# *Scaling invariance breaking in Four-boson systems and beyond*

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OUTLINE

1. Intro: Scale invariance and Breaking: example integral equation and $1/r^2$ potential

2. Three-bosons: Thomas and Efimov effects

3. Three-Bosons: SKM equations & Danilov's UV solution

4. Limit cycles: scaling plots

5. Mass imbalanced systems

6. Dimensional reduction

7. Faddeev-Yakubovski eqs (4-bosons), zero-range int., reg. and renor.: Scaling-plot

8. LLHH, LLLHH … systems: B.O. approximation

9. FY scale invariance in UV & scale-invariance breaking: 4-body scale

10. Scale inv. breaking in relativistic bound states with Bethe-Salpeter eq.

11. Summary

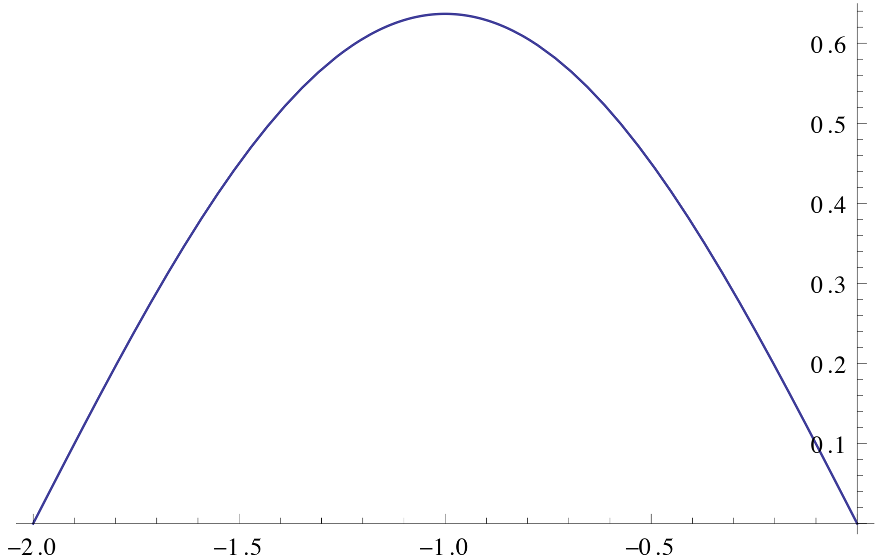
## 1. Scale invariance and Breaking: example integral equation

$$f(k) = \lambda \int_0^\infty dp\, p \frac{f(p)}{k^2+p^2}$$

int. eq. invariant under: $k \to \xi k$ and $p \to \xi p$

$f(k)$ and $f(\xi k)$ solutions $f(k) = k^\eta$

transcendental eq.: $\lambda = -\frac{2}{\pi} \sin\left(\frac{\pi\eta}{2}\right)$




$$\lambda < \lambda_c = \frac{2}{\pi} \text{ for } -2 < \eta < 0$$

Maximum value

$$\text{IF } \lambda > \lambda_c = \frac{2}{\pi} \quad \text{then} \quad \eta = -1 + \imath s_0$$

$$\text{Solution: } f(k) = k^{-1} \sin(s_0 \log k/k^*)$$

*Continuous symmetry breaking to a discrete one & $k^*$ dimensional scale*

$$k \to \exp(n\pi/s_0)\, k$$

*Applies to 3bosons, 4bosons @unitarity, relativistic bound states (Bethe-Salpeter eq.)*

***Scale invariance and Breaking: example $1/r^2$ potential***

$$-\frac{d^2}{dr^2}\psi(r) - \frac{K}{r^2}\psi(r) = E\psi(r)$$

***Continuous symmetry breaking to a discrete one & $r^*$ dimensional scale***

$$\psi(r)|_{r\sqrt{E}\ll 1} \to r^{\frac{1}{2}} \sin(\sqrt{4K-1}\log(r/r^*))$$

$$K > \frac{1}{4} \text{ discrete scale symmetry}$$

(”fall to the center” Landau Quantum Mechanics)

***Efimov effect & Thomas collapse***

**2. Three-boson system:** Subtle three-body phenomenum in $L_{total}=0$:

# The Efimov effect

## Nuclear Physics

Vitaly Efimov Phys. Lett. B 33, 563 (1970).

Vol 440|16 March 2006|doi:10.1038/nature04626 nature

LETTERS

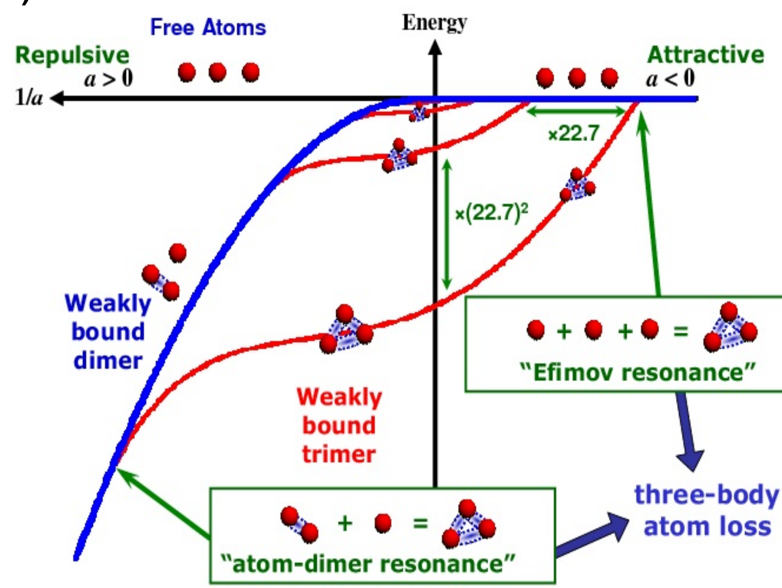
### Evidence for Efimov quantum states in an ultracold gas of caesium atoms

T. Kraemer[1], M. Mark[1], P. Waldburger[1], J. G. Danzl[1], C. Chin[1,2], B. Engeser[1], A. D. Lange[1], K. Pilch[1], A. Jaakkola[1], H.-C. Nägerl[1] & R. Grimm[1,3]

nature physics LETTERS
PUBLISHED ONLINE: 22 FEBRUARY 2009 | DOI: 10.1038/NPHYS1203

### Observation of an Efimov-like trimer resonance in ultracold atom-dimer scattering

S. Knoop[1]*, F. Ferlaino[1], M. Mark[1], M. Berninger[1], H. Schöbel[1], H.-C. Nägerl[1] and R. Grimm[1,2]



# 2. Three-bosons: Thomas and Efimov effects

L. H. Thomas, Phys. Rev. 47, 903 (1935) V. Efimov, Phys. Lett. B 33, 563 (1970).

| Thomas collapse (1935) | Efimov effect (1970) |
|---|---|
| $r_o \rightarrow 0$ | $\lvert a \rvert \rightarrow \infty$ |
| Route to collapse! | infinitely many bound states condensing at E=0 |

$$|a|/r_o \rightarrow \infty$$

Adhikari, Delfino,TF,Goldman,Tomio, PRA37 (1988) 3666

***One three-body scale*** is necessary to represent short-range physics !!!!

Jensen, Riisager, Fedorov, Garrido, RMP76, 215 (2004)
Braaten, Hammer Phys. Rep.428, 259 (2006)

# *Qualitative view Thomas-Efimov effect*

- State of maximum symmetry in s-wave
- Effective interaction $V(\rho)$ hyper-radius $\rho = \left(\sum r_{ij}^2\right)^{\frac{1}{2}}$

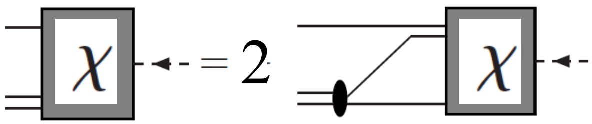
$$-\frac{d^2}{d\rho^2}\psi(\rho) - V(\rho)\psi(\rho) = 0$$

- When $a^{-1} \to 0$ no dimensional scale!!!!
- $V(\rho) = -\frac{K}{\rho^2}$ if K > ¼ $\psi(\rho) \sim \sin\left(s_0 \log \rho/\rho*\right)$
- Efimov factor $s_0 = 1.00624$
- Three-boson energies $E_{n+1} = E_n e^{-2\pi/s_0}$ ***Discrete symmetry!***

E. Nielsen, D. V. Fedorov, A. S. Jensen, and E. Garrido, Phys. Rep. **347**, 373 (2001).

# *3. Three-Bosons: SKM equations & Danilov's UV solution*

Skorniakov and Ter-Martirosian equations (1956)




Dirac-delta interaction

$$\chi(\vec{k}) = \frac{\pi^{-2}}{\pm\sqrt{-E_2} - \sqrt{-E_3 + \frac{3}{4}k^2}} \int d^3p \left( \frac{1}{E_3 - k^2 - p^2 - \vec{p}\cdot\vec{k}} + \frac{1}{\mu_3^2 + k^2 + p^2 + \vec{p}\cdot\vec{k}} \right) \chi(\vec{p})$$

Adhikari, TF, Goldman, PRL74, 487 (1995); Adhikari, TF, *ibid.* 74, 4572 (1995)

$\hbar = m = 1$ (+) dimer bound & (−) dimer virtual

Thomas collapse: $E_2$ finite & $\mu_3 \to \infty$ & $\epsilon_2 = E_2/(\mu_3)^2 \to 0$

Efimov effect: $E_2 \to 0$ & $\mu_3$ finite & $\epsilon_2 = E_2/(\mu_3)^2 \to 0$

Thomas-Efimov effect!

# *Scale invariance at the unitary limit and breaking*

G.S. Danilov, Sov. Phys. JETP 13 (1961) 349

$\epsilon_2 = \epsilon_3 = 0$ and $\mu_3 \to \infty$ or scatt lengths → infinity

s-wave: $$\chi(y) = \frac{4}{\pi\sqrt{3}y}\int_0^\infty dx\ x^2\,\chi(x)\int_{-1}^{1} dz\frac{1}{x^2+y^2+x\ y\ z}$$

Solution: $$\chi(y) = y^{s-2}$$

Efimov equation: $$\boxed{1 = \frac{8}{\sqrt{3}s}\frac{\sin(\pi s/6)}{\cos(\pi s/2)} \qquad s = \pm i s_0 \qquad s_0 \approx 1.00624}$$

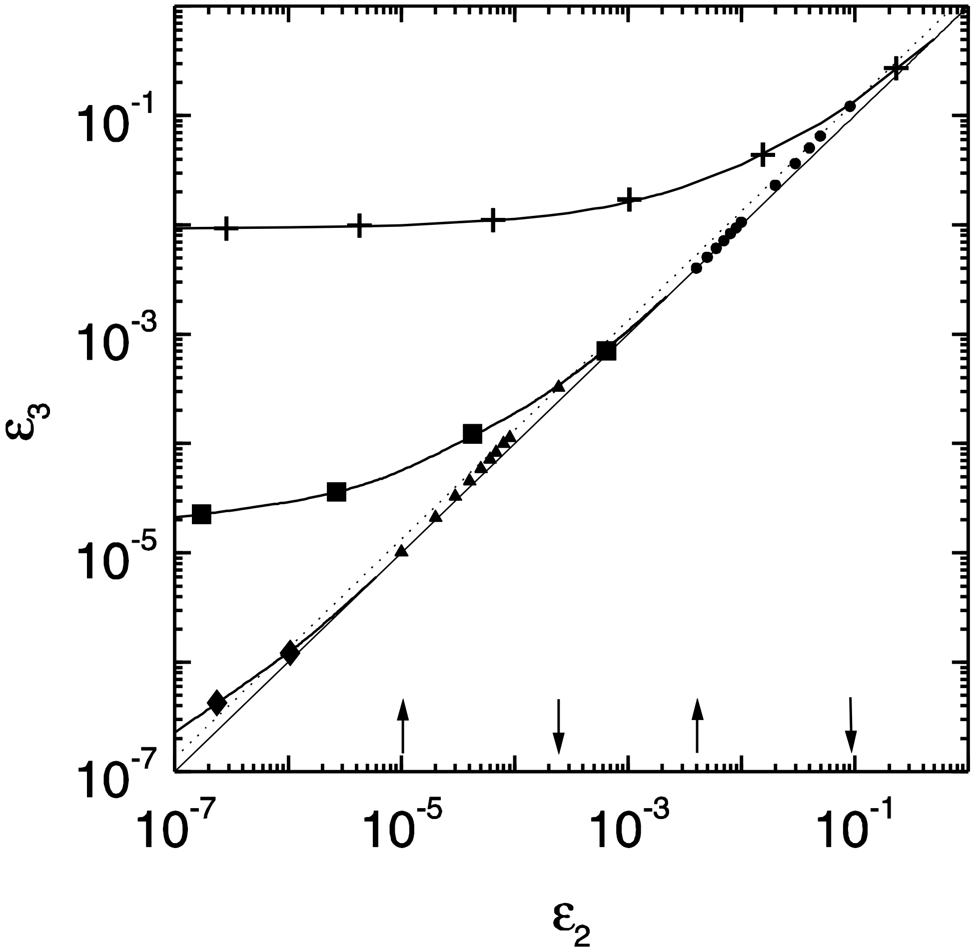
$$\boxed{\chi(y) = a_+ y^{\imath s_0 - 2} + a_- y^{-\imath s_0 - 2}} \qquad \chi(y) = y^{-2}\sin\left(s_0 \ln y + c\right)$$

One <u>*parameter*</u> to fix the solution → <u>*3-body scale*</u>

*Continuum scale invariance broken to a discrete one*

*Efimov effect*

# Efimov States – Bound and virtual states (3 identical bosons) (3D)




**Bound-states (lines with simbols)**

With Plus - Fundamental state

With squares – 1st. excited

With diamonds – 2nd. excited

**Virtual-states (just simbols)**

circles – 1st. Excited state

triangles – 2nd. Excited state

**$\varepsilon_2$ bound**

↓ the virtual state starts (dotted line)

↑ Virtual-state turns to an excited state (continuous line)

S. K. Adhikari, A. C. Fonseca and LT *Phys. Rev.* **C27**, 1826 (1983).

# 4. Limit cycles: scaling plots

$$\epsilon_3^{(N)} \equiv \epsilon_3^{(N)}(\pm\sqrt{\epsilon_2})$$

$$\xi \equiv \pm\sqrt{\epsilon_2} = \pm\left(E_2\,\epsilon_3^{(N)}/E_3^{(N)}\right)^{1/2}$$

$$\boxed{\frac{E_3^{(N+1)}}{E_3^{(N)}} = \lim_{N\to\infty}\frac{\epsilon_3^{(N+1)}(\xi)}{\epsilon_3^{(N)}} = \mathcal{F}\left(\pm\sqrt{\frac{E_2}{E_3^{(N)}}}\right)}$$

Scaling function

$$\boxed{\mathcal{F}(0) = e^{2\pi/s_0} = 1/515}$$

Efimov 1970

***Scaling limit*:**

Frederico et al PRA60 (1999)R9

Yamashita et al PRA66(2003)052702

***Limit cycle*:**

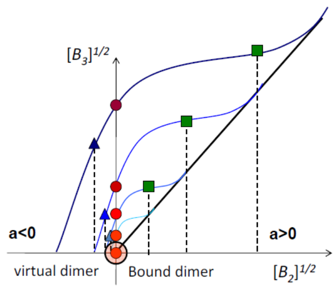
Bedaque, Hammer, van Kolck, PRL 82 (1999) 463

Mohr et al Ann. Phys. 321 (2006) 225

# Scaling function & Limit Cycle

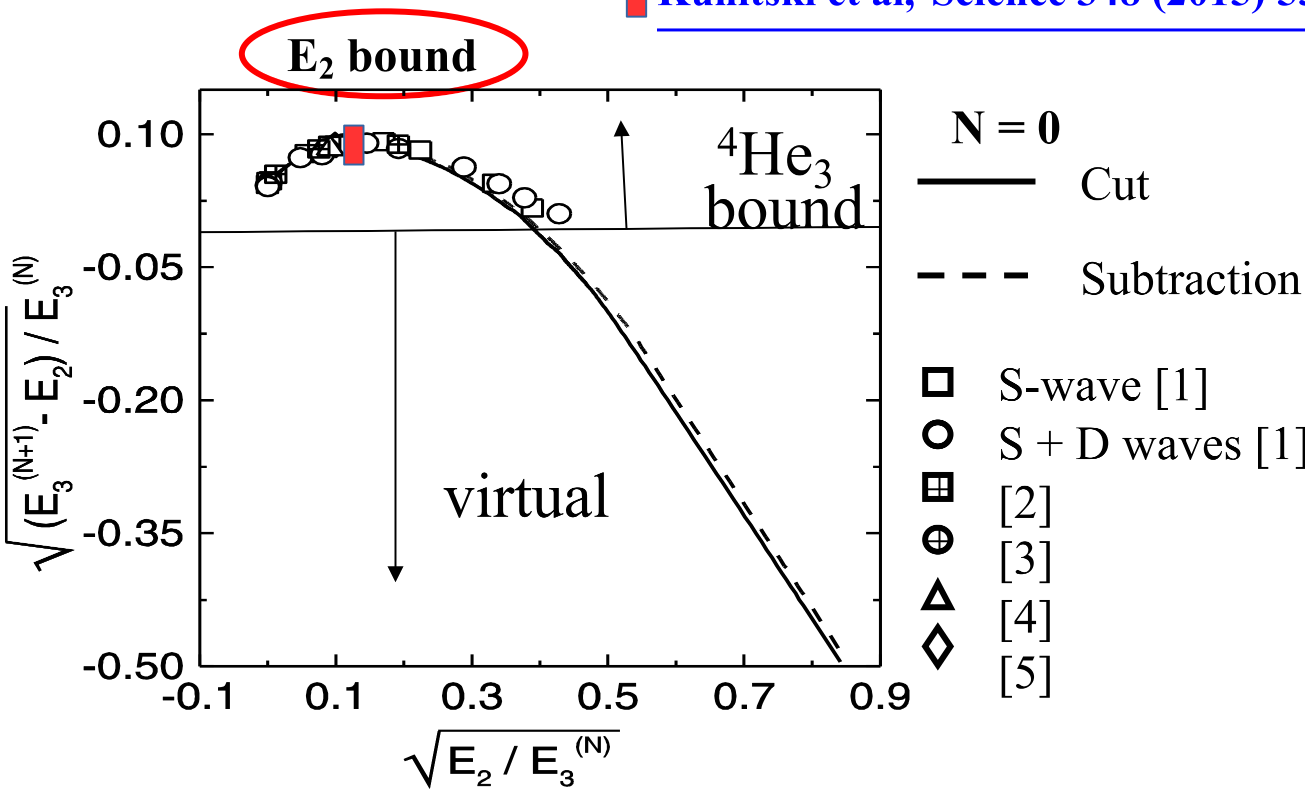
T. Frederico, LT, A. Delfino and E. A. Amorim. *Phys. Rev.* **A60**, R9 (1999).

Yamashita et al PRA66(2003)052702




Scaling plot

Kunitski et al, Science 348 (2015) 551





[1] Th. Cornelius e W. Glöckle. *J. Chem. Phys.* **85**, 1 (1996).

[2] S. Huber. *Phys. Rev.* **A31**, 3981 (1985).

[3] P. Barletta e A. Kievsky. *Phys. Rev.* **A64**, 042514 (2001).

[4] D. V. Fedorov e A. S. Jensen. *J. Phys.* **A34**, 6003 (2001).

[5] E. A. Kolganova, A. K. Motovilov e S. A. Sofianos. *Phys. Rev.* **A56**, R1686 (1997).


Range correction: Thogersen, Fedorov, Jensen PRA78(2008)020501(R)

# 5. Mass imbalanced systems

## Generalization of Danilov's method to AAB systems @ unitary limit

M. T. YAMASHITA *et al.* PHYSICAL REVIEW A **87**, 062702 (2013)

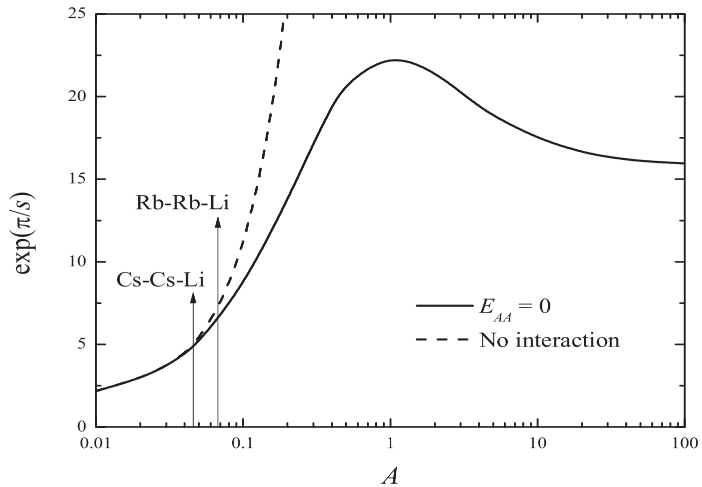


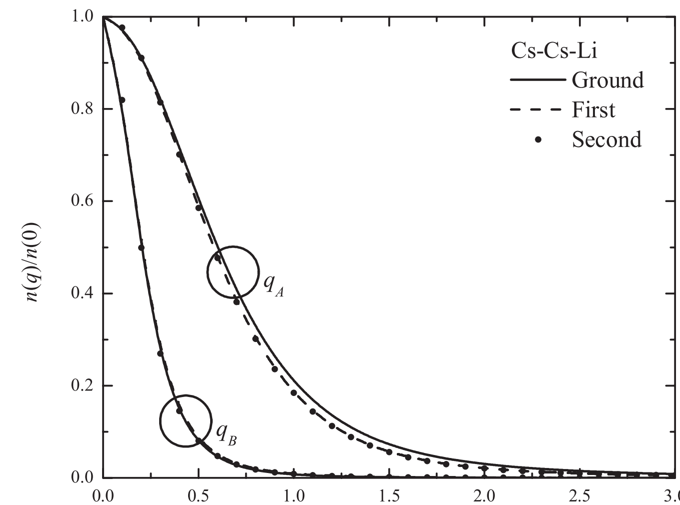

FIG. 1. Scaling parameter $s$ as a function of $\mathcal{A} = m_B/m_A$ for $E_{AA} = 0$ and $E_{AB} = 0$ (resonant interactions) (solid line) and for the situation where $E_{AB} = 0$ but with no interaction between AA (dashed line). The arrows show the corresponding mass ratios for $^{133}$Cs-$^{133}$Cs-$^{6}$Li and $^{87}$Rb-$^{87}$Rb-$^{6}$Li.

A. S. Jensen and D. V. Fedorov, Europhys. Lett. **62**, 336 (2003).

$$\boxed{\frac{\mathcal{A}}{\pi}\left(\frac{\mathcal{A}+1}{2\mathcal{A}}\right)^{3/2}\sqrt{\frac{2(\mathcal{A}+1)}{\mathcal{A}+2}}\,I_1(s) = 1}$$

$$\mathcal{A} = m_B/m_A$$

M. T. YAMASHITA *et al.*




The momentum distributions for the particles $A$ and $B$ are

$$n(q_B) = \int d^3 p_B |\langle \vec{q}_B \vec{p}_B | \Psi \rangle|^2,$$
$$n(q_A) = \int d^3 p_A |\langle \vec{q}_A \vec{p}_A | \Psi \rangle|^2 \qquad (10)$$

**Observed 3B Recombination peaks in atomic traps (Heidelberg group)**

**$^{133}$Cs - $^{133}$Cs - $^{6}$Li**

**Pires et al. PRL112(2014)250404 (a < 0)**

**Ulmanis et al PRL117(2016)153201 (a > 0)**

# *6. Dimensional reduction D = 3 → 2*

- ***No Efimov effect in 2D! Bruch & Tjon PRA 19 (1979) 425***

- Compactification (periodic bound. conditions) 3D→2D→1D (3body)
  Sandoval et al, JPB 51 (2018) 065004

- Danilov's equations in fractional dimensions (3body)
  Rosa, TF, Krein, Yamashita, PRA97, 050701(R) (2018)

- EFT compactification & dim reg 4D→3D→2D, 4D→2D (2body)
  Beane & Jafry, JPB52(2019) 035001

❖ Compactification of one dimension

J H Sandoval *et al*

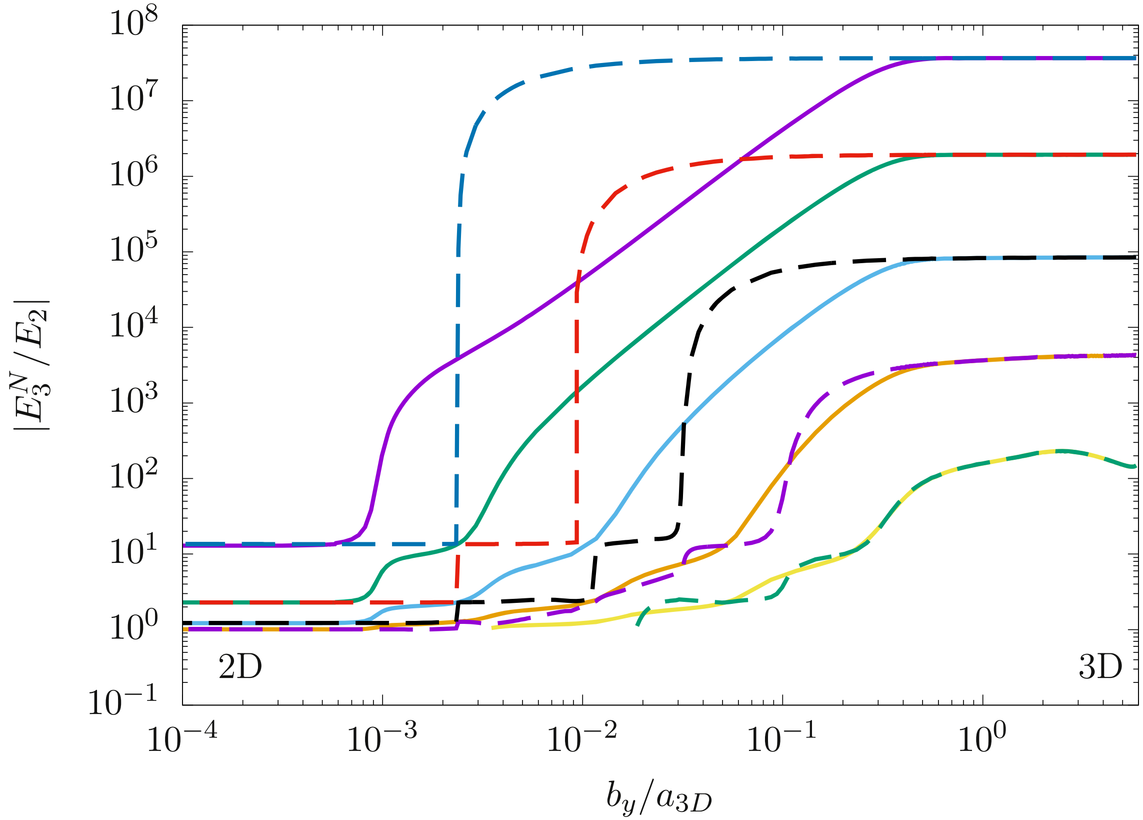



**Figure 2.** Trimer energies plotted in units of the two-body energy for $m_B/m_A = 6/133$ as functions of $b_y/a_{3\mathrm{D}}$. For the solid lines the two-body energy varies with $b_y$ while for the dashed lines it is kept constant (see text for discussion). Solid and dashed lines have different colors for visibility.

JPB 51 (2018) 065004

# *Danilov's equations in fractional dimensions AAB system*

Rosa et al. PRA97, 050701(R) (2018)

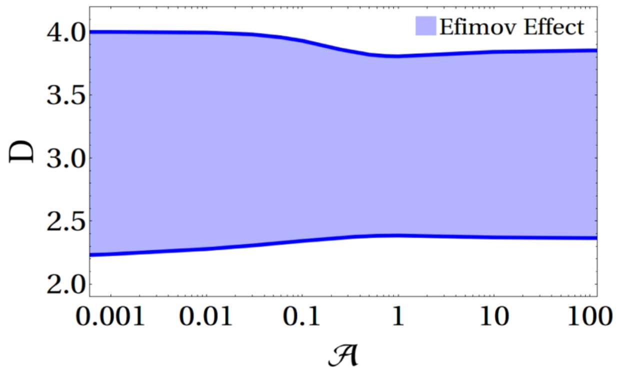



FIG. 1. Regions (in blue) where there is a real solution for the scaling factor $s$, solution to Eq. (8); outside this "dimensional band," the Efimov effect does not exist. For $\mathcal{A} = 1$ we reproduce exactly the result in Ref. [7], where the dimensional limits are given by $2.3 < D < 3.8$.

$$\mathcal{A} = m_B/m_A$$

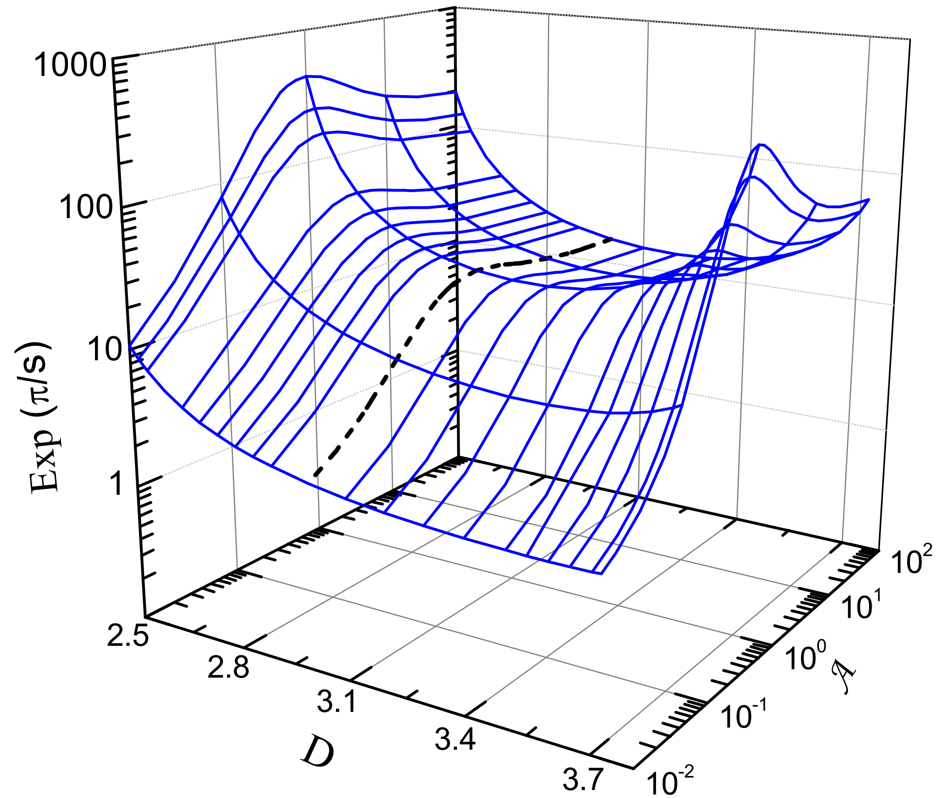
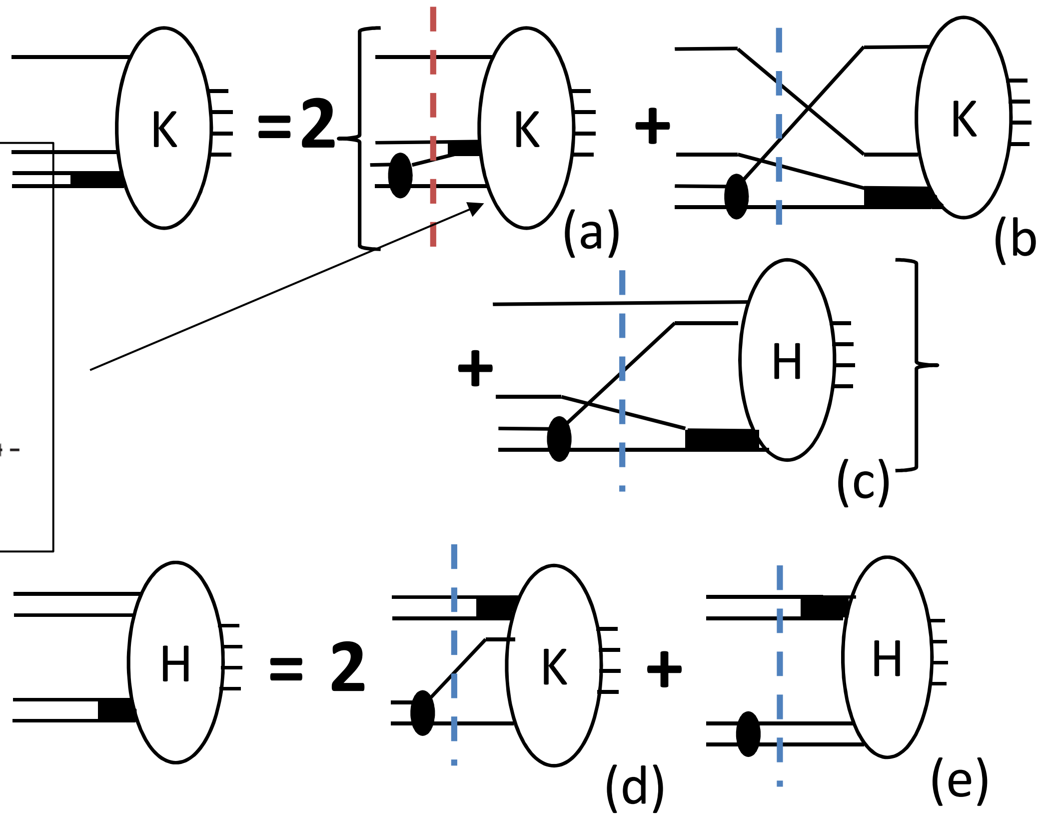



FIG. 2. Discrete scaling factor as a function of the mass ratio $\mathcal{A} = m_B/m_A$, and dimension $D$. The black dashed line shows the well-known situation of $D = 3$.

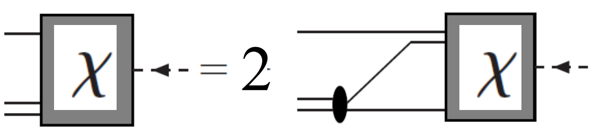
# 7. Faddeev-Yakubovski eqs (4-bosons), zero-range int., reg. and renor.: Scaling-plot

### *Collapse of the 4B system & 3B energy fixed*

Yamashita, Tomio, Delfino, TF, EPL 75 (2006) 555



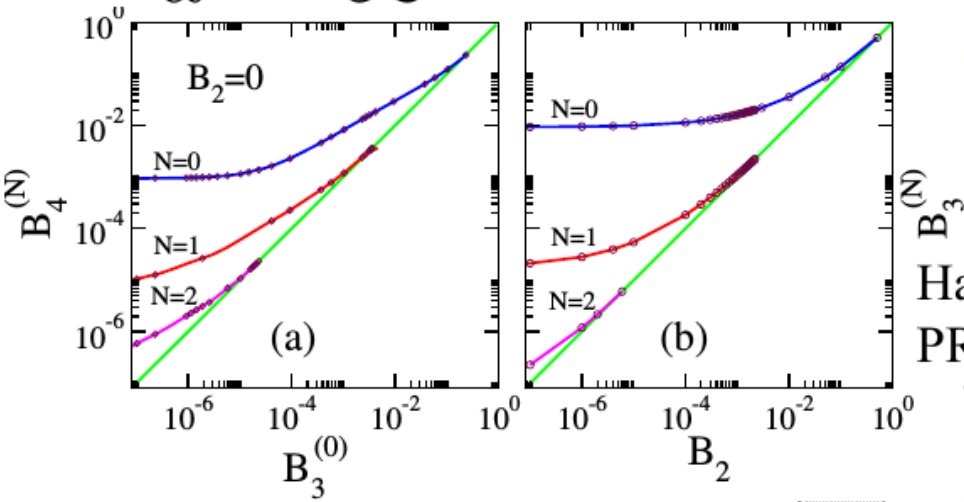

Skorniakov and Ter-Martirosian (1956)




Subtracted Green's Functions: $G_0^{(N)} = \frac{1}{E - H_0} - \frac{1}{-\mu_N^2 - H_0}$

with $\mu_3$ (RED): 3B scale & $\mu_4$ (BLUE): 4B scale

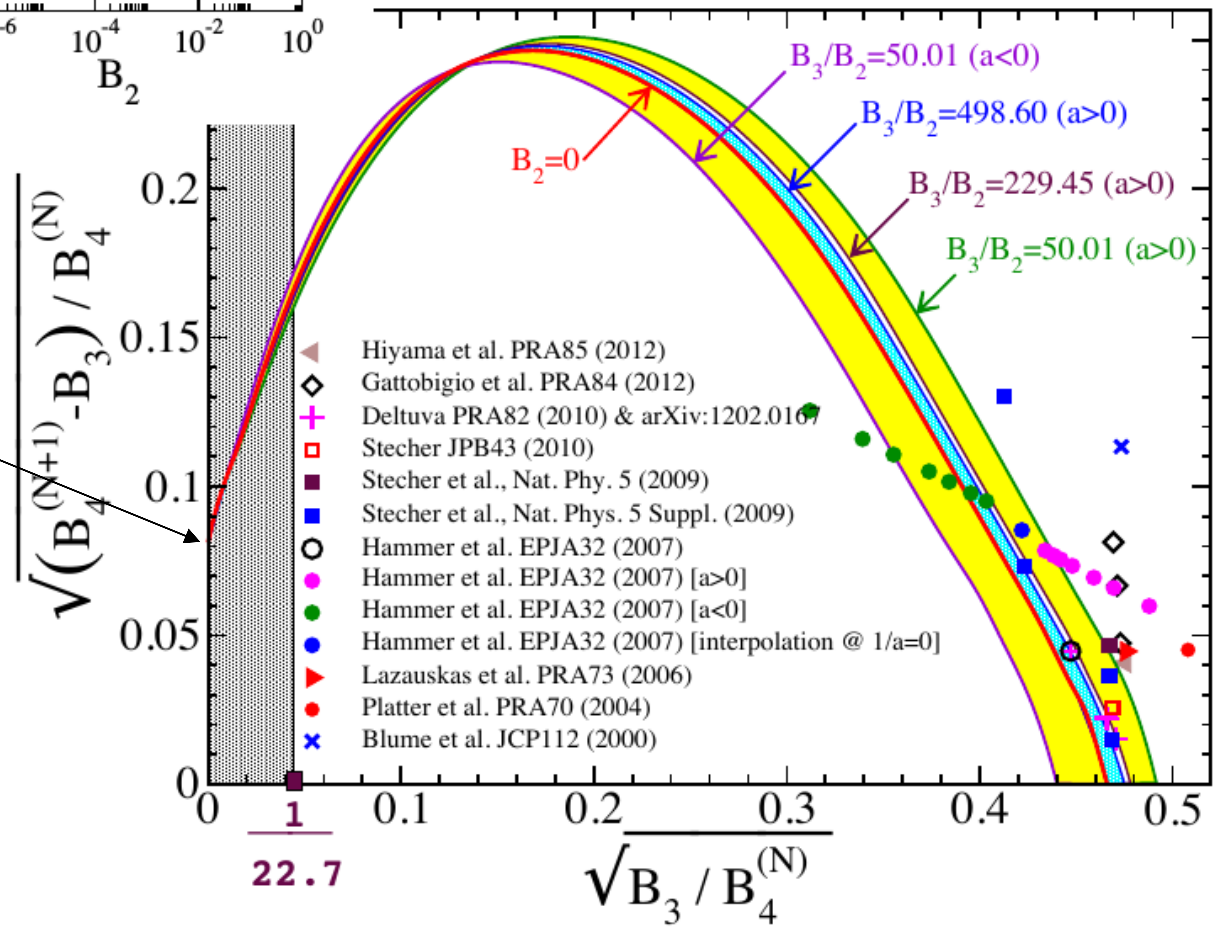
$a = \infty$




# Scaling plot

Hadizadeh, Yamashita,Tomio, Delfino, TF, PRL107, 135304 (2011)

$$\boxed{B_4^{(N)}/B_4^{(N+1)} \sim 151}$$



# 8. LLHH, LLLHH … systems: B.O. approximation

**LLHH Naidon, Few-Body Syst. 59, 64 (2018)**

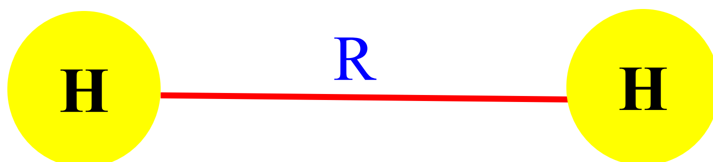
$m_H >> m_L$ *L-H interaction only*

**"Interwoven limit cycles in the spectra of mass imbalanced many-boson system"**

**De Paula, Delfino, TF, Tomio arXiv:1903.10321v1 [quant-ph]**

Born-Oppenheimer approx.

**Fonseca, Redish, Shanley, Nucl. Phys. A320 (1979) 273**
**Bhaduri, Chatterjee, van Zyl, Am. J. Phys. 79 (2011) 274-281; Am. J. Phys. 80 (2012) 94.**




$$\left[\frac{d^2}{dR^2} + \frac{s_N^2 + \frac{1}{4}}{R^2} - \mathcal{B}_N\right] u = 0 \quad (N \geq 3)$$

$$\boxed{s_N \equiv s_N(A) \equiv \sqrt{\left(\frac{2+A}{4A}\right)(N-2)\gamma^2 - \frac{1}{4}}}$$

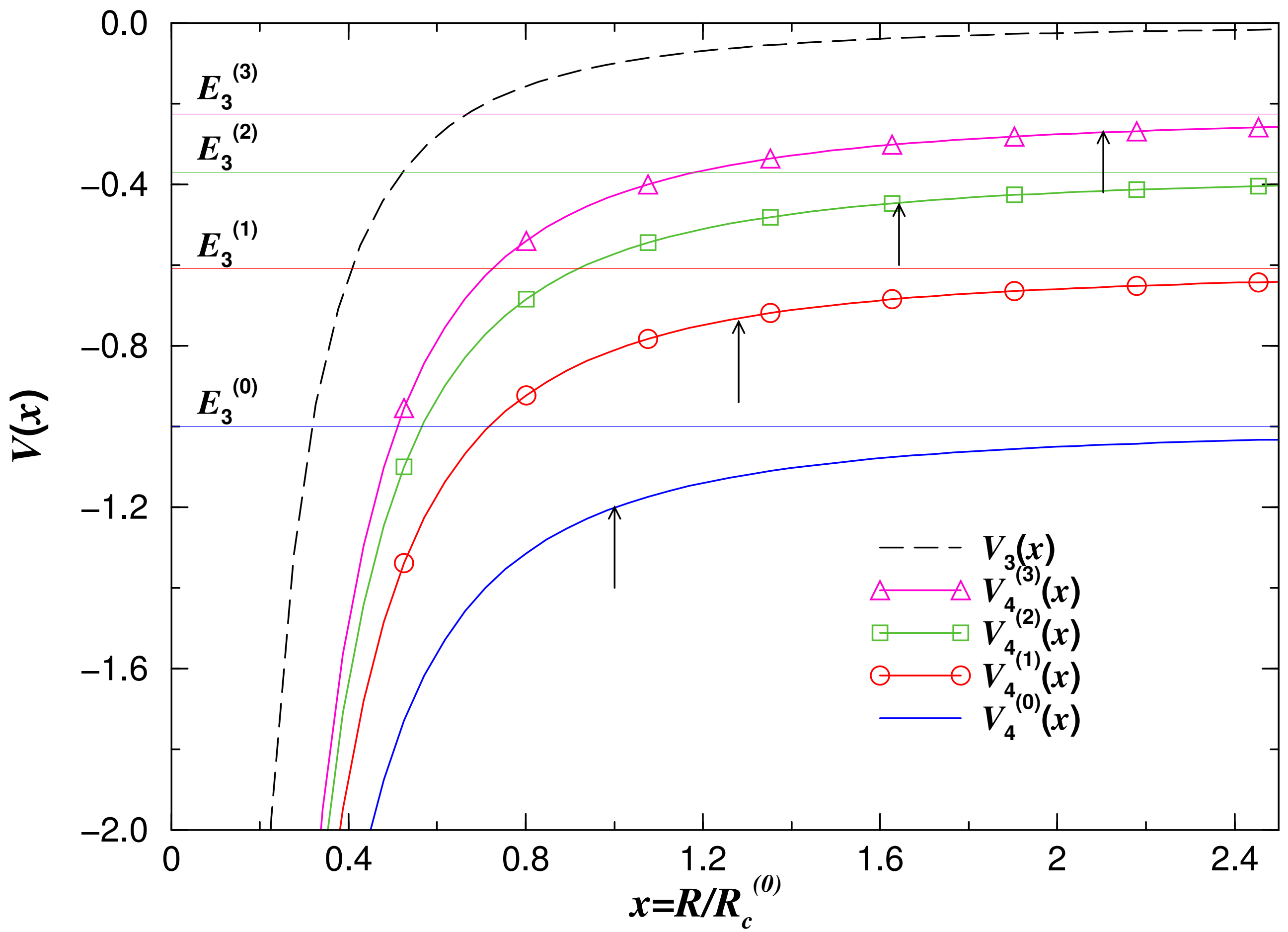
A=$m_L$ / $m_H$

$\gamma = e^{-\gamma} = 0.5671433$

$(N-2)$ Light bosons

New limit cycles beyond 3-body!

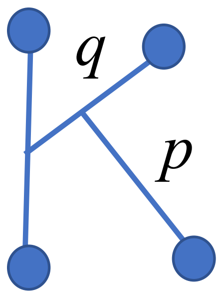
# ***H-H B.O. potential 4-body system HHLL*** @ unitarity



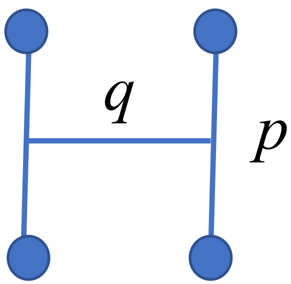

(up-arrow) size of the three-body LHH cut the B.O. HH potential

# 9. FY scale invariance in UV & scale-invariance breaking: 4-body scale

## "Four-Boson continuous scale symmetry breaking" TF, de Paula, Delfino, Tomio, FBS 2019




$$\mathcal{K}(q,p)=\frac{2}{\sqrt{(3/4)q^2+(2/3)p^2}}\int d\Omega dk k^2\left\{\frac{\mathcal{K}(k,p)}{q^2+k^2+(2/3)p^2+q\,k\,z_0}\right.$$
$$+\frac{27\,\mathcal{K}\left(k,3\sqrt{k^2+p^2-2\,p\,k\,z_1}\right)}{q^2+(70/9)p^2+9k^2-16p\,k\,z_1-(8/3)pq\,z_2+3\,k\,q\,z_0}$$
$$\left.+\frac{\mathcal{H}\left(k,\sqrt{k^2/4+p^2-\,p\,k\,z_1}\right)}{q^2+(10/9)p^2+k^2+q\,k\,z_0-(4/3)pk\,z_1-(2/3)pq\,z_2}\right\}, \qquad (2)$$




$$\mathcal{H}(q,p)=\frac{1}{\sqrt{q^2/2+p^2}}\int d\Omega dk k^2\left\{\frac{\mathcal{H}(q,k)}{(q^2/2+p^2+k^2)}\right.$$
$$\left.+\left(\frac{27}{4}\right)\frac{\mathcal{K}\left(k,(3/2)\sqrt{k^2+q^2+\,k\,q\,z_0}\right)}{(3/2)q^2+p^2+(9/4)k^2+3\,q\,k\,z_0}\right\}, \qquad (3)$$

SCALE INVARIANT!

where $k$ is within the interval $[0,\infty[$, $z_0\equiv z_1z_2+\sqrt{(1-z_1^2)(1-z_2^2)}\cos\phi$, $d\Omega\equiv(2\pi)^{-2}\,dz_1dz_2d\phi$, with $-1\leq z_{i=1,2}\leq 1$, and $0\leq\phi\leq 2\pi$.

$$\boxed{\mathcal{K}(t\,q,t\,p)\;=\;t^a\mathcal{K}(q,p)\;\text{ and }\;\mathcal{H}(t\,q,t\,p)\;=\;t^a\mathcal{H}(q,p)}$$

# Solution: UV FY eqs.

$$\mathcal{K}(q,p) = \frac{q^\eta}{\sqrt{\frac{3}{4}q^2 + \frac{2}{3}p^2}} f_K\left(q/p\right) \quad \text{and} \quad \mathcal{H}(q,p) = \frac{q^\eta}{\sqrt{\frac{1}{2}q^2 + p^2}} g_H\left(p/q\right)$$

**Approximate UV form of FY eqs.:**

$$\overbrace{f_K\left(x\right) = \frac{4\,x^{-\eta}}{\sqrt{3}}\int d\Omega dy\, \frac{y^{1+\eta}}{x^2+y^2+xy\,z_0}\left\{f_K\left(y\right)}^{\text{3-boson eq. SKTM}} + \left(\tfrac{1}{3}\right)^\eta f_K\left(\tfrac{1}{3}\right) + g_H\left(\tfrac{1}{2}\right)\right\}$$

$$g_H\left(x\right) = \frac{2}{\pi}\int_0^\infty \frac{dy\,y}{y^2+x^2}\left\{g_H\left(y\right) + 2\left(\tfrac{2y}{3}\right)^\eta f_K\left(\tfrac{2}{3}\right)\right\}.$$

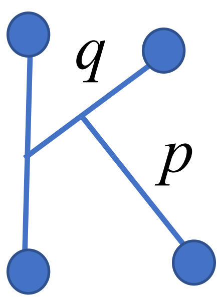
$$\boxed{f_K(x) = f_0 \quad \& \quad g_H(x) = x^\eta}$$

$$\boxed{1 = \frac{8}{\sqrt{3}\,(\eta+1)}\,\frac{\sin\left[(\eta+1)\frac{\pi}{6}\right]}{\cos\left[(\eta+1)\frac{\pi}{2}\right]}\left\{1 - \frac{1}{3^\eta}\left[\frac{1-\sin\left(\eta\frac{\pi}{2}\right)}{1+\sin\left(\eta\frac{\pi}{2}\right)}\right]\right\}}$$

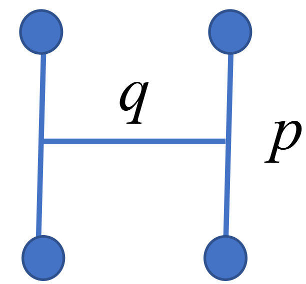
## Scale symmetry breaking to a Discrete scale symmetry

***Solution of the transcendental equation*** $\eta \; = \; -0.346 \,\pm\, 1.552\mathrm{i}$

$$\mathcal{K}(q,p) \approx f_0 \frac{\sin(s_4 \log q/\Lambda^*)}{\sqrt{\frac{3}{4}q^2 + \frac{2}{3}p^2}} \quad \& \quad \mathcal{H}(q,p) \approx \frac{\sin(s_4 \log p/\Lambda^*)}{\sqrt{\frac{1}{2}q^2 + p^2}}$$




***4-body scale***




***Compare to imaginary part:*** ***1.25 i*** *from Hadizadeh et al. PRL107 (2011) 135304*

$$B_4^{(N)}/B_4^{(N+1)} = 151 = \exp(2\pi/s_4) \quad \& \quad s_4 = 1.25$$

In EFT 4-body scale @ NLO - Bazak et al. PRL 122 (2019) 143001

## *10. Scale inv. breaking in relat. bound states with Bethe-Salpeter eq.*

*Broad thoughts on scale symmetry breaking in QFT*

- *Beyond non-relativistic physics*

- *Spontaneous Chiral symmetry breaking & Miransky scaling, N.Cim. A90(1985)149*
  Kaplan,Lee,Son PRD80 (2009)12005

- *Relativistic bound states within Bethe-Salpeter approach:*

*Fermions coupled to scalar, vector etc fields: coupling constant is dimensionless (QCD) - instabilities above critical value associated with log-periodic solutions… Efimov physics!*

***Fermion-fermion:*** Dorkin, Beyer, Semikh, Kaptari, Few Body Syst. 42 (2008) 1

***Fermion-fermion:*** Carbonell, Karmanov, EPJA 46 (2010) 387

***Fermion-boson:*** Alvarenga Nogueira***,*** Gherardi, TF, Salmè, Colasante, Pace
PRD100 (2019)016021

# Example: Fermion-boson Bethe-Salpeter equation ½⁺

*Alvarenga Nogueira et al. in preparation*

$$\Phi^\pi(k,p,J_z) = \Big[O_1(k)\ \phi_1(k,p) + O_2(k)\ \phi_2(k,p)\Big]\ U(p,J_z)$$

$$O_1(k) = \mathbb{I}\ , \qquad O_2(k) = \frac{\not{k}}{M}\ , \qquad (\not{p} - M)\ U(p,J_z) = 0$$

**Ladder BSE in Euclidean space – vector exchange**

$$k_4 = K\cos\varphi \quad \text{and} \quad k = K\sin\varphi \qquad 0 < \varphi < \pi$$

$$-5 < \mathrm{Real}[\eta] < -4$$

Maximum value of the couplings product

$$\alpha_c = 1.18691... \qquad \alpha^V = \frac{\lambda_F^v\ \lambda_S^v}{8\pi}$$

$$\phi_1(k_4,k) = K^{\eta+1} \quad \text{and} \quad \phi_2(k_4,k) = 0 \qquad \eta = -4.08918...$$

$$\phi_1(k_4,k) = 0 \quad \text{and} \quad \phi_2(k_4,k) = K^{\eta} \qquad \eta = -4.91082....$$

*Alvarenga Nogueira et al. in preparation*

$$\psi_i(\xi,\gamma;\kappa^2) = iM \int_{-\infty}^{\infty} \frac{dk^-}{2\pi} \phi_i(k,p) \sim \gamma^{1+\frac{\eta_i}{2}}$$

Solution of the Ladder BS equation in Minkowski space via Nakanishi integral representation [PRD100 (2019)016021]

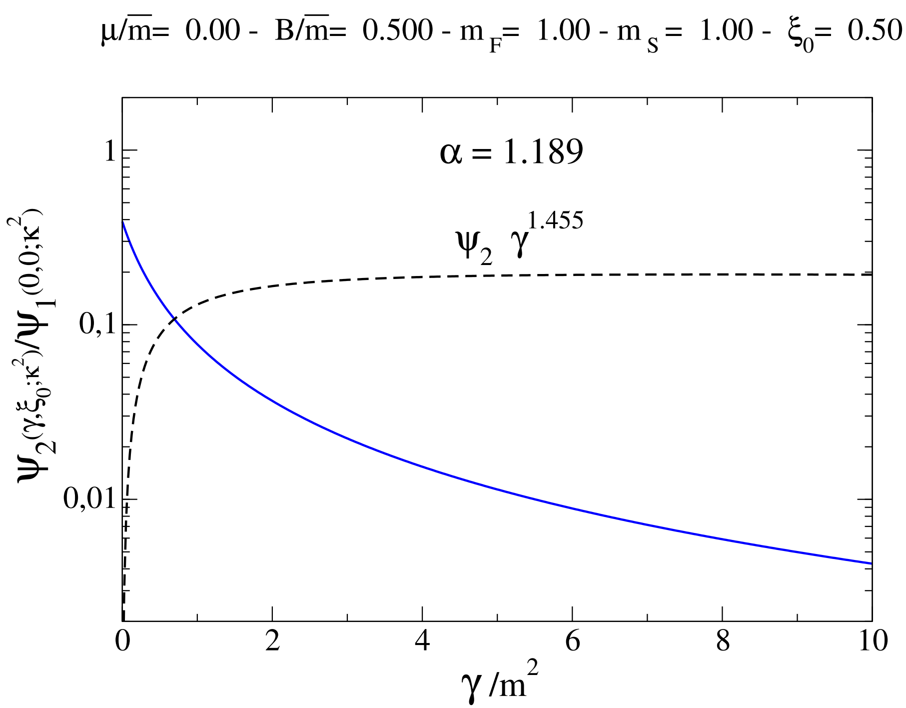



**Figure 5.4.** The light-front wave function $\psi_2(\gamma, z_0 = 0)$ obtained from the solution of the original equation (5.8) as a function of $\gamma$ (solid blue curve) and its product with the asymptotic limit found in the high momentum limit (dashed black curve).

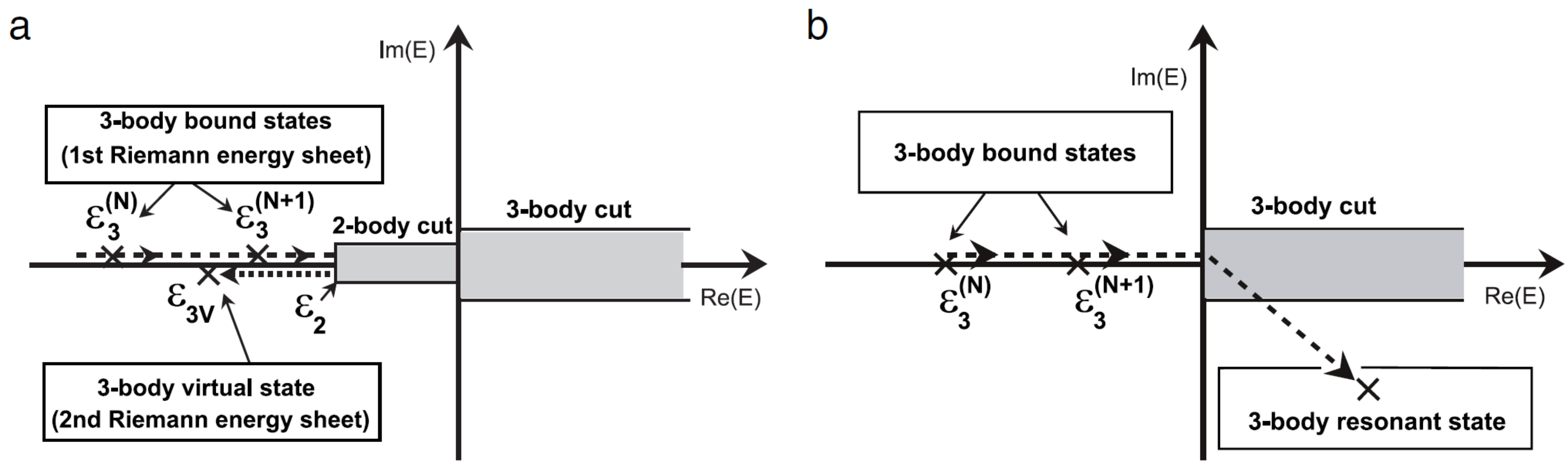
# Summary

- ✓ *Scale invariance breaking & Efimov and Thomas effects;*
- ✓ *Dimensional reduction & suppresion Thomas-Efimov effects;*
- ✓ *Scale invariance breaking in 4-boson systems: 4body scale;*
- ✓ *More particles with short-range interactions: B.O. approx. suggests new scales;*
- ✓ *Scale invariance breaking & Relativistic bound states.*

## *THANK YOU!*

**Thanks to:**

# *Analytic structure & Efimov state trajectory*




S.K. Adhikari and L. Tomio, Phys. Rev. C **26**, 83 (1982); S.K. Adhikari, A.C. Fonseca, and L. Tomio, *ibid.* **26**, 77 (1982).

F. Bringas, M.T. Yamashita and T. Frederico, Phys. Rev. A **69**, 040702(R) (2004).

Yamashita et al PRA66 (2002) 052702 (atoms)
Rupak, Vaghani, Higa,van Kolck PLB(2018) (n-d)
arXiv:1806.01999 [nucl-th]

Continuum resonances of Borromean systems: observation in atomic traps!

Resonant 3-body recombination (Innsbruck, Rice, Heidelberg, Bar Ilan, Florence…)