Recent Developments in Non-Relativistic String Theory

Eurostrings 2022, Lyon, April 26, 2022

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based on work:

2107.006542 (JHEP) (Bidussi,Harmark,Hartong,NO,Oling)

2011.02539 (JHEP) (Harmark,Hartong,NO,Oling)

1907.01663 (JHEP) (Harmark,Hartong,Menculini,NO,Oling)

& 1810.05560 (JHEP) (Harmark,Hartong,Menculini,NO,Yan)

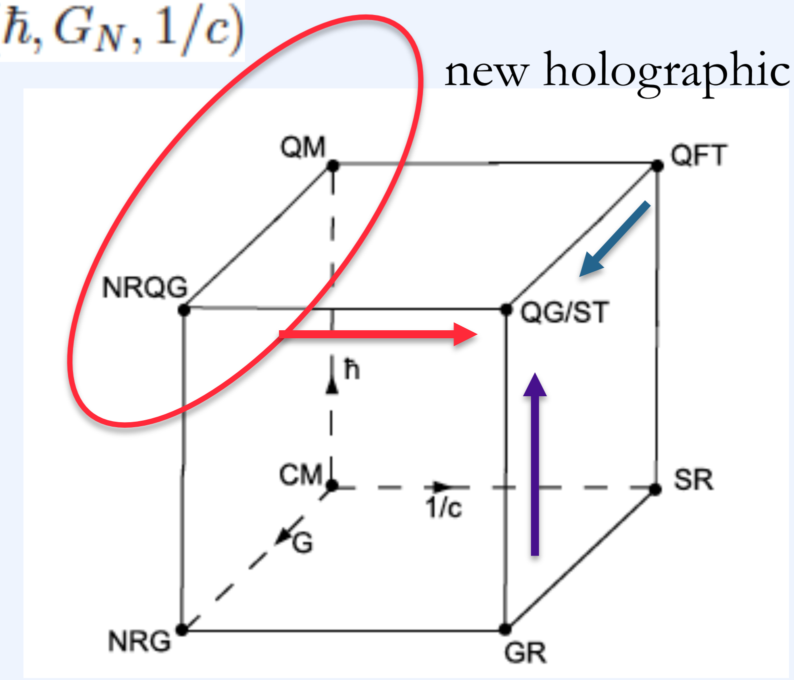
1705.03535 (PRD) (Harmark,Hartong,NO)

& work to appear with Bidussi,Harmark,Hartong,Oling

Non-relativistic physics and cube of physical theories

$(\hbar, G_N, 1/c)$

new holographic dualities ?



a third route towards
(relativistic) quantum gravity

how does this fit with
string theory/holography ?

already (classical) non-relativistic gravity (NRG)
is more than just Newtonian gravity

Non-Lorentzian geometries

recent progress in understanding non-relativistic corners of:
gravity, quantum field theory and string theory:

→ builds on improved understanding of non-Lorentzian geometries
= spacetimes with local symmetries other than Lorentz

NL geometries appear in:

- bdry geometries in non-AdS holography (e.g. Lifshitz flat space)
- covariant formulations of PN approximation in GR
- covariant formulations of non-Lorentzian fluids and CMT systems (FQHE, fractons, ..)
- Horava–Lifshitz gravity, non-relativistic versions of CS, JT
- cosmology, black hole horizons (Carroll)
- double field theory
- **non-relativistic corners of String Theory**
- **near-BPS limits of string theory on AdS5 × S5**

Non-perturbative string theory

complete understanding of non-perturbative regime is still lacking despite much progress made in last many decades:

- non-perturbative dualities

- Matrix theory:
  infinite boost limit of ST on spacelike circle = DLCQ of ST

  can be viewed as ST on light-like circle → non-relativistic behavior

- NRST as a novel way to study corners of relativistic string theory

Why non-relativistic (NR) string theory ?

- perhaps simpler (UV complete) theory
- non-relativistic gravity via beta functions
- limit of AdS/CFT and novel sigma models
- certain NR strings contained in double field theory
- rich limit of string theory

→ what is the landscape of NR string theories ?
& non-Lorentzian holography (see discussion)

NR strings

NR strings on flat spacetime = Gomis-Ooguri string

Gomis,Ooguri(2000); Danielsson et al.(2000);

→ Newton-Cartan geometries when spacetime is curved

Andringa et al (2012), Harmark,Hartong,NO(2017); Bergshoeff,Gomis,Yan(2018);
Harmark,Hartong,Menculini,NO,Yan(2018); Gomis,Oh,Yan(2019);
Gallegos,Gursoy,Zinnato(2019), Harmark,Hartong,Menculini,NO,Oling(2019);
Bergshoeff,Gomis,Rosseel,Simsek,Yan(2019); Kluson (2018/19), …….
Yan (2021), Bergshoeff,,Lahnsteiner,,Romano,Rosseel,Simsek(2021);
Bidussi, Harmark,Hartong,NO,Oling(2021);

also:

- tensionless strings — e.g.Lindstrom,Sundborg,Theodoridis(1991) Bagchi,Gopakumar(2009) Bagchi,Banerjee,Parekh(2019)
- Galilean strings — Battle,Gomis,Not(2016))
- relation to double field theory — Ko,Melby-Thompson,Meyer,Park(2015) Morand,Park(2017);Berman,Blair,Otsuki(2019);Blair(2019)

NR strings (on flat spacetime)

Gomis,Ooguri(2000); Danielsson et al.(2000)

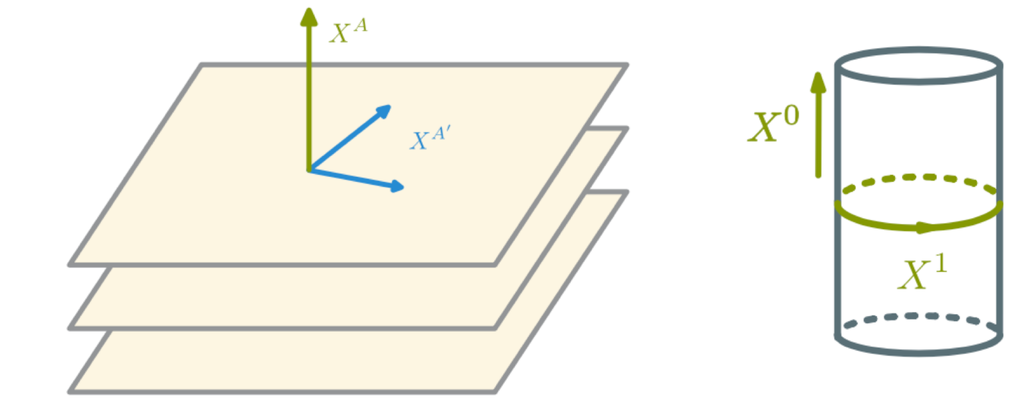
zero Regge slope limit of relativistic string theory in near-critical B-field

$$S = \frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \sqrt{h} \left(h^{\alpha\beta}\, \partial_\alpha X^{A'}\, \partial_\beta X_{A'} + \lambda \bar{\mathcal{D}} X + \bar{\lambda} \mathcal{D} \overline{X} \right),$$

in conformal gauge:
$$S = \frac{1}{4\pi\alpha'} \int_\Sigma d^2\sigma \left(\partial_\alpha X^{A'}\, \partial^\alpha X_{A'} + \lambda \bar{\partial} X + \bar{\lambda} \partial \overline{X} \right),$$

- Galilean invariant dispersion relation
- no massless physical states
- low-energy effective theory described by Newton-like gravity
- all asymptotic states carry non-zero winding along (compact) X_1
- space-time S-matrix with NR symmetry

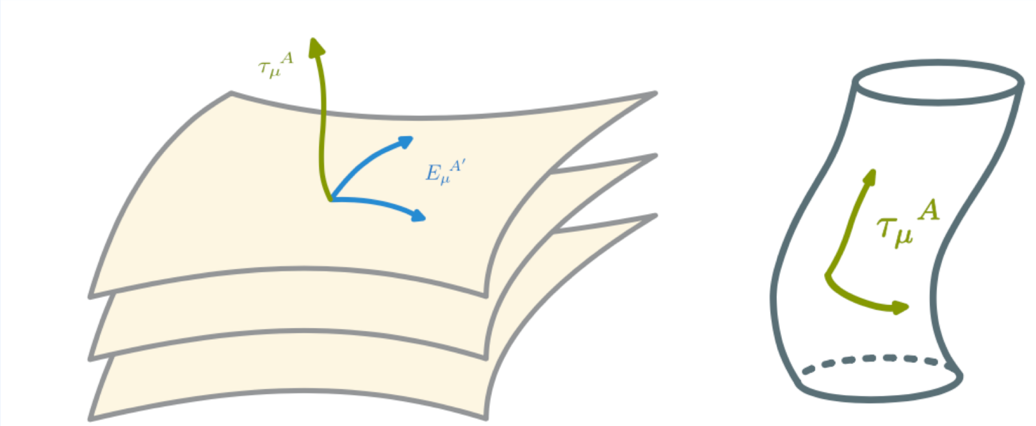
Gomis/Ooguri NR string lives in flat space



figures from
review on NRST
Gerben Oling & Ziqi Yan
(2202.12698)

Main part of talk:

Q: what is the general target space probed by NR strings ?



Main result

→ find formulation in which geometry contains a 2-form field that couples to tension current and transforming under string Galilei boosts

i.e. 2-form is intrinsic part of the geometry
(in parallel with NR particle and its coupling to Newton-Cartan geometry)

- follows from both null reduction & $c \to$ infinity limit

- geometry arises from gauging novel algebra:
  F-string Galilei algebra
  = Inonu-Wigner contraction of
  Poincare algebra + syms underlying Kalb-Ramond field

Outline

- intro to Newton-Cartan geometry for particles: null reduction and c → infinity limit

- Torsional string Newton-Cartan geometry (TSNC) from c → infinity limit
  - preliminaries: KR B-field from string Poincare
  - NR string action with TSNC target space/symmetries
  - Remarks: null reduction; limits vs. expansions; beta-fns

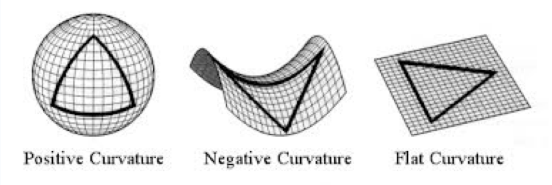
- NR world-sheet models from limits of NR strings & limits of AdS/CFT

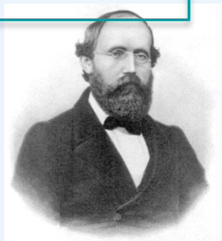
- Outlook & discussion

Space-Time symmetries and Geometry

local symmetries of space and time ←→ geometry of space and time

Einstein: Lorentz ←→ (pseudo-)Riemannian geometry





Cartan: Galilean ←→ Newton-Cartan geometry

[Eisenhart,Trautman,Dautcourt,Kuenzle,Duval,Burdet,Perrin,Gibbons,Horvathy,Julia,Nicolai,…] ..

- geometrize Poisson equation of Newtonian gravity
  falling observers see Galilean laws of physics

TNC geometry from null reduction

Lorentzian metric with null isometry

$$ds^2 = g_{MN} dX^M dX^N = 2\tau_\mu dx^\mu (du - m_\nu dx^\nu) + h_{\mu\nu} dx^\mu dx^\nu \,,$$

$$\tau_\mu h^{\mu\nu} = 0$$

torsional Newton–Cartan (TNC) geometry: τ_μ , $h_{\mu\nu}$, m_μ ,

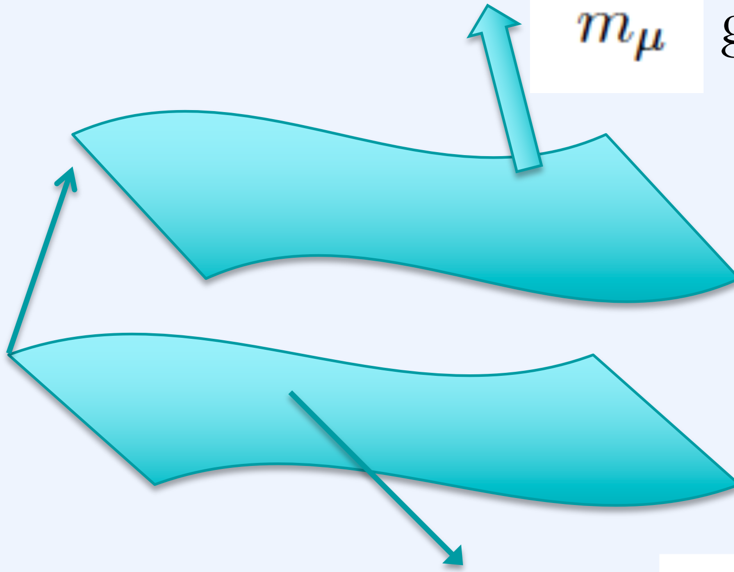
local syms:

$$\delta\tau_\mu = \mathcal{L}_\xi \tau_\mu \,, \quad \delta h_{\mu\nu} = \mathcal{L}_\xi h_{\mu\nu} + \lambda_\mu \tau_\nu + \lambda_\nu \tau_\mu \,,$$
$$\delta m_\mu = \mathcal{L}_\xi m_\mu + \lambda_\mu + \partial_\mu \sigma \,,$$

λ_μ Galilean (Milne) boosts

σ U(1) (mass) parameter

torsional Newton-Cartan geometry



m_μ gauge field (of mass generator)

time τ_μ

space $h_{\mu\nu}$

$\nabla_\mu \tau_\nu = 0$

gives connection with intrinsic torsion $\sim d\tau$

NC = no torsion $\rightarrow$ $d\tau = 0$ absolute time

TTNC = twistless torsion $\rightarrow$ $\tau \wedge d\tau = 0$ preferred foliation equal time slices

TNC no condition on τ_μ

Christensen,Hartong,NO,Rollier(2013)

TNC geometry as background geometry for NRFTs

putting relativistic field theory on a curved spacetime

$$\delta S_{\text{rel.matter}} \sim \int d^4x \; T_{\mu\nu} \; \delta g^{\mu\nu}$$

- non-relativistic FT naturally couples to torsional Newton-Cartan:

$$\delta S_{\text{non-rel matter}} \sim \int d^3x [E^\mu \delta\tau_\mu + S^{\mu\nu}\delta h_{\mu\nu} + T^\mu \delta m_\mu]$$

energy current — spatial stress & momentum current — mass current

see e.g. Son (2013),Hartong,Kiritsis,NO(2014),Jensen(2014)

Warmup: Non-Relativistic particle from null reduction

null-reduction of relativistic particle $S = \int \frac{1}{2e} g_{MN} \dot{X}^M \dot{X}^N d\lambda =$

→ reduce on target space with null Killing vector :

probe mass is conserved momentum in null direction: $p_u = m$

$$\boxed{S = \frac{m}{2} \int \frac{h_{\mu\nu} \dot{X}^\mu \dot{X}^\nu}{\tau_\rho \dot{X}^\rho} d\lambda - m \int m_\mu \dot{X}^\mu d\lambda}$$

[Kuchar], [Bergshoeff et al]

kinetic term

potential term: coupling to m_μ

m_0 ~ Newtonian potential

$$T^\mu = m \int d\tau \, \partial_\tau X^\mu \delta(x - X(\tau))$$

mass current

- action has TNC local target space symmetries

Other properties

- geodesic equation on flat NC space with:

$$m_t = \Phi_{\mathrm{Newt}}$$

→ Newton's law

- TNC geometry can also be obtained by gauging Bargmann algebra

Andringa,Bergshoeff,Gomis,de Roo (2012)

$$[G_a, P_b] = -\delta_{ab} N \quad , \qquad [G_a, H] = -P_a$$

& rotations

mass generator

(just as pseudo-Riemannian geometry follows from gauging Poincare)

NR particle from limit of extremal particle

action of charged relativistic particle:

$$S = -mc\int\sqrt{-g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu}d\lambda + q\int A_\mu\dot{x}^\mu d\lambda$$

- time-space split in metric: $g_{\mu\nu} = -c^2 T_\mu T_\nu + h_{\mu\nu}$

expand for large c:

$$S = -mc^2\int\left[T_\mu - \frac{q}{mc^2}A_\mu\right]\dot{x}^\mu d\lambda + \frac{m}{2}\int\frac{h_{\mu\nu}\dot{x}^\mu\dot{x}^\nu}{T_\rho\dot{x}^\rho}d\lambda + \mathcal{O}(c^{-2})$$

NR particle from limit of extremal particle

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extremal particle

$$q = mc^2.$$

divergent term. cancels with:

$$T_\mu = \tau_\mu + \frac{1}{2c^2}m_\mu\,,$$

$$A_\mu = \tau_\mu - \frac{1}{2c^2}m_\mu\,,$$

algebra level:

IW contraction

$$H = cP_0 + Q\quad,\qquad N = \frac{1}{2c^2}(cP_0 - Q)$$

energy

mass

Mimic the procedure for strings

fundamental strings are extremally charged under B-field
(tension = charge)

what is the analogue of Poincare x U(1)
for strings ?

→ understand the spacetime symmetry underlying
the Kalb-Ramond B-field

Kalb-Ramond B-field from string Poincare

metric and B-field symmetries

$$\bar{\delta} g_{\mu\nu} = \mathcal{L}_\xi g_{\mu\nu} \quad , \qquad \bar{\delta} B_{\mu\nu} = \mathcal{L}_\xi B_{\mu\nu} + 2\partial_{[\mu}\lambda_{\nu]}.$$

→ can be obtained from string extension of Poincare:
(with extra set of translational generators (cf. double field theory)

$$\begin{aligned}
[M_{\underline{ab}}, M_{\underline{cd}}] &= \eta_{\underline{ac}} M_{\underline{bd}} - \eta_{\underline{bc}} M_{\underline{ad}} + \eta_{\underline{bd}} M_{\underline{ac}} - \eta_{\underline{ad}} M_{\underline{bc}}, \\
[M_{\underline{ab}}, P_{\underline{c}}] &= \eta_{\underline{ac}} P_{\underline{b}} - \eta_{\underline{bc}} P_{\underline{a}}, \\
[M_{\underline{ab}}, Q_{\underline{c}}] &= \eta_{\underline{ac}} Q_{\underline{b}} - \eta_{\underline{bc}} Q_{\underline{a}},
\end{aligned}$$

Lie algebra valued connection:

$$\mathcal{A}_\mu = e_\mu^{\underline{a}} P_{\underline{a}} + \frac{1}{2}\omega_\mu{}^{\underline{ab}} M_{\underline{ab}} + \pi_\mu^{\underline{a}} Q_{\underline{a}};$$

$$\boxed{g_{\mu\nu} = \eta_{\underline{ab}}\, e_\mu^{\underline{a}} e_\nu^{\underline{b}}. \qquad B_{\mu\nu} = \eta_{\underline{ab}}\, e_{[\mu}^{\underline{a}} \pi_{\nu]}^{\underline{b}}.}$$

(see e.g. Ne'eman,Regge/D'Auria,Fre)

NR string action from c → infinity limit

$$S = S_{\rm NG} + S_{\rm WZ},$$

$$S_{\rm NG} = -cT_{\rm F}\int d^2\sigma\sqrt{-\det g_{\alpha\beta}}, \qquad S_{\rm WZ} = -c\frac{T_{\rm F}}{2}\int d^2\sigma B_{\alpha\beta}\epsilon^{\alpha\beta}.$$

- use vielbein decomposition of the NSNS target space:

$$g_{\mu\nu} = \eta_{\underline{ab}}e_{\mu}^{\underline{a}}e_{\nu}^{\underline{b}} \quad , \qquad B_{\mu\nu} = \eta_{\underline{ab}}e_{[\mu}^{\underline{a}}\pi_{\nu]}^{\underline{b}},$$

- split tangent space into
A=0,1: longitudinal
a=2,..d-1: transverse

$$e_{\mu}^{\underline{a}} = (cE_{\mu}^{A}, e_{\mu}^{a}) \quad , \qquad \pi_{\mu}^{\underline{a}} = (c\Pi_{\mu}^{A}, \pi_{\mu}^{a}),$$

- reparametrize longitudinal vielbeins:

$$E_{\mu}^{A} = \tau_{\mu}^{A} + \frac{1}{2c^2}\pi_{\mu}^{B}\epsilon_{B}{}^{A},$$

$$\Pi_{\mu}^{A} = \epsilon^{A}{}_{B}\tau_{\mu}^{B} + \frac{1}{2c^2}\pi_{\mu}^{A},$$

divergent term in action cancels since F-string is extremal

NRST action on TSNC target space

after limit:

kinetic potential

$$S_{\rm NR} = -\frac{T}{2}\int d^2\sigma\left[\sqrt{-\tau}\,\eta^{AB}\tau_A^\alpha\tau_B^\beta h_{\alpha\beta} + \epsilon^{\alpha\beta}m_{\alpha\beta}\right],$$

$$h_{\mu\nu} = e_\alpha^a e_\beta^b \delta_{ab}$$

$$m_{\mu\nu} = \eta_{AB}\tau_{[\mu}^A\pi_{\nu]}^B + \delta_{ab}e_{[\mu}^a\pi_{\nu]}^b.$$

$$\boxed{\text{torsional string Newton–Cartan geometry}: \quad \tau_\mu^A, \quad h_{\mu\nu}, \quad m_{\mu\nu}.}$$

$m_{\mu\nu}$. couples to worldsheet tension current

$$J_{\rm T}^{\mu\nu} = T\int d^2\sigma\,\epsilon^{\alpha\beta}\partial_\alpha X^\mu\partial_\beta X^\nu\delta(x - X(\sigma^\alpha)),$$

conserved charges: $M^\mu = \int d\sigma J^{0\mu}.$

gravitational mass: $M^v = 2\pi TR.$ (for compact longitudinal direction v)

m_{0v} = gravitational potential

- weak equivalence principle for NR string

Symmetries of the action

- gauge: $$\bar{\delta} m_{\mu\nu} = 2\partial_{[\mu}\lambda_{\nu]}\,.$$

- string Galilean boosts:

$$\bar{\delta} h_{\mu\nu} = -\lambda_{Ab}\left(\tau_\mu^{\ A} e_\nu^{\ b} + \tau_\nu^{\ A} e_\mu^{\ b}\right) \quad , \qquad \bar{\delta} m_{\mu\nu} = -2\epsilon_{AB}\lambda^B{}_c \tau_{[\mu}^{\ A} e_{\nu]}^{\ c}\,.$$

→ string analogue of the symmetries of NR particle coupling to Newton-Cartan

Question: what is underlying NR symmetry algebra ?

F-string Galilean (FSG) algebra

- decompose string Poincare algebra:

$\underline{a} = (A, a)$

longitudinal, transverse

$$P_A, \quad Q_A, \quad P_a, \quad Q_a, \quad J_{AB} = \epsilon_{AB} J = M_{AB}, \quad J_{ab} = M_{ab}, \quad c\, G_{Ab} = M_{Ab}.$$

$$H_A = c(P_A + Q_B \epsilon^B{}_A) \quad , \quad N_A = \frac{1}{2c}(\epsilon_A{}^B P_B + Q_A)$$

(basis transformation)

after IW contraction (c → infinity):

$$[G_{Ab}, H_C] = \eta_{AC} P_b + \epsilon_{AC} Q_b,$$
$$[G_{Ab}, P_c] = -\delta_{bc} \epsilon_A{}^B N_B,$$
$$[G_{Ab}, Q_c] = -\delta_{bc} N_A,$$

& further commutators involving SO(1,1) x SO(d-2) rotations

- symmetry trafos follow from FSG-valued connection:

$$\mathcal{A}_\mu = \tau_\mu^A H_A + e_\mu^a P_a + \omega_\mu J + \frac{1}{2} \omega_\mu{}^{ab} J_{ab} + \omega_\mu{}^{Ab} G_{Ab} + \pi_\mu^A Z_A + \pi_\mu^a Q_a,$$

Non-relativistic strings from null reduction

- start from Polyakov action (including NSNS) and reduce along null isometry

- implement conservation of string momentum along null isometry using Lagrange multipliers

- go to dual formulation that exchanges the (fixed) momentum along null direction for fixed winding of string along compact dual direction

→ action of non-relativistic strings moving in torsional string Newton-Cartan target space

& FSG symmetries can also be derived

Limit vs. 1/c expansion

- limit geometry: type I (cancellation of divergent term)

- geometry from expansion: type II
 (each term in the action generates more gauge fields)

type II studied for:

- NR particle (and coupling to non-relativistic gravity from expanding GR) van den Bleeken (2018), Hansen,Hartong,NO (2019, 2020)
- NR string Hartong,Have (2021)

spectrum:
(compact long. direction)
center of mass velocity << c

$$E = \frac{c^2 w R_{\text{eff}}}{\alpha'_{\text{eff}}} + \frac{N_{(0)} + \tilde{N}_{(0)}}{w R_{\text{eff}}} + \frac{\alpha'_{\text{eff}}}{2 w R_{\text{eff}}} p_{(0)}^2 + \mathcal{O}(c^{-2})$$

Beta-functions

beta functions/effective spacetime actions for the NR string obtained in various different formulations/using different methods

Gomis,Oh,Yan(2019)
Bergshoeff,Gomis,Rosseel,Simsek,Yan(2019)
Yan,Yu(2019)
Bergshoeff et al (2021), Yan (2021)
Gallegos,Gursoy,Zinnato(2019)
Gallegos,Gursoy,Verma,Zinnato(2020

→ describe the dynamics of (versions of) non-relativistic gravity

see also Hansen,Hartong,NO(2019,2020)

Applications to AdS/CFT

can take a further world-sheet NR limit

-→ new class of sigma models with NR target spacetime
that are also non-relativistic on worldsheet:

exhibits 2D GCA (classically)

$$[L_n\,, L_m] = (n-m)L_{n+m}\,, \qquad [L_n\,, M_m] = (n-m)M_{n+m}\,.$$

- NR WS theories directly related to
  near-BPS limits of AdS/CFT (spin-matrix theory (SMT))

simplest example: LL model appearing from continuum limit of Heisenberg spin chains

Spin Matrix Theory (intermezzo)

Harmark,Orselli(1409)

- SMT limits of AdS/CFT obtained by zooming in to unitarity bounds of N=4 SYM on RxS3:

$$\boxed{\lambda \to 0 \quad , \quad \frac{E - Q}{\lambda} = \text{fixed}}$$

Q = linear sum of Cartan charges of PSU(2,2|4)

→ N=4 SYM simplifies and becomes QM theory

- reduces to nearest-neighbor spin chains in planar N limit

Spin Matrix Theory (intermezzo)

- SMT limits of AdS/CFT obtained by zooming in to unitarity bounds of N=4 SYM on RxS3:

$$\lambda \to 0 \quad , \quad \frac{E-Q}{\lambda} = \text{fixed}$$

Q = linear sum of Cartan charges of PSU(2,2|4)

→ N=4 SYM simplifies and becomes QM theory

- reduces to nearest-neighbor spin chains in planar N limit

- low energy excitations of spin chains = magnons

$$E - Q = \sqrt{1 + \frac{\lambda}{\pi^2}\sin^2\frac{p}{2}} - 1$$

[Beisert(0511)]

becomes in SMT limt:

$$H - Q = \frac{g}{2\pi^2}\sin^2\frac{p}{2}$$

non-relativistic

- semi-classical limits of spin chains become sigma models:

Kruczenski (0311)

e.g. Landau-Lifshitz model for SU(2) sector

$$\mathcal{L}_{\rm LL} = \frac{J}{4\pi}\left[\sin\theta\dot{\phi} - \frac{1}{4}\left((\theta')^2 + \cos^2\theta(\phi')^2\right)\right]$$

Stringy side of SMT gives NR sigma models

- using AdS/CFT dictionary: SMT (near-BPS) limit can be formulated as limit of type IIB string theory on AdS5xS5

  - correspond to non-relativistic world-sheet string theories !

→ LL model (and generalizations for other near-BPS sectors) is example of our novel class of non-relativistic worldsheet STs with a Newton-Cartan type target spacetime

- one of target space dimensions = position along the spin chain (zero momentum because of cyclicity of trace)

- strongly suggests: bulk description of SMT is a type of NR gravity

  - new class of flat-fluxed backgrounds obtained recently: analogue of flat Minkowski space using Penrose type limits → natural starting point to quantize the theory

Outlook (non-relativistic string theory)

- open strings and branes:

  - non-relativistic open string sector and DBI actions

    Gomis,Yan,Yu (2020)

  - connection to NR D/M-branes

    Kluson/Blair,Gallegos,Zinnato (2021)/Ebert,Sun,Yan(2021)

  - strings/branes as background solutions

    Bergshoeff,Lahnsteiner,Romano,Rosseel(2022)

  - generalize procedure to non-relativistic limit of extremal p-branes

    TSNC analogue for p-branes (incl. D/M)

    Bidussi,Harmark,Hartong,NO,Oling (in progress

- SUSY generalization of stringy Poincare (include RR fields)

  NR limit & relations to DFT/exceptional FT

  - non-perturbative dualities in NR string theory

- connection to integrable models

  Gomis,Gomis,Kamimura(2005)/Roychowdhury(2019/
  Fontanella,NietoGarcia,Torielli(2021),Fontanello,van Tongeren(2022)

Outlook (non-relativistic worldsheet models)

- further study (quantization) of NR world-sheet theories
  - role of GCA

- Hamiltonian analysis (including for non-relativistic world-sheet models)

  Kluson (2021), Bidussi,Harmark,Hartong,NO,Oling (to appear)

- obtain beta functions for NR worldsheet models

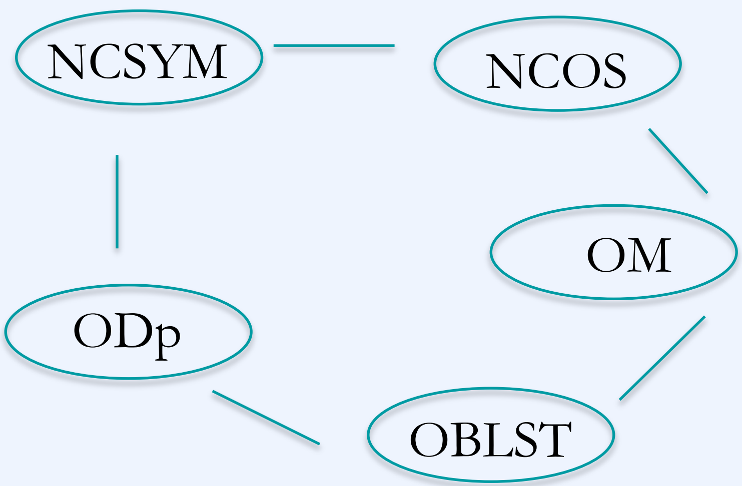
- connection with explicit construction of SMT using classical reduction of N=4 SYM & suitable quantization method

  Harmark,Wintergerst (2019),Baiguera,Harmark,Wintergerst(2020)
  Baiguera,Harmark,Lei,Wintergerst (2020)

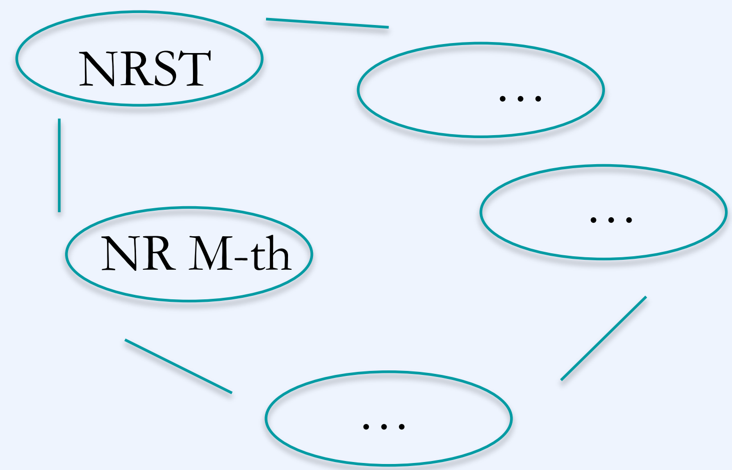
- Carrollian (small speed of light) gravity and strings….

Duality web of `non-Lorentzian' string theories?

web of decoupled non-gravitational theories
(`open string sector')



web of non-Lorentzian gravitational string theories
(`closed string sector'_)



back to 2000s…

- self-contained corners of ST w. own geometry
- new window on non-perturbative effects ?

Non-AdS holography & NR holography

bulk: Lorentzian gravity (GR) | non-Lorentzian gravity

AdS

non-AdS
(e.g. Lifshitz)

NC type gravities

boundary: CFT | NonLor-FT with scaling | NonLor-FT

non-Lorentzian holography

Routes towards non-Lorentzian holography

I. branes

- Dp-branes as probes of TSNC geometry
- Dp-branes as backgrounds solutions of NR (super) gravity actions

Can one find decoupling limits giving rise to avatars of AdS/CFT ?

II. limits of AdS/CFT

- SMT-limit dual to NR world-sheet theories
- study quantization
- Hamiltonian analysis
- beta-functions

→ tractable limit of AdS/CFT, finite N,
simpler moduli space/genus expansion ?