THE QUINTESSENTIAL EXOTIC X(3872)

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My talk is devoted to the most famous of all "exotic" mesons, the X(3872).

So let me first explain what we mean by "exotic".

- The label "exotic" is put on any hadron which does not easily fall in the two classical hadron species we all know, the $|q\bar{q}\rangle$ mesons, and the $|qqq\rangle$ baryons, made of the six quarks, u, d, s, c, b, t, and the corresponding antiquarks.
- In essence, "exotics" mean those hadrons whcih we do not understand.

  This, as usual, means that theorists have a field day with attempts to explan what they might be.
- X(3872) is one such hadron. I will talk about it, and I promise you that at the end of my talk **you will still not know** what X(3872) is!

To put the interest in X(3872) in perspective, let me simply quote the authority, GOOGLE:

There are **30.4 million** entries for X(3872), and

11.0 million entries for HIGGS!!

The Landscape of Mesons

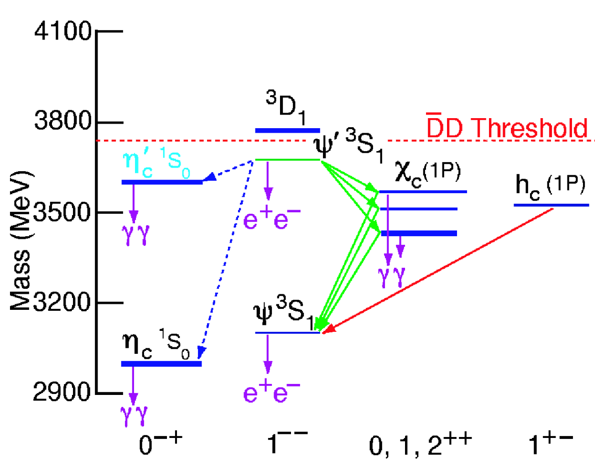
The landscape of $|q\bar{q}\rangle$ mesons is populated by a large number of well–established, and mostly well–understood mesons.

- In the Particle Data Group (PDG) compilation of 2010 there are listed 45 light quark (u, d, s) mesons with **hidden flavor**, i.e., $S = C = B = 0$. The masses of these range from 135 MeV to 2340 MeV. Of these 45 mesons, only four ($a_0(980)$, $f_0(980)$, $\pi_1(1400)$, and $\pi_1(1600)$) are occaisionally described as non–$q\bar{q}$. I will not be talking about them.
- Also well established are **open flavor** mesons, 20 kaons (with s–flavor), 12 D mesons (with c–flavor), and 8 B mesons (with b–flavor). I will also not talk about them.
- Claims have been made about the existance of as many as 16 mesons with masses in the 0.9 GeV region, 3.8 GeV to 4.7 GeV, all of which decay into final states containing a **charm quark and a charm antiquark**. They do not fit in the conventional picture of $|c\bar{c}\rangle$ charmonium states, and fall in the category of "exotics".

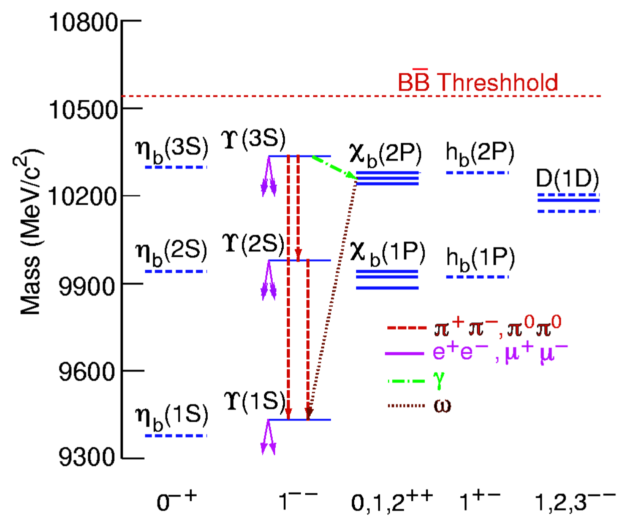
  X(3872) is one such exotic.

Charmonium & Bottomium

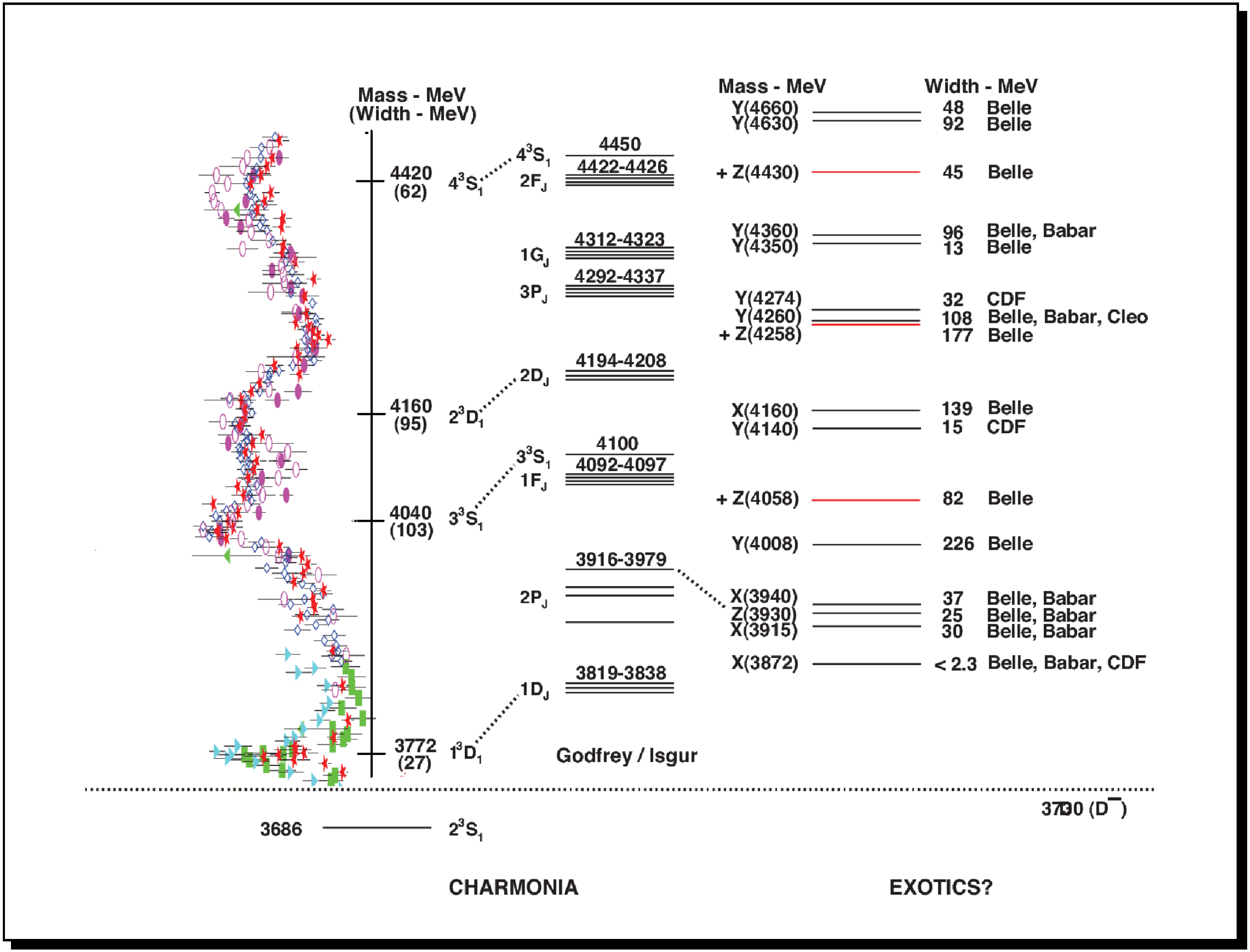
- Very recently the full spectrum of all bound states of charmonium has been completed by the discovery of long–elusive singlet states, 1^1S_0, 2^1S_0, and 1^1P_1. Also, of the 17 bound states of bottomonium, 13 states have been identified.
- However, the excitement of the "exotics" rests in what happens above the respective break–up thresholds, $M(c\bar{c}) > 3.73$ GeV and $M(b\bar{b}) > 10.5$ GeV.
  So far the action about "exotics" has all been in the charmonium sector.



Charmonium



Bottomonium


Mass - MeV
(Width - MeV)
4420
(62)
4^3S_1
4160
(95)
2^3D_1
4040
(103)
3^3S_1
3772
(27)
1^3D_1
3686
2^3S_1
4^3S_1
$2F_J$
4450
4422-4426
$1G_J$
4312-4323
$3P_J$
4292-4337
$2D_J$
4194-4208
3^3S_1
$1F_J$
4100
4092-4097
3916-3979
$2P_J$
3819-3838
$1D_J$
Godfrey / Isgur
Mass - MeV
Width - MeV
Y(4660) 48 Belle
Y(4630) 92 Belle
+ Z(4430) 45 Belle
Y(4360) 96 Belle, Babar
Y(4350) 13 Belle
Y(4274) 32 CDF
Y(4260) 108 Belle, Babar, Cleo
+ Z(4258) 177 Belle
X(4160) 139 Belle
Y(4140) 15 CDF
+ Z(4058) 82 Belle
Y(4008) 226 Belle
X(3940) 37 Belle, Babar
Z(3930) 25 Belle, Babar
X(3915) 30 Belle, Babar
X(3872) < 2.3 Belle, Babar, CDF
3730 (D $\bar{D}$)
CHARMONIA
EXOTICS?

X(3872) — MASS and WIDTH

THE DISCOVERY ERA

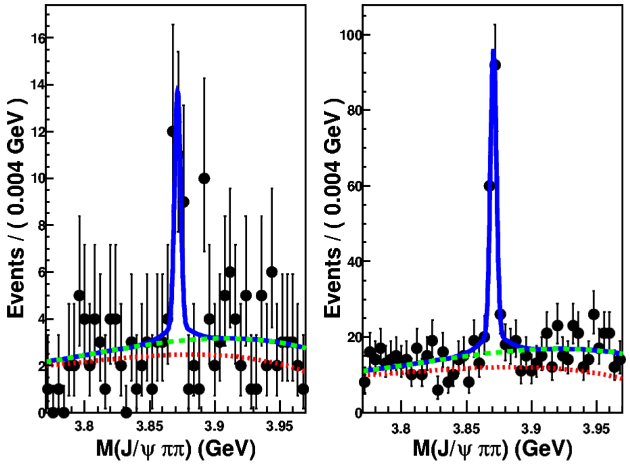
Year	Expt. [ref]	$X \to J/\psi\pi^+\pi^-$	$N(X)$	$M(X)$, MeV	$\Gamma(X)$, MeV	$\mathcal{L}$
2003	Belle [1]	$B^+ \to K^+X$	26 ± 4	3872.0 ± 0.8	< 2.3	152M $B\overline{B}$
2004–5	BaBar [2,3]	$B^+ \to K^+X$	25 ± 9	3873.4 ± 1.4		117M $B\overline{B}$
2004	CDF [4]	$p\bar{p}$ Incl.(X)	730 ± 90	3871.3 ± 0.8	3.5 ± 0.7	220 pb^{-1}
2004	DØ [5]	$p\bar{p}$ Incl.(X)	522 ± 100	3871.8 ± 4.2		230 pb^{-1}

THE PRESENT ERA

Year	Expt. [ref]	$X \to J/\psi\pi^+\pi^-$	$N(X)$	$M(X)$, MeV	$\Gamma(X)$, MeV	$\mathcal{L}$
2008	BaBar [6]	$B^+ \to K^+X$	103 ± 18	3871.4 ± 0.6	< 3.3	455M $B\overline{B}$
2011	Belle [7]	$B^+ \to K^+X$	173 ± 16	3871.84 ± 0.33	< 1.2	772M $B\overline{B}$
2009	CDF [8]	$p\bar{p}$ Incl.(X)	~ 6000	3871.65 ± 0.25		2.4 fb^{-1}
2011	LHCb [9]	$p\bar{p}$ Incl.(X)	585 ± 74	3871.96 ± 0.46		35 pb^{-1}

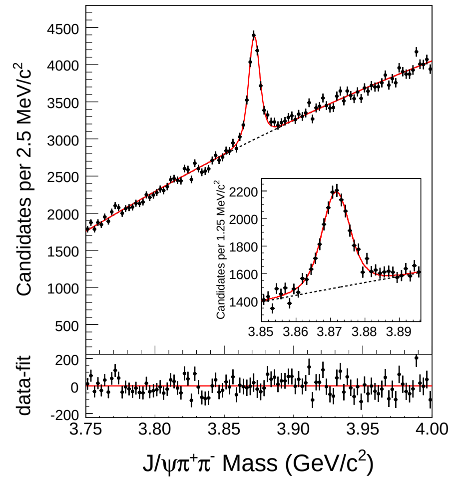
$$\boxed{M(X) = 3871.71 \pm 0.17\ \text{MeV} \qquad \Gamma(X) < 1.2\ \text{MeV}}$$

- With this mass of X, and the best measurements of $M(D^0)$, the binding energy of X appears to be **BE $<$ 100 keV**, which corresponds to the **radius of X = 14 fm, or 3 times that of the deuteron.**
- Despite earlier suggestions, it has now been firmly established that there is no evidence for a second resonance near X(3872), and no charged candidates for X exist.
  $\Delta M(X)(B^+ - B^0\ \text{production}) = -0.69 \pm 0.99$ MeV [7]
  $\Delta M(X)(J/\psi\pi^+\pi^- - D^0\overline{D}^{*0})\ \text{decay} = 1.1^{+0.6}_{-0.5}$ MeV [10]



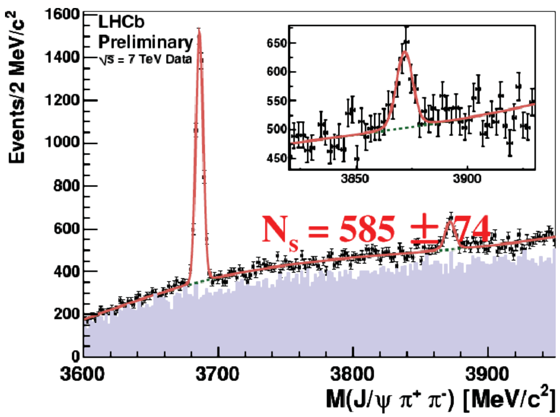
[7] Belle (772M $B\overline{B}$)

$N(\mathrm{X}) = 152$ events



[8] CDF (2.4 fb^{-1} $p\bar{p}$)

$N(\mathrm{X}) = \sim 6000$ events



[9] LHCb (35 pb^{-1} pp)

$N(\mathrm{X}) = 585 \pm 74$ events

X(3872) Decays

Other than the above discovery decay, the other decays of X which have been extensively studied are:

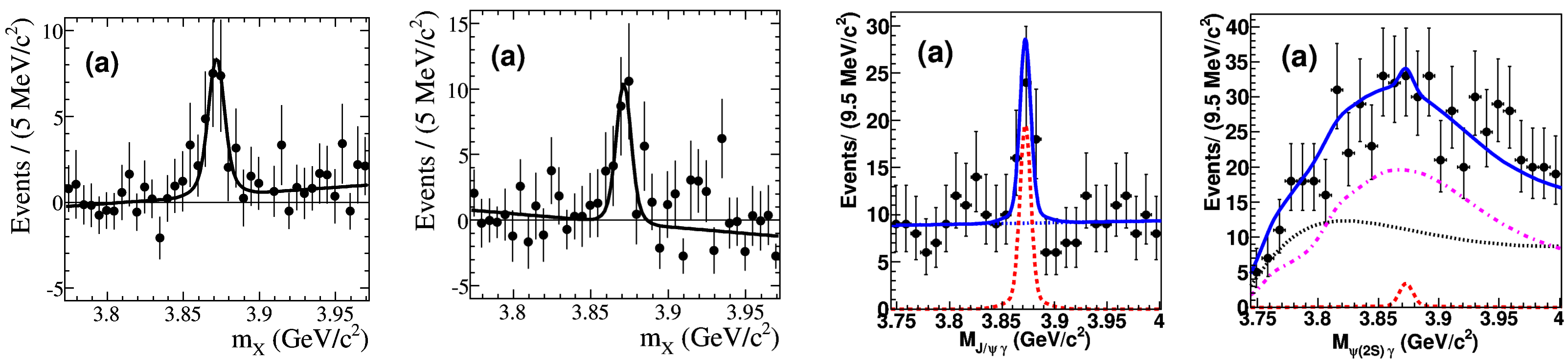
$\mathrm{X} \to \pi^+\pi^-\pi^0 J/\psi$

$\mathrm{X} \to \gamma J/\psi, \quad \gamma\psi(2S)$

$\mathrm{X} \to \overline{D}^0 D^{*0}$

The Decays $\mathrm{X} \to \gamma J/\psi,\ \gamma\psi(2S)$

Both BaBar and Belle have observed these decays. Their existance firmly establishes that the charge conjugation, $\boldsymbol{C(\mathrm{X}(3872)) = +}$.



BaBar(2009) 465M $B\overline{B}$ Belle(2011) 772M $B\overline{B}$

$$\mathcal{B}(B^{\pm} \to K^{\pm}\mathrm{X}) \times \mathcal{B}(\mathrm{X} \to \gamma J/\psi) = (2.8 \pm 0.8) \times 10^{-6}\ \text{(BaBar)},\ = (1.8 \pm 0.5) \times 10^{-6}\ \text{(Belle)}.$$

$$\mathcal{B}(B^{\pm} \to K^{\pm}\mathrm{X}) \times \mathcal{B}(\mathrm{X} \to \gamma\psi(2S)) = (9.5 \pm 2.8) \times 10^{-6}\ \text{(BaBar)},\ < 3.45 \times 10^{-6}\ \ 90\%\ \mathrm{CL}\ \text{(Belle)}.$$

$$\boldsymbol{\therefore \mathcal{B}(\mathrm{X} \to \gamma\psi(2S))/\mathcal{B}(\mathrm{X} \to \gamma J/\psi) = 3.4 \pm 1.4\ (\mathrm{BaBar}),\ \ < 2.1\ \ 90\%\ \mathrm{CL}\ (\mathrm{Belle}).}$$

The large $\gamma\psi(2S)/\gamma(J/\psi)$ ratio is inconsistent with pure $\overline{D}^0 D^{*0}$ interpretation of X(3872).

The Decays $\mathrm{X}(3872) \to 2\pi J/\psi, \;\; 3\pi J/\psi$

$\boldsymbol{M(\mathrm{X}(3872)) = 3871.71 \pm 0.17}$ **MeV** (2011 Average)

$M(D^0) + M(D^{*0}) = 3871.81 \pm 0.36$ MeV $\quad \mathrm{BE(X)} = 0.10 \pm 0.40$ MeV (CLEO 2007)

$M(D^{\pm}) + M(D^{*\pm}) = 3879.85 \pm 0.21$ MeV $\quad > M(\mathrm{X})$ by ~ 8 MeV

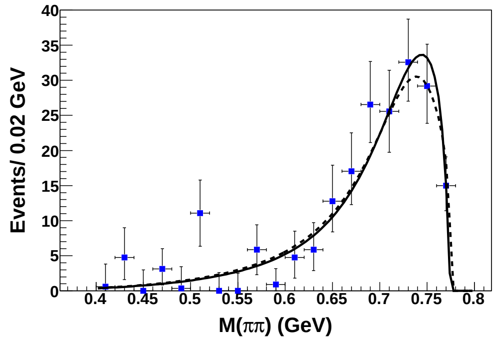
$M(J/\psi) + M(\rho) = 3872.4 \pm 0.3$ MeV, $\quad \Gamma(\rho) = 149$ MeV, X is at threshold

$M(J/\psi) + M(\omega) = 3879.6 \pm 0.1$ MeV, $\quad \Gamma(\omega) = 8.5$ MeV, $> M(\mathrm{X})$ by ~ 8 MeV

$M(\psi(2S)) + M(2\pi, 3\pi) \geq 3965$ MeV, $\quad > M(\mathrm{X})$ by ≥ 100 MeV

The Discovery Decay: $\mathrm{X}(3872) \to \pi^+\pi^- J/\psi$

- $\mathcal{B}(B^+ \to K^+\mathrm{X}) \times \mathcal{B}(\mathrm{X} \to J/\psi\pi^+\pi^-) = (8.6 \pm 1.0) \times 10^{-6}$ (Belle), $(8.4 \pm 1.7) \times 10^{-6}$ (BaBar)
- **$\pi^+\pi^-$ mass distribution** confirms $\pi^+\pi^-$ in P–wave, are primarily from ρ, with $< 5\%$ admixture of $\omega \to \pi^+\pi^-$.



  - **This decay implies an isospin $I = 1$ component in X(3872) wave function.**
  - **The $I = 1$ component implies that X can not be a normal $I = 0$ charmonium state.**

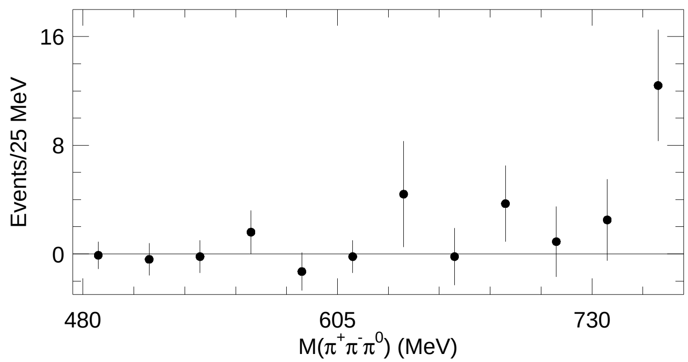
- **Angular Correlation Studies and $J^{PC}(\mathrm{X})$**

  CDF(2007): With 2300 events of $\mathrm{X} \to \pi^+\pi^- J/\psi$ CDF made very detailed angular correlation studies, and concluded that only $\boldsymbol{J^{PC}(\mathrm{X}) = 1^{++}}$ **and** $\boldsymbol{2^{-+}}$ were possible.

  Other J^{PC} had $> 10^3$ times smaller probability.

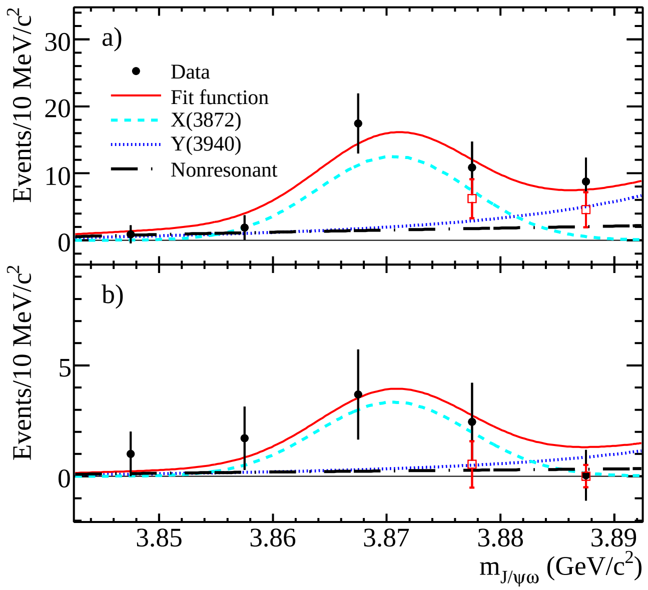
  Belle(2011): With the present 152 events of $\mathrm{X} \to \pi^+\pi^- J/\psi$ Belle has now made angular correlation studies, and confirms $\boldsymbol{J^{PC}(\mathrm{X}) = 1^{++}}$ **and** $\boldsymbol{2^{-+}}$ as equally possible.

$X(3872) \to \pi^+\pi^-\pi^0 J/\psi, \quad M(\pi^+\pi^-\pi^0) = M(\omega)$



Belle(2005, 75M $B\overline{B}$), 12.4 ± 4.1 evts

$$\omega J/\psi / \rho J/\psi = \mathbf{1.0 \pm 0.5}$$



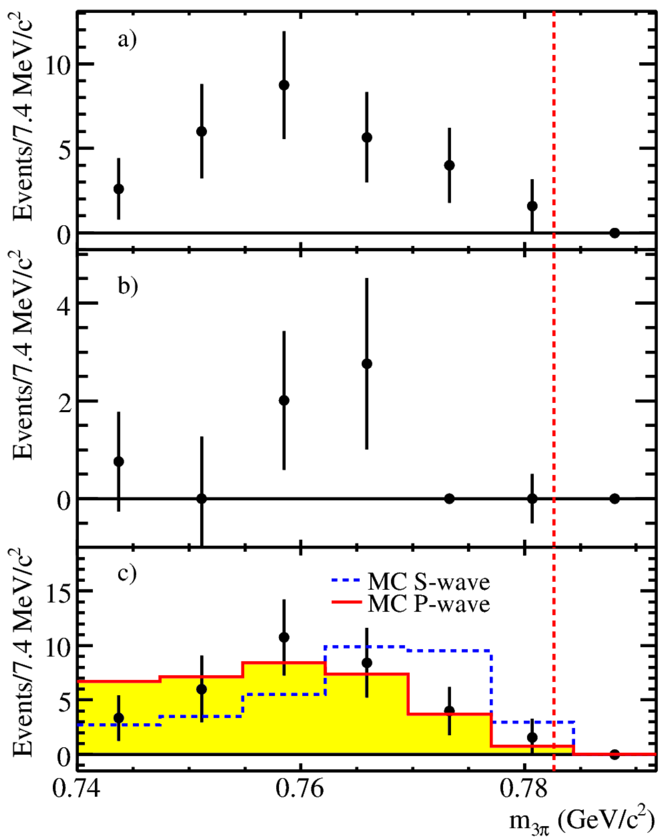
BaBar(2010, 476M $B\overline{B}$), 26.7 ± 7.6 evts

$$\mathcal{B}(B \to K\mathrm{X})\mathcal{B}(\mathrm{X} \to \omega J/\psi) = (6 \pm 2) \times 10^{-6}$$

$$\omega J/\psi / \rho J/\psi = \mathbf{0.7 \pm 0.3}$$

- The existence of this $\omega J/\psi$ decay, and the $\rho J/\psi$ decay establishes that X(3872) is a state of almost **50/50 mixture of isospin 0 and 1, or does it?**

- A most important and upsetting claim of the BaBar $\mathrm{X} \to \omega J/\psi$ measurement is that P-wave between ω and J/ψ is favoured, so that $J^{PC}(\mathrm{X}) = 2^{-+}$ is preferred. This is such a big monkey wrench in the generally assumed $J^{PC}(\mathrm{X}) = 1^{++}$, which is essentially required by the $\overline{D}^0 D^{*0}$ molecular model of X(3872), that I will have you judge the evidence yourself.



BaBar(2010), 476M $B\overline{B}$

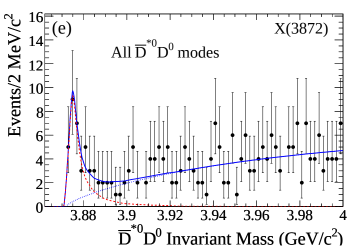
$X(3872) \to \overline{D}^0 D^{*0}, \quad D^{*0} \to D^0\pi^0, \; D^0\gamma$

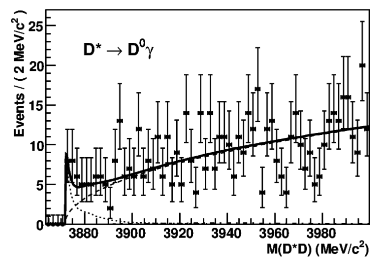
This is a very important decay, particularly for the $\overline{D}^0 D^{*0}$ molecular model for X(3872). However, it is plagued by the fact that $M(\mathrm{X})$ is so close ($\sim \pm 100$ keV) to $M(D^0) + M(D^{*0})$ that it appears as a **highly distorted, non–Breit Wigner, enhancement** near threshold. The difficulty in analyzing this enhancement is illustrated by the fact that **Belle and BaBar results differ by more than a factor 2.**

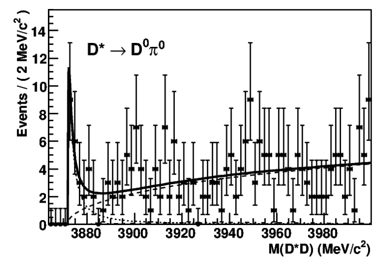
[11] BaBar(2008) $\mathcal{B}(B \to K\mathrm{X})\mathcal{B}(\mathrm{X} \to \overline{D}^0 D^{*0} = (1.8 \pm 0.5) \times 10^{-4}$ (383M $B\overline{B}$, 33 ± 7 evts)

[12] Belle(2010) $\mathcal{B}(B \to K\mathrm{X})\mathcal{B}(\mathrm{X} \to \overline{D}^0 D^{*0} = (0.8 \pm 0.2) \times 10^{-4}$ (657M $B\overline{B}$, 50 ± 10 evts)

BaBar

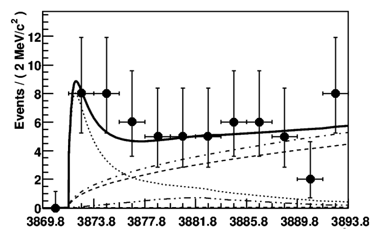


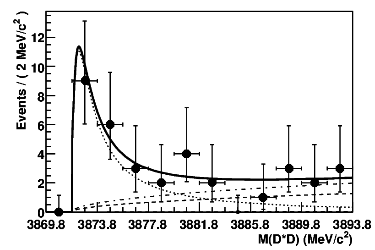




Belle

Expected $N_\gamma / N_{\pi^0} \approx 1/2$





Belle

$N_\gamma = 8.4^{+4.5}_{-3.6}$ $\qquad N_{\pi^0} = 41.3^{+9.1}_{-8.1}$

- It makes me very uncomfortable that such an important conclusion about $\mathrm{X} \to \overline{D}^0 D^{*0}$ is based on so few counts, and such questionable fits to such a questionable threshold enhancement.

Summary of Experimental Measurements

1. X(3872) definitely exists (based on ~ 8000 observed in 5 experiments)
2. $M(\mathrm{X}) = 3871.71 \pm 0.17$ MeV, $\Gamma(\mathrm{X}) < 1.2$ MeV (90% CL), $\boldsymbol{J^{PC}(\mathrm{X}) = 1^{++}}$ **or** $\boldsymbol{2^{-+}}$.
3. Decays: $\mathcal{B}_1(B \to K\mathrm{X}) \times \mathcal{B}_2(\mathrm{X} \to \text{final state}) \times 10^6$ events:
   (a) $\mathcal{B}_2(\mathrm{X} \to \pi^+\pi^- J/\psi) = 8.4 \pm 1.7$ (BaBar), 8.6 ± 1.0 (Belle), $\mathbf{Av = 8.6 \pm 0.9}$, $N = 103, 173$
   $\pi^+\pi^-$ from ρ, $\boldsymbol{I(\mathrm{X}) = 1}$
   (b) $\mathcal{B}_2(\mathrm{X} \to \pi^+\pi^-\pi^0) = 6 \pm 2$ (BaBar), $8.6 \pm 4.3(?)$ (Belle), $\mathbf{Av = 6.5 \pm 1.8}$, $N = 27, 12$
   $(\mathrm{X} \to \omega J/\psi)/(\mathrm{X} \to \rho J/\psi) = 0.7 \pm 0.3$ (BaBar), 1.0 ± 0.5 (Belle),
   $\mathbf{Av = 0.78 \pm 0.26}$
   mixed isospin $\boldsymbol{I(\mathrm{X}) = 0 + 1}$, $(50:50?)$, $\boldsymbol{J^{PC}(\mathrm{X}) = 2^{-+}}$ preferred (BaBar)
   (c) $\mathcal{B}_2(\mathrm{X} \to \gamma J/\psi) = 2.8 \pm 0.8$ (BaBar), 1.8 ± 0.5 (Belle), $\mathbf{Av = 2.1 \pm 0.4}$, $N \approx 35.35$
   $(\mathrm{X} \to \gamma J/\psi)/(\mathrm{X} \to \pi^+\pi^- J/\psi) = 0.24 \pm 0.05$
   * (d) $\mathcal{B}_2(\mathrm{X} \to \gamma\psi(2S)) = 9.5 \pm 2.8$ (BaBar), < 3.5 (Belle), $\mathbf{Av = ?}$
   establish $\boldsymbol{C(\mathrm{X}) = +}$, large ratio $\psi(2S)/J/\psi$ (?)
   * (e) $\mathcal{B}_2(\mathrm{X} \to \overline{D}^0 D^{*0}) = 180 \pm 50$ (BaBar), 80 ± 20 (Belle), $N = 33, 50$
   $(\mathrm{X} \to \overline{D}^0 D^{*0})/(\mathrm{X} \to \pi^+\pi^- J/\psi) = 21.4 \pm 7.4$ (BaBar), 9.3 ± 2.6 (Belle),
   $\mathbf{Av = 16.7 \pm 5.8}$

- Note that except for $\mathrm{X} \to \pi^+\pi^- J/\psi$ all decays are based on $\leq$ **50 observed counts**, and Belle and BaBar have large quantitative disagreements on very important results (*), even with up to 800 fb^{-1} e^+e^- luminosity measurements.

The Theoretical Landscape

I have described in detail the half a dozen experimental measurements of the properties of X(3872). These have given rise to scores (who is keeping count) of theoretical papers suggesting different explanations of what X(3872) is. That there are scores of suggestions means that none of them is certain. To mention a few, X(3872) is

(a) a charmonium $|c\bar{c}\rangle$ state

(b) a hybrid $|c\bar{c}g\rangle$ state

(c) a 4–quark state

(d) a molecule made of $\overline{D}^0 D^{*0}$ mesons

(e) a dynamically generated state

(f) manifestation of a threshold cusp

Let us examine these suggestions, although I must confess that with all the distinguished theorists present here, I am being too presumptuous in the following.

- To be safe, let me point out that many theoretical reviews of the exotics, including X(3872) exist. Just to name three:
  - "The new heavy mesons: A status report", E.S. Swanson, Phys. Reports **429**, 243–305 (2006).
  - "The Exotic X,Y,Z Charmonium-like Mesons", S. Godfrey and S.L. Olsen, Ann. Rev. Nucl. Part. Sci. **58**, 51–73 (2008).
  - "Heavy quarkonium: progress, puzzles, and opportunities", QWG Report, N. Brambilla et al., arXiv:1010.5827[hep-ph].

- **X(3872) is manifestation of a cusp close to $M(D^0) + M(D^{*0})$**

  This suggestion was first made by David Bugg [13], who is an expert on such things. Cusps exist, but they are generally not narrow and do not have as beautiful a Breit–Wigner shape as X(3872) has. I therefore express my personal opinion that **X(3872) is not a cusp.**

- **X(3872) is a dynamically generated resonance.**

  Every resonance is the result of some dynamics, and the distinction between an "intrinsic" and "dynamically generated" resonance is to me, and many others, artificial.

- **X(3872) is a hybrid $|c\bar{c}g\rangle$ meson**

  The idea of X being a $|c\bar{c}g\rangle$ hybrid was first examined by Close and Page [14] and later by Li [15], but it has a serious mass problem. Lattice and flux tube model calculations predict charmonium hybrid masses in the range 4200–4400 MeV, and the idea of X being a hybrid can be safely put aside.

  Let us move on to more plausible suggestions. These include X(3872) as a conventional $|c\bar{c}\rangle$ charmonium state, or one or another type of state involving four quarks ($cu\bar{c}\bar{d}$, $cd\bar{c}\bar{u}$, $cu\bar{c}\bar{u}$, $D\overline{D}^*$, etc.).

X(3872) is a conventional $|c\bar{c}\rangle$ Charmonium Resonance

This is the most obvious proposition to examine.

- If we accept that it has been established that the J^{PC} of X is 1^{++} or 2^{-+}, the only possibilities for a narrow charmonium state are $2^3P_1(1^{++})$ or $1^1D_2(2^{-+})$.

The $2^3P_1(1^{++})$ χ'_{c1} State of Charmonium

In potential model calculations (with and without coupled channels) this state is generally predicted to have a mass of ~ 3950 MeV, which is ~ 75 MeV too large to be X(3872). If, however, one tries to put it at 3872 MeV, as Barnes and Godfrey do [16], it has a predicted total width of ~ 1.7 MeV, making it a possible candidate for X. It also has then the interesting result: $\mathcal{B}(^3P_1 \to \gamma\psi(2S))/\mathcal{B}(^3P_1 \to \gamma J/\psi) \approx 6$, which is in essential agreement with that observed for X(3872). This may be important because, as Swanson [17] has observed, this ratio for X is "difficult to accomodate in a molecular scenario".

- There is an interesting variant of the conventional charmonium 2^3P_1 scenario. Kalashnikova and Nefediev have constructed a coupled channel model of the charmonium spectrum. Using the $^3P_0$ model they couple the charmonium states to various $D\bar{D}$ and $D_S\bar{D}_S$ scalar and vector states in the continuum and find that besides the modified 2^3P_1 state they obtain a **virtual 1^{++} state** just above the $\bar{D}^0D^{0*}$ threshold, which could be identified with the X(3872). However, as Swanson has pointed out, this model creates problems with the properties of the normal charmonium states.

The $1^1D_2(2^{-+})$ χ'_{c1} State of Charmonium

The 1^1D_2 state is predicted to have a mass of $\sim$ **3840 MeV**, not to far from X(3872). For the $^1D_2$ state at 3872 MeV, Barnes and Godfrey [16], who use a $^3P_0$ model for strong decays, predict a total width $\boldsymbol{\Gamma(^1D_2) = 0.86}$ **MeV**. Eichten, Lane, and Quigg [18], who use the Cornell coupled channel model, predict $\Gamma(^1D_2) = 0.03$ MeV. In other words, the mass and width of X are no problem in this assignment. So what else is a problem?

- The problem is $\Delta M \equiv M(^1D_2) - M(^3D_1)$. The 3772 MeV state in charmonium is generally assigned as $^3D_1$. Therefore if the X is identified as $^1D_2$, $\Delta M = 3872 - 3772 = 100$ MeV. Unfortunately, most potential model calculations predict $\Delta M \approx 15 - 30$ MeV. However, there are exceptions. For example, BG and ELQ both predict $\Delta M = (3838 - 3772) = 66$ MeV. So ΔM is not such a big problem.

- What else is the problem? Kalashnikova and Nefediev [19] claim that the experimental ratio $\mathcal{B}(\mathrm{X} \to \gamma\psi(2S))/\mathcal{B}(\mathrm{X} \to \gamma J/\psi)$ and $\mathcal{B}(B \to K\overline{D}^0 D^{*0})$ are incompatible with the $^1D_2$ identification. However, their arguments are entirely based on the Babar estimate $\mathcal{B}(B^\pm \to K^\pm \mathrm{X}(3872)) < 3.2 \times 10^{-4}$, which itself was based on $\mathbf{15 \pm 39}$ **observed counts** (with a significance of 0.4σ) in their kaon spectrum! This can not be taken seriously.

  So, as far as I am concerned, the $1^1D_2(2^{-+})$ state is still alive as a candidate for X(3872) if $\boldsymbol{J^{PC}(\mathrm{X}) = 2^{-+}}$.

- **Of course, $\boldsymbol{J^{PC} = 2^{-+}}$ makes it essentially impossible to make a $\boldsymbol{\overline{D}^0 D^{*0}}$ molecule which must have a P–wave between $\boldsymbol{\overline{D}^0}$ and $\boldsymbol{D^{*0}}$.**

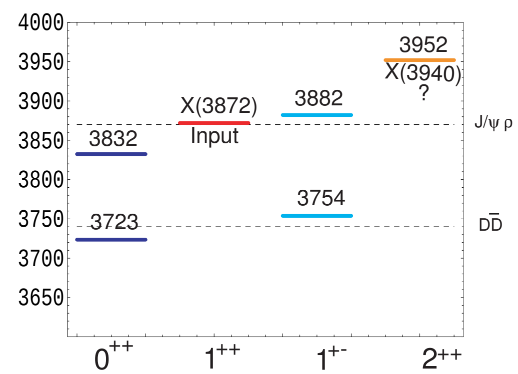
X(3872) Models Involving Four Quarks

If you are going to make X(3872) as any construct of four quarks, two of which are charm and anticharm, you have room only for up and down quarks. So you can have the combinations $(qc)(\bar{q}\bar{c})$, $(q\bar{q})(c\bar{c})$, or $(q\bar{c})(\bar{q}c)$, where q denotes u or d quarks.

The first, $(qc)(\bar{q}\bar{c})$ model is the one proposed by Maiani et al. The second one, $(q\bar{q})(c\bar{c})$ would admit X as $|\omega J/\psi\rangle$, which Karliner and Lipkin have considered seriously. The third one is the $\overline{D}^0 D^{*0}$ molecule which wins in the popularity contest.

The $(qc)(\bar{q}\bar{c})$ Model of Maiani et al. [20]

In this model one or both combinations of c and q can be scalar or vector, and q can be either the up or down quark. The result is that besides the 1^{++} X(3872) as $(uc)_s(\bar{u}\bar{c})_v$ the model predicts six states of various J^{PC} as shown. It also predicts charged partners $X^+ = (uc)(\bar{d}\bar{c})$ and $X^- = (dc)(\bar{u}\bar{c})$. There is no evidence for the existence of any of these states, and it is difficult to take the model seriously. Besides, it would appear that the color–octet pair $(uc)(\bar{u}\bar{c})$ would have difficulty decaying dominantly into the singlet pair $(\bar{u}c)_s(u\bar{c})_v$, or $\overline{D}^0 D^{0*}$.



The Tetraquark Model of Karliner and Lipkin [21]

The tetraquark model of Karliner and Lipkin is motivated by two observed properties of X(3872): X decays into $\rho^0 J/\psi(I=1)$ as well as $\omega J/\psi(I=0)$, and X is formed with comparable rates in $B^+ \to K^+ X_u$ and $B^0 \to K^0 X_d$. Karliner and Lipkin basically arrange their four quarks in the $(q\bar{q} : \omega)(c\bar{c} : J/\psi)$ configuration with $I=0$, and explain the $I=1$ decay into $(\rho J/\psi)$ as being an electromagnetic, rather than strong decay. The quantitative predictions of the model, especially for the dominant DD^* decay have yet to come.

The Chromomagnetic Model of Hogassen et al. [22]

Høgassen et al. use a model of chromomagnetic interaction between four quarks $(cu\bar{c}\bar{u})$ in color octet and singlet combinations to obtain two neutral states and two charged states with masses near that of X. This model has problems similar to those of the Maiani model as none of the other predicted states have been seen.

That leaves us with the favorite among models with four quarks, the $\overline{D}^0 D^{*0}$ molecular model of X(3872).

The $\overline{D}^0 D^{*0}$ Molecular Model of X(3872)

As soon as the X(3872) was discovered in 2003, it was noted that its mass was extremely close to the sum of the masses of the D^0 and D^{0*} mesons, which suggests that X is a $\overline{D}^0 D^{*0} + c\bar{c}$ molecule. It was recalled that way back in 1977 De Rugula, Georgi, and Glashow [23], and Voloshin and Okun [24] suggested that molecules made of D mesons, in particular a $\overline{D}^0 D^{*0}$ molecule, may very well exist.

In 1994 Tornqvist [25] constructed deuteron-like molecules (he called them deusons) with D mesons and B mesons, and predicted that the lowest mass one would be $\overline{D}^0 D^{*0}$ molecule with mass $\approx 3870\ \mathrm{MeV}$. What prescience!!

The $\overline{D}^0 D^{*0}$ molecular model has been examined in great detail by Swanson, Braaten, Suzuki, Voloshin, Oset, Faessler and others. In essence the various treatments differ only in the proposed dynamics, how isospin mixing arises, how the near equality of X formation in B^+ and B^0 decay can be explained, and how much charmonium 2^3P_1 state and other $D\overline{D}$ configurations are mixed into a dominantly $\overline{D}^0 D^{*0}$ wave function. In many cases numerical predictions are lacking.

To list the problems still requiring theoretical resolution for the $\bar{D}^0 D^{0*}$ molecular model:

1. the near equality of the X production in B^+ and B^0 decays,
2. the near equality of the $I = 0(X \to \omega J/\psi)$ and $I = 1(X \to \rho J/\psi)$ decays,
3. the large radiative decay ratio, $(X \to \gamma\psi(2S)/(X \to \gamma J/\psi))$,
4. the very large branching for the decay, $X \to \overline{D}^0 D^{*0}$,
5. the difficulty of survival if $J^{PC} = 2^{-+}$,
6. the very large cross section for X production in Tevatron $p\bar{p}$ measurements,
7. and finally, what is the consequence of all the above with the vanishingly small binding energy of the $\overline{D}^0 D^{*0}$ molecule. The present value, $\mathrm{BE} = 0.1 \pm 0.4$ MeV, leads to the radius $\mathrm{X} = 14$ fm, three times as large as the deuteron.

To be fair, the problem is not just with the theoretical models. As I pointed out earlier, some of the crucial experimental parameters are based on very marginal measurements. And that is with $\sim 800\mathrm{fb}^{-1}$ of e^+e^- luminosity thrown at them. Only Super B's can improve on the e^+e^- situation. For other ways of shining light on X(3872) we can only look forward to PANDA and LHCb.

As I warned you in the beginning, you very likely do not feel any wiser now about what X(3872) is than you were before my talk!!

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