Current Quantum Gravity Theories, Experimental Evidence, Philosophical Implications

carlo rovelli
IHES 2017

1. We have quantum gravity theories

2. We have have empirical evidence

3. There is some understanding on some issues of major philosophical relevance

    i: nature of physical space

    ii: nature of physical time

    iii: relation between physical and experiential time

    iv: connection between relational aspects of GR and QM

1. **We do have quantum gravity theories**

Many directions of investigation

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loop quantum gravity,
string theory,
asymptotic safety,
Hořava–Lifshitz theory,
supergravity,
AdS-CFT-like dualities
twistor theory,
causal set theory,
entropic gravity,
emergent gravity,
non-commutative geometry,
group field theory,
Penrose nonlinear quantum dynamics
causal dynamical triangulations,
shape dynamics,
’t Hooft theory
non-quantization of geometry
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Vastly different numbers of researchers involved

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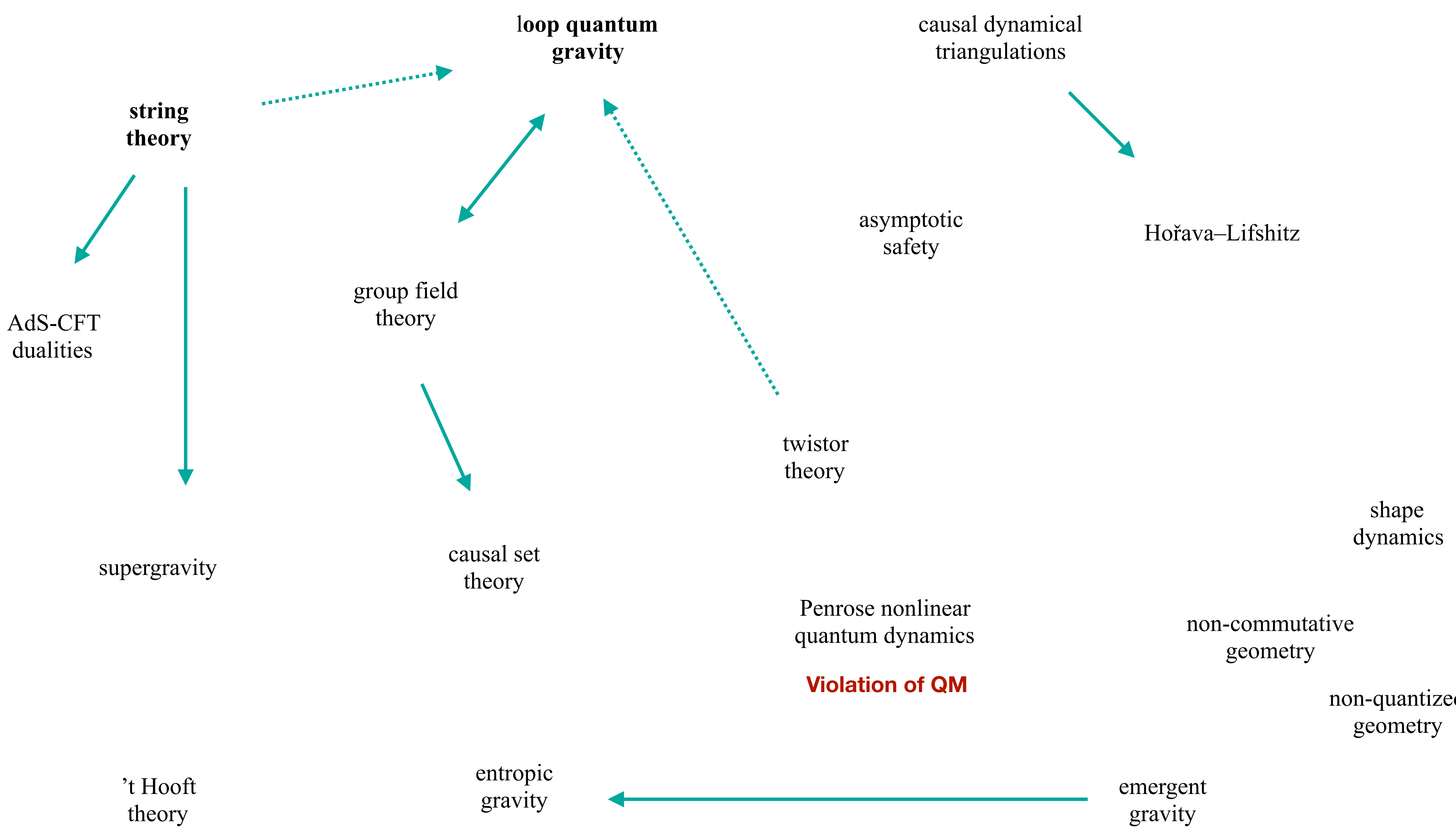
A few offer rather complete
tentative theories of quantum gravity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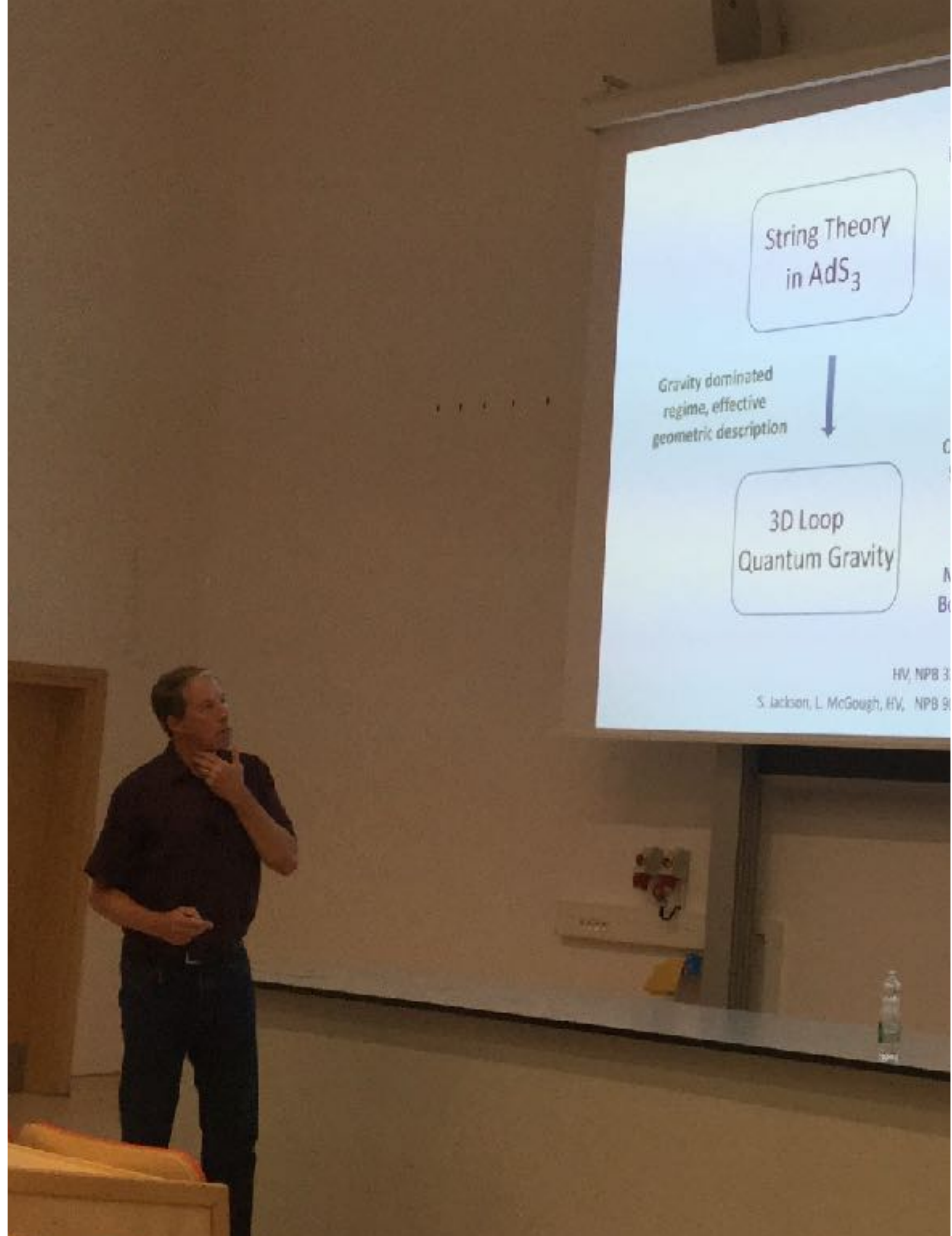
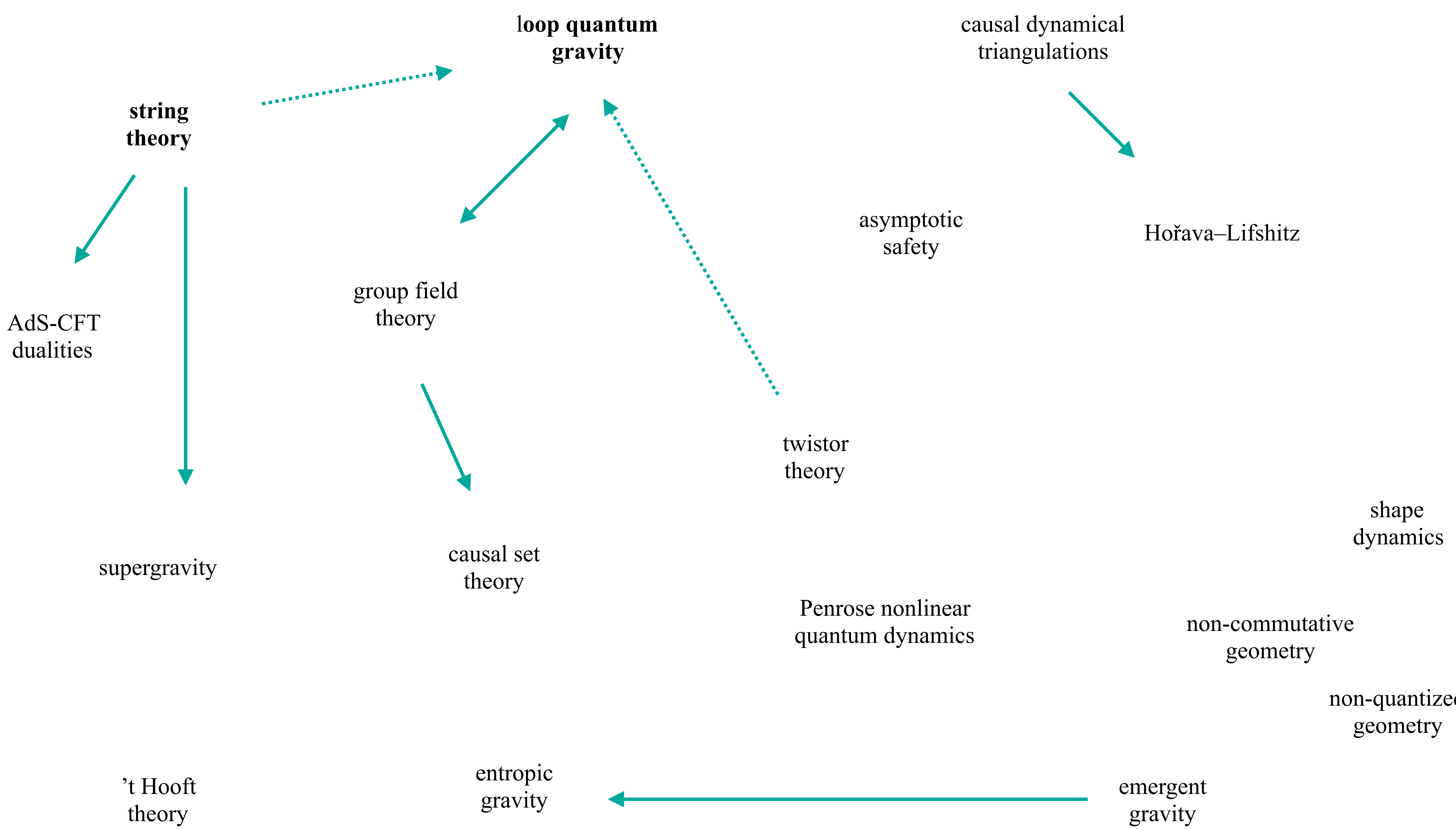


Herman Verlinde
at LOOP17 in Warsaw



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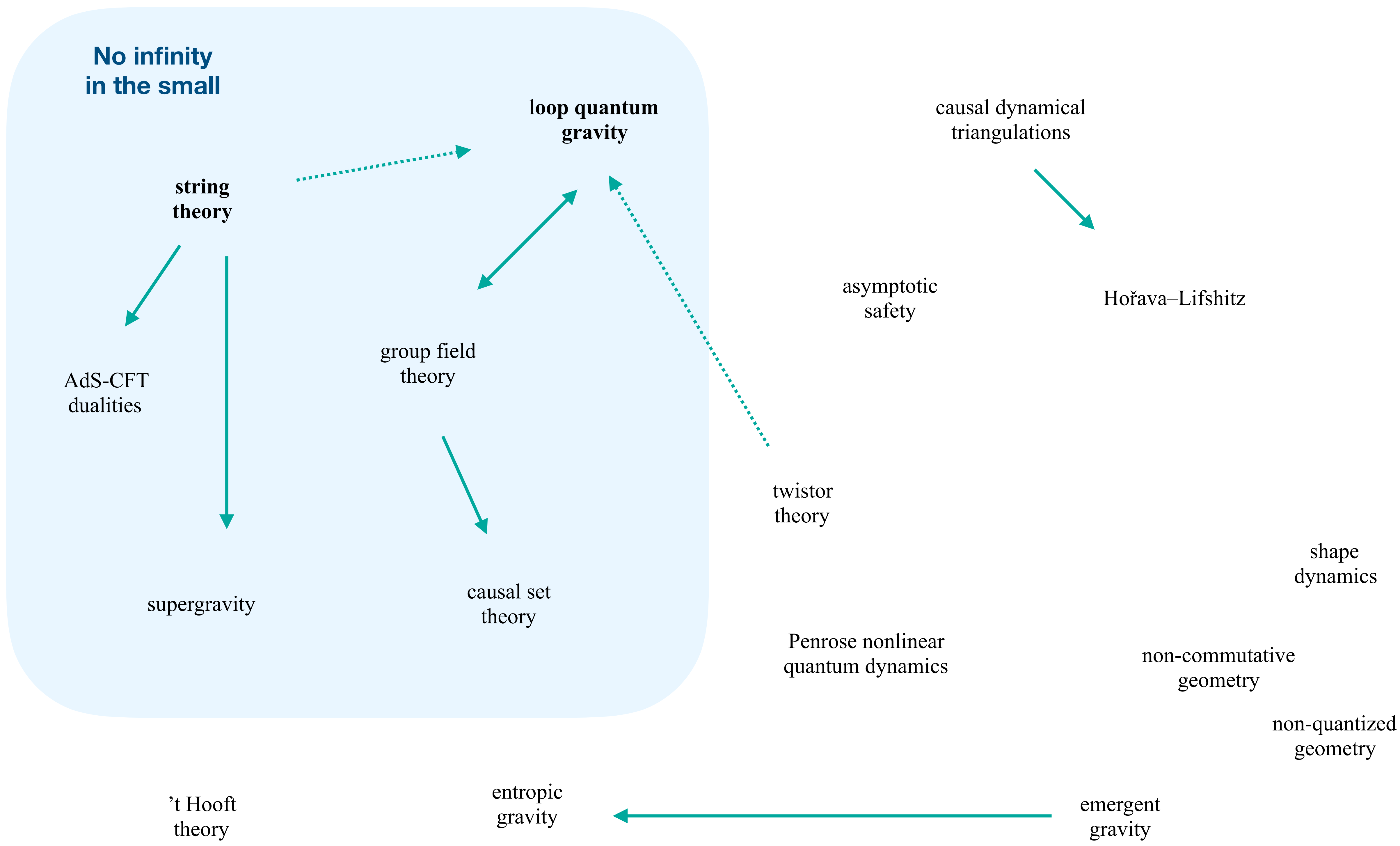
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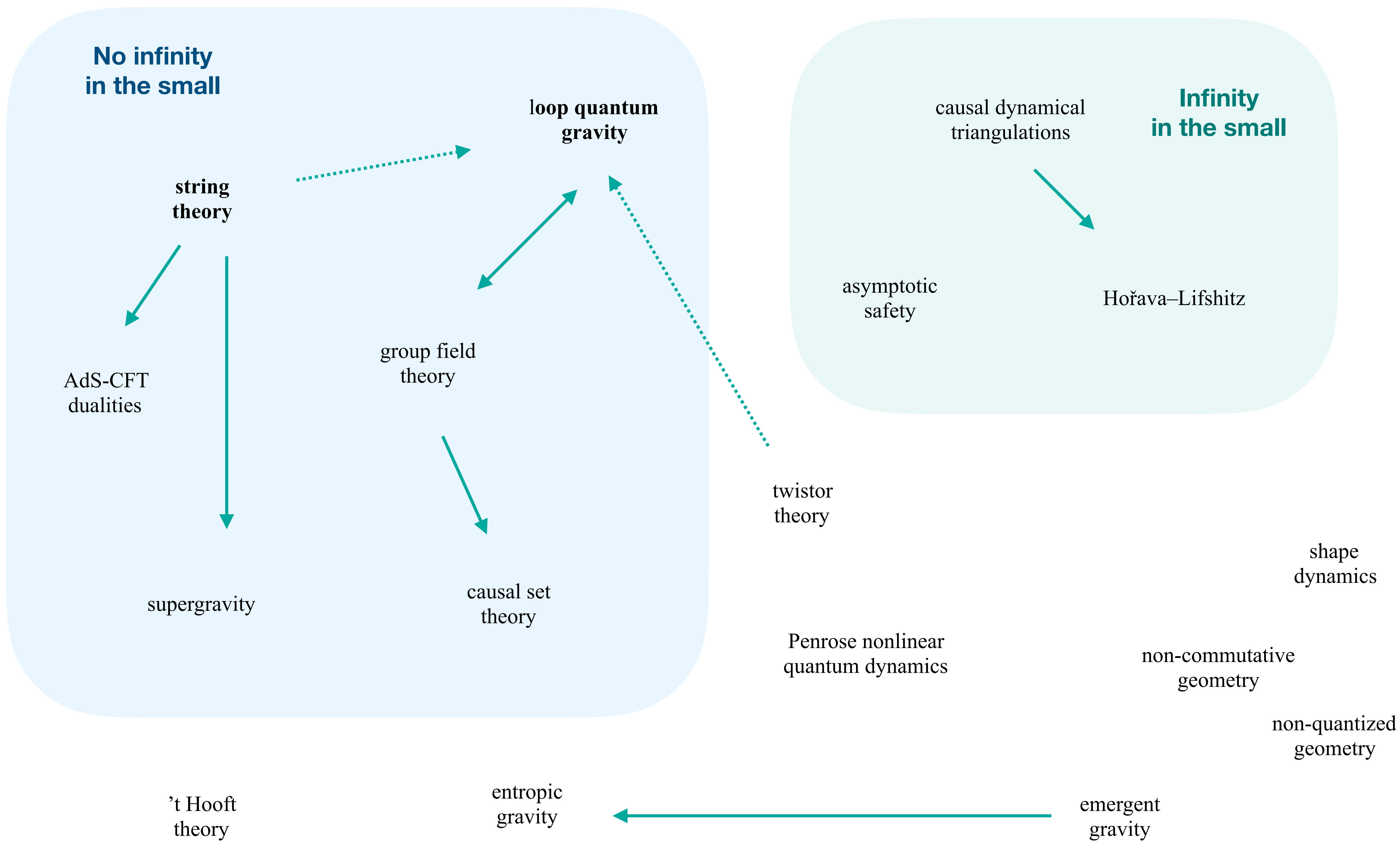
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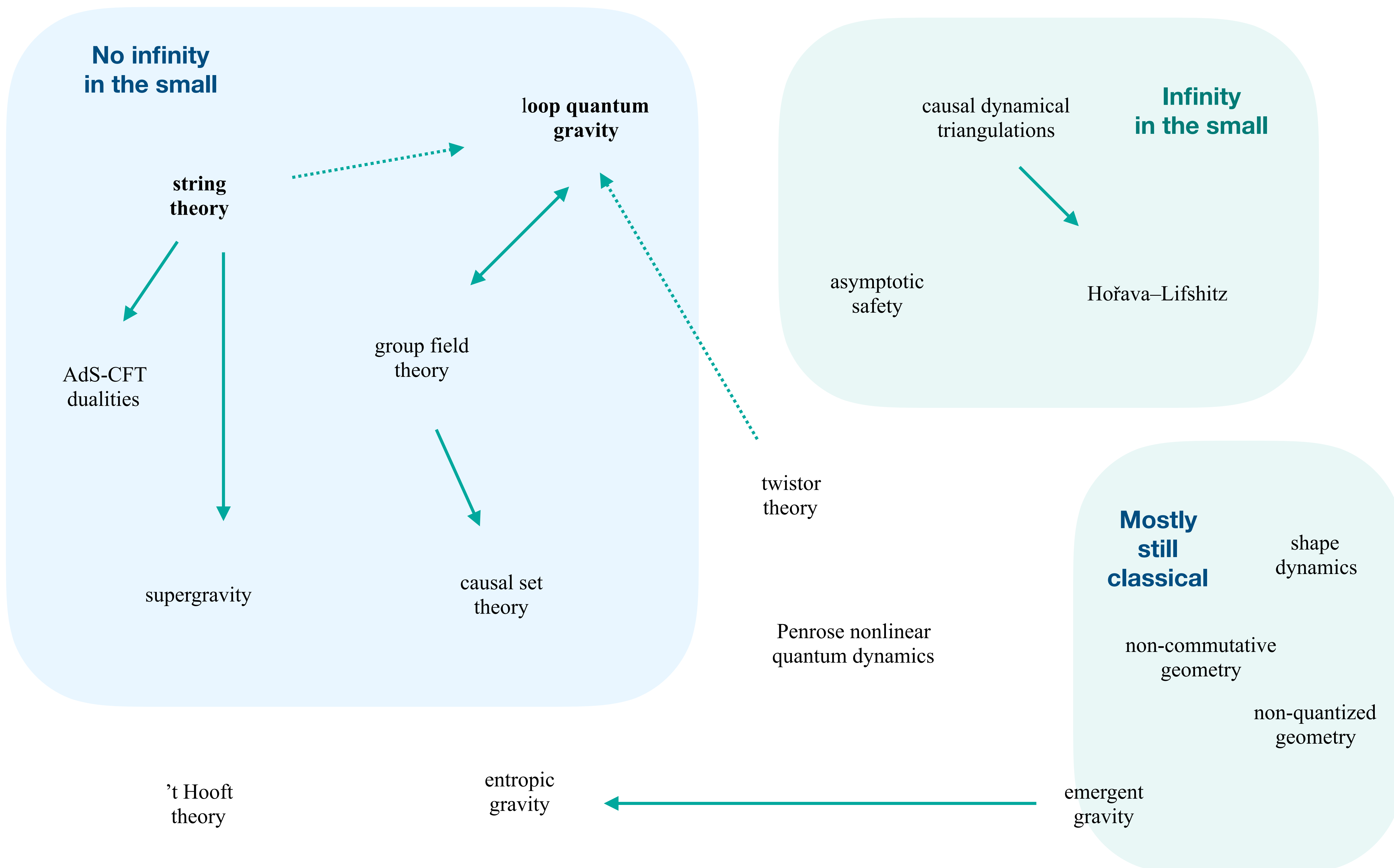
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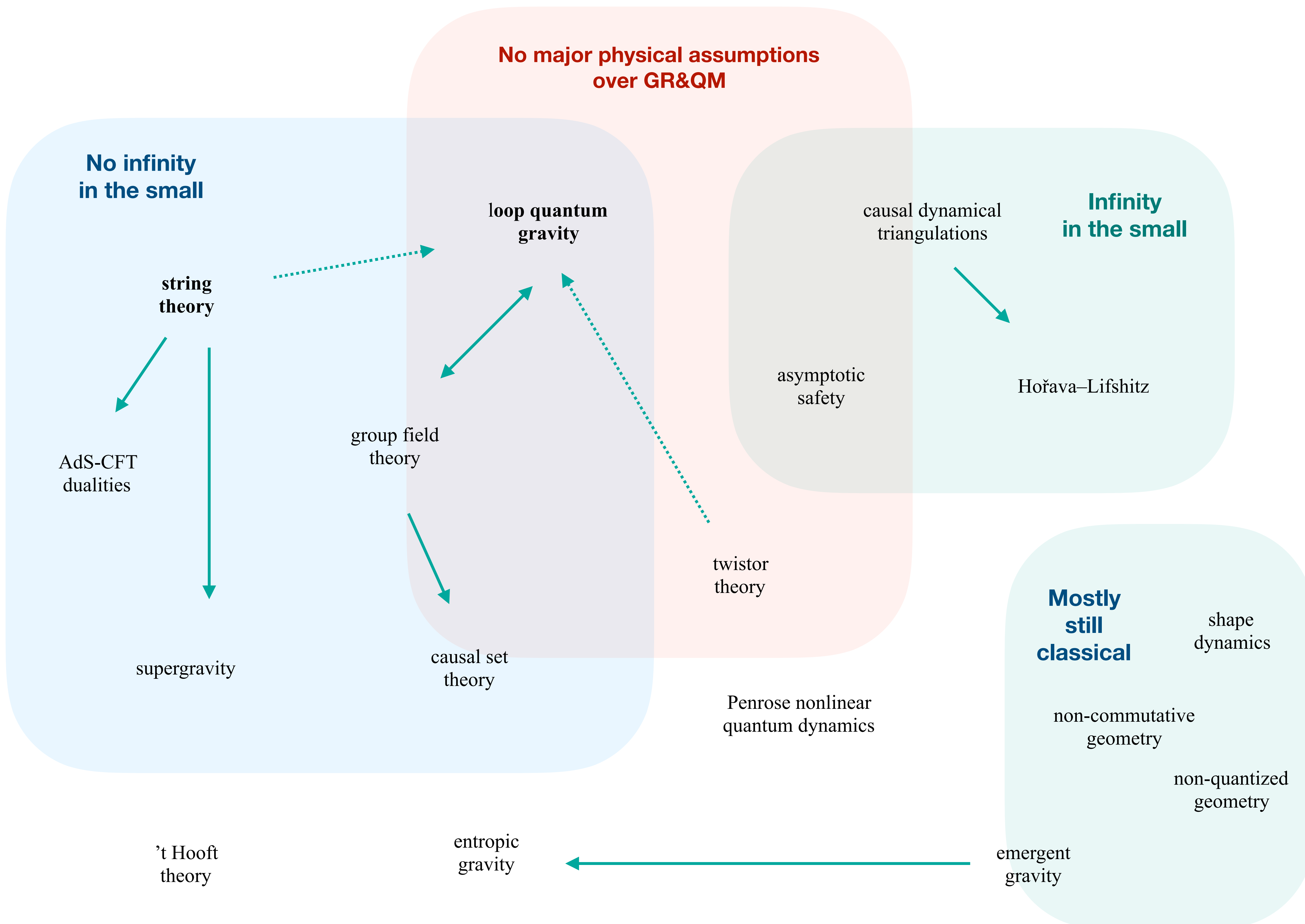
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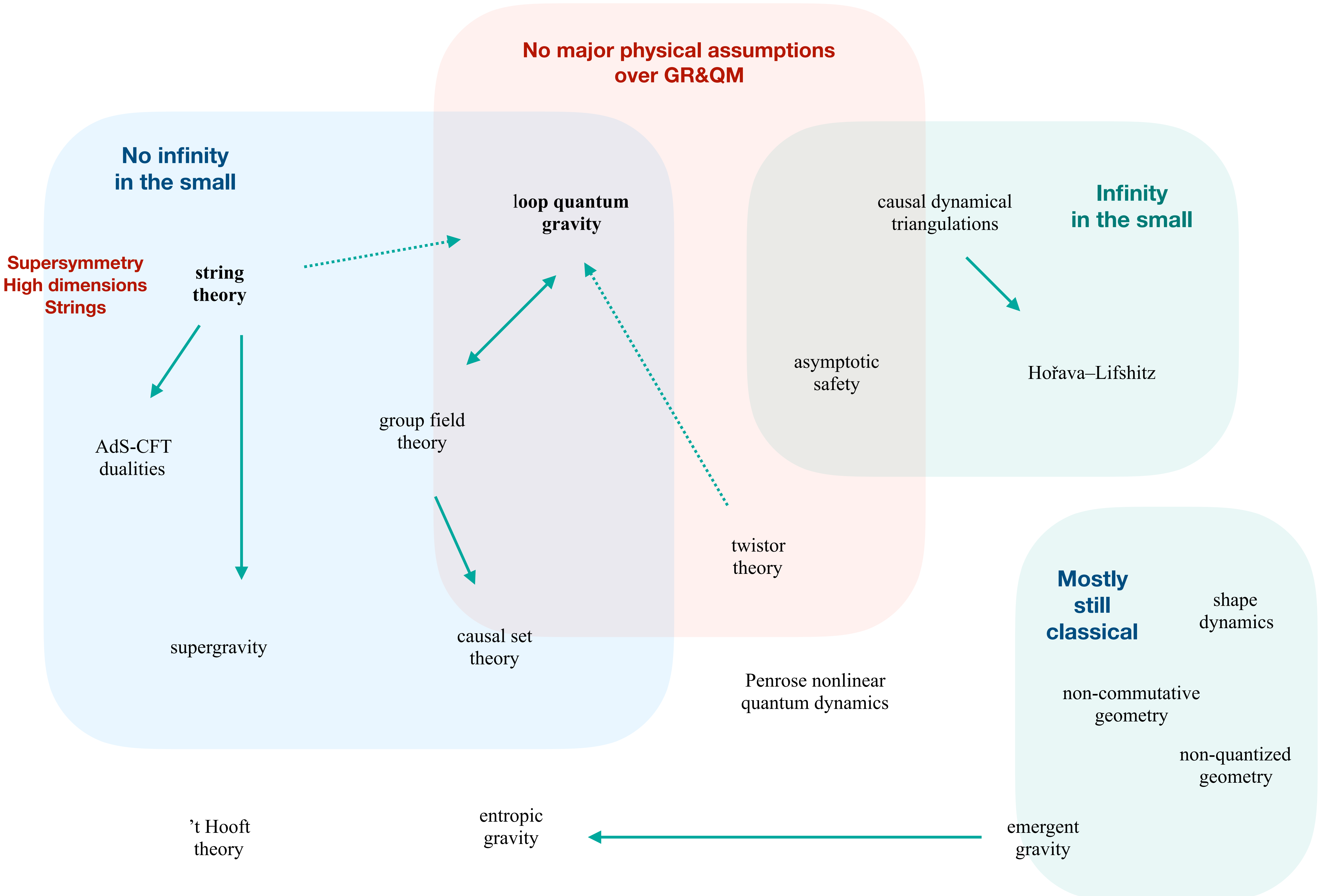
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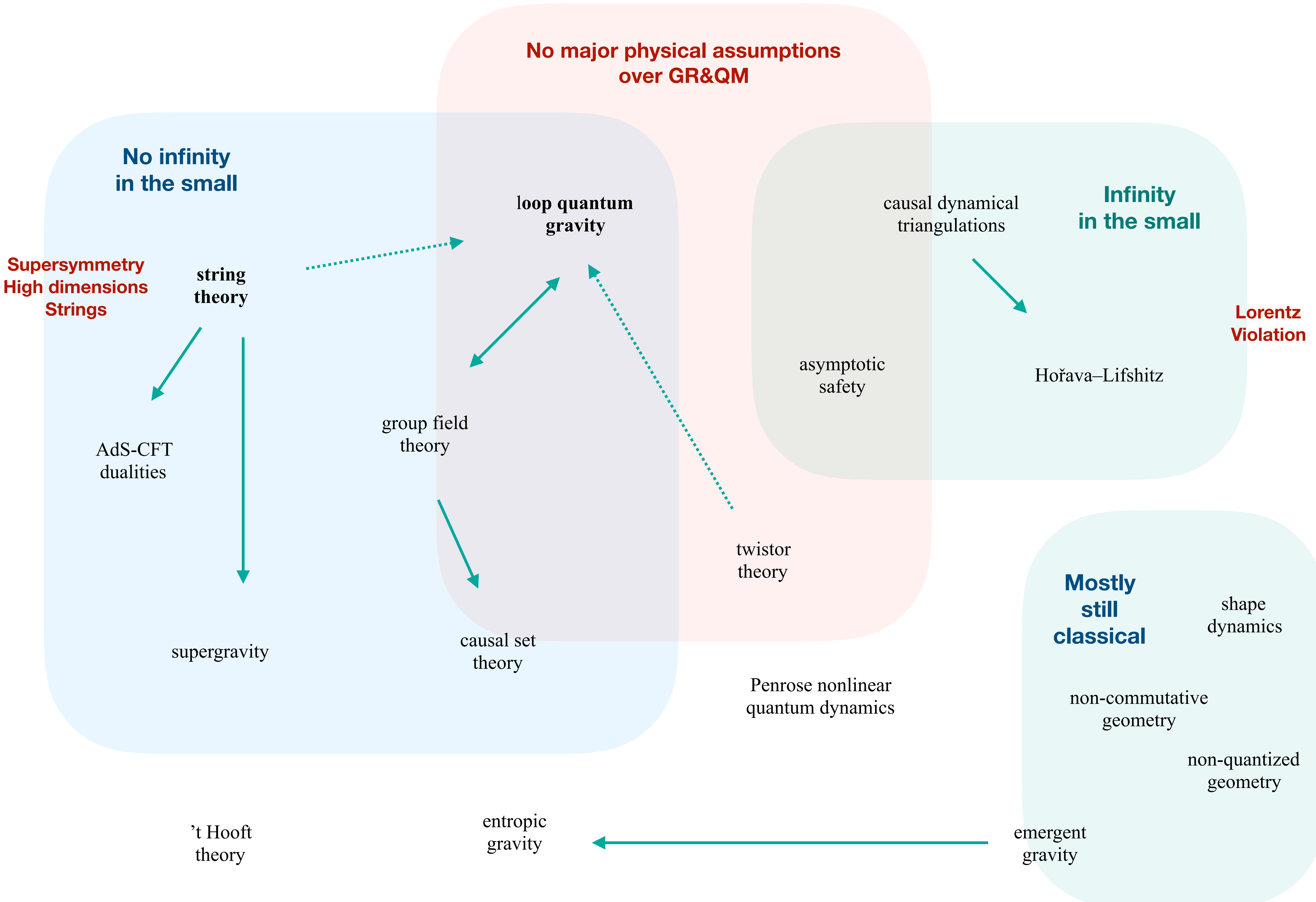
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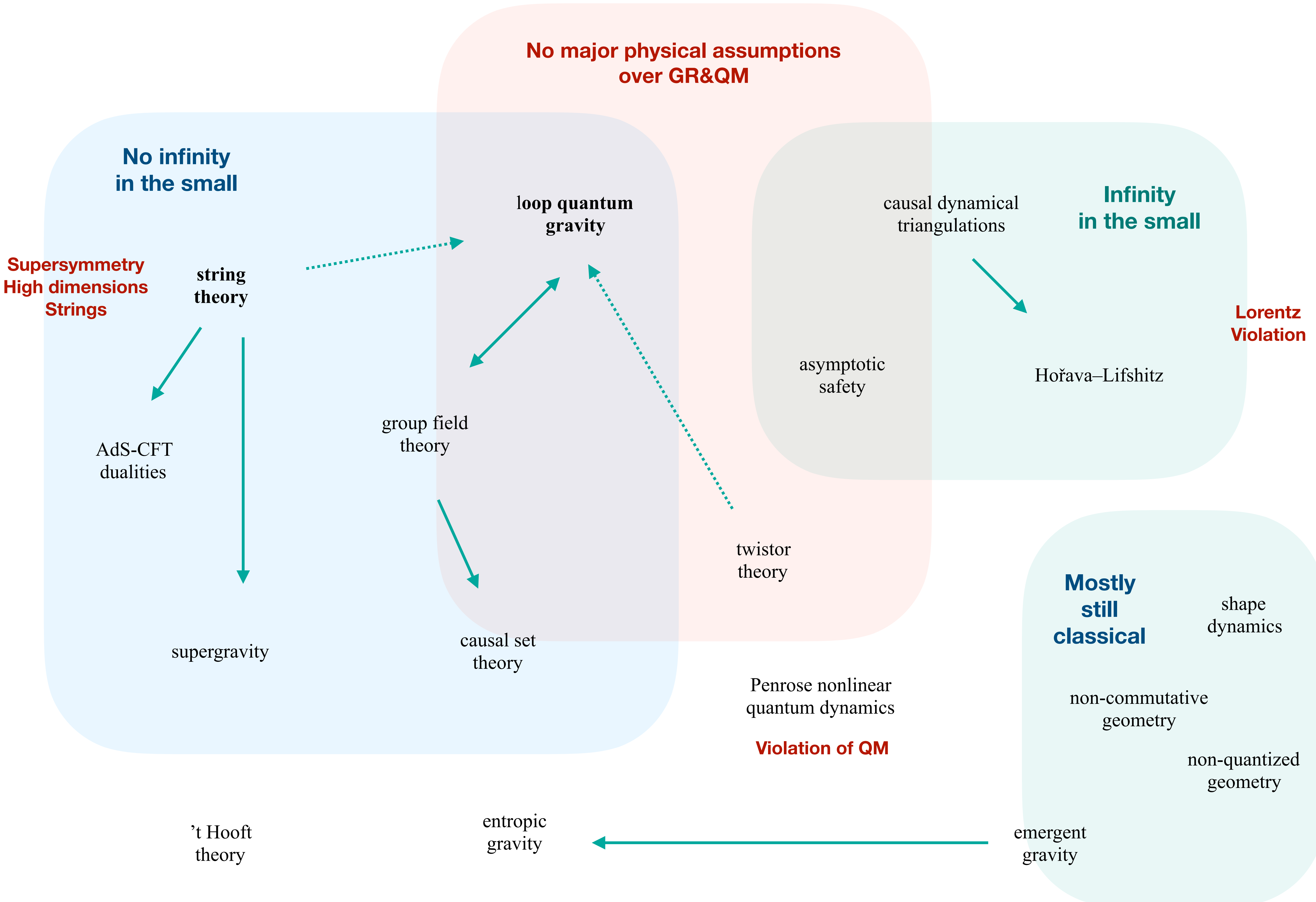
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Discriminatory questions:

Is **Lorentz symmetry** violated at the Planck scale or not?

Are there **supersymmetric** particles or not?

Is **Quantum Mechanics violated** in the presence of gravity or not?

Are there physical degrees of freedom at any **arbitrary small scale** or not?

Is geometry **discrete** i the small?

	Lorentz violations at Planck scale	Infinite d.o.f. at Planck scale	Supersymmetry	QM violations	Geometry is discrete?
Strings	No	No	Yes	No	No
Loops	No	No	No	No	Yes
Hojava Lifshitz	Yes	Yes	No	No	No
Asymptotic safety	No	Yes	No	No	No
Nonlinear quantum dynamics	No	Yes	No	Yes	No
Your favorite	…	…	…	…	…

2. We do have empirical evidence

Empirical evidence: 1: Lorentz invariance

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Violation of Lorentz invariance → Renormalizability

Observation has already ruled out theories

$$E^2 = k^2 + c_n \frac{k^n}{m_{Pl}^{n-2}}$$

Order	photon	e^-/e^+	Protrons	Neutrinos[a]
n=2	N.A.	$O(10^{-16})$	$O(10^{-20})$ (CR)	$O(10^{-8} \div 10^{-10})$
n=3	$O(10^{-16})$ (GRB)	$O(10^{-16})$ (CR)	$O(10^{-14})$ (CR)	$O(40)$
n=4	$O(10^{-8})$ (CR)	$O(10^{-8})$ (CR)	$O(10^{-6})$ (CR)	$O(10^{-7})^*$ (CR)

Table 2. Summary of typical strengths of the available constrains on the SME at different n orders for rotational invariant, neutrino flavour independent LIV operators. GRB=gamma rays burst, CR=cosmic rays. [a] From neutrino oscillations we have constraints on the difference of LIV coefficients of different flavors up to $O(10^{-28})$ on dim 4, $O(10^{-8})$ and expected up to $O(10^{-14})$ on dim 5 (ICE3), expected up to $O(10^{-4})$ on dim 6 op. * Expected constraint from future experiments.

S. Liberati, Class. Quant. Grav. 30, 133001 (2013)

Lorentz violating solutions of QG are under empirical stress

Is Lorentz invariance compatible with discreteness ?

Yes!

Classical discreteness breaks Lorentz invariance.

Quantum discreteness does not !

Cfr rotational invariance:
If a *classical* vector component can take only discrete values only,
then SO(3) is broken.
But if *quantum* vector can have discrete eigenvalues in a SO(3) invariant theory

$$L_z|m\rangle = \hbar m|m\rangle$$

$$L_z(\theta)|m\rangle_\theta = R(\theta)L_zR(\theta)^{-1}|m\rangle_\theta = \hbar m|m\rangle_\theta$$

$$[L_z, L_z(\theta)] \neq 0$$

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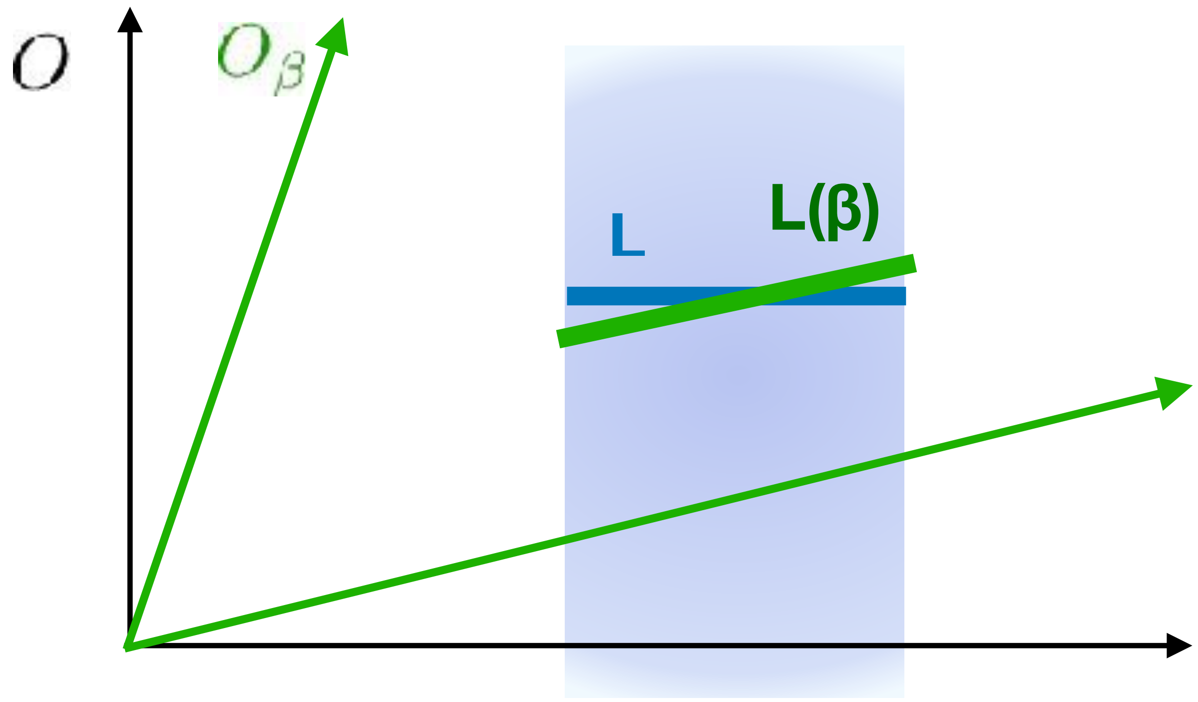

$$[L, L(\beta)] \neq 0$$

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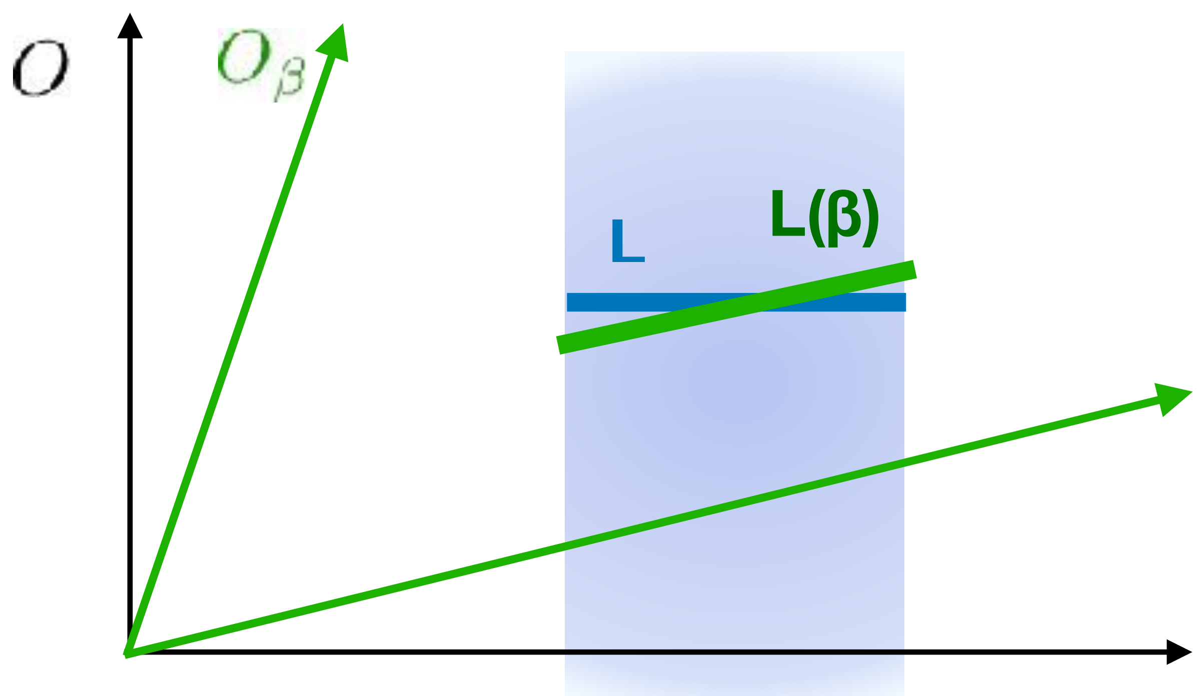

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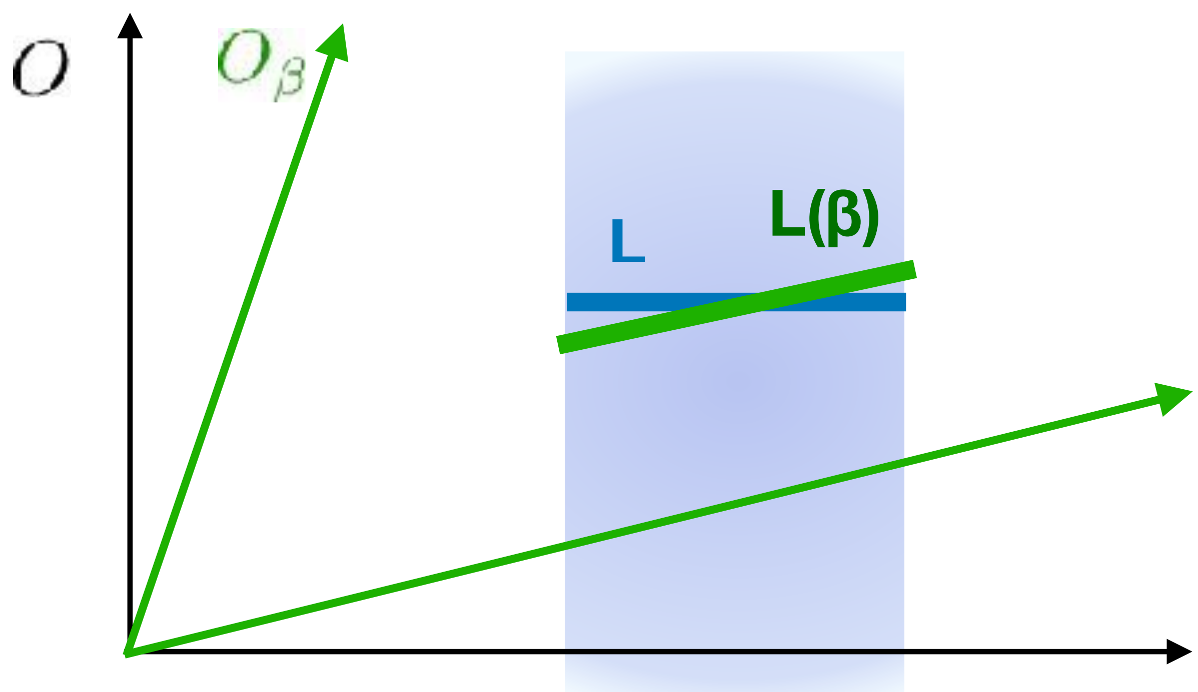

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Lorentz invariance and quantum discreteness <u>are</u> compatible

=> Geometry is quantum geometry

Empirical evidence: 2: Supersymmetry

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arXiv.org > hep-ex > arXiv:1708.02794

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High Energy Physics – Experiment

Search for new phenomena with large jet multiplicities and missing transverse momentum using large-radius jets and flavour-tagging at ATLAS in 13 TeV pp collisions

ATLAS Collaboration

(Submitted on 9 Aug 2017)

A search is presented for particles that decay producing a large jet multiplicity and invisible particles. The event selection applies a veto on the presence of isolated electrons or muons and additional requirements on the number of b-tagged jets and the scalar sum of masses of large-radius jets. Having explored the full ATLAS 2015-2016 dataset of LHC proton-proton collisions at $\sqrt{s} = 13$ TeV, which corresponds to 36.1 fb^{-1} of integrated luminosity, no evidence is found for physics beyond the Standard Model. The results are interpreted in the context of simplified models inspired by R-parity-conserving and R-parity-violating supersymmetry, where gluinos are pair-produced. More generic models within the phenomenological minimal supersymmetric Standard Model are also considered.

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A point about philosophy of science:

- Popper's *falsification*: theories are either "OK" or "proved wrong".

Karl Popper

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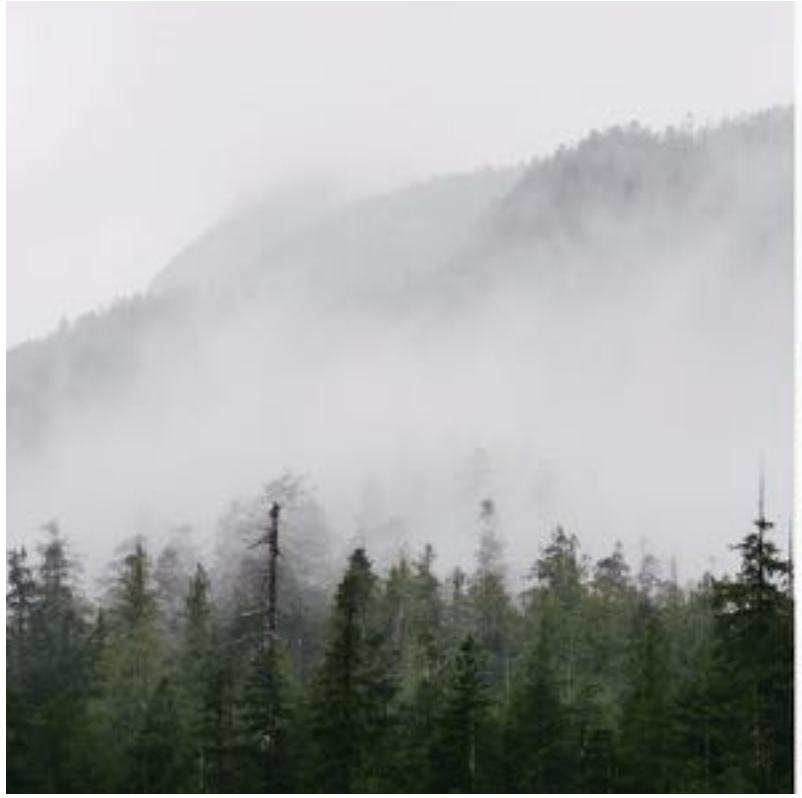

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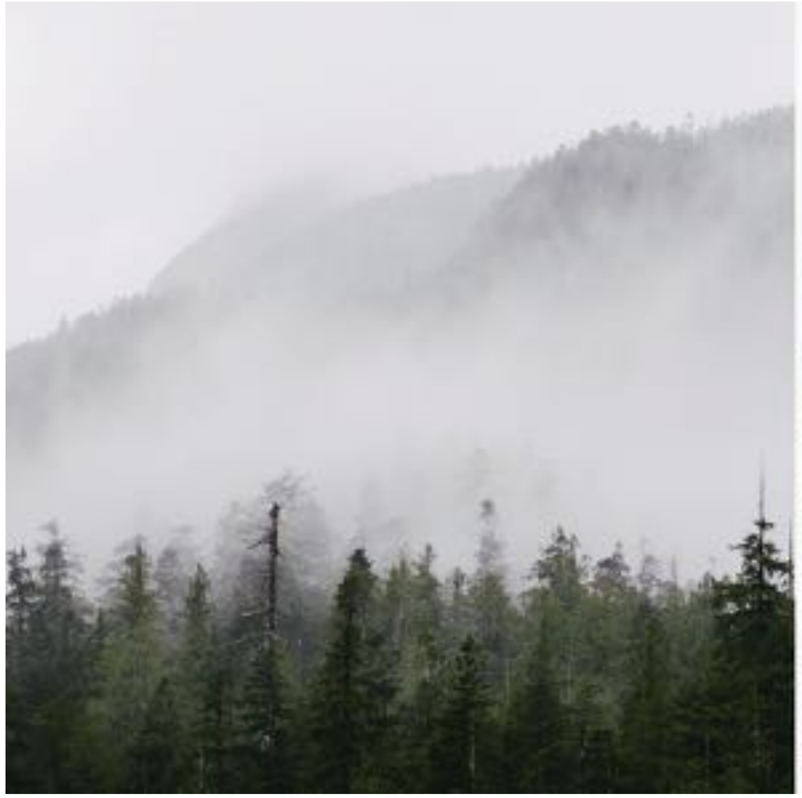

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Solution of QG using supersymmetry are under empirical stress

Empirical evidence: 3: Lab experiments (future)

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Analog systems

Planck scale effects
in the lab

Violations of QM
suggested by QG

Quantum property
of the metric

Empirical evidence: 3: Lab experiments

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Test the **consequences** of an assumption.
Not the **assumption** themselves.

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Quantum property
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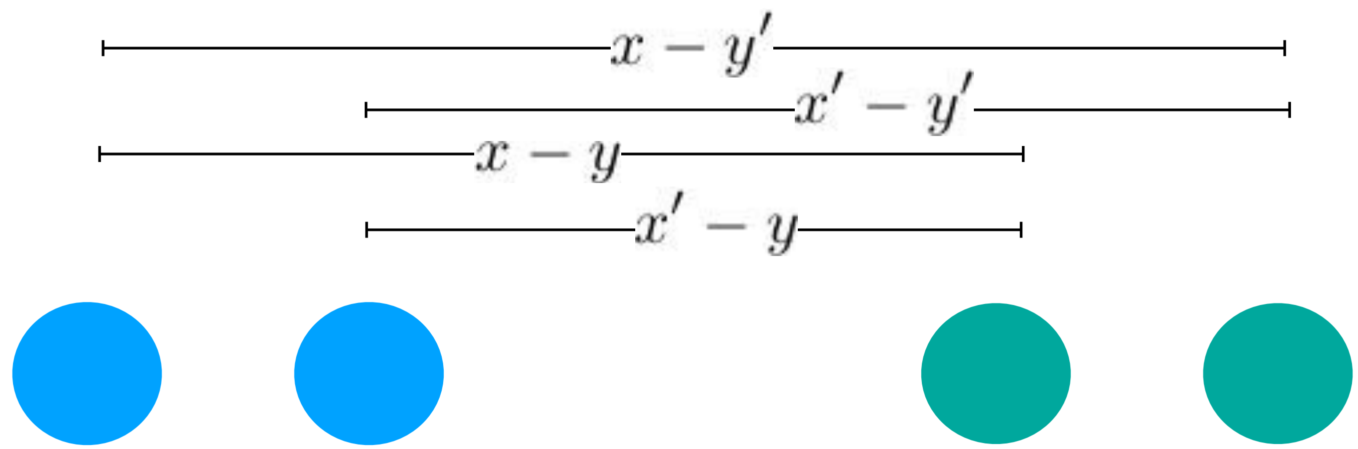
Can falsify the hypothesis that the
gravitational field is classical.

Is the metric a quantum entity?



$$|\psi\rangle = (|1x\rangle + |1x'\rangle) \otimes (|2y\rangle + |2y'\rangle)$$

$$\begin{aligned}|\psi\rangle = &|1x\rangle \otimes |2y\rangle + \\ &|1x'\rangle \otimes |2y\rangle + \\ &|1x\rangle \otimes |2y'\rangle + \\ &|1x'\rangle \otimes |2y'\rangle\end{aligned}$$

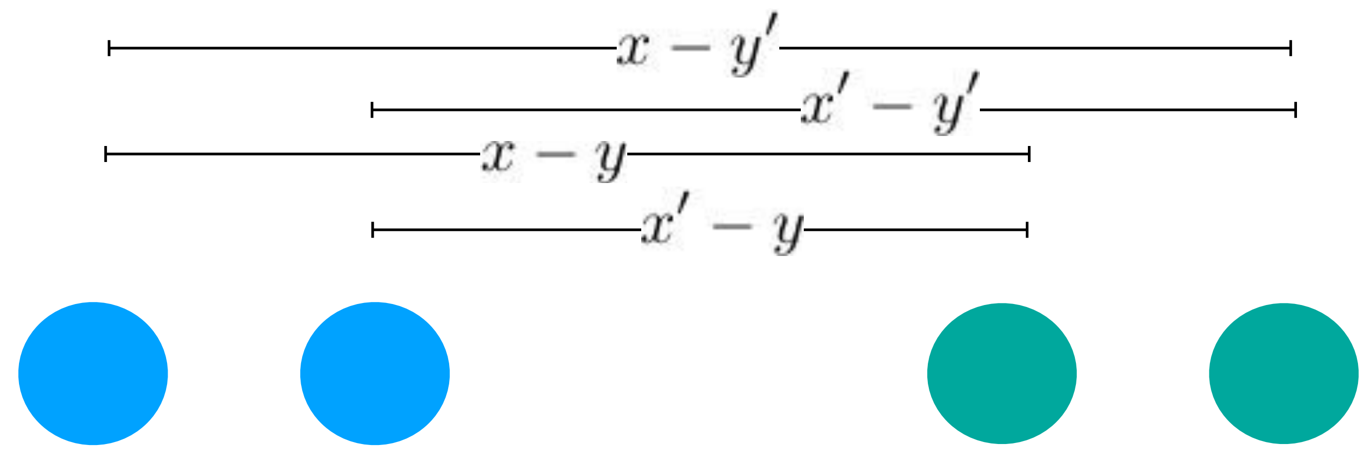
$$\begin{aligned}|\psi(t)\rangle = &|1x\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y}t} + \\ &|1x'\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t} + \\ &|1x\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y'}t} + \\ &|1x'\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t}\end{aligned}$$

$$\frac{Gm^2}{\hbar\Delta x}t \sim \pi$$

S Bose, A Mazumdar, GW Morley, H Ulbricht, M Toroš, M Paternostro, A Geraci, P Barker, MS Kim, G Milburn: *A Spin Entanglement Witness for Quantum Gravity*, 2017.
C Marletto, V Vedral: *An entanglement-based test of quantum gravity using two massive particles*, 2017.

Is the metric a quantum entity?

Can falsify the hypothesis that the gravitational field is classical.



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$$
\begin{aligned}
|\psi\rangle = & |1x\rangle \otimes |2y\rangle + \\
& |1x'\rangle \otimes |2y\rangle + \\
& |1x\rangle \otimes |2y'\rangle + \\
& |1x'\rangle \otimes |2y'\rangle
\end{aligned}
$$

$$
\begin{aligned}
|\psi(t)\rangle = & |1x\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y}t} + \\
& |1x'\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t} + \\
& |1x\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y'}t} + \\
& |1x'\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t}
\end{aligned}
$$

$$\frac{Gm^2}{\hbar \Delta x} t \sim \pi$$

S Bose, A Mazumdar, GW Morley, H Ulbricht, M Toroš, M Paternostro, A Geraci, P Barker, MS Kim, G Milburn: *A Spin Entanglement Witness for Quantum Gravity*, 2017.
C Marletto, V Vedral: *An entanglement-based test of quantum gravity using two massive particles*, 2017.

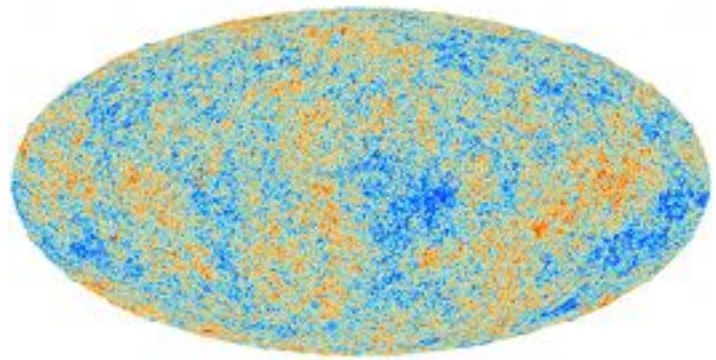
Empirical evidence: 4: The Sky (future)

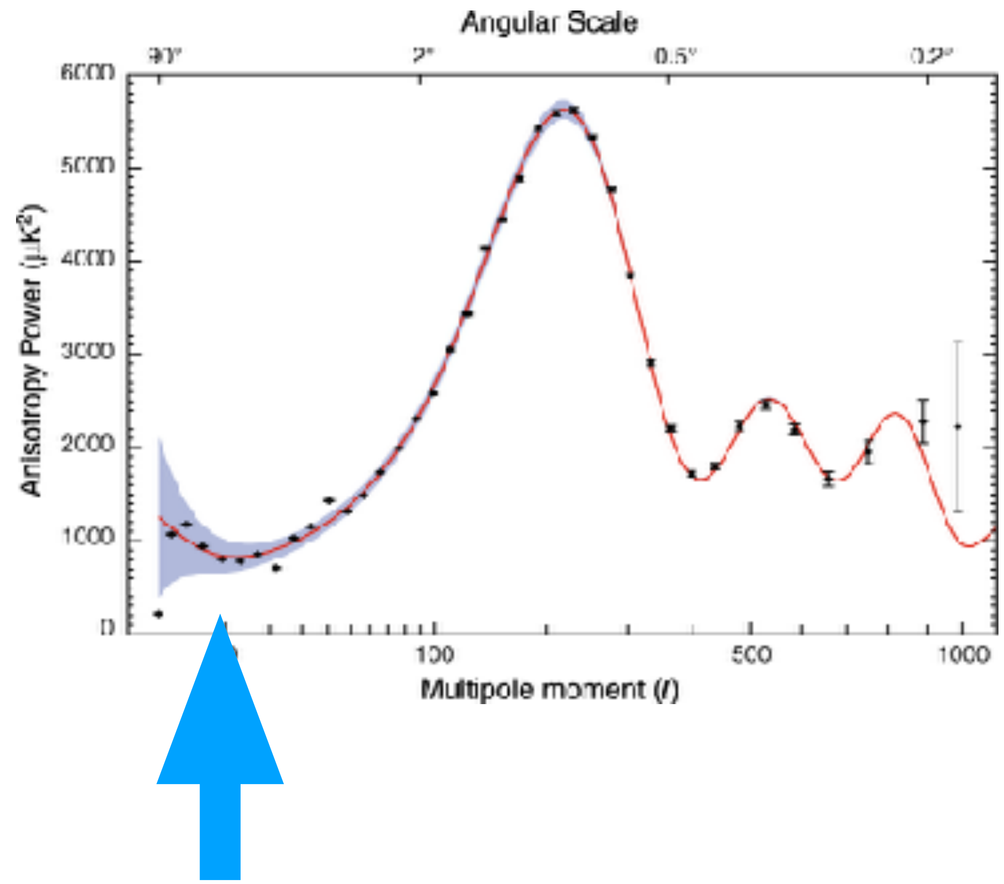
Empirical evidence: 4: The Sky

a) Early Universe: "Quantum cosmology"

b) Black holes: Disruption of the photon ring

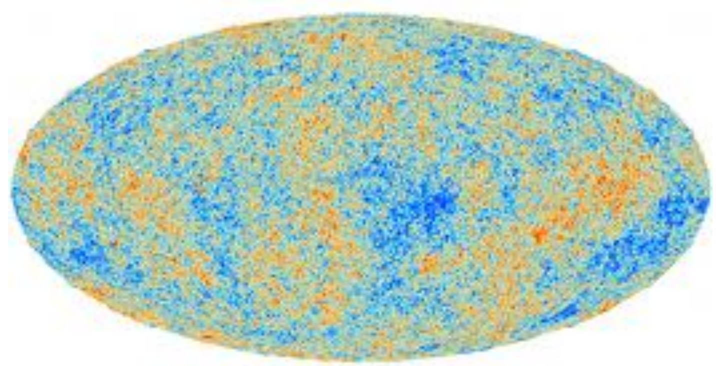
Planck Stars

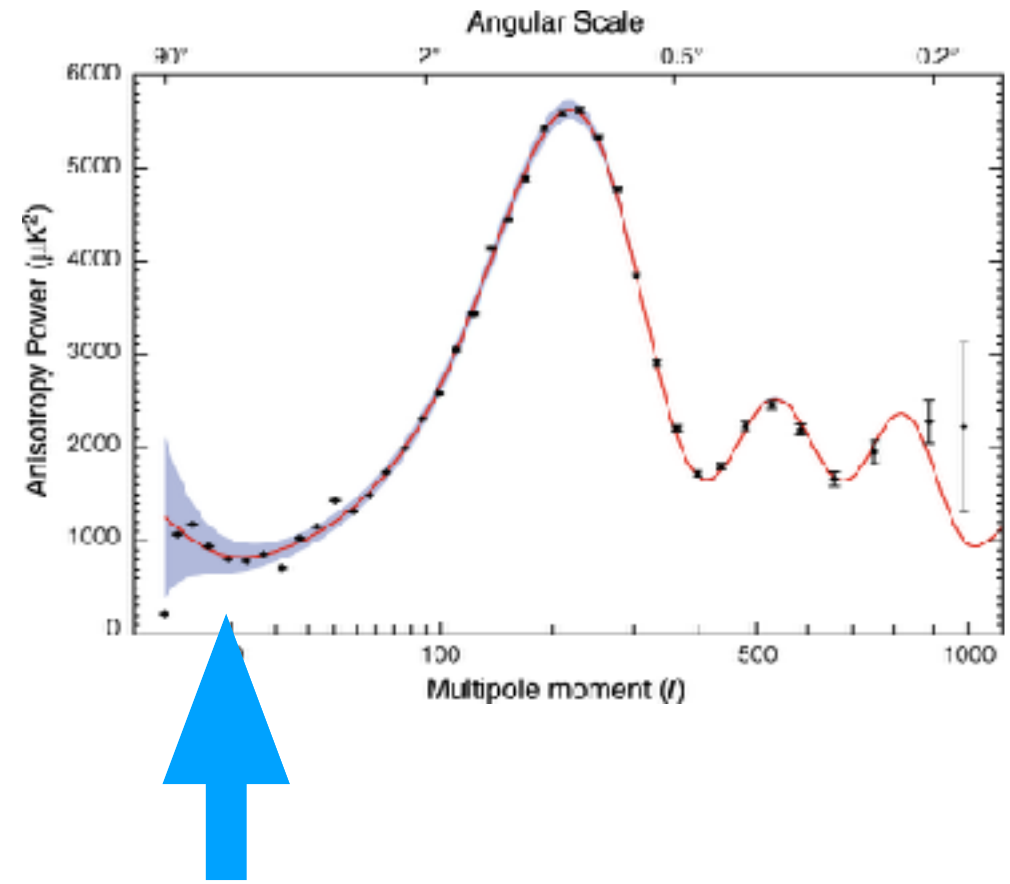




Large activity to describe the physics of the very early universe, and find traces in the CMB

Notice: this is all physics of **few** degrees of freedom!



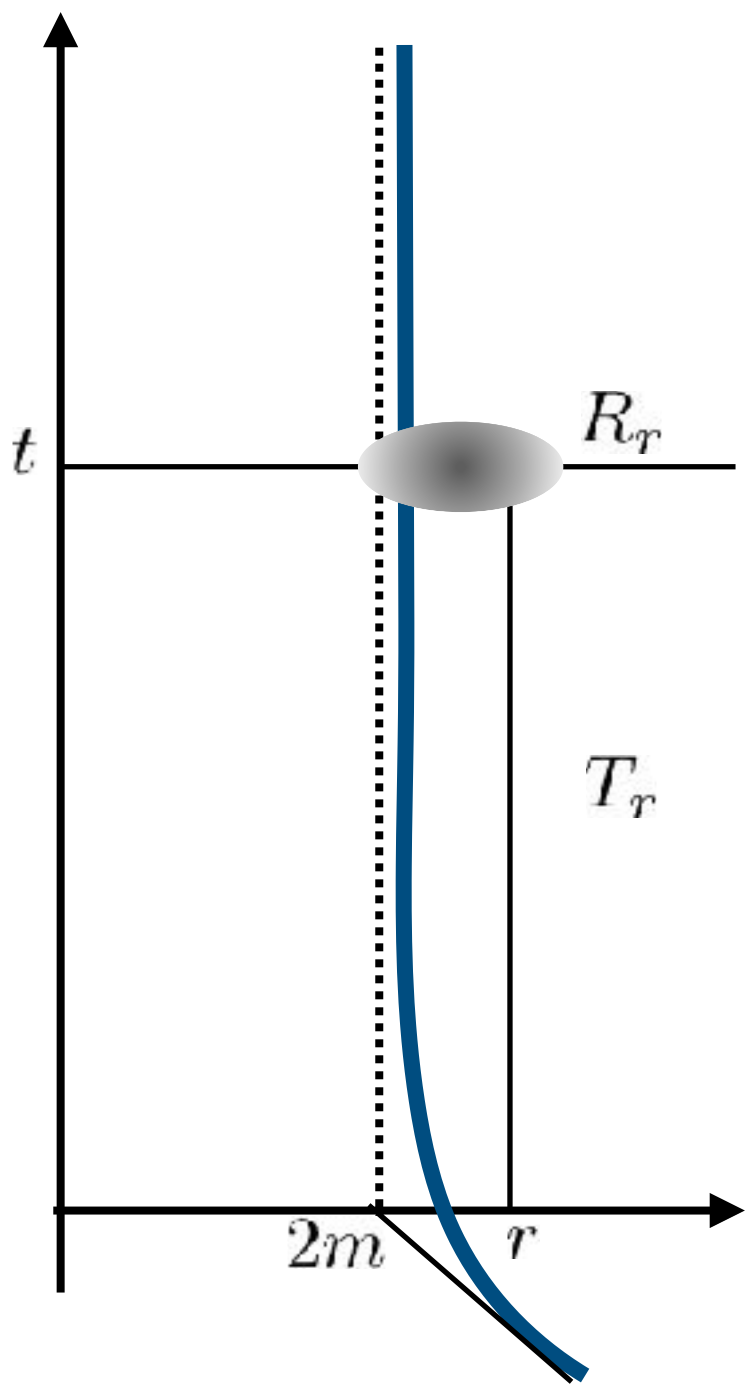


Large activity to describe the physics of the very early universe, and find traces in the CMB

Notice: this is all physics of **few** degrees of freedom!

Great effort to find testable consequences of the theories in course

Small effects pile up over time



$$R_r T_r \sim \frac{m}{r^3}(1-\frac{2m}{r})t$$

$$r_{(max\, R_r T_r)} = \frac{7}{3}m$$

$$R_r T_r \sim \frac{l}{l_{Pl}} \to T \sim m^2$$

- Wide quantum fluctuations of the metric

Giddings

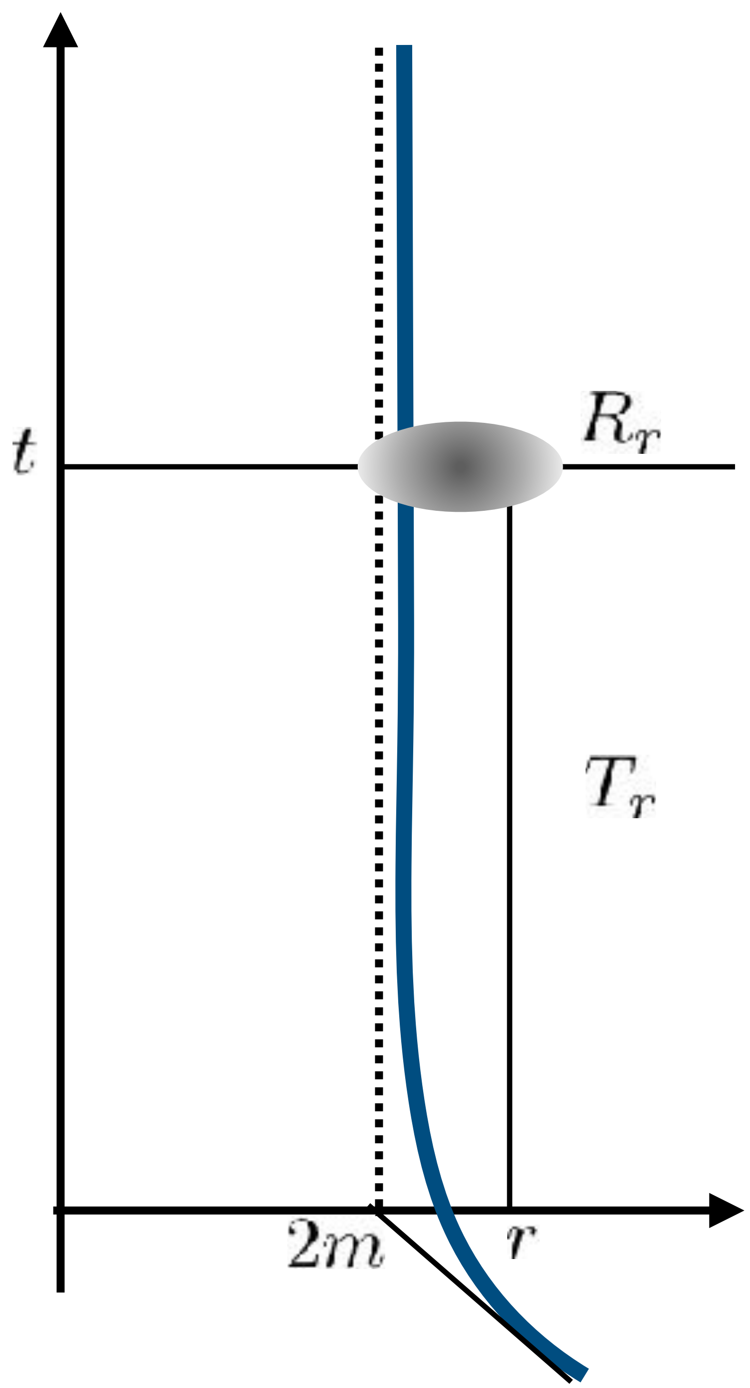
- Boson condensate of low energy gravitons

Dvali

- Fluctuations of the causal structure allowing black hole to decay

Haggard, Barrau, Vidotto, CR

Small effects pile up over time



$$R_r T_r \sim \frac{m}{r^3}\left(1-\frac{2m}{r}\right)t$$

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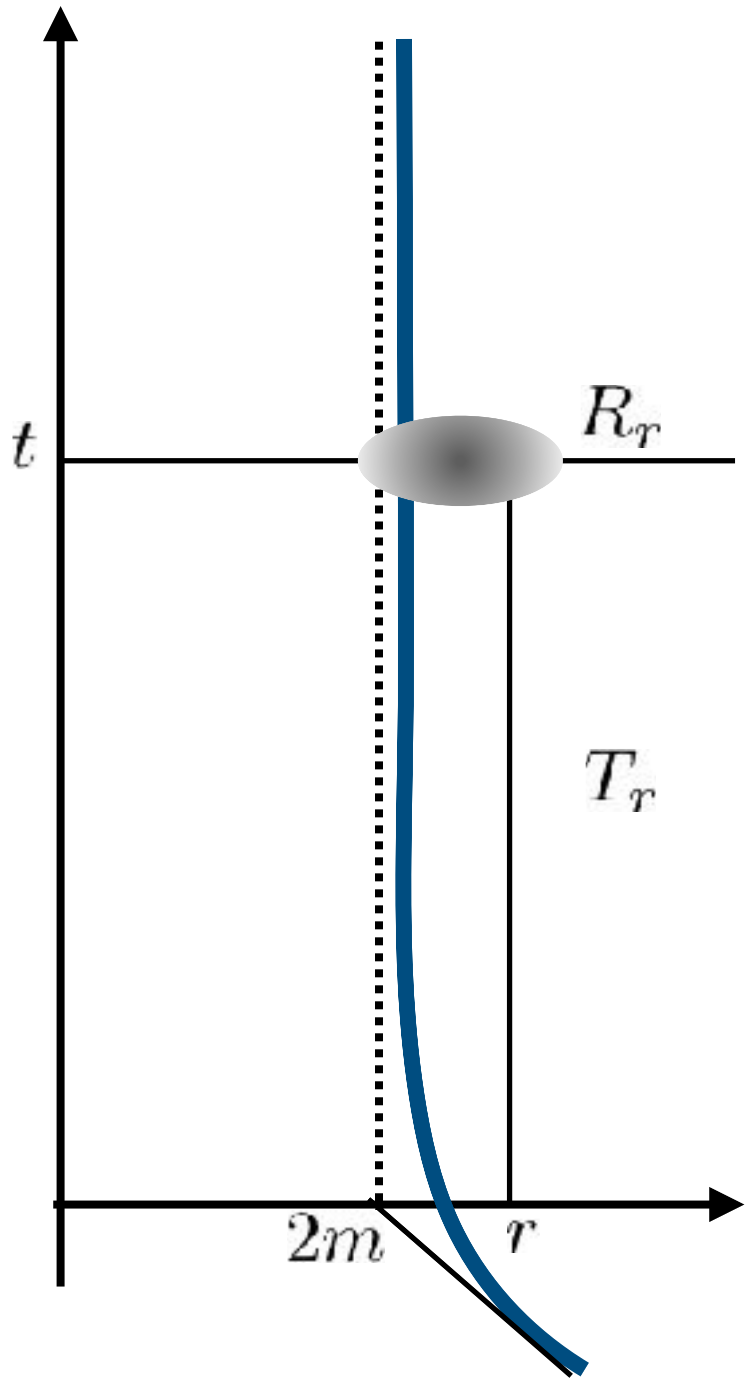

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Giddings

- Boson condensate of low energy gravitons

Dvali

- Fluctuations of the causal structure allowing black hole to decay

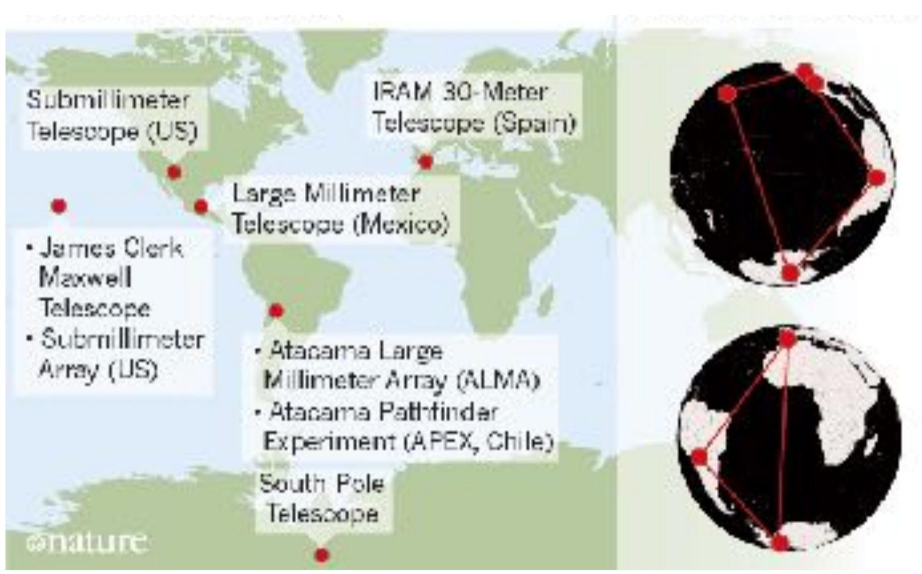
Haggard, Barrau, Vidotto, CR

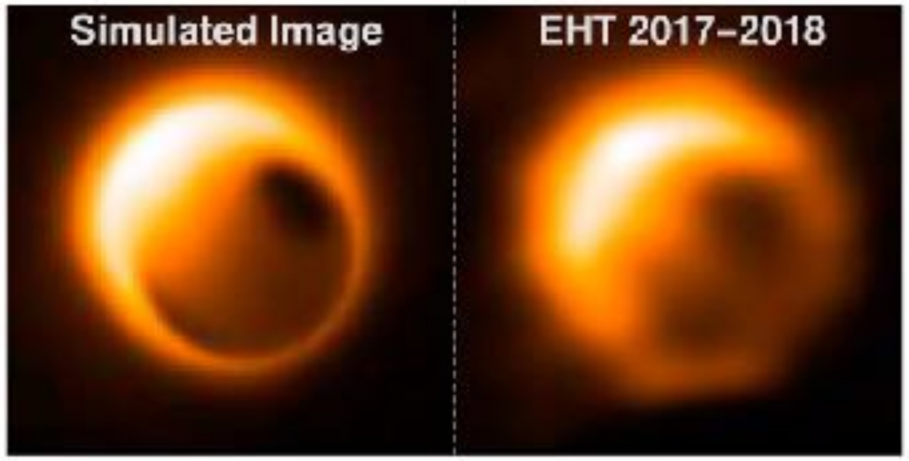
- Wide quantum fluctuations of the metric

Theoretical reason: to bring information out of the hole

Observable consequence: Event Horizon Telescope

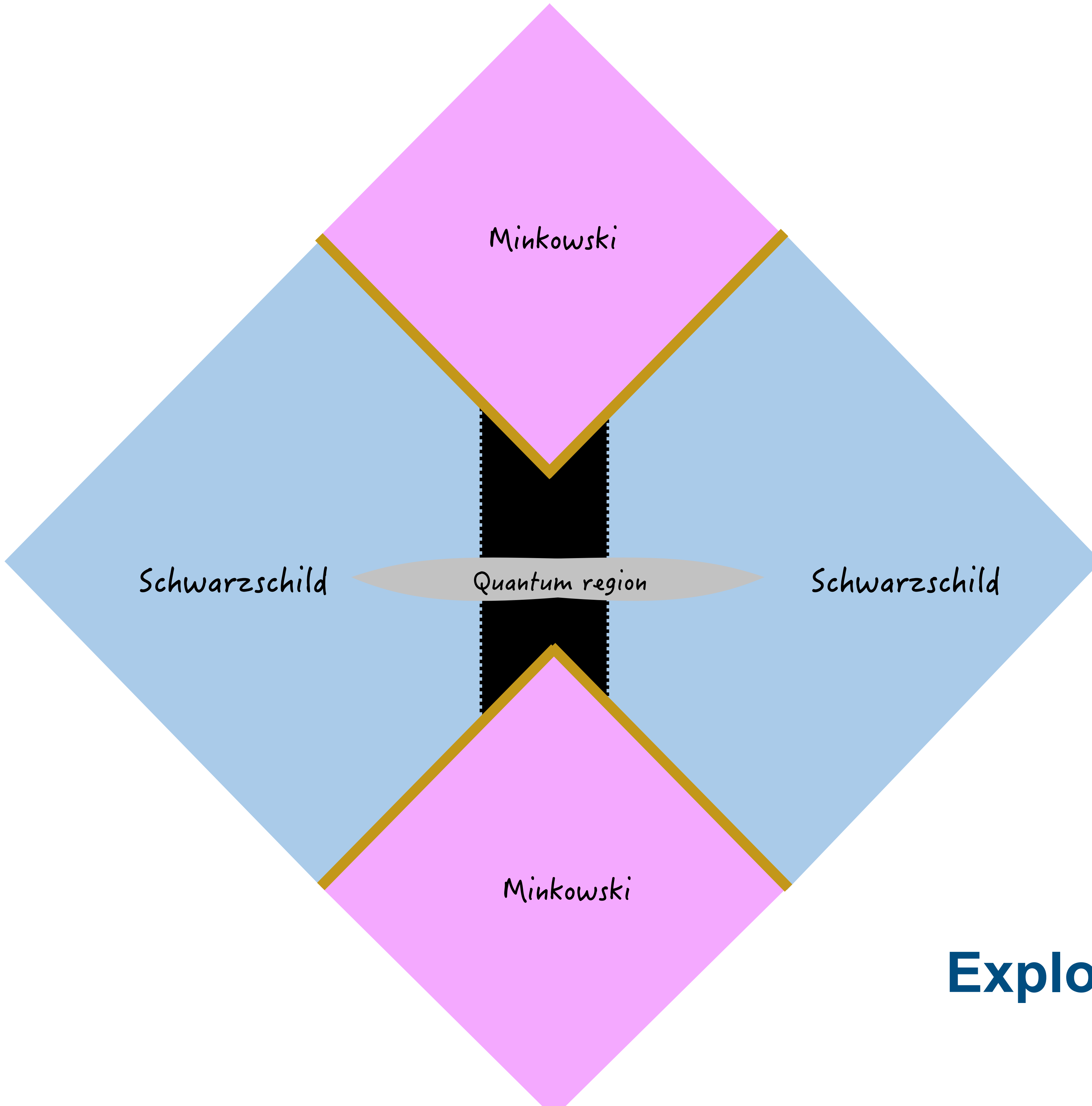
Possibly visible distortion of the photon ring



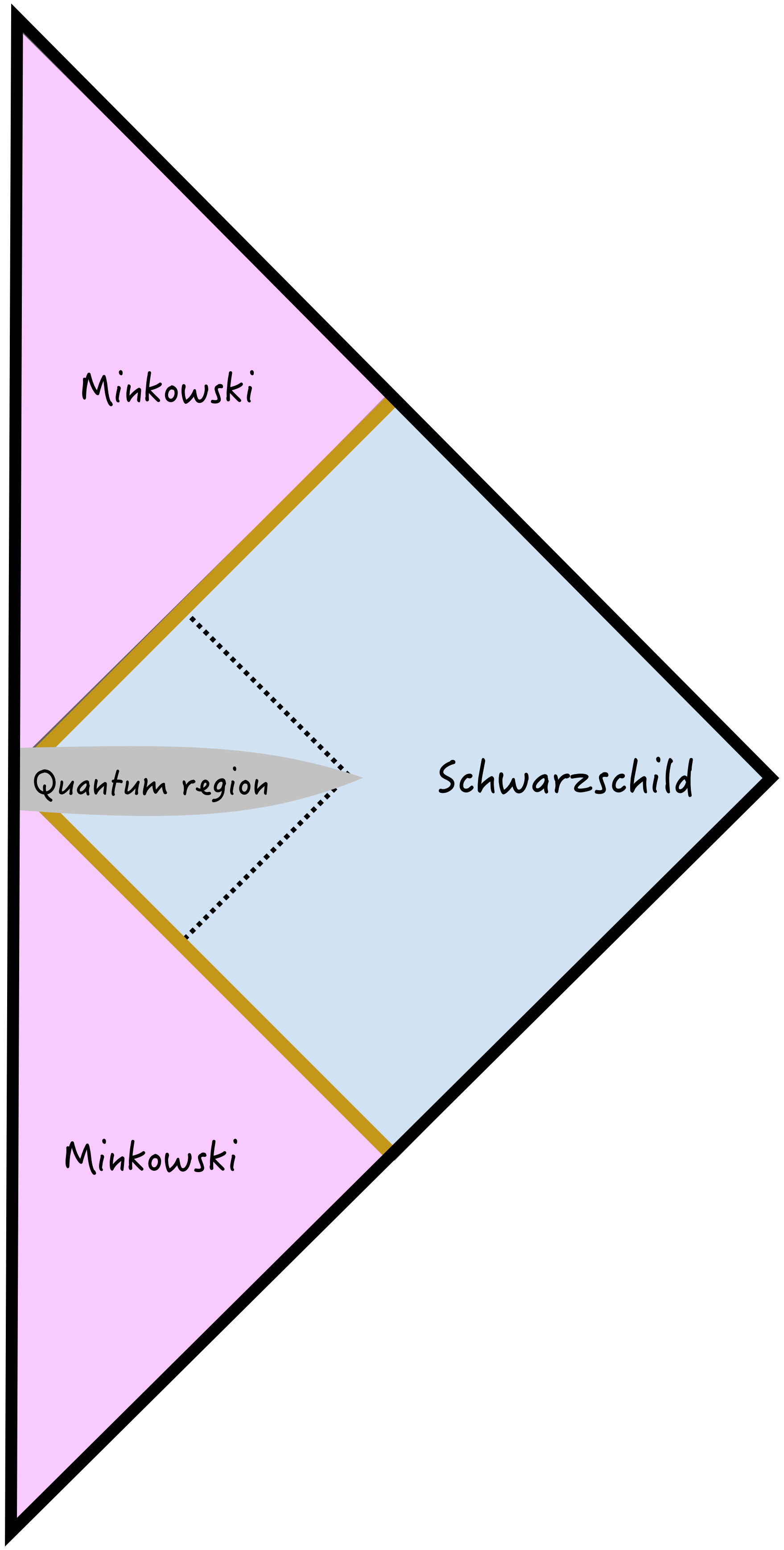


Imaging an Event Horizon: Mitigation of Scattering toward Sagittarius A* Fish et al 2014

- Fluctuations of the causal structure allowing black hole to decay

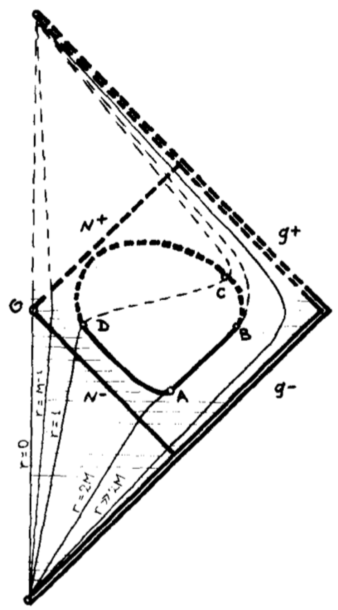


Exploding holes


Minkowski
Quantum region
Schwarzschild
Minkowski

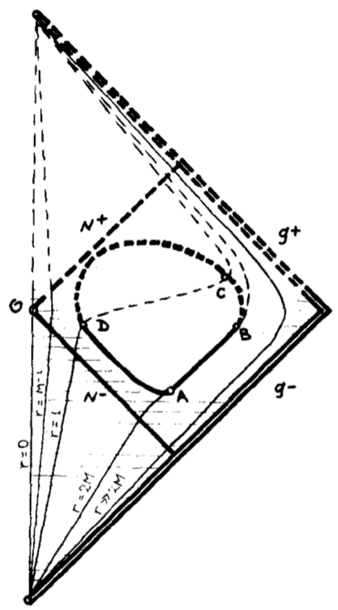
Exploding holes

Exploding holes



- Frolov, Vilkovinski '79

Exploding holes



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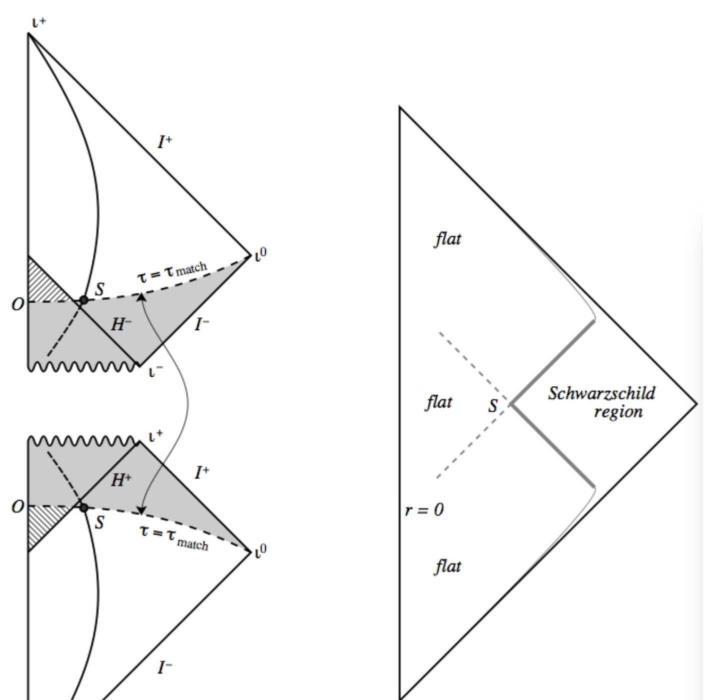
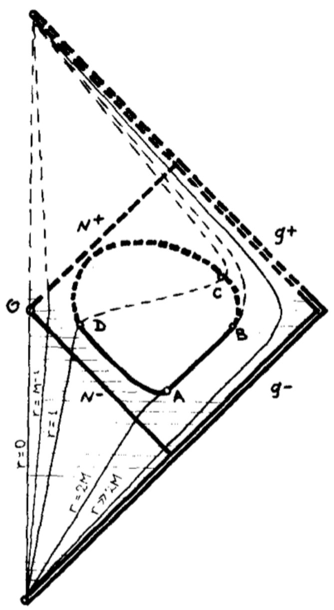
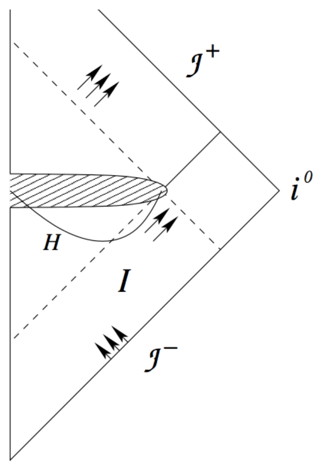


Fig. 2a Fig. 2b

Exploding holes





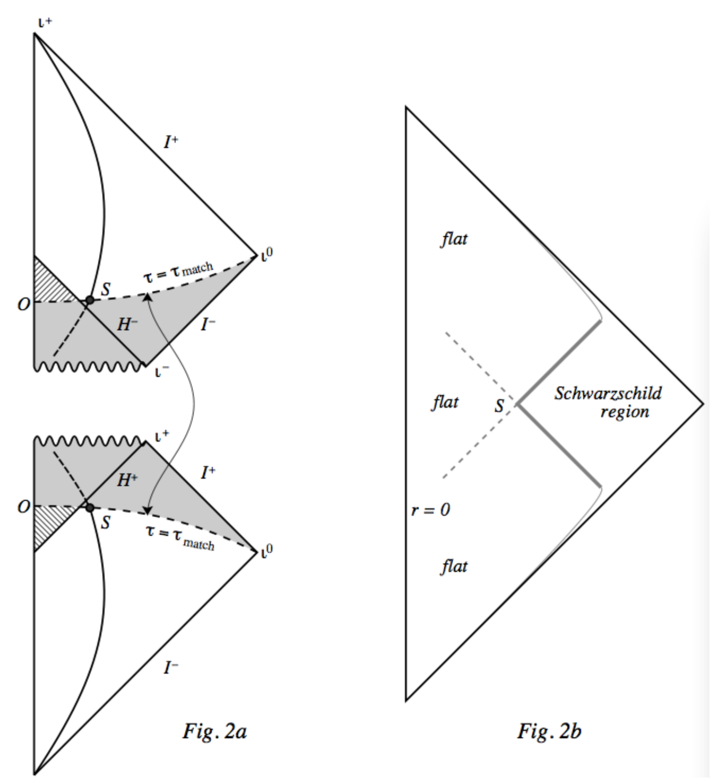
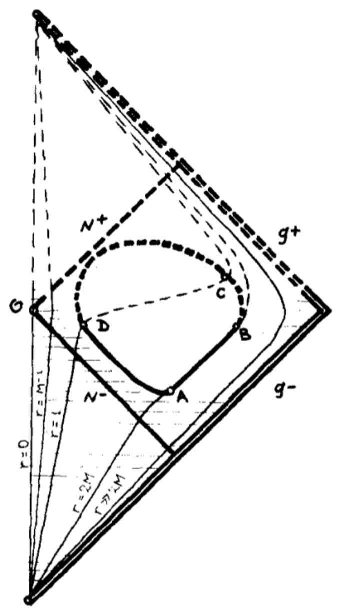
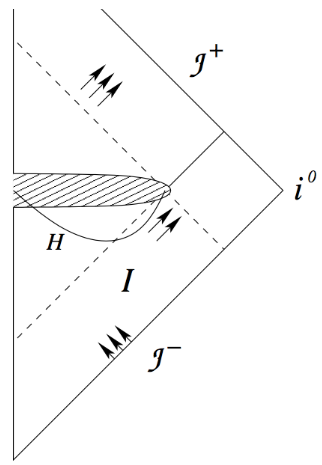


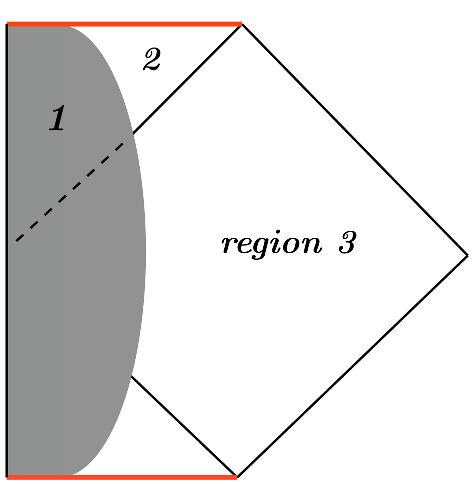
Fig. 2a *Fig. 2b*

- Frolov, Vilkovinski '79
- Stephen, t'Hooft, Whithing '93
- Ashtekar, Bojowald '05

Exploding holes







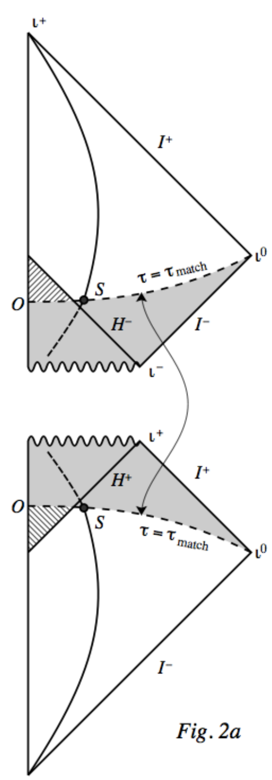


Fig. 2a

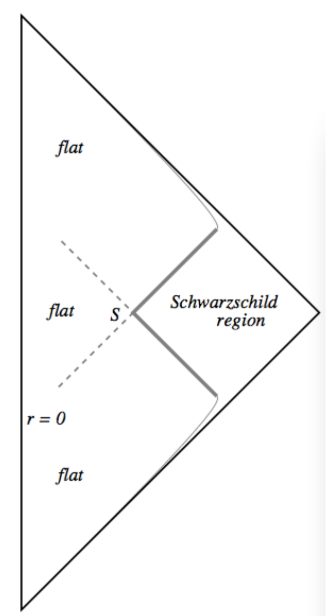
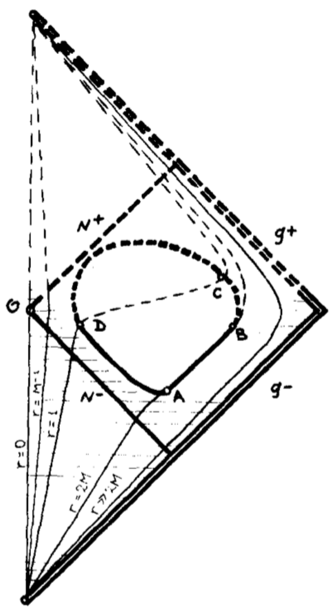
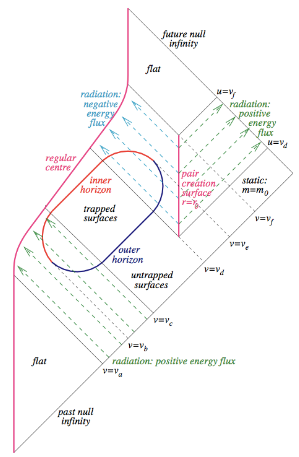


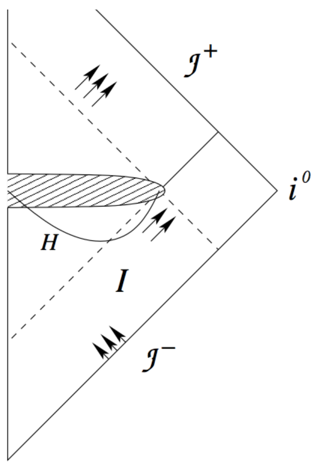
Fig. 2b

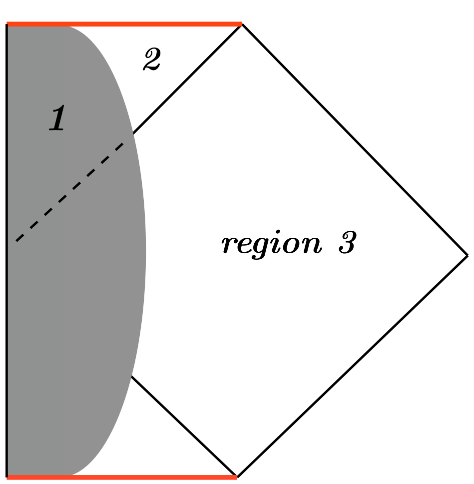
- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93
- Ashtekar, Bojowald ’05
- Modesto ‘06

Exploding holes









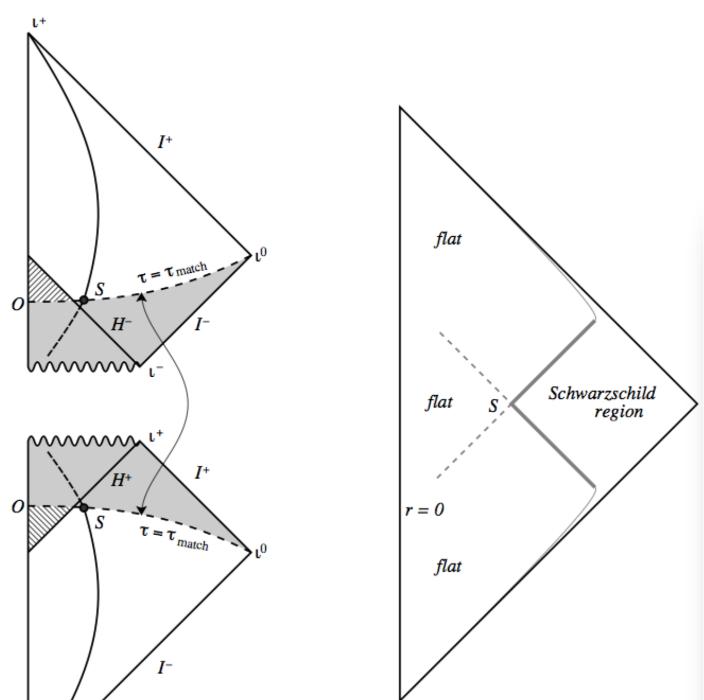
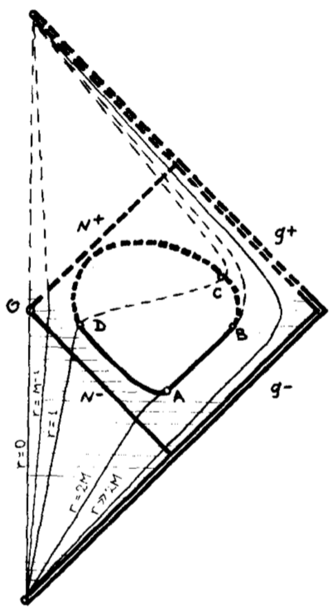
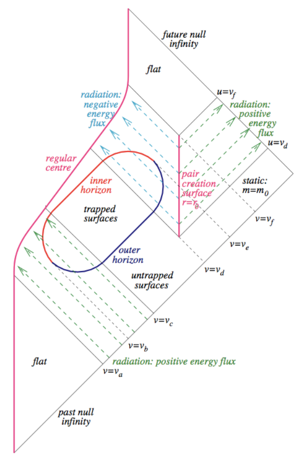


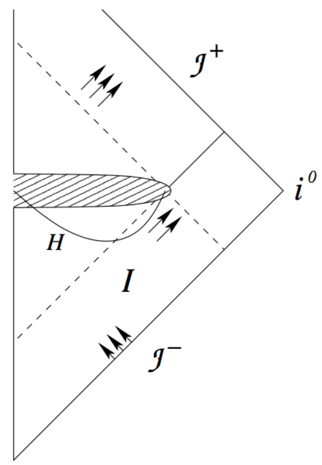
Fig. 2a Fig. 2b

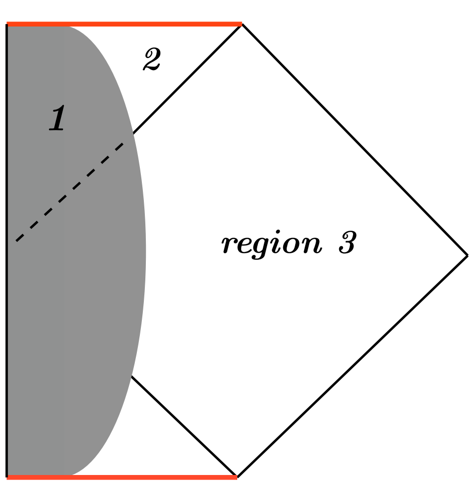
- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93
- Ashtekar, Bojowald ’05
- Modesto ‘06
- Hayward ’06

Exploding holes









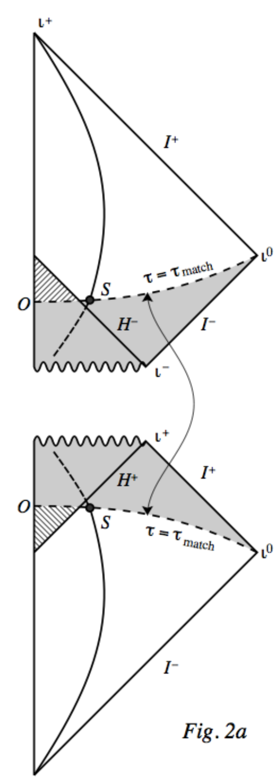


Fig. 2a

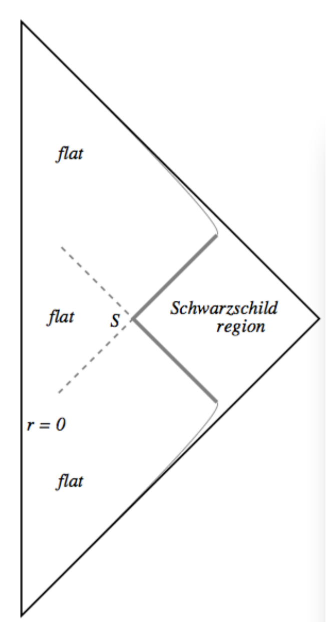
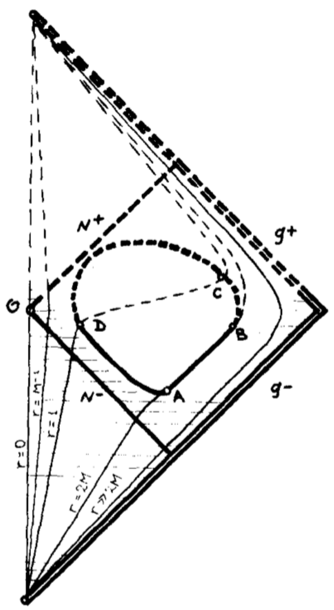
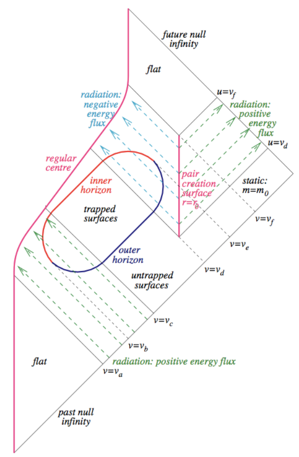


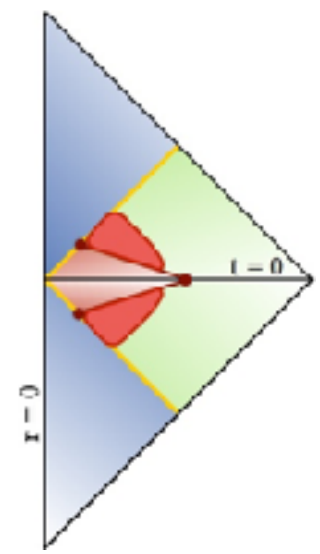
Fig. 2b

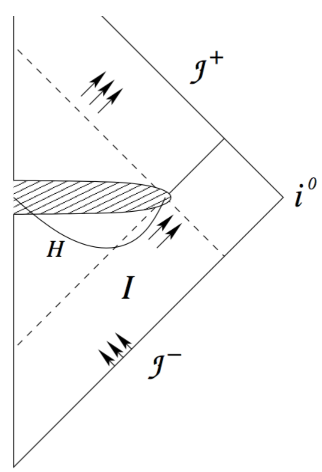
- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93
- Ashtekar, Bojowald ’05
- Modesto ‘06
- Hayward ’06
- Hajicek Kieffer ’01

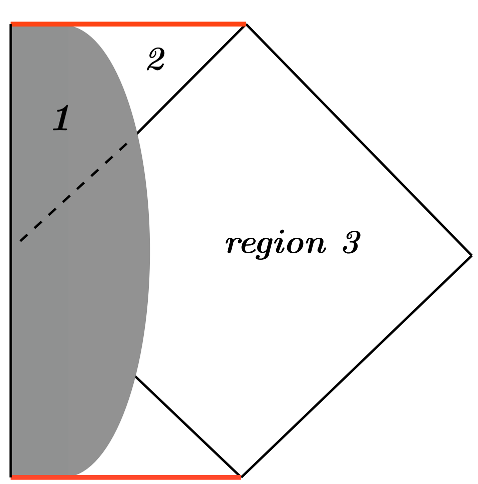
Exploding holes











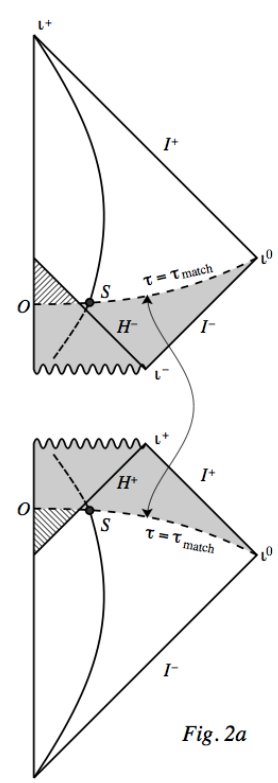


Fig. 2a

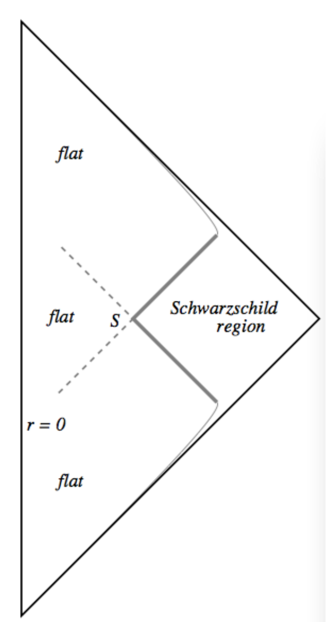


Fig. 2b

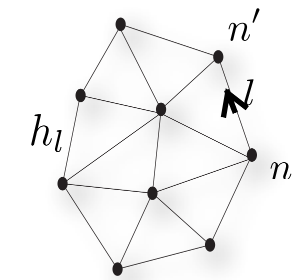
- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93
- Ashtekar, Bojowald ’05
- Modesto ‘06
- Hayward ’06
- Hajicek Kieffer ’01
- Haggard, Rovelli ’15

Covariant loop quantum gravity. Full definition.

Kinematics **Boundary**

State space $\mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma \quad \ni \psi(h_l) \qquad \mathcal{H} = \lim_{\Gamma\to\infty} \mathcal{H}_\Gamma$

Operators: $\vec{L}_l = \{L^i_l\}, i = 1,2,3$ where $L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$

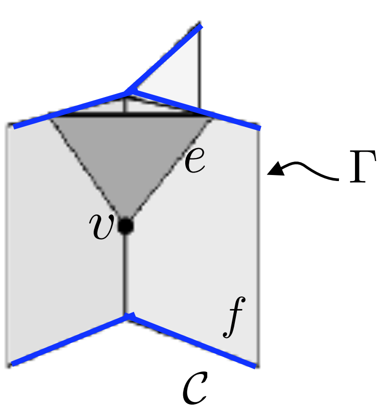


Γ spin network (nodes, links)

Dynamics **Bulk**

Transition amplitudes $W_{\mathcal{C}}(h_l) = N_{\mathcal{C}} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$ $\qquad h_f = \prod_v h_{vf}$

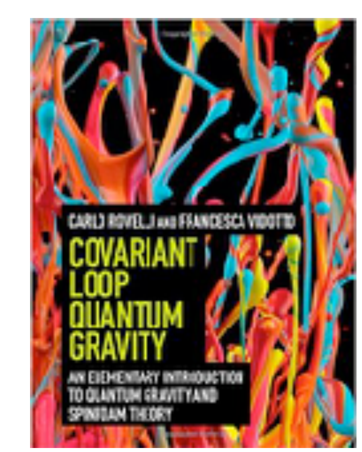
Vertex amplitude $A(h_{vf}) = \int_{SL(2,\mathbb{C})} dg'_e \prod_f \sum_j \, (2j+1)\; D^j_{mn}(h_{vf}) D^{\gamma(j+1)\,j}_{jmjn}(g_e g^{-1}_{e'})$



$$W = \lim_{\mathcal{C}\to\infty} W_{\mathcal{C}}$$

spinfoam (vertices, edges, faces)

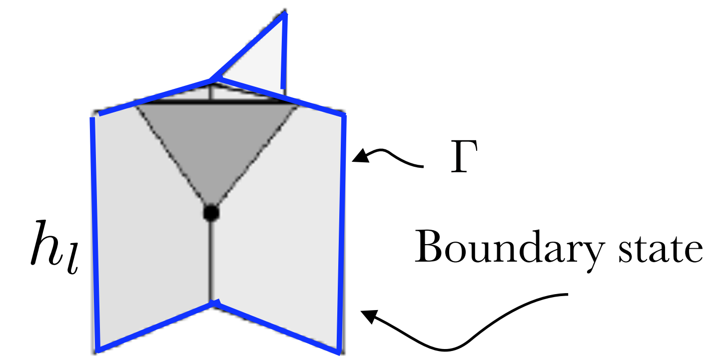
$$8\pi\gamma\hbar G = 1$$



Satisfies all “requirements” listed by Steve Carlip in the last talk

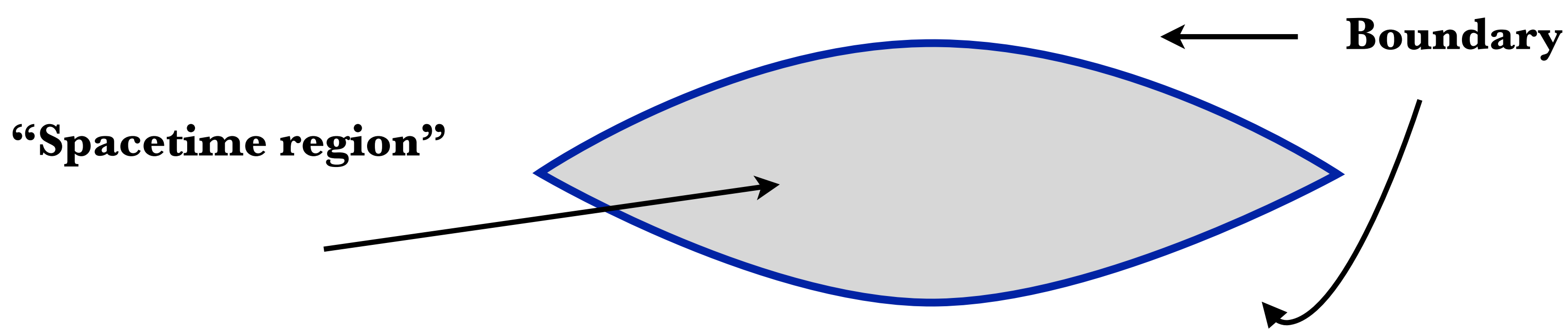
- **Quantum theory** (Hilbert space, operators, transition amplitudes)
- **Classical limit: GR** (Barrett’s theorems)
- **UV qft divergences** (Han and Fairbairn’s theorems)
- **Minimum length** (Spectral properties of operators)
- **Black hole thermodynamics**

A process and its amplitude



Boundary state $\Psi = \psi_{in} \otimes \psi_{out}$

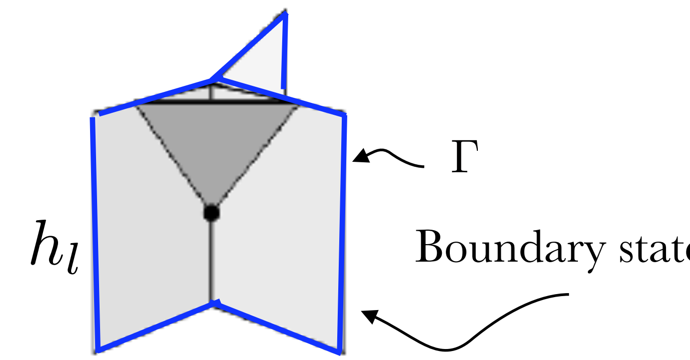
Amplitude $A = W(\Psi)$



Quantum system = Spacetime region

➜ **Hamilton function: S(q,t,q',t')**

A process and its amplitude



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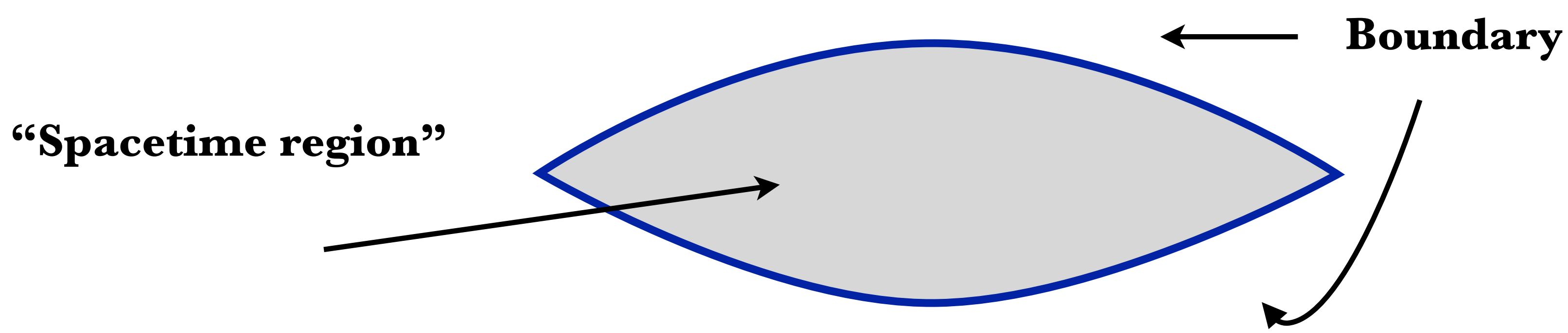


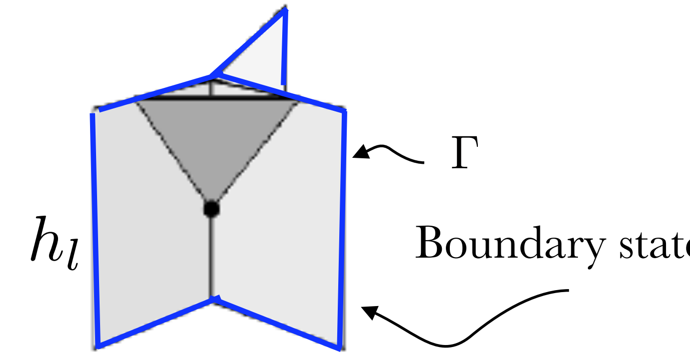
Quantum system
=
Spacetime region

➜ **Hamilton function: S(q,t,q',t')**

In GR, distance and time measurements are field measurements like any other one: they are part of the **boundary data** of the problem

Boundary values of the gravitational field = geometry of box surface = distance and time separation of measurements

A process and its amplitude



Boundary state $\quad \Psi = \psi_{in} \otimes \psi_{out}$

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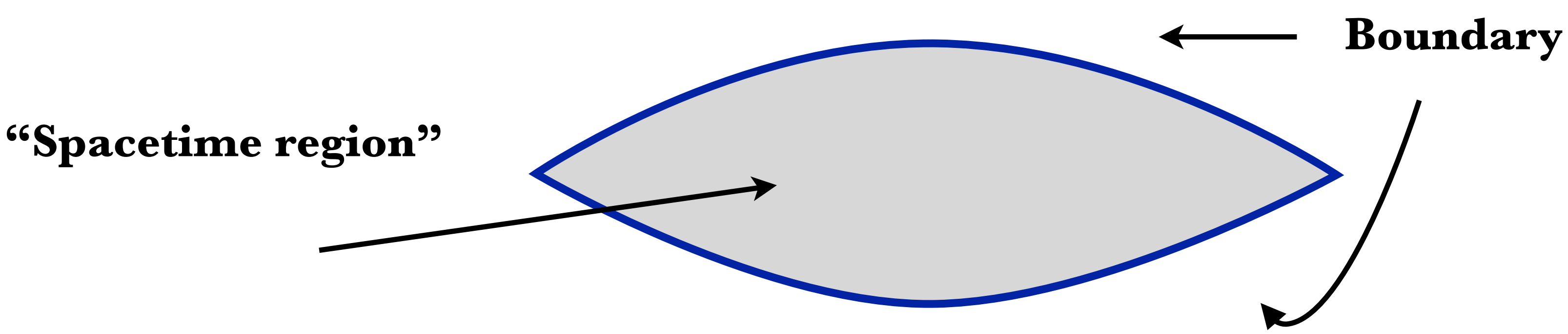

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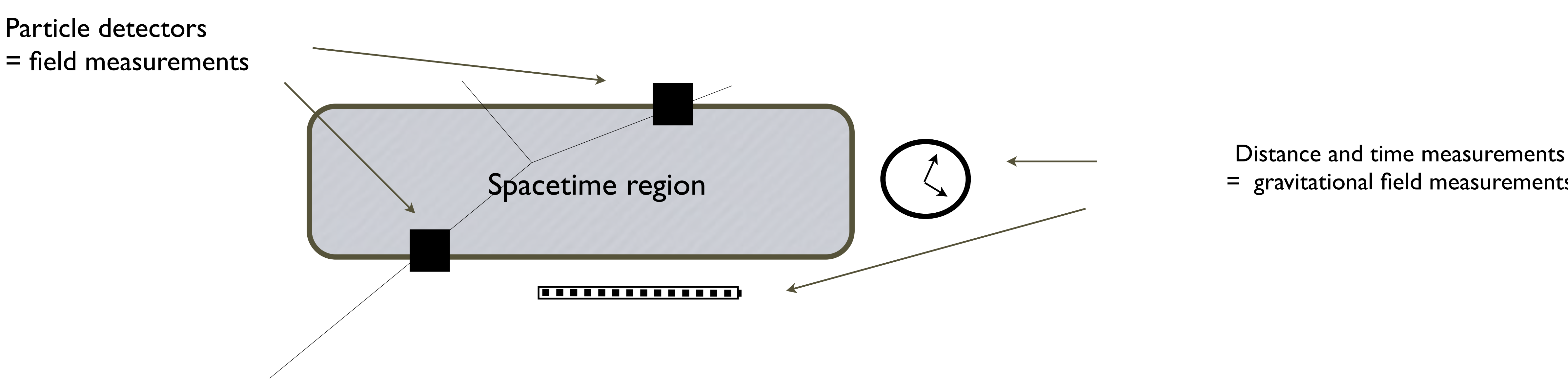
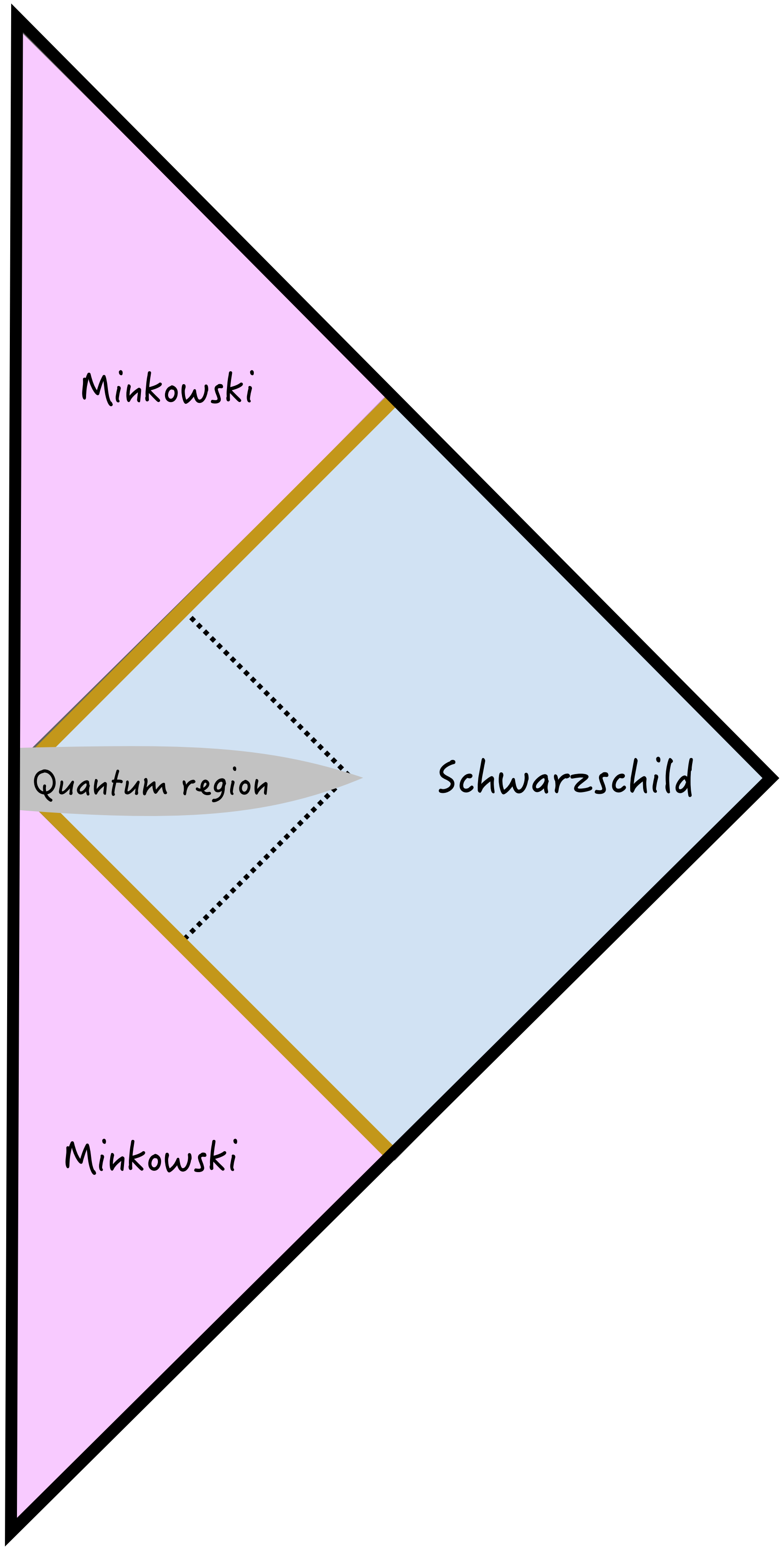



Minkowski
Quantum region
Schwarzschild
Minkowski

Full expression for the transition amplitude:

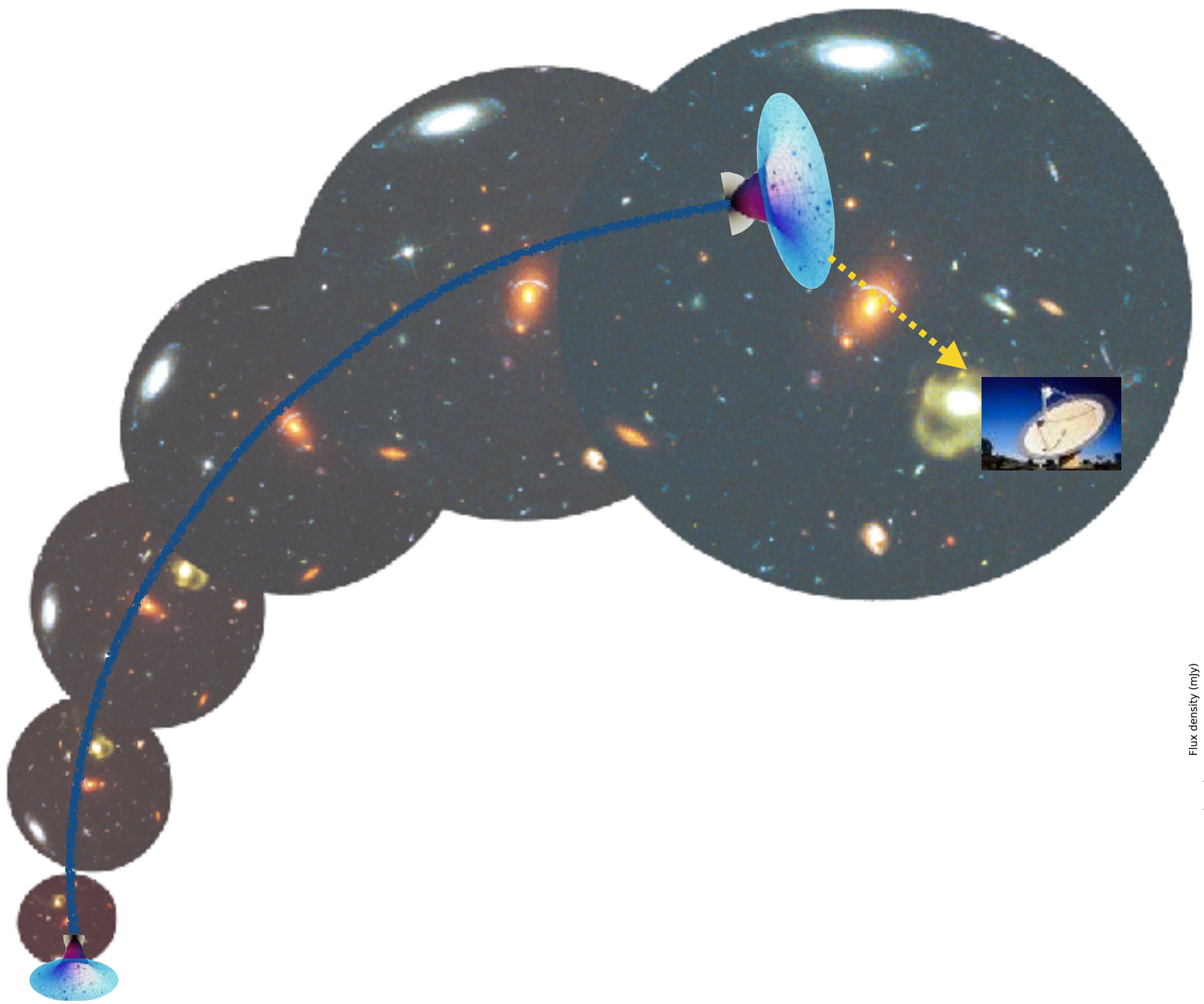
$$W(m,T) = \sum_{\{j_\ell\}} w(m,T,j_\ell) \sum_{\{J_n\},\{K_n\},\{l_\ell\}} \left(\bigotimes_n N^{J_n}_{\{j_n\}}(\{\nu_n\},\{\alpha_n\})\, f^{J_n,K_n}_{\{j_n\}\{l_n\}} \right) \left(\bigotimes_n i^{K_n,\{l_n\}} \right)_\Gamma$$

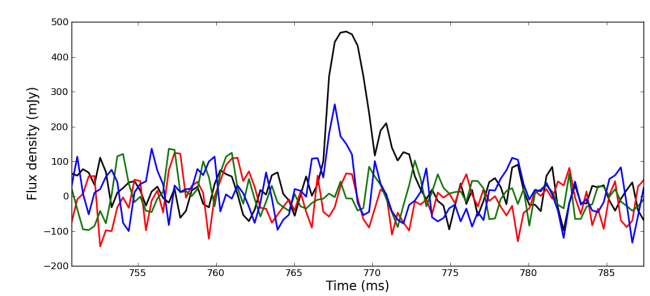
$$w(m,T,j_\ell) = c(m) \prod_\ell d_{j_\ell}\, e^{-\frac{1}{2\eta_\ell}(j_\ell - \frac{(2\eta_\ell^2-1)}{2})^2}\, e^{i\gamma\zeta_\ell j_\ell} \quad , \; \eta_\ell^2 \sim m^2$$

$$N^{J_n}_{\{j_n\}} = \left(\overleftarrow{\bigotimes_{\ell\in n}} D^{j_\ell}_{m_\ell j_\ell}(\{\nu_n\},\{\alpha_n\}) \right) i^{J_n,\{j_n\}}_{\{\overrightarrow{m}_n\}}$$

$$f^{K_n,J_n}_{\{j_n\}\{l_n\}} \equiv d_{J_n}\; i^{J_n,\{j_n\}}_{\{\overrightarrow{p}_n\}} \left(\int dr_n \frac{\sinh^2 r_n}{4\pi} \overrightarrow{\bigotimes_{\ell\in n}} d_{j_\ell l_\ell p_\ell}(r_n) \right) i^{K_n,\{l_n\}}_{\{\overleftarrow{p}_n\}}\; d_{K_n}$$

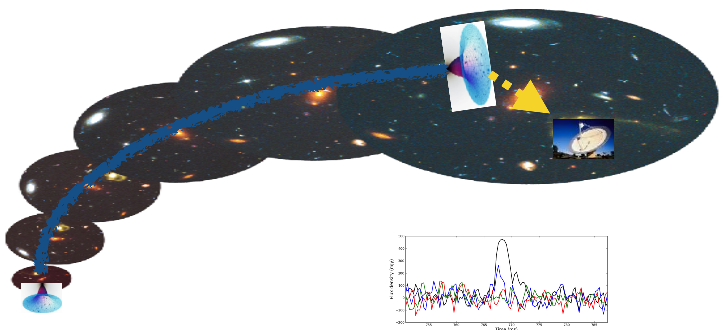
Primordial black holes!



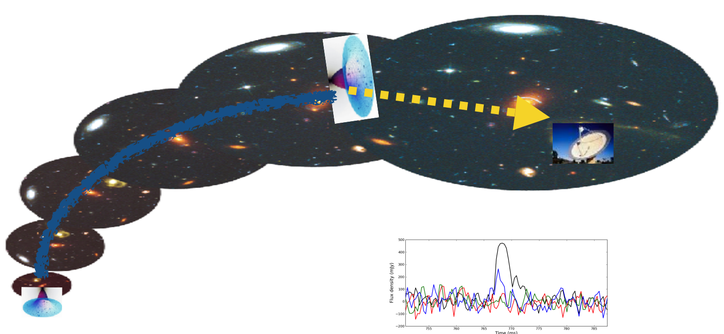


Signature: distance/energy relation

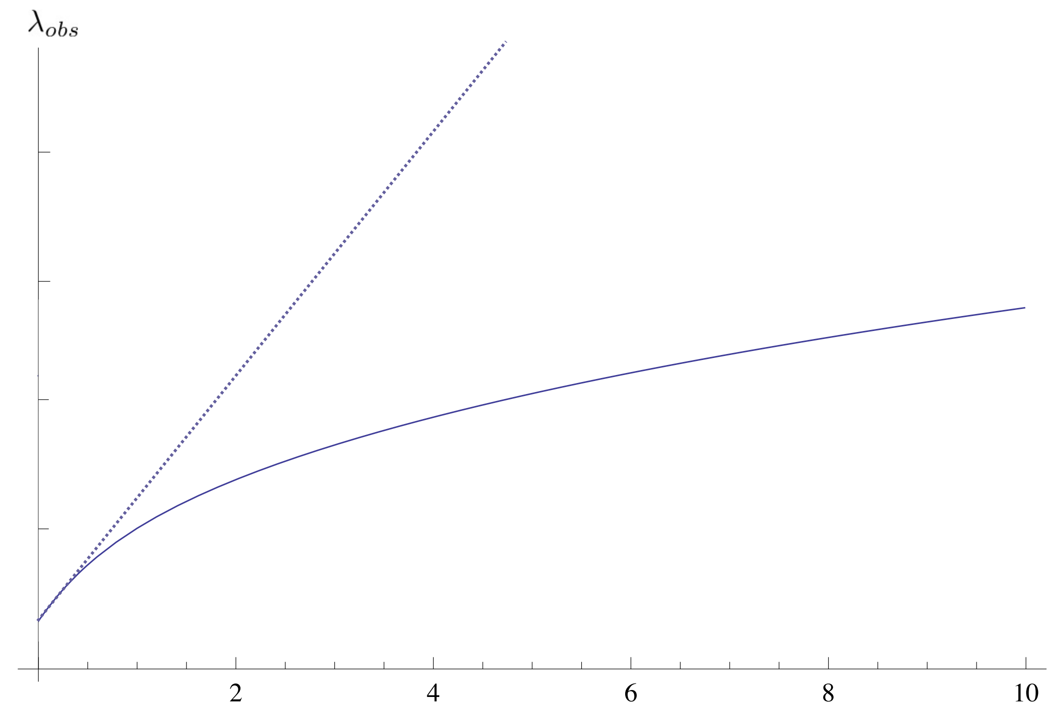
$$\lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



m_1



$m_2 < m_1$



Fast Radio Bursts and White Hole Signals
Aurélien Barrau, Carlo Rovelli, Francesca Vidotto.

Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2017.xxx.

Fundamental Physics with the SKA: Dark Matter and Astroparticles

K. Kelley[1], S. Riemer-Sørensen[2], E. Athanassoula[3], C. Bœhm[4,5], G. Bertone[6], A. Bosma[7], M. Brüggen[8], C. Burigana[9,10,11], F. Calore[6,12], S. Camera[13,14,15], J.A.R. Cembranos[16], R.M.T. Connors[17], Á. de la Cruz-Dombriz[18,19], P.K.S Dunsby[2], N. Fornengo[13,14,15], D. Gaggero[6], M. Méndez-Isla[18,19], Y. Ma[21,22,23], H. Padmanabhan[24], A. Pourtsidou[25], P.J. Quinn[1], M. Regis[13,14], M. Sahlén[26], M. Sakellariadou[27], L. Shao[28], J. Silk[29,30,31,32], T. Trombetti[10,33,9], F. Vazza[34,35], F. Vidotto[36], F. Villaescusa-Navarro[37], C. Weniger[6] and L. Wolz[38]

3.9.2 PBHs and Quantum Gravity

To date the search for PBHs and for constraints on PBHs has mostly considered an almost monochromatic mass spectrum, and the presence of Hawking evaporation for PBHs of small mass. Monochromatic mass spectrum has been challenged by different authors as unrealistic (for example Carr et al. (2017a)). An extended mass function is compatible with different PBHs formation mechanics, from critical collapse to cosmic strings. Hawking evaporation is a phenomenon that becomes relevant on a time scale that depends on the mass of the BH. Its time scale is M_{BH}^3 in Planck units. This implies that within the age of the universe only PBHs with mass smaller than 10^{12} kg could have evaporated, and possibly produced very high-energy cosmic rays (Barrau, 2000). As cosmic rays of such energies are rare, constraints are derived on the very-small-mass end of the PBH mass spectrum.

Hawking evaporation, however, is a phenomenon predicted in the context of quantum field theory on a fixed curved background. This is a theory with a regime of validity that may likely break down when approximately half of the mass of the hole has evaporated, as indicated for instance by the 'firewall' no-go theorem (Almheiri et al., 2013). The geometry around a BH can indeed undergo quantum fluctuations on a time scale shorter than M_{BH}^3, when the effects of the Hawking evaporation have not not yet significantly modified the size of the hole. As any classical system, the hole has a characteristic timescale after which the the departure from of this discreteness on the dynamics can be modeled at the effective level by an effective potential that prevents the gravitational collapse from forming the singularity and triggers a bounce. The bounce connects a collapsing solution of the Einstein equation, that is the classical black hole, to an explosive expanding one, a white hole (Haggard & Rovelli, 2014), through an intermediate quantum region. This process is a typical quantum tunnelling event, and the characteristic time at which it takes place, the hole lifetime, can be as a decaying time, similar to the lifetime of conventional nuclear radioactivity. The resulting picture is conservative in comparison to other models of non-singular BHs. The collapse still produces a horizon, but it is now a dynamical horizon with a finite lifetime, rather then a perpetual event horizon. The collapsing matter continues its fall after entering the trapping region, forming a very dense object whose further collapse is prevented by quantum pressure (referred to with the suggesting name of *Planck Star* Rovelli & Vidotto (2014)).

The collapsing matter that forms PBHs in the radiation dominated epoch is mainly constituted by photons. Seen from the center of the hole, those photons collapse through the trapping region, then expands passing through an anti-trapping region and eventually exits the white-hole horizon, always at the speed of light, the process is thus extremely fast. On the other hand, for an observer sitting outside the horizon, a huge but finite redshift stretches this time to cosmological times. This time, properly called the hole lifetime, as discussed before has

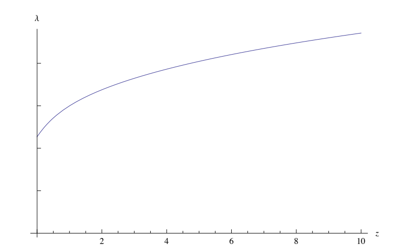
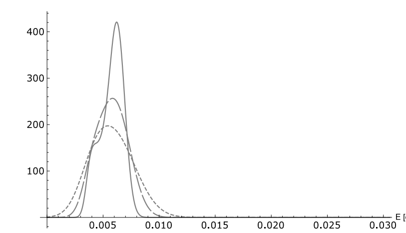
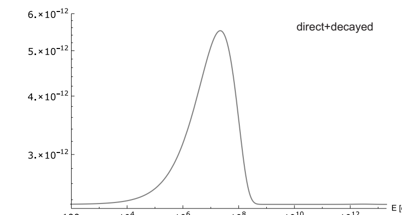


Figure 21. The expected wavelength (unspecified units) of the





Quantum Gravity observations are not absurd anymore.

- Decrease the Bayesian confidence of some current theories (absence of supersymmetry at energy where it was expected)
- Already rules out theories (Lorentz invariance)
- Suggested astrophysical observations motivating astronomers (Cosmology+Black holes)
- Interesting laboratory experiments (Entanglement via gravity)

(Result of a pool at a recent conference (3rd Karl Schwarzschild Meeting on Gravitational Physics and the Gauge/Gravity Correspondence, Frankfurt am Main, July 2017): 80% of the participants expect observational evidence for quantum gravity observations within the next decade.)

Progress has happened along some research directions

	Empirical success	Empirical failure	Theoretical success	Theoretical failure	Key open issue
Strings	None	Low-energy super symmetry	AdS-CFT Non-fundamental appliacations	Standard model parameters	Lack of predictivity
Loops	None		Low energy limit		Infinite graph limit
Hojava-Lifshitz	None	Lorentz violation at Planck scale	Renormalizability		Other scale?
Asymptotic savety	None		Increase evidence of fixed point		Computing amplitudes
Your favorite	…	…	…	…	…

Loops
open problems
in the late 80’

Loops open problems in the late 80’

- Definition of the Hilbert space
- Mathematical foundation
- Coupling matter
- Recovering low energy GR
- Problem of time
- Observables
- Application to early universe
- Produce verifiable physical predictions

Loops
open problems
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Strings open problems in the late 80’

- Finding a fundamental formulation of the theory
- Deriving SU(3)xSU(2)xU(1) from first principles
- Computing the parameters of the standard model
- Supersymmetry breaking
- Compactification
- Extend to the non-perturbative regime
- Produce tentative verifiable physical predictions

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3. There is some convergence on some issues of major philosophical relevance

i: nature of physical space

ii: nature of physical time

iii: relation between physical and experiential time

iv: connection between relational aspects of GR and QM

i: nature of physical space

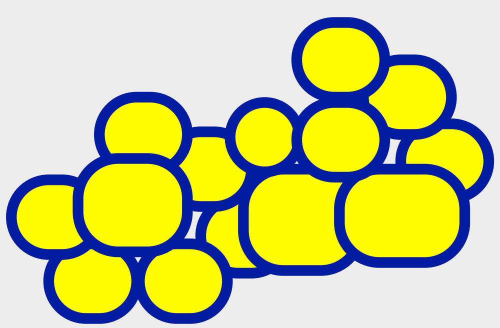
space

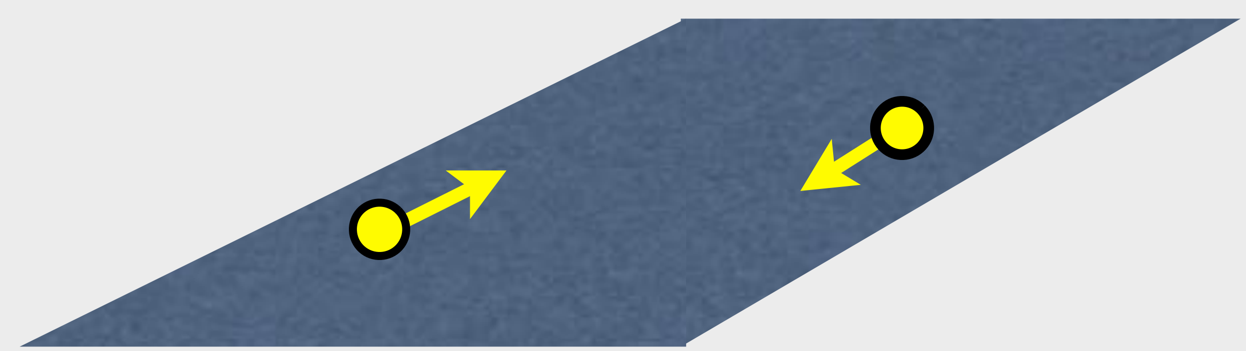
relation

Aristotle
Descartes

entity

Newton





Space is an entity independent from its content

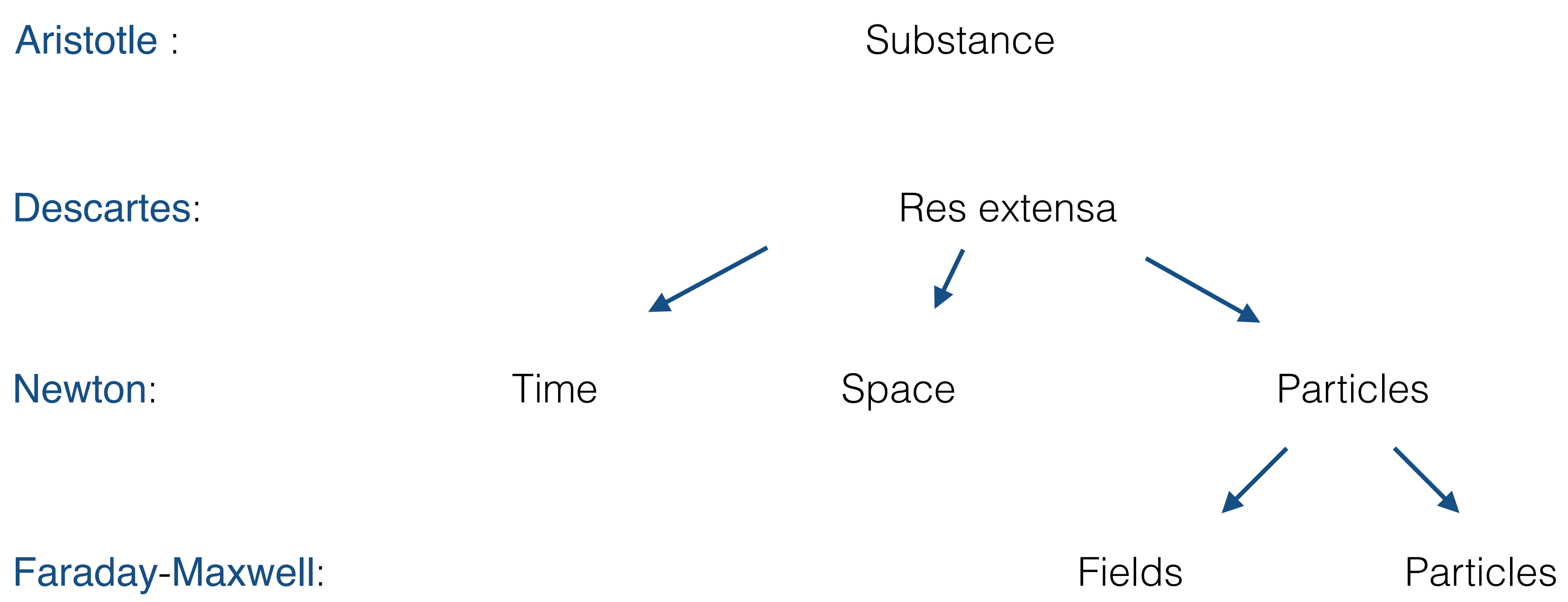
Aristotle : Substance

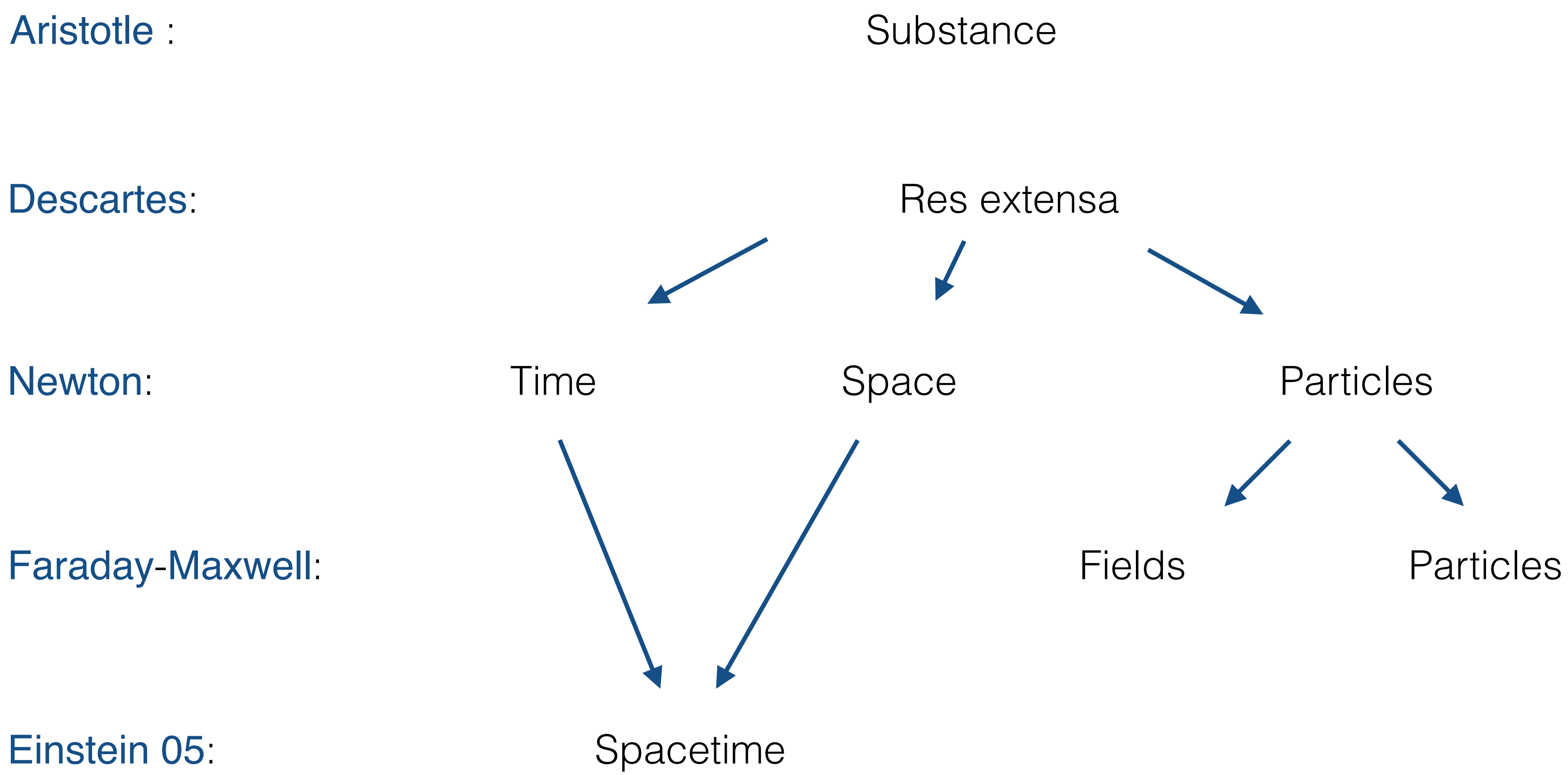
Aristotle :	Substance
Descartes:	Res extensa

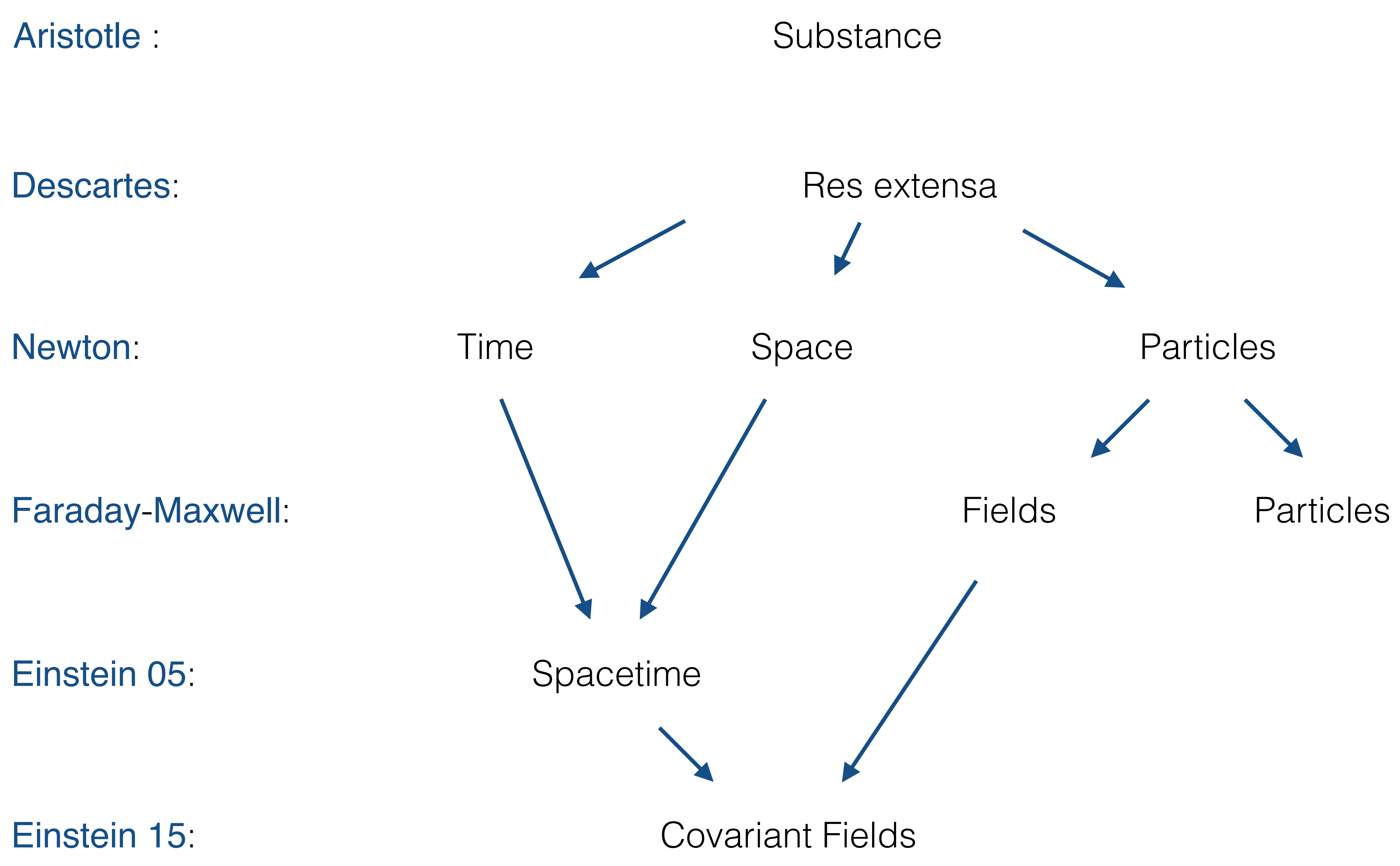
Aristotle : Substance

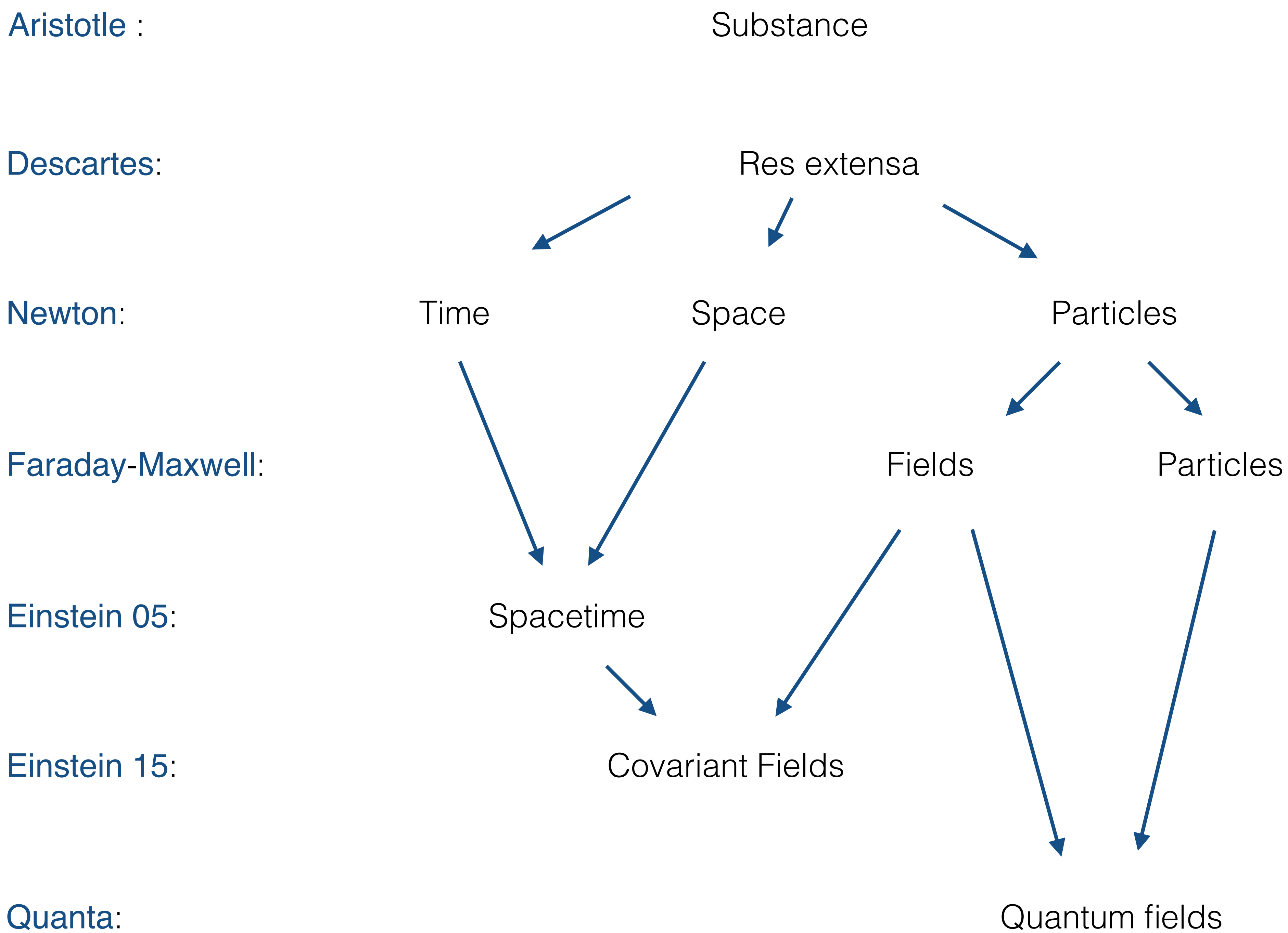
Descartes: Res extensa

Newton: Time Space Particles

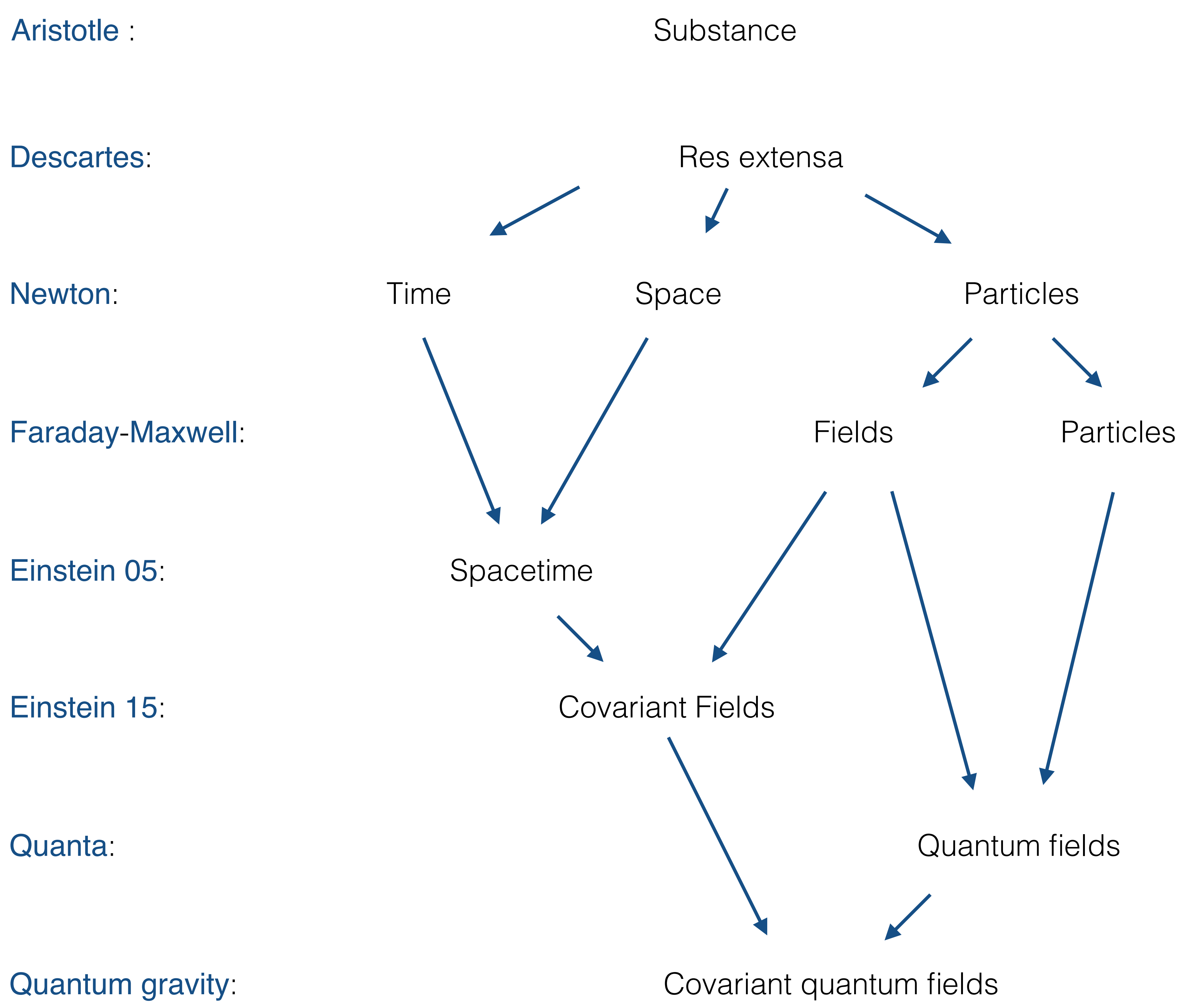

Aristotle :
Substance
Descartes:
Res extensa
Newton:
Time
Space
Particles
Faraday-Maxwell:
Fields
Particles


Aristotle :
Substance
Descartes:
Res extensa
Newton:
Time
Space
Particles
Faraday-Maxwell:
Fields
Particles
Einstein 05:
Spacetime

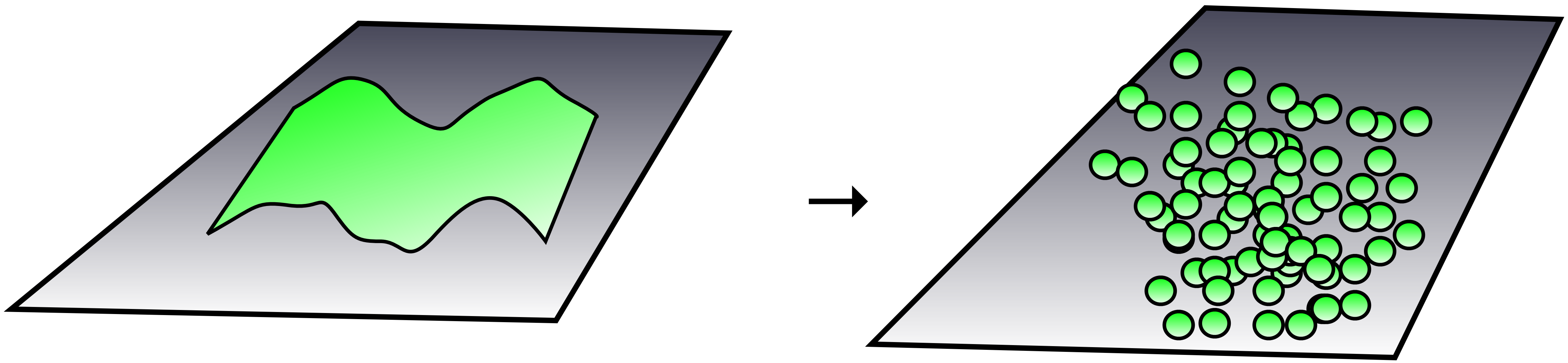

Aristotle :
Substance
Descartes:
Res extensa
Newton:
Time
Space
Particles
Faraday-Maxwell:
Fields
Particles
Einstein 05:
Spacetime
Einstein 15:
Covariant Fields



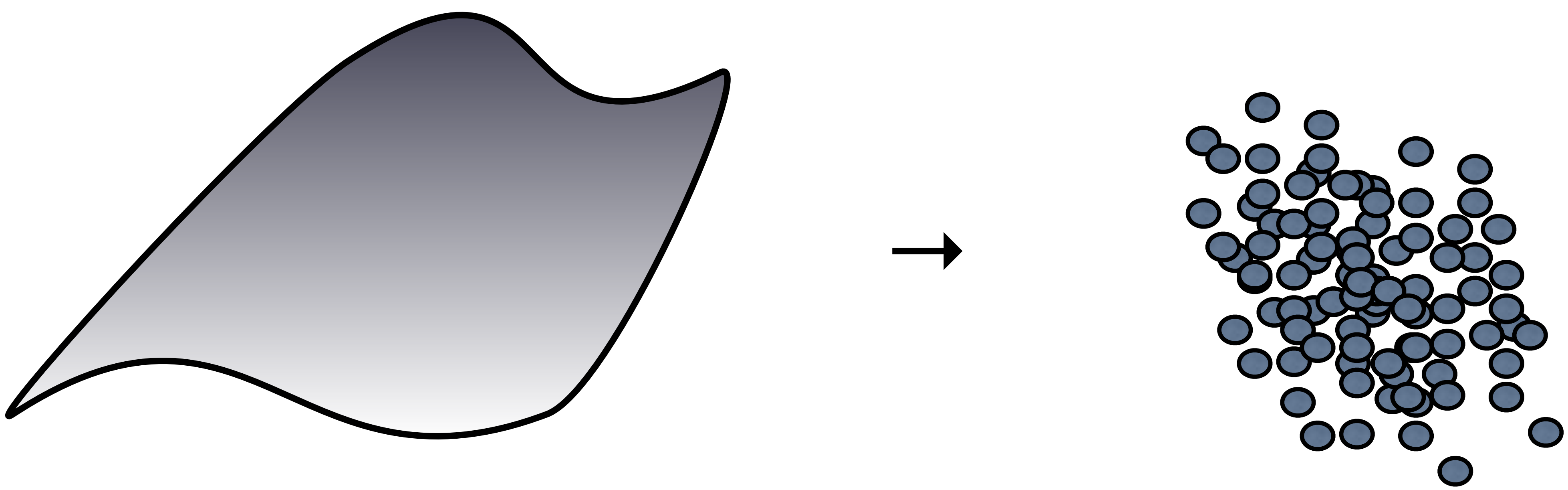
Aristotle :
Substance
Descartes:
Res extensa
Newton:
Time
Space
Particles
Faraday-Maxwell:
Fields
Particles
Einstein 05:
Spacetime
Einstein 15:
Covariant Fields
Quanta:
Quantum fields



Aristotle :
Substance
Descartes:
Res extensa
Newton:
Time
Space
Particles
Faraday-Maxwell:
Fields
Particles
Einstein 05:
Spacetime
Einstein 15:
Covariant Fields
Quanta:
Quantum fields
Quantum gravity:
Covariant quantum fields



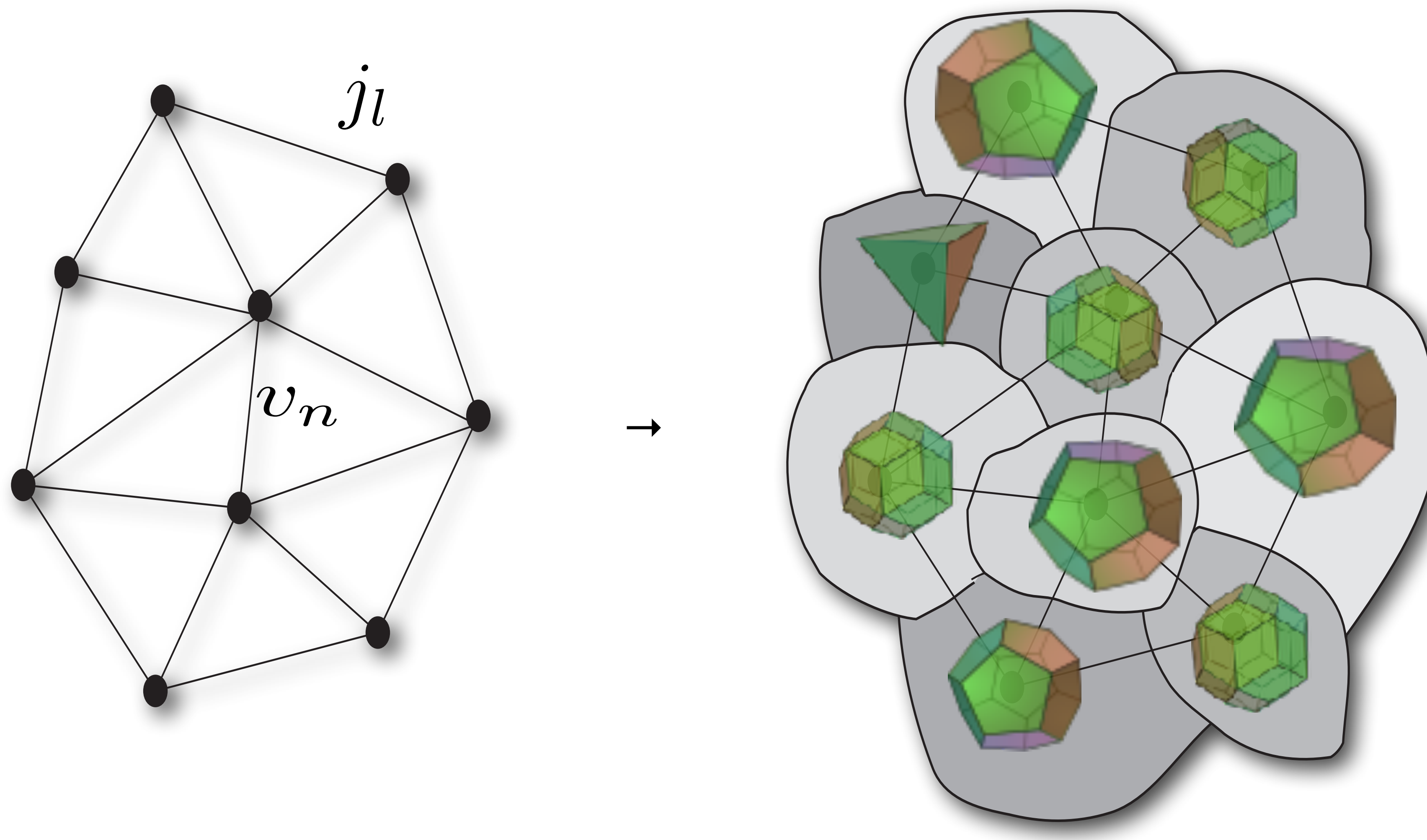
Quantum electromagnetic field: quanta of light



Quantum gravitational space: quanta of space

“Emergence” ←

physical space is granular



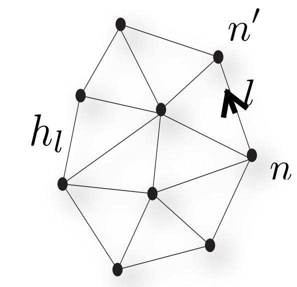
Space has a granular structure: spin networks

Covariant loop quantum gravity. Full definition.

Kinematics **Boundary**

State space $\mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma \quad \ni \psi(h_l) \qquad \mathcal{H} = \lim_{\Gamma\to\infty} \mathcal{H}_\Gamma$

Operators: $\vec{L}_l = \{L_l^i\}, i = 1,2,3$ where $L^i\psi(h) \equiv \left.\frac{d}{dt}\psi(he^{t\tau_i})\right|_{t=0}$

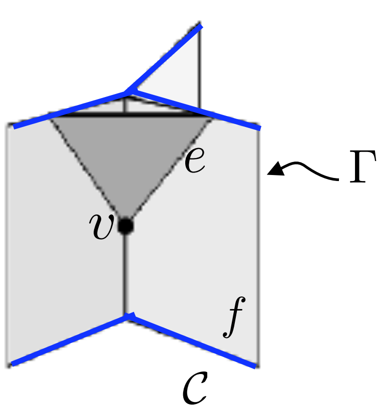


Γ spin network (nodes, links)

Dynamics **Bulk**

Transition amplitudes $W_\mathcal{C}(h_l) = N_\mathcal{C} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$ $\qquad h_f = \prod_v h_{vf}$

Vertex amplitude $A(h_{vf}) = \int_{SL(2,\mathbb{C})} dg'_e \prod_f \sum_j (2j+1)\ D^j_{mn}(h_{vf}) D^{\gamma(j+1)\,j}_{jmjn}(g_e g_{e'}^{-1})$



$$W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C}$$

spinfoam
(vertices, edges, faces)

$$8\pi\gamma\hbar G = 1$$

ii: nature of physical time

Covariant loop quantum gravity. Full definition.

Kinematics **Boundary**

State space $\mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma \quad \ni \psi(h_l) \qquad \mathcal{H} = \lim_{\Gamma\to\infty} \mathcal{H}_\Gamma$

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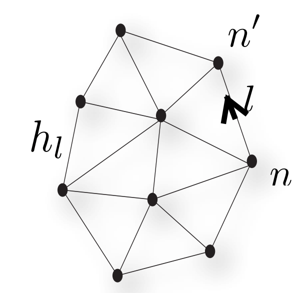

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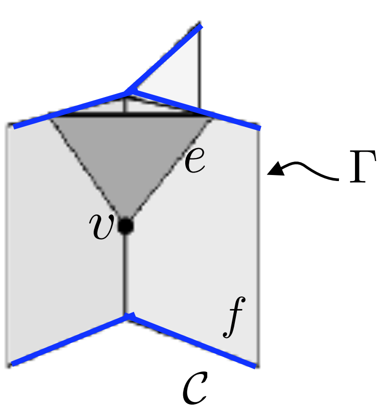
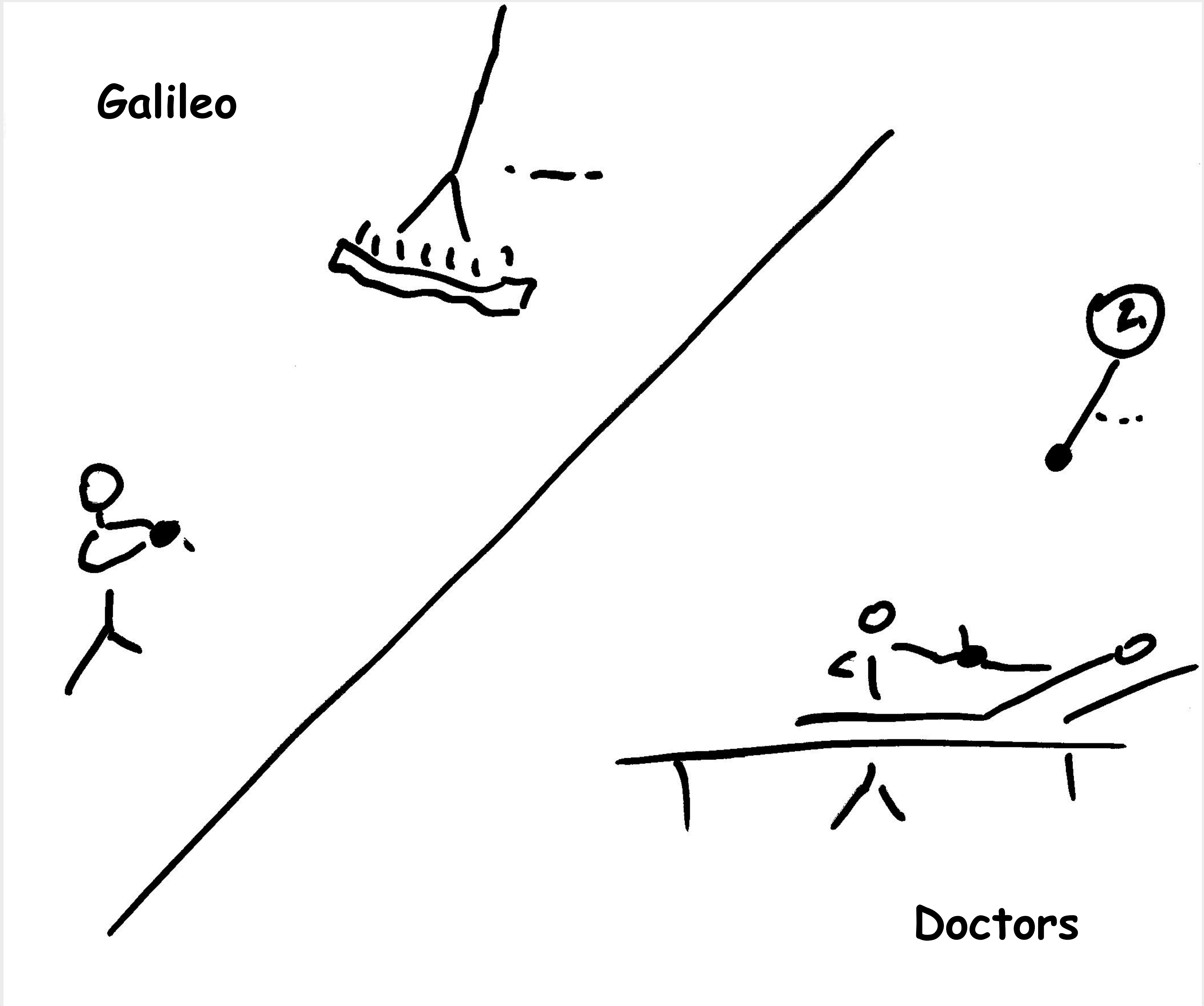
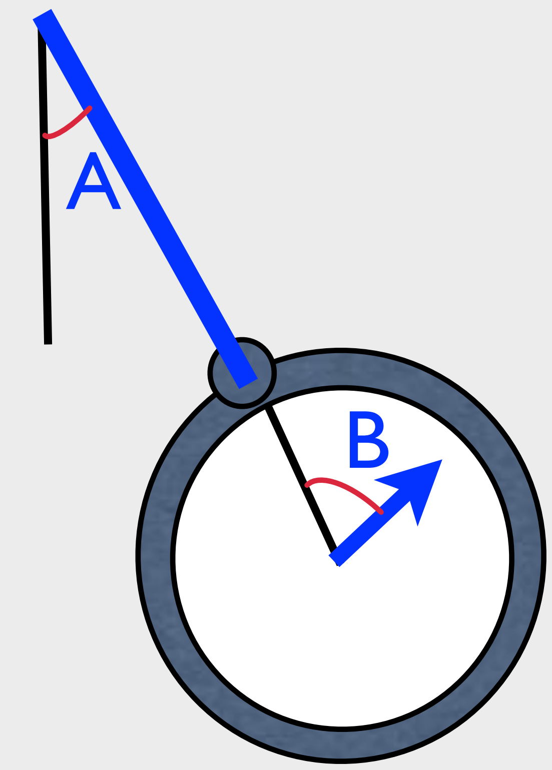


$$W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C}$$

spinfoam
(vertices, edges, faces)

$8\pi\gamma\hbar G = 1$


Galileo
Doctors



Time: t

What we observe: A, B, ...

Newton: A(t), B(t), ...

But we actually only see: A(B), B(A) ....

→ the world can be described without t

At the elementary level Nature is not organized in terms of evolution in time.

iii: relation between physical and experiential time

“Experiential Time” is a complex layer of structures and properties which appear (emerge) at different level of approximations and descriptions of the world:

Internal flow: Diff invariant qft — Connes’s flow of the vonN. algebra

Connes, A. & Rovelli, C. Von Neumann algebra automorphisms and time thermodynamics relation in general covariant quantum theories. Class.Quant. Grav. 11, 2899–2918 (1994).

Flow and energy: Statistical mechanics: — Thermal time (Tomita flow)

Unicity, present: — Non-relativistic limit

Orientation -> traces — (Perspectival?) low past entropy:

Price, H. Time’s Arrow. (Oxford University Press, 1996).
Rovelli, C. Is Time’s Arrow Perspectival? 6 (2015).

Replicating systems with memory: — Biology and evolution

“Sense of flowing time”, identity as narration — Brain’s memory and anticipation

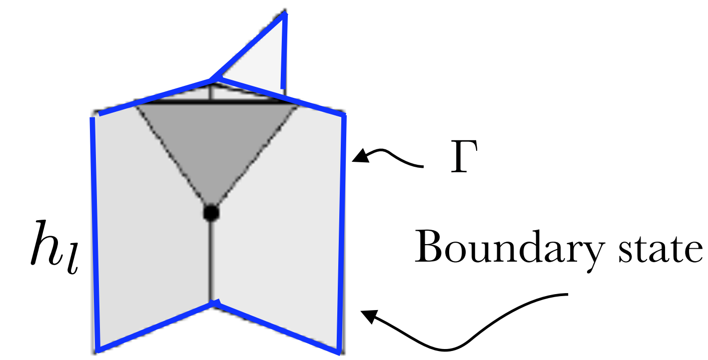
D. Buonomano, Your Brain is a Time Machine: The Neuroscience and Physics of Time, Norton, New York, 2017.

Moral:

do not search in elementary physics what is not in elementary physics

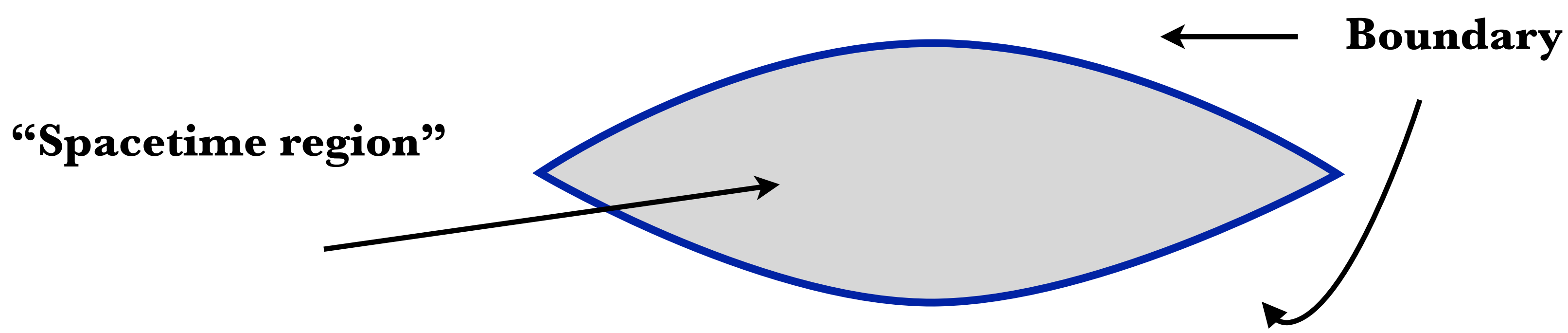
iv: connection between relational aspects of GR and QM

A process and its amplitude



Boundary state $\Psi = \psi_{in} \otimes \psi_{out}$

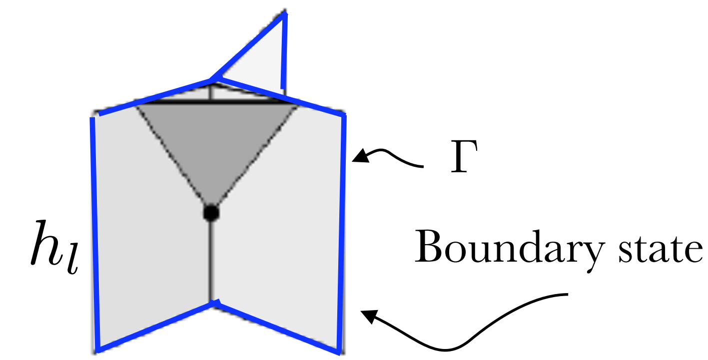
Amplitude $A = W(\Psi)$



Quantum system
=
Spacetime region

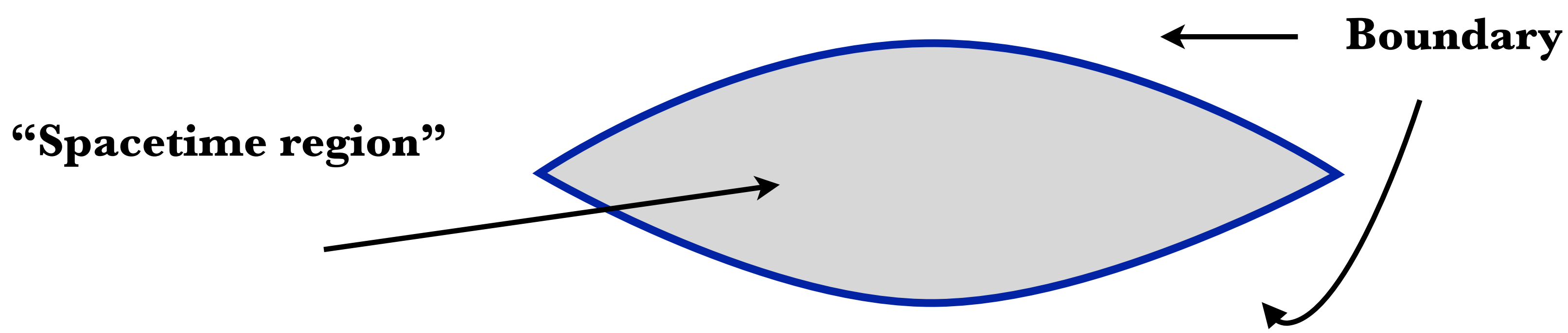
➜ **Hamilton function: S(q,t,q’,t’)**

A process and its amplitude



Boundary state $\Psi = \psi_{in} \otimes \psi_{out}$

Amplitude $A = W(\Psi)$



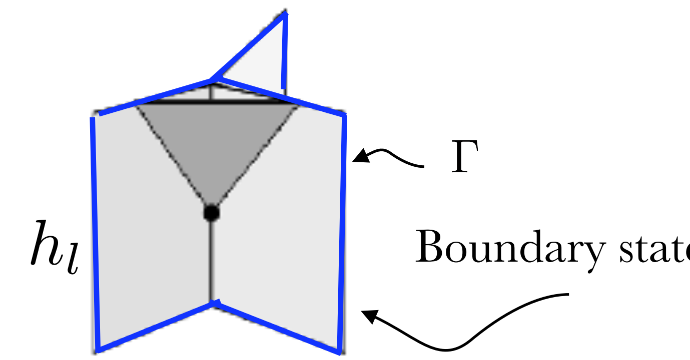
Quantum system = Spacetime region

➜ **Hamilton function: S(q,t,q',t')**

In GR, distance and time measurements are field measurements like any other one: they are part of the **boundary data** of the problem

Boundary values of the gravitational field = geometry of box surface = distance and time separation of measurements

A process and its amplitude



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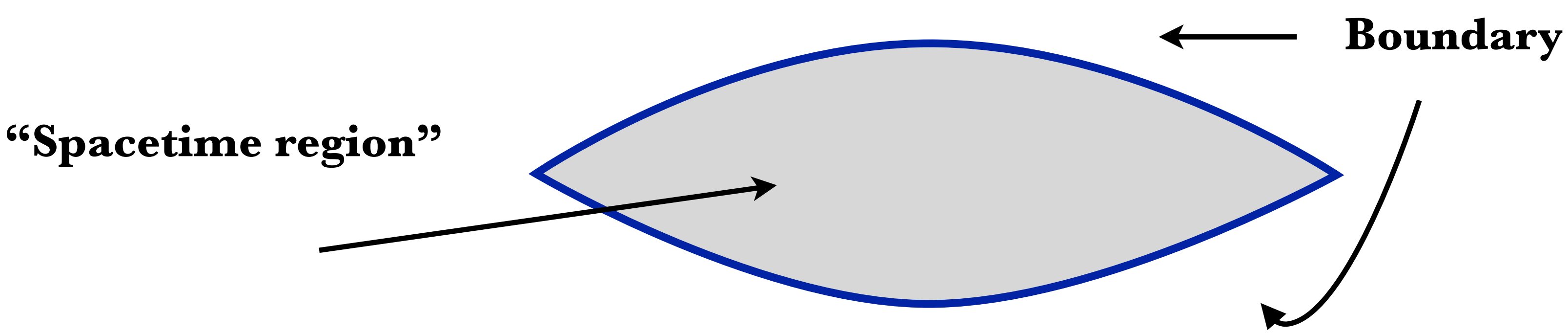

Quantum system = Spacetime region

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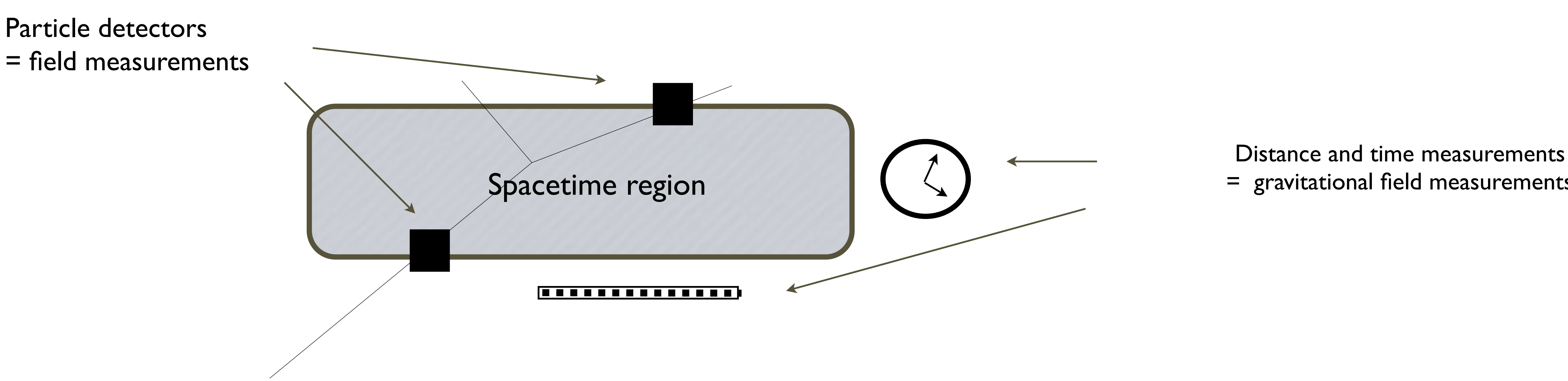
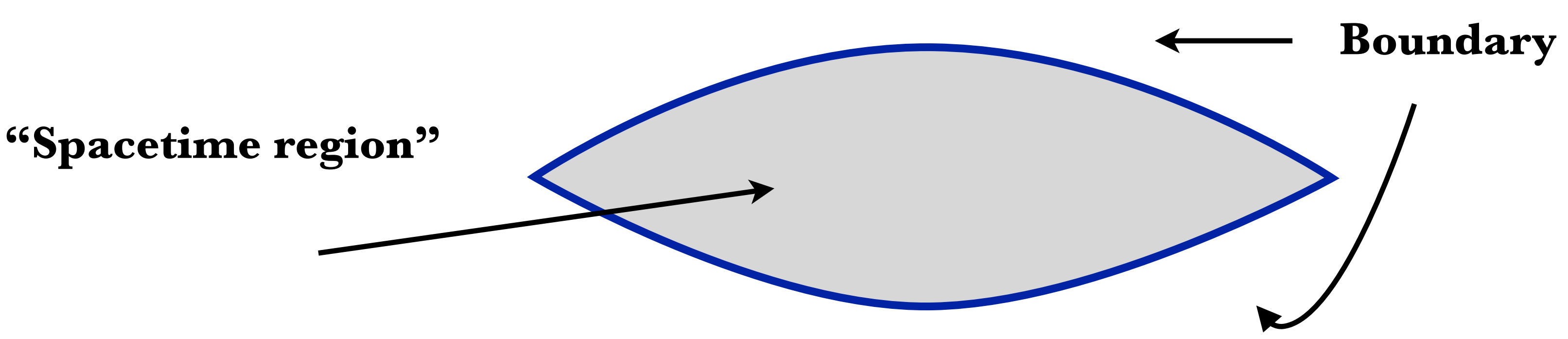


GR: localization of a system is relative to other systems

QM: events for system isare relative to other systems



Understand the world as a net of system influencing one another

1. We do have quantum gravity theories

(We do not know which is right)

2. We do have have some empirical evidence

(Rule out and/or disfavour some theories,
but no positive support yet)

3. Results towards issues of philosophical relevance

i: nature of physical space (“material”, discrete)

ii: nature of physical time (absent at the fundamental level)

iii: relation between physical and experiential time

(Time is a multilayer concept,
Experiencial time is understood in terms of
theormodynamics, biology, brain sciences.)

iv: connection between relational aspects of GR and QM

(Understand the world as a net of system
influencing one another.)