

# Phases of Higher-Dimensional Black Holes

Strings 07

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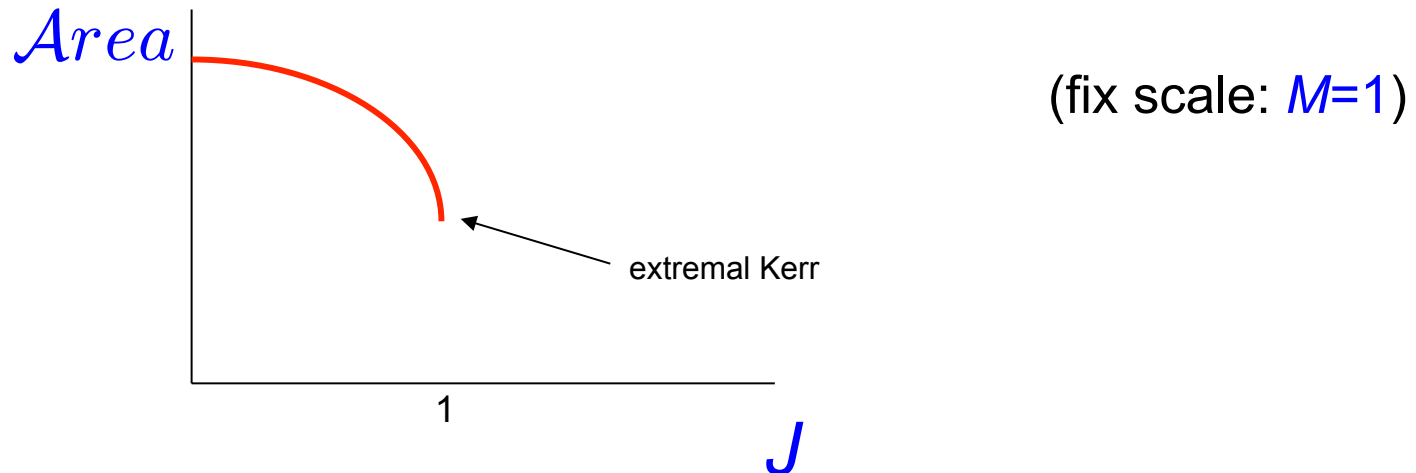
- Earlier work w/ R.Myers, H.Reall, H.Elvang, P.Figueras
- To appear, w/ T.Harmark, N.Obers, V.Niarchos, M.J.Rodríguez

# Phases of black holes

- Find all **stationary** solutions
  - of Einstein's equations  $\rightarrow R_{mn} = 0$
  - with specified **boundary conditions**  $\rightarrow$  *Asymp Flat*
  - non-singular on and outside **event horizons**
- What does the phase diagram look like?
- Which solutions maximize the total horizon area (ie entropy)?
- *NB: Classical stability? Not today...*

# Phases of 4D black holes

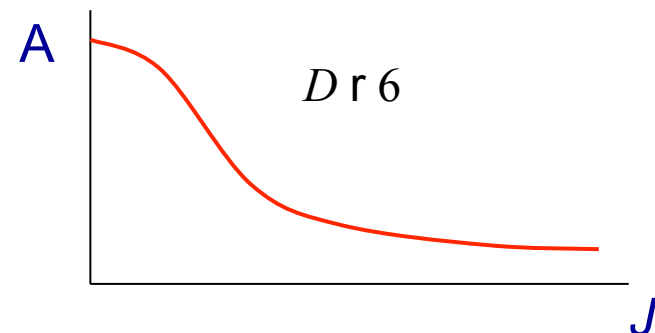
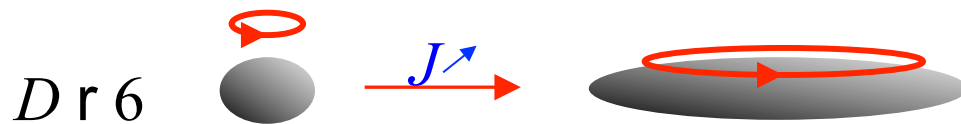
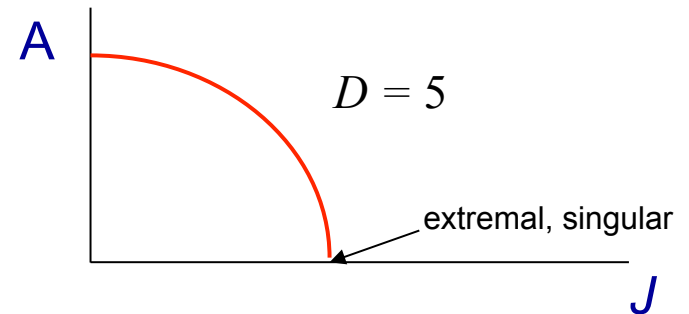
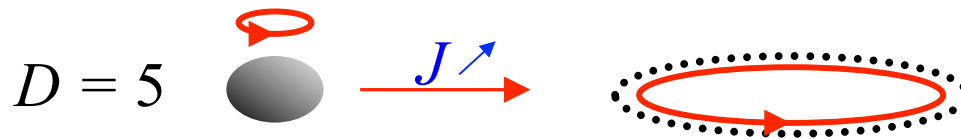
- Just the Kerr black hole: Uniqueness thm



No multi-bhs (eg multi-Kerr can't be stationary)

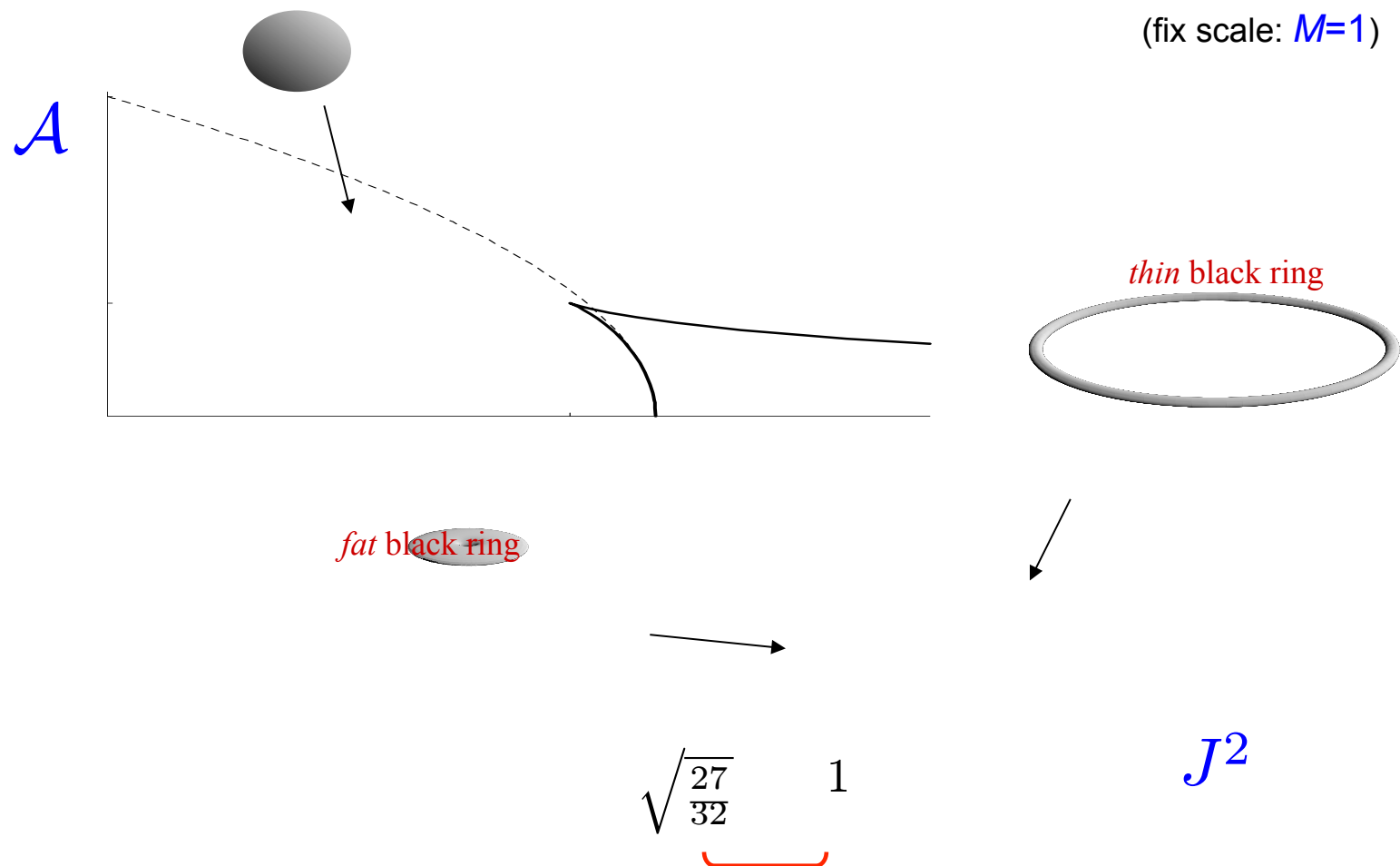
# Myers-Perry black holes in $D$ dimensions

- Spherical topology  $S^{D-2}$
- Consider a **single spin**:



no upper limit on  $J$   
for fixed  $M$

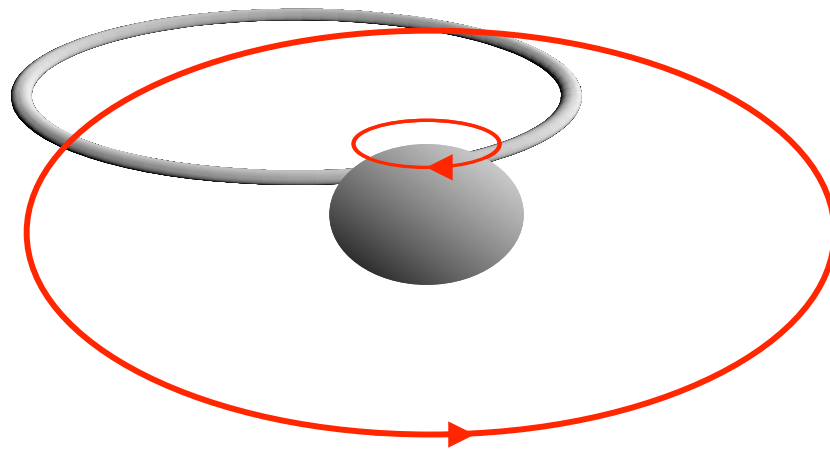
# 5D: one-black hole phases



**3** different black holes with the same value of  $M, J$

# Multi-black holes

- *Black Saturn:*

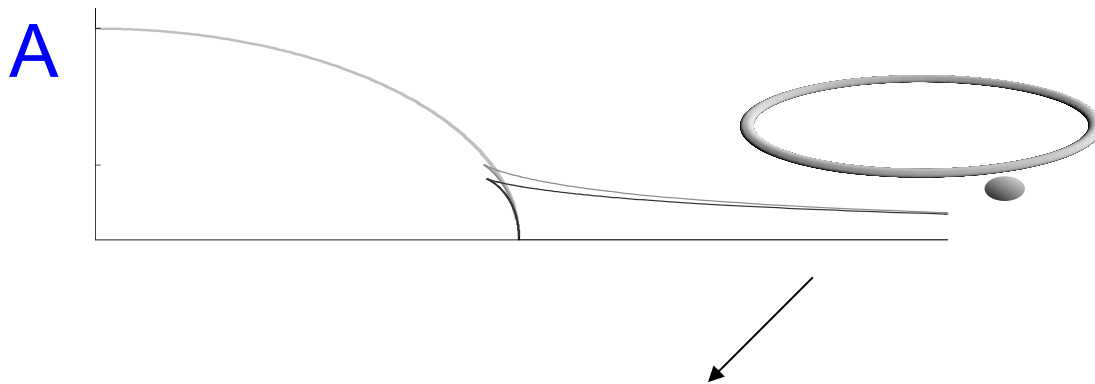


- Exact solutions available
- Double *continuous* non-uniqueness:
  - eg, fix total  $M, J$ , vary  $M_{ring}, J_{ring}$

*Elvang+Figueras*

# 5D phases in thermal equilibrium

$$T_{bh} = T_{br} , \quad W_{bh} = W_{br}$$



J

is there anything else?

# Towards a complete classification of 5D black holes

- **Topology:**  $S^3, S^1 \times S^2$  (+ finite connected sums) *Galloway+Schoen*
- **Rigidity:** stationarity  $\Rightarrow$  one axial  $U(1)$ , but not (yet?) necessarily two *Hollands et al*
- $U(1)_t \times U(1)_f \times U(1)_y \Rightarrow$  complete integrability
  - All bh solutions may have been found already:  
**MP, black rings, multi-bhs** (saturns & multi-rings)

(including also with two spins *Pomeransky+Sen'kov*)  
(what about bubbly black holes?)



# Dr6: Black Holes galore

Why is  $Dr6$  different?

1. Centrifugal repulsion wins over gravitational attraction at large distance

$$-\frac{GM}{r^{D-3}} + \frac{J^2}{M^2 r^2} \Rightarrow \text{ultra-spinning black holes}$$

2. Black p-branes w/  $p \geq 2$

→ *may* give much richer *blackfold* topologies

eg:  $\mathbf{R}^2 \times S^2 \Rightarrow \mathbf{S}^1 \times \mathbf{S}^1 \times S^2, \mathbf{S}^2 \times S^2, (\mathbf{H}^2/\Gamma)_g \times S^2$

*So, let's go find them?*

- *Very limited* success in extending 4D & 5D approaches to  $D=6$ 
  - Known explicit construction techniques don't apply
  - Higher-D topologies are poorly understood

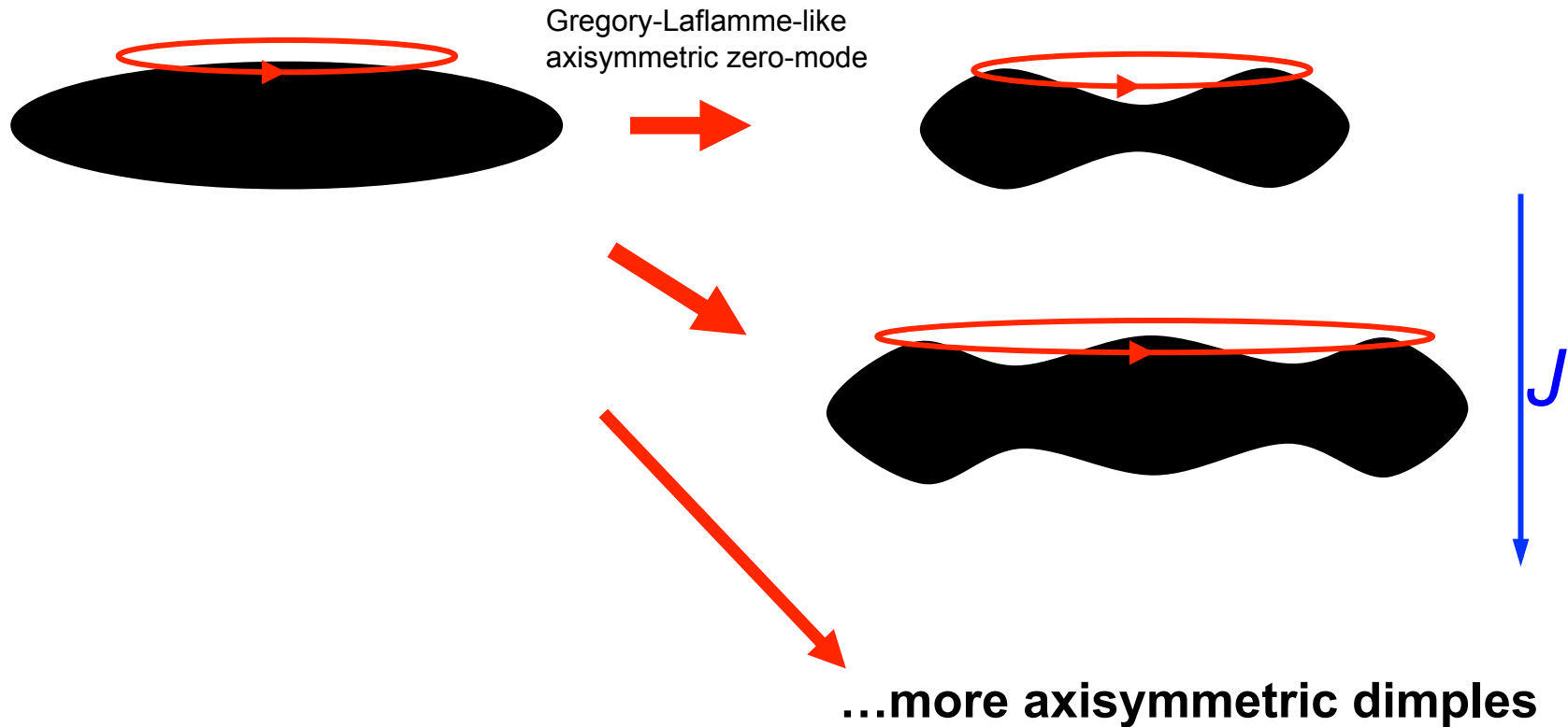
⇒ Need new approaches

- more qualitative & less rigorous methods (physics-guided)
- may guide later numerical attacks

# Lumpy black holes in $D=6$

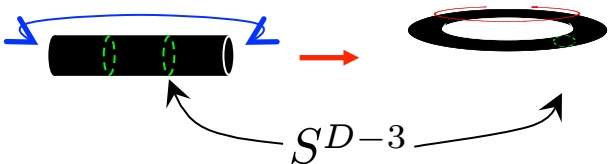
*RE+Myers*

Ultra-spinning  $\rightarrow$  membrane-like



Dual *pinched plasma balls* recently found by *Lahiri+Minwalla!*

# Thin black rings in $D=6$

- Heuristic:  seems plausible

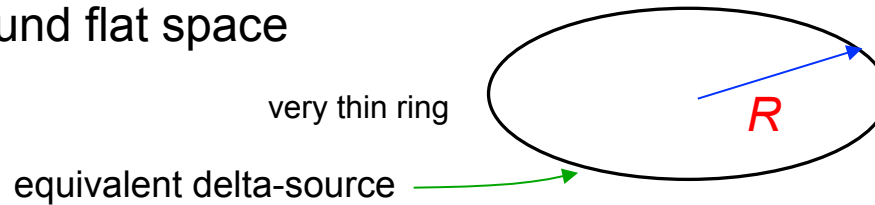
- Thin black rings  $\triangleright$  circular boosted black strings
- Equilibrium can be analyzed in linearized gravity:
  - balance between **tension** and **centrifugal repulsion**;  
gravitational self-attraction is subdominant
- Can we construct approximate thin ring solutions?

# Matched asymptotic expansion

Harmark  
Gorbonos+Kol

1- linearized solution around flat space

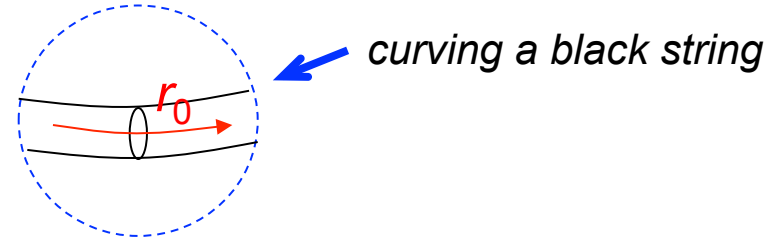
$$\frac{r_0}{r} \ll 1$$



2- perturbations of a boosted black string

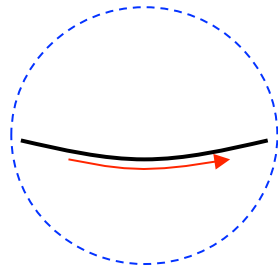
$$\frac{r}{R} \ll 1$$

need bdry conditions to fix integration constants



3- match in overlap zone

$$r_0 \ll r \ll R$$

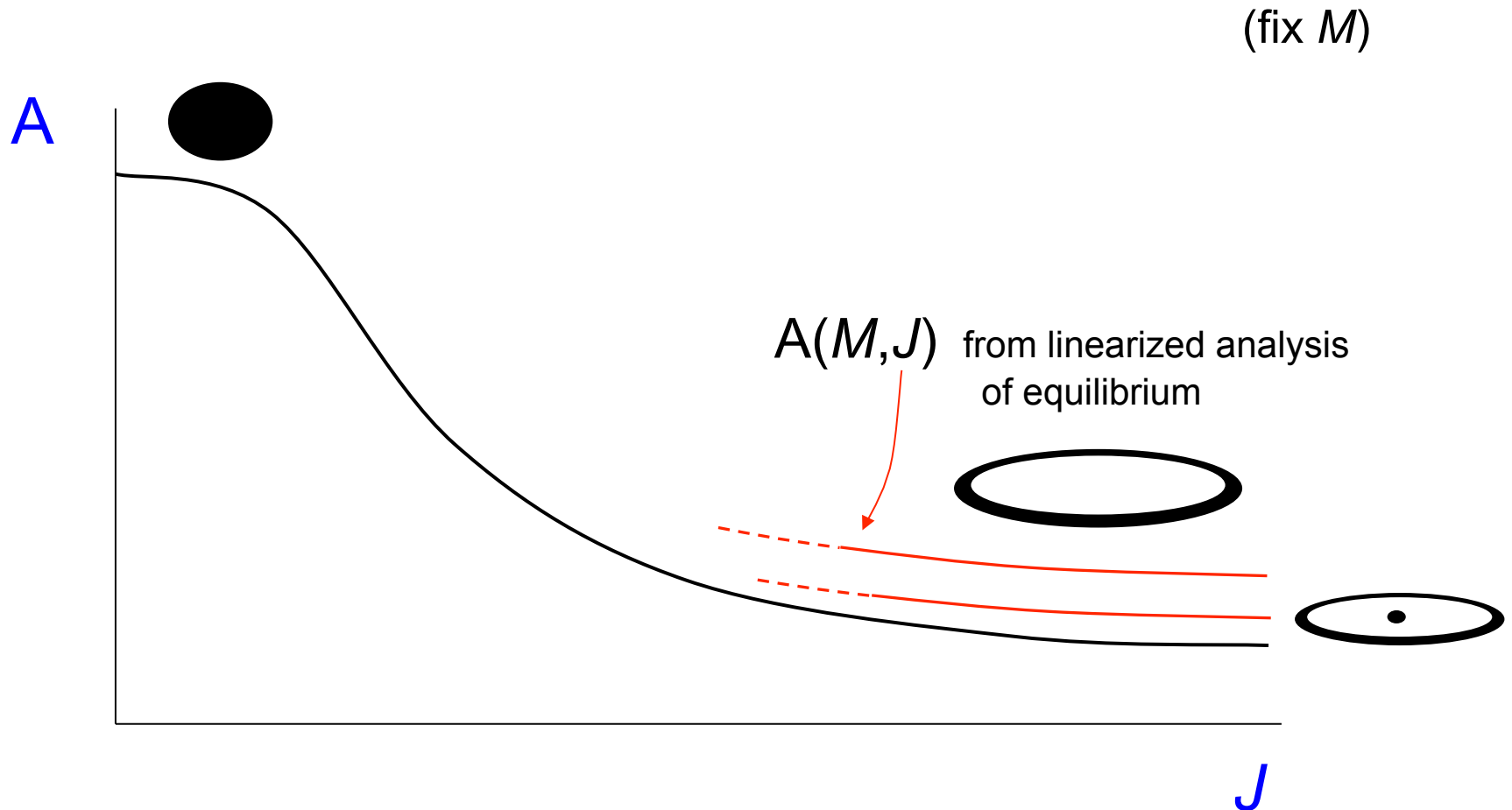


$1/R$  corrections are **singular** unless  $T_{zz}=0$

$$\Rightarrow R = \frac{D-2}{\sqrt{D-3}} \frac{J}{M} \quad (\nabla_\mu T^{\mu\nu} = 0)$$

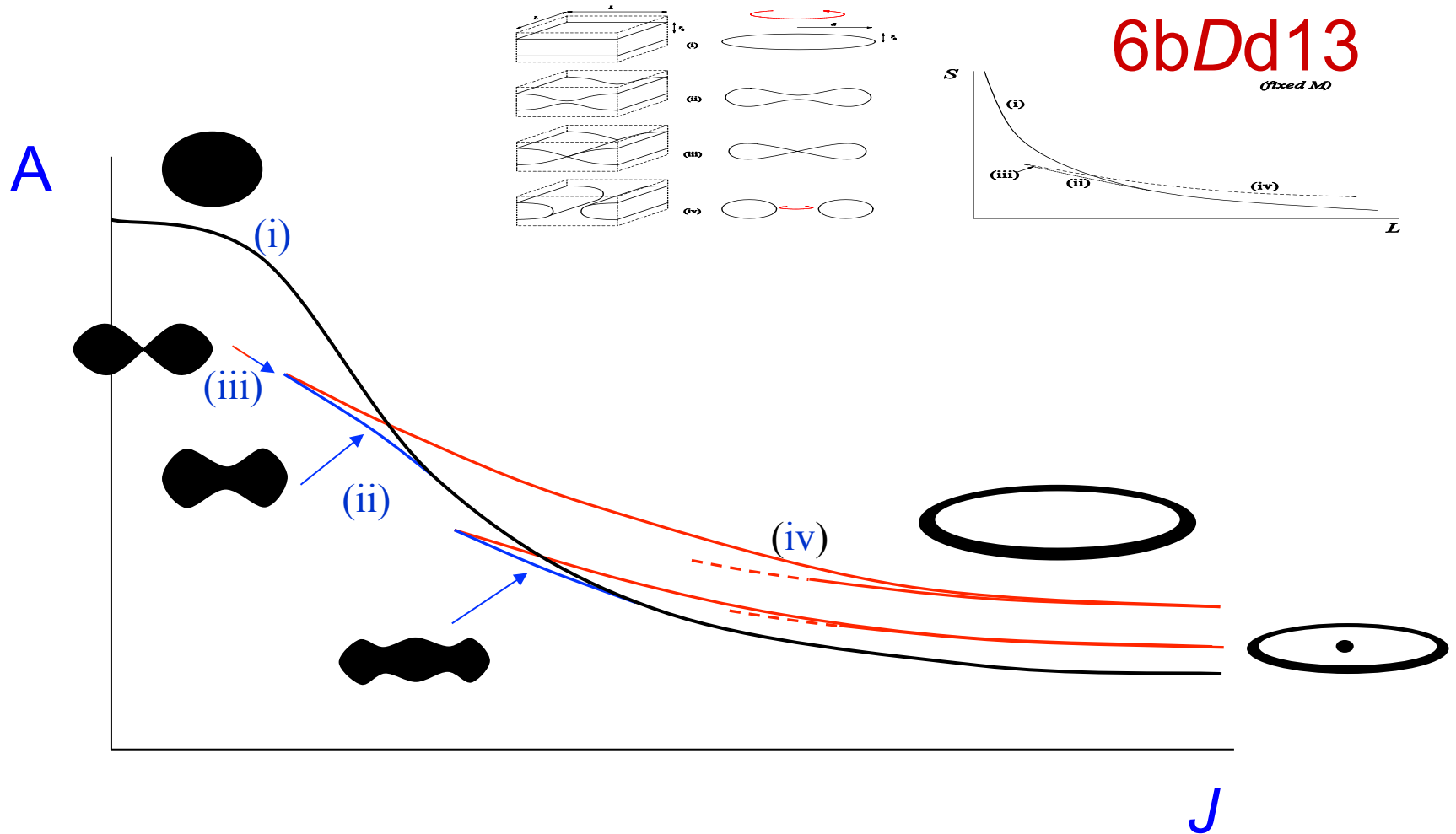
$$A(M, J, R) \Rightarrow A(M, J)$$

# Dr6 phase diagram



→ Black rings dominate the entropy at large  $J$

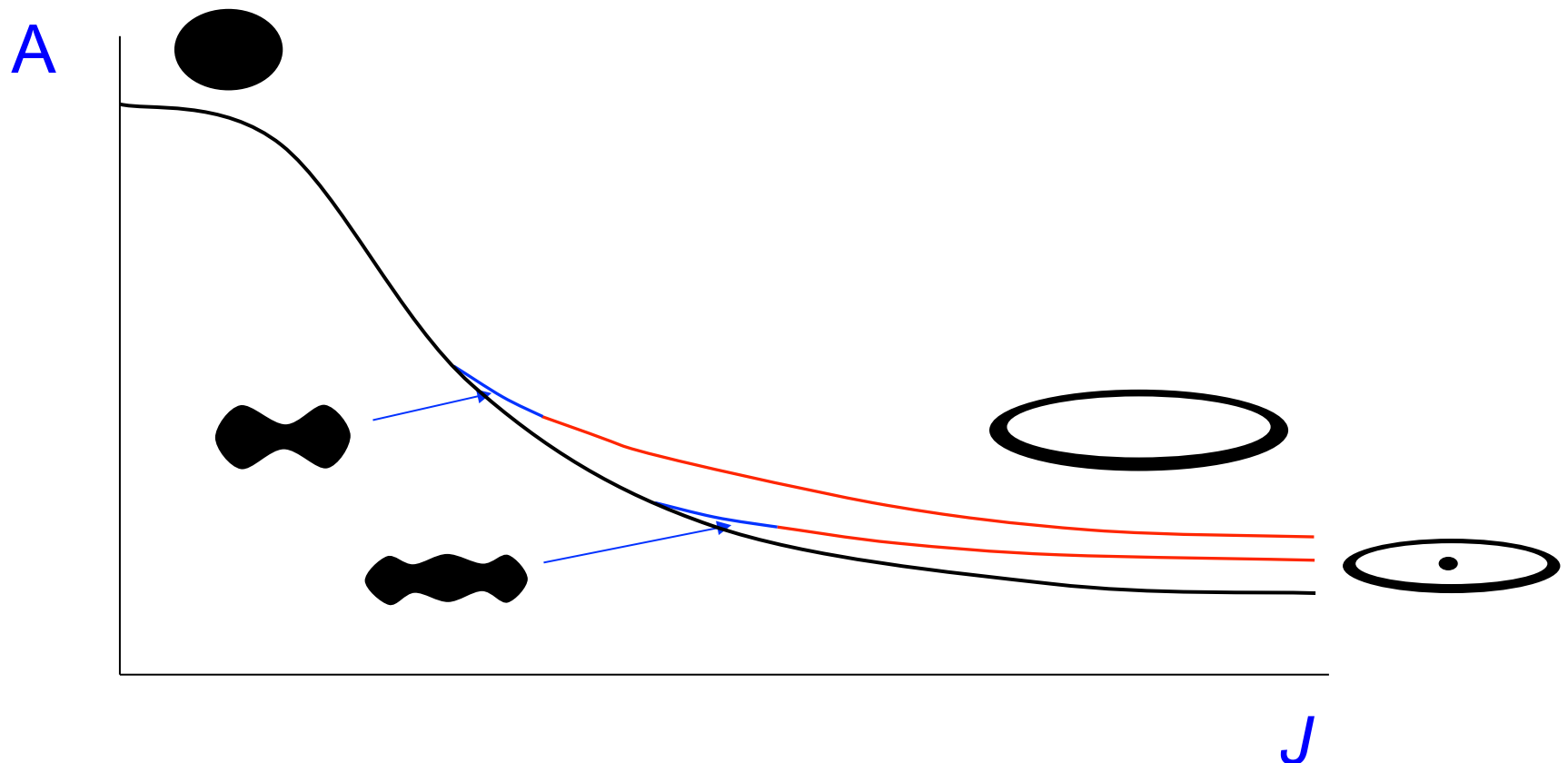
# Dr6 phase diagram: a conjecture



...infinite sequence of multi-lumps + multi-rings

# *Dr6* phase diagram: a conjecture

*Dt13*



...infinite sequence of multi-lumps + multi-rings



# Conclusion: *More is different*

Vacuum gravity  $R_{mn} = 0$  in

- $D=3$  has **no** black holes
  - $GM$  is **dimensionless**  $\rightarrow$  can't construct a length scale  
( $\Lambda$ , or  $h$ , provide length scale)
- $D=4$  has **one** black hole
  - but no 3D bh  $\rightarrow$  no 4D black strings  $\rightarrow$  no 4D black rings
- $D=5$  has **three** black holes (two topologies);
  - black strings  $\rightarrow$  black rings, infinitely many multi-bhs...
- $D=6$  seem to have **infinitely many** black holes
  - many topologies & lumpy horizons
  - black branes  $\rightarrow$  blackfolds, infinitely many multi-bhs...

*and we've just begun...*