Non-Local Star as A Blackhole Mimicker

Review on non-local gravity

Phenomenology in astrophysics
&
A laboratory test via spin entanglement

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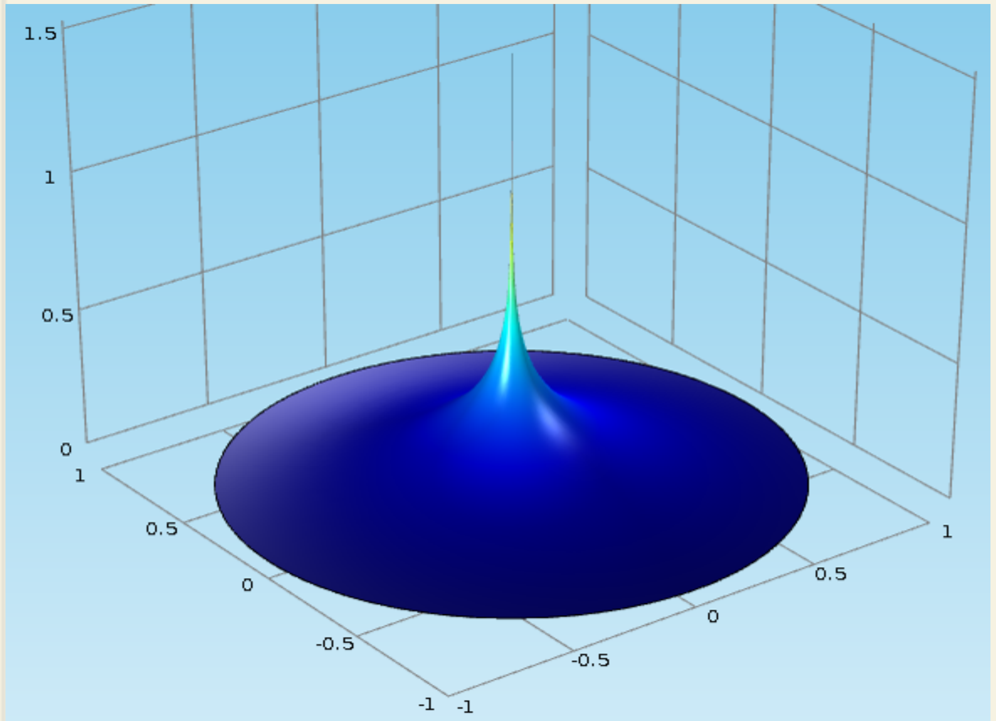
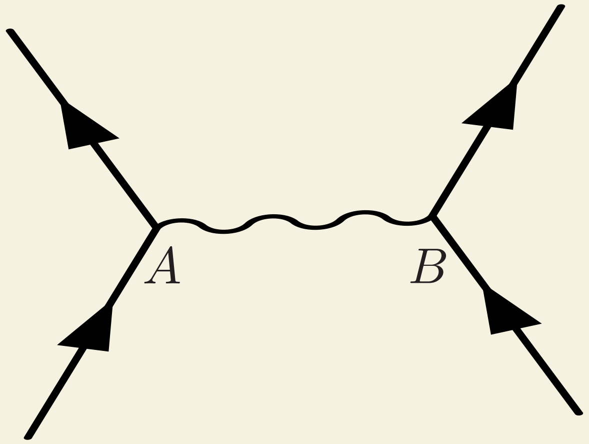
Hot Topics in Modern Cosmology, 5-11 May, 2019, IESC, Cargese

university of groningen
faculty of science and engineering
van swinderen institute for particle physics and gravity

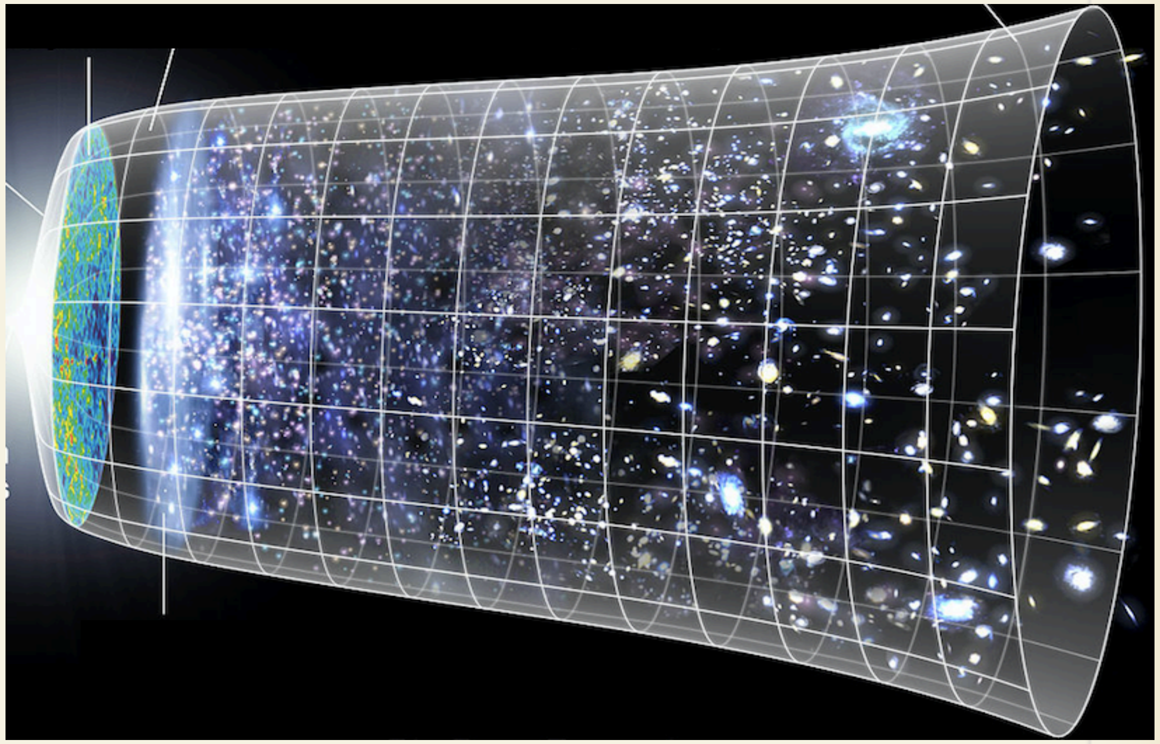
Locality in Spacetime & Singularities





$$V \sim \frac{1}{r}$$

Graviton or Photon
(mediator is massless)



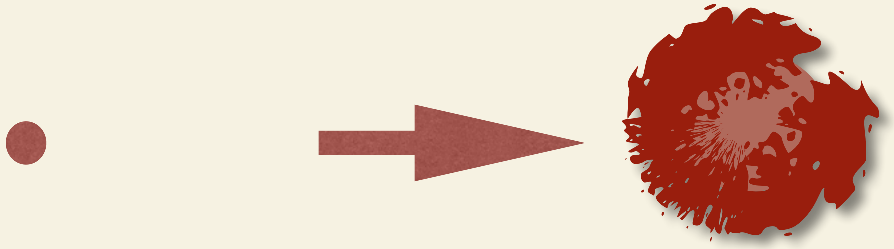
Note on Locality

Finite derivative theory always has a point support

$$x^n\delta^n(x) = (-1)^n n!\delta(x)$$

Infinite derivatives acting on a delta source does not have any point support

$$e^{\alpha\nabla_x^2}\delta(x) = \frac{1}{\sqrt{2\pi}}\int dk e^{-\alpha k^2} e^{ik\cdot x} = \frac{1}{\sqrt{2\alpha}} e^{-x^2/4\alpha}$$



A point becomes a blob

Non-locality is the key perhaps for addressing Singularities!

Finite Derivative Gravity

$$S = \int \sqrt{-g} d^4x \left(\frac{R}{16\pi G} \right)$$

One loop pure gravitational action is renormalizable. The theory is not scale invariant, suffers from cosmological and Schwarzschild/Ring singularities

$$S = \int \sqrt{-g} d^4x \left[M_p^2 R + \alpha C^2 \right]$$

← **Weyl term alone does not introduce singularities**

◆

$$S = \int \sqrt{-g} d^4x \left[M_p^2 R + \alpha R^2 + \beta R_{\mu\nu} R^{\mu\nu} \right]$$

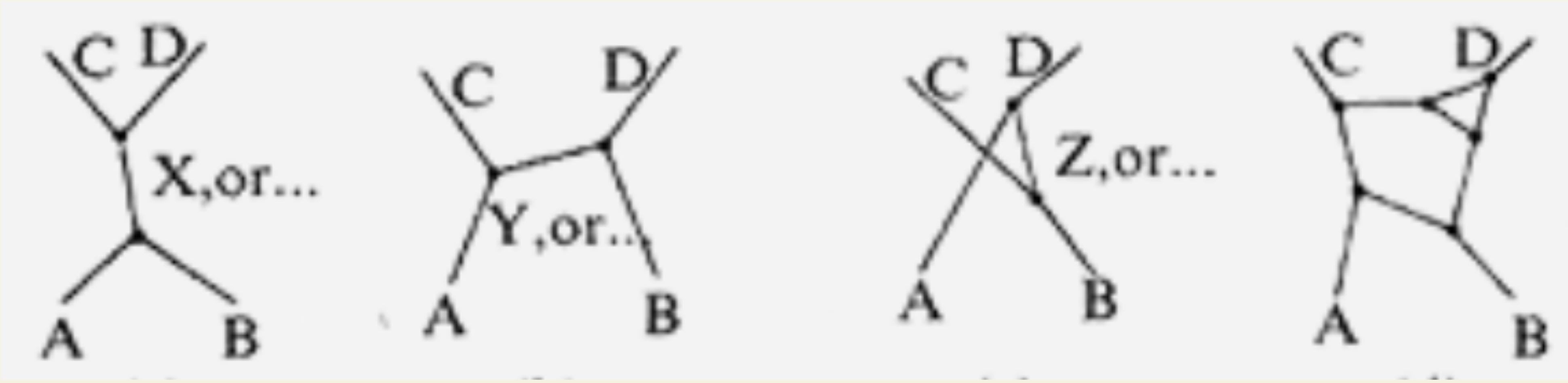
Quadratic Curvature Gravity is renormalizable, but contains “Ghosts”: Vacuum is Unstable + Cosmological/B-H Singularities remain

◆

$$S = \int \sqrt{-g} d^4x \left[M_p^2 R + \alpha (R \Box R + R \Box^2 R + \text{finite order}) + \beta (R^{\mu\nu} \Box R_{\mu\nu} + R^{\mu\nu} \Box^2 R_{\mu\nu} + \text{finite order}) + \cdots \right]$$

Utiyama (1961), De Witt (1961), Stelle (1977), t’Hooft, Veltman (1974)

Out of fashion: Perturbative Quantum Gravity

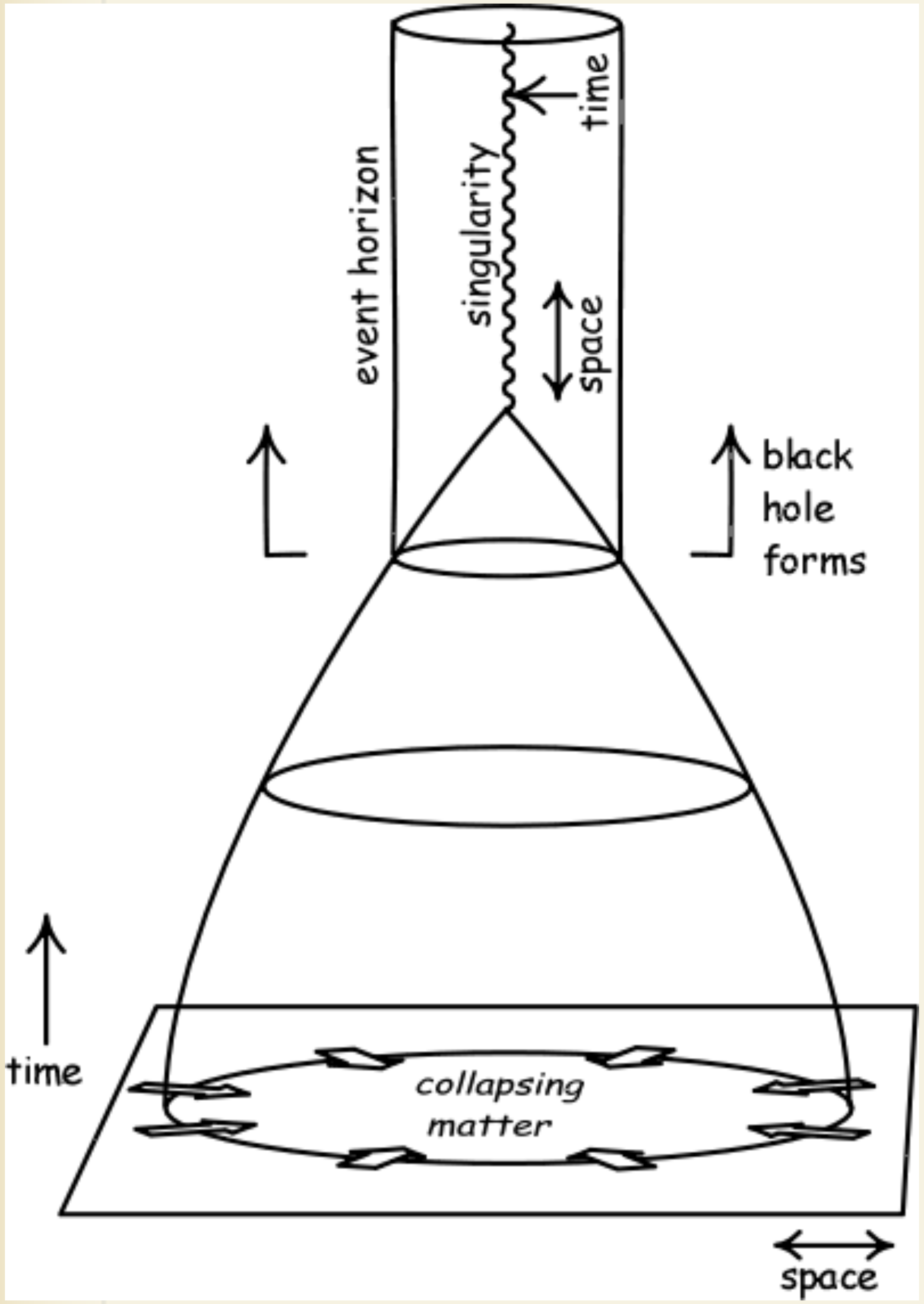


Rise of String Theory

Return of Perturbative Quantum Gravity.

Inspired by String Field Theory

String Theory & Time Dependence



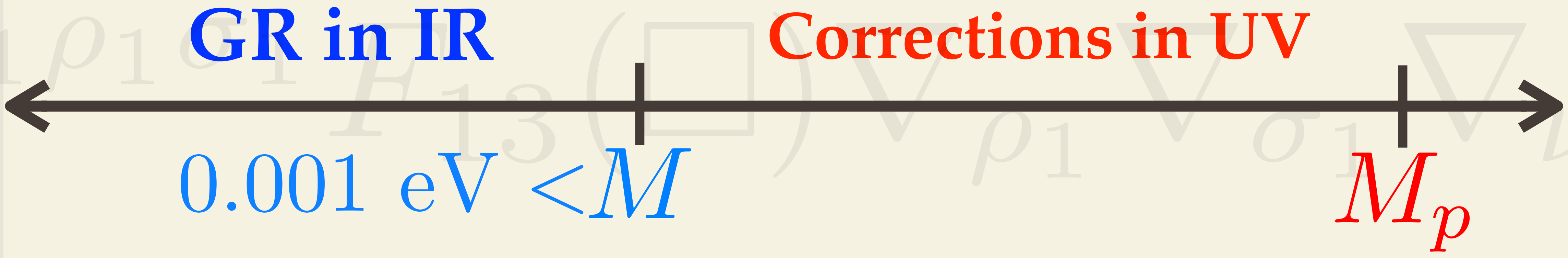
Near The Singularity adiabatic collapse approximation breaks down !

Higher curvature corrections become important, such as alpha' corrections

Supersymmetry is not helpful

Singularity problems in String Theory remains extremely hard !

Phenomenology with UV Gravity



GR in IR

Corrections in UV

$0.001\ \text{eV} < M$

M_p

$M \to \infty$(Theory reduces to GR)

(1) **Allow higher derivative contributions in metric by maintaining diffeomorphism invariance and Bianchi identities. This will lead to non-local interactions** (Biswas,AM, Siegel, hep-th/0508194, Biswas, Gerwick, Koivisto, AM, 1110.5249)

(2) **Study the degrees of freedom around Maximally symmetric spacetimes and in general, e.g. Einstein spacetime.** (Biswas, Koshelev, AM, 1606.01250, 1602.08475, 1905.0XXX)

(3) **Construct higher derivative theory of gravity with spacetime torsion** (Dombriz, Torralba, AM, 1812.04037)

Higher Curvature Gravity

$$S_q = \int d^4x\sqrt{-g}R_{\mu_1\nu_1\lambda_1\sigma_1}\mathcal{O}^{\mu_1\nu_1\lambda_1\sigma_1}_{\mu_2\nu_2\lambda_2\sigma_2}R^{\mu_2\nu_2\lambda_2\sigma_2}$$

All possible terms allowed by symmetry, parity invariant and torsion free

Motivation:

String Field Theory

Unknown Infinite Functions of Covariant Derivatives

$$\begin{aligned}
S_q \;=\; & \int d^4x\sqrt{-g}[RF_1(\Box)R + RF_2(\Box)\nabla_\mu\nabla_\nu R^{\mu\nu} + R_{\mu\nu}F_3(\Box)R^{\mu\nu} + R^\nu_\mu F_4(\Box)\nabla_\nu\nabla_\lambda R^{\mu\lambda} \\
+ & \; R^{\lambda\sigma}F_5(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\lambda R^{\mu\nu} + RF_6(\Box)\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\lambda}F_7(\Box)\nabla_\nu\nabla_\sigma R^{\mu\nu\lambda\sigma} \\
+ & \; R^\rho_\lambda F_8(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\rho R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1}F_9(\Box)\nabla_{\mu_1}\nabla_{\nu_1}\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma} \\
+ & \; R_{\mu\nu\lambda\sigma}F_{10}(\Box)R^{\mu\nu\lambda\sigma} + R^\rho_{\mu\nu\lambda}F_{11}(\Box)\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\rho_1\nu\sigma_1}F_{12}(\Box)\nabla^{\rho_1}\nabla^{\sigma_1}\nabla_\rho\nabla_\sigma R^{\mu\rho\nu\sigma} \\
+ & \; R_\mu^{\nu_1\rho_1\sigma_1}F_{13}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1\rho_1\sigma_1}F_{14}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_{\mu_1}\nabla_\mu\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma}]
\end{aligned}$$

1110.5249 [gr-qc], PRL (2012)

Gravitational Form Factors

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + R\mathcal{F}_1\left(\frac{\Box}{M^2}\right)R + R_{\mu\nu}\mathcal{F}_2\left(\frac{\Box}{M^2}\right)R^{\mu\nu} + R_{\mu\nu\lambda\sigma}\mathcal{F}_3\left(\frac{\Box}{M^2}\right)R^{\mu\nu\lambda\sigma}\right]$$

Einstein-Hilbert Recovers IR

Ultra-violet modifications

$$\frac{\Box}{M^2}$$

$M \to \infty$ (Theory reduces to GR)

Infinite Derivative Gravity (IDG)

Biswas, AM, Siegel, hep-th/0508194
Biswas, Gerwick, Koivisto, AM, gr-qc/1110.5249
Biswas, Koshelev, AM, (extension for de Sitter & Anti-deSitter): arXiv:1602.08475 , arXiv:1606.01250

Perturbative Unitarity

$$S=\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}+R\mathcal{F}_1\left(\frac{\Box}{M^2}\right)R+R_{\mu\nu}\mathcal{F}_2\left(\frac{\Box}{M^2}\right)R^{\mu\nu}+R_{\mu\nu\lambda\sigma}\mathcal{F}_3\left(\frac{\Box}{M^2}\right)R^{\mu\nu\lambda\sigma}\right]$$

$$2\mathcal{F}_1+\mathcal{F}_2+2\mathcal{F}_3=0 \qquad a(\Box)=1-\frac{1}{2}\mathcal{F}_2(\Box)\frac{\Box}{M_s^2}-2\mathcal{F}_3(\Box)\frac{\Box}{M_s^2}$$

$$\Pi(k^2)=\frac{1}{a(k^2)}\left[\frac{P^{(2)}}{k^2}-\frac{P^0}{2k^2}\right] \qquad a(k^2)=e^{\gamma(k^2)}$$

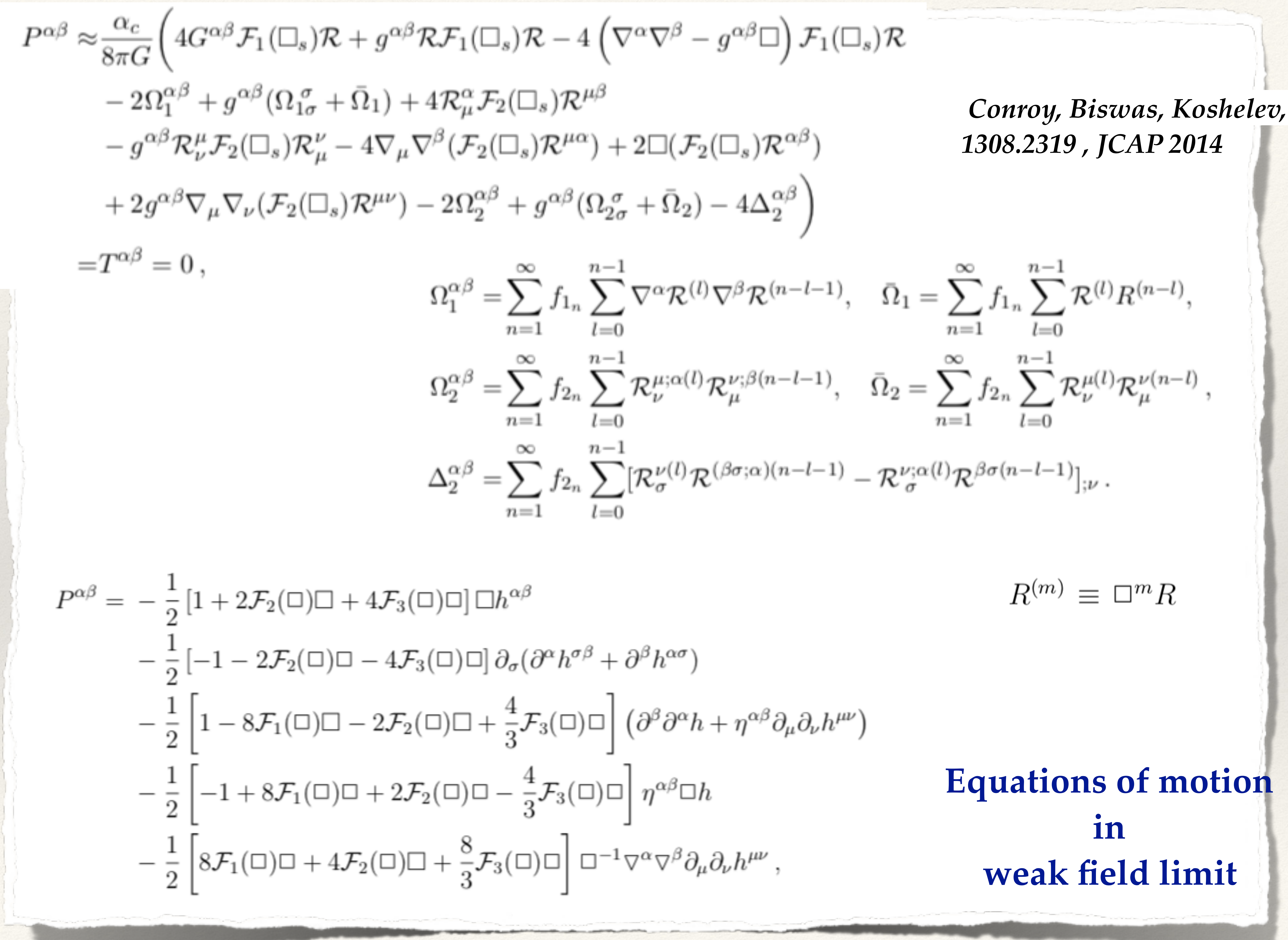
Entire Function

Demand no extra poles other than massless graviton in GR

Simplest choice: $a(k^2)=e^{k^2/M_s^2}$

Biswas, Gerwick, Koivisto, AM, 1110.5249 [gr-qc], PRL (2012)

Complete Equations of Motion



$$P^{\alpha\beta} \approx \frac{\alpha_c}{8\pi G}\Big(4G^{\alpha\beta}\mathcal{F}_1(\Box_s)\mathcal{R} + g^{\alpha\beta}\mathcal{R}\mathcal{F}_1(\Box_s)\mathcal{R} - 4\left(\nabla^\alpha\nabla^\beta - g^{\alpha\beta}\Box\right)\mathcal{F}_1(\Box_s)\mathcal{R}$$

$$- 2\Omega_1^{\alpha\beta} + g^{\alpha\beta}(\Omega_{1\sigma}^{\sigma} + \bar{\Omega}_1) + 4\mathcal{R}_\mu^\alpha\mathcal{F}_2(\Box_s)\mathcal{R}^{\mu\beta}$$

$$- g^{\alpha\beta}\mathcal{R}_\nu^\mu\mathcal{F}_2(\Box_s)\mathcal{R}_\mu^\nu - 4\nabla_\mu\nabla^\beta(\mathcal{F}_2(\Box_s)\mathcal{R}^{\mu\alpha}) + 2\Box(\mathcal{F}_2(\Box_s)\mathcal{R}^{\alpha\beta})$$

$$+ 2g^{\alpha\beta}\nabla_\mu\nabla_\nu(\mathcal{F}_2(\Box_s)\mathcal{R}^{\mu\nu}) - 2\Omega_2^{\alpha\beta} + g^{\alpha\beta}(\Omega_{2\sigma}^{\sigma} + \bar{\Omega}_2) - 4\Delta_2^{\alpha\beta}\Big)$$

$$= T^{\alpha\beta} = 0\,,$$

$$\Omega_1^{\alpha\beta} = \sum_{n=1}^{\infty} f_{1_n}\sum_{l=0}^{n-1}\nabla^\alpha\mathcal{R}^{(l)}\nabla^\beta\mathcal{R}^{(n-l-1)}, \quad \bar{\Omega}_1 = \sum_{n=1}^{\infty} f_{1_n}\sum_{l=0}^{n-1}\mathcal{R}^{(l)}R^{(n-l)},$$

$$\Omega_2^{\alpha\beta} = \sum_{n=1}^{\infty} f_{2_n}\sum_{l=0}^{n-1}\mathcal{R}_\nu^{\mu;\alpha(l)}\mathcal{R}_\mu^{\nu;\beta(n-l-1)}, \quad \bar{\Omega}_2 = \sum_{n=1}^{\infty} f_{2_n}\sum_{l=0}^{n-1}\mathcal{R}_\nu^{\mu(l)}\mathcal{R}_\mu^{\nu(n-l)}\,,$$

$$\Delta_2^{\alpha\beta} = \sum_{n=1}^{\infty} f_{2_n}\sum_{l=0}^{n-1}[\mathcal{R}_\sigma^{\nu(l)}\mathcal{R}^{(\beta\sigma;\alpha)(n-l-1)} - \mathcal{R}_\sigma^{\nu;\alpha(l)}\mathcal{R}^{\beta\sigma(n-l-1)}]_{;\nu}\,.$$

$$P^{\alpha\beta} = -\frac{1}{2}\left[1 + 2\mathcal{F}_2(\Box)\Box + 4\mathcal{F}_3(\Box)\Box\right]\Box h^{\alpha\beta}$$

$$-\frac{1}{2}\left[-1 - 2\mathcal{F}_2(\Box)\Box - 4\mathcal{F}_3(\Box)\Box\right]\partial_\sigma(\partial^\alpha h^{\sigma\beta} + \partial^\beta h^{\alpha\sigma})$$

$$-\frac{1}{2}\left[1 - 8\mathcal{F}_1(\Box)\Box - 2\mathcal{F}_2(\Box)\Box + \frac{4}{3}\mathcal{F}_3(\Box)\Box\right](\partial^\beta\partial^\alpha h + \eta^{\alpha\beta}\partial_\mu\partial_\nu h^{\mu\nu})$$

$$-\frac{1}{2}\left[-1 + 8\mathcal{F}_1(\Box)\Box + 2\mathcal{F}_2(\Box)\Box - \frac{4}{3}\mathcal{F}_3(\Box)\Box\right]\eta^{\alpha\beta}\Box h$$

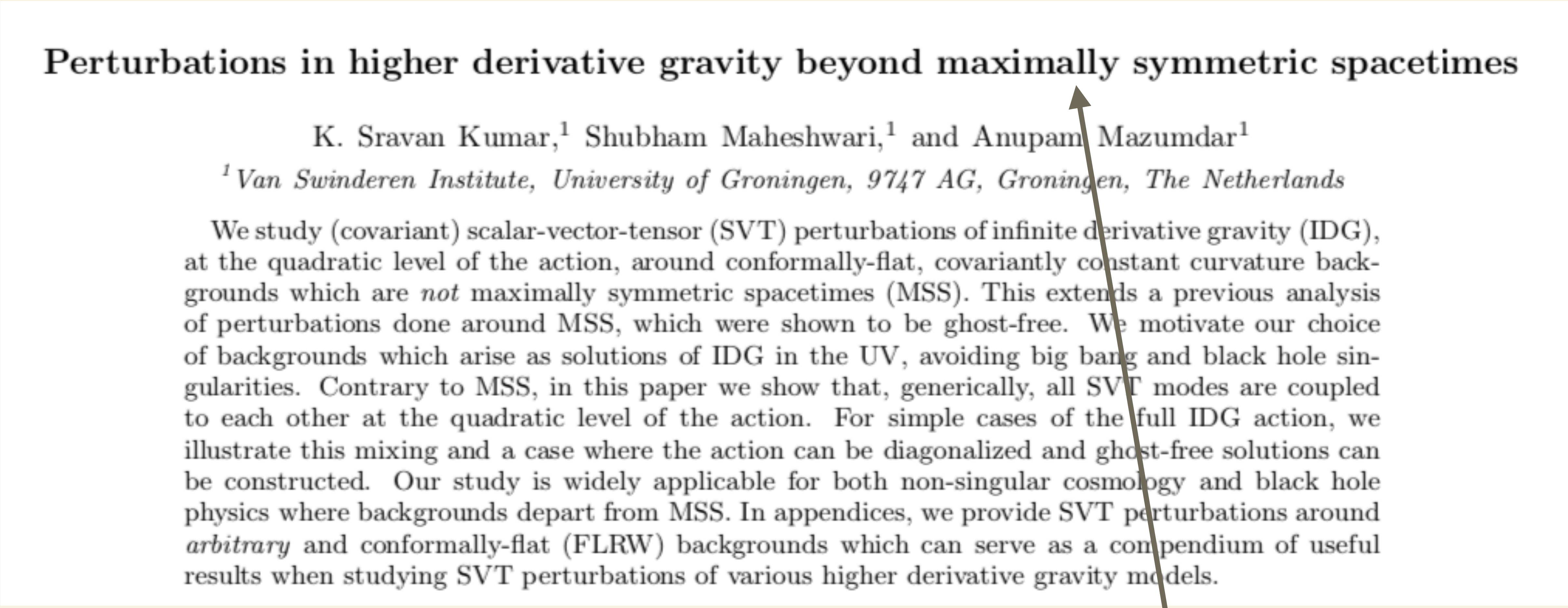
$$-\frac{1}{2}\left[8\mathcal{F}_1(\Box)\Box + 4\mathcal{F}_2(\Box)\Box + \frac{8}{3}\mathcal{F}_3(\Box)\Box\right]\Box^{-1}\nabla^\alpha\nabla^\beta\partial_\mu\partial_\nu h^{\mu\nu}\,,$$

$$R^{(m)} \equiv \Box^m R$$

Conroy, Biswas, Koshelev, AM
1308.2319 , JCAP 2014

Equations of motion
in
weak field limit

2nd order perturbations of the full action



Perturbations in higher derivative gravity beyond maximally symmetric spacetimes

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We study (covariant) scalar-vector-tensor (SVT) perturbations of infinite derivative gravity (IDG), at the quadratic level of the action, around conformally-flat, covariantly constant curvature backgrounds which are *not* maximally symmetric spacetimes (MSS). This extends a previous analysis of perturbations done around MSS, which were shown to be ghost-free. We motivate our choice of backgrounds which arise as solutions of IDG in the UV, avoiding big bang and black hole singularities. Contrary to MSS, in this paper we show that, generically, all SVT modes are coupled to each other at the quadratic level of the action. For simple cases of the full IDG action, we illustrate this mixing and a case where the action can be diagonalized and ghost-free solutions can be constructed. Our study is widely applicable for both non-singular cosmology and black hole physics where backgrounds depart from MSS. In appendices, we provide SVT perturbations around *arbitrary* and conformally-flat (FLRW) backgrounds which can serve as a compendium of useful results when studying SVT perturbations of various higher derivative gravity models.

Any generic spacetime background

1. $\delta^2\mathcal{L}_{EH+\Lambda} = \frac{M_P^2}{2}\delta^2\left[\sqrt{-g}(R-2\Lambda)\right] = \frac{M_P^2}{2}\delta_0$
2. $\delta^2\mathcal{L}_{R^2} = \delta^2\left[\frac{1}{2}\sqrt{-g}\;R\mathcal{F}_1(\Box_s)R\right]$
3. $\delta^2\mathcal{L}_{S^2} = \delta^2\left[\frac{1}{2}\sqrt{-g}\;S^{\nu}{}_{\mu}\mathcal{F}_2(\Box_s)S^{\mu}{}_{\nu}\right]$
4. $\delta^2\mathcal{L}_{C^2} = \delta^2\left[\frac{1}{2}\sqrt{-g}\;C^{\rho\sigma}{}_{\mu\nu}\mathcal{F}_3(\Box_s)C^{\mu\nu}{}_{\rho\sigma}\right]$

Scalar-Vector-Tensor decomposition

$$h_{\mu\nu} = \widehat{h}_{\mu\nu} + \bar{\nabla}_\mu A_\nu + \bar{\nabla}_\nu A_\mu + \left(\bar{\nabla}_\mu\bar{\nabla}_\nu - \frac{1}{4}\bar{g}_{\mu\nu}\bar{\Box}\right)B + \frac{1}{4}\bar{g}_{\mu\nu}h$$

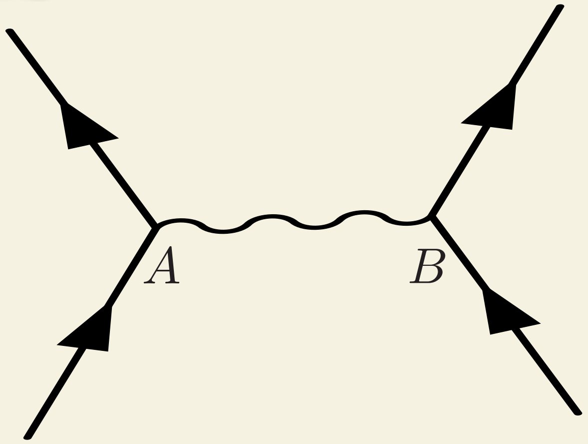
$$\bar{\nabla}^\mu\widehat{h}_{\mu\nu} = 0\,,\quad \bar{g}^{\mu\nu}\widehat{h}_{\mu\nu} = 0\,,\quad \bar{\nabla}^\mu A_\mu = 0$$

A Simple Action

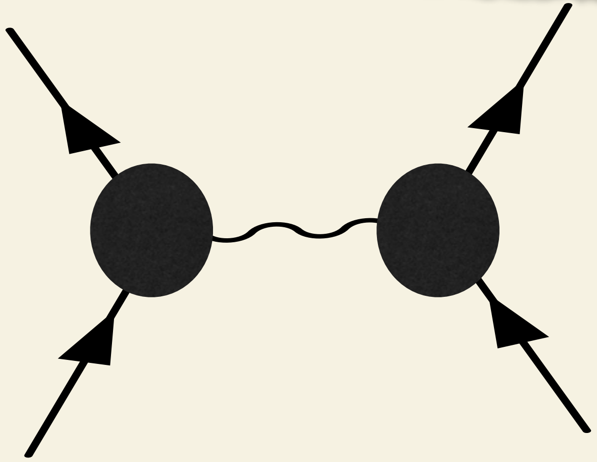
By perturbative unitarity constraints:

$$S = \int d^4x \sqrt{-g}\left[M_p^2 \frac{R}{2} + R\left[\frac{e^{-\Box/M_s^2} - 1}{\Box}\right] R - 2R_{\mu\nu}\left[\frac{e^{-\Box/M_s^2} - 1}{\Box}\right] R^{\mu\nu}\right]$$

$k < M_s$



$k \geq M_s$



$$\Pi(k^2) = \frac{1}{a(k^2)}\left[\frac{P^{(2)}}{k^2} - \frac{P^0}{2k^2}\right] \quad a(k^2) = e^{k^2/M_s^2}$$

Massless Graviton: massless spin-2 and spin-0 components propagate

Biswas, AM, Siegel (2006) JCAP, Biswas, Gerwick, Koivisto, AM (2012) Phy. Rev. Lett.

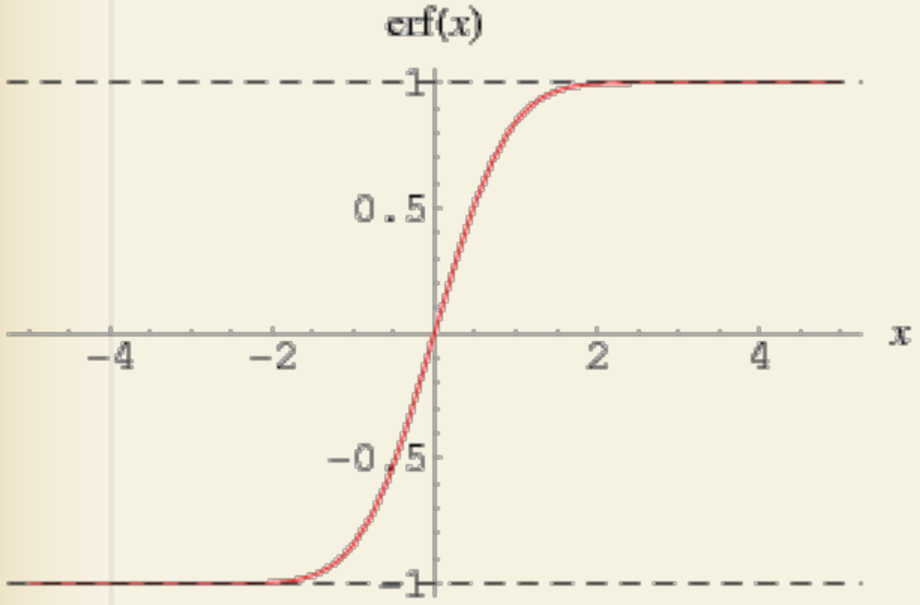
Gravitational Potential

$$S = \int d^4x \, \sqrt{-g} \left[\frac{R}{2} + R \left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box} \right] R - 2R_{\mu\nu} \left[\frac{e^{-\frac{\Box}{M^2}} - 1}{\Box} \right] R^{\mu\nu} \right]$$

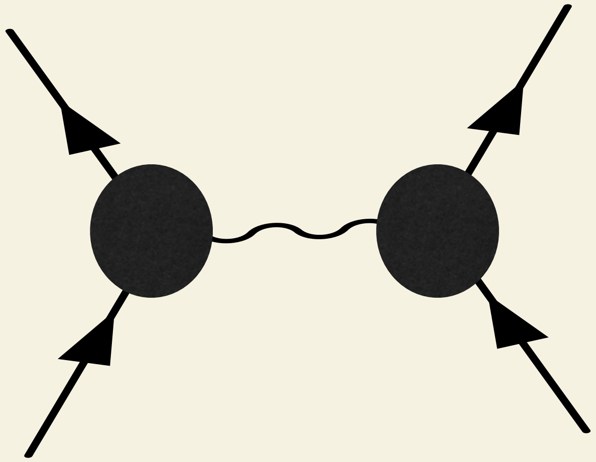
$$ds^2 = -(1 - 2\Phi)dt^2 + (1 + 2\Psi)dr^2$$

$$\Phi = \Psi = \frac{Gm}{r} \mathbf{erf} \left(\frac{rM}{2} \right)$$

$$\Phi \sim \frac{mM_s}{M_p^2} < 1 \Rightarrow mM_s < M_p^2$$

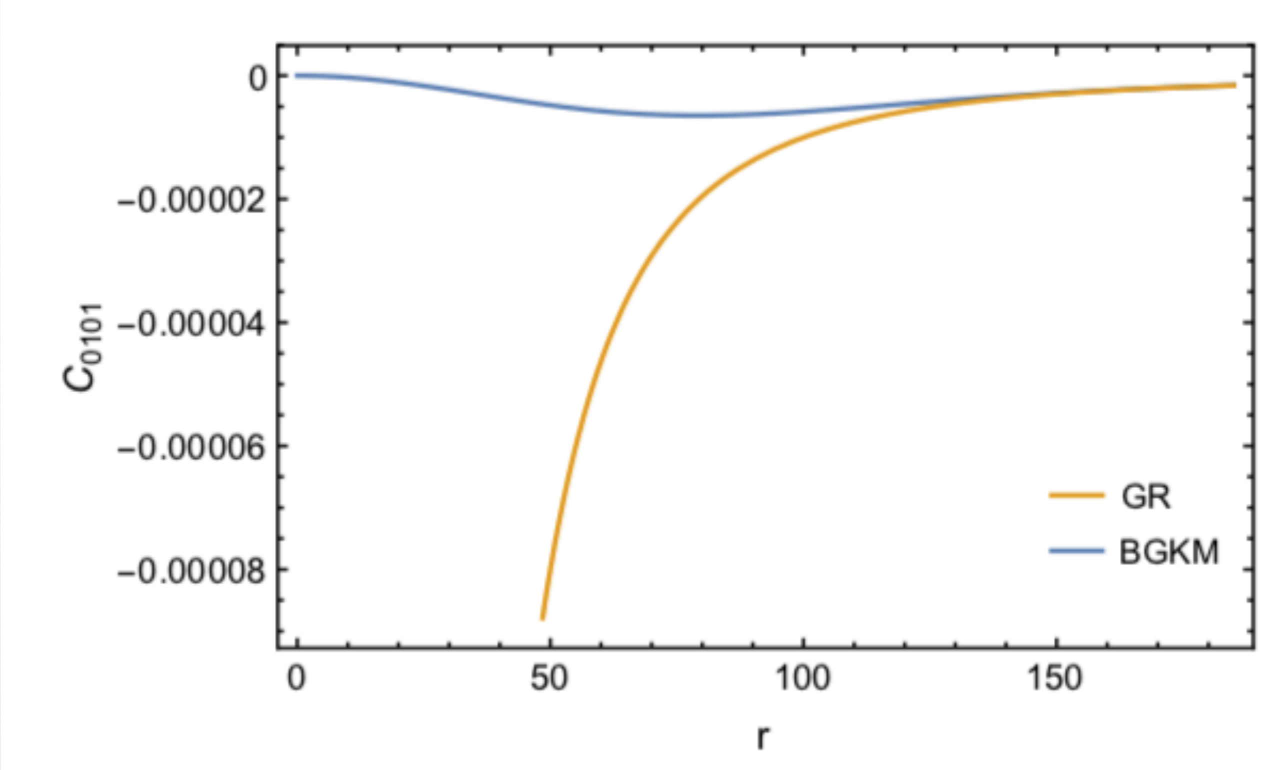


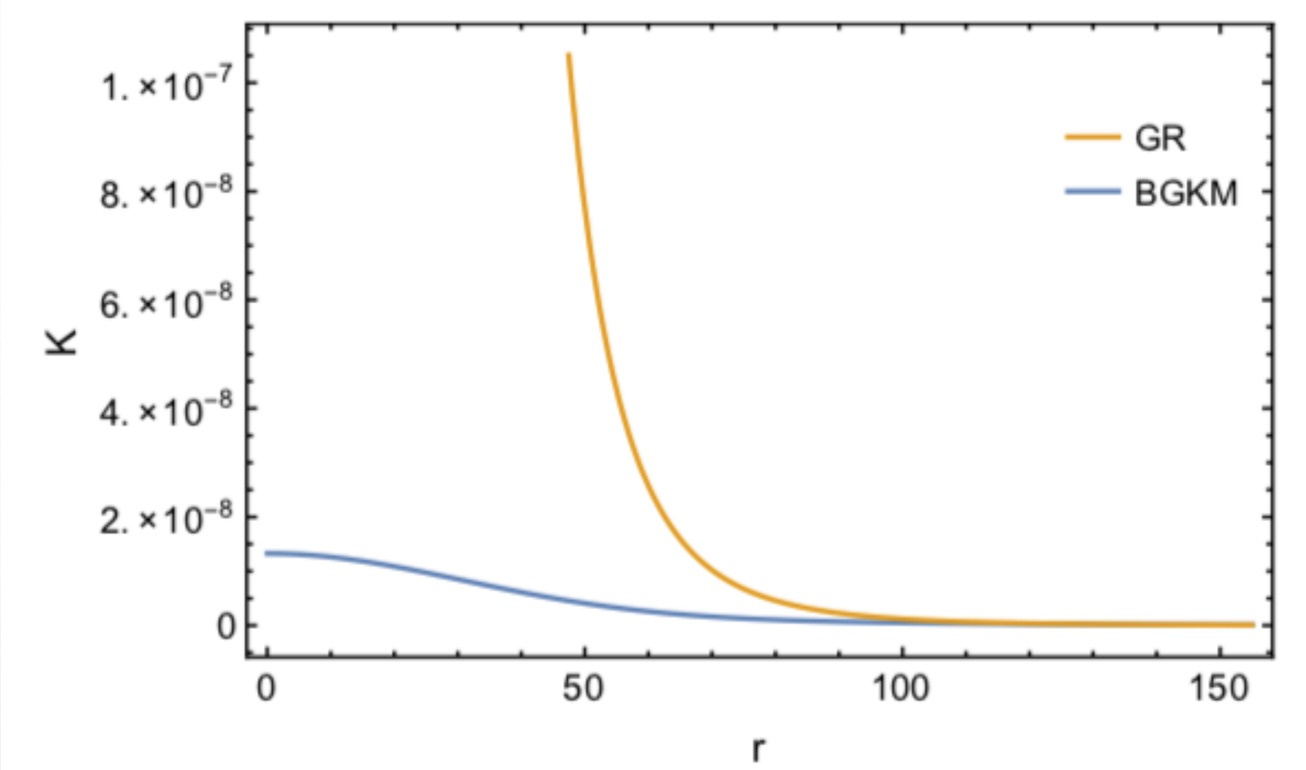
Interaction becomes Non-Local

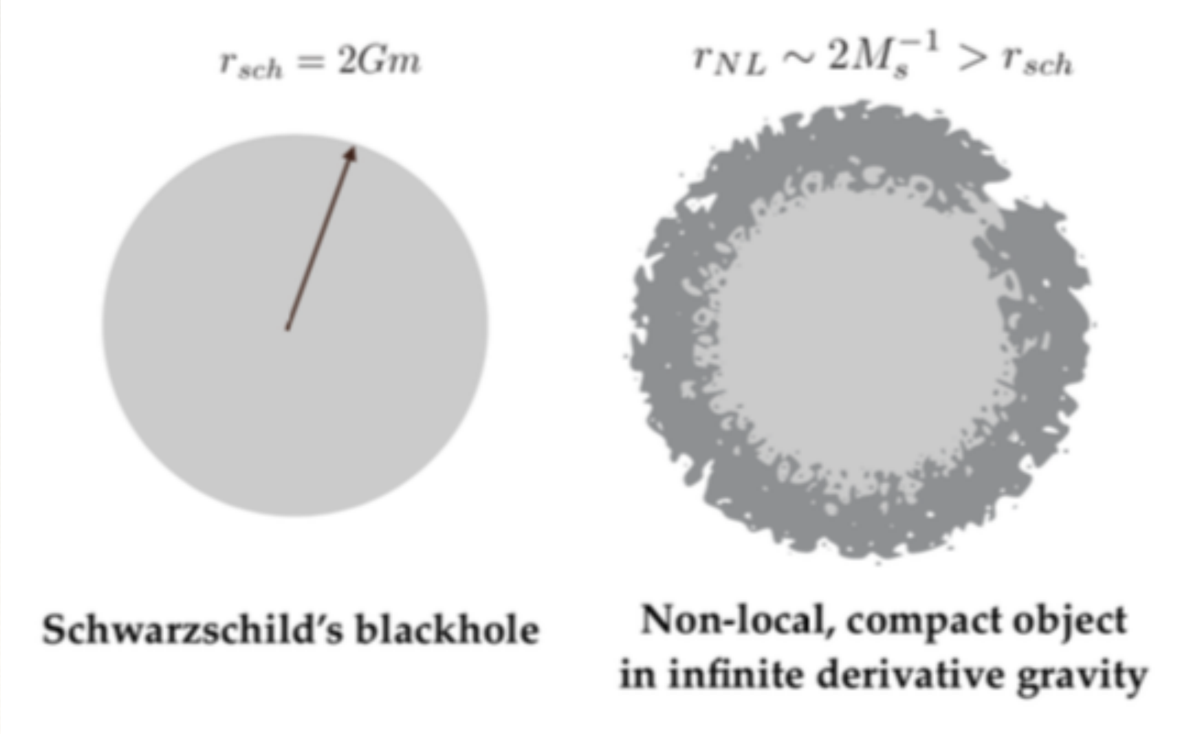


Biswas, Gerwick, Koivisto, AM, Phys. Rev. Lett. (2012) (gr-qc/1110.5249)

Towards Conformal Solution



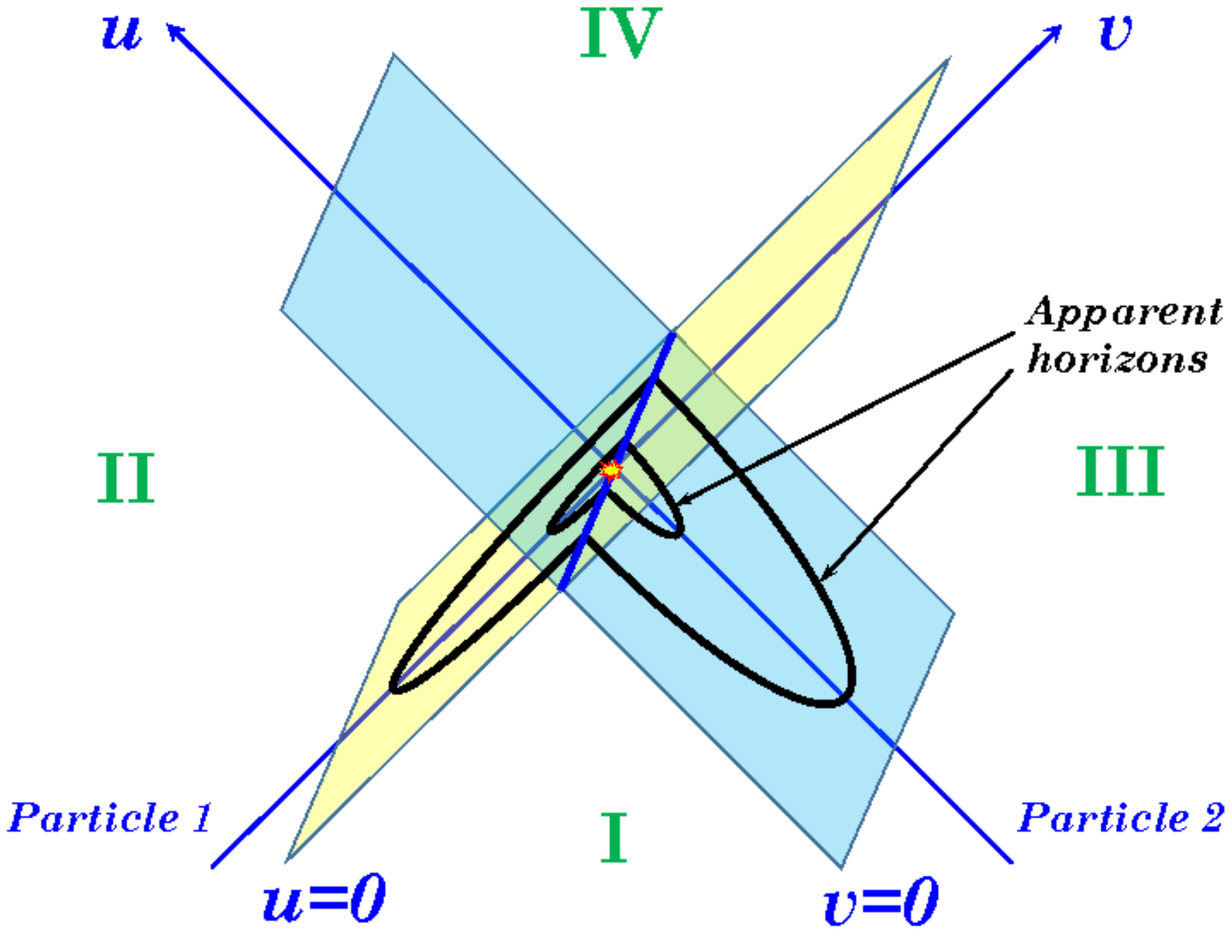




Such non-local objects could be BHs provided linear solution is promoted all the way to non-linear level.

[arXiv:1802.00399 [gr-qc]]

Head-on Collisions



$$ds^2 = -(1+2\varphi_d)\,dt^2 + (1-2\psi_d+2\varphi_d)(dy^2+d\zeta_\perp^2)$$
$$x=(y,\zeta_\perp), \qquad \zeta_\perp=(\zeta^2,\dots,\zeta^{d+1}).$$

Aichelburg-Sexl metric

Take Penrose limit (Ultra-relativistic limit)

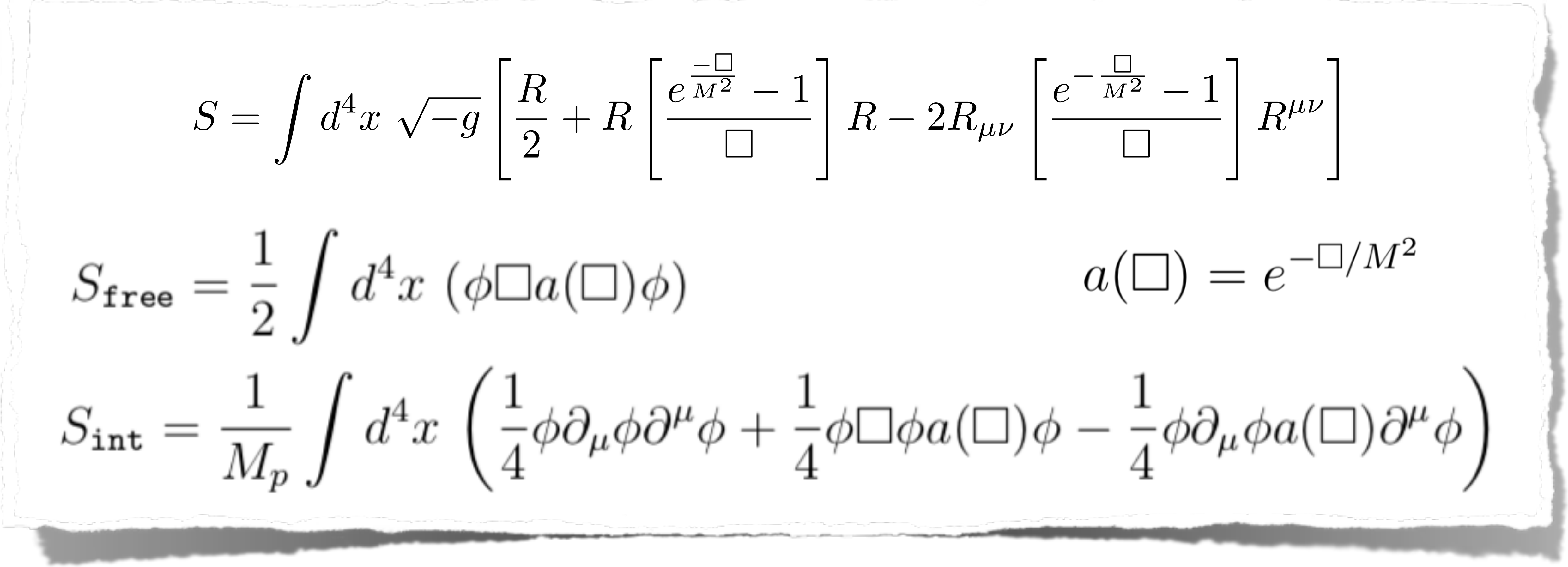
No formation of apparent horizon

No Singularity

Very consistent with the quantum picture

Frolov+ Zelnikov, PRD (2015), 1509.0336, Kilicarlsan (2019)

Collective Behavior & Emergent Scale

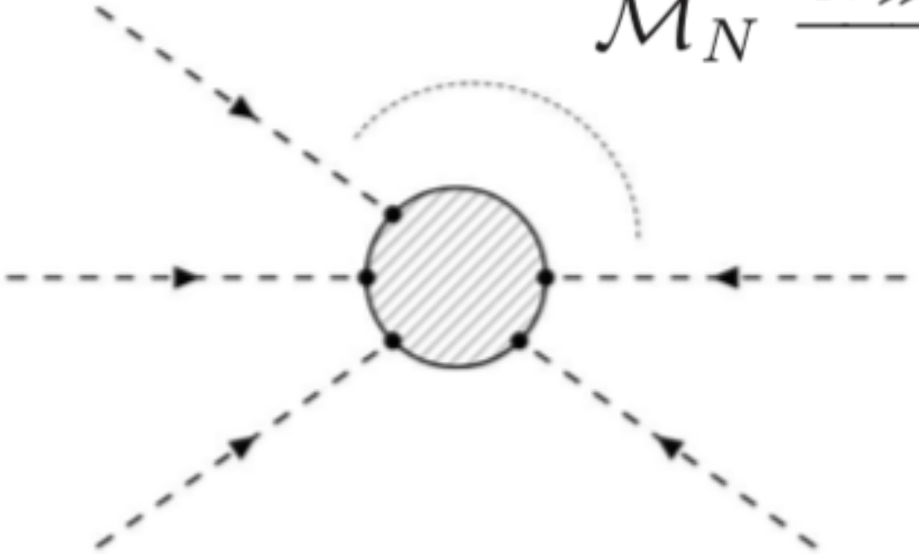


$$S = \int d^4x \, \sqrt{-g} \left[\frac{R}{2} + R \left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box} \right] R - 2R_{\mu\nu} \left[\frac{e^{-\frac{\Box}{M^2}} - 1}{\Box} \right] R^{\mu\nu} \right]$$

$$S_{\texttt{free}} = \frac{1}{2} \int d^4x \, (\phi \Box a(\Box) \phi) \qquad a(\Box) = e^{-\Box/M^2}$$

$$S_{\texttt{int}} = \frac{1}{M_p} \int d^4x \left(\frac{1}{4} \phi \partial_\mu \phi \partial^\mu \phi + \frac{1}{4} \phi \Box \phi a(\Box) \phi - \frac{1}{4} \phi \partial_\mu \phi a(\Box) \partial^\mu \phi \right)$$

$$\mathcal{M}_N \xrightarrow{N \gg 1} \lambda^{3(N-2)} e^{-Np^2/M_s^2} = \lambda^{3(N-2)} e^{-p^2/M_{\text{eff}}^2}$$



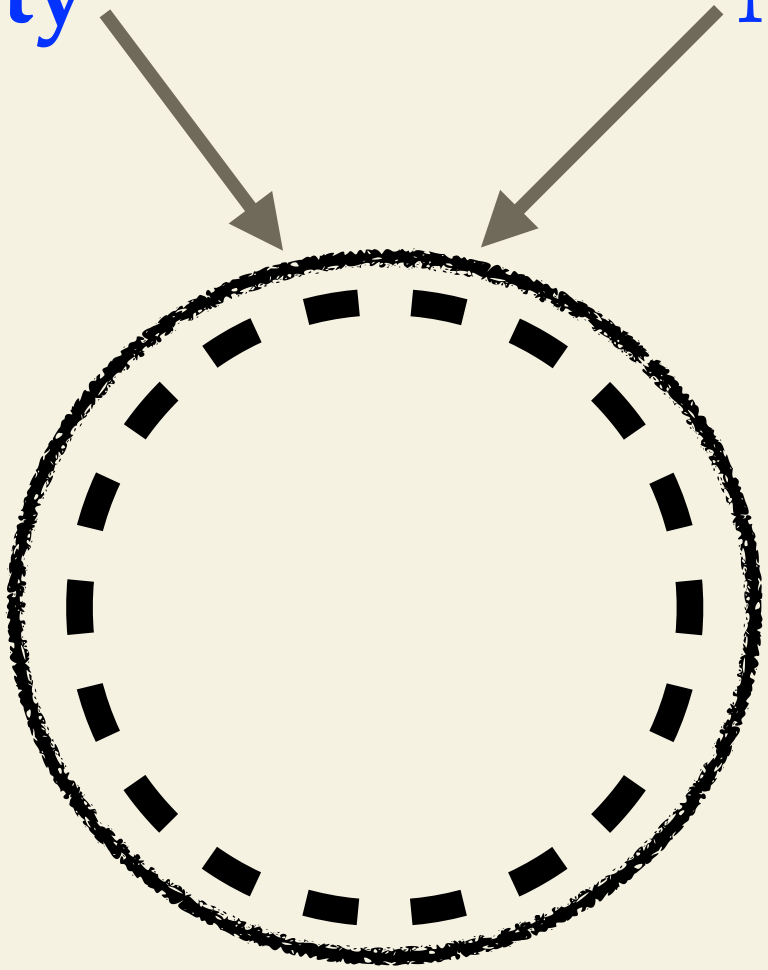
$$M_{\text{eff}} \sim \frac{M_s}{\sqrt{N}}$$

Persists with zero external momenta

N- gravitons behave like a condensate

PRD (2019) 1812.01441 [hep-th]

Gravitationally Bound System



No Singularity

No Event Horizon

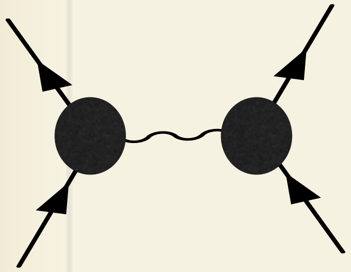
$$R_{Sch} = 2M$$

$$R_{Buch} = 2.25M$$

Buchdahl Star: for constant energy density: Most Compact after Black hole

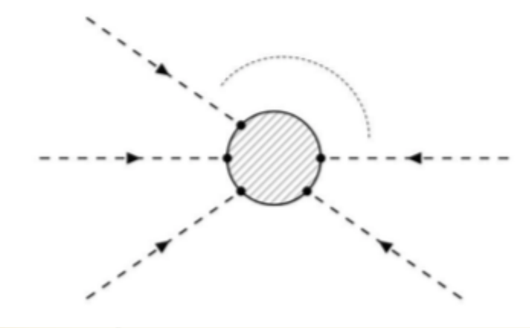
Q: Could we realize Buchdahl Star in Quantum Gravity?

Complementarity Principle



$$\Phi \sim \frac{mM_s}{M_p^2} < 1 \Rightarrow mM_s < M_p^2$$

$$r_{NL} \sim 1/M_s$$



$$\Phi \sim \frac{m_o M_{\text{eff}}}{M_p^2} < 1 \Rightarrow m_o M_{\text{eff}} < M_p^2$$

$$M_{\text{eff}} = \frac{M_s}{\sqrt{N}} \qquad r_{NL} \sim 1/M_{\text{eff}}$$

Gravitational potential remains weak throughout the regime :
We can promote linear solution in the entire manifold

Compact Non-local Star

$$\lambda \sim M_{\text{eff}}^{-1} = \sqrt{N} M_s^{-1}$$ **Radius**

$$E_g \sim M_{\text{eff}} = M_s/\sqrt{N}$$ **Energy of Gravitons**

Forms a gravitationally bound system

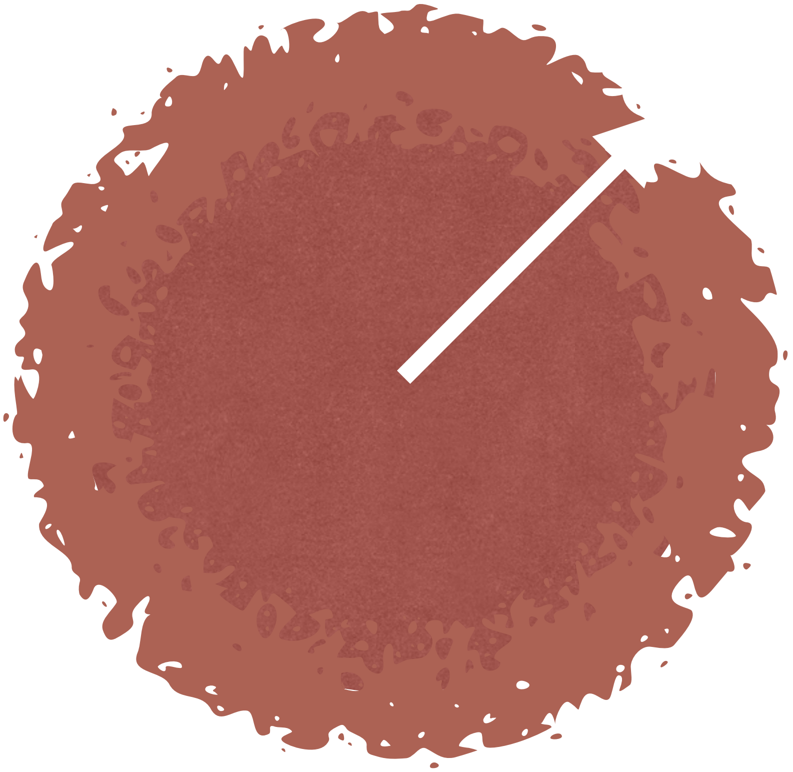
Mass of N gravitons interacting non – locally

$$E_{\text{tot}} = m_\circ = N M_{\text{eff}} = N \frac{M_s}{\sqrt{N}} = \sqrt{N} M_s$$

For a solar mass object : $N \sim 10^{82}$

Ensemble of large *N weakly coupled-Gravitons*

Bekenstein States



$$S = \int d^4x \, \sqrt{-g} \left[\frac{R}{2} + R \left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box} \right] R - 2R_{\mu\nu} \left[\frac{e^{-\frac{\Box}{M^2}} - 1}{\Box} \right] R^{\mu\nu} \right]$$

$$S \sim \hbar \left(\frac{4G^2 m_\circ^2}{L_p^2} + \frac{L_{\text{eff}}^2}{L_p^2} \right) \equiv \hbar \, s,$$

$$s \sim \frac{L_{\text{eff}}^2}{L_p^2} = N \frac{L_s^2}{L_p^2} = N \frac{M_p^2}{M_s^2}$$

Bekenstein States $\mathcal{N} \sim e^{N(L_s/L_p)^2} = e^{N(M_p/M_s)^2}$

For a solar mass object : $\mathcal{N} = e^{10^{82}(M_p/M_s)^2}$

What happens when I throw a chalk, neutrino, …., anything…. inside?

$$\tau = \left(\frac{L_s}{L_p} \right)^9 \tau_{bh} = \left(\frac{M_p}{M_s} \right)^9 \tau_{bh}$$

Longer life time than a Blackhole

The Non-local star absorbs everything, even better than a Blackhole!!!

Metric of a Non-local Star

$$ds^2 = -(1+2\Phi)dt^2 + (1-2\Psi(r))dr^2 + r^2 d\Omega^2,$$

where

$$\Phi(r) = \begin{cases} -\frac{Gm}{r}\mathrm{Erf}\left(\frac{r}{2L_{\mathrm{eff}}}\right), & r \lesssim r_{\mathrm{NL}}, \\ -\frac{Gm}{r}, & r > r_{\mathrm{NL}}, \end{cases}$$

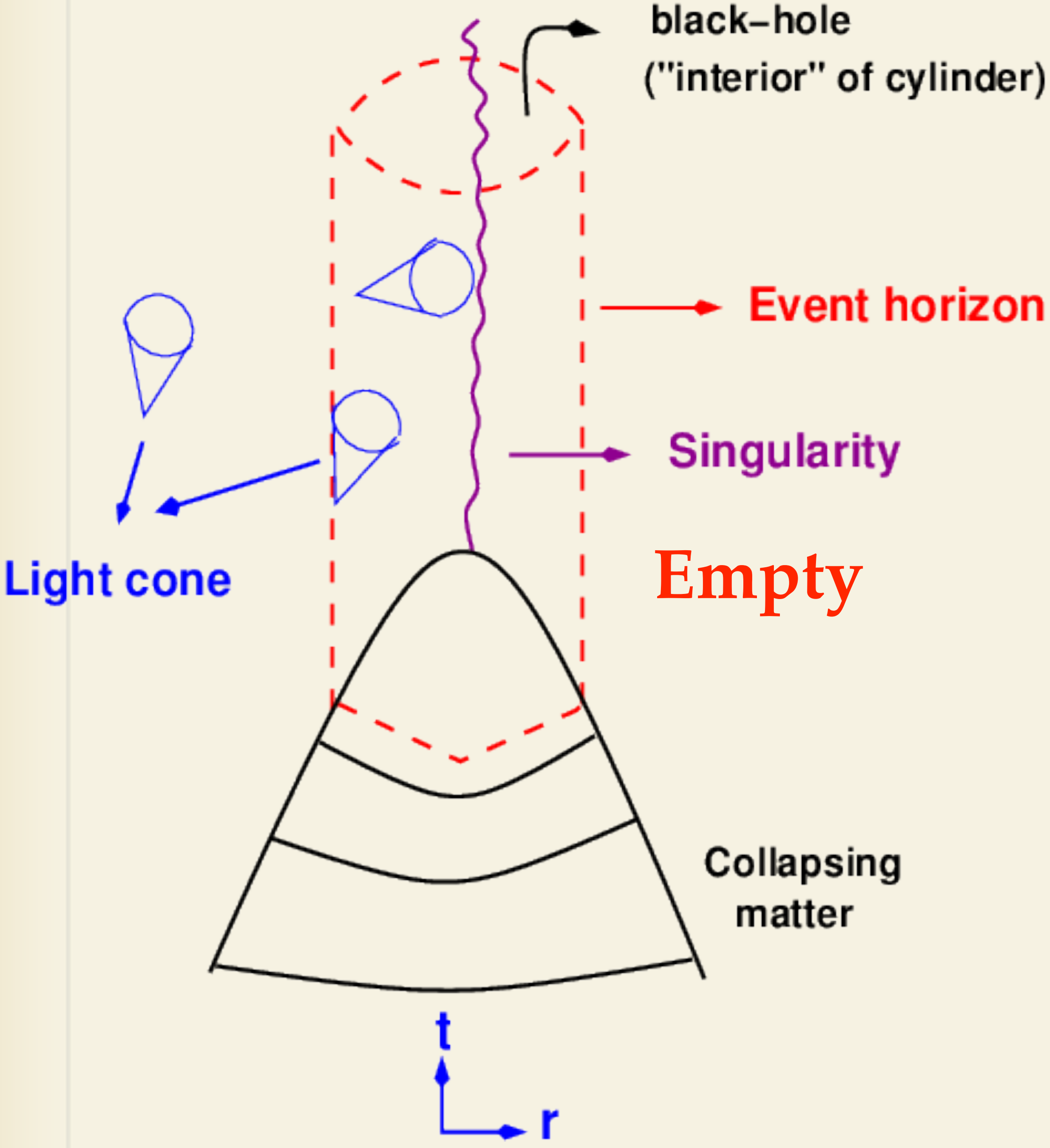
and

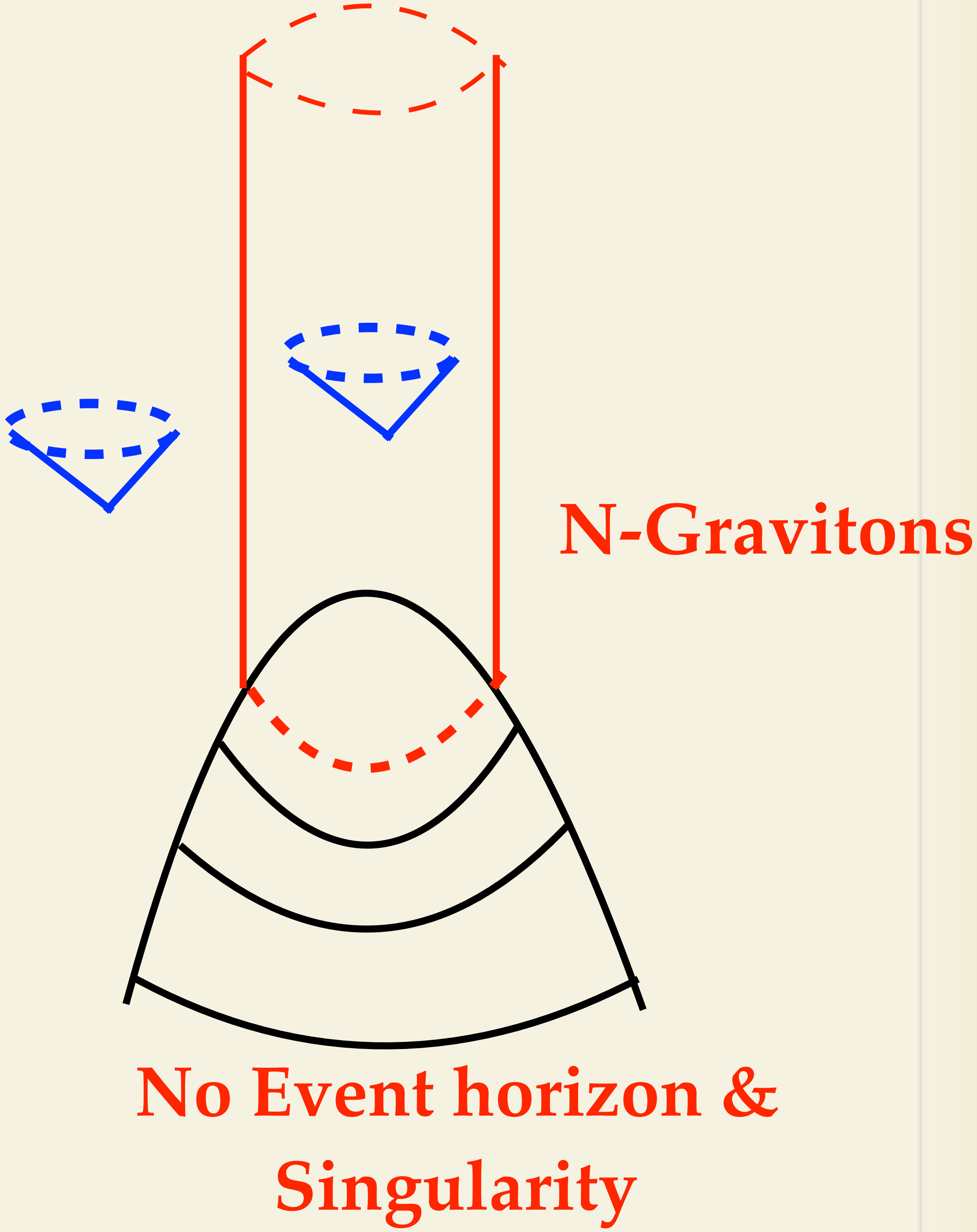
$$\Psi(r) = \begin{cases} -\frac{Gm}{r}\mathrm{Erf}\left(\frac{r}{2L_{\mathrm{eff}}}\right) + \frac{Gm\, e^{-r^2/4L_{\mathrm{eff}}^2}}{\sqrt{\pi}L_{\mathrm{eff}}}, & r \lesssim r_{\mathrm{NL}} \\ -\frac{Gm}{r}, & r > r_{\mathrm{NL}} \end{cases}$$

$$r_{\mathrm{NL}} \sim 2L_{\mathrm{eff}} = r_{\mathrm{sch}}(1+\epsilon) > 2Gm\frac{2}{\sqrt{\pi}}. \qquad \epsilon \gtrsim 0.128$$

$$r > 2.256M$$

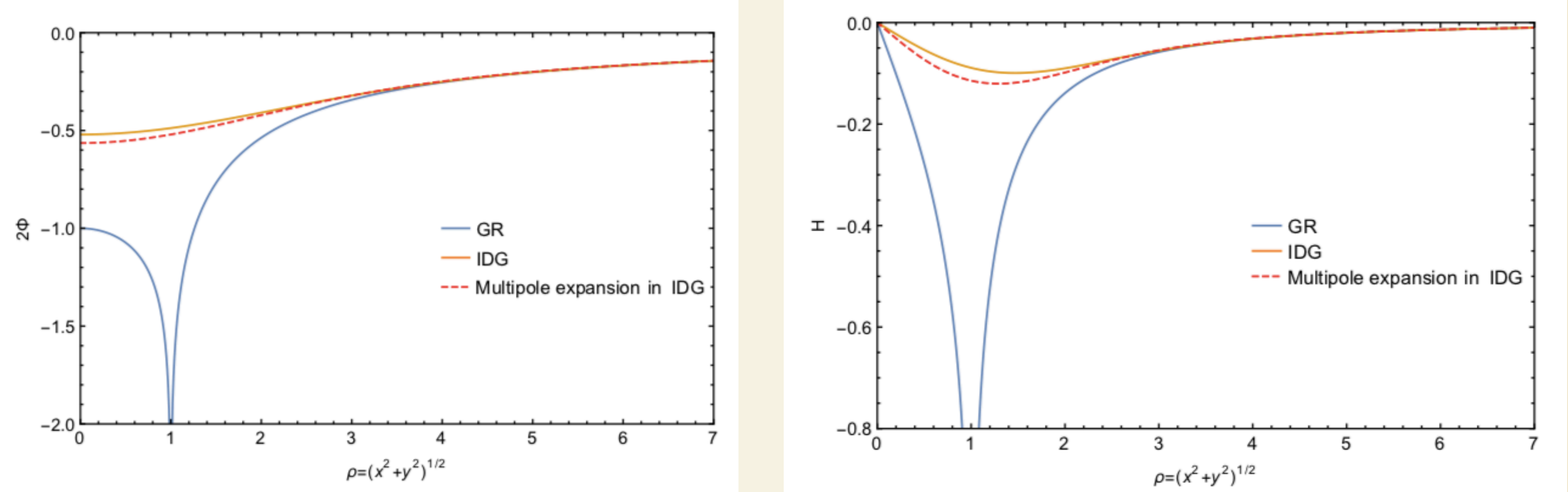
Schwarzschild vs. Non-local Stars

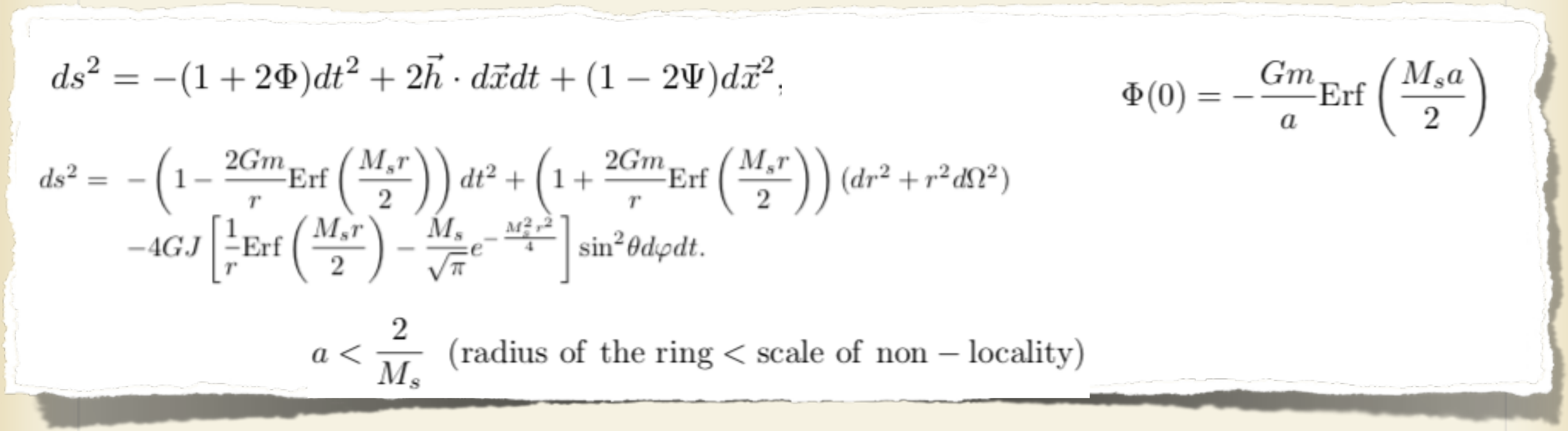




How Compact is the Non-local Star?

Conformally flat: Rotating solution with No Ring Singularity





$$ds^2 = -(1+2\Phi)dt^2 + 2\vec{h}\cdot d\vec{x}dt + (1-2\Psi)d\vec{x}^2,$$

$$\Phi(0) = -\frac{Gm}{a}\mathrm{Erf}\left(\frac{M_s a}{2}\right)$$

$$\begin{aligned} ds^2 = &-\left(1-\frac{2Gm}{r}\mathrm{Erf}\left(\frac{M_s r}{2}\right)\right)dt^2 + \left(1+\frac{2Gm}{r}\mathrm{Erf}\left(\frac{M_s r}{2}\right)\right)(dr^2+r^2d\Omega^2) \\ &-4GJ\left[\frac{1}{r}\mathrm{Erf}\left(\frac{M_s r}{2}\right) - \frac{M_s}{\sqrt{\pi}}e^{-\frac{M_s^2 r^2}{4}}\right]\sin^2\theta d\varphi dt. \end{aligned}$$

$$a < \frac{2}{M_s} \quad (\text{radius of the ring} < \text{scale of non}-\text{locality})$$

At non-linear level only solution survives is a conformally flat metric

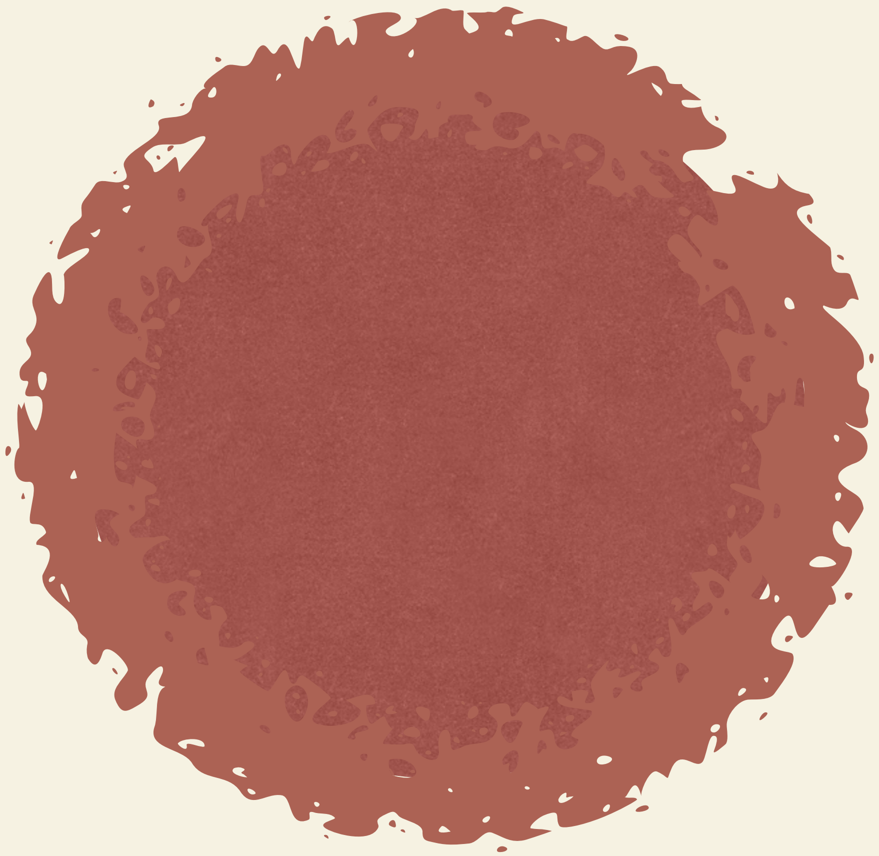
[arXiv:1807.08896 [gr-qc]]

Non-Local Star

No Horizon

No Singularity

Ultra Stable



Ultra-Compact

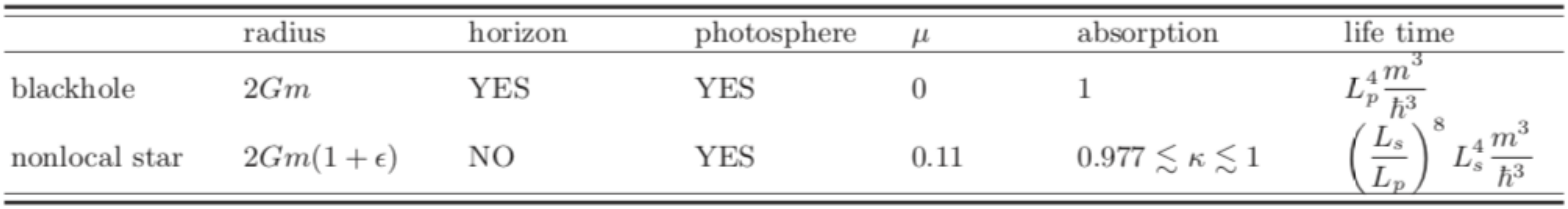
$r > 2.256M$

Satisfies Buchdahl bound

$r > 2.5M$

Shadow: *5.84 M*

As a Blackhole Mimicker !

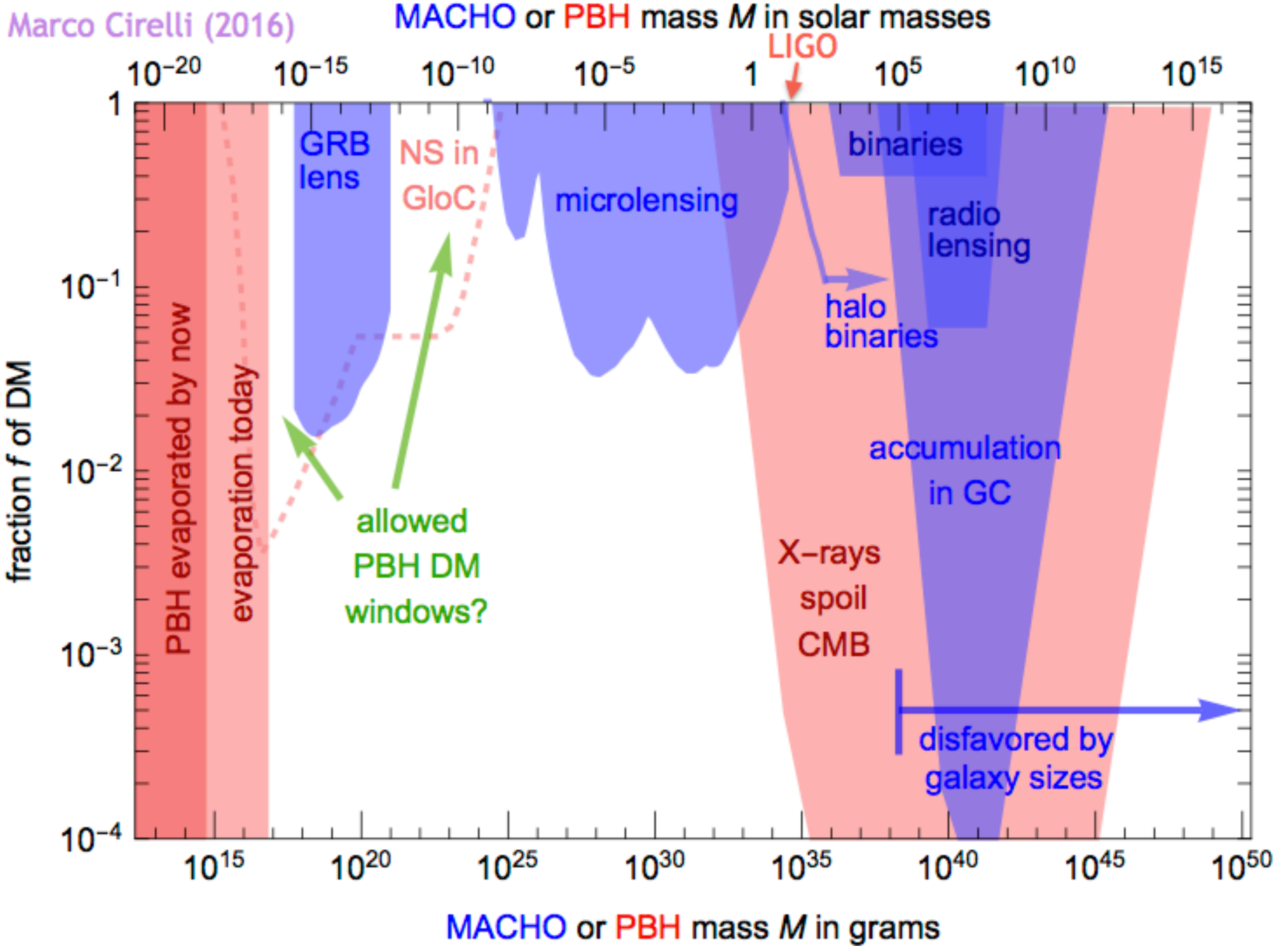


	radius	horizon	photosphere	μ	absorption	life time
blackhole	$2Gm$	YES	YES	0	1	$L_p^4 \frac{m^3}{\hbar^3}$
nonlocal star	$2Gm(1+\epsilon)$	NO	YES	0.11	$0.977 \lesssim \kappa \lesssim 1$	$\left(\frac{L_s}{L_p}\right)^8 L_s^4 \frac{m^3}{\hbar^3}$

A self consisted solution within Ghost free, singularity free IDG

Buoninfante, AM, 1903.01542

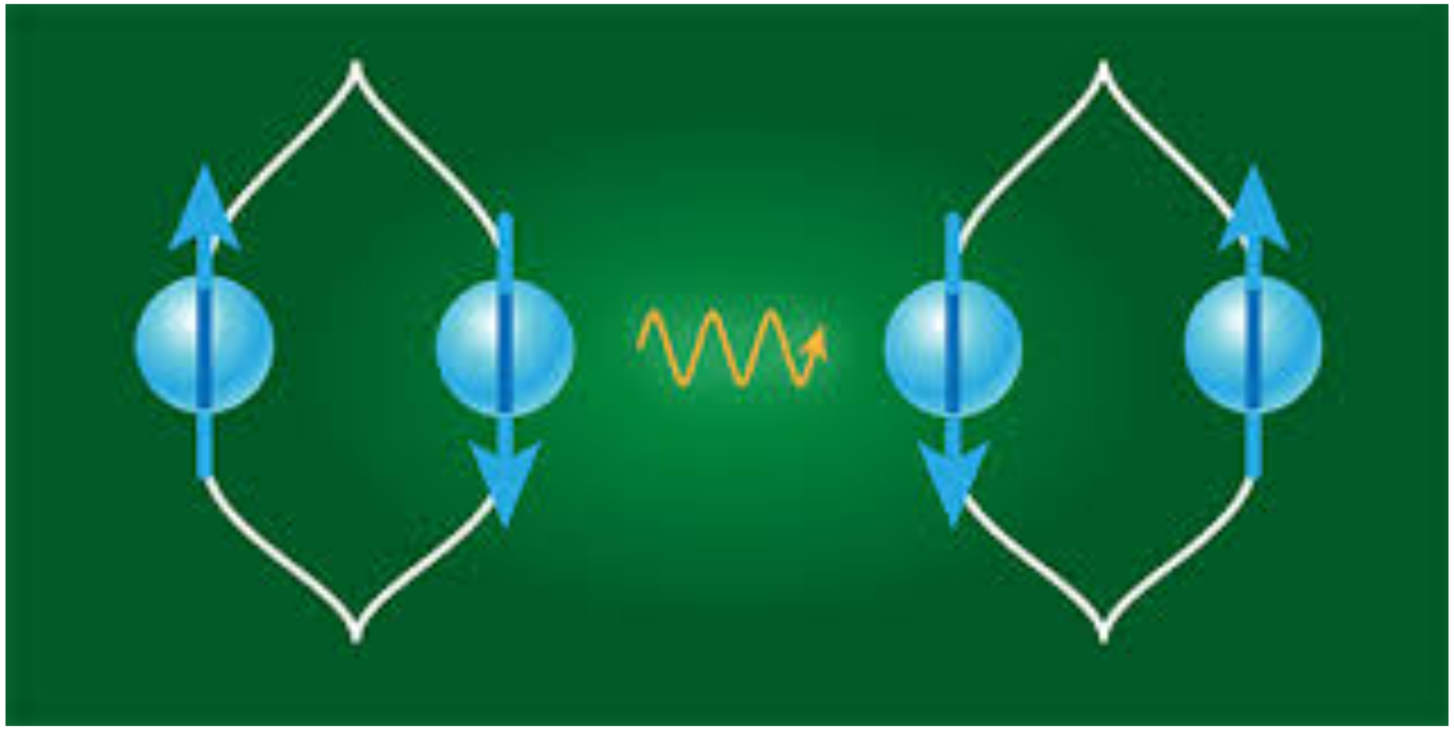
Non-local Star & Dark Matter Candidate



$$m_\circ > 10^{14}\left(\frac{M_s}{M_p}\right)^3 \text{g} \qquad M_s \sim 10^{16}\ \text{GeV}, \quad M_p \sim 10^{19}\ \text{GeV}; m_\circ > 10^9\text{g}$$

Perfect candidate for a dark Matter, which opens up a new parameter space as compared to primordial blackholes

Testing Quantum Aspects of Linearized Gravity in a Lab



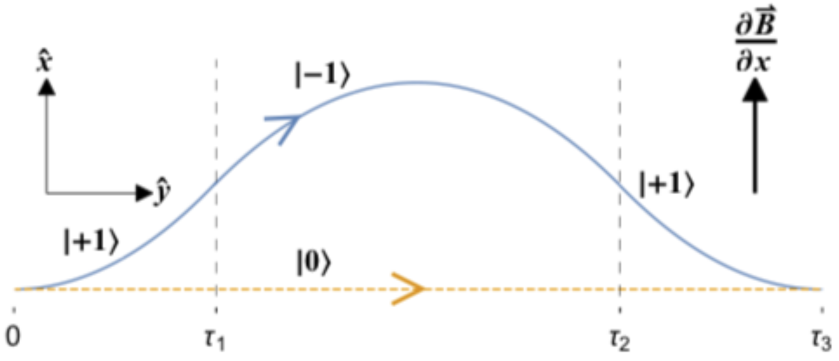
Bose + AM + Morley + Ulbricht + Toros + Paternostro + Geraci + Barker + Kim + Milburn,
Phy. Rev. Lett. [ArXiv: 1707.06050]

See Also: Marletto and Vedral appeared on the same day [1707.06036], Phys. Rev. Lett.
Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmyer [1807.0715], Phys. Rev. D
M. Christodoulou and C. Rovelli, 1808.05842 [gr-qc]

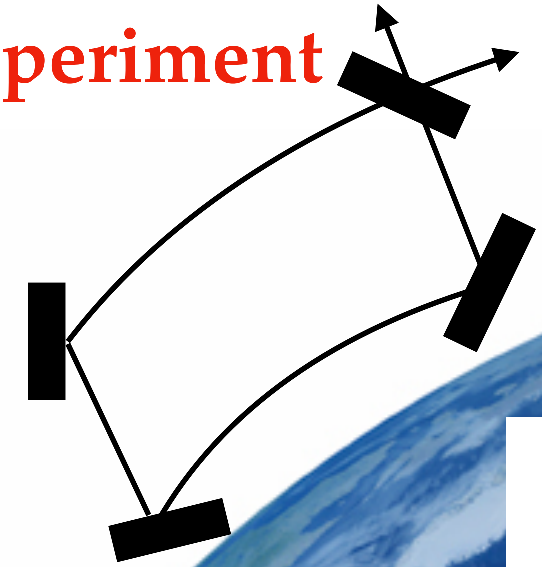
Gravitational Induced Phase is Detectable !

$$\Delta\phi \sim i\frac{S(G,\cdots)}{\hbar}$$

MIMAC

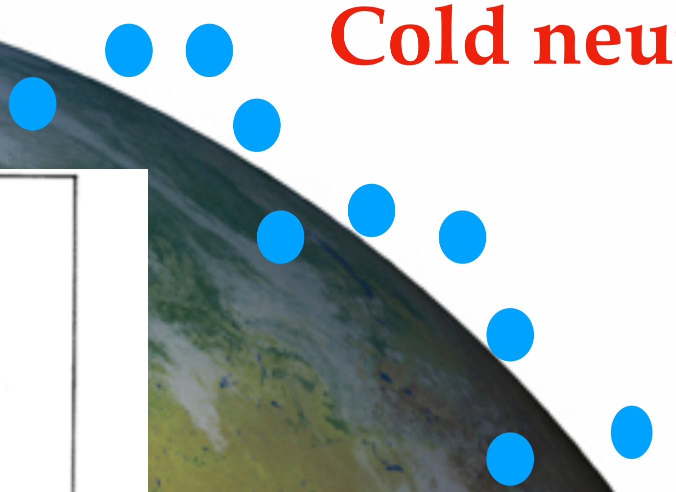


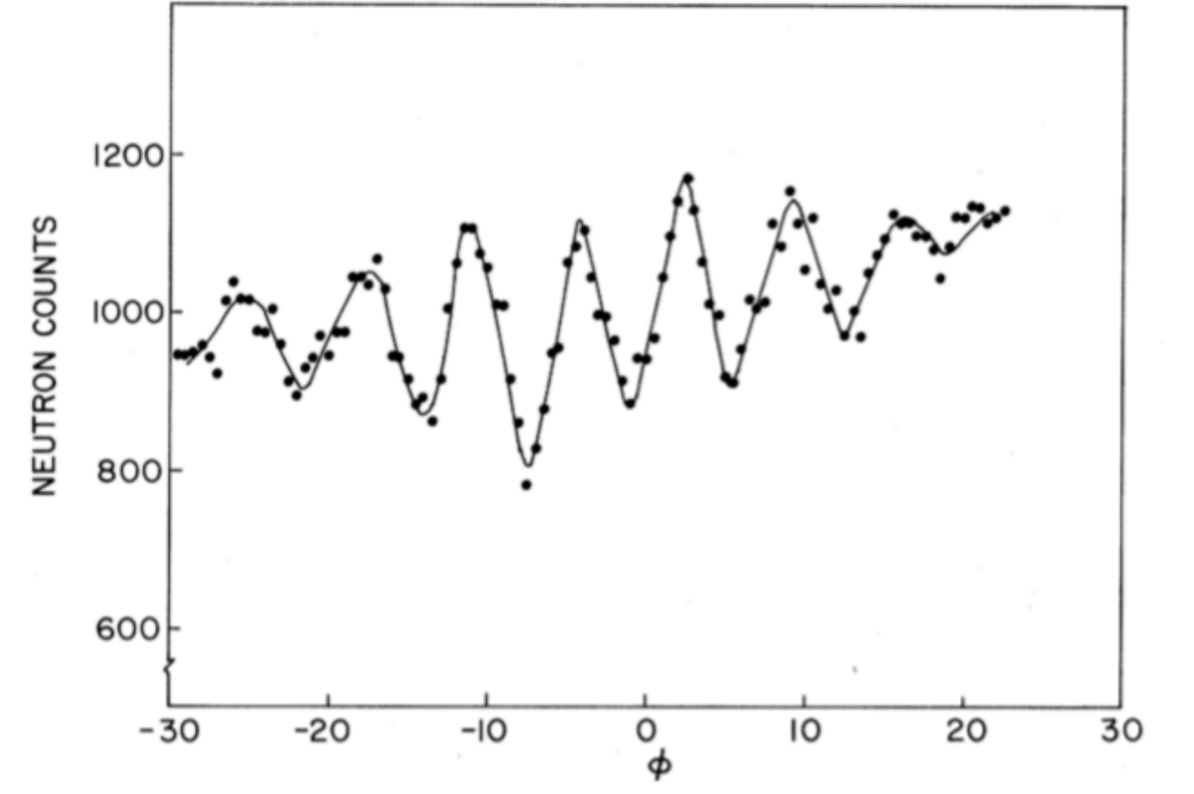
COW Experiment



Bouncing

Cold neutron





Levels of Excitements …

Can we put a graviton in a quantum superposition?

Can we study coalescing atoms, and see the loss of gravitons (quantized) in a laboratory?

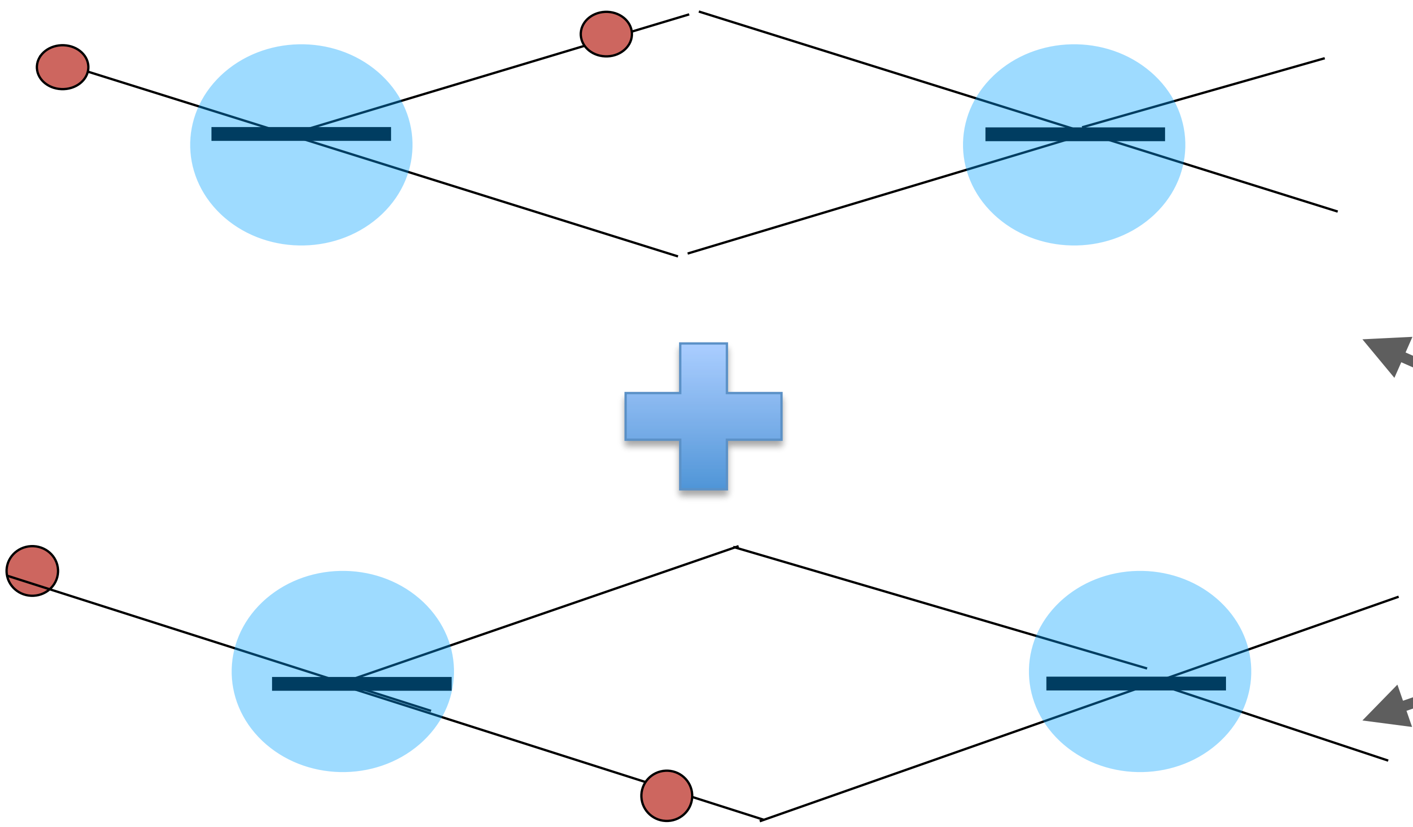
Can we witness quantum entanglement due to gravitons ?

Lively discussion with Markus Aspelmeyers on these issues last week in Vienna

Quantum World: “Off-Shell/Virtual”

The Superposition Principle **Underpins** Quantum Mechanics

Very familiar
in experiments

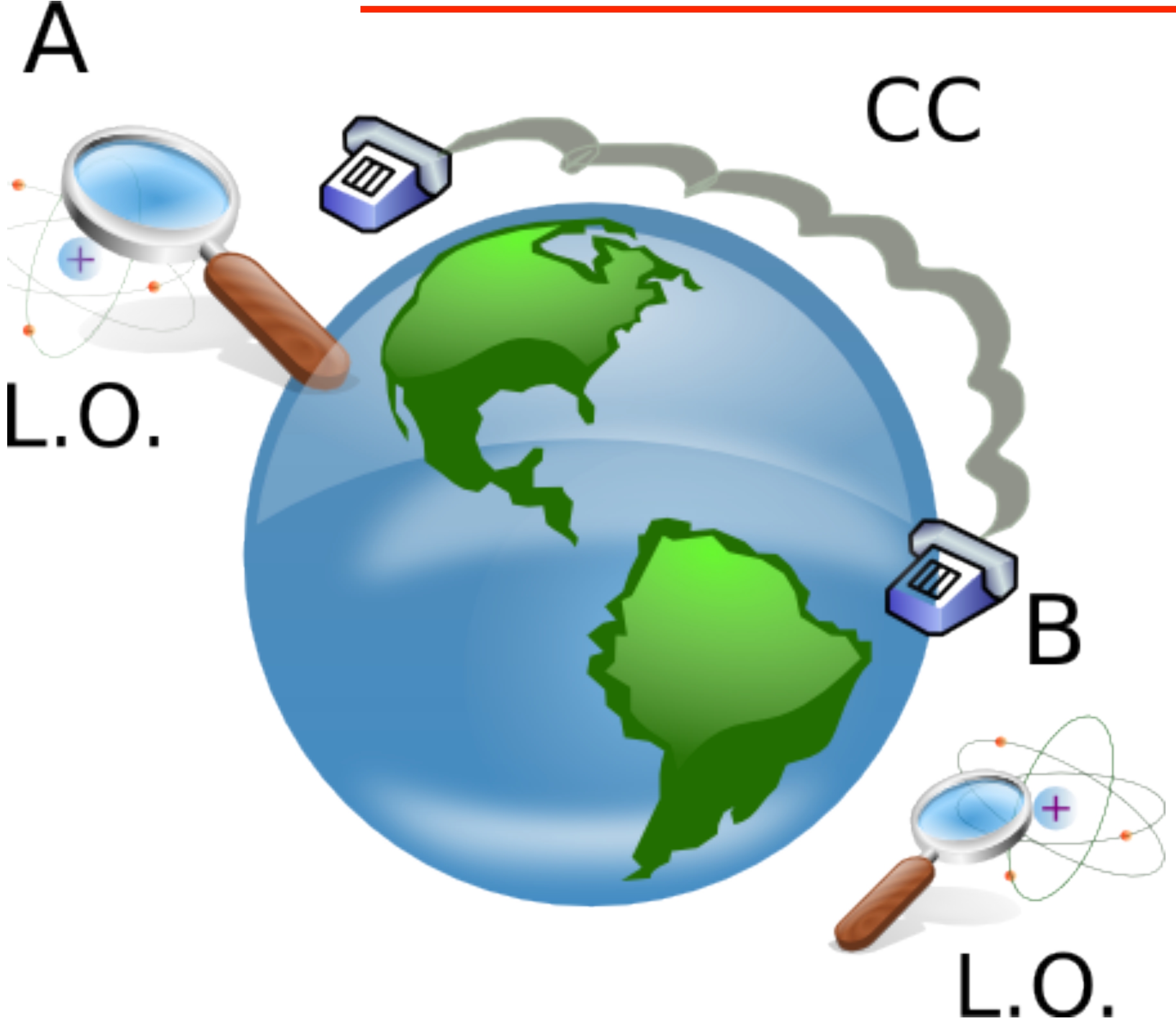


Off-shellness is critical even before creating superposition of macroscopic objects in a lab!!

Localization of 2 distinct classical paths

If you *decohere* (kill superpositions) nonclassical features of quantum mechanics go away.
Even old quantum mechanics: the right difference between energy levels obtained only through a superposition of localized states.

Local Operations & Classical Communication (LOCC)



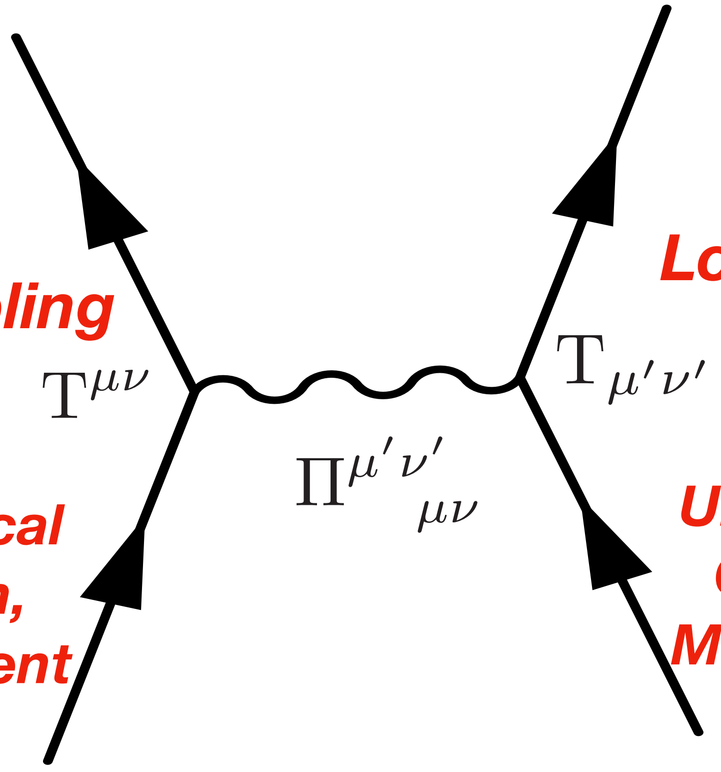
Cannot create Entanglement

Bennett, et.al, (1996)

LOCC keeps Separable state remains Separable (Cannot create entanglement)

Quantumness of the Mediator

Graviton as an Off-shell/Virtual mediator



Local coupling

Local coupling

Unitary Local Operation, Measurement

Unitary Local Operation, Measurement

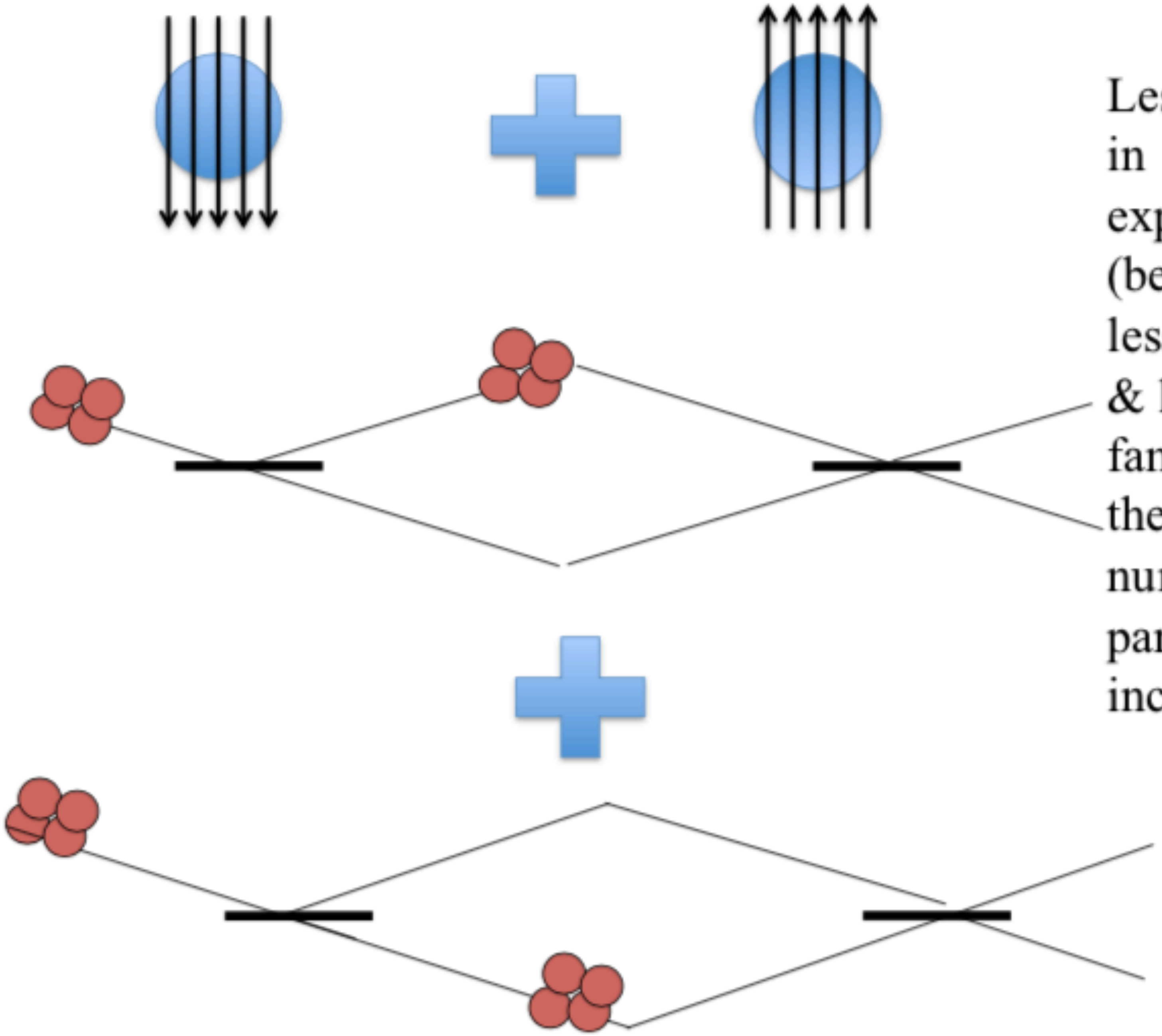
Virtual communication or Quantum communication via off shell mediator

$$\Pi(k^2) \sim \frac{P^{(2)}}{k^2} - \frac{P^{(0)}}{2k^2} \dashrightarrow V \sim \frac{1}{r}$$

Graviton propagator in terms of spin projection operators in 4d, Minkowski space time

P. Van Nieuwenhuizen, Nucl. Phys. B60, 478-492 (1973)
T. Biswas, T. Koivisto and A. Mazumdar,
``Nonlocal theories of gravity: the flat space propagator,''
arXiv:1302.0532 [gr-qc]

Challenges: Macroscopic & Maintaining the Superposition



Such superpositions are also called **GHZ** states or NOON states or **Schroedinger** Cat States

Less familiar in experiments (becomes less & less familiar as the number of particles increase)

Any mechanism from cooling to creating a potential is a source for Decoherence!

Arndt, Zeilinger and collaborators have demonstrated that superposition is attainable for 10^5 amu (Girlich, et.al., Nature, Arndt group)

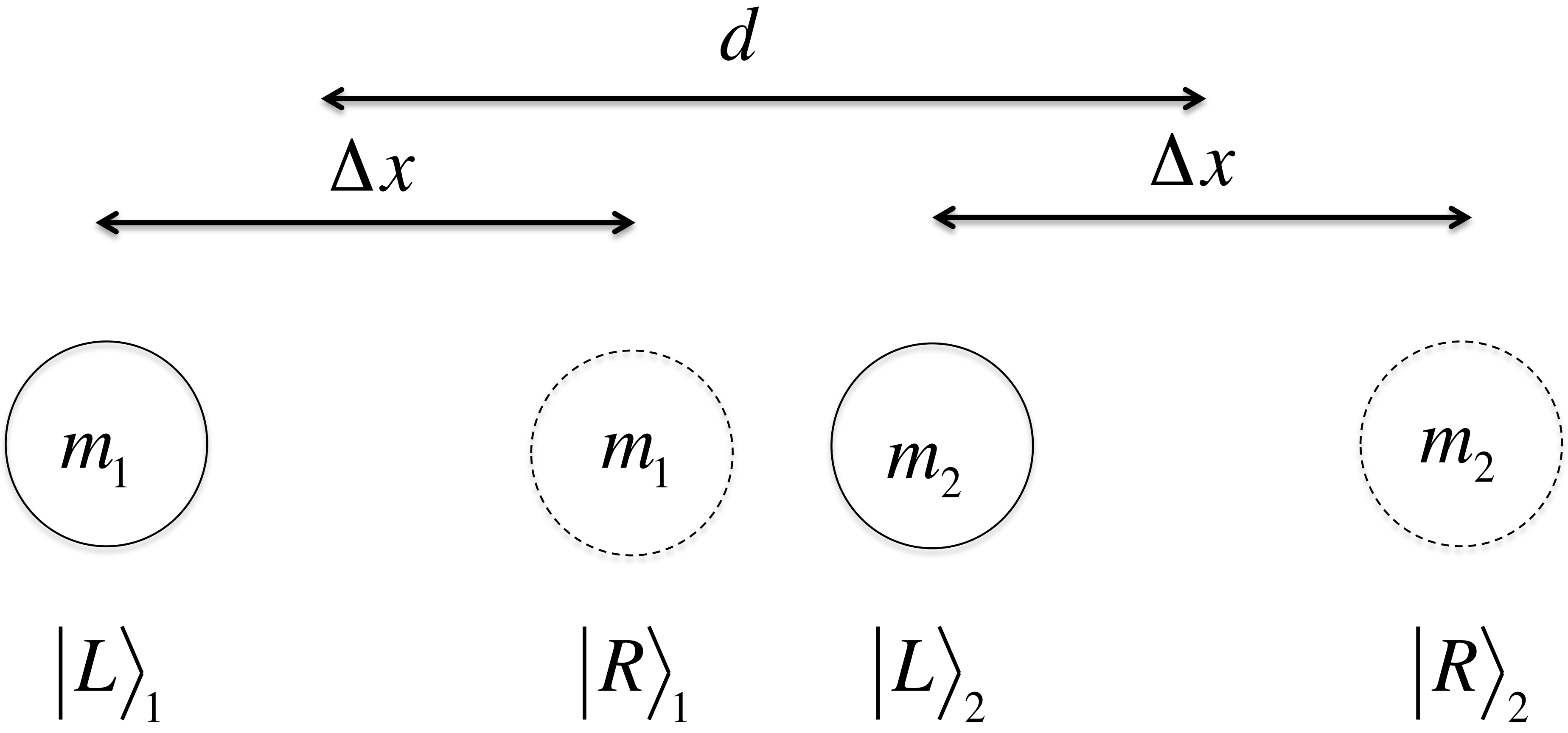
S. Bose, K. Jacobs, P. L. Knight, Phys. Rev. A 59 (5), 3204 (1999). [arXiv: 1997], S. Bose, PRL (2006)

Armour, Blencowe, Schwab, PRL 2002, Marshall, Simon, Penrose, Bouwmeester, PRL 2003.

M. Scala, M. S. Kim, G. W. Morley, P. F. Barker, S. Bose, PRL 111, 180403 (2013),

2 Masses & Virtual Graviton

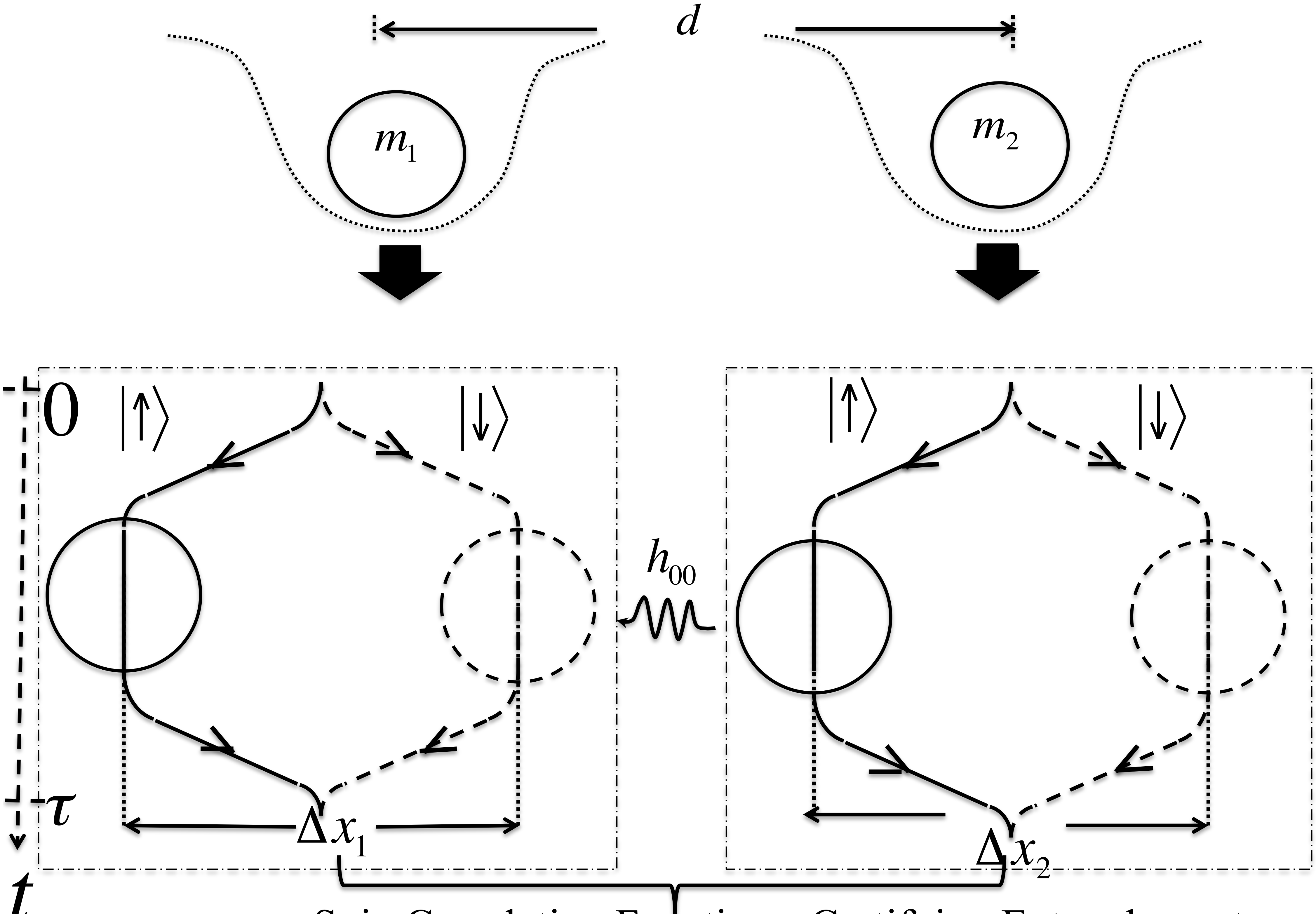
A Schematic of two matter-wave interferometers near each other



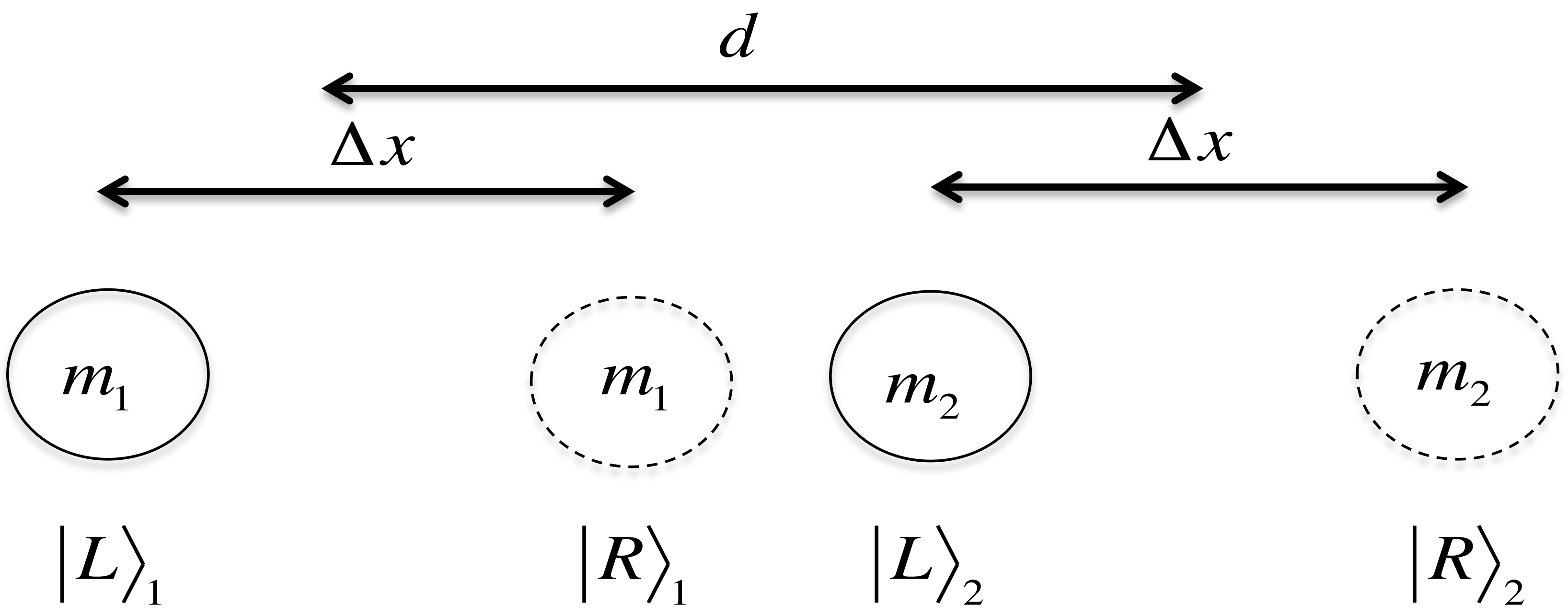
Consider two neutral test masses *held* in a superposition, each exactly as a path encoded qubit (states |L> and |R>), near each other.

Assume there are no other interactions for the time being other than pure gravitation

2 Stern Gerlachs



Spin Correlation Functions Certifying Entanglement



$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2)$$

$$= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2)$$

$$\to |\Psi(t=\tau)\rangle_{12} = \frac{1}{2}(e^{i\phi_{LL}}|L\rangle_1|L\rangle_2 + e^{i\phi_{LR}}|L\rangle_1|R\rangle_2 + e^{i\phi_{RL}}|R\rangle_1|L\rangle_2 + e^{i\phi_{RR}}|R\rangle_1|R\rangle_2),$$

where

$$\phi_{RL} \sim \frac{Gm_1m_2\tau}{\hbar(d-\Delta x)}, \phi_{LR} \sim \frac{Gm_1m_2\tau}{\hbar(d+\Delta x)},$$

$$\phi_{LL} = \phi_{RR} \sim \frac{Gm_1m_2\tau}{\hbar d}$$

Entanglement Phase

Step 4: Witness spin entangled state:

$$|\Psi(t=t_{\mathrm{End}})\rangle_{12} = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1 \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2) + |\downarrow\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2)\}|C\rangle_1|C\rangle_2$$

through the correlations:

$$\mathcal{W} = |\langle\sigma_x^{(1)}\otimes\sigma_z^{(2)}\rangle - \langle\sigma_y^{(1)}\otimes\sigma_z^{(2)}\rangle|$$

we have

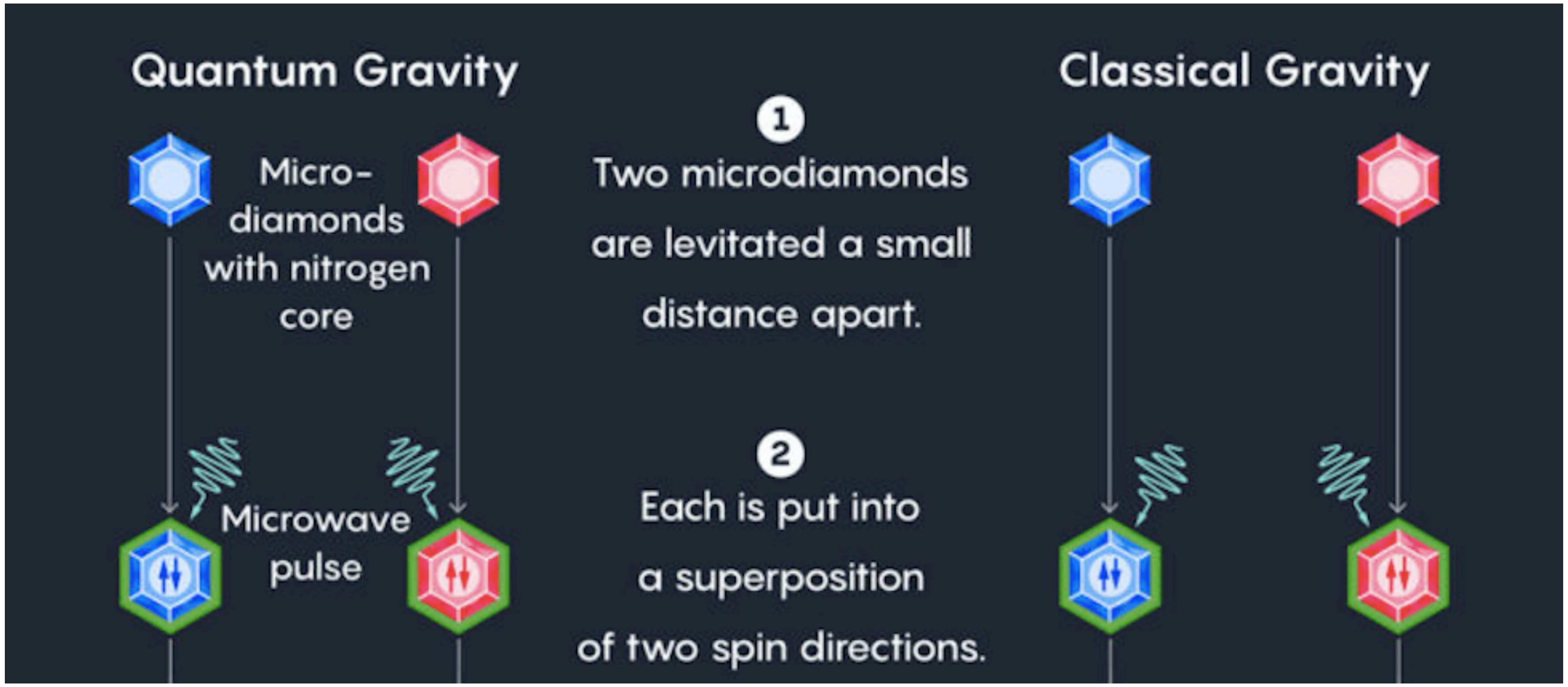
$$\Delta\phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar(d-\Delta x)} >> \Delta\phi_{LR}, \Delta\phi_{LL}, \Delta\phi_{RR}$$

$$\Delta\phi_{LR} + \Delta\phi_{RL} \sim \mathcal{O}(1)$$

For mass ~ 10^(-14) kg (microspheres), separation at closest approach of the masses ~ 200 microns (to prevent Casimir interaction), **time ~ 1 seconds**, gives:
Scale of superposition ~ 100 microns, **Delta phi_{RL} ~ 1**

Planck's Constant fights Newton's Constant!

Experimental Protocol



① Two microdiamonds are levitated a small distance apart.

② Each is put into a superposition of two spin directions.

$10^{-14} Kg$ Radius : 100nm Frequency of harmonic potential : 0.1MHz

Temperature : mK

Neutralising e.m. charges

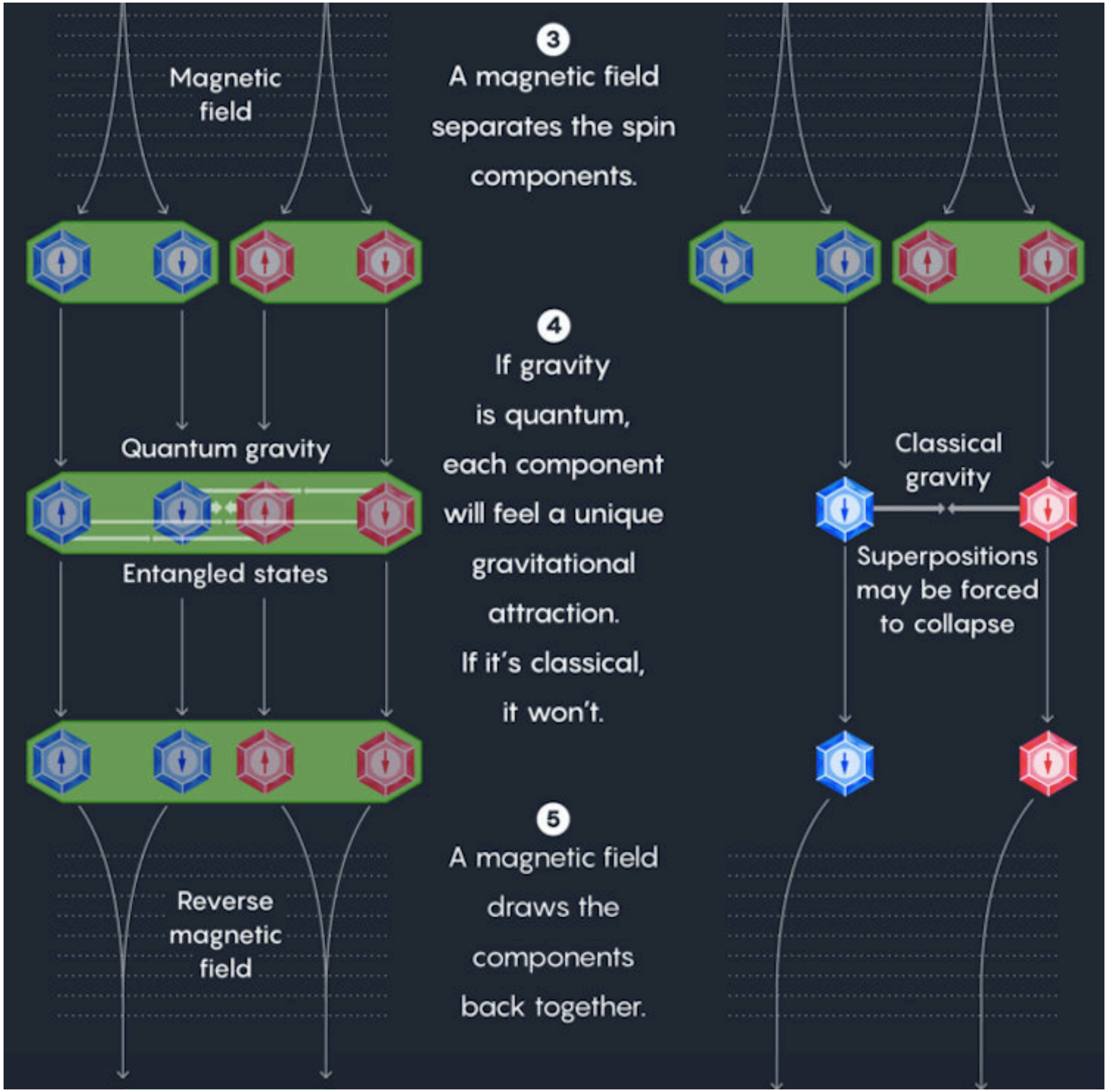
A magnetic field gradient of ~ 10^6 T/m and a time τacc ~ 500 m/s^2,
Δx ~ 250μm, d-Δx ~200μm

T. Krisnanda, M. Zuppardo, M. Paternostro, T. Paterek, arXiv:1607.01140. Superconducting sphere with half a micrometer separation (magnetically levitating)

C. Wan, M. Scala, G. W. Morley, ATM. A. Rahman, H. Ulbricht, J. Bateman, P. F. Barker, S. Bose, and M. S. Kim, Phys. Rev. Lett. 117, 143003 (2016); M. Frimmer, K.Luszcz, S. Ferreiro, V. Jain, E.Hebestreit, and L.Novotny, Phys. Rev. A95, 061801 (2017).

H. Pino, J. Prat-Camps, K. Sinha, B. P. Venkatesh, and O. Romero-Isart, arXiv:1603.01553v2

Challenges & Sources of Decoherence



Electronic spins coherent for 1s (in steps 1 and 3), which should be possible for macro-diamond below 77 K

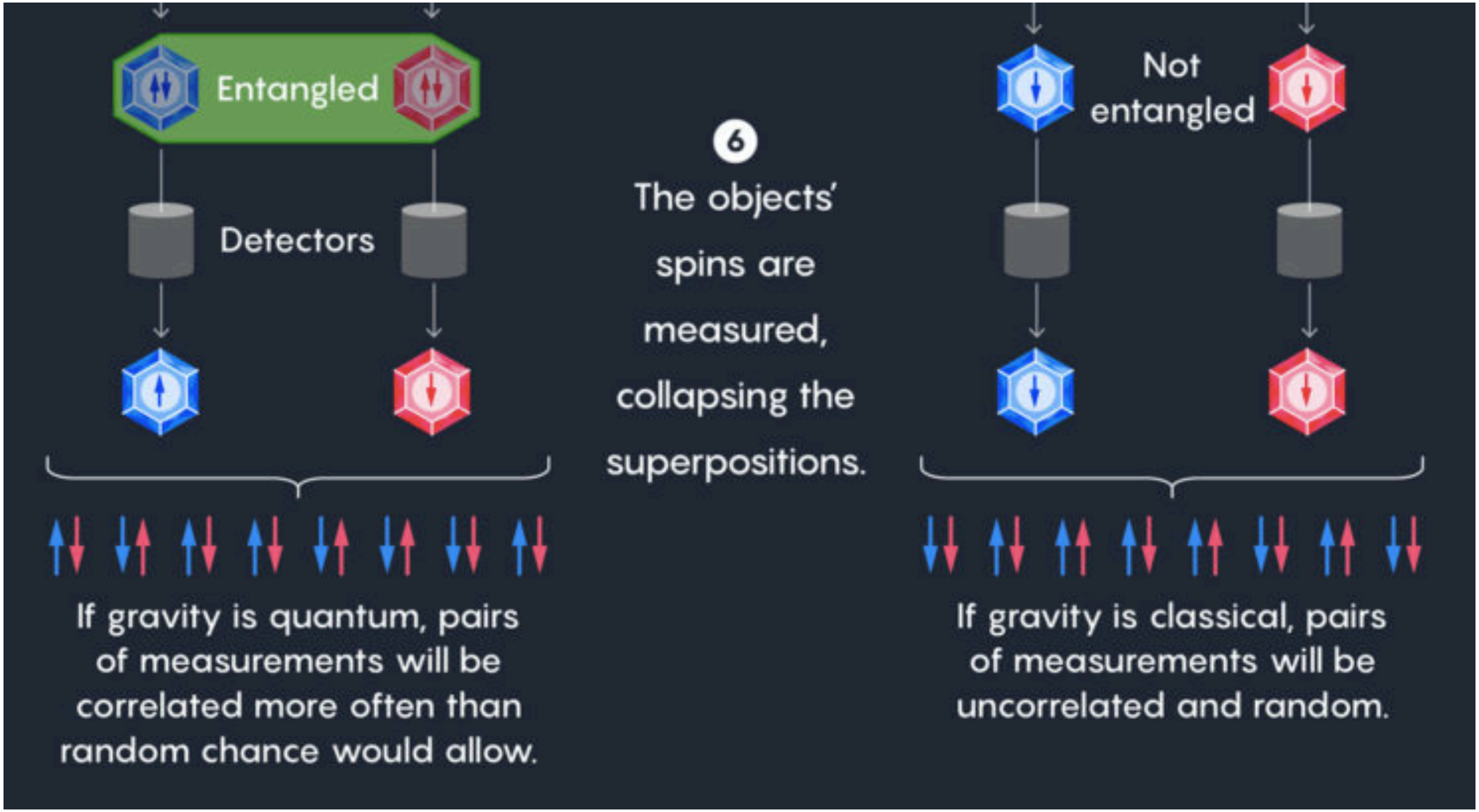
N. Bar-Gill, L.M. Pham, A. Jarmola, D. Budker, R. L. Walsworth, Nature Comm, 4, 1743 (2013),

S. Knowles, D. M. Kara and M. Atatu¨re, Nature Materials 13, 21 (2014),

Kaltenbaek, Aspelmeyer, (2015)

To estimate collisional and thermal decoherence times of the orbital degree of freedom we consider the pressure P = $10^{-15} Pa$ and the temperature 0.15 K. the collisional decoherence time for a superposition size of Δx ~ 250μm is the same order of magnitude as the total microsphere's fall time τ + 2τacc ~ 3.5 s

Measuring Spin Correlation & Establishing the Entanglement



The objects' spins are measured, collapsing the superpositions.

If gravity is quantum, pairs of measurements will be correlated more often than random chance would allow.

If gravity is classical, pairs of measurements will be uncorrelated and random.

$\mathcal{W} = |\langle \sigma_x^{(1)} \otimes \sigma_z^{(2)} \rangle - \langle \sigma_y^{(1)} \otimes \sigma_z^{(2)} \rangle|$ If $\mathcal{W} > 1 \implies$ *Graviton is quantum*

Basis Dependent Witness, similar to Bell's

Basis Independent Witness: $S_\mathrm{A} = -\mathrm{Tr}_\mathrm{A} \rho_\mathrm{A} \log \rho_\mathrm{A} = S_\mathrm{B}$

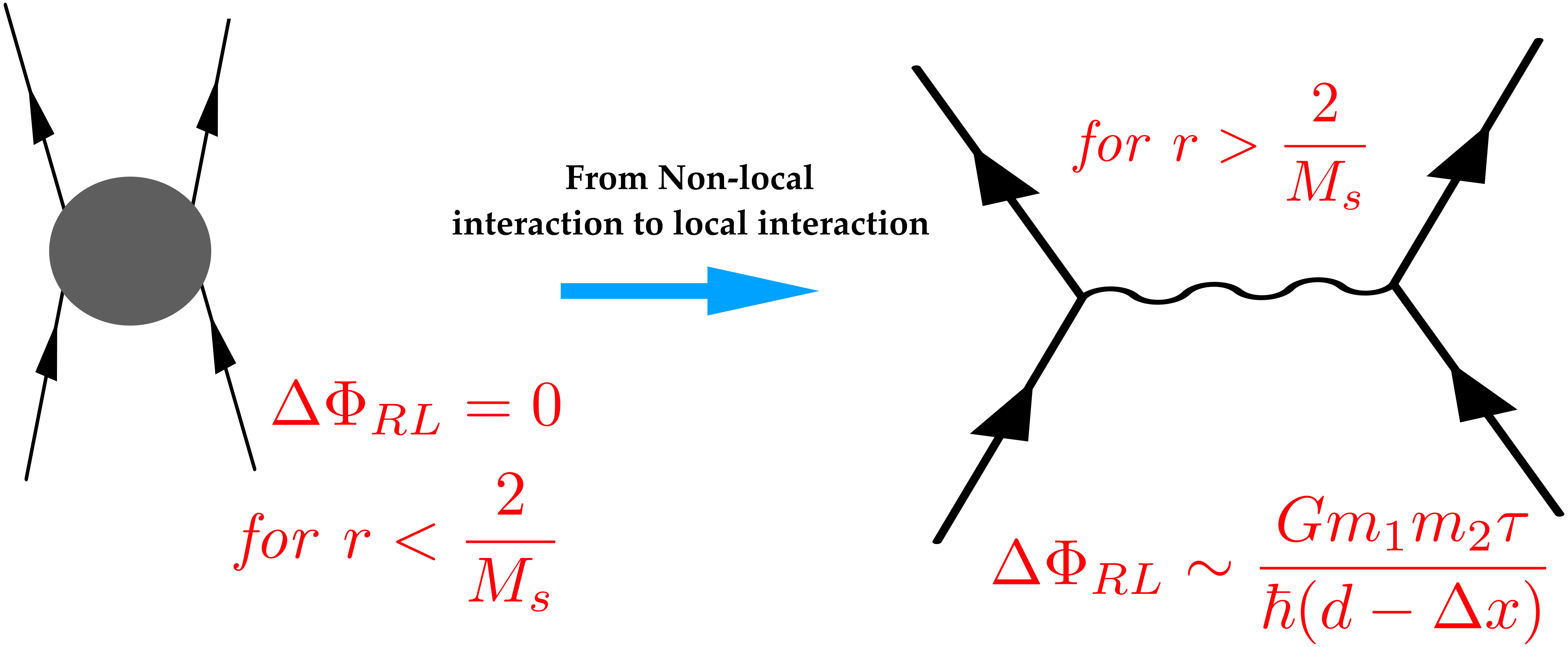
Quantum Entanglement Vanishes as we resolve Gravitational Singularity

Step 4: Witness spin entangled state:

$$
\begin{aligned}
|\Psi(t=t_{\mathrm{End}})\rangle_{12} = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1 \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2) \\
+ |\downarrow\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2)\}|C\rangle_1|C\rangle_2
\end{aligned}
$$

through the correlations:

$$\mathcal{W} = |\langle\sigma_x^{(1)}\otimes\sigma_z^{(2)}\rangle - \langle\sigma_y^{(1)}\otimes\sigma_z^{(2)}\rangle|$$



From Non-local interaction to local interaction

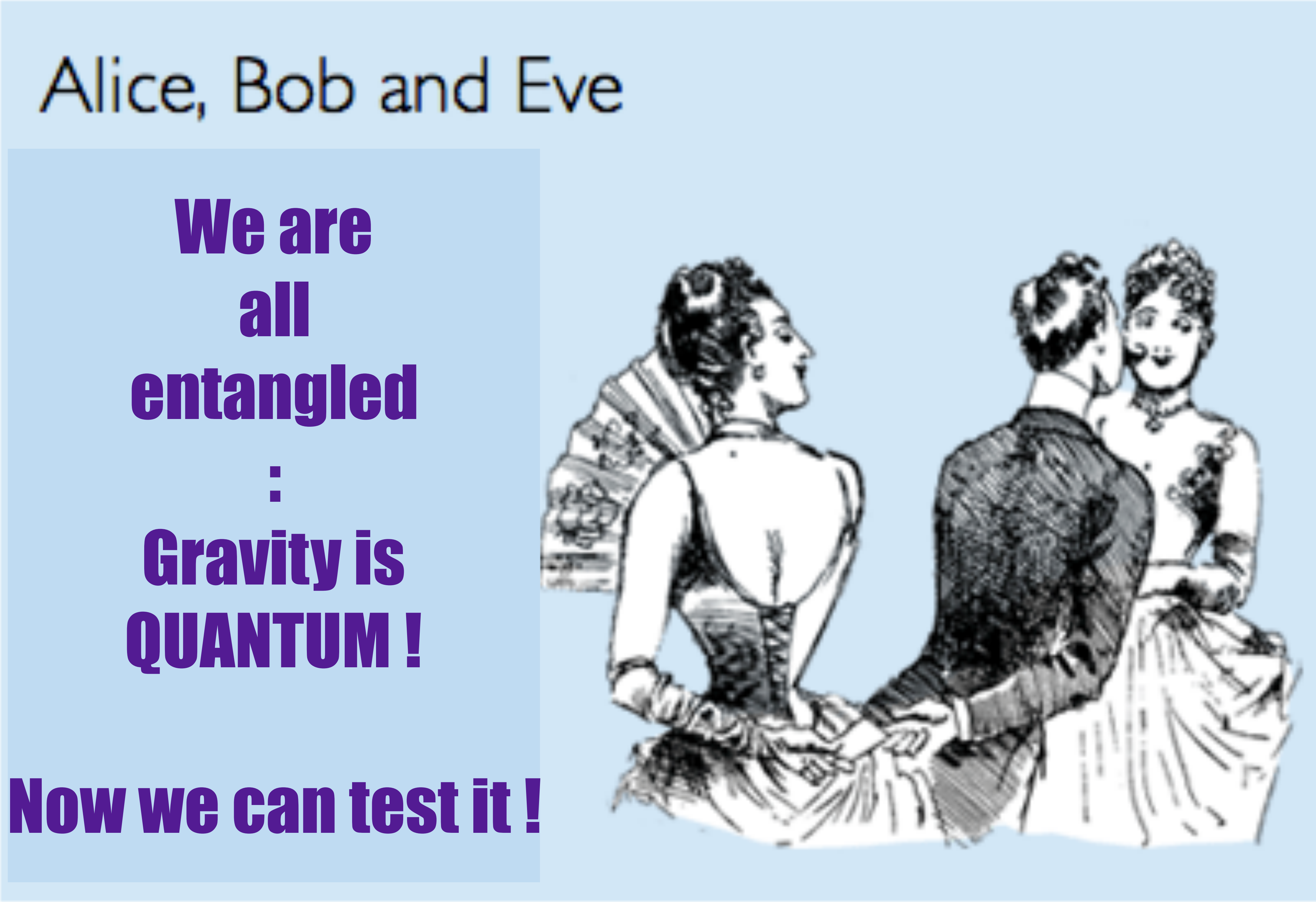
$$\Delta\Phi_{RL} = 0$$

$$for\ r < \frac{2}{M_s}$$

$$for\ r > \frac{2}{M_s}$$

$$\Delta\Phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar(d-\Delta x)}$$

Conclusion: We can potentially test linearized Quantum Gravity in a Lab !



Alice, Bob and Eve

We are
all
entangled
:
Gravity is
QUANTUM !

Now we can test it !

Bose+AM+Morley+Ulbricht+Toros+Paternostro+Geraci+Barker+Kim+Milburn, PRL (2017) [1707.06050]

Relevant Publications

T. Biswas, E. Gerwick, T. Koivisto and A. Mazumdar,
``Towards singularity and ghost free theories of gravity,'' [arXiv:1110.5249 [gr-qc]].

T. Biswas, A. Mazumdar and W. Siegel,
``Bouncing universes in string-inspired gravity,'' [hep-th/0508194].

L. Buoninfante, A. S. Koshelev, G. Lambiase and A. Mazumdar,
``Classical properties of non-local, ghost- and singularity-free gravity,'' [arXiv:1802.00399 [gr-qc]].

L. Buoninfante, A. S. Koshelev, G. Lambiase, J. Marto and A. Mazumdar,
``Conformally-flat, non-singular static metric in infinite derivative gravity,'' [arXiv:1804.08195 [gr-qc]].

L. Buoninfante, A. S. Cornell, G. Harmsen, A. S. Koshelev, G. Lambiase, J. Marto and A. Mazumdar,
``Towards nonsingular rotating compact object in ghost-free infinite derivative gravity,'' [arXiv:1807.08896 [gr-qc]].

L. Buoninfante, A. Ghoshal, G. Lambiase and A. Mazumdar,`
`Transmutation of nonlocal scale in infinite derivative field theories,'' arXiv:1812.01441 [hep-th].

A. Ghoshal, A. Mazumdar, N. Okada and D. Villalba,
``Stability of infinite derivative Abelian Higgs models,' [arXiv:1709.09222 [hep-th]].

Bose+AM+Morley+Ulbricht+Toros+Paternostro+Geraci+Barker+Kim+Milburn, PRL (2017) [1707.06050]

Extra Slides

Degrees of freedom & Ghosts

$$\Pi(k^2) = \frac{1}{k^2}\left[P^{(2)} - \frac{P^{(0)}}{2}\right] - \frac{P^{(2)}}{k^2 - m_2^2} + \frac{P^{(0)}}{2(k^2 - m_0^2)}$$

$$m_2 = -(\beta/2)^{-1/2}, \quad m_0 = (\alpha + \beta)^{-1/2}$$

Massive Spin-0 & Massive Spin-2 (Ghost) Stelle (1977)

Utiyama (1960), De Witt (1961), Stelle (1977)

Modification of Einstein's GR

Modification of Graviton Propagator

Extra propagating degrees of freedom

Challenge: How to get rid of the extra dof ?

Avoiding Ghosts: Stability

Higher derivative theories generically carry Ghosts (-ve Risidue)

$$S = \int d^4x \ \phi\Box(\Box + m^2)\phi \Rightarrow \Box(\Box + m^2)\phi = 0$$

$$\Delta(p^2) \sim \frac{1}{p^2} - \frac{1}{p^2 - m^2}$$

Propagator with first order poles

Ghosts cannot be cured order by order, finite terms in perturbative expansion will always lead to Ghosts !!

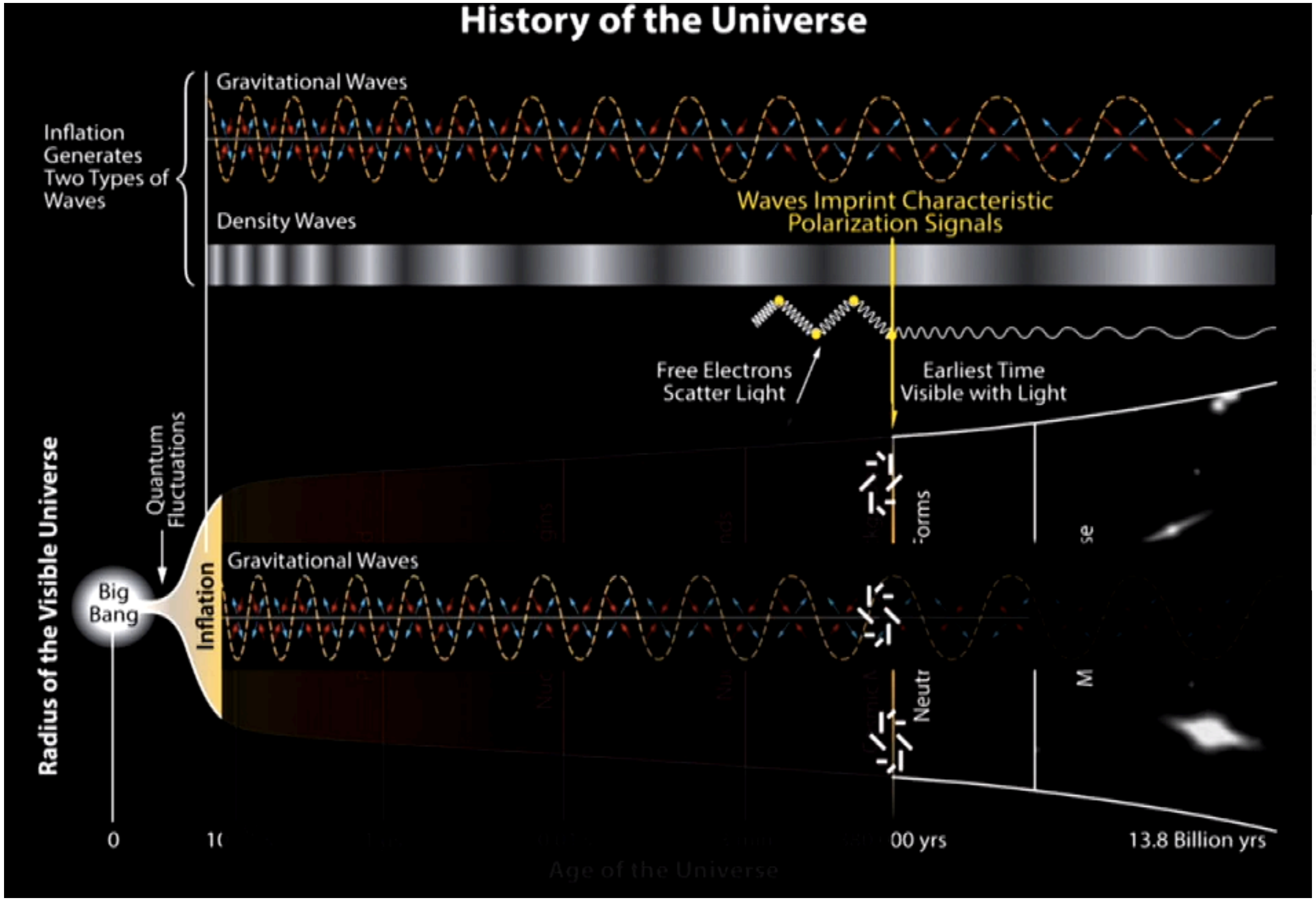
$$S = \int d^4x \ \phi e^{-\Box/M^2}(\Box + m^2)\phi \Rightarrow e^{-\Box/M^2}(\Box + m^2)\phi = 0$$

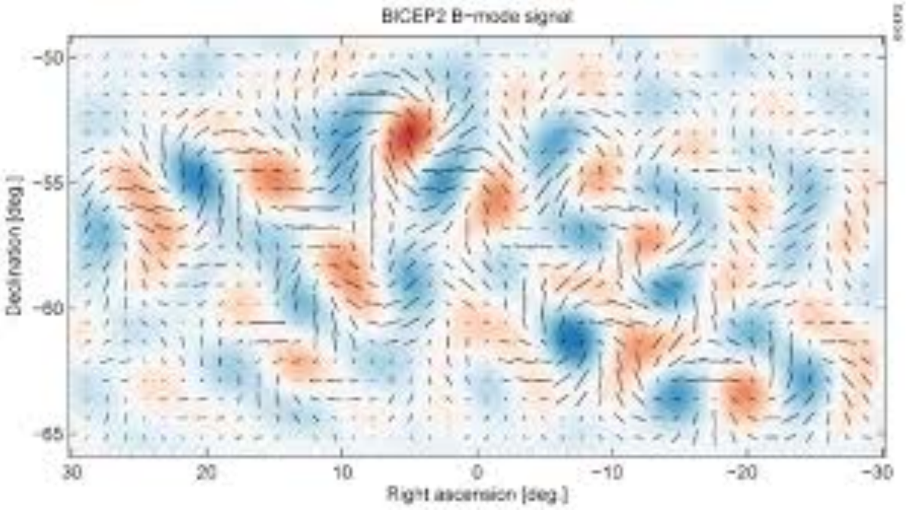
$$\Delta(p^2) = \frac{e^{-p^2/M^2}}{p^2 - m^2}$$

No extra states other than the original dof.

Woodard (1991), Moffat (1991), Tomboulis (1997), Tseytlin (1997), Siegel (2003), Biswas, Grisaru, Siegel (2004), Biswas, Mazumdar, Siegel (2006), Witten (2015), Sen (2016, 2017), ….

Gravity being Classical or Quantum



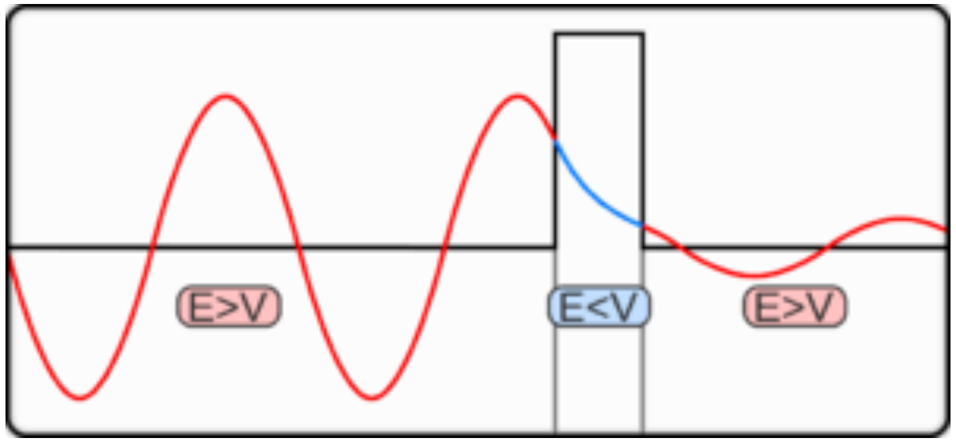


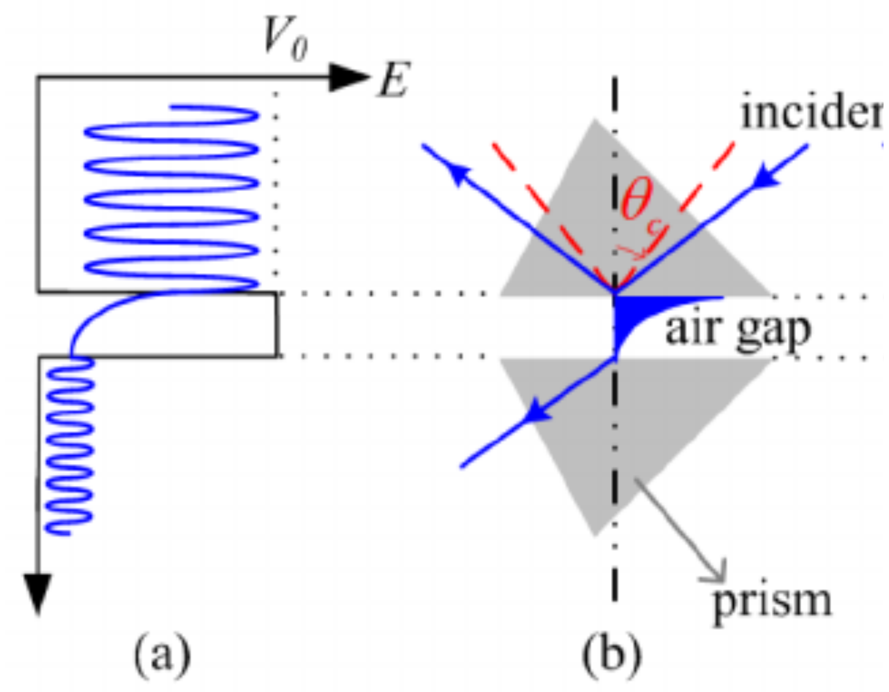
Correct observation, but wrong interpretation

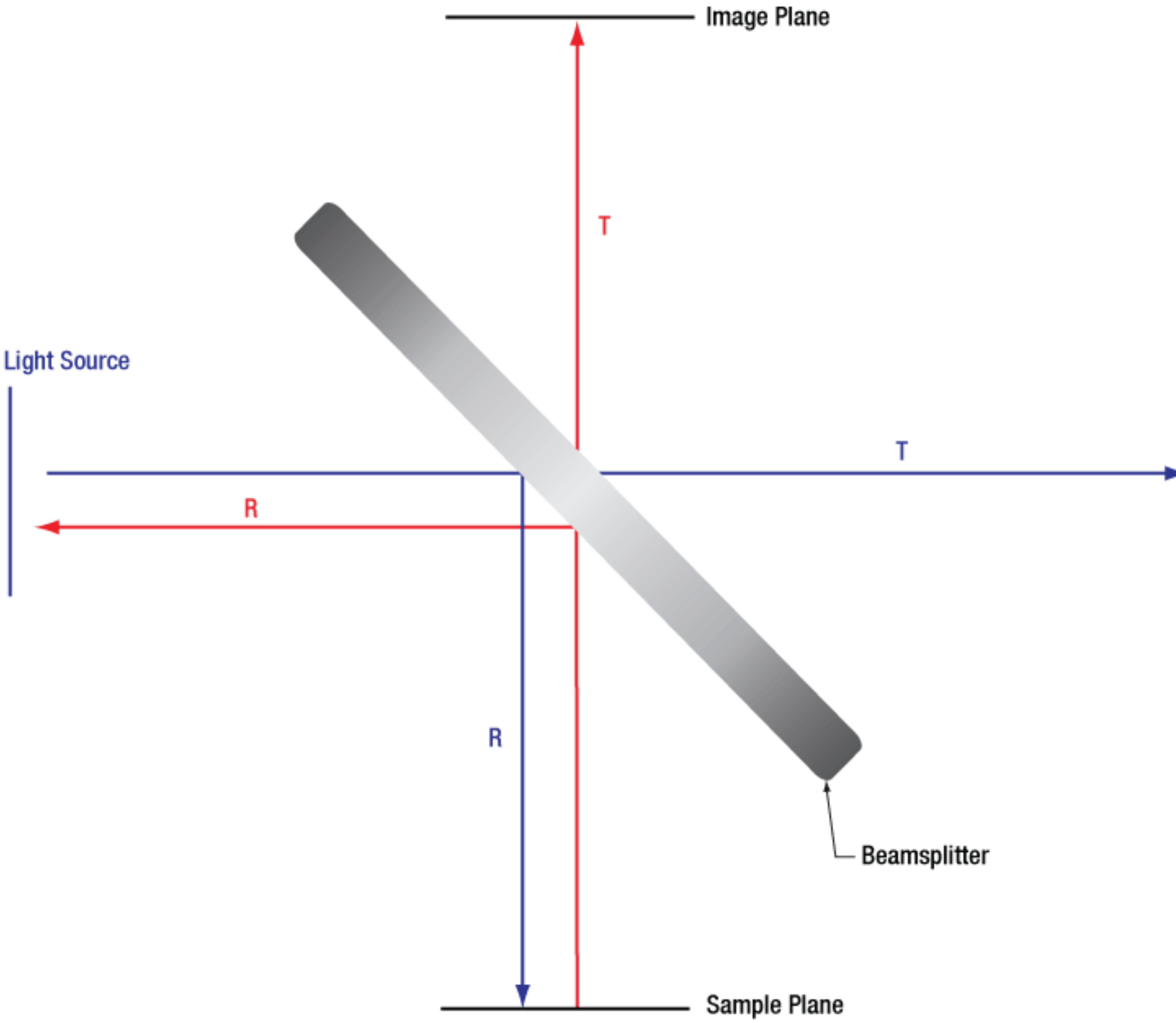
A. Ashoorioon, P. S. Bhupal Dev and A. Mazumdar,
``Implications of purely classical gravity for inflationary tensor modes,''
Mod. Phys. Lett. A 29, no. 30, 1450163 (2014)
[arXiv:1211.4678 [hep-th]].

L. M. Krauss and F. Wilczek,
``Using Cosmology to Establish the Quantization of Gravity,''
Phys. Rev. D 89, no. 4, 047501 (2014)
[arXiv:1309.5343 [hep-th]].

Quantum "Off-shell"



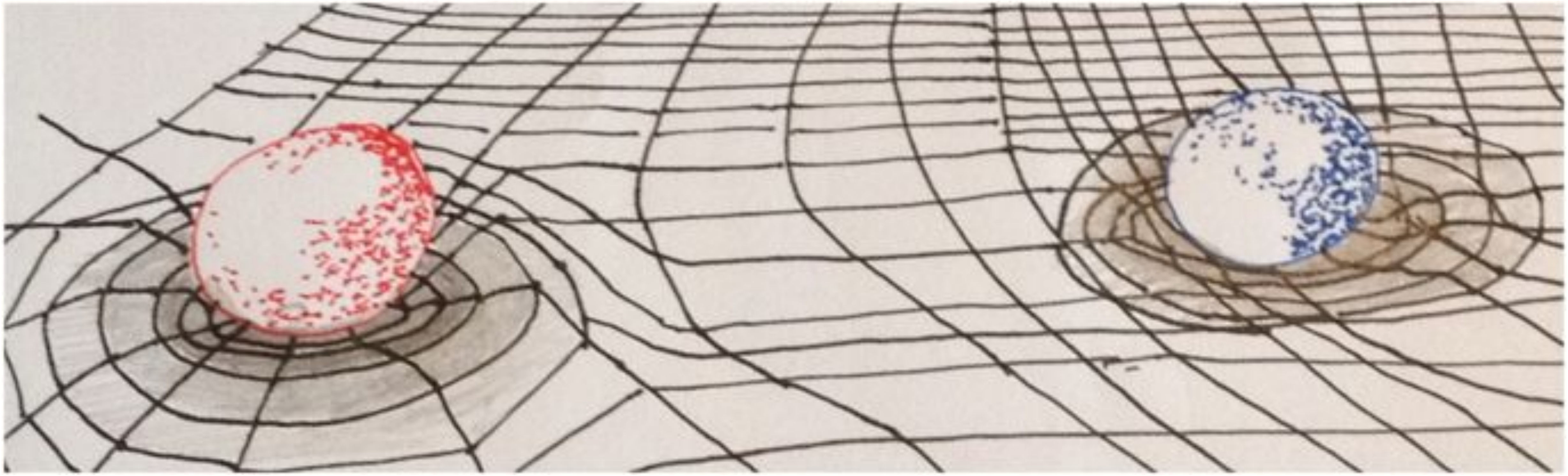




Quantum Tunnelling is an off-shell process

Linearized Quantum Gravity

Graviton must obey the quantum superposition principle



$h_{\mu\nu}$ are also localized

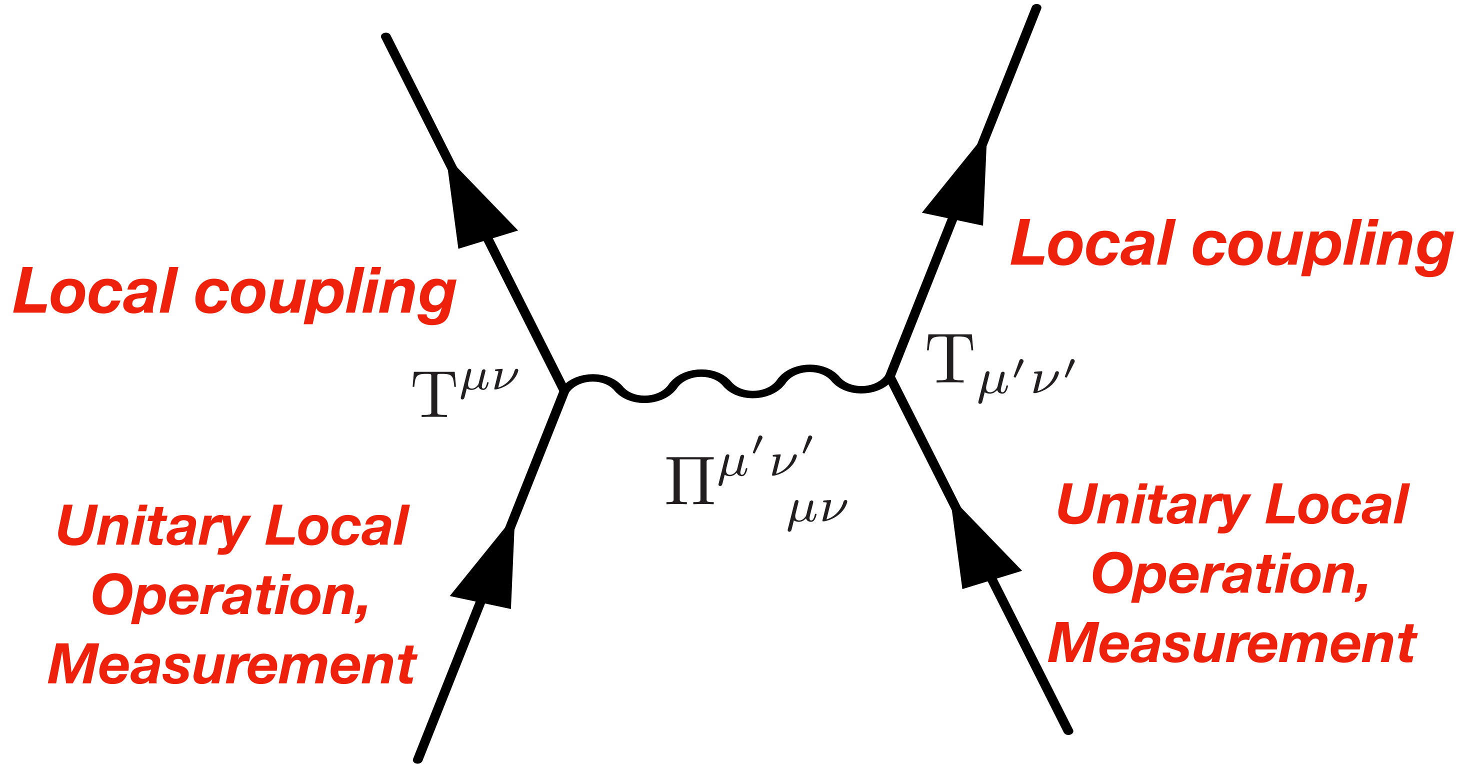
$G_{\mu\nu} \propto T_{\mu\nu}$

Provided we can prepare masses in Fock state & control decoherence.

This will not be so for Bose-Einstein Condensate, or if matter is in a Coherent state!!

Linearized Quantum Gravity

Graviton as an Off-shell/Virtual mediator



Local coupling

$T^{\mu\nu}$

Local coupling

$T_{\mu'\nu'}$

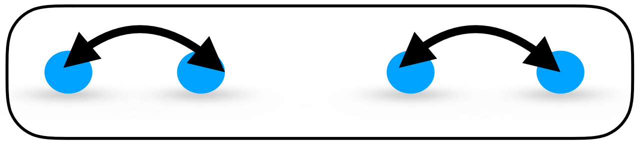
$\Pi^{\mu'\nu'}{}_{\mu\nu}$

Unitary Local Operation, Measurement

Unitary Local Operation, Measurement

Virtual communication or Quantum communication via off shell mediator

Product State

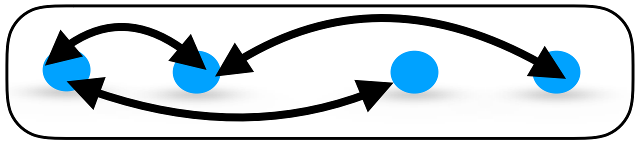


A | **B**

$$|\Psi\rangle = |\Psi\rangle_{\mathrm{A}} \otimes |\Psi\rangle_{\mathrm{B}}$$

Pure | **Trace**

Entangled State



A | **B**

$$|\Psi\rangle \neq |\Psi\rangle_{\mathrm{A}} \otimes |\Psi\rangle_{\mathrm{B}}$$

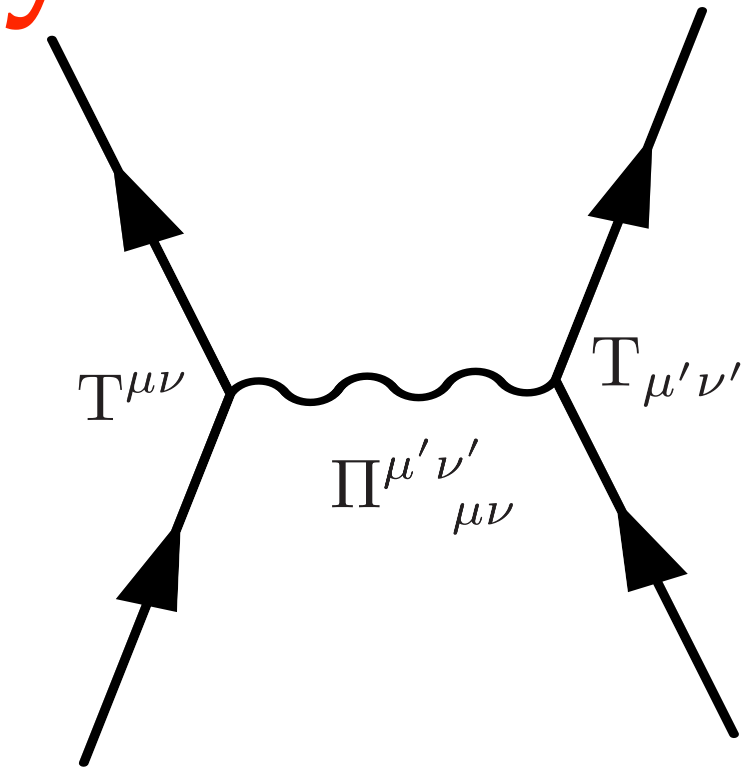
Mixed | **Trace**

$$\Pi(k^2) \sim \frac{P^{(2)}}{k^2} - \frac{P^{(0)}}{2k^2}$$

$$\Downarrow$$

$$V \sim \frac{1}{r}$$

Probing UV gravity



(1) GR: $\lim_{k^2\to 0} \Pi = (\mathcal{P}^2/k^2) - (\mathcal{P}^0_s/2k^2) \equiv \Pi_{GR}$

(2) F(R) Gravity:

$$\mathcal{L}(R) = \mathcal{L}(0) + \mathcal{L}'(0)R + \frac{1}{2}\mathcal{L}''(0)R^2 + \cdots$$

$$\Pi = \Pi_{GR} + \frac{1}{2}\frac{\mathcal{P}^0_s}{k^2+m^2}, \qquad m^2 = \frac{1}{3\mathcal{L}''(0)}$$

$$V \sim \frac{1}{r}e^{-mr} + \cdots$$

(3) Weyl Gravity:

$$\mathcal{L} = R - \frac{1}{m^2}C^2 \qquad C^2 = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 2R_{\mu\nu}R^{\mu\nu} + \frac{1}{3}R^2$$

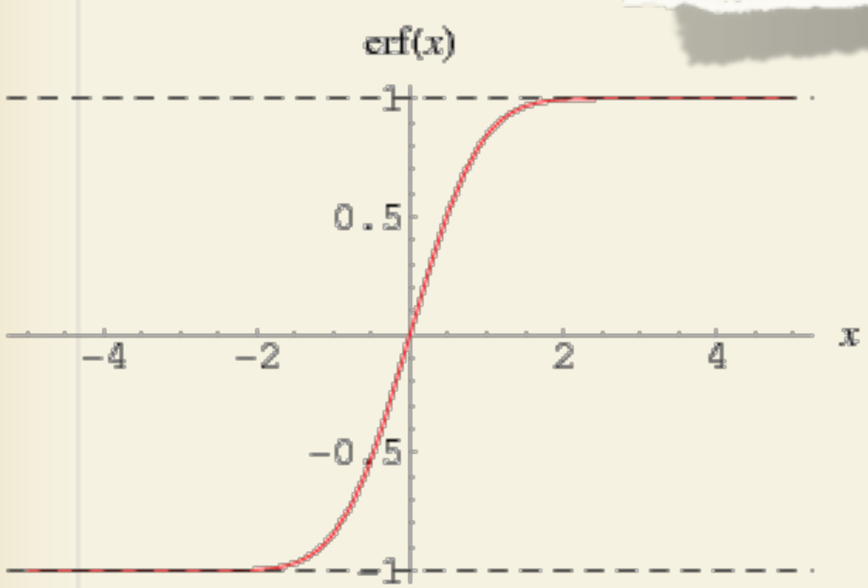
$$\Pi = \frac{\mathcal{P}^2}{k^2\left(1-(k/m)^2\right)} - \frac{\mathcal{P}^0_s}{2k^2} = \Pi_{GR} - \frac{\mathcal{P}^2}{k^2+m^2}$$

Infinite Derivative Gravity (IDG): Non-Singular gravity

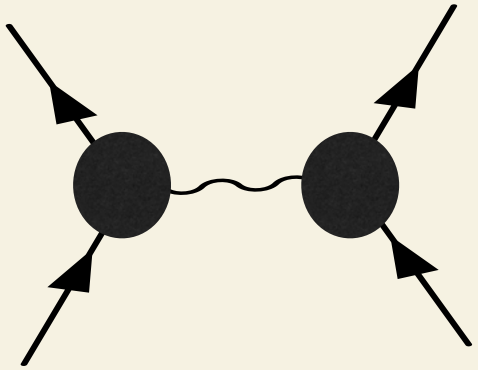
$$S = \int d^4x \, \sqrt{-g} \left[\frac{R}{2} + R \left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box} \right] R - 2R_{\mu\nu} \left[\frac{e^{-\frac{\Box}{M^2}} - 1}{\Box} \right] R^{\mu\nu} \right]$$

$$ds^2 = -(1 - 2\Phi)dt^2 + (1 + 2\Psi)dr^2$$

$$\Phi = \Psi = \frac{Gm}{r}\mathbf{erf}\left(\frac{rM}{2}\right)$$



Interaction becomes Non-Local

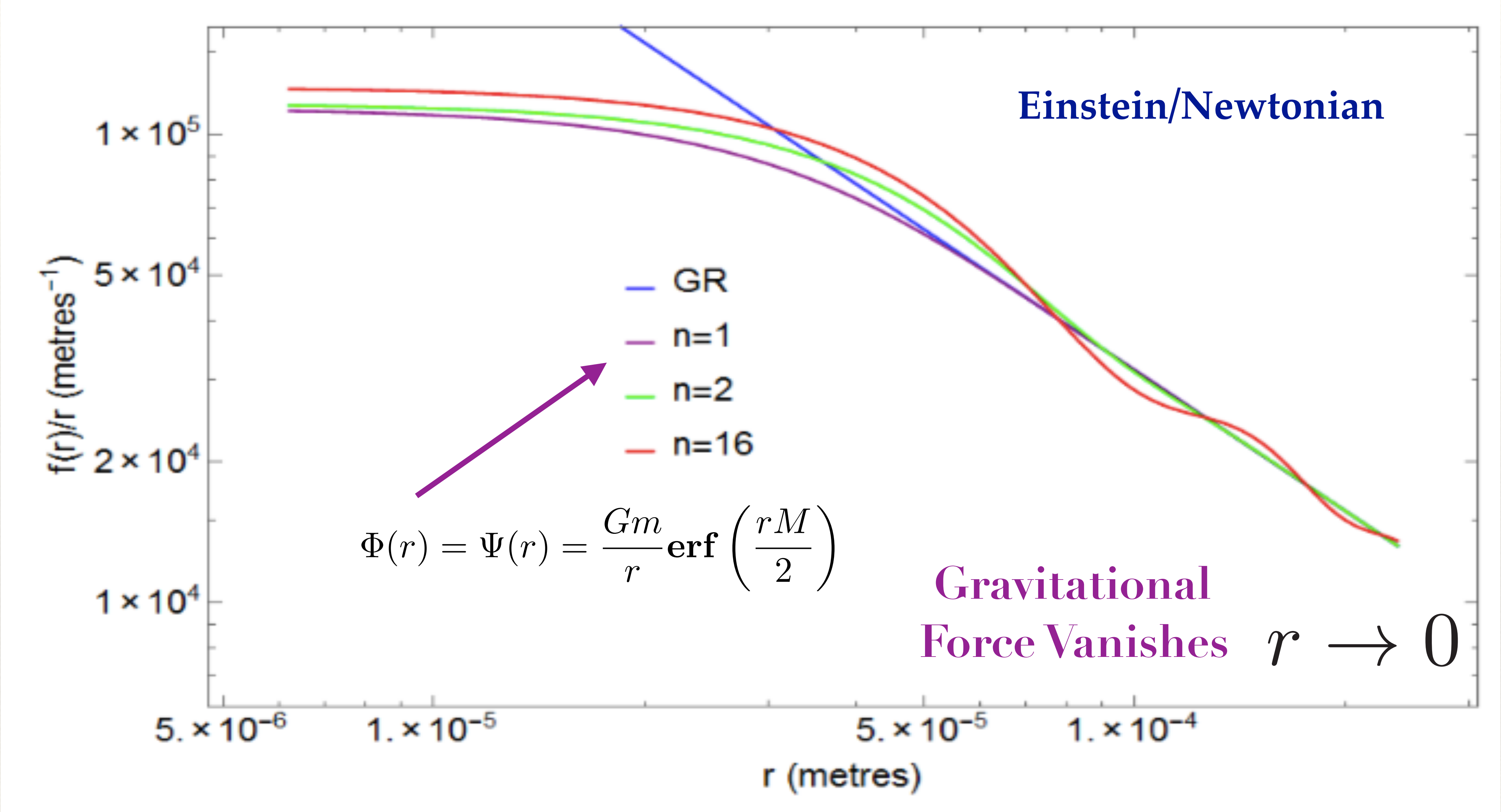


Biswas, Mzumdar, Siegel, JCAP (2005),
Biswas, Gerwick, Koivisto, Mazumdar, Phys. Rev. Lett. (2012) (gr-qc/1110.5249)
Dombriz, Jose, Mazumdar, With Space-time Torsion: 1812.04037

Resolution of Singularity at short distances

$$a(\Box) = e^{\gamma(\Box)}$$

Any Entire Function: $\gamma(\Box) = -\frac{\Box}{M^2} - \sum_N a_N \left(\frac{\Box}{M^2}\right)^N$



Einstein/Newtonian

$$\Phi(r) = \Psi(r) = \frac{Gm}{r}\mathbf{erf}\left(\frac{rM}{2}\right)$$

Gravitational Force Vanishes $r \to 0$

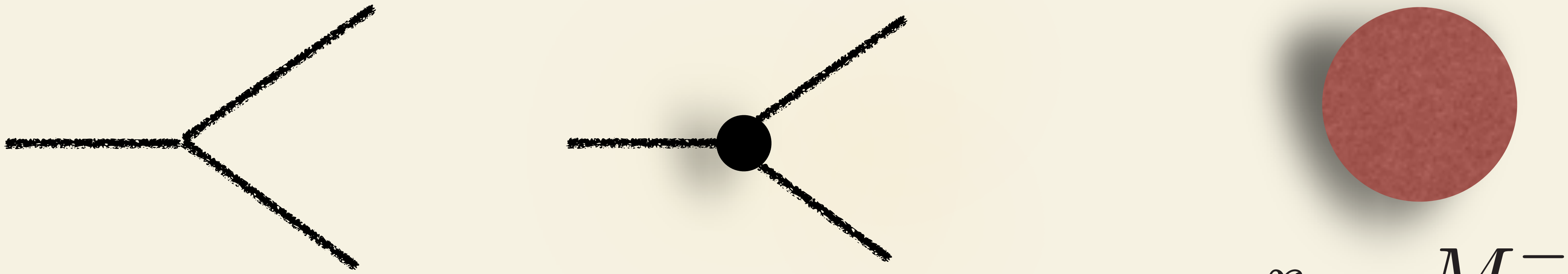
$$mM \ll M_p^2 \implies m \ll M_p$$

Current Bound : M > 0.01 eV $m \le 10^{25}$ grams

Biswas, Gerwick, Koivisto, AM (2012), Edholm, Koshelev, AM (2016), Frolov & Zelnikov (2015, 2016)

Local vs Non-Local Field Theory

$$S = \int d^4x \left[-\frac{1}{2}\phi e^{\frac{\Box + m^2}{M^2}} (\Box + m^2)\phi - \frac{\lambda}{4!}\phi^4 \right] \qquad \Pi(p^2) = -\frac{i e^{-\frac{p^2+m^2}{M^2}}}{p^2 + m^2}$$



$P^2 < M^2$

$P^2 \geq M^2$

$r \sim M^{-1}$

Scale of Non-Locality

$$\delta m^2 \sim \lambda M^2 \qquad \Gamma_4 \sim -\lambda^2 e^{-2m^2/M^2}\left[1 + \mathcal{O}(m^2/M^2)\right]$$

$$\sigma_{NL}(f\bar{f} \to f'\bar{f}') = e^{-s/M^2}\sigma_L(f\bar{f} \to f'\bar{f}')$$

Moffat Phys.Rev.D (1990), Biswas + Okada, Nucl. Phys. B (2016)