Loop Quantum Gravity

Planckian discreteness of spacetime geometry and possible implications

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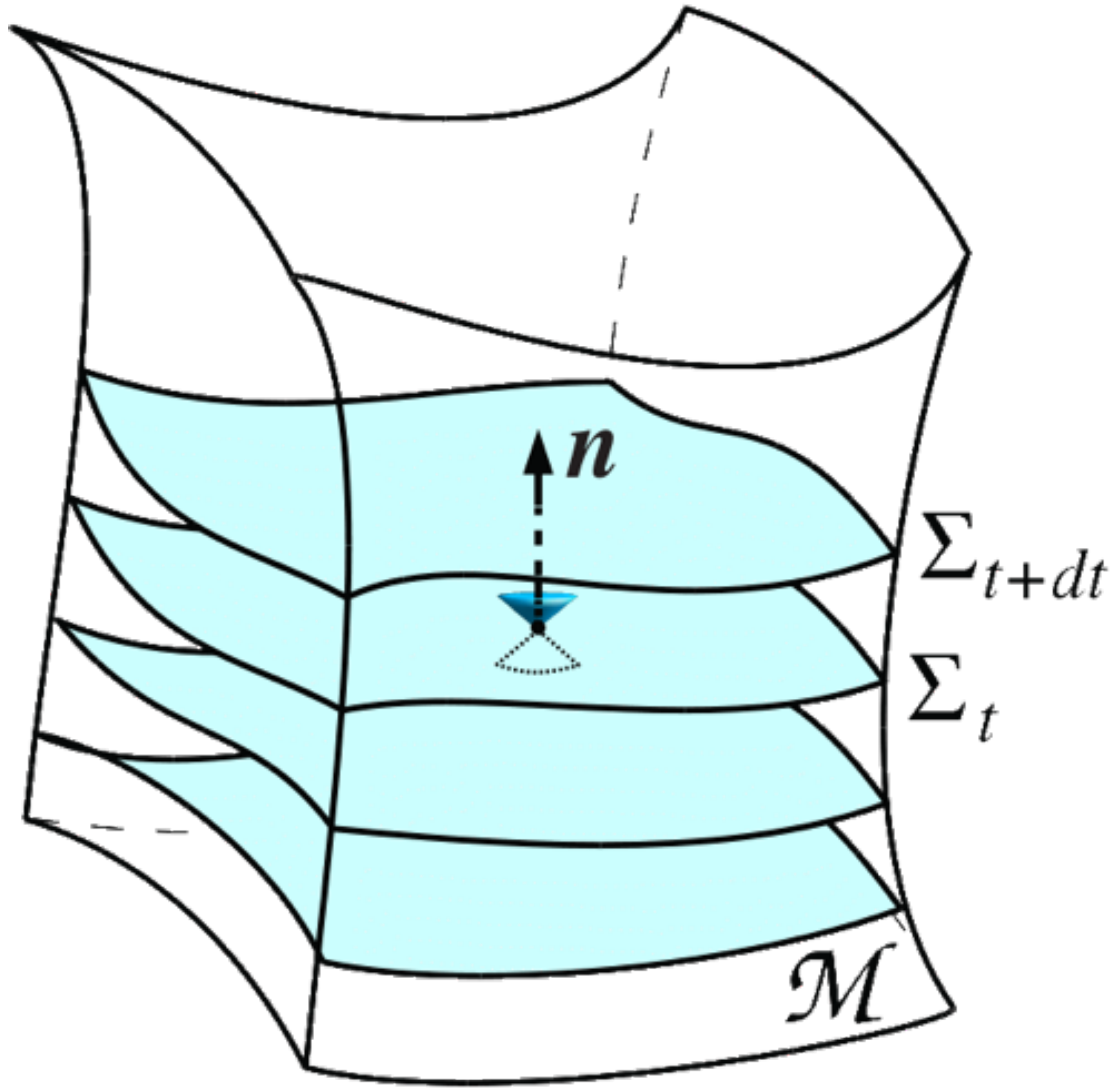
Alejandro Perez
Centre de Physique Théorique,
Marseille, France.

Loop Quantum Gravity
Planckian discreteness in a nut-shell

The phase space of GR in connection variable

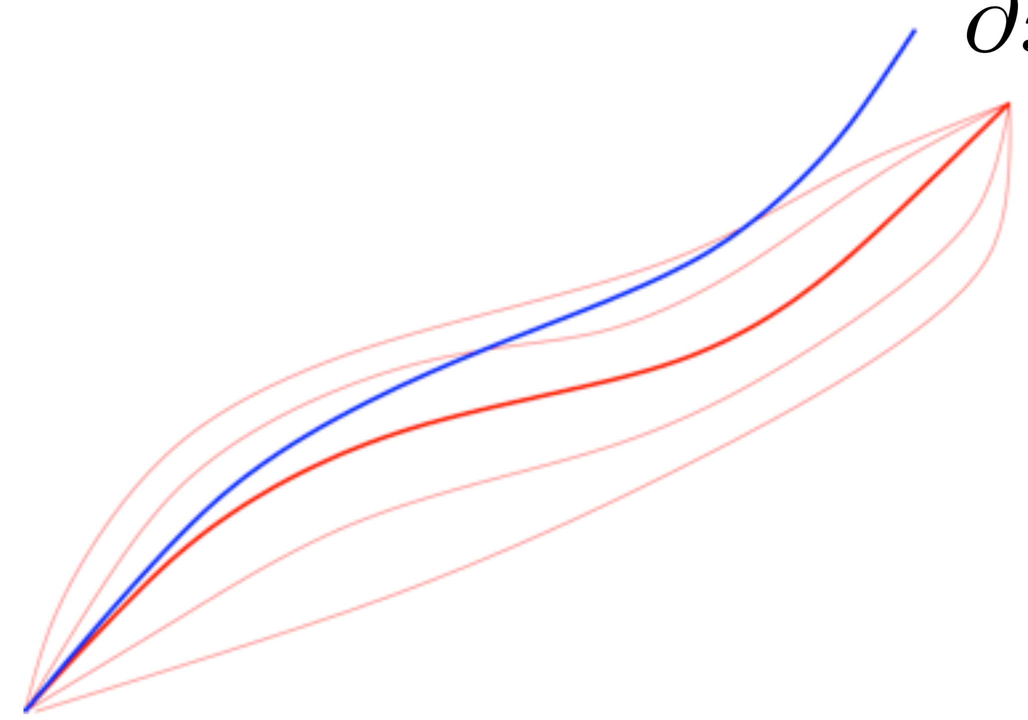


$$\partial M \equiv \Sigma$$

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

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

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

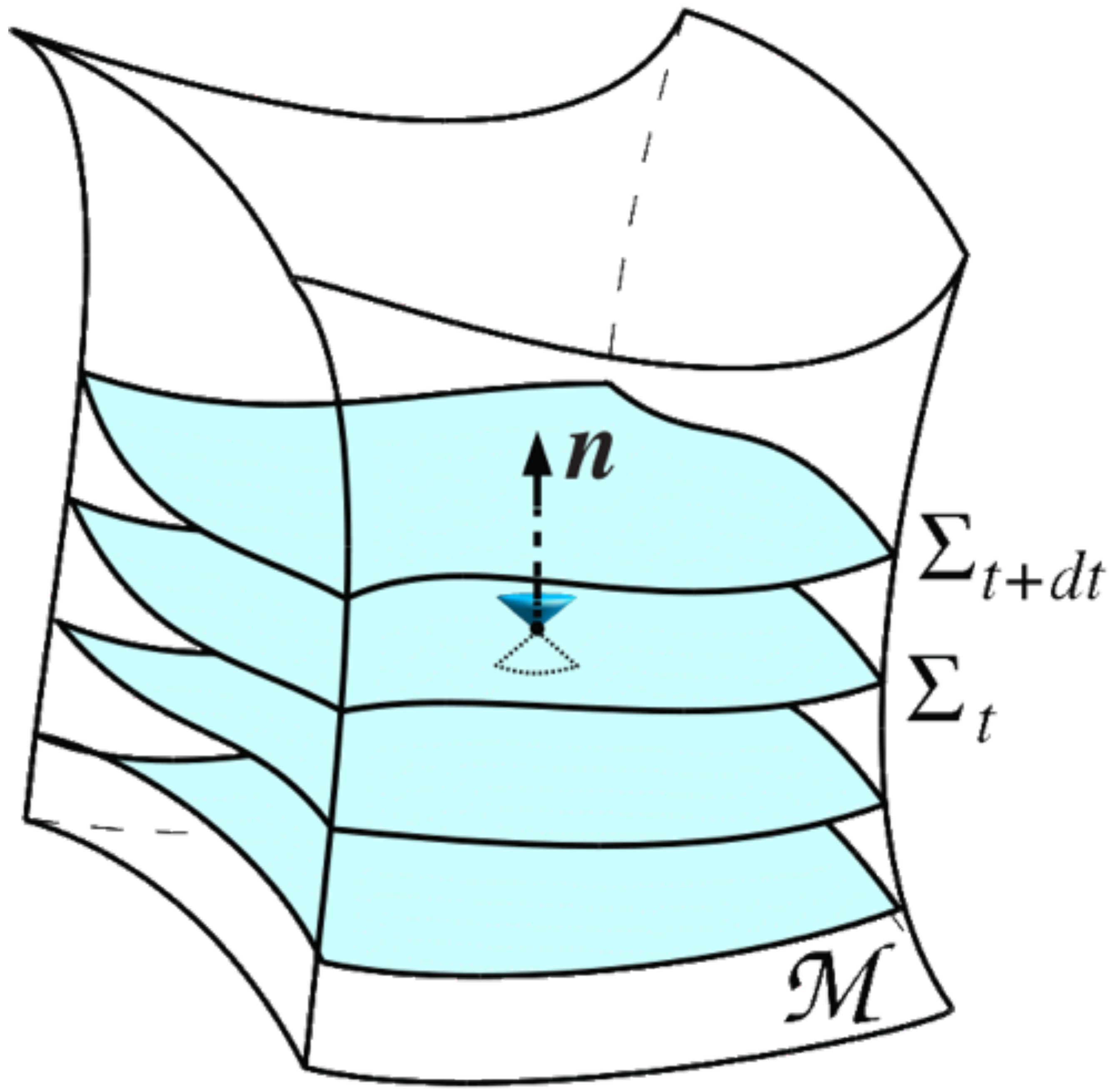


The symplectic potential

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

The phase space of GR in connection variables

A. Ashtekar, PRL 57 (1986)



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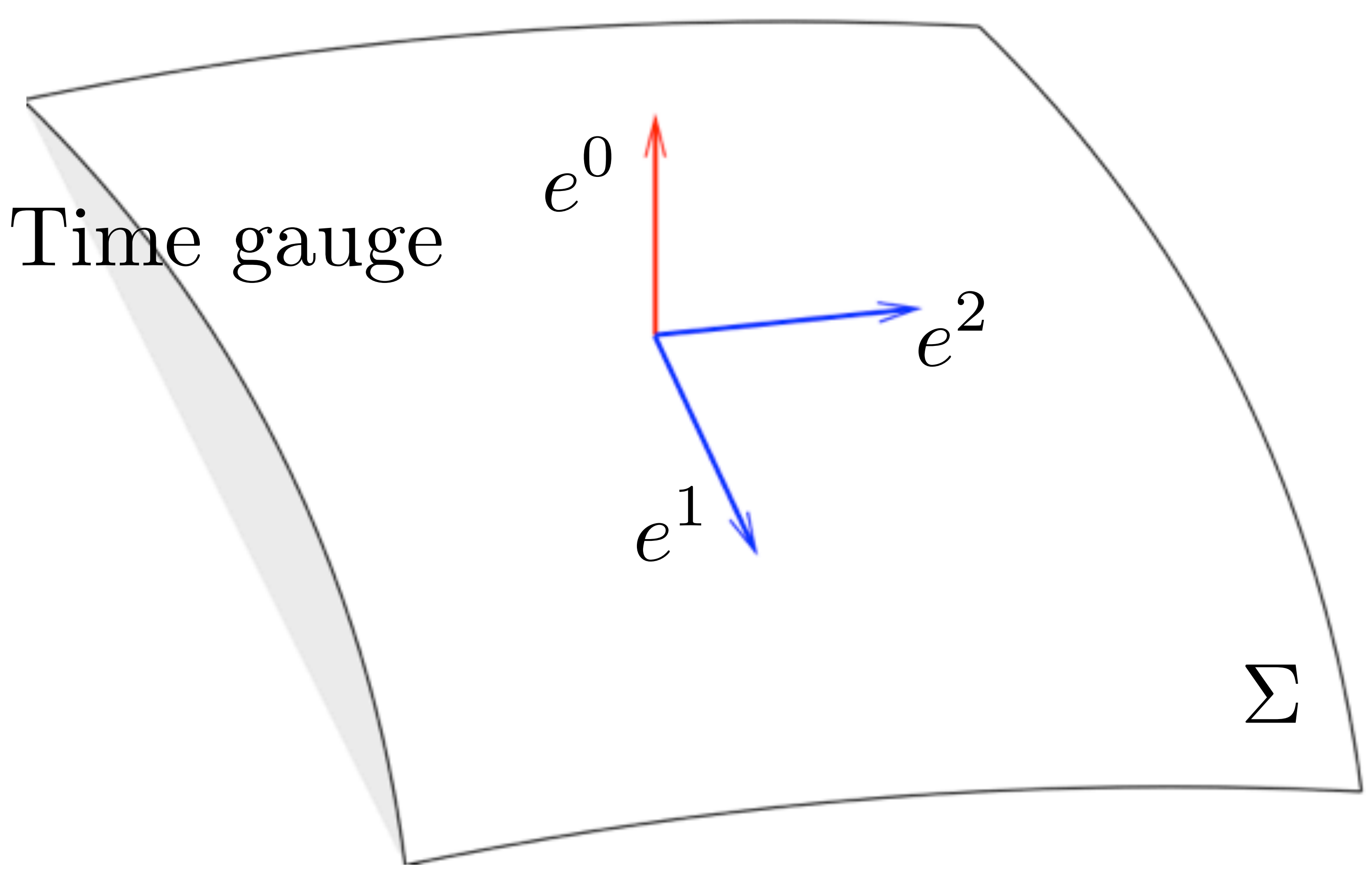
&= \int_M 2\delta e^I \left(\epsilon_{IJKL} \wedge e^K \wedge F^{KL}(\omega)\right) - \left(d_\omega(\epsilon_{IJKL} e^I \wedge e^K)\right) \wedge \delta\omega^{KL} \\
&+ \int_{\partial M} (\epsilon_{IJKL} e^I \wedge e^K) \wedge \delta\omega^{KL}
\end{aligned}$$

$$\partial M \equiv \Sigma$$

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

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

Une transformation canonique

pour retrouver les variables de connexion

$\gamma \equiv$ Immirzi parameter

The symplectic potential

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

Une transformation canonique
pour retrouver les variables de connexion

$\gamma \equiv$ Immirzi parameter

The spin connection

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

The symplectic potential

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

Une transformation canonique

pour retrouver les variables de connexion

$\gamma \equiv$ 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

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

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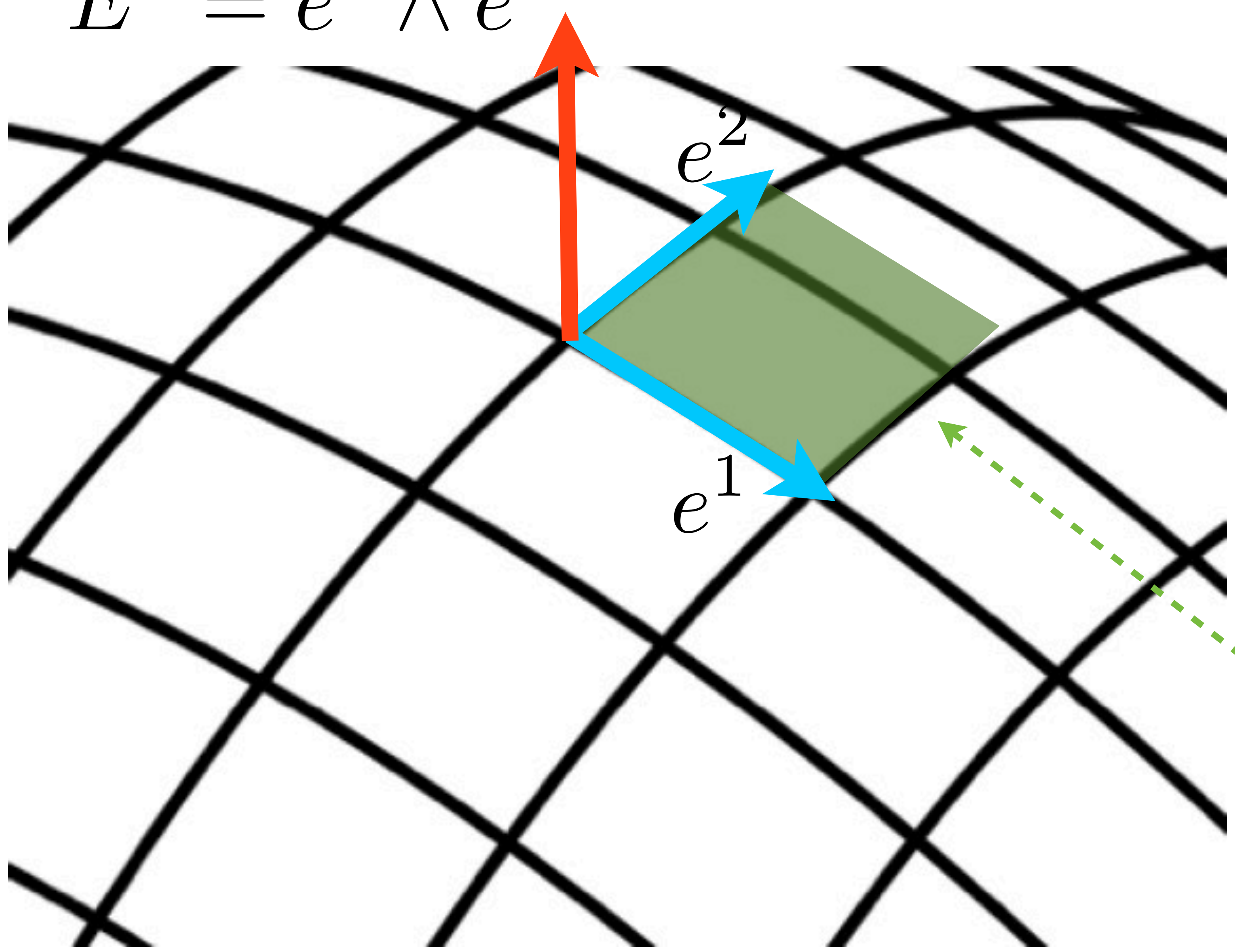
&= \frac{1}{\gamma}\int_\Sigma (\epsilon_{ijk} e^i \wedge e^j) \wedge \delta A^k - \frac{1}{\gamma}\int_{\partial\Sigma} e^i \wedge \delta e^i
\end{aligned}$$

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

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

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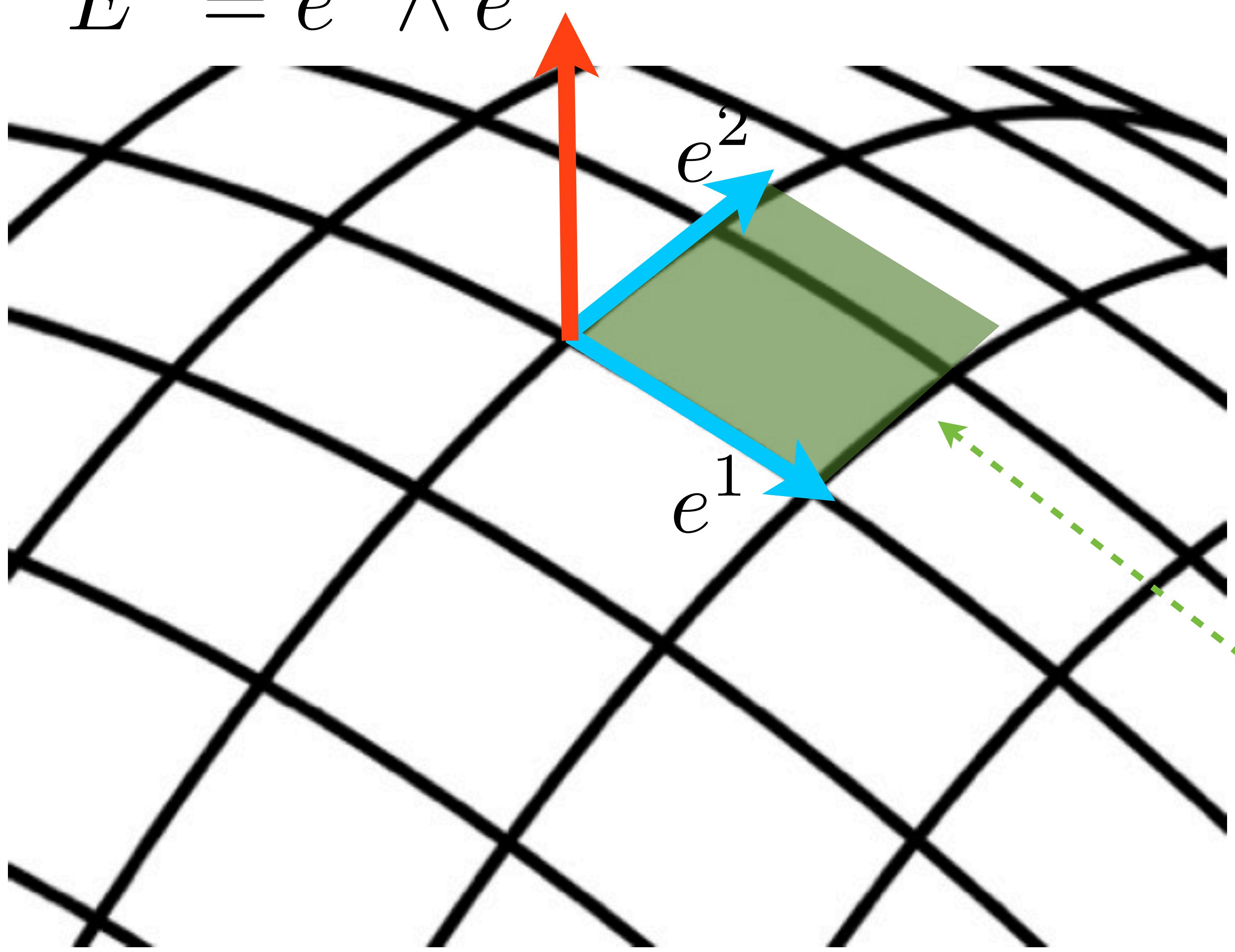

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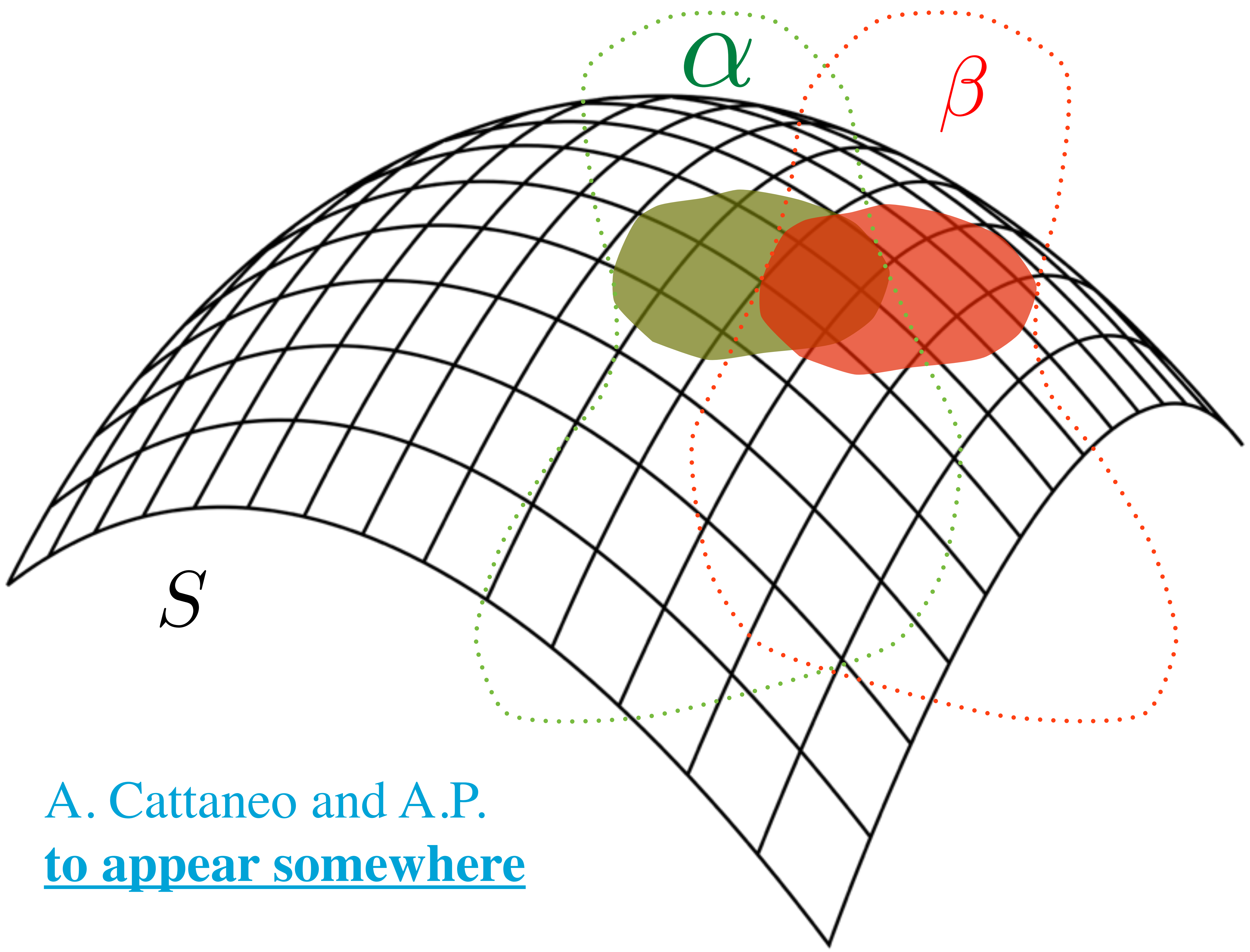
$$\{E^i(x), E^j(y)\} = \epsilon_{ijk} E^k \delta^{(2)}(x,y)$$

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

Quantization of area in a nut-shell



$$E(\alpha, S) = \int_S \alpha^i e^j \wedge e^k \epsilon_{ijk}$$

$$\begin{aligned} E(\alpha, S) &\equiv \int_S \mathrm{Tr}[\alpha E] \\ &= \int_{\mathrm{Int}(S)} d(\mathrm{Tr}[\alpha E]) \\ &= \int_{\mathrm{Int}(S)} (\mathrm{Tr}[d_A(\alpha) E] + \mathrm{Tr}[\alpha\, d_A(E)]) \\ &= \int_{\mathrm{Int}(S)} \mathrm{Tr}[(d\alpha + [A, \alpha])E] \end{aligned}$$

A. Cattaneo and A.P.
to appear somewhere

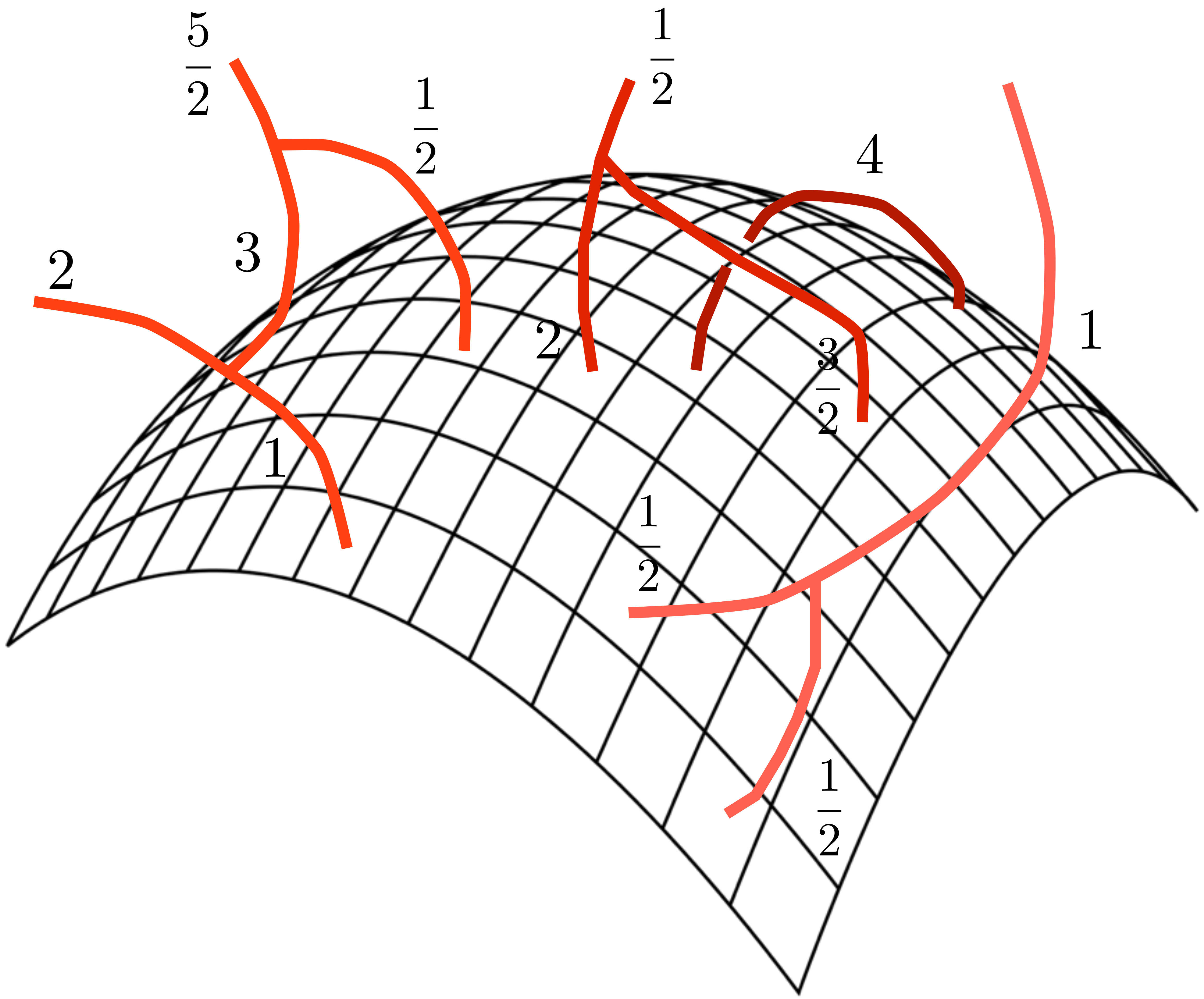
$$\{E(\alpha, S), E(\beta, S)\} = \int_{\mathrm{Int}(S)} \int_{\mathrm{Int}(S)} \{\mathrm{Tr}[(d\alpha + [A, \alpha])E], \mathrm{Tr}[(d\beta + [A, \beta])E]\}$$

$$\boxed{\{E(\alpha, S), E(\beta, S)\} = E([\alpha, \beta], S)}$$

Quantization of area

C. Rovelli and L. Smolin. (1995)

A. Ashtekar and J. Lewandowski. (1997)



$\gamma \equiv$ Immirzi parameter

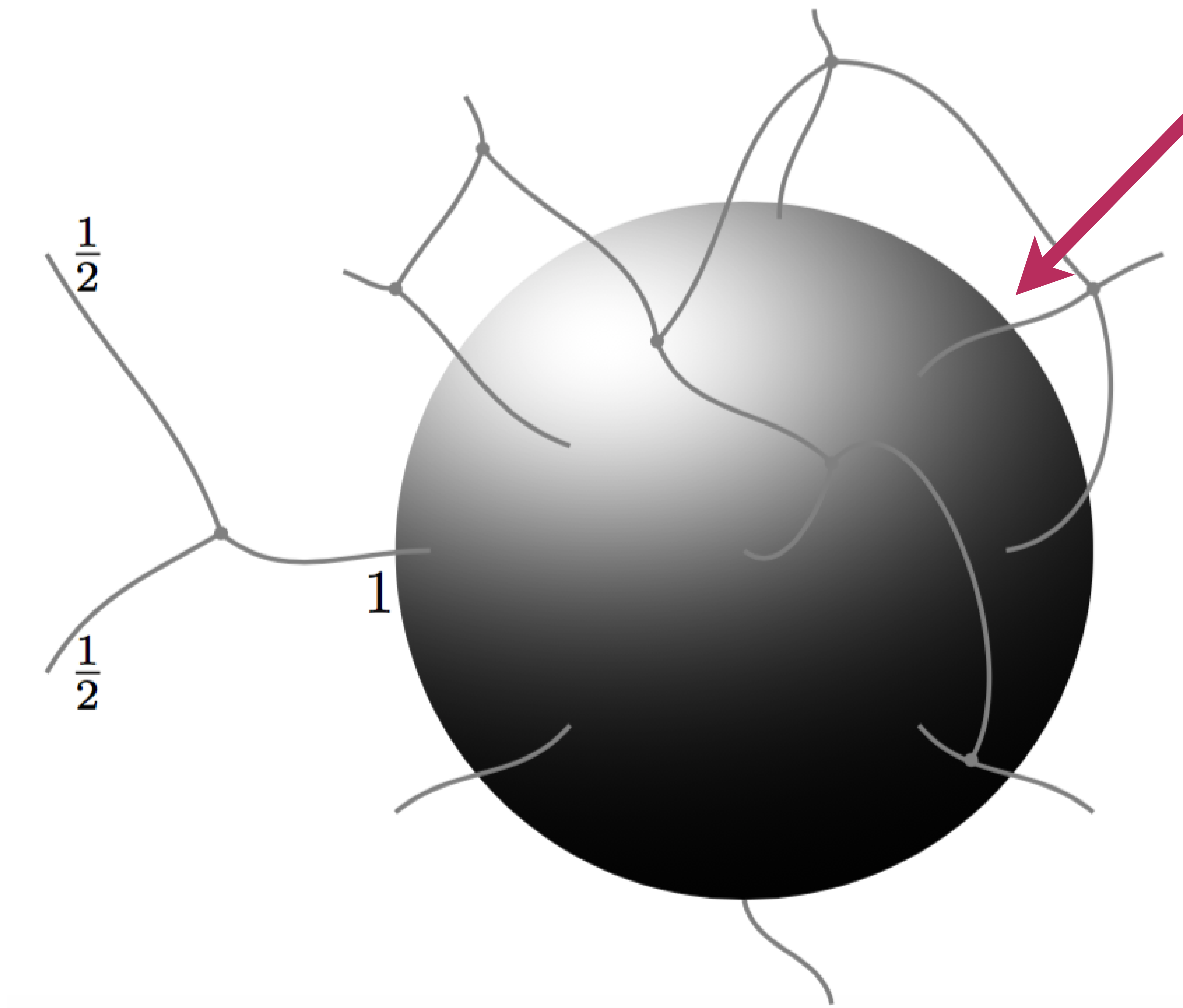
$$\text{area quantum} = \gamma \ell_p^2 \sqrt{j(j+1)}$$

Implications of discreteness
a brief status report

The black hole area spectrum

The area gap

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



Isolated Horizon boundary conditions
Ashtekar et al. (1999)

Boundary DOF described by $SU(2)$ Chern-Simons theory
Engle, AP, Noui, PRL 105 (2010)

Entropy Calculation: the status in few lines

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

Pure quantum geometry approach

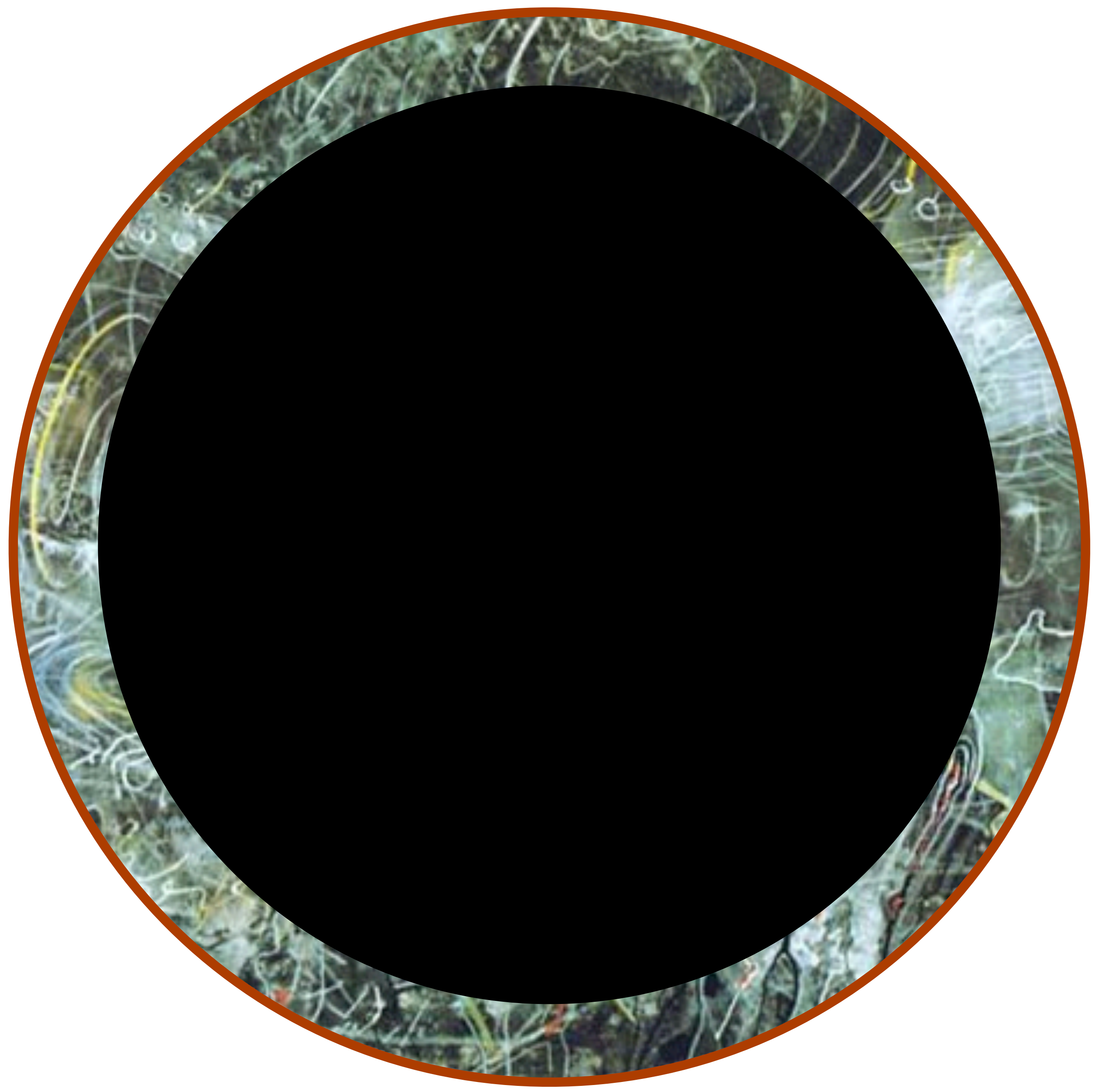
$$S_{bh} = \frac{\gamma_0}{\gamma}\frac{A}{4\ell_p^2}$$

Rovelli (1996),
Ashtekar-Baez-Krasnov-Corichi (1999),
etc

Barbero-Villasenor (2008)

$$\gamma = \gamma_0$$

Taking into account matter excitations



Analysis in standard QFT implies

$$S_{\text{matter}} = \lambda \frac{A}{\epsilon^2} + \text{corrections}$$

λ = undetermined constant due to:
UV regularisation dependence,
the species problem, etc.

ϵ =UV cut-off

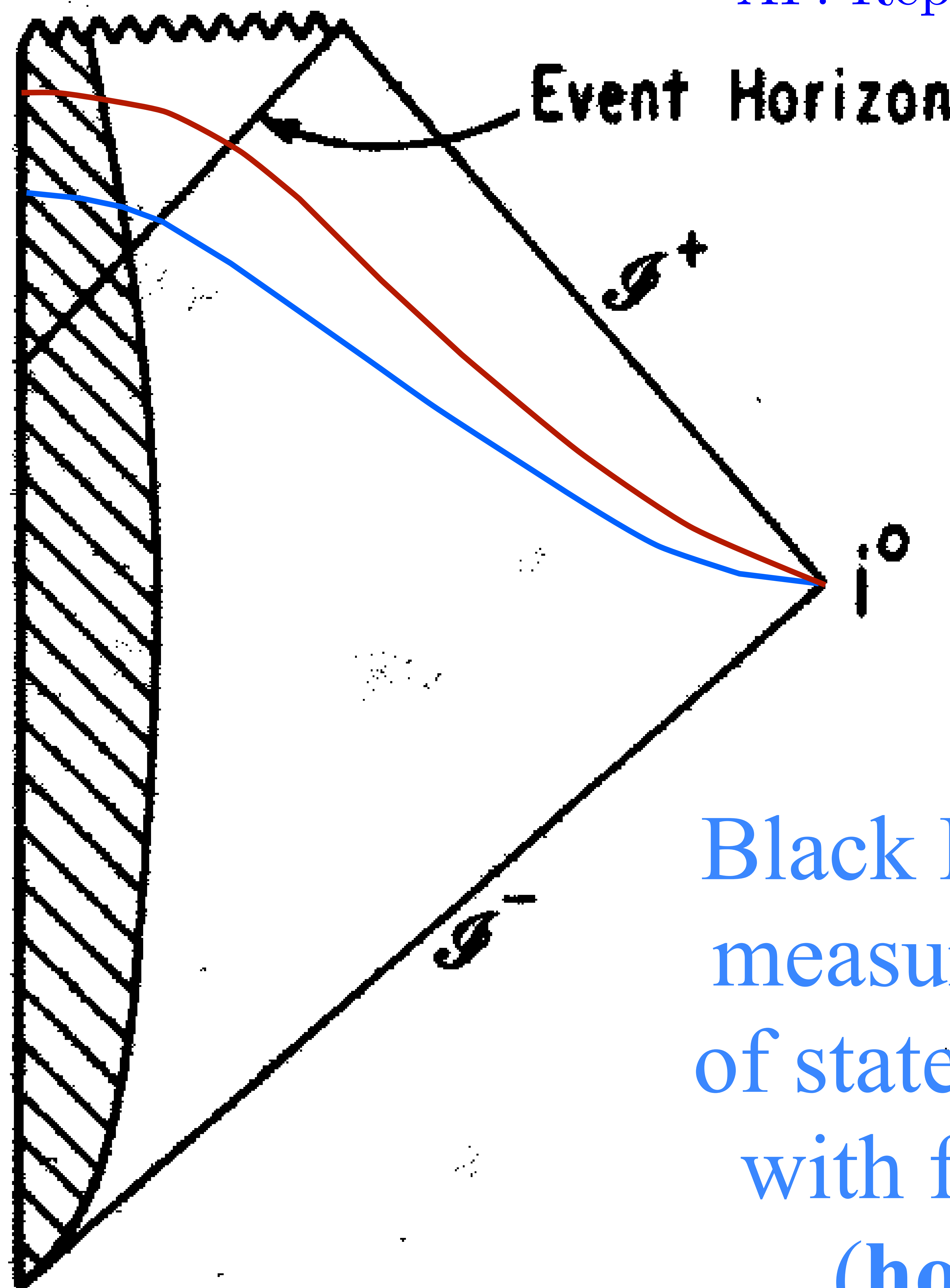
$$S_{bh} = \frac{A}{4G\hbar}$$

Ghosh-Noui-AP, PRD (2014)

Loop Quantum Gravity: a non-holographic approach

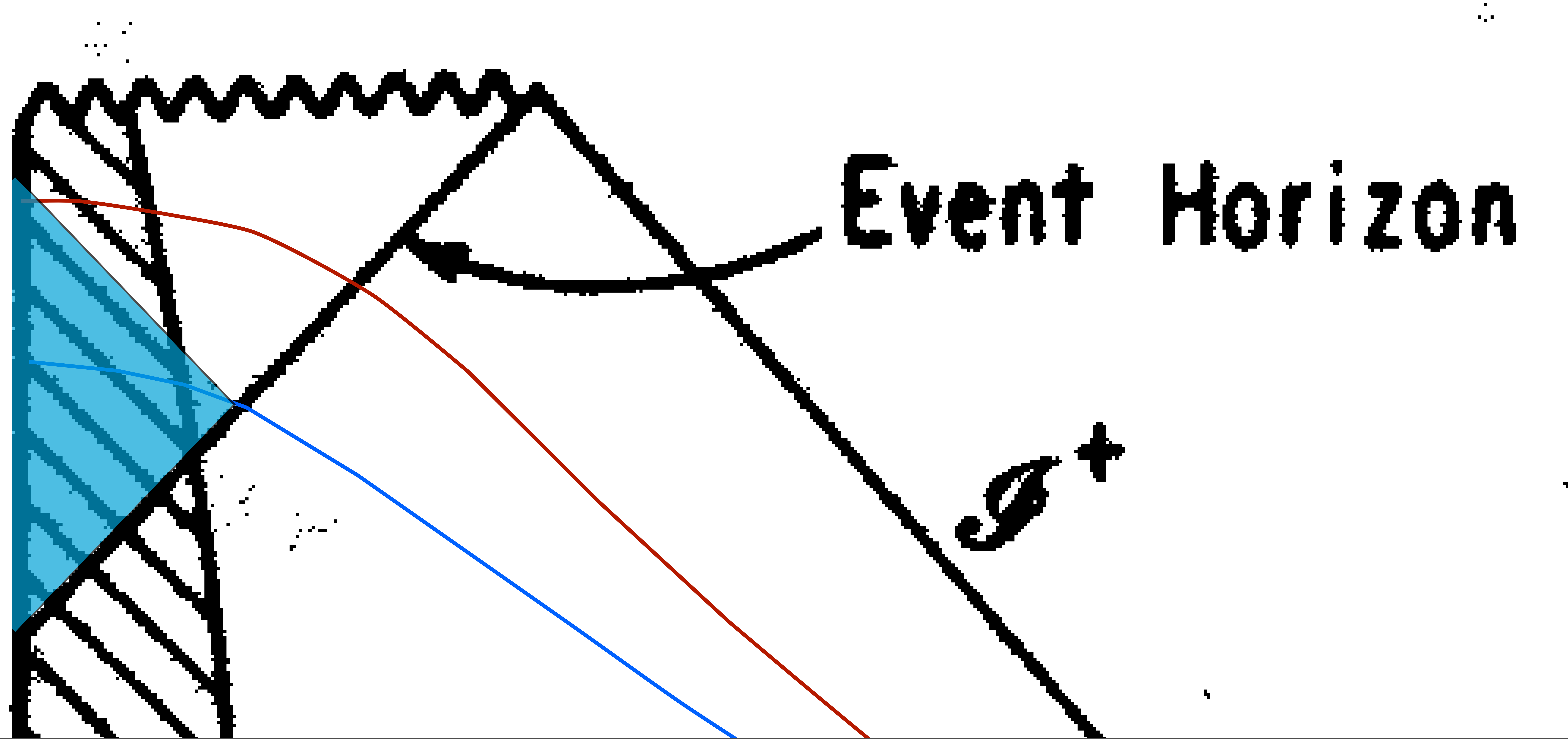
AP. Rept. Prog. Phys. 80 (2017)

Black Hole Entropy **is not** a measure of the number of internal states of a Black Hole

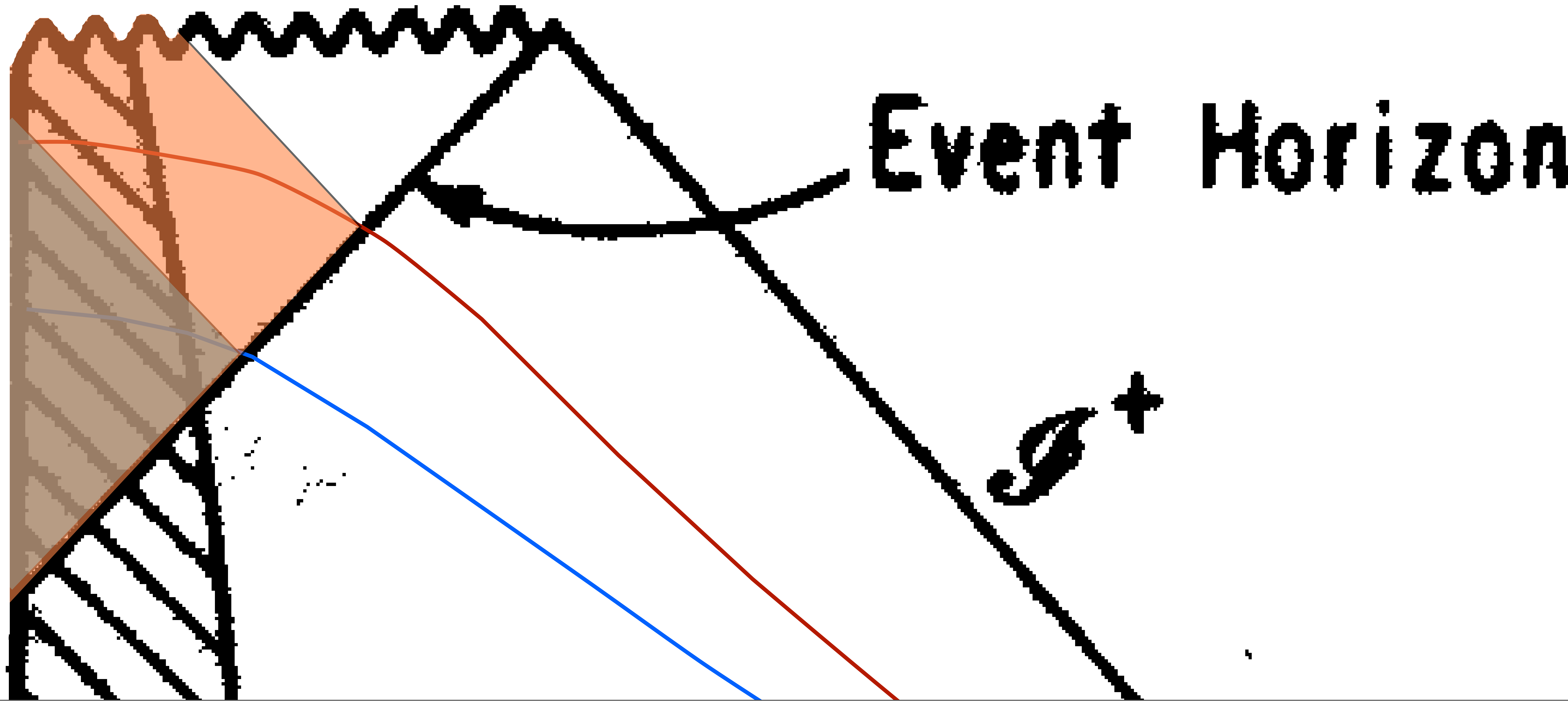


Black Hole entropy **is** a measure of the number of states we can interact with from the outside (**horizon states**)

Loop Quantum Gravity: a non-holographic approach



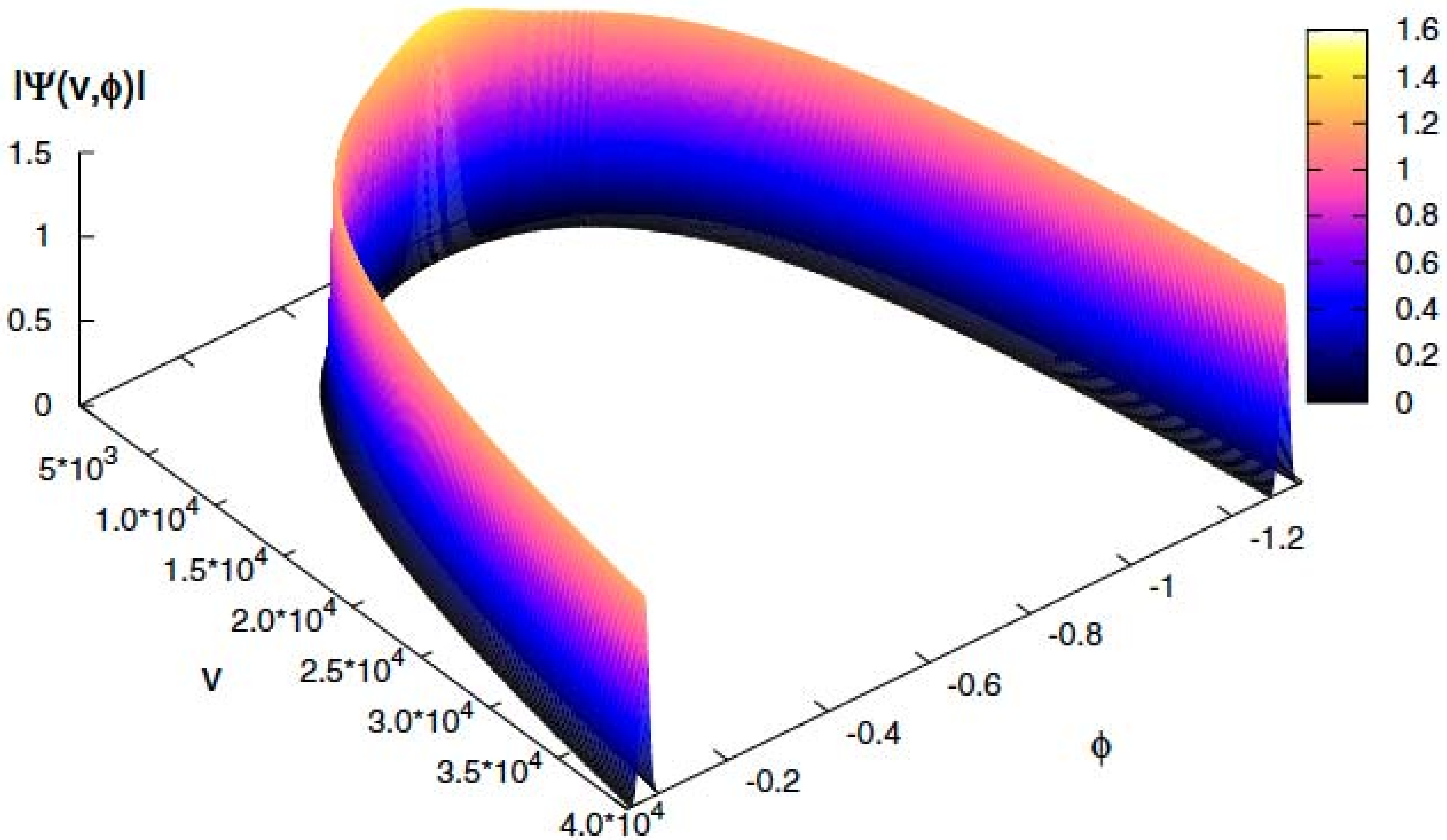
Loop Quantum Gravity: a non-holographic approach

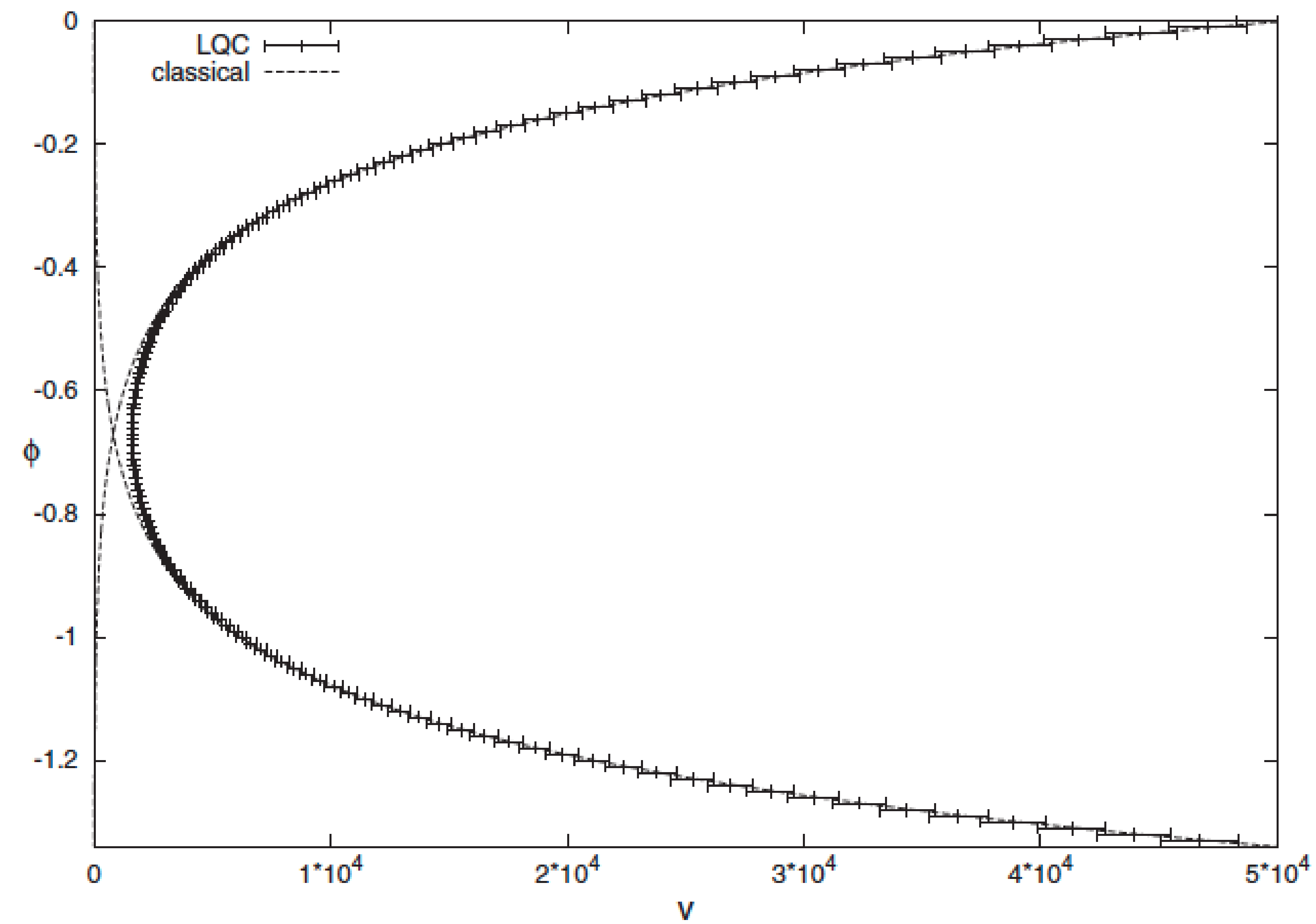


Loop Quantum Gravity: in cosmology

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

Bojowald (2001), Ashtekar, Singh, etc.





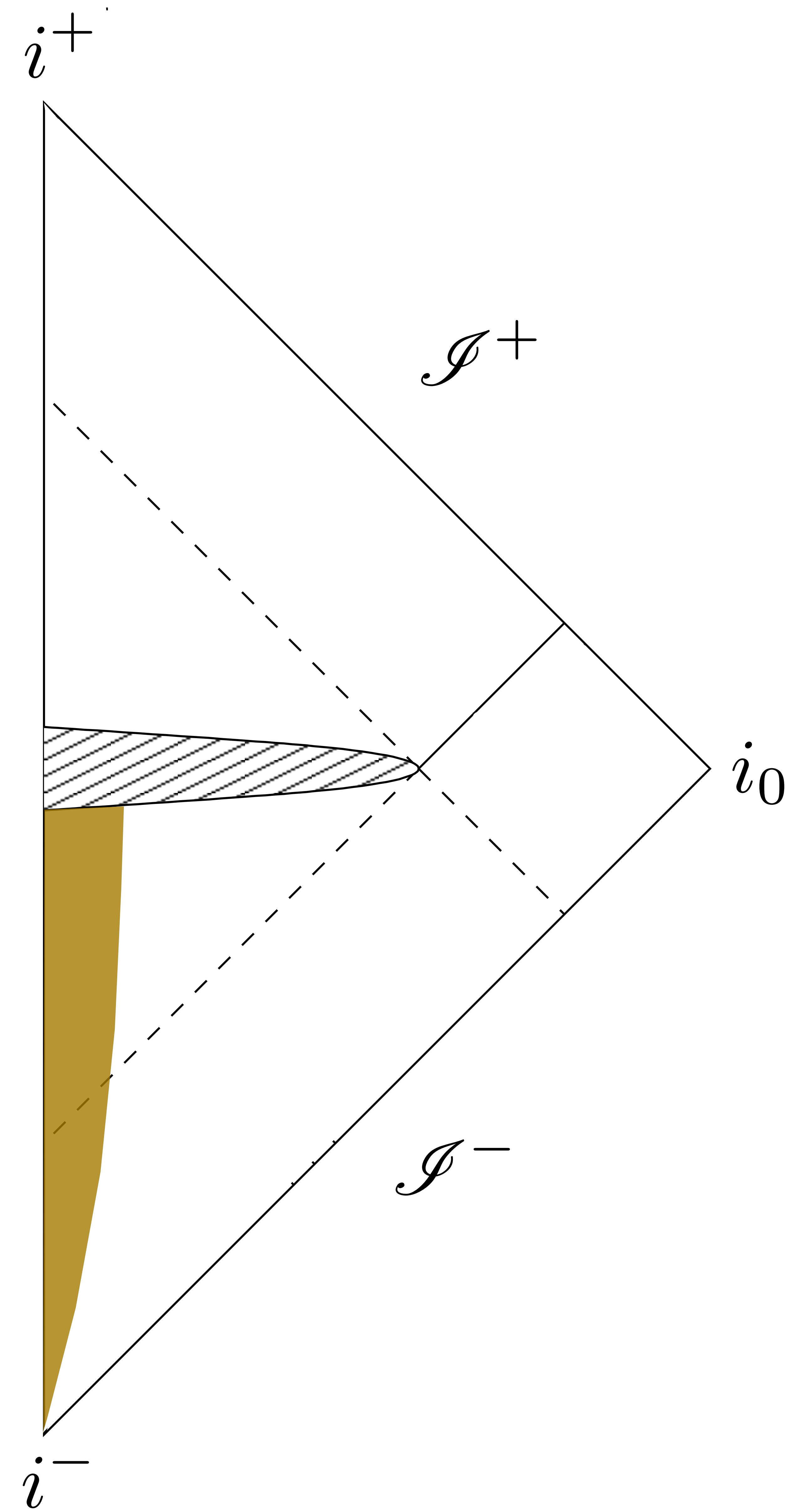
From Ashtekar, Pawlowski, Singh PRD (2006)

Loop Quantum Gravity: collapse, singularities, and information.

There is the expectation that the same would hold for **Black Hole** singularities

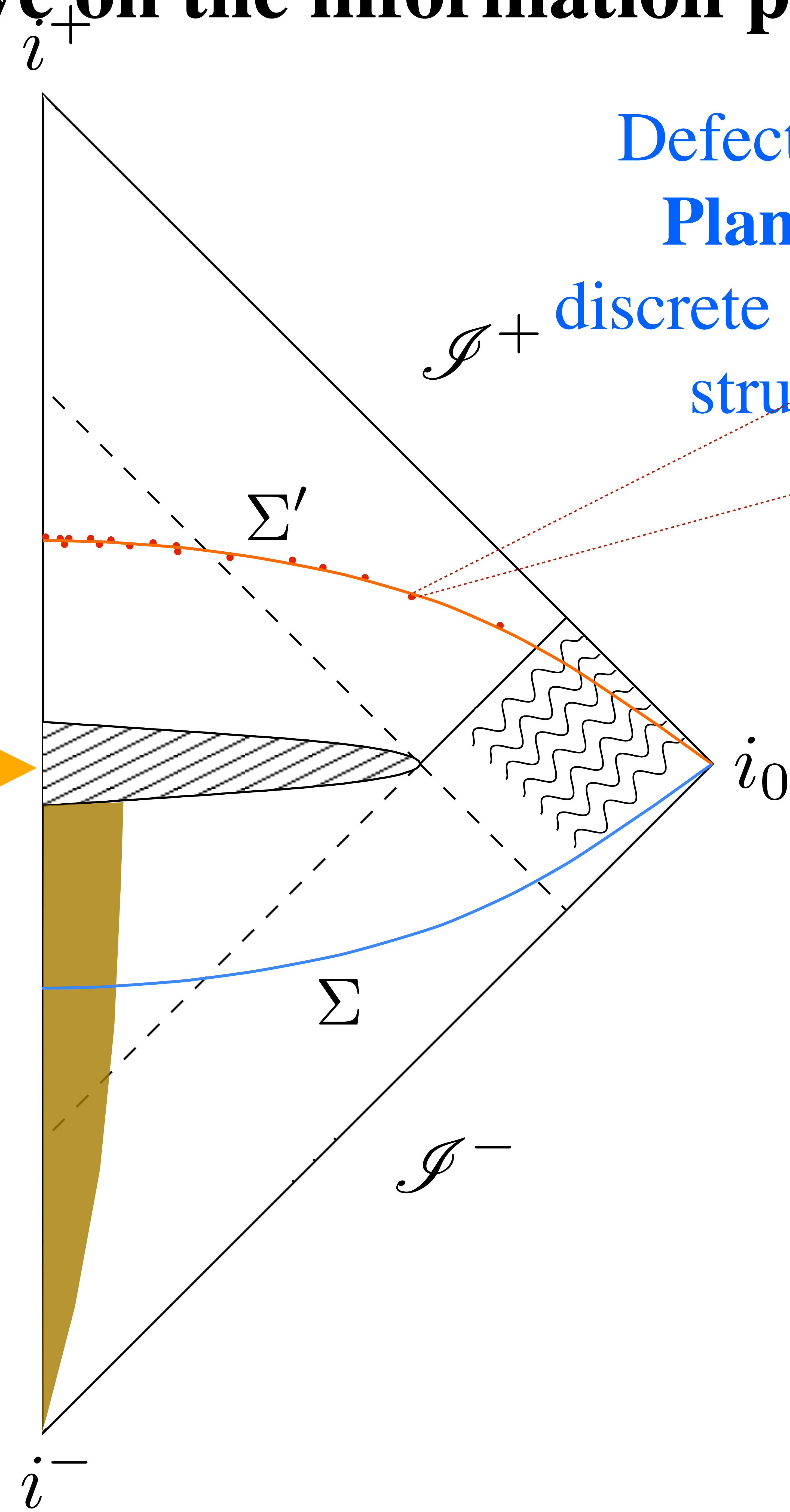
Simplified models support this expectation (Modesto, Ashtekar-Singh, Rovelli-Haggard, Rovelli, Pullin, Corichi-Singh, etc.)

Unitarity: Information should be recovered after BH evaporation

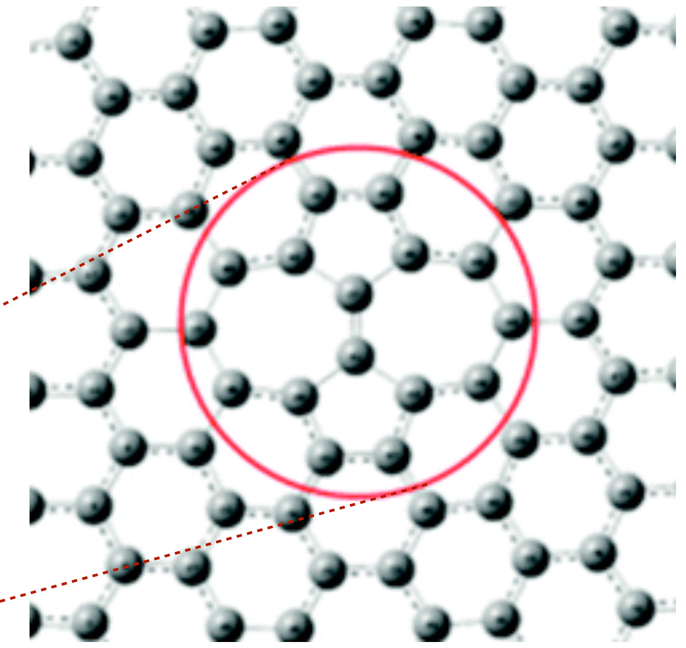


New perspective on the information paradox

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



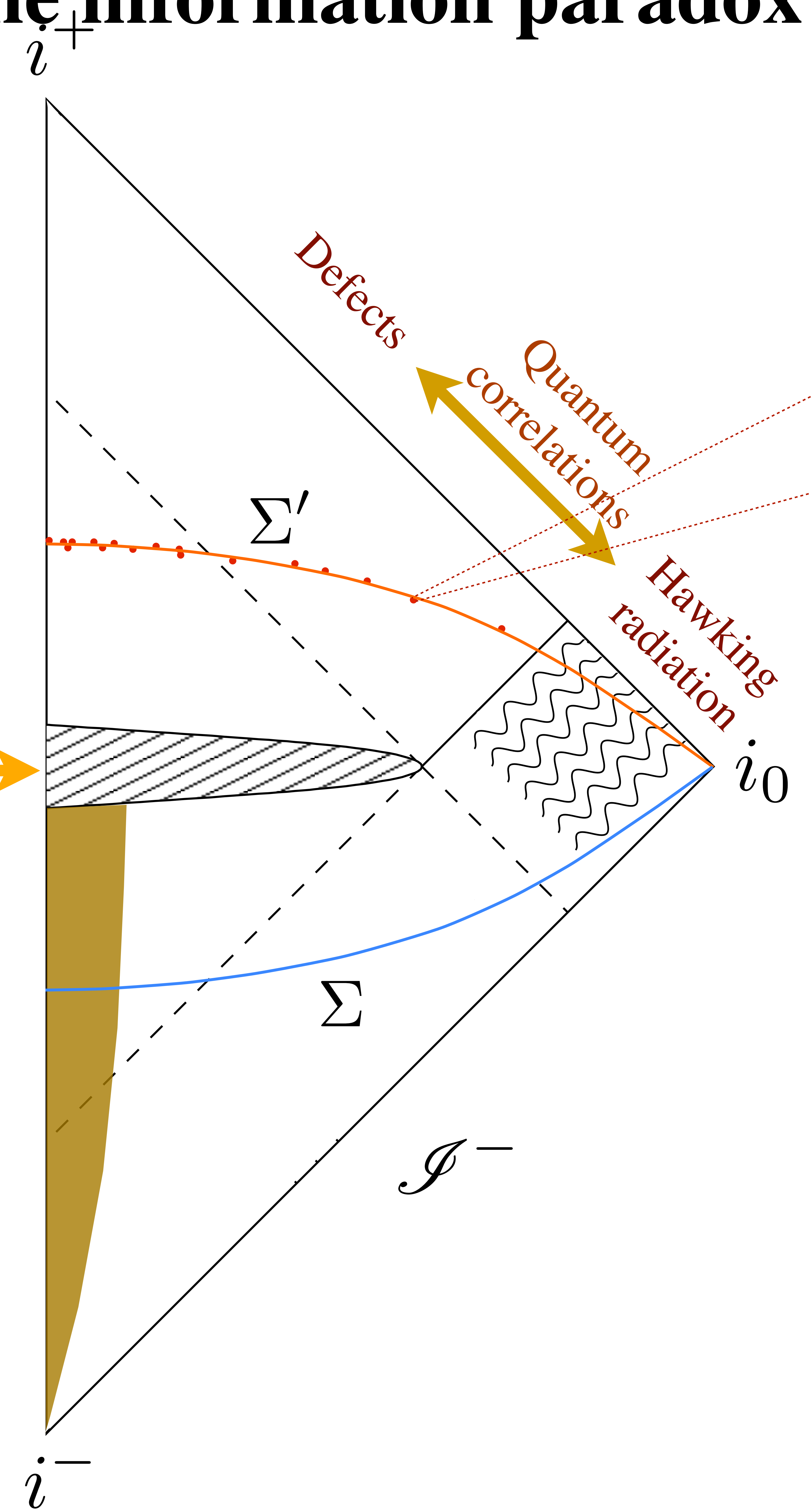
Defects in the **Planckian** discrete spacetime structure

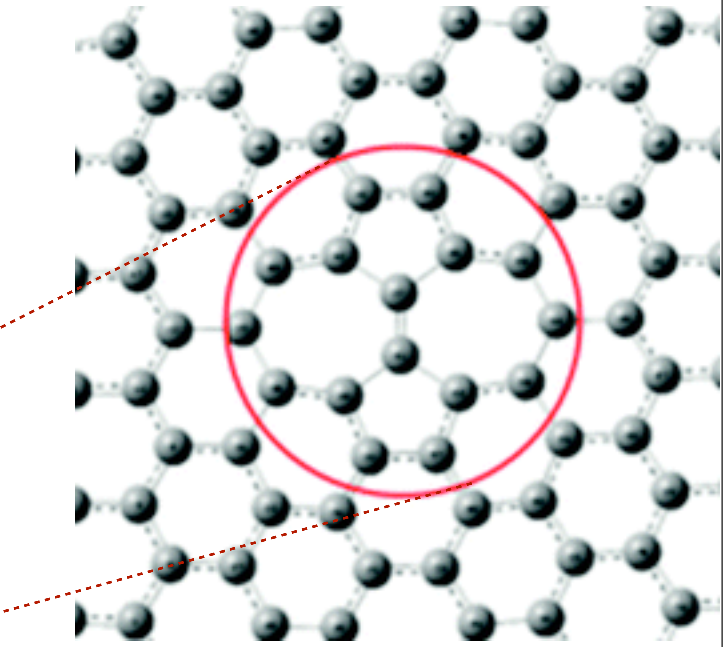


Defects are **hidden** for the probes of low energy observers. No nontinuum field theory description. They can be essentially "**zero energy**"

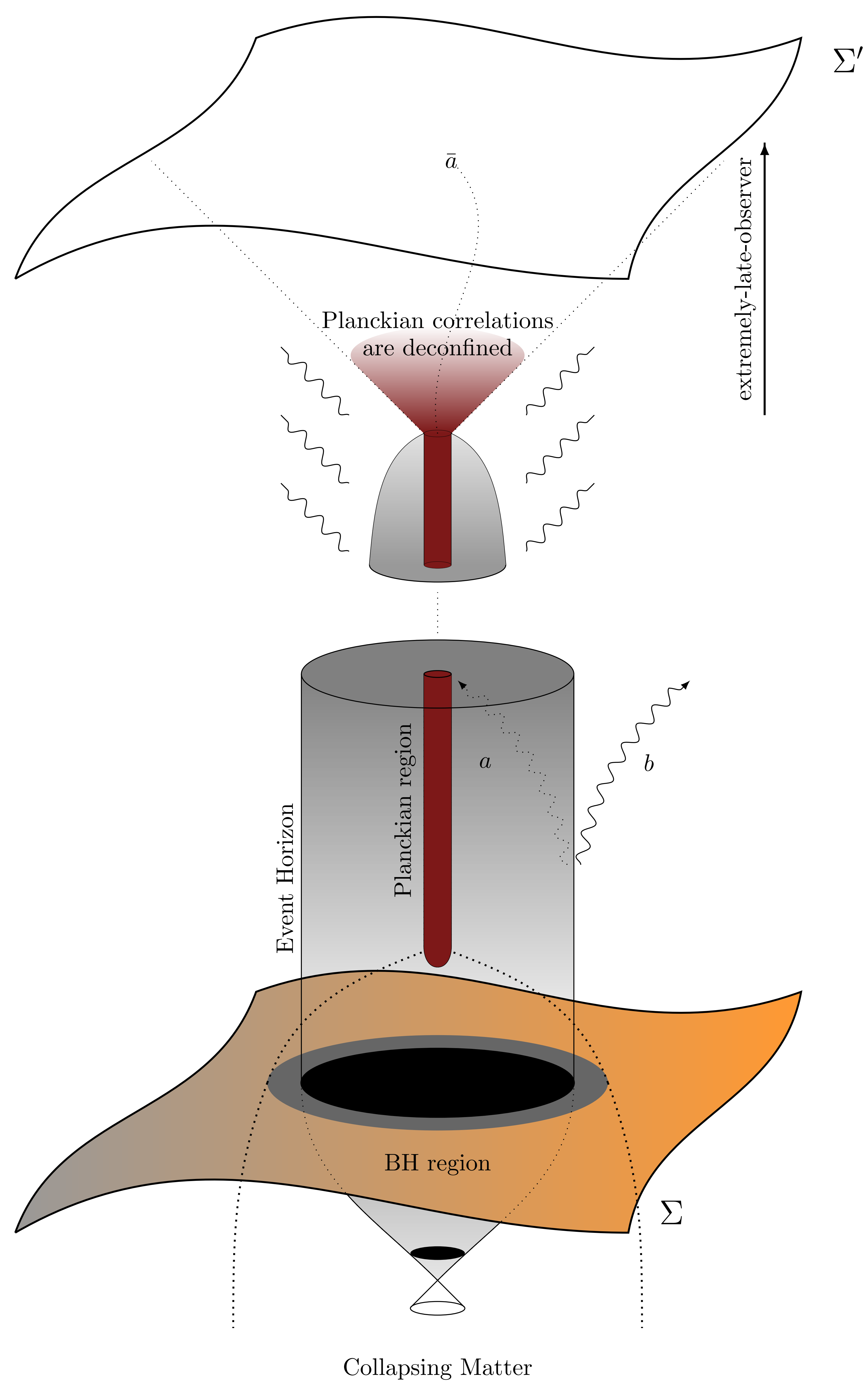
New perspective on the information paradox

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





New perspective on the information paradox

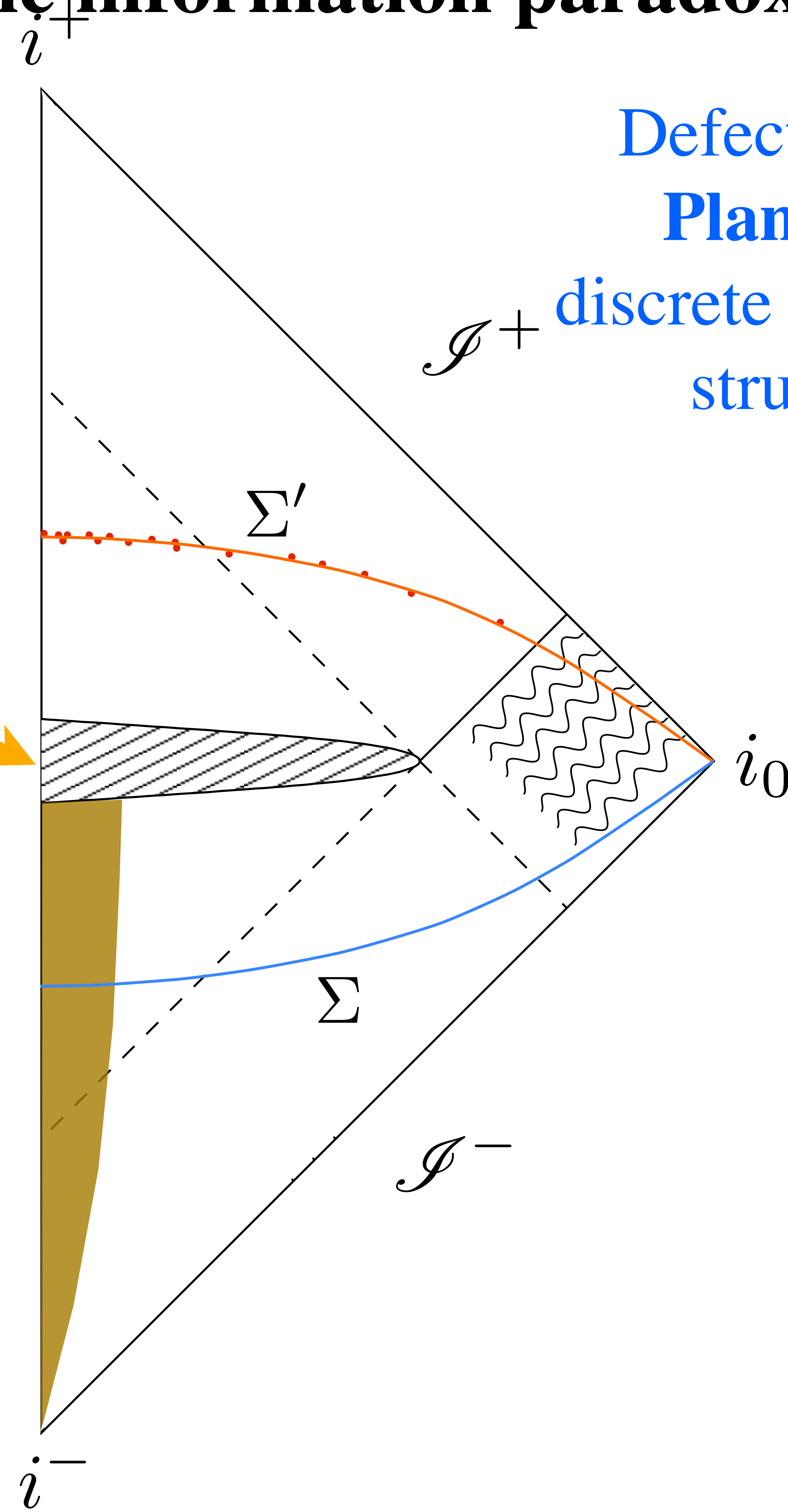


New perspective on the information paradox

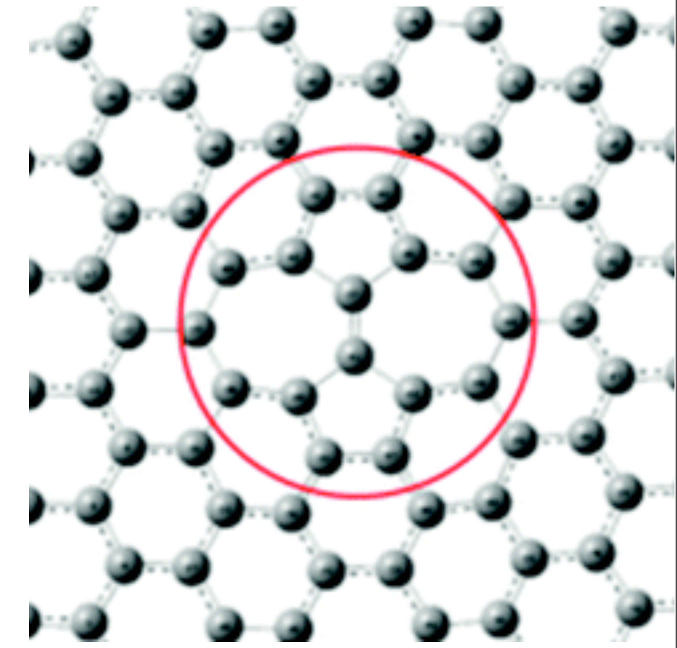
AP, *Class. Quant. Grav.* 32, 2015.

Decoherence with discrete micro-structure: **violations** of **energy conservation** in the **smooth effective description**!

Banks, Peskin, Susskind (1984) - Unruh, Wald (1995)



Defects in the **Planckian** discrete spacetime structure



Q-Correlated

Hawking **thermal radiation**

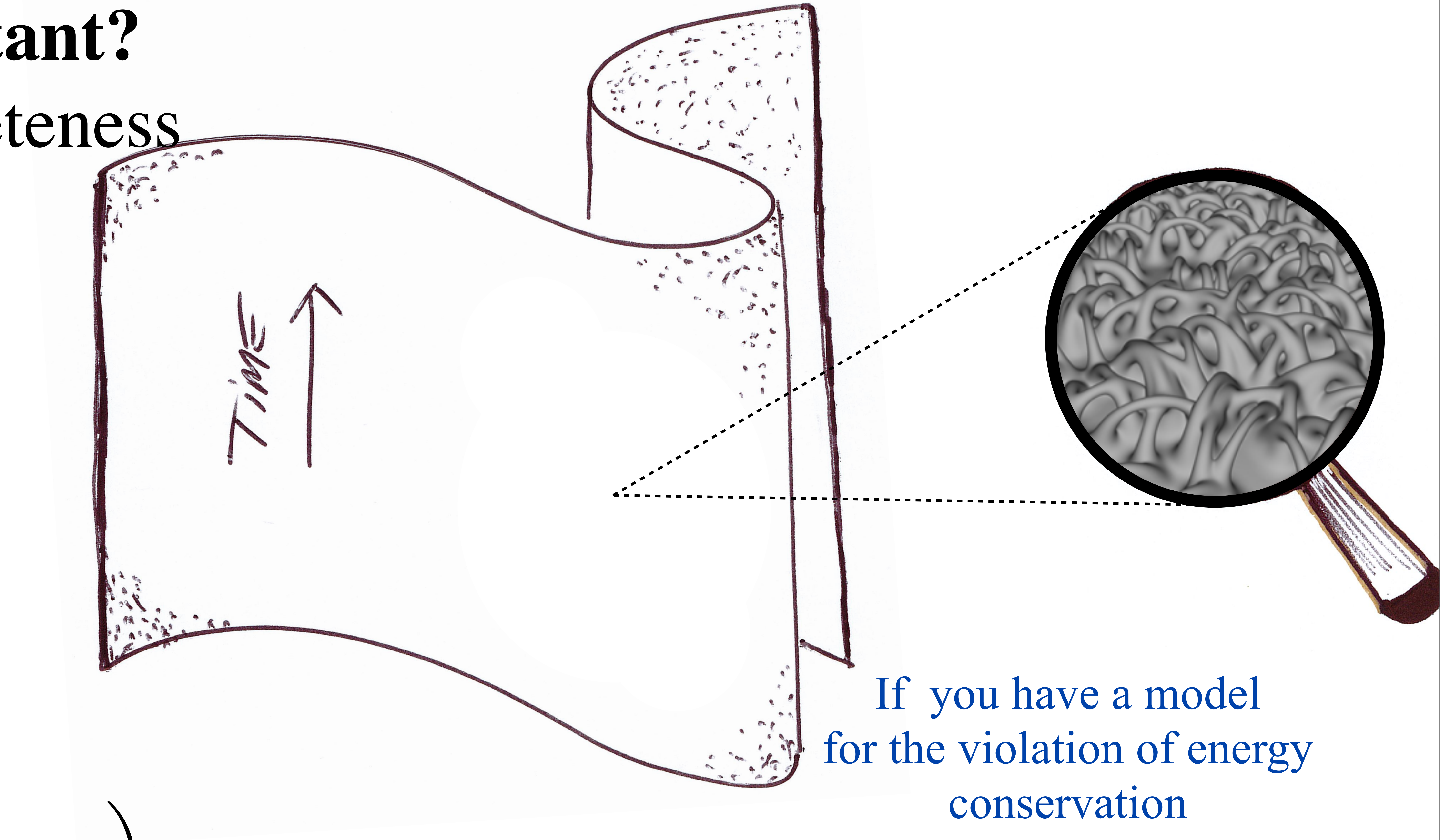
An emergent cosmological constant?

phenomenology arising from discreteness

T. Josset, AP, D. Sudarsky.
PRL 118, (2017)

AP, D. Sudarsky.
arXiv:1711.05183, (2017)

AP, D. Sudarsky, J.D. Bjorken.
Int.J.Mod.Phys. D27 (2018)



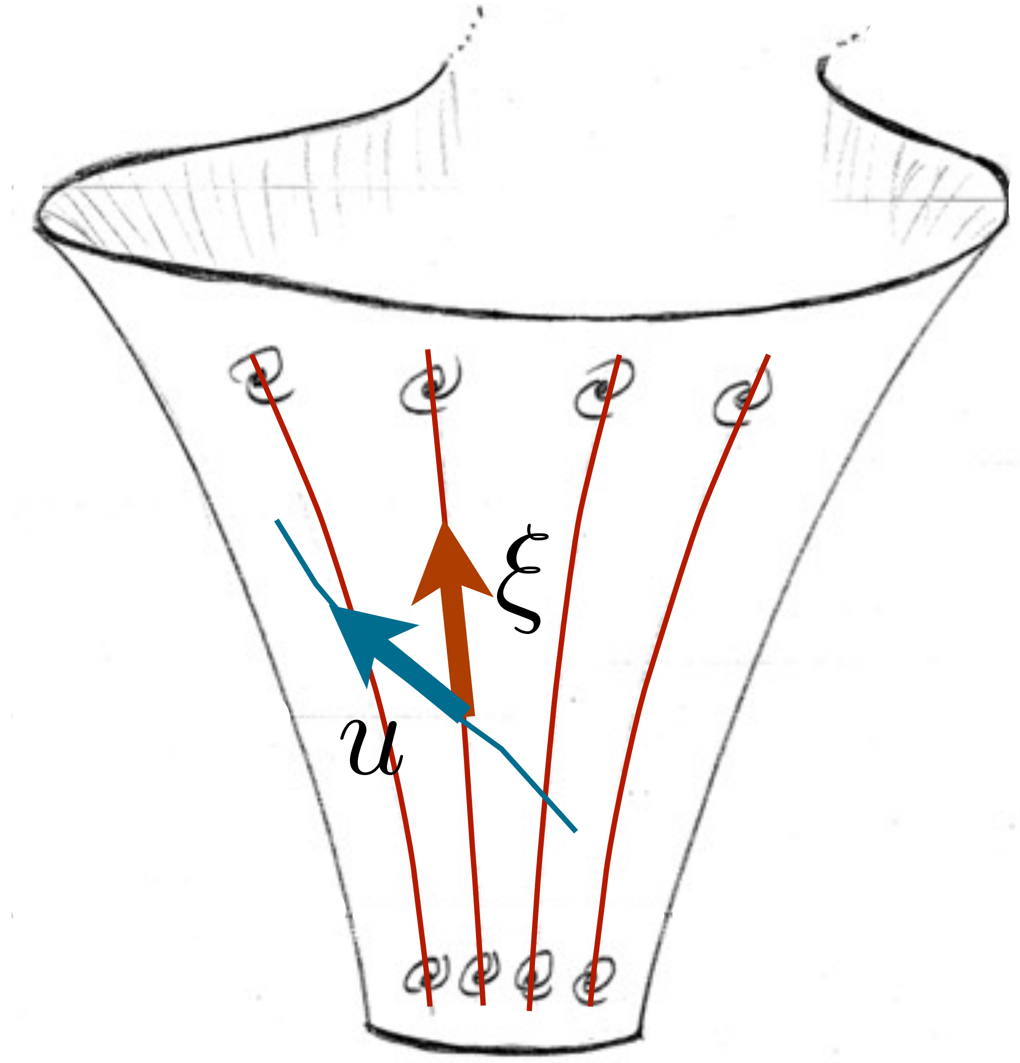
If you have a model for the violation of energy conservation

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

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

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

Diffusion from Planckian discretenss



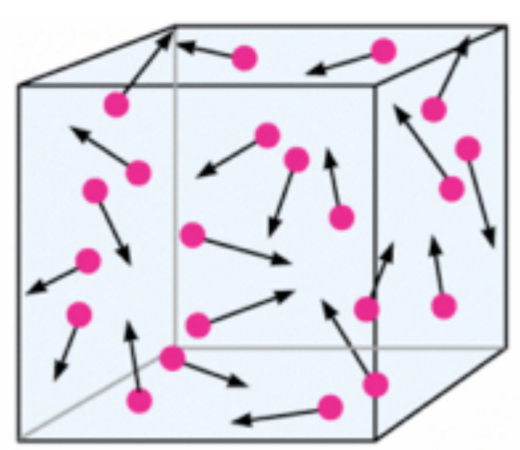
Langevin-Papapetrou like equation; noisy diffusion due to discreteness.

$$a^b = u^a \nabla_a u^b = \alpha \, \mathrm{sign}(s \cdot \xi) \frac{m \mathbf{R}}{m_p^2} \, s^b$$

Single particle energy diffusion.

$$\dot{E} \equiv -m u^\mu \nabla_\mu (u^\nu \xi_\nu) = -\alpha \frac{m^2}{m_p^2} |(s \cdot \xi)| \mathbf{R} - m u^\mu u^\nu \nabla_{(\mu} \xi_{\nu)}$$

Multiparticle Energy-Momentum diffusion in cosmology.



$$\mathbf{J}_b \equiv 8\pi \nabla^a \mathbf{T}_{ab} = -4\pi\alpha\hbar \frac{T\mathbf{R}}{m_p^2} \left[8\pi G \sum_i |s^i| \mathbf{T}_i \right] \xi_b$$

$$\approx 2\pi\alpha\hbar \frac{T\mathbf{R}^2}{m_p^2} \xi_b$$

Top quark approximation

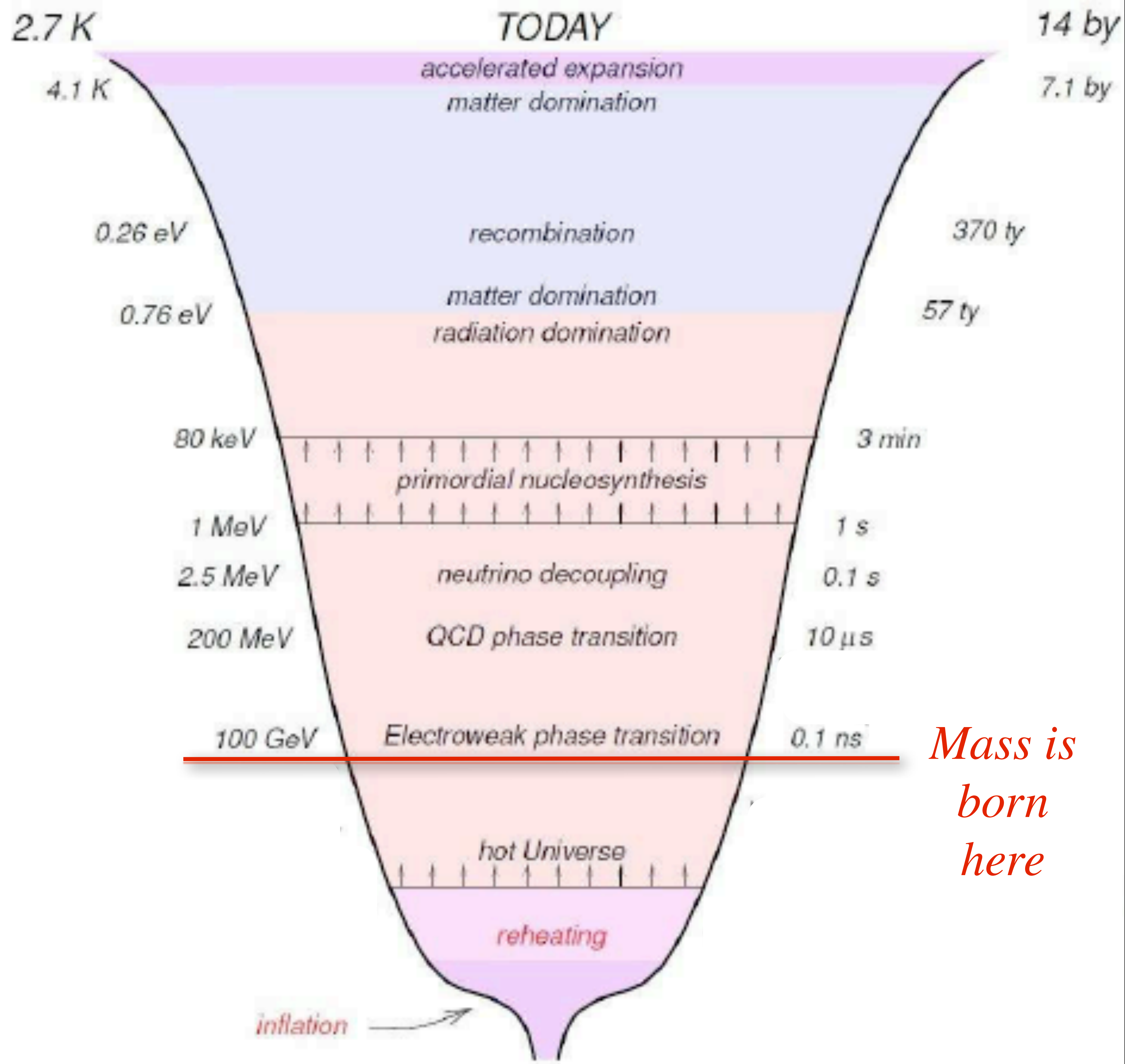
Sum over species of the standard model

Results are in suggesting agreement with observations

$$\mathbf{J}_b = \frac{2\pi\alpha\hbar}{m_p^2} T\mathbf{R}^2 \xi_b$$

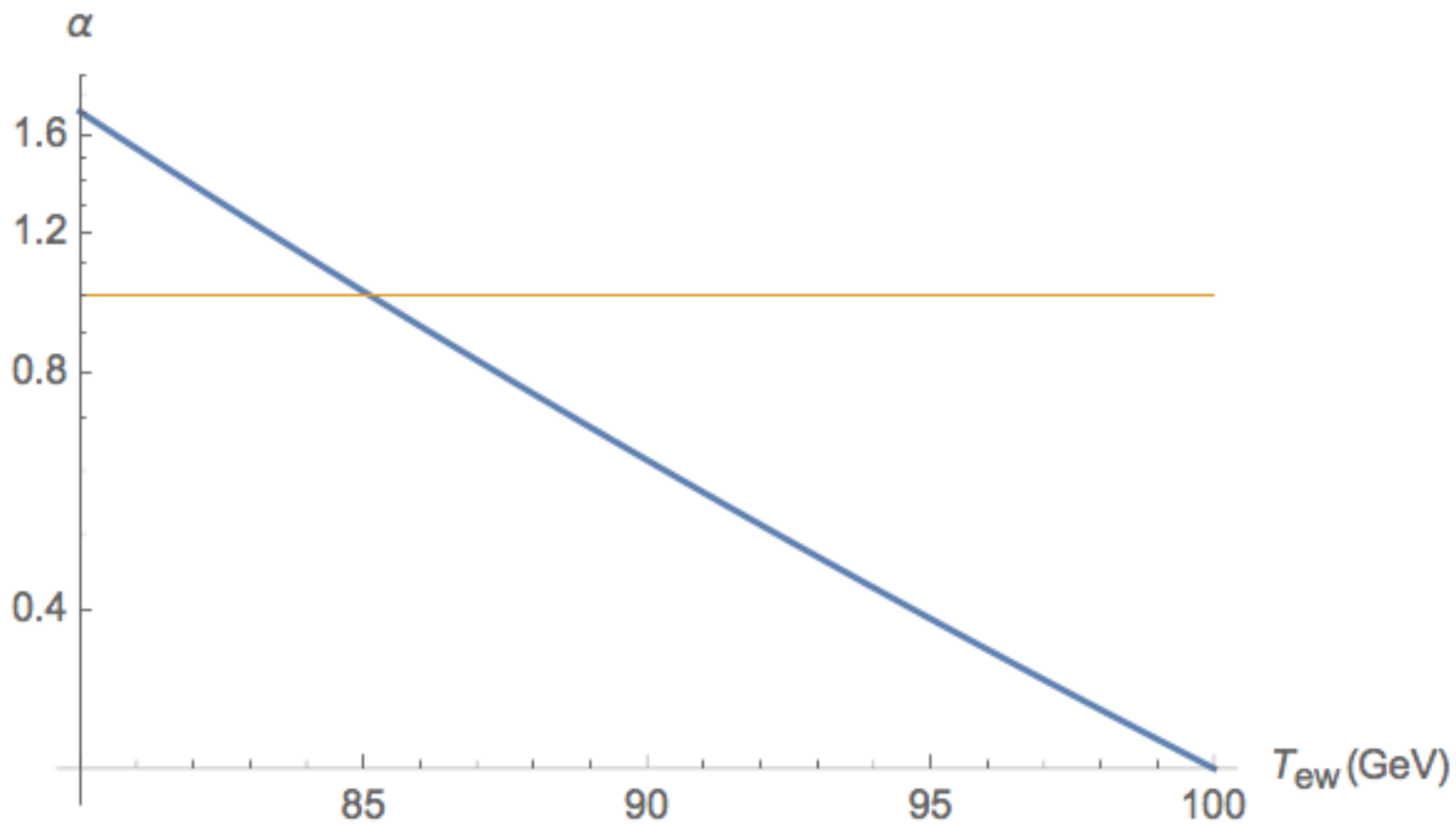
$$\Lambda = \int \mathbf{J}_b dx^b = \frac{2\pi\alpha\hbar}{m_p^2} \int_{t_0}^{t} T\mathbf{R}^2 dt$$

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



Mass is born here

Results are in suggesting agreement with observations



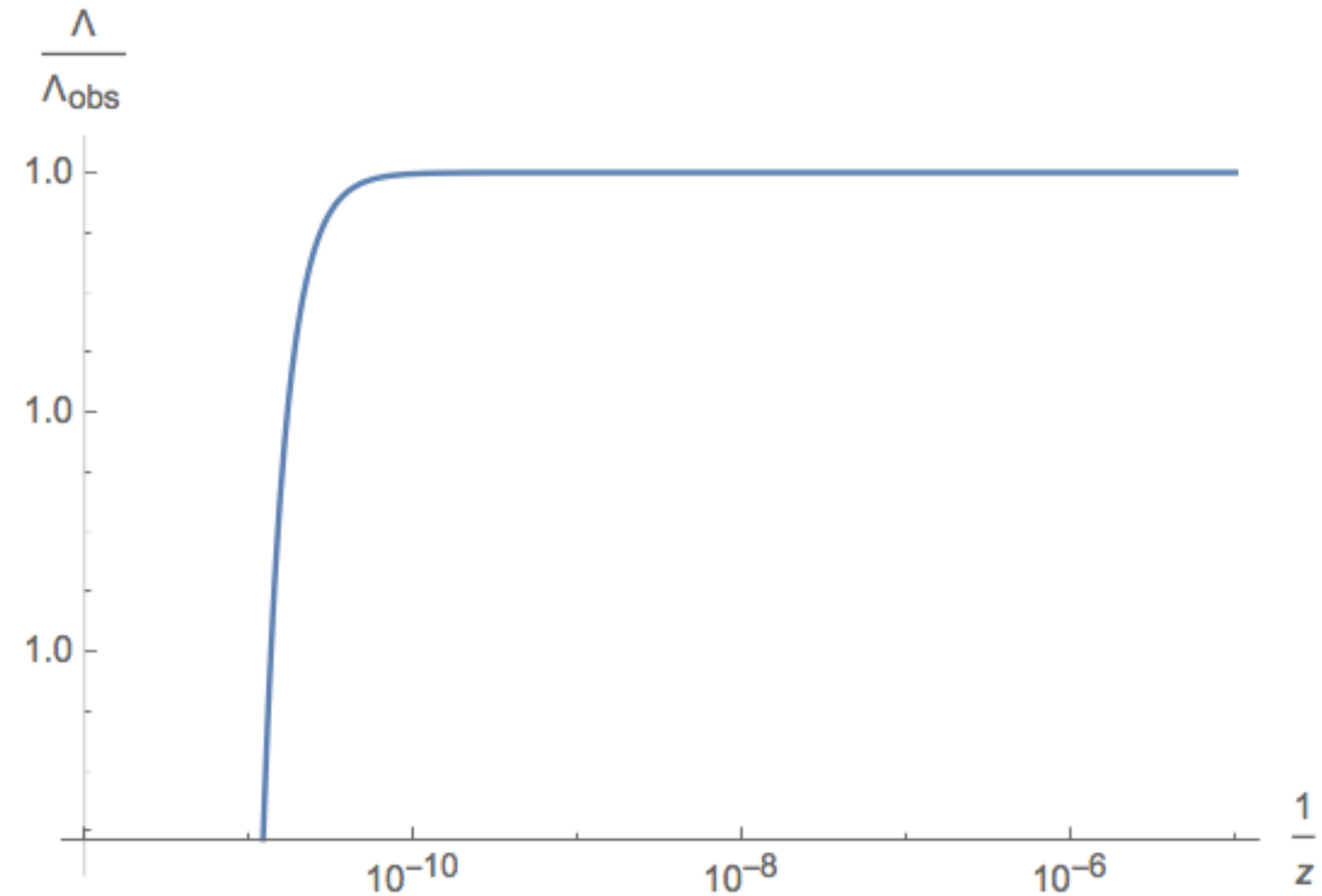


Figure 1: **Left:** The value of the phenomenological parameter α that fits the observed value of Λ_{obs} as a function of the EW transition scale $T_{\rm ew}$ in GeV. We see that for $T_{\rm ew} \approx 100GeV$ $\alpha \approx 1$. **Right:** The time dependence of Λ expressed in terms of the inverse redshift factor $1/z$.

Discussion

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

2. 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).

3. 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, ...)).

4. Decoherence with discrete microstructure is a 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.

5. 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,...) description of matter...


NGC 4526 with SN 1994D
Thank you!