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Perspectives On

Non Singular Black Holes

Online Lecture

Virtual Institute of Astroparticle Physics

February 5th, 2016

Black Holes ⟶ Event Horizon

- Predicted by General Relativity.
- Any sufficiently massive star will collapse forming a Black Hole.
- “Perfect objects”: no hair theorem $\longrightarrow$ M,J,Q.
- Observations: very active field Event Horizon Telescope.

MOTIVATIONS

I. Singularity: infinite curvature and density; point of geodesics incompleteness.

THE SINGULARITY IS UNAVOIDABLE.

[Penrose '65, Hawking ...]

II. Information Loss Paradox: evolution of quantum fields on a BH background is not unitary.

CONTRADICTS QUANTUM MECHANICS POSTULATES.

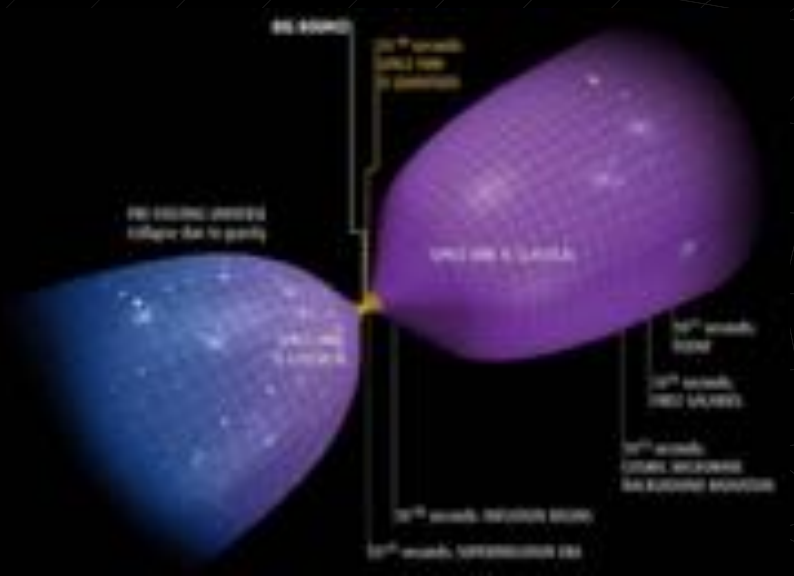
[Hawking '74]

Singularity Resolution

The Main Idea

WHEN COLLAPSING MATTER REACHES PLANCK DENSITY,
QUANTUM GRAVITY DOMINATES,
PRODUCING AN EFFECTIVE REPULSIVE FORCE.

Minisuperpace in Loop Quantum Gravity



Cosmology: Big ~~Bang~~
Bounce

[Bojowald; Ashtekar]

Black Holes: ~~Singularity~~
Regular center

[Gambini, Pullin & Olmedo; Modesto]

Regular BHs

Asymptotic Safety
[Litim, Sauressing …]

Loop Quantum Gravity
[Gambini, Pullin, Olmedo, Modesto …]

Non-Commutative Geometries
[Ansoldi, Nicolini, Spallucci, Smailagic …]

Non-Linear Electromagnetism
[Stelle, Ayon-Beato, Garcia, Berej …]

Bose-Einsteins Condensate
[Mottola, Mazur, Visser …]

Shape Dynamics
[Gryb, Herczeg …]

OUR APPROACH: EFFECTIVE DESCRIPTION
[Bardeen, Hayward, Dymnikova, Frolov …]

Hayward Example

Big Bounce: New effective cosmological parameter

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\,\rho\left(1 - \frac{\rho}{\rho_c}\right)$$

Black Hole: New effective internal parameter

$$ds^2 = -F(r)dt^2 + F(r)^{-1}dr^2 + r^2 d\Omega^2$$

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

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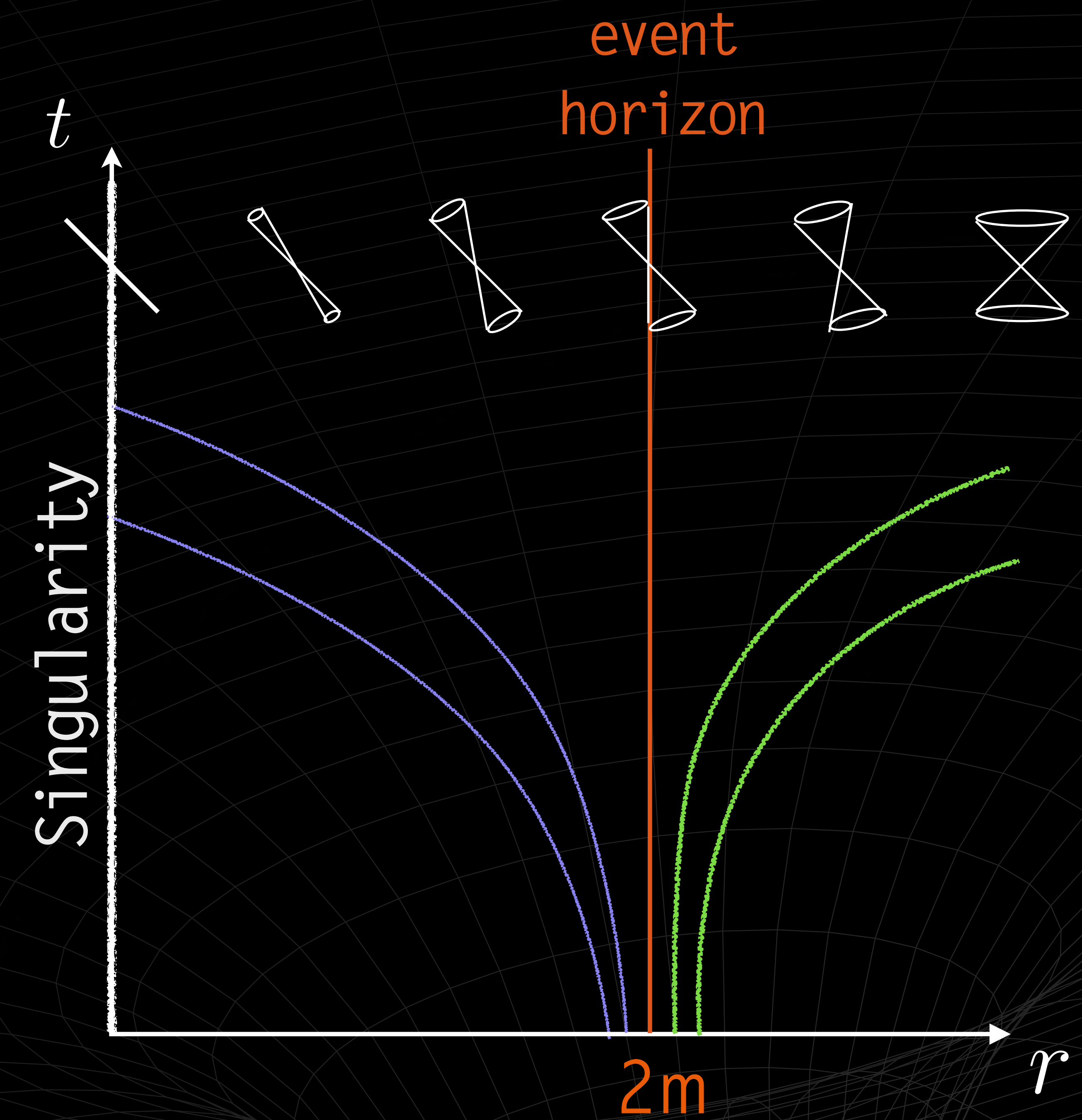
$M(r, L)$

$$M(r, L) = \frac{m\,r^3}{r^3 + 2m\,L^2}$$

[Hayward '06]



event
horizon
t
Singularity
2m
r

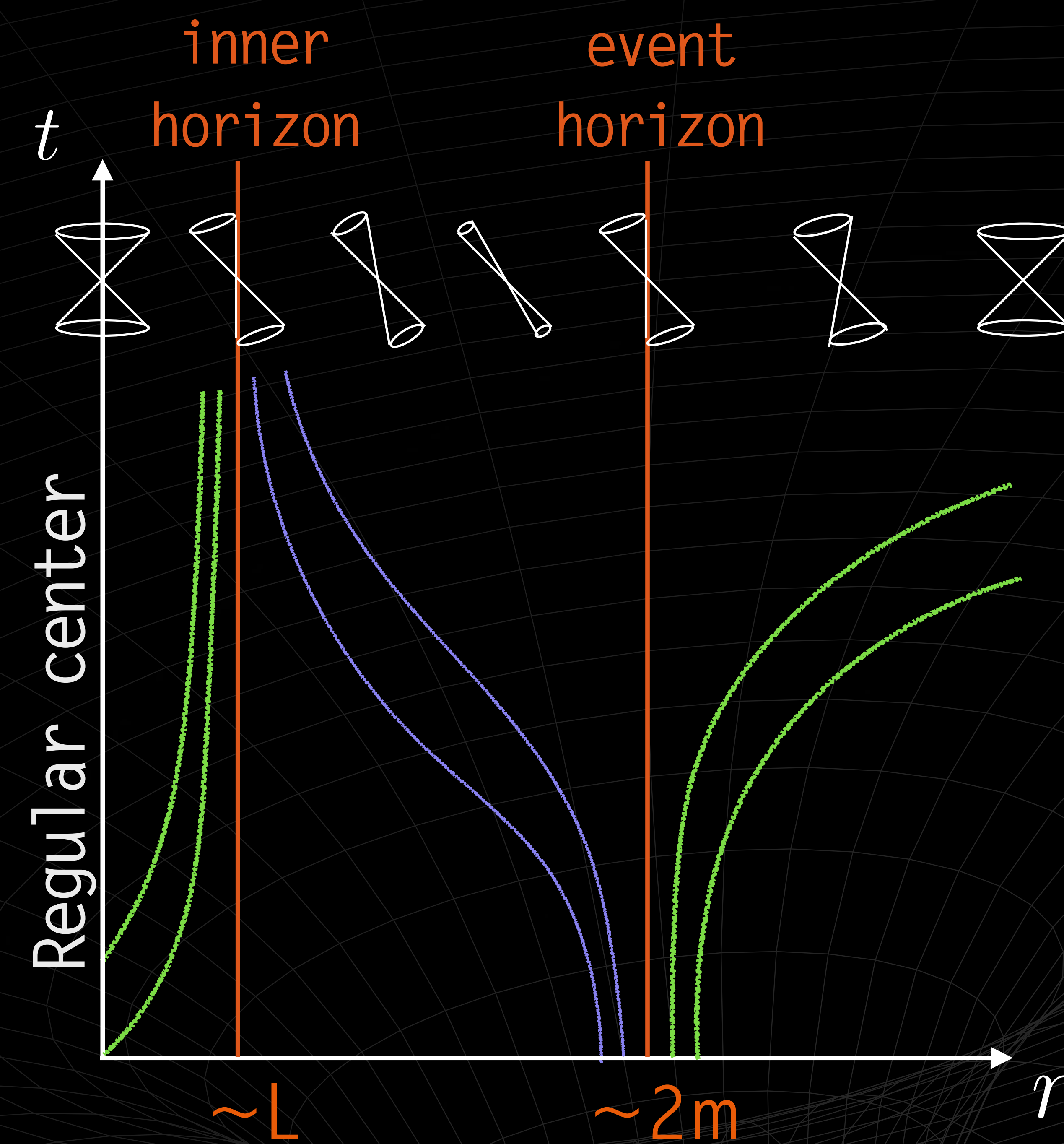
- Schwarzschild outside.

$$F(r) \to 1 - \frac{2m}{r}\,, \quad r \to \infty$$

- New inner horizon ~ L.
- Light cones un-squeezed.
- deSitter near the center.

$$F(r) \to 1 - \frac{r^2}{L^2}\,, \quad r \to 0$$

- Weak Energy Condition.
- Causal structure ~ RN.



Two Shortcomings

[TDL, Pacilio, Speziale & Rovelli '15]

- No time dilatation in the potential well.

$$\delta\tau = \sqrt{F(r)}\,\delta t \quad \Longrightarrow \quad \delta\tau(r\to\infty) = \delta\tau(r\to 0)$$

- Asymptotic behavior does not match the 1-loop corrections to the Newton's potential.

$$\Phi(r) = -\tfrac{1}{2}(1+g_{00}) \quad + \quad g_{00} = -1 + \frac{2m}{r} - \frac{4L^2m^2}{r^4} + o\left(\tfrac{1}{r^5}\right)$$

$$\not\approx \quad \Phi(r) = -\frac{G\,m}{r}\left(1 + \beta\,\frac{l^2_{\text{planck}}}{r^2}\right) + o\left(\tfrac{1}{r^4}\right)$$

[Donoghue, Holstein & Bjerrum-Bohr '03]

Modified Hayward

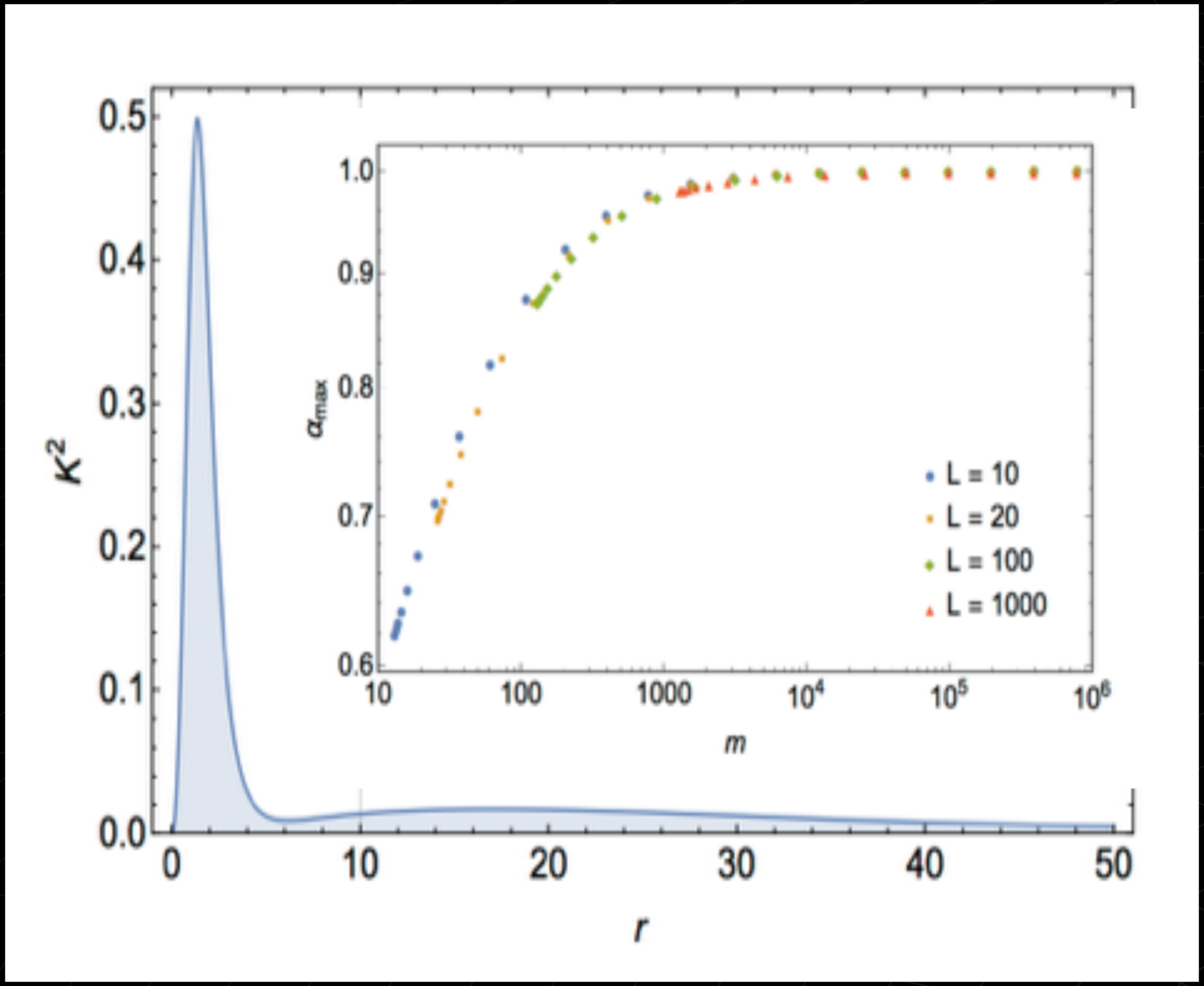
[TDL, Pacilio, Speziale & Rovelli '15]

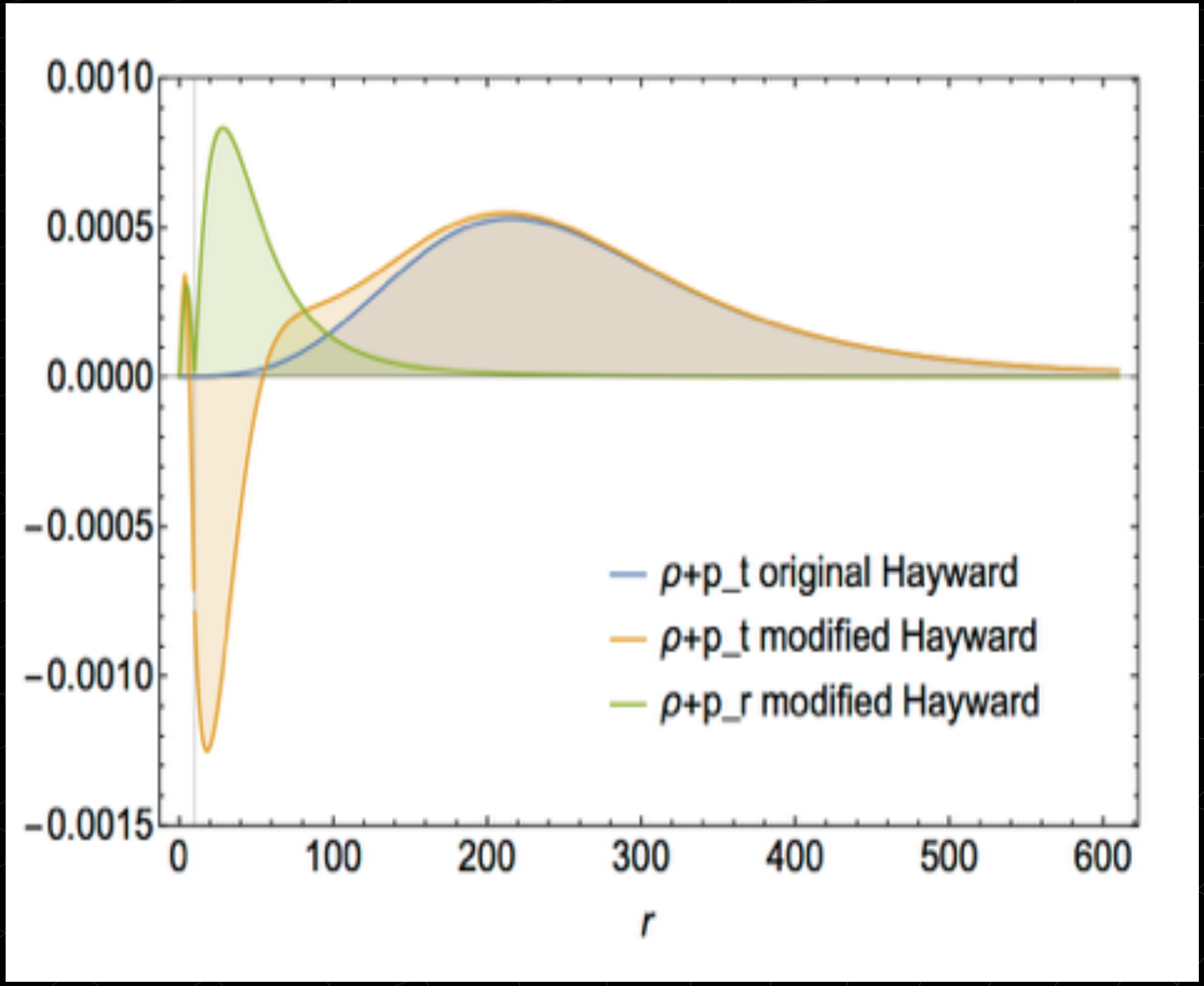
$$ds^2 = -G(r)F(r)dt^2 + F(r)^{-1}dr^2 + r^2 d\Omega^2$$

Simple proposal:

$$G(r) = 1 - \frac{\beta\, m}{r^3 + \frac{\beta\, m}{\alpha}} \quad \begin{cases} \frac{(\delta\tau_\infty - \delta\tau_0)}{\delta\tau_\infty} \simeq \frac{1}{2}\alpha \\ \Phi(r) = -\frac{G\, m}{r}\left(1 + \beta\,\frac{l_{\text{planck}}^2}{r^2}\right) \end{cases}$$

A more physical (static) non-singular black hole!





Sub-planckian curvature implies a (non-stringent) bound on alpha.

WEC is violated.

[TDL, Pacilio, Speziale & Rovelli '15]

ADDING ROTATION

STRATEGY: NEWMAN-JANIS ALGORITHM

$g(m,\ldots) \longrightarrow g(m, J, \ldots)$

[Newman & Janis '65]

Applied to Hayward (and Bardeen) metric $g(m,L) \longrightarrow g(m, L, J)$

[Bambi & Modesto '13]

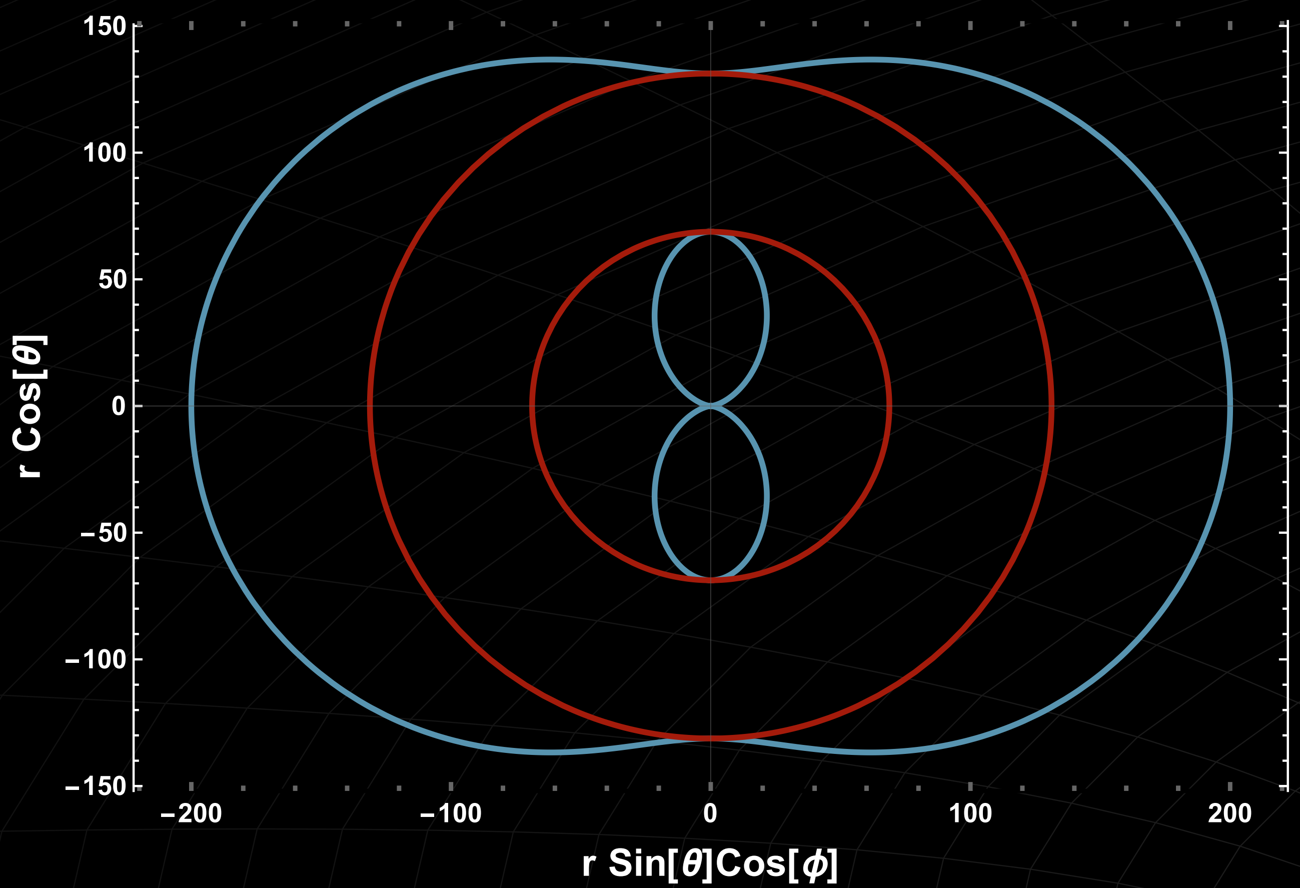
<u>KERR METRIC WITH m REPLACED BY M(r,L): NO SINGULARITY.</u>

- Not rotating deSitter in the center.
- Weak Energy Condition is violated.

} Non-trivial behavior of NJA.

- L decreases the maximal energy extraction.
- L displaces the horizons, qualitatively as a charge Q.
- L allows the time delay to be still measured by g_{00}.

Kerr



Bambi-Modesto

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- L allows the time delay to be still measured by g_{00}.

Rotation + Time Delay

[TDL, Giusti, Speziale '16]

STRATEGY: NEWMAN-JANIS ALGORITHM

$$g(m,L,\alpha) \longrightarrow g(m,L,\alpha,J)$$

$$\mathcal{K}|_{r=0} \sim \frac{c_1}{(\theta-\frac{\pi}{2})^6} + \frac{c_2}{(\theta-\frac{\pi}{2})^4} + \frac{c_3}{(\theta-\frac{\pi}{2})^4} + O(1)$$

Rotating metric, but a singularity is (generally) reintroduced.

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[TDL, Giusti, Speziale '16]

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STRATEGY: MODIFY THE BAMBI-MODESTO METRIC

Kerr-like non-singular black hole with a time delay in the center and good asymptotic behavior.

Information Paradox Resolution

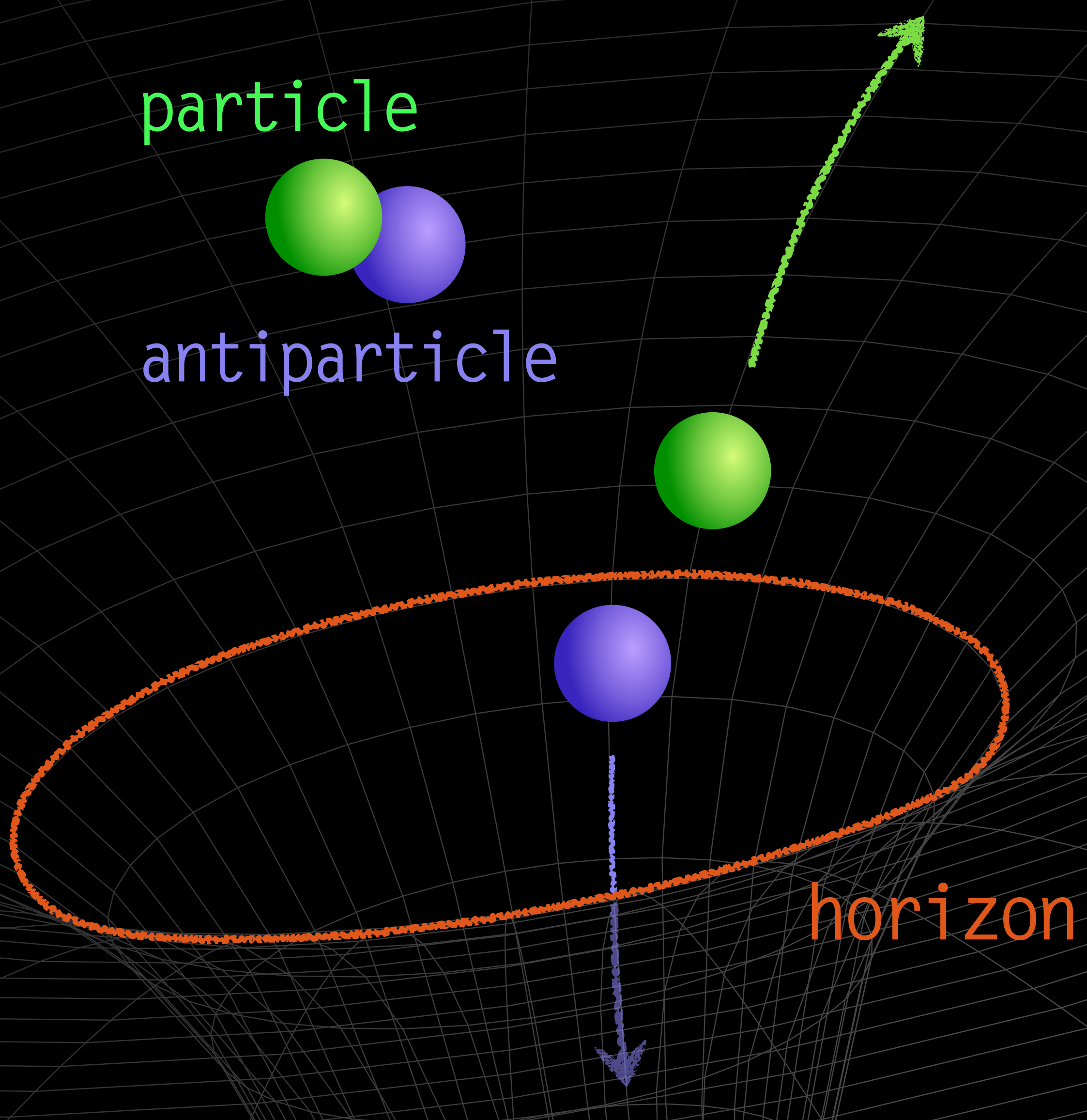
Hawking Evaporation

When evolution of Quantum Fields on the Curved Background is considered

a Black Hole emits particles. Conservation of the energy forces its mass to decrease and the Black Hole to completely evaporate.

$$t_{\text{ev}} \sim m^3$$

[Hawking '74]



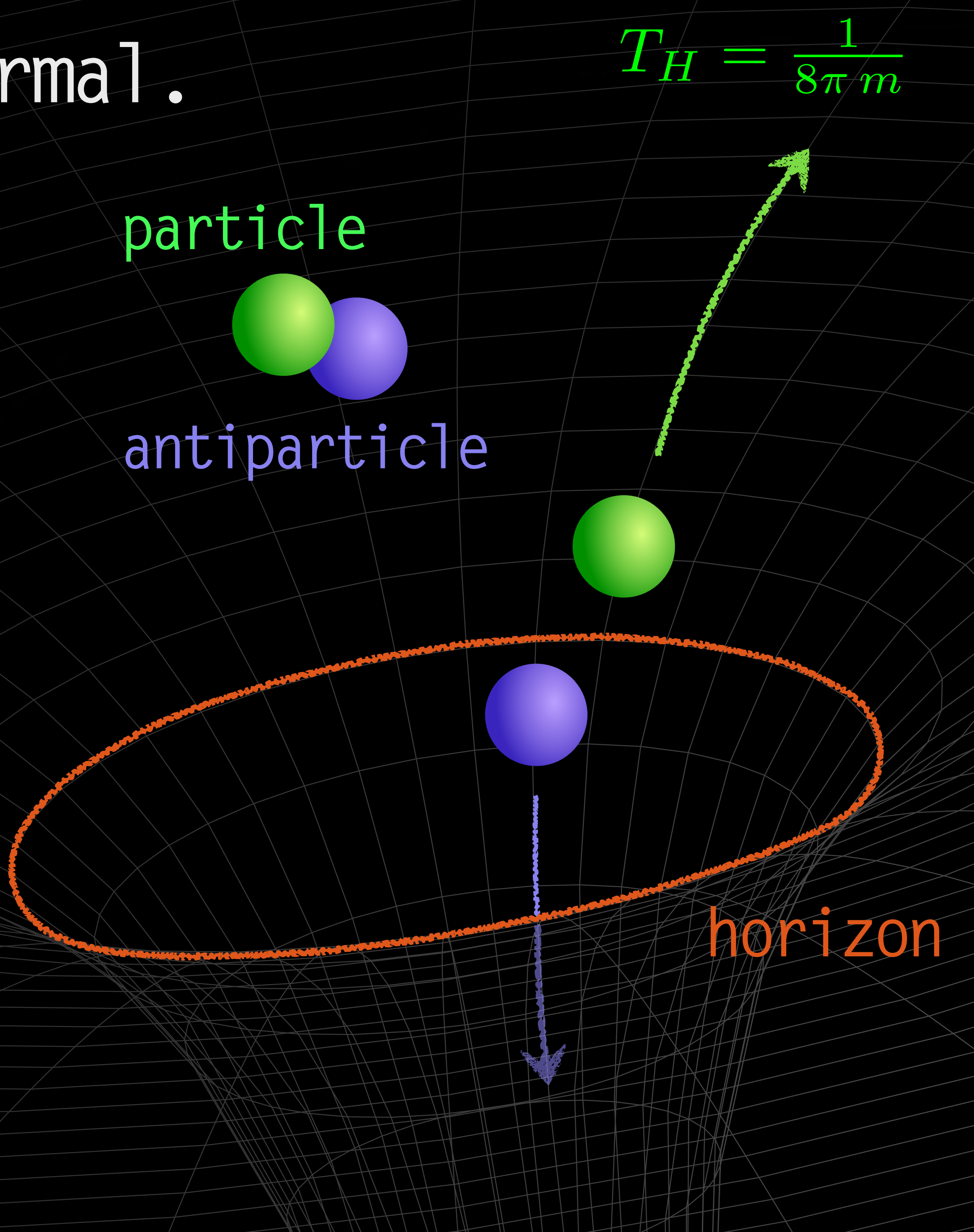
INFORMATION PARADOX

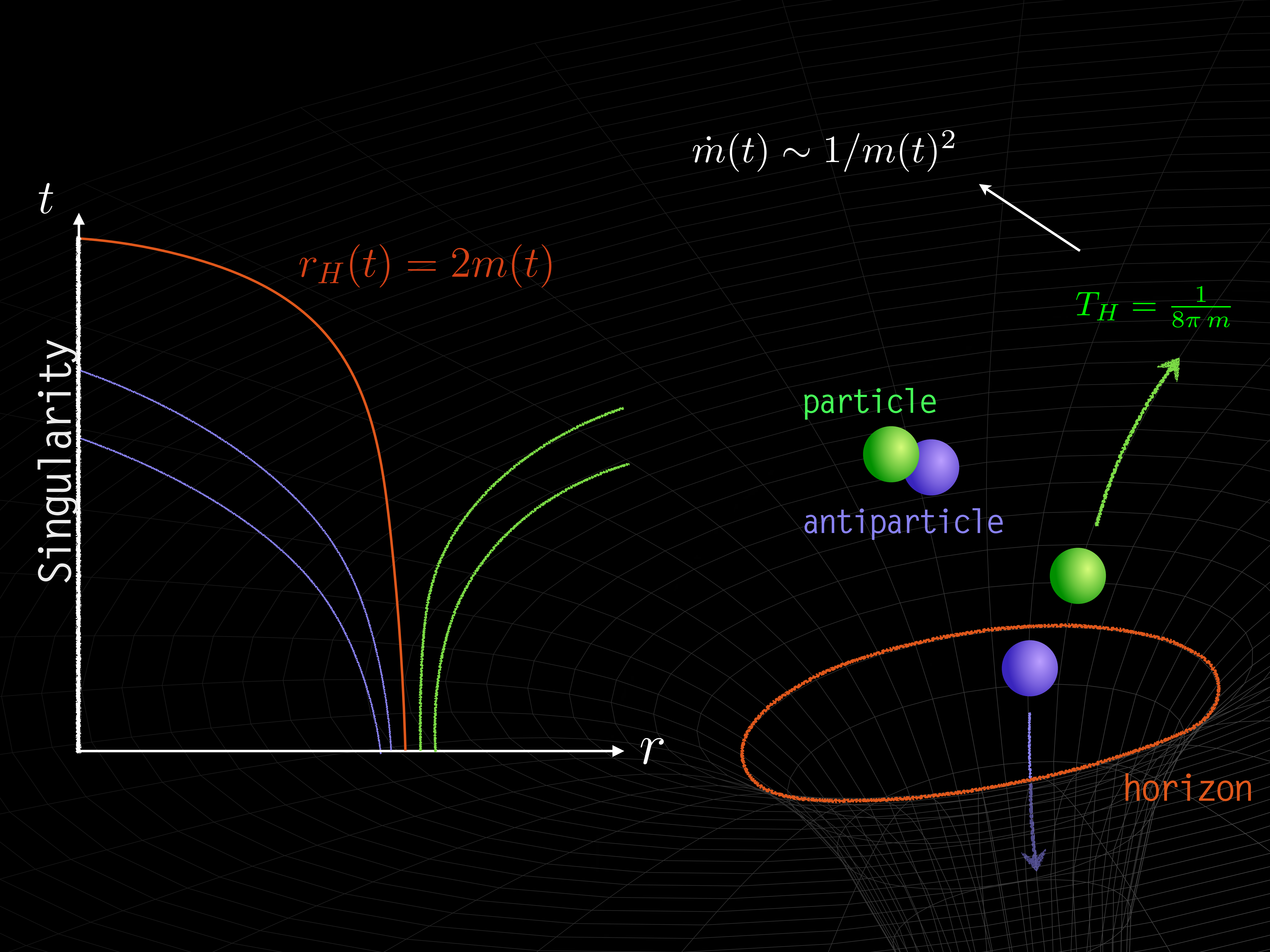
The spectrum of emission is thermal.

$$T_{\odot} \simeq 10^{-7} K$$

THE VACUUM (<u>PURE</u>) STATE EVOLVES INTO A THERMAL (<u>MIXED</u>) STATE.

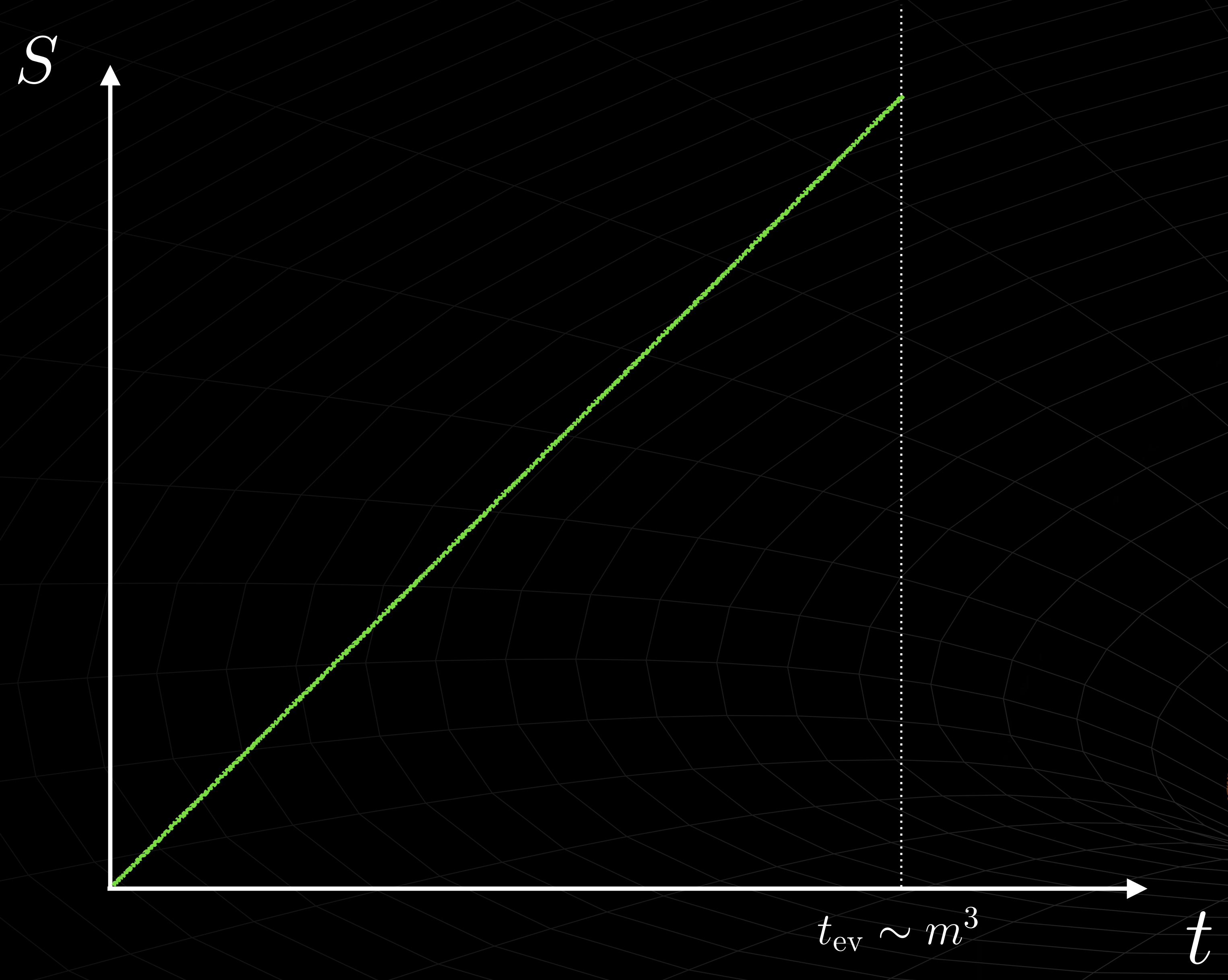
Non-unitary evolution.

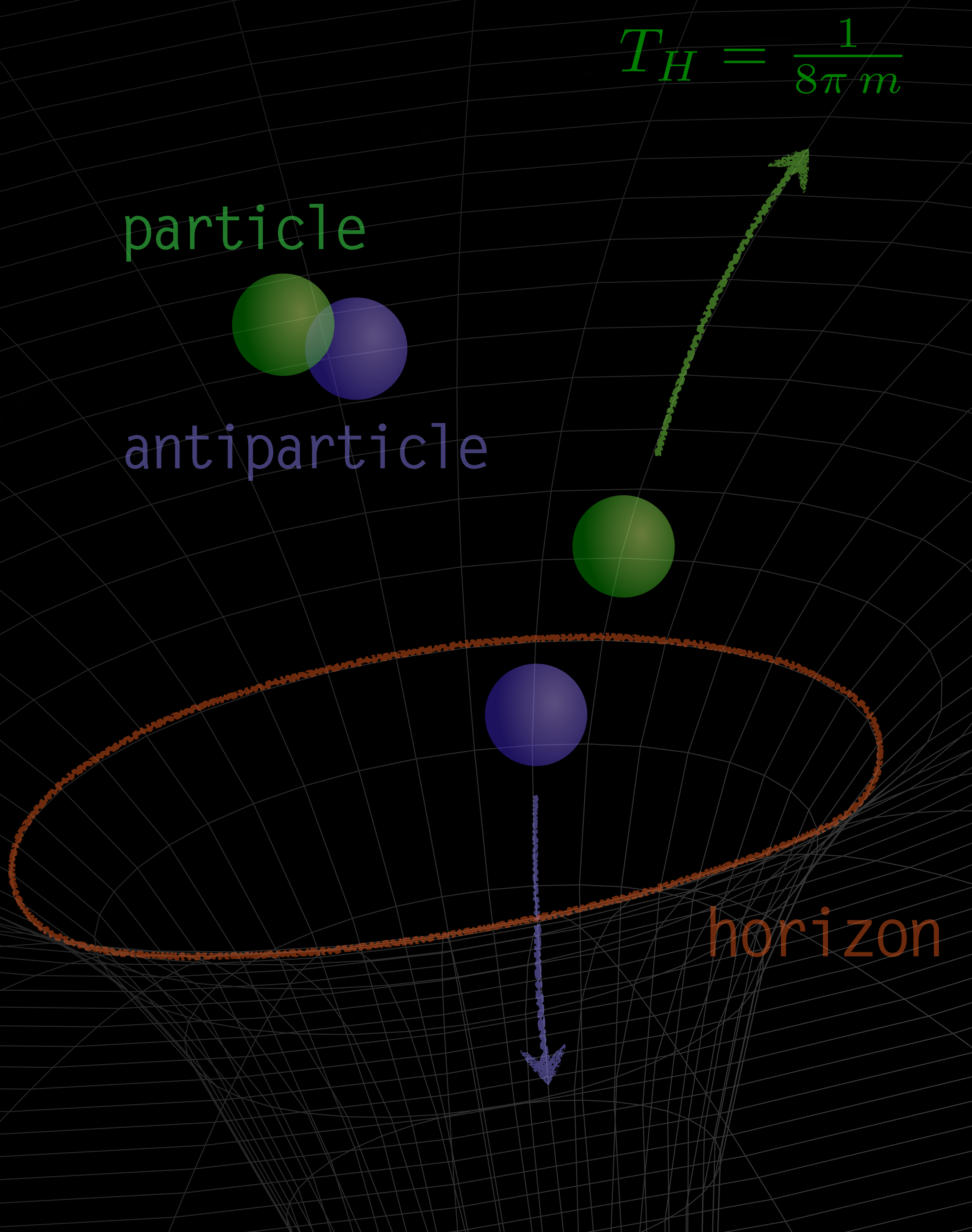




$\dot{m}(t) \sim 1/m(t)^2$
t
$r_H(t) = 2m(t)$
Singularity
r
$T_H = \frac{1}{8\pi\, m}$
particle
antiparticle
horizon

Entanglement Entropy

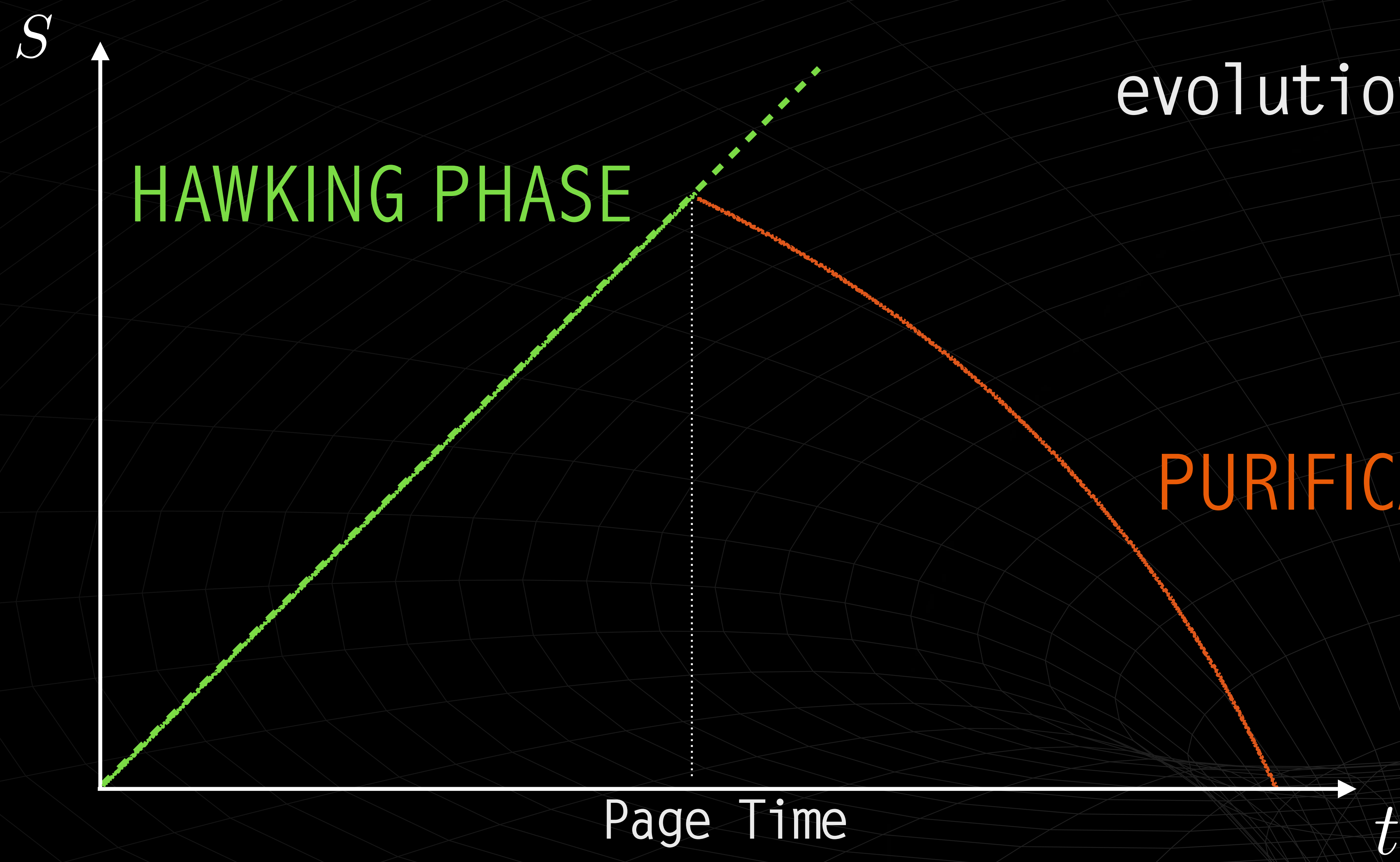




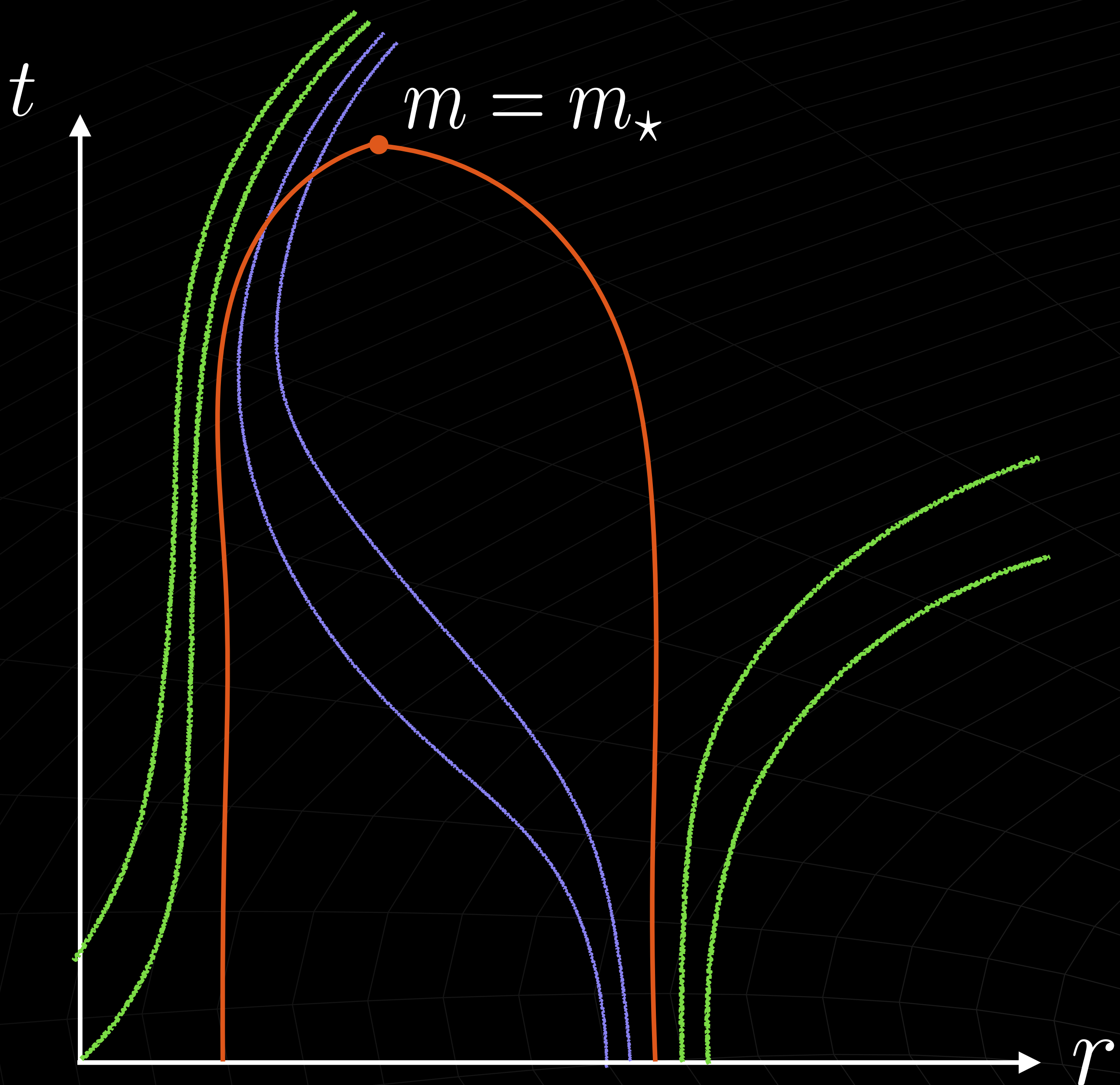
Page Curve

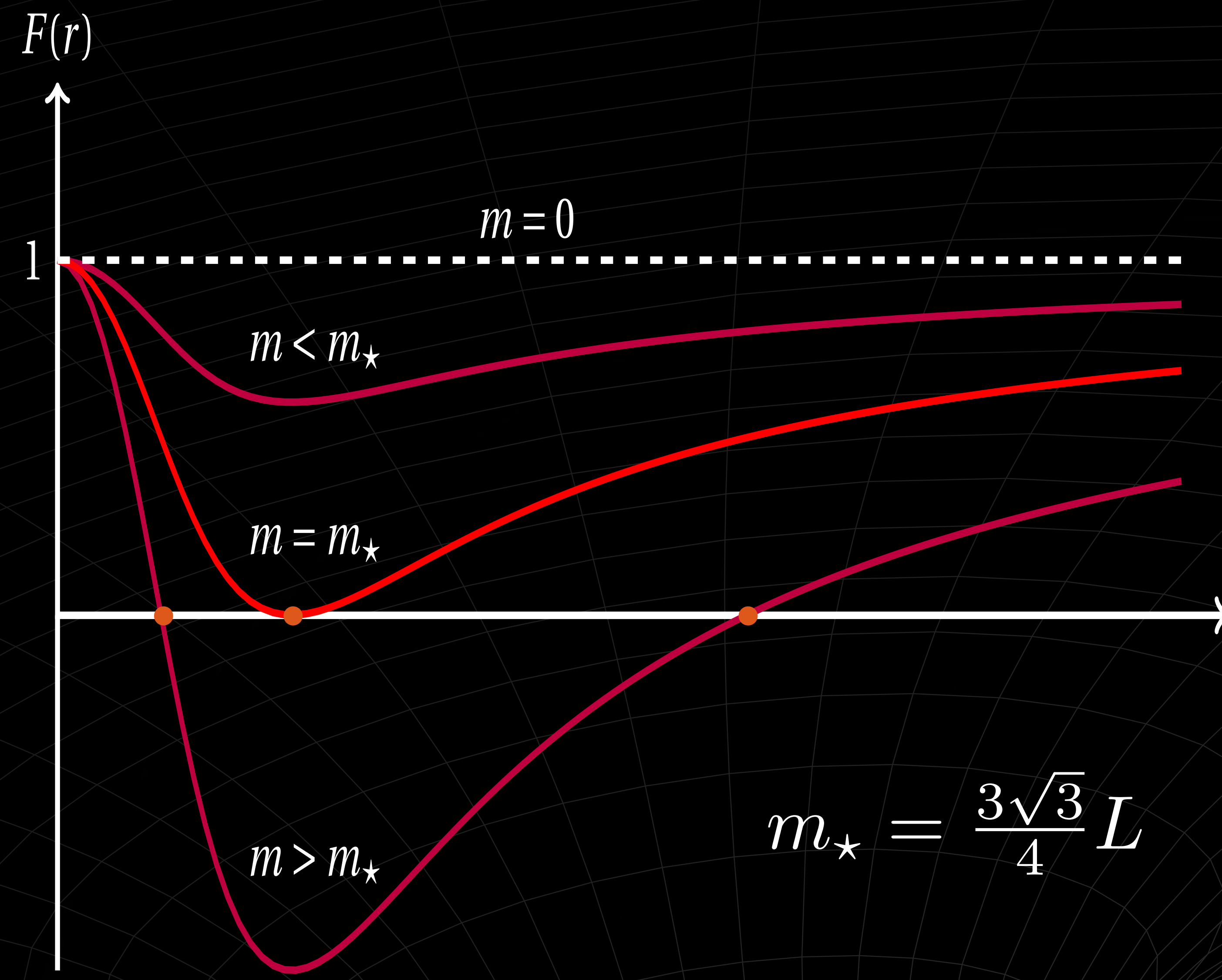
If we want the evolution to be pure.

[Page '93]



Horizons: $F(r) = 0$

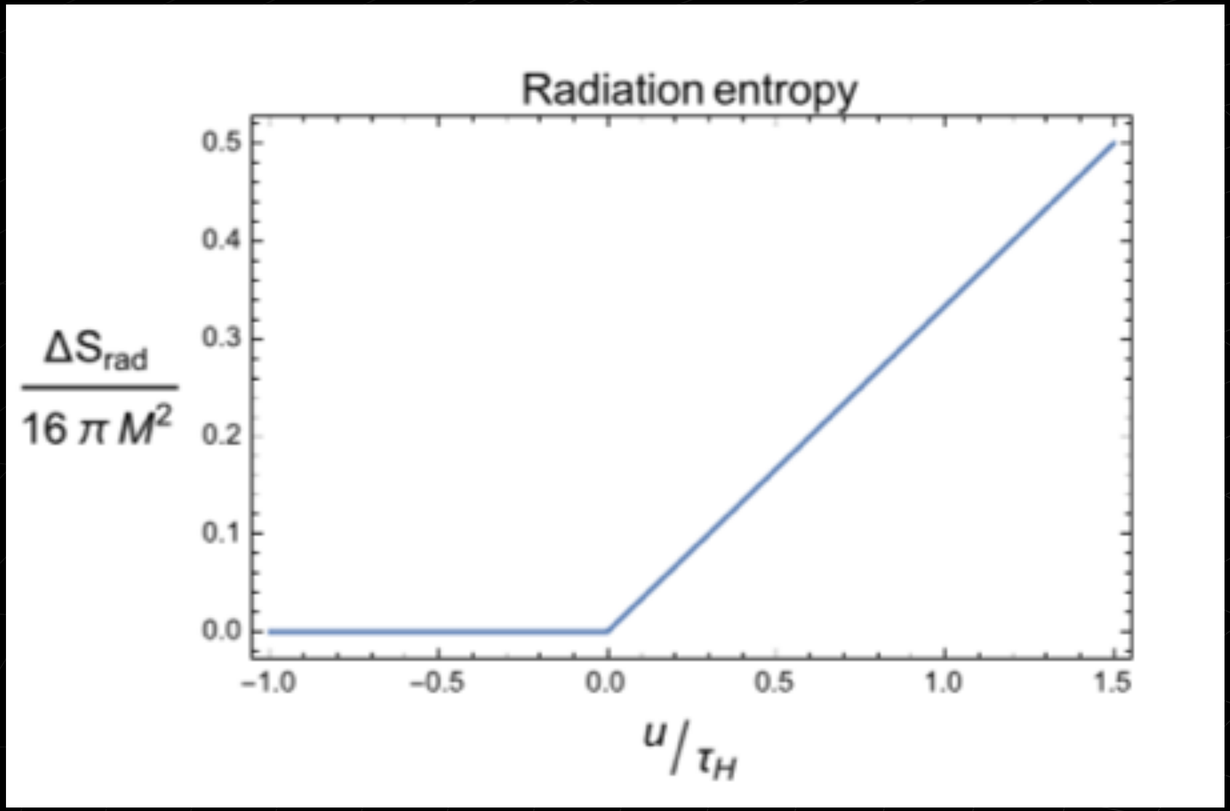


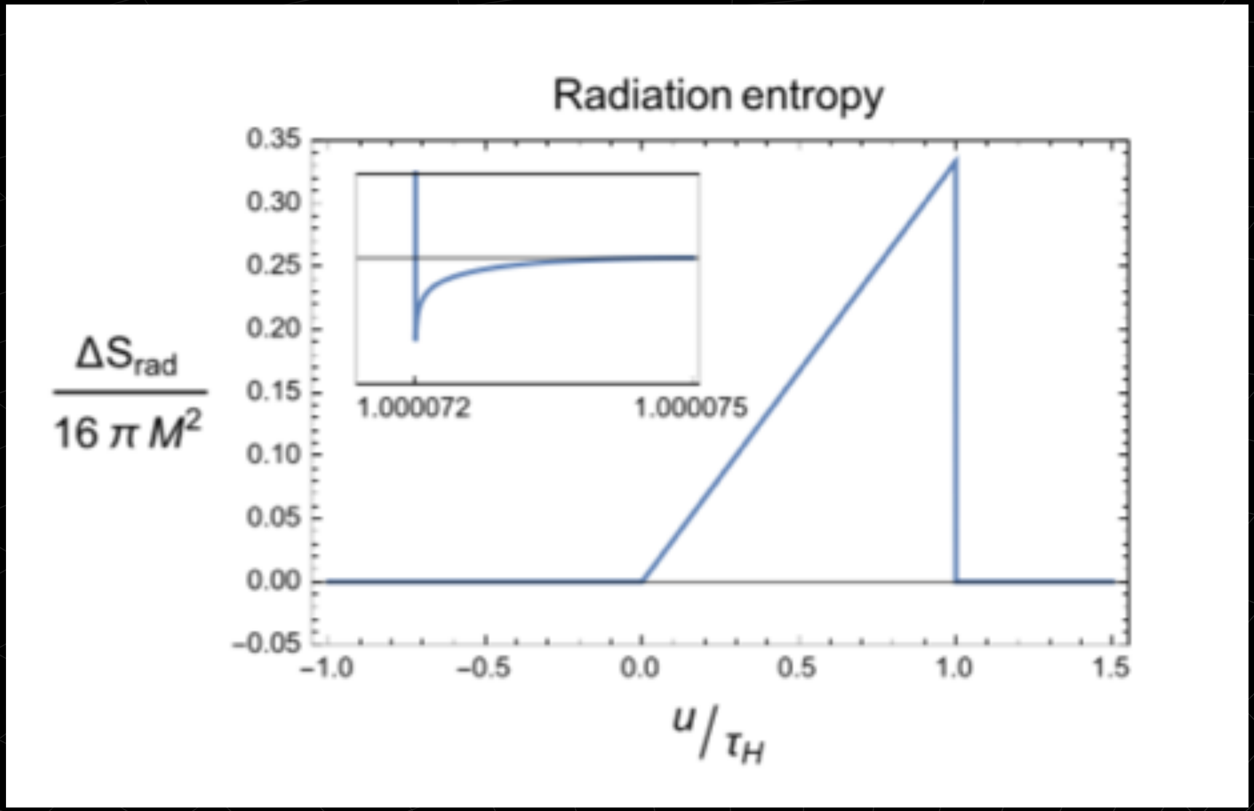


$$m_\star = \frac{3\sqrt{3}}{4} L$$

After the horizons merge, everything is free to escape.

PAGE CURVE COMPUTATION





(1+1) dimensions, neglecting backscattering, neglecting multipole l>0.

[Bianchi, TDL & Smerlak '15]

PROBLEMS

- Initial Hawking phase.
- Entanglement entropy goes back to its initial value.
- Energy radiated is more then the initial ADM mass.

THE PURIFICATION PHASE MUST BE SLOW.

$$\Delta\tau_p \gtrsim \frac{16\pi\left(m^2 - m_\star^2)\right)^2}{m_\star}$$

[Carlitz & Willey '87, Bianchi & Smerlak ?]

Take-Home Message

- We expect quantum gravity to stop the collapse: No Singularity!
- Modified Hayward: a more physically viable static metric.
- Proposal for rotating non-singular black holes.
- Information is free to escape: No Information-loss!
- Purification phase is too short.

Questions & Next Steps

- Is it possible to design a metric without these problems?
- Is the (1+1) dimension approximation too simplified?
- Are we pushing the semiclassical approach too far?
- Does quantum gravity give a completely different scenario?

[Haggard & Rovelli '14, TDL & Perez '15, Perez '14]

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Thank you!