Workshop Summary

as a basis for discussion immediately after this

Caution:
This is based on talks that I listened to during the workshop and thus does not necessarily reflect my own view on the subject. Moreover, this may differ from what the speakers originally intended (e.g.because of my misunderstanding).

Shinji Mukohyama (Kavli IPMU)

Monday (14:00-18:00)

- Cedric Deffayet (APC Paris)
  Ghost free massive gravity with vierbeins
- Fawad Hassan (Stockholm)
  Higher Derivative and Conformal Gravity Actions from Bimetric and Partially Massless Bimetric Theories
- Keisuke Izumi (LeCosPA)
  Is there acausality in Massive Gravity?
- Robert Caldwell (Dartmouth)
  Nonlinearity of Superposition in Massive Gravity

Deffayet “Ghost free massive gravity with vierbeins”

- Fierz-Pauli
  10 (metric components) – 4 (Bianchi) – 1 (extra constraint) = 5 d.o.f. of massive spin-2
- Nonlinear FP
  $m^2V(M)$ with $M^\mu{}_\nu = g^{\mu\rho}f_{\rho\nu}$
  BD ghost @ nonlinear level
- Metric dRGT
  $m^2\,\beta_{1,2,3}\,F_{1,2,3}(\gamma)$
  $\gamma^\mu{}_\sigma\,\gamma^\sigma{}_\nu = g^{\mu\sigma}\,f_{\sigma\nu}$
  no BD ghost

$F_1(X) = [X]$

$F_2(X) = ([X]^2-[X^2])/2$

$F_3(X) = ([X]^3-3[X][X^2]+2[X^3])/6$

- 2 metrics → 2 vielbeins
  $\eta_{AB}E^{A}{}_{\mu}E^{B}{}_{\nu} = g_{\mu\nu}$ $\eta_{AB}L^{A}{}_{\mu}L^{B}{}_{\nu} = f_{\mu\nu}$
  $E_{A}{}^{\mu}L_{B\mu} = E_{B}{}^{\mu}L_{A\mu}$ → 6 constraints
  16 (vielbein components) – 6 (constraints) =
  10 (metric components)
- Vielbein dRGT

$$S = M_P^{D-2}\int \Omega^{AB}\wedge E^{*}_{AB} - M_P^{D-2}m^2\sum_{n=0}^{D-1}\beta_n\int L^{A_1}\wedge\cdots\wedge L^{A_n}\wedge E^{*}_{A_1\ldots A_n}$$

  $G_A = t_A$
- 10 – 4 (Dt_A=0) – 1 ($m^A \wedge G_A = m^A \wedge t_A$?) = 5?
  works when only $\beta_1 \neq 0$ or when only $\beta_2 \neq 0$
  not clear for general cases

Hassan "Higher Derivative and Conformal Gravity Actions from Bimetric and Partially Massless Bimetric Theories"

- FP, nonlinear FP, BD ghost
- dRGT: decoupling limit analysis of $g^{-1}f$ theory
  → necessary condition
  HR "it is indeed sufficient"
- Give dynamics to f → bi-metric theory
  solutions with $f = c^2 g$ ($c \leftarrow \Lambda_f = \Lambda_g/c^2$)
  FP mass around $f = c^2 g$ → 2 + 5 = 7 d.o.f.
- New gauge symmetry @Higuchi bound →
  partially massless FP theory with 5 -1 = 4 d.o.f.

- Nonliner extension → PM bimetric
  new gauge symmetry would detune the c of $f = c^2 g$ → c undetermined by $\Lambda_f = \Lambda_g / c^2$ → one-parameter (β_2) subset of bimetric theories
- HD (or conformal) gravity from bigravity (or PM bigravity)
  solve g-eom w.r.t. f & substitute to the action & derivative expansion → series of higher curvature terms
  truncation at finite order → ghost
  infinite sum → no-ghost completion of HD (or conformal) gravity?

Izumi "Is there acausality in Massive Gravity?"

- Deser-Waldron' claim on acausality of dRGT is due to misuse of characteristics analysis
- Characteristics analysis: det (time kinetic matrix) = 0 AFTER solving constraints → instantaneous mode → acausality
- dRGT eliminates BD ghost → would-be BD ghost has vanishing time kinetic term → det (time kinetic matrix) = 0 before solving constraints → this does NOT imply acausality

Caldwell "Nonlinearity of Superposition in Massive Gravity"

- Nonlinearity → Vainshtein screening
- What happens if two Vainshtein regions overlap?
- Nonlinear solution < naive superposition
- Modified gravity effects tend to be hidden
- Relaxation time scale >> dynamical time scale? If yes, then we may still hope to see modified gravity effects unsuppressed.

Tuesday (9:45-15:00)

- Mikhail Volkov (Tours U, CNRS)
  Self-accelerated cosmologies and black holes in the ghost-free bigravity
- Emir Gumrukcuoglu (Kavli IPMU)
  Stability of cosmological solutions in massive gravity
- Chunshan Lin (Kavli IPMU)
  Cosmological perturbations in extended massive gravity

Volkov "Self-accelerated cosmologies and black holes in the ghost-free bigravity"

- Solution in dRGT → solution in bigravity
  2 more excitations → more solutions in bigravity
- FLRW with non-bidiagonal metrics
  f & g separately FLRW
  f-commoving observers ≠ g-commoving observers
  spherical symmetry & $T^t_r = T^t_t - T^r_r = 0$ & constraint eq
  → PDE → infinite # of solutions
  massive gravity limit ➔ 2-parameter (k,q) family of special solutions
- FLRW with bidiagonal metrics
  constraint eq → 3 branches of solutions
  homothetic one (c.f. Soda) & other two with a/b=const.

- Static black holes
  f & g share the same horizon and surface gravity
  $f = c^2 g$ → S ($\Lambda_g=0$), SdS ($\Lambda_g>0$), SAdS ($\Lambda_g<0$)
- SAdS can carry short hair while S and SdS cannot. For S and SdS, would-be hair inevitably accretes toward BH.
- The hair survives in $r_h = 0$ limit ➔ lump solution
- Regular star solution with matter source ➔ Vainshtein screening in dRGT and bigravity

Gumrukcuoglu “Stability of cosmological solutions in massive gravity”

- Homogeneous & isotropic FLRW cosmological solution exists in dRGT
- Linear perturbation analysis → vanishing kinetic terms for 3 out of 5 d.o.f. → nonlinear analysis is needed
- Almost FLRW Bianchi I + liner perturbation → leading nonlinear perturbation on FLRW
- Negative kinetic term inevitable @ cubic order → all FLRW solutions in dRGT are unstable…

- In analogy with tachyon/ghost condensation, why don't we consider large deviation from FLRW?
  → anisotropic FLRW attractor solution: FLRW $g_{\mu\nu}$ but O(1) anisotropy in $f_{\mu\nu}$
- Stable dynamics near anisotropic FLRW possible

Lin “Cosmological perturbations in extended massive gravity”

- All FLRW solutions in dRGT are unstable…
- We need (i) to break FLRW symmetry or (ii) to extend the theory. Let’s consider (ii).
- dRGT < quasi-dilaton, varying mass < bi-metric
- Self-accelerating solution in quasi-dilaton always have a ghost in scalar sector.
- Varying mass theory may have stable regime. However, a viable self-accelerating solution has not yet been found.

Tuesday (16:00-18:00)

- Tsutomu Kobayashi (Rikkyo U)
  Vainshtein mechanism in Horndeski's general scalar-tensor theory (and in massive gravity)
- Tetsuya Shiromizu (Kyoto U)
  Concern on "ground state" of spacetimes with/without black holes
- Rampei Kimura (Hiroshima U)
  Vainshtein mechanism in quasi-dilaton massive gravity

Kobayashi "Vainshtein mechanism in Horndeski's general scalar-tensor theory (and in massive gravity)"

- Vainshtein screening due to nonlinearlity: $r_c^2 dd\pi$ can be O(1) even if $\pi << 1$
- Horndeski's theory (= covariant Galileon) → 2nd order eom
- Spherically-symmetric, static perturbation around Minkowski → 2nd order ode → 1st integral gives algebraic eq's for 1st derivatives with source A(r) ~ $M(r)/r^3$ if we consider various coefficients as constants → can be solved @ each r

- Can we connect almost GR inner solution to asymptotically flat outer solution?
- Condition for smooth matching:
  $P(x,A)=0$ has a single root in $(x_-,0)$ for any $A>0$
  → no local extrema in $x<0$
- 2nd derivative may become large near transition region if the above condition is marginally fulfilled → observable signature in e.g. cluster lensing?

Shiromizu "Concern on ground state of spacetimes with/without black holes"

- Various theorems in GR
  Positive mass theorem
  Strictly stationary vacuum →Minkowski
  BH no hair (static, stationary)
- Even in Einstein Gauss-Bonnet in D>4,
  Strictly stationary vacuum →Minkowski
- In dynamical Chern-Simons gravity,
  Strictly stationary vacuum →Minkowski
  BH no hair (static)
- How about massive gravity?

Kimura "Vainshtein mechanism in quasi-dilaton massive gravity"

- Quasi-dilaton: dRGT + scalar
- Decoupling limit → galileon & bi-galileon terms
- Spherically-symmetric, static perturbation around Minkowski → 2^{nd} order ode → 1^{st} integral gives algebraic eq's for 1^{st} derivatives with source $A(r) \sim M(r)/r^3$ → can be solved @ each r
- Can we connect almost GR inner solution to asymptotically flat outer solution?
- However, there is a ghost (c.f. Lin). Can we found a healthy background?

Wednesday (9:45-12:00)

- Kei-ichi Maeda (Waseda U)
  Anisotropic universes in bigravity theory and homothetic metrics
- Jiro Soda (Kyoto U)
  Inflation in bimetric gravity

Maeda "Anisotropic universes in bigravity theory and homothetic metrics"

- Classical stability of FLRW
  Validity of cosmic no hair conjecture
- f & g of the same Bianchi type (in class A)
  $C^{c}_{ab} = n^{cd}\,\varepsilon_{dab} + \alpha\,(\delta^{1}_{a}\delta^{c}_{b} - \delta^{1}_{b}\delta^{c}_{a})$ with $\alpha = 0$
- g- & f-potentials depend only on difference between f-anisotropy and g-anisotropy
- $f = c^2 g$ solution is an attractor
- massive GW → shear density ~ $1/a^3$ → may remain until now → observable signature?

Soda "Inflation in bimetric gravity"

- If m < H → sheer may slow roll → cosmic no-hair violated? Higuchi bound as hair censorship?
- Small anisotropy on top of homothetic dS massless mode & massive mode → graviton mass in FP action is identified
- Higuchi bound always satisfied by homothetic dS
- Slow-roll pot → almost homothetic dS attractor
- [Multi-metric gravity in metric formulation absence of BD ghost → loops forbidden]

Let’s start discussion now!