Aspects of Traversable Wormholes

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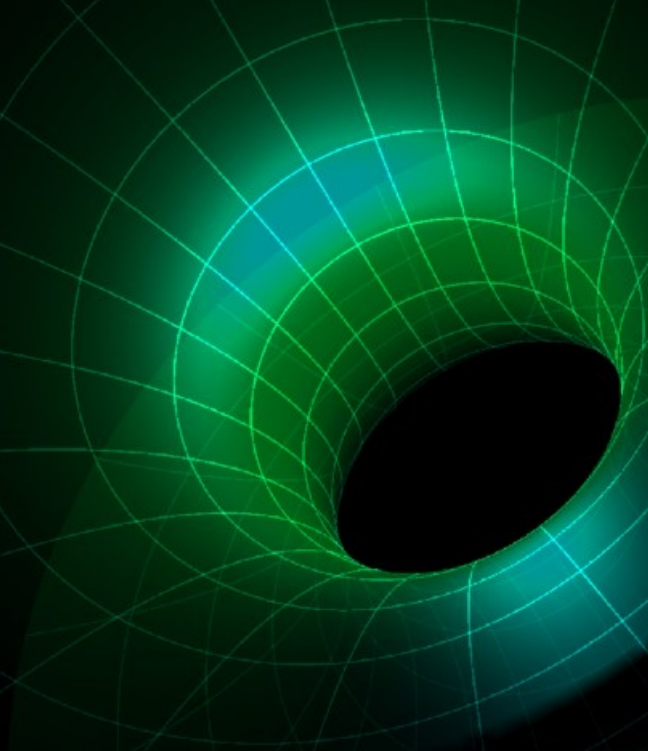
Black Holes, BPS and Quantum Information

Lisboa

21 September 2021

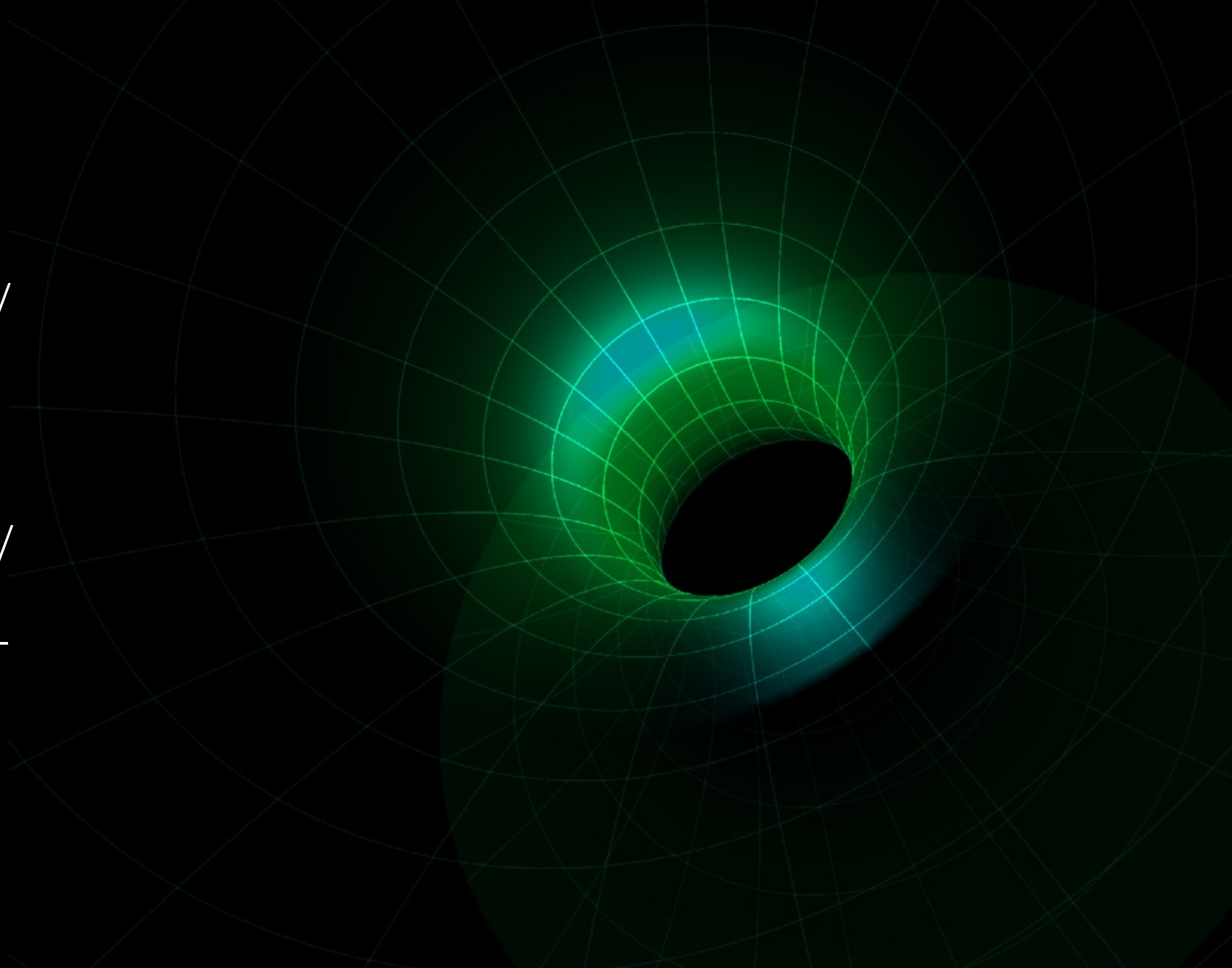


European Research Council
Established by the European Commission
ERC AdG 692951-GravBHs

Based on

2012.07821 [hep-th] w/
Brianna Grado-White
Don Marolf
Marija Tomašević

and work in progress w/
Marija Tomašević

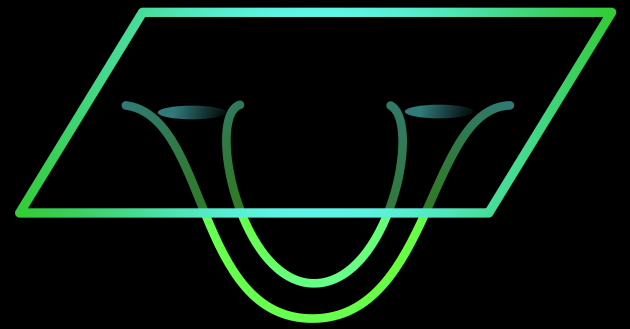


Wormholes in this talk

Lorentzian

Traversable

In a single universe



What can spacetime do?

What topologies?

What connectivity in space and in time?

Classical or quantum matter?

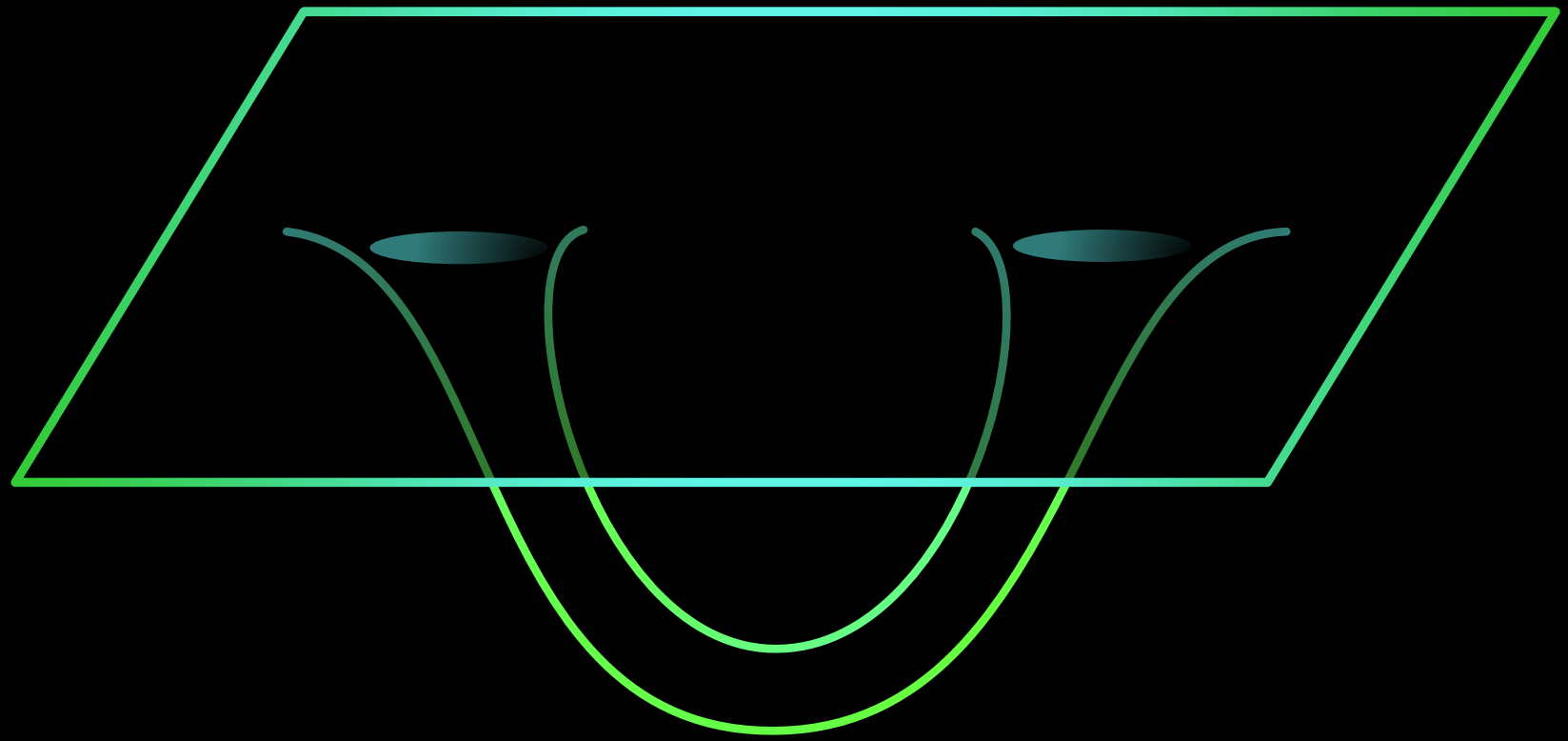
What does it mean?

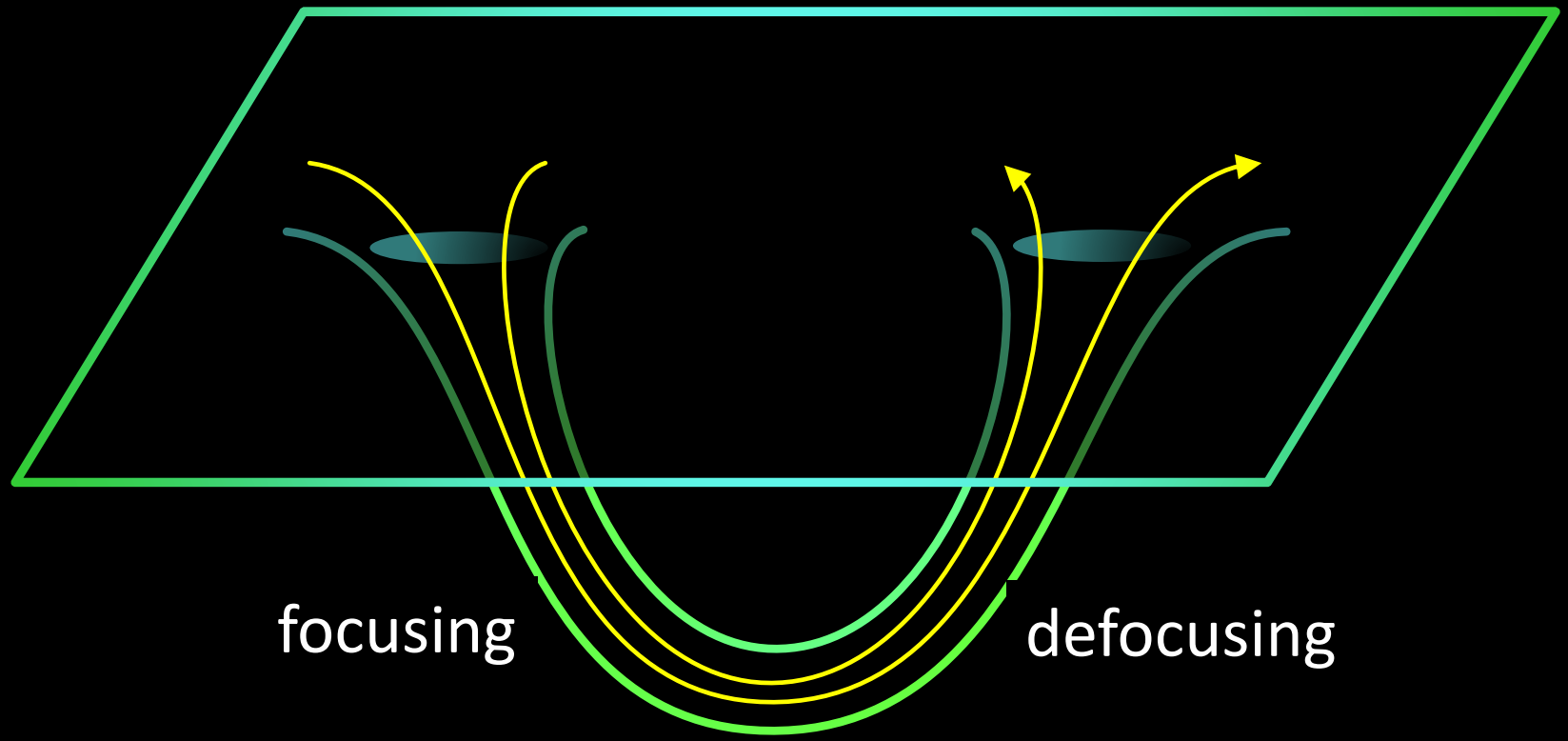
Geometric duals of quantum teleportation

Patterns of holographic entanglement

Are they possible?

Negative energy required





Repulsive effect on light rays
Negative null energy

$$T_{\mu\nu}\ell^{\mu}\ell^{\nu} < 0$$

Topological censorship

Assume Null Energy Condition (NEC)

$$T_{\mu\nu}\ell^{\mu}\ell^{\nu} \geq 0$$

Then, causal curves are deformable

to boundary of spacetime

$\Rightarrow \nexists$wormholes

Galloway+Schleich+Witt+Woolgar

Weaker assumption

Averaged (integrated) Null Energy Condition (ANEC)

$$\int_\gamma T_{\mu\nu}\ell^\mu\ell^\nu \geq 0$$

γ: complete null curve

is enough for theorem

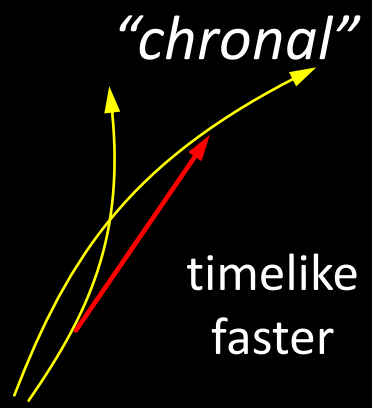
Even weaker assumption

Graham+Olum 2007

Achronal Averaged Null Energy Condition (AANEC)

$\int_\gamma T_{\mu\nu}\ell^\mu\ell^\nu \geq 0$ along achronal null lines

achronal light ray = “fastest path”



Classical Matter

Null Energy is positive (NEC)

Cannot defocus

Traversable wormholes impossible

Quantum Matter

Null Energy can be negative ~~NEC~~

$\Rightarrow$ traversable wormholes become possible

Quantum Matter

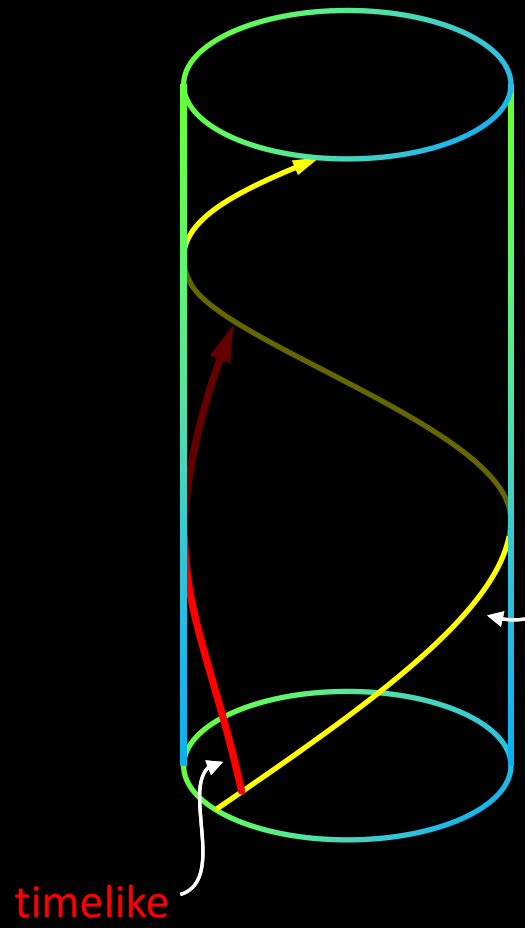
Null Energy can be negative ~~NEC~~

$\Rightarrow$ traversable wormholes become possible

Achronal ANEC holds

What wormholes?

~~ANEC~~ in Casimir cylinder



Casimir energy <0

$$\int_\gamma T_{\mu\nu}\ell^\mu\ell^\nu < 0$$

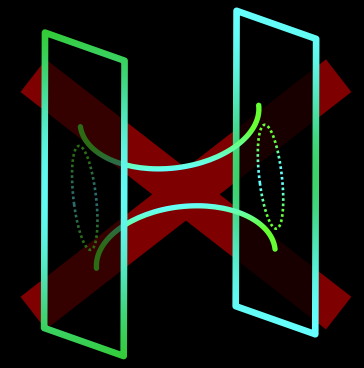
but this null geodesic is not achronal

Achronal ANEC holds

Quantum Physics

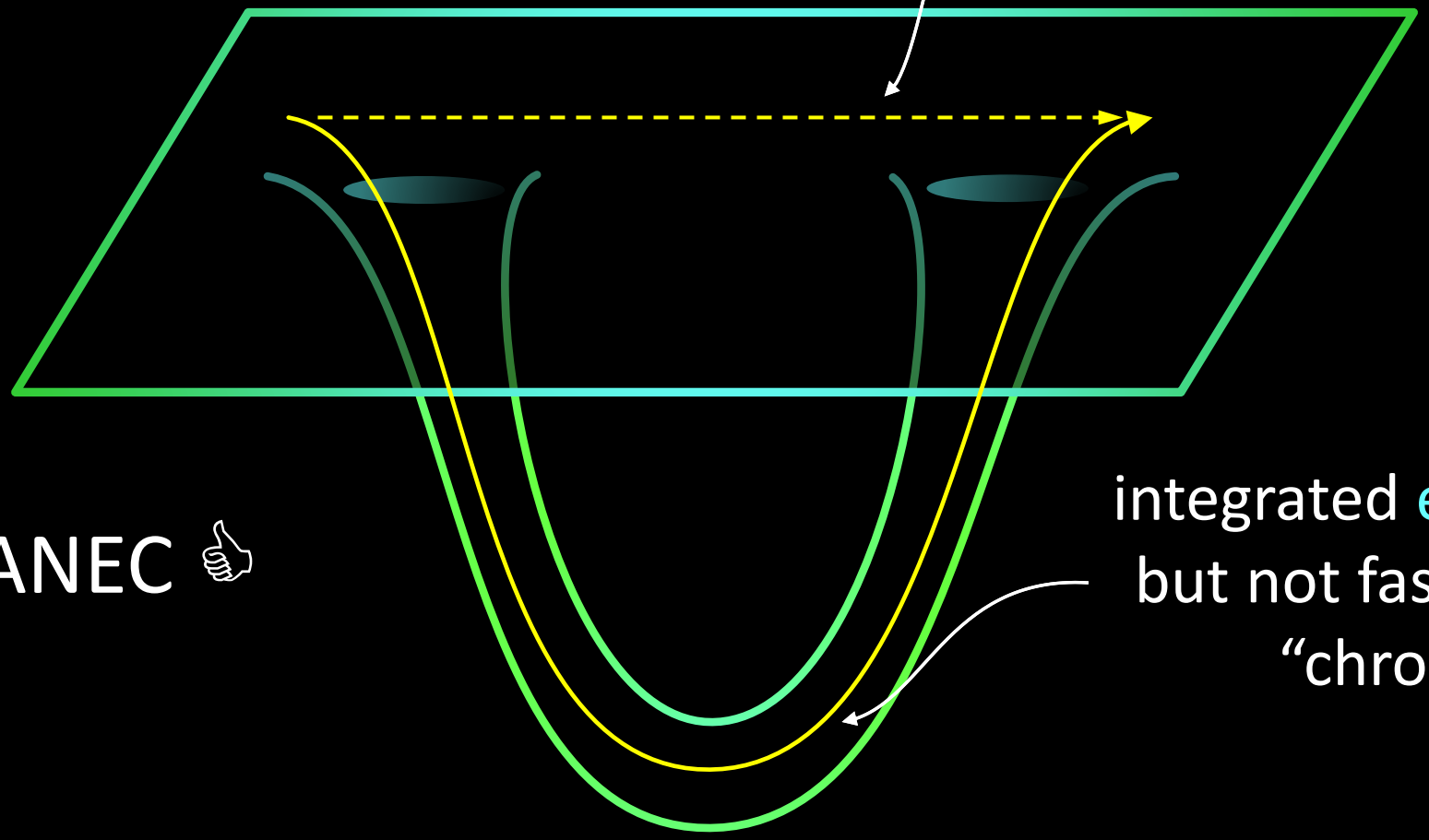
Achronal ANEC implies:

- Short wormholes impossible
- Inter-universe wormholes impossible
- Long wormholes **possible**



Long wormhole

integrated energy > 0
achronal

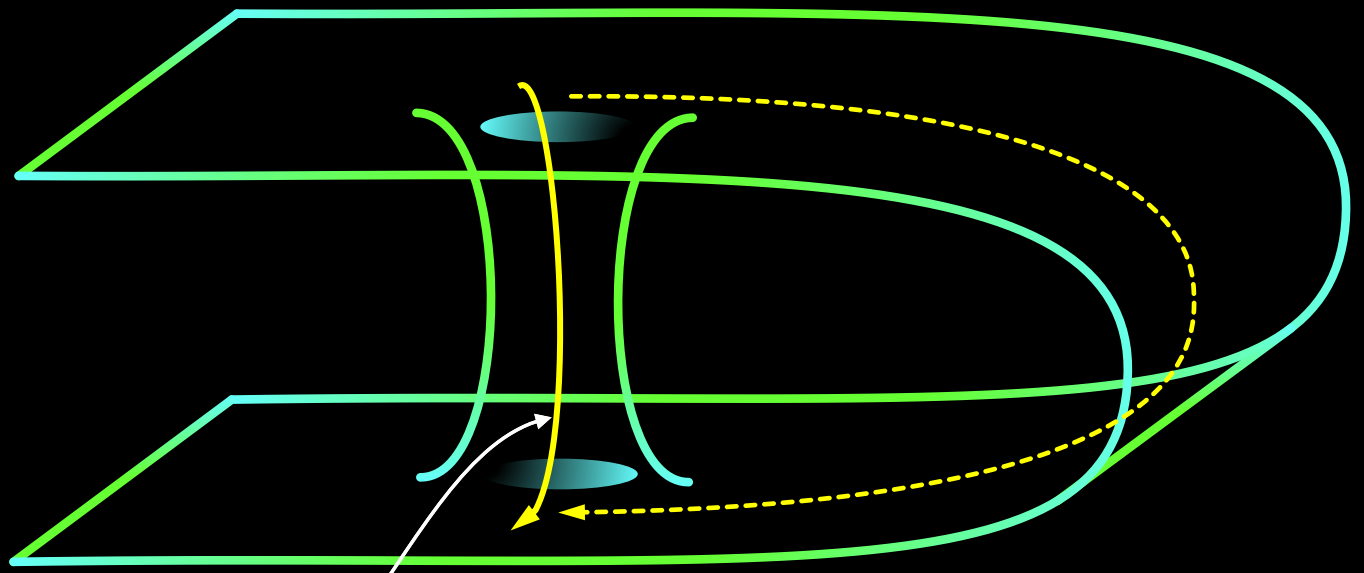


integrated energy < 0
but not fastest path
“chronal”

Achronal ANEC 👍

Short wormhole

~~Achronal ANEC~~ 👎

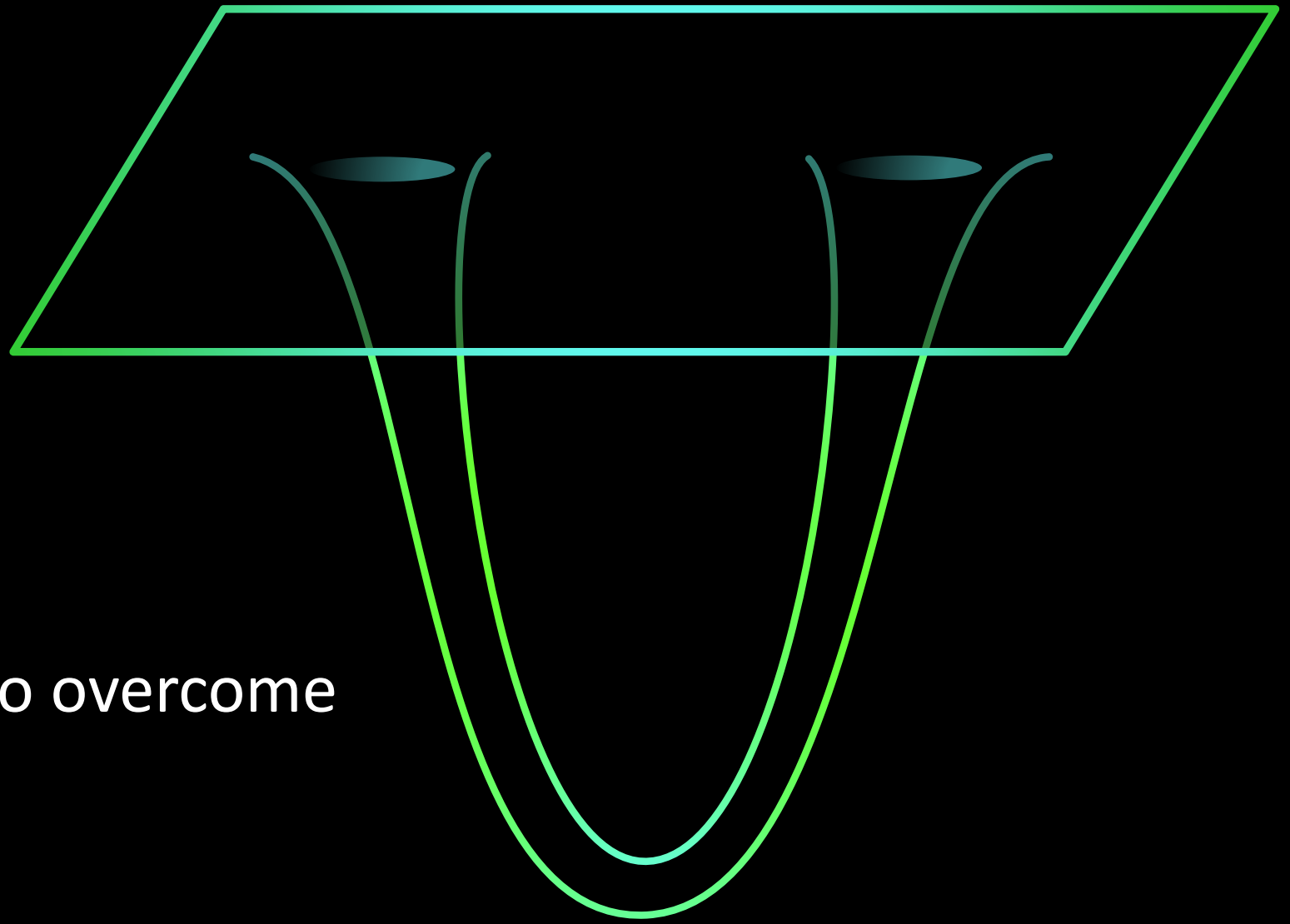


integrated energy < 0

fastest path

achronal

inter-universe wormhole: ultra-short



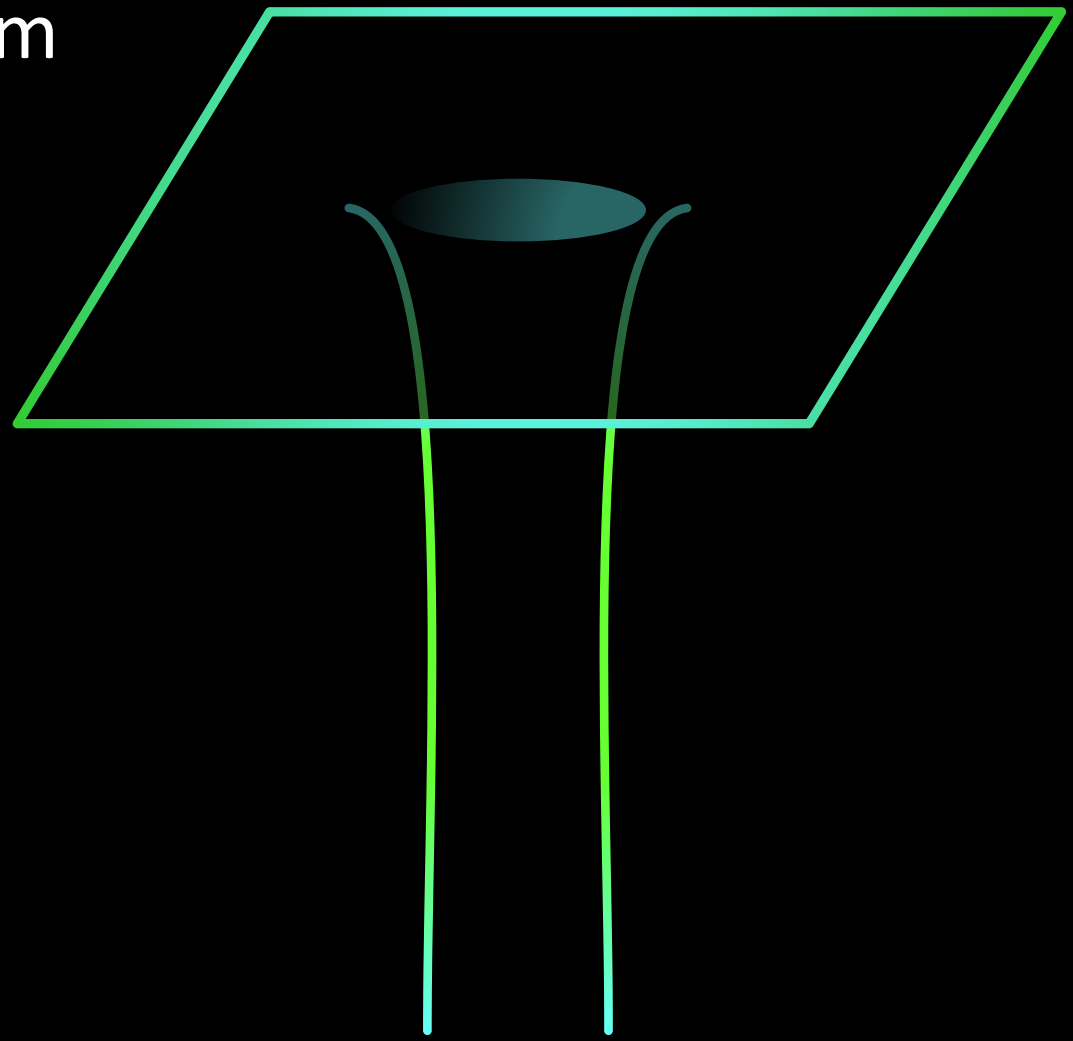
Need

- long throats
- quantum -ve energy to overcome

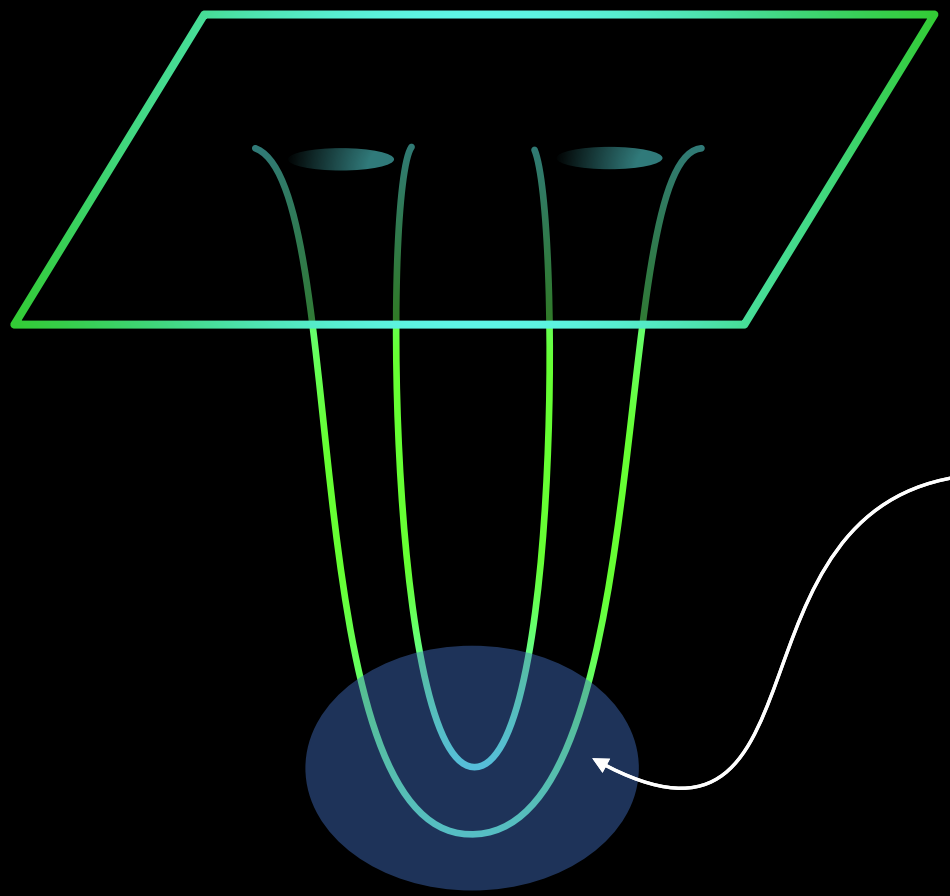
  +ve classical energy

Near-extremal Reissner-Nordstrom

- long throat
- large redshift: small energies



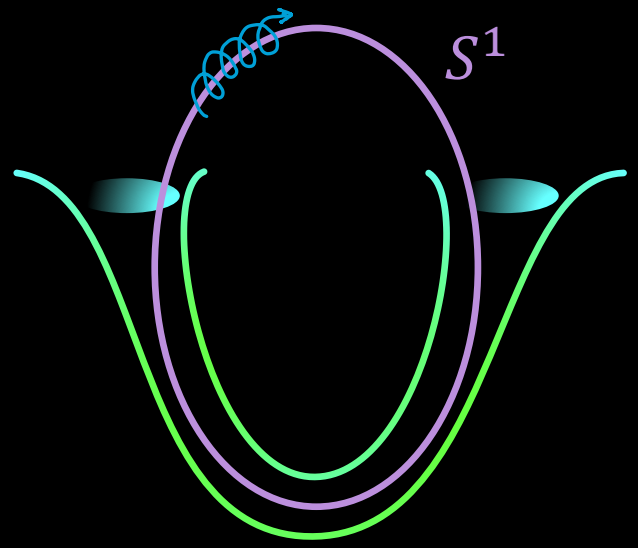
Maldacena+Milekhin+Popov 2018



Perturb M>Q Reissner-Nordstrom w/

negative-energy quantum matter

Negative Casimir energy from massless (conformal) effective 1+1 fields along S^1



Electrons in magnetic RN

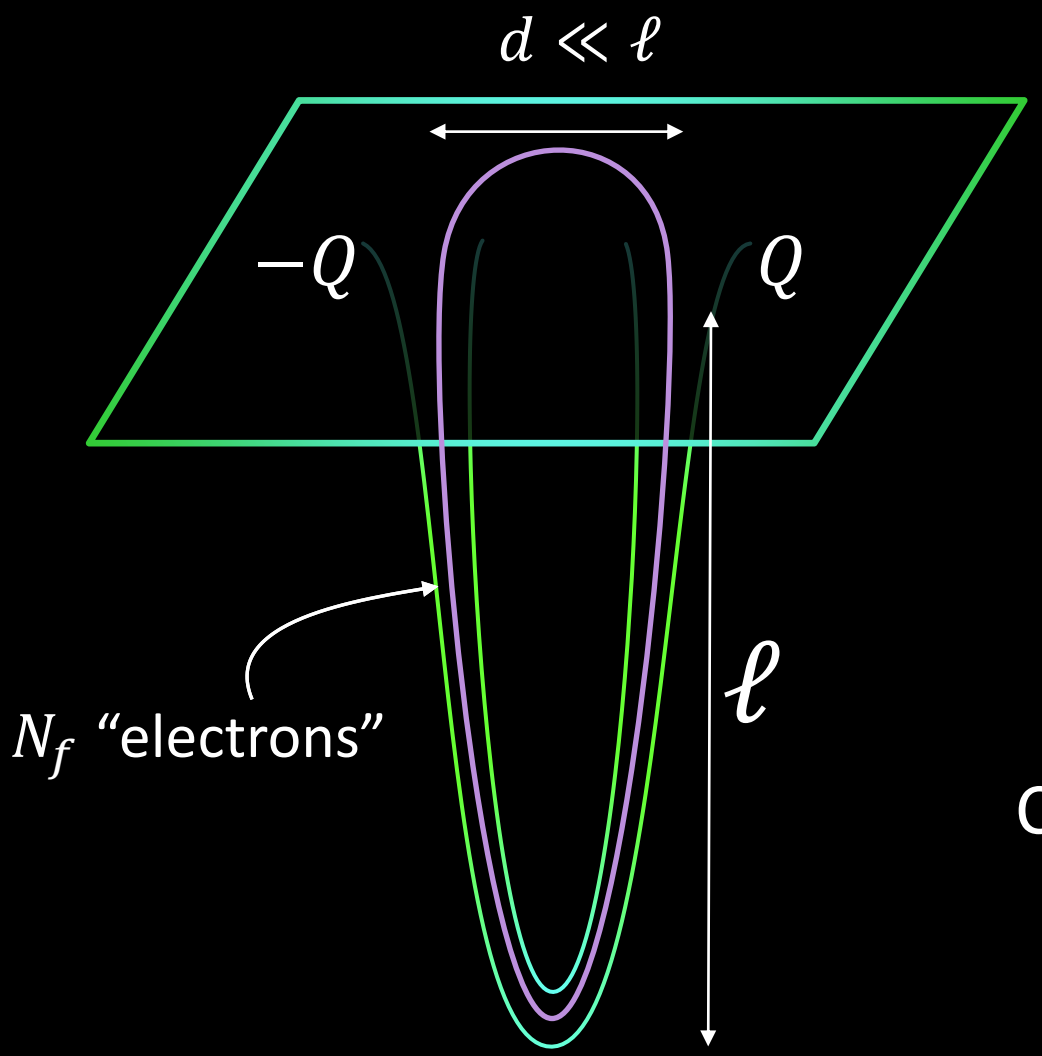
Landau ground state level

Maldacena+Milekhin+Popov 2018

"Dark CFT" from 5D bulk

Maldacena+Milekhin 2020

Energetics



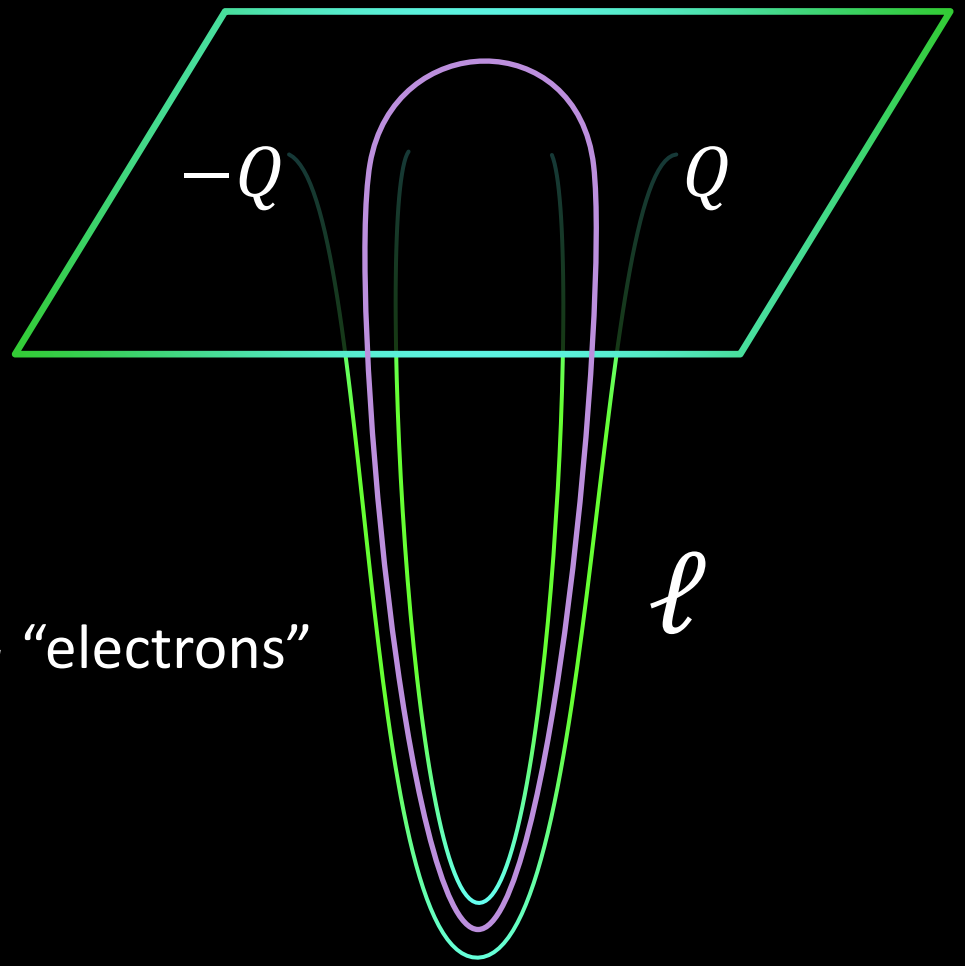
Energy "above" extremality

$$E = \frac{\pi^{3/2} Q^3 l_P}{\ell^2} - \frac{N_f Q}{8\ell}$$

Classical, from RN
redshift → small

Quantum
Casimir in S^1

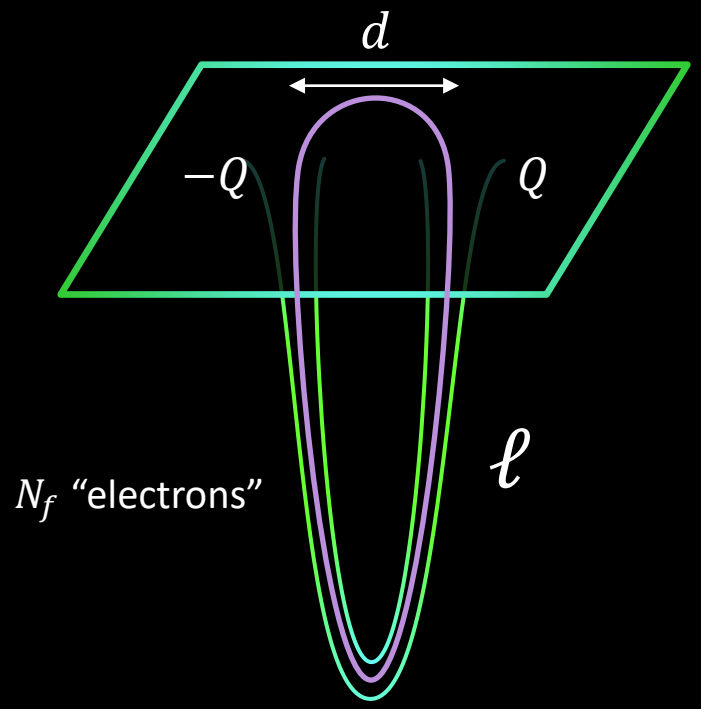
Energetics



minimize $E \Rightarrow \ell \sim \frac{Q^2}{N_f} l_{Planck}$

Energy "above" extremality

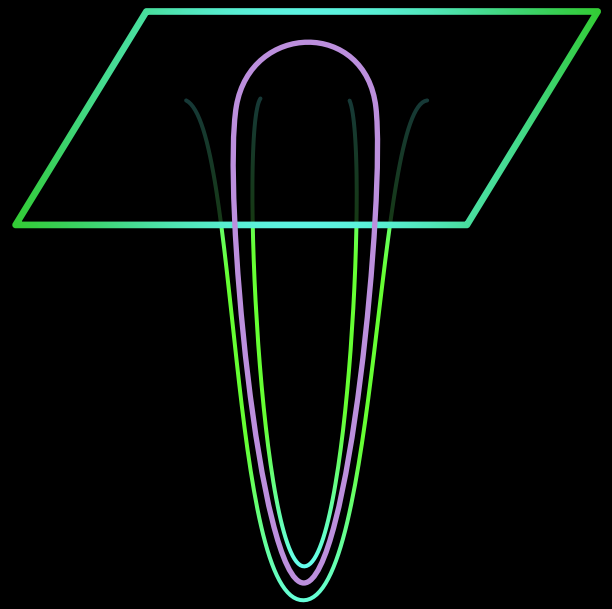
$$E_{binding} \sim -\frac{N_f^2}{Q} E_{Planck}$$



Remarks

- Small binding energy: *fragile* wormhole
- Can only make single-universe wormholes
- Attraction between mouths?
  - merger time $\sim d^{3/2}$, long enough to cross
  - may balance w/ fluxtube, strings, rotation…

Variations on the theme of wormholes



More versatile constructions:

- Casimir from cosmic string zero-modes on S^1

Fu+Grado-White+Marolf 2018

- Several $U(1)$s

Digging more holes

Multiple wormholes?

Fragile!

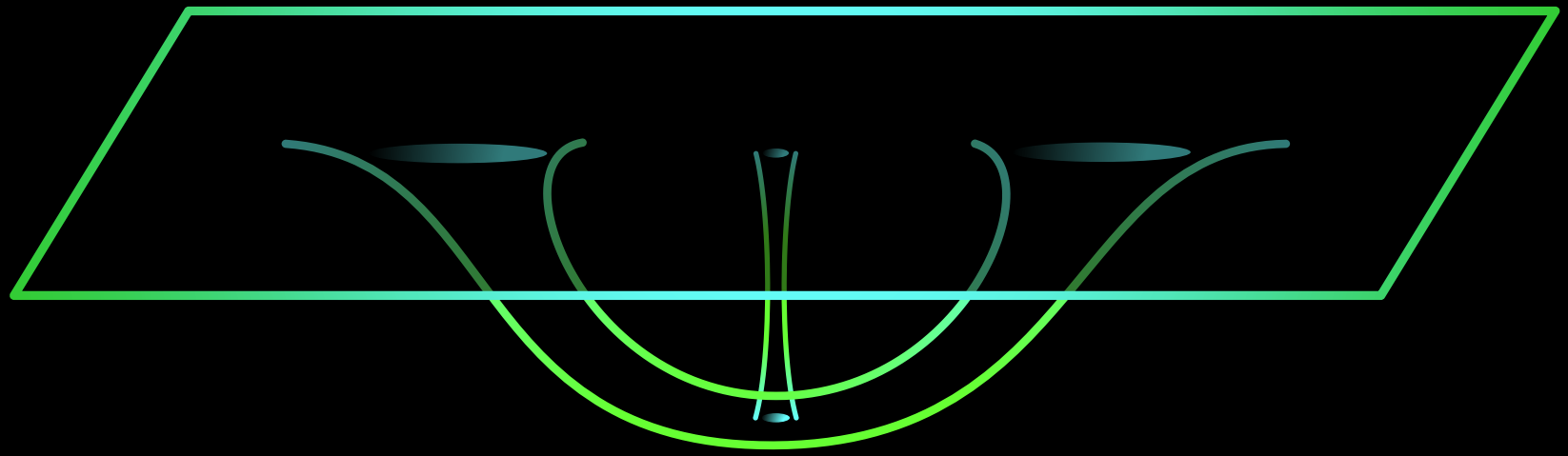
Make *small corrections*

Three-mouth wormholes

Acquire a ready-made wormhole

Insert a small black hole in it

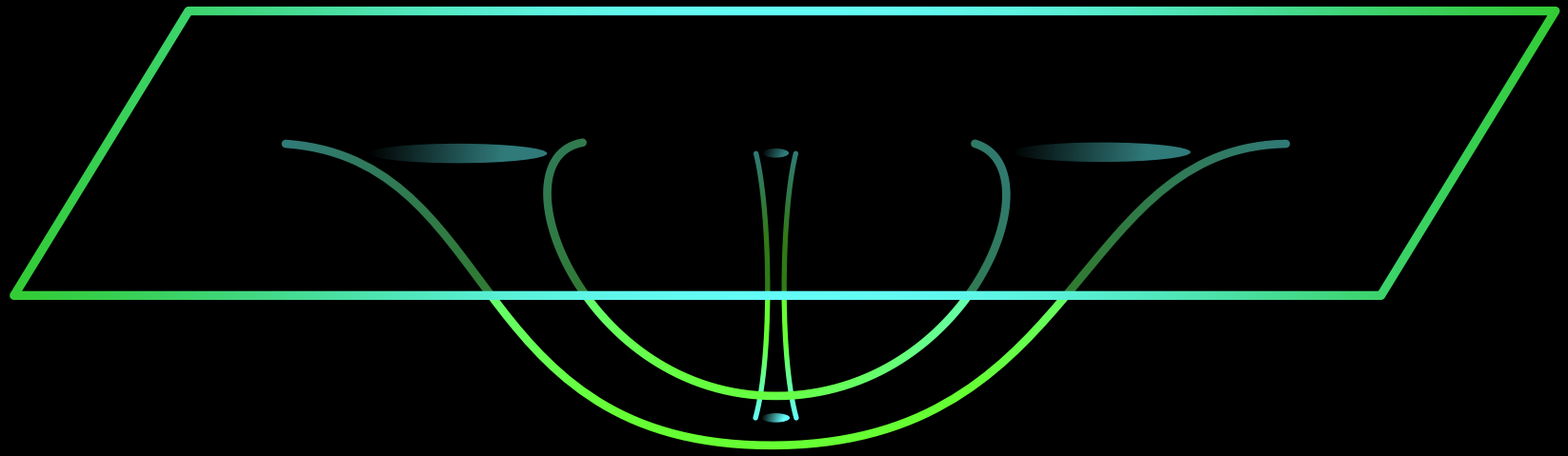
Connect to small black hole outside



Inserting the small mouth

Technically straightforward:

Perturbations w/ matched asymptotics

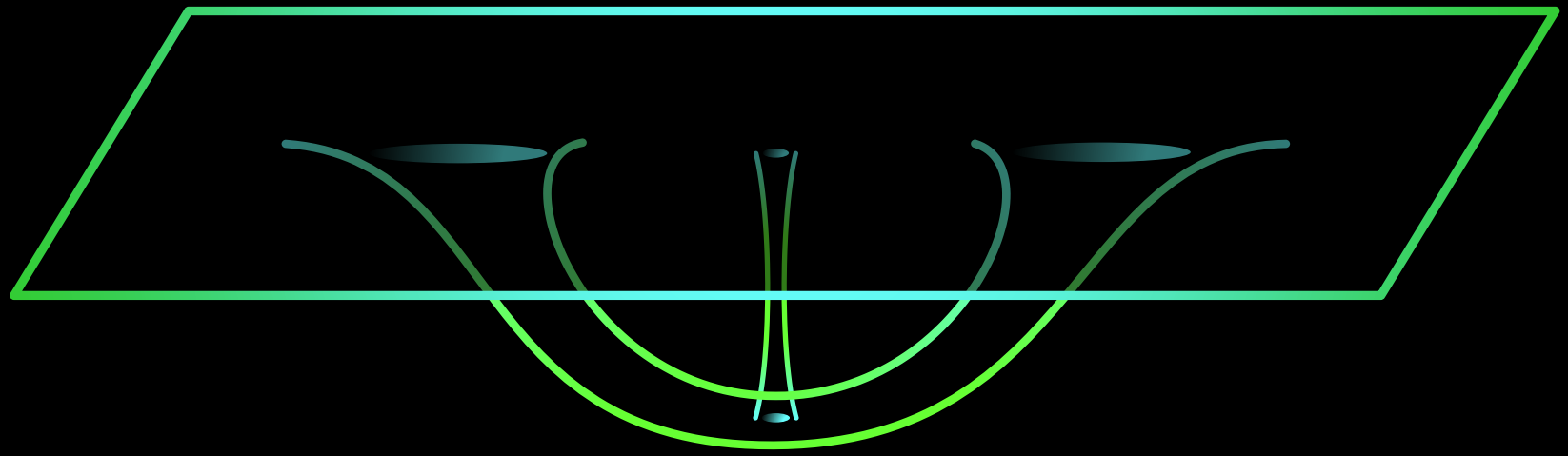


How large the third black hole?

Choking the throat?

Semiclassical black holes have $m \gg m_{Planck}$

Throat redshift helps, but how large can m be?



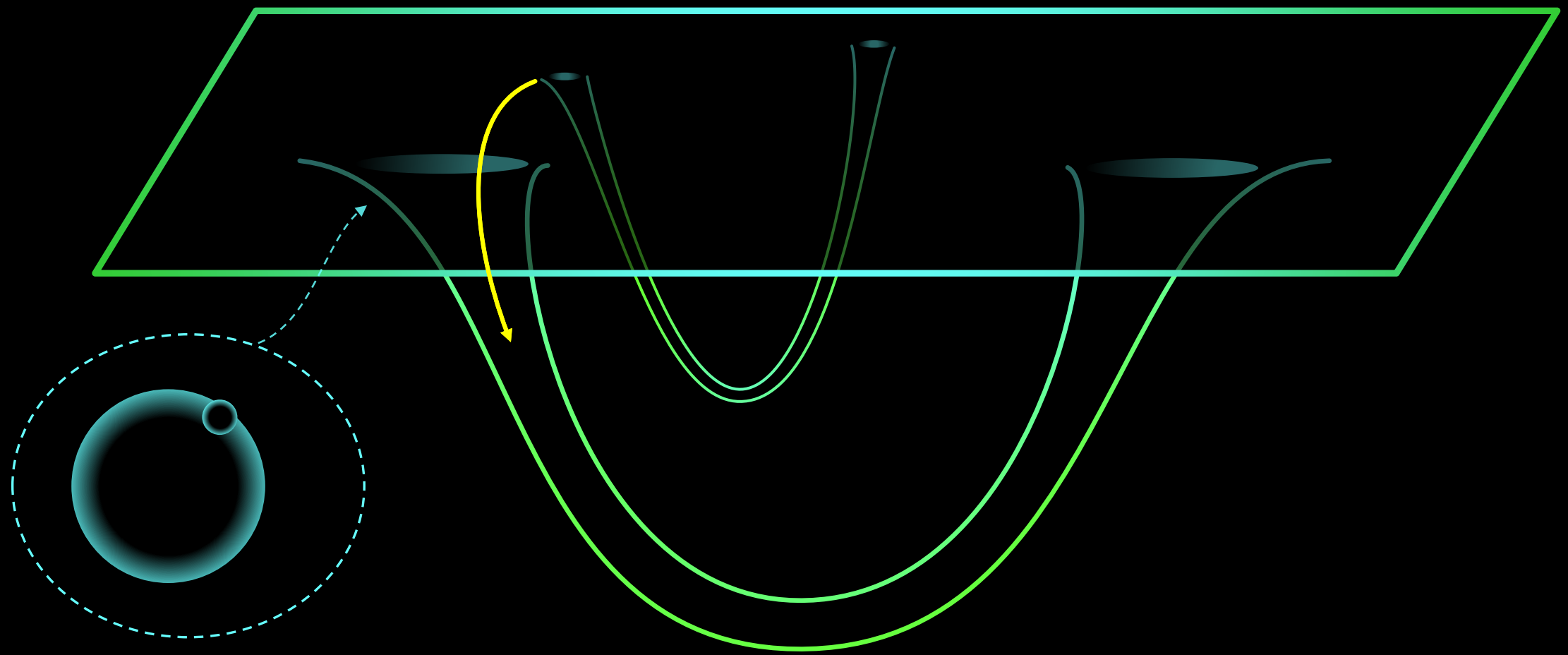
Small, but still semiclassical

Backreaction calculation shows that if $N_f \gg 1$ then a

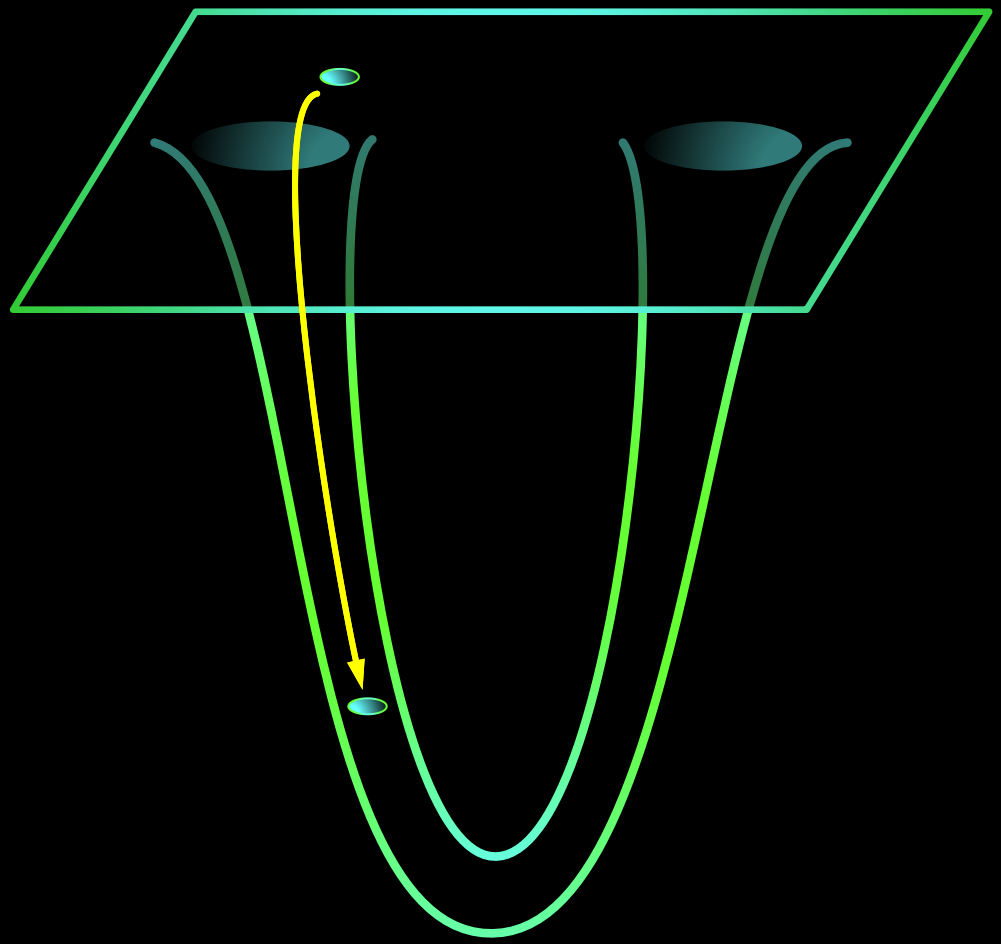
semiclassical three-mouth wormhole is possible

(also need small enough bh radius to fit inside throat – can do it)

Tri-wormhole from wormhole merger



Mass down the throat

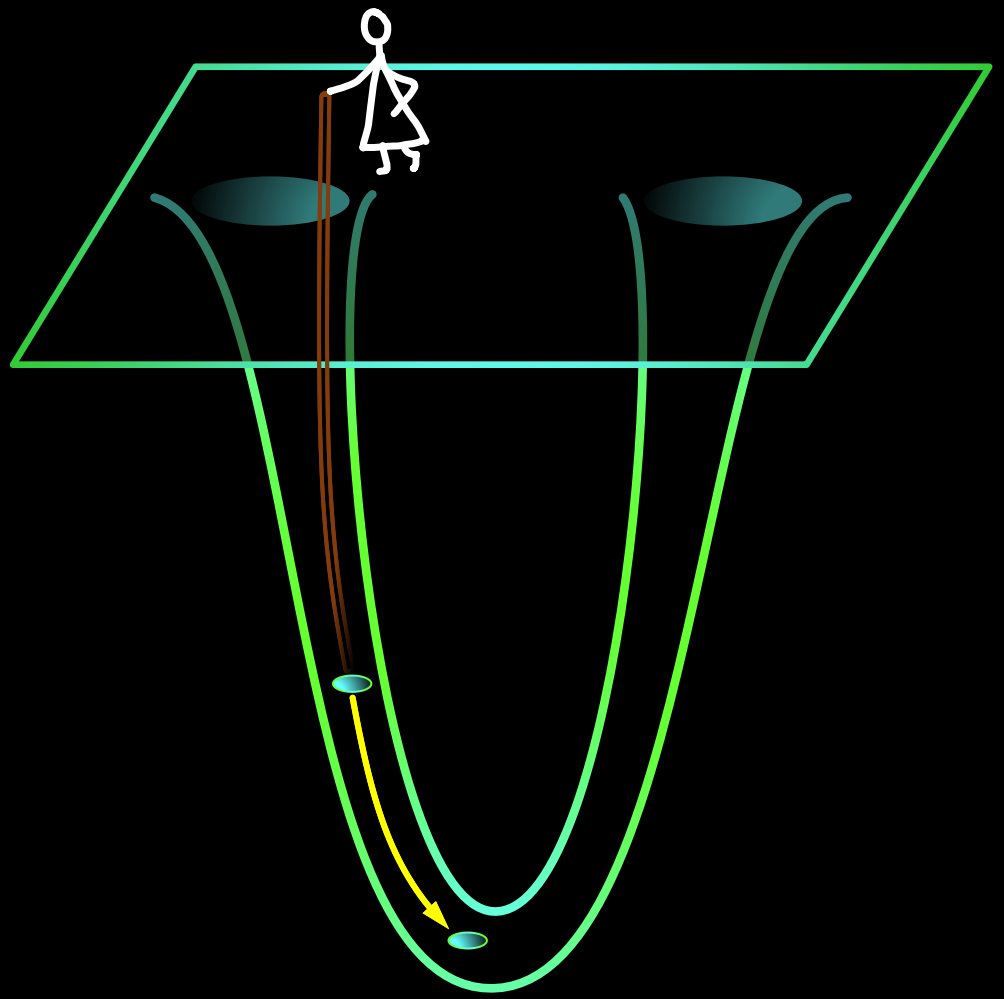


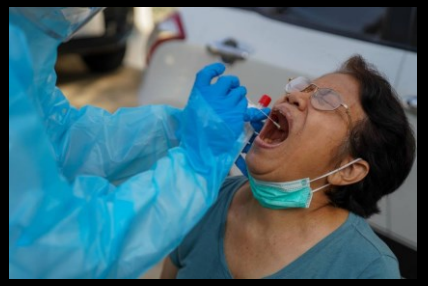
Choking the throat, now?

Near the big mouth

$$m \gg |E_{binding}|$$

Mass down the throat





Lower it *à la Geroch*

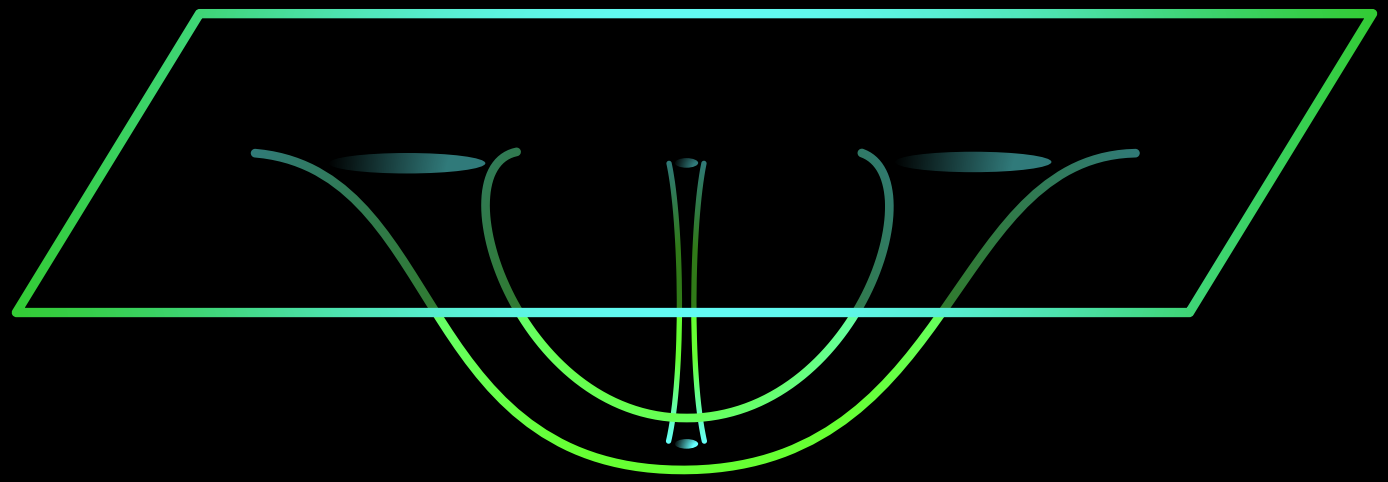
Slowly, hanging from a string

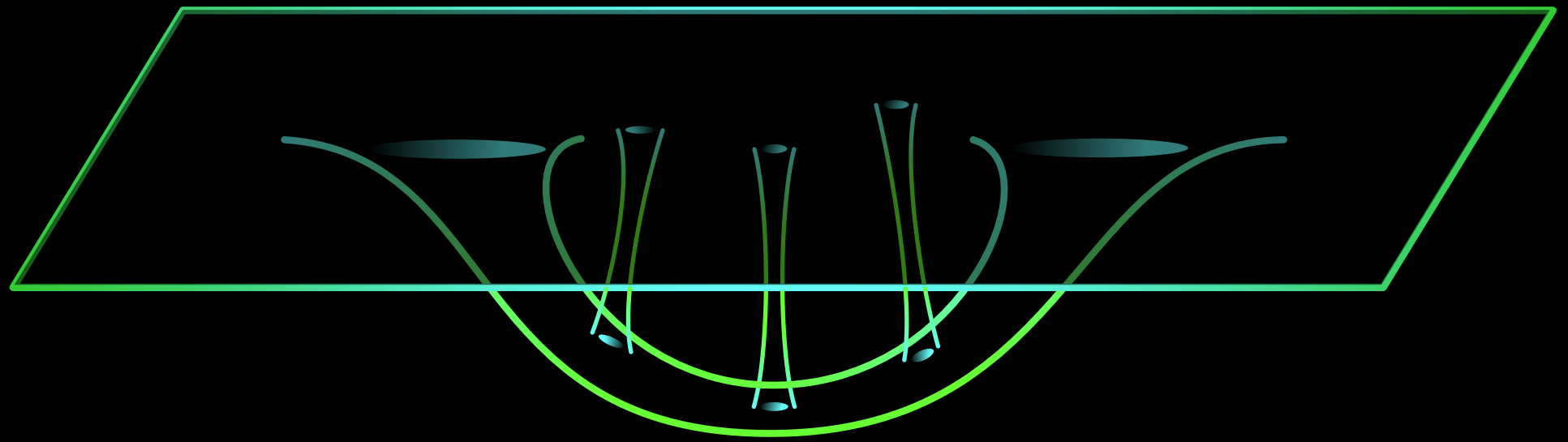
Safe for $m < \frac{1}{8\sqrt{\pi}} N_f \, m_{Planck}$

So

It is possible to construct three-mouth wormholes

with two big mouths + one small mouth





Many small mouths

as long as $\sum_i E_{bh,i} < |E_{binding}|$

Entanglement and Wormholes

Gao+Jafferis+Wall 2016
Maldacena+Qi 2018

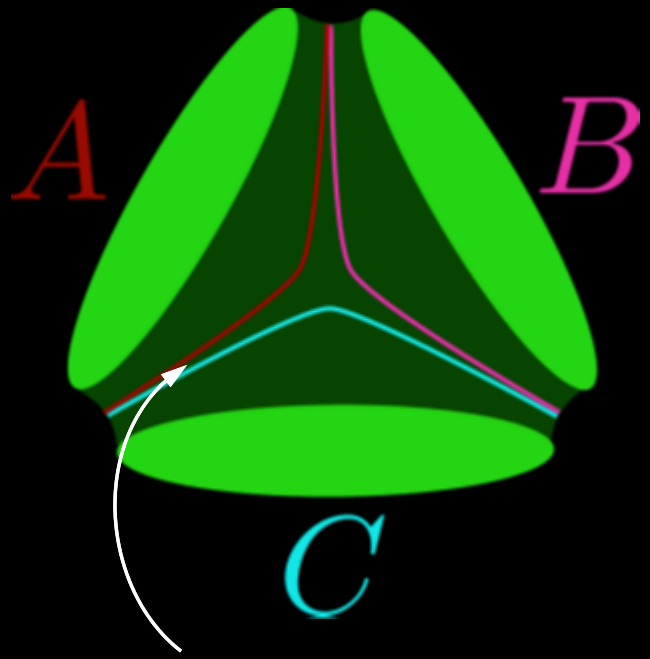
The two “black hole mouths” are entangled

Microscopic degrees of freedom in Bell-like state

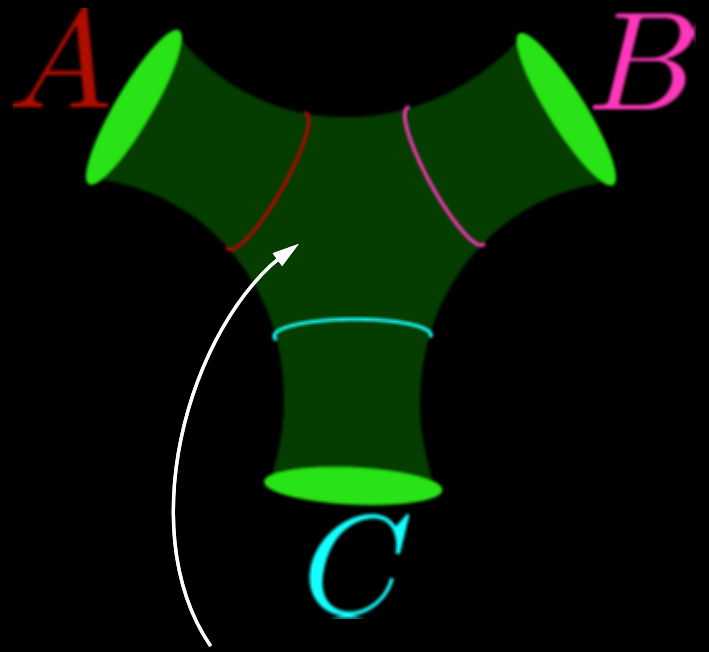
Sending a particle through a wormhole is dual to using entanglement as resource for quantum teleportation

Bi- vs Tri- partite entanglement

Marolf+Maxfield+Peach+Ross 2015
Al Balushi+Wang+Marolf 2020

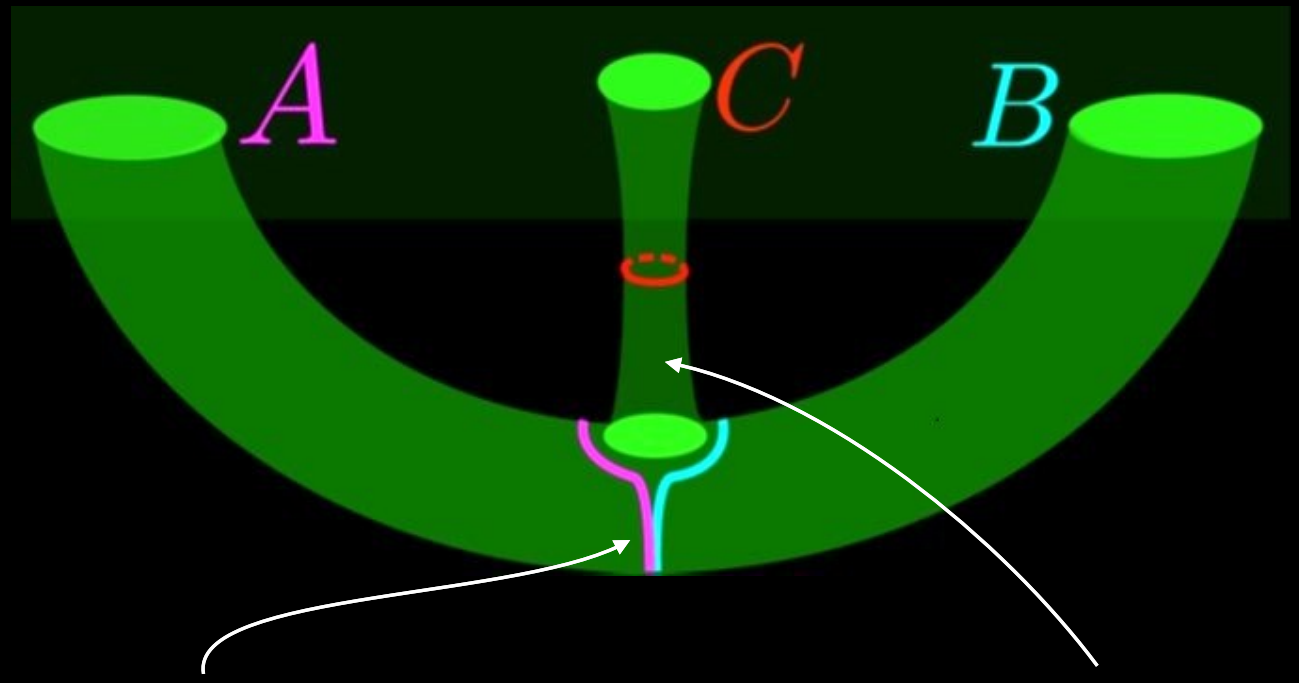


Mostly bipartite entanglement

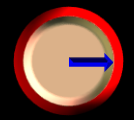


Tripartite entanglement

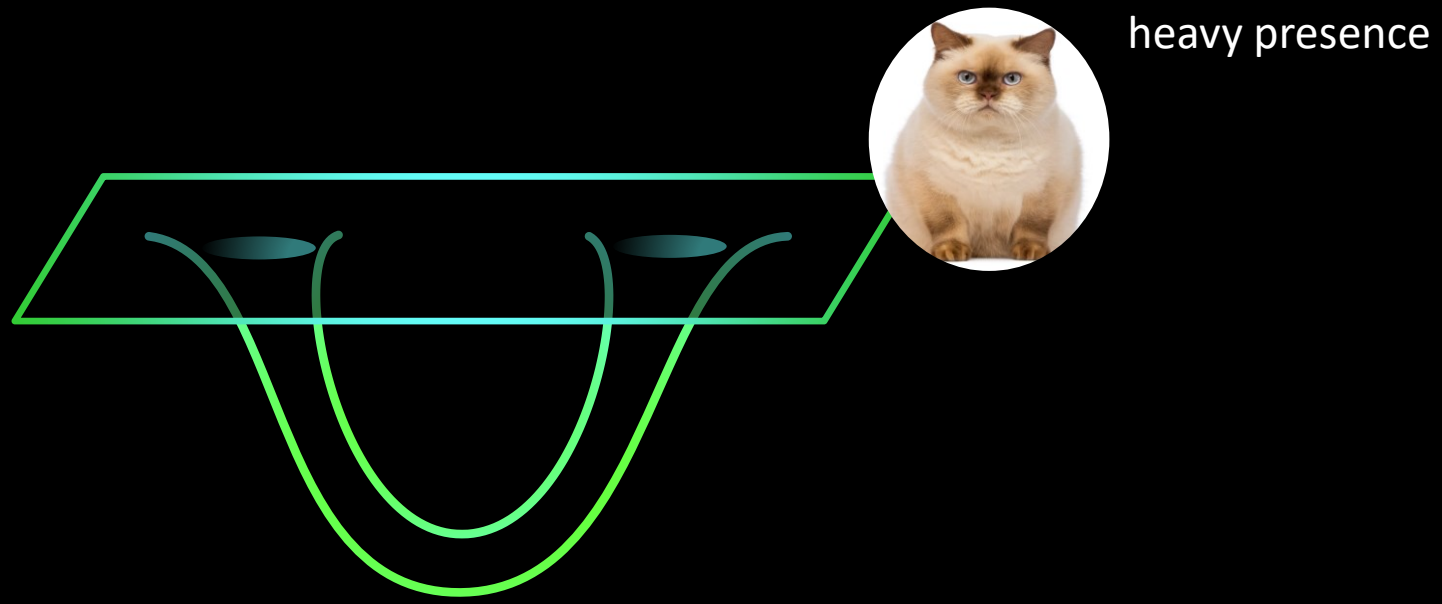
Bi+tri-partite entanglement



Wormhole time machines?



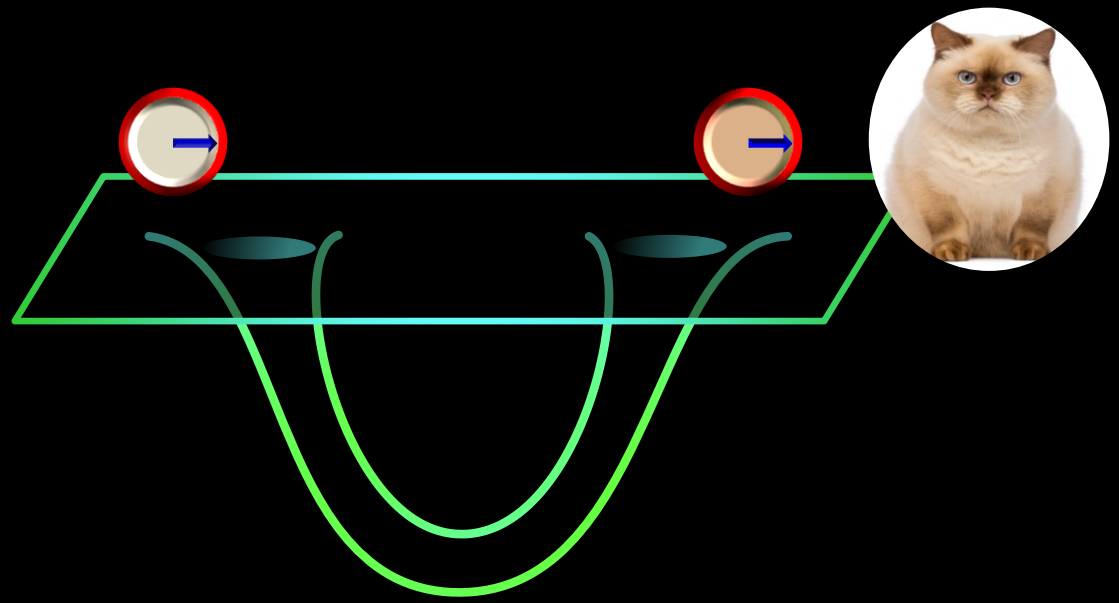
Mouths out of step



heavy presence

Morris+Thorne+Yurtsever 1988
Frolov+Novikov 1990

Mouths out of step



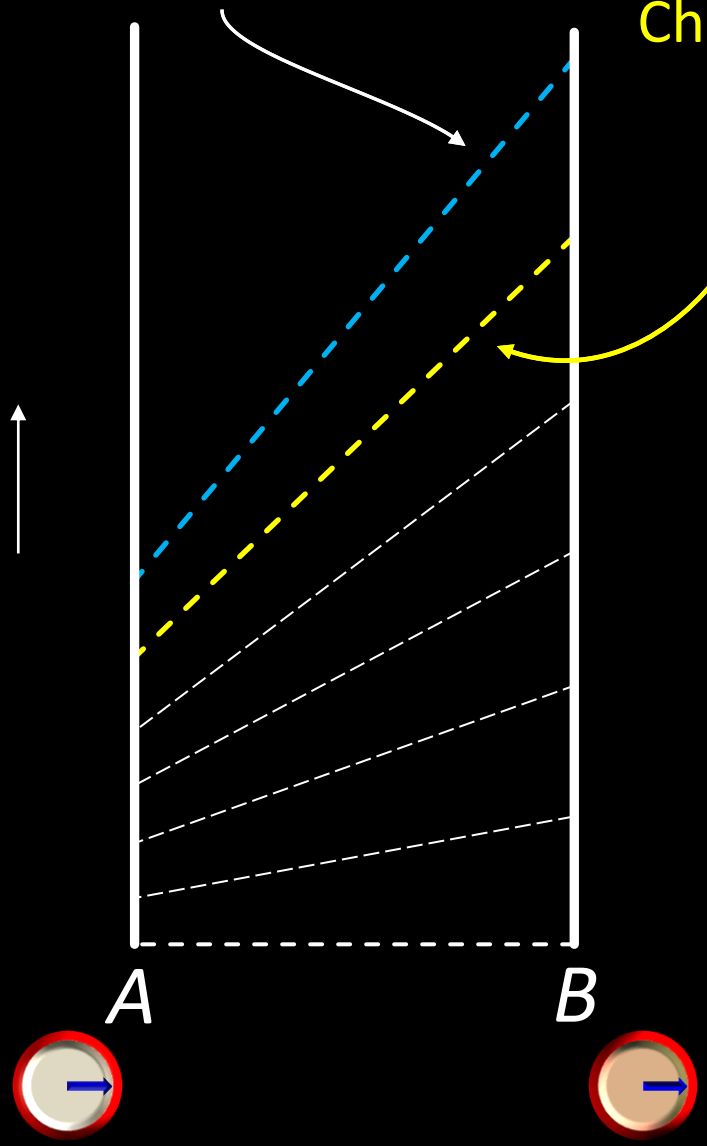
heavy presence

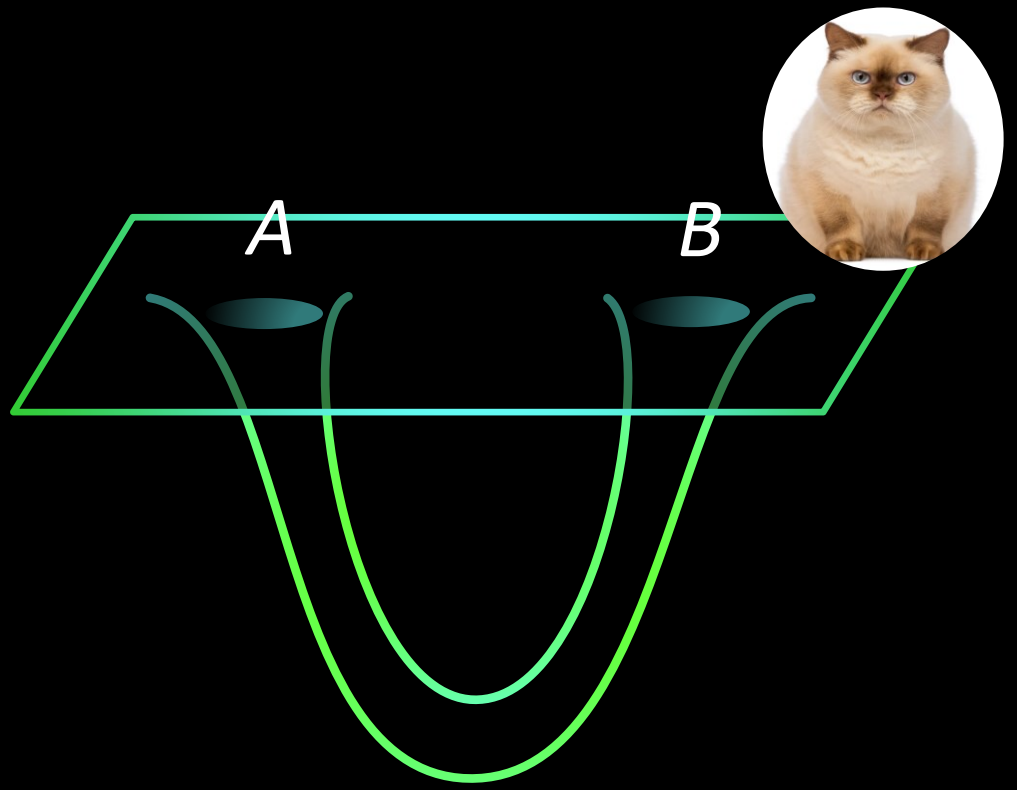
wormhole time runs at uniform rate

Morris+Thorne+Yurtsever 1988
Frolov+Novikov 1990

closed timelike curve

closed null curve
Chronology Horizon (CH)





Achronal ANEC, again

Tube *can be very long*

but if ∃CTCs, light rays through tube are

fastest paths

Achronal ANEC ⇒ ∄ wormhole time machines

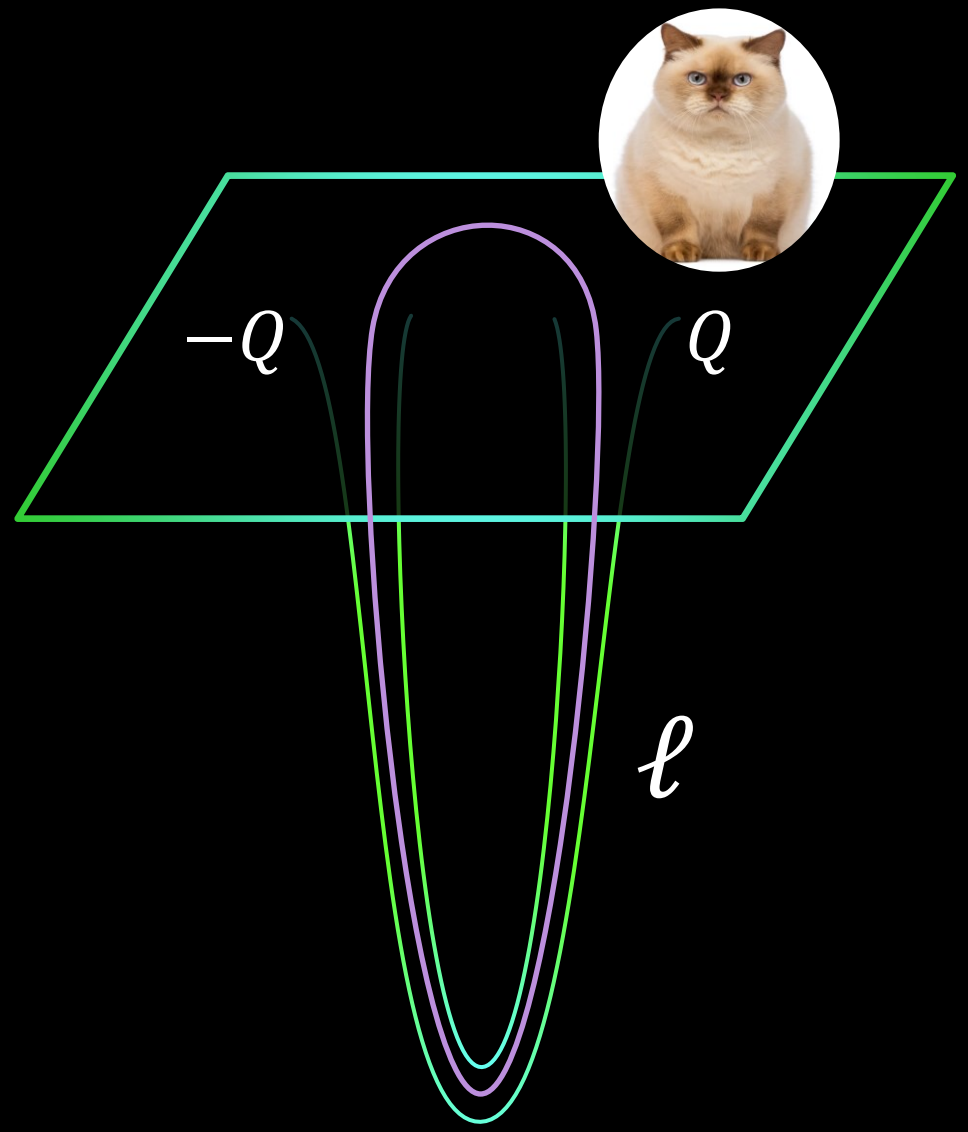
Achronal ANEC is violated well before onset of CTCs (= CH formation)

Chronology protection
low-energy ($< E_{Planck}$) phenomenon

in progress w/ M Tomašević

Wormhole negative energy flows to heavier mouth, countering the time-shifting effect

No Planck-scale physics enters



Recent work w/ M Tomašević

- Holographic bulk dual of CFT in a time machine

  e-Print: 2107.14200 [hep-th]

- Quantum backreaction on chronology horizons

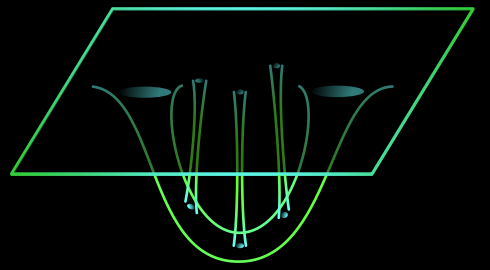
  e-Print: 2109.03611 [hep-th]

Conclusions

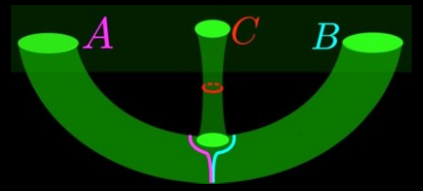
- Intra-universe traversable wormholes are physically allowed

Maldacena+Milekhin+Popov
Fu+Grado-White+Marolf

- Multi-mouth traversable wormholes also allowed – two big mouths + small mouths

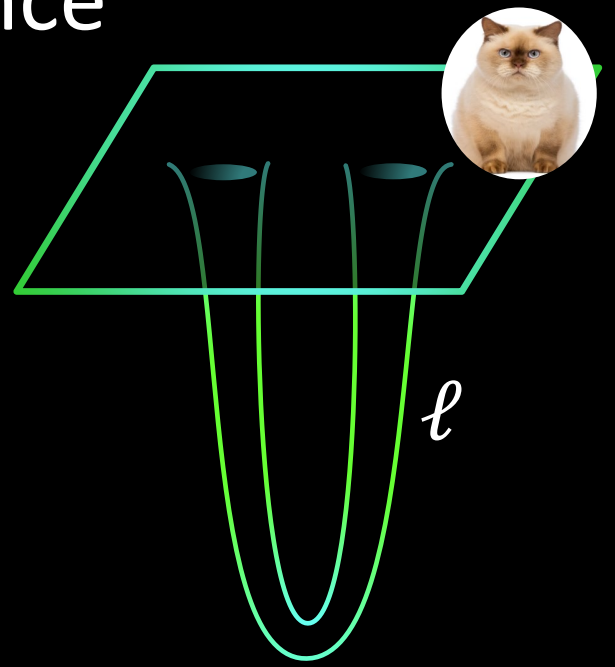


- Multi-wormholes reveal new multi-partite holographic entanglement structures



Conclusions

- Wormhole time machine fails to form for low-energy reasons – it self-protects against redshifting time imbalance



Thank you