The Black Hole - Tower Correspondence
&
the Origin of Species Thermodynamics

Alvaro Herraez

Based on [arXiv:2406.xxxxx] with D. Lüst, J. Masías, M.Scalisi

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The Black Hole - Tower Correspondence
&
the Origin of Species Thermodynamics

1. Species Scale
2. Covariant Entropy Bound and Gravitational Collapse
3. Field Theory Entropy vs. Species Entropy
4. Black Hole-Tower Correspondence

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[C. Montella's talk]

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3. ~~Field Theory Entropy vs. Species Entropy~~ [J. Masías' talk]
4. Black Hole-Tower Correspondence

The species Scale

- Maximum UV cut-off in QG in the presence of N light species [Dvali '07] [Dvali, Reedi '08] [Dvali, Lüst '10] [Dvali, Gómez '10]

$$M_{\text{Pl,d}} \longrightarrow \Lambda_{\text{sp}} = \frac{M_{\text{Pl,d}}}{N_{\text{sp}}^{\frac{1}{d-2}}}$$

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- Tower of states with $m_n = n^{1/p}\, m_t$

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$$\Lambda_{\text{sp}} \simeq m_t \left(\frac{m_t}{M_{\text{Pl},d}}\right)^{\dfrac{d-2}{d+p-2}} \qquad N_{\text{sp}} \simeq \left(\frac{M_{\text{Pl},d}}{m_t}\right)^{\dfrac{p(d-2)}{d+p-2}}$$

[Castellano, AH, Ibáñez ´21]

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$$\Lambda_{\mathrm{sp}} \simeq m_t \left(\frac{m_t}{M_{\mathrm{Pl},d}}\right)^{\frac{d-2}{d+p-2}} \longrightarrow M_s \qquad N_{\mathrm{sp}} \simeq \left(\frac{M_{\mathrm{Pl},d}}{m_t}\right)^{\frac{p(d-2)}{d+p-2}} \longrightarrow \left(\frac{M_{\mathrm{Pl},d}}{M_s}\right)^{d-2} = \frac{1}{g_s^2}$$

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[Castellano, AH, Ibáñez ´21]

Species Scale of the d-dim EFT = $M_{{\rm Pl},\, d+p}$ (decompactification of p dimensions)
$M_{\rm str}$ (weakly coupled string limits)

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[Castellano, AH, Ibáñez ´21]

- Radius of the smallest BH *in the EFT*

$$S = \frac{A}{4G_{N,d}} \sim \left(\frac{M_{{\rm Pl},d}}{\Lambda_{\rm sp}}\right)^{d-2} \simeq N_{\rm sp}$$

Gravitational Collapse and the Covariant Entropy Bound

- Configuration of energy E in a box of size L can collapse gravitationally unless

$$L \geq R_{\mathrm{BH}}(E) = \left(\frac{E}{M_{\mathrm{Pl},d}}\right)^{\frac{1}{d-3}} M_{\mathrm{Pl},d}^{-1}$$

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- Covariant Entropy Bound

[Bousso´99]

$$S \leq \frac{A}{4G_{N,d}} \sim (LM_{{\rm Pl},d})^{d-2}$$

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$$L \geq R_{\rm BH}(E) = \left(\frac{E}{M_{{\rm Pl},d}}\right)^{\frac{1}{d-3}} M_{{\rm Pl},d}^{-1} \longrightarrow E \lesssim L^{d-3} \qquad S \lesssim \frac{L^{d-3}}{T}$$

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$$S \leq \frac{A}{4G_{N,d}} \sim (LM_{{\rm Pl},d})^{d-2} \xrightarrow{S \sim \frac{E}{T}} E \lesssim TL^{d-2} \qquad S \lesssim L^{d-2}$$

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Can we approach the maximum entropy for some non-black hole configuration?

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- Coincide for $T \simeq 1/L$

[Castellano, AH, Ibáñez ´21] [AH, Lüst, Masías, Scalisi ´24]

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- Coincide for $T \simeq 1/L$ $\longrightarrow$ $E_{\rm max}(T) \simeq \dfrac{1}{T^{d-3}} \geq \dfrac{1}{\Lambda_{\rm sp}^{d-3}} \simeq \dfrac{N_{\rm sp}}{\Lambda_{\rm sp}}$

[Castellano, AH, Ibáñez ´21] [AH, Lüst, Masías, Scalisi ´24]

All one-particle states in the box with non-zero momentum have a large Boltzmann suppression $\sim e^{-E_m/T}$

$E_m = \sqrt{m_m + p_m}$ $\qquad p = n^2/L^2$

$$S_{\rm max}(T) \simeq \frac{1}{T^{d-2}} \geq \frac{1}{\Lambda_{\rm sp}^{d-2}} \simeq N_{\rm sp}$$

Species Entropy from EFT thermodynamics in the limit

- CEB and Gravitational Collapse Bound coincide for $T \simeq 1/L$
  [AH, Lüst, Masías, Scalisi ´24]

$$E(T) \simeq T N_T \leq \frac{1}{T^{d-3}} \qquad S(T) \simeq N_T \lesssim \frac{1}{T^{d-2}} \qquad S \sim \frac{E}{T}$$

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- Saturated when $T \simeq \frac{M_{\mathrm{Pl},d}}{N_T^{\frac{1}{d-2}}} \simeq N_T^{\frac{1}{p}}\, m_t \longrightarrow T \simeq \Lambda_{\mathrm{sp}} \qquad N_T \simeq N_{\mathrm{sp}}$

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Appropriate Towers

[J. Masías' talk]

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Appropriate Towers

[J. Masías' talk]

$$E \simeq \Lambda_{\text{sp}} N_{\text{sp}} = \sum_i m_i \qquad S \simeq N_{\text{sp}}$$

Species Thermodynamics

[Cribiori, Lüst, Montella, ´23]

Black Hole-String Correspondence

[Susskind ´93]
[Horowitz, Polchinski ’96 ’97]

[Chen, Maldacena, Witten ’21]
[Susskind ’21]
[Ceplack, Emparan, Puhm, Tomasevic ‘22]
[Bedroya, Vafa, Wu ‘23]

Black Hole-String Correspondence

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Black Hole

$$\ell_{\mathrm{Pl,d}}^{d-2} = g_{s,d}^2 \ell_{\mathrm{str}}^{d-2}$$

$$M_{\mathrm{BH}} \sim \frac{R_{\mathrm{BH}}^{d-3}}{\ell_{\mathrm{Pl,d}}^{d-2}} \sim \frac{R_{\mathrm{BH}}^{d-3}}{g_{s,d}^2 \ell_{\mathrm{str}}^{d-2}}$$

$$S_{\mathrm{BH}} \sim \left(R_{\mathrm{BH}}/\ell_{\mathrm{Pl,d}}\right)^{d-2} \sim g_{s,d}^{\frac{2}{d-3}} \left(M_{\mathrm{BH}}\ell_{\mathrm{str}}\right)^{\frac{d-2}{d-3}}$$

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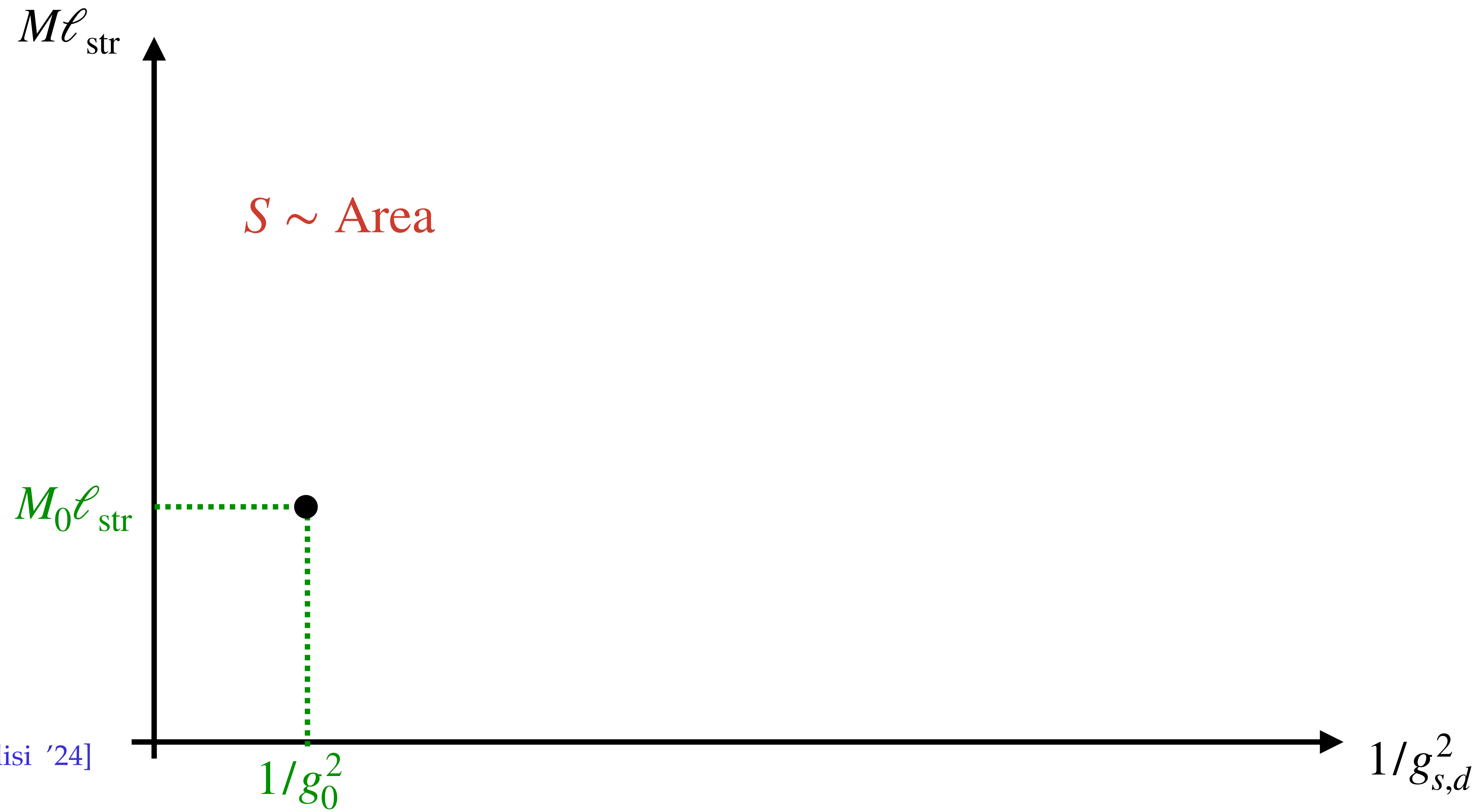

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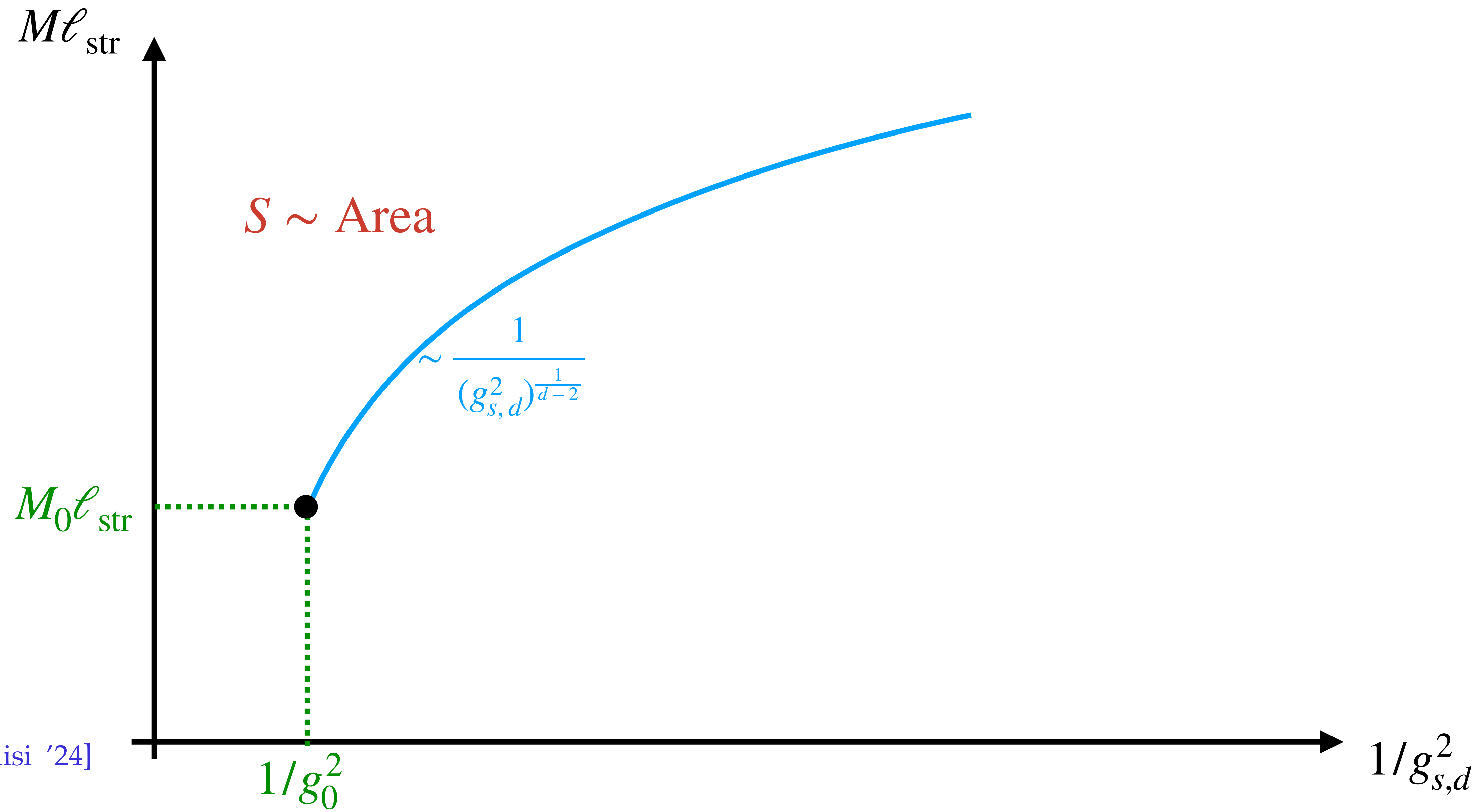

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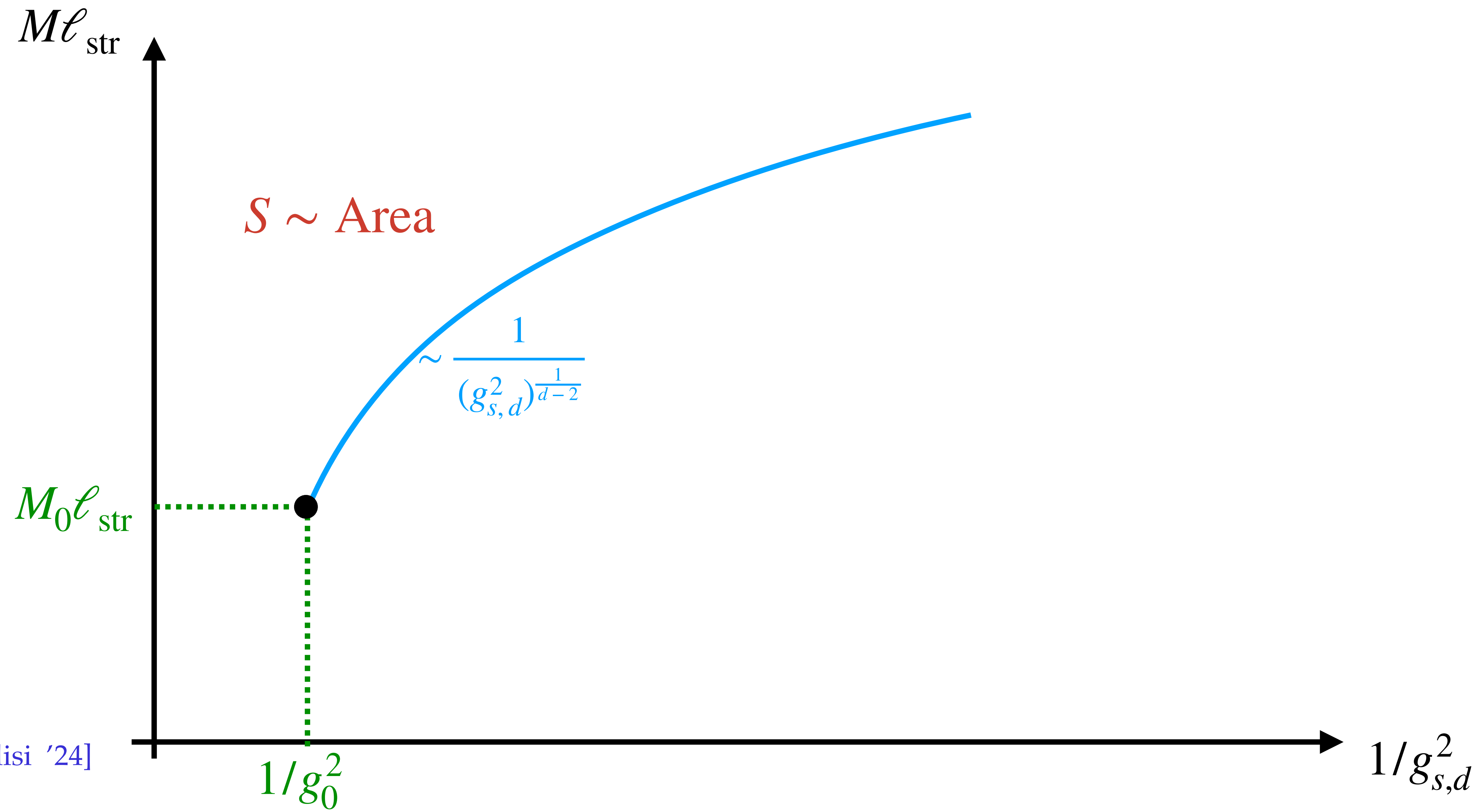
(Free) String

$$M_{\rm str} \sim \frac{L_{\rm str}}{\ell_{\rm str}^2}$$

$$S_{\rm str} \sim L_{\rm str}/\ell_{\rm str} \sim M_{\rm str}\ell_{\rm str}$$



[AH, Lüst, Masias, Scalisi '24]

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[Susskind ´93]
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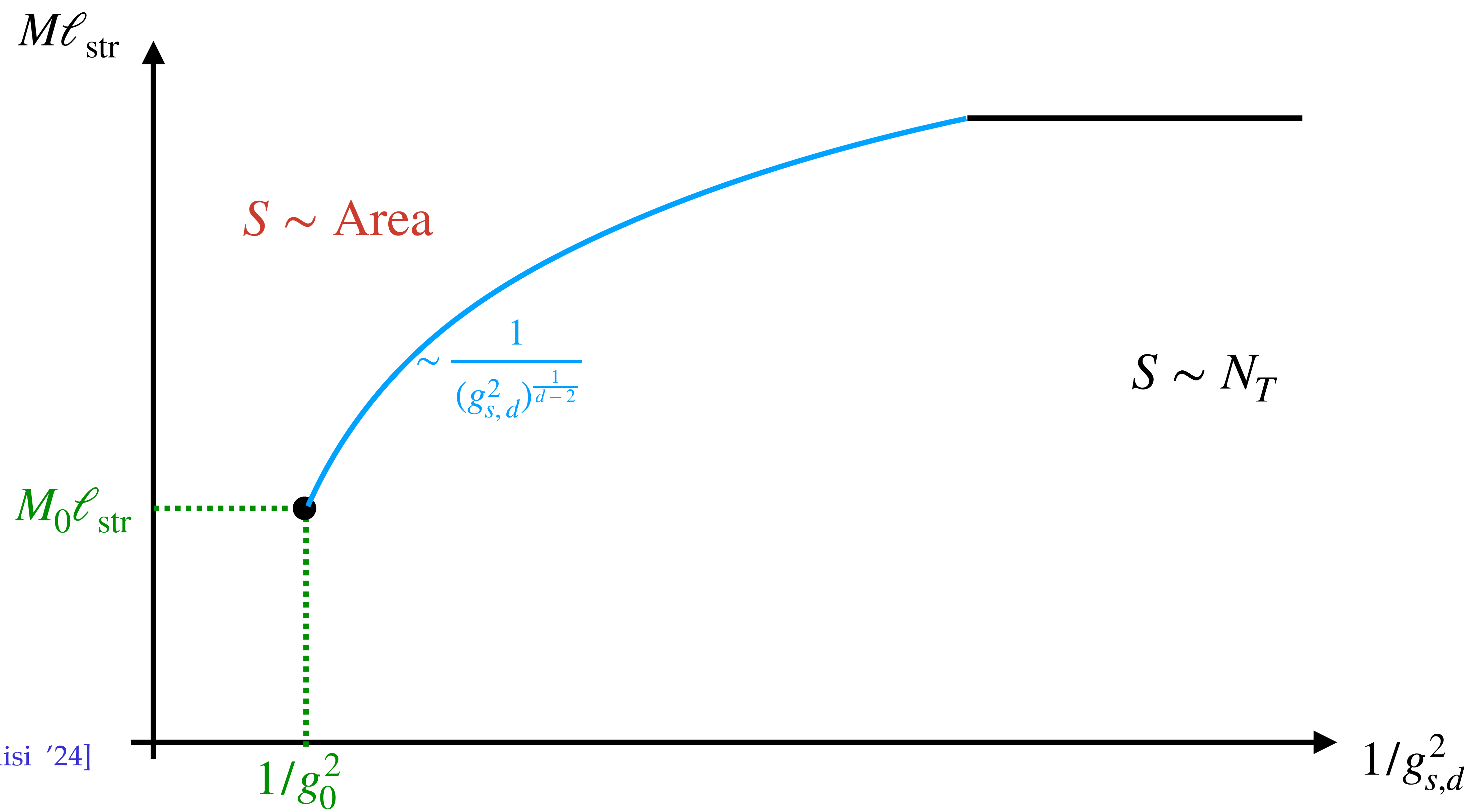

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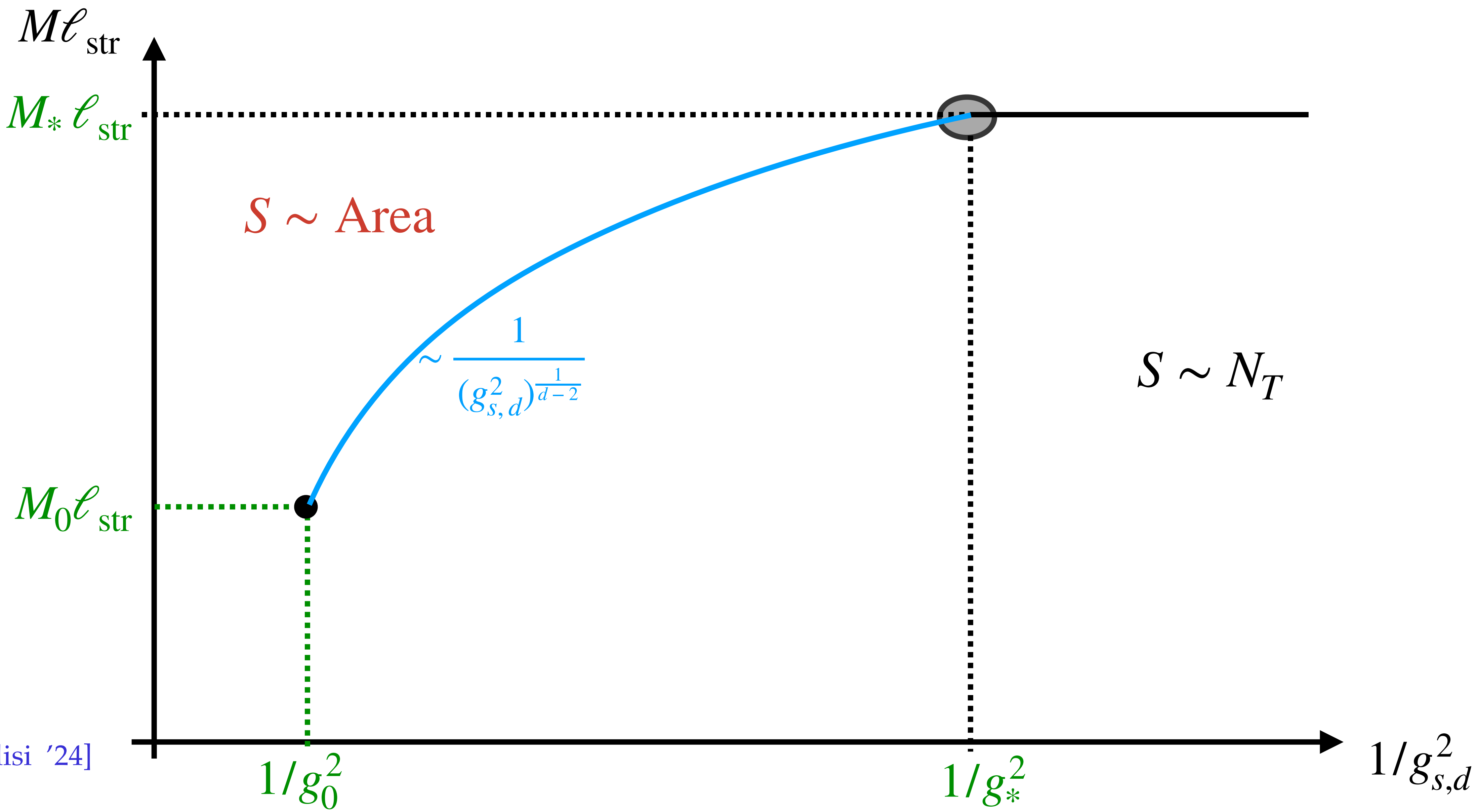
$$M_{\rm str} \sim \frac{L_{\rm str}}{\ell_{\rm str}^2}$$

$$S_{\rm str} \sim L_{\rm str}/\ell_{\rm str} \sim M_{\rm str}\ell_{\rm str}$$

Correspondence point

$$R_{\rm BH} \sim \ell_{\rm str}$$

$$S = \frac{1}{g_{s,*}^2} = N_{\rm sp}$$



[AH, Lüst, Masias, Scalisi ’24]

Black Hole-String Correspondence

[Susskind ´93]
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	Black Hole	(Free) String
$\ell_{\rm Pl,d}^{d-2} = g_{s,d}^2 \ell_{\rm str}^{d-2}$	$M_{\rm BH} \sim \frac{R_{\rm BH}^{d-3}}{\ell_{\rm Pl,d}^{d-2}} \sim \frac{R_{\rm BH}^{d-3}}{g_{s,d}^2 \ell_{\rm str}^{d-2}}$	$M_{\rm str} \sim \frac{L_{\rm str}}{\ell_{\rm str}^2}$
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Correspondence point (line)

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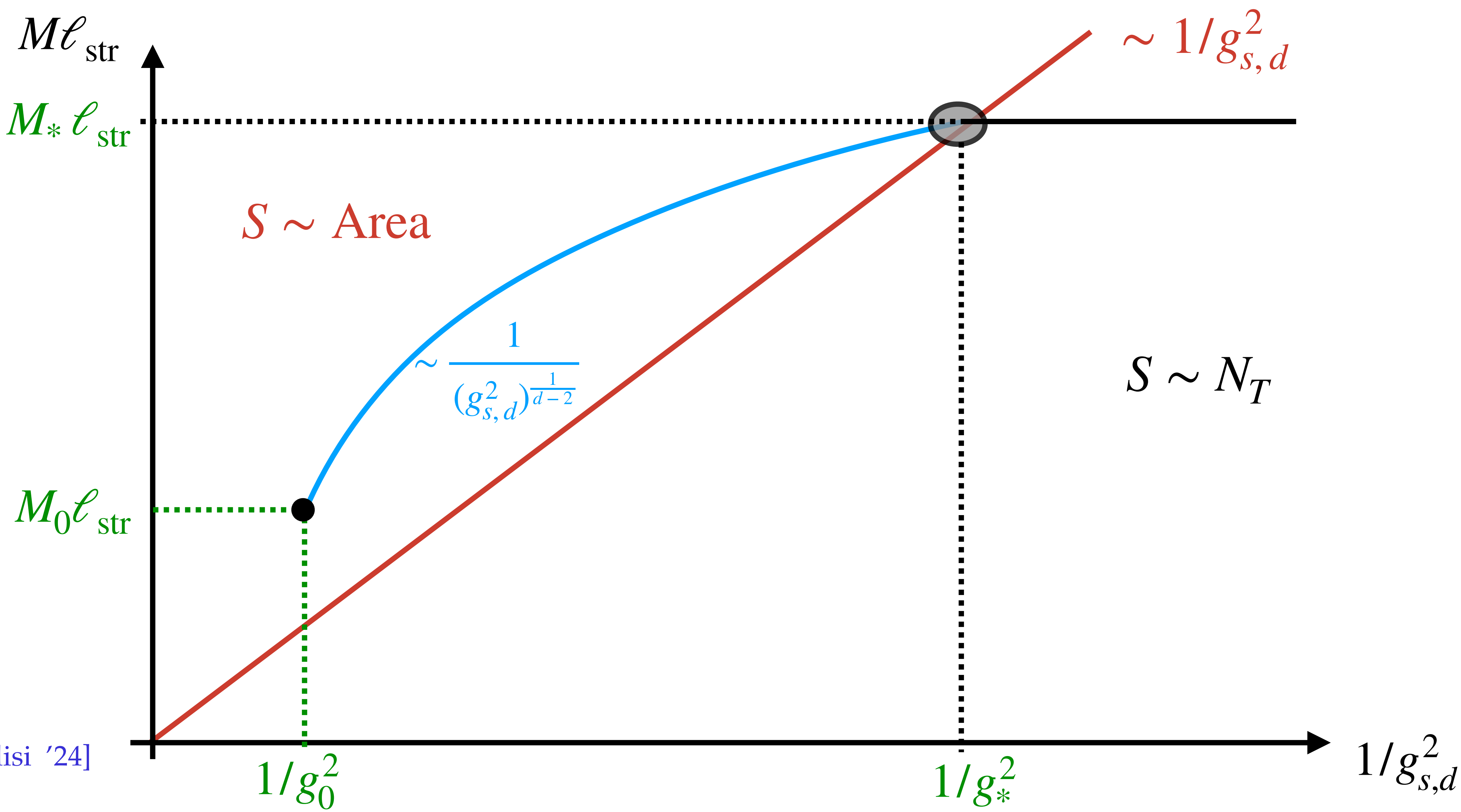

[AH, Lüst, Masias, Scalisi ’24]

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Black Hole

$$M_{\text{BH}} \sim \frac{R_{\text{BH}}^{d-3}}{\ell_{\text{Pl,d}}^{d-2}} \sim \frac{R_{\text{BH}}^{d-3}}{g_{s,d}^2 \ell_{\text{str}}^{d-2}}$$

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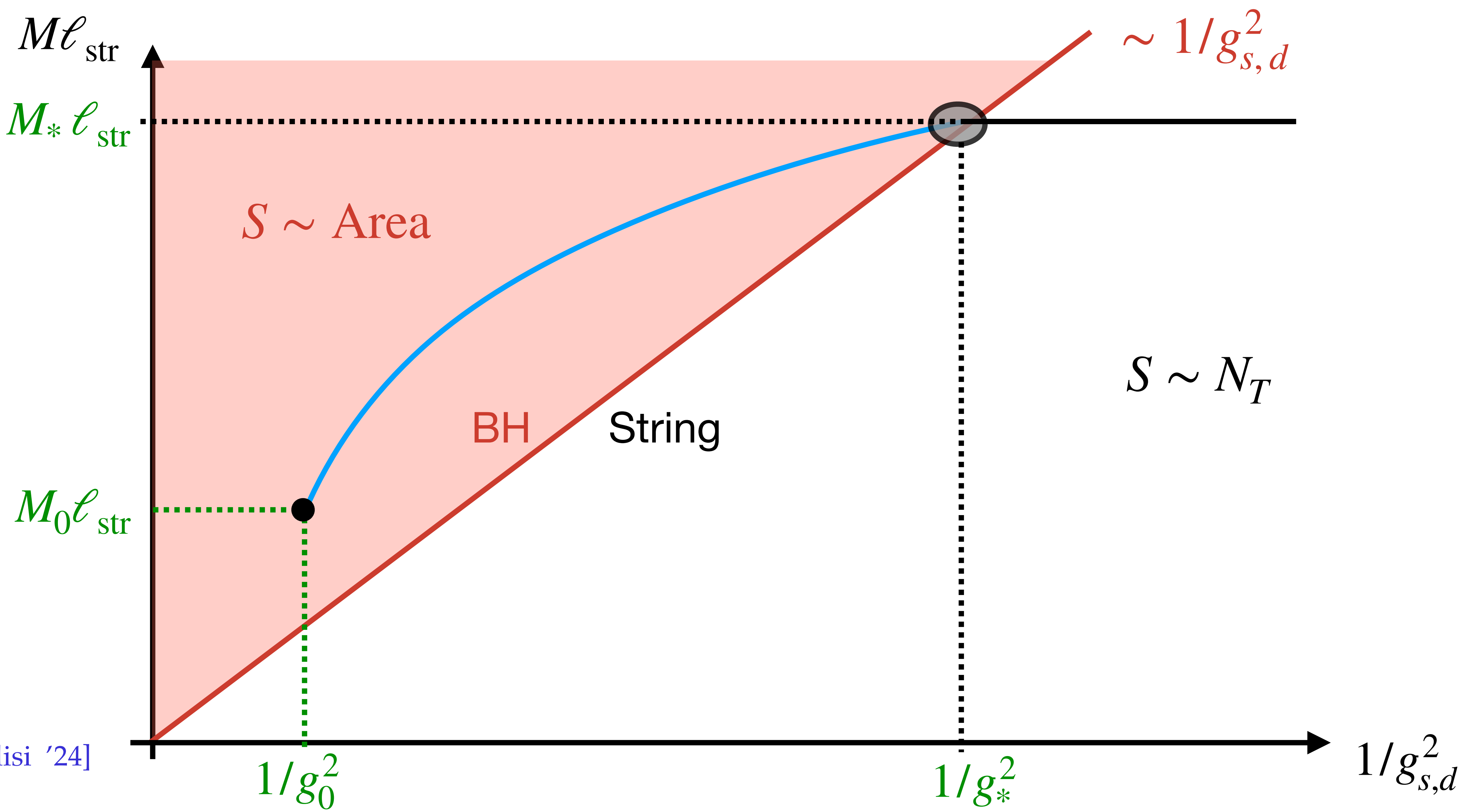


[AH, Lüst, Masias, Scalisi ’24]

Black Hole - (Species) Tower Correspondence

$$\ell_{\rm Pl,d}^{d-2} = \frac{\ell_{\rm sp}^{d-2}}{\mathscr{V}}$$

$$\ell_{\rm str} \to \ell_{sp} = \Lambda_{\rm sp}^{-1}$$
$$g_s^{-2} \to \mathscr{V}$$

Black Hole

$$M_{\rm BH} \sim \frac{R_{\rm BH}^{d-3}}{\ell_{\rm Pl,d}^{d-2}} \sim \frac{R_{\rm BH}^{d-3}\,\mathscr{V}}{\ell_{\rm sp}^{d-2}}$$

$$S_{\rm BH} \sim \left(R_{\rm BH}/\ell_{\rm Pl,d}\right)^{d-2} \sim \left(\frac{M_{\rm BH}^{d-2}\ell_{\rm sp}^{d-2}}{\mathscr{V}}\right)^{\frac{1}{d-3}}$$

Box of species

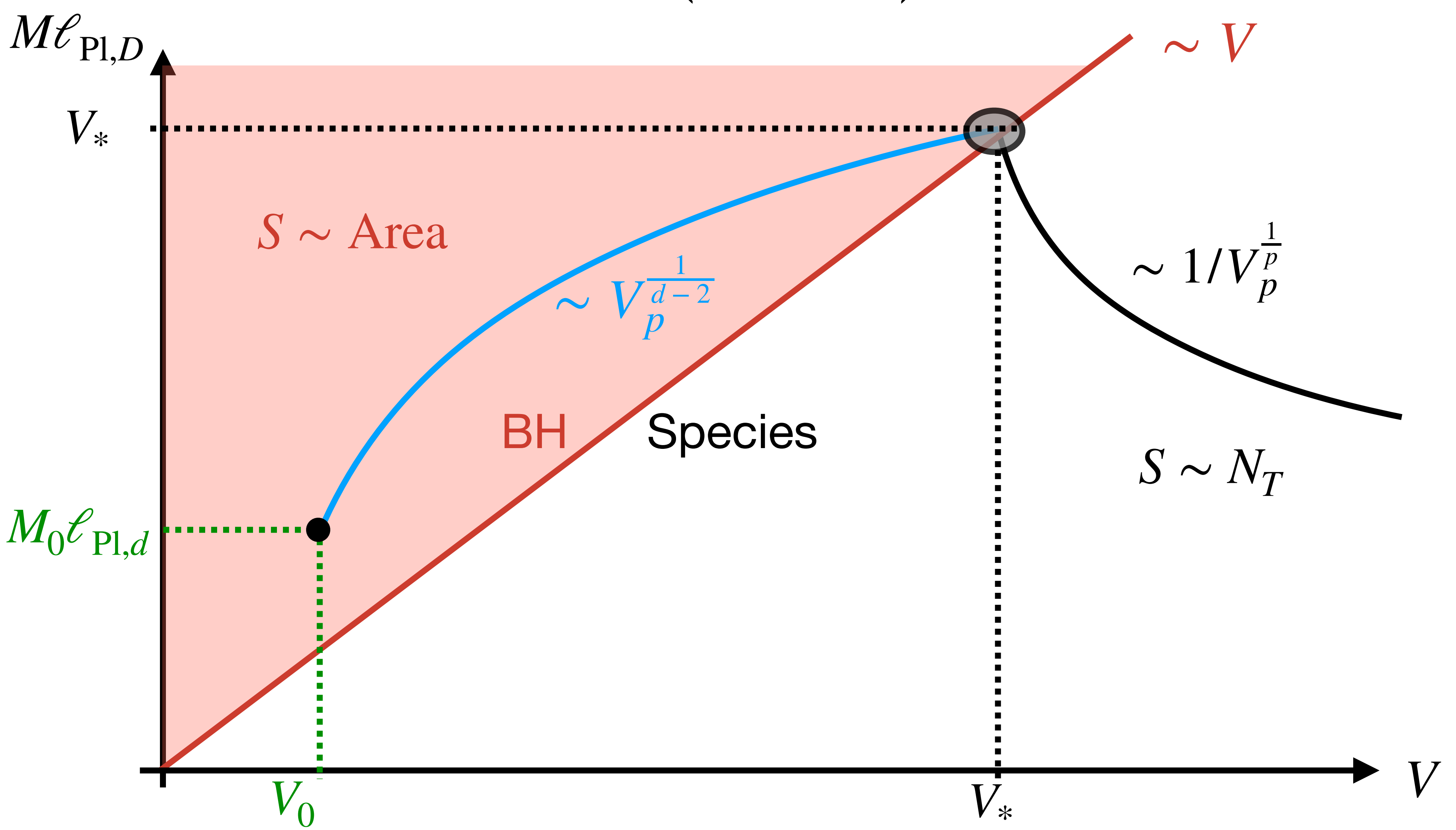
$$L^{-1} = T \leq \Lambda_{\rm sp}$$

$$S \sim N_T\,(T\,L)^{d-1}$$

Correspondence point (line)

$$R_{\rm BH} \sim \ell_{\rm sp}$$

$$S = \mathscr{V}_* = N_{\rm sp,*}$$



[AH, Lüst, Masias, Scalisi '24]

Take-home message

- Weakly coupled string oscillators & KK-like towers can give rise to the right entropy & energy to allow a black hole - tower correspondence
- *Appropriate* towers $\longleftrightarrow$ Entropy to allow for black hole - tower correspondence

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Food for thought

Take-home message

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- *Appropriate* towers $\longleftrightarrow$ Entropy to allow for black hole - tower correspondence

Food for thought $\longrightarrow$ Answers in J. Masías' talk

- Are there any other tower that can give rise to the right entropy & mass?
  [See also C. Montella's talk]
- Can we understand the thermodynamics of these towers from the EFT thermodynamics?

Take-home message

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- *Appropriate* towers ⟷ Entropy to allow for black hole - tower correspondence

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Grazie mille!