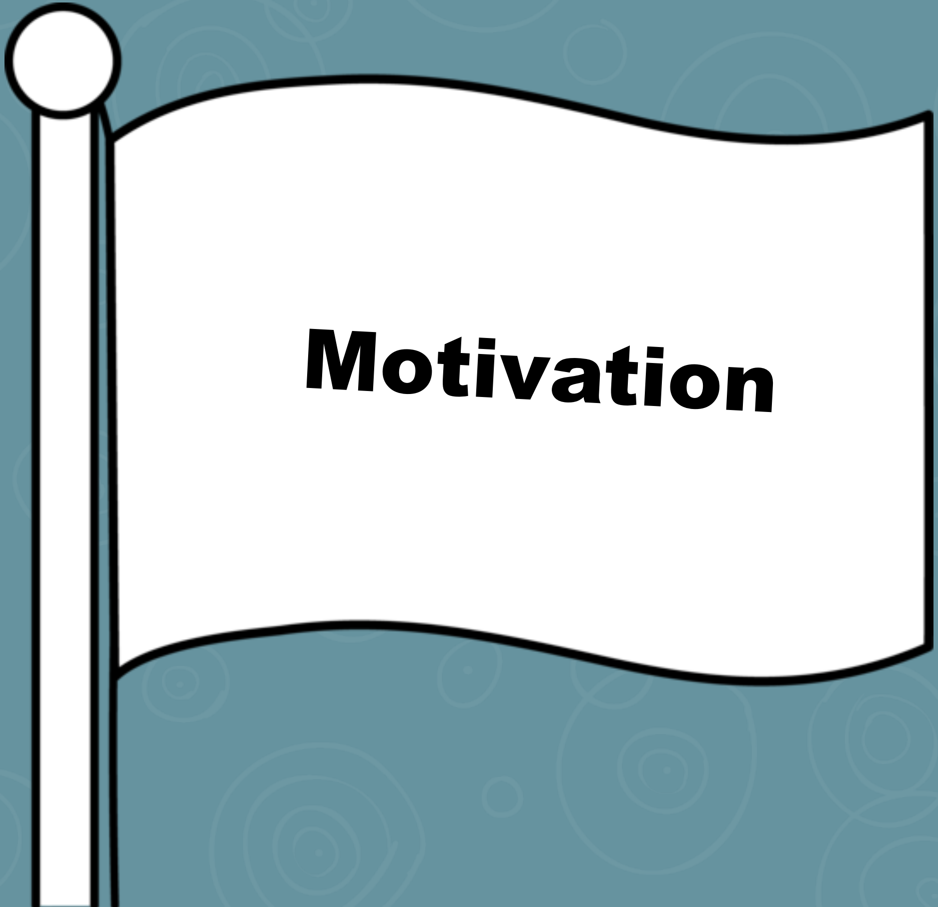
Introduction to Bimetric Theory

Angnis Schmidt-May

DESY THEORY WORKSHOP
Hamburg, 27.09.17

Navigation



Motivation

Consistent Field Theories

Standard Model of Particle Physics & General Relativity

Spin 0:	Higgs boson ϕ
Spin 1/2:	leptons, quarks ψ^a
Spin 1:	gluons, photon, W- & Z-boson A_μ
Spin 2:	graviton $g_{\mu\nu}$

Consistent Field Theories

Standard Model of Particle Physics & General Relativity

Spin 0: Higgs boson ϕ

Spin 1/2: leptons, quarks ψ^a

Spin 1: gluons, photon, W- & Z-boson A_μ

Spin 2: graviton $g_{\mu\nu}$

\+ Supersymmetry

Consistent Field Theories

Standard Model of Particle Physics
& General Relativity

Spin 0: Higgs boson ϕ

Spin 1/2: leptons, quarks ψ^a

Spin 1: gluons, photon, W- & Z-boson A_μ

Spin 2: graviton $g_{\mu\nu}$

new models are usually built using more copies of these particles

less understood...

Consistent Field Theories

Standard Model of Particle Physics & General Relativity

Spin 0:	Higgs boson	ϕ
Spin 1/2:	leptons, quarks	ψ^a
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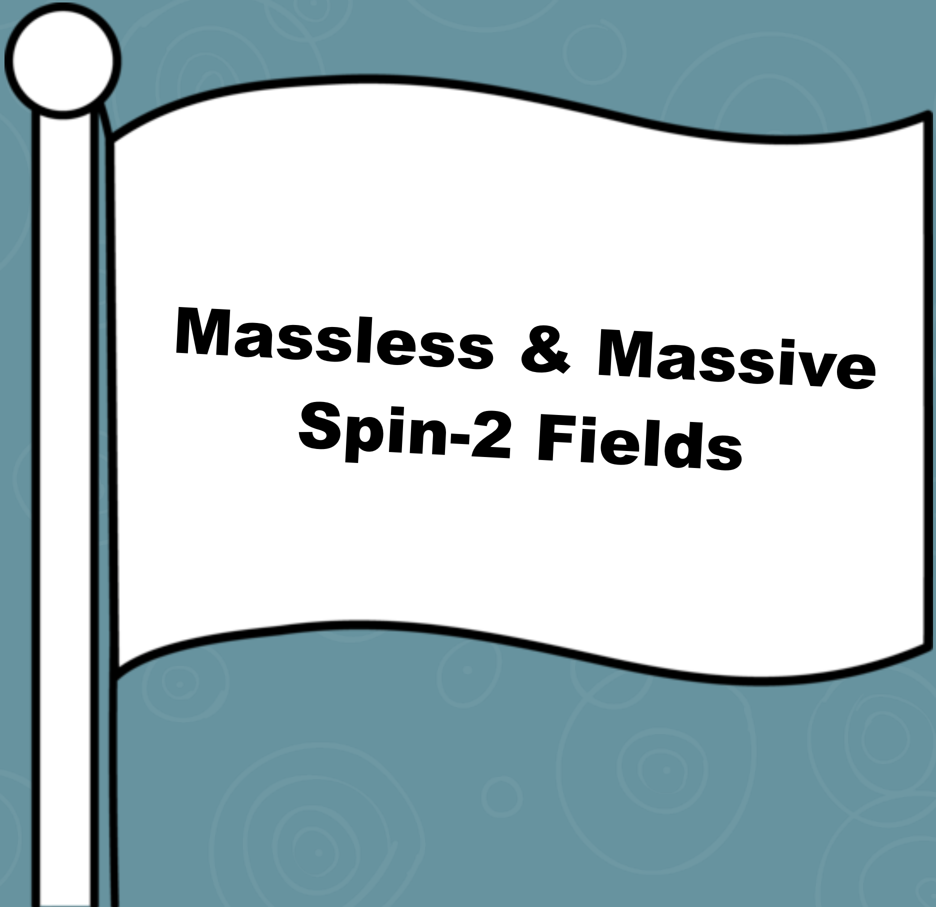
massless
& massive

MASSLESS !

How do we make a spin-2 field massive ?



Massless & Massive Spin-2 Fields

Massless Theory

General Relativity

= classical nonlinear field theory for metric tensor $g_{\mu\nu}$

- **Einstein-Hilbert action:** $$S_{\mathrm{EH}}[g] = M_{\mathrm{P}}^2 \int \mathrm{d}^4x\sqrt{g}\,\Big(R(g) - 2\Lambda\Big)$$

- **Einstein's equations:** $$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 0$$

➡ describes the two degrees of freedom
of a self-interacting, massless spin-2 particle

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two derivatives
⇨ kinetic term

⇨ describes the two degrees of freedom of a self-interacting, massless spin-2 particle

General Relativity

=

unique description of
self - interacting massless
spin-2 field

Mass Term

... should not contain derivatives nor loose indices.

Examples: scalar (spin 0)

$$-\partial_\mu\phi\partial^\mu\phi - m^2\phi^2$$

vector (spin 1)

$$-F^{\mu\nu}F_{\mu\nu} - m^2 A^\mu A_\mu$$

Mass Term

... should not contain derivatives nor loose indices.

Examples: scalar (spin 0) vector (spin 1)

$$-g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m^2\phi^2 \qquad - g^{\mu\rho}g^{\nu\sigma}F_{\rho\sigma}F_{\mu\nu} - m^2 g^{\mu\nu}A_\mu A_\nu$$

For the spin-2 tensor contracting indices of the metric gives: $g^{\mu\nu}g_{\mu\nu} = 4$

This is not a mass term.

Mass Term

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Simplest way out: Introduce second "metric" to contract indices:

$$g^{\mu\nu}f_{\mu\nu} = \mathrm{Tr}\left(g^{-1}f\right) \qquad f^{\mu\nu}g_{\mu\nu} = \mathrm{Tr}\left(f^{-1}g\right)$$

Mass Term

… should not contain derivatives nor loose indices.

Examples: scalar (spin 0) vector (spin 1)

$$-g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m^2\phi^2 \qquad - g^{\mu\rho}g^{\nu\sigma}F_{\rho\sigma}F_{\mu\nu} - m^2 g^{\mu\nu}A_\mu A_\nu$$

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$$g^{\mu\nu}f_{\mu\nu} = \mathrm{Tr}\,(g^{-1}f) \qquad f^{\mu\nu}g_{\mu\nu} = \mathrm{Tr}\,(f^{-1}g)$$

⇨ Massive gravity action: $S_{\mathrm{MG}}[g] = \underbrace{S_{\mathrm{EH}}[g]}_{\text{kinetic term}} - \underbrace{\int \mathrm{d}^4x\; V(g,f)}_{\text{mass term}}$

Mass Term

... shoul indices.

Examples: scalar (s

$$-g^{\mu\nu}\partial_\mu\phi\partial_\nu$$

For the spin-2 tensor cont

This is not a mass term.

Simplest way out: Introduce se

$$g^{\mu\nu}f_{\mu\nu} = \mathrm{Tr}\,(g \qquad g)$$

What determines $f_{\mu\nu}$?

Shouldn't it be dynamical ?

Massive gravity action: $$S_{\mathrm{MG}}[g] = \underbrace{S_{\mathrm{EH}}[g]}_{\text{kinetic term}} - \underbrace{\int \mathrm{d}^4x\, V(g,f)}_{\text{mass term}}$$

Bimetric Theory

Nonlinear action for two interacting tensors:

$$\begin{aligned} S_{\mathrm{b}}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\left(R(g) - 2\Lambda\right) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\left(R(f) - 2\tilde{\Lambda}\right) - \int \mathrm{d}^4x \, V(g,f) \end{aligned}$$

- both metrics are dynamical and treated on equal footing
- should describe massive & massless spin-2 field (5+2 d.o.f.)

Bimetric Theory

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- both metrics are dynamical and treated on equal footing
- should describe massive & massless spin-2 field (5+2 d.o.f.)

This looks good, but there is a major problem...

Ghosts

Ghost = field with negative kinetic energy

$$\mathcal{L} = (\partial_t \phi)^2 \cdots \quad \text{healthy}$$

$$\mathcal{L} = -(\partial_t \phi)^2 \cdots \quad \text{ghost}$$

- consequences: classical instability, negative probabilities at quantum level
  - ➪ must be avoided!
- explicit check for ghosts by computing the Hamiltonian

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Modifications of General Relativity tend to be haunted by ghosts.
Modifying gravity is EXTREMELY difficult!

Ghosts

Ghost = field with negative kinetic energy

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- consequences: classical instability, negative probabilities at quantum level
  - ➔ must be avoided!
- explicit check for ghosts by computing the Hamiltonian

- massive spin-2: six instead of five propagating degrees of freedom
  - ➔ need extra constraint to remove the ghost

Avoiding the Ghost ?

$$\begin{aligned} S_{\mathrm{b}}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\left(R(g) - 2\Lambda\right) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\left(R(f) - 2\tilde{\Lambda}\right) - \int \mathrm{d}^4x \, V(g,f) \end{aligned}$$

For generic interaction potentials the theory suffers from a ghost.
Is there a particular potential which avoids the ghost ?

Fierz & Pauli (1939): Linear mass term avoiding the ghost ☺

Avoiding the Ghost ?

$$
\begin{aligned}
S_{\mathrm{b}}[g,f] \;&=\; m_g^2 \int \mathrm{d}^4x\sqrt{g}\,\Big(R(g) - 2\Lambda\Big) \\
&+\; m_f^2 \int \mathrm{d}^4x\sqrt{f}\,\Big(R(f) - 2\tilde{\Lambda}\Big) \;-\; \int \mathrm{d}^4x\, V(g,f)
\end{aligned}
$$

For generic interaction potentials the theory suffers from a ghost.
Is there a particular potential which avoids the ghost ?

Fierz & Pauli (1939): Linear mass term avoiding the ghost ☺

Boulware & Deser (1972): Beyond linear order it is impossible! ☹

No consistent nonlinear massive gravity / bimetric theory ?

The Ghost-Free Theory

👻 - free Bimetric Theory

de Rham, Gabadadze, Tolley (2010);
Hassan, Rosen, ASM, von Strauss (2011/12)

$$\begin{aligned} S_{\mathrm{b}}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\, R(g) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\, R(f) - \int \mathrm{d}^4x\, V(g,f) \end{aligned}$$

$$\boxed{V\,(g,f) = m^4 \sqrt{g} \sum_{n=0}^{4} \beta_n\, e_n\left(\sqrt{g^{-1}f}\right) = m^4 \sqrt{f} \sum_{n=0}^{4} \beta_{4-n}\, e_n\left(\sqrt{f^{-1}g}\right)}$$

- arbitrary spin-2 mass scale m
- 3 interaction parameters β_n
- square-root matrix S defined through $S^2 = g^{-1}f$

- free Bimetric Theory

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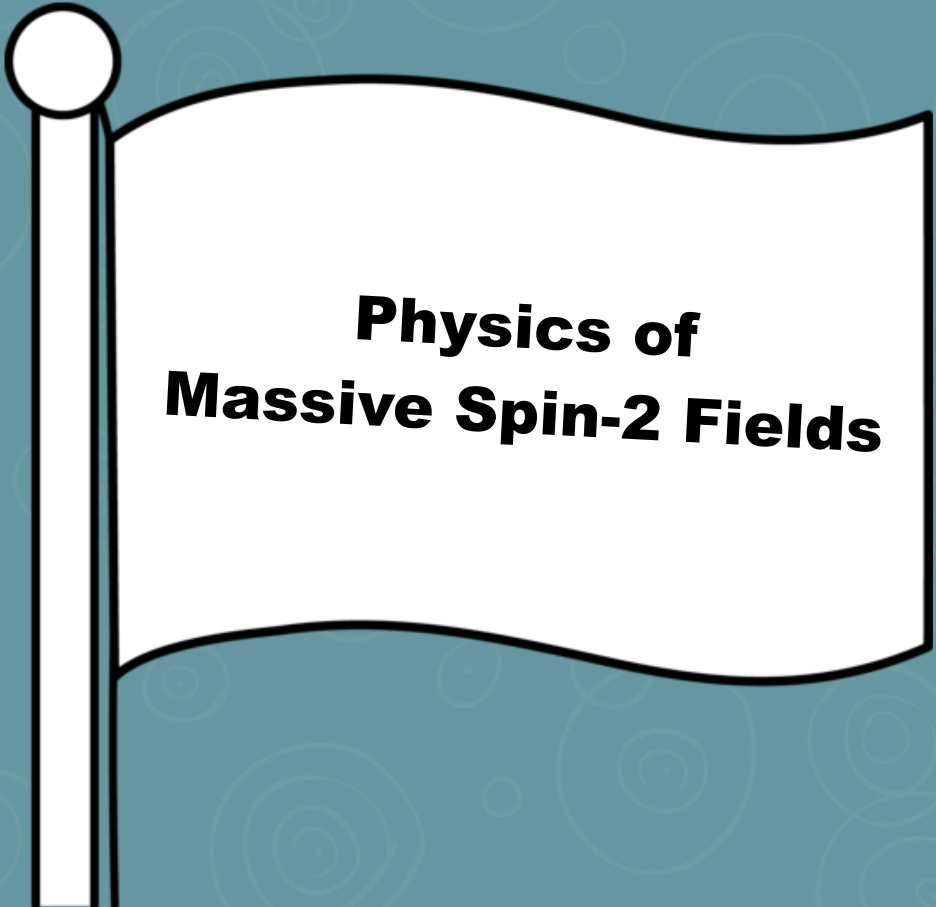
elementary symmetric polynomials:

$$e_1(S) = \mathrm{Tr}[S] \qquad e_2(S) = \tfrac{1}{2}\left((\mathrm{Tr}[S])^2 - \mathrm{Tr}[S^2]\right)$$

$$e_3(S) = \tfrac{1}{6}\left((\mathrm{Tr}[S])^3 - 3\,\mathrm{Tr}[S^2]\mathrm{Tr}[S] + 2\,\mathrm{Tr}[S^3]\right)$$



Physics of Massive Spin-2 Fields

Mass spectrum

Hassan, ASM, von Strauss (2012)

Perturbations around proportional backgrounds:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu} \qquad f_{\mu\nu} = \bar{g}_{\mu\nu} + \delta f_{\mu\nu}$$

Can be diagonalised into mass eigenstates ($\alpha = m_f/m_g$):

$$\begin{aligned} \delta G_{\mu\nu} &= \delta g_{\mu\nu} + \alpha^2 \delta f_{\mu\nu} && \text{massless (2 d.o.f.)} \\ \delta M_{\mu\nu} &= \delta f_{\mu\nu} - \delta g_{\mu\nu} && \text{massive (5 d.o.f.)} \end{aligned}$$

Linearised equations: $\bar{\mathcal{E}}_{\mu\nu}^{\rho\sigma} \delta G_{\rho\sigma} = 0$

$$\bar{\mathcal{E}}_{\mu\nu}^{\rho\sigma} \delta M_{\rho\sigma} + \tfrac{m_{\rm FP}^2}{2} \left(\delta M_{\mu\nu} - \bar{g}_{\mu\nu} \delta M\right) = 0$$

with mass $m_{\rm FP} = m_{\rm FP}(\alpha, \beta_n)$ and kinetic operator $\bar{\mathcal{E}} \sim \nabla\nabla + \Lambda$

Ghost-free bimetric theory

=

unique description of
massless + massive
spin-2 field

What is the physical metric ?

How does matter couple to the tensor fields ?

Matter Coupling

Yamashita, de Felice, Tanaka;
de Rham, Heisenberg, Ribeiro (2015)

$$\begin{aligned} S_{\mathrm{b}}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\, R(g) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\, R(f) - \int \mathrm{d}^4x\, V(g,f) \\ &\qquad + \int \mathrm{d}^4x\, \sqrt{g}\, \mathcal{L}_{\mathrm{matter}}(g,\phi) \end{aligned}$$

Absence of ghosts: only one metric can couple to matter!

➡ $g_{\mu\nu}$ is gravitational metric

Mass Eigenstates

Hassan, ASM, von Strauss (2012)

$$\begin{aligned} S_\mathrm{b}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\, R(g) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\, R(f) - \int \mathrm{d}^4x\, V(g,f) \\ &\qquad + \int \mathrm{d}^4x\, \sqrt{g}\, \mathcal{L}_\mathrm{matter}(g,\phi) \end{aligned}$$

(linearised) gravitational metric:

$$\delta g_{\mu\nu} \propto \underbrace{\delta G_{\mu\nu}}_{\text{massless}} - \alpha^2 \underbrace{\delta M_{\mu\nu}}_{\text{massive}} \qquad (\alpha \equiv m_f/m_g)$$

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The gravitational metric is not massless but a superposition of mass eigenstates.
Max, Platscher, Smirnov (2017): analysis of gravitational wave oscillations

Mass Eigenstates

Hassan, ASM, von Strauss (2012)

$$S_{\mathrm{b}}[g,f] = m_g^2 \int \mathrm{d}^4x \sqrt{g}\, R(g)$$

$$+ \; m_f^2 \int \mathrm{d}^4x$$

(linearised) gravitational

$\delta g_{\mu\nu}$ $m_g)$

mo

See Moritz Platscher’s talk
Wednesday, 17:47
Seminar room 4b

The gravitational metric is not massless but a superposition of mass eigenstates.
Max, Platscher, Smirnov (2017): analysis of gravitational wave oscillations

Mass Eigenstates

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(linearised) gravitational metric:

$$\delta g_{\mu\nu} \propto \underbrace{\delta G_{\mu\nu}}_{\text{massless}} - \alpha^2 \underbrace{\delta M_{\mu\nu}}_{\text{massive}} \qquad (\alpha \equiv m_f/m_g)$$

- for small $\alpha = m_f/m_g$ gravity is dominated by the massless mode
- the massive spin-2 field interacts only weakly with matter

Mass Eigenstates

Baccetti, Martin-Moruno, Visser (2012);
Hassan, ASM, von Strauss (2012/14);
Akrami, Hassan, Koennig, ASM, Solomon (2015)

$$\begin{aligned} S_{\mathrm{b}}[g,f] &= m_g^2 \int \mathrm{d}^4x \sqrt{g}\, R(g) \\ &+ m_f^2 \int \mathrm{d}^4x \sqrt{f}\, R(f) - \int \mathrm{d}^4x\, V(g,f) \\ &+ \int \mathrm{d}^4x\, \sqrt{g}\, \mathcal{L}_{\mathrm{matter}}(g,\phi) \end{aligned}$$

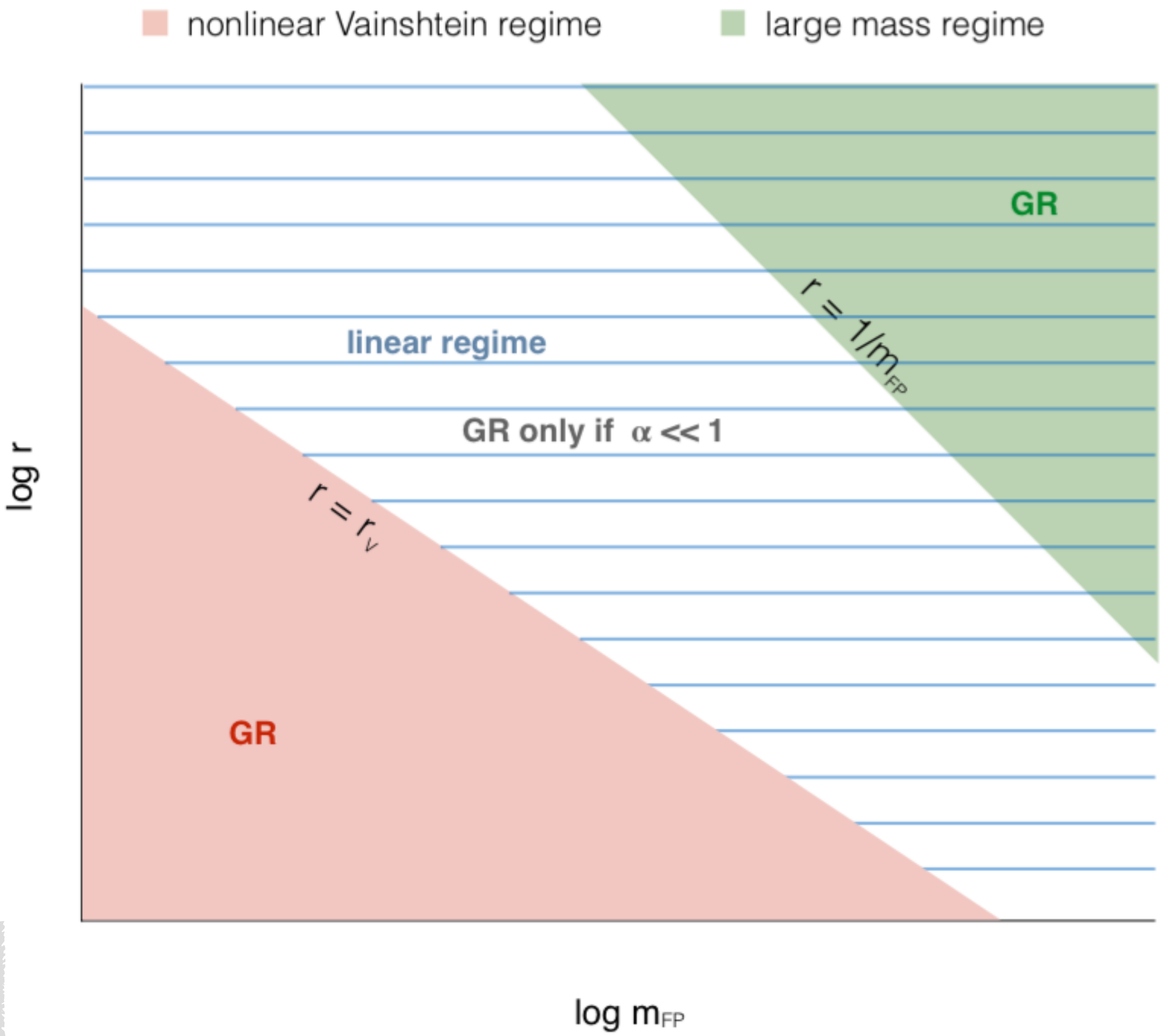
$$\alpha = m_f/m_g \to 0$$

is the General Relativity limit of bimetric theory

Recovery of GR

$$r_{\rm V} = \left(\frac{r_{\rm S}}{m_{\rm FP}^2}\right)^{1/3}$$

$$V_{\rm Yuk} \sim \frac{e^{-m_{\rm FP} r}}{r}$$



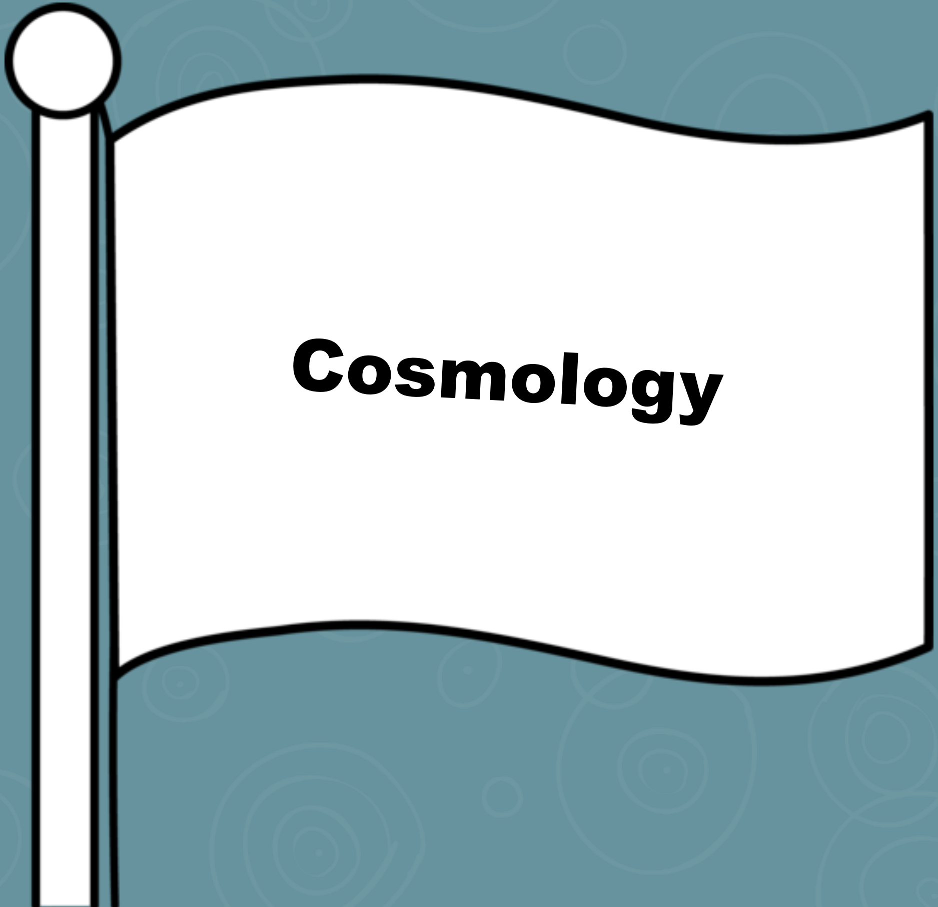
Babichev, Marzola, Raidal, ASM, Urban, Veermäe, von Strauss (2016)

Ghost-free bimetric theory

=

General Relativity + additional tensor field

What are the consequences for cosmology ?



Cosmology

The cosmological cake

25%
Dark Matter

70%
Dark Energy

5%
normal
matter

The cosmological cake

Λ?

25%
Dark Matter

70%
Dark Energy

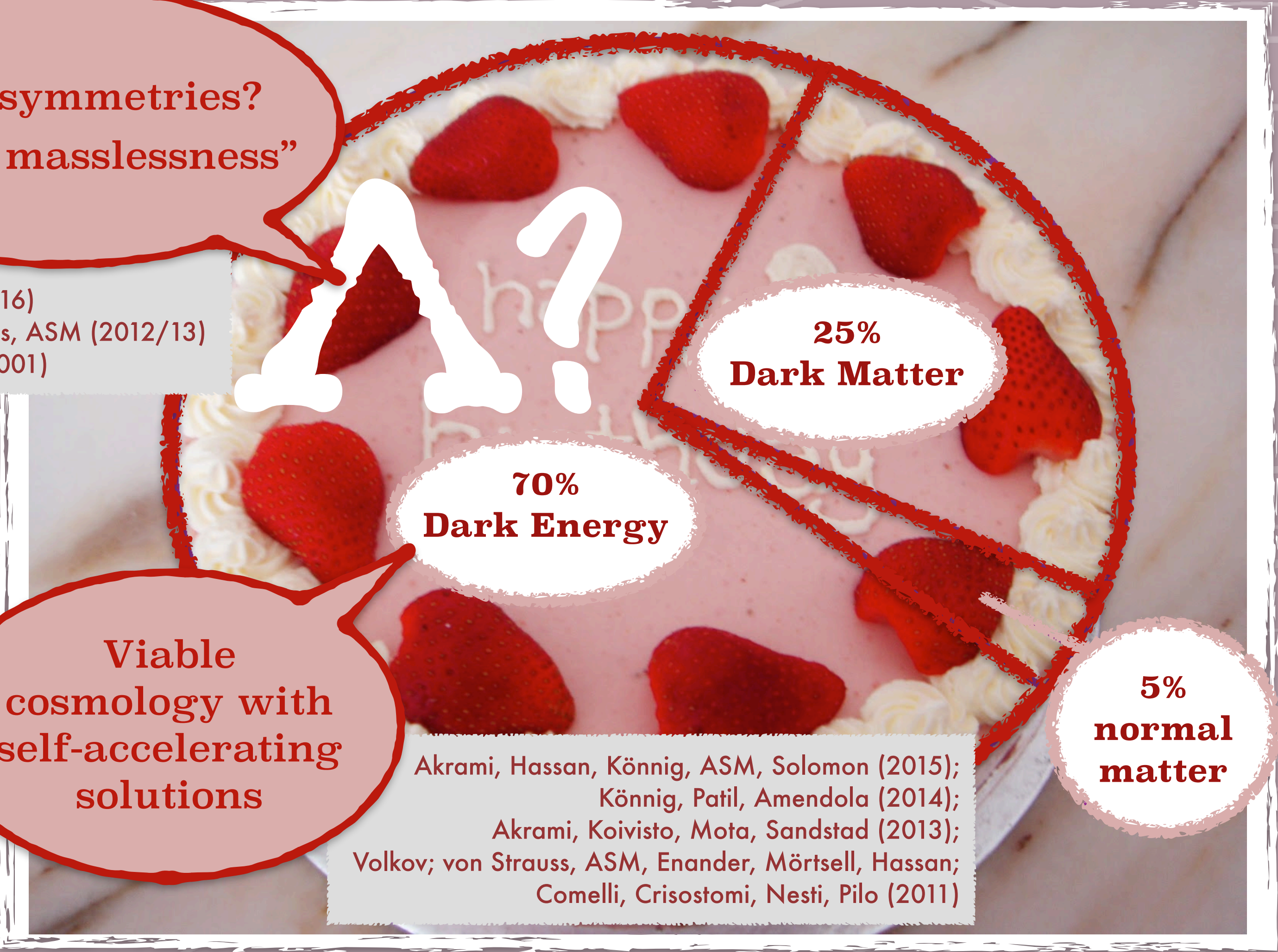
5%
normal
matter

Viable cosmology with self-accelerating solutions

Akrami, Hassan, Könnig, ASM, Solomon (2015);
Könnig, Patil, Amendola (2014);
Akrami, Koivisto, Mota, Sandstad (2013);
Volkov; von Strauss, ASM, Enander, Mörtsell, Hassan;
Comelli, Crisostomi, Nesti, Pilo (2011)

Extra symmetries?
“partial masslessness”

Apolo, Hassan (2016)
Hassan, von Strauss, ASM (2012/13)
Deser, Waldron (2001)



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Deser, Waldron (2001)

massive spin-2 ?

Babichev, Marzola, Raidal, ASM,
Urban, Veermäe, von Strauss;
Aoki, Mukohyama (2016)

25%
Dark Matter

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Viable cosmology with self-accelerating solutions

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Spin-2 Dark Matter

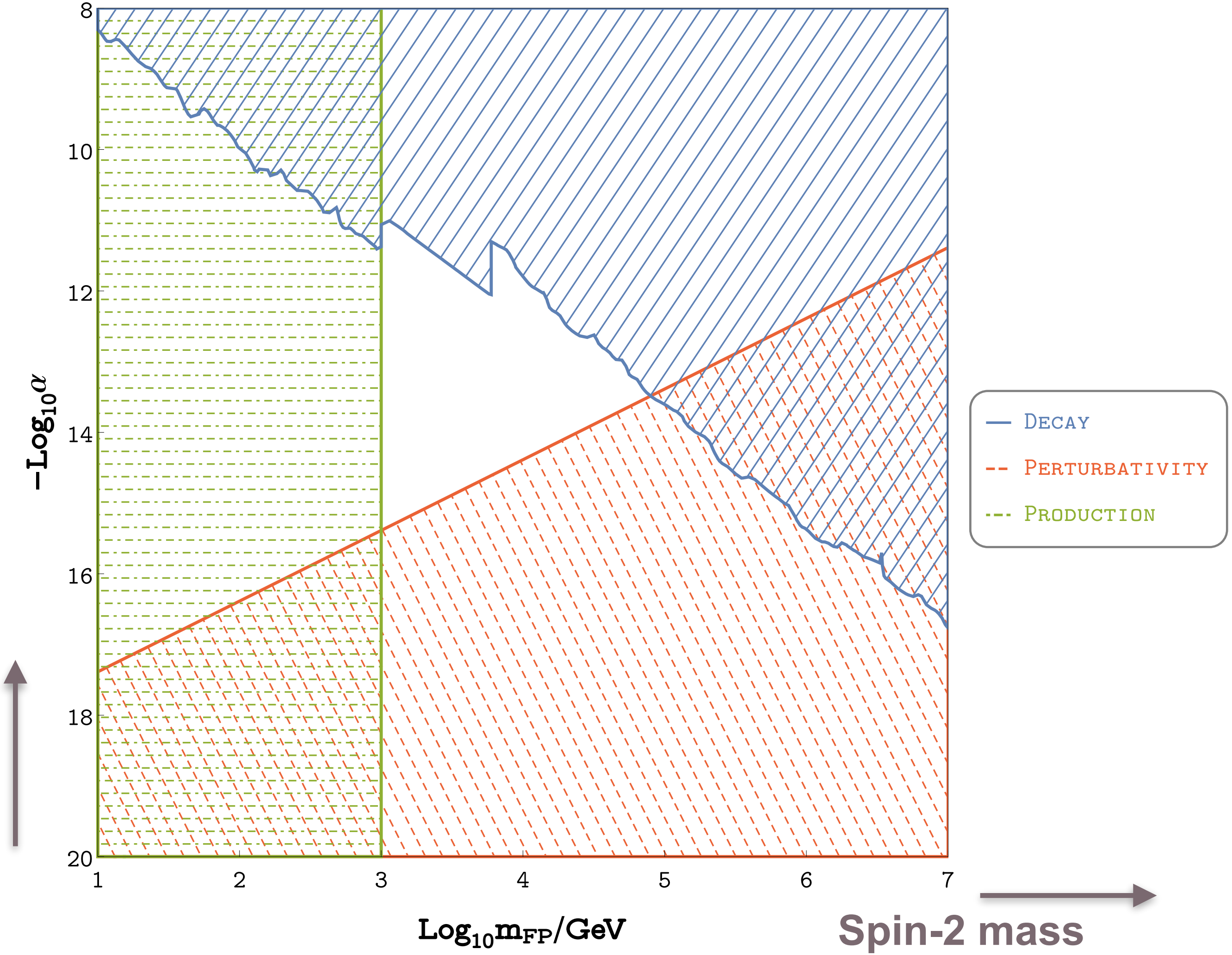
Babichev, Marzola, Raidal, ASM,
Urban, Veermäe, von Strauss (2016)

Recall the (linearised) gravitational metric: $\delta g_{\mu\nu} \propto \underbrace{\delta G_{\mu\nu}}_{\text{massless}} - \alpha^2 \underbrace{\delta M_{\mu\nu}}_{\text{massive}}$

and the General Relativity limit of bimetric theory: $\alpha = m_f / m_g \to 0$

- ⇨ gravity is weak because the physical Planck mass is large
- ⇨ massive spin-2 field decouples from matter, interacts only with gravity

Constraints



ratio of
Planck masses

Spin-2 mass

Features

Babichev, Marzola, Raidal, ASM, Urban, Veermäe, von Strauss (2016)

- heavy spin-2 field automatically resembles dark matter when gravity resembles General Relativity
- interactions with baryonic matter are suppressed by the Planck mass
- spin-2 mass and interaction scale are on the order of a few TeV

Features

Babichev, Marzola, Raidal, ASM,
Urban, Veermäe, von Strauss (2016)

- heavy spin-2 field automatically resembles dark matter when gravity resembles General Relativity
- interactions with baryonic matter are suppressed by the Planck mass
- spin-2 mass and interaction scale are on the order of a few TeV

Chu & Garcia-Cely (2017): may be lowered to MeV by taking into account self-interactions of massive spin-2

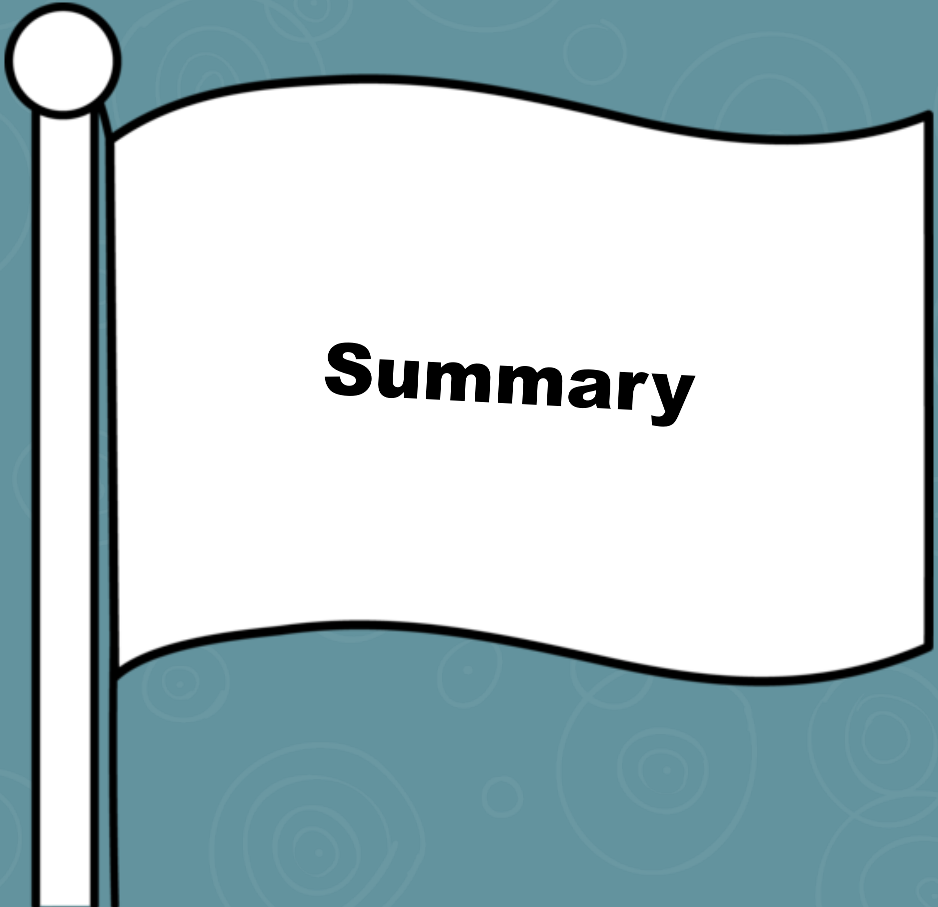
Gonzalez, ASM, von Strauss (2017): interesting new effects for more than one massive spin-2 field

Features

Babichev, Marzola, Raidal, ASM, Urban, Veermäe, von Strauss (2016)

- heavy spin-2 field automatically resembles dark matter when gravity resembles General Relativity
- interactions with baryonic matter are suppressed by the Planck mass
- spin-2 mass and interaction scale are on the order of a few TeV

- ⇨ no need for extra fields, artificial symmetries or fine tuning
- ⇨ bimetric theory could explain dark matter in the context of gravity
- ⇨ massive spin-2 field is a natural addition to the Standard Models



Summary

Bimetric Theory …

review: ASM, Mikael von Strauss; 1512.00021

- is one of the few known consistent modifications of General Relativity
- can be interpreted as gravity in the presence of an extra spin-2 field
- contains an interesting dark matter candidate whose coupling to baryonic matter is suppressed by the Planck scale

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- Larger theoretical framework: String Theory ?
- Can we detect/observe the massive spin-2 ?

Thank you for your attention!

Back-up slides

Proportional solutions

Hassan, ASM, von Strauss (2012)

Ansatz: $\bar{f}_{\mu\nu} = c^2 \bar{g}_{\mu\nu}$ **with** $c =$ const.

- gives two copies of Einstein's equations $(\alpha \equiv m_f/m_g)$:

$$R_{\mu\nu}(\bar{g}) - \tfrac{1}{2}\bar{g}_{\mu\nu}R(\bar{g}) + \Lambda_g(\alpha, \beta_n, c)\bar{g}_{\mu\nu} = 0$$
$$R_{\mu\nu}(\bar{g}) - \tfrac{1}{2}\bar{g}_{\mu\nu}R(\bar{g}) + \Lambda_f(\alpha, \beta_n, c)\bar{g}_{\mu\nu} = 0$$

- consistency condition: $\Lambda_g(\alpha, \beta_n, c) = \Lambda_f(\alpha, \beta_n, c)$ determines c

⇨ Maximally symmetric backgrounds with $R_{\mu\nu}(\bar{g}) = \Lambda_g \bar{g}_{\mu\nu}$

Dark Energy

Volkov; von Strauss, ASM, Enander, Mörtsell, Hassan; Comelli, Crisostomi, Nesti, Pilo (2011)

➡ Cosmological solutions in analogy to GR

- Homogeneous & isotropic ansatz for both metrics
- Use bimetric equations to eliminate components of $f_{\mu\nu}$
- Obtain modified Friedmann equation for scale factor of physical metric:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} + F\left[\rho(t)\right]$$

GR: $F\left[\rho(t)\right] = \frac{\rho(t)}{3M_{\mathrm{P}}^2}$

- Use full bimetric equations to compute linearised perturbations

Comparison to Data

Akrami, Koivisto, Mota, Sandstad (2013);
Könnig, Patil, Amendola (2014);
Akrami, Hassan, Könnig, ASM, Solomon (2015)

- set vacuum energy to zero and look for self-accelerating solutions
- impose conditions for viable cosmology (background & perturbations)
- fit to data

Outcome: self-accelerating solutions exist, meet the viability conditions and fit the data as well as ΛCDM

Perturbations are well-behaved in the GR limit, i.e. for small $\alpha = m_f/m_g$

Structure of Vertices

(bimetric action expanded in mass eigenstates)

Quadratic (Fierz-Pauli)

δG^2	$\delta G \delta M$	δM^2
$1\,,\Lambda$	0	$1\,,\Lambda\,,m_{\mathrm{FP}}^2$

$$\begin{aligned} \delta G_{\mu\nu} &= \delta g_{\mu\nu} + \alpha^2 \delta f_{\mu\nu} \\ \delta M_{\mu\nu} &= \delta f_{\mu\nu} - \delta g_{\mu\nu} \end{aligned}$$

massless

massive

$$S_{(2)} = \tfrac{1}{2}\int \mathrm{d}^4x \Big[\delta G_{\mu\nu}\mathcal{E}^{\mu\nu\rho\sigma}\delta G_{\rho\sigma} + \delta M_{\mu\nu}\mathcal{E}^{\mu\nu\rho\sigma}\delta M_{\rho\sigma} \\ -\tfrac{m_{\mathrm{FP}}^2}{2}(\delta M^{\mu\nu}\delta M_{\mu\nu} - \delta M^2) - \tfrac{1}{m_{\mathrm{Pl}}}\Big(\delta G^{\mu\nu} - \alpha\,\delta M^{\mu\nu}\Big)T_{\mu\nu}\Big]$$

Structure of Vertices

(bimetric action expanded in mass eigenstates)

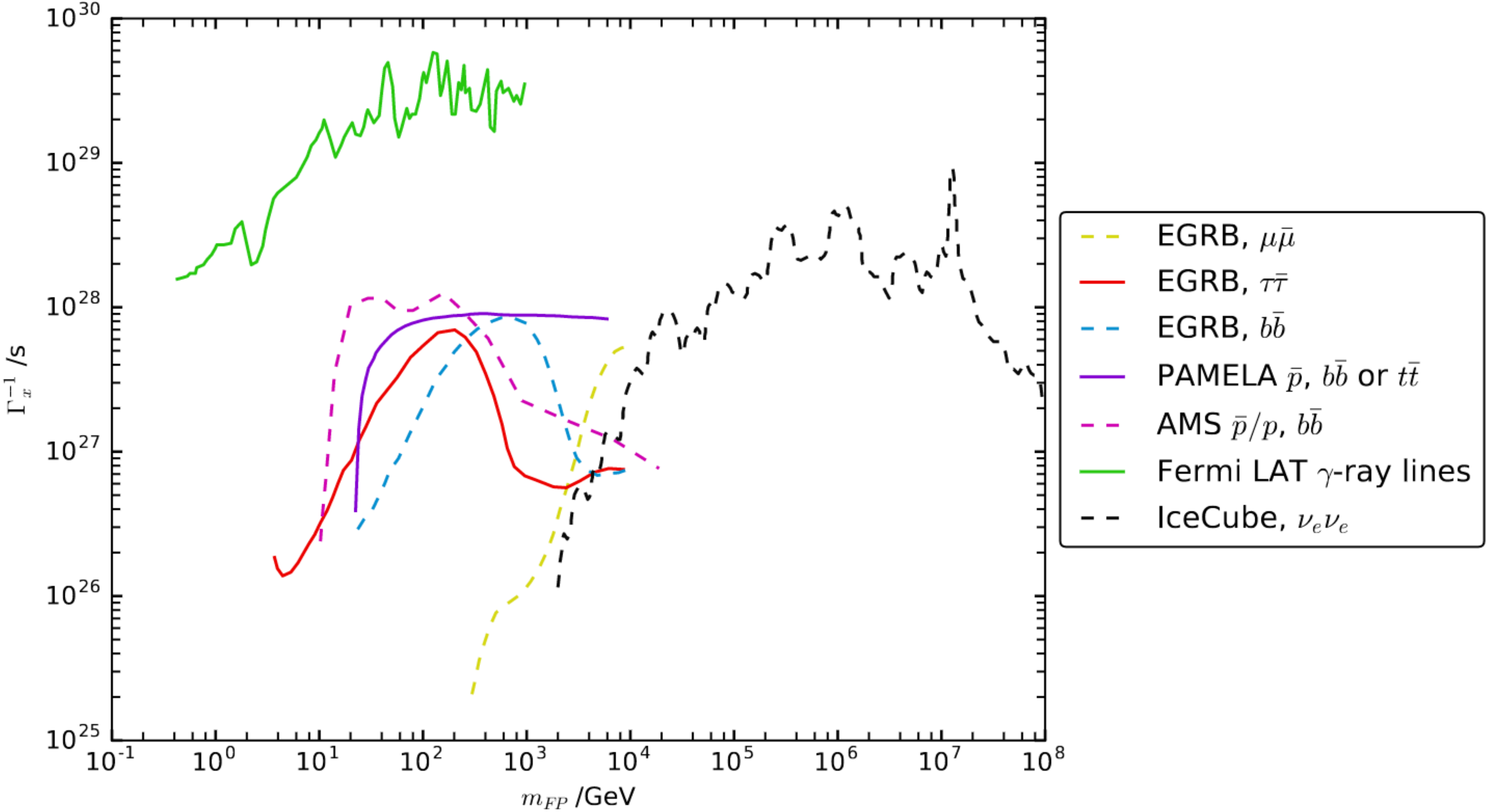
Quadratic (Fierz-Pauli)

δG^2	$\delta G \delta M$	δM^2
$1\,,\Lambda$	0	$1\,,\Lambda\,,m_{\rm FP}^2$

Cubic

δG^3	$\delta G^2 \delta M$	$\delta G \delta M^2$	δM^3
$1\,,\Lambda$	0	$1\,,\Lambda\,,m_{\rm FP}^2$	$\alpha\,,\alpha\Lambda\,,\alpha m_{\rm FP}^2$ $\frac{1}{\alpha}\,,\frac{1}{\alpha}\Lambda\,,\frac{1}{\alpha}m_{\rm FP}^2$

- self-interactions of massless spin-2 sum up to General Relativity
- no vertices giving rise to decay of massive into massless spin-2
- massive spin-2 particle gravitates like baryonic matter
- self-interactions of massive spin-2 are enhanced in the GR limit


10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
Γ_x^{-1} /s
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
m_{FP} /GeV
EGRB, $\mu\bar{\mu}$
EGRB, $\tau\bar{\tau}$
EGRB, $b\bar{b}$
PAMELA $\bar{p}$, $b\bar{b}$ or $t\bar{t}$
AMS $\bar{p}/p$, $b\bar{b}$
Fermi LAT γ-ray lines
IceCube, $\nu_e\nu_e$