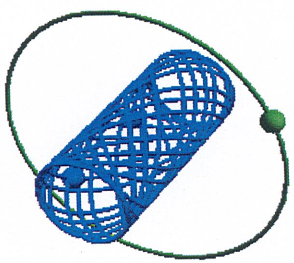
ABC

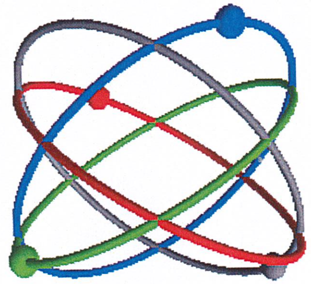
or

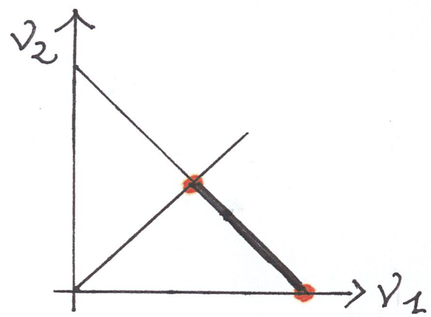
N-BODY RELATIVE EQUILIBRIA IN HIGHER DIMENSIONS



Alain Chenciner

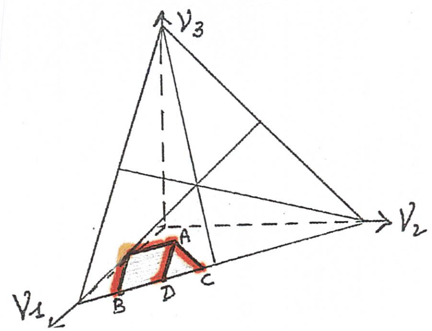
IMCCE & PARIS 7





GDM

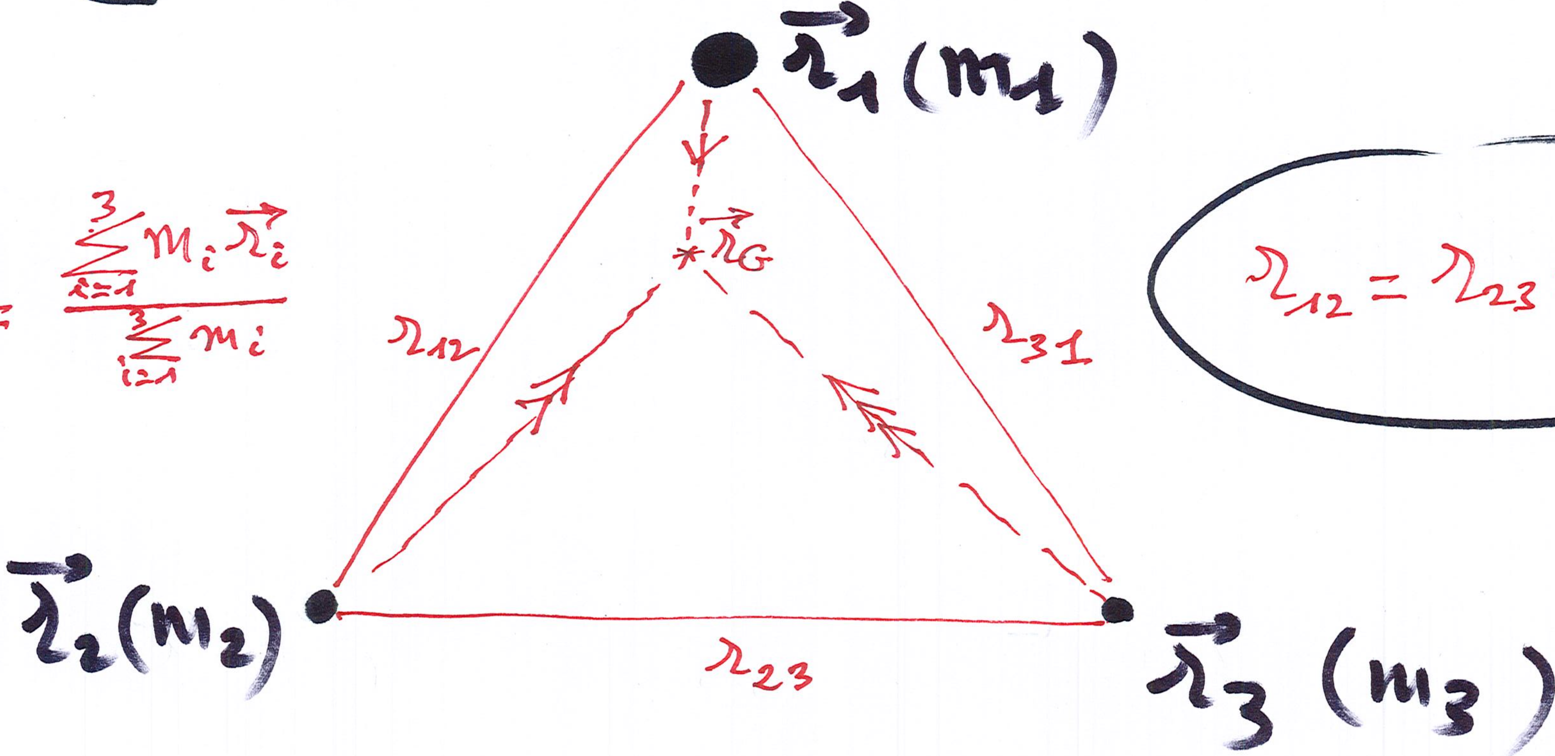
May 11 2021



LAGRANGE 1772

$\exists\, 1!$ non colinear central configuration

$$\vec{r}_G = \frac{\sum_{i=1}^{3} m_i \vec{r}_i}{\sum_{i=1}^{3} m_i}$$



$$\boxed{r_{12} = r_{23} = r_{31}}$$

$\exists$ also 3 colinear C.C. (Euler)

PROOF

$$\forall i, \quad \ddot{\vec{r}}_i = \sum_{j \neq i} \frac{m_j (\vec{r}_j - \vec{r}_i)}{r_{ij}^3} \quad \Longrightarrow \quad \ddot{\vec{r}}_G = 0$$

$$\text{C.C.} \iff \exists \lambda, \forall i, \quad \ddot{\overline{\vec{r}_i - \vec{r}_G}} = -\lambda (\vec{r}_i - \vec{r}_G)$$

$$\Updownarrow$$

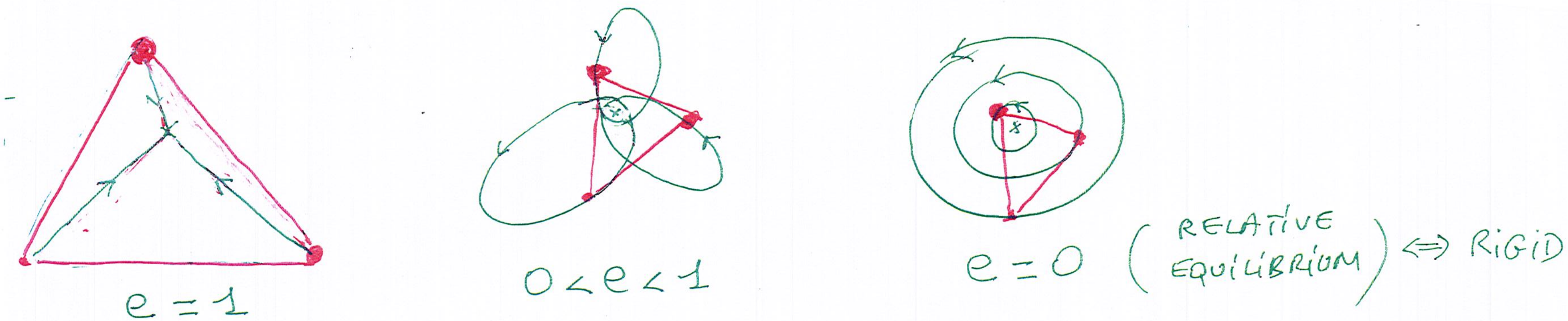
$$\forall i, \quad \sum_{j \neq i} m_j \left(\frac{1}{r_{ij}^3} - \frac{\lambda}{\sum_{j=1}^{3} m_j} \right) \underbrace{(\vec{r}_j - \vec{r}_i)}_{\text{independents}} = 0$$

Each C.C. admits HOMOGRAPHIC MOTIONS

necessarily planar if in $\mathbb{R}^3$ (Lagrange)

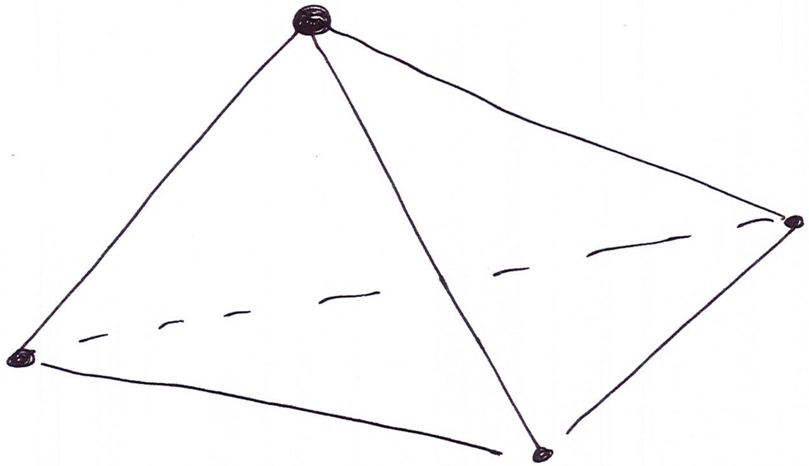
in $(\mathbb{R}^2)^3 = (\mathbb{C})^3$, $\boxed{x(t) = \zeta(t)\, x(0), \quad \underbrace{\ddot{\zeta}(t) = -\frac{k\,\zeta(t)}{|\zeta(t)|^3}}_{\text{Kepler}} \in \mathbb{C}}$

$x(t) = \left(\vec{r}_1(t) - \vec{r}_G(t), \vec{r}_2(t) - \vec{r}_G(t), \vec{r}_3(t) - \vec{r}_G(t)\right)$



EVERYTHING THE SAME FOR 4 BODIES

$\exists\, 1!$ NON COPLANAR C.C.,



THE REGULAR TETRAHEDRON

EXCEPT THAT $\nexists$ HOMOGRAPHIC NON HOMOTHETIC MOTIONS IN $\mathbb{R}^3$

SUCH MOTIONS ARE ONLY POSSIBLE IN $\mathbb{R}^4$ or $\mathbb{R}^6$

N-BODY CONFIGURATIONS MOD. TRANSLATIONS IN AN EUCLIDEAN SPACE (E,ε)

A. Albouy & A.C.

$$\begin{array}{ll}\mathcal{D} & \text{dispositions} := \mathbb{R}^n/\mathbb{R}(1,\dots,1) \\ \cong\big\downarrow \mu & \\ \mathcal{D}^* & \text{codispositions} = \left\{\xi=(\xi_1,\dots,\xi_n)\in\mathbb{R}^n,\ \sum_{i=1}^{n}\xi_i = 0\right\}\end{array}$$

$$\mu(x_1,\dots,x_n) = \big(m_1(x_1-x_G),\dots,m_n(x_n-x_G)\big)$$

$$\boxed{X \in \mathcal{D}\otimes E \equiv \mathrm{Hom}(\mathcal{D}^*, E) \qquad \xi \longmapsto \sum_{i=1}^{n}\xi_i\,\vec{r}_i}$$

$\mu\otimes\varepsilon$

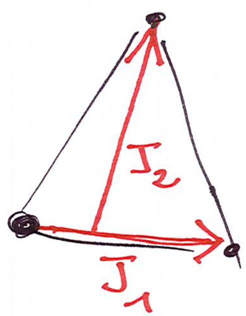
$\|$

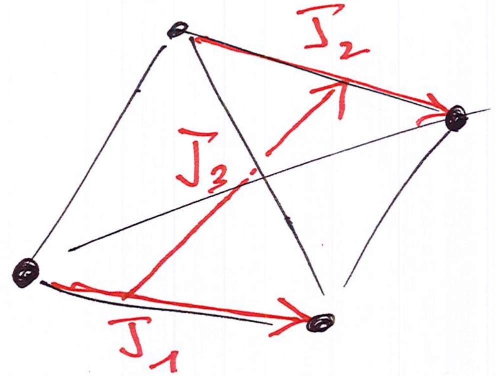
mass scalar product: $(\vec{r}\,'_1,\dots,\vec{r}\,'_n)\cdot(\vec{r}\,''_1,\dots,\vec{r}\,''_n) = \sum_{i=1}^{n} m_i\langle \vec{r}\,'_i-\vec{r}\,'_G,\ \vec{r}\,''_i-\vec{r}\,''_G\rangle_\varepsilon$

in orthogonal bases of $(\mathcal{D}^*,\mu^{-1})$ and (E,ε):

$$X = \begin{array}{c} \begin{array}{ccc} J_1 & \cdots & J_{n-1} \end{array} \\ \begin{pmatrix} \Big| & \cdots & \Big| \end{pmatrix} \end{array}$$

J_i Jacobi vectors





N.BODY CONFIGURATIONS MOD. ISOMETRIES

SIDE OF BODIES

$$\begin{array}{ccccccccc}
\mathcal{D}^* & \xrightarrow{X} & E & \overset{\varepsilon}{\equiv} & E^* & \xrightarrow{X^{tr}} & \mathcal{D} & \overset{\mu}{\equiv} & \mathcal{D}^* \\
\downarrow & & & & & & & & \downarrow \\
\mathbb{R}^n & & & \xrightarrow{\quad 1!\ \text{extension s.t.} \quad} & & & & & \mathbb{R}^n \\
 & (m_1,\dots,m_n) & & \longmapsto & & (0,\dots,0) & & &
\end{array}$$

$$B = X^{tr} X \qquad \mu^{-1}\text{-symmetric}$$

$$\begin{pmatrix}
m_1 |\vec{r}_1 - \vec{r}_G|^2_\varepsilon & \cdots & m_1 \langle \vec{r}_1 - \vec{r}_G, \vec{r}_n - \vec{r}_G \rangle_\varepsilon \\
\vdots & \cdots & \vdots \\
m_n \langle \vec{r}_n - \vec{r}_G, \vec{r}_1 - \vec{r}_G \rangle_\varepsilon & \cdots & m_n |\vec{r}_n - \vec{r}_G|^2_\varepsilon
\end{pmatrix}$$

intrinsic inertia matrix

$O(E)$ - invariant

Z This is a representation in the canonical basis of $\mathbb{R}^n$, not in a μ^{-1} orthonormal basis.

SIDE OF AMBIENT SPACE

$$E \overset{\varepsilon}{\equiv} E^* \xrightarrow{X^{tr}} \mathcal{D} \overset{\mu}{\equiv} \mathcal{D}^* \xrightarrow{X} E \ (\text{dim. } d)$$

$$\vec{r}_k - \vec{r}_G = (X_{1k}, \dots, X_{dk})$$

$$S = X X^{tr} \qquad \varepsilon\text{-symmetric}$$

$$\begin{pmatrix}
\sum_{k=1}^n m_k X_{1k}^2 & \cdots & \sum_{k=1}^n m_k X_{1k} X_{dk} \\
\vdots & \cdots & \vdots \\
\sum_{k=1}^n m_k X_{dk} X_{1k} & \cdots & \sum_{k=1}^n m_k X_{dk}^2
\end{pmatrix}$$

inertia matrix

$$\underbrace{O(\mathcal{D}^*)}_{\text{democracy group}} \text{- invariant}$$

FORCES

$\forall i, \quad \ddot{\vec{r}}_i = \sum_{j \neq i} m_j \frac{\vec{r}_j - \vec{r}_i}{r_{ij}^3}$ can be written as follows:

$$\begin{pmatrix} \ddot{\vec{r}}_1 & \cdots & \ddot{\vec{r}}_n \\ | & & | \\ | & & | \end{pmatrix} = \begin{pmatrix} \vec{r}_1 & \cdots & \vec{r}_n \\ | & & | \\ | & & | \end{pmatrix} \underbrace{\begin{pmatrix} -\sum_{l \neq 1} \frac{m_l}{r_{1l}^3} & \frac{m_1}{r_{12}^3} & \cdots & \frac{m_1}{r_{1n}^3} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{m_n}{r_{n1}^3} & \frac{m_n}{r_{n2}^3} & \cdots & -\sum_{l \neq n} \frac{m_l}{r_{nl}^3} \end{pmatrix}}$$

$$\begin{tikzcd} \mathbb{R}^n \arrow[r, "1!\text{ extension s.t.}"', "(m_1,\dots,m_n)\mapsto(0,\dots,0)"'] & \mathbb{R}^n \\ \mathcal{D}^* \arrow[u, hook] \arrow[r, "2A"] & \mathcal{D}^* \arrow[u, hook] \end{tikzcd}$$

WINTNER-CONLEY ENDOMORPHISM

(μ^{-1} symmetric)

$\Downarrow$ mod. translations

$$\boxed{\ddot{X} = 2XA}$$

what is A ?

If $\hat{U}(B) = \sum_{i<j} \frac{m_i m_j}{r_{ij}}$,

$$\boxed{d\hat{U}(B)\Delta B = \operatorname{trace}(A \Delta B)}$$

RELATIVE EQUILIBRIA (= RIGID MOTIONS)

E = space where motion really takes place

Theorem (A. Albouy & A.C.) $\dim E = d = 2p$ and

$\exists\, \Omega : E \to E$ ε-antisymmetric non degenerate independent of t

s.t. $\boxed{X(t) = e^{\Omega t} X(0)}$

$$\Downarrow$$

$$\ddot{X} = \Omega^2 X = 2XA$$

SIDE OF BODIES

$$X^{tr}\Omega^2 X = 2BA$$

$$\Downarrow$$

BALANCED CONFIGURATIONS $\boxed{[A,B]=0}$

$$\Updownarrow$$

SIDE OF AMBIENT SPACE

$$\Omega^2 S = 2XAX^{tr}$$

$$\Downarrow$$

$$\boxed{[\Omega^2, S] = 0}$$

B critical pt of $\hat{U}\big|_{\text{Isospectral}\,(B)}$

(recall C.C. $\Longleftrightarrow$ B critical pt of $\hat{U}\Big|_{\substack{I=\operatorname{trace} B = \text{cste} \\ \operatorname{rank} B = \text{cste}}}$

$$\Updownarrow$$

$$A|_{\operatorname{Im} B} = \lambda\, Id \implies \underline{\Omega = \omega J,\ J^2 = -Id}$$

HOW MANY FREQUENCIES ?

B balanced $\Longrightarrow$ $\exists$ orthogonal bases resp. of $(\mathcal{D}^*, \mu^{-1})$ and $(E, \mathcal{E})$

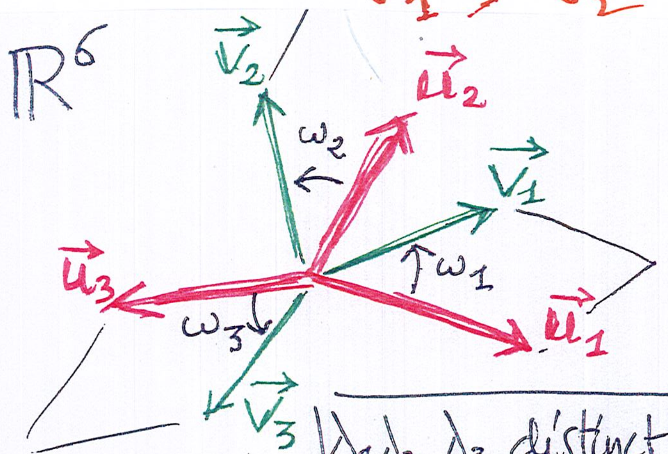
s.t. $2A = \begin{pmatrix} -\lambda_1 & & 0 \\ & \ddots & \\ 0 & & -\lambda_{n-1} \end{pmatrix}$, $B = \begin{pmatrix} b_1 & & 0 \\ & \ddots & \\ 0 & & b_{n-1} \end{pmatrix}$, $\Omega^2 = \begin{pmatrix} -\omega_1^2 & & 0 \\ & \ddots & \\ 0 & & -\omega_d^2 \end{pmatrix}$, $S = \begin{pmatrix} \sigma_1 & & 0 \\ & \ddots & \\ 0 & & \sigma_d \end{pmatrix}$

$\Longrightarrow X = \begin{array}{cc} \overbrace{}^{\mathrm{Im}B} & \\ \begin{pmatrix} V & 0 \\ 0 & 0 \end{pmatrix} & \big\}\mathrm{Im}S \end{array}$, V invertible

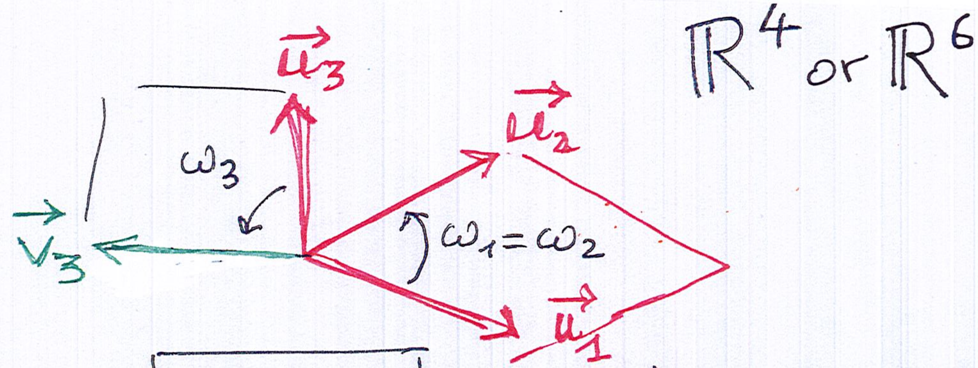
$\Longrightarrow$ (after possible permutation of the basis of $\mathcal{D}^*$) $\boxed{\omega_i^2 = \underbrace{\lambda_i}_{\text{spectrum of } A|_{\mathrm{Im}B}}, \quad i = 1, \dots, \mathrm{rank}\, B}$

Case of a generic set of 4 masses forming a 3dim. configuration ($\Longleftrightarrow$ not 3 masses equal)

$\sigma_1 > \sigma_2 > \sigma_3$



$\boxed{\lambda_1, \lambda_2, \lambda_3 \text{ distinct}}$ (6-BALANCED)



$\boxed{\lambda_1 = \lambda_2}$ (4-BALANCED)

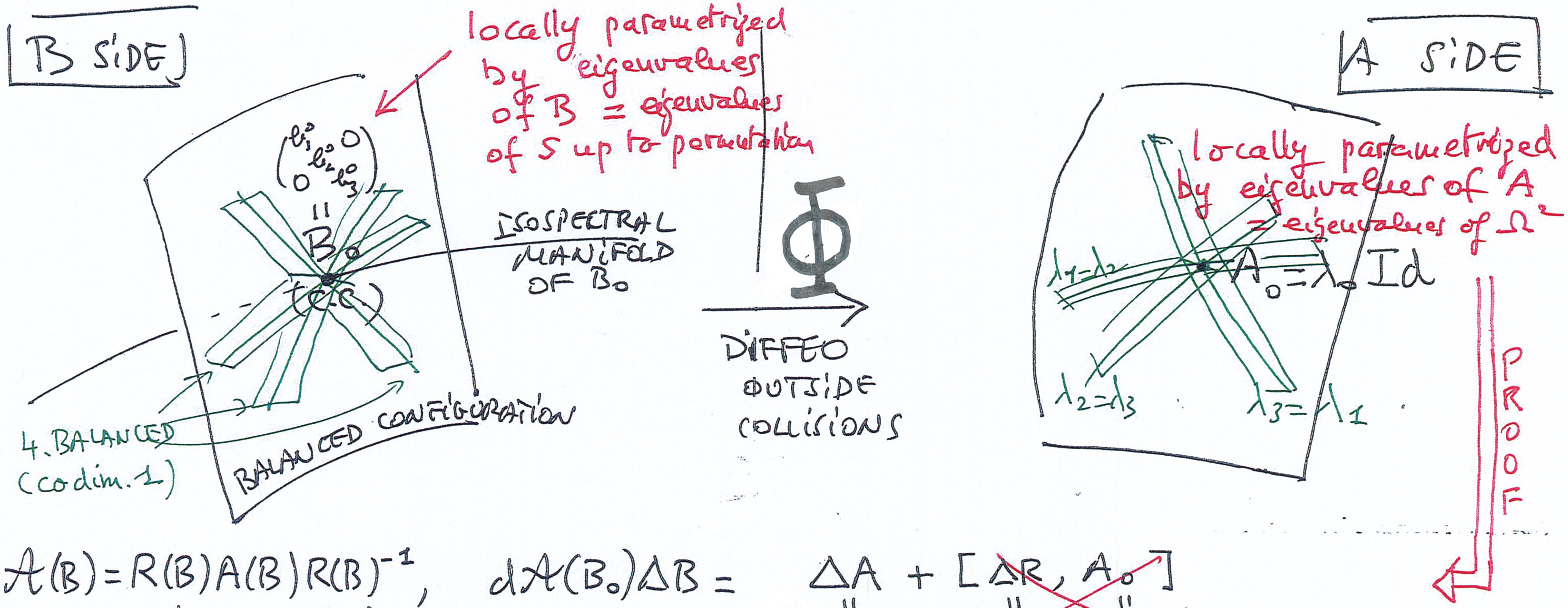
$\{\vec{u}_1, \vec{u}_2, \vec{u}_3\}$ common eigenbasis of S and Ω^2

c.c. $\Updownarrow$ $\lambda_1 = \lambda_2 = \lambda_3$

BIFURCATION OF QUASI-PERIODIC RELATIVE EQUIL. FROM THE RELATIVE EQUIL. OF A REGULAR TETRAHEDRON WITH GENERIC MASSES (1) SHAPES

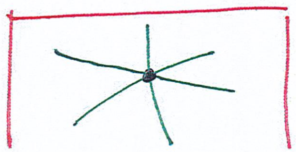
- IN THE UNIQUE ORTHONORMAL EIGENBASIS OF B_0, BOTH B_0 AND A_0 ARE DIAGONAL
- IF B BALANCED CLOSE TO B_0, $\exists 1!$ $R = R(B)$ SUCH THAT

$$RBR^{-1} = \mathrm{diag}(b_1, b_2, b_3), \quad RAR^{-1} = \mathrm{diag}(\lambda_1, \lambda_2, \lambda_3)$$



$$\text{IF } \mathcal{A}(B) = R(B)A(B)R(B)^{-1} = \mathrm{diag}(\lambda_1, \lambda_2, \lambda_3), \quad d\mathcal{A}(B_0)\Delta B = \underset{\underset{\text{ISO}}{d\Phi(B_0)\Delta B}}{\Delta A} + \cancel{[\underset{dR(B_0)\Delta B}{\Delta R}, \underset{\lambda_0 \mathrm{Id}}{A_0}]}$$

HENCE, AFTER SCALING



BIFURCATION OF Q.P.R.E (2) ANGULAR MOMENTUM

$X(0)$ c.c. , $X(t) = e^{\omega J t} X(0)$ RELATIVE EQUILIBRIUM IN $E^{d=2p}$

$$\boxed{\mathcal{C} = -X\dot{X}^{tr} + \dot{X}X^{tr} = \omega\underbrace{(S_0 J + J S_0)}_{\text{J-skew hermitian}} = \omega J\underbrace{(J^{-1}S_0 J + S_0)}_{\text{J-hermitian}}}$$

FREQUENCY MAP $\mathcal{F}: J \longmapsto \{\nu_1 \geq \dots \geq \nu_p\} = \text{spectrum}(J^{-1}S_0 J + S_0)$

Theorem (A.C & H. Jimenez-Perez) $\text{Im}\,\mathcal{F}$ is a convex polytope

$$\left\{(\nu_1, \dots, \nu_p),\ \sum_{i=1}^{p} \nu_i = I(X) = \text{trace}\, B\right\}$$

- More precisely : if $\left(\begin{array}{l}\text{Spectrum } S_0 = \{\sigma_1 \geq \dots \geq \sigma_{2p}\} \\ \vec{u}_1, \dots, \vec{u}_{2p} \text{ eigenbasis of } S_0\end{array}\right.$

$$\text{Im}\,\mathcal{F} = \text{Im}\left\{J \,\middle|\, \{\vec{u}_1, \vec{u}_3, \dots, \vec{u}_{2p-1}\} \xrightarrow{J} \{\vec{u}_2, \vec{u}_4, \dots, \vec{u}_{2p}\}\right\}$$

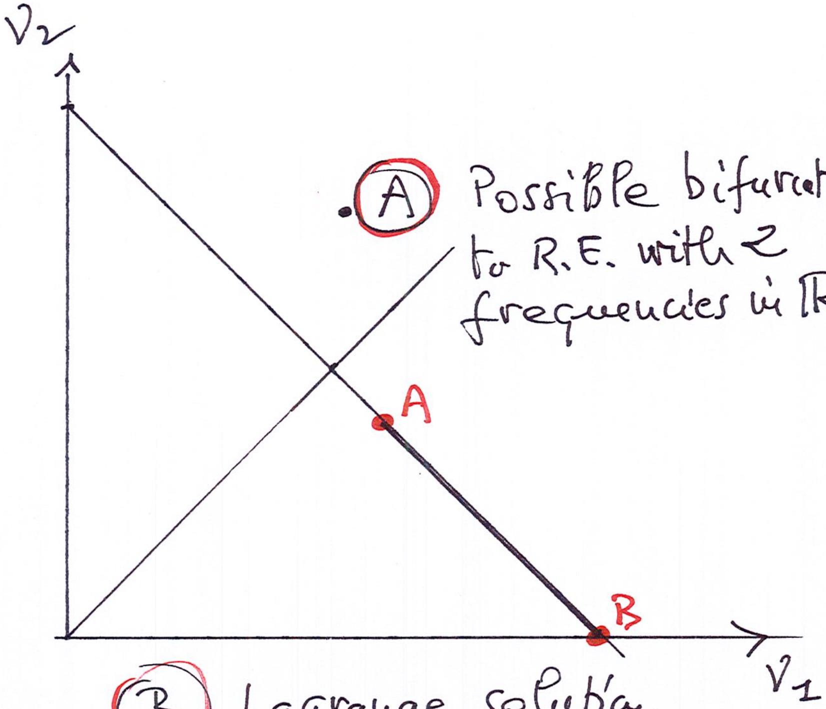
$$= \text{Horn polytope}\left\{\begin{array}{l}\text{ordered spectra} \\ \text{of } \alpha + \beta\end{array} \,\middle|\, \begin{array}{l}\text{spectrum } \alpha = \{\sigma_1, \sigma_3, \dots, \sigma_{2p-1}\} \\ \text{spectrum } \beta = \{\sigma_2, \sigma_4, \dots, \sigma_{2p}\}\end{array}\right\}$$

- Other partition into two halves of Spectrum S_0 give rise to subpolytopes of $\text{Im}\,\mathcal{F}$.

BIFURCATIONS TO QUASI-PERIODIC RELATIVE EQUILIBRIA (3)

FROM R.E. OF EQUILATERAL △

$$S_0 = \mathrm{diag}(\sigma_1, \sigma_2, 0, 0)$$

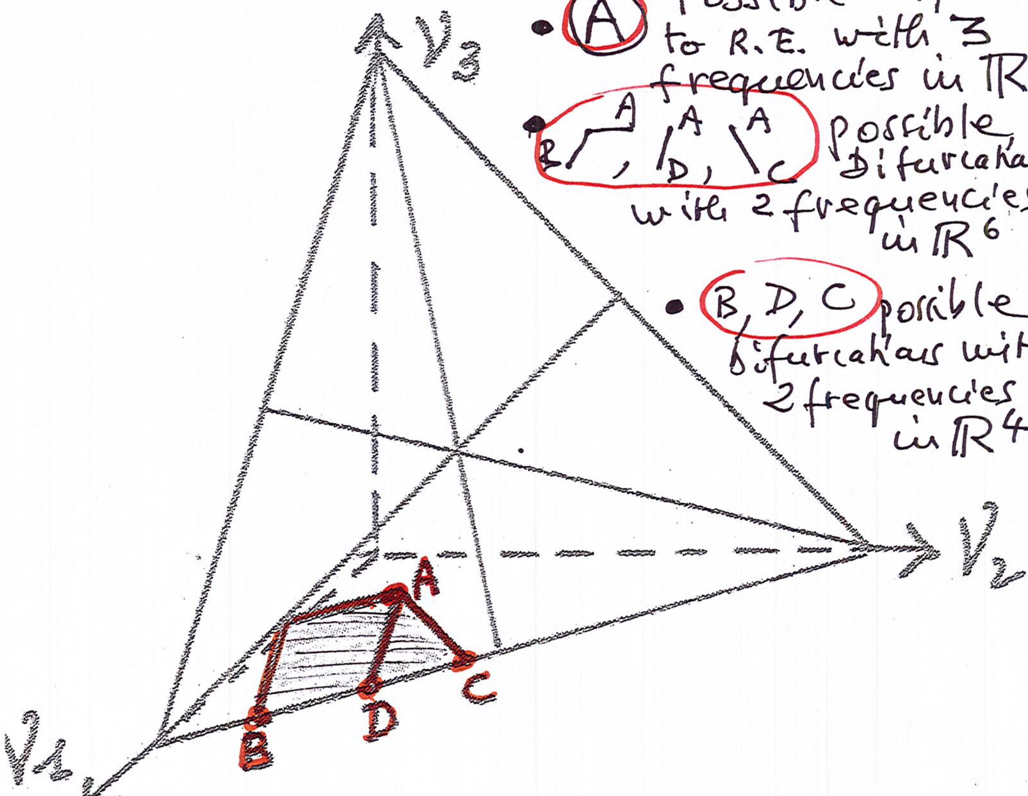


- (A) Possible bifurcation to R.E. with 2 frequencies in $\mathbb{R}^4$
- (B) Lagrange solution in $\mathbb{R}^2$. No possible bifurcation.

FROM R.E. OF REGULAR

$$S_0 = \mathrm{diag}(\sigma_1, \sigma_2, \sigma_3, 0, 0, 0)$$

- (A) Possible bifurcations to R.E. with 3 frequencies in $\mathbb{R}^6$
- $\overline{BA}$, $\overline{DA}$, $\overline{CA}$ possible bifurcations with 2 frequencies in $\mathbb{R}^6$
- B, D, C possible bifurcations with 2 frequencies in $\mathbb{R}^4$



(case $\sigma_1 > \sigma_2 + \sigma_3 > \sigma_2 > \sigma_3 > 0$)

TWO OPEN QUESTIONS

(1) B_0 Central configuration

Is the map

$$\left\{\begin{array}{l}\text{Balanced}\\ \text{configurations}\end{array}\right\} \ni B \longmapsto A|_{\mathrm{Im}\,B}$$

a local diffeomorphism near B_0 ?

(2) Does there exist balanced configurations of 4 equal masses without any symmetry ?