The generation of gravitational waves by orbiting charges

Master's Thesis in Physics

Presented by

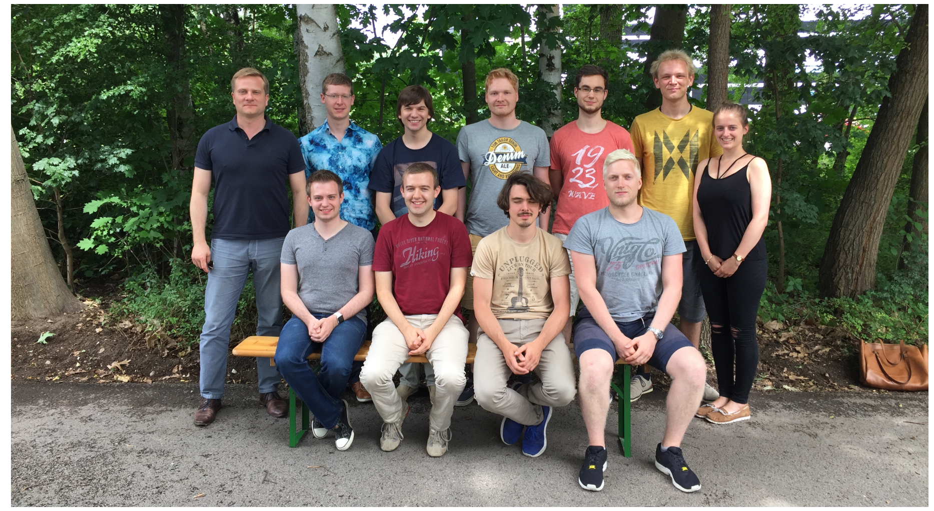
Moritz Möller

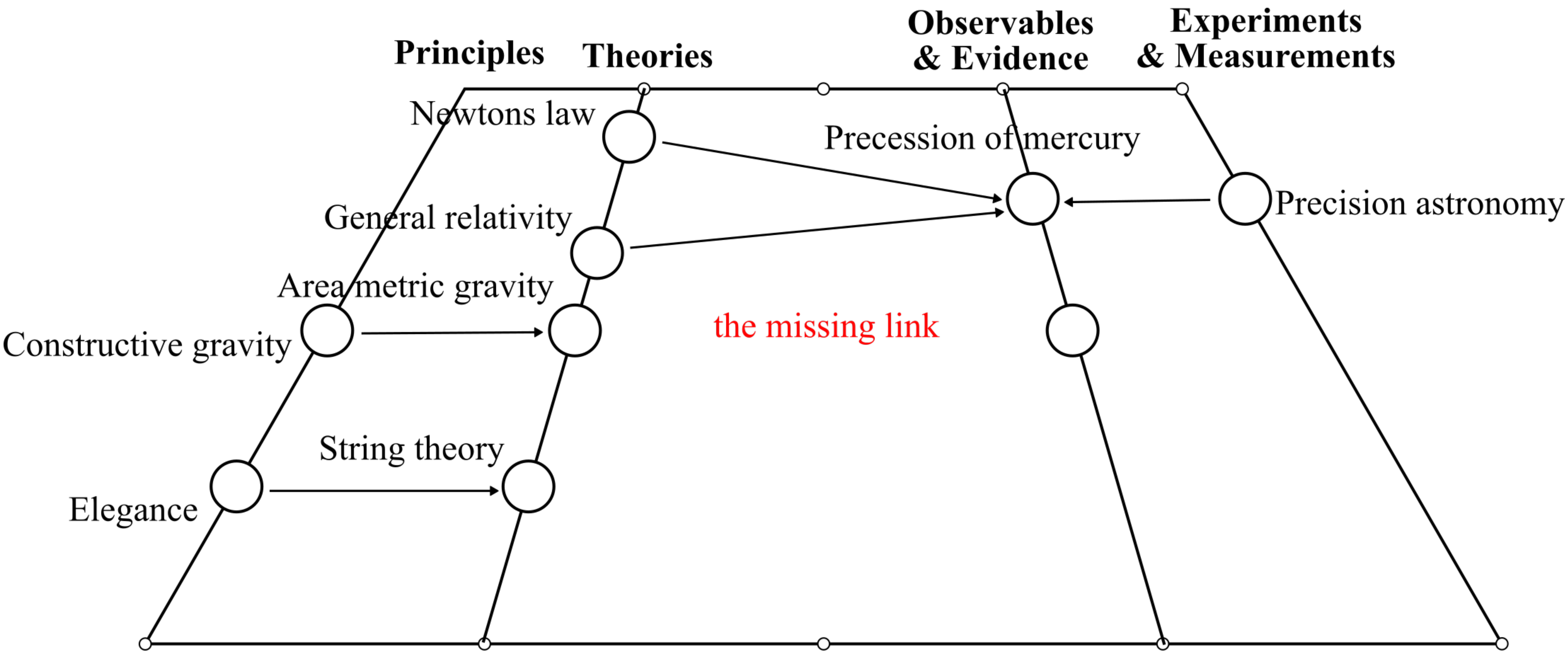
25 June 2018

Friedrich-Alexander-Universität Erlangen-Nürnberg

Supervisor: Dr. Frederic P. Schuller

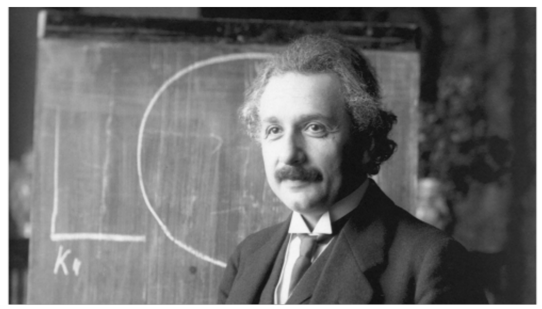
Erstgutachter: Prof. Dr. Gerd Leuchs



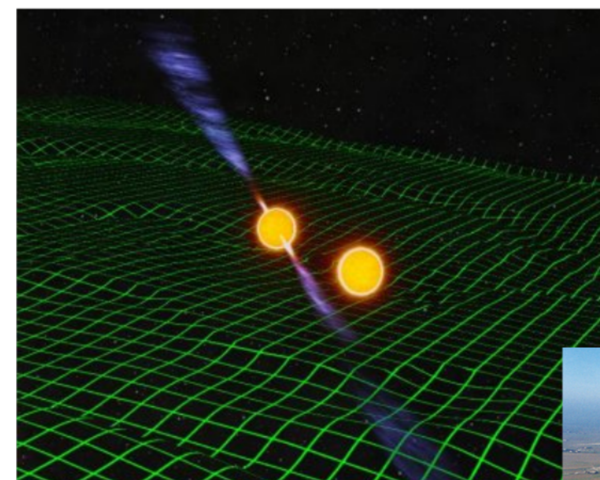


Principles
Theories
Observables & Evidence
Experiments & Measurements
Newtons law
Precession of mercury
Precision astronomy
General relativity
Area metric gravity
Constructive gravity
the missing link
String theory
Elegance

1900



1918 Einstein publishes "Gravitationswellen"



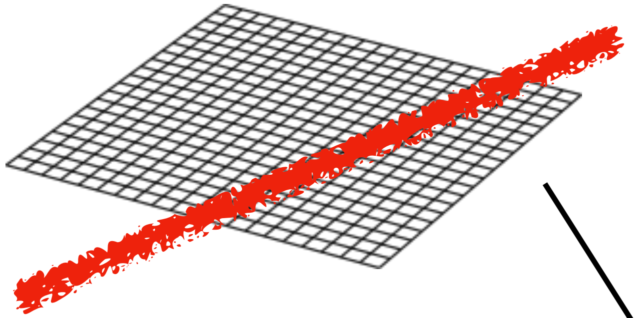
Virgo

1974 Discovery of the Hulse-Taylor binary pulsar

1993 Nobel prize awarded for pulsar discovery

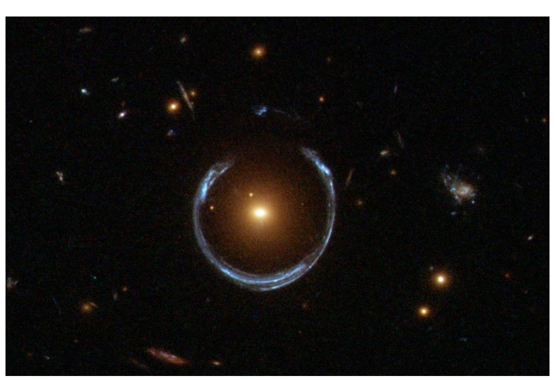
2016 LIGO/VIRGO report a direct measurement of gravitational waves

2017 Nobel prize awarded to LIGO/VIRGO



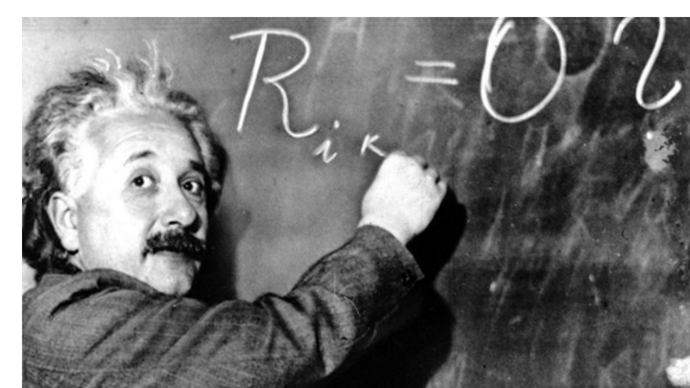
$$\partial_{[a}F_{bc]} = 0$$

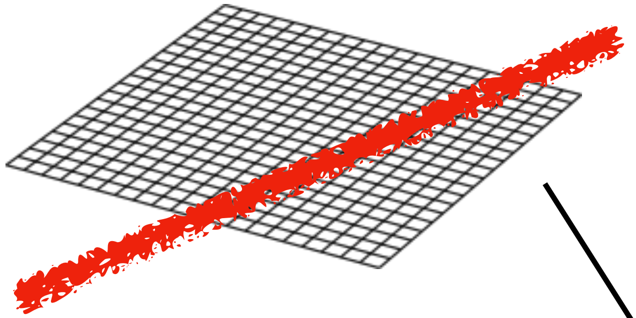
$$\partial_a\left(\sqrt{-g}F_{mn}\,g^{am}g^{bn}\right) = 0$$



"Gravity and and matter should respect the same causality structure!"

$$G_{ab}\left[g\right] = \frac{8\pi G}{c^4}T_{ab}$$





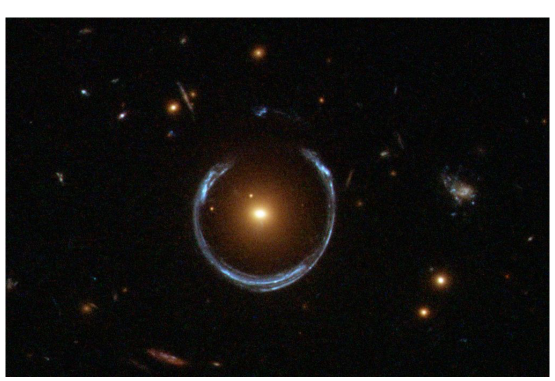
$$\partial_{[a}F_{bc]} = 0$$

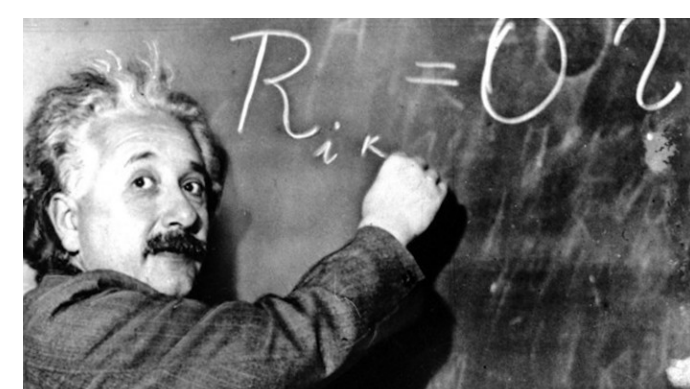
$$\partial_a\left(\sqrt{-g}F_{mn}\,g^{am}g^{bn}\right) = 0$$

Schuller et al. (2018)

Constructive gravity:
What is the most general
gravity that respects
matter’s causal structure?

$$G_{ab}\left[g\right] = \frac{8\pi G}{c^4}T_{ab}$$

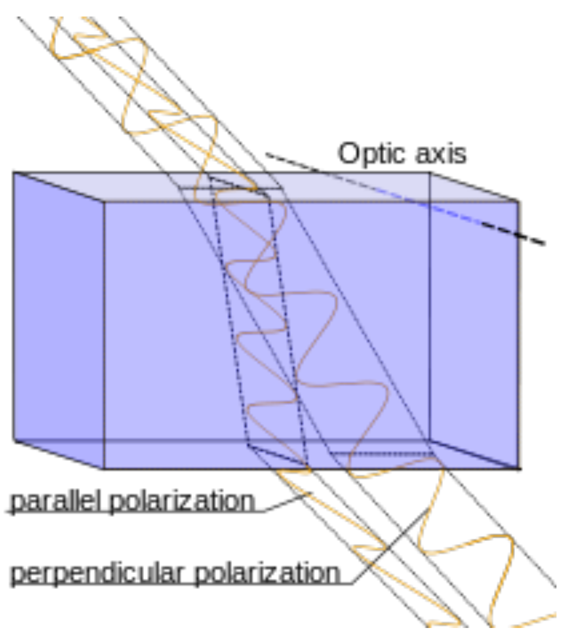




$$\partial_{[a}F_{bc]} = 0$$

$$\partial_a \left(\omega\left(G\right) F_{mn}\, G^{mnab} \right) = 0$$

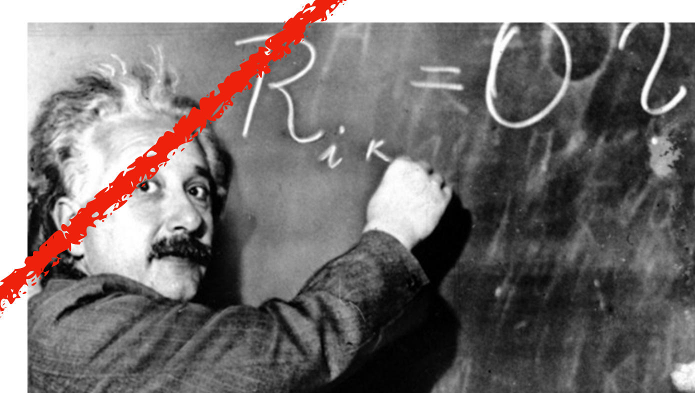
Schuller et al. (2018)



Hehl & Obukhov (2012)

Constructive gravity:
What is the most general
gravity that respects
matter's causal structure?

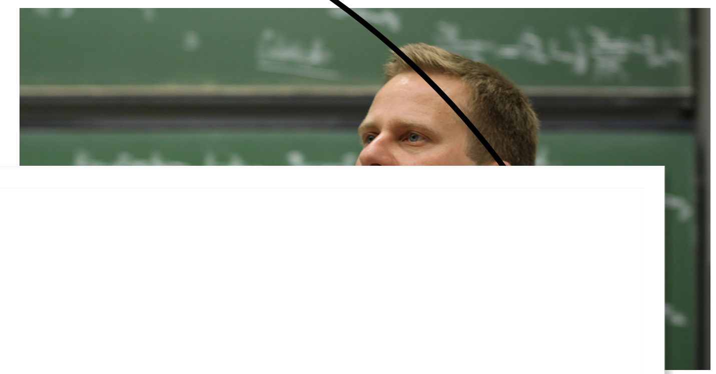
$$\cancel{G_{ab}\left[g\right] = \frac{8\pi G}{c^4} T_{ab}}$$



$$\partial_{[a}F_{bc]} = 0$$

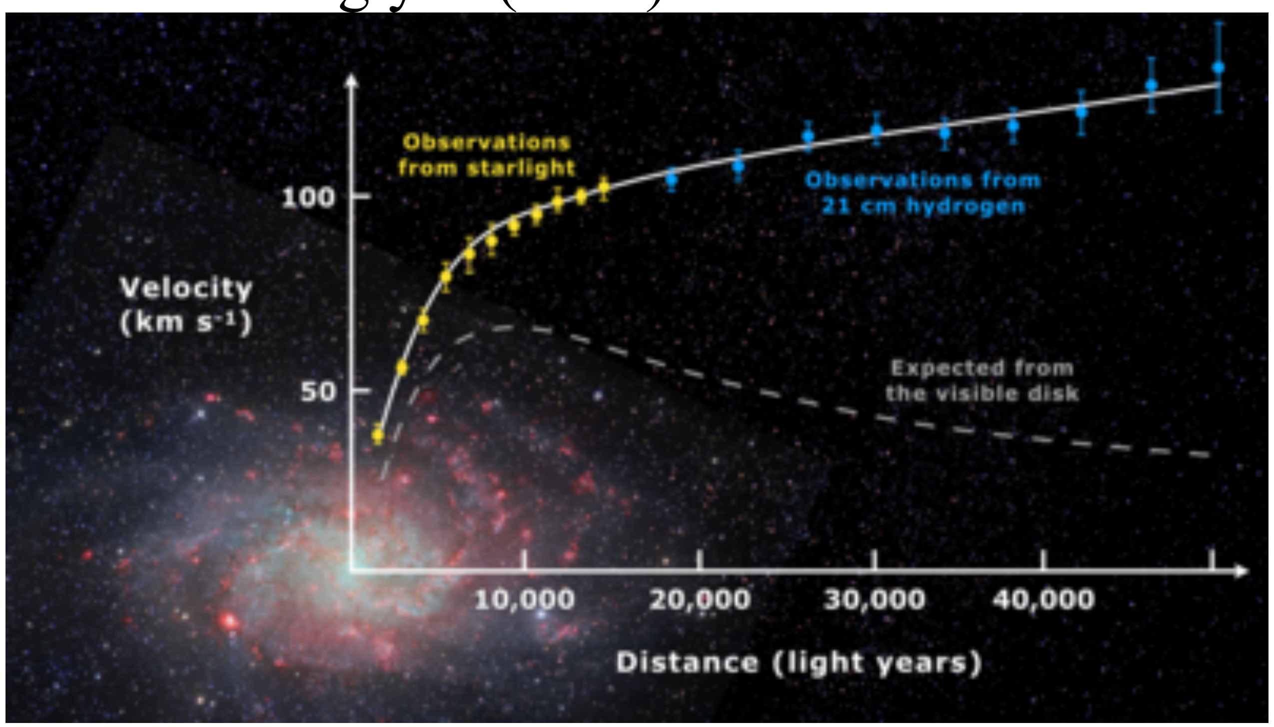
$$\partial_a\left(\omega(G)\,F_{mn}\,G^{mnab}\right) = 0$$

Schuller et al. (2018)

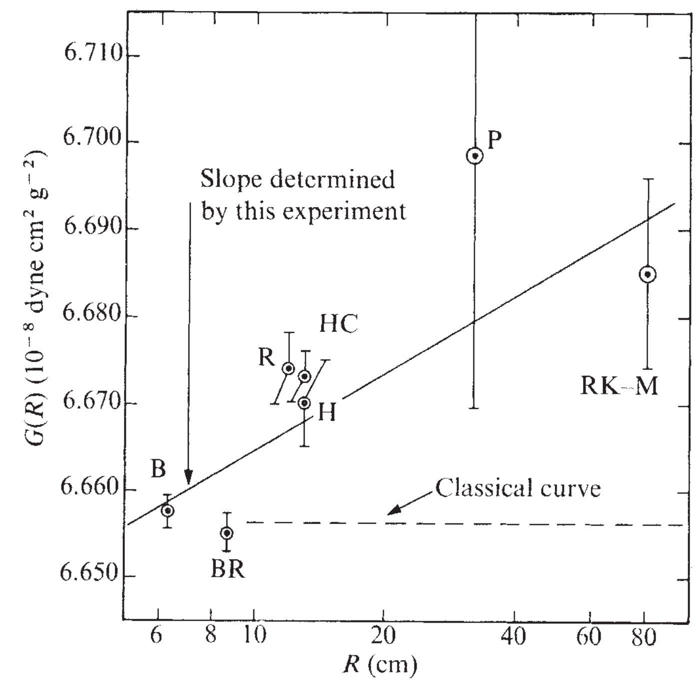


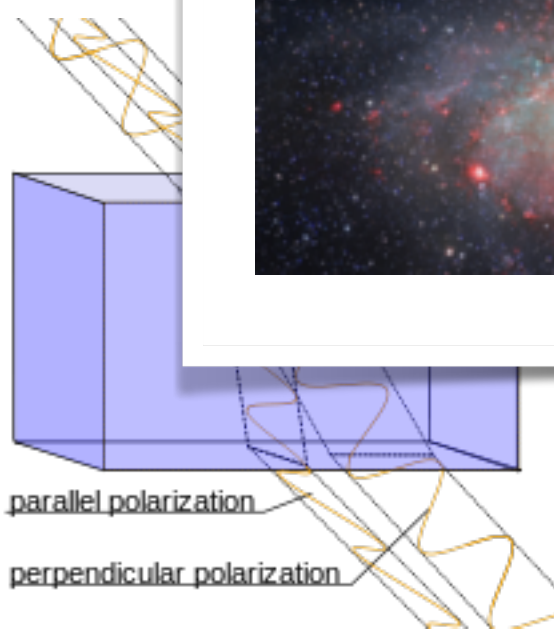
But why?

Kuhn & Kruglyak (1987)



Long (1976)





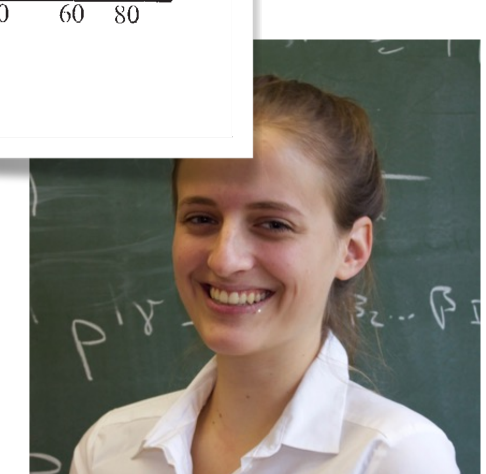
Hehl & Obukhov (2012)

Constraint equtions:

$$\frac{\delta H_{\mathrm{M}}}{\delta N} + (6(s_1+s_2)+4s_8)\,\Delta\tilde{U} = 2(s_1+s_2)\,\Delta^2 V \qquad (193)$$

$$-\frac{\delta H_{\mathrm{M}}}{\delta N} - 2\gamma^{\alpha\beta}\left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} - \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}}\right] - (18(s_1+s_2)+12s_8)\,\ddot{\tilde{U}} - (12(s_1+s_2)-4s_8)\,\Delta\tilde{U} = 24(s_1+s_2)\,\Delta A \qquad (194)$$

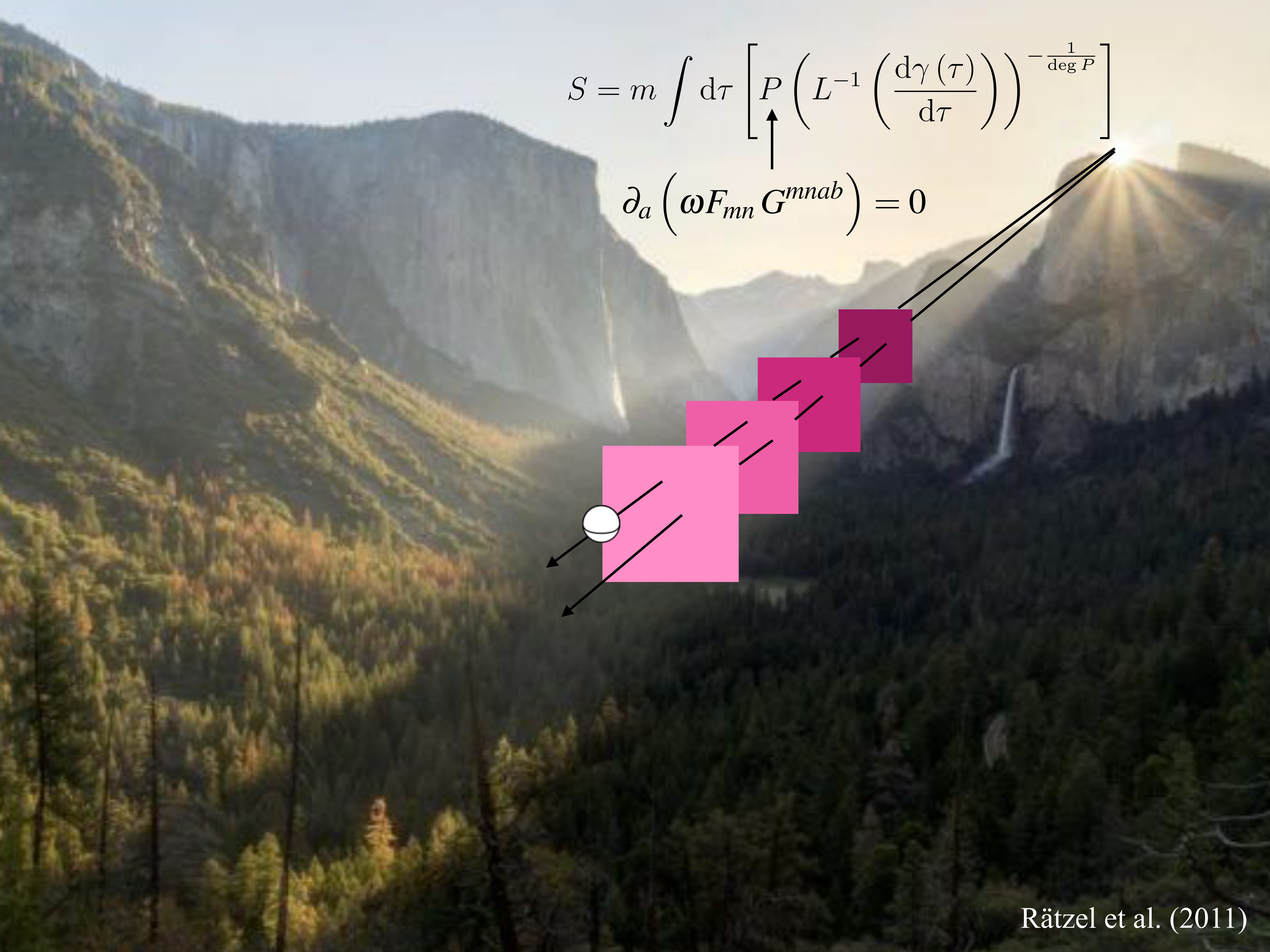
$$-\left[\frac{\delta H_{\mathrm{M}}}{\delta N^\alpha}\right]^{\mathrm{V}} = 2(v_1+v_2)\,\Delta\dot{V}_\alpha \qquad (195)$$



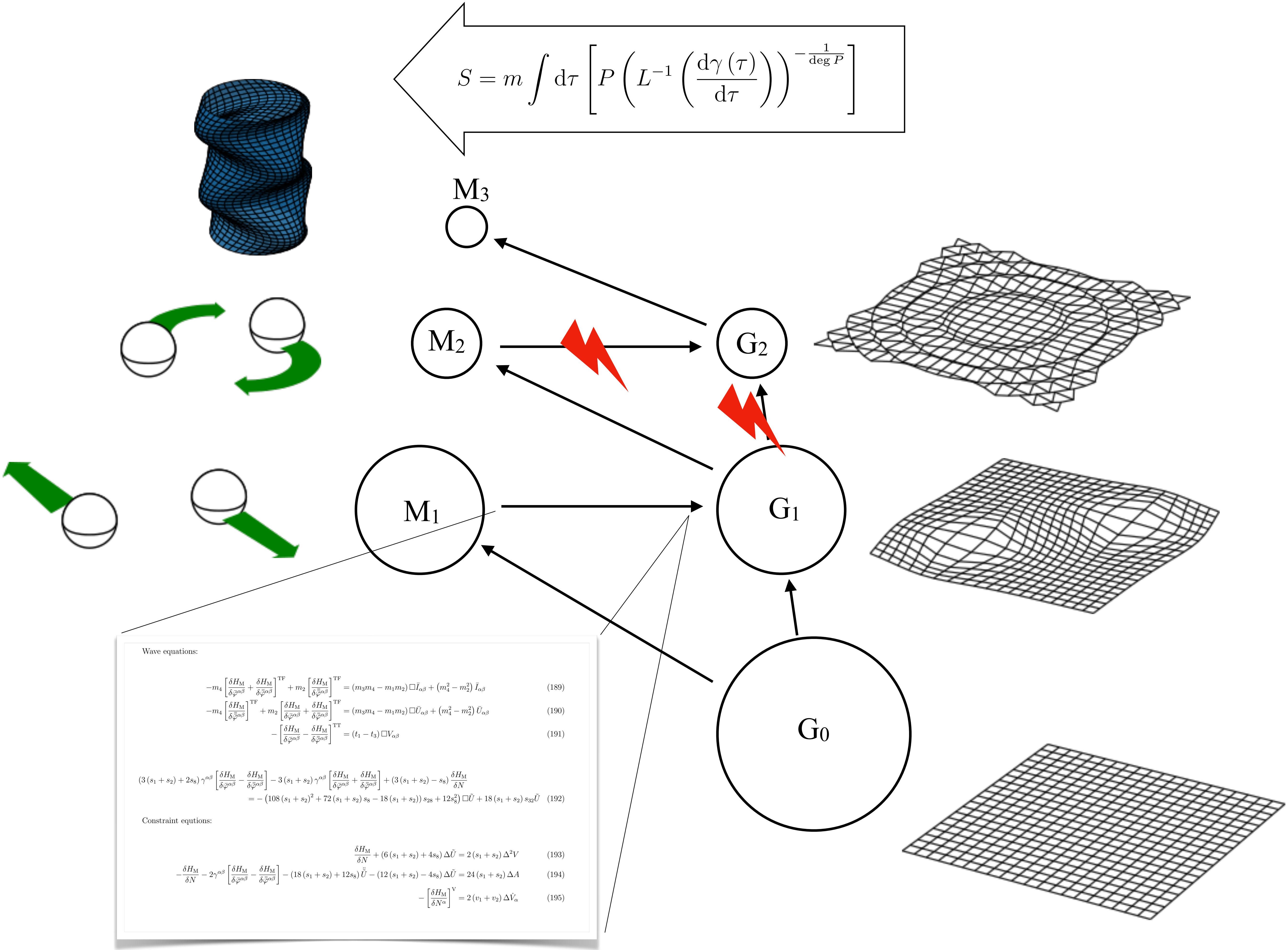
Stritzelberger et al. (2017)

$$S = m \int \mathrm{d}\tau \left[P \left(L^{-1} \left(\frac{\mathrm{d}\gamma(\tau)}{\mathrm{d}\tau} \right) \right)^{-\frac{1}{\deg P}} \right]$$

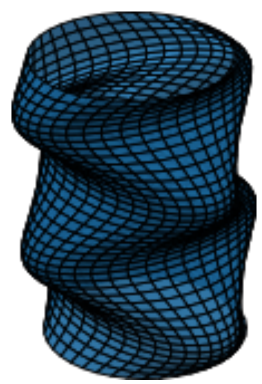
$$\partial_a \left(\omega F_{mn} G^{mnab} \right) = 0$$

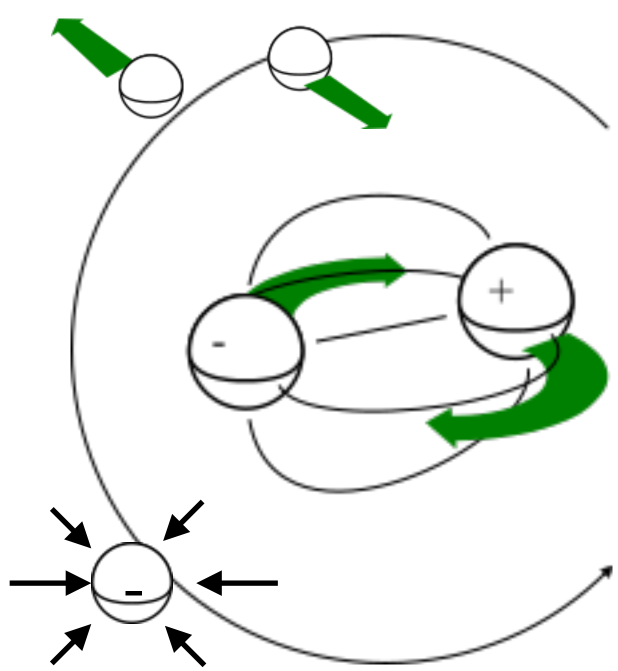


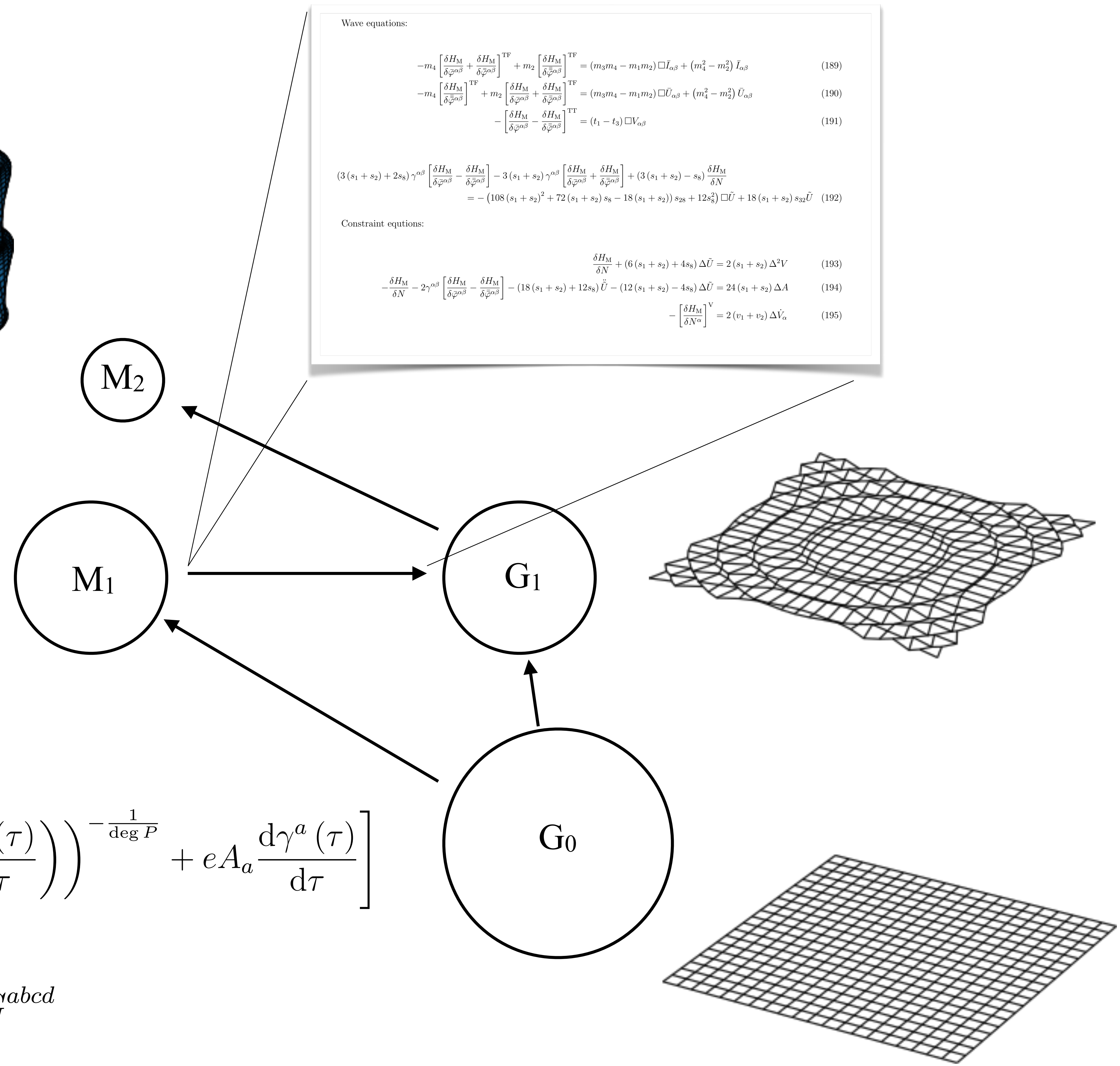
Rätzel et al. (2011)



$S = m \int \mathrm{d}\tau \left[P \left(L^{-1} \left(\frac{\mathrm{d}\gamma(\tau)}{\mathrm{d}\tau} \right) \right)^{-\frac{1}{\deg P}} \right]$
M_3
M_2
G_2
M_1
G_1
G_0
Wave equations:
$$-m_4 \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} + \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right]^{\mathrm{TF}} + m_2 \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\bar{\varphi}}}^{\alpha\beta}} \right]^{\mathrm{TF}} = (m_3 m_4 - m_1 m_2) \Box \bar{I}_{\alpha\beta} + \left(m_4^2 - m_2^2 \right) \bar{I}_{\alpha\beta} \quad (189)$$
$$-m_4 \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\bar{\varphi}}}^{\alpha\beta}} \right]^{\mathrm{TF}} + m_2 \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} + \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right]^{\mathrm{TF}} = (m_3 m_4 - m_1 m_2) \Box \bar{U}_{\alpha\beta} + \left(m_4^2 - m_2^2 \right) \bar{U}_{\alpha\beta} \quad (190)$$
$$-\left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} - \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right]^{\mathrm{TT}} = (t_1 - t_3) \Box V_{\alpha\beta} \quad (191)$$
$$(3(s_1+s_2)+2s_8)\gamma^{\alpha\beta} \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} - \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right] - 3(s_1+s_2)\gamma^{\alpha\beta} \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} + \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right] + (3(s_1+s_2)-s_8) \frac{\delta H_{\mathrm{M}}}{\delta N}$$
$$= -\left(108 (s_1+s_2)^2 + 72 (s_1+s_2) s_8 - 18 (s_1+s_2)) s_{28} + 12 s_8^2 \right) \Box \tilde{U} + 18 (s_1+s_2) s_{32} \tilde{U} \quad (192)$$
Constraint equtions:
$$\frac{\delta H_{\mathrm{M}}}{\delta N} + (6(s_1+s_2)+4s_8) \Delta \tilde{U} = 2(s_1+s_2) \Delta^2 V \quad (193)$$
$$-\frac{\delta H_{\mathrm{M}}}{\delta N} - 2\gamma^{\alpha\beta} \left[\frac{\delta H_{\mathrm{M}}}{\delta \bar{\varphi}^{\alpha\beta}} - \frac{\delta H_{\mathrm{M}}}{\delta \bar{\bar{\varphi}}^{\alpha\beta}} \right] - (18(s_1+s_2)+12s_8) \ddot{\tilde{U}} - (12(s_1+s_2)-4s_8) \Delta \tilde{U} = 24(s_1+s_2) \Delta A \quad (194)$$
$$-\left[\frac{\delta H_{\mathrm{M}}}{\delta N^{\alpha}} \right]^{\mathrm{V}} = 2(v_1+v_2) \Delta \dot{V}_{\alpha} \quad (195)$$







Wave equations:

$$-m_4\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}+\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]^{\mathrm{TF}}+m_2\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\bar{\varphi}}}^{\alpha\beta}}\right]^{\mathrm{TF}}=\left(m_3m_4-m_1m_2\right)\Box\bar{I}_{\alpha\beta}+\left(m_4^2-m_2^2\right)\bar{I}_{\alpha\beta} \tag{189}$$

$$-m_4\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\bar{\varphi}}}^{\alpha\beta}}\right]^{\mathrm{TF}}+m_2\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}+\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]^{\mathrm{TF}}=\left(m_3m_4-m_1m_2\right)\Box\bar{U}_{\alpha\beta}+\left(m_4^2-m_2^2\right)\bar{U}_{\alpha\beta} \tag{190}$$

$$-\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}-\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]^{\mathrm{TT}}=\left(t_1-t_3\right)\Box V_{\alpha\beta} \tag{191}$$

$$\begin{aligned}&\left(3\left(s_1+s_2\right)+2s_8\right)\gamma^{\alpha\beta}\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}-\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]-3\left(s_1+s_2\right)\gamma^{\alpha\beta}\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}+\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]+\left(3\left(s_1+s_2\right)-s_8\right)\frac{\delta H_{\mathrm{M}}}{\delta N}\\&\quad=-\left(108\left(s_1+s_2\right)^2+72\left(s_1+s_2\right)s_8-18\left(s_1+s_2\right)\right)s_{28}+12s_8^2\right)\Box\tilde{U}+18\left(s_1+s_2\right)s_{32}\tilde{U}\end{aligned} \tag{192}$$

Constraint equtions:

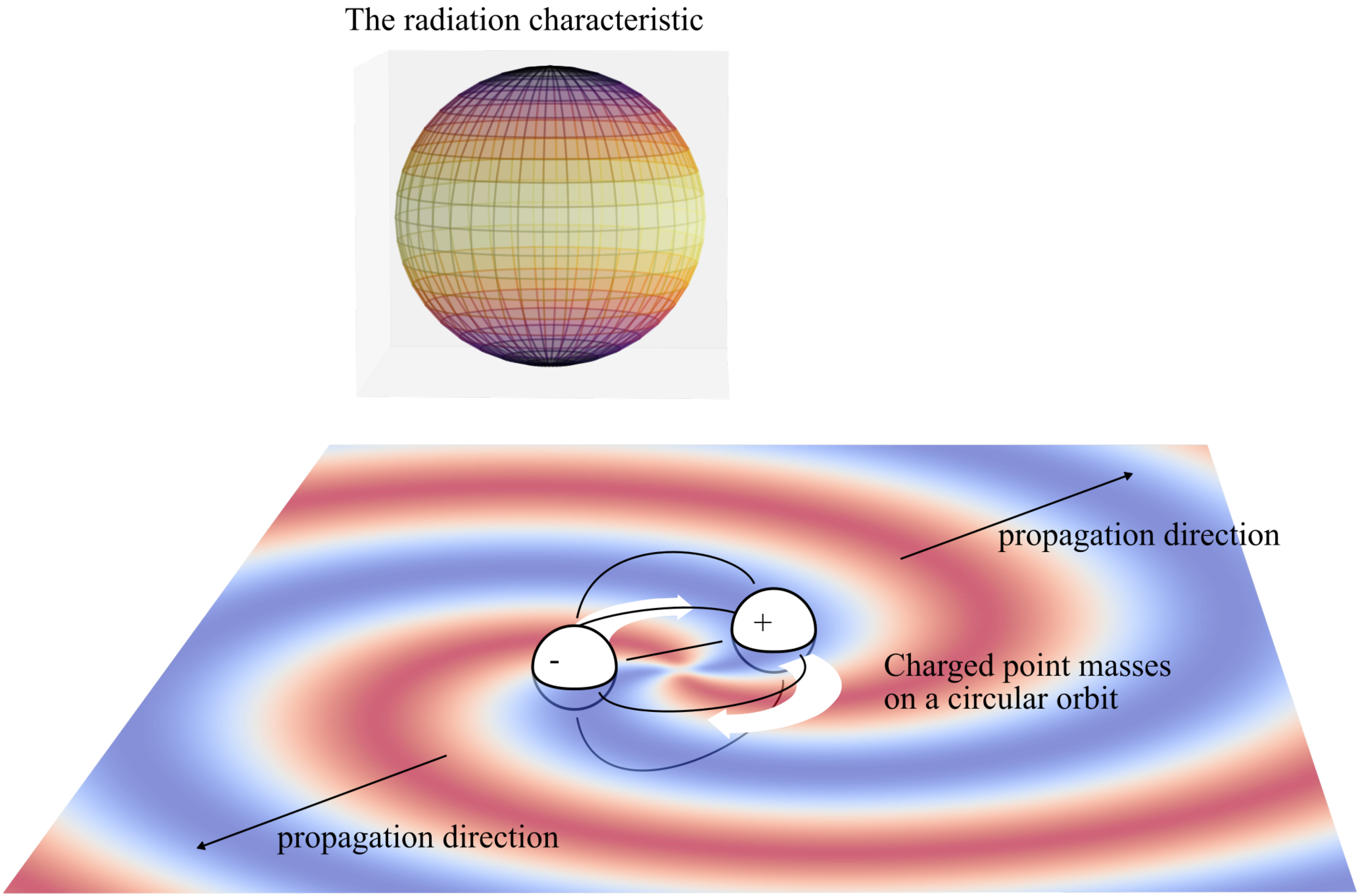
$$\frac{\delta H_{\mathrm{M}}}{\delta N}+\left(6\left(s_1+s_2\right)+4s_8\right)\Delta\tilde{U}=2\left(s_1+s_2\right)\Delta^2V \tag{193}$$

$$-\frac{\delta H_{\mathrm{M}}}{\delta N}-2\gamma^{\alpha\beta}\left[\frac{\delta H_{\mathrm{M}}}{\delta\bar{\varphi}^{\alpha\beta}}-\frac{\delta H_{\mathrm{M}}}{\delta\bar{\bar{\varphi}}^{\alpha\beta}}\right]-\left(18\left(s_1+s_2\right)+12s_8\right)\ddot{\tilde{U}}-\left(12\left(s_1+s_2\right)-4s_8\right)\Delta\tilde{U}=24\left(s_1+s_2\right)\Delta A \tag{194}$$

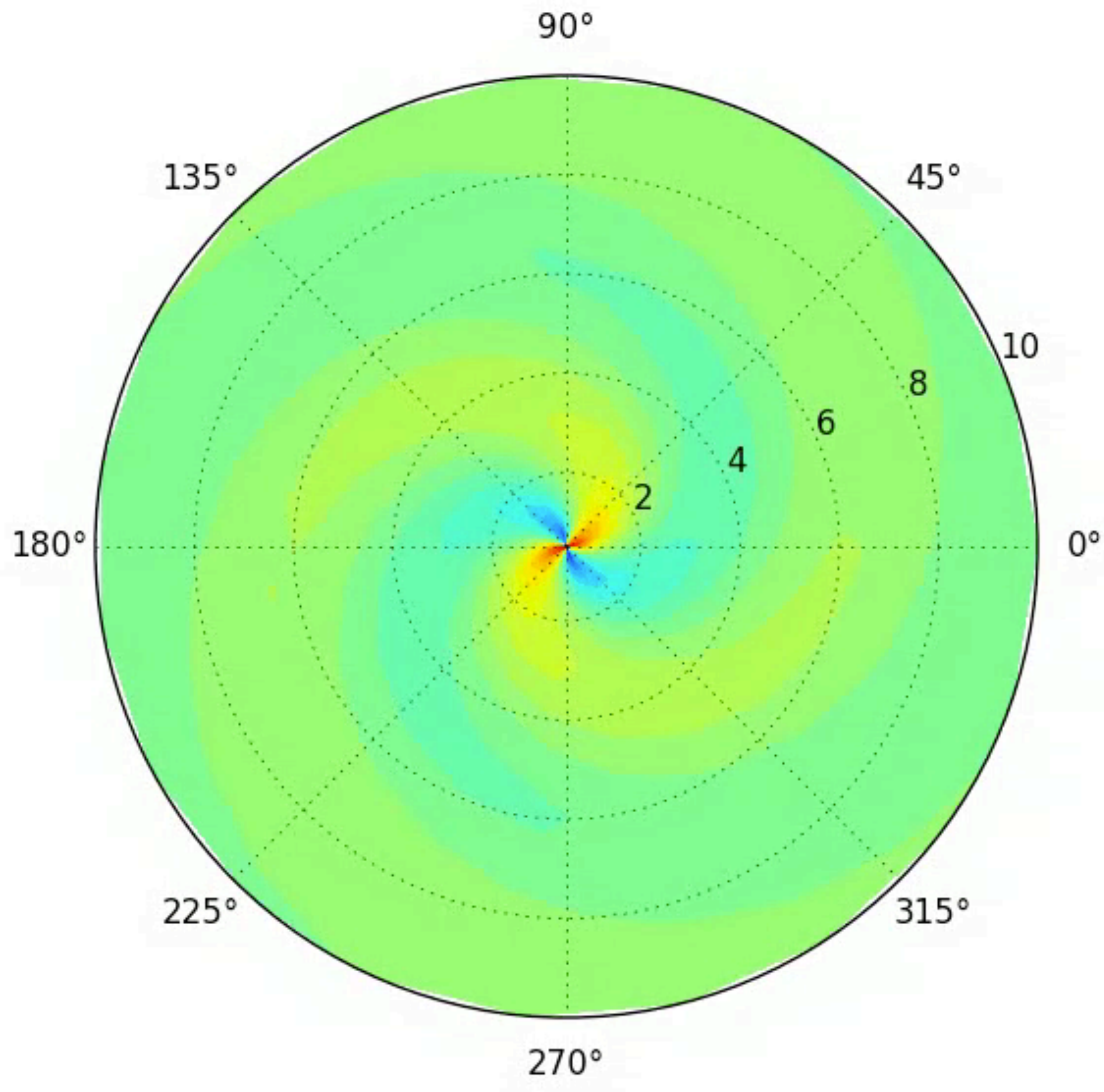
$$-\left[\frac{\delta H_{\mathrm{M}}}{\delta N^{\alpha}}\right]^{\mathrm{V}}=2\left(v_1+v_2\right)\Delta\dot{V}_{\alpha} \tag{195}$$

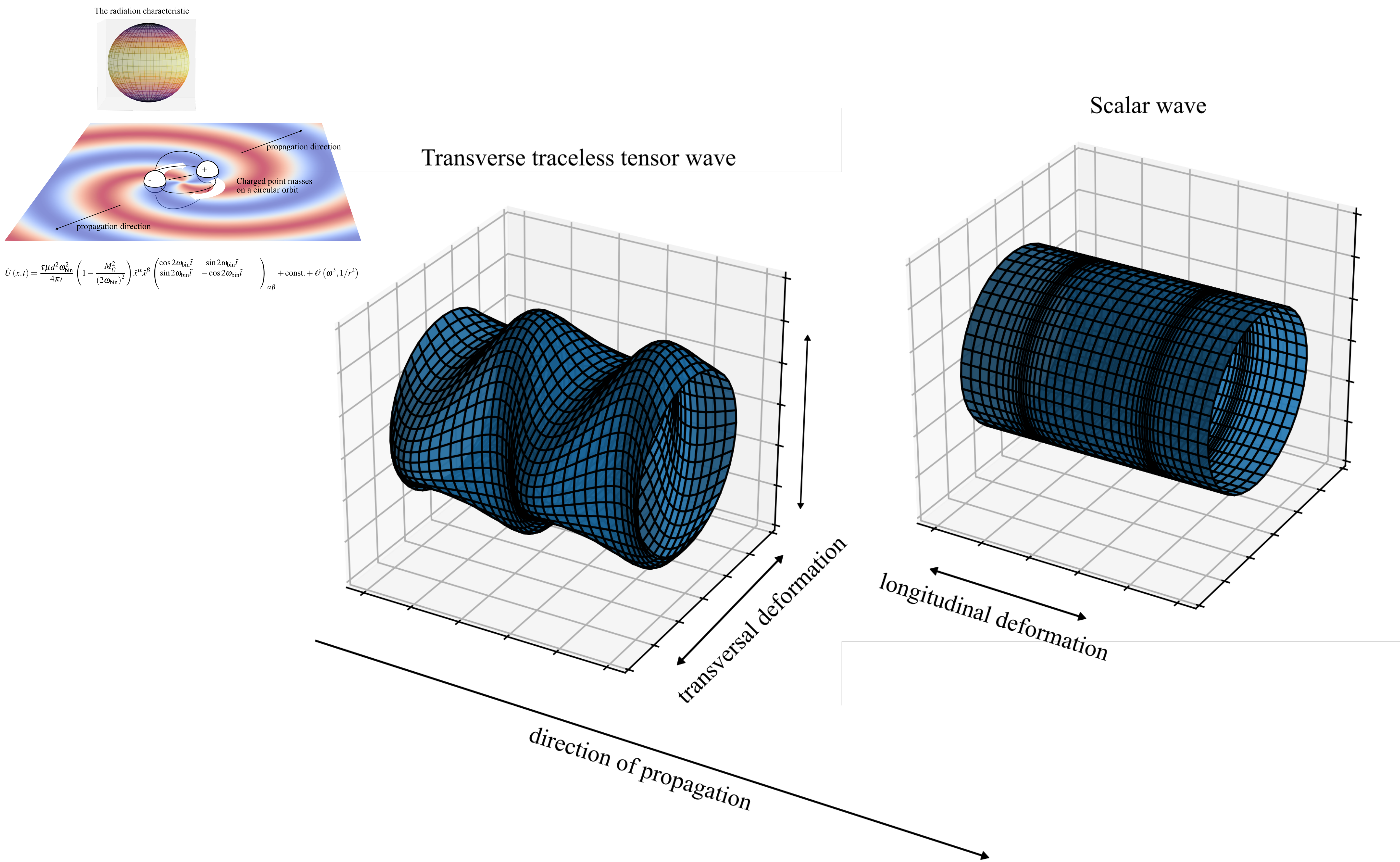
$$S=m\int\mathrm{d}\tau\left[P\left(L^{-1}\left(\frac{\mathrm{d}\gamma\left(\tau\right)}{\mathrm{d}\tau}\right)\right)^{-\frac{1}{\deg P}}+eA_a\frac{\mathrm{d}\gamma^a\left(\tau\right)}{\mathrm{d}\tau}\right]$$

$$S=\frac{1}{32\pi}\int\mathrm{d}^4x\omega F_{ab}F_{cd}\;G^{abcd}$$



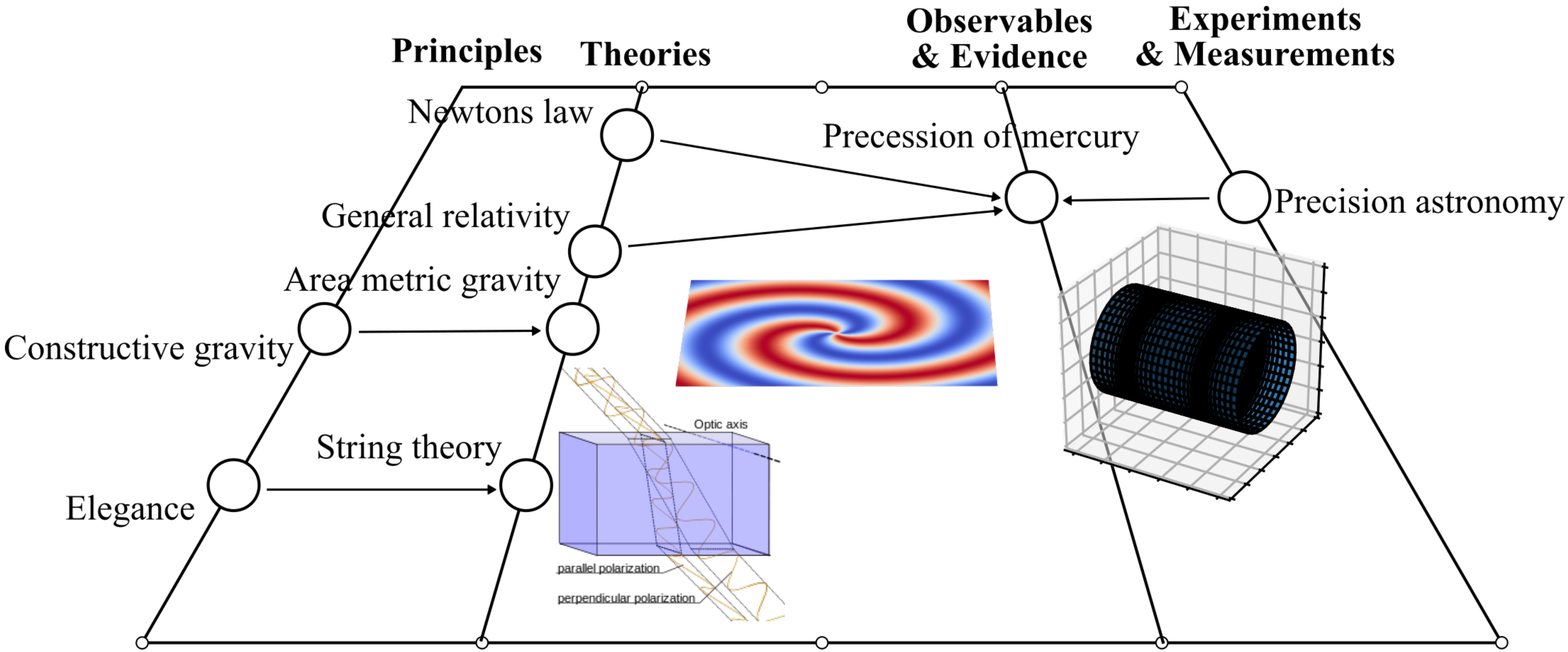
$$\tilde{U}\left(x,t\right)=\frac{\tau\mu d^{2}\omega_{\mathrm{bin}}^{2}}{4\pi r}\left(1-\frac{M_{\tilde{U}}^{2}}{\left(2\omega_{\mathrm{bin}}\right)^{2}}\right)\hat{x}^{\alpha}\hat{x}^{\beta}\begin{pmatrix}\cos 2\omega_{\mathrm{bin}}\tilde{t} & \sin 2\omega_{\mathrm{bin}}\tilde{t} & \\ \sin 2\omega_{\mathrm{bin}}\tilde{t} & -\cos 2\omega_{\mathrm{bin}}\tilde{t} & \\ & & \end{pmatrix}_{\alpha\beta}+\mathrm{const.}+\mathscr{O}\left(\omega^{3},1/r^{2}\right)$$


90°
135°
45°
10
8
6
4
2
180°
0°
225°
315°
270°



$$\tilde{U}\,(x,t) = \frac{\tau\mu d^2\omega_{\mathrm{bin}}^2}{4\pi r}\left(1-\frac{M_{\tilde{U}}^2}{(2\omega_{\mathrm{bin}})^2}\right)\hat{x}^{\alpha}\hat{x}^{\beta}\begin{pmatrix}\cos 2\omega_{\mathrm{bin}}\tilde{t} & \sin 2\omega_{\mathrm{bin}}\tilde{t} \\ \sin 2\omega_{\mathrm{bin}}\tilde{t} & -\cos 2\omega_{\mathrm{bin}}\tilde{t}\end{pmatrix}_{\alpha\beta} + \mathrm{const.} + \mathscr{O}\left(\omega^3, 1/r^2\right)$$

$$d = d_0 - \frac{2A_0}{\omega}\sqrt{1-M_{\tilde{U}}^2/\omega^2}\,\sin\left(\frac{d_0}{\lambda}\pi\right)\sin\left(\omega t + \frac{d_0}{\lambda}\pi\right) + \mathscr{O}\left(1/r^2\right).$$


Principles
Theories
Observables & Evidence
Experiments & Measurements
Newtons law
Precession of mercury
Precision astronomy
General relativity
Area metric gravity
Constructive gravity
String theory
Elegance
Optic axis
parallel polarization
perpendicular polarization