LIO 2024

UV-Completion Beyond Asymptotic Safety: Vainshtein Screening, UV/IR Mixing & Electroweak Naturalness

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Based on arXiv:2307.11741 & arXiv:2311.08311

CNRS NUCLÉAIRE & PARTICULES

Lyon 1

iP2i LES 2 INFINIS LYON

Summary:

→ 1. UV/IR Mixing

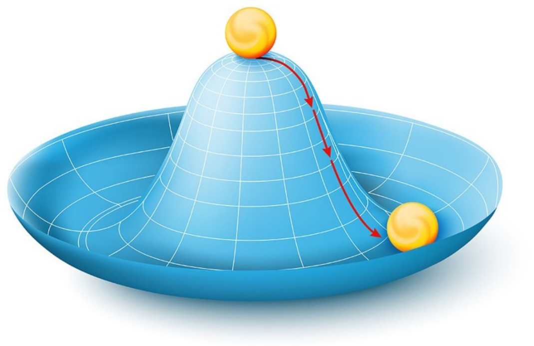
2. Fuzziness

3. Conclusion & Outlook

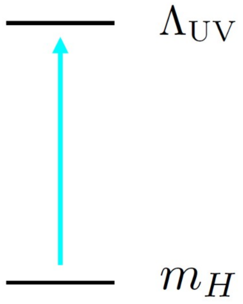
1. UV/IR Mixing → Beating Electroweak Naturalness

Higgs Mechanism

EWSB → light scalar = Higgs boson



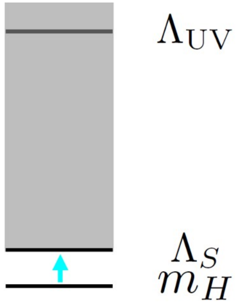
Wilsonian EFT → EW Naturalness:



$$\left(m_H^{\rm nat}\right)^2 \sim \frac{y_t^2}{16\pi^2}\Lambda_{UV}^2$$

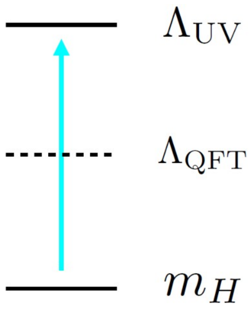
Gauge Hierarchy: Λ_{EW} ~ 100 GeV << Λ_P ~ 10^{18} GeV

$m_H^{\rm nat} \gg m_H^{\rm exp}$ —New Symmetry?→



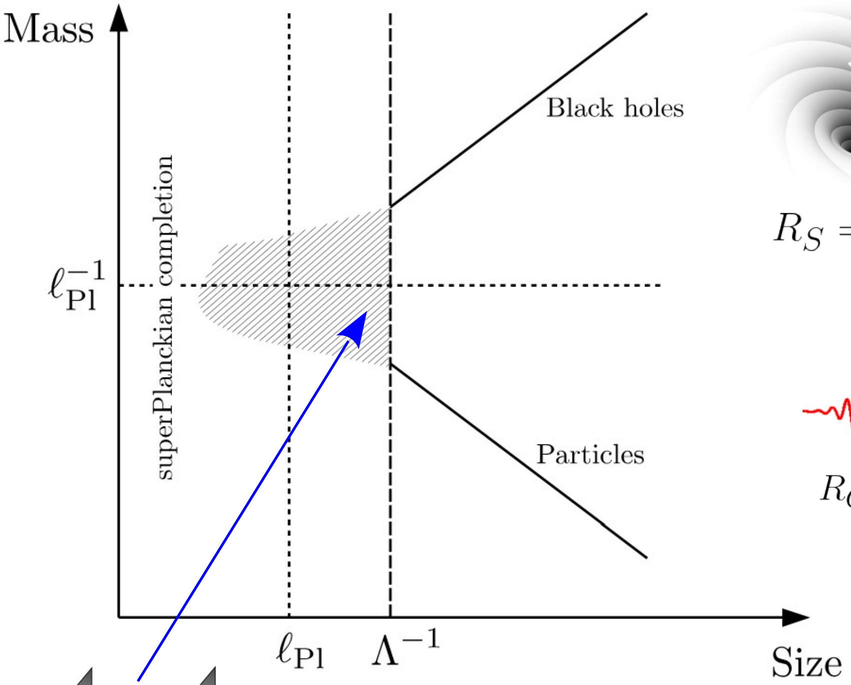
→ Bunch of new particles @ Λ_S ~ EW/TeV Scale (LHC)

→ Little Hierarchy Problem!

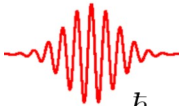


Radical: Breakdown of (local) QFT
(e.g. UV/IR mixing, Gravity)

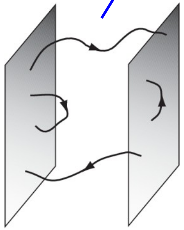
1. UV/IR Mixing → Asymptotic Darkness in Gravity (1/3)



$R_S = 2G_N M$



$R_C = \frac{\hbar}{M}$



String Theory?
or String-like bound states?

Einstein Gravity → Self-Completion

Minimal Length Scale → Weak Nonlocality

Deep-UV = Deep-IR

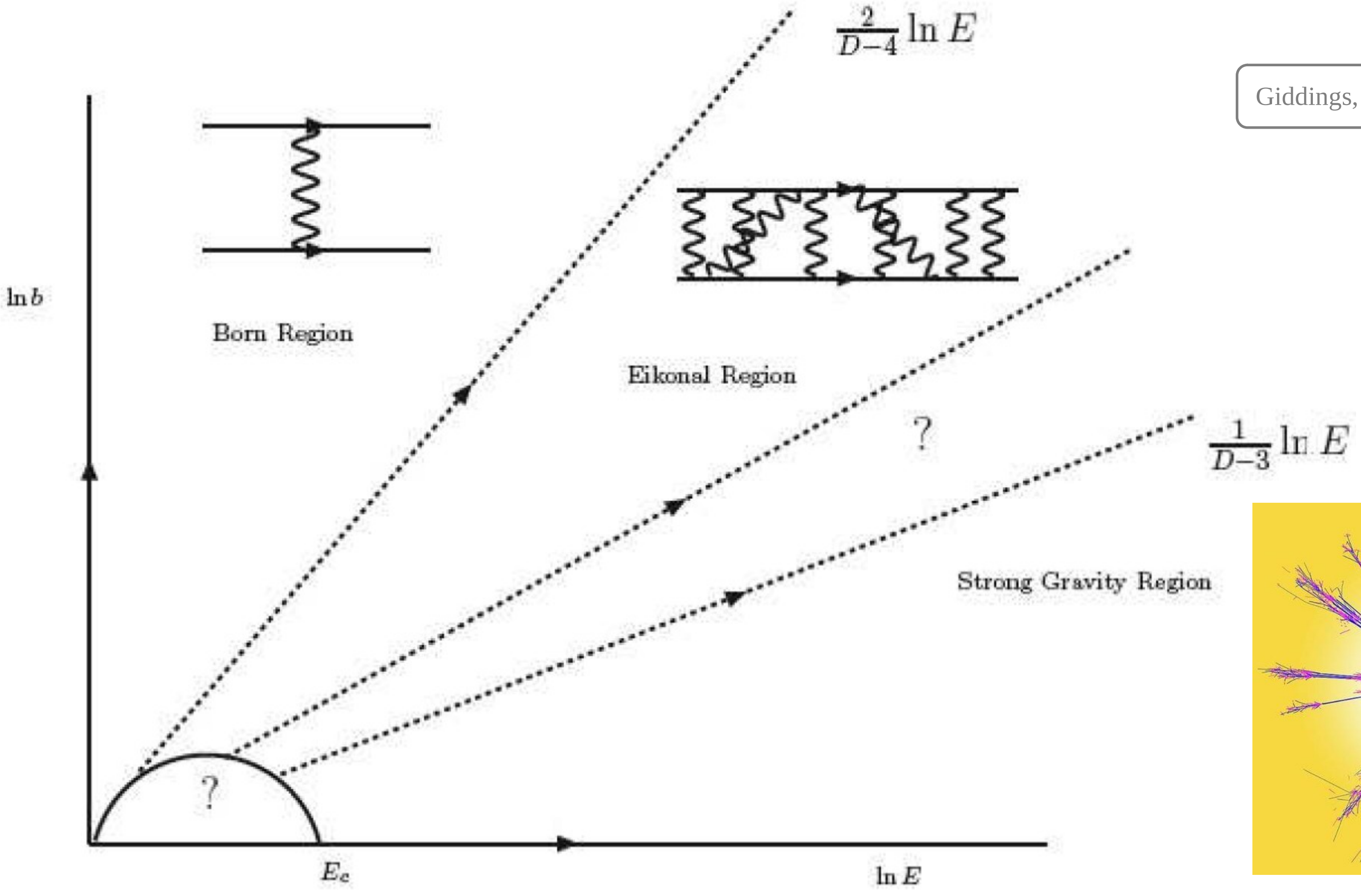
Black Holes ~ BE Condensates of Gravitons

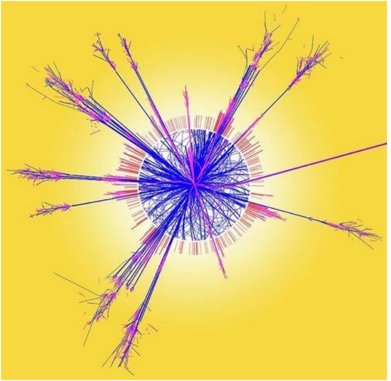
Quantum Field Theory
→ Locality

Aharony, Banks, arXiv:hep-th/9812237
Dvali, Gomez, arXiv:1005.3497
Dvali, Gomez, Kehagias, arXiv:1103.5963
Dvali, Gomez, arXiv:1207.4059
Dvali, Gomez, Isermann, Lüst, Stieberger, arXiv:1409.7405
Dvali, Gomez, arXiv:1312.4795

1. UV/IR Mixing → Asymptotic Darkness in Gravity (2/3)

Giddings, Porto, arXiv:0908.0004





1. UV/IR Mixing → Asymptotic Darkness in Gravity (3/3)

Maybe, Gravity is not the Problem…

Perhaps, Gravity is the Key!

1. UV/IR Mixing → Species Scale & Unitarity

Dvali-Gomez-Lüst Species Conjecture:

Self-completion of gravity → $N_{\text{grav}} \geq N_{\text{mat}}$

Energy

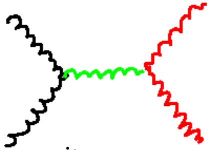
Black Holes

$M_{\text{species}} = N_{\text{species}}^{-1/2}\, M_P$

Particles

Gravitational Species N_{grav}

$\sum$ grav $\sum$ spec



Energy

Black Holes

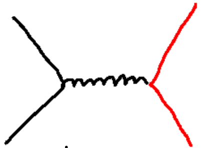
$M_{\text{BH}} = N_{\text{species}}^{1/2}\, M_P$

$M_{\text{unitarity}} = N_{\text{species}}^{-1/4}\, M_P$

Particles

Matter Species N_{mat}

$\sum$ spec



In the SM + GR:

$N_{\text{grav}} \sim 1 \ll N_{\text{mat}} \sim 100$

Dvali, Gomez, Lüst, arXiv:1206.2365

1. UV/IR Mixing → Gravitizing the Standard Model

An Exotic Program:

Matter Species (IR) → Gravitational Species (UV)

Summary:

1. UV/IR Mixing

2. Fuzziness

3. Conclusion & Outlook

1. Fuzziness → Exorcizing Higher-Derivative QFT's

∂^4-Scalar QFT → Polynomial in ∂ → Local

$$S = \int d^4x \left[\frac{1}{2}\phi(\Box - \alpha\Box^2)\phi - \frac{1}{2}m^2\phi^2\right]$$

Propagator: UV ~ $1/k^4$ → Better UV behavior!

$$m = 0 \rightarrow G(k^2) = -\frac{1}{k^2(1+\alpha k^2)} = -\frac{1}{k^2} + \frac{\alpha}{1+\alpha k^2}$$

Poles: $k^2 = 0$ & $k^2 = -1/\alpha < 0$

Particle ✓

Ghost ✗

~~Stability~~ ($-i\varepsilon$)
or
~~Unitarity~~ ($+i\varepsilon$)

Woodard, arXiv:1506.02210
Platania, arXiv:2206.04072
Kubo, Kugo, arXiv:2308.09006

Prototype → ∂^∞-Scalar QFT → Weakly Nonlocal!

$$S = \int d^4x \left[\frac{1}{2}\phi(x)\gamma(\Box)\phi(x) - V(\phi)\right], \quad \gamma(\Box) = \sum_{n=0}^{\infty} c_n \Box^n$$

Ghost-free form factor → UV finiteness!

$$\gamma(\Box) = (\Box - m^2)e^{-l_*^2\Box} \Rightarrow G(k^2) = -\frac{e^{-l_*^2k^2}}{k^2+m^2}$$

Scalar Naturalness: $\lambda\,\phi^4$

$$\delta m^2 = \frac{\lambda}{32\pi^2}\Lambda^2, \quad \Lambda = 1/l_*$$

↓

Stabilization of EWSB?

↓

TeV Fuzziness! → LHC?

Pole: $k^2 = -m^2$

Particle ✓

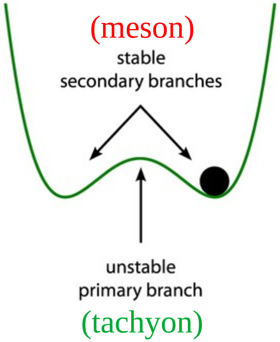
Biswas, Okada, arXiv:1407.3331
Buoninfante, Lambiase, Mazumdar, arXiv:1805.03559

2. Fuzziness → The Ghosts Strikes Back

Tachyon Condensation $\phi^4 \to \mu^2 > 0$

→ Z_2 spontaneous symmetry breaking

$$\mathcal{L} = \frac{1}{2}\phi\left(\Box + \mu^2\right)e^{-l_*^2\Box}\phi - \frac{\lambda}{4!}\phi^4$$



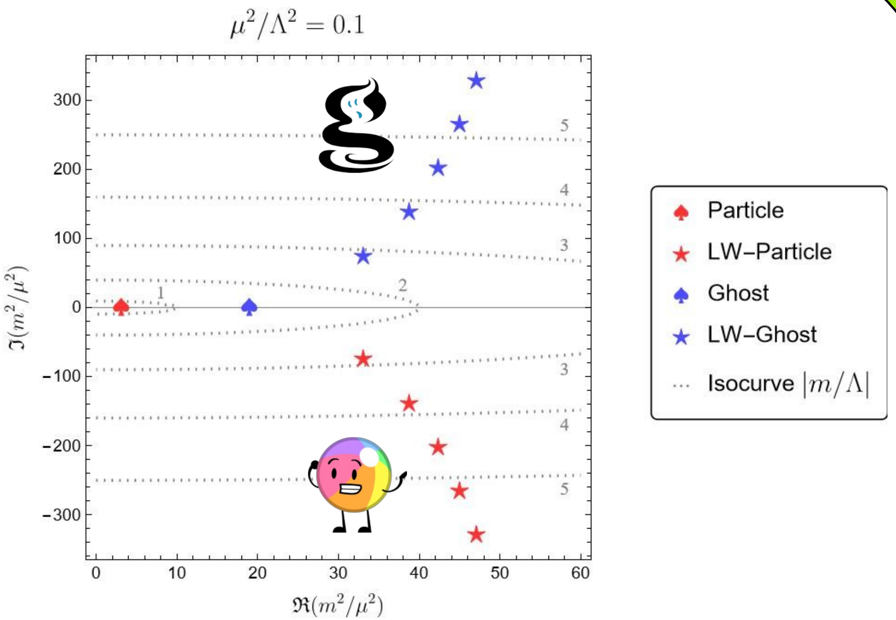
$\phi(x) = v + \sigma(x)$

nonlocal mass   local mass

no ghost-free factorization!

$$G(k^2) = -\frac{e^{-l_*^2 k^2}}{k^2 + m^2}$$

∞ tower
of ghost-lilke excitations!



→ Problem also for Higgs mechanism!
(gauge sector haunted by ghost-like tower)

Hashi, Isono, Noumi, Shiu, Soler, arXiv:1805.02676
Nortier, arXiv:2307.11741

2. Fuzziness → Star-Product: A New Hope!

$\Phi(x)$ = field in a representation r of the gauge group

$\vartheta(z)$ = entire function on complex plane

$$\forall z \in \mathbb{C},\ e^{\vartheta_r(z)} = \sum_{n=0}^{+\infty} c_r^{(n)}\, z^n, \quad c_r^{(n)} \in \mathbb{R}$$

Non-covariant star-product (asterisk) of fields:

$$\Phi^\dagger(x) *_r \Phi(x) = \Phi^\dagger(x)\, e^{\vartheta_r\left(\overleftarrow{\partial_\mu}\, \eta_r^{\mu\nu}\, \overrightarrow{\partial_\nu}\right)}\, \Phi(x)\,, \qquad \eta_r^{\mu\nu} = \ell_r^2\, \eta^{\mu\nu}\,,$$
$$= \Phi^\dagger(x) \cdot \Phi(x) + c_r^{(1)} \ell_r^2\, \partial_\mu \Phi^\dagger(x) \cdot \partial^\mu \Phi(x)$$
$$+\, c_r^{(2)} \ell_r^4\, \partial_\mu \partial_\nu \Phi^\dagger(x) \cdot \partial^\mu \partial^\nu \Phi(x) + \mathcal{O}\left(\ell_r^6\right)$$

→ Linear & commutative but non-associative in general!

Important property: $v * \Phi(x) = v \cdot \Phi(x)$

Nortier, arXiv:2307.11741

Chattopadhyay, Nortier, arXiv:2311.08311

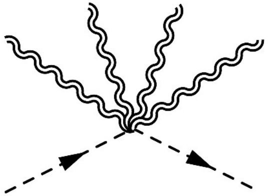
Covariant star-product of fields:

$$\Phi^\dagger(x) \star_r \Phi(x) = \Phi^\dagger(x)\, e^{\vartheta_r\left(\overleftarrow{\mathcal{D}_\mu}\, \eta_r^{\mu\nu}\, \overrightarrow{\mathcal{D}_\nu}\right)}\, \Phi(x)\,,$$
$$= \Phi^\dagger(x) \cdot \Phi(x) + c_r^{(1)} \ell_r^2 \left[\mathcal{D}_\mu \Phi(x)\right]^\dagger \cdot \mathcal{D}^\mu \Phi(x)$$
$$+\, c_r^{(2)} \ell_r^4 \left[\mathcal{D}_\mu \mathcal{D}_\nu \Phi(x)\right]^\dagger \cdot \mathcal{D}^\mu \mathcal{D}^\nu \Phi(x) + \mathcal{O}\left(\ell_r^6\right)\,,$$
$$= \Phi^\dagger(x) *_r \Phi(x) + \mathcal{O}\left(g \ell_r^2\, |\Phi|^2 A\right)$$

non-covariant star-product

covariant dressing = gauge cloud

$$v \star v = v^2 + \mathcal{O}\left(A^2\right)$$



2. Fuzziness → Ghost-Free Higgs Mechanism

Goal → Propagators ~
→ Ghost-free!

$$G_h(k) = -\frac{e^{-\vartheta_h\left(\frac{k^2}{\Lambda_h^2}\right)}}{k^2 + m_h^2}$$

$$G_A(k) = -\frac{e^{-\vartheta_0\left(\frac{k^2}{\Lambda_0^2}\right)}}{k^2 + m_A^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{m_A^2}\right)$$

$$\mathcal{L} = -\frac{1}{4}\,\mathcal{A}_{\mu\nu} *_0 \mathcal{A}^{\mu\nu} - (\mathcal{D}_\mu H^*) \star_h (\mathcal{D}^\mu H) + \mu^2\,|H|^2 - \lambda\,|H|^2 *_0 |H|^2$$

drop gauge cloud: $\star \mapsto *$

unitary gauge: $H(x) = \frac{1}{\sqrt{2}}\,[v + h(x)]$

$$\mathcal{L}_U \supset -\frac{1}{4}\,\mathcal{A}_{\mu\nu} *_0 \mathcal{A}^{\mu\nu} - \partial_\mu H *_h \partial^\mu H - g^2\,(H \cdot A_\mu) *_h (H \cdot A^\mu) + \mu^2\,|H|^2 - \lambda\,H^2 *_0 H^2$$

Ghost-free factorization

$$\Rightarrow \quad *_0 \equiv *_h \quad \Rightarrow \quad \ell_0 \equiv \ell_h \;\;\&\;\; \vartheta_0(z) \equiv \vartheta_h(z)$$

$$\mathcal{L}_U \supset -\frac{1}{4}\,\mathcal{A}_{\mu\nu} *_0 \mathcal{A}^{\mu\nu} - \frac{g^2 v^2}{2}\,A_\mu *_0 A^\mu - \frac{1}{2}\,\partial_\mu h *_0 \partial^\mu h - \lambda v^2\,h *_0 h - \lambda v\,h *_0 h^2 - \frac{\lambda}{4}\,h^2 *_0 h^2$$

Nortier, arXiv:2307.11741

Chattopadhyay, Nortier, arXiv:2311.08311

Generalization to Fuzzy Standard Model (FSM):

$$-\frac{1}{2}\,\mathrm{tr}\left[\mathcal{G}_{\mu\nu} \star_c \mathcal{G}^{\mu\nu}\right] - \frac{1}{2}\,\mathrm{tr}\left[\mathcal{W}_{\mu\nu} \star_w \mathcal{W}^{\mu\nu}\right] - \frac{1}{4}\,\mathcal{B}_{\mu\nu} *_w \mathcal{B}^{\mu\nu}$$

Yukawa couplings (N generations):

$$-\lambda_d^{ij}\left(\overline{Q}_L^i \cdot H\right) \star_q d_R^j - \lambda_u^{ij}\left(\overline{Q}_L^i \cdot \overline{H}\right) \star_q u_R^j - \lambda_e^{ij}\left(\overline{L}_L^i \cdot H\right) \star_\ell e_R^j + \mathrm{H.c.}$$

Linearity of star-product → Same flavor structure as SM!

2. Fuzziness → Vainshtein Screening & Naturalness

Pure Higgs Sector Toy Model: $2H \to 2H$

Hard scattering limit: $\vartheta(z) = -z$

$$s \to +\infty\,, \quad t \to -\infty\,, \quad s/t \text{ fixed}$$

$$A(s,t) \sim -\frac{16\lambda^2 v^2 e^{\ell_w^2 s}}{s}$$

→ Unitarity violation? E >> nonlocal scale

Field redefinition + Form factor expansion:

$$\alpha \ell_w^2 \; H^\dagger H \cdot \partial_\mu H^\dagger \partial^\mu H + \mathcal{O}\left(\ell_w^4\right)$$

→ Classicalizing operator! (Vainshtein screening)

→ Classicalons production (~ BH in gravity):

Vainshtein radius: $R_V \sim \sqrt{s}\,\ell_w^2$

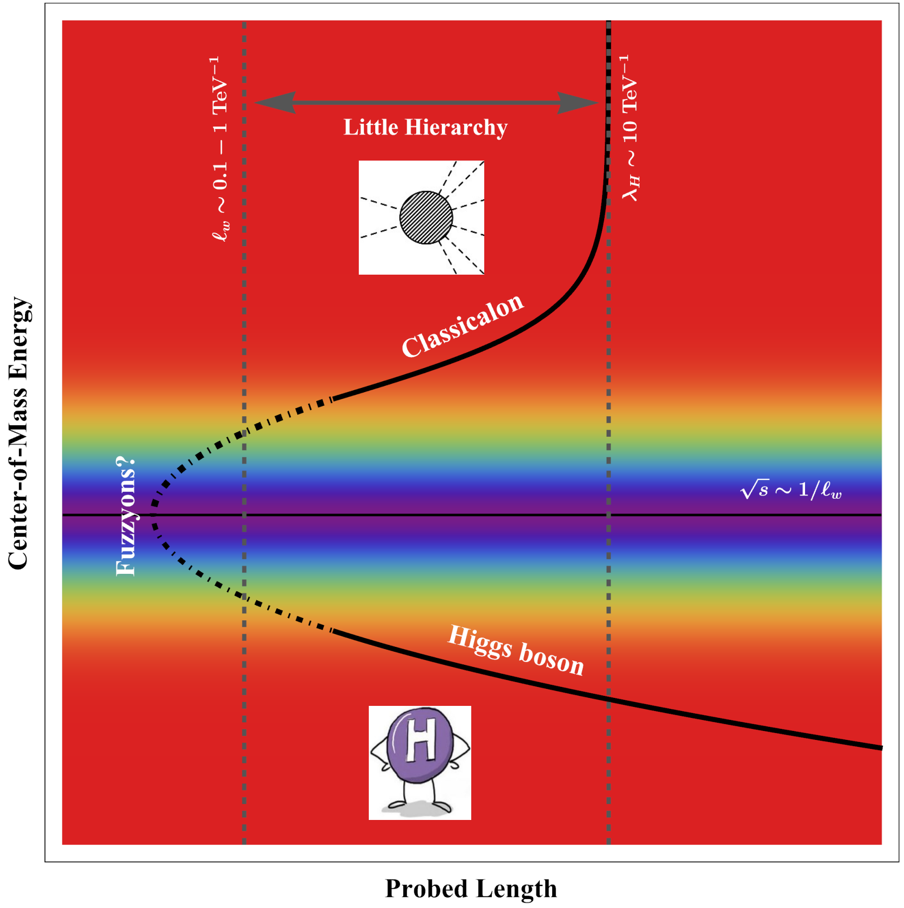
$$2H \to N \times H\,, \quad N \gg 1$$

Dvali, Giudice, Gomez, Kehagias, arXiv:1010.1415

Grojean, Gupta, arXiv:1110.5317

Chattopadhyay, Nortier, arXiv:2311.08311

UV/IR Mixing: Classicalization via Fuzziness



Summary:

1. UV/IR Mixing

2. Fuzziness

→ 3. Conclusion & Outlook

3. Conclusion & Outlook

Recap:

Self-Completion of Gravity → Asymptotic Darkness → Gravitizing the SM with Fuzziness

Fuzzy Interactions → Vainshtein Screening → Naturalness & Little Hierarchy!

Ghost-Free Condition → Issues with Tachyon Condensation! → New Star-Product & FSM

Other attempts:

Hashi, Isono, Noumi, Shiu, Soler, arXiv:1805.02676

Modesto, arXiv:2103.05536

Outlook:

→ Fuzzy Gauge & Yukawa Couplings → Vainshtein Screening?

→ Understanding of “Fuzzy Regime”, Quantum Corrections, etc

→ TeV Scale Phenomenology? → Classicalons & Fuzzyons?

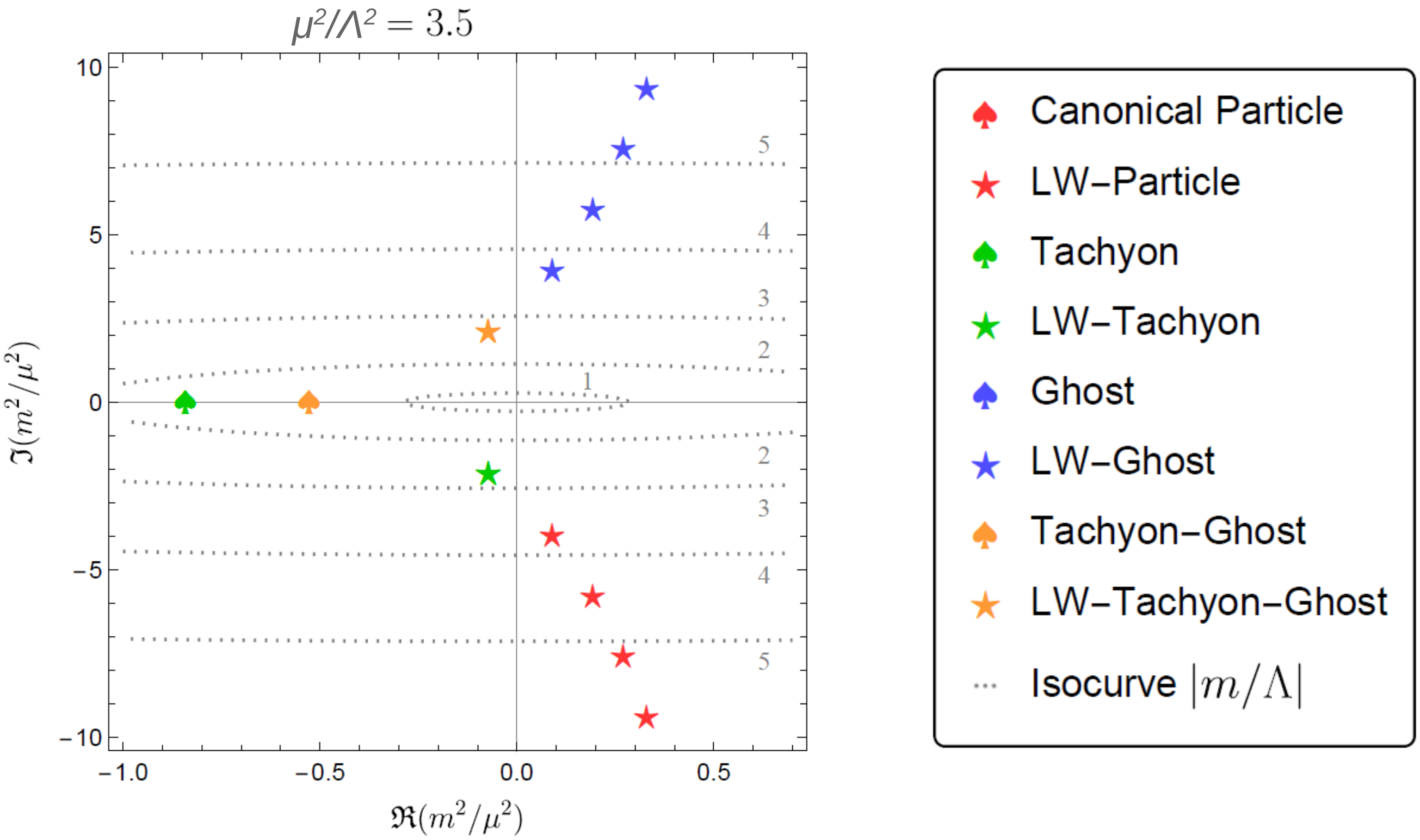
→ ...

Fuzziness → Another "Flashy" BSM Scenario?

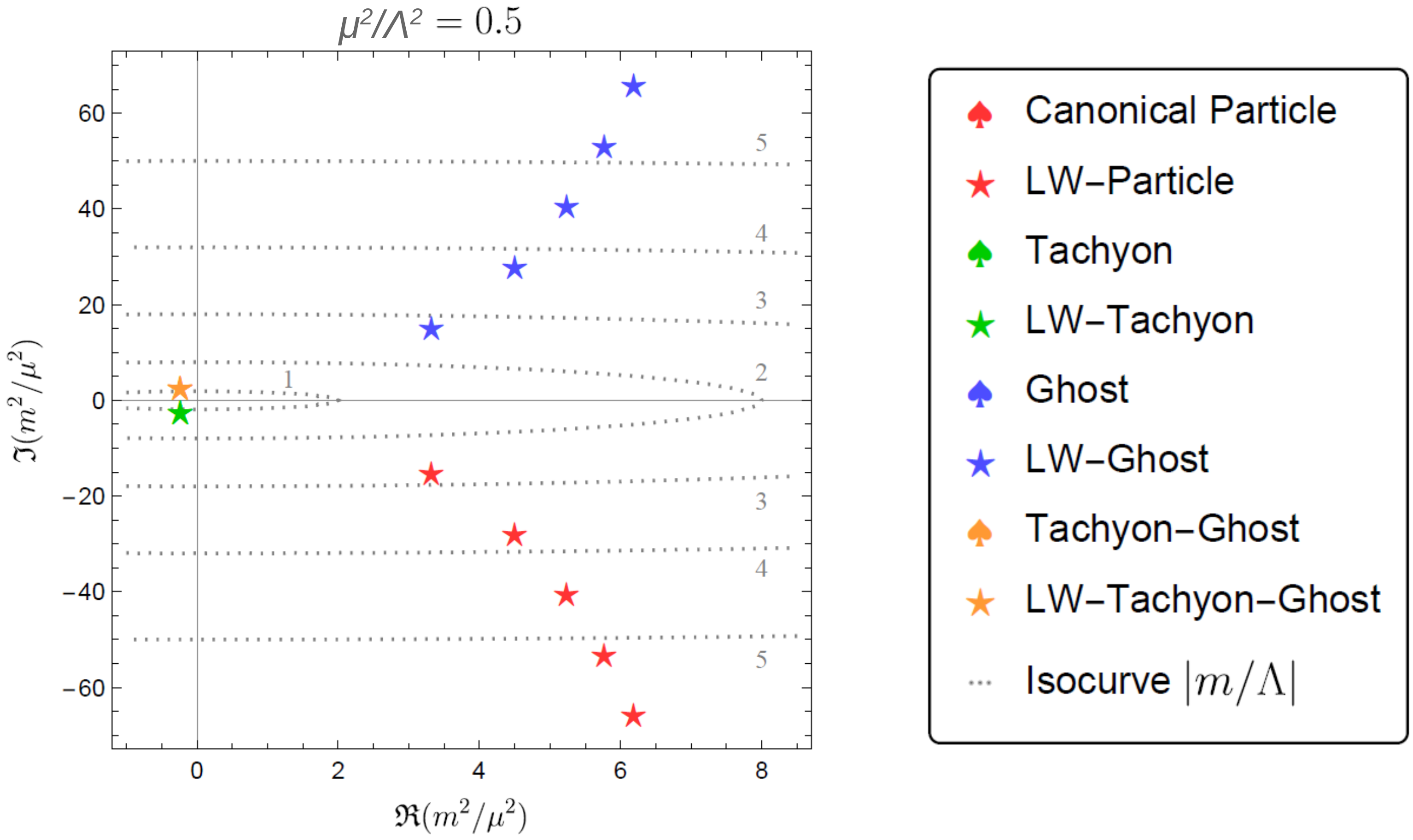
"Barbenheimer" Meme

Thank You for your Attention!

Appendix → Inverted Hierarchy



Appendix → Ahierarchy



Appendix → No Ghosts in an EFT (Weinberg's Footnote, arXiv:0804.4291)

[1] This is equivalent to what is generally done in deriving Feynman rules in effective flat-space quantum field theories. Consider for instance the very simple effective Lagrangian

$$\mathcal{L} = -\frac{1}{2}[\partial_\mu\varphi\partial^\mu\varphi + m^2\varphi^2 + M^{-2}(\Box\varphi)^2] + J\varphi$$

where $M \gg m$ is some very large mass, and J is a c-number external current. We can easily find the connected part Γ of the vacuum persistance amplitude:

$$\Gamma = i\int d^4k \frac{|J(k)|^2}{k^2 + m^2 + k^4/M^2} \, .$$

If we took this result seriously, then we would conclude that in addition to the usual particle with mass $m + O(m^3/M^2)$, the theory contains an unphysical one particle state with mass $M + O(m^2/M)$. But if we regard $\mathcal{L}$ as just the first two terms in a power series in $1/M^2$, then we must treat the term $M^{-2}(\Box\varphi)^2$ as a first-order perturbation, so that the vacuum persistence amplitude is

$$\Gamma = i\int d^4k |J(k)|^2 \left[\frac{1}{k^2 + m^2} - \frac{k^4}{M^2(k^2 + m^2)^2} + \ldots\right] ,$$

and the only pole is at $k^2 = -m^2$. This is just the same result for Γ that we would find if we were to eliminate the second time derivatives in the $O(M^{-2})$ term in $\mathcal{L}$ by using the field equation derived from the leading term in the Lagrangian

$$\Box\varphi = m^2\varphi - J \, .$$

In this case the effective Lagrangian becomes

$$\mathcal{L} = -\frac{1}{2}[\partial_\mu\varphi\partial^\mu\varphi + m^2\varphi^2 + m^4M^{-2}\varphi^2] + (1 + m^2/M^2)J\varphi - J^2/2M^2 \, .$$

Taking into account all J-dependent terms, it is straightforward to see that with this Lagrangian we get the same vacuum persistence amplitude as found above for the the original Lagrangian, when $M^{-2}(\Box\varphi)^2$ is treated as a first-order perturbation.

Appendix → String Field Theory

String Field $\Psi \equiv$ Infinite Tower of Spins [Witten, NPB 268 (1986) 253-294]:

$$|\Psi\rangle = \left[\phi(x) + A_\mu(x)\alpha^\mu_{-1} + B_{\mu\nu}(x)\alpha^\mu_{-1}\alpha^\nu_{-1} + \cdots\right] c_1|0\rangle\,.$$

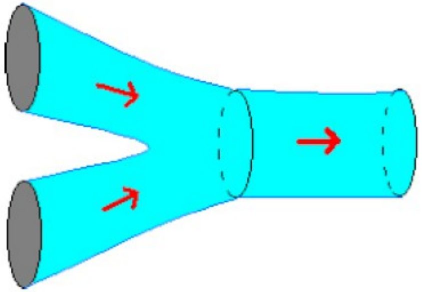
Open String Field Theory ($M_s = 1$), 0-level Truncated Action $(-++\cdots+)$:

$$S = \frac{1}{g_s^2}\int d^d x\left[\frac{1}{2}\phi\Box\phi - \frac{e^{3r_*}}{3}\tilde{\phi}^3\right]\,,\quad \tilde{\phi}(x) = e^{r_*\Box}\phi(x)\,,\quad r_* = \log\left(\frac{3^{3/2}}{4}\right) \simeq 0.2616\,.$$

$\tilde{\phi}(x) \equiv$ Smeared Field via Nonlocality from ∞-Derivative Operator (Nonlocal Length Scale η):

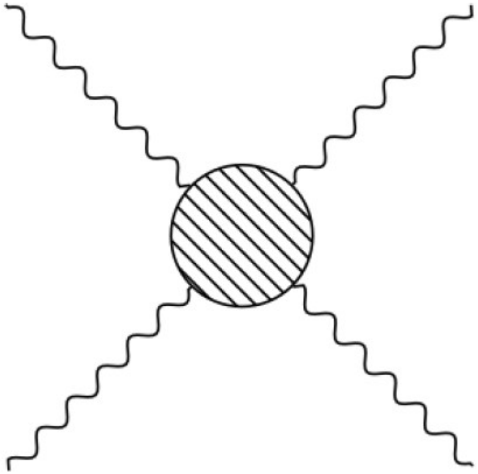
$$e^{\eta^2\partial_x^2}\,\delta(x) = \sqrt{\frac{1}{4\pi\eta^2}}\,e^{-\frac{x^2}{4\eta^2}}\,,$$

$$= \delta(x) + \sum_{n=1}^{N-1}\frac{\eta^{2n}}{n!}\,\delta^{(n)}(x) + \mathcal{O}(\eta^{2N})\,.$$

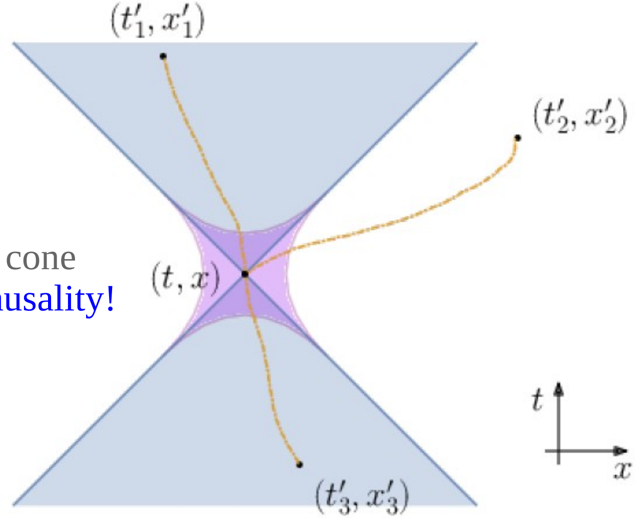


Appendix → Macrocausality

- Initial Value Problem: ∞-Derivatives $\not\Rightarrow$ ∞ Number of Initial Data N_0.
  $\Rightarrow N_0 = 2 \times$ Number of Poles [Barnaby, Kamran, JHEP 02 (2008) 008].
- No Superluminal Propagation [Erbin, Firat, Zwiebach, JHEP 01 (2022) 167].
- Weak Nonlocality $\Rightarrow$ Smeared Vertices $\Rightarrow$ Minimal Uncertainty in Time Resolution!
  [Carone, PRD 95 (2017) 4, 045009] & [Giaccari, Modesto (2018), arXiv:1803.08748]:

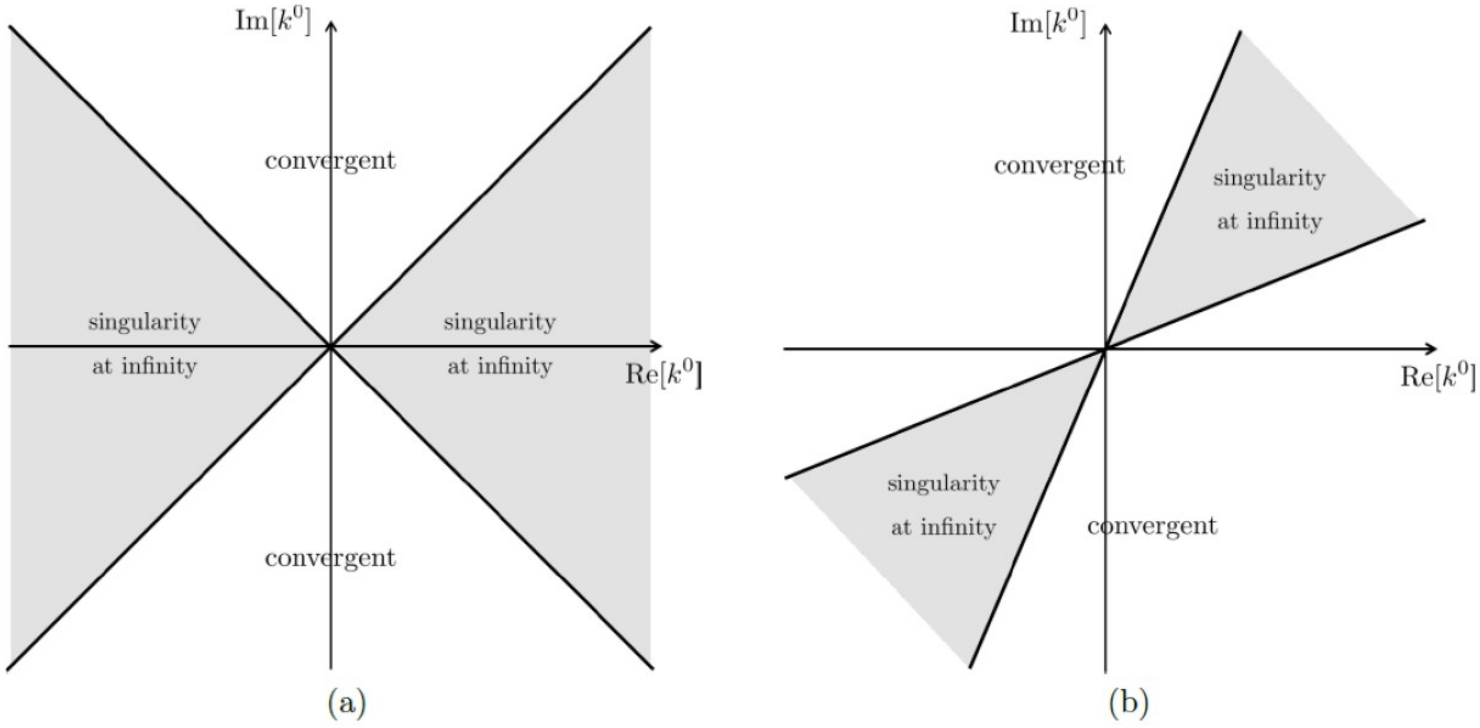


Fuzzy light cone
→ Macrocausality!



Appendix → Analyticity & Unitarity (1/2)

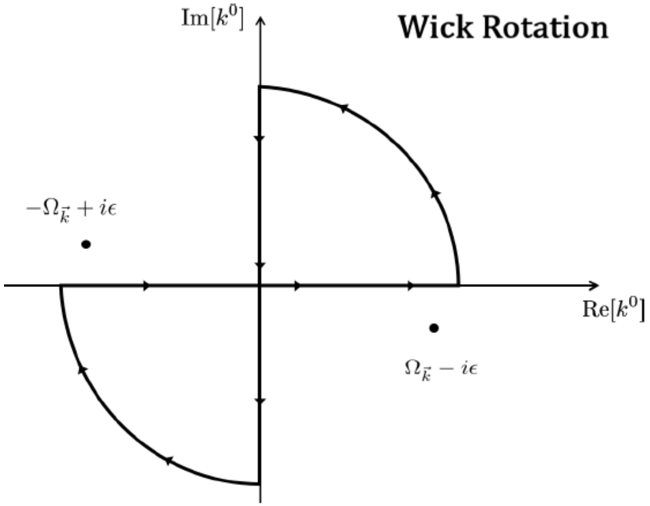
Some Form Factors Blow Up for $E \gg \Lambda_\phi \Rightarrow$ Perturbative Unitarity Lost!
[Koshelev, Tokareva, PRD 104 (2021) 2, 025016]

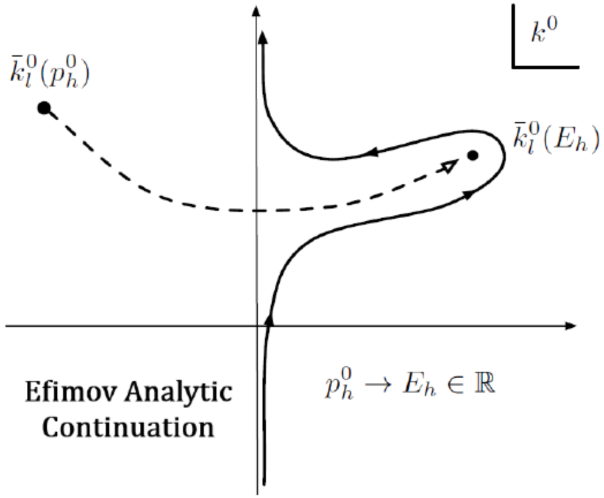


(a) Stringy Form Factor $e^{-\Box/\Lambda_\phi^2}$. (b) Form Factor $e^{\Box^2/\Lambda_\phi^4}$.

Appendix → Analyticity & Unitarity (2/2)

- Essential Singularity at Complex Infinity ⇒ Wick Rotation is Forbidden!
- Kallen–Lehmann Spectral Representation ⇏ Unitarity Violation!
  [Calcagni, Rachwal (2022), arXiv:2210.04914]
- Euclidean → Minkowskian Signature by Efimov Analytic Continuation ⇒ Cutkosky Rules:
  - Contour Prescription: [Efimov, Sov.J.Nucl.Phys. 4 (1967) 2, 309-315].
  - SFT: [Pius, Sen, JHEP 10 (2016) 024] & [de Lacroix, Erbin, Sen, JHEP 05 (2019) 139].
  - Review Nonlocal Scalars: [Buoninfante, PRD 106 (2022) 12, 126028].





Appendix → Kuz'min-Tomboulis Form Factors (1/2)

Kuz'min, Sov.J.Nucl.Phys. 50 (1989) 1011

Tomboulis, arXiv:hep-th/9702146

Modesto, Rachwal, arXiv:1503.00261

Fuzziness + Gauge invariance (local) → Competition: propagators vs vertices

$$\mathcal{L}_{YM} = -\frac{1}{2}\,\mathrm{tr}\left[F_{\mu\nu}\, e^{H(-\ell_*^2 \mathcal{D}^2)}\, F^{\mu\nu}\right] \qquad \text{(Yang-Mills)}$$

$$\mathcal{L}_{GR} = -\frac{2}{\kappa_D^2}\sqrt{-g}\left[R - G_{\mu\nu}\,\frac{e^{H(-\ell_*^2 \Box)} - 1}{\Box}\, R^{\mu\nu}\right] \qquad \text{(Gravity)}$$

Power Counting Theorem → Asymptotically Polynomial: *p(z)*

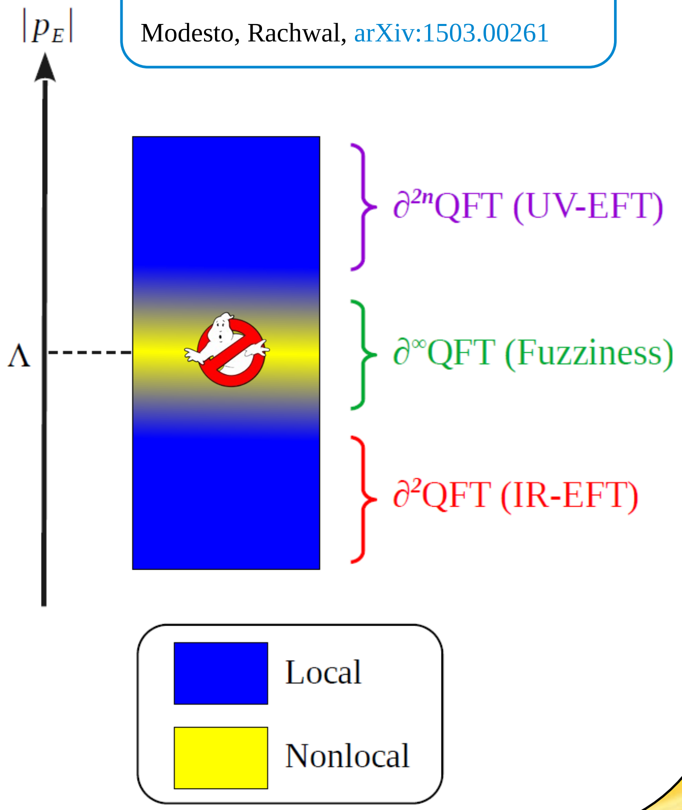
$$e^{H(z)} = e^{\frac{1}{2}\left[\Gamma\left(0,p(z)^2\right)+\gamma_E+\log\left(p(z)^2\right)\right]}$$

$$= \underbrace{e^{\frac{\gamma_E}{2}}\sqrt{p(z)^2}}_{\text{UV Locality}}\left\{1+\underbrace{\left[\frac{e^{-p(z)^2}}{2p(z)^2}\left(1+O\left(\frac{1}{p(z)^2}\right)\right)+O\left(e^{-2p(z)^2}\right)\right]}_{\text{IR Nonlocal Dressing}}\right\}$$

→ Interpolates btw "Normal QFT's" & "Higher-Derivative QFT's"

Even *D* → Super-renormalizability! (at least 1 loop UV-divergences)

Odd *D* → UV finiteness!



Appendix → Kuz'min-Tomboulis Form Factors (2/2)

- Renormalized ∞-Derivative Yang-Mills Lagrangian [Tomboulis (1997), arXiv:hep-th/9702146]:

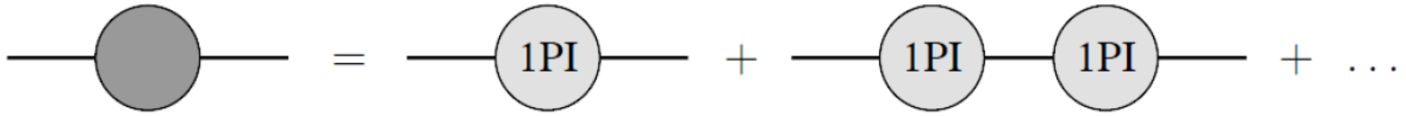
$$\mathcal{L}_{YM} = \underbrace{-\frac{1}{2g_{YM}^2(\eta)}\,\mathrm{Tr}\left[\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}\right]}_{\text{Local YM (Renormalized)}} \underbrace{-\frac{\alpha}{2}\,\mathrm{Tr}\left[\mathcal{F}_{\mu\nu}\left(e^{\vartheta\left(\eta^2 D_\mu^2\right)}-1\right)\mathcal{F}^{\mu\nu}\right]}_{\text{Higher-Deriv. (Not Renormalized)}} + \text{G.F. terms} + \text{counterterms}$$

Ghost-Free Renormalization Scheme: $\alpha\, g_{YM}^2(\eta) = 1$ at Scale $Q_0 \sim 1/\eta$.

- No Ghosts at Perturbative Level as in SFT!
  [Pius, Sen, JHEP 10 (2016) 024] & [de Lacroix, Erbin, Sen, JHEP 05 (2019) 139].

- Dressed Propagator ⇒ Nonperturbative Resummation of 1PI Diagrams:
  - Shapiro: Infinite Tower of Complex Conjugate Poles [Shapiro, PLB 744 (2015) 67-73].
  - Modesto: Shapiro Ghosts Outside Radius of Convergence of Dressed Propagator ⇒ Not an Issue!

⇒ No Proof of Ghost-Freedom at Nonperturbative Level (Open Issue).

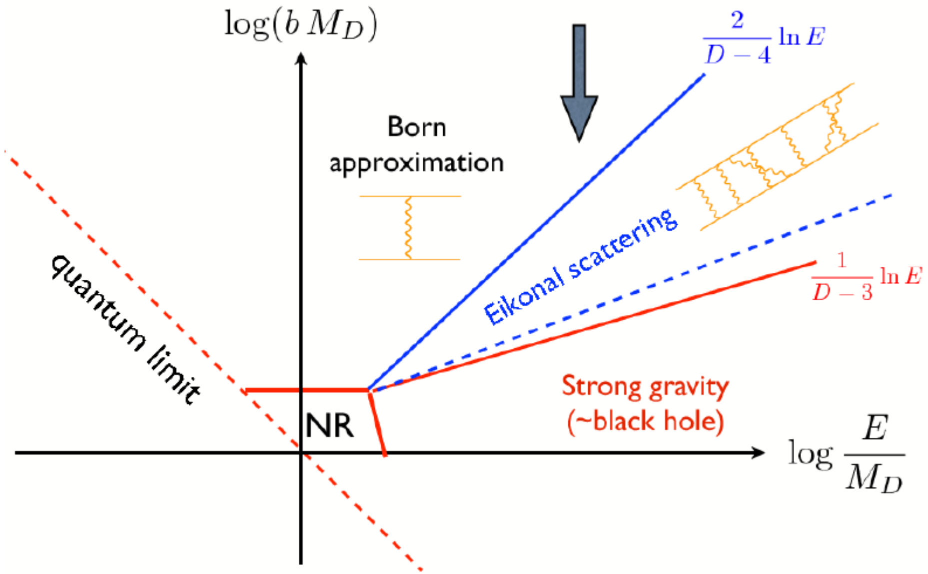


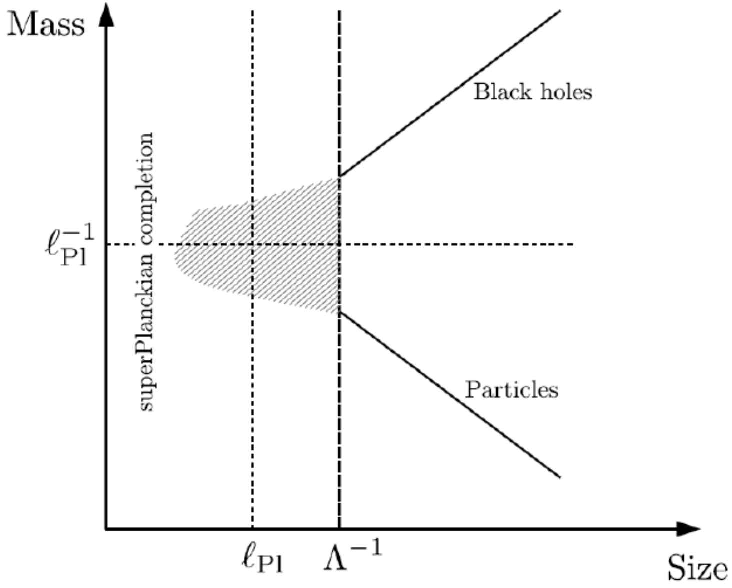
Appendix → Black Holes vs Fuzzstar (1/2)

- $\sqrt{s} \gg \Lambda_P$ & $b \lesssim r_{sch} = 2G\sqrt{s} \Rightarrow$ Black Hole Production (Mass $m = \sqrt{s}$):
[Dvali, Gomez, Isermann, Lust, Stieberger, NPB 893 (2015)]

$$G + G \longrightarrow BH \longrightarrow N \gg 1\,.$$

- Multiparticle Scattering $\Rightarrow$ Collective Transmutation of $\Lambda_{nloc} \Rightarrow \eta_{eff} = N^{\beta}\,\eta$ with $\beta > 0$.
[Buoninfante, Ghoshal, Lambiase, Mazumdar, PRD 99 (2019) 4, 044032].





Appendix → Black Holes vs Fuzzstar (2/2)

- String-Inspired Nonlocal Gravity [Biswas, Gerwick, Koivisto, Mazumdar, PRL 108 (2012) 031101]:

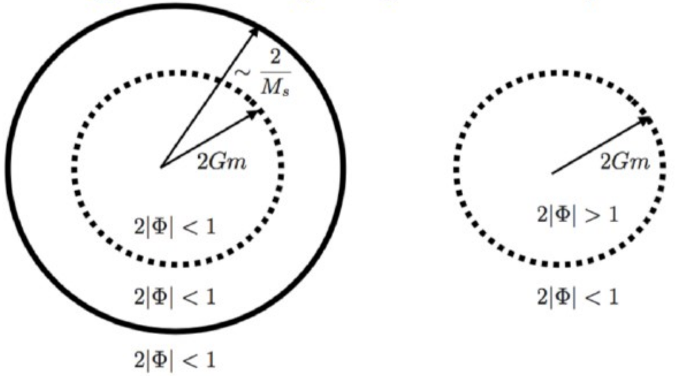
$$S_{GR} = \frac{1}{2\kappa^2} \int d^4x \sqrt{g} \left[\mathcal{R} + \mathcal{G}_{\mu\nu} \frac{e^{-\Box/M_s^2} - 1}{\Box/M_s^2} \mathcal{R}^{\mu\nu} \right] , \quad M_s \mapsto \frac{M_s}{\sqrt{N}} .$$

- BH $\mapsto$ Fuzzstar (No Singularity & Horizon) $\sim$ Fuzzball in String Theory:
    - [Koshelev, Mazumdar, PRD 96 (2017) 8, 084069];
    - [Buoninfante, Koshelev, Lambiase, Mazumdar, JCAP 09 (2018) 034];
    - [Buoninfante, Koshelev, Lambiase, Marto, Mazumdar, JCAP 06 (2018) 014];
    - Echoes in Gravitational Waves? [Buoninfante, Mazumdar, Peng, PRD 100 (2019) 10, 104059].
- Regular Gravitational Potential:

$$\Phi(r) = -\frac{Gm}{r} \operatorname{erf}\left(\frac{M_s r}{2}\right) ,$$

$$\xrightarrow[r \gg 2/M_s]{} -\frac{Gm}{r} ,$$

$$\xrightarrow[r \ll 2/M_s]{} \frac{GmM_s}{\sqrt{\pi}} .$$



(a) BGKM (b) Einstein's GR