Loop Quantum Gravity
basic structure and recent developements

Theorie Univers et Gravitation
Montpellier
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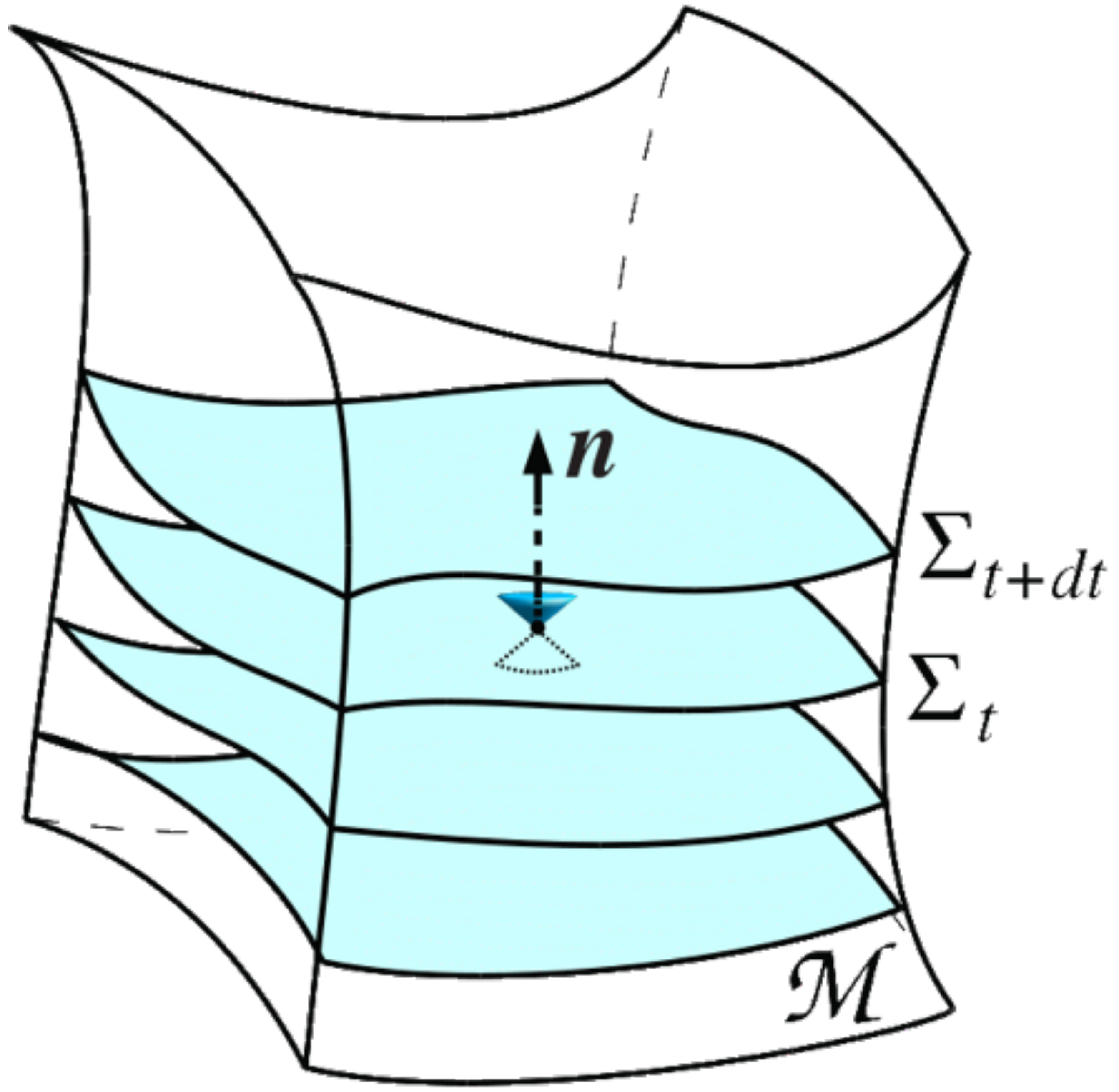
Loop Quantum Gravity
Planckian discreteness in a nut-shell

The phase space of GR in connection variable

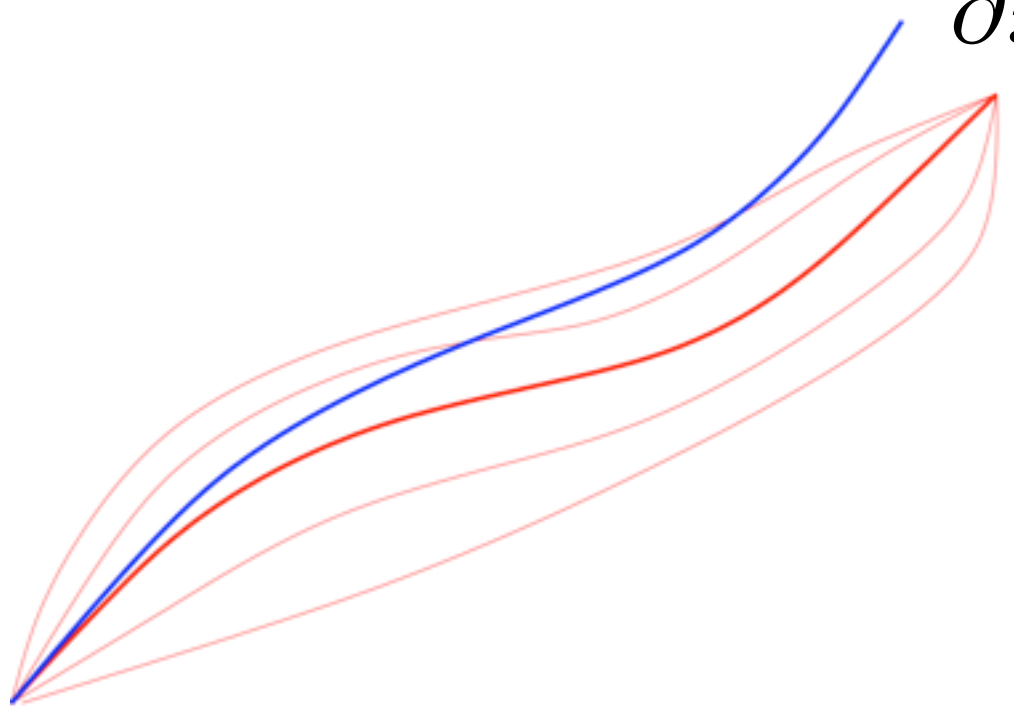


$$\partial M \equiv \Sigma$$

$$S[e,\omega] = \int_M \epsilon_{IJKL} e^I \wedge e^K \wedge F^{KL}(\omega)$$

$$\begin{aligned} \delta S &= \int_M 2\delta e^I (\epsilon_{IJKL} \wedge e^K \wedge F^{KL}(\omega)) + e^I \wedge e^K \wedge d_\omega(\delta\omega^{KL}) = \\ &= \int_M 2\delta e^I (\epsilon_{IJKL} \wedge e^K \wedge F^{KL}(\omega)) - (d_\omega(\epsilon_{IJKL} e^I \wedge e^K)) \wedge \delta\omega^{KL} \\ &+ \underbrace{\int_{\partial M} (\epsilon_{IJKL} e^I \wedge e^K) \wedge \delta\omega^{KL}}_{p\delta x} \end{aligned}$$

$$\frac{\partial S}{\partial x} = p$$

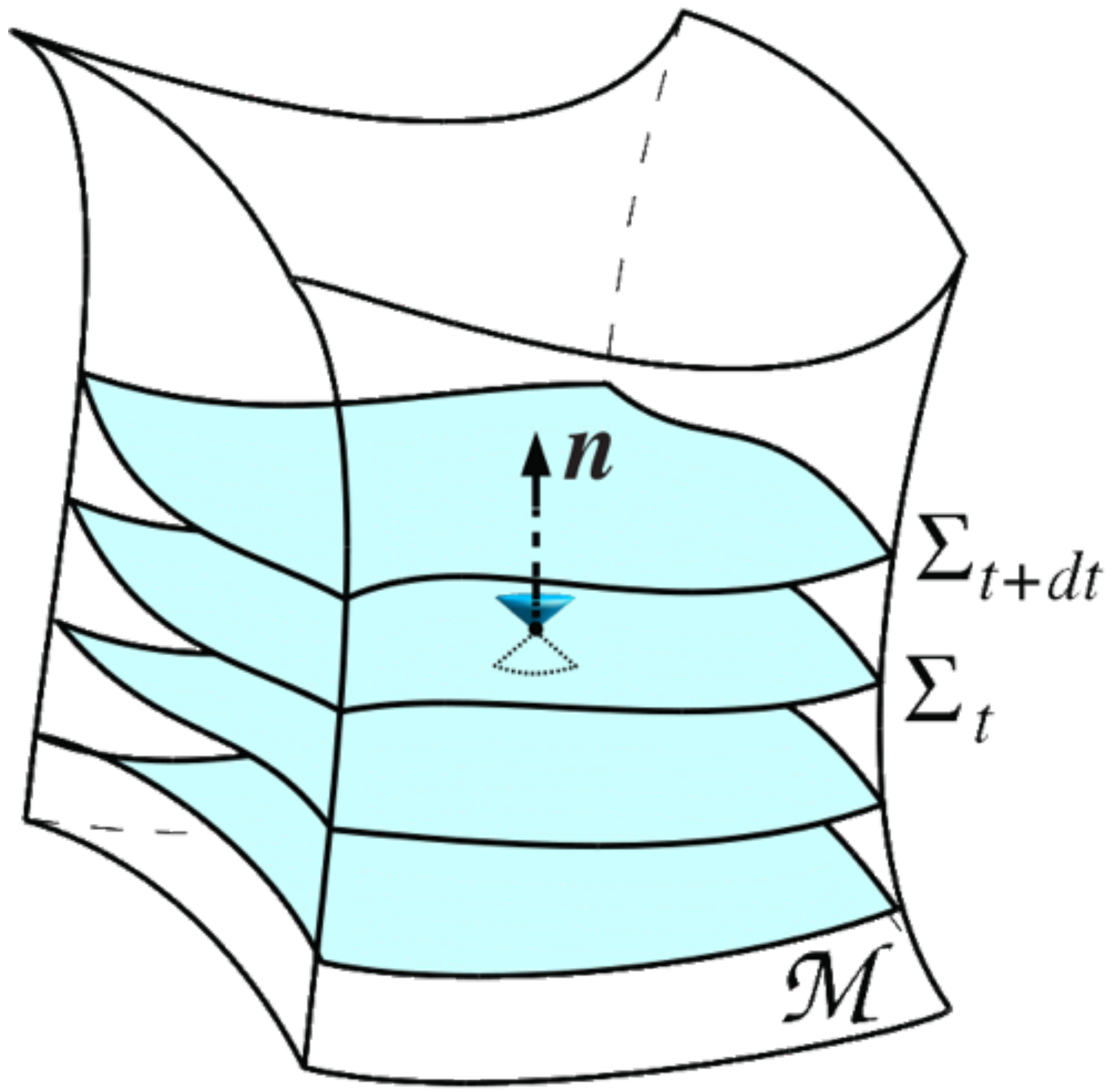


The symplectic potential

$$\phi(\delta) \;=\; \int_\Sigma (\epsilon_{IJKL} e^I \wedge e^K) \wedge \delta\omega^{KL}$$

The phase space of GR in connection variables

A. Ashtekar, PRL 57 (1986)



$$\partial M \equiv \Sigma$$

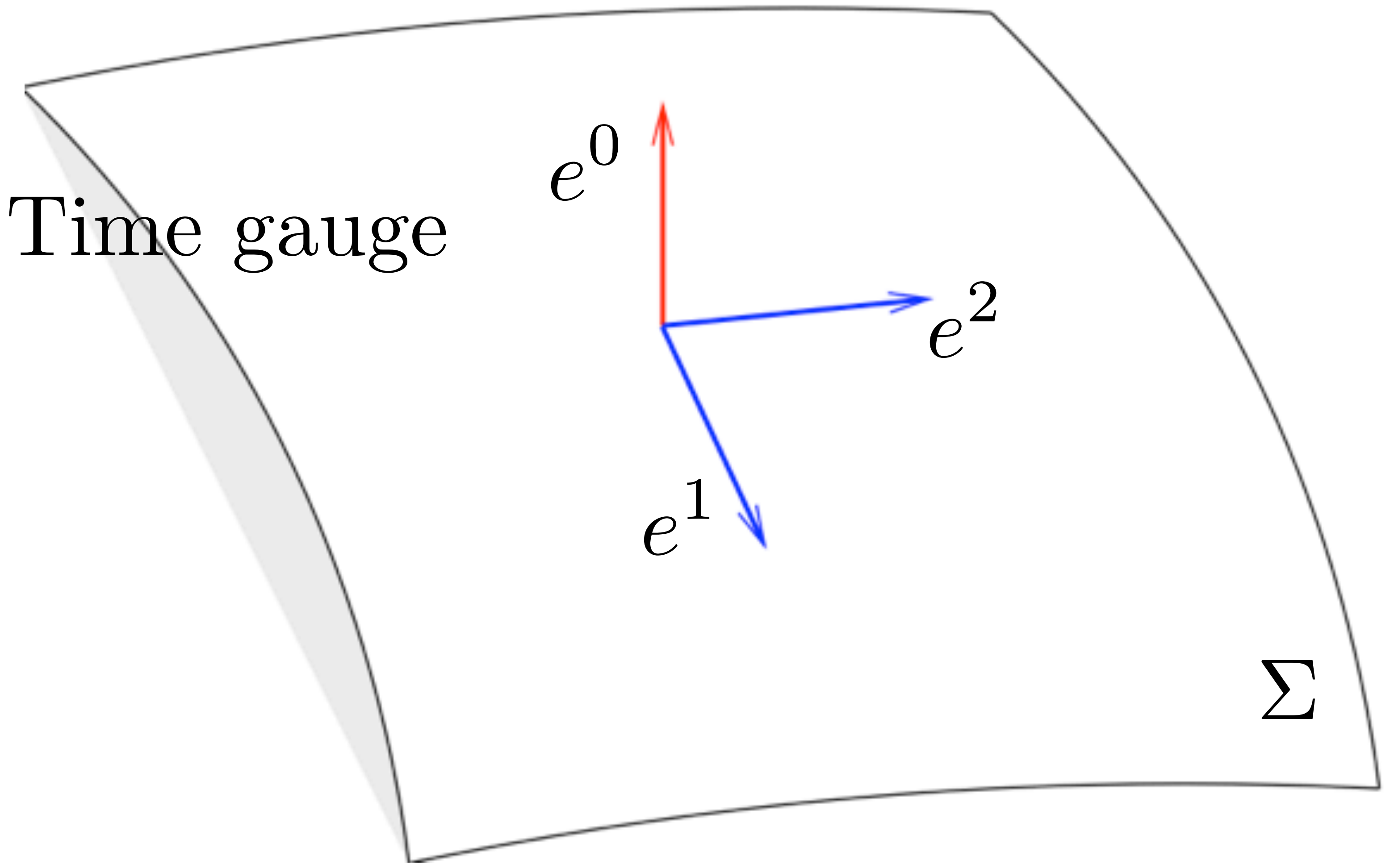
$$S[e,\omega] = \int_M \epsilon_{IJKL} e^I \wedge e^K \wedge F^{KL}(\omega)$$

$$\begin{aligned}
\delta S &= \int_M 2\delta e^I \left(\epsilon_{IJKL} \wedge e^K \wedge F^{KL}(\omega)\right) + e^I \wedge e^K \wedge d_\omega(\delta\omega^{KL}) = \\
&= \int_M 2\delta e^I \left(\epsilon_{IJKL} \wedge e^K \wedge F^{KL}(\omega)\right) - \left(d_\omega(\epsilon_{IJKL} e^I \wedge e^K)\right) \wedge \delta\omega^{KL} \\
&+ \int_{\partial M} (\epsilon_{IJKL} e^I \wedge e^K) \wedge \delta\omega^{KL}
\end{aligned}$$

Number of components:
12 for e^I_a versus **18** for ω^{IJ}_a

The symplectic potential

$$\begin{aligned}
\phi(\delta) &= \int_\Sigma (\epsilon_{IJKL} e^I \wedge e^K) \wedge \delta\omega^{KL} = \\
&= \int_\Sigma (\epsilon_{0jkl} e^0 \wedge e^j) \wedge \delta\omega^{kl} + (\epsilon_{0jkl} e^j \wedge e^k) \wedge \delta\omega^{l0} = \\
&= \int_\Sigma (\epsilon_{jkl} e^j \wedge e^k) \wedge \delta\omega^{l0}
\end{aligned}$$



A canonical transformation
to get back the connection variables

The symplectic potential

$$\phi(\delta) \quad = \quad \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0}$$

A canonical transformation

to get back the connection variables

$\gamma \equiv$ Immirzi parameter

The symplectic potential

$$\begin{aligned} \phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\ &= \frac{1}{\gamma} \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \end{aligned}$$

A canonical transformation

to get back the connection variables

$\gamma \equiv$ Immirzi parameter

The spin connection

$$de^i + \epsilon^{ijk}\, \Gamma_j \wedge e_k = 0$$

The symplectic potential

$$\begin{aligned}
\phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0} + \Gamma^k(e)) - \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\Gamma^k(e))
\end{aligned}$$

A canonical transformation
to get back the connection variables

$\gamma \equiv$ Immirzi parameter

The spin connection

$$de^i + \epsilon^{ijk}\,\Gamma_j \wedge e_k = 0$$

$$d(\delta e^i) + \epsilon^{ijk}\,\delta\Gamma_j \wedge e_k + \epsilon^{ijk}\,\Gamma_j \wedge \delta e_k = 0$$

$$(\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\Gamma^k = d(e^i \wedge \delta e_i)$$

The symplectic potential

$$\begin{aligned}
\phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0} + \Gamma^k(e)) - \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\Gamma^k(e))
\end{aligned}$$

Une transformation canonique
pour retrouver les variables de connexion

$\gamma \equiv$ le paramètre d'Immirzi

The spin connection

$$de^i + \epsilon^{ijk}\,\Gamma_j \wedge e_k = 0$$

$$d(\delta e^i) + \epsilon^{ijk}\,\delta\Gamma_j \wedge e_k + \epsilon^{ijk}\,\Gamma_j \wedge \delta e_k = 0$$

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The symplectic potential

$$\begin{aligned}\phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\ &= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \\ &= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\overbrace{\gamma\omega^{k0} + \Gamma^k(e)}) - \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\Gamma^k(e)) \\ &= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta A^k - \frac{1}{\gamma}\int_{\partial\Sigma} e^i \wedge \delta e^i\end{aligned}$$

Ashtekar-Barbero connection

Poisson brackets

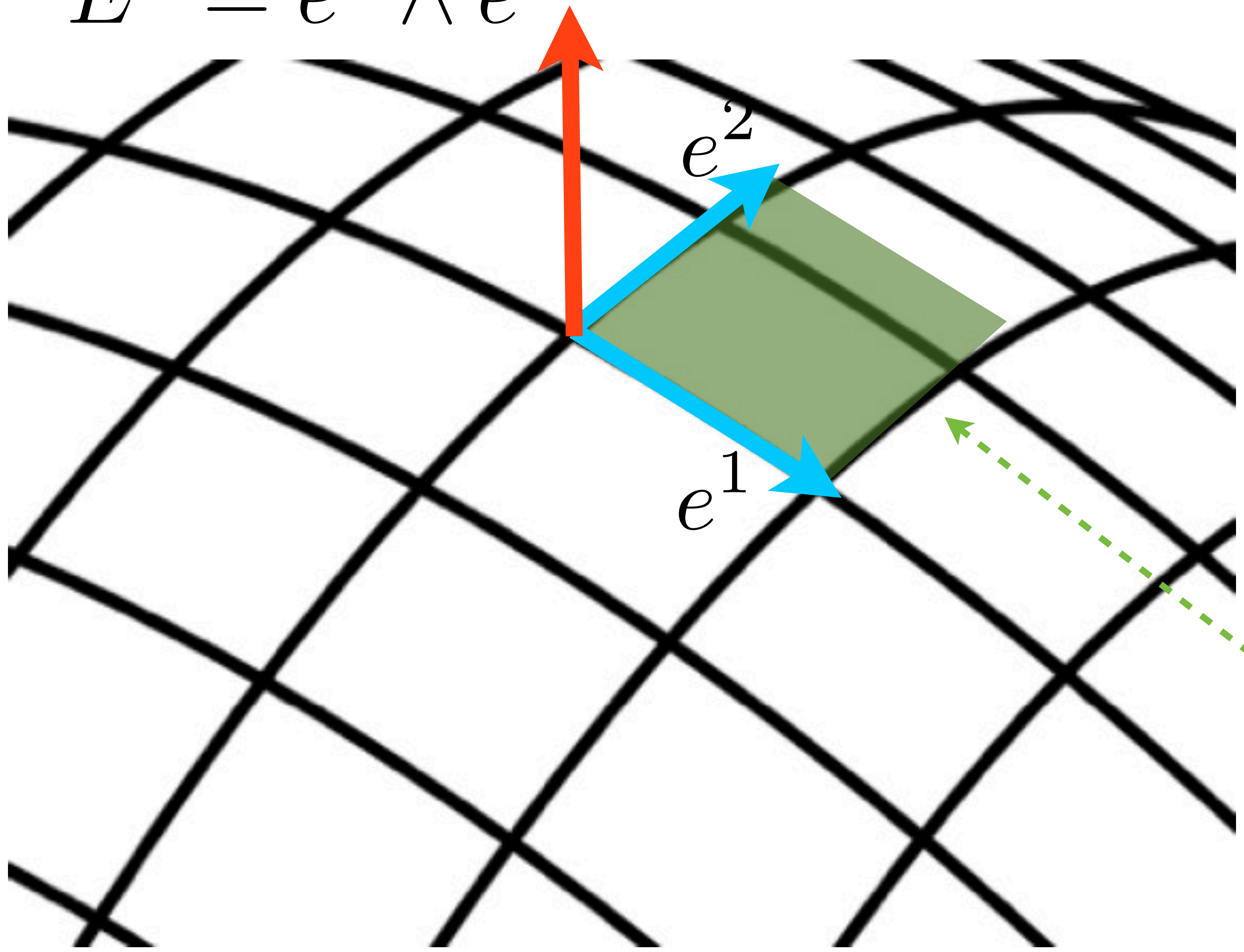
$$\{\epsilon_{ilm} e^l_a(x) e^m_b(x), A^j_c(y)\} = \gamma \delta^j_i \epsilon_{abc}\delta(x, y)$$

Quantization of area in a nut-shell

$$
\begin{aligned}
\phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0} + \Gamma^k(e)) - \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\Gamma^k(e)) \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta A^k - \frac{1}{\gamma}\int_{\partial\Sigma} e^i \wedge \delta e^i
\end{aligned}
$$

J. Engle, Noui, AP, D. Pranzetti
Phys.Rev. D82 (2010) 044050

$E^3 = e^1 \wedge e^2$



area element

$dS^2[e]$

In a 2-boundary

$$\{e^i_a(x), e^j_b(y)\} = \gamma\epsilon_{ab}\delta^{ij}\delta^{(2)}(x,y)$$

$$E^i \equiv \frac{1}{\gamma}\epsilon_{jkl} e^j \wedge e^k$$

$$\gamma\sqrt{E^i E_i} = \sqrt{h^{(2)}}$$

$$\{E^i(x), E^j(y)\} = \epsilon_{ijk} E^k \delta^{(2)}(x,y)$$

Quantization of area in a nut-shell

$$
\begin{aligned}
\phi(\delta) &= \int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta\omega^{k0} \\
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta(\gamma\omega^{k0}) \\
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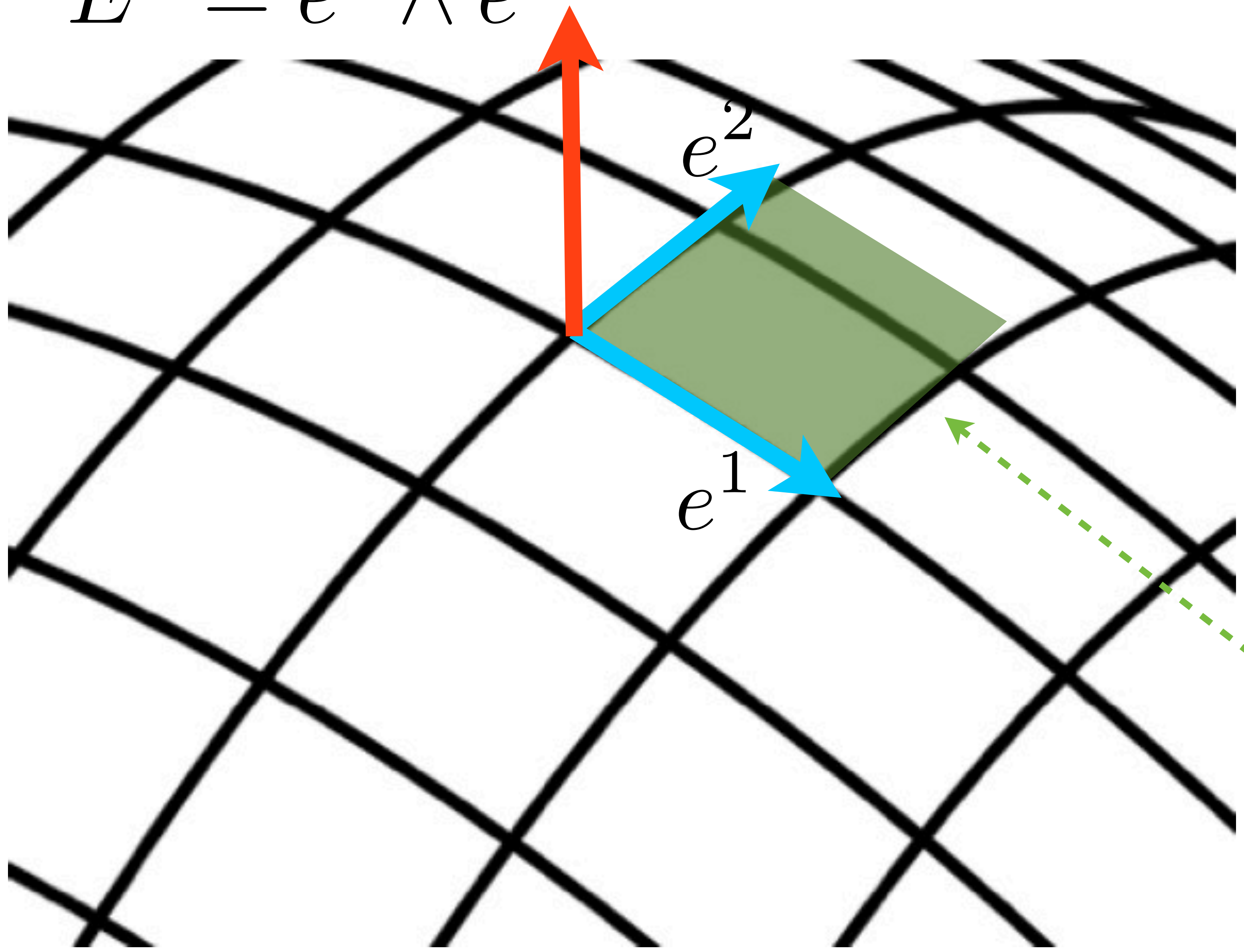
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta A^k - \frac{1}{\gamma}\int_{\partial\Sigma} e^i \wedge \delta e^i
\end{aligned}
$$

$E^3 = e^1 \wedge e^2$



area element

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$$\{e^i_a(x), e^j_b(y)\} = \gamma\epsilon_{ab}\delta^{ij}\delta^{(2)}(x,y)$$

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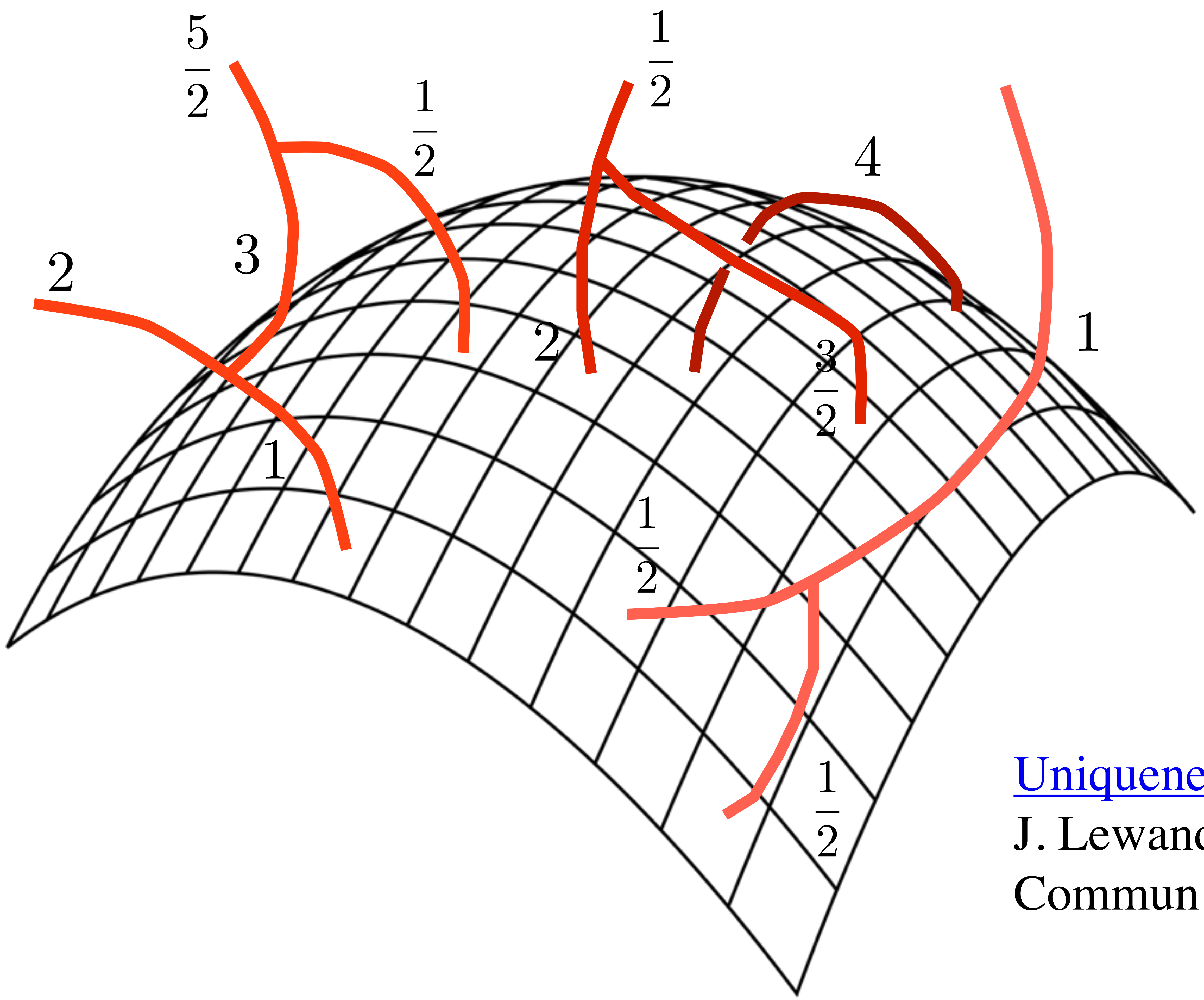
$$\{E^i(x), E^j(y)\} = \epsilon_{ijk} E^k \delta^{(2)}(x,y)$$

$$\text{area quantum} = \gamma\ell_p^2\sqrt{j(j+1)}$$

Quantization of area

C. Rovelli and L. Smolin. (1995)

A. Ashtekar and J. Lewandowski. (1997)



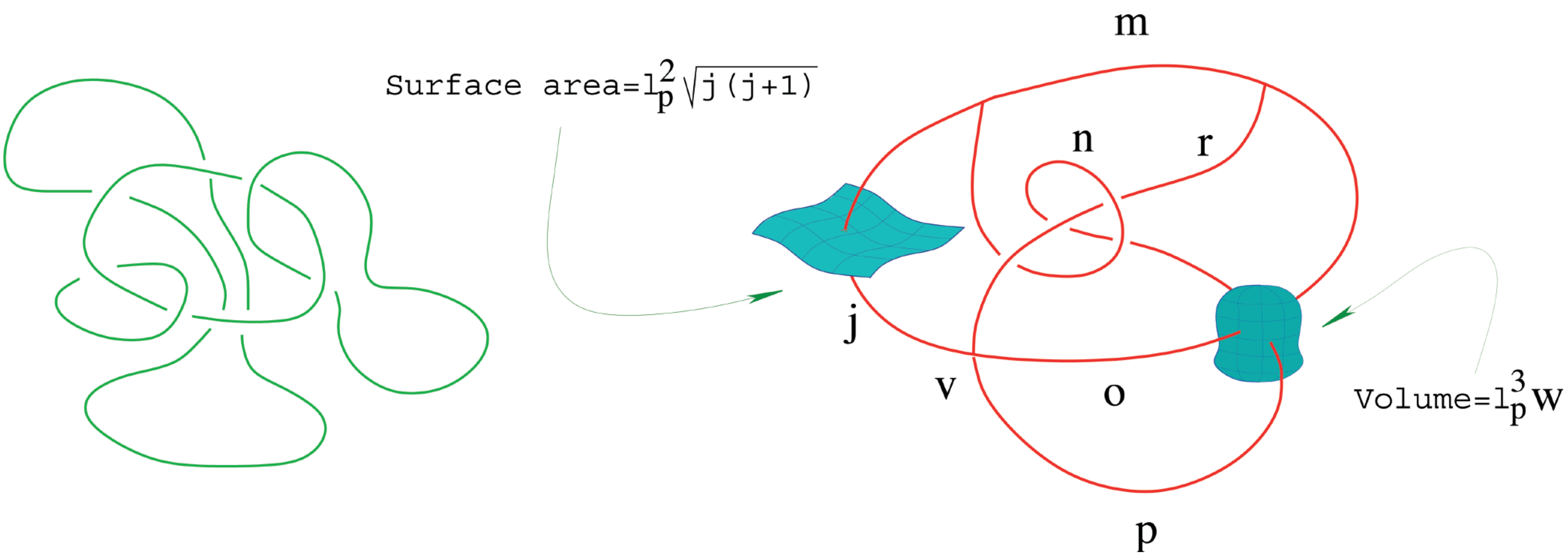
$\gamma \equiv$ Immirzi parameter

$$\text{area quantum} = \gamma \ell_p^2 \sqrt{j(j+1)}$$

Uniqueness of diffeomorphism invariant states on holonomy-flux algebras

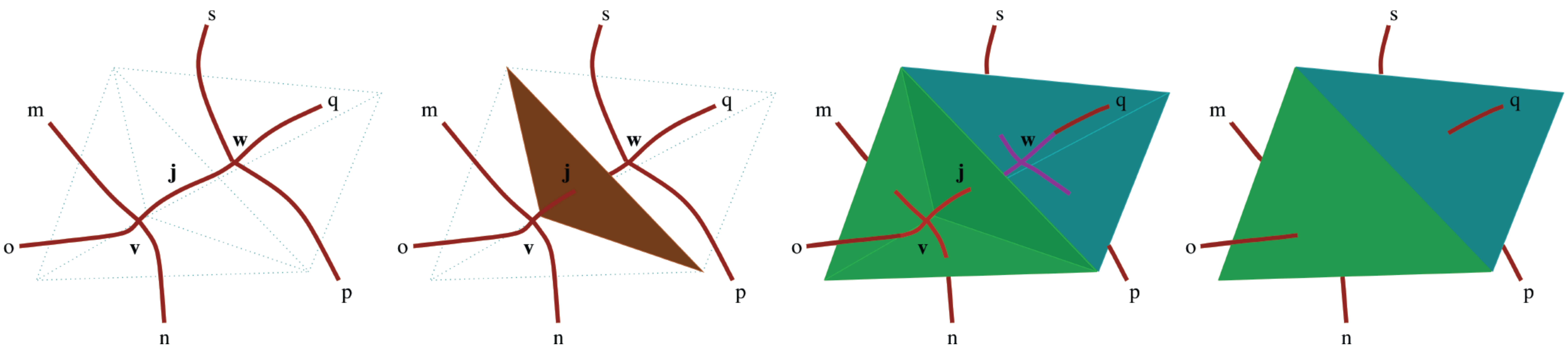
J. Lewandowski, A. Okolow, H. Sahlmann, T. Thiemann.

Commun.Math.Phys. 267 (2006) 703-733. e-Print: gr-qc/0504147



▲ **Fig. 1:** The basic loop excitations of geometry are combined into states of an orthonormal basis of the Hilbert space called *spin network states*. These states are labelled by a graph in space and assignment of spin quantum numbers to edges and intersections ($j, n, m, r, o, p \in \mathbb{Z}/2$). The edges are quantized lines of *area*: a spin network link labelled with the spin j that punctures the given surface is an eigenstate of its area with eigenvalue $\sqrt{j(j+1)}$ times the fundamental Planck area. Intersections can be labelled by discrete quantum numbers of volume (v, and w here). In order for this page to have the observed area one would need about 10^{68} spin network punctures with $j = 1/2$!

AP. Europhys.News 37N3 (2006) 17-21

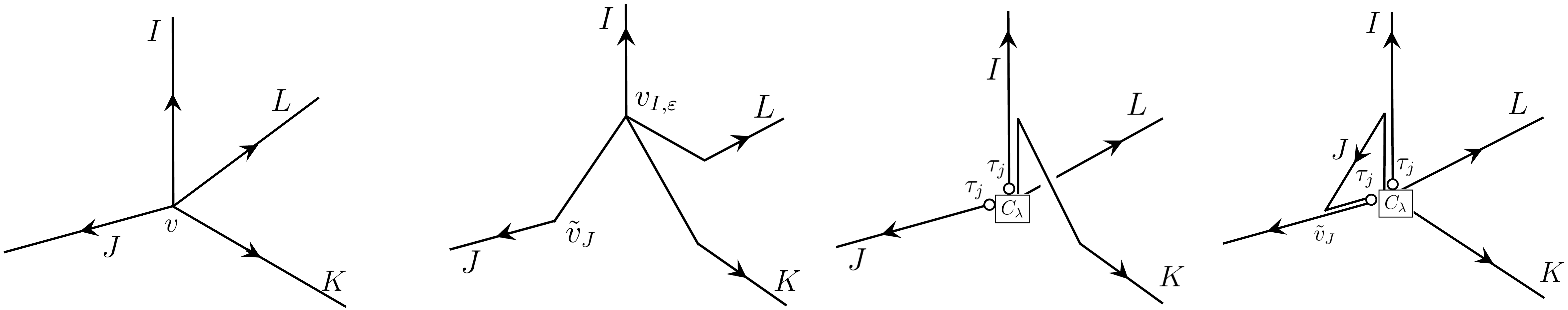


▲ **Fig. 3:** Spin network intersections are quantum excitations of space volume. They are fundamental *atoms* of space related to one another through spin network links carrying quanta of the area associated to the extension shared by neighbouring *atoms*. The information about how the atoms are interconnected to form a quantum geometry is contained in the combinatorics of the underlying abstract graph. Here we show two 4-valent vertices connected by a link carrying spin *j*. We can interpret this portion of a spin network as being represented by two *tetrahedra* of volume $\ell_P^3 v$ and $\ell_P^3 w$ respectively sharing a face of their boundary (the brown triangle in the second diagram) with area $\ell_P^2\sqrt{j(j+1)}$.

Quantum Dynamics
(Hamiltonian perspective)

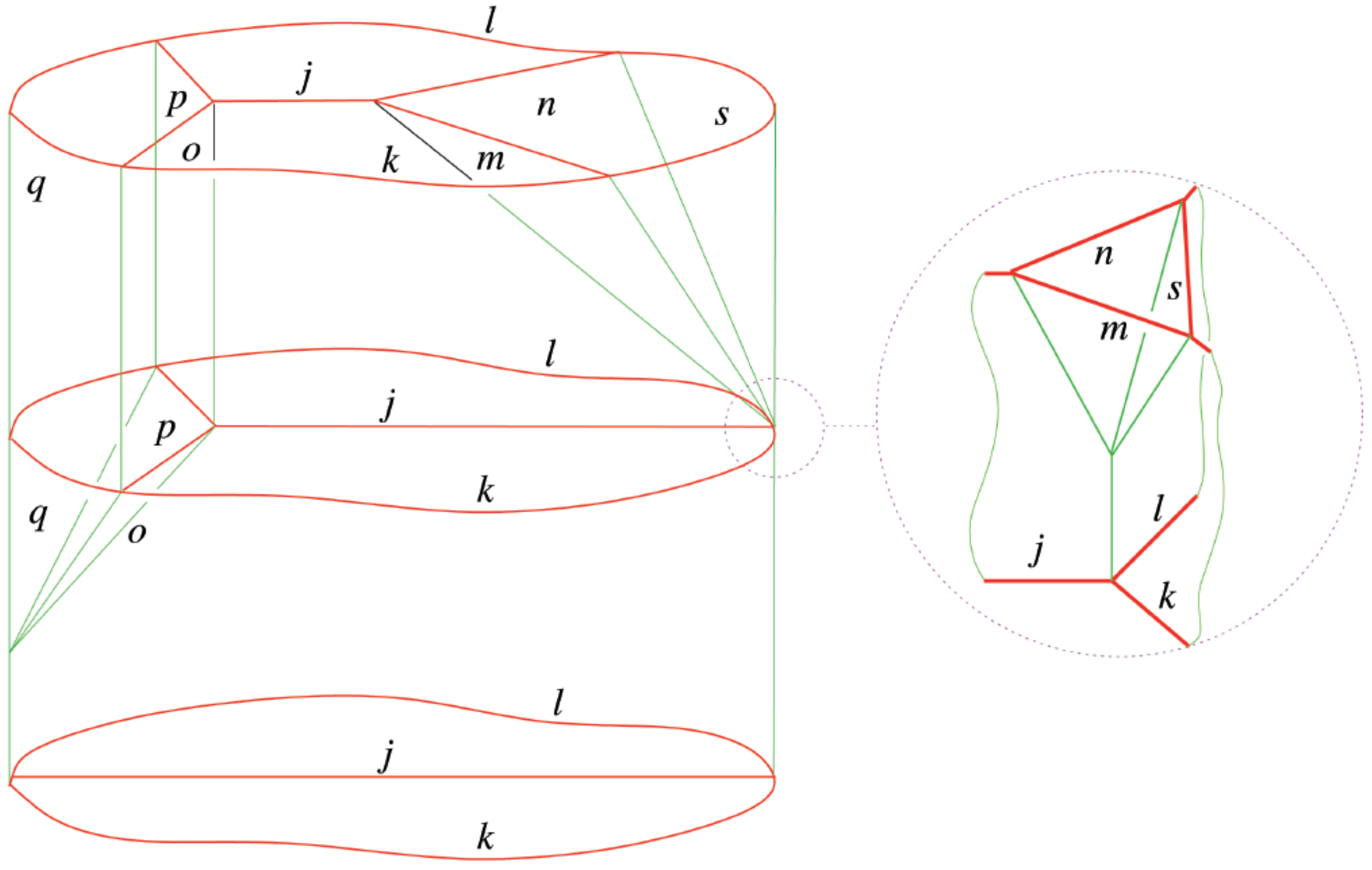
Anomaly free quantum dynamics for Euclidea LQG
M. Varadarajan. e-Print: 2205.10779 [gr-qc]

Gravitational Dynamics—A Novel Shift in the Hamiltonian Paradigm
Abhay Ashtekar, M. Varadarajan.
Class.Quant.Grav. 38 (2021) 13, 135020 e-Print: 2101.03115



$S_{undeformed}$ $S^{(\epsilon)}_{electric\ diffeo}$ $S^{(\epsilon)}_{propagation}$ $S^{(\epsilon)}_{propagation}$

Quantum Dynamics
(spin foams: the path integral perspective)

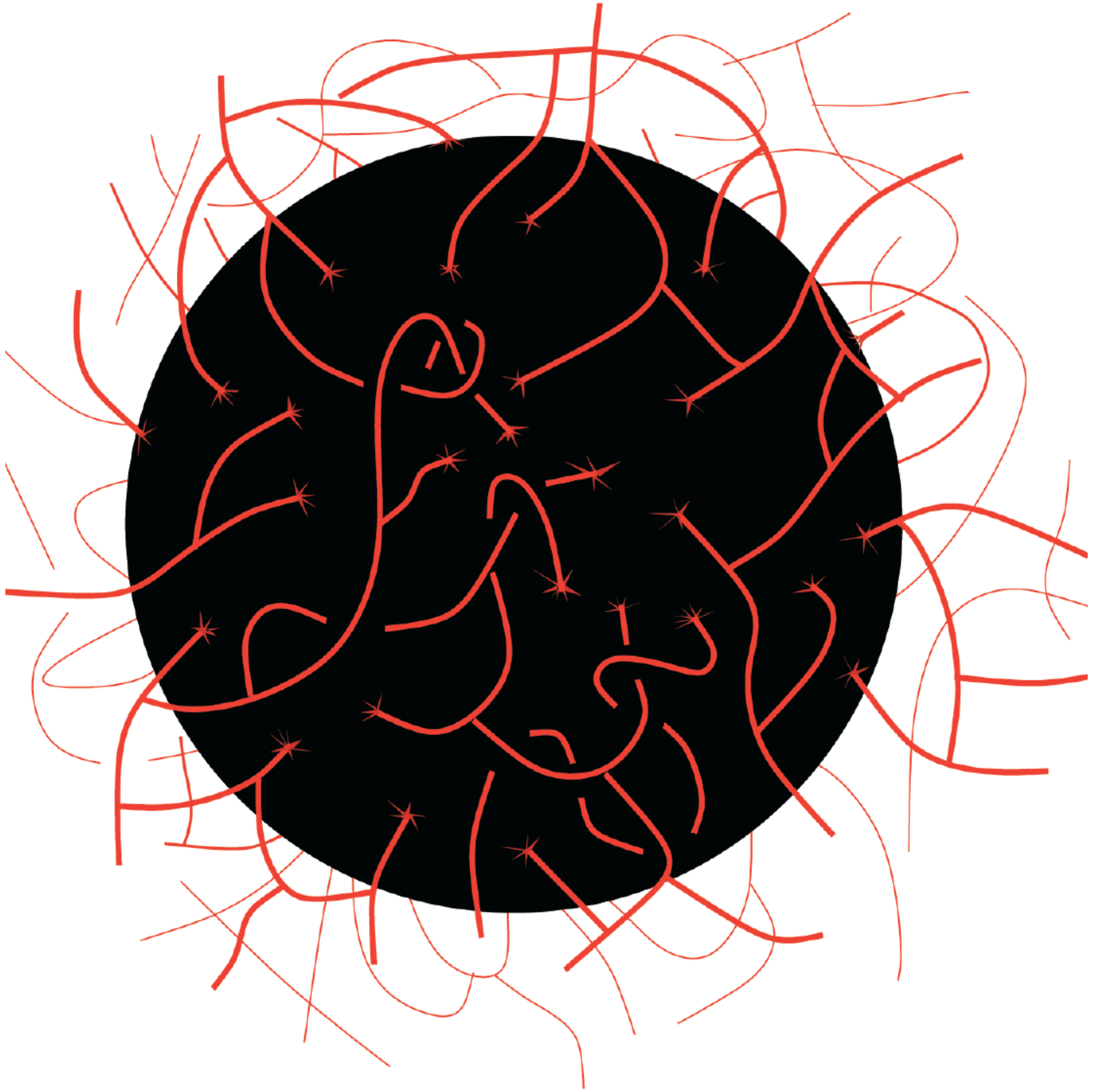


▲ **Fig. 5:** A systematic control of the space of solutions is necessary to fully understand the dynamics implied by LQG. Feynman's path integral formulation can be adapted to the formalism in order to investigate this issue. Transition amplitudes that encode the dynamics of quantum gravity can be computed as sums of amplitudes of combinatorial objects representing histories of spin network states. These histories can be interpreted as quantum space-time processes and are called *spin foams*. In the figure we show a simple spin foam obtained interpolating between an 'initial' and 'final' spin network. An intermediate spin network state is emphasized as well as a vertex where new links are created as a result of the action of the quantum Hamiltonian constraint.

LQG vertex with finite Immirzi parameter
J. Engle, E. Livine, R. Pereira, C. Rovelli.
Nucl.Phys.B 799 (2008) 136-149. e-Print: 0711.0146

Implications of discreteness

some emblematic examples



▲ **Fig. 2:** In loop quantum gravity the Bekenstein-Hawking entropy formula for a black hole of area A, $S_{bh} = A/(4\ell_p^2)$, can berecovered from the quantum theory as $S_{bh} = \log(N)$, where N is the number of microstates (spin network states puncturing the 2-dimensional horizon with arbitrary spins) compatible with the macroscopic horizon area of the black hole.

Black Hole Entropy Calculation

AP. Rept. Prog. Phys. ***80*** *(2017)*

$$\widehat{A}_S\,|j_1, j_2\cdots\rangle = \left[8\pi\gamma\ell_p^2 \sum_p \sqrt{j_p(j_p+1)}\right]|j_1, j_2\cdots\rangle$$

$$S_{bh} = \frac{\gamma_0}{\gamma}\frac{A}{4\ell_p^2}$$

Including matter vacuum fluctuations there are indications that:

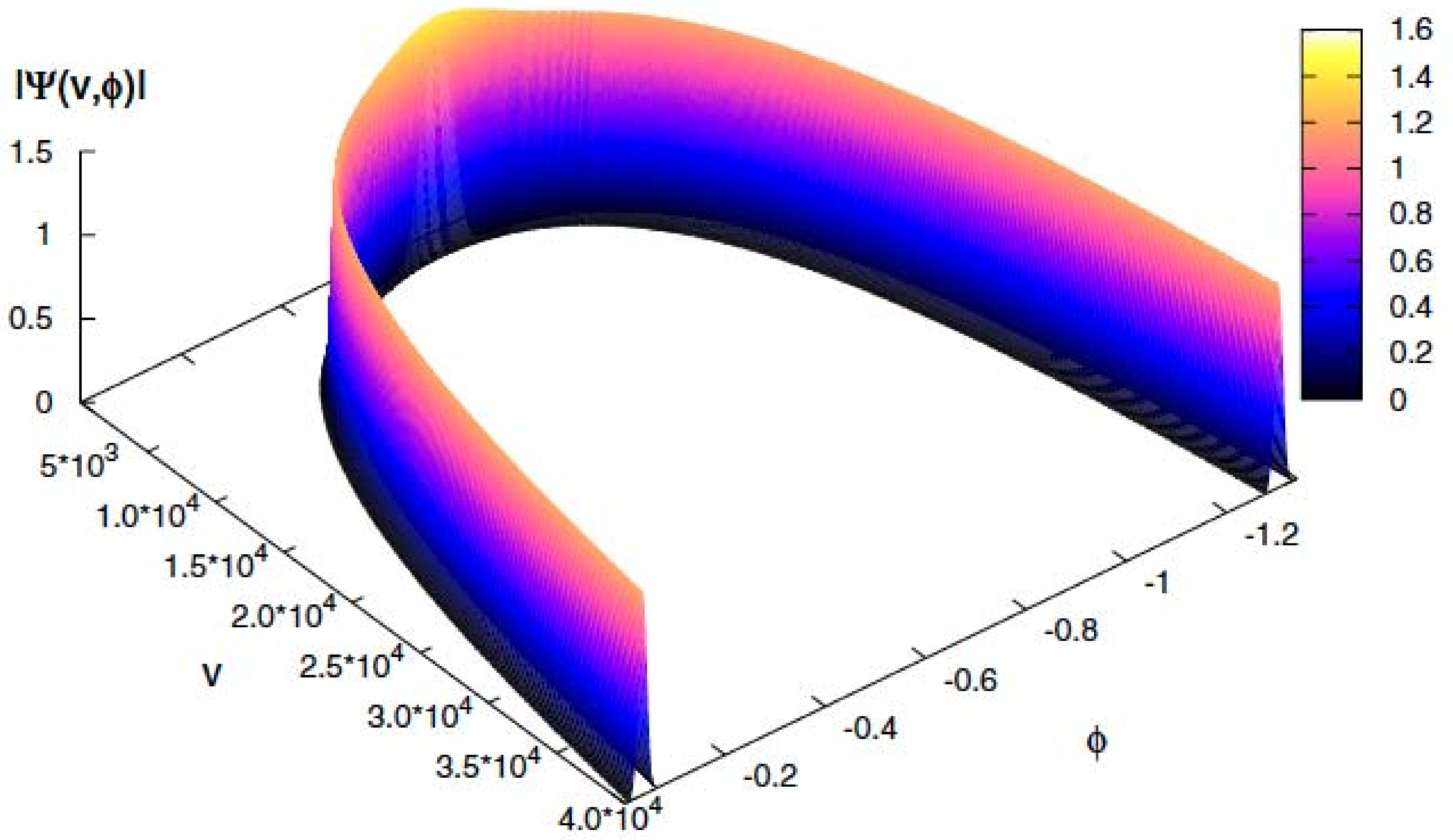
$$S_{bh} = \frac{A}{4G\hbar}$$

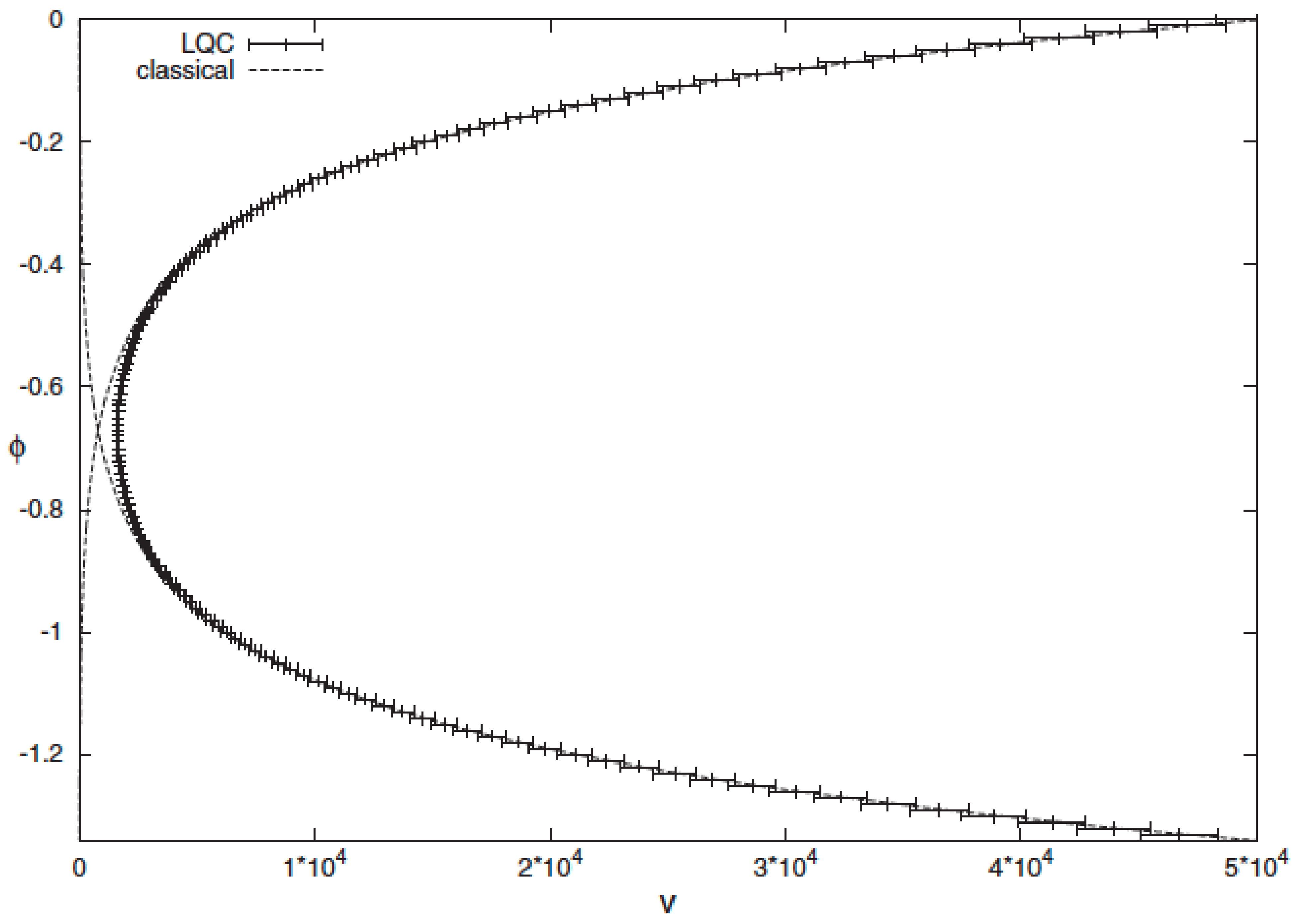
Ghosh-Noui-AP, PRD (2014)

Loop Quantum Gravity: in cosmology

Planckian discreteness resolves **big-bang** singularity.

Bojowald (2001), Ashtekar, Singh, etc.



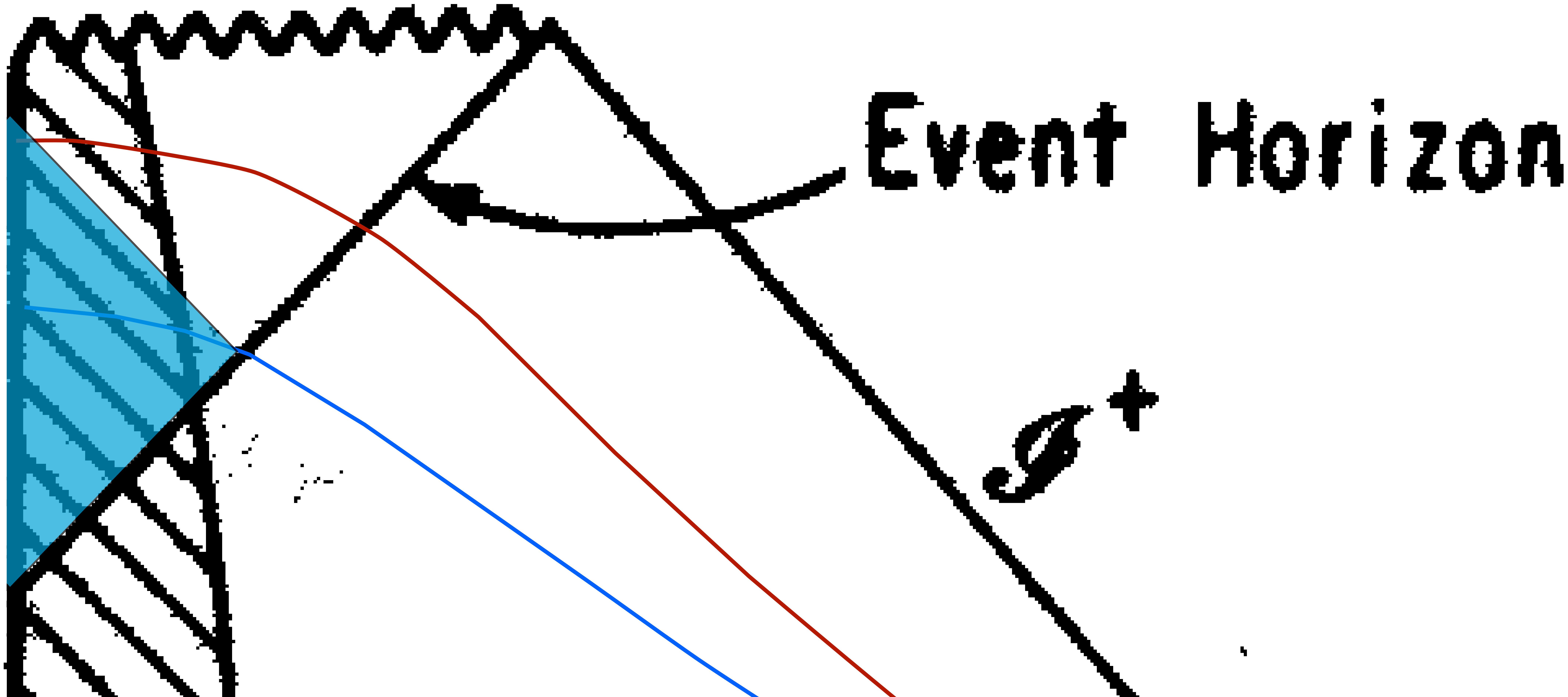


From Ashtekar, Pawlowski, Singh PRD (2006)

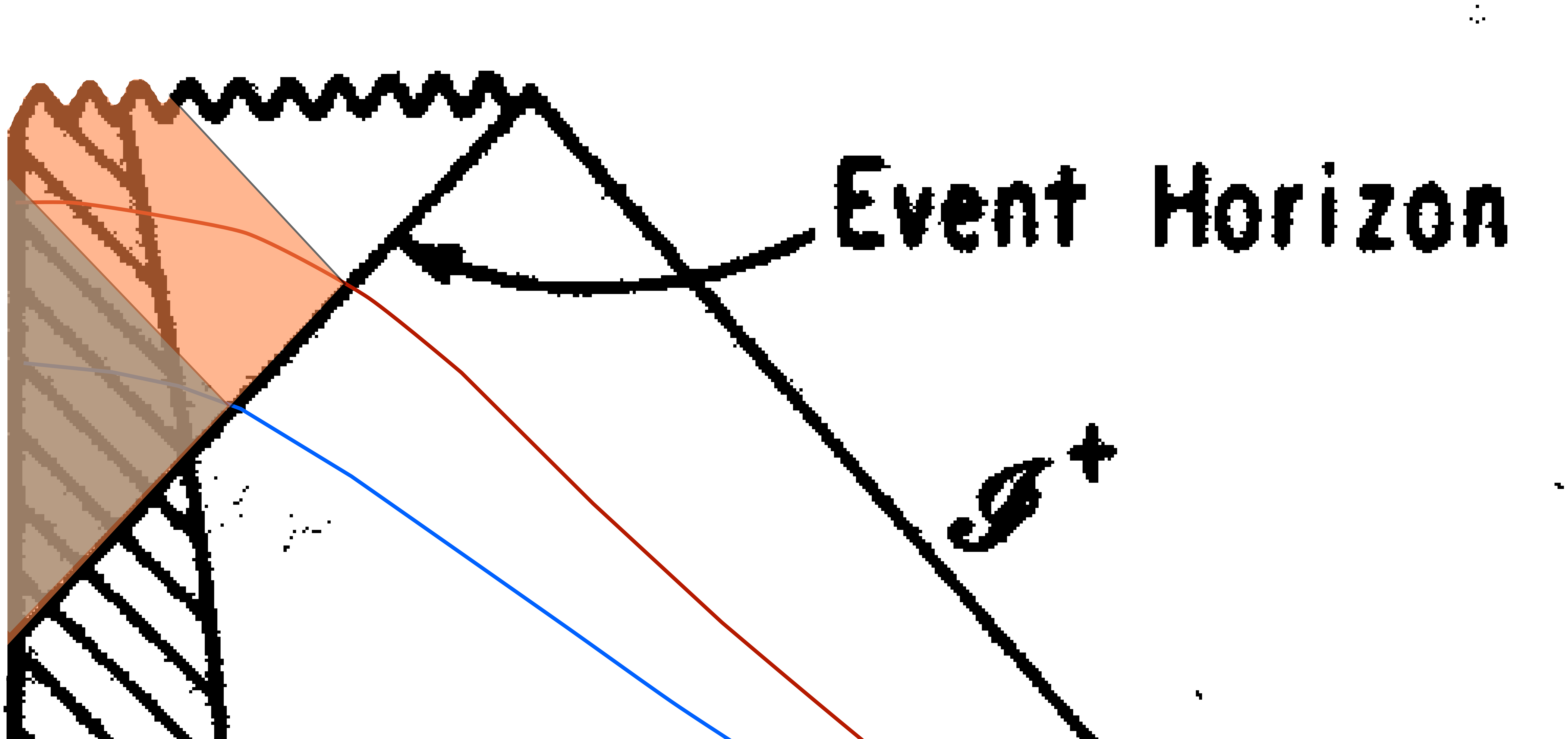
Unitarity in BH evaporation

AP. Rept. Prog. Phys. **80** (2017)

Loop Quantum Gravity: a non-holographic approach



Loop Quantum Gravity: a non-holographic approach

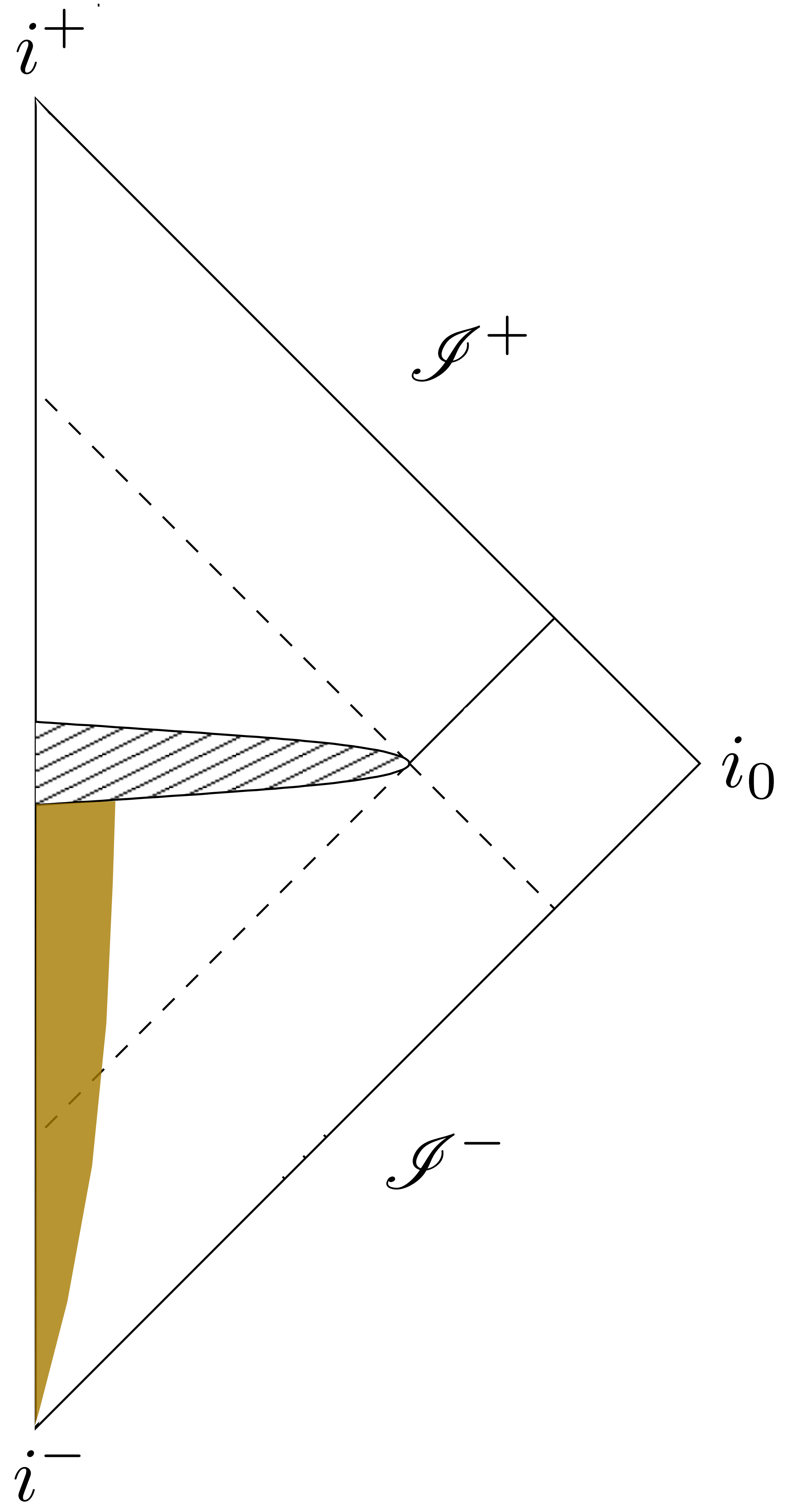


Loop Quantum Gravity: collapse, singularities, and information.

There is the expectation that (as in cosmology) evolution across BH singularities should be well defined.

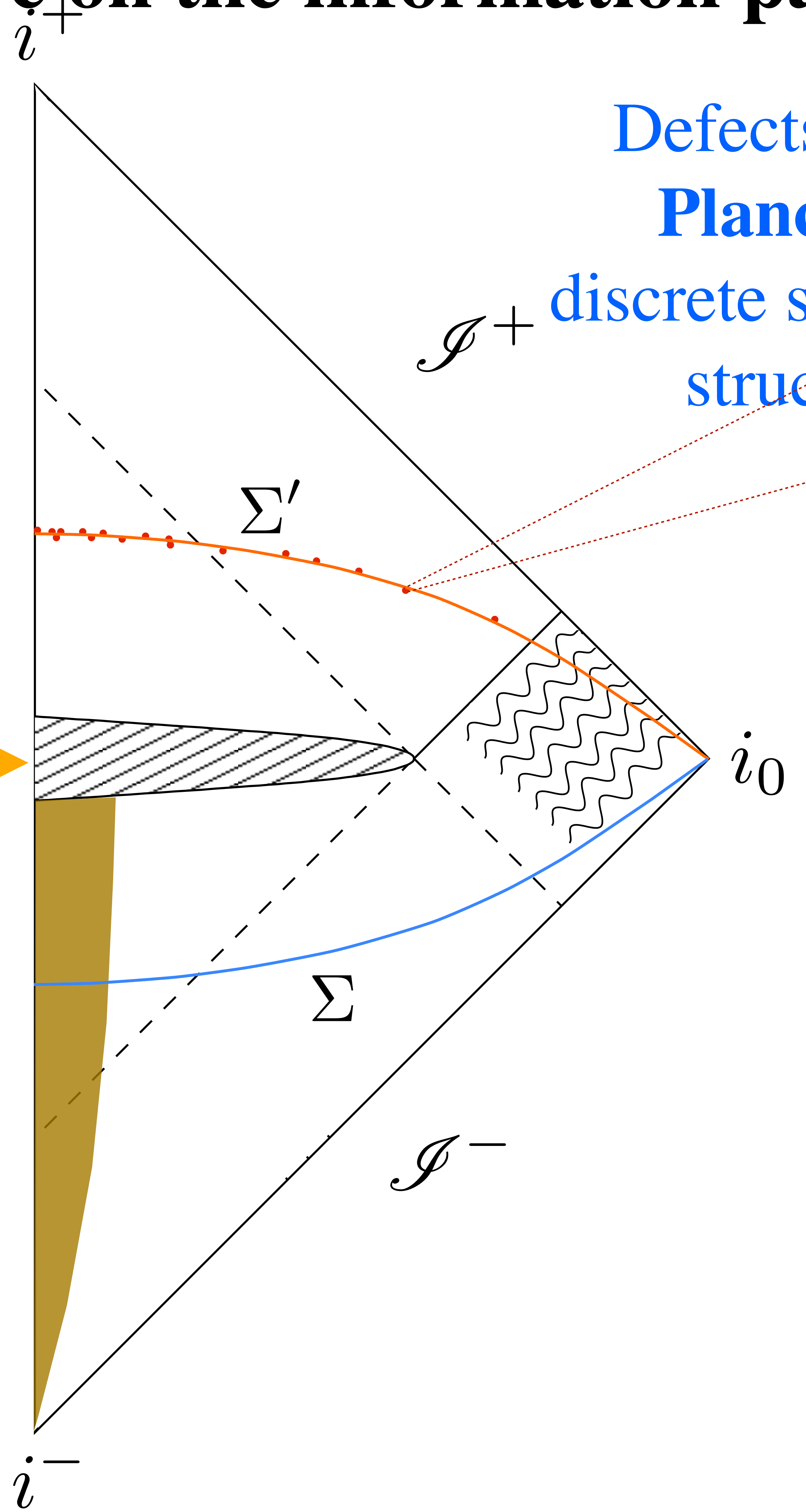
Simplified models support this expectation (Modesto, Ashtekar-Singh, Rovelli-Haggard, Rovelli, Pullin, Corichi-Singh, etc.)

Unitarity: Information should be recovered after BH evaporation

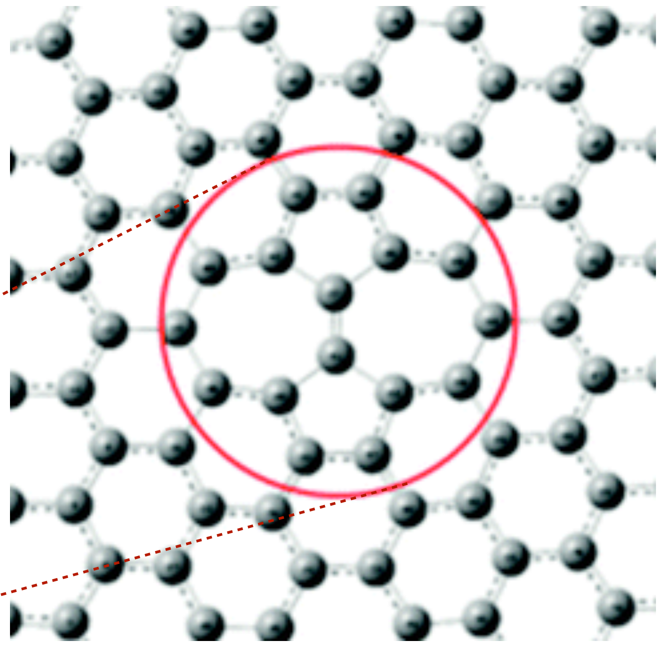


New perspective on the information paradox

AP, *Class. Quant. Grav.* 32, 2015.



Defects in the **Planckian** discrete spacetime structure

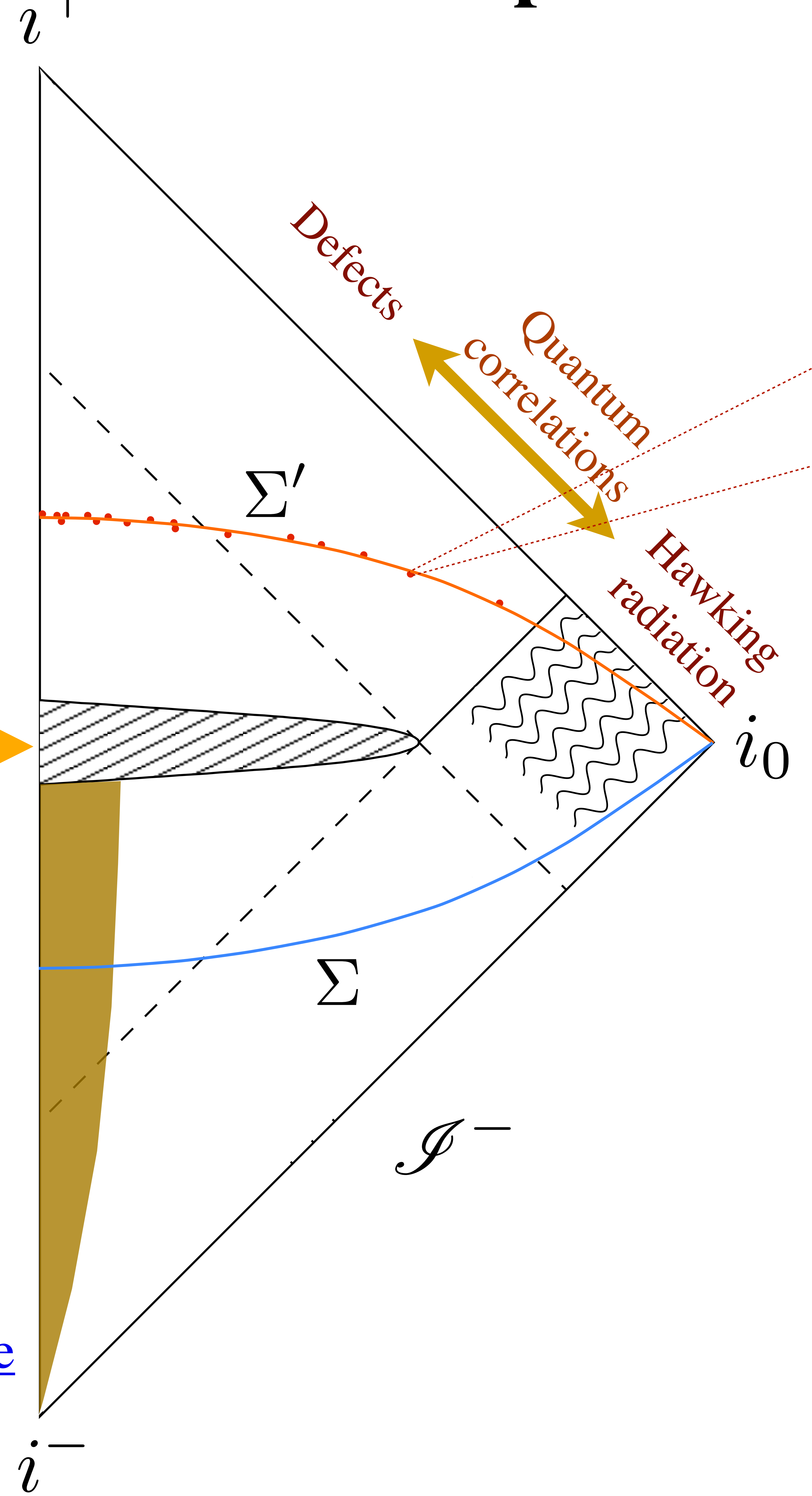


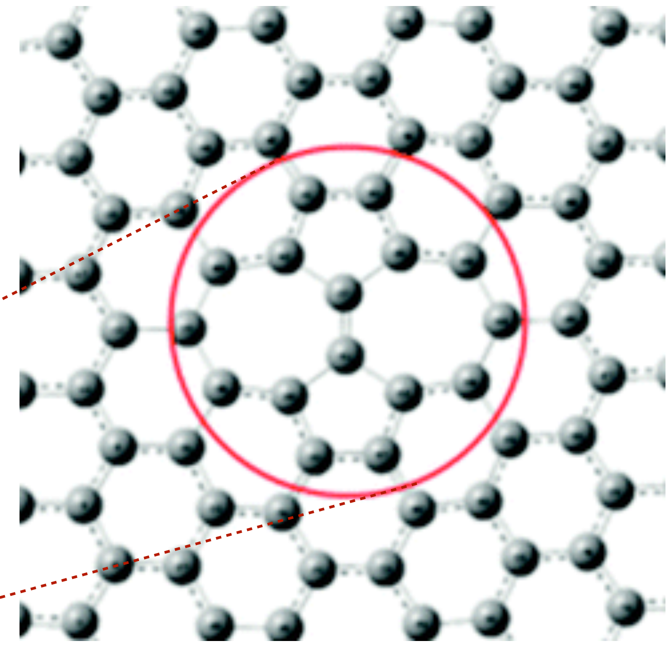
Defects are **hidden** for the probes of low energy observers. No nontinuum field theory description. They can be essentially "**zero energy**"

New perspective on the information paradox

AP, *Class. Quant. Grav.* 32, 2015.

The scenario is realized in simple quantum cosmology models that show decoherence of this type in the evolution across the singularity.





Unitarity and information in quantum gravity: a simple example

L. Amadei, H. Liu, AP. Front.Astron.Space Sci. 8 (2021) 46.

Implications of discreteness
more recent investigations

Dark Energy from diffusion into Planckian granularity

Dark Energy from Violation of Energy Conservation.
T. Josset, AP, D. Sudarsky. *Phys.Rev.Lett*. 118 (2017) 2, 021102. e-Print: 1604.04183.

Dark energy from quantum gravity discreteness
AP, D. Sudarsky. *Phys.Rev.Lett*. 122 (2019) 22, 221302. e-Print: 1711.05183 [gr-qc]

A microscopic model for an emergent cosmological constant
AP, Daniel Sudarsky, James D. Bjorken. *Int.J.Mod.Phys.D* 27 (2018) 14, 1846002. e-Print:1804.07162

The cosmological constant problem

$$\mathbf{R}_{ab} - \frac{1}{2} g_{ab}\mathbf{R} = 8\pi \mathbf{T}_{ab} - \Lambda g_{ab}$$

$$\Lambda_{\rm obs} \approx 1.19 \ 10^{-52} \ \mathrm{m}^{-2}$$

How does the vacuum gravitate?

$$\langle \mathbf{T}_{ab} \rangle = \frac{\Lambda_{vac}}{8\pi G} \ g_{ab}$$

$$\rho_{vac} \equiv \frac{\Lambda_{vac}}{8\pi G} \approx m_p^4$$

$$\rho_{\Lambda_{obs}} \approx 10^{-120} m_p^4 \approx (10^{-2} eV)^4$$

The field equations emerging from discreteness are expected to be the trace-free Einsteins equations

$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab}\mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab}\mathbf{T} \right)$$

being pure trace vacuum energy does not gravitate

A model predicting the observed cosmological constant

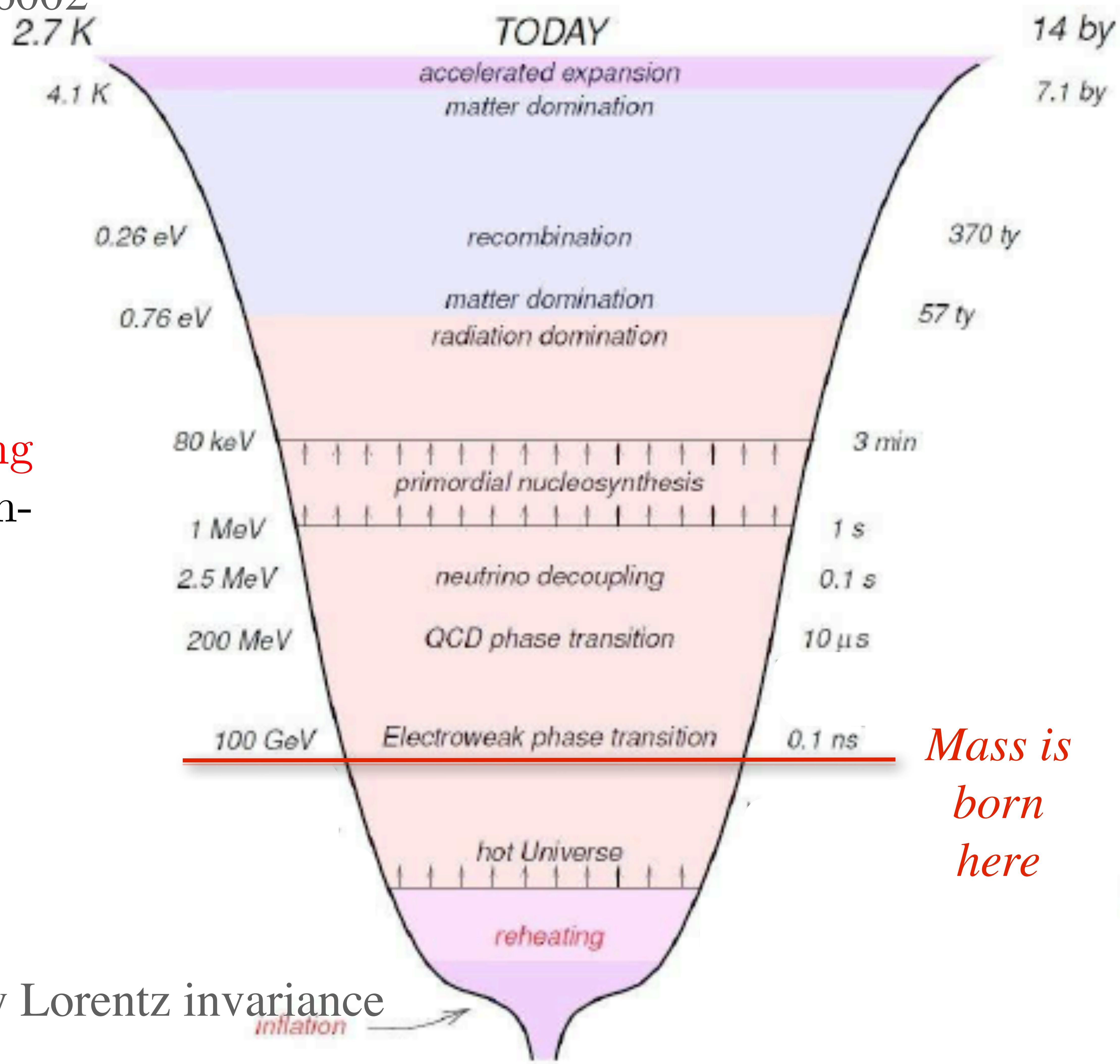
T. Josset, AP and D. Sudarsky, *Phys.Rev.Lett*. 118 (2017) 2, 021102.
AP. D. Sudarsky and J.D. Bjorken *Int.J.Mod.Phys.D* 27 (2018) 14, 1846002
AP and D. Sudarsky, *Phys.Rev.Lett*. 122 (2019) 22, 221302

$$\mathbf{J}_b \equiv (8\pi G)\nabla^a \mathbf{T}_{ab}$$

$$\mathbf{R}_{ab} - \frac{1}{2}\mathbf{R}g_{ab} = 8\pi\mathbf{T}_{ab} - \underbrace{\left[\Lambda_0 + \int_\ell \mathbf{J}\right]}_{\text{Dark Energy } \Lambda} g_{ab}$$

Assuming that the cosmological constant $\Lambda = 0$ at the big-bang then the diffusion effect generates it during the electro-weak transition when massive-spinning particles first appear.

$$\Lambda \approx \gamma \frac{m_t^4 T_{\rm ew}^3}{m_p^7} m_p^2 \approx \gamma \underbrace{\left(\frac{T_{\rm ew}}{m_p}\right)^7}_{\approx 10^{-120}} m_p^2$$



Mass is born here

The model is compatible with the constraints imposed by low energy Lorentz invariance
Collins, AP, Sudarsky, Urrutia, Vusetich;
Phys. Rev. Letters. 93 (2004).

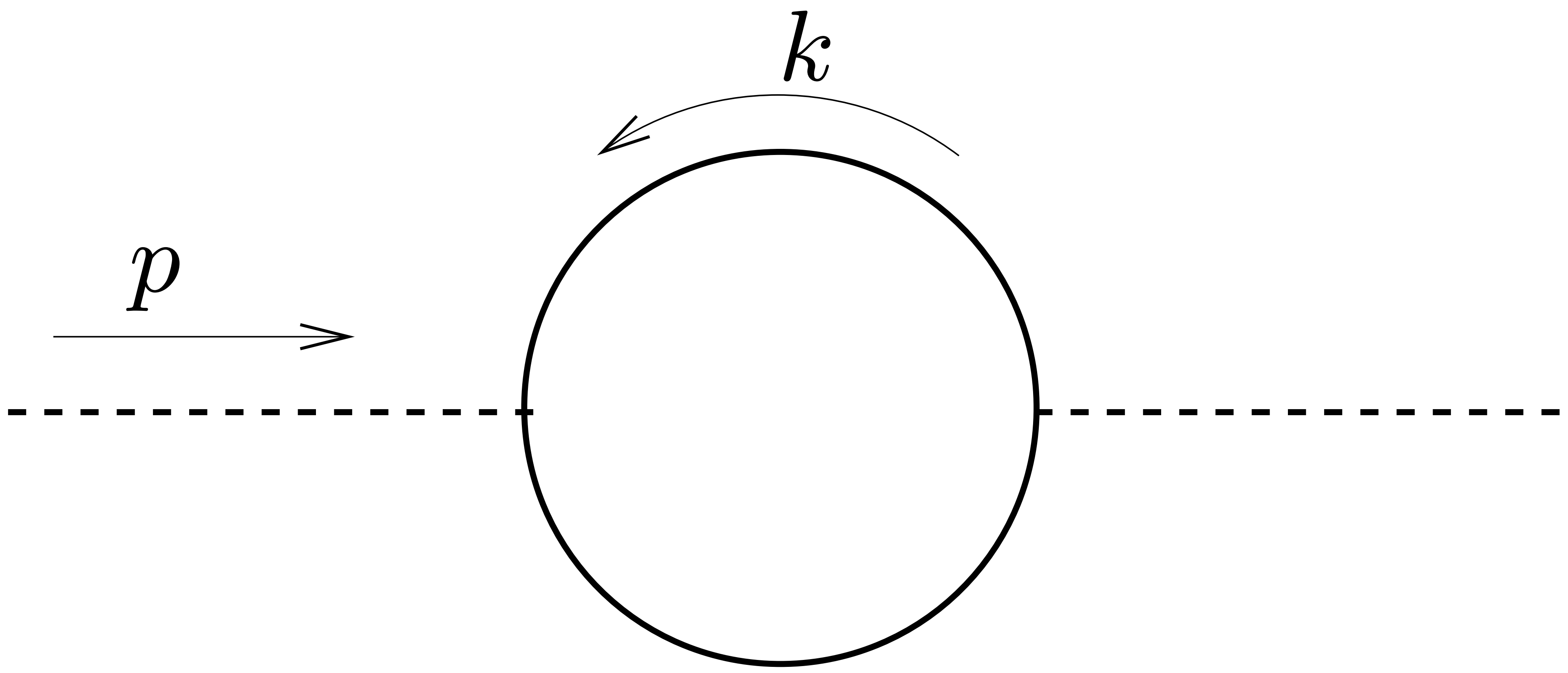
What effects could be observable after the EW era?

Collins, AP, Sudarsky, Urrutia, Vusetich;
Phys. Rev. Letters. 93 (2004).

Lorentz violating operators in EQFT must be suppressed by the scalar curvature. The leading operators dimensionally allowed are:

$$O_1 = \lambda_1 \, \xi^\mu \nabla_\mu \phi \mathbf{R} = \lambda_1 \dot{\phi} \mathbf{R}$$

$$O_2 = \lambda_2 \xi^\mu \bar{\psi} \gamma_\mu \psi \frac{\mathbf{R}}{m_p}$$



Constraints from present experiments and observations

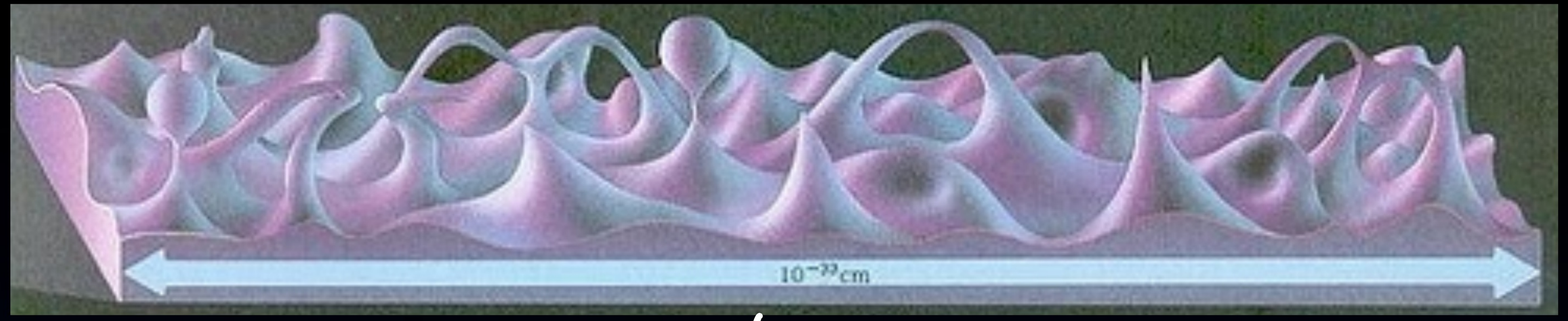
$$T > 10^{-8} T_p = 10^{11} \mathrm{GeV}$$

V. Alan Kostelecky and Neil Russell. Data Tables for Lorentz and CPT Violation. Rev. Mod. Phys., 2011.

Discreteness as a source of primordial inhomogeneities in cosmology

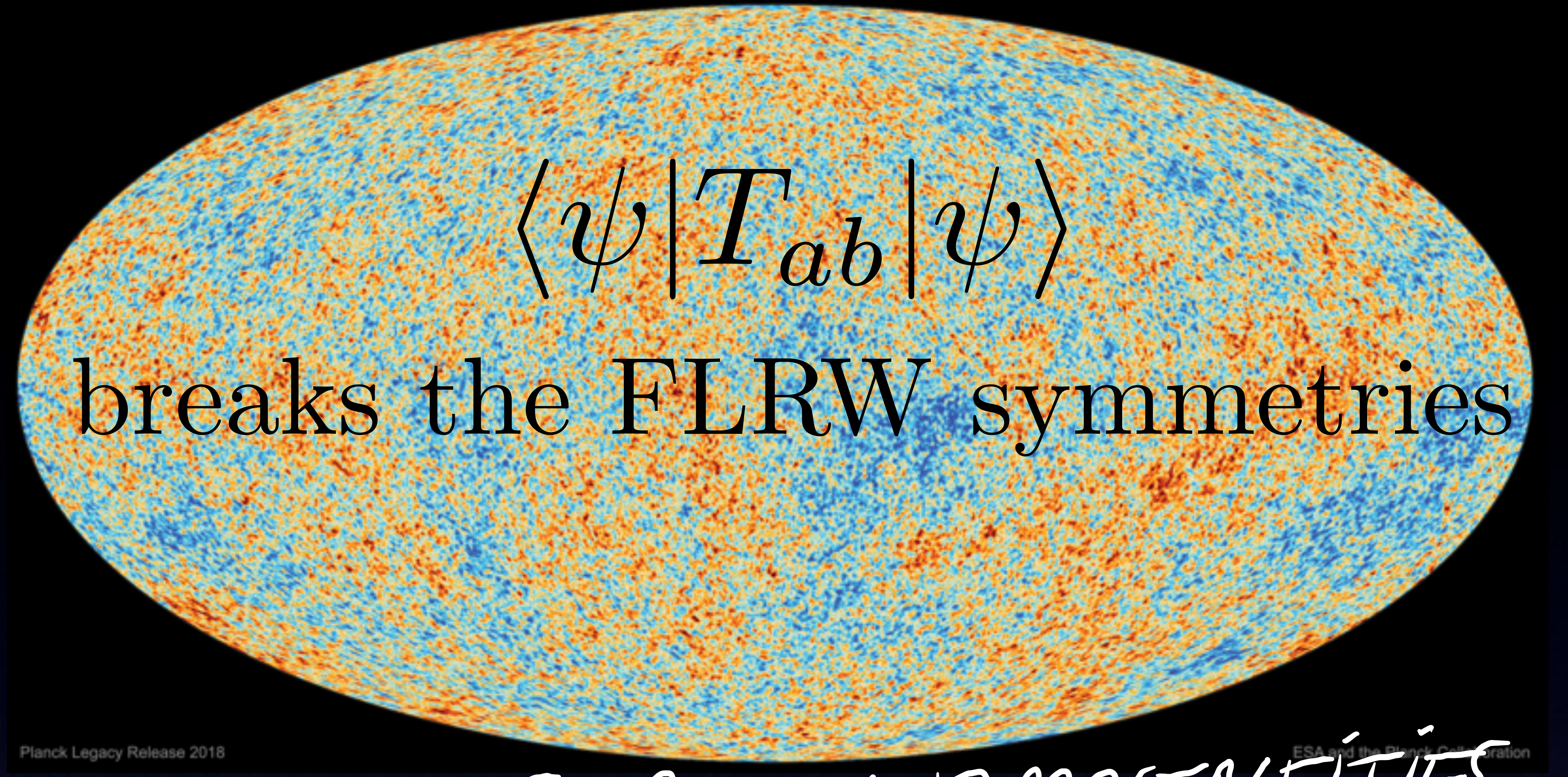
Planckian discreteness as seeds for cosmic structure

L. Amadei, AP. *Phys.Rev.D* 106 (2022) 6, 063528 e-Print: 2104.08881



PLANCKIAN GRANULARITY

INFLATION →



CMB INHOMOGENEITIES

A COSMOLOGICAL MODEL WHERE:

1) THE COSMOLOGICAL CONSTANT DECAYS FROM ITS INITIAL PLANCK SCALE NATURAL VALUE

2) INHOMOGENEITIES IN THE CMB ARISE FROM PLANCKIAN DISCRETENESS

Energy cost of inhomogeneities: Einstein detail balance

We model the production of inhomogeneities by a stochastic process creating fluctuations in a scalar field at the Planck scale during inflation.

$$\delta\ddot{\phi}_k + 3H_0\delta\dot{\phi}_k + \gamma_k\delta\dot{\phi}_k + \frac{k^2}{a^2}\delta\phi_k + \frac{d^2V(\phi_0)}{d\phi^2}\delta\phi_k = \alpha_k\delta(t - t^k_{\rm int})$$

$$\Delta\delta\phi_k = \frac{\alpha_k}{H_0(4+\gamma_k)}$$

$$\langle\delta\phi_{\vec{k}}\delta\phi_{\vec{q}}\rangle = P_{\delta\phi}(k)\delta^{(3)}(\vec{k}+\vec{q}),$$

$$\langle T_{ab}\rangle \equiv \langle T_{ab}(P_{\delta\phi})\rangle$$

The power spectrum of perturbations and the stochastic mean of the energy momentum tensor

Work per unit time necessary to create inhomogeneities

$$\frac{dW^{\rm pert.}(P_{\delta\phi})}{da} = \text{stochastic source}$$

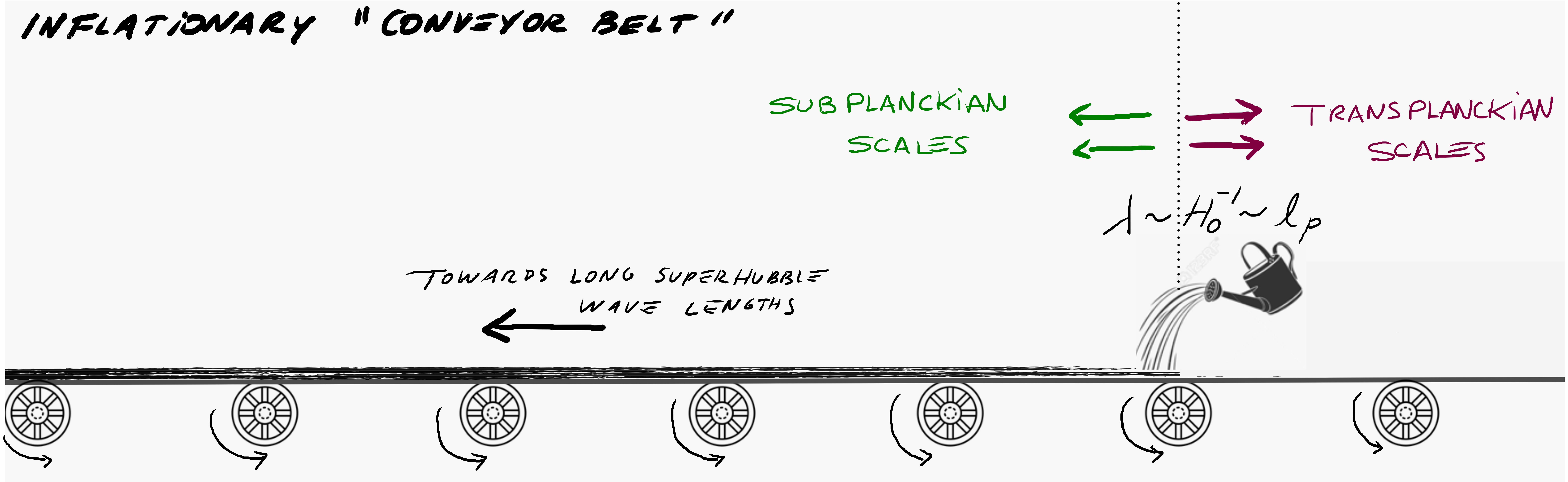
Solving detail balance

$$\frac{dW^{\text{pert.}}(P_{\delta\phi})}{da} = \text{stochastic source}$$

$$\frac{dW^{\text{pert.}}(P_{\delta\phi})}{da} \equiv \frac{d\left\langle \delta\rho^{(2)}\right\rangle}{da} + \frac{2}{a}\left\langle \delta\rho^{(2)}\right\rangle - \frac{1}{a}\frac{d^2V(\phi_0)}{d\phi^2}\left\langle \delta\phi^2\right\rangle = \gamma\frac{H^4}{a}$$

The stochastic source is assumed to be driven by the local geometry (the Hubble rate during inflation)

$$P_{\delta\phi}(k) = \frac{P_0}{k^3} \qquad P_0 = 4\pi^2\gamma\frac{H_0^3}{m_p}$$



Assuming the standard model matter content and natural initial conditions!

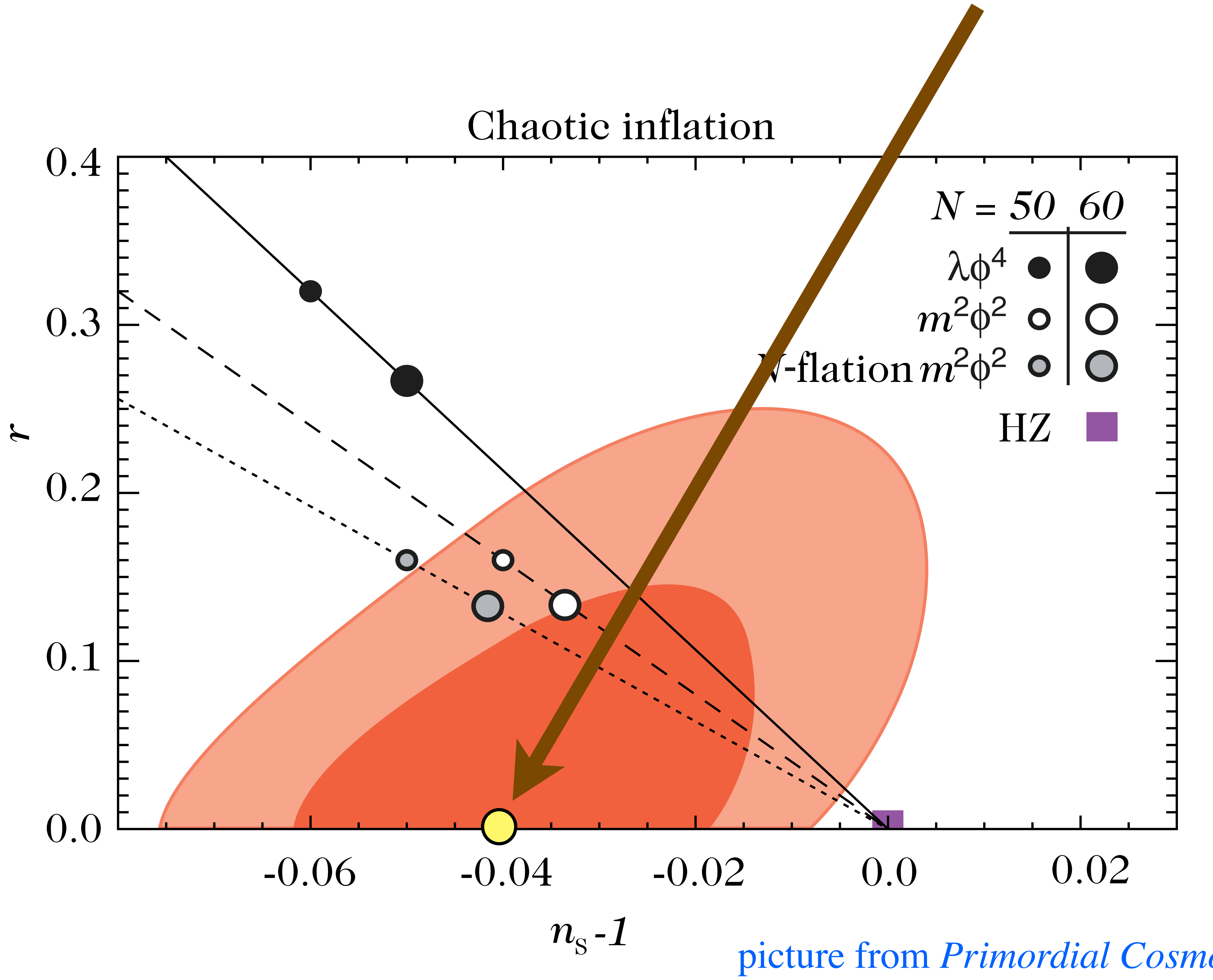
$$n_{\rm s} - 1 \equiv \frac{d\log(k^3 P_{\mathcal{R}})}{d\log k} \approx 4\lambda + \mathcal{O}\left[\lambda^2 \log\left(\frac{k_{\max}}{k_0}\right)\right]$$

Planck, Y. Akrami et al., "Planck 2018 results. X. Constraints on inflation," Astron. Astrophys. 641 (2020) A10, arXiv: 1807.06211.

$$\left.\begin{aligned} dn_{\rm s}/d\ln k &= -0.0045 \pm 0.0067, \\ n_{\rm s} &= 0.9641 \pm 0.0044, \\ n_{\rm s,0.002} &= 0.979 \pm 0.021, \end{aligned}\right\} \begin{array}{l} 68\,\%, \text{TT,TE,EE} \\ \text{+lowE+lensing,} \end{array}$$

$$\left.\begin{aligned} dn_{\rm s}/d\ln k &= -0.0041 \pm 0.0067, \\ n_{\rm s} &= 0.9659 \pm 0.0040, \\ n_{\rm s,0.002} &= 0.979 \pm 0.021, \end{aligned}\right\} \begin{array}{l} 68\,\%, \text{TT,TE,EE} \\ \text{+lowE+lensing} \\ \text{+BAO,} \end{array}$$

Our model



picture from *Primordial Cosmology, P. Peter, P. Uzan, CUP (2009)*

Running of the spectral index

$$\frac{dn_{\rm s}}{d\log k} = -0.0005 + \mathcal{O}(\lambda^3).$$

Nearly vanishing tensor to scalar ratio

$$r \approx 0$$

Dark matter as primordial Planckian BHs

At the end of the inflationary era reheating raises the temperature to close to the Planck temperature and Planck mass remnants could be created via thermal fluctuations if thermal equilibrium density is achieved. In order for this to happen one needs the remnant interaction rate $\Gamma_{\rm pbh} > H$, where the interaction rate is given by $\Gamma = n\sigma v$ with n the number density, σ the interaction cross section, and v the velocity. For remnants of mass $m_{\rm pbh}$ the interaction cross section is $\sigma_{\rm pbh} \approx m_{\rm pbh}^2/m_p^4$ while their number density n while in thermal equilibrium goes like $n \approx T^3$. Using that in the radiation dominated era $H \approx (T/m_p)T$, we conclude that remnants decouple from thermal equilibrium when

$$T \lesssim \frac{m_p^2}{m_{\rm pbh}^2} m_p \equiv T_{\rm D}.$$

If thermal equilibrium can hold up to $T_{\rm D} \lesssim T_{\rm end}$ then the thermal remnant abundance of dark matter today can be estimated to be about (see equation 4.38 in Peter-Uzan)

$$\frac{\rho_{\rm pbh}^{\rm thermal}(T_{\rm D})}{m_p^4} \approx \left(\frac{m_{\rm pbh}}{m_p}\right)^4 \left(\frac{T_{\rm today}}{T_{\rm D}}\right)^3 \left(\frac{T_{\rm D}}{m_{\rm pbh}}\right)^{\frac{3}{2}} e^{-\frac{m_{\rm pbh}}{T_{\rm D}}}.$$

One can easily check that it is possible to obtain a remnant density compatible with dark energy density today—which would correspond to evaluating the previous line to about 10^{-120}—with a $m_{\rm pbh}$ slightly larger than but of the order of m_p. This shows that the framework provided by our model could also fit dark energy genesis from the production of stable PBHs via thermal fluctuations at the end of the De Sitter phase without extreme fine tuning where the necessary suppression is brought by the standard Gibbs factor. After completion of this work we discovered that very similar arguments are put forward in A. Barrau, K. Martineau, F. Moulin, and J.-F. Ngono, "Dark matter as Planck relics without too exotic hypotheses," Phys. Rev. D **100** (2019), no. 12, 123505, arXiv:1906.09930.

Discussion

1. Loop Quantum Gravity predicts discreteness of spacetime geometry at the Planck scale (*Rovelli-Smolin*).

2. The anomaly free quantization of the Hamiltonian operator defining the dynamics of LQG has been recently shown to exist (*Varadarajan M. 2022*). Although procedure reduces ambiguities some seem to remain.

3. Solution of the quantum dynamics remains a difficult challenge. The path integral or spin foam formulation is defined to address this question (some interesting points: contact with classical limit on fixed lattices; numerics is developing fast).

4. Open hard problems in LQG: The continuum limit (*E. Bianchi, B. Dittrich, ...*), dynamics (spin-foams, *S. Speziale, M. Han,...*), fundamental observables (*L. Freidel, J. Lewandowski, T. Thiemann, K. Giesel,...*), inclusion of matter...

Interesting phenomenology

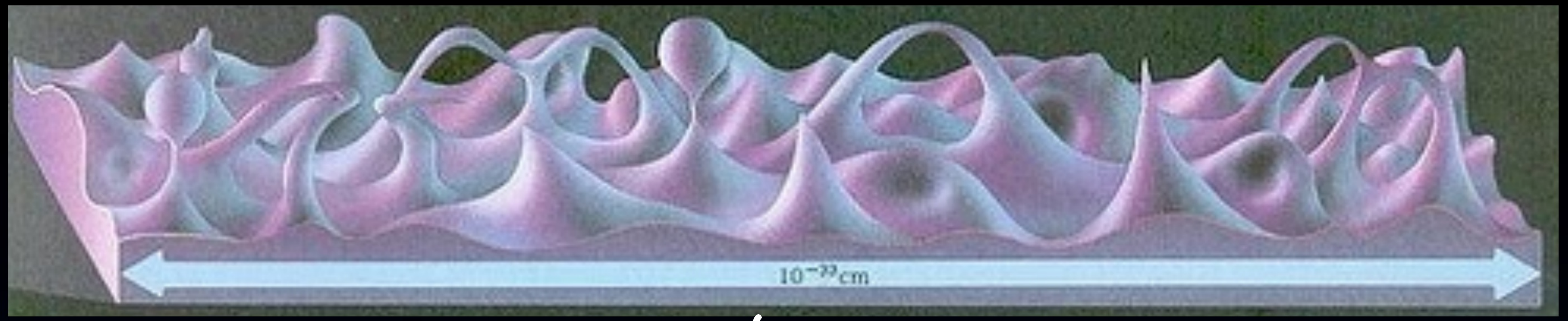
1. Discreteness opens the way for a fundamental account of black hole entropy. The approach of LQG is fundamentally **not** holographic. This avoids contradictions with standard QFT and GR in the regimes where we expect both to be valid approximations (e.g. the firewall problem).

2. The resolution of information problem requires dynamics across the singularity. Discreteness of LQG regularises singularities (in models of cosmology (*Ashtekar, Bojowald, Singh,...*) and BH collapse (*Ashtekar, Rovelli, Pullin, ...*)).

3. Decoherence with discrete microstructure is natural and provides a resolution of the information problem. But decoherence implies diffusion; this leads to a simple phenomenological model for an emergent cosmological constant which agrees with observations.

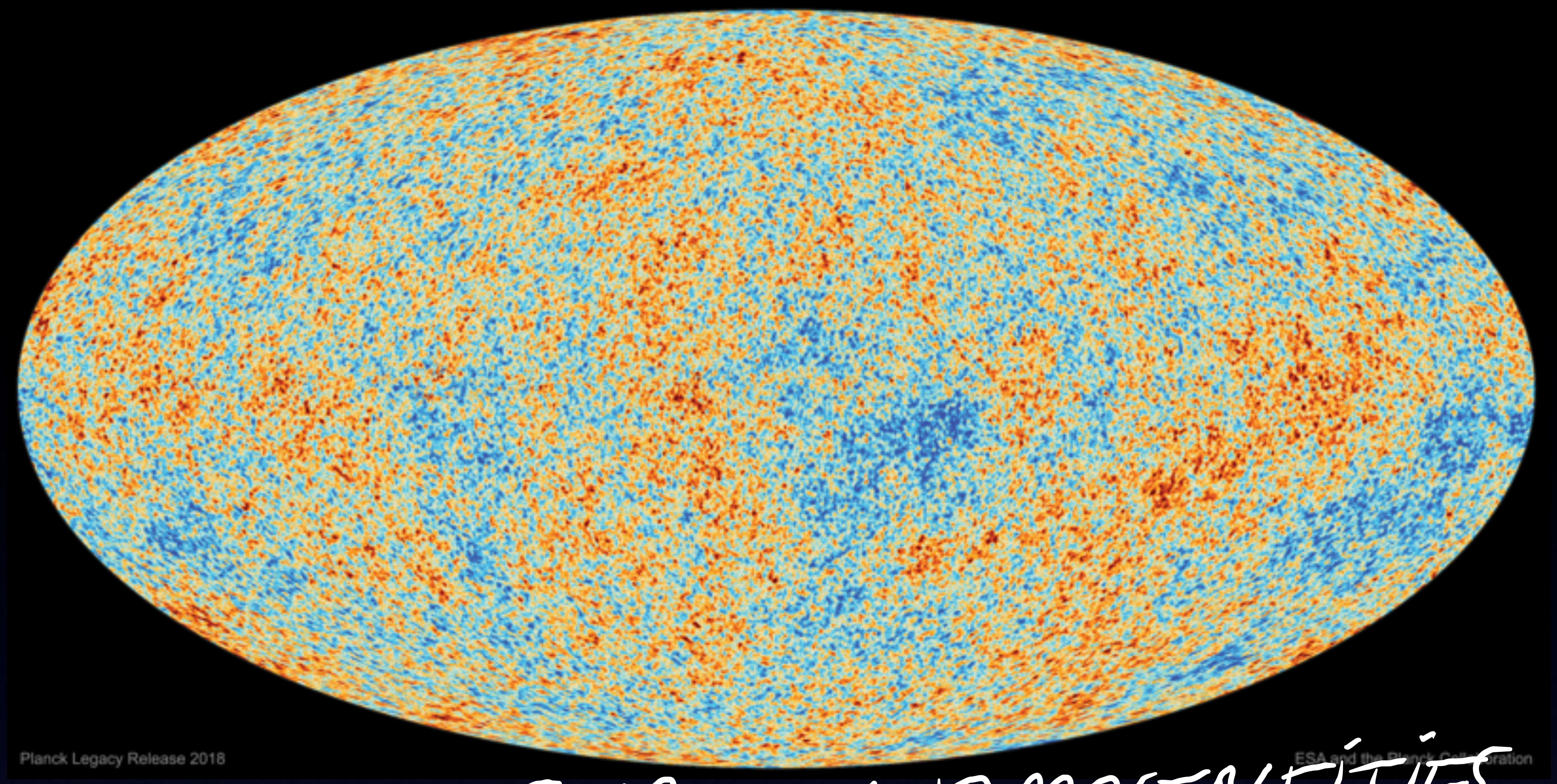
4. Discreteness provides a natural candidate for producing the seeds of structure formation in cosmology (recall trans Planckian issue of standard accounts) where symmetry breaking (inhomogeneities) is fundamentally present at the primordial level (no quantum to classical transition involved).

5. Primordial Planckian black holes (defects) as dark matter candidates.



PLANCKIAN GRANULARITY

INFLATION →



CMB INHOMOGENEITIES

Thank you very much!