Title: Introduction to Quantum Gravity

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Abstract:

Quantum Gravity is not a finished theory yet. There are many approaches to quantum gravity. I can only mention a few (and discuss only one).

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e four fundamental forces

- quantum electrodynamics
- strong interaction
- weak interaction
- quantum gravity?

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Despite approx. 70 years of research we do not have a quantum theory of gravity.

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Despite approx. 70 years of research we do not have a quantum theory of gravity.

What is so difficult about quantum gravity?

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antum space–time

- Gravity = property of space–time[1]

quantum gravity = quantum theory of space and time

[1]Einstein

antum space–time

- Gravity = property of space–time[1]

quantum gravity = quantum theory of space and time

- Eliminating space and time as fundamental classical attributes and replacing them with something new/quantum.
- Hard part: Reconstruct space–time in low energy limit.
- Different approaches follow this to a different degree.
- Quantum gravity will probably give us new model(s) of time, but may not explain all aspects completely.

[1] Einstein

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antum geometry

- gravity encoded in geometry
  ⇒ measure distances, areas, volumes, . . .
  ⇒ (coordinate dependent) metric

Aim:

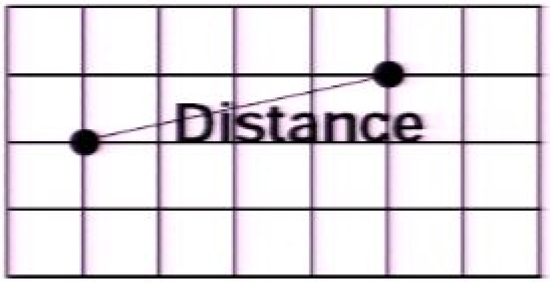
- quantum operators/measurements for lenghts, areas, volumes
- dynamics for these/ change in time

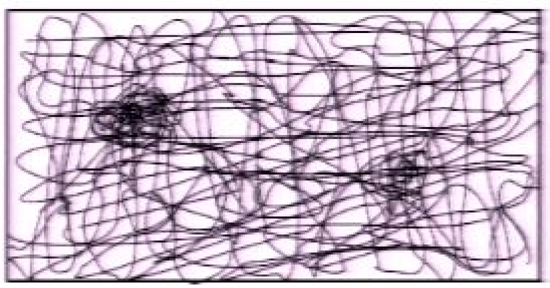
ckground Independence

- want to quantize space–time
- treat it as fully dynamical
- (space–time) background has to emerge dynamically in low–energy limit
- post–diction of geometrical features of our universe: dimension, nearly flatness, . . .

at is a point?

n–point functions: basic tool in standard quantum field theory





What is an observable in (quantum) gravity?[2]

[2] Einstein, deWitt, Rovelli et al, Westman, BD

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ıantum Gravity: Early approaches

- perturbative [3]
  - gauge fixing and Faddeev-Popov ghosts
  - background field method, effective action
  - constrained systems
  - 1986 Goroff and Sagnotti: (non–super) gravity non–renormalizable

[3] deWitt, Feynman, Veltman, 't Hooft, . . .

[4] Dirac, deWitt, Wheeler, Hartle, Hawking, Kuchař, Isham . . .

[5] Regge, Hamber, Williams, Ambjorn, Loll

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  - 1986 Goroff and Sagnotti: (non–super) gravity non–renormalizable
- canonical quantization and path integral [4]
  - Dirac quantization, constrained systems
  - problem of time
  - quantum cosmology
  - black hole thermodynamics (saddle point approximation)
  - Regge calculus, dynamical triangulations: effective dimension dynamical (you can get is easily wrong; to get it right implement causality)[5]

[3] deWitt, Feynman, Veltman, 't Hooft, . . .

[4] Dirac, deWitt, Wheeler, Hartle, Hawking, Kuchař, Isham . . .

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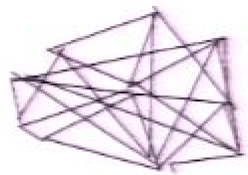
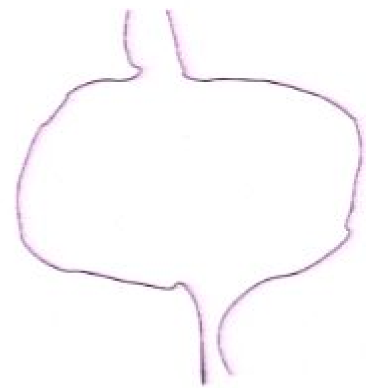
ective dimension

ean dynamical
lations
1

ed polymer phase



Euclidean dynamical
triangulations
2
$d = \infty$
crumbled phase



Causal dynamical triangulations[a]
$d = 4$

[a] Ambjorn, Jurkiewicz, Loll '05, Benedetti, Henson

nonical Quantization

- Hilbert space representation of metric in a background independent way?
- difficult/impossible[6] in metric variables

[6] Ashtekar 2007

[7] Ashtekar 1986, Sen 1982, (complex), Barbero 1995 (real) (canonical)

[8] Samuel, Jacobson, Smolin (1987)(Lagrangean)

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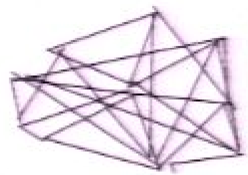

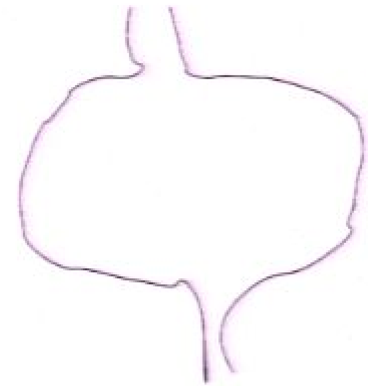

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Use Ashtekar variables instead[7][8]

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nonical Quantization

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Use Ashtekar variables instead[7,8]

- allows for gauge theory formulation
  - **connection** A
    $\rightarrow$ Wilson loops; encodes time derivative of spatial metric
  - **triads (electric field)** E
    $\rightarrow$ electric flux through surfaces; encodes spatial metric

[6] Ashtekar 2007

[7] Ashtekar 1986, Sen 1982, (complex), Barbero 1995 (real) (canonical)

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op Quantum Gravity

- Hamiltonian hugely simplified (in complex variables)
  $\rightarrow$ one (formal) solution Kodama state
- background independent Hilbert space formulation[9]
  $\rightarrow$ (kinematical) spectra of geometrical operators discrete[10]
  $\rightarrow$ black hole entropy[11]
- (dynamical) lattice gauge theory formulation
  $\rightarrow$ provides regulator for Hamiltonian[12]
- unique (kinematical) vacuum state/ representation[13]
- motivation for / better connection to path integral approach
  $\rightarrow$ spin foams

[9] Ashtekar, Baez, Isham, Jacobson, Lewandowski, Rovelli, Smolin, ...
[10] Rovelli, Smolin, Ashtekar, Lewandowski,...
[11] Ashtekar, Baez, Corichi, Krasnov '97,...
[12] Thiemann 1996
[13] Fleischhack Lewandowski Okolow Sahlmann Thiemann '04/05

e Hamiltonian

$$H = \frac{1}{\sqrt{\det(g)}}(p_{ab}p^{ab} - (p^{ab}g_{ab})^2) - \sqrt{\det(g)}R$$

$$R = g^{ab}(\partial_c\Gamma^c_{ab} - \partial_a\Gamma^c_{cb} + \Gamma^d_{ab}\Gamma^c_{dc} - \Gamma^d_{bc}\Gamma^c_{ad})$$

$$\Gamma^c_{ab} = \frac{1}{2}g^{cd}(\partial_a g_{bd} + \partial_b g_{ad} - \partial_d g_{ab})$$

- non–polynomial, inverse metric

$$\tilde{H} = F^j_{ab}\epsilon_{jkl}E^a_k E^b_l$$

$$F^j_{ab} = \partial_a A^j_b - \partial_b A^j_a + \epsilon^j{}_{kl}A^k_a A^l_b$$

- polynomial, 4th order
- more complicated in real variables

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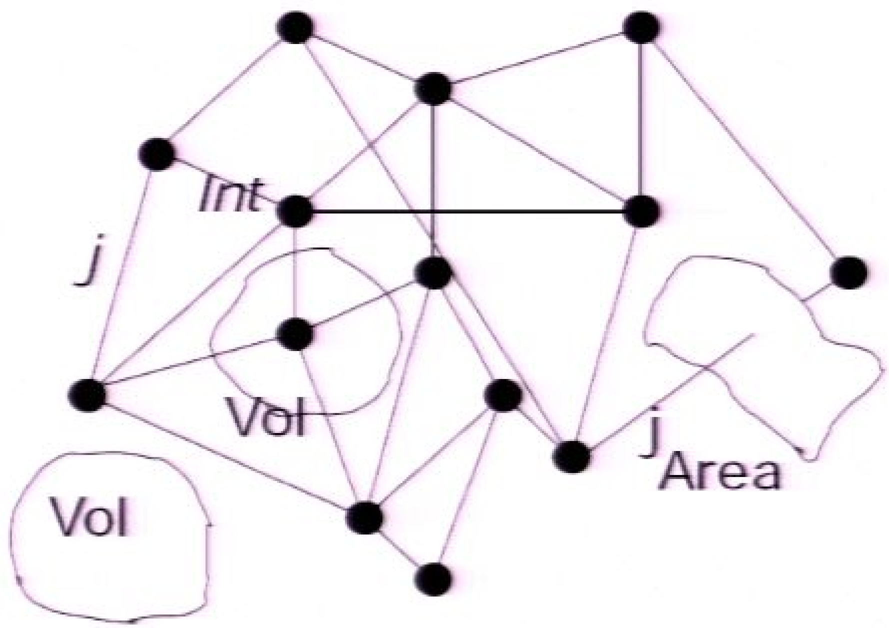
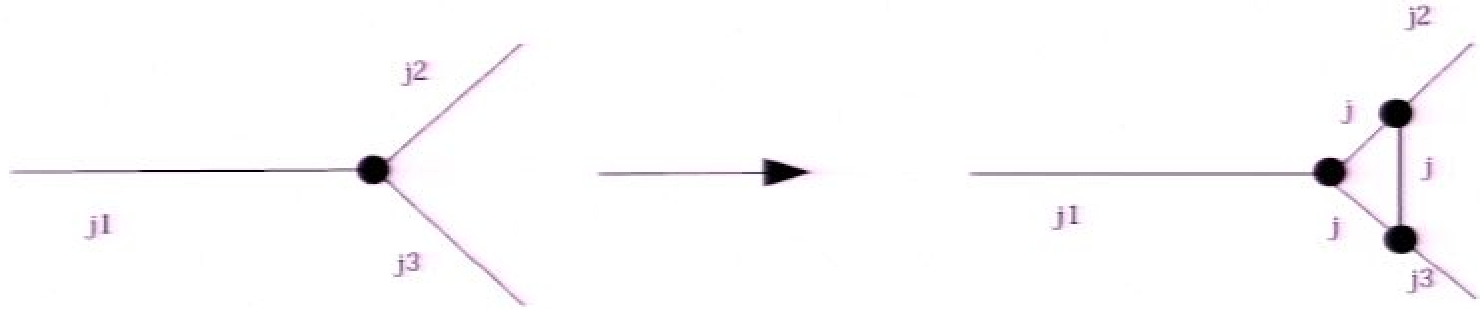
bert space of loop quantum gravity: spin works

- excitations of geometry along lines and at vertices: graphs
- (kinematical) vacuum: nothing is excited
  $\rightarrow$ no geometry (also no vacuum fluctuations)
- Wilson loop operators: excite/annihilate edges of graph: dynamical graph/lattice with (spin) labels
- flux operators: discrete spectra for geometric operators



namics

- defined by Hamiltonian
- anomaly–free, uv–finite quantization of Hamiltonian[14]
- changes graph and labels → dynamical graph



- ambiguities[15]
- action (for this version) might be too local[16]
- difficulty: to have a consistent (slicing independent) evolution: would ensure 4–dim diffeomorphism invariance

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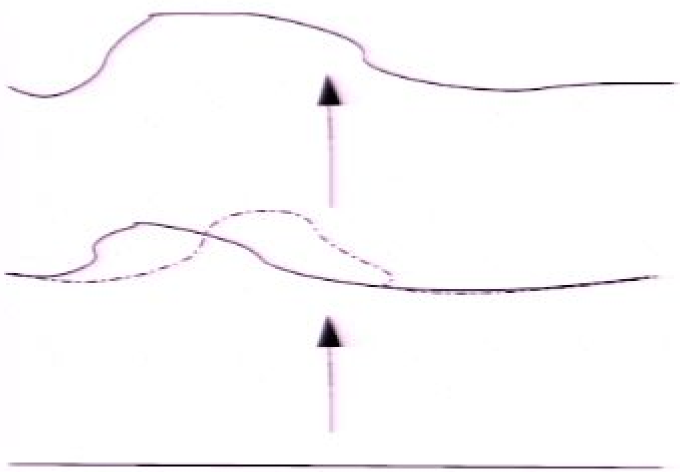
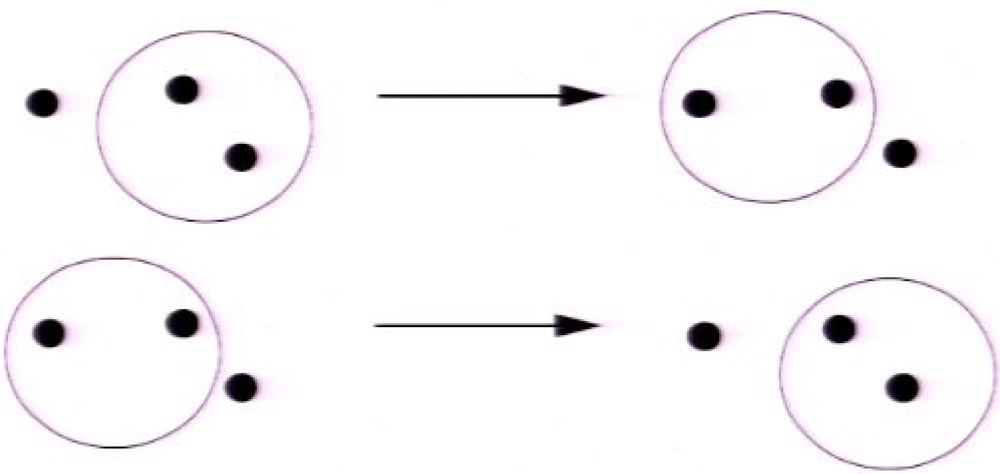
[14] Thiemann '96

[15] Perez, loop quantum cosmology: Bojowald, . . .

[16] Smolin '96, master constraint program: Thiemann '03

nsistent evolution





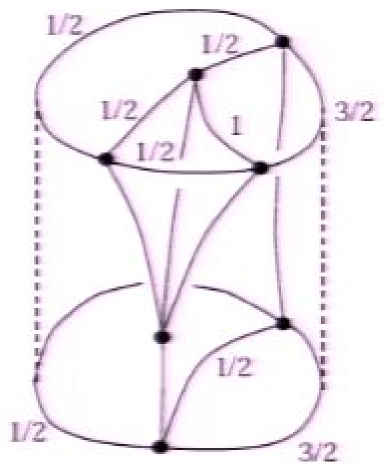
- general covariance: locally independent evolution steps should be possible
- path independence: final state should not depend on the in–between state[17]
- this is difficult to achieve even for free scalar field theory in $d > 2$[18]
- satisfied for topological field theories

[17] Kuchar

[18] Kuchar, Torre, Varadarajan

n foams

- one motivation: time evolution of spin networks[19]
- gravity action → (topological) BF–action plus constraint[20] → implement constraint into path integral for BF–action



A spin foam model:

- (dual) triangulations of n–dim manifold with labels
- attach amplitudes to vertices and edges
- sum over labels
- (sum over triangulations)
- Barrett-Crane model '97

[19] Reisenberger, Rovelli '97

[20] Freidel, Krasnov, Reisenberger, De Pietri '98

oup Field Theory

- spin foam models can be formulated as group field theories [21]
- Feynman diagram expansion for "atoms of space–time": sum over diagrams realizes sum over triangulations
- finiteness result: this expansion can be made finite order by order[22]
- general framework for background independent path integrals[23], tool for model building, generalization of matrix models

[21] Boulatov, Ooguri, DePietri, Freidel, Krasnov, Reisenberger, Rovelli, . . . , Ryan

[22] Perez, Rovelli '00

[23] Oriti

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v energy limit

- Hard part: reconstruct semi–classical space–time
- covariant
  - background independent generalization of n–point functions[24]
  - 2–point function scales correctly with distance for diagonal tensor components[25]
  - non–diagonal components incorrect for Barret-Crane: motivated new models[26]
  - calculations lowest order in group field expansion

[24] Oeckl, Rovelli, Conrady, Doplicher, Bianchi, Modesto, Speziale

[25] Alesci, Rovelli '07

[26] Engle Pereira Rovelli; Freidel, Krasnov; Livine, Speziale 07

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v energy limit

- Hard part: reconstruct semi–classical space–time
- canonical
  - weave states[27]
  - coherent states[28]
  - can be used to probe semi–classical limit (on fixed graphs)[29]
  - dynamical semi–classical states?

  - loop quantum cosmology: use symmetry to drastically reduce degrees of freedom[30]
  - dynamics solvable, semi–classical limit can be discussed
  - singularity resolution

[27] Ashtekar, Rovelli, Smolin, Zegwaard,. . .

[28] Thiemann, Ashtekar, Lewandowski, Winkler, Bahr

[29] Thiemann, Sahlmann, Giesel

[30] Bojowald, Ashtekar, Lewandowski, Singh

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v energy limit

- Hard part: reconstruct semi–classical space–time
- this is rather an (extrem) many–body–problem
- we should use statistical physics tools[31]
- space–(time) as emergent/ in a phase transition

[31] Markopoulou, Konopka, Smolin '07

tter

Does a theory of quantum gravity without matter exist?
Or does a quantum theory of gravity have to include matter couplings?

[32] Thiemann '96

[33] Bilson–Thompson, Markopoulou, Smolin '06

[34] Lisi 07

tter

Does a theory of quantum gravity without matter exist?
Or does a quantum theory of gravity have to include matter couplings?

- LQG: add matter as additional fields: Hamiltonians uv–finite[32]
- matter degrees of freedom encoded in the topology of the graph: braiding and knotting[33]
- unification of forces based on connection (*BF*–type) formulation[34]

[32] Thiemann '96

[33] Bilson–Thompson, Markopoulou, Smolin '06

[34] Lisi 07

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nclusions

Despite approx. 70 years of research we do not have a quantum theory of gravity.

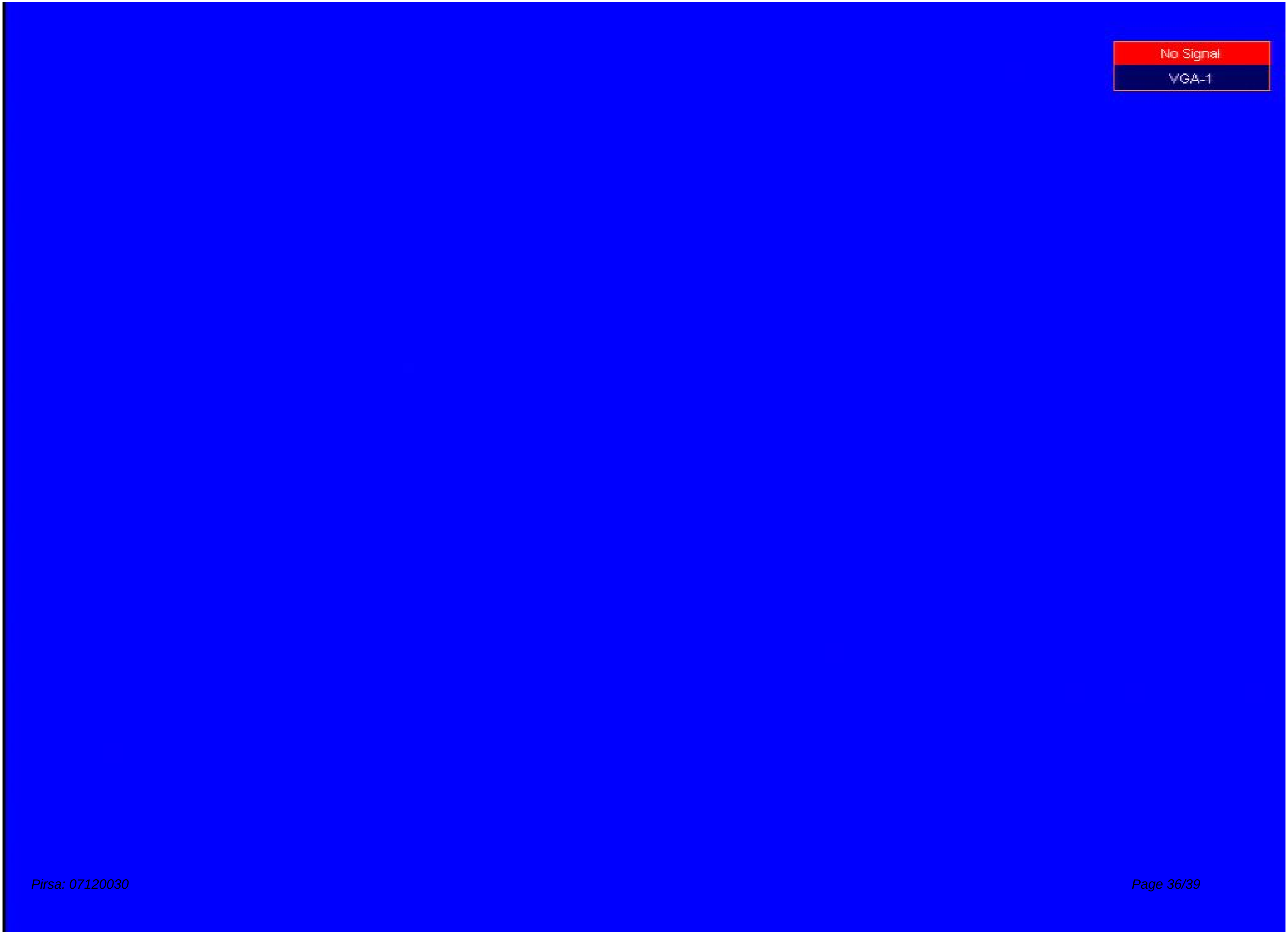
- but we have learnt a lot
- models for background independent physics
- understand kinematical features very well
- approaching low energy limit
- quantum gravity predictions/phenomenology[35]
- experimental results might come in pretty soon/ are already there!

[35] Amelino-Camelia, Smolin, Arzano, Hossenfelder

No Signal

VGA-1

No Signal
VGA-1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