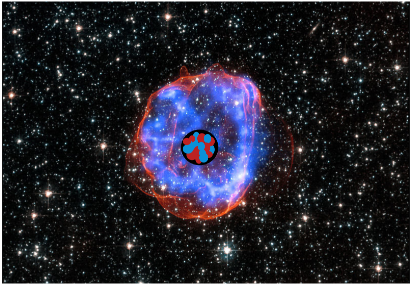
Quantum Tunneling
&
Black Hole Horizons

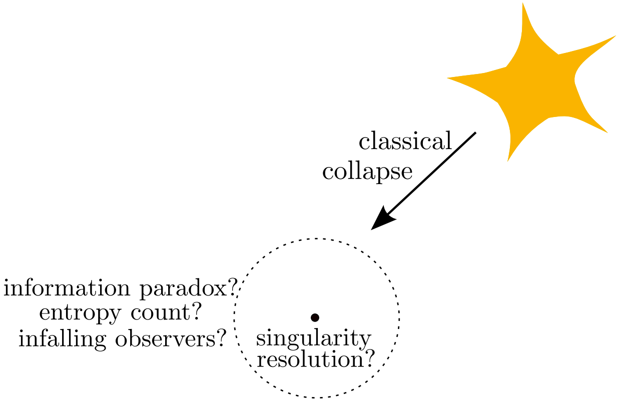


1512.05376 with I. Bena, D.R. Mayerson and B. Vercnocke

Andrea Puhm *UC Santa Barbara* $\longrightarrow$ *Harvard University*

Nordita "Inward Bound" Conference - August 18, 2016

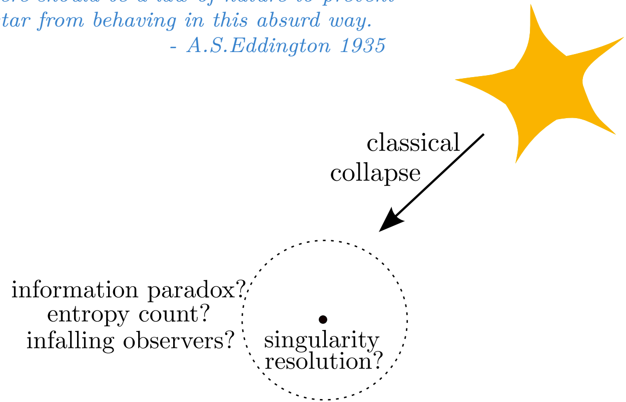
Motivation



classical
collapse
information paradox?
entropy count?
infalling observers?
singularity
resolution?

Motivation

There should be a law of nature to prevent a star from behaving in this absurd way.
- A.S.Eddington 1935



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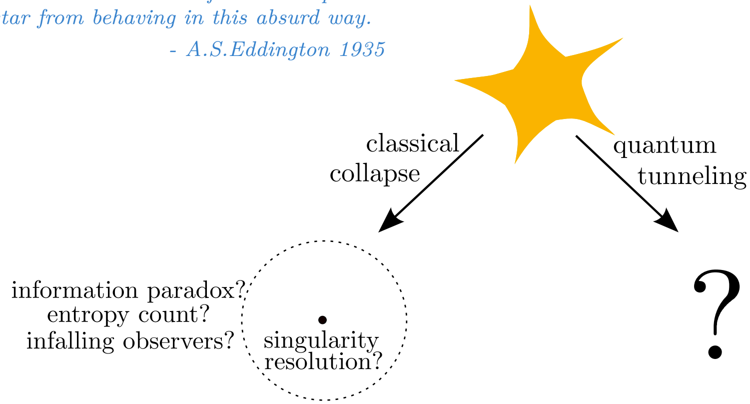
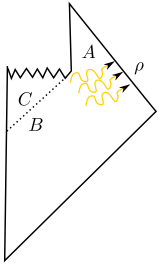


Information Paradox

Information paradox as strong subadditivity paradox:

$$S_{AB} + S_{BC} \geqslant S_B + S_{ABC}$$

AB	entanglement	unitarity (purity)
BC		smooth horizon



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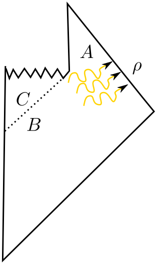

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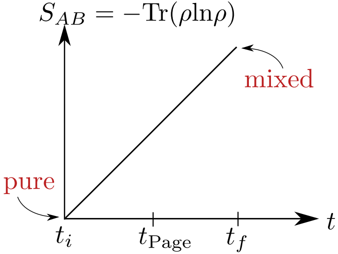

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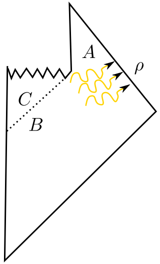

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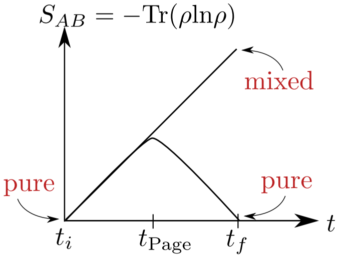

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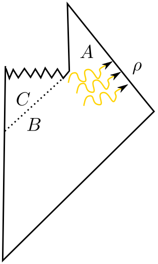

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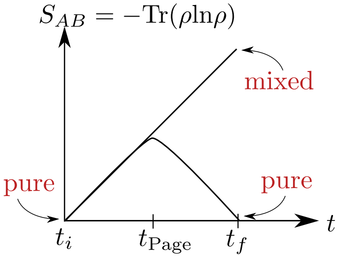

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Other potential ways out:
[Silverstein, Dodelson]: string-effects
[Papadodimas, Raju], *[Maldacena, Susskind]*,
[Kabat, Lifschytz]: A,B,C not independent
[Hawking, Perry, Strominger]: soft hair

3 increasingly complicated systems to tackle

$T = 0$ (yet $S_{\mathrm{BH}} \neq 0$!):

I. Extreme charged $Q = M$

AdS/CFT *[Maldacena'97;Witten'98;...]*

SUSY: large classes of microstate geometries constructed

*[Bena,Warner'04;Bena,Kraus'05,Berglund,Gimon,Levi'05;...
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Highly charged: not realistic.

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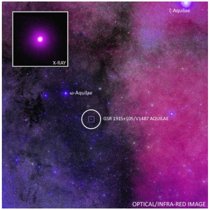
Highly rotating: in the sky!

GRS 1915+105: $J \sim 0.98 M^2$



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$T \neq 0$:

III. Non-extreme charged $Q < M$, rotating $J < M^2$

~~SUSY~~: general existence proof *[Gibbons,Warner'13]*

perturbative construction *[Bena,AP,Vercnocke'11+'12]*

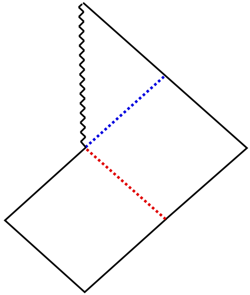
non-perturbative constructions in the making

Challenges

General Relativity & Quantum Mechanics

$\Rightarrow$ structure at the horizon!

- **Not ordinary matter (falls in/dilutes)**
- **Must form in astrophysical process**



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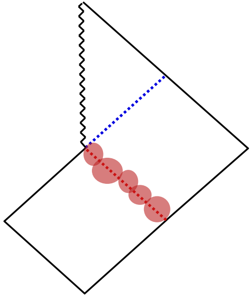

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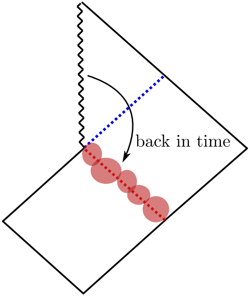

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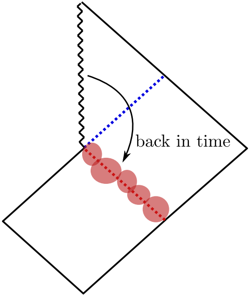
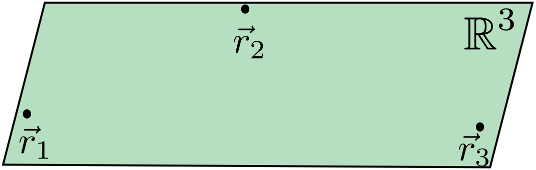


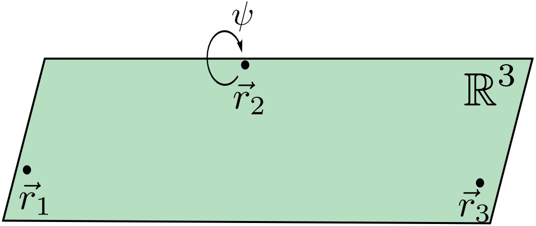
String theory: extra dimensions, topology and fluxes ☺

The Microstate Mechanism



The Microstate Mechanism

- extra dimensions: 5D



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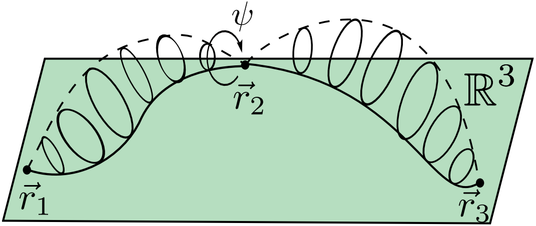

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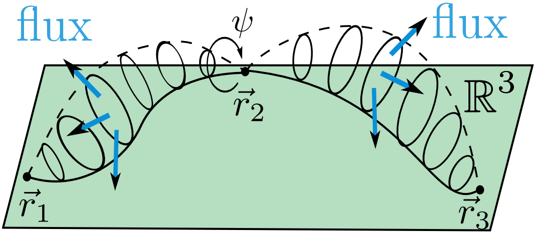
  $A \wedge F \wedge F \quad \rightarrow \quad d \star F = F \wedge F$ instead of $d \star F = \delta(r)$



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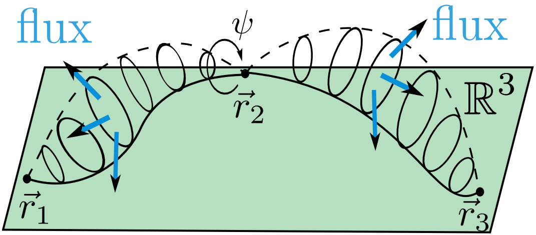
5D Geometry: $\mathbb{R}_t \times \mathbb{R}^3 \times S^1_\psi$



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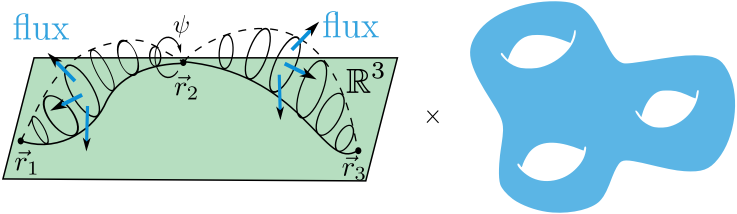
11D Geometry: $\mathbb{R}_t \times \mathbb{R}^3 \times S^1_\psi \times T^6$



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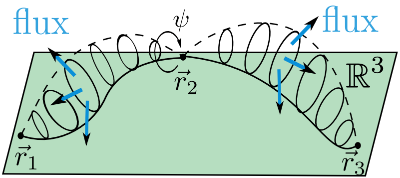
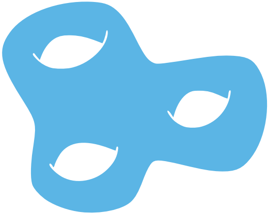


$\times$



See talk by B. Vercnocke:

[Gibbons,Warner'13]: found loophole in *"No solitons without horizons"*

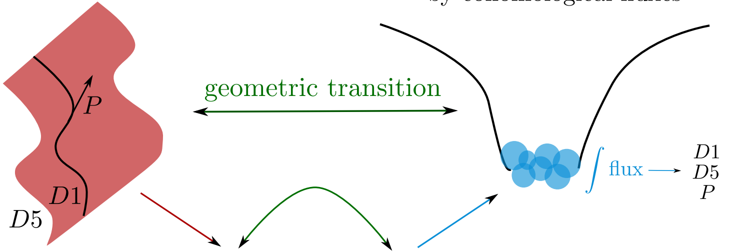
⇒ *"No solitons without topology"* - not just BPS!

Geometric *bubbling* transition

[Bena,Warner]:

potentially singular brane sources

microstate geometries supported by cohomological fluxes



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Geometric *bubbling* transition

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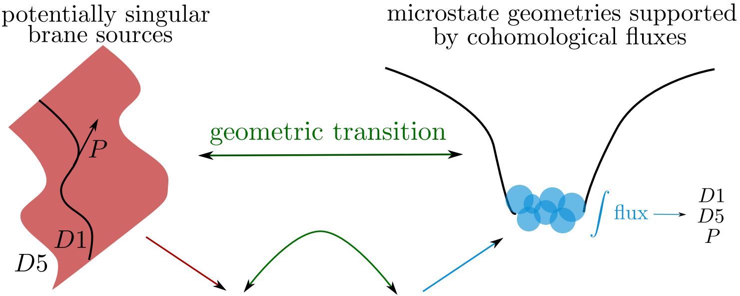

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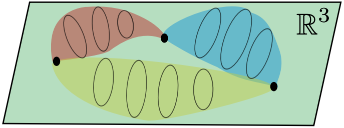
Phase transition driven by Chern-Simons coupling

New scales in addition to $\ell_P,\ R_H$:

- size of bubble threaded by flux: *order parameter* (0 for BH)
- throat depth: *gap* (∞ for BH)

Typical Black Hole Microstates



Extremal microstate geometries from solving the *bubble equations:*

$$\boxed{\langle \Gamma_i, H(r_i) \rangle = 0}$$

- $\Gamma_i = (KK, M5, M2, J)$ charges at r_i
- $H(r_i) = \sum_i (h_i + \frac{\Gamma_i}{r_i})$ harmonic background functions

Typical microstate geometries: deep throat

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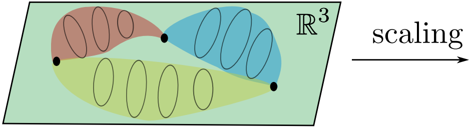

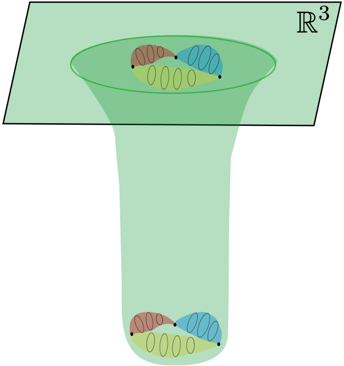

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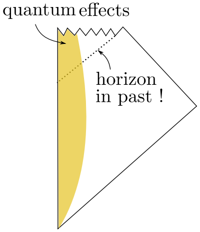
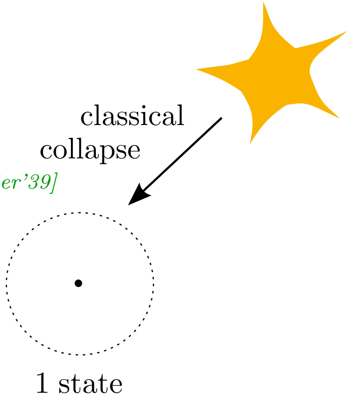
Typical microstate geometries: deep throat $\Rightarrow$ Scaling Solutions

Black Holes Microstate Dynamics



[Oppenheimer,Snyder'39]



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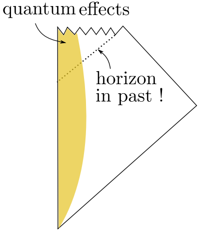

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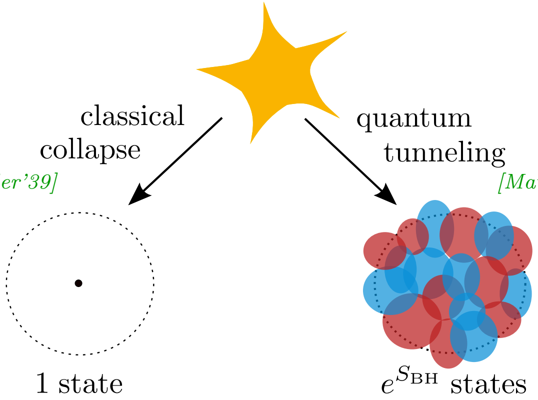

[Mathur'08]

The Tunneling Argument

Probability of a collapsing shell $\xrightarrow{\text{tunnel}}$ fuzzball with $r_{\mathrm{FB}} \sim r_{\mathrm{BH}}$:

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$$P = \mathcal{N} \cdot \Gamma_{tunnel}$$

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... very small number!

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The two exponentials play off against each other if $\alpha \sim \mathcal{O}(1)$:

$$\boxed{t_{\text{tunnel}} \sim P^{-1} \sim e^{-S_{BH}} e^{\alpha S_{BH}}} \quad \Rightarrow \textit{fast} \text{ for } \alpha \lesssim 1\ !$$

The shell tunnels into fuzzballs before a horizon can form!

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"Nature abhors a horizon" [Kraus,Mathur'15]

Black hole emitting Hawking radiation with backreaction:

$$\Gamma_{tunnel} \sim e^{S_{\mathrm{BH}}(M-\omega)-S_{\mathrm{BH}}(M)}$$

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- P(black hole $\xrightarrow{tunnel}$ shell) = P(shell $\xrightarrow{tunnel}$ fuzzball)
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Goals:

- compute Γ_{tunnel} into explicitly known microstate geometries
- study Γ_{tunnel} for different microstates: *non-scaling and scaling*
  $\rightarrow$ universal features?

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- P(black hole $\xrightarrow{tunnel}$ shell) = P(shell $\xrightarrow{tunnel}$ fuzzball)
- $r_{\rm FB} \sim r_{\rm BH}$
- fuzzball exterior = black hole exterior

Goals:

- compute Γ_{tunnel} into explicitly known microstate geometries
- study Γ_{tunnel} for different microstates: *non-scaling and scaling* $\to$ universal features?

Upshot: $\boxed{\alpha \lesssim 1}$ and *no need for above assumptions!*

Modeling gravitational collapse

How to compute $\Gamma_{tunnel} = A e^{-B}$?

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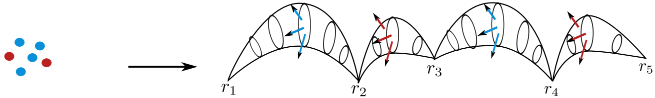
General idea is to tunnel branes into bubbling microstate solutions:



- 10+1D problem: branes wrap extra dimensions

Modeling gravitational collapse

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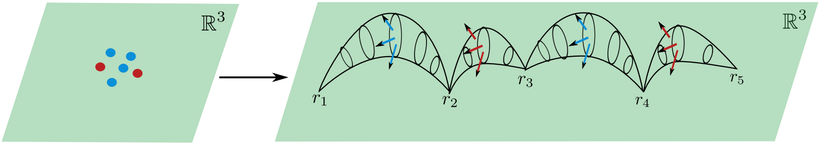

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  ↓ reduction
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Modeling gravitational collapse

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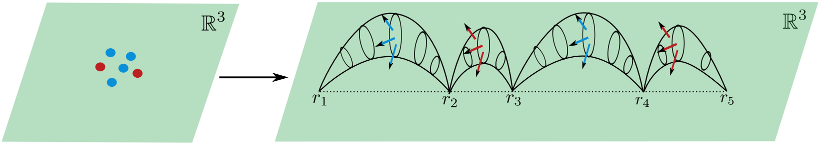
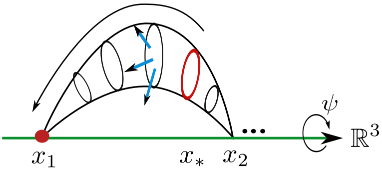


- 10+1D problem: branes wrap extra dimensions
  ↓ reduction
- 3+1D problem: branes become particles
  ↓ symmetry
- 1+1D problem: quantum mechanics!

Tunneling building blocks

Decay of supertubes into branes:



Excess energy → (Hawking) radiation. *[Bena,AP,Vercnocke'11]*

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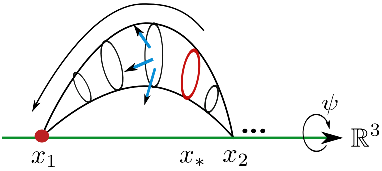

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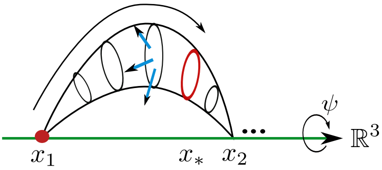

[Bena,Mayerson,AP,Vercnocke'15]

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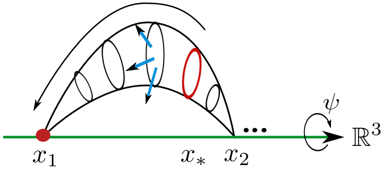

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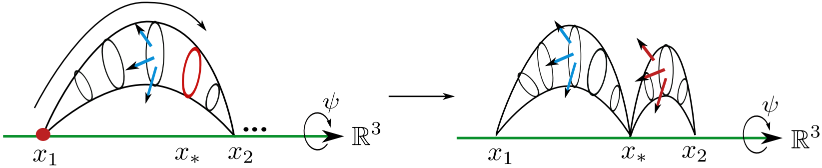
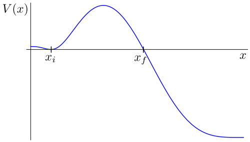


[Bena,Mayerson,AP,Vercnocke'15]

Quantum Tunneling into Microstates

On-shell Euclidean action integrated over path of 'least resistance':



$$B = S_E = \int_{t_i}^{t_f} dt\, L_E(x(t), \dot{x}(t)) = \int_{\vec{x}_i}^{\vec{x}_f} |dx|\, |p(x)|$$

$$\uparrow$$

$$H_E = p\dot{x} - L_E = 0 \text{ with } p = \frac{\partial L_E}{\partial \dot{x}}$$

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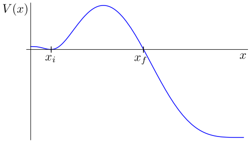

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Relativistic particle with mass $m(x)$ and charge q:

$$L_E = \int m(x) + \int qA_t(x)$$

$$|p(x)| = (g_{tt}(x))^{-1/2} \sqrt{|g_{tt}(x)| m(x)^2 - (qA_t(x))^2}$$

Quantum Tunneling into Microstates

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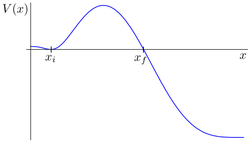

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Supertube with electric q_1, q_2, dipole d_3 and ang. mom. $q_1\, q_2/d_3$:

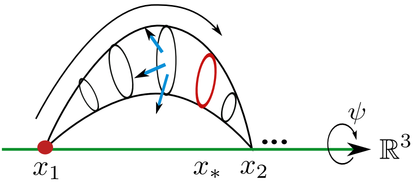
$\Gamma = (d_3, q_1, q_2, q_1\, q_2/d_3)$ poles $= N - 1$ bubbles

$$\boxed{|p(x)| = \langle \Gamma, H(x) \rangle = \frac{1}{|d_3|} |q_1^{\text{eff}}(x)\, q_2^{\text{eff}}(x)\, V(x) - d_3^2\, Z_3(x)|}$$

harmonic functions describing the bubbling microstate

Tunneling Amplitude

One tunneling event:



$$\boxed{B = \int_{r_1}^{r_2} dr\, \langle \Gamma, H(r) \rangle}$$

$\langle \Gamma_i, H(r_i) \rangle = 0$ *Bubble equations!*

$\langle \Gamma, H(r_{susy}) \rangle = 0$ susy probe min

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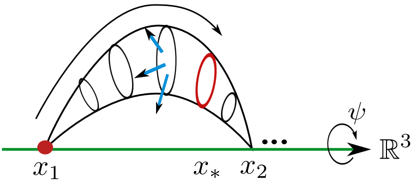

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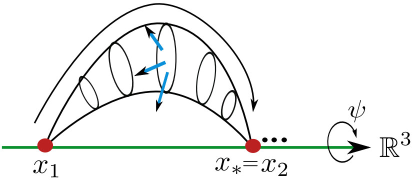
Bound on tunneling timescale from slowest process:



$$\boxed{B = |d_3| r_{12}}$$

Extremely simple result!

Tunneling Before a Horizon Forms

Make N-centered solution from multiple tunneling events:

$$e^{-\alpha S_{BH}} \equiv \boxed{\Gamma_{tunnel} \sim e^{-\alpha_0 S_{\mathrm{BH}}/N^{\beta}}} \quad \rightarrow \quad \boxed{\alpha \sim 1/N^{\beta}}$$

- α_0 depends on the details of the collapse
- $\beta > 0$ (non-scaling: $\beta = 3/2$ and scaling $\beta = 0.93$)

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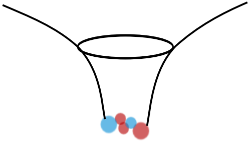
Tunneling into N-bubbled microstate:

$$\boxed{\alpha \ll 1} \quad \text{for N large}$$

$\uparrow$

before the shell reaches the horizon !



Shell quantum tunnels into microstate before horizon forms!

[Bena,Mayerson,AP,Vercnocke'15]

Conclusions

◇ Summary:

Tunneling amplitude into multi-bubbled microstates *not* parametrically suppressed $\boxed{\Gamma_{tunnel} = e^{-\alpha S_{BH}} \text{ with } \alpha \lesssim 1}$

$\Rightarrow$ *can be fast enough to avoid formation of horizon!*

◇ Open Questions:

- *Total tunneling amplitude*: $P = \mathcal{N}\, \Gamma_{tunnel}$
- **Typical** microstates: *size* of bubbles *vs.* *number* of bubbles ?
  See talk by D. Turton.
- **Infalling observers**: tunnel into microstate ?
- *Emergence of spacetime* from collective microstate excitations ?