String theory, gravity and cosmology (SGC2020)

Based on 2006.11717

Unitarity of Entanglement and Islands in Two-sided Janus Black Holes

Junggi Yoon

KIAS

November 19, 2020

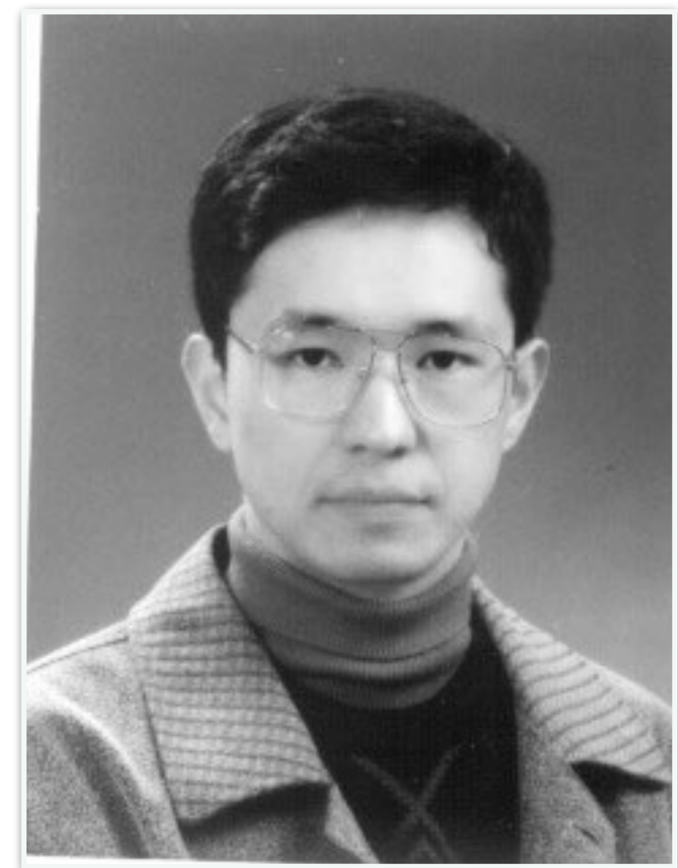
with Dongsu Bak, Chanju Kim, Sang-Heon Yi

Unitarity of Entanglement and Islands in Two-sided Janus Black Holes

D. Bak, C. Kim, S. Yi and JY
arXiv: 2006.11717

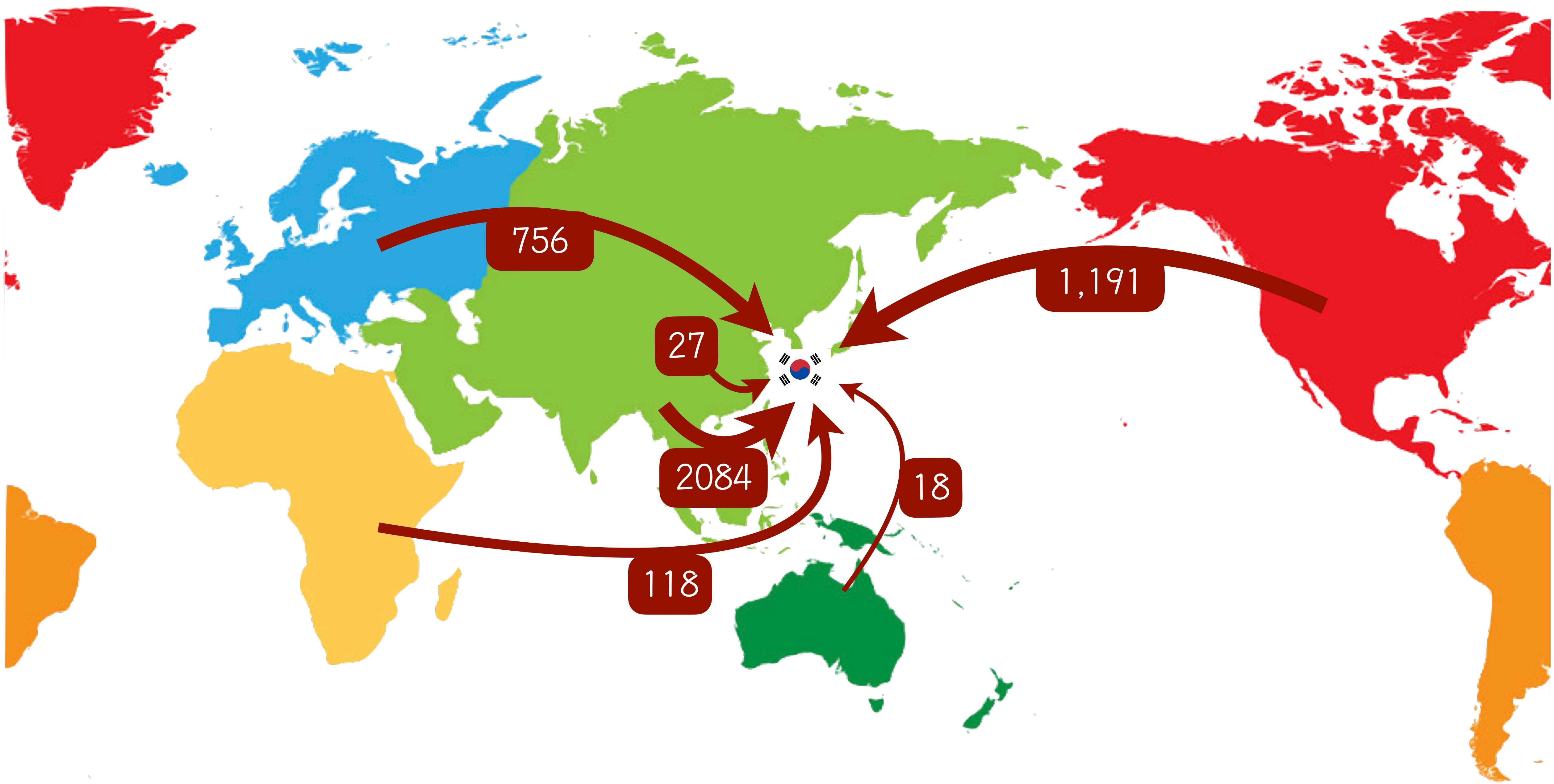
Dongsu Bak
University of Seoul

Chanju Kim
Ewha Women's University



Sang-Heon Yi
CQUEST

COVID-19: Imported Cases from Outside of Korea



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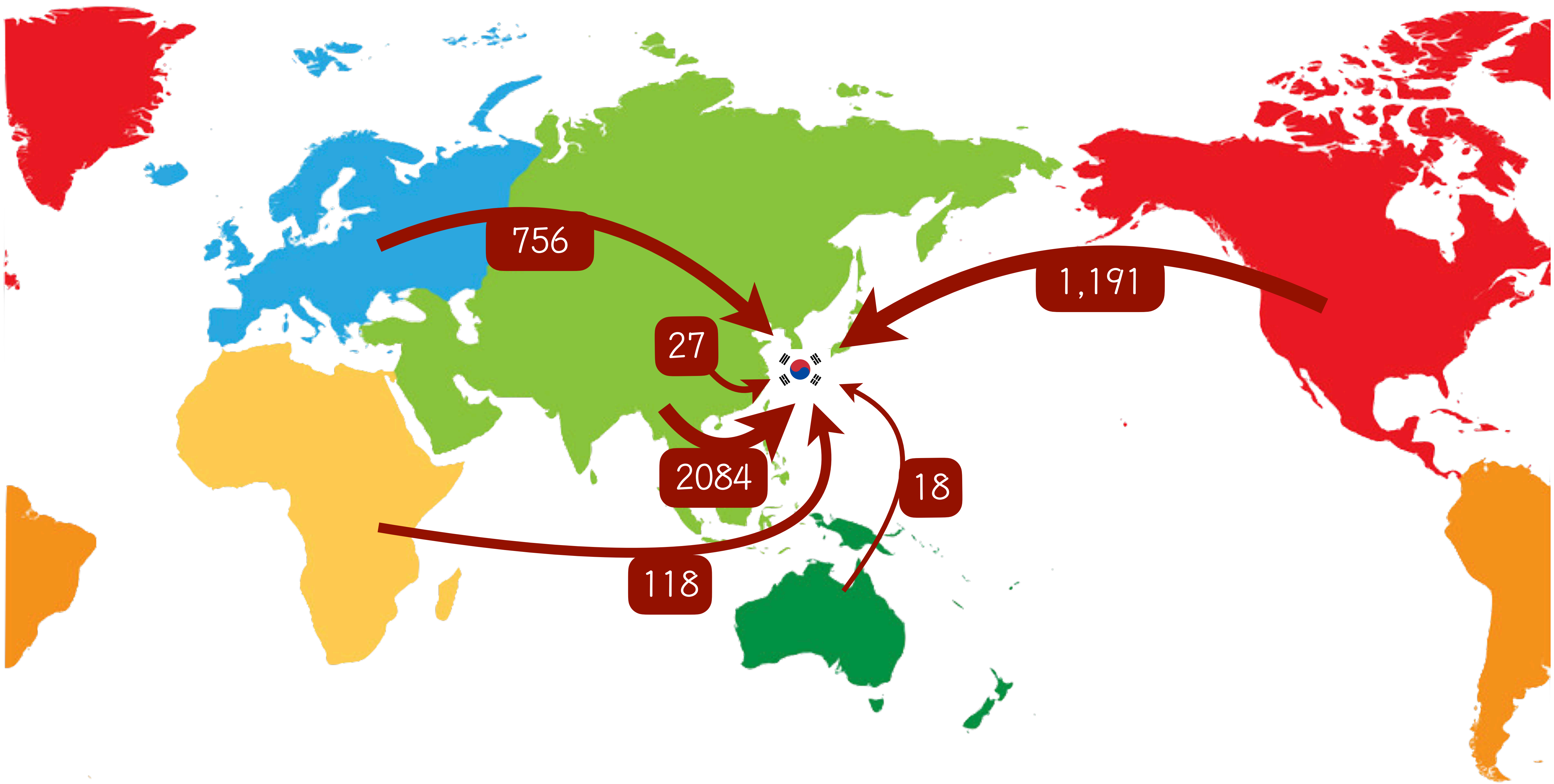
How can we reduce the number of
the imported cases?

COVID-19: Imported Cases from Outside of Korea



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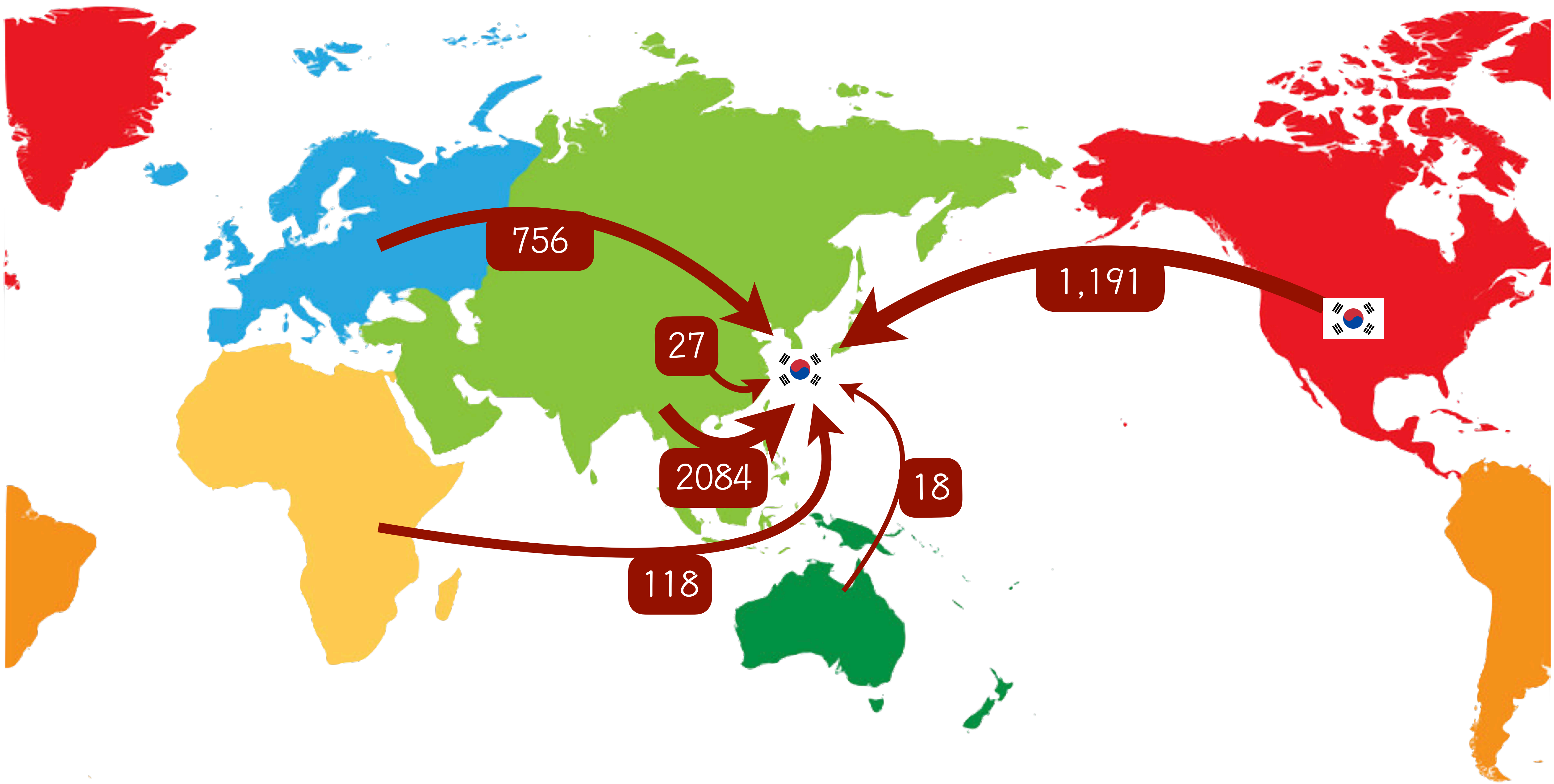

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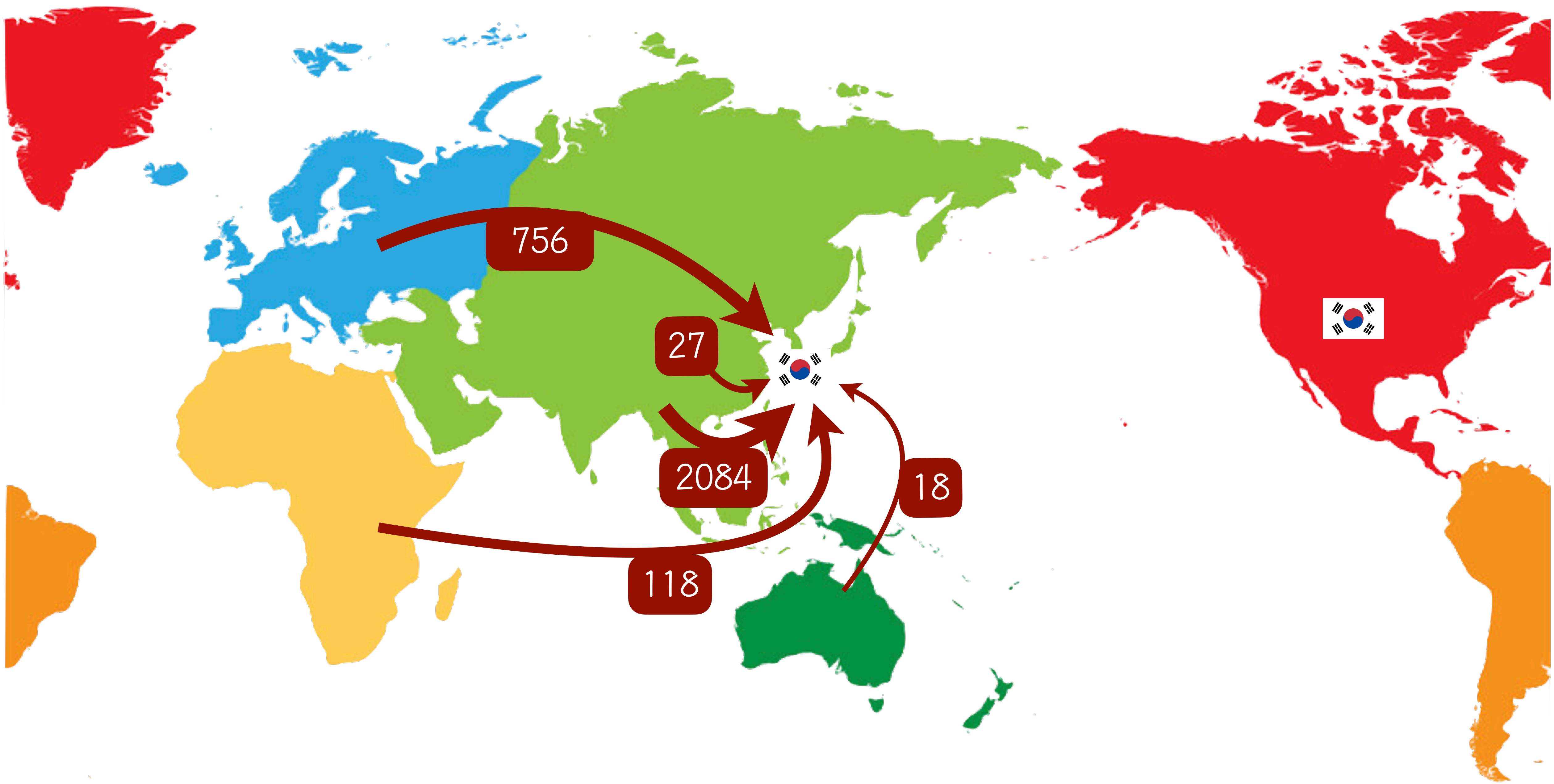

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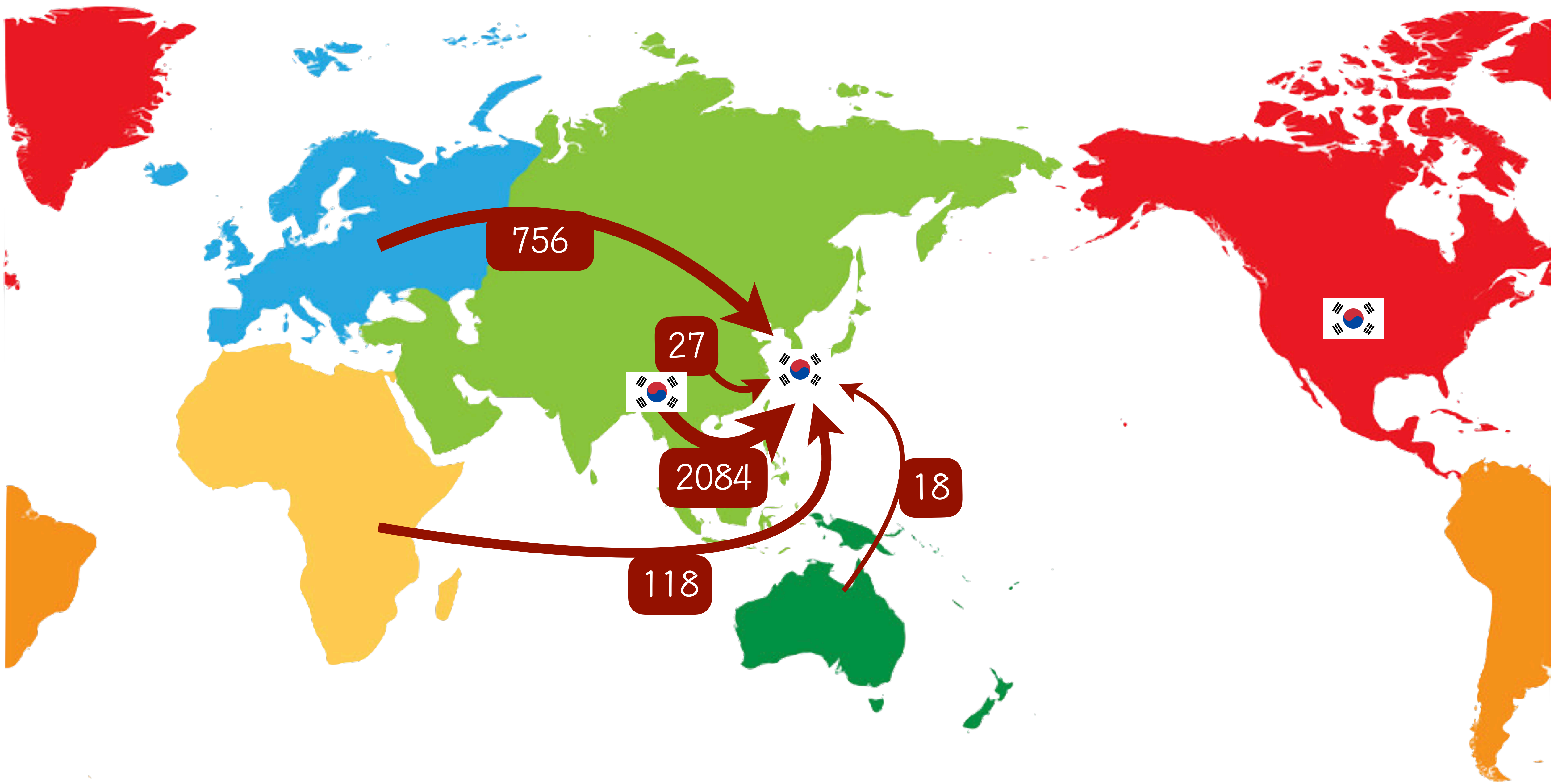

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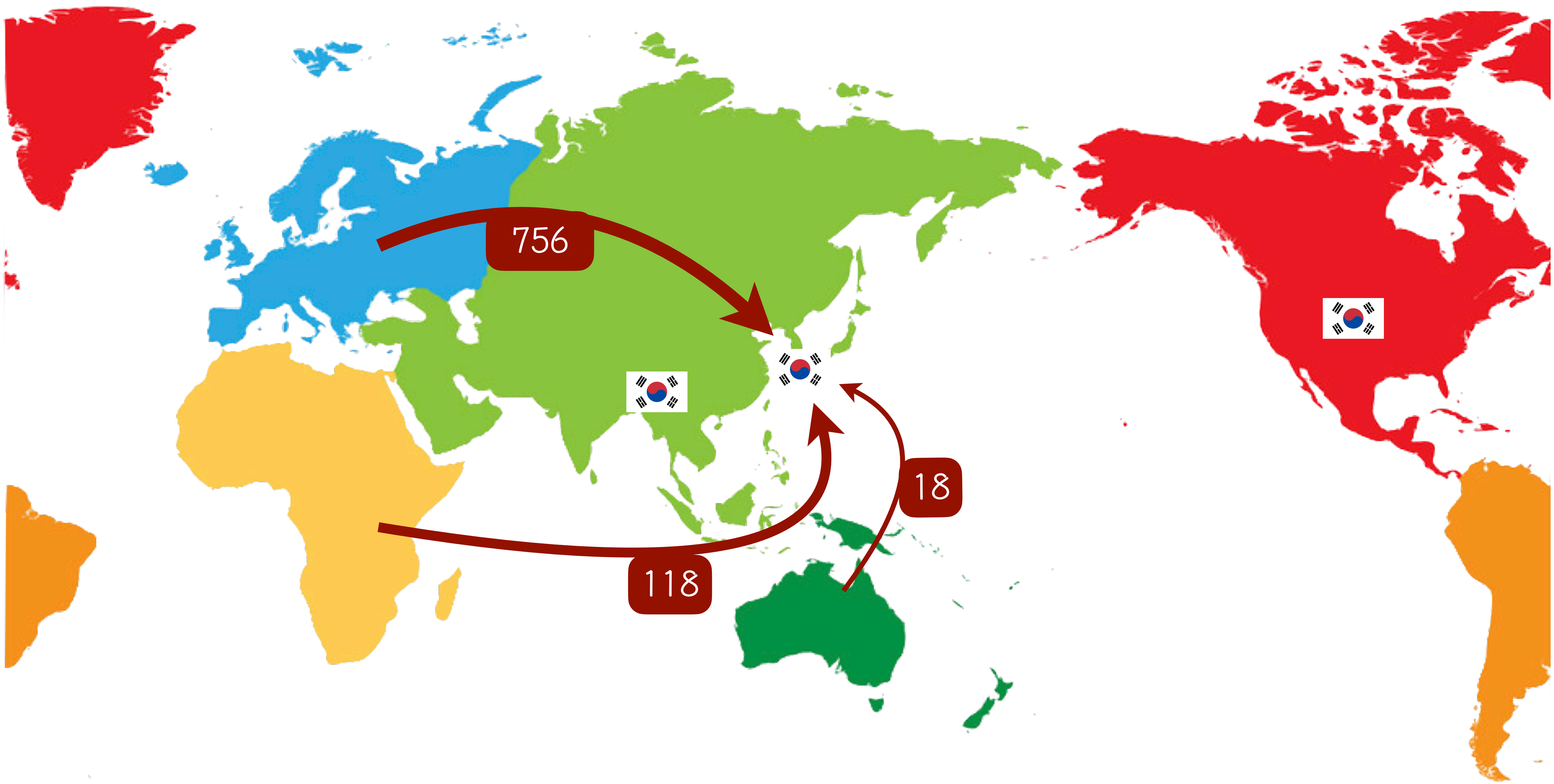

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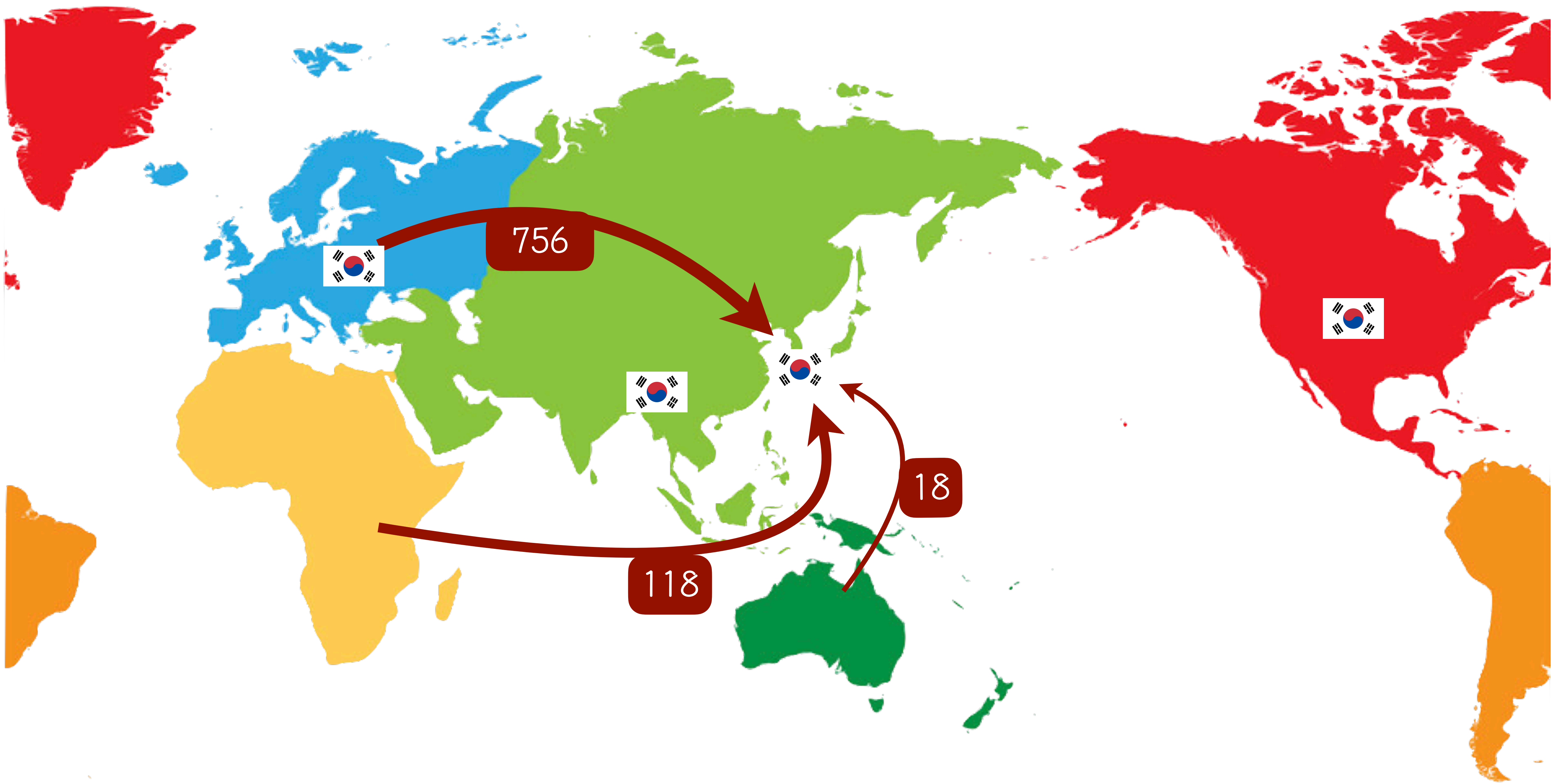

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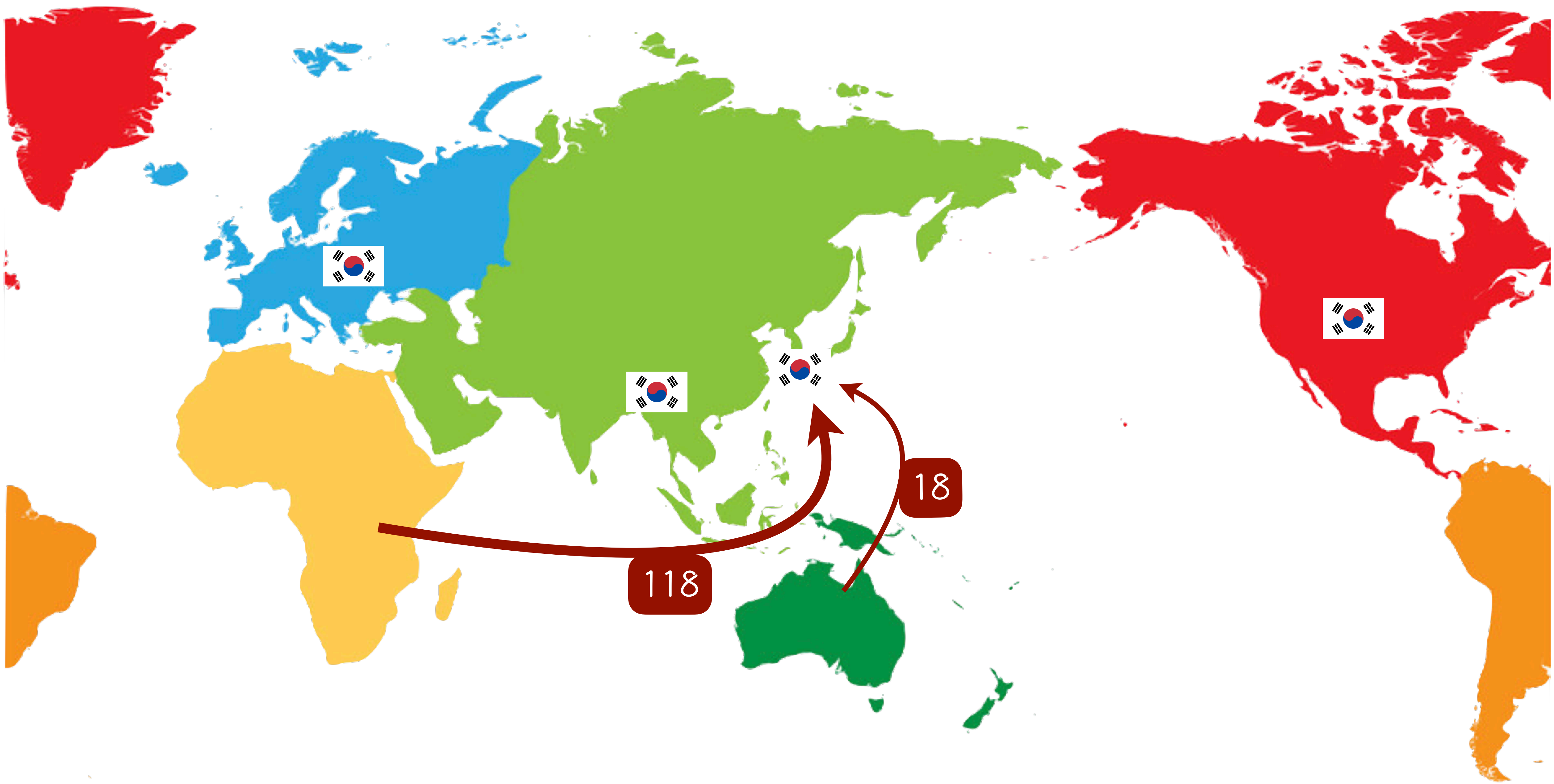

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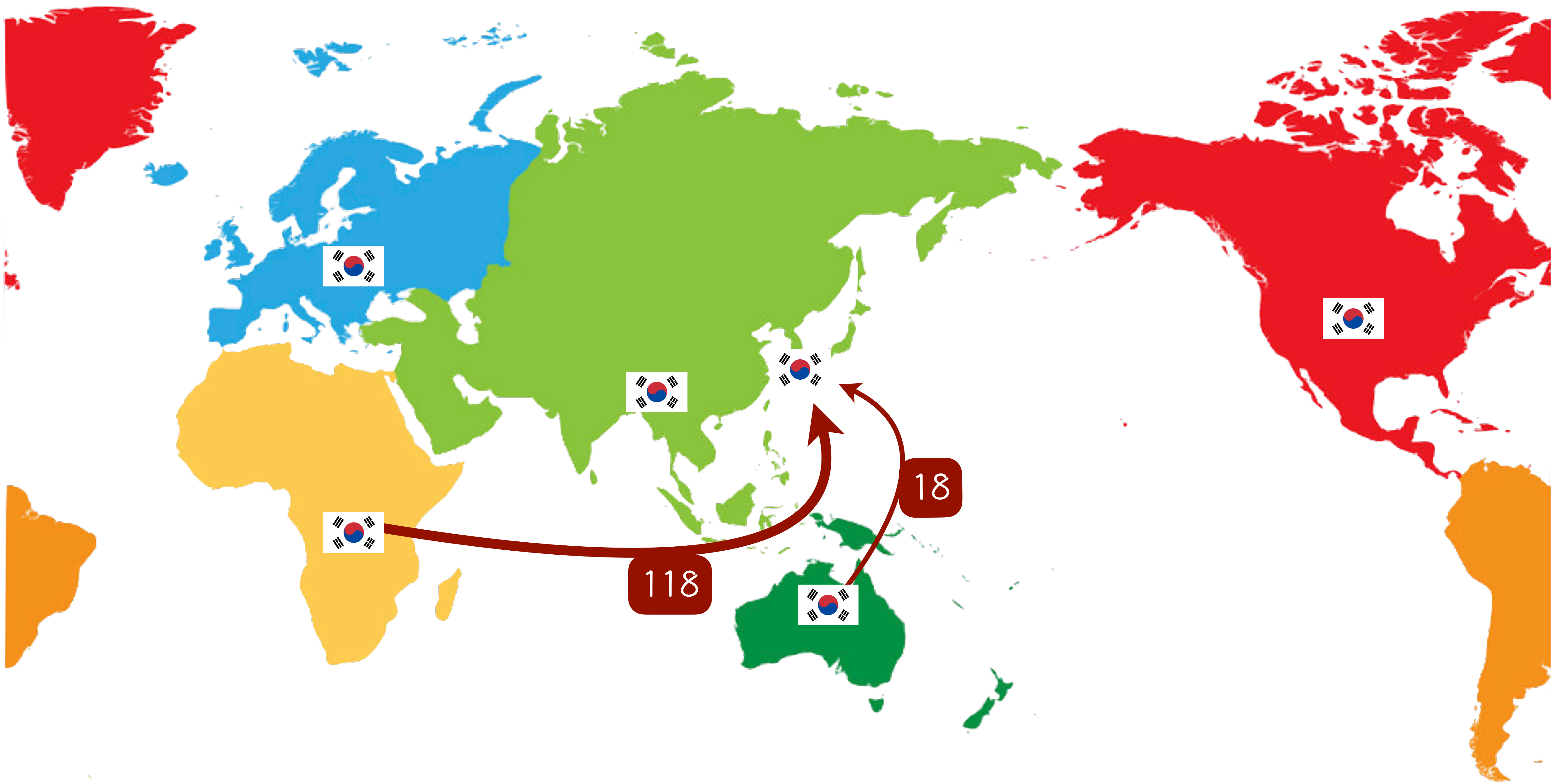

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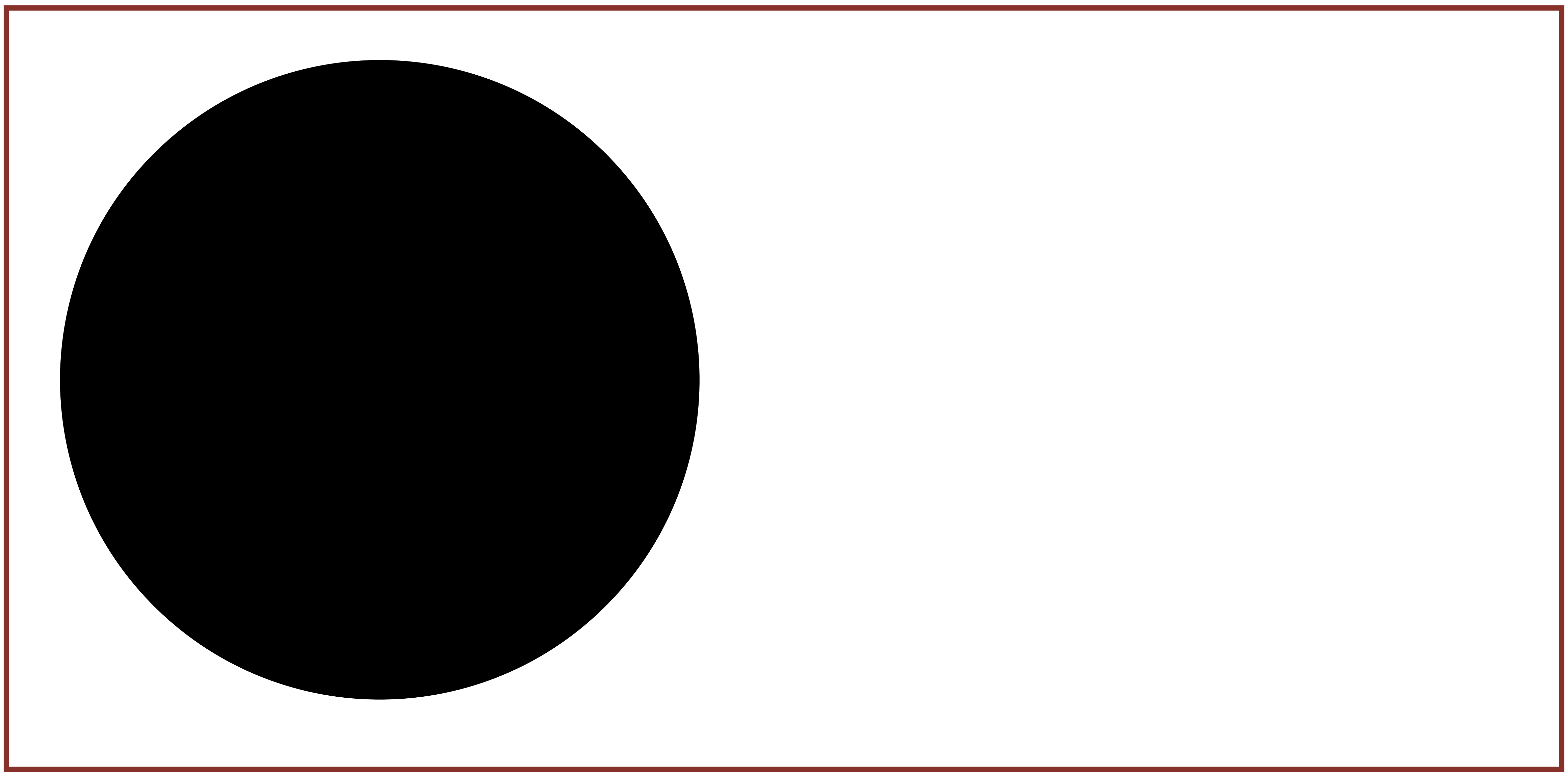
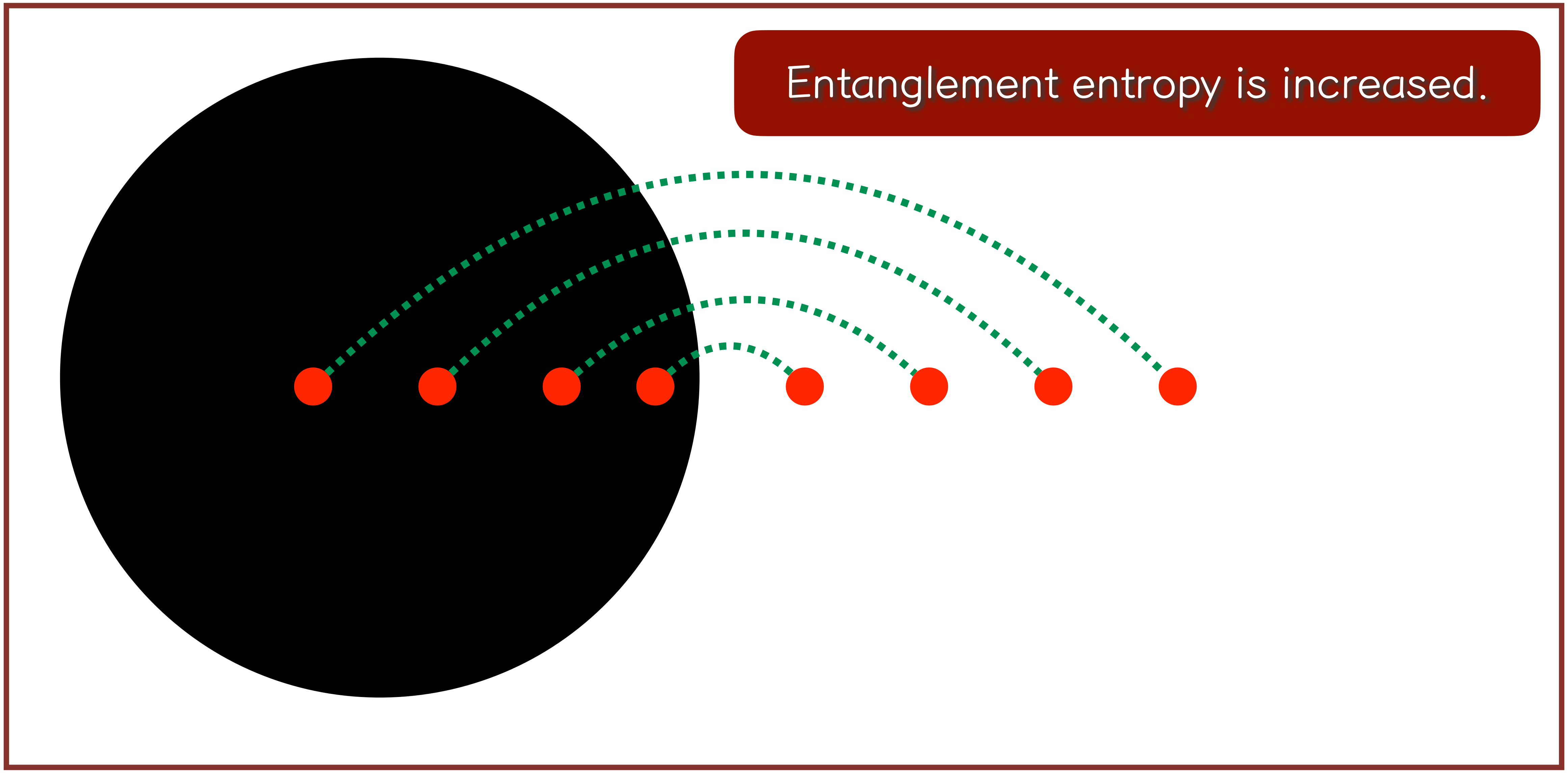
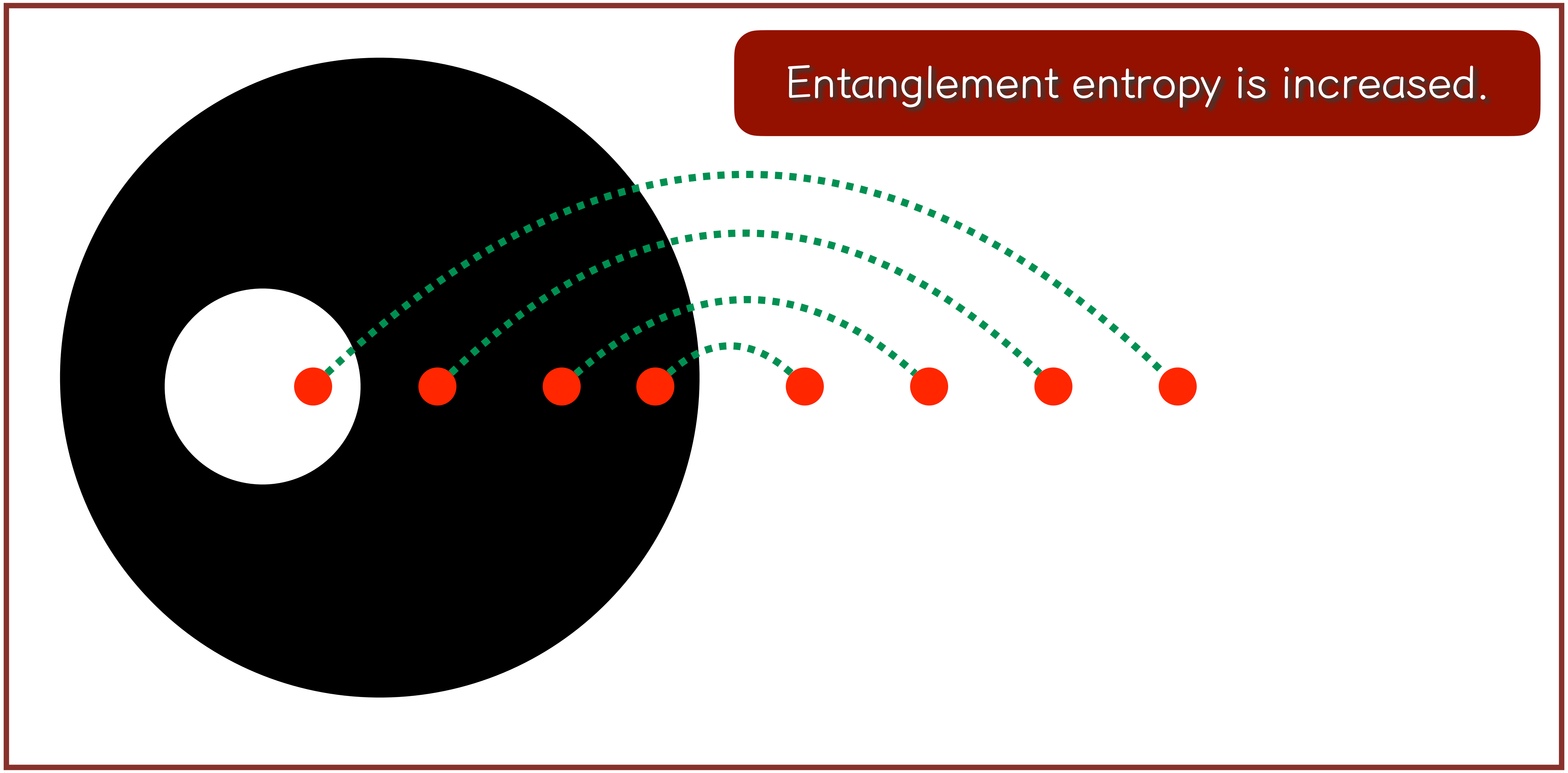
Island inside Black Hole



Island inside Black Hole



Island inside Black Hole



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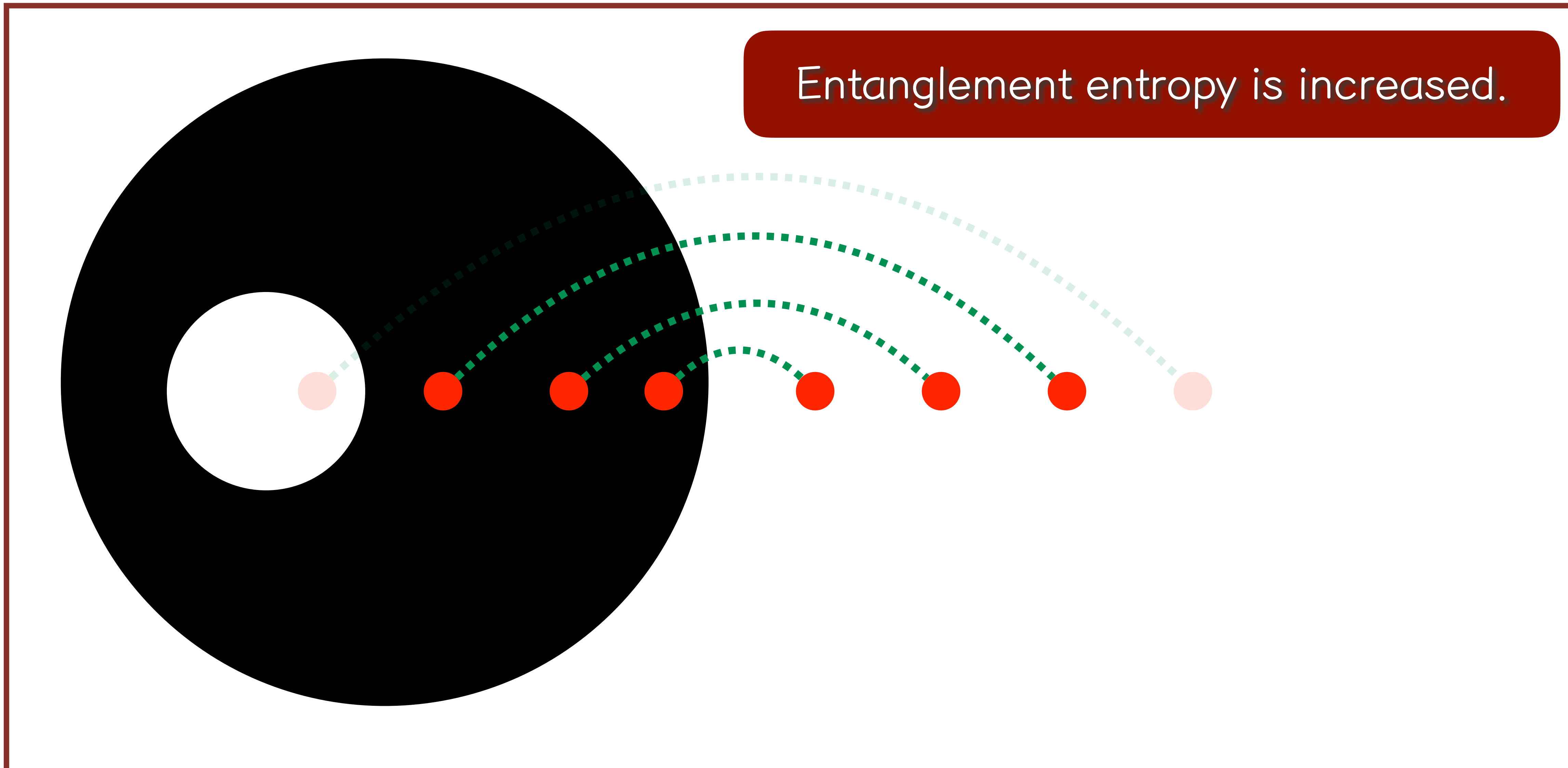
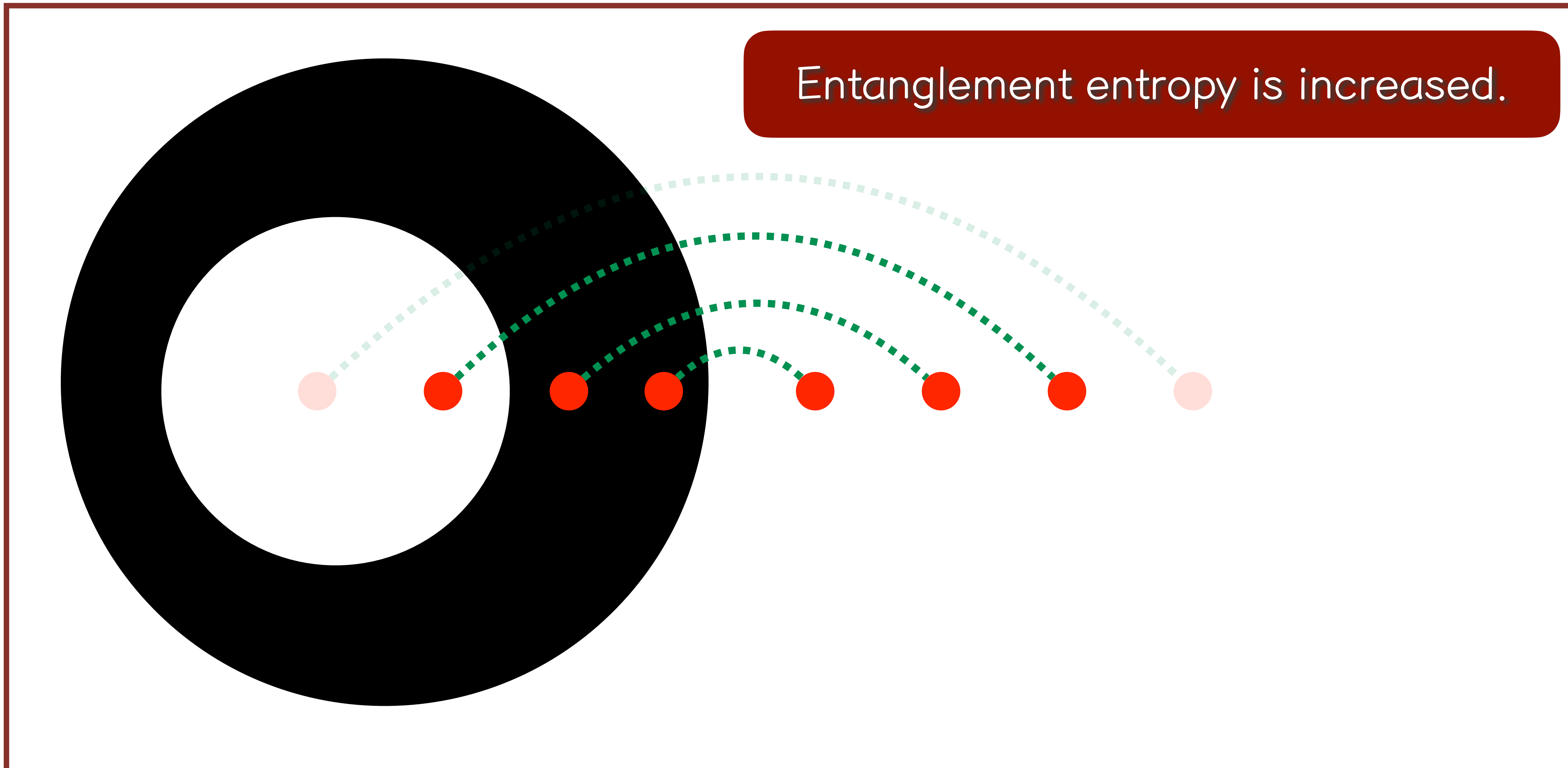
Island inside Black Hole

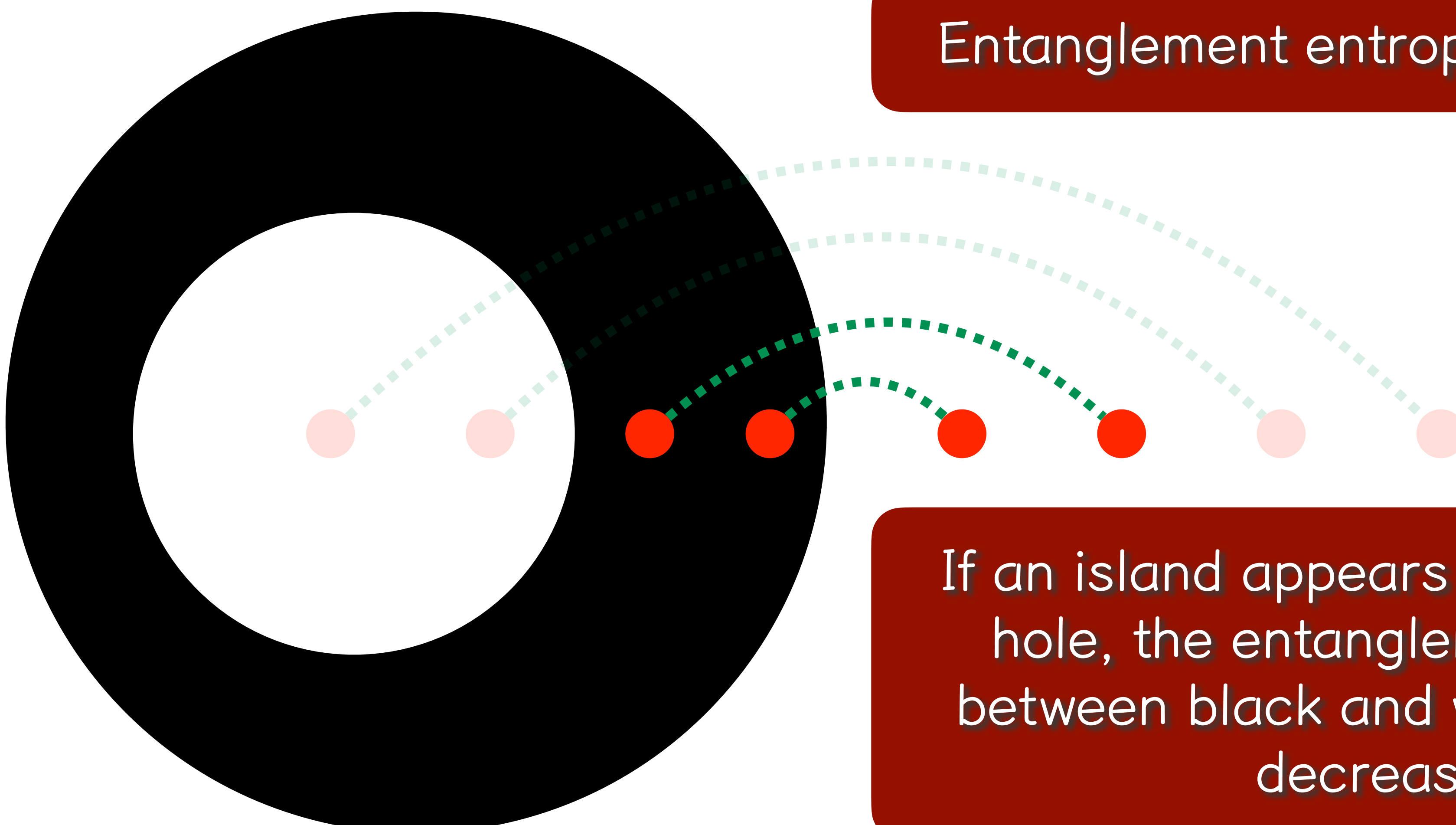


Island inside Black Hole



Island inside Black Hole

Entanglement entropy is increased.



If an island appears inside of black hole, the entanglement entropy between black and white region is decreased

Nature of Island?

- What is the nature of island?
  - ✓ Does it exist physically?
  - ✓ Is is nothing but ad hoc to explain the Page curve?
- Unfortunately, I can't answer those questions.
  - ✓ In this talk, I will try to explain a possible scenario to have Island. But, this does not prove anything.
  - ✓ Then, assuming the existence of Island, I will present some calculations to reproduce the Page curve.

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Contents

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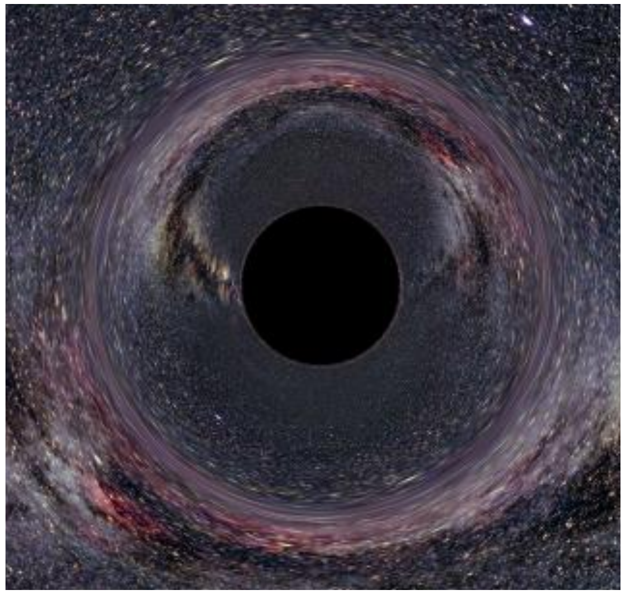
Short Review:
Black Hole Information Paradox

What is the state of black hole?

Is it pure or thermal (mixed)?

Black Hole Information Paradox



- Black hole seems to be thermal object
- Bekenstein-Hawking entropy of black hole:

$$S = \frac{A}{4G}$$

A: Area of horizon

✓ 1st law of thermodynamics: $dM = \frac{\kappa}{2\pi} d\left(\frac{A}{4G}\right)$

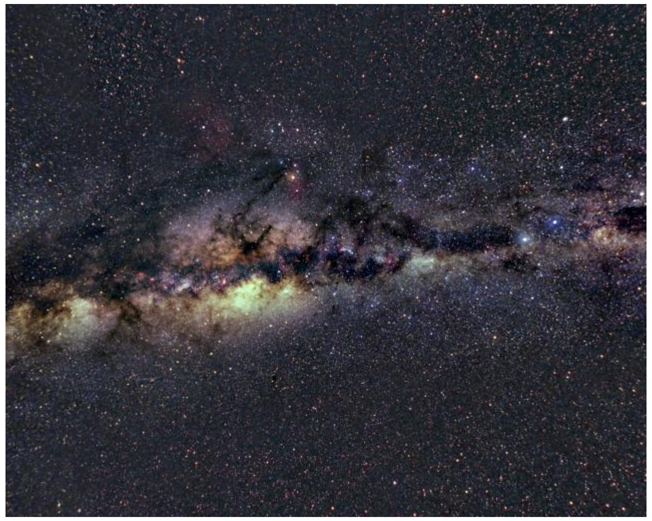
$$\Updownarrow$$

$$dE = TdS$$

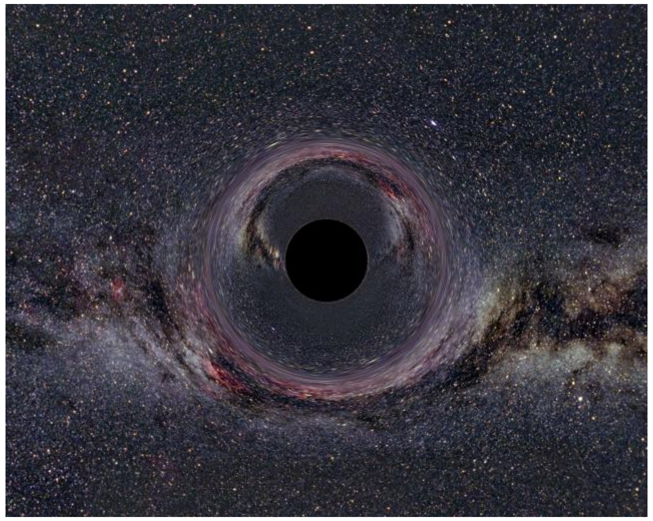
- Is Black hole in mixed state?

Black Hole Information Paradox

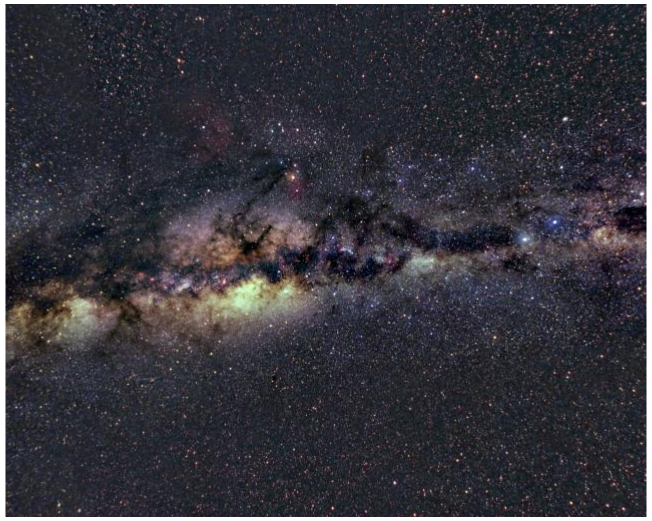
* Try Gedanken experiment for black hole formation and evaporation
  * Assumption
    * ✓ Initial state (before black hole is formed): pure state
    * ✓ Unitary evolution



Before formation
pure state



Black hole



evaporated

* The final state should be pure if the time evolution is unitary

Black Hole Information Paradox

- When BH is in pure state, how does pure state look like thermal state?
- The pure density matrix is very close to the thermal density matrix
  - ✓ Difficult to distinguish density matrix of pure state and thermal state

$$\rho_{\mathrm{pure}} = \frac{1}{Z} e^{-\beta H} + e^{-S}\delta$$

exponentially suppressed
non-perturbative

- At early time, semi-classical perturbative calculation is valid
  - ✓ e.g. Hawking's calculation
- In a long time later, one cannot ignore the difference $e^{-S}\delta$
  - ✓ non-perturbative

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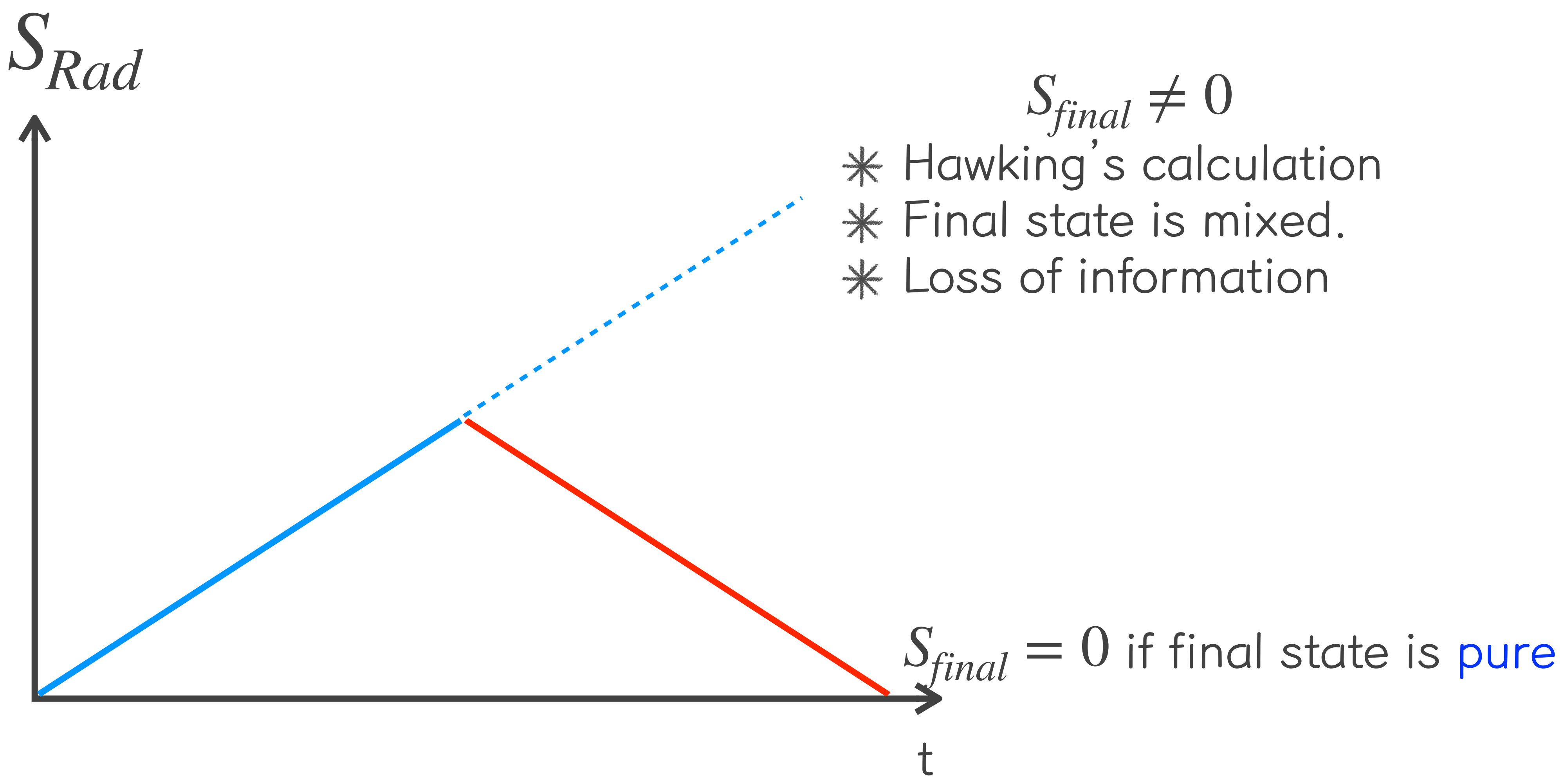
Page Curve

✳ Assumption for Page curve: unitary, closed quantum system



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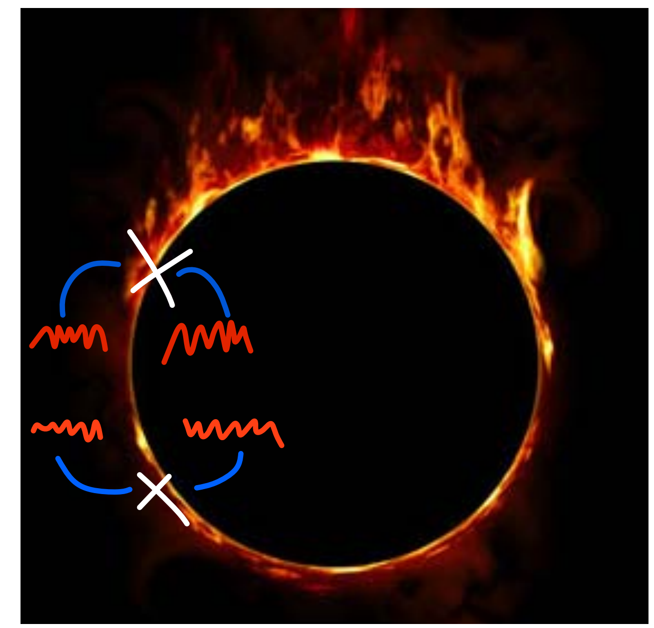
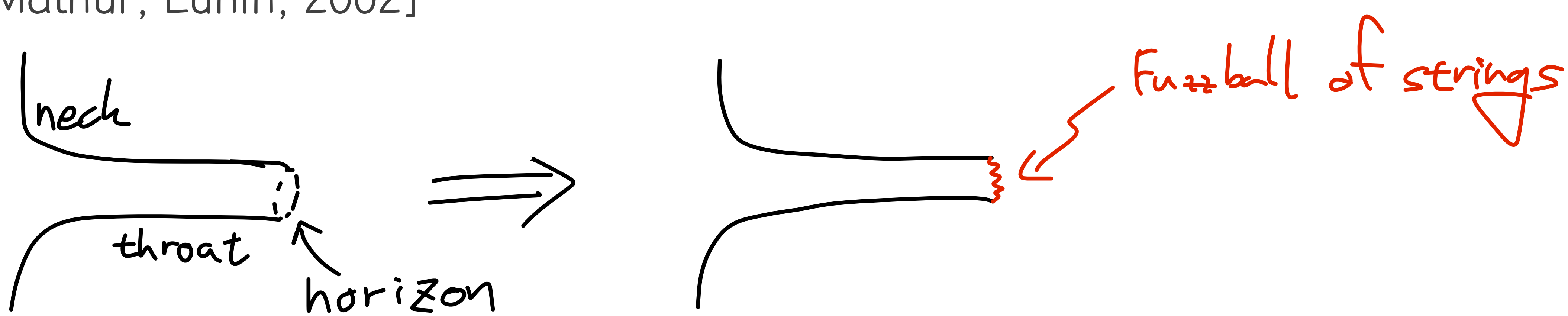
Proposed Resolutions

✳ Firewall at horizon [AMPS, 2012]



- ✓ proposed to resolve strong subadditivity (SSA) paradox of black hole
- ✓ non-unitarity (by firewall)
- ✓ Recall Wontae Kim's talk.

✳ Fuzzball [Mathur, Lunin, 2002]



- ✓ No inside of black hole, no singularity

✳ Black hole complementarity (next slide)

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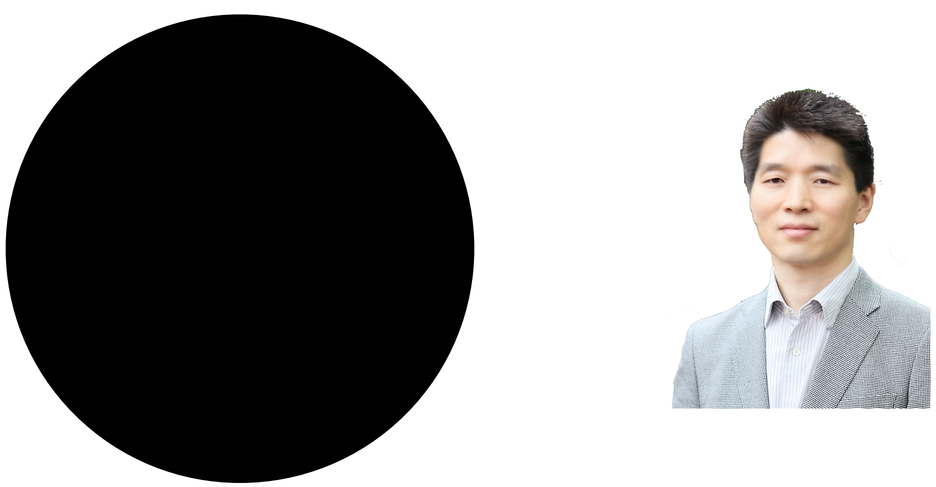
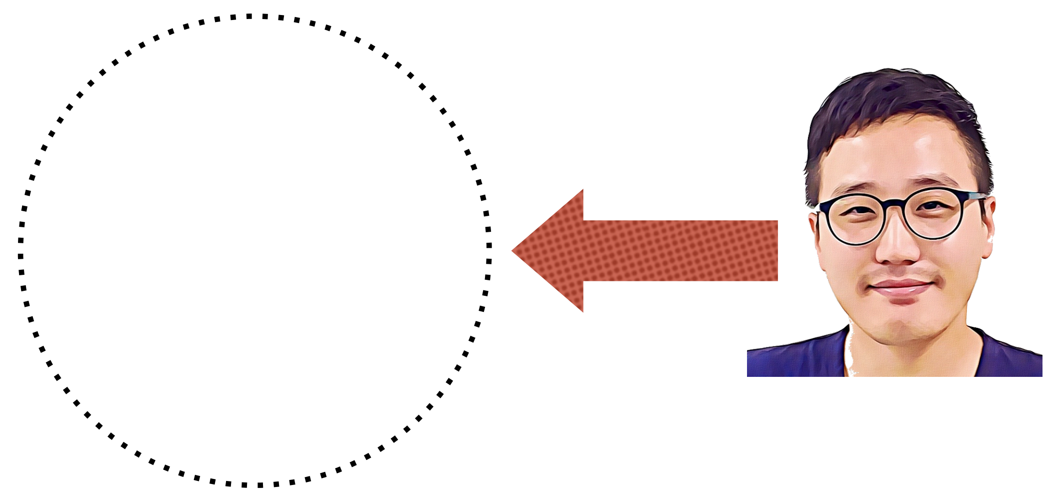
Black Hole Complementary

Original Black Hole Complementarity

- Black Hole Complementary [Susskind, Thorlacius, 1993
  - Two alternative descriptions of black hole
    - ✓ observer outside of horizon vs infalling observer



vs

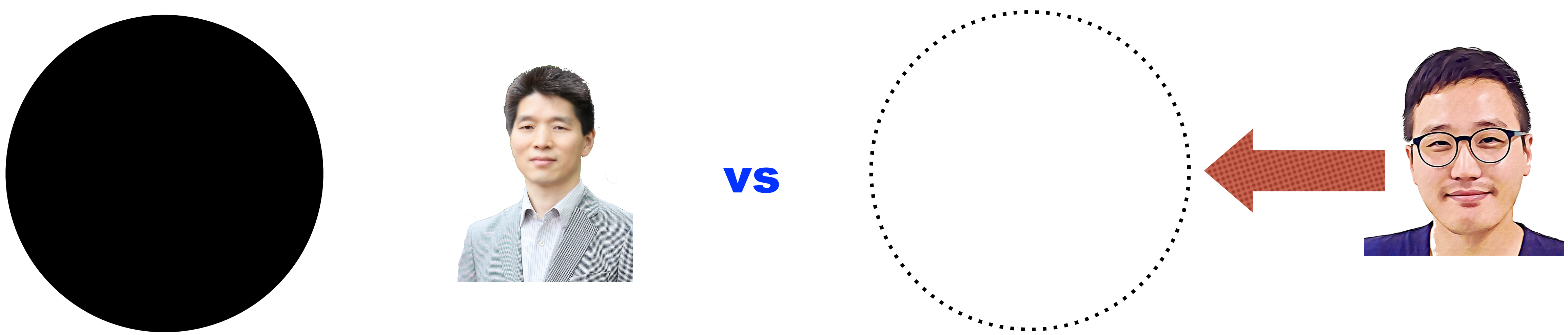


Stationary observer sees
“membrane” at stretched horizon

Infalling observer sees nothing,
and ends up with singularity

Original Black Hole Complementarity

- Black Hole Complementary [Susskind, Thorlacius, 1993
  - Two alternative descriptions of black hole
    - ✓ observer outside of horizon vs infalling observer

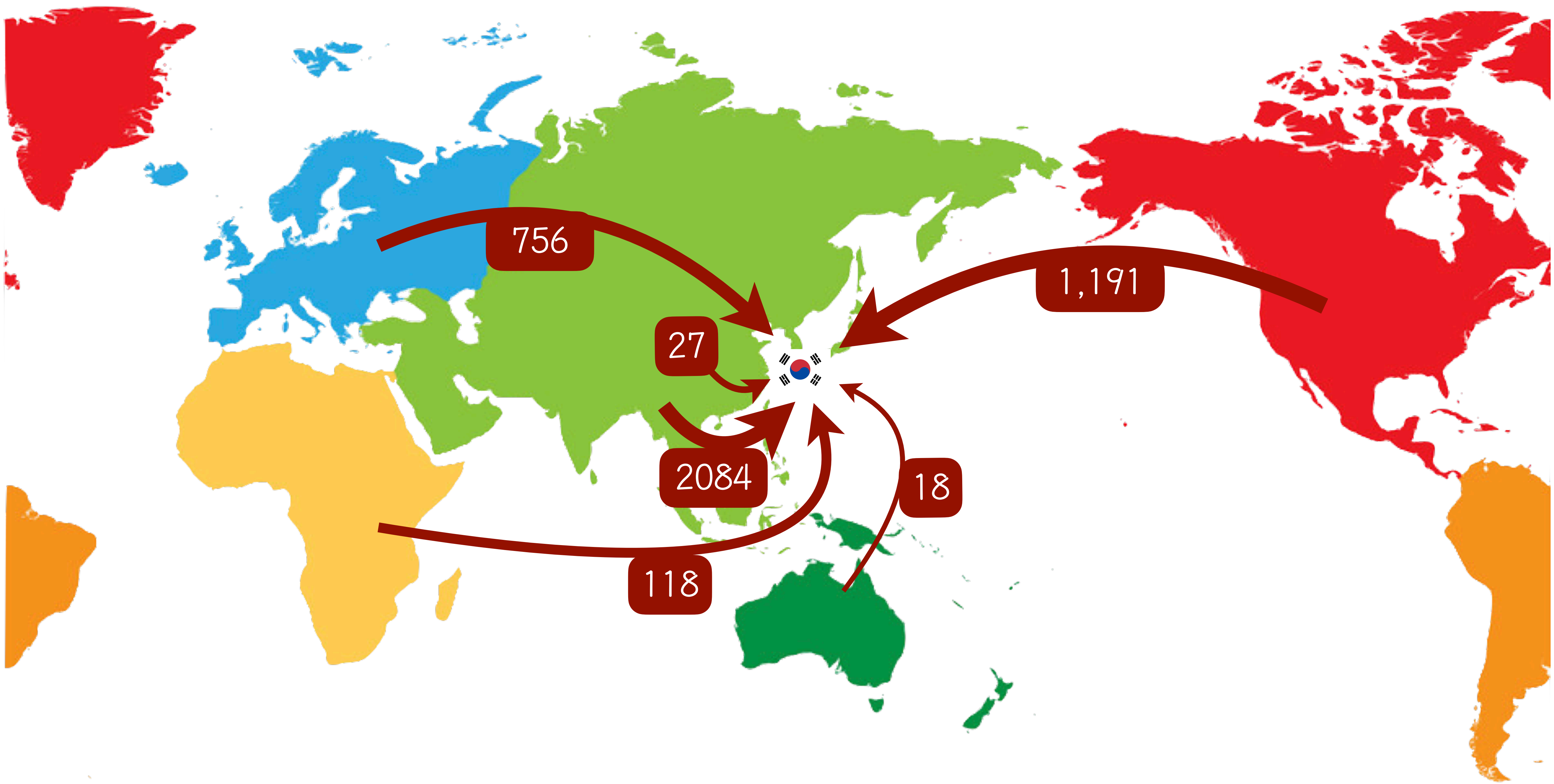


Stationary observer sees
"membrane" at stretched horizon

Infalling observer sees nothing,
and ends up with singularity

Two descriptions need not to be equal.

Recap: Imported Cases from Outside of Korea



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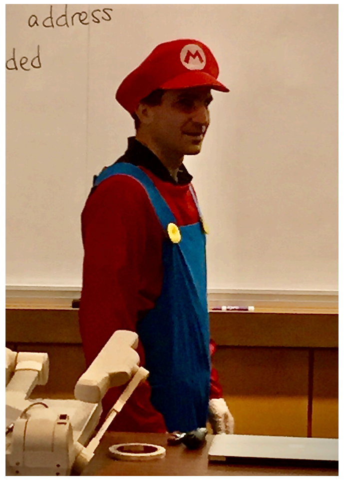
We are the World

Australopithecus africanus



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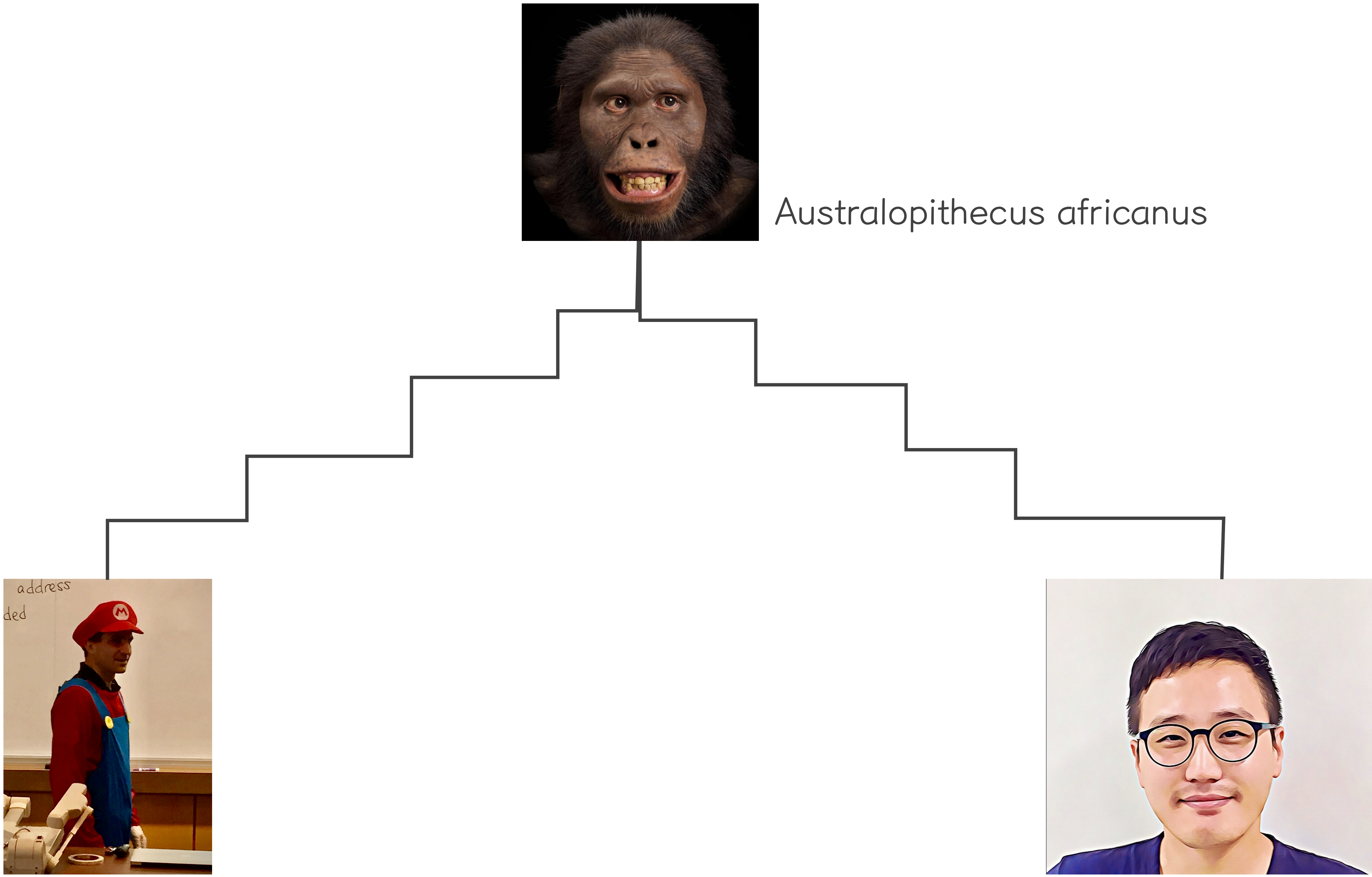
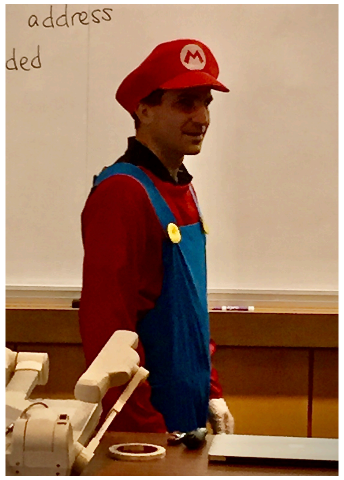
We are the World



We are the World



⁕ It is difficult to track the family tree practically so that we are divided into many countries.

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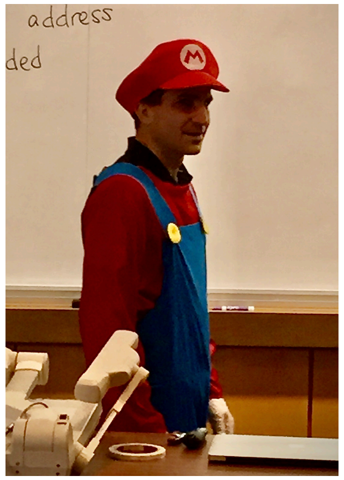
We are the World



⁎ It is difficult to track the family tree practically so that we are divided into many countries.

⁎ This could be an analogy of the black hole complementary. i.e. Hilbert space of inside and outside of horizon

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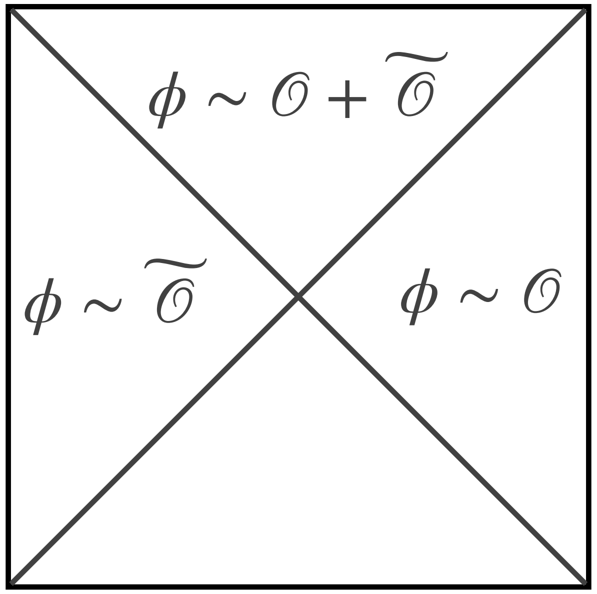
Factorization of Hilbert Space

- Quantization of scalar field in the eternal black hole background.



- ✓ B.C. on the horizon identifies d.o.f. across the horizon
- ✓ In AdS/CFT, $\mathcal{O}$ lives CFT$_R$ and $\widetilde{\mathcal{O}}$ lives CFT$_L$.
- ✓ We usually think the Hilbert space is factorized into $H_L \times H_R$.
  e.g. Thermofield dynamics (TFD) of CFT

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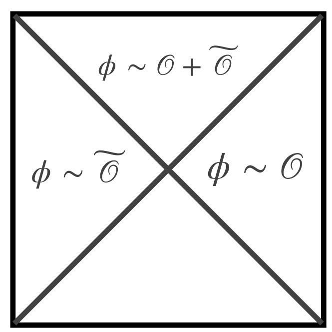
Black Hole Complementarity

* d.o.f inside of horizon is not independent of d.o.f outside of horizon
  - ✓ $\widetilde{\mathcal{O}}$ is a (complicated) function of $\mathcal{O}$'s.

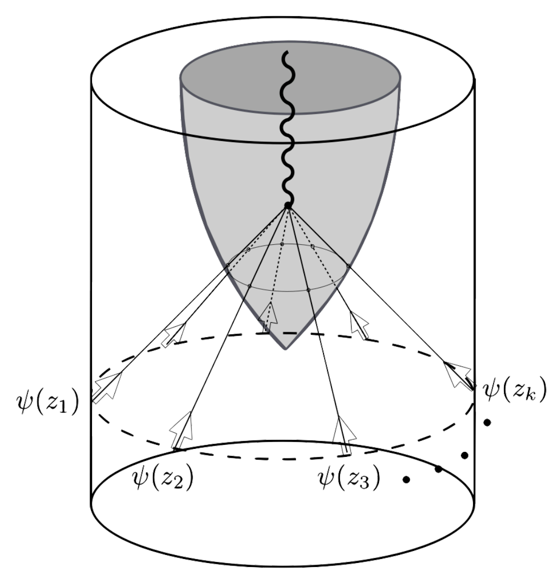


$$\widetilde{\mathcal{O}} = f[\mathcal{O}]$$

  - ✓ The degree of the function is very large. e.g. $\deg[f] = e^S$
  - ✓ This is failure of the factorization of the Hilbert space.
* Tomita-Takesaki theory in math provides underlying mechanism.
  - ✓ For given $\{\mathcal{O}\}$, there exists an operator J such that $\widetilde{\mathcal{O}} = J\mathcal{O}J$

"Small Hilbert Space" for Effective Field Theory

- ✳ For Physics, we need additional ingredient to Tomita-Takesatki theorem.
- ✳ For effective field theory (EFT) on the curved background, we take a small Hilbert space.
  - ✓ For example, we don't consider 100 black holes moving in our spacetime.
  - ✓ We consider a small d.o.f which does not background too much for EFT.
  - ✓ e.g. EFT will be broken down when we calculate a correlation functions of n operators ($n > e^S$)
    [Anous, Hartman, Rovai, Sonner, 1603.04856]
    [Ghosh, Raju, 1706.07424]
  - ✓ cf) code space



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Black Hole Complementary

[Raju, Papadodimas, 2012]

Full Hilbert Space

$\mathcal{O}, \mathcal{O}^2, \cdots$

Simple operators describes
the outside of black hole

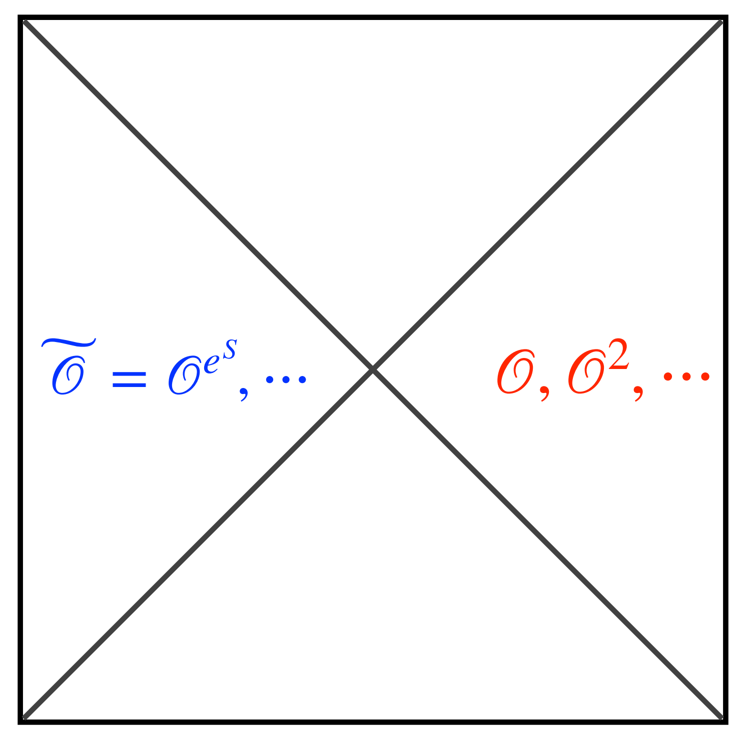
→ EFT for outside of black hole

$\mathcal{O}^{e^S}, \cdots$

Complicated operators describes
the inside of black hole

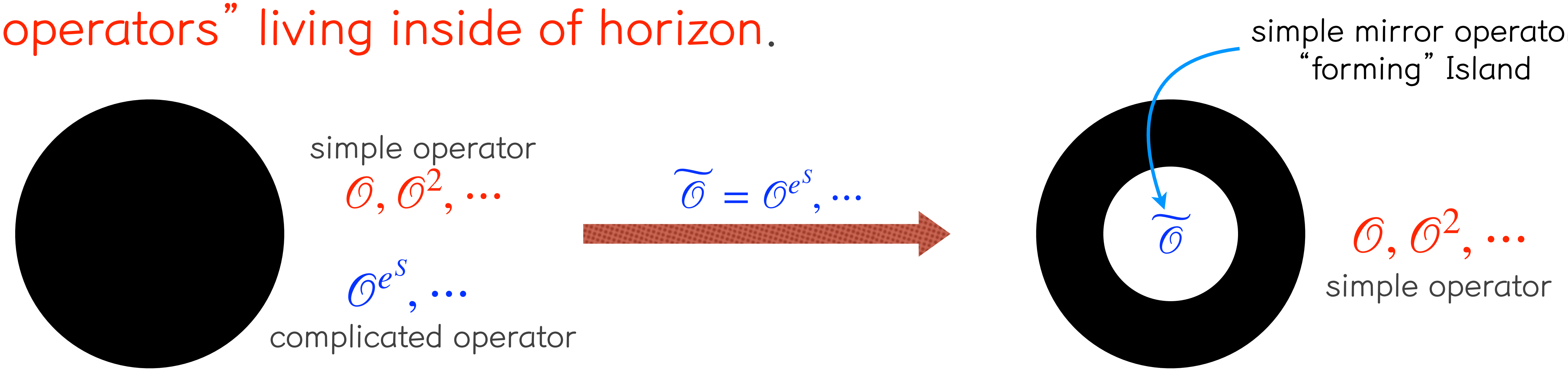
→ corresponds to mirror operator $\widetilde{\mathcal{O}}$

- The full Hilbert space is effectively factorized into $\{\mathcal{O}\}$ and $\{\widetilde{\mathcal{O}}\}$ within EFT.
- This will hold until you measure large d.o.f.
- The construction of the mirror operator $\widetilde{\mathcal{O}}$ depends on the state: State-dependence
- The bulk causality and locality is not exact.



Island and Black Hole Complementary

- After Page time, half of black hole d.o.f. comes out. For entanglement entropy between black hole and outside of Hawking radiations, it is inevitable to consider Hilbert space including complicated operators.
  - ✓ EFT cannot usually describe this large Hilbert space.
- We might be able to think complicated operators as "simple operators" living inside of horizon.

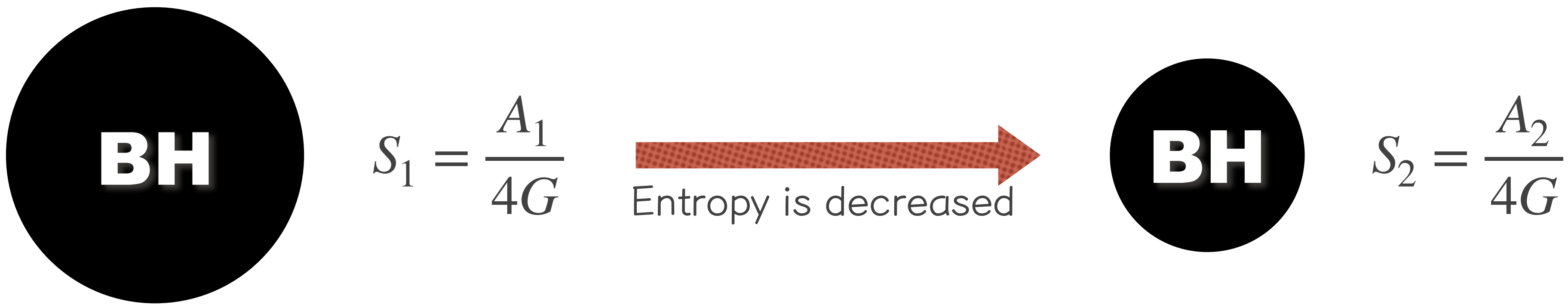


- As I mentioned in the beginning, this is nothing but speculation.

Quantum Extremal Surface

Generalized Entropy

- Bekenstein-Hawking entropy: $S = \dfrac{A}{4G}$
- Entropy of black hole is decreased as black hole evaporates.



- Need to include matter (radiation) contribution for 2nd law of thermodynamics.

✓ Define Generalized Entropy: $S_{\text{gen}} = \dfrac{A}{4G} + S_{\text{outside}}$

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Quantum Extremal Surface (QES)

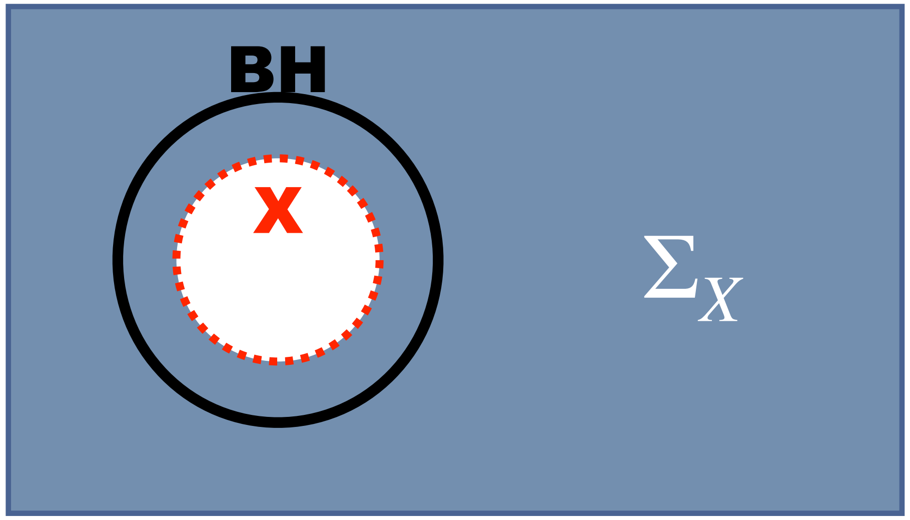
* Consider generalized entropy with (codim-2) surface X instead of horizon.

  ✓ Include matters in Σ_X

  $$S_{\text{gen}}(X) = \frac{A(X)}{4G} + S_{\text{matter}}(\Sigma_X)$$

  ✓ Semi-classical calculation

  - $A(X)$: Area from the fixed background
  - $S_{\text{matter}}(\Sigma_X)$: Quantum calculation from ETF on the fixed background



* Quantum Extremal Surface: Extremize $S_{\text{gen}}(X)$

$$S_{\text{QES}} = \min_X \left[\text{Ext}_X \, S_{\text{gen}}(X) \right]$$

  ✓ In extremization, there could be several local extrema.

  ✓ Among local extrema, choose global minima

  ⇒ Transition between minima leads to Page curve!

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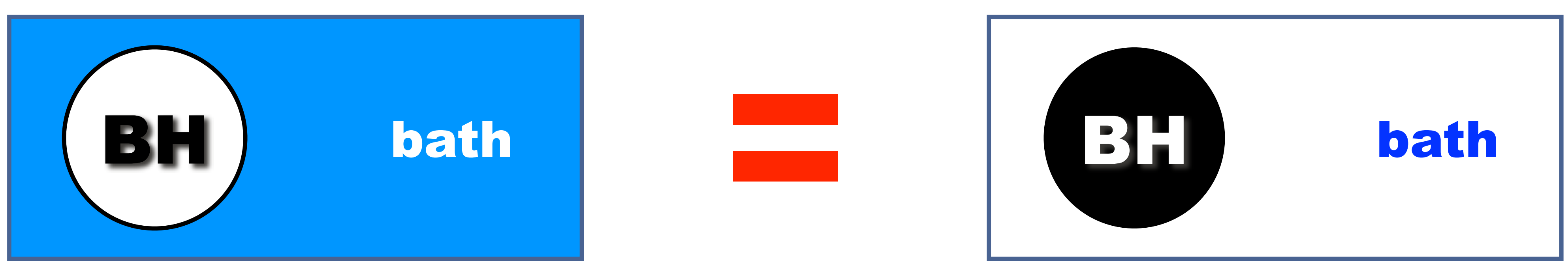
Calculation of QES

- In higher dimension, the calculation of QES is difficult.

$$S_{\text{gen}}(X) = \frac{A(X)}{4G} + S_{\text{matter}}(\Sigma_X)$$

  - ✓ The calculation of entanglement entropy $S_{\text{matter}}(\Sigma_X)$ is very difficult in general except for 2D.
  - ✓ The 2D conformal symmetry allows us to evaluate $S_{\text{matter}}(\Sigma_X)$.
  - ✓ You can learn the detailed calculations (for 2D case) in APCTP winter school from Jan 7 ~ Jan 16 2021 by Raghu Mahajan.

- One may calculate the entanglement entropy between black hole and environments (bath) from the point of view of black hole or from the point of view of bath.



  - ✓ e.g. $S_{EE}(A) = S_{EE}(B)$ if $A \cup B$ is pure state

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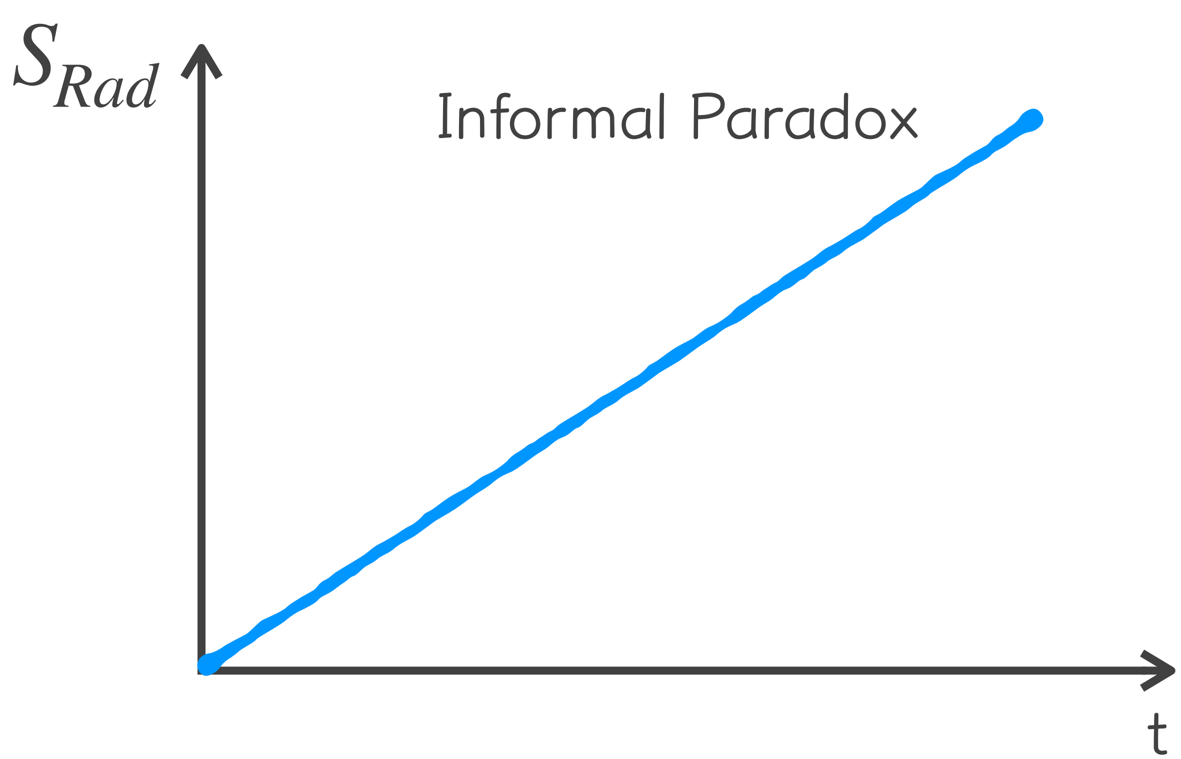
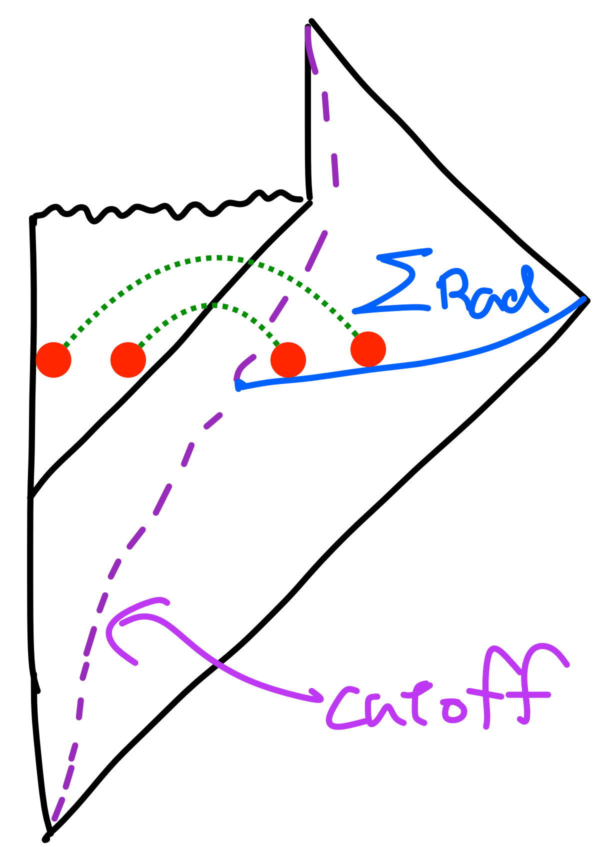
Old Version: Information Loss

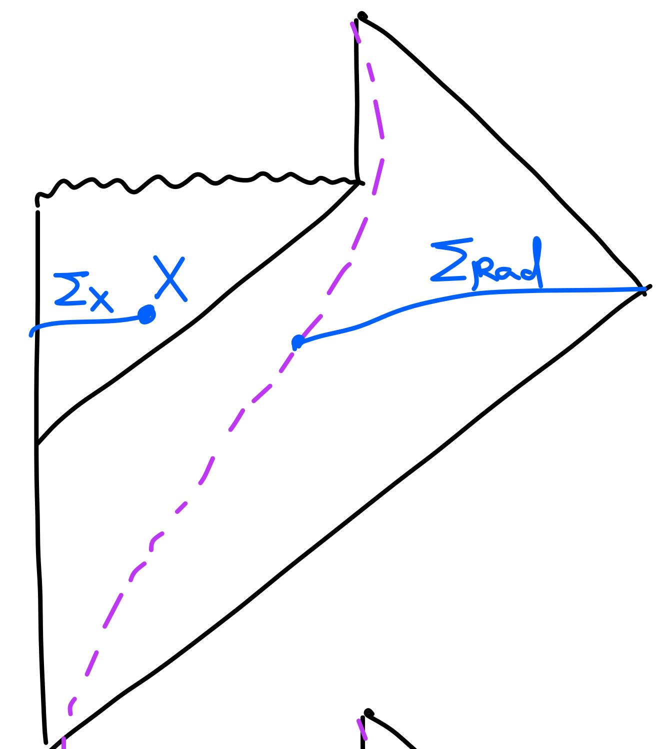
- ✴ Let us consider time slice Σ_{Rad} outside of horizon.
- ✴ We will count EPR pairs between black hole and Σ_{Rad}.
    - ✓ The number of EPR pairs is increased as time passes.
    - ✓ This is equivalent to Hawking's calculation.





Island Conjecture

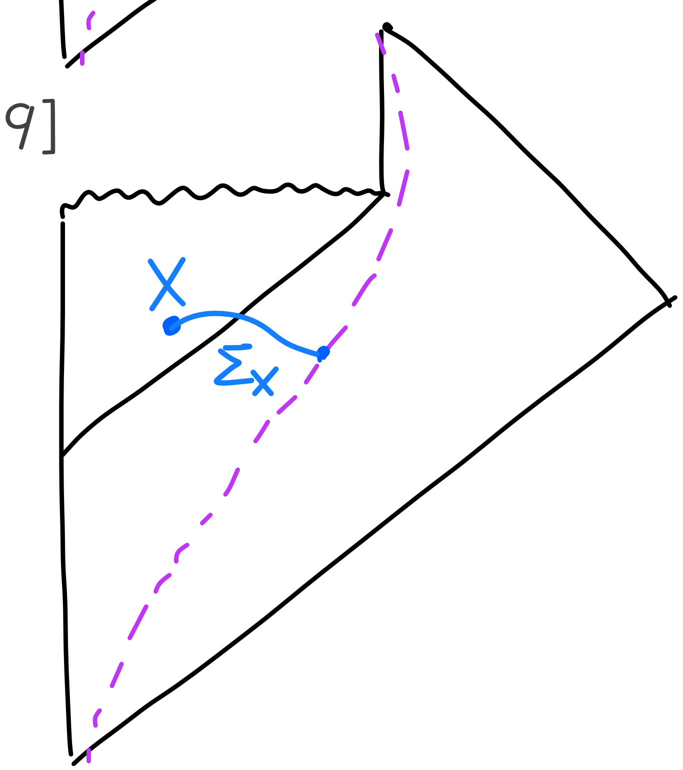
based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]



✴ New version: introduce an island inside of horizon

$$S_{\text{radiation}} = \min_X \left[\text{Ext}_X \left(\frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X \cup \Sigma_{\text{rad}}) \right) \right]$$

✓ Including Σ_X seems counter-intuitive.
cf) Recall imported cases of COVID-19.



✴ The first paper [Almheiri, Engelhardt, Marolf, Maxfield, 2019] considered the complementary region

✓ EE from the point of view of black hole)

$$S_{BH} = \min_X \left[\text{Ext}_X \frac{A(X)}{4G} + S_{semiclass}(\Sigma_X) \right]$$

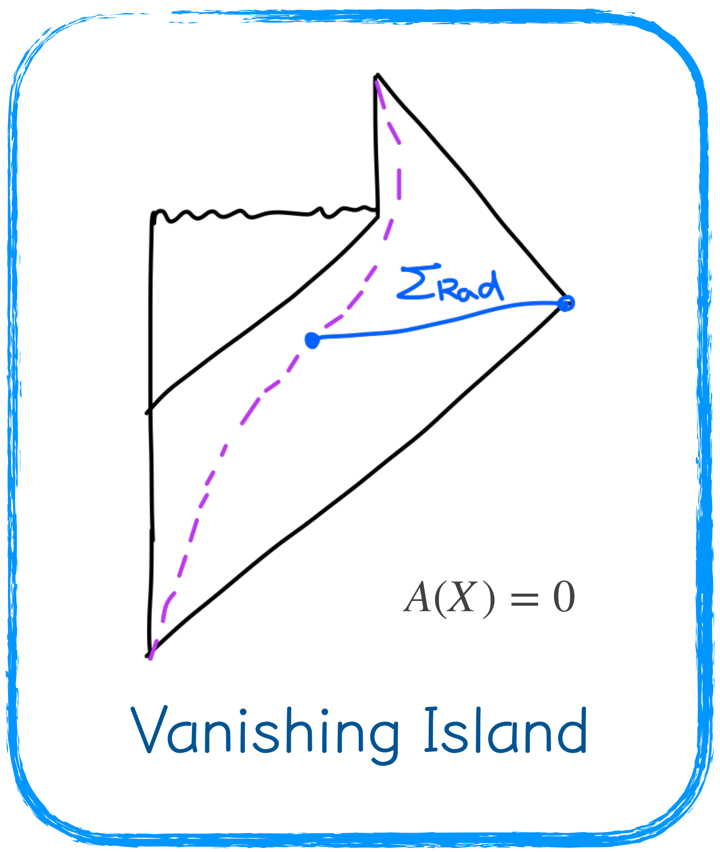
✓ Gives equivalent result.

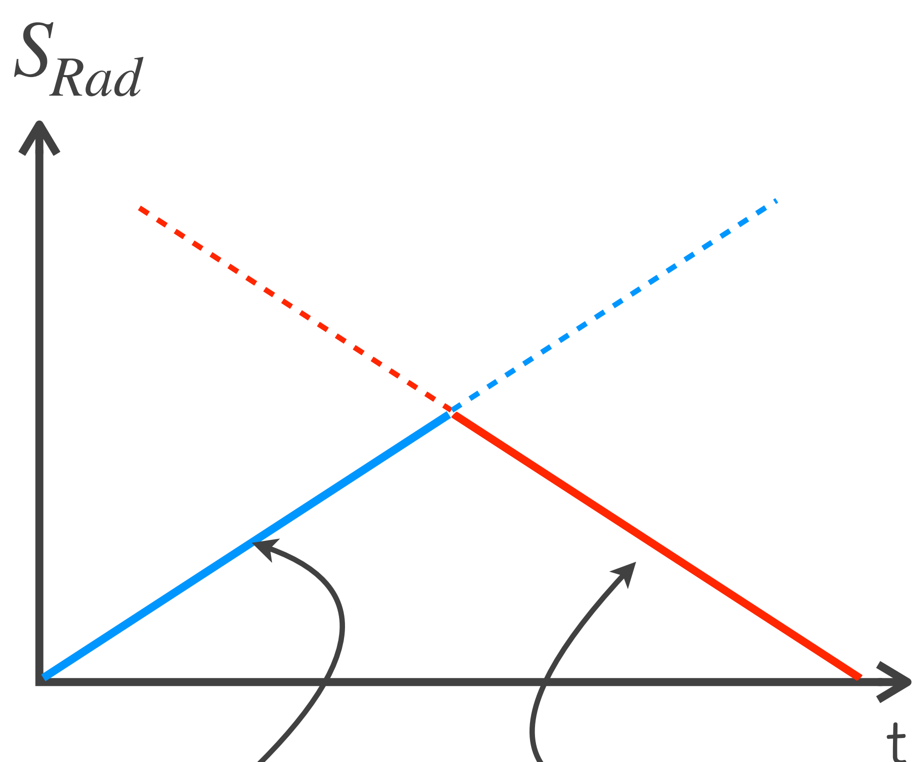
Two Local Extrema

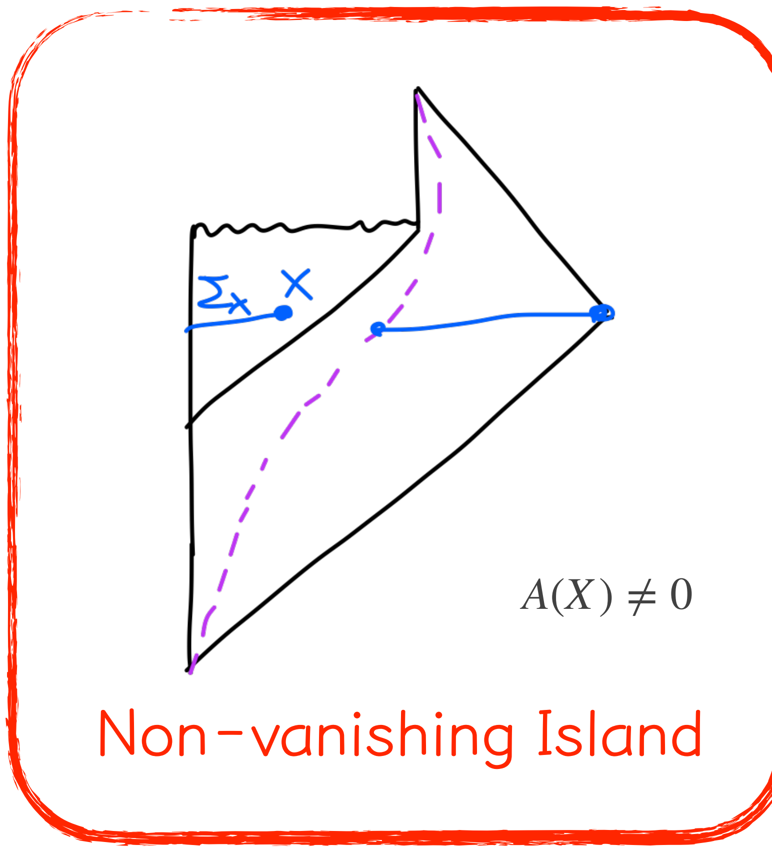
based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]

- When extremizing the generalized entropy, one can find

$$S_{\rm radiation} = \min_X \left[{\rm Ext}_X \left(\frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X \cup \Sigma_{\rm rad}) \right) \right]$$



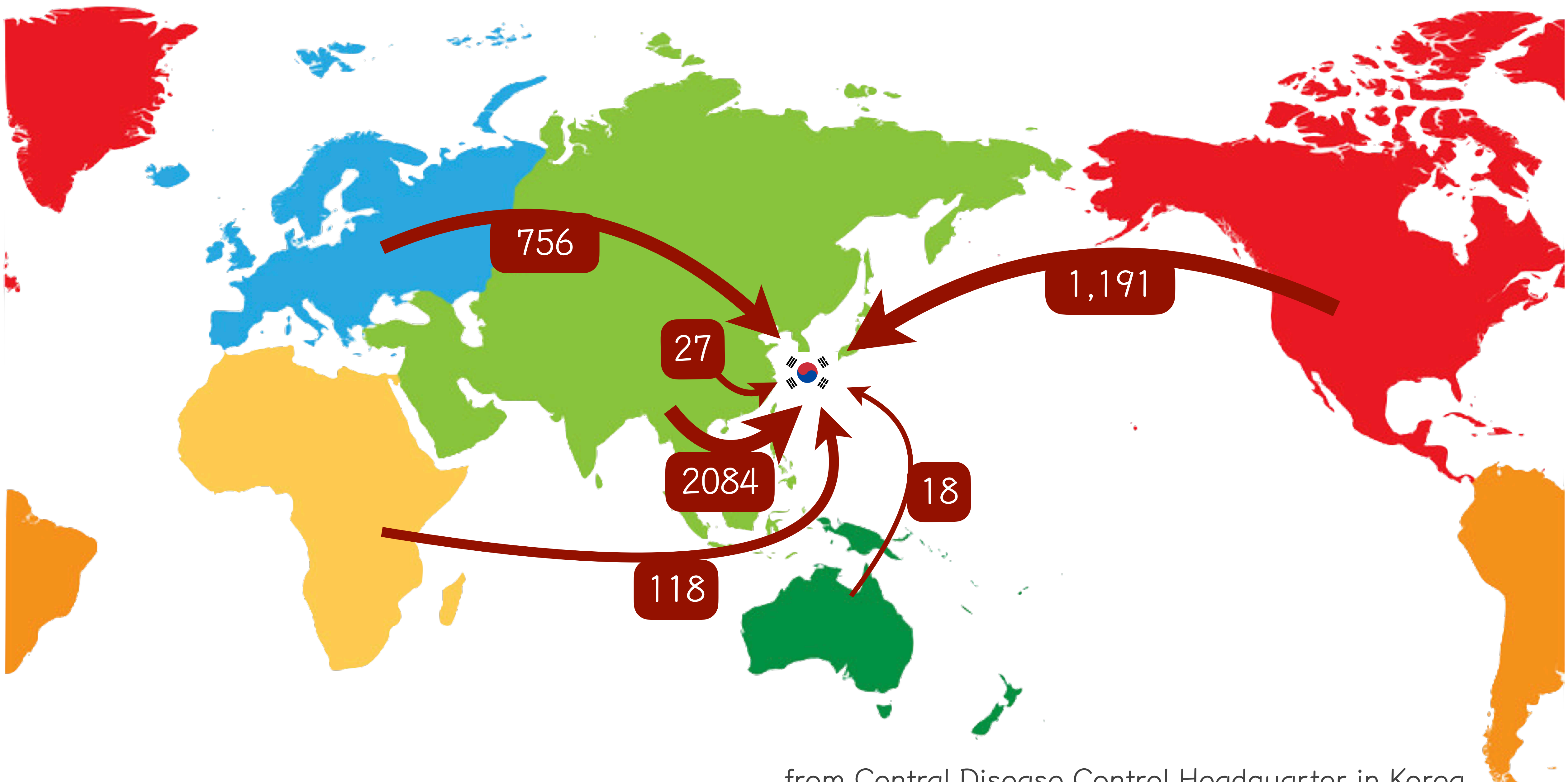




Extremum with vanishing Island

Extremum with Non-vanishing Island

Mechanism for Decreasing EE



from Central Disease Control Headquarter in Korea

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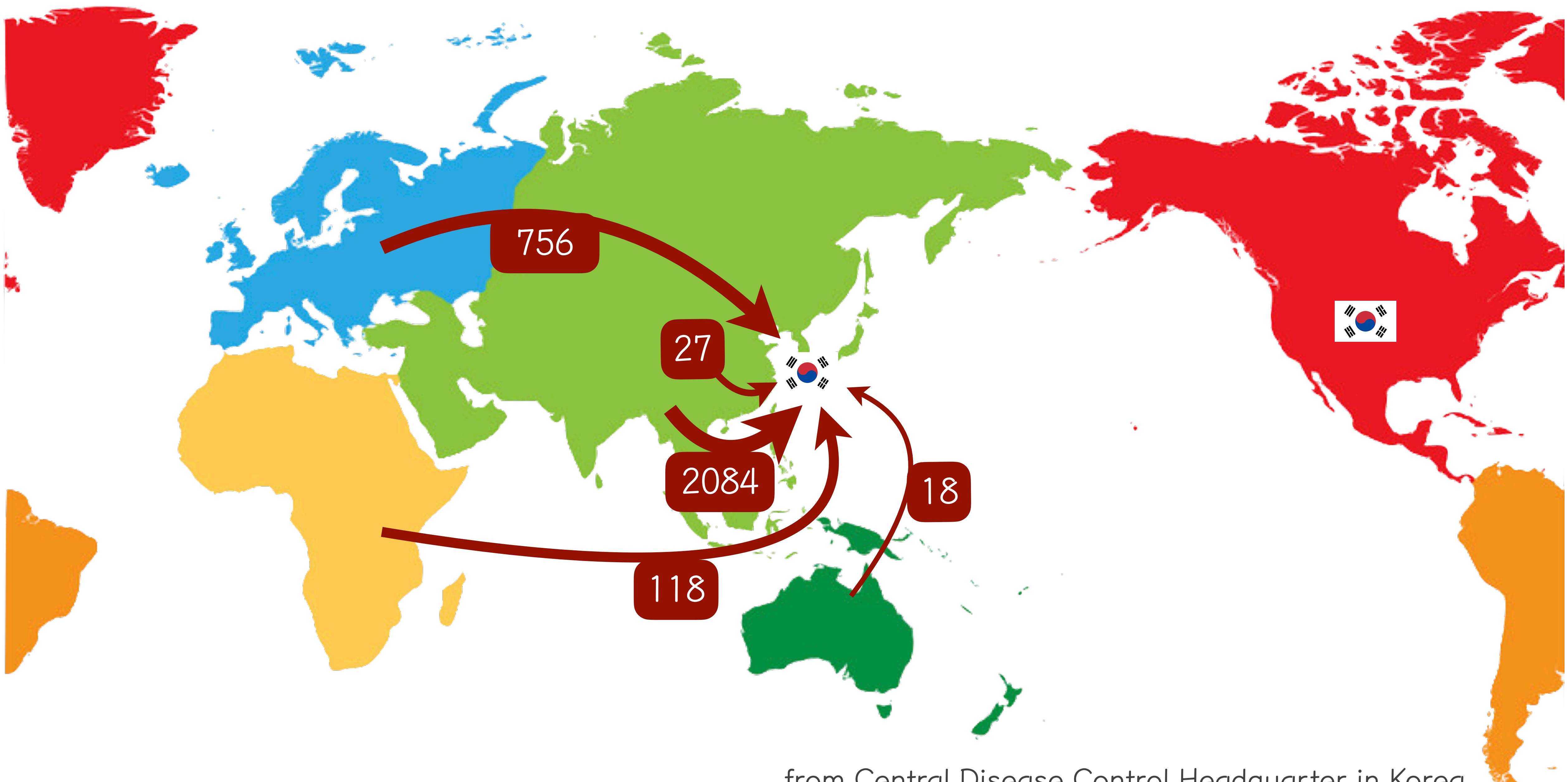
Mechanism for Decreasing EE



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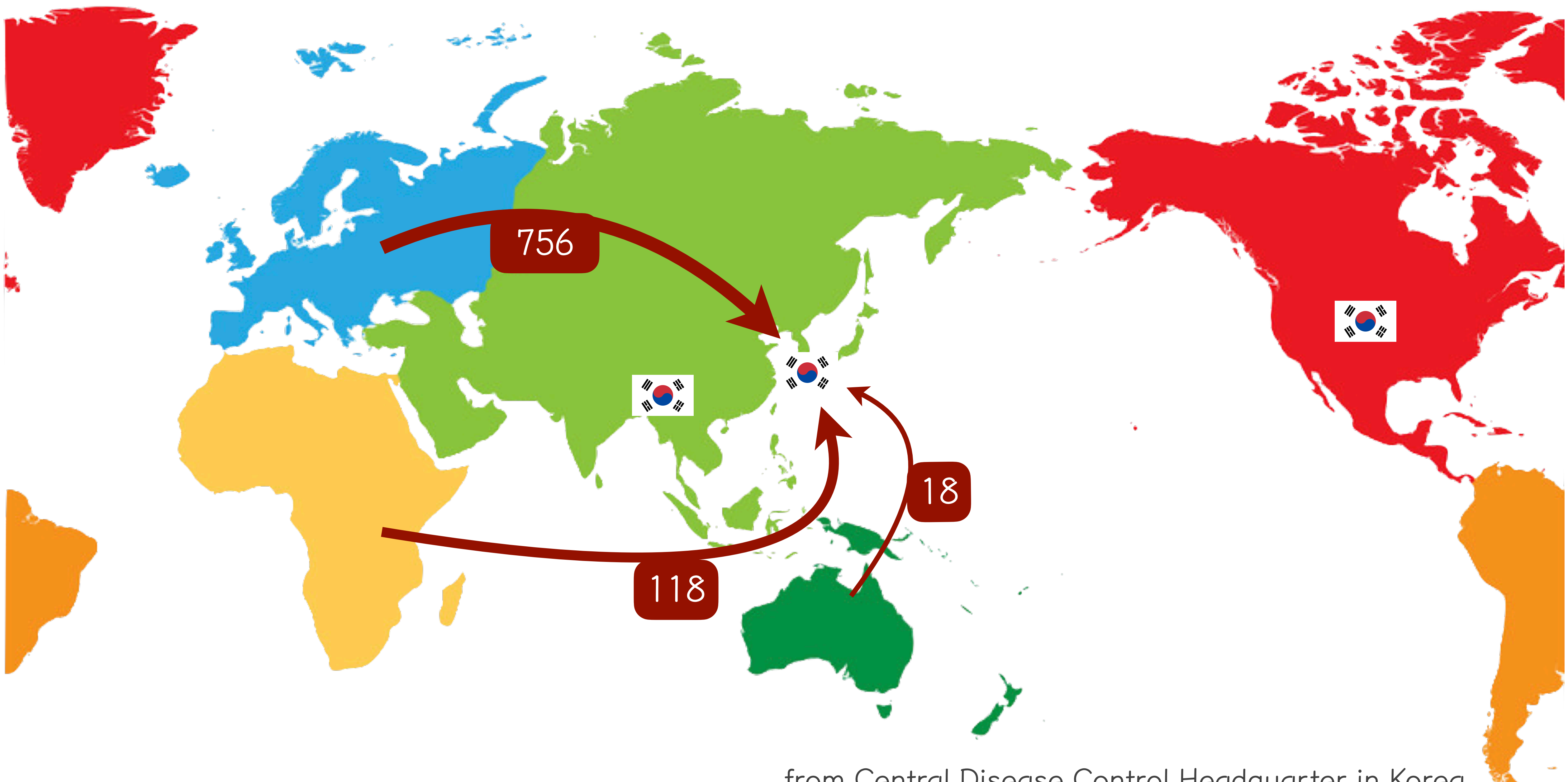

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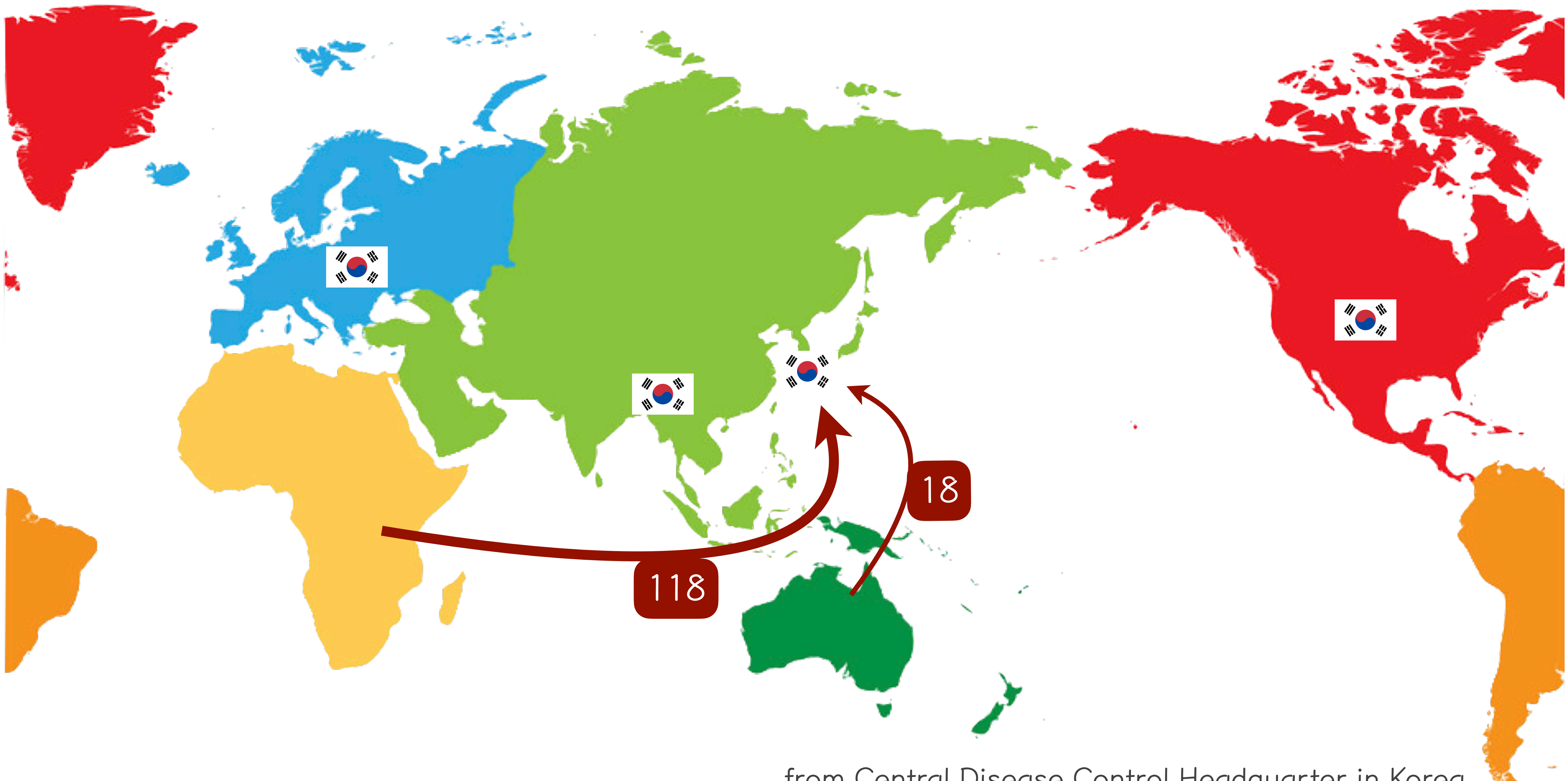

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Mechanism for Decreasing EE

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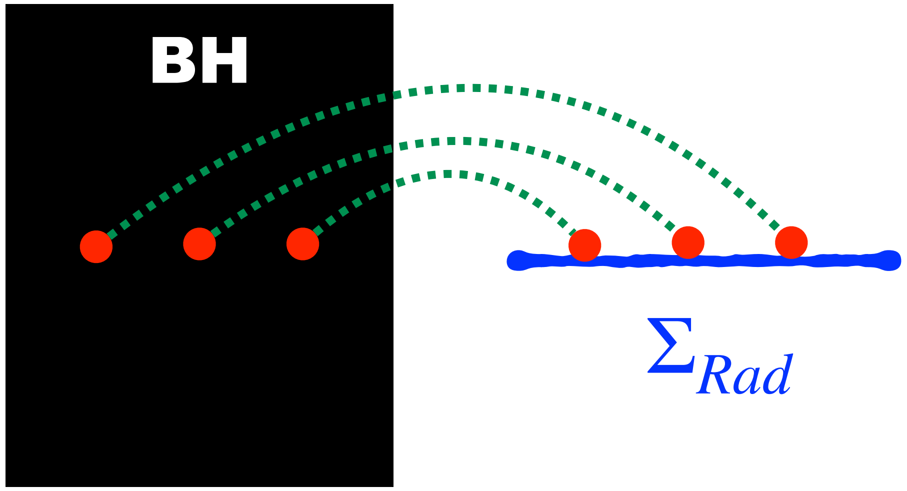
based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]



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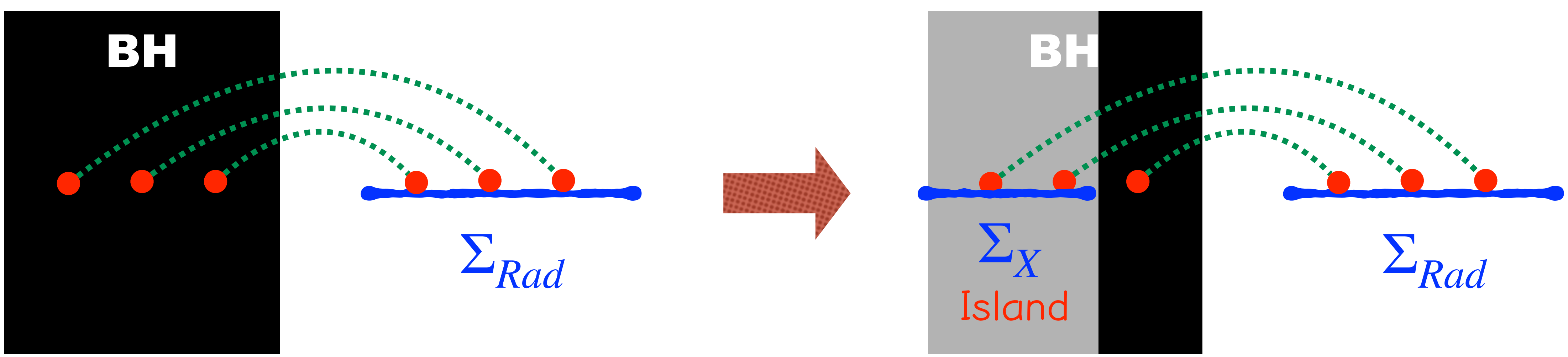

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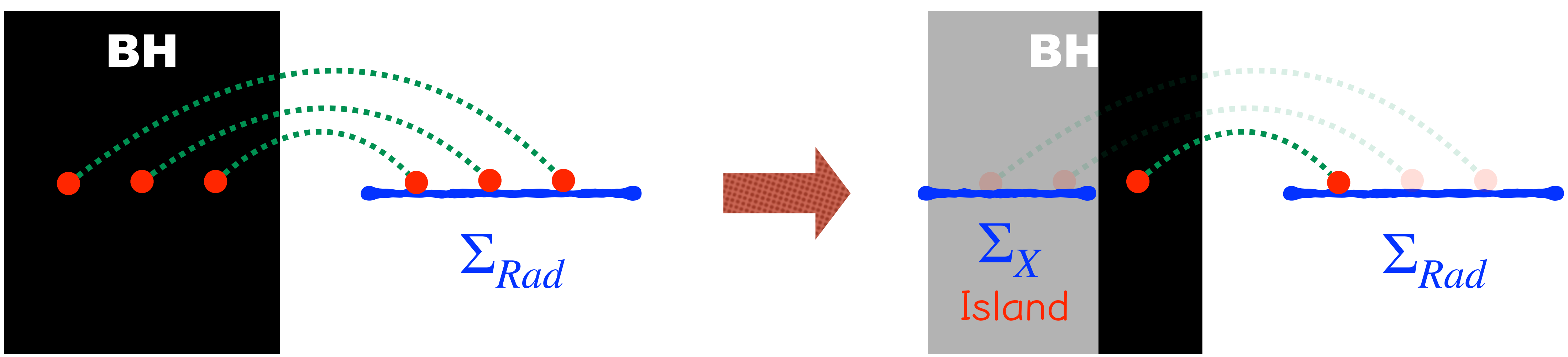

Island "purifies" the EPR pair of Hawking radiation.

This decreases the entanglement entropy.

Doubly-Holography

Low-Dimensional Model (Bottom-up)

* Quantum Mechanics (1+0)dim
  + CFT_2 (1+1)dim

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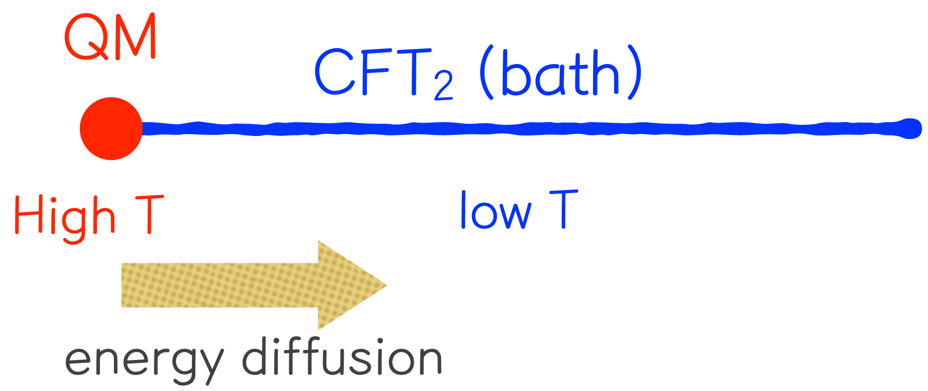

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Low-Dimensional Model (Bottom-up)

⁕ Holography:
AdS_2 (1+0)dim + CFT_2 (1+1)dim
[Almheiri, Engelhardt, Marolf, Maxfield, 2019]

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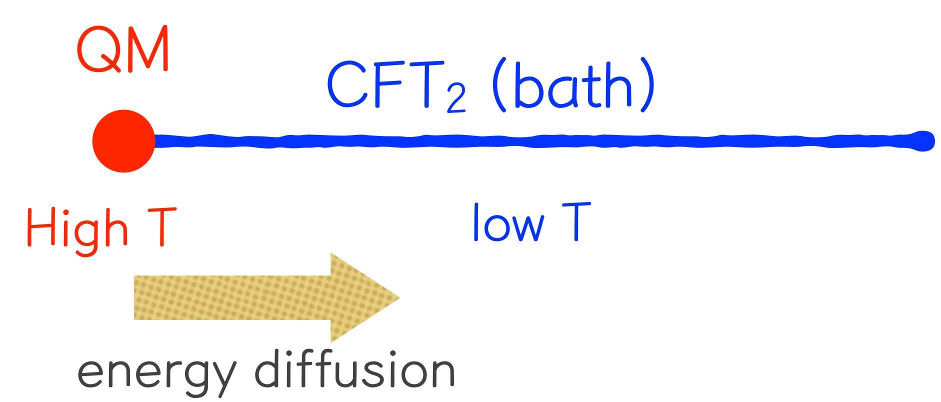

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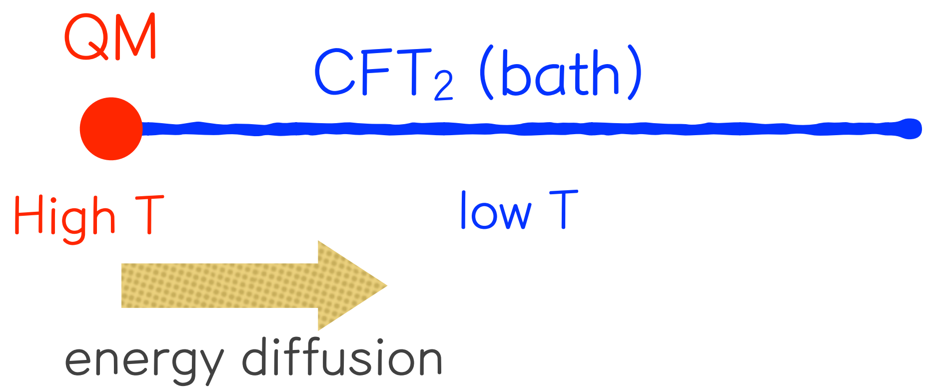

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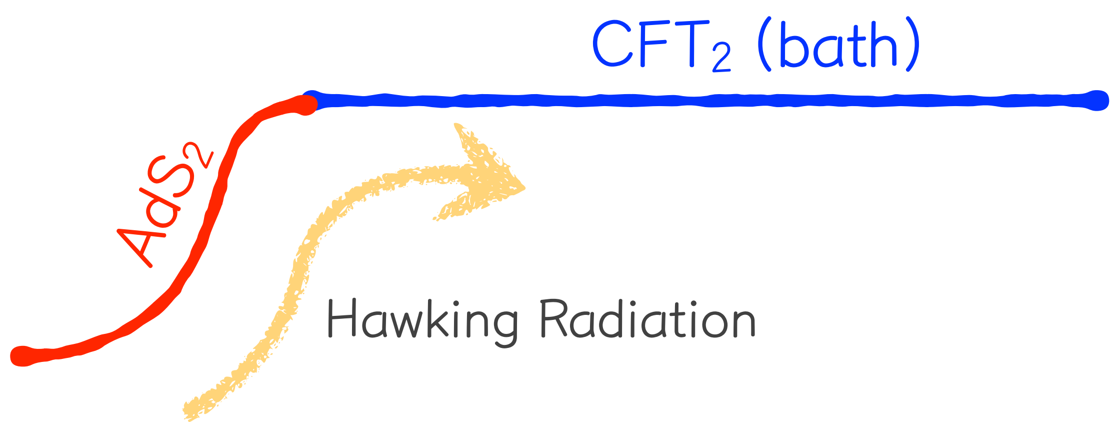

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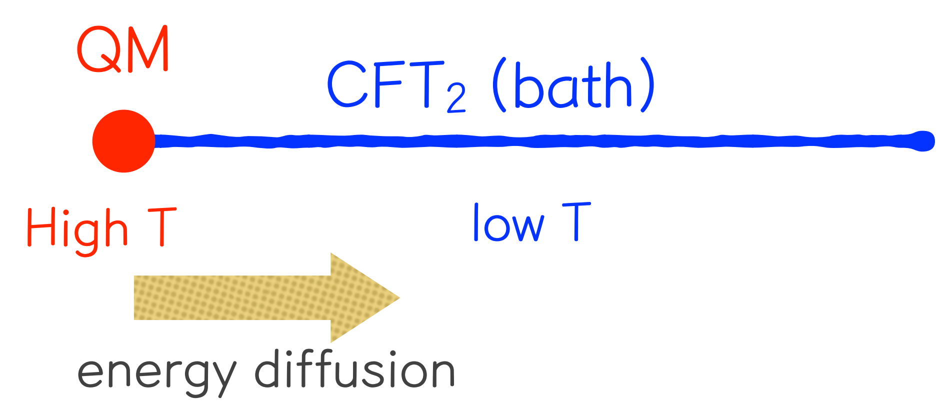

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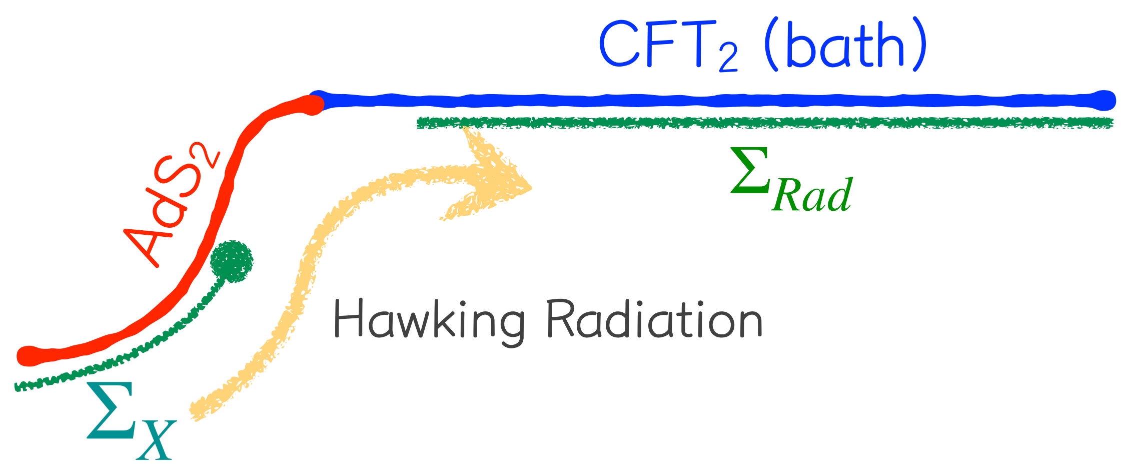
S_{QES} can be calculated by using
conformal symmetry
e.g. twist operator



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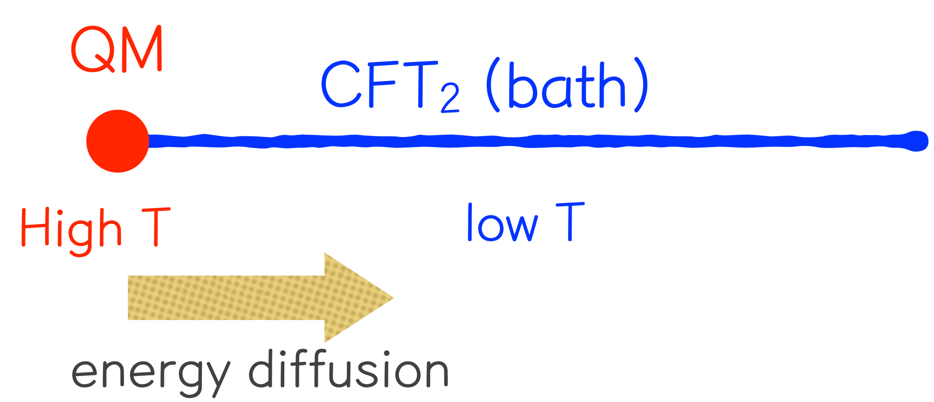

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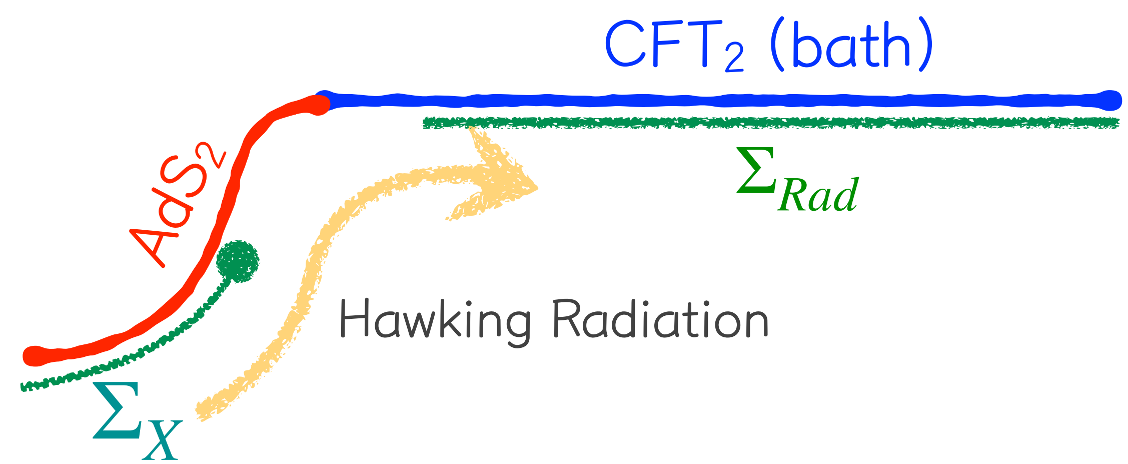
Low-Dimensional Model (Bottom-up)

∗ Doubly-holography:
AdS_3 (1+2)dim
[Almheiri, Mahajan, Maldacena, Zhao, 2019]
Also, recall Kusuki's lecture



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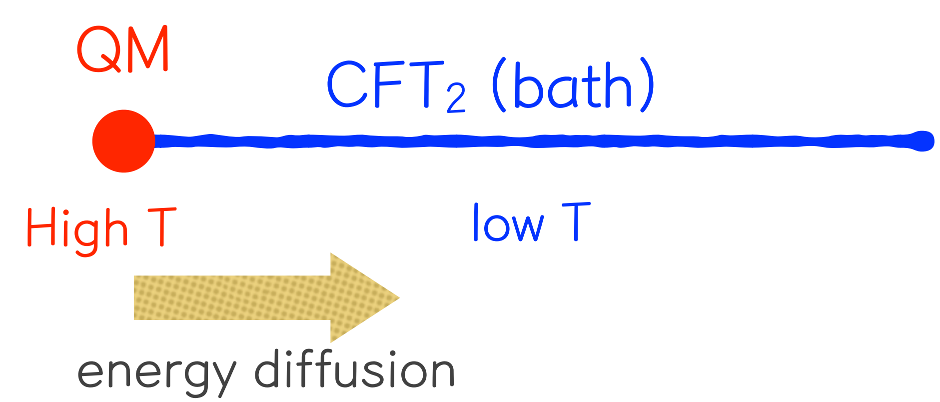

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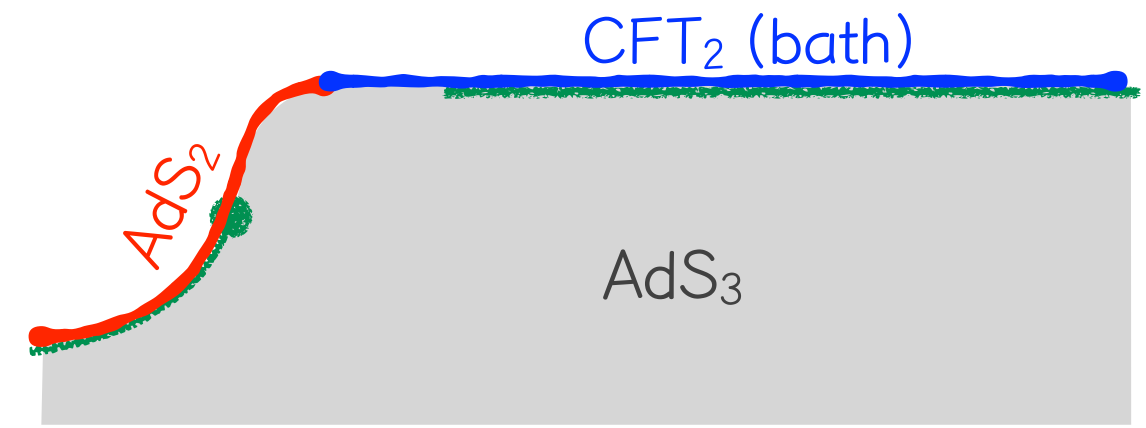

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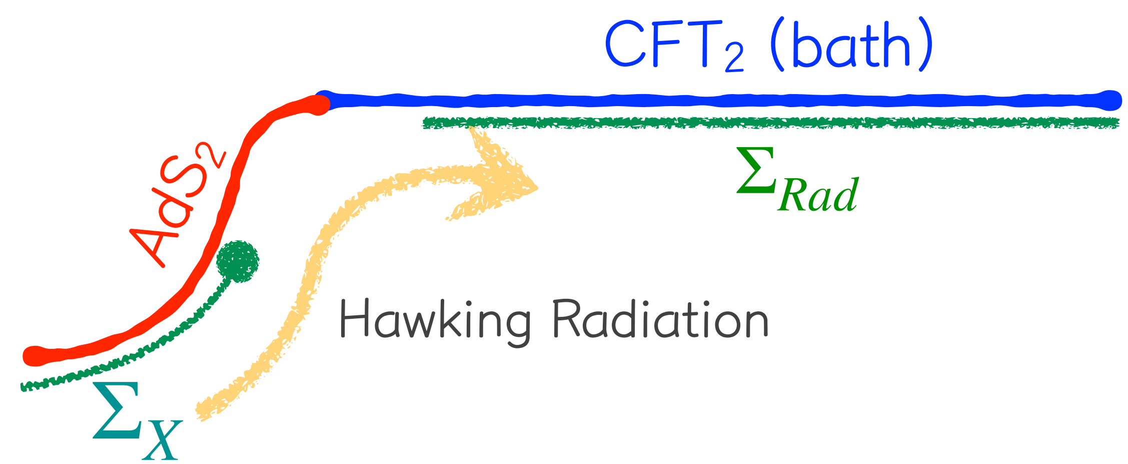

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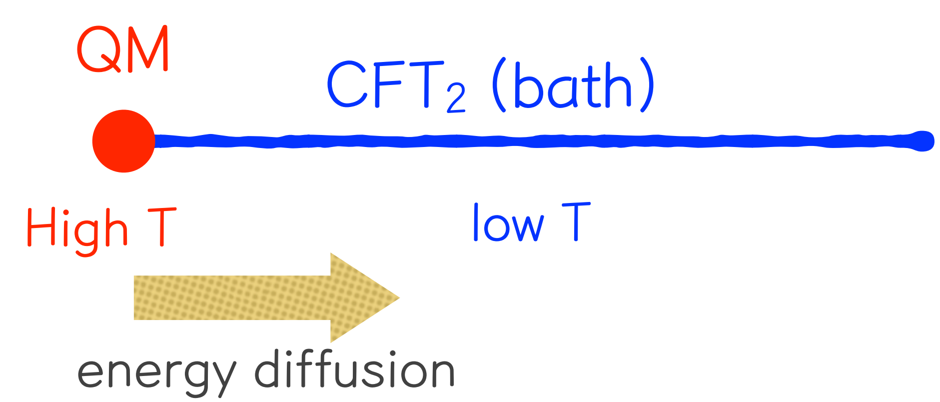

Low-Dimensional Model (Bottom-up)

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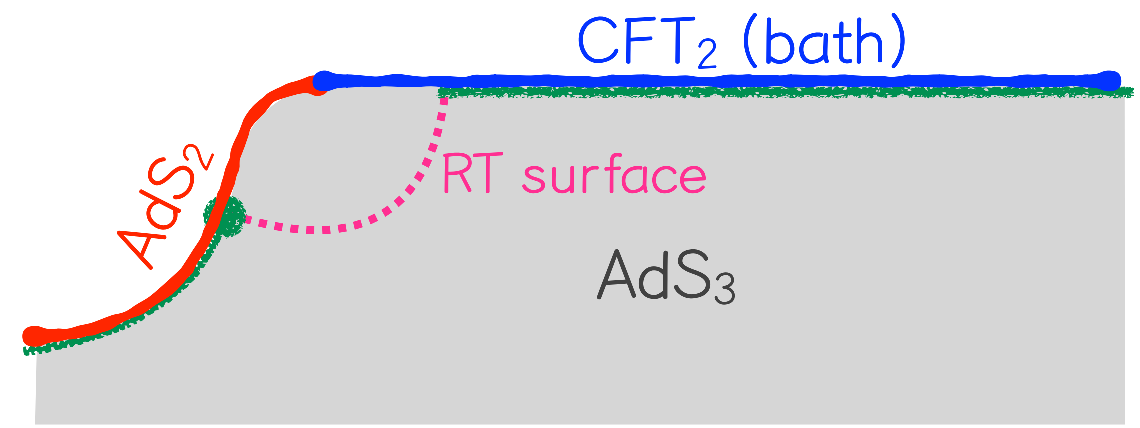
  AdS$_3$ (1+2)dim
  [Almheiri, Mahajan, Maldacena, Zhao, 2019]
  Also, recall Kusuki's lecture

  S_{QES} can be calculated by using
  RT surface



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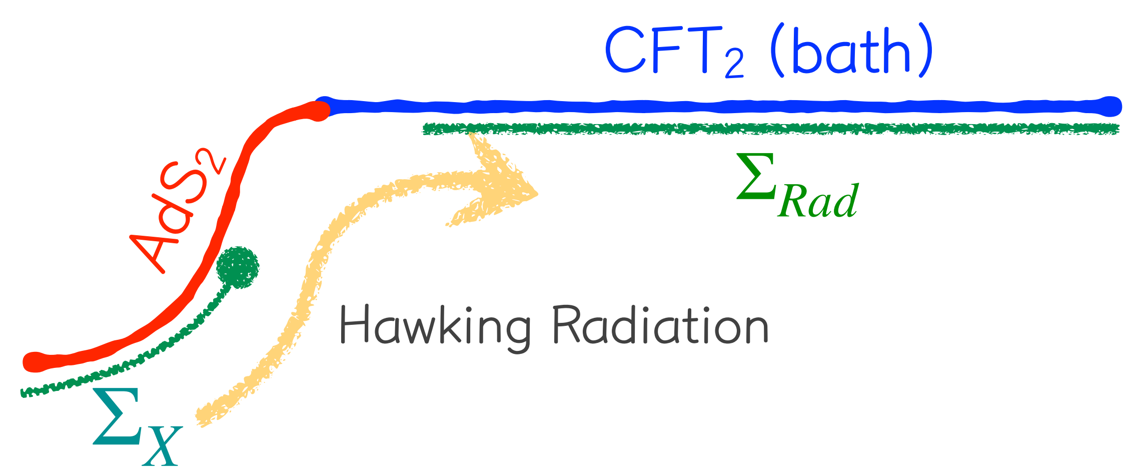

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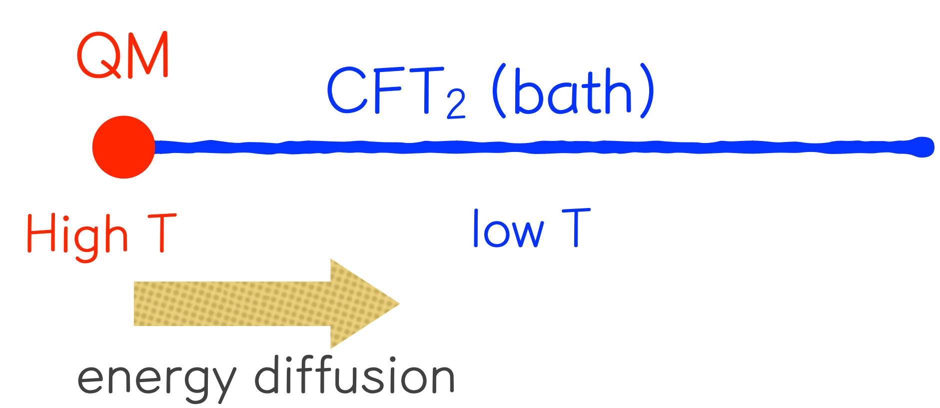


Doubly-holography:
3D Janus Black Hole

Eternal Janus Black Hole Solutions

- Einstein gravity coupled with massless scalar field

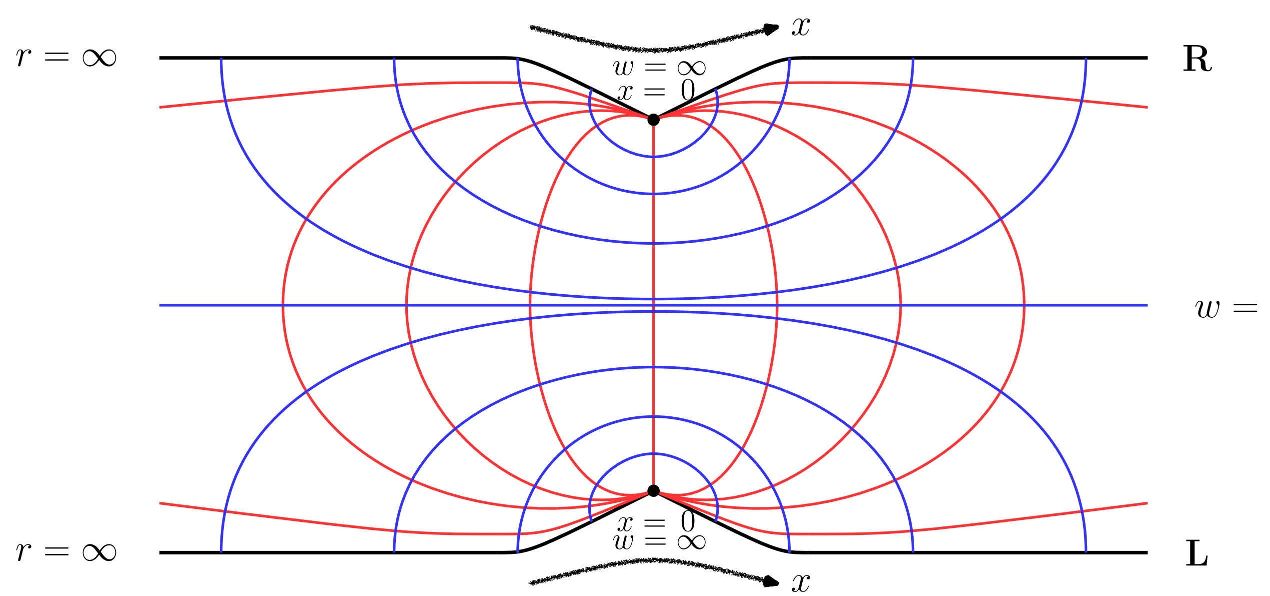
$$I = \frac{1}{16\pi G}\int d^3x \left[R - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{2}{\ell^2}\right]$$

- Three-dimensional two-sided Janus black hole solution

$$ds^2 = \ell[dy^2 + f(y)ds^2_{AdS_2}]$$

$$f(y) = \frac{1}{2}(1+\sqrt{1-2\gamma^2}\cosh 2y)$$

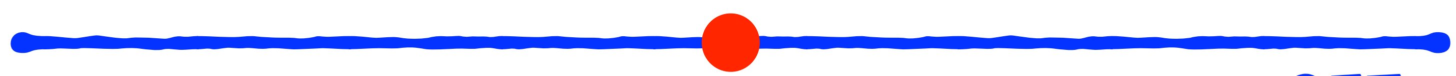
$$\phi(y) = \frac{1}{\sqrt{2}}\log\left[\frac{1+\sqrt{1-2\gamma^2}+\sqrt{2}\gamma\tanh y}{1+\sqrt{1-2\gamma^2}-\sqrt{2}\gamma\tanh y}\right]$$



time slice

Holographic Dual

* Janus black hole is holographically dual to Interface CFT_2 (ICFT_2).



CFT_2

(1+0) dim interface d.o.f. at $x = 0$

- ✓ Janus deformation induces interface d.o.f. at $x = 0$.

  $\dim(H_{interface}) \sim \log \frac{1}{\sqrt{1-2\gamma^2}}$

- ✓ Interface d.o.f. breaks conformal symmetry (partially).
  c.f. BCFT

* Eternal Janus black hole is dual to TFD of ICFT_2.

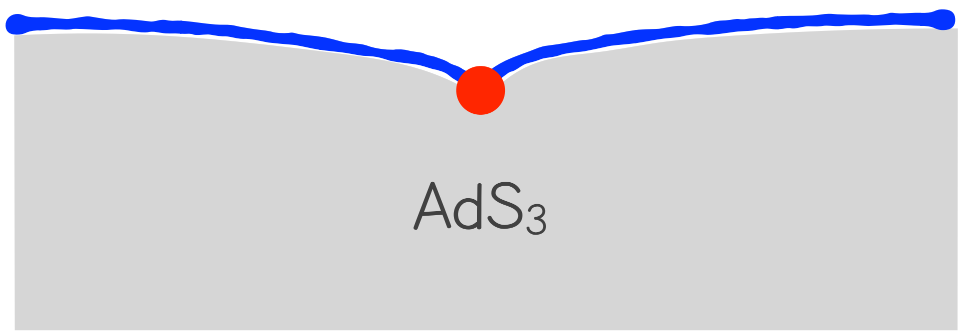
- ✓ ICFT_L and ICFT_R lives on the boundary of eternal Janus black hole, respectively.

- ✓ Maximally entangled state of ICFT_L and ICFT_R.

$$|TFD(t)\rangle = \frac{1}{\sqrt{Z}} \sum_n e^{-\frac{\beta}{2}E_n - 2itE_n} |n\rangle_L \otimes |n\rangle_R$$

Top-down Approach

* Eternal Janus Black Hole
  AdS_3 (1+2)dim



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Top-down Approach

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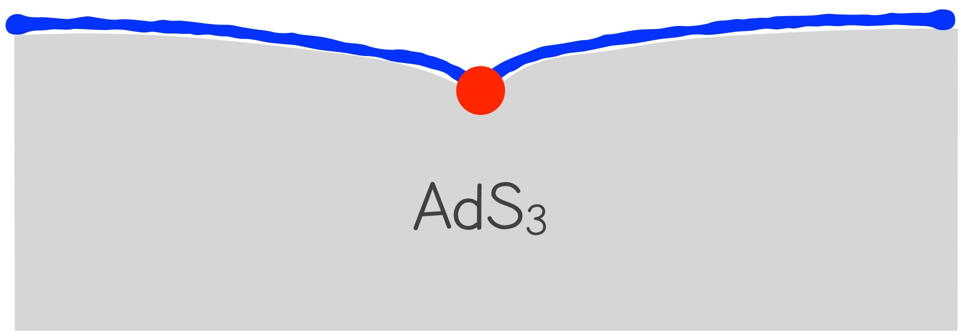
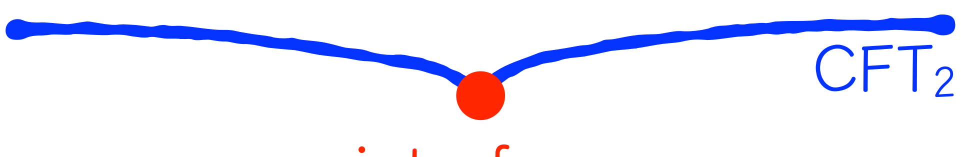


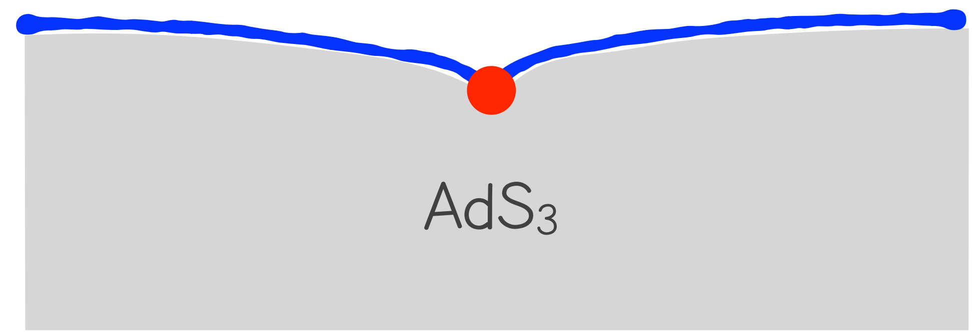
* "Doubly-holography"
  Interface (QM) (1+0)dim
  + CFT_2 (1+1)dim



This is usual holography for Janus black hole.

Top-down Approach

⁕ Eternal Janus Black Hole
AdS_3 (1+2)dim



⁕ AdS_2 (1+0)dim + CFT_2 (1+1)dim

?

Emergence of 2D gravity is not clear for general γ.

⁕ "Doubly-holography"
Interface (QM) (1+0)dim
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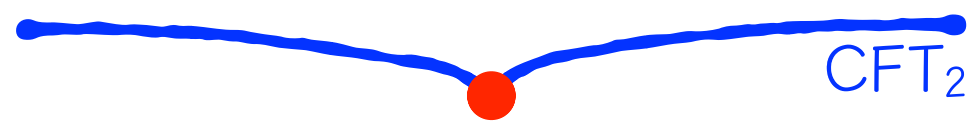

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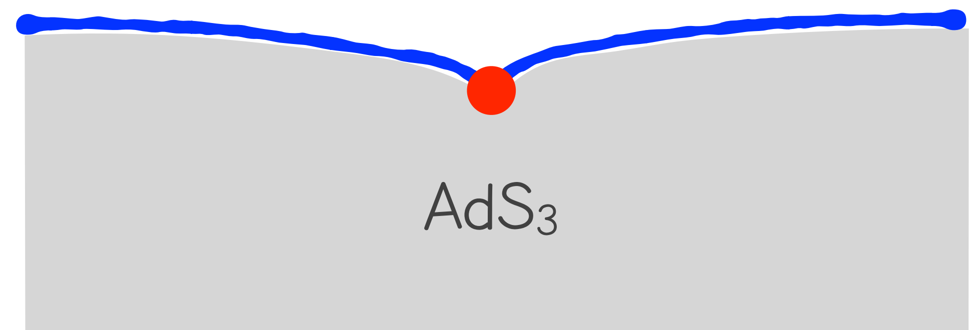

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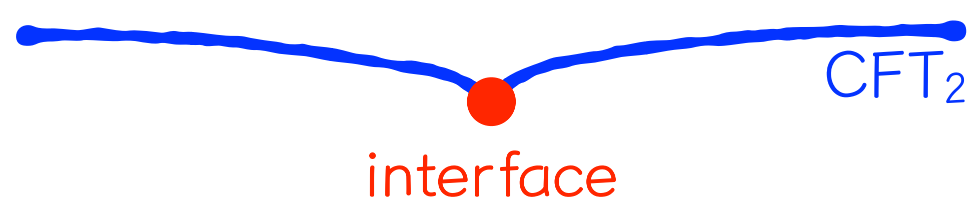

This is usual holography for Janus black hole.

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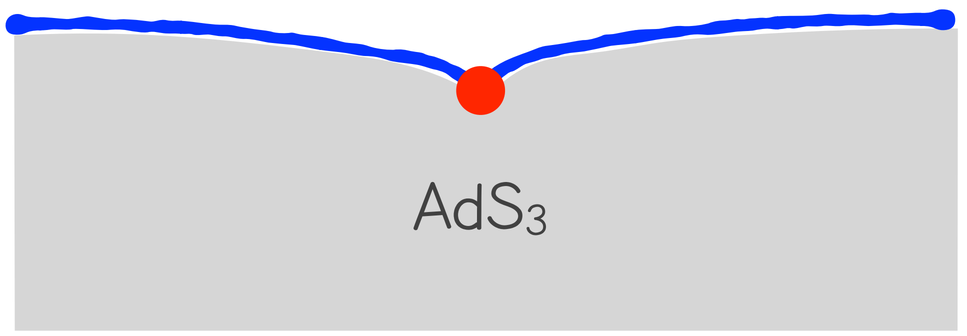
⁂ Eternal Janus Black Hole
AdS$_3$ (1+2)dim

As γ approaches to $\frac{1}{\sqrt{2}}$, interface d.o.f increases.

Shadow region gets larger.



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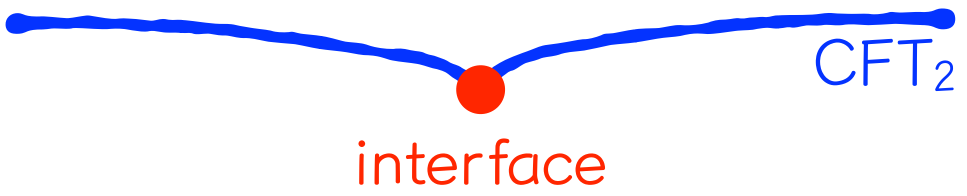

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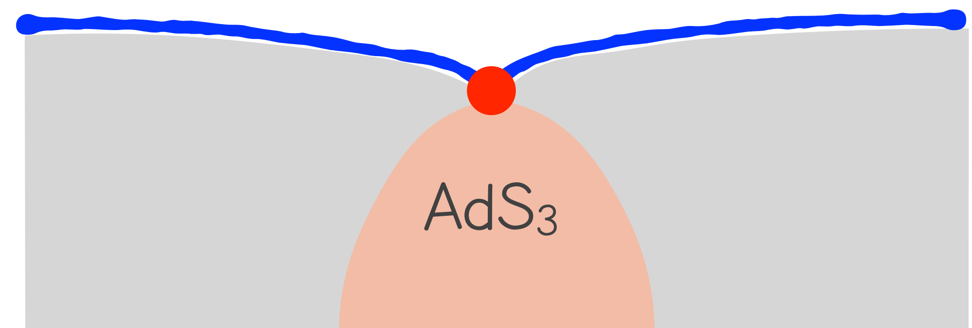

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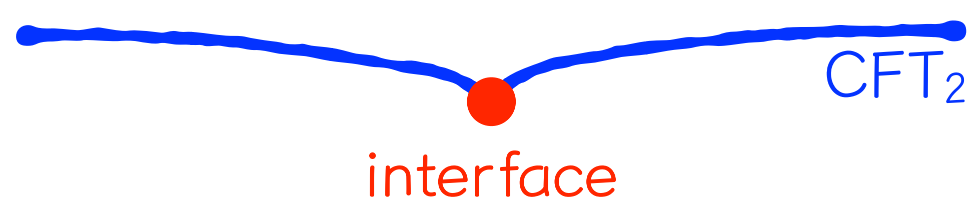

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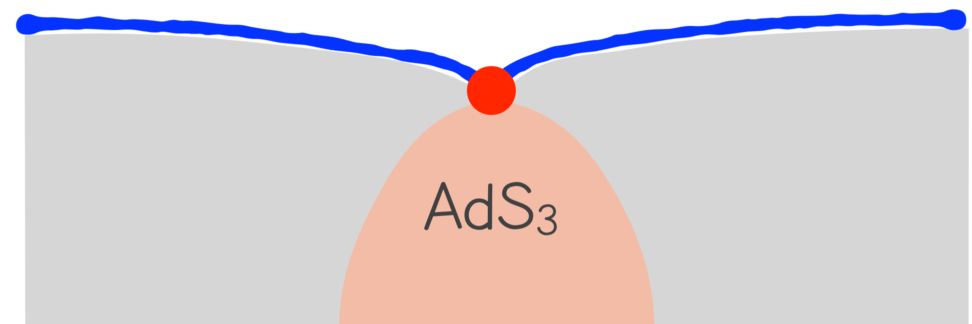

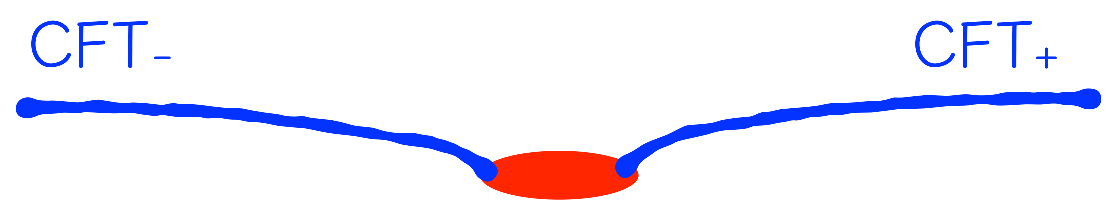

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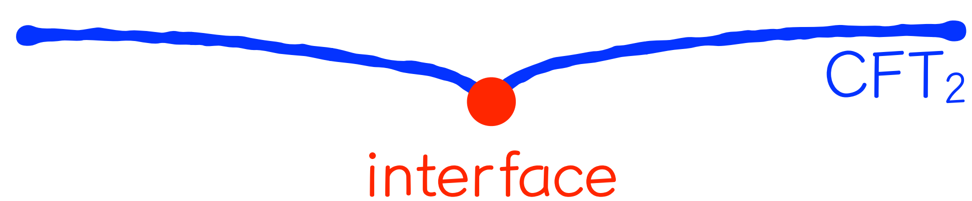

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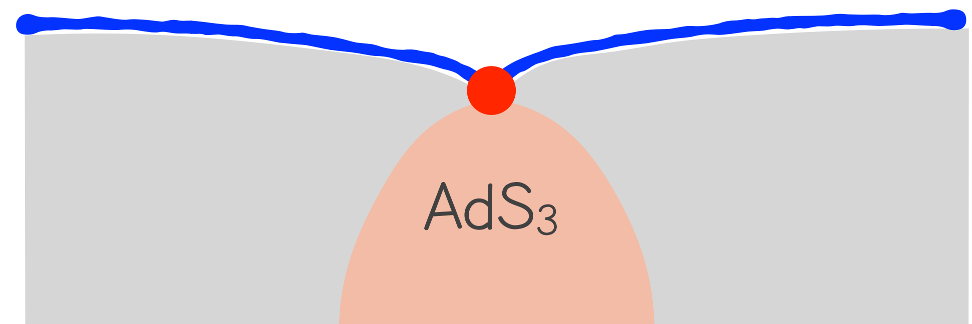
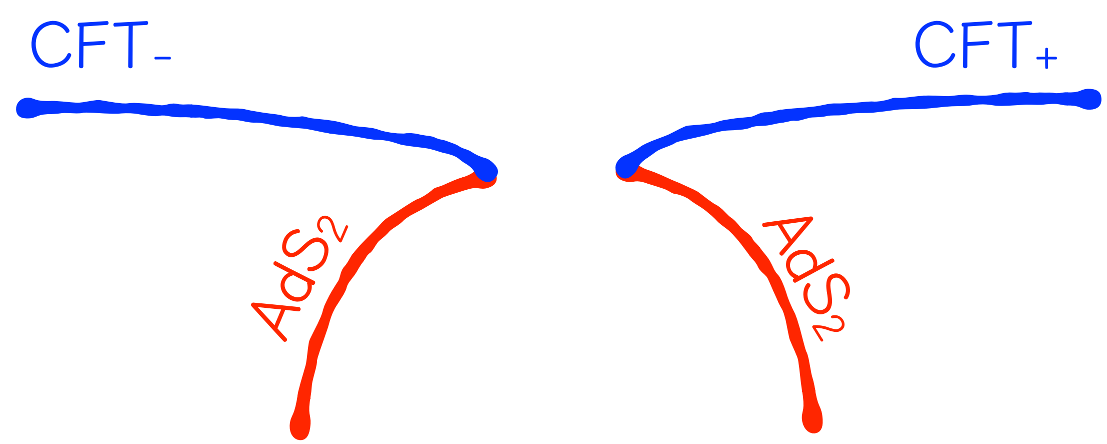


⁎ AdS$_2$ (1+0)dim + CFT$_2$ (1+1)dim

$x > 0$ and $x < 0$ regions are “almost” decoupled.



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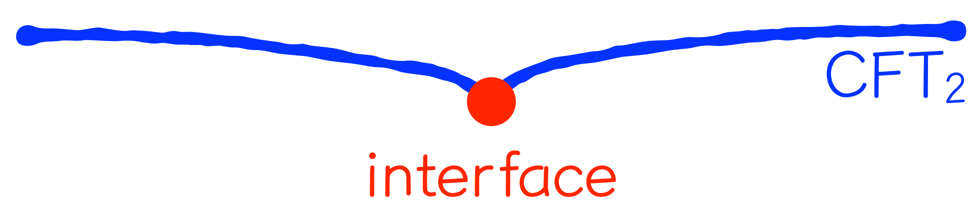


This is usual holography for Janus black hole.

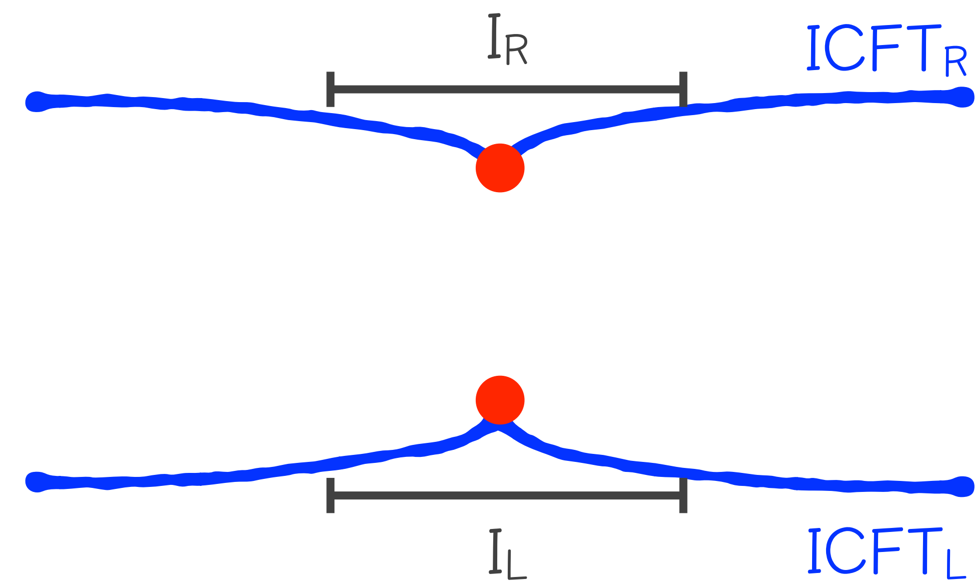
Entanglement Entropy

* We will study the entanglement entropy of $I_R \cup I_L$.

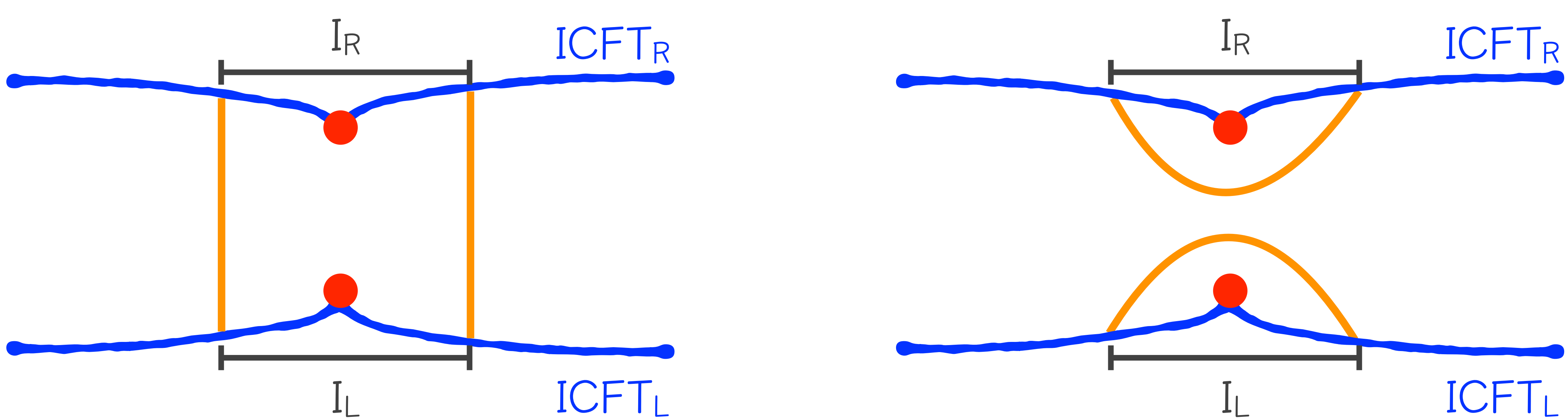
    ✓ I_R and I_L is interval in ICFT$_R$ and ICFT$_L$, respectively

    ✓ In AdS$_3$, this can be evaluated by RT surface.

    ✓ This is classical calculation.



* There are two phases for RT surface.



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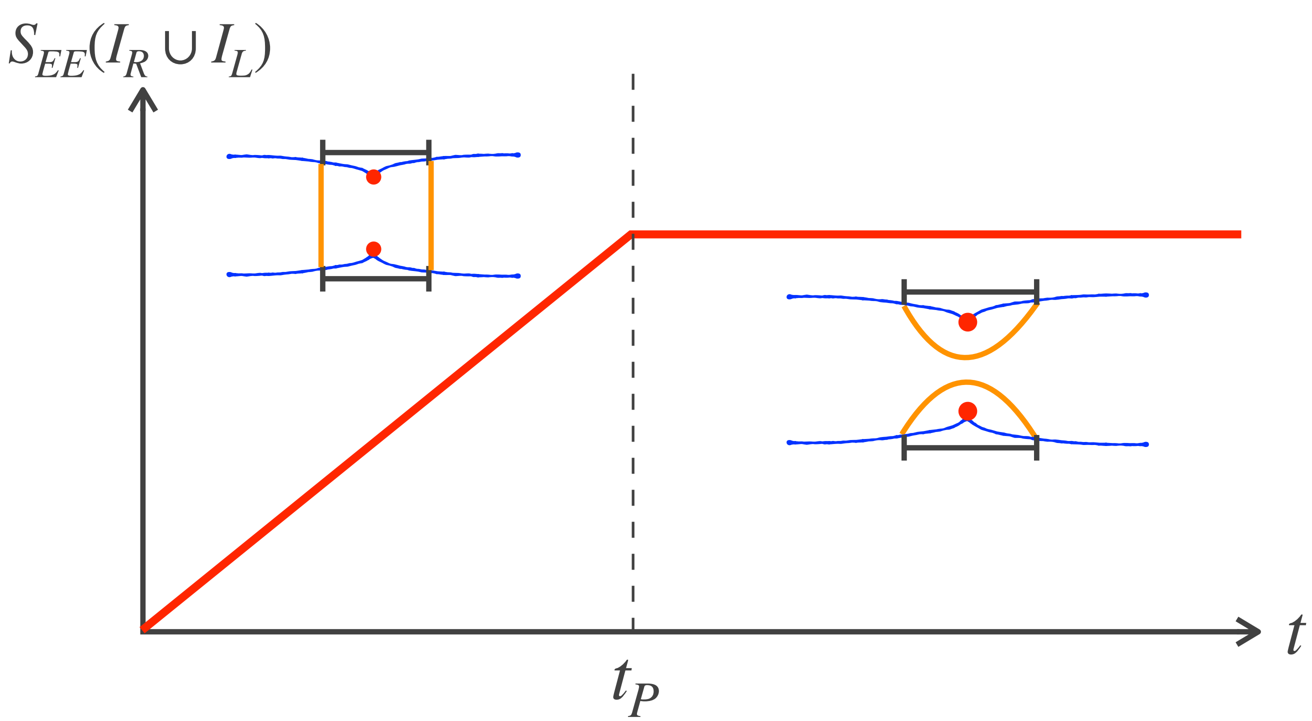
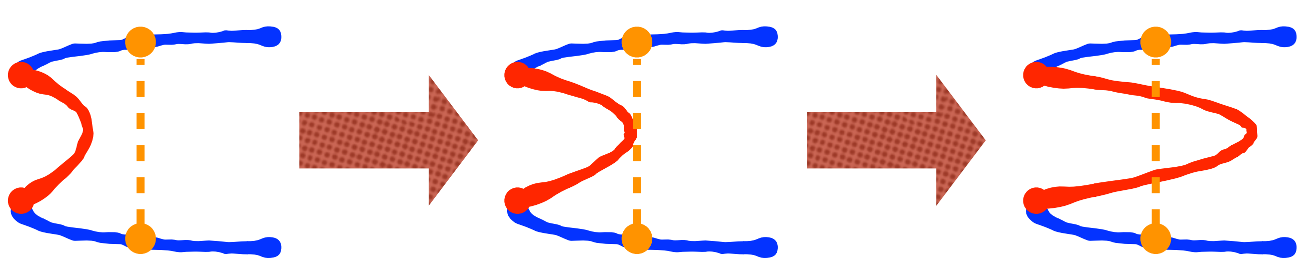
Page Curve

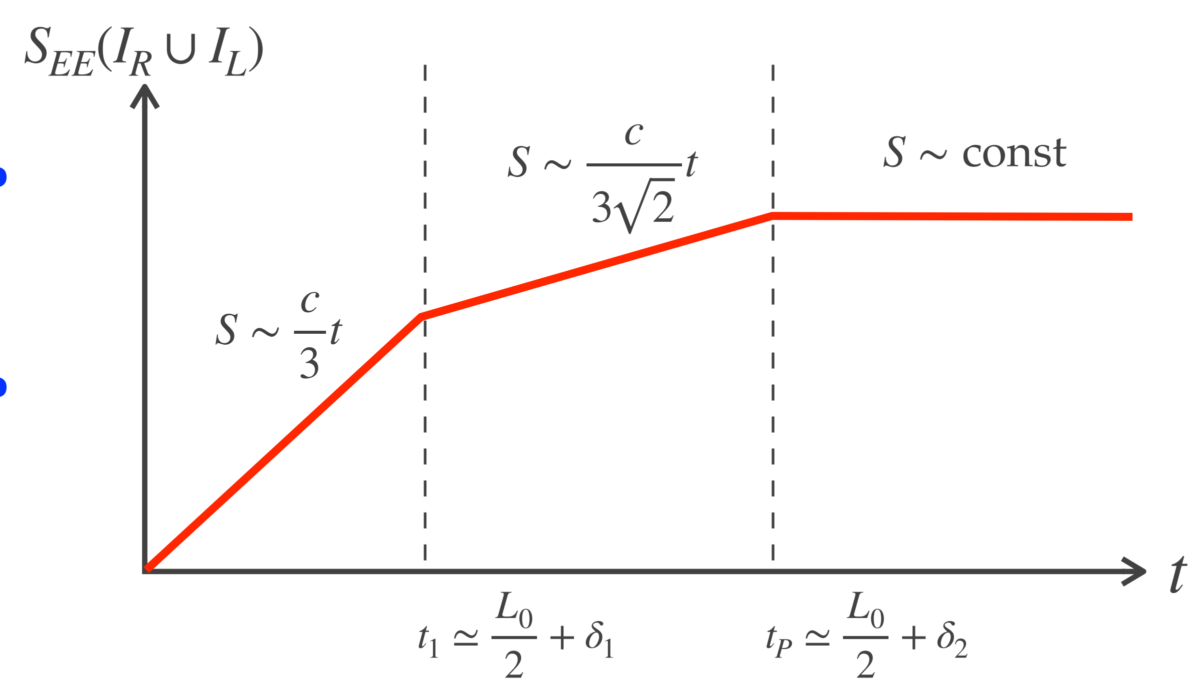
- ✳ Transition between two RT surfaces leads to Page curve for eternal Janus black hole
  - ✓ Page time: $t_p = \frac{L_0}{2} + \cdots$ where $I_L = I_R = \left[-\frac{L_0}{2}, \frac{L_0}{2}\right]$
  - ✓ Before Page time, the connected RT surface gives EE which increases in time.
  - ✓ After Page time, the disconnected RT surface leads to time-independent EE. This is the sum of thermal EE of each interval I_R and I_L.



New Phase before Page Time

- As time passes, the shadow region gets larger. For small interface d.o.f., a transition to disconnected RT surface occurs before the shadow region touches the connected RT surface.
- When the interface d.o.f. is large enough, we have enough time window to exhibit new behavior before Page transition (disconnected RT surface). i.e. the shadow region intersects with connected RT surface.





$$\delta_1 \ll \delta_2 \sim S_{interface}$$

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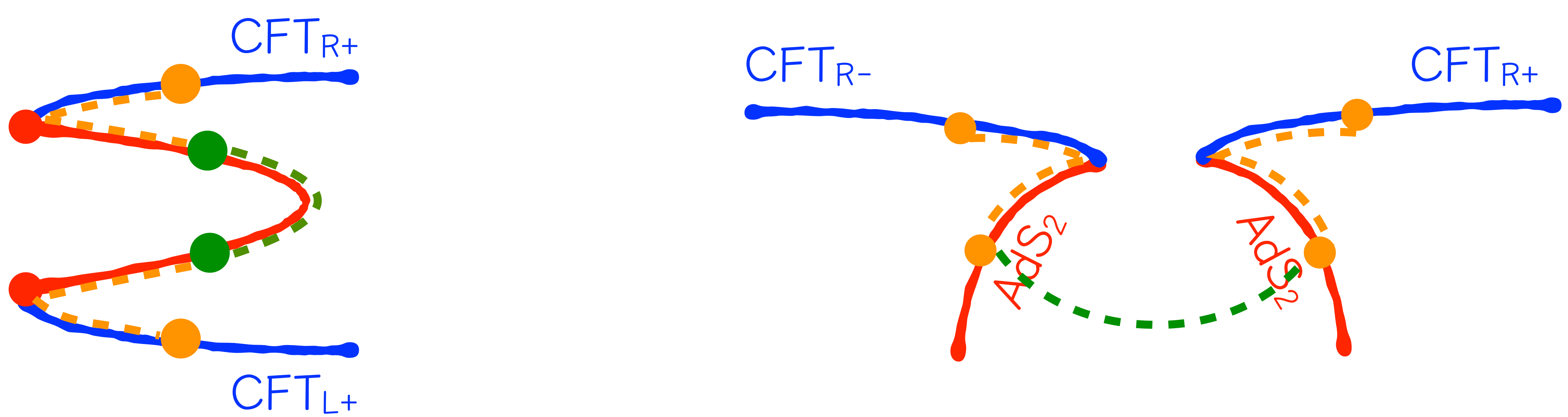
From Lower-Dim Point of View

- ✳ For large interface d.o.f., we have “2D gravity” description.
- ✳ We can calculate QES from the point of view of 2D gravity + CFT_2.



  - ✓ can confirm the results from 3D calculations.
- ✳ Also, we calculate EE from the point of view of $ICFT_2$ ($QM+CFT_2$)
  - ✓ consistent with 3D calculations.

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Conclusion

- ✳ Eternal Janus black hole is a top-down example of Island conjecture.
  - ✓ "2D gravity" description and doubly-holography is available.
  - ✓ 1D, 2D and 3D calculations of EE are consistent.
- ✳ Existence of Island is still not proven yet.
  - ✓ We accepted assumption of the existence of Island (or, QES). But, this does not prove it.
  - ✓ The essence of Island might lie in black hole complementary.

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Outlook

- Is there other observables to test Island conjecture?
- How can we extract information from Island?
- What is the origin of the Island?
- Can we calculate the same thing in higher dimension?
  e.g. SYM/AdS_5

Thank You