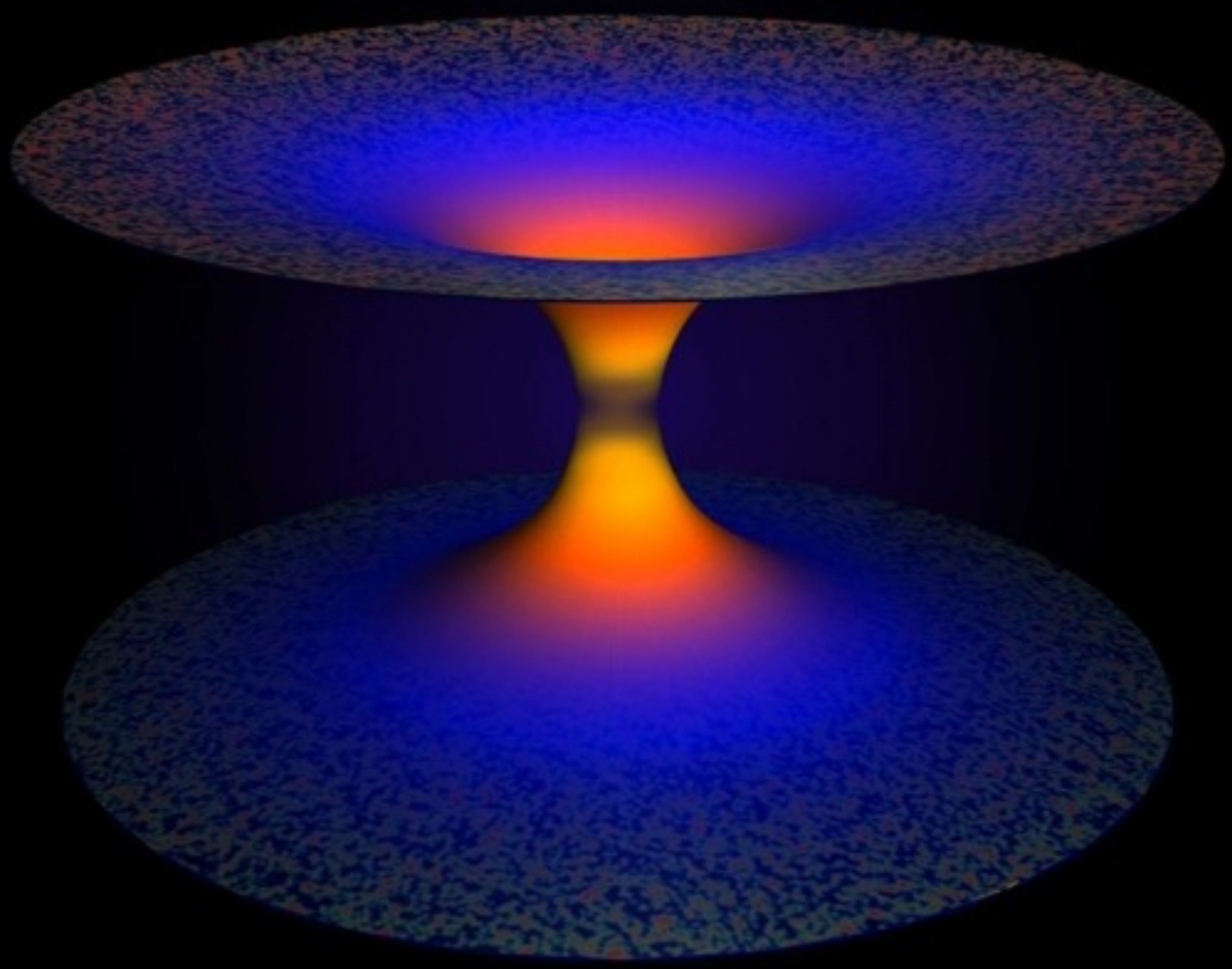
What can we learn from **Loop Quantum Cosmology***?*

the case of **Planck Stars**



Francesca Vidotto

569. WE-Heraeus-Seminar: "Quantum Cosmology"
31 July 2014 Physikzentrum Bad Honnef (Germany)

Netherlands Organisation for Scientific Research

Radboud University Nijmegen

In this talk:

- Quantum cosmology from the full theory:

  Spinfoam Cosmology

- A new look at singularity resolution:

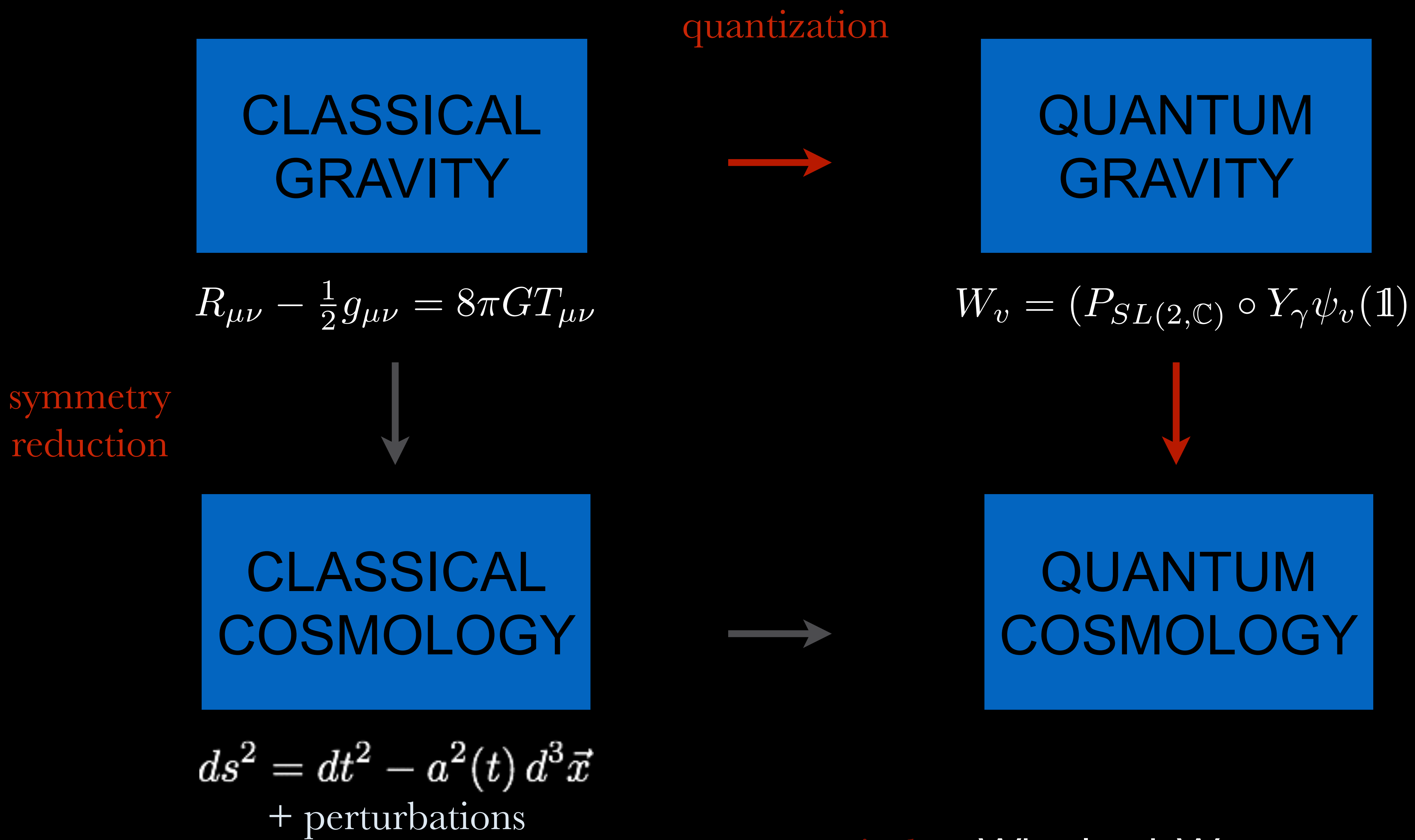
  maximal acceleration

- Black holes tunnels into withe holes:

  Planck Stars

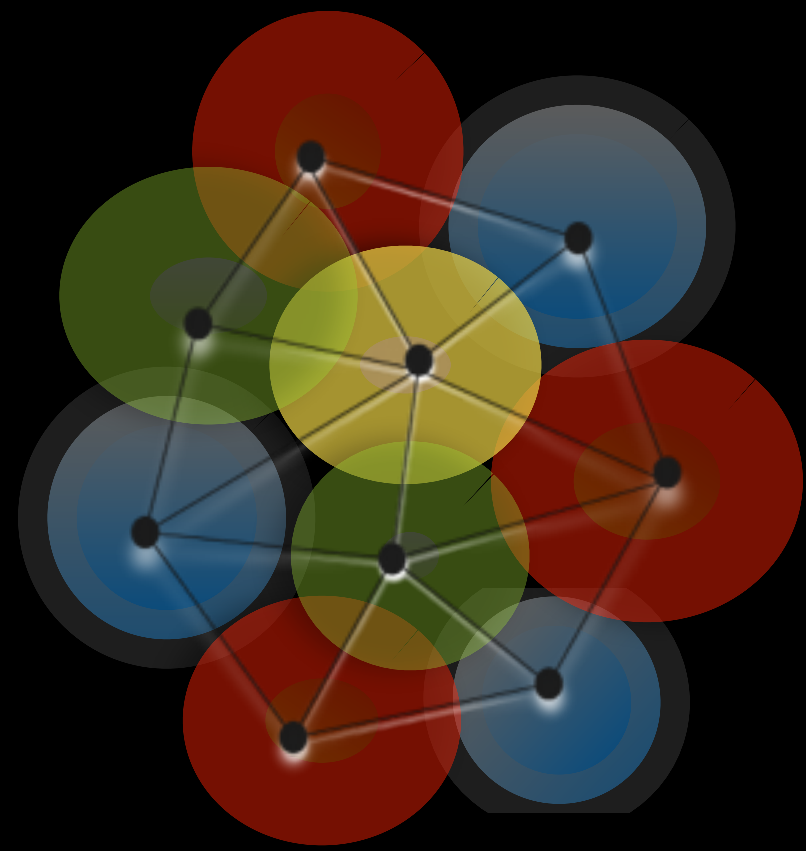
Quantum Cosmology from the full theory

(Ryan's diagram)

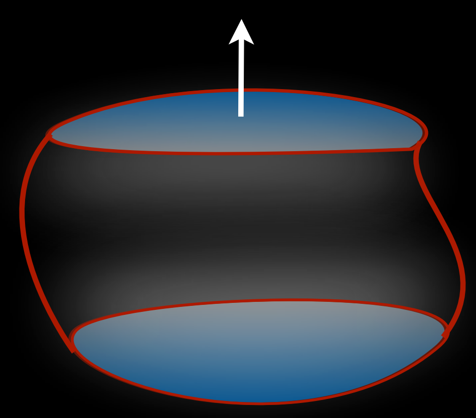


- canonical: Wheeler-deWitt eq.
- covariant: Hartle-Hawking state

Loop Quantum Gravity

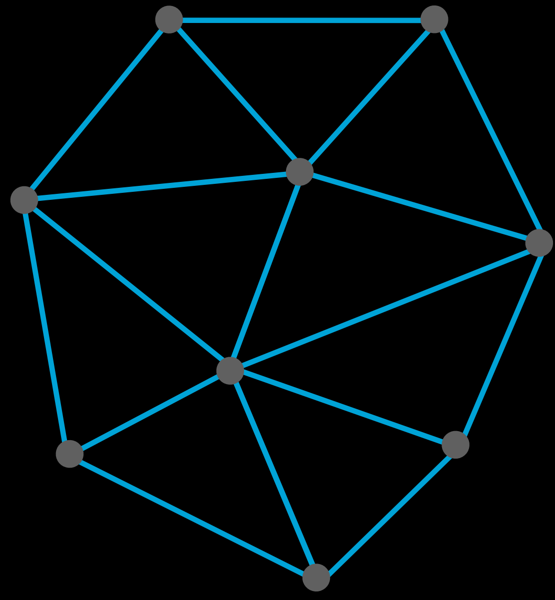


- It is a theory about quanta of spacetime
- Local Lorentz invariance
- The states are boundary states at fixed time
- The physical phase space is spanned by SU(2) group variables



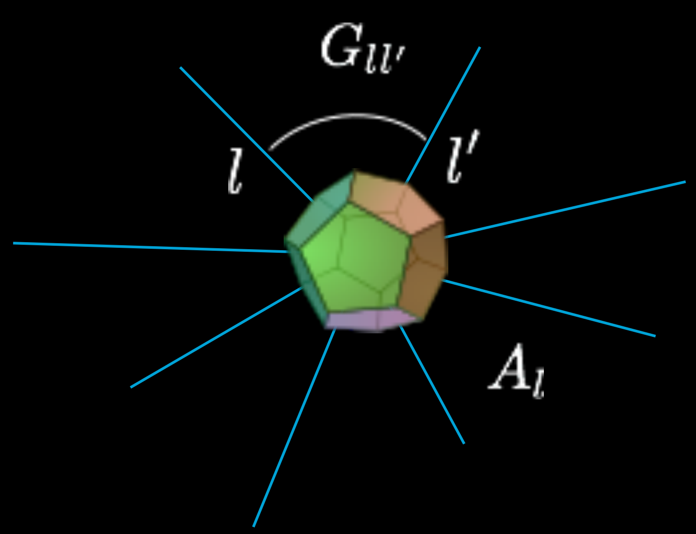
$SL(2,\mathbb{C}) \to SU(2)$

Hilbert space and operator algebra



- Group variables: $\begin{cases} h_l \in SU(2) \\ \vec{L}_l \in su(2) \end{cases}$
- Adjacency: Γ={N,L}
- Graph Hilbert space: $\mathcal{H}_\Gamma = L_2[SU(2)^L/SU(2)^N]$
- The space $\mathcal{H}_\Gamma$ admits a basis $|\Gamma, j_\ell, v_n\rangle$
- Gauge invariant operator $G_{ll'} = \vec{L}_l \cdot \vec{L}_{l'}$ with $\sum_{l\in n} G_{ll'} = 0$

  Penrose's **spin-geometry theorem** (1971)



- h_l "Holonomy of the Ashtekar-Barbero connection along the link"
- $\vec{L}_l = \{L_l^i\}, i = 1,2,3$ SU(2) generators $L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$ *(tetrad)*

- Area $A_\Sigma = \sum_{l\in\Sigma} \sqrt{L_l^i L_l^i}.$
- Volume $V_R = \sum_{n\in R} V_n, \qquad V_n^2 = \frac{2}{9}\,|\epsilon_{ijk} L_l^i L_{l'}^j L_{l''}^k|.$
- Angles $L_l^i L_{l'}^i$

- eigenvalues are discrete
- the operators do not commute
- quantum superposition

  → *coherent states*

Spinfoam amplitudes

Engle, Pereira, Livine, Rovelli 0711.0146

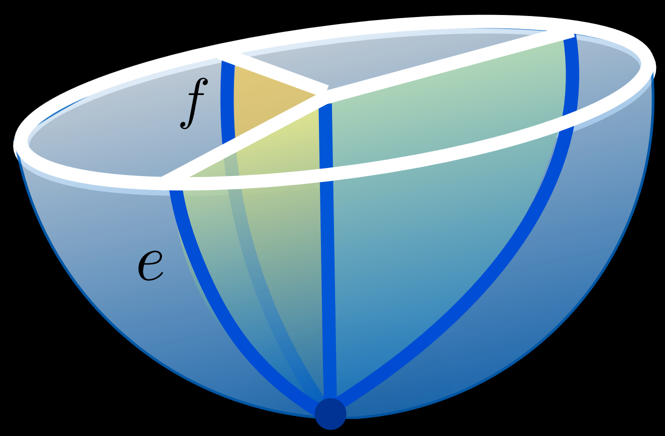
Probability amplitude $P(\psi) = |\langle W|\psi\rangle|^2$
for a state ψ associated to the boundary of a 4d region

$$W(q) \sim \int_{\partial g = q} Dq \; e^{iS[q]}$$

- Superposition principle $\langle W|\psi\rangle = \sum_\sigma W(\sigma)$
- Locality: vertex amplitude $W(\sigma) \sim \prod_v W_v.$
- Lorentz covariance $W_v = (P_{SL(2,\mathbb{C})} \circ Y_\gamma \, \psi_v)(\mathbb{1})$
- UV and IR finite (with Λ)
- Classical limit: GR (with Λ)
  (via Regge discretisation)

Barrett et al. 0907.2440
Han, Zhang 1109.0499

Spinfoam Hartle-Hawking state



www.cpt.univ-mrs.fr/~rovelli/IntroductionLQG.pdf

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Probability amplitude $P(\psi) = |\langle W|\psi\rangle|^2$

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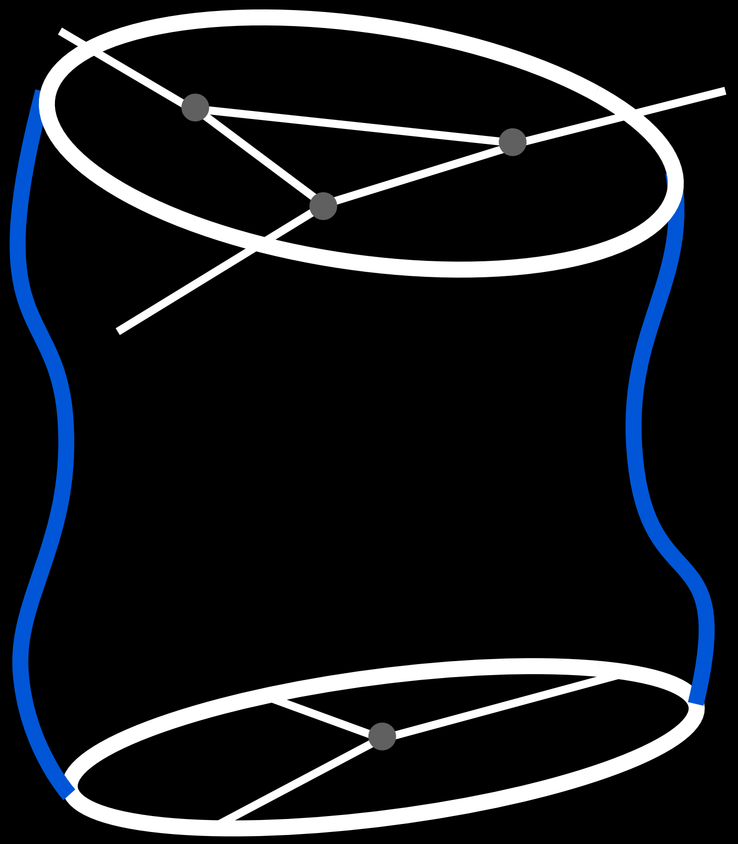
$$W(q'_{ij}, q_{ij}) \sim \int_{\partial g = q', q} Dq \; e^{iS}$$



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For more details see: Rovelli, Vidotto "Introduction to Covariant Loop Quantum Gravity" CUP 2014

Cosmological transition amplitudes

Vidotto 1011.4705

Philosophy:

- Fixed graph with N nodes: approx kinematics of the universe — Rovelli, Vidotto 0805.4585
- The graph captures large scale dof
- The full theory can be regarded as an expansion for growing N

Results:

- **Coherent States** peaked on Homogeneous and Isotropic geometry
- Friedmann Equation recovered in the classical limit: Minkowski, de Sitter, Bianchi I

  Bianchi, Rovelli, Vidotto 1003.3483
  Bianchi, Krajeski, Rovelli, Vidotto 1101.4049
  Rennert, Sloan 1308.0687

- The result holds for:
  - every regular graph in the boundary — Vidotto 1107.2633
  - considering radiative corrections in the bulk — Puchta 1307.4747, Riello 1310.2174

Hope:

- Understanding the quantum state at the bounce

(similar results in: Calcagni, Gielen, Oriti 1201.4151)

Spinfoam Dynamics

Unitary irr reps of $SU(2)$ $|j;m\rangle \in \mathcal{H}_j$ and $SL(2,\mathbb{C})$ $|k,\nu;j,m\rangle \in \mathcal{H}_{k,\nu} = \bigoplus_{j=k,\infty} \mathcal{H}^j_{k,\nu}$

- γ-simple representations: $\nu = \gamma(k+1)$
- $SU(2) \to SL(2,\mathbb{C})$ map: $Y_\gamma : \mathcal{H}_j \to \mathcal{H}_{j,\gamma j}$ with image s.t. $j = k$

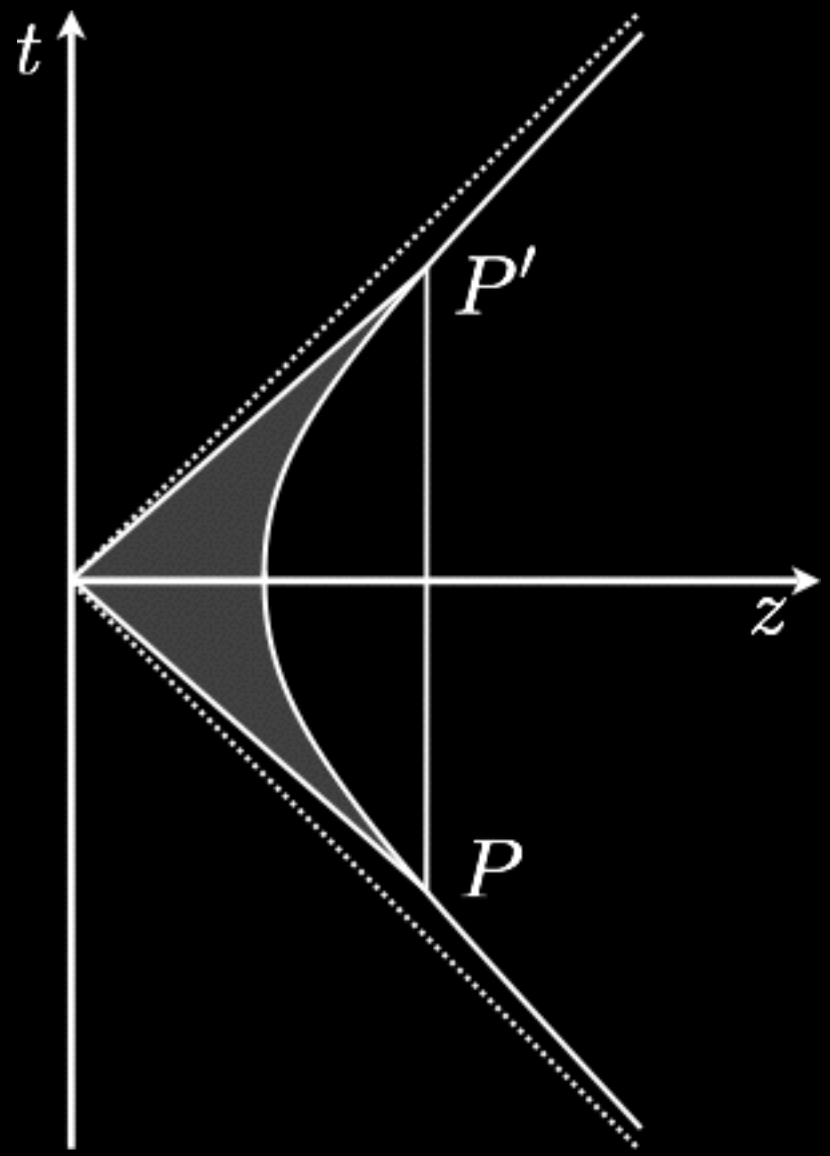
  $|j;m\rangle \mapsto |(j,\gamma(j+1))\,;\; j,m\rangle$
- Simplicity constraint $\vec{K} + \gamma\vec{L} = 0$ satisfied weakly on the image of Y_γ

  Boost generator ($\vec{K}$) Rotation generator ($\vec{L}$)
- L^i is the area operator: the Lorentzian area $A = \int_{\mathcal{R}} L^i$ has a minimal value!

  simplicity constant: $A = \int_{\mathcal{R}} \gamma K^i$ has also a minimal value!

Rovelli, Vidotto 1307.3228

Lorentzian Area



$$A = \int_{\mathcal{R}} e^o \wedge e^i = \int_{\mathcal{R}} \gamma K^i = \int_{\mathcal{R}} L^i$$

$$\ell = 1/a$$

$$A = \frac{\ell^2}{2}\,\eta = \frac{1}{2a^2}\,\eta$$

η is the boost parameter along the trajectory from P to P′

- Lorentzian area $A_{min} = 4\pi G\hbar$
- Max acceleration $a_{max} = \sqrt{\frac{1}{8\pi G\hbar}}$
- Min length $\ell_{max} = \sqrt{8\pi G\hbar}$

[Cainiello '81]
[Cainiello, Gasperini, Scarpetta '91]
[Bozza, Feoli, Lambiase, Papini, Scarpetta]

Spinfoam “wedge” amplitudes

- motion of an accelerated observer in spacetime
- evolution of spacetime seen by an observer

$$W(g, g', h) = \sum_j (2j+1)\ \mathrm{Tr}_j[Y^\dagger \underbrace{g' g^{-1}} Y h]$$

$g, g' \in SL(2, C)\ h \in SU(2)$

- $g' g^{-1}$ is a boost:

$$W(\eta, h) = \sum_j (2j+1)\ \mathrm{Tr}_j[Y^\dagger e^{i\eta K_z} Y h]$$

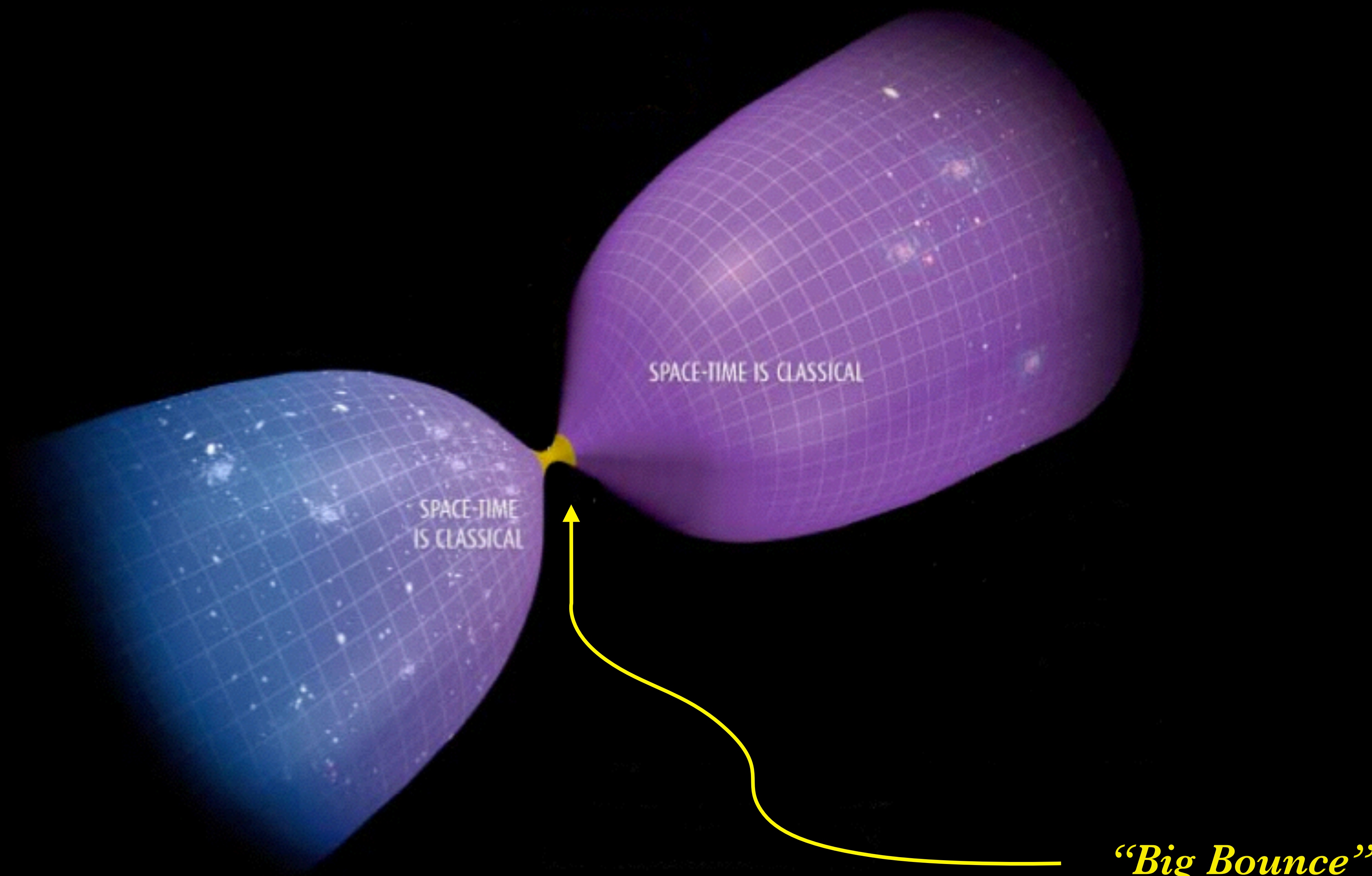
- Fourier transform:

$$W(\eta, j, m, m') = \langle j, m | Y^\dagger e^{i\eta K_z} Y | j, m' \rangle \xrightarrow{m = m' = j} W(\eta, j) = \langle j, j | Y^\dagger e^{i\eta K_z} Y | j, j \rangle$$

Bianchi 1204.5122

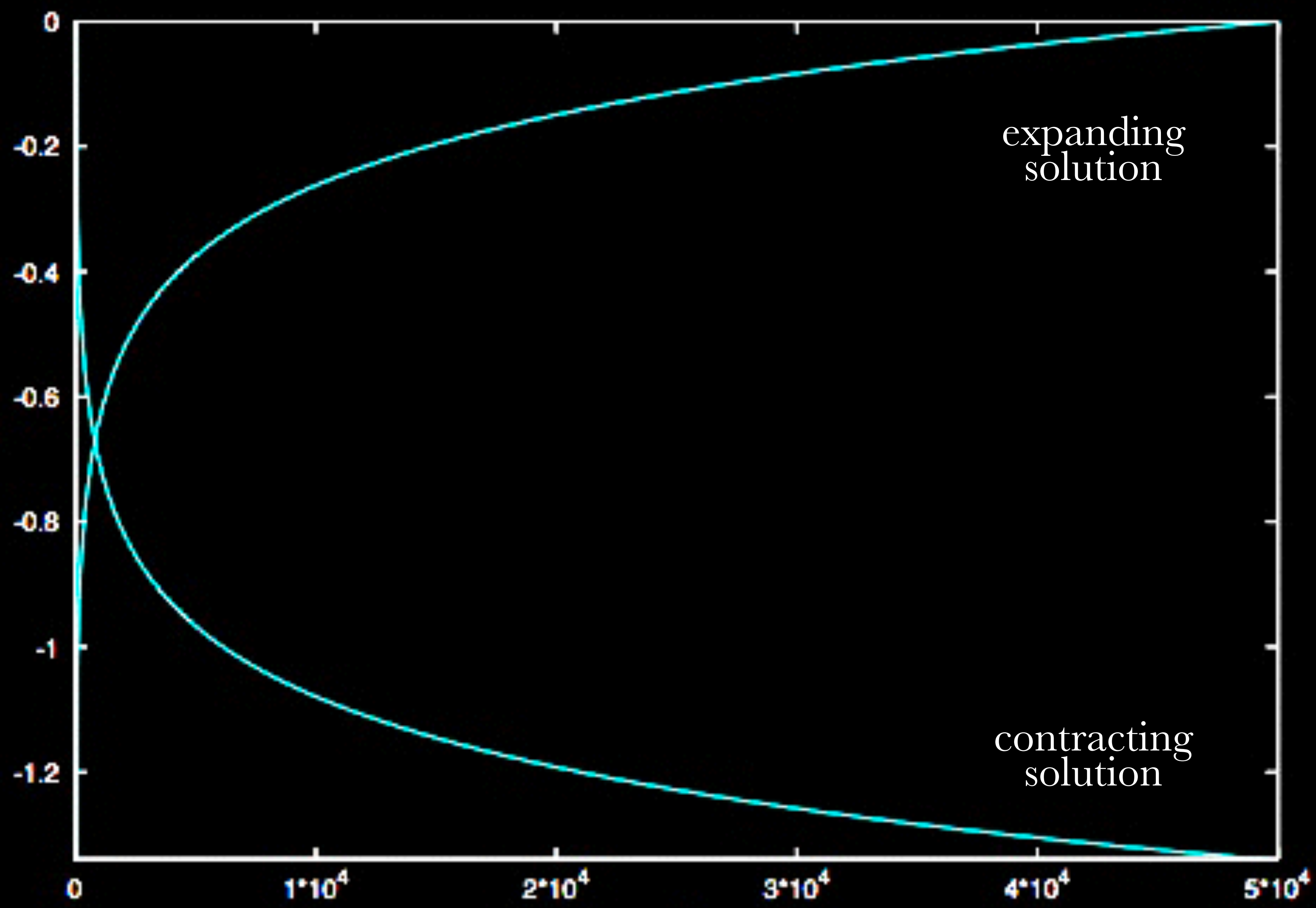
Singularity resolution

Bojowald 1999



See also talk by Piechocki

What have we learnt from **Loop Quantum Cosmology***?*



Big Bounce

- Quantum Tunneling
  - superposition
- Effective repulsive force
  - Planck density
- Size ≫ Planck length

$$V_b \sim \frac{m}{m_P}\,\ell_P^3 \approx 10^{24} cm^3$$

Ashtekar,Pawlowski, Singh, Vandersloot 0612104

See talks by Bojowalk and Mielczarek

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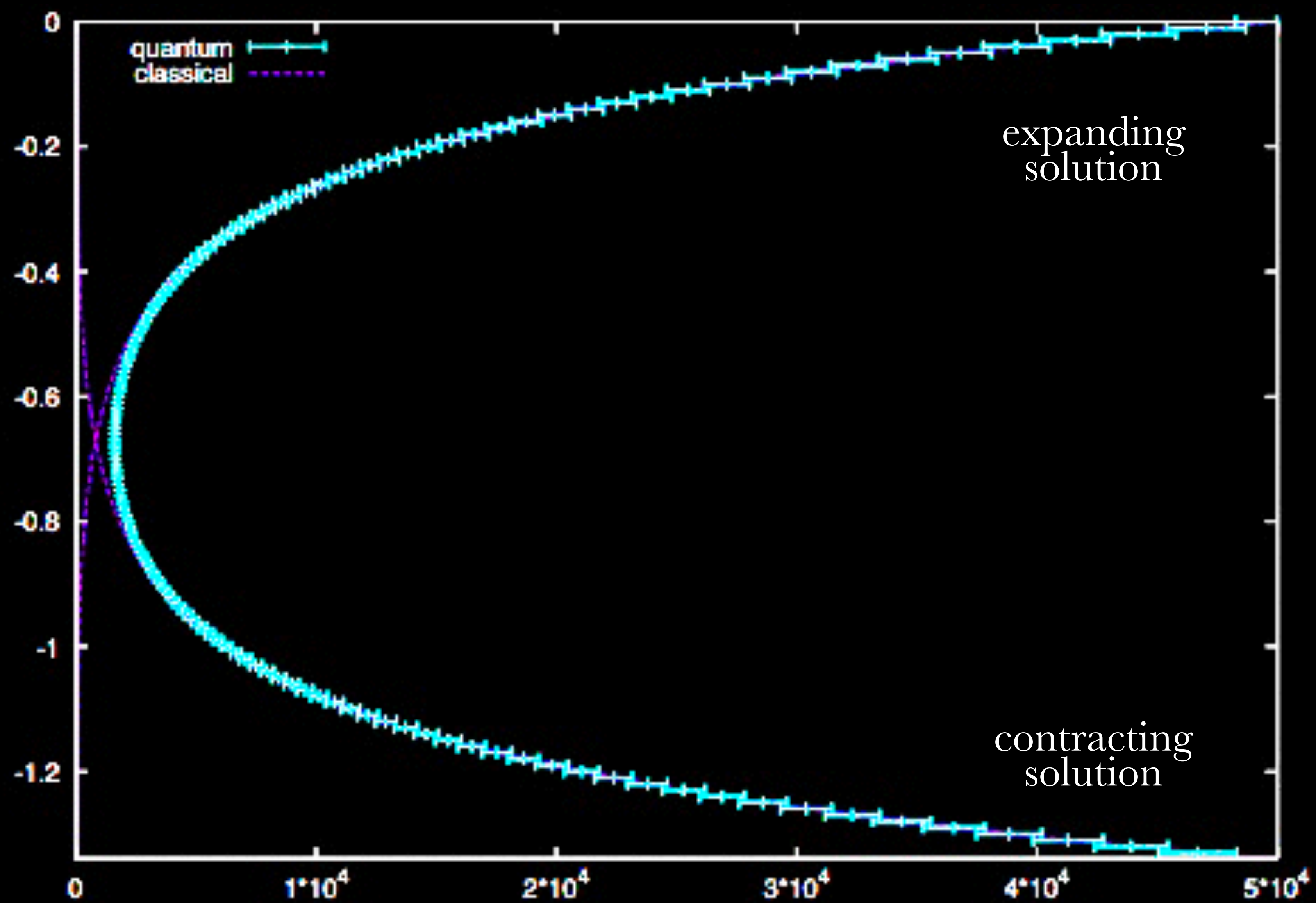

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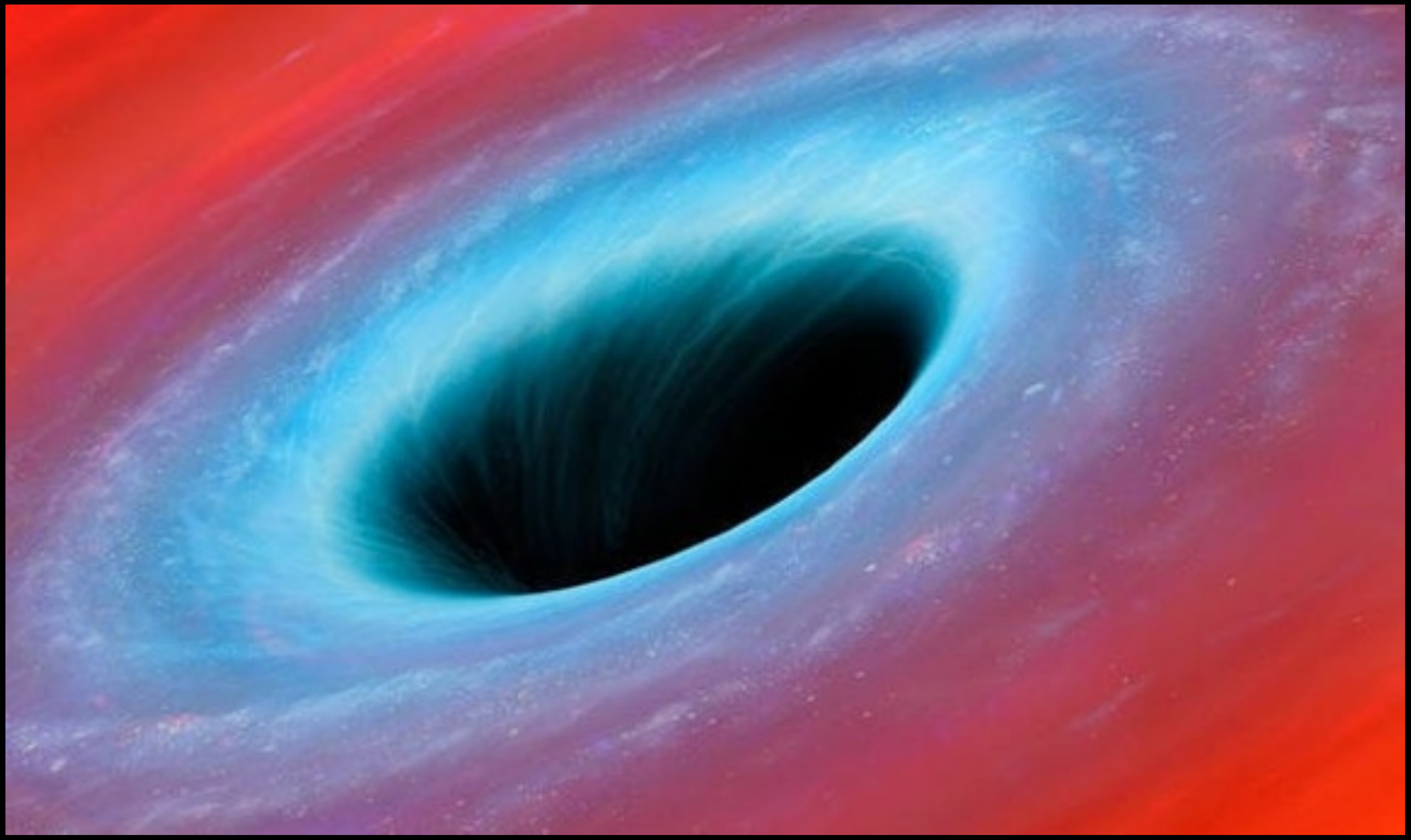
Where does matter falling into a **Black Hole** *go?*



Planck Star

- Quantum Tunneling
  - superposition
- Effective repulsive force
  - Planck density
- Size $\gg$ Planck length

$$r_b \sim \left(\frac{m}{m_P}\right)^{\frac{1}{3}} \ell_P$$

Rovelli, Vidotto 1401.6562

Barrau, De Lorenzo, Haggard, Pacillo, Speziale…

See also recent work by Bianchi, Perez, Pullin…

(similar ideas in: Mersini-Houghton 1406.1525)

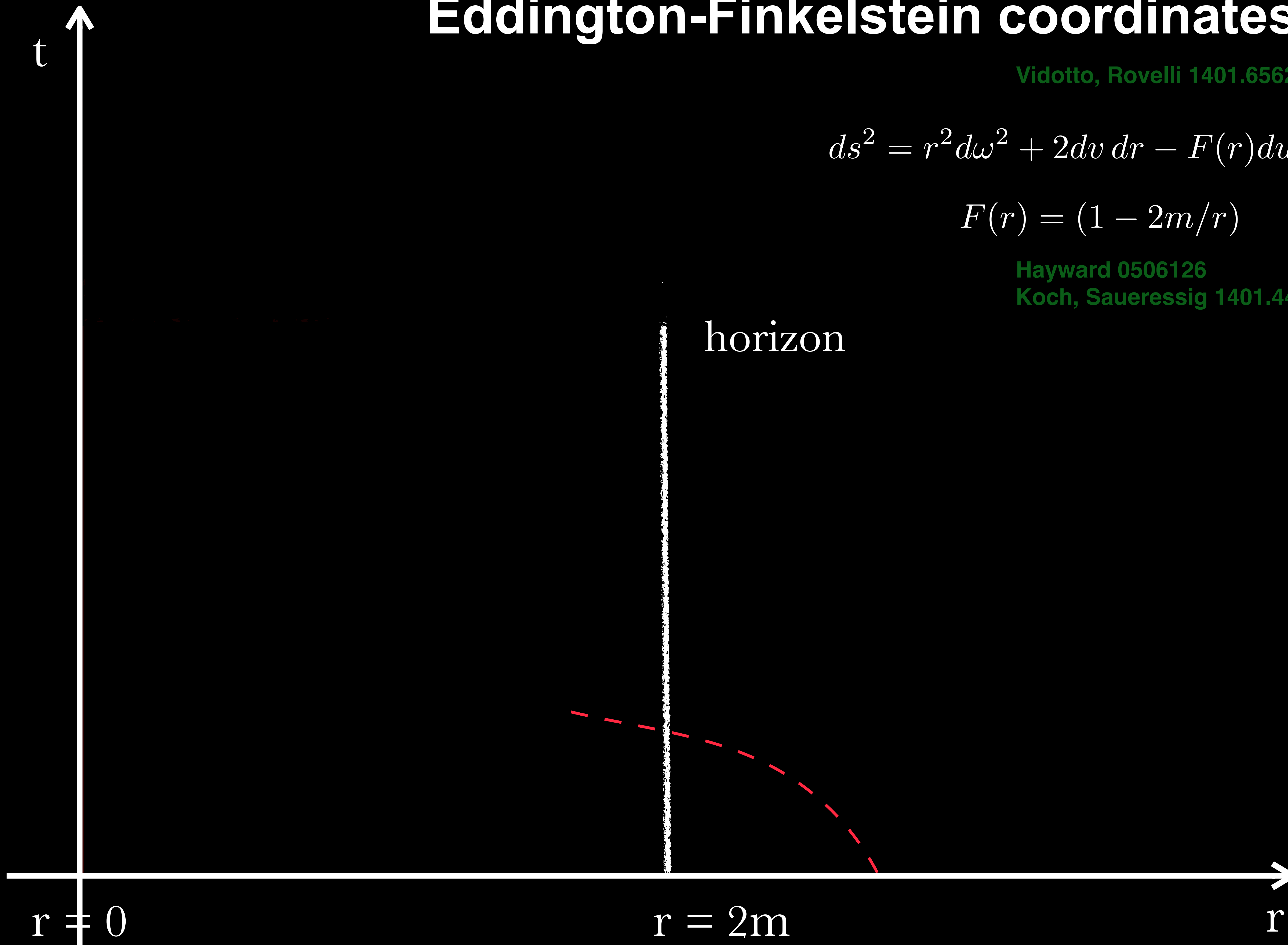
Eddington-Finkelstein coordinates

Vidotto, Rovelli 1401.6562

$$ds^2 = r^2 d\omega^2 + 2dv\,dr - F(r)du^2$$

$$F(r) = (1 - 2m/r)$$

Hayward 0506126
Koch, Saueressig 1401.4452



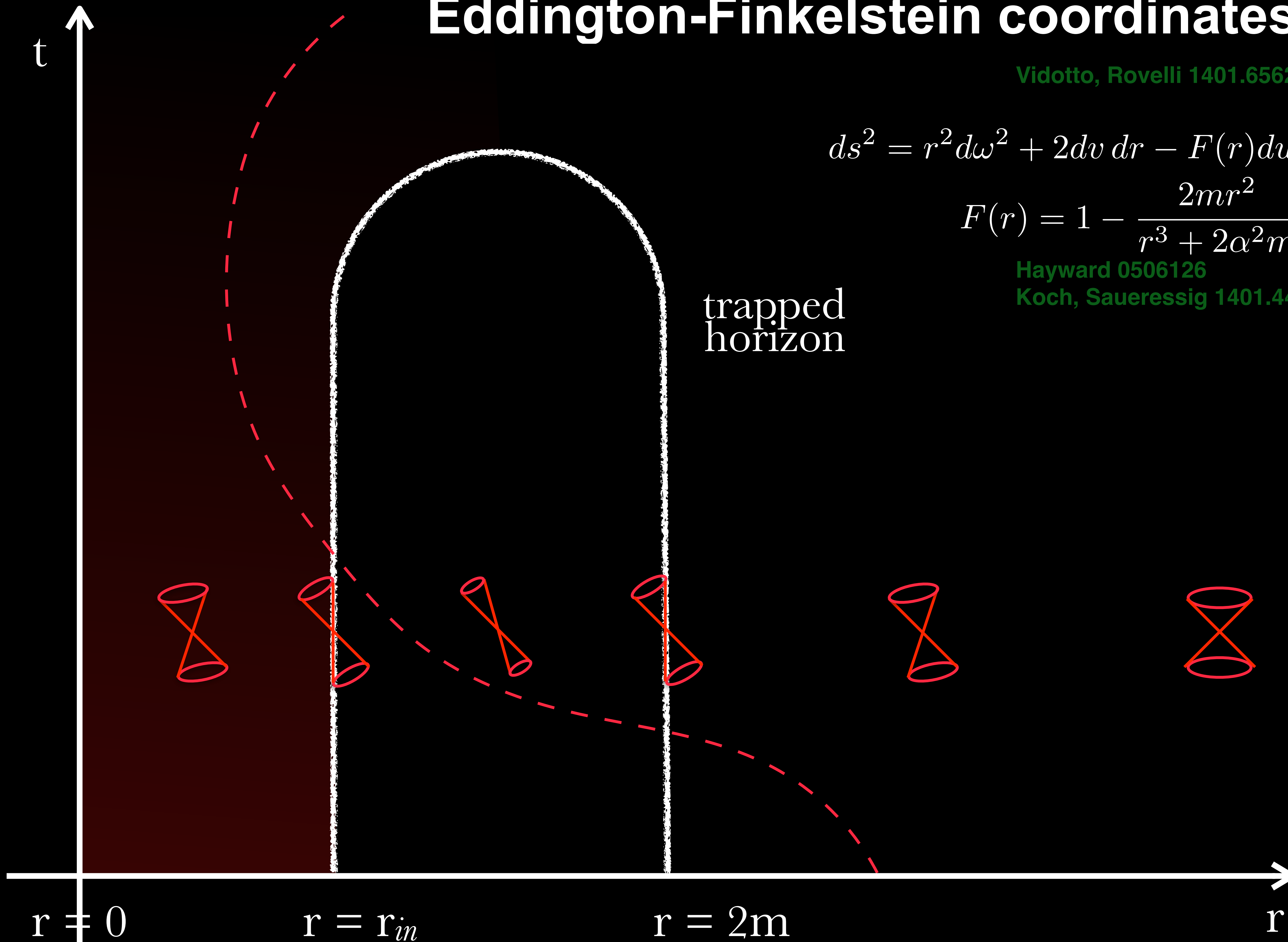
Eddington-Finkelstein coordinates

Vidotto, Rovelli 1401.6562

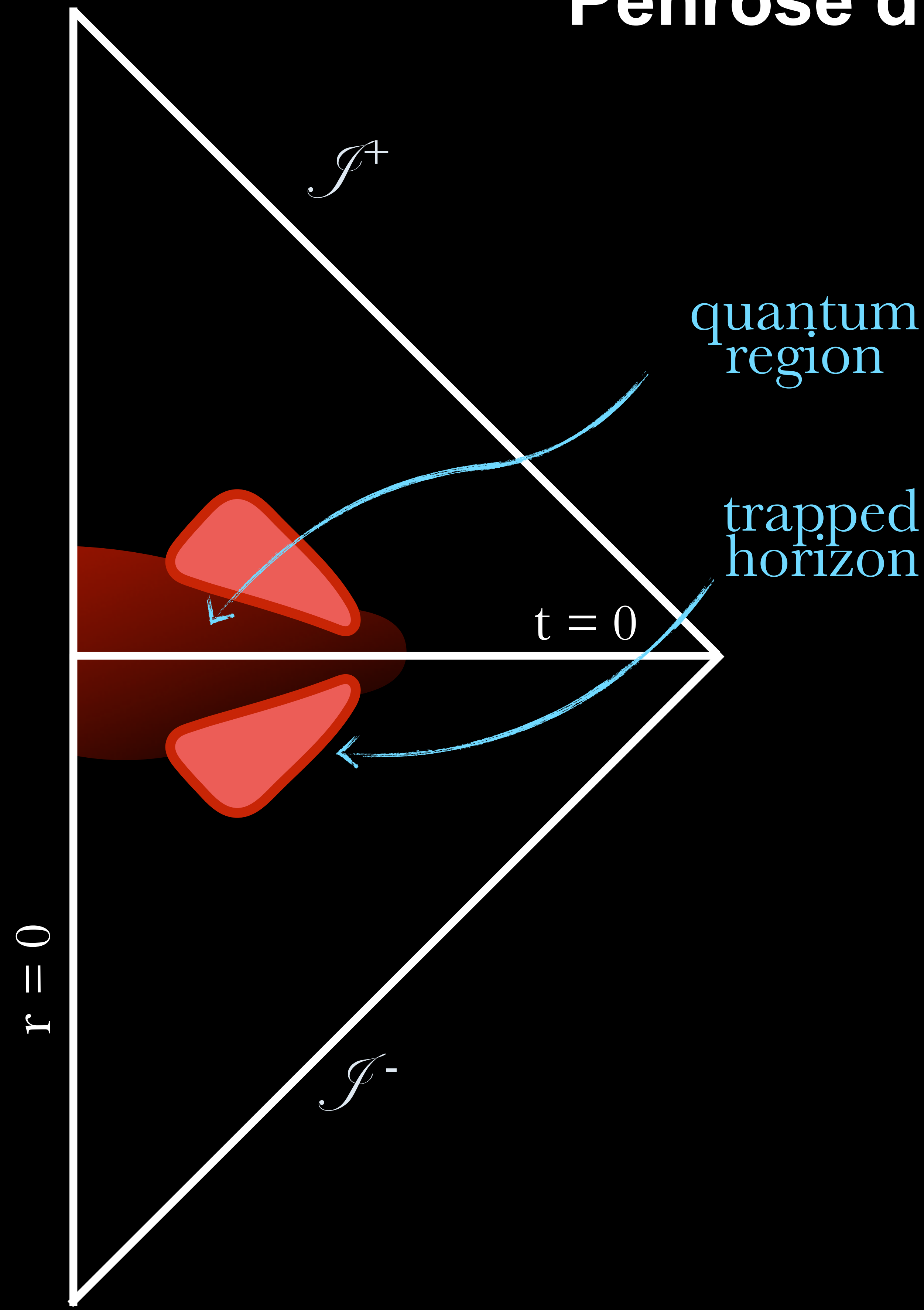
$$ds^2 = r^2 d\omega^2 + 2dv\,dr - F(r)du^2$$

$$F(r) = 1 - \frac{2mr^2}{r^3 + 2\alpha^2 m}$$

Hayward 0506126
Koch, Saueressig 1401.4452



Penrose diagram



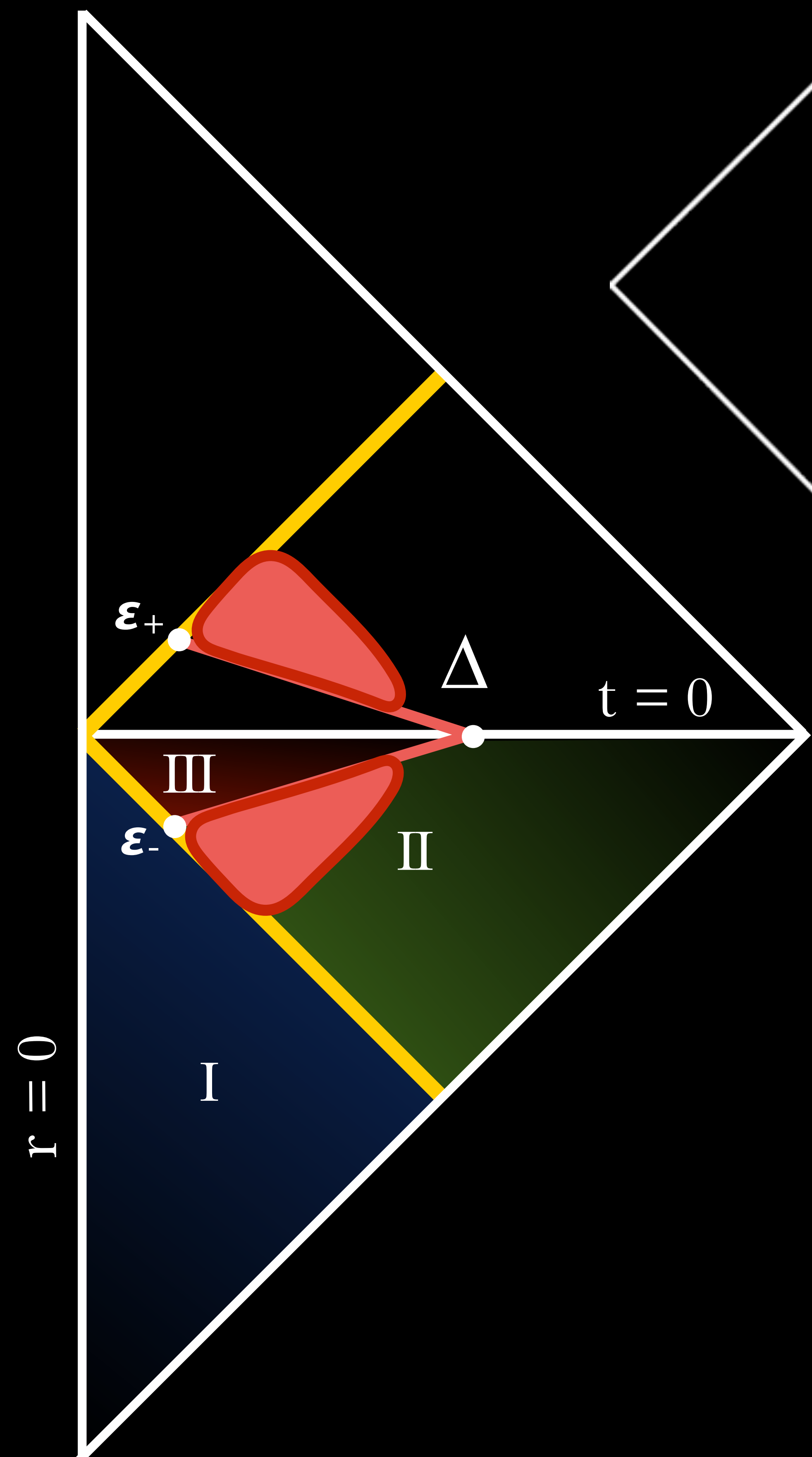
Hájíček, Kiefer 0107102

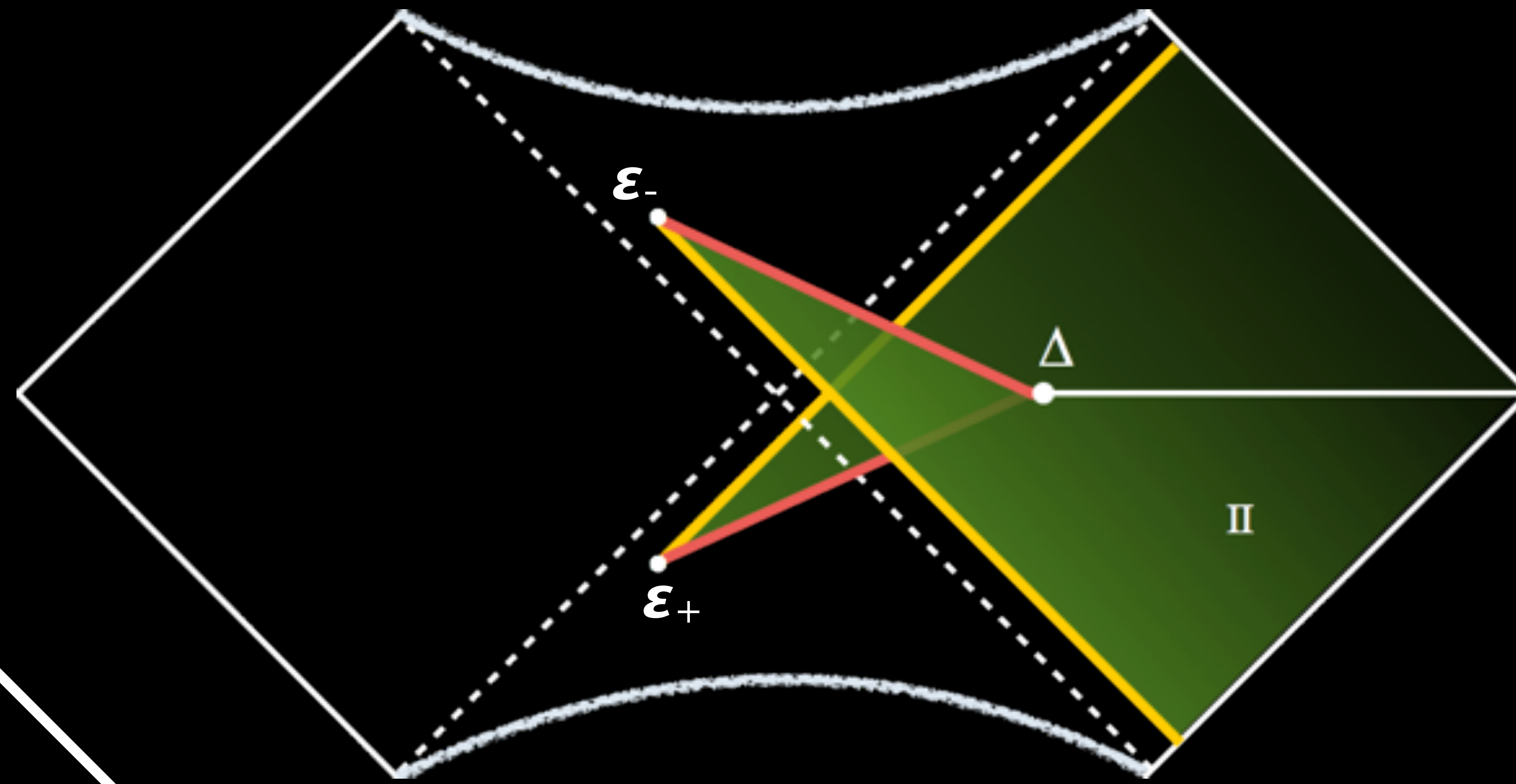
a collapsing quantum light-like shell bounces and re-expands

time-symmetric process:
white hole

Black hole → white hole

quantum tunneling





Metric that describe the process

vacuum solution of Einstein equations

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

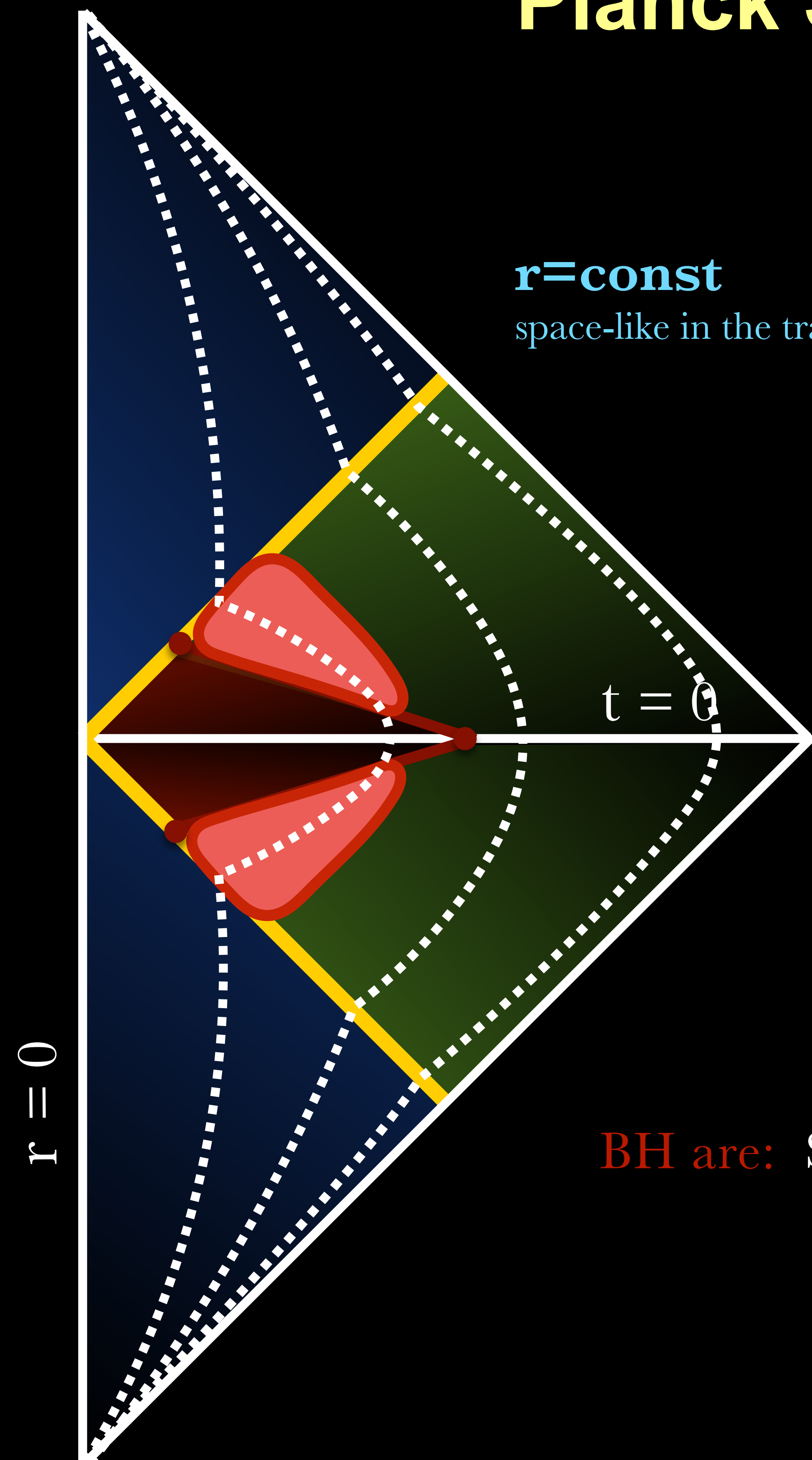
I. Minkowski

II. Schwarzschild

III. Quantum Gravity

Haggard, Rovelli 1407.0989

Planck Star: Black Hole → White Hole



r=const

space-like in the trapped region

quantum tunneling

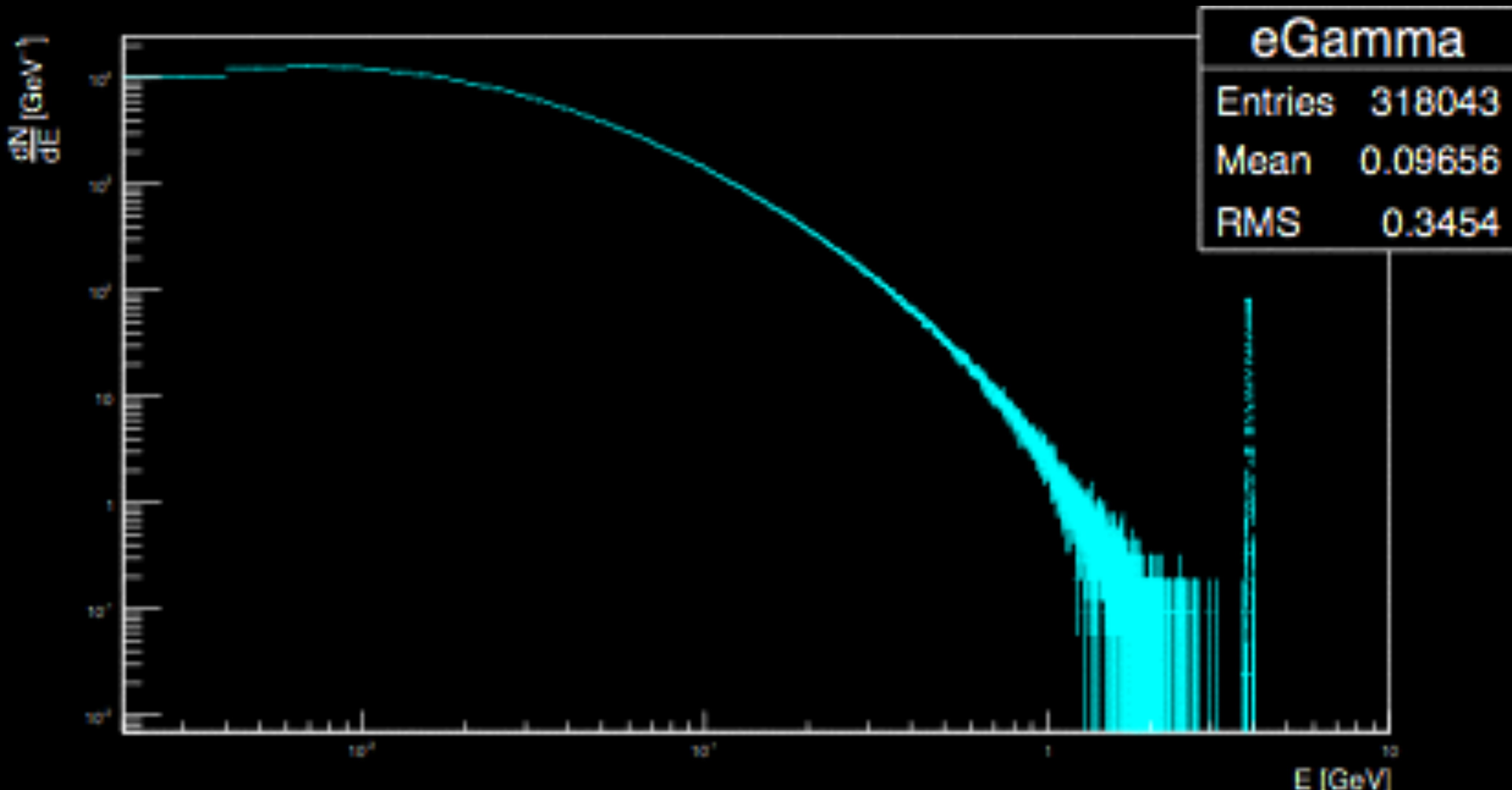
- Quantum pressure
- Planck density object radius $\gg$ Planck length $\quad r_b \sim \left(\frac{m}{m_P}\right)^{\frac{1}{3}} \ell_P$
- quantum effects appear at $\quad r \sim \frac{7}{6}\, 2m$
- asymptotic proper time $\quad \tau \sim \frac{m^2}{\ell_P}$

BH are: Shortcut to the future / Bounce seen in slow motion

- emission at $\quad E_{burst} = \frac{hc}{2\, r_f} \approx 3.9\, Gev$

Energy spectrum of photons

Barrau, Rovelli 1404.5821



”Lund Monte Carlo” PYTHIA code

$$E_{burst} = \frac{hc}{2\, r_f} \approx 3.9\, Gev$$

Detectable?

- ~10 MeV
- One event per day
- Isotropic
- Short gamma-ray burts
- From ~200 light years

Caveat

Summary:

- Quantum cosmology from the full theory:

Spinfoam Cosmology

- A new look at singularity resolution:

maximal acceleration

- Black holes tunnels into withe holes:

Planck Stars

- Quantum Tunneling
- Effective repulsive force
- Size $\gg$ Planck length

→

- Metric for Black-to-White process
- BH are bounce in slow motion
- Quantum Gravity Phenomenology!