Quantum Gravity

past, present and future

carlo rovelli
vancouver 2017

Many directions of investigation

loop quantum gravity,
string theory,
Hořava–Lifshitz theory,
supergravity,
asymptotic safety,
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
…

Vastly different numbers of researchers involved

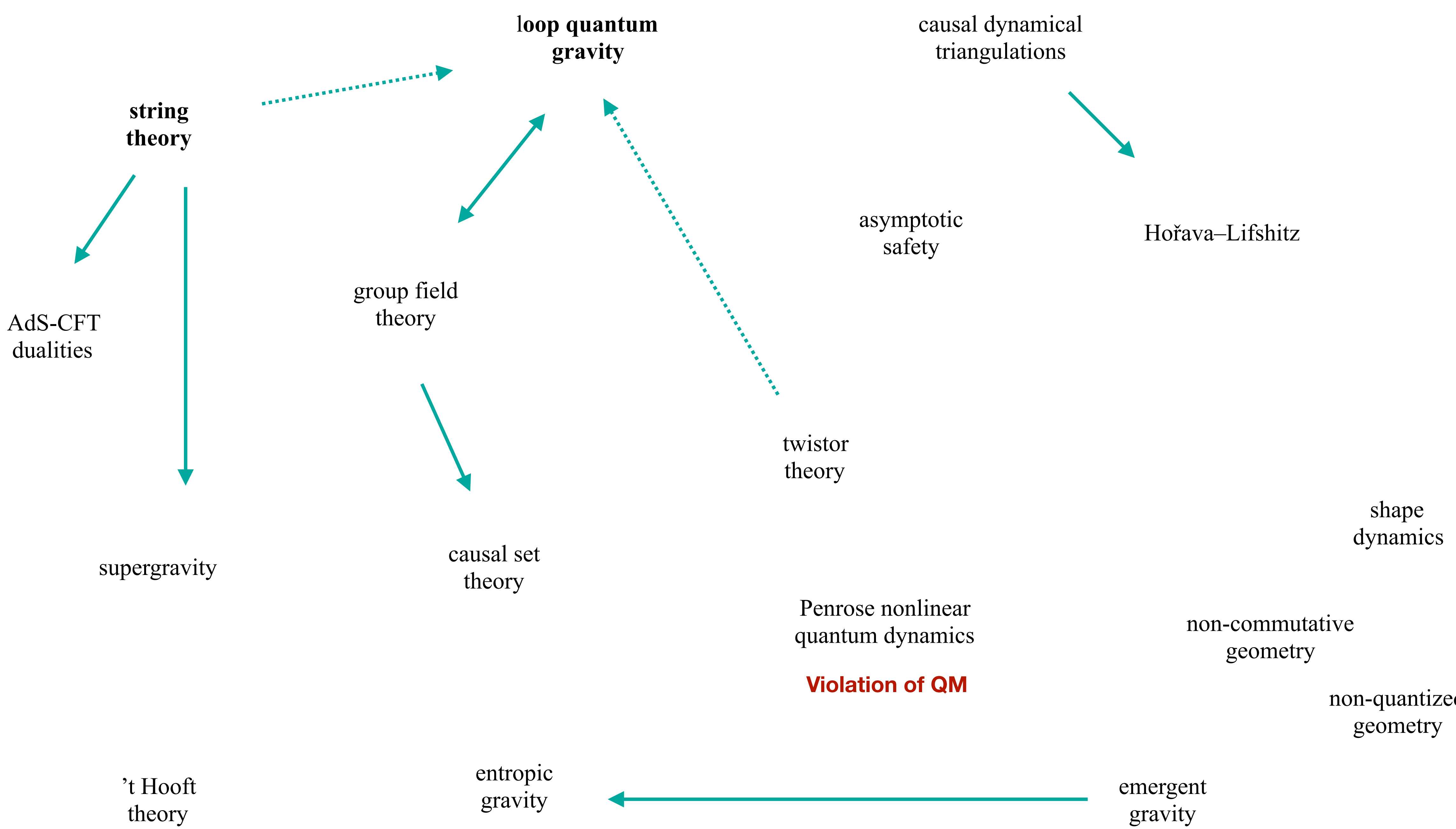
A few offer rather complete tentative theories of quantum gravity

Most are highly incomplete

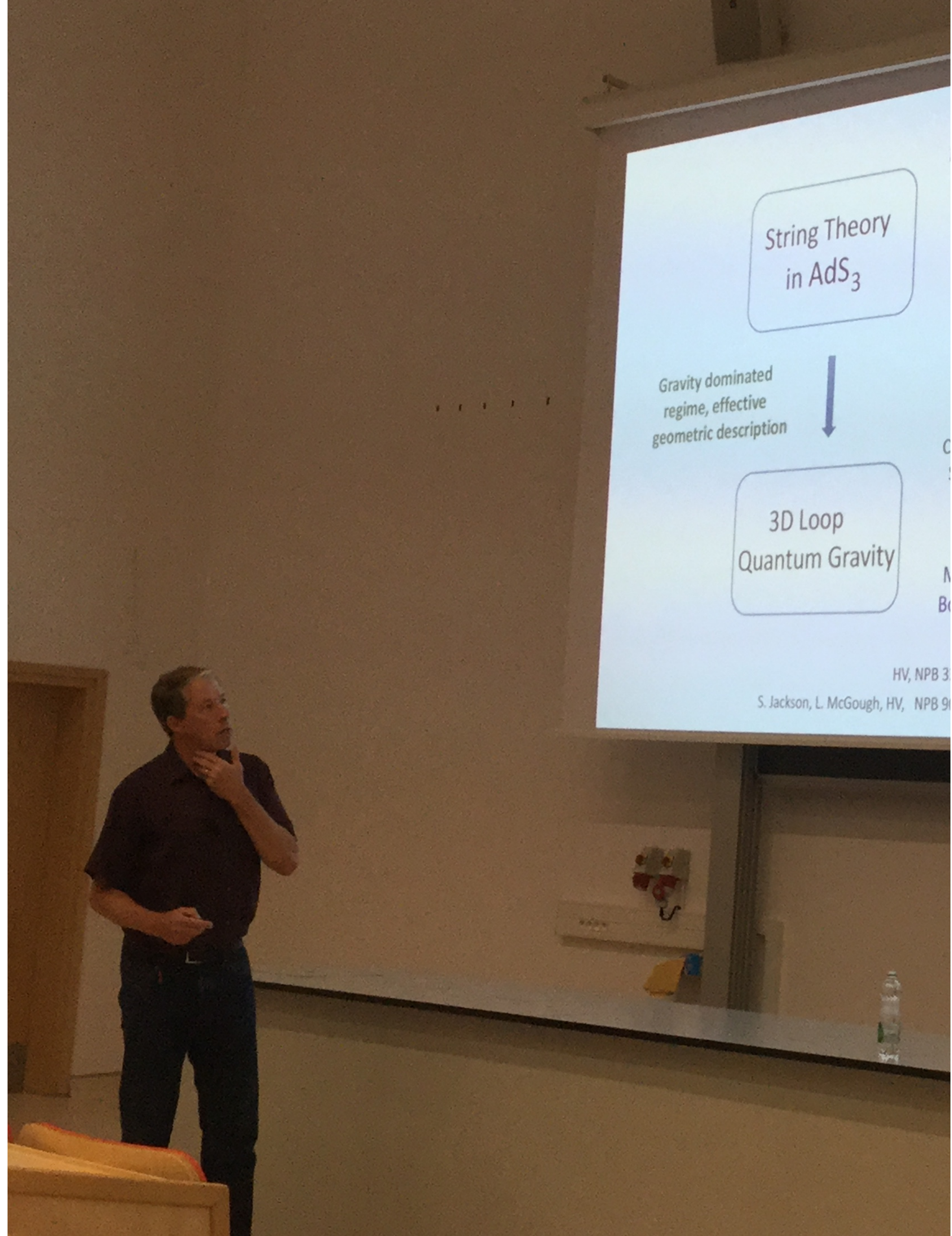
Several are related, boundaries are fluid

Several are only vaguely connected to the actual problem of quantum gravity

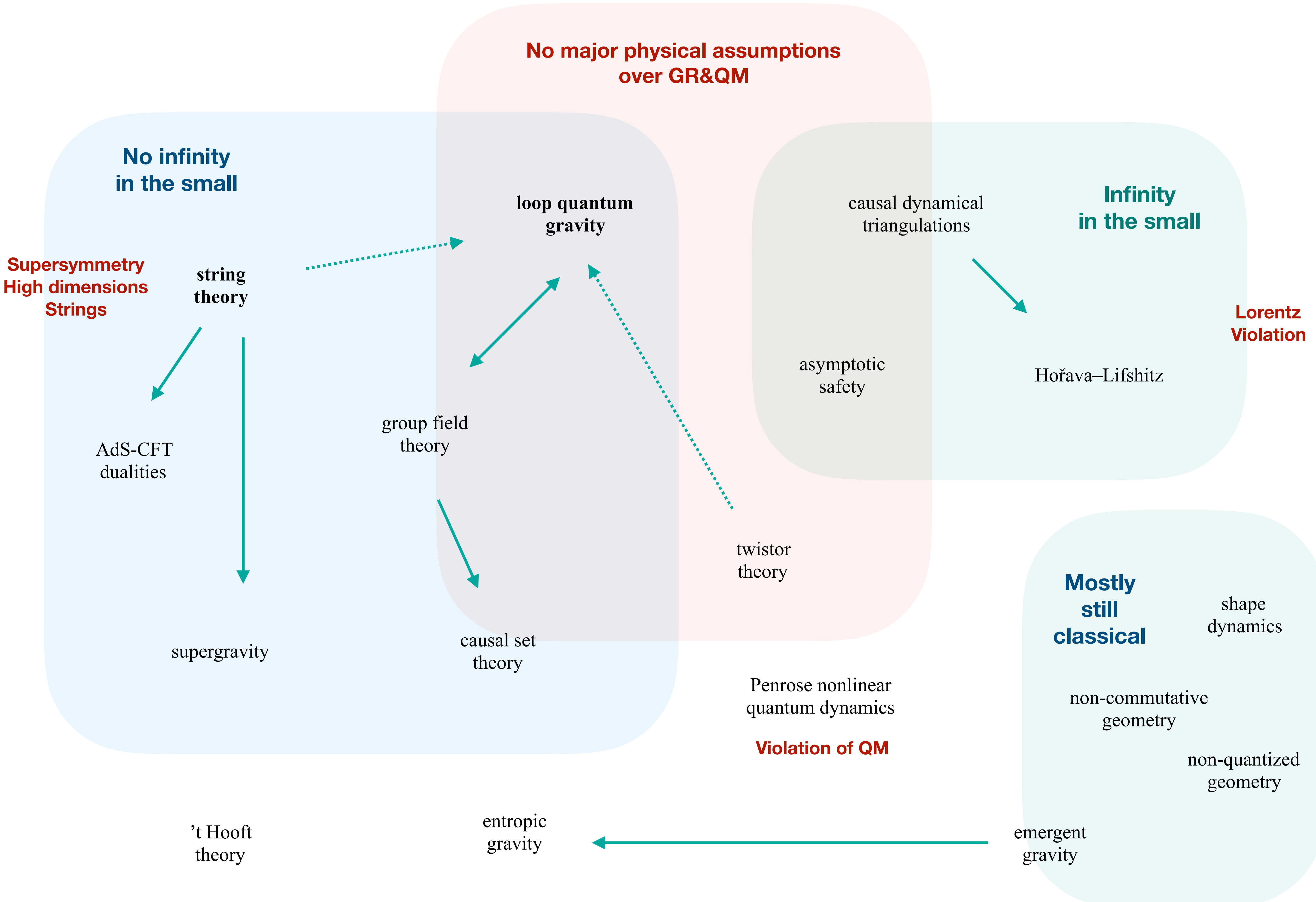
Many offer useful insights


loop quantum gravity
causal dynamical triangulations
string theory
asymptotic safety
Hořava–Lifshitz
group field theory
AdS-CFT dualities
twistor theory
shape dynamics
supergravity
causal set theory
Penrose nonlinear quantum dynamics
non-commutative geometry
Violation of QM
non-quantized geometry
't Hooft theory
entropic gravity
emergent gravity

Several are related



Herman Verlinde
at LOOP17 in Warsaw



No major physical assumptions over GR&QM
No infinity in the small
Infinity in the small
Supersymmetry
High dimensions
Strings
string theory
loop quantum gravity
causal dynamical triangulations
Lorentz Violation
asymptotic safety
Hořava–Lifshitz
AdS-CFT dualities
group field theory
twistor theory
Mostly still classical
shape dynamics
supergravity
causal set theory
Penrose nonlinear quantum dynamics
non-commutative geometry
Violation of QM
non-quantized geometry
't Hooft theory
entropic gravity
emergent gravity

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	…	…	…	…	…

We do have existing and possibly developing
empirical evidence

Empirical evidence: 1: Lorentz invariance

Violation of Lorentz invariance → Renormalizability

Observation has already ruled out theories

$$E^2 = k^4 + c_n \frac{k^n}{m_{Pl}^{n-2}}$$

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 <u>are</u> under empirical stress

Is Lorentz invariance compatible with discreteness ?

Yes!

Classical discreteness breaks Lorentz invariance.

Quantum discreteness does not !

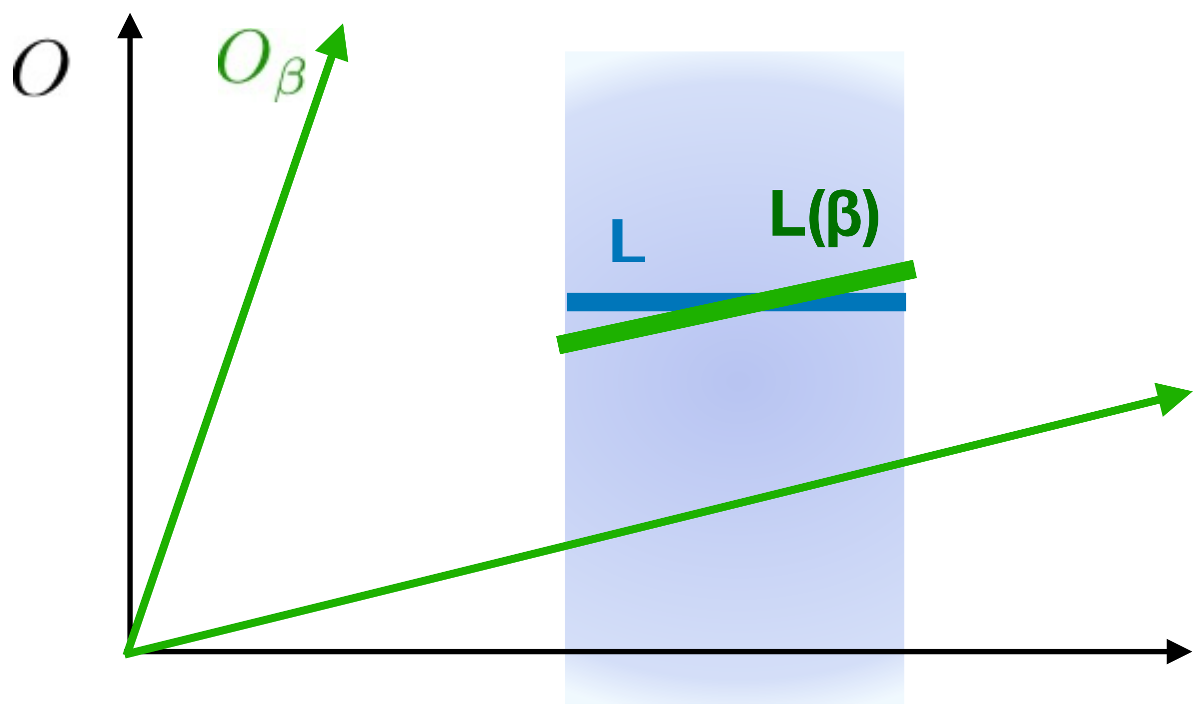
Cfr rotational invariance:
If a *classical* vector component can take only discrete values only,
then SO(3) is broken.
But if *quantum* vector can have discrete eigenvalues in a SO(3) invariant theory

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

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

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

$$|m\rangle_\theta = R(\theta)|m\rangle = \sum_n R_{mn}(\theta)|n\rangle$$



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

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

=> Geometry is quantum geometry

Empirical evidence: 2: Supersymmetry

arXiv.org > hep-ex > arXiv:1708.02794

Search or Article I
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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.

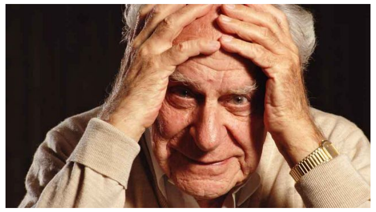
Comments:	Comments: 53 pages in total, author list starting page 37, 7 figures, 5 tables, submitted to JHEP, All figures including auxiliary figures are available at this http URL
Subjects:	**High Energy Physics – Experiment (hep-ex)**
Report number:	CERN-EP-2017-138
Cite as:	**arXiv:1708.02794 [hep-ex]**

Once again, no sign of supersymmetry

Solution of QG using supersymmetry are under empirical stress

A point about philosophy of science:

- Popper's *falsification*: theories are either "OK" or "proved wrong".
- Bayesian "*confirmation"*: we have "degrees of confidence" in theories; these are are lowered, of enhanced, by empirical (dis-)confirmation.



Karl Popper

Bruno De Finetti

Not seeing a giraffe in the forests of Canada during a hike,
does not prove that there are no giraffes in the forests of Canada

A point about philosophy of science:

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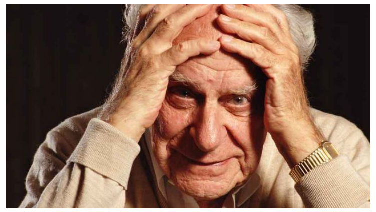


Karl Popper

Bruno De Finetti

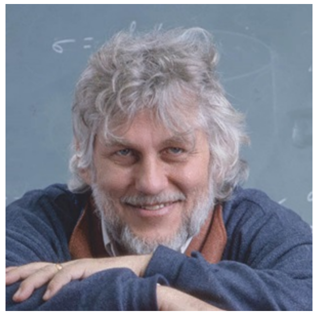
Not seeing a giraffe in the forests of Canada during a hike,
does not prove that there are no giraffes in the forests of Canada

But if for thirty years nobody sees a giraffe…

And we have now heard that supersymmetry is "going to be seen soon"
for more than thirty years….

Empirical evidence: 3: Lab experiments

Analog systems



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

Planck scale effects
in the lab

NOT predicted by most QG theories

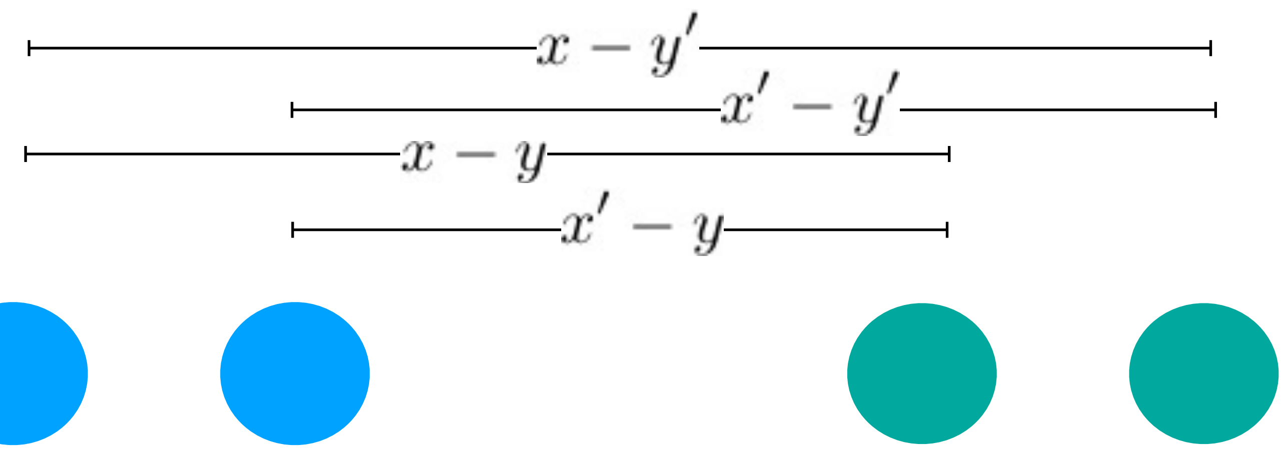
Violations of QM
suggested by QG

Quantum property
of the metric

Can falsify the hypothesis that the
gravitational field is classical.

Is the metric a quantum entity?

Can falsify the hypothesis that the gravitational field is classical.



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

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

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

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

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.

Empirical evidence: 4: The Sky

a) Early Universe: "Quantum cosmology"

b) Black holes: Disruption of the photon ring

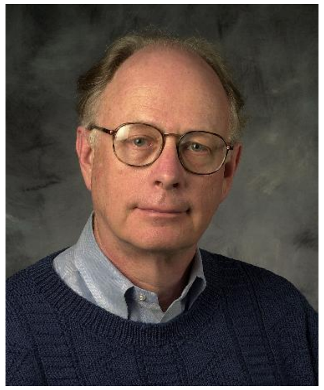
Planck Stars

- ***Quantum Cosmology A***:

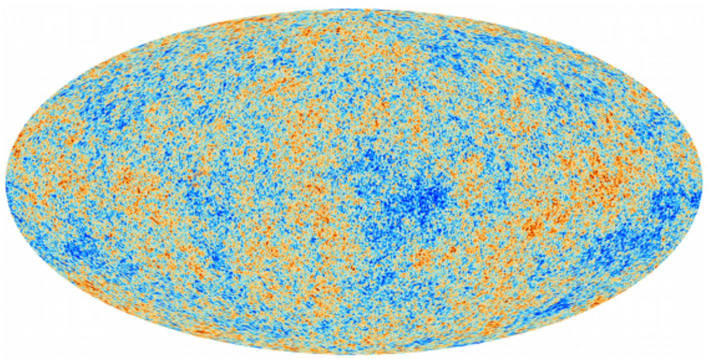
  In the early universe, quantum gravity effects cannot be disregarded
  These leave traces in the current universe.
  Few degrees of freedom.
  Gravity is quantum, spacetime is dynamical
  Schrödinger equation → Wheeler de Witt equation
  Absence of a preferred time variable.

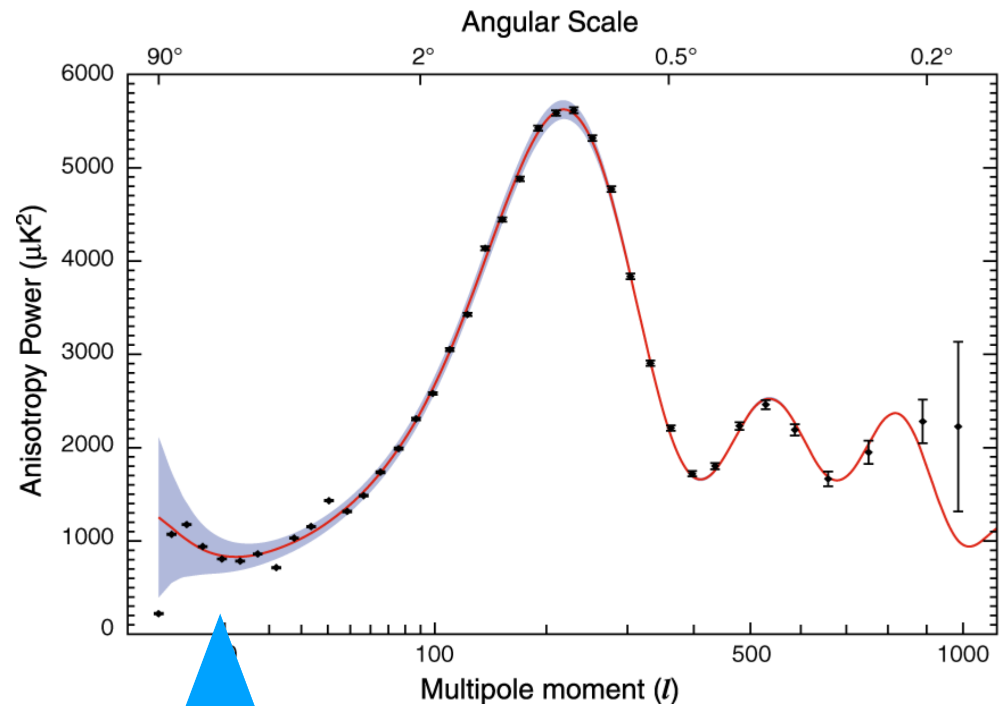
- ***Quantum Cosmology H***:

  How to understand quantum theory of "the whole".
  All degrees of freedom of the Universe.
  Absence of external observer?
  The problems raised by this would exist also if relativistic gravity did not exist.



Quantum Cosmology A is a totally different problem from *Quantum Cosmology H*





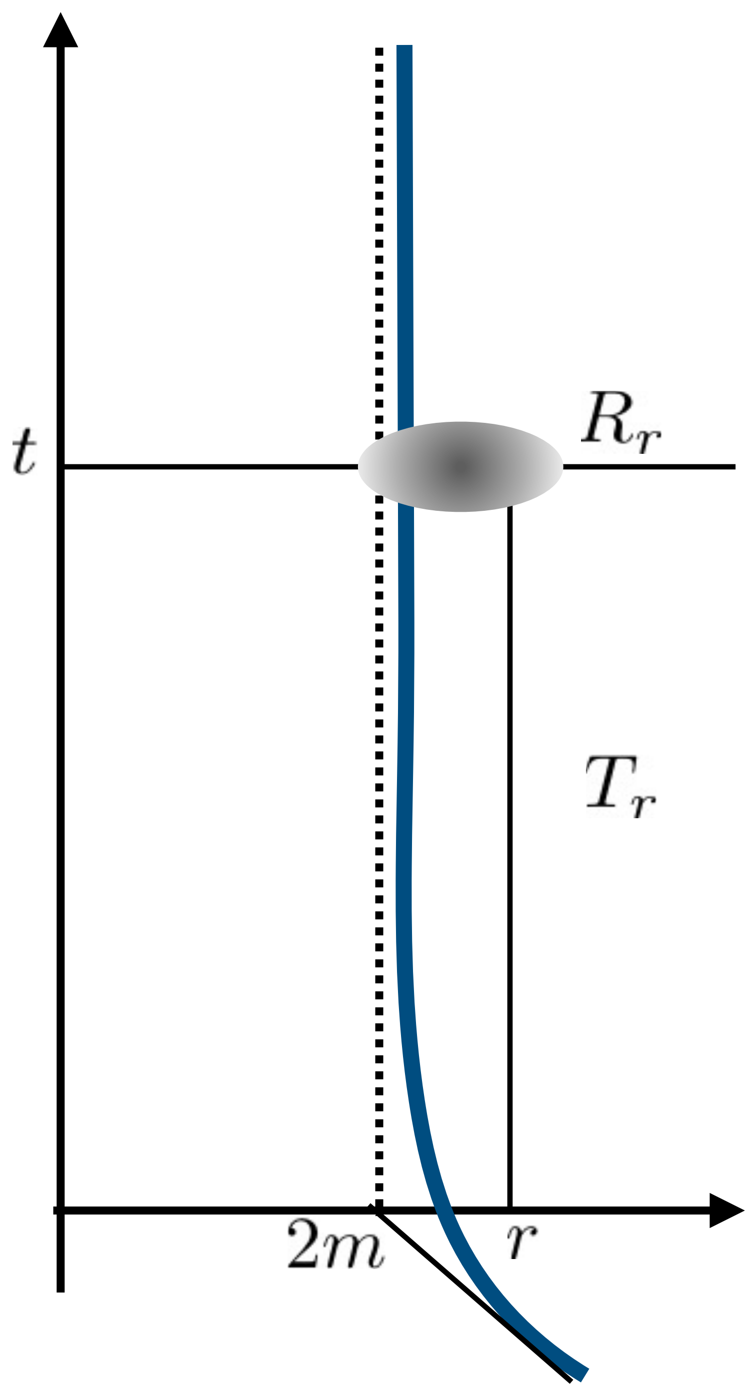
Large activity to describe the physics of the very early universe, and find traces in the CMB

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

Great effort to find testable consequences of the theories in course

b) Black holes

Small effects pile up over time



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

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

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

- **Wide quantum fluctuations of the metric**

  Giddings

- **Boson condensate of low energy gravitons**

  Dvali

- **Fluctuations of the causal structure allowing black hole to decay**

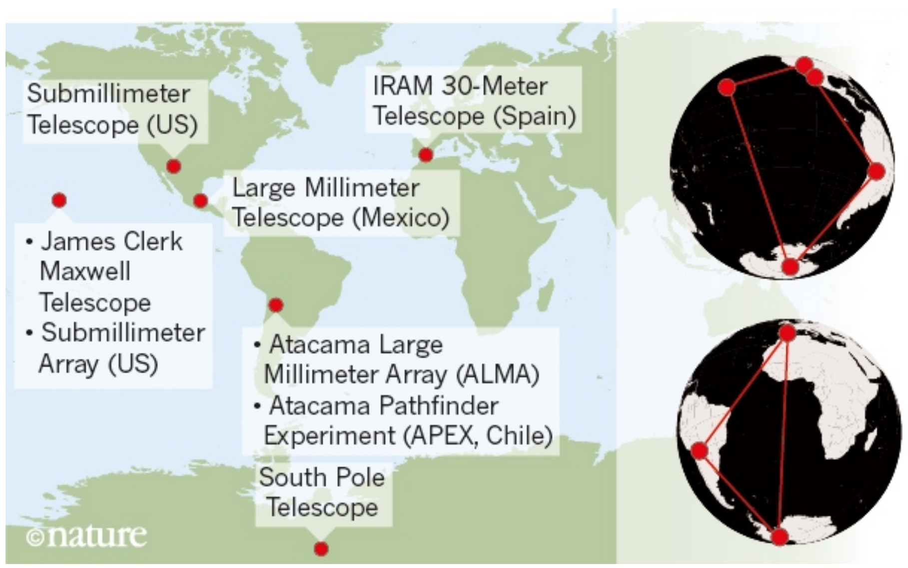
  Haggard, Barrau, Vidotto, CR

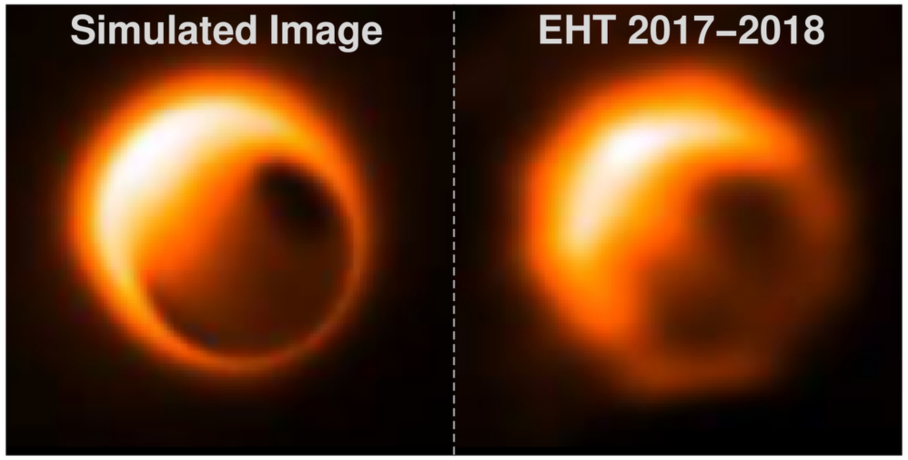
- Wide quantum fluctuations of the metric

Theoretical reason: to bring information out of the hole

Observable consequence: Event Horizon Telescope

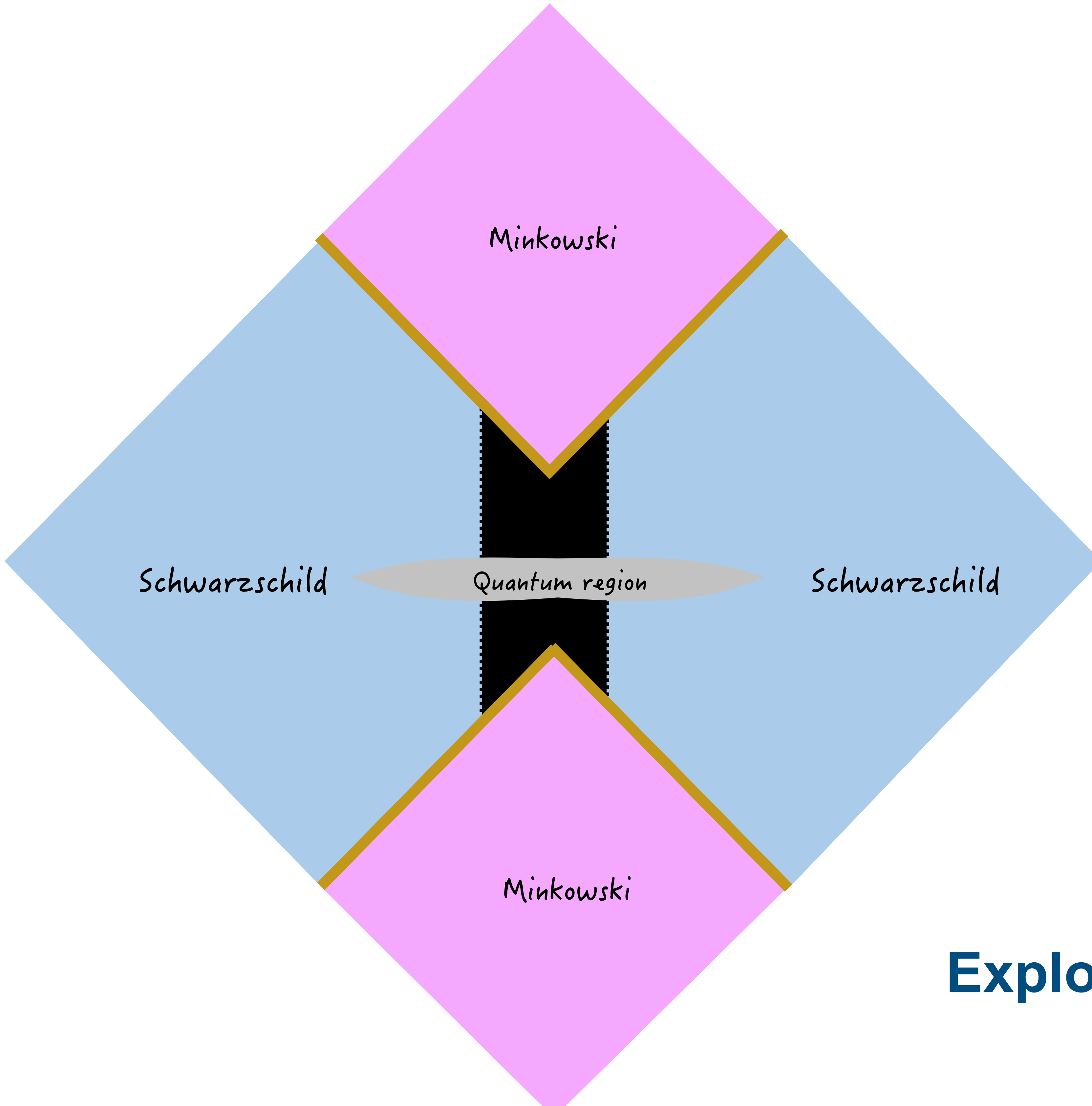
Possibly visible distortion of the photon ring



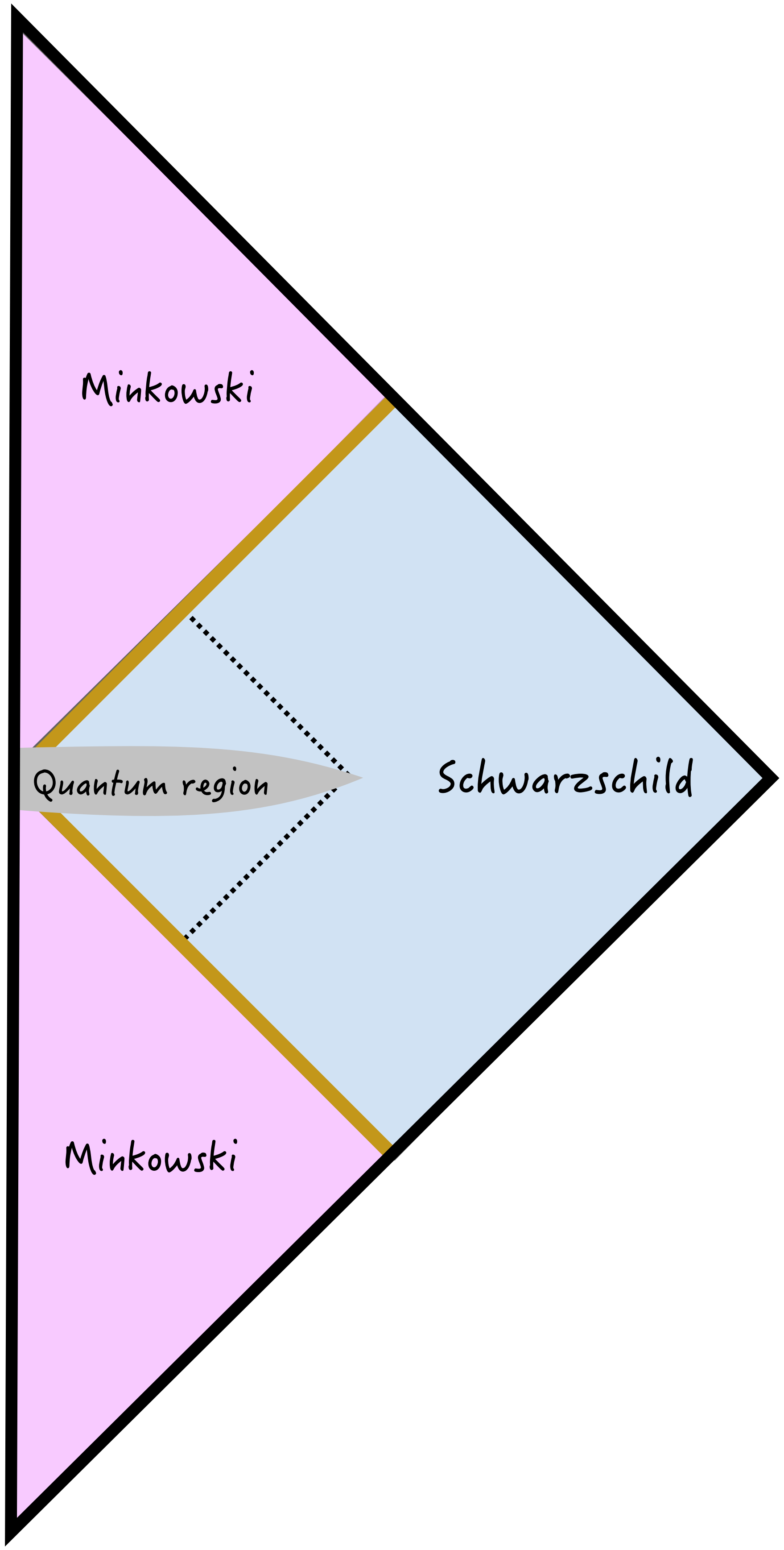


Imaging an Event Horizon: Mitigation of Scattering toward Sagittarius A* Fish et al 2014

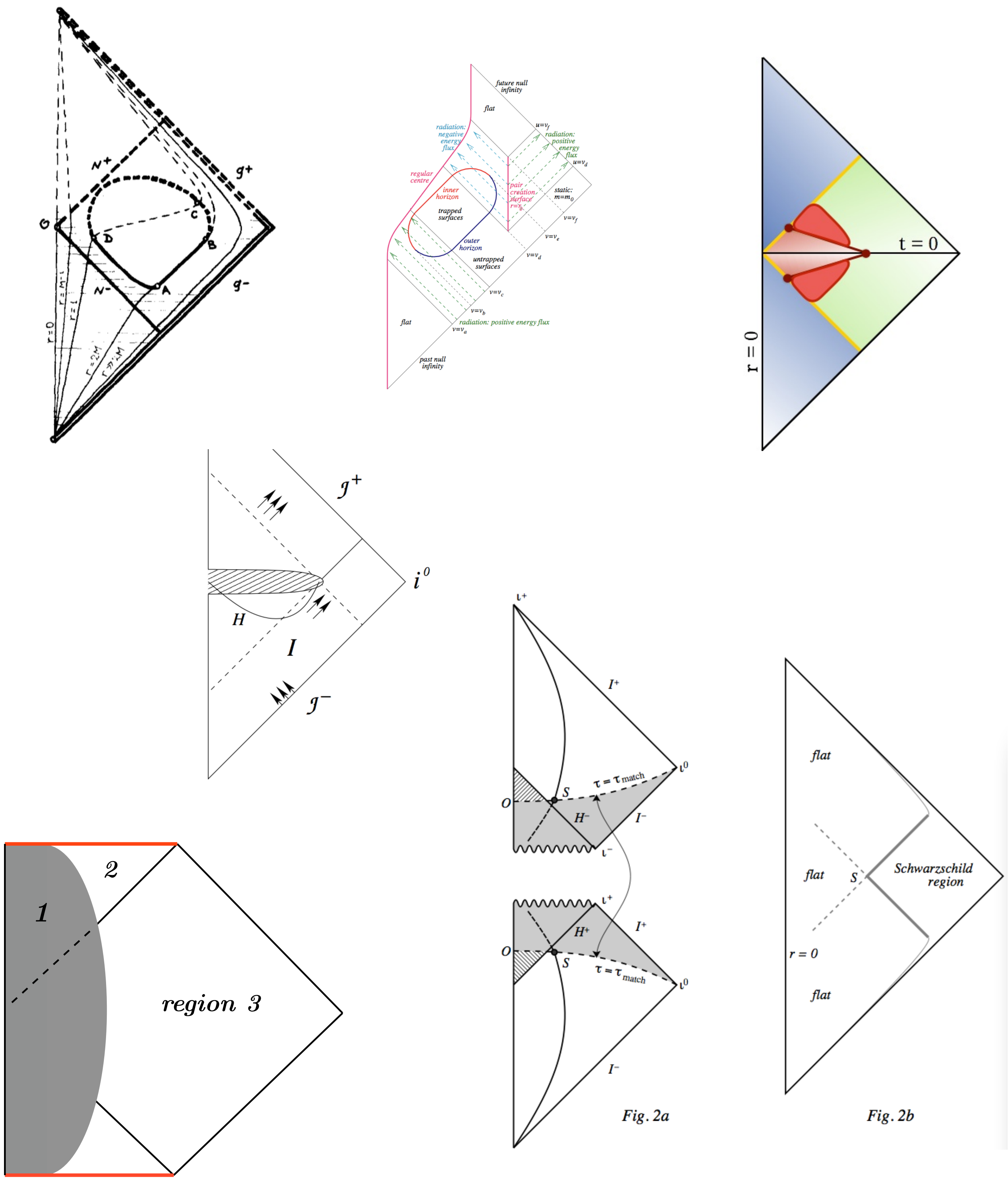
- Fluctuations of the causal structure allowing black hole to decay



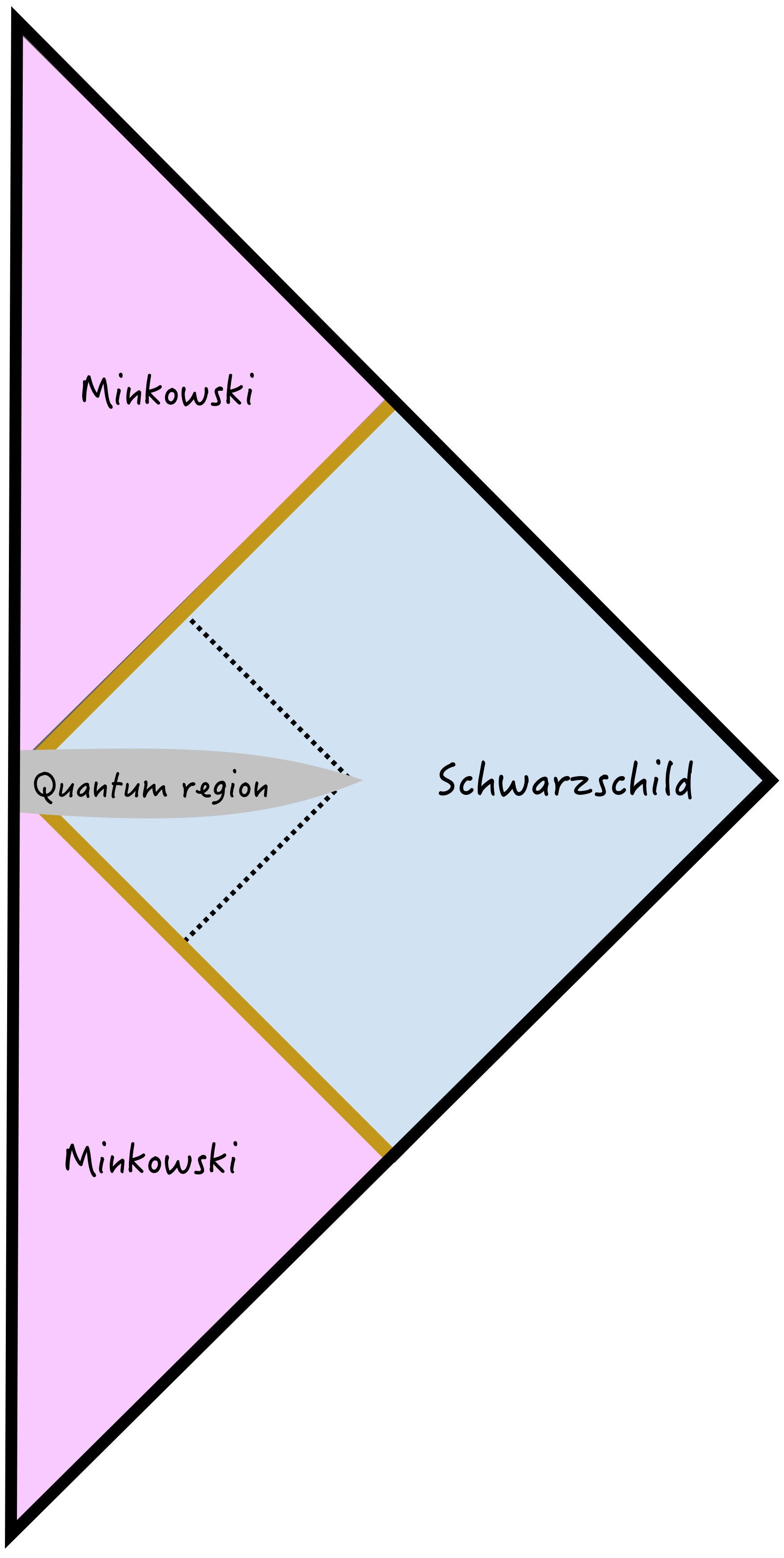
Exploding holes


Minkowski
Quantum region
Schwarzschild
Minkowski

Exploding holes



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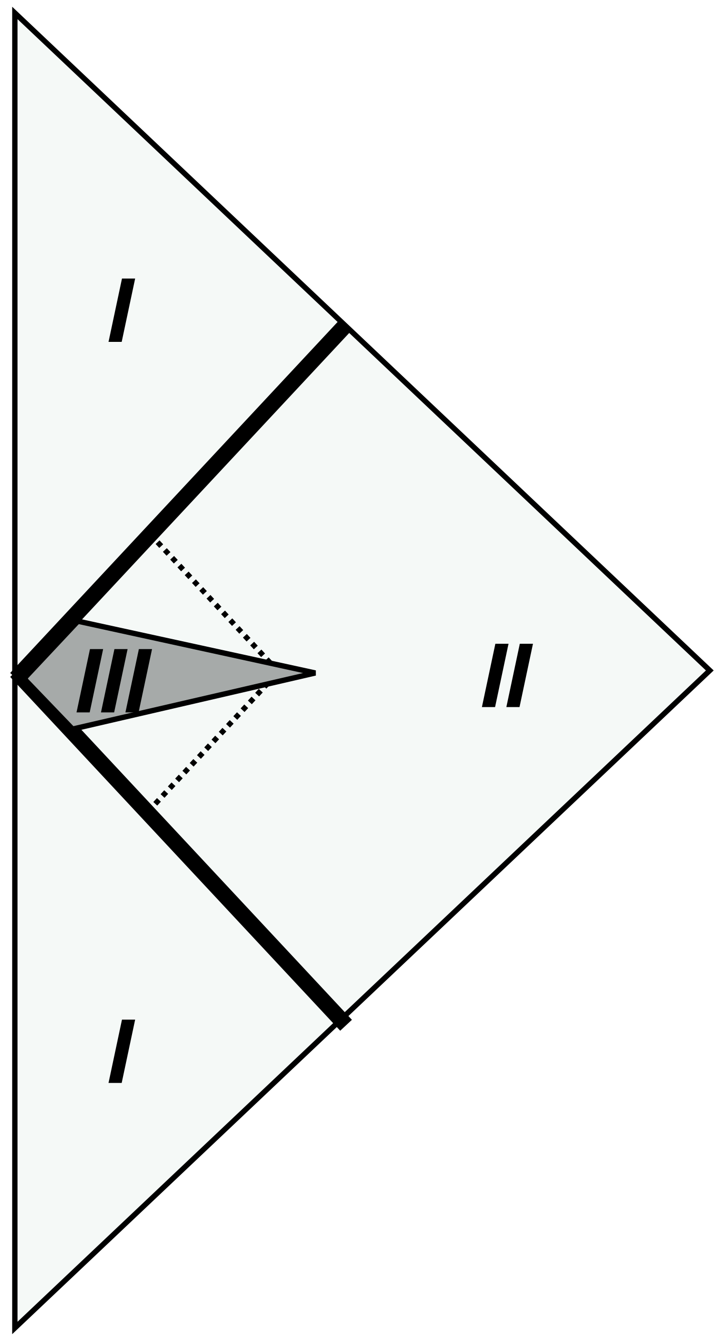


A technical result in classical GR:

The following metric is an **exact** vacuum solution,
of the Einstein equations outside a finite spacetime region (grey),
plus an ingoing and outgoing null shell,

The metric is determined by two constants: m, T

$$ds^2 = -F(u,v)dudv + r^2(u,v)(d\theta^2 + sin^2\theta d\phi^2)$$

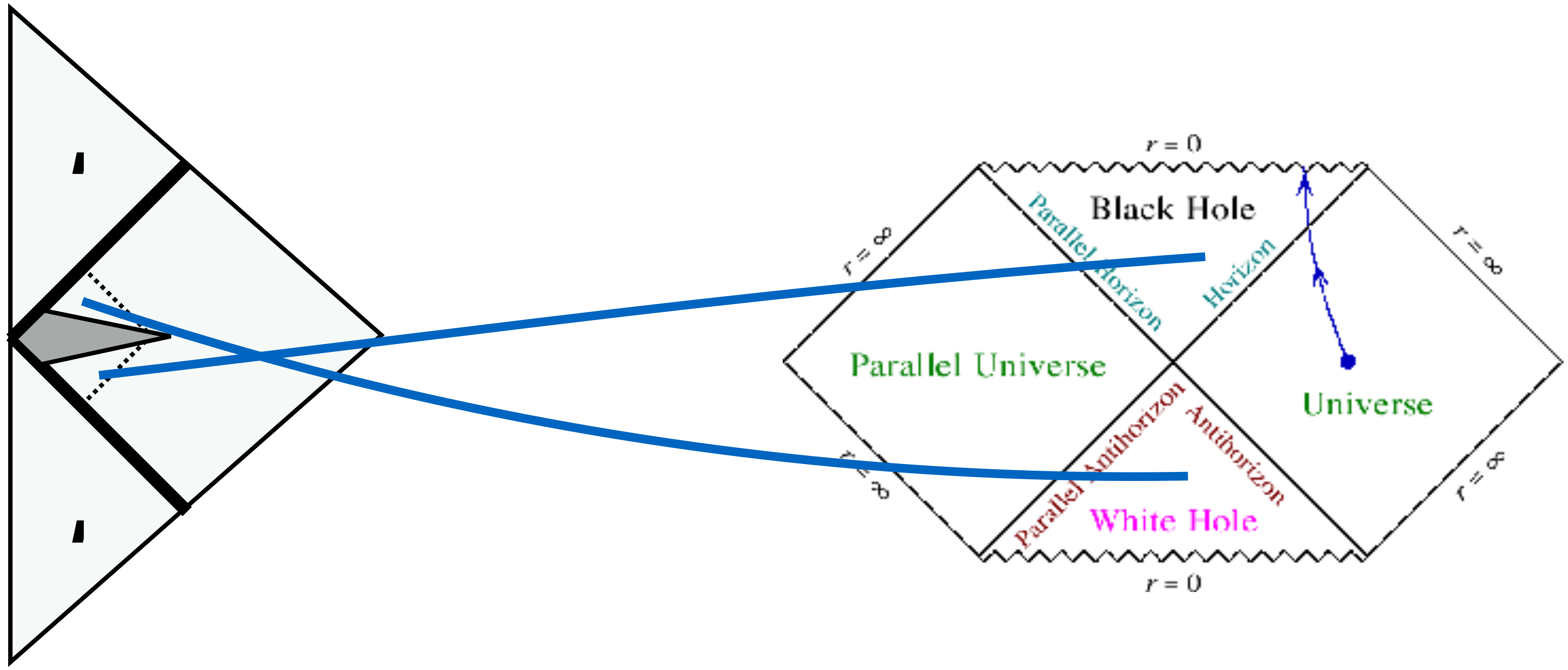
Region I $F(u_I, v_I) = 1, \qquad r_I(u_I, v_I) = \frac{v_I - u_I}{2}.$
$v_I < 0.$

Region II $F(u,v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$

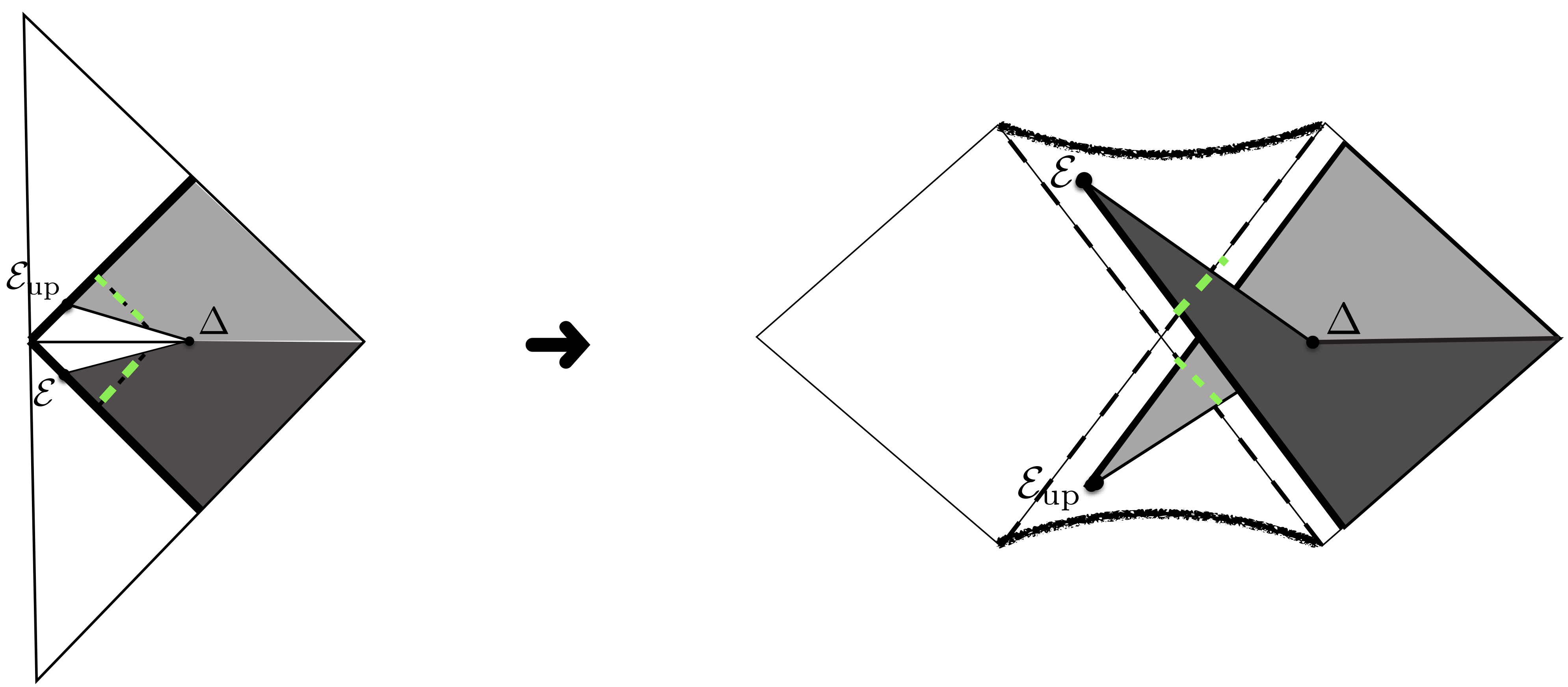
Matching $r_I(u_I, v_I) = r(u,v) \longrightarrow u(u_I) = \frac{1}{v_o}\left(1 + \frac{u_I}{4m}\right) e^{\frac{u_I}{4m}}.$

Region III $F(u_q, v_q) = \frac{32m^3}{r_q} e^{\frac{r_q}{2m}}, \qquad r_q = v_q - u_q.$

Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling
Hal Haggard, CR



r = 0
Black Hole
Parallel Horizon
Horizon
r = ∞
r = ∞
Parallel Universe
Universe
Parallel Antihorizon
Antihorizon
r = ∞
r = ∞
White Hole
r = 0



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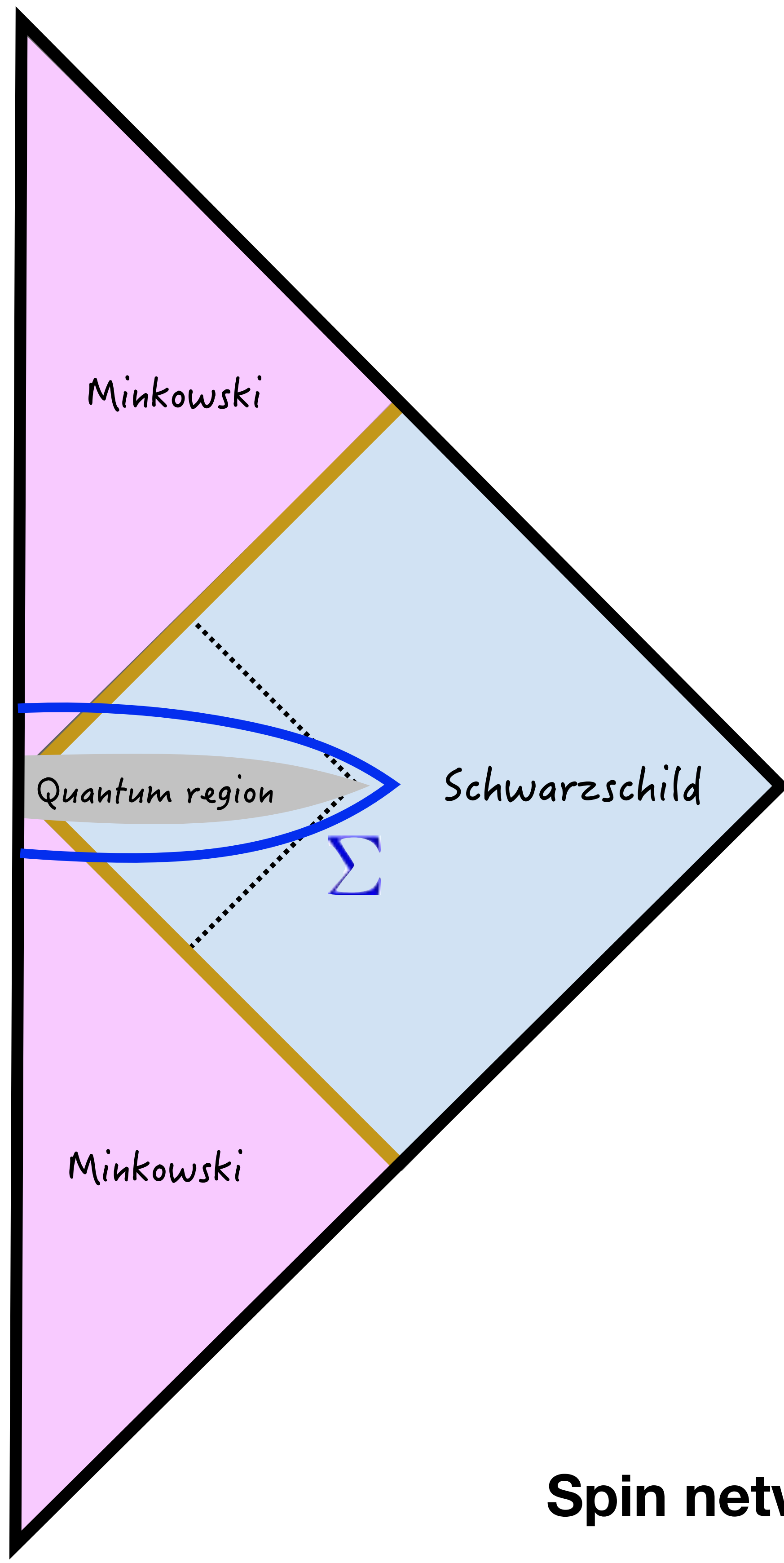
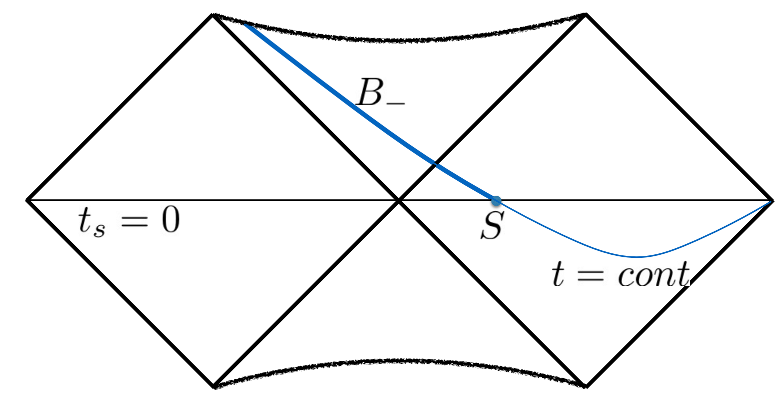
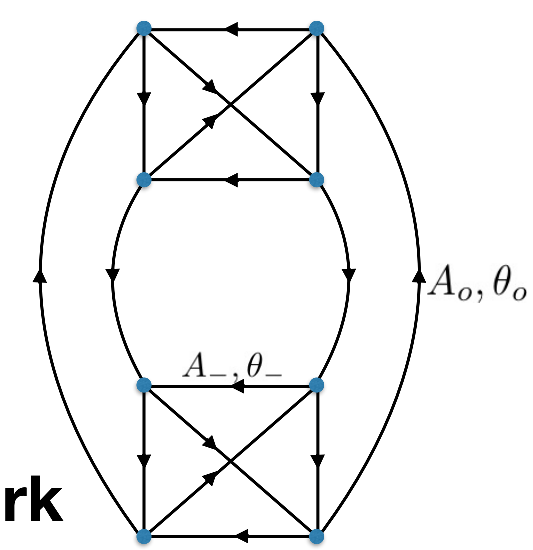


Choose a “Boundary” surface
around the quantum region.

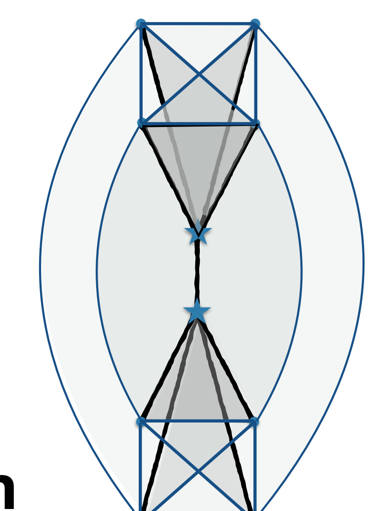
$$\Sigma = B_- \cup B_+$$



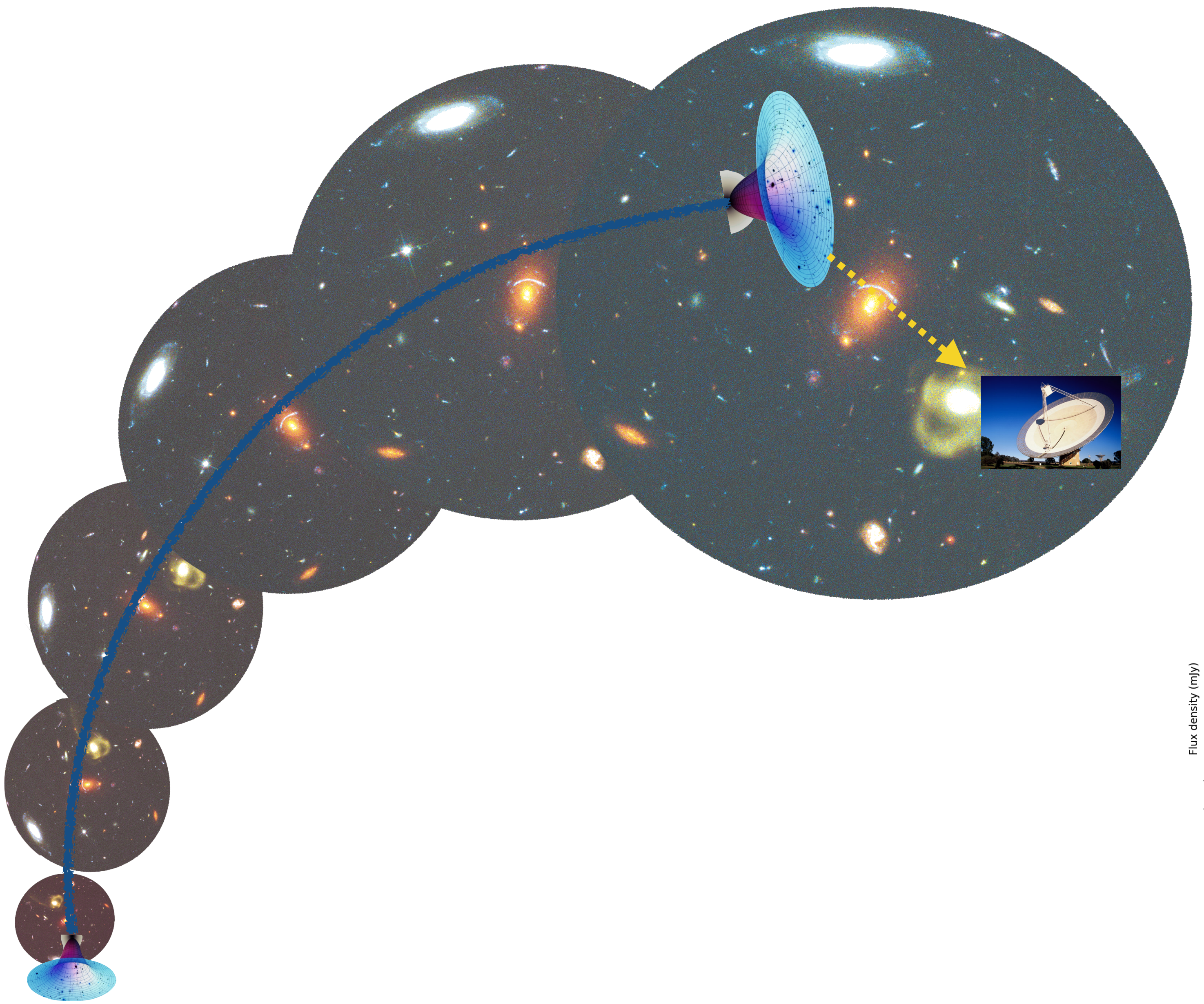
Spin network

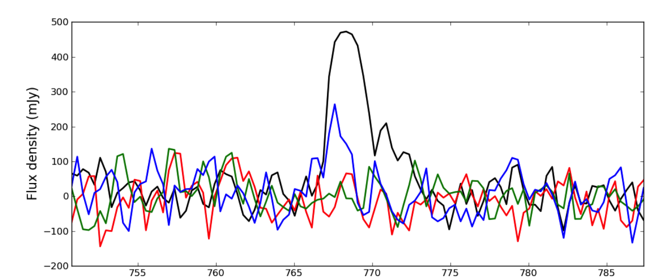


Spinfoam



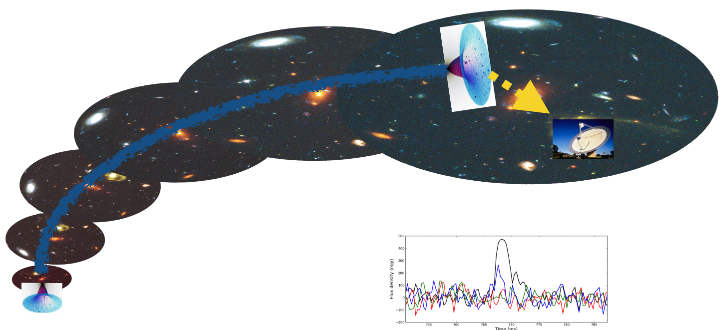
Primordial black holes!



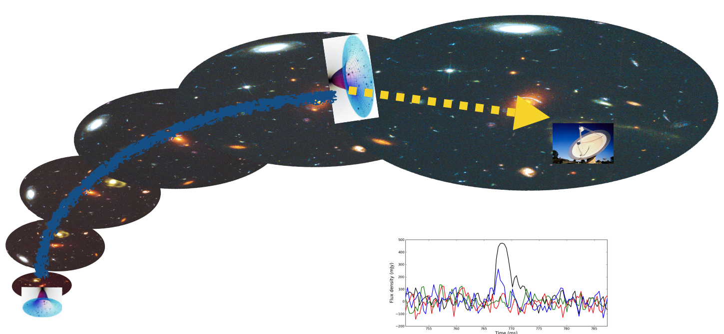


Signature: distance/energy relation

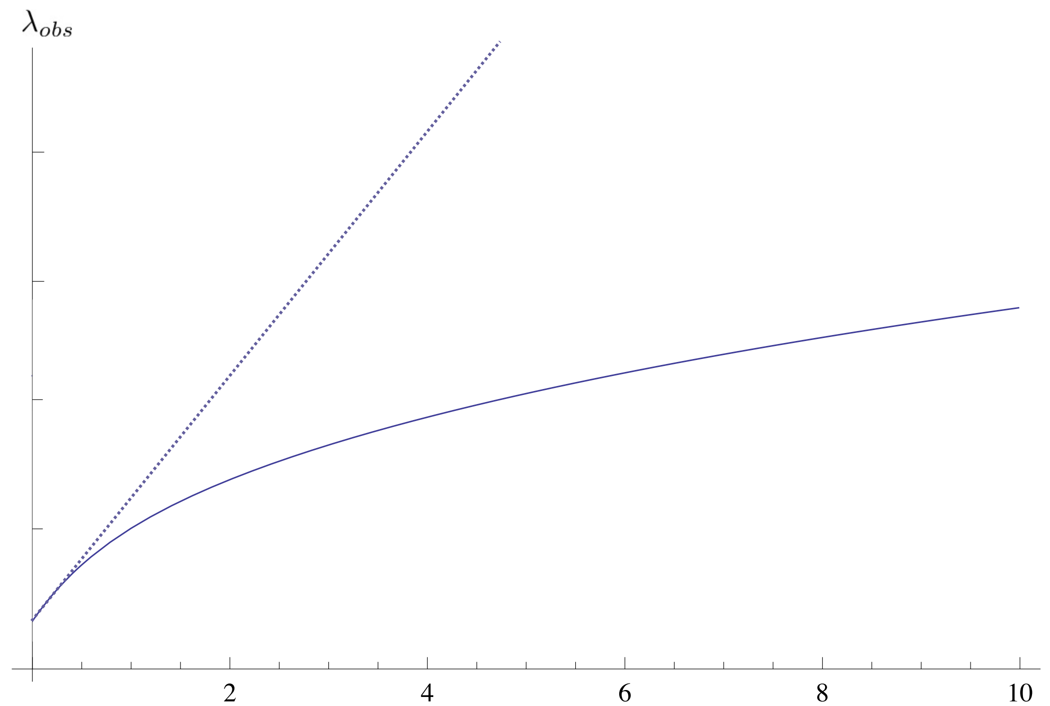
$$\lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



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

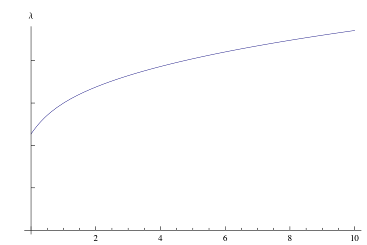
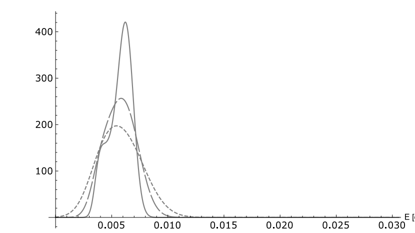
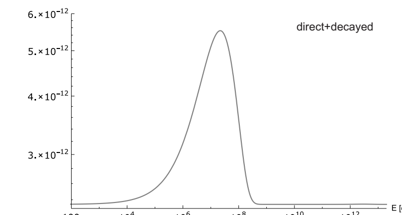


Figure 21. The expected wavelength (unspecified units) of the





Quantum Gravity Observations are not absurd anymore.

There are:

- Already concerete results (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.)

General lesson and convergences between theories

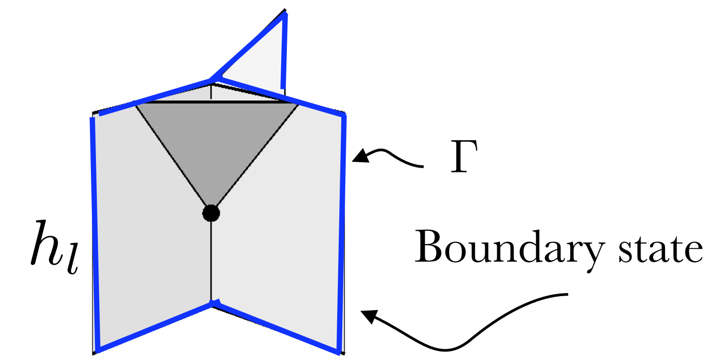
- Quantum effects can be “strong” and “soft”: strong quantum effects at large wavelength,

- Local QFT can be strongly violated (Firewall theorem)
  Quantum Gravity requires overcoming
  Local Field Operators.

  On information loss in AdS/CFT
  A. Liam Fitzpatrick, Jared Kaplan, Daliang Li, Junpu Wang.

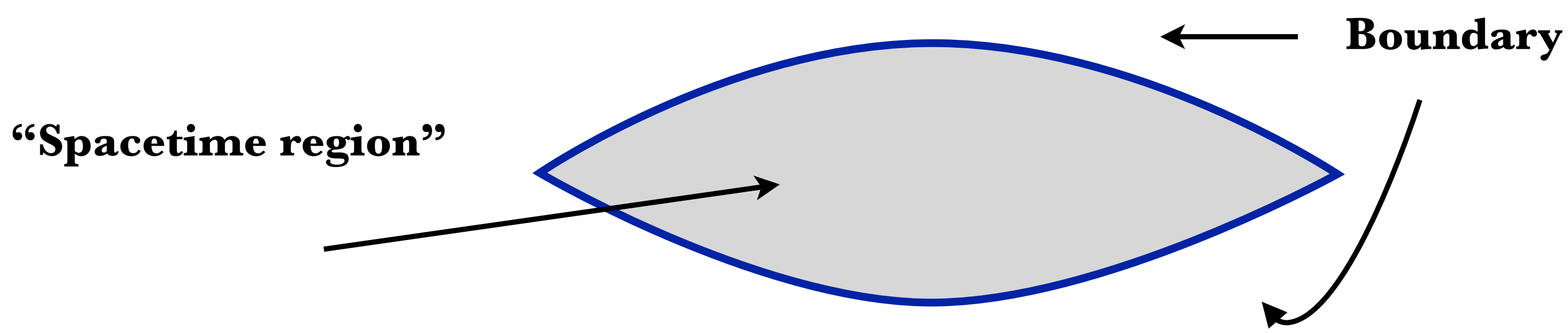
- Boundaries: Strings: AdS-CFT
  Loops: boundary formalism (covariant version)

A process and its amplitude



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

Amplitude $A = W(\Psi)$

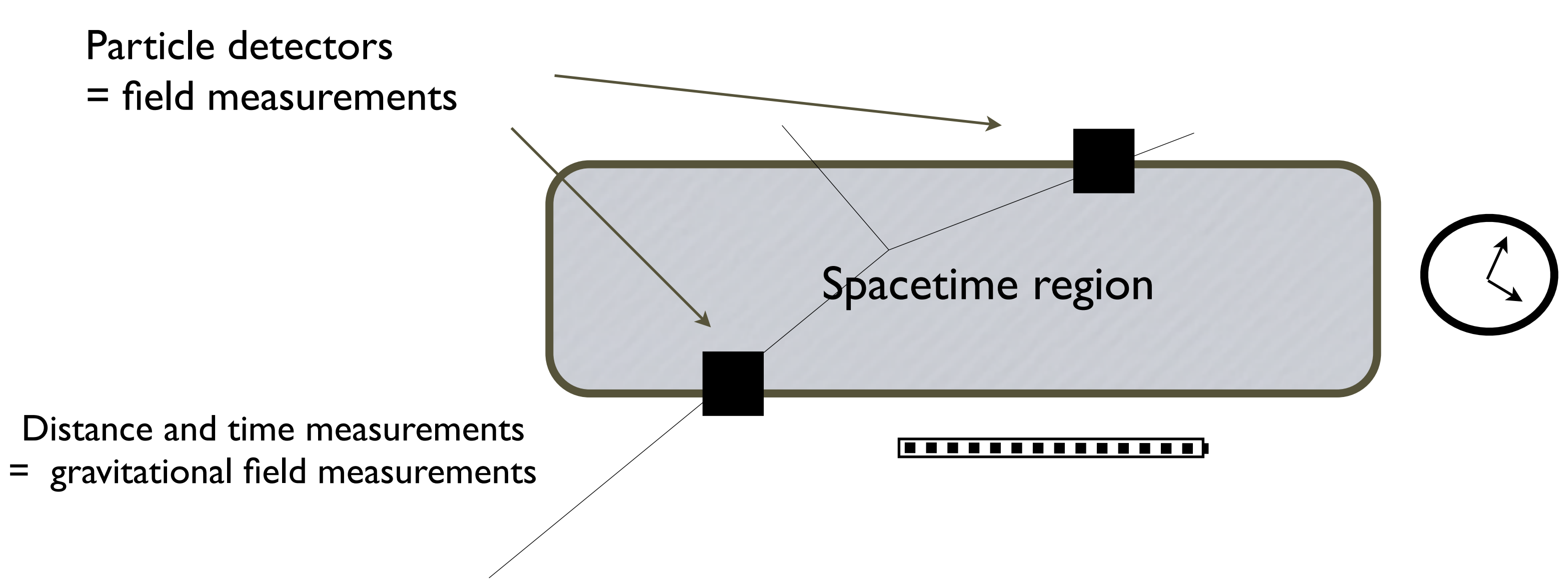


Quantum system
=
Spacetime region

➜ **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

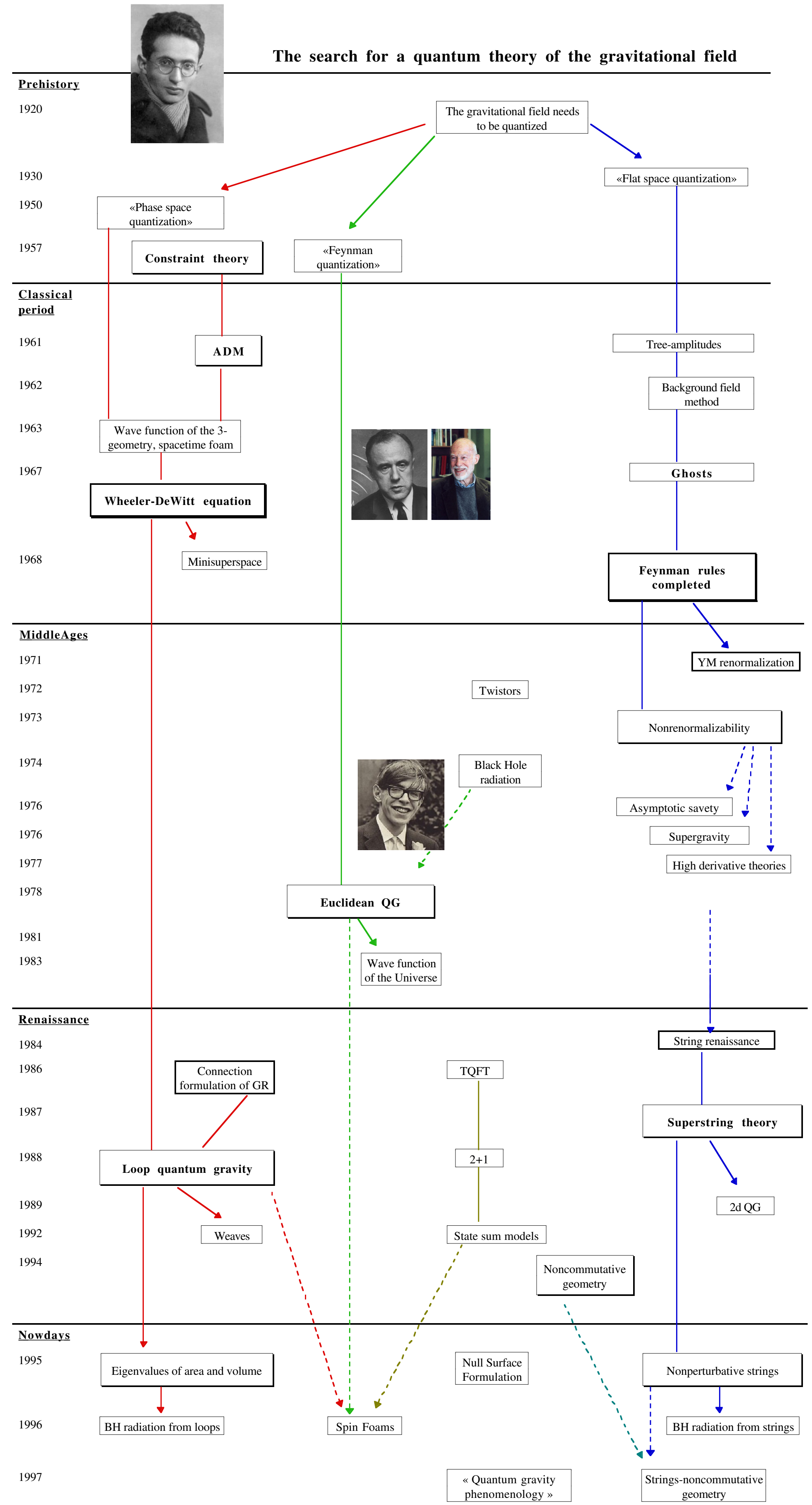
Boundary values of the gravitational field = geometry of box surface = distance and time separation of measurements



Quantum relationalism
=
Spacetime relationalism

The general landscape of the research directions has remained quite stable

But definite progress has happened along some research directions



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 ✓ ✗

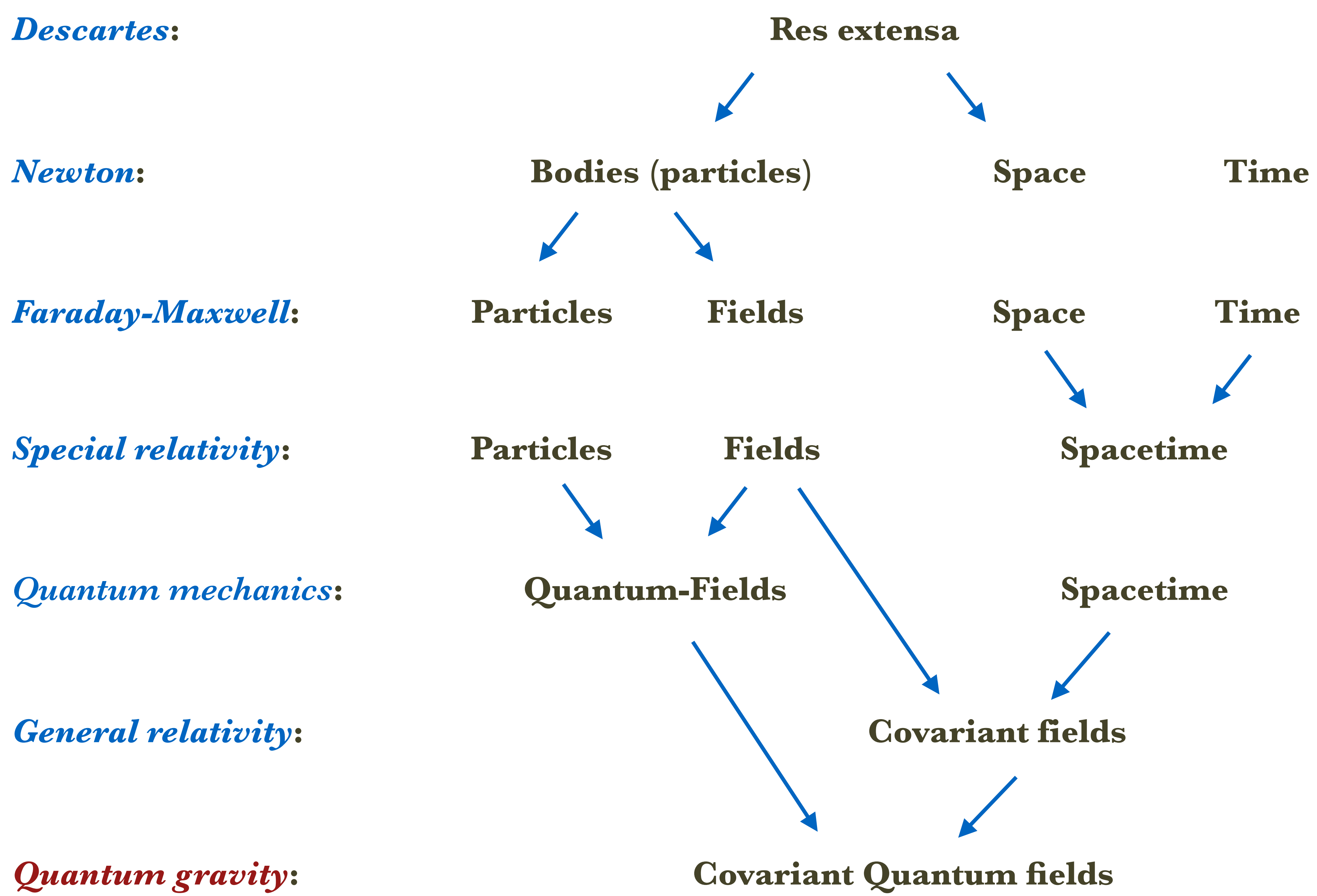
Loops open problems in the late 80'

- 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 ✗

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	…	…	…	…	…

How do we best describe physical reality?



Matter, time and space: all aspects of a single entity