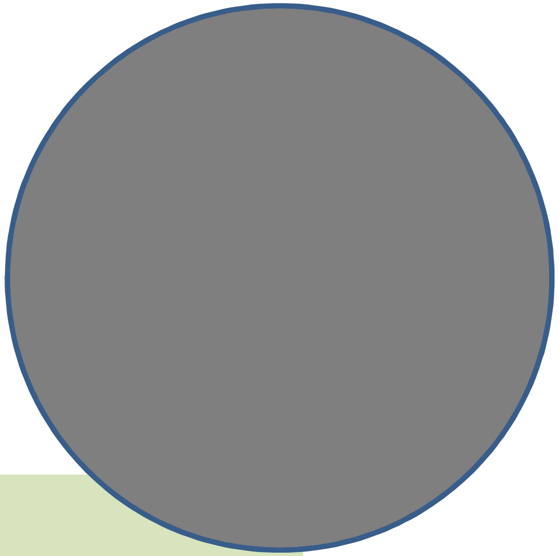
Variations on dark matter…

And, in part 2:
Which Scalar Boson?

Jean-Marie Frère, ULB, Bruxelles

Dark matter – the standard lore.



- Needed (at least) to explain galactic rotation curves
- Most likely particles (search for Jupiter-like objects did not find enough candidates
- At best, weakly interacting (and in fact, solution favoured to account for density by decoupling) in the cooling Universe
- (Nearly) spherical halo (few tests, …) , low (0) angular momentum
- Ab-initio simulations
- In our galaxy: 0.3 GeV/cm^3 at Sun's location

Could there be more structure?

- Dark disk ?

- Dark matter at Solar system scale ?

Dark disc:
Possible, notably if there is accretion after collision with other galaxies; existing disk then concentrates the accreted matter.
Simulations (Athanassoula et al..
NOT the main contribution to mass, but a co-rotating disc can increase considerably the capture rate in the Sun or in the Earch

Some conservative numbers from
F-S Ling **Phys.Rev. D82 (2010) 023534**

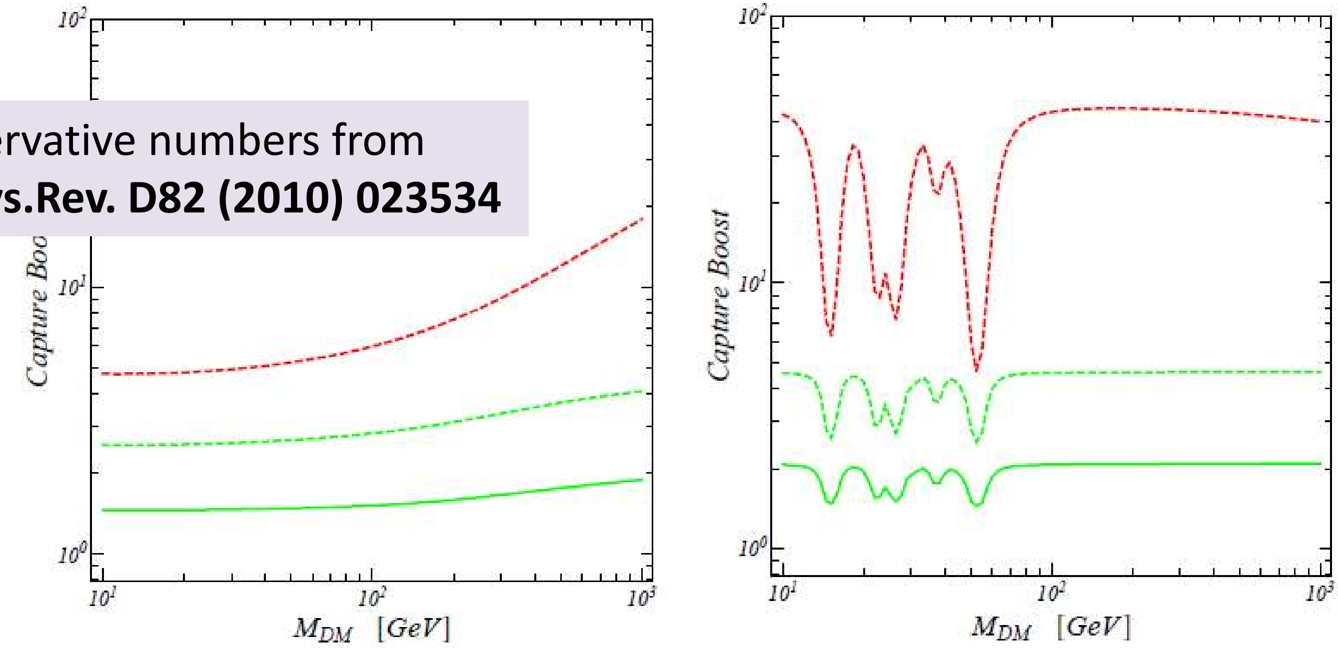


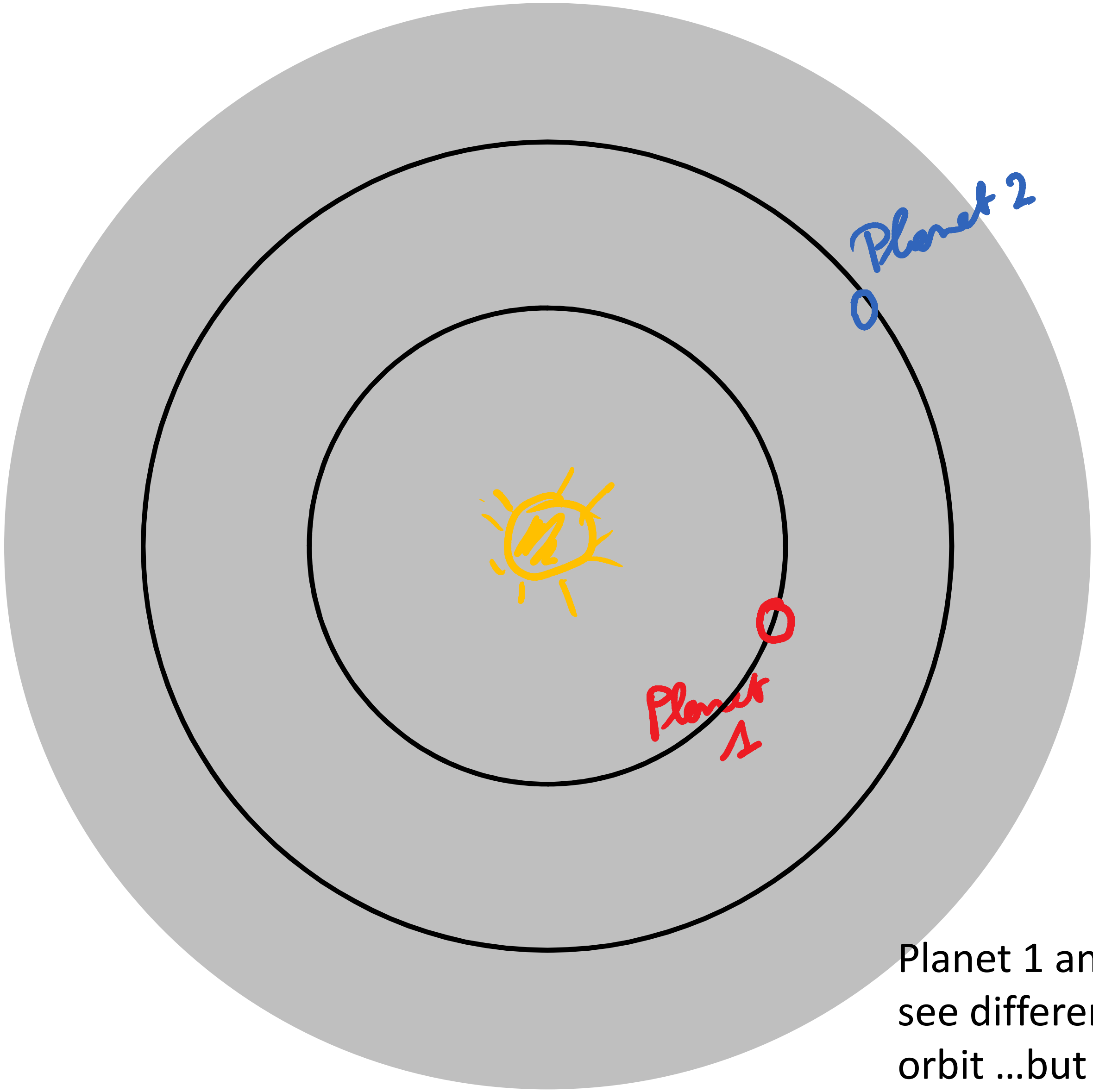
Figure 4. Indirect detection : *Enhancement factor of the DM capture rate in the Sun (left) and in the Earth (right) compared to the prediction for a standard Maxwellian halo, as a function of the DM mass.* Red dashed : *halo with a strong dark disc,* Green solid : *halo with a mild dark disc and* $\rho_D/\rho_H = 1/3$, Green dashed : *halo with a mild dark disc and* $\rho_D/\rho_H = 1/1$.

The effect may be important for INDIRECT detection,
For direct detection, it may affect the phase of the effect.

Dark matter in the Solar system?

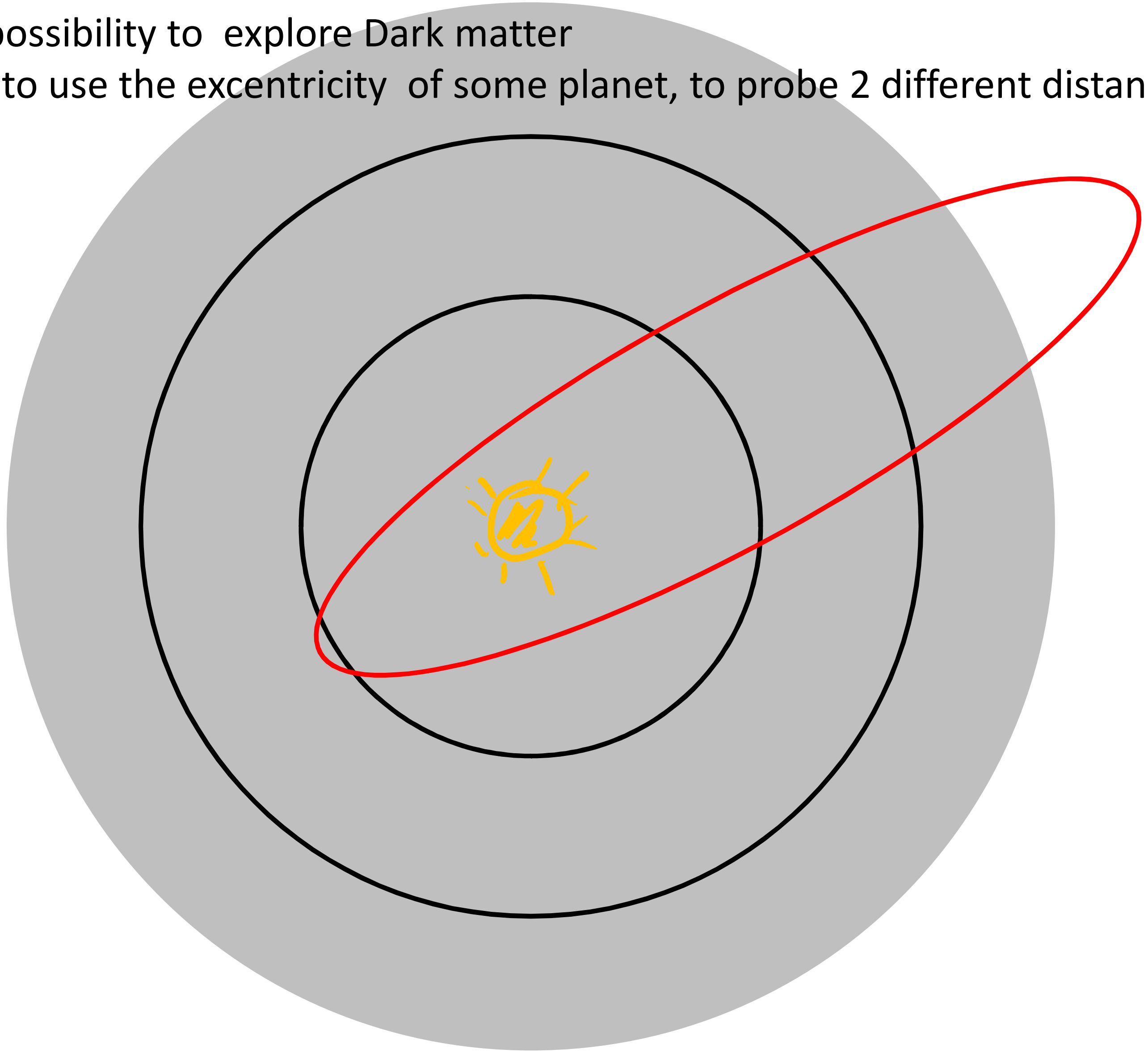
- Accretion unlikely
- …but could be there from the start (simulations ab initio of DM evolution suggest structure at all scales.. Even though their resolution > galaxy

The sasfest way is to take an empirical attitude,
…and to SEARCH for it.



Planet 1 and Planet 2
see different masses inside their orbit …but the mass of the Sun alone is not known
→ need to compare 2 orbits

Another possibility to explore Dark matter
would be to use the excentricity of some planet, to probe 2 different distances.



Some usual notations

$$K_0 \equiv G(M_\odot + m_P)$$

$$\begin{aligned} K_0 &= 4\pi^2 \frac{a^3}{T^2} \,, \\ E_0 &= \frac{K_0}{2a} \,, \\ L_0^2 &= K_0 p \,, \quad p = a(1-e^2) \end{aligned}$$

$$U_0(r) = -K_0/r$$

$$\Theta_0 = 2 \int_{r_{min}}^{r_{max}} \frac{L_0/r^2 \, dr}{\sqrt{-2\left(E_0 + U_0(r)\right) - L_0^2/r^2}}$$

Introduce Dark matter, and calculate the change in dynamical parameters for given orbits…

$$\begin{aligned} E &= E_0 + \Delta E \,, \\ L^2 &= L_0^2 + \Delta L^2 \\ K &= K_0 + \Delta K \end{aligned}$$

For a power-law potential,

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma}$$

Excess mass due to Dark matter

$$M(r) = \frac{4\pi\rho_0}{(3-\gamma)r_0^{-\gamma}}\ r^{3-\gamma}$$

$$\begin{aligned} \Delta K(\rho_0,\gamma) &= -(4-\gamma)GM(a) \\ \Delta\Theta(\rho_0,\gamma) &= -\pi(3-\gamma)\frac{M(a)}{M_\odot} \end{aligned}$$

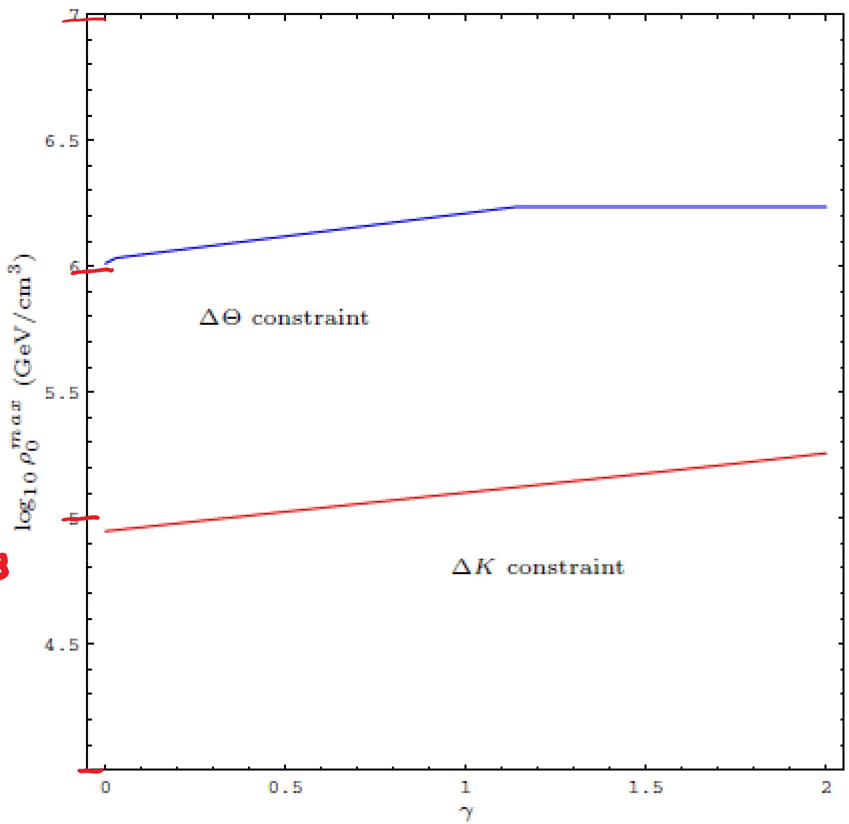
Table 2: Experimental limits (from [10],[11],[17])

Planet	$\Delta\Theta$ (arcsec/century)	Δa (m)	ΔK_P ($m^3 s^{-2}$)
Mercury	-0.0036(50)	0.105	$9.14\ 10^8$
Venus	0.53(30)	0.329	$6.0\ 10^6$
Earth	-0.0002(4)	0.146	$2.45\ 10^7$
Mars	0.0001(5)	0.657	$2.8\ 10^5$
Jupiter	0.0062(360)	639	$9.68\ 10^8$
Saturn	-0.92(2.9)	4222	$1.08\ 10^9$
Uranus	0.57(13.)	38484	$7.59\ 10^9$
Neptune	no data	3463309	$1.4\ 10^{10}$

Table 1: Planets keplerian parameters a, e, T and $K_P \equiv Gm_P$ (from [17]). Notice that $GM_\odot$ $1.327\ 10^{20}\ m^3 s^{-2}$.

Planet	Period (days)	a (AU)	e	K_P ($m^3 s^{-2}$)
Mercury	87.96935	0.38709893	0.20563069	$2.20\ 10^{13}$
Venus	224.70096	0.72333199	0.00677323	$3.25\ 10^{14}$
Earth	365.25696	1.0000001124	0.01671022	$4.04\ 10^{14}$
Mars	686.9601	1.52366231	0.09341233	$4.28\ 10^{13}$
Jupiter	4335.3545	5.20336301	0.04839266	$1.27\ 10^{17}$
Saturn	10757.7365	9.53707032	0.05415060	$3.79\ 10^{16}$
Uranus	30708.16002	19.19126393	0.04716771	$5.79\ 10^{15}$
Neptune	60224.9036	30.06896348	0.00858587	$6.84\ 10^{15}$

J-M. F, F-S Ling, G. Vertongen **Phys.Rev. D77 (2008) 083005**



10^6

10^5 GeV/cm^3

at Earth

A number of papers

Adler, (Planet-bound DM)
Pitjev, Pitjeva,
Iorio
Kriplovich,
Sereno,Jetzer
....

Pitjev, N.; Pitjeva, E. Constraints on Dark Matter in the Solar System. *Astronomy Letters* **2013**, *39*, 141–149.

Planet	$\Delta\dot{\varpi}$ (mas cty^{-1})	$\sigma_{\Delta\dot{\varpi}}$ (mas cty^{-1})
Mercury	-2.0	3.0
Venus	2.6	1.6
Earth	0.19	0.19
Mars	-0.020	0.037
Jupiter	58.7	28.3
Saturn	-0.32	0.47

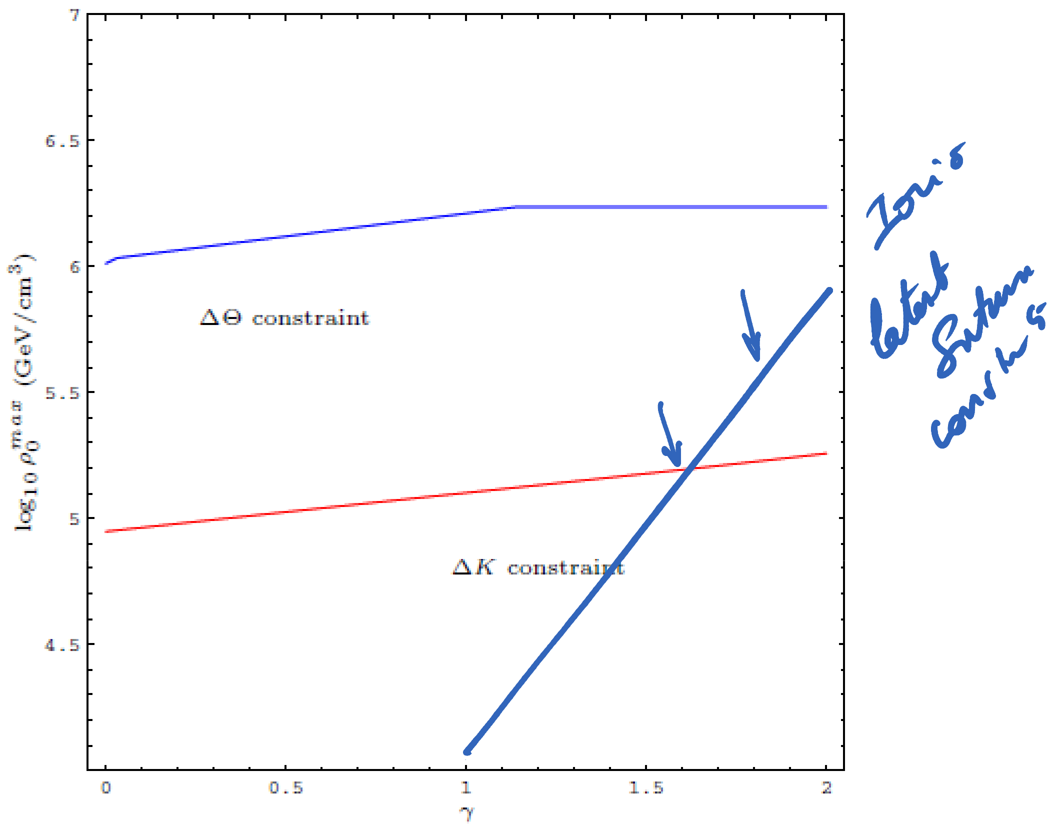
Residual unaccounted for precession,
After taking into account many effects,
Including minor asteroids, Kuyper , …
….!

.

Lorenzo Iorio in Galaxies 1 (2013) 6-30

Latest results seem to lead to more severe constraints (mostly from improved Saturn parameters) ..but are formulated in terms of density at Saturn's distance, ρ 5-8 10^{-3}GeV/cm^3 for γ = 0-4

$$\left\langle \frac{d\varpi}{dt} \right\rangle \approx -\frac{\pi G \rho_0}{n_\mathrm{b}} \left(\frac{\lambda}{a}\right)^\gamma \left\{2 + \left[\frac{\gamma(\gamma-1)-4}{4}\right] e^2 \right\} + \mathcal{O}\left(e^4\right).$$


ΔΘ constraint
ΔK constraint
log10 ρ0max (GeV/cm3)
γ
7
6.5
6
5.5
5
4.5
0
0.5
1
1.5
2
Zoni's latest Saturn constr's

Pioneer Anomaly?

Pioneer X and XI experienced unexplained centripedal acceleration at distances 20-70 AU and 20-40 AU respectively

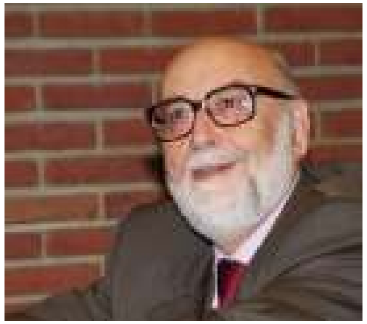
$$a_P = (8.74 \pm 1.33) \cdot 10^{-10} \text{ m/s}^2.$$

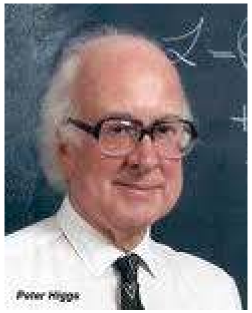
But this would necessitate

$$\gamma = 1 \text{ and } \rho_0 \approx 8 \cdot 10^9 \text{ GeV/cm}^3$$

which is completely excluded by the other measurements


PHYSICAL REVIEW LETTERS



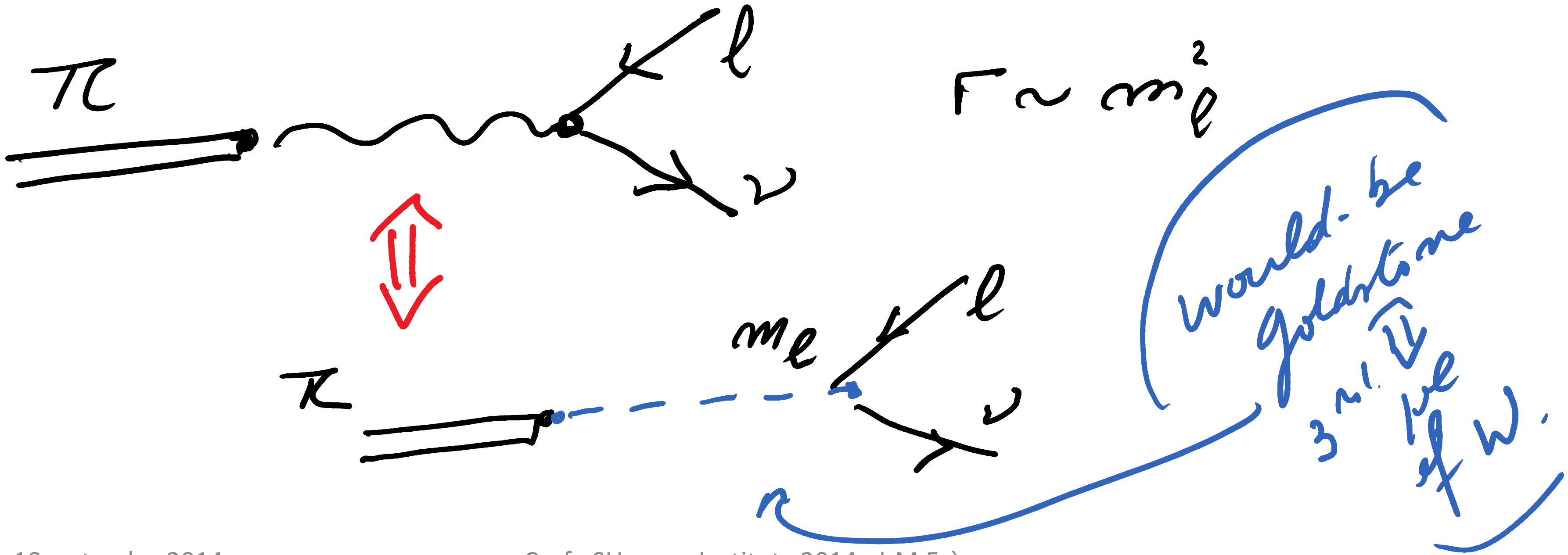


Corfu,
Ionian Academy
September 2001,

The Mechanism or the Boson ?

The mechanism is probably the most important,
It allows for a renormalizable theory of weak interactions,
and is actually well-proven (precision calculations),

Its early manifestation is actually already seen in π decays..



Some like to claim that Brout-Englert → mechanism , while Higgs → Boson
Some even claim that the Scalar boson is hard to find in Brout-Englert paper ..

?

Let us look closer …
… we need to go all the way to
Equation 1

ization to an arbitrary compact Lie group.
The interaction between the φ and the A_μ fields is

$$H_{\mathrm{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu, \qquad (1)$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that

This is the Abelian case, and φ1 is « The » Scalar, φ2 being absorbed…

Looks familiar ?
From you SM course?

FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a)$\rightarrow (2\pi)^4 ie^2 g_{\mu\nu} \langle\varphi_1\rangle^2$, (b)$\rightarrow -(2\pi)^4 ie^2 (q_\mu q_\nu/q^2) \times \langle\varphi_1\rangle^2$.

Now that we have found the Scalar particle in Eq. 1, *it is still possible to argue it should be named otherwise ….*

- **Higgs pointed out a massive scalar boson**

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$

- ” “… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence

(from John Ellis’s talk in *Higgs Hunting 2011*)

(interesting comparison : the P-Q axion …)

In fact, this potential / mass issue was well-known
….. For example , Goldstone

IL NUOVO CIMENTO VOL. XIX, N. 1 1° Gennaio 1961

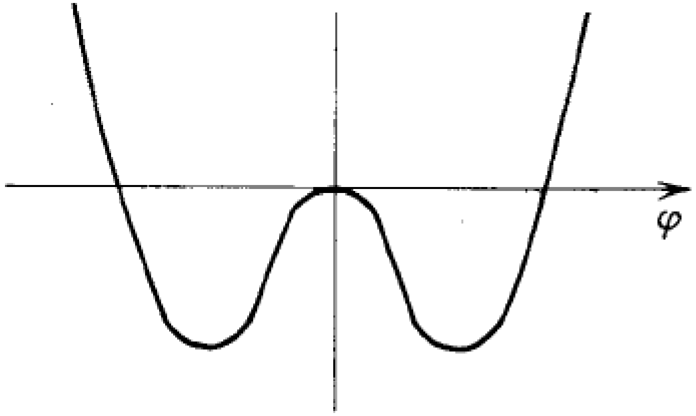


Fig. 7.

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4 ,$$

is as shown in Fig. 7.

The classical equations

$$(\Box^2 + \mu_0^2)\varphi + \frac{\lambda_0}{6}\varphi^3 = 0 ,$$

now have solutions $\varphi = \pm\sqrt{-6\mu_0^2/\lambda_0}$ corresponding to the minima of this curve. Infinitesimal oscillations round one of these minima obey the equation

$$(\Box^2 - 2\mu_0^2)\,\delta\varphi = 0 .$$

These can now be quantized to represent particles of mass $\sqrt{-2\mu_0^2}$. This is simply done by making the transformation $\varphi = \varphi' + \chi$

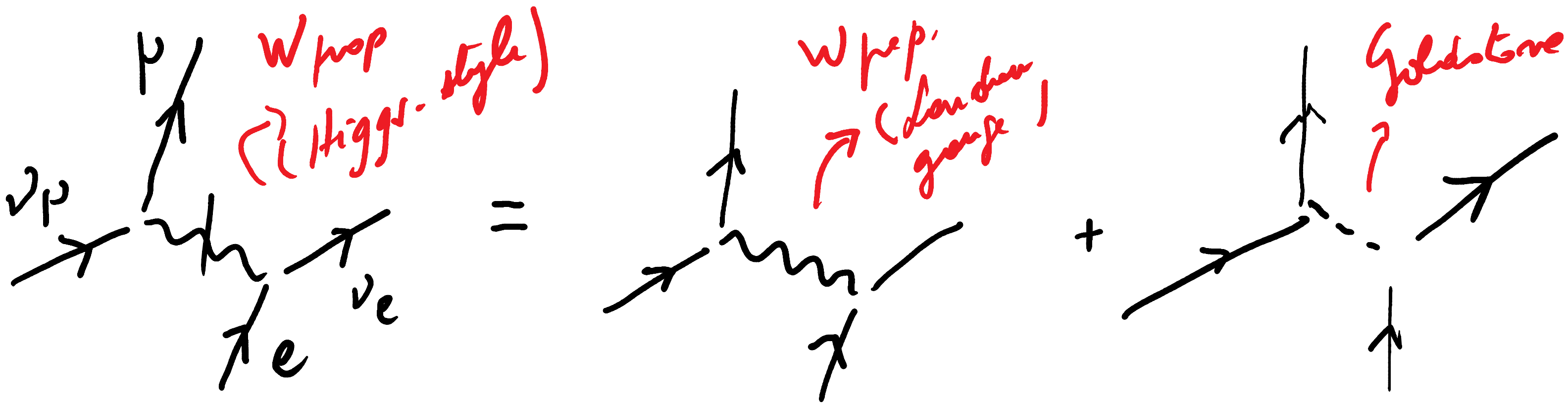
The (almost simultaneous) Brout-Englert and Higgs papers are perfectly complementary,
While Higgs shows at the classical level the disappearance of Goldstone bosons,

Brout and Englert tackle the problem at quantum level (Feynman diagrams)
in what will later be known as a « renormalizable » gauge.
They pave to way to the renormalizability of the theory (although for the non-Abelian case the proofs of ‘t Hooft and Veltman will be needed).

Together, they give the full picture

⚠ only on shell !

In fact, it is a standard (and instructive) exercise
for our students to prove the equivalence of the 2 approaches in a scattering process:



	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters 13 (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters 12 (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters 13 (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters 13 (1964) 585	12/10/1964	16/11/1964

Physics Lett B 12:
failure of NambuGoldstone
in presence of gauge fields

A quote from GHK,
About their remaining scalar (masslesss in their case ….)

part. The two degrees of freedom of A_k^- combine with φ_1 to form the three components of a massive vector field. While one sees by inspection that there is a massless particle in the theory, it is easily seen that it is completely decoupled from the other (massive) excitations,

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

and has nothing to do with the Goldstone theorem.

was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$+\varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$