Emergence of Species Scale Black Hole Horizons

José Calderón Infante

Based on 2310.04488 with Matilda Delgado and Ángel Uranga

Geometry, Strings and the Swampland Program, Ringberg Castle, 22/03/2024

The Scale of Quantum Gravity

Einstein gravity is a non-renormalizable theory ➡ It is an EFT, valid until some cutoff Λ_{QG}

Quantum Gravity
effects become relevant

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This talk: Leading order in this limit

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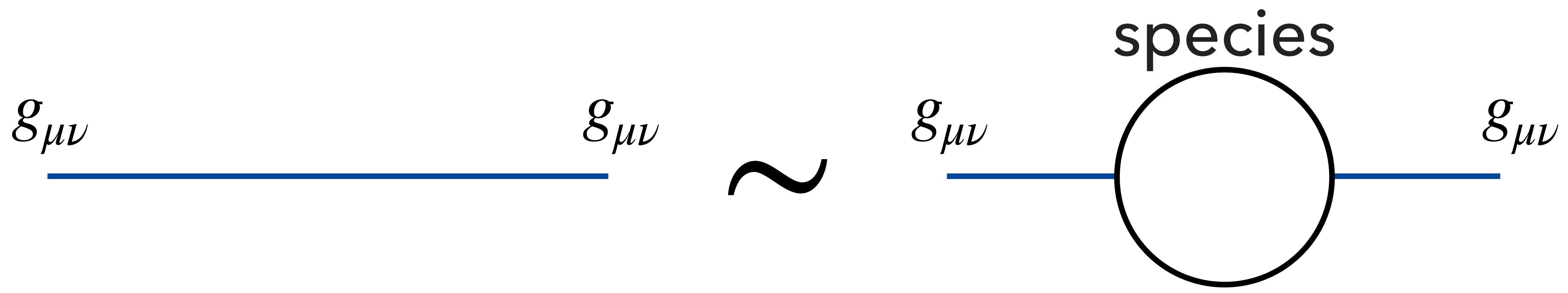

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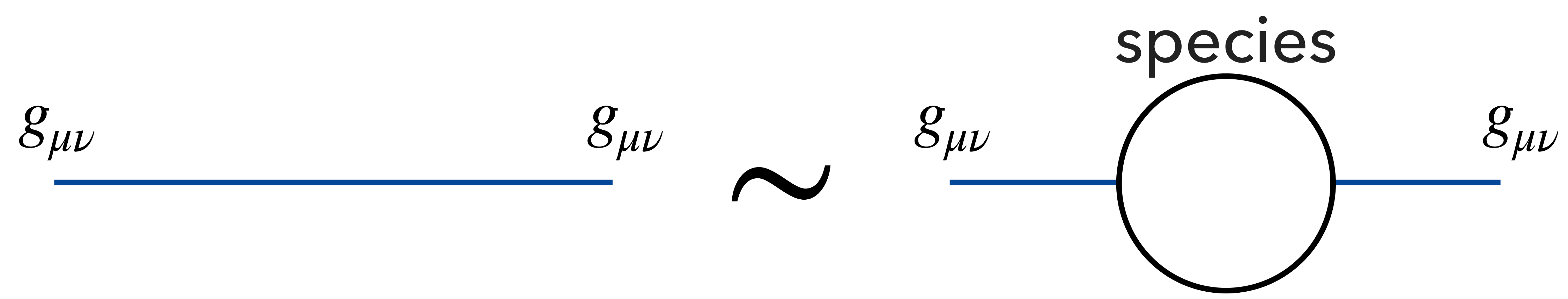

$$\Rightarrow \quad \Lambda_s \sim \frac{M_{Pl}}{N_s^{\frac{1}{d-2}}}$$

[Dvali, (Redi) '07]
(see also [Castellano, Herráez, Ibáñez '22],
[Cribiori, Lust, Montella '23]
and [Blumenhagen, Gligovic, Paraskevopoulou '23])

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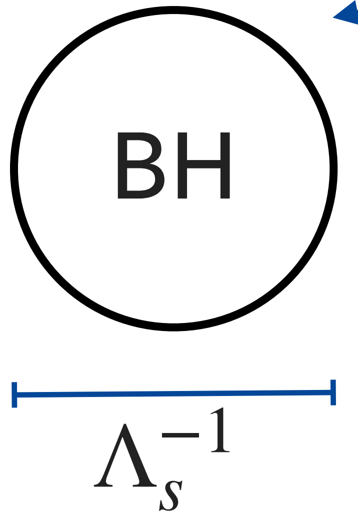

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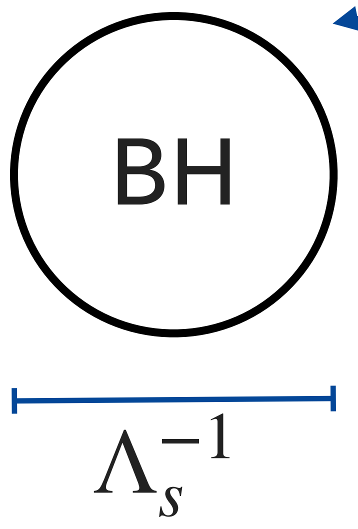

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$$S_{BH} \sim \Lambda_s^{2-d}$$

But! vs

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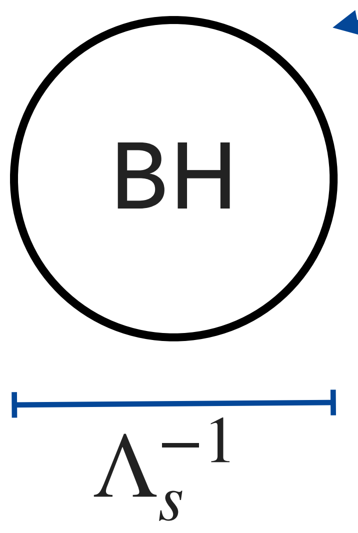

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But! $S_{BH} \sim \Lambda_s^{2-d}$ vs $S_{species} \sim N$ $\Rightarrow$ $\Lambda_s \lesssim \dfrac{1}{N^{\frac{1}{d-2}}}$ [Agmon, Bedroya, Kang, Vafa '22]

Similar one in [Dvali, (Redi) '07]

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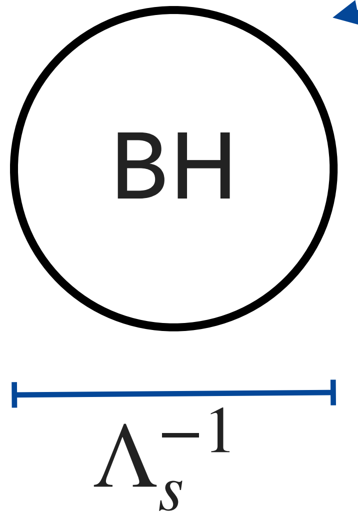

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Sort of a new definition for N_s [van de Heisteeg, Vafa, Wiesner '23]

Checked that $N \sim N_s$ (at leading order!)

[Blumenhagen, Gligovic, Paraskevopoulou '23] [Basile, Lüst, Montella '23]

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[van de Heisteeg, Vafa, Wiesner, (Wu) '22-'23]+[Cribiori, Lüst '23]+[Castellano, Herráez, Ibáñez '23]

Coincide with previous notions asymptotically!

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Three different notion, that seem to agree (at least asymptotically)… **why?**

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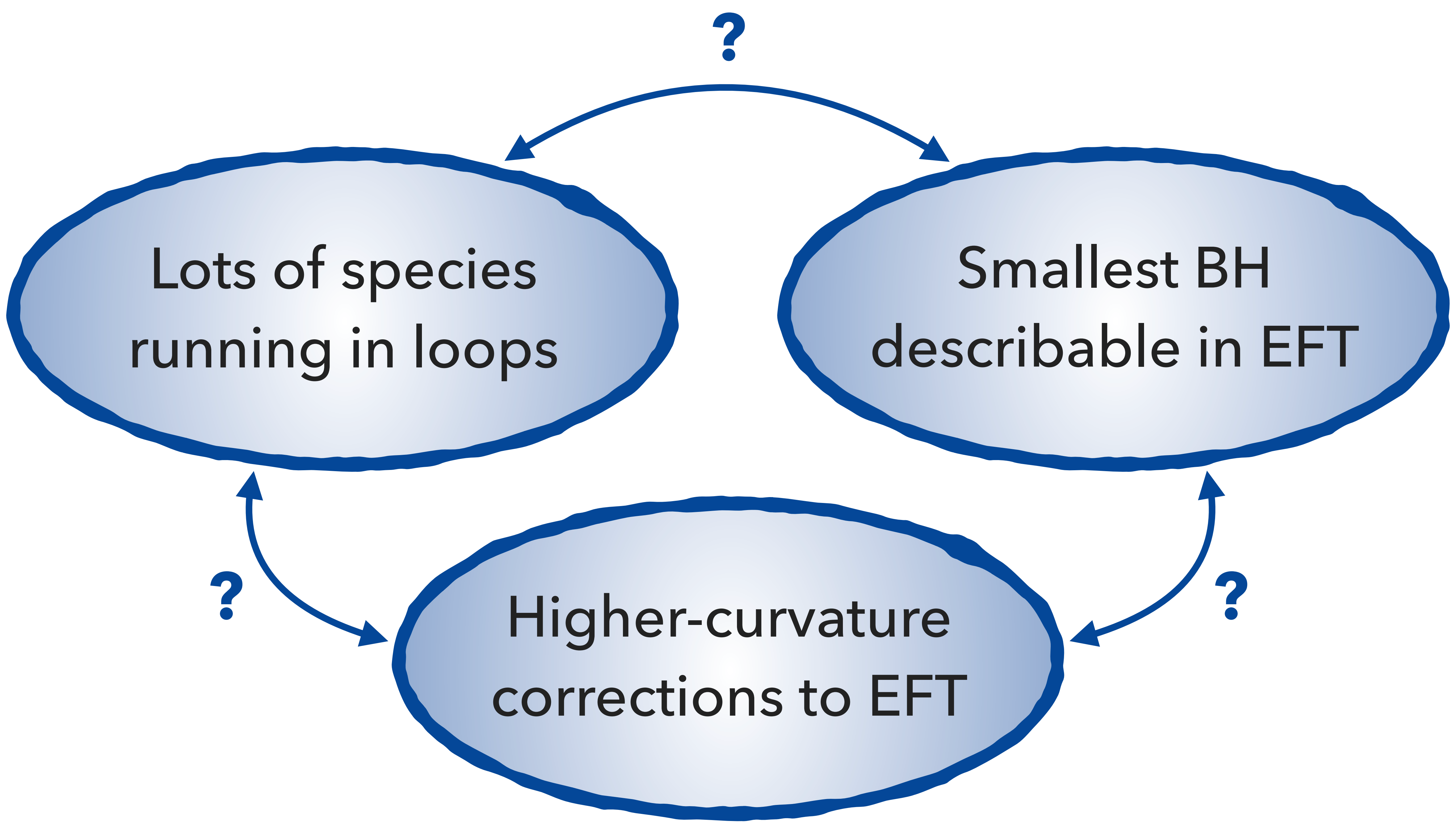

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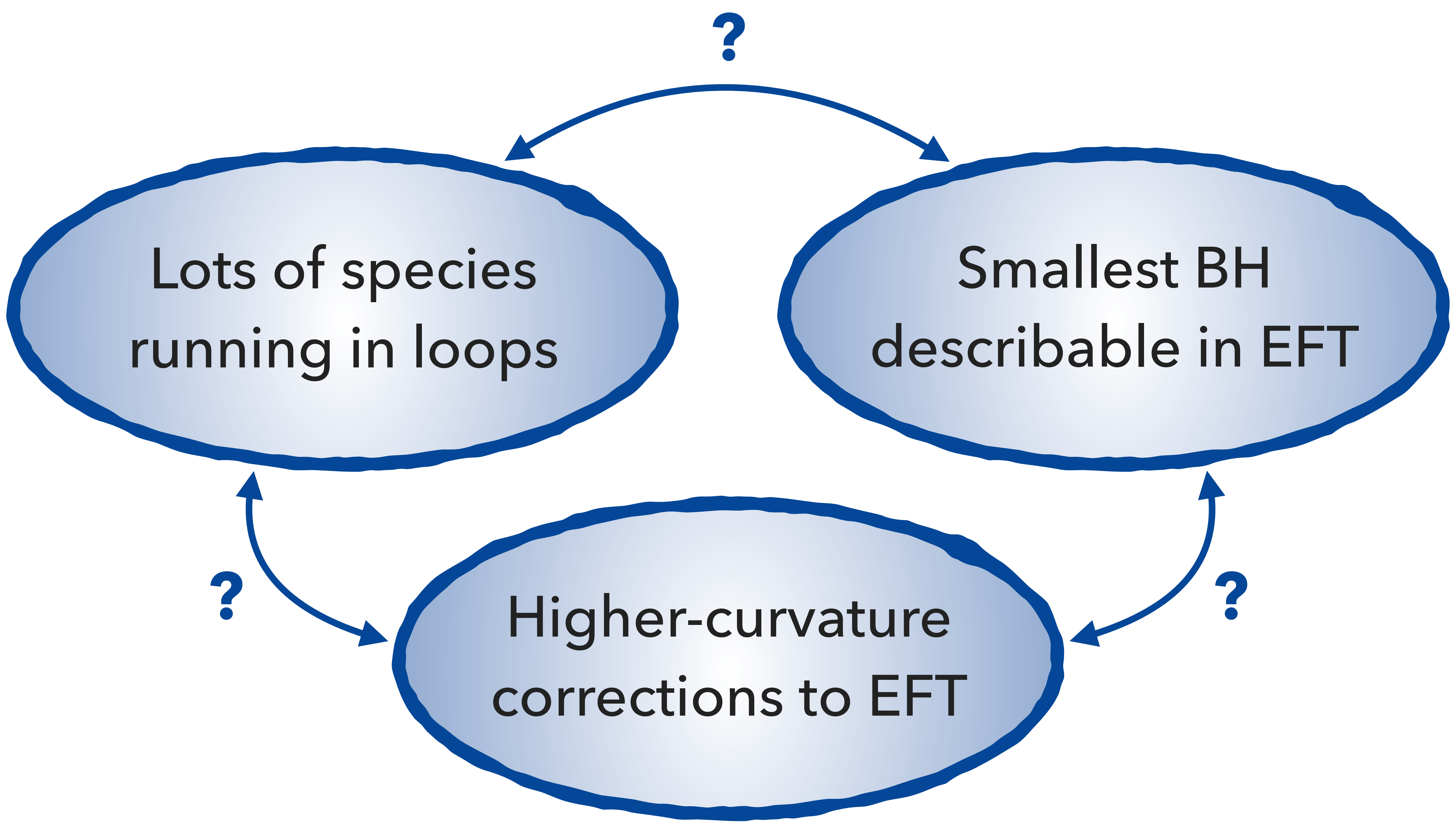

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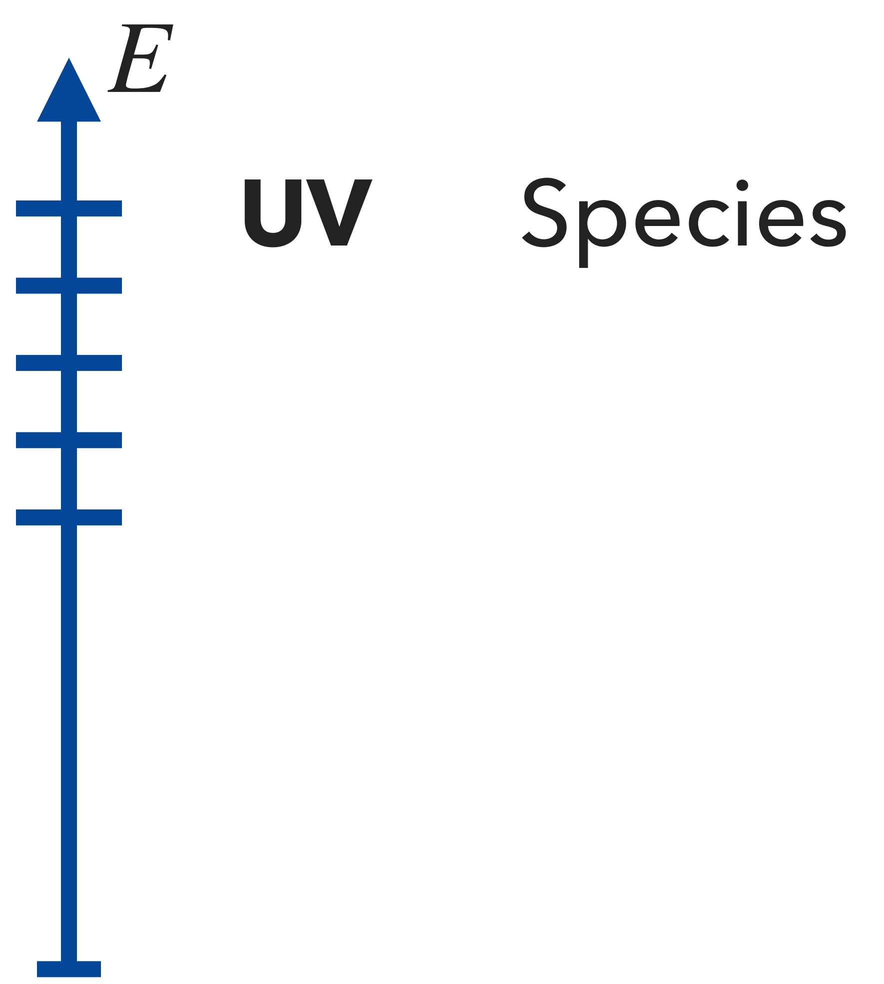

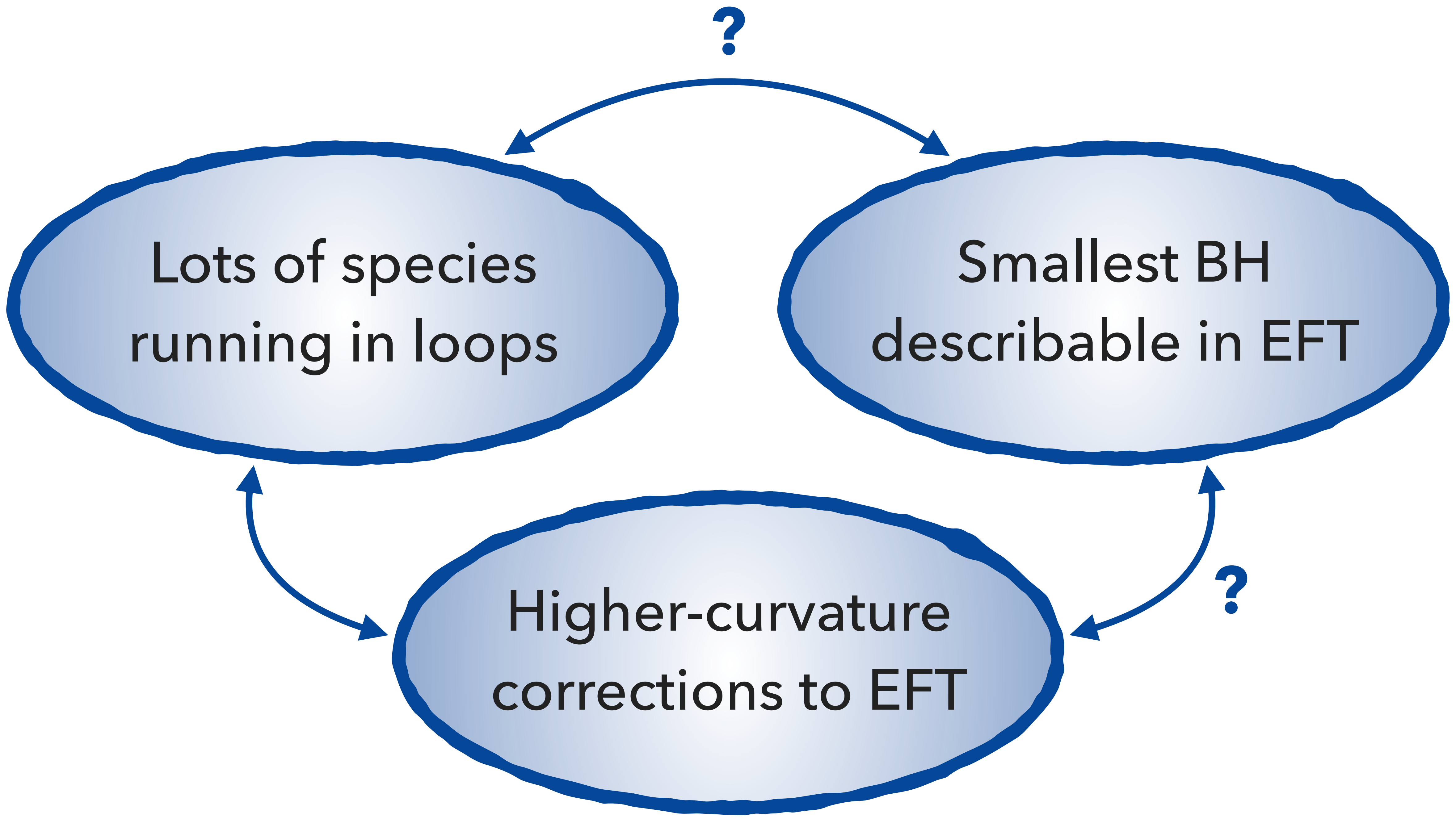

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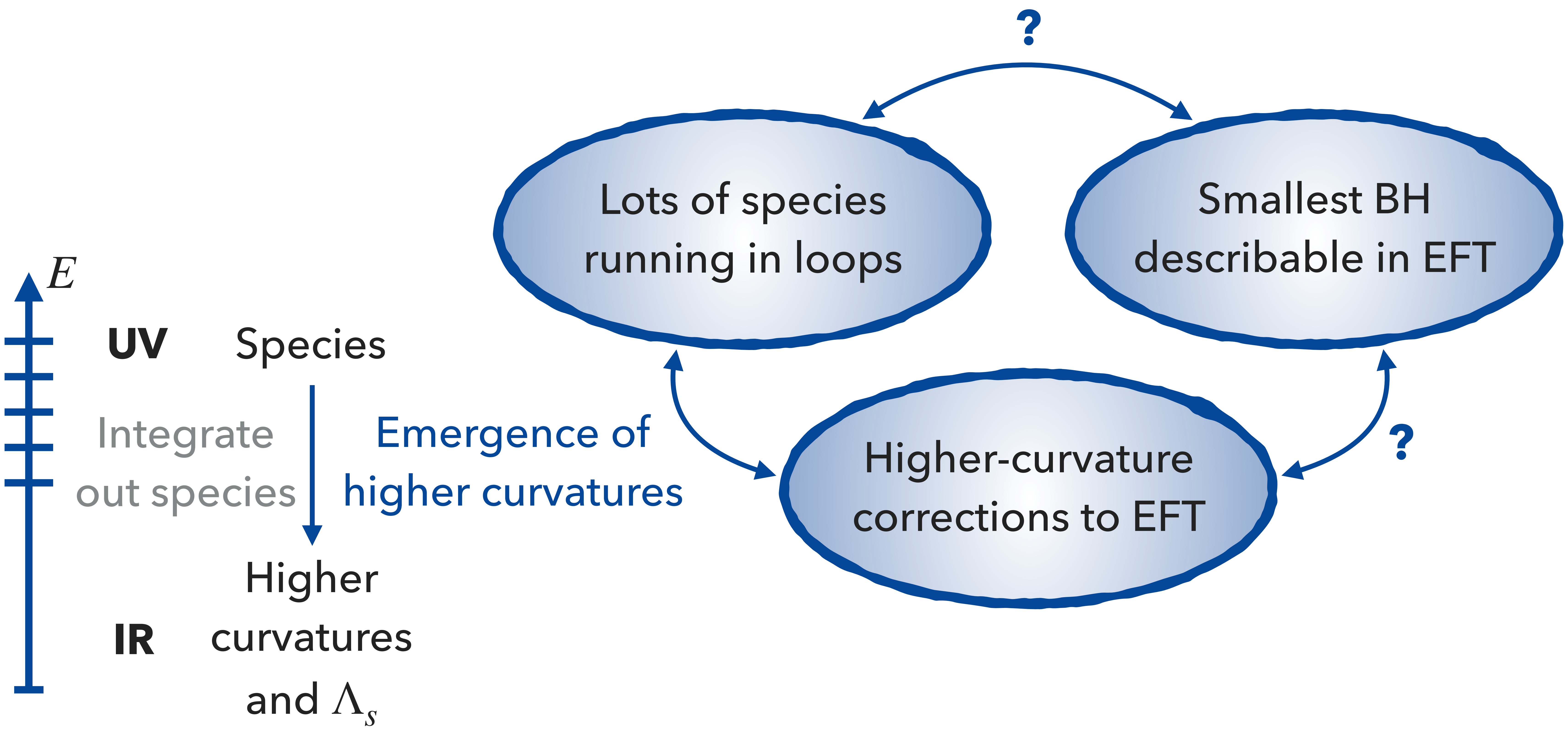

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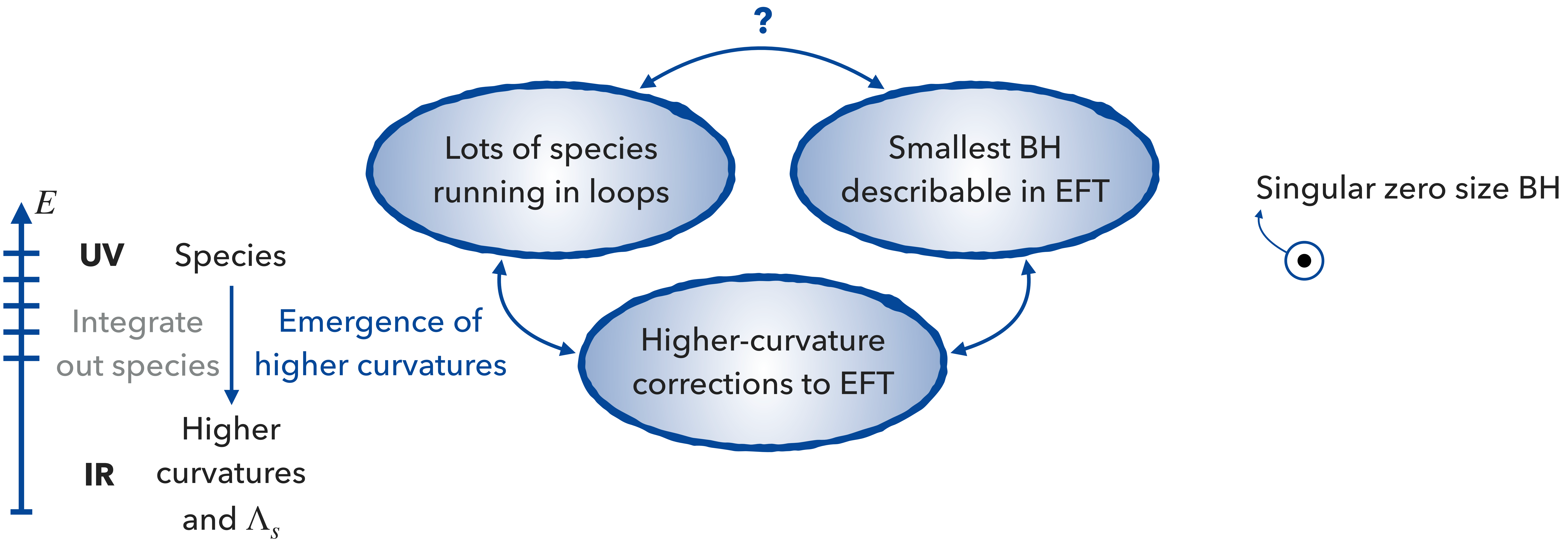

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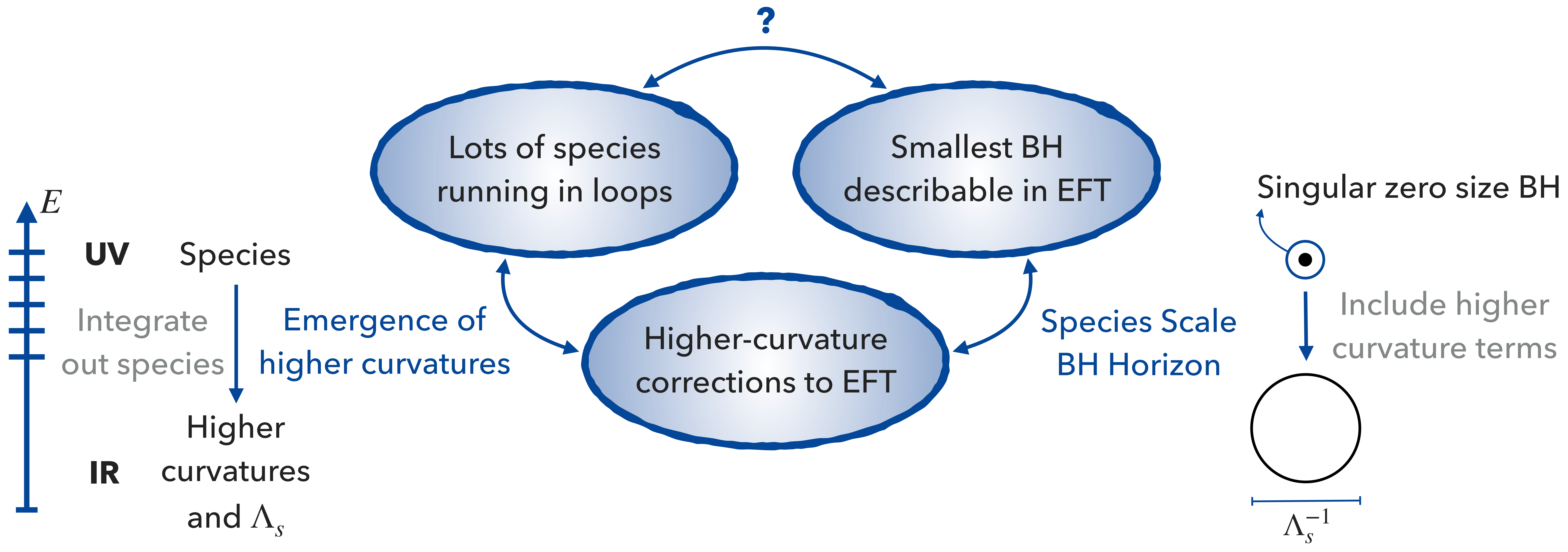

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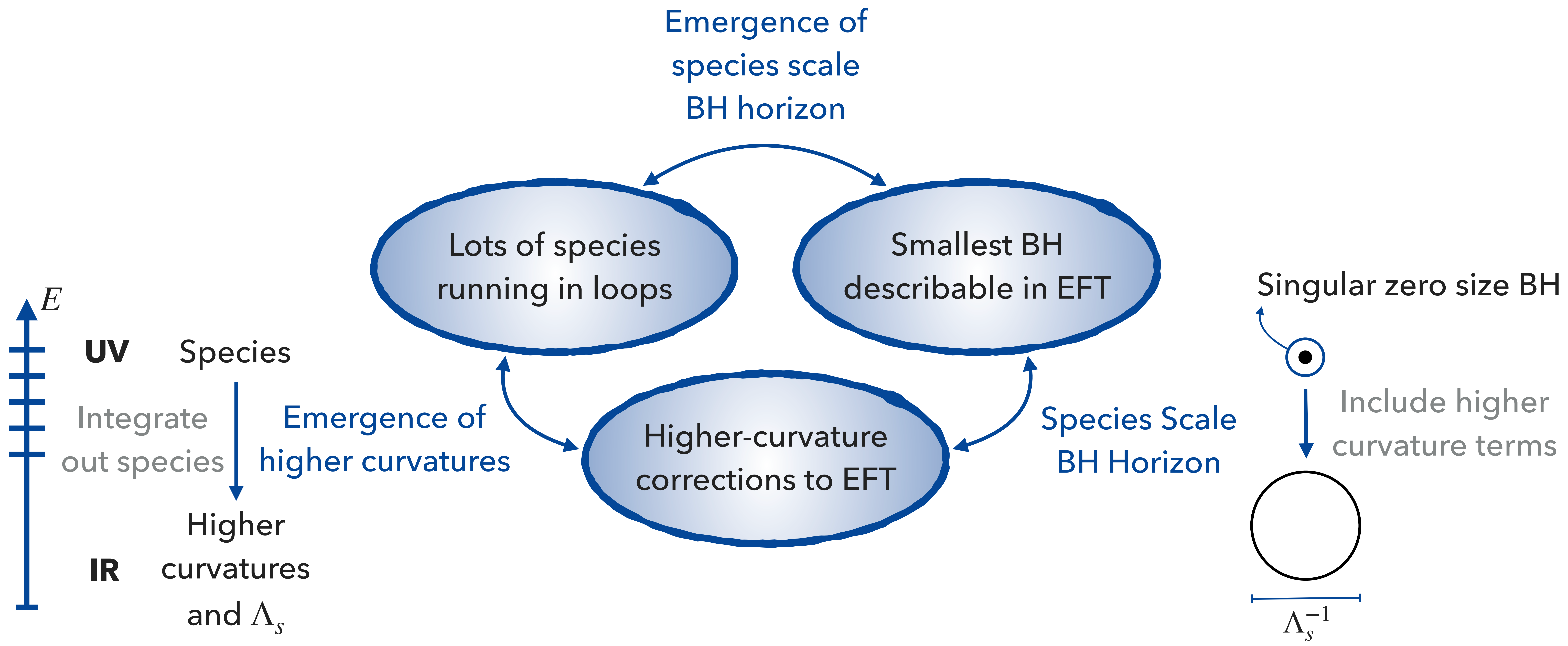

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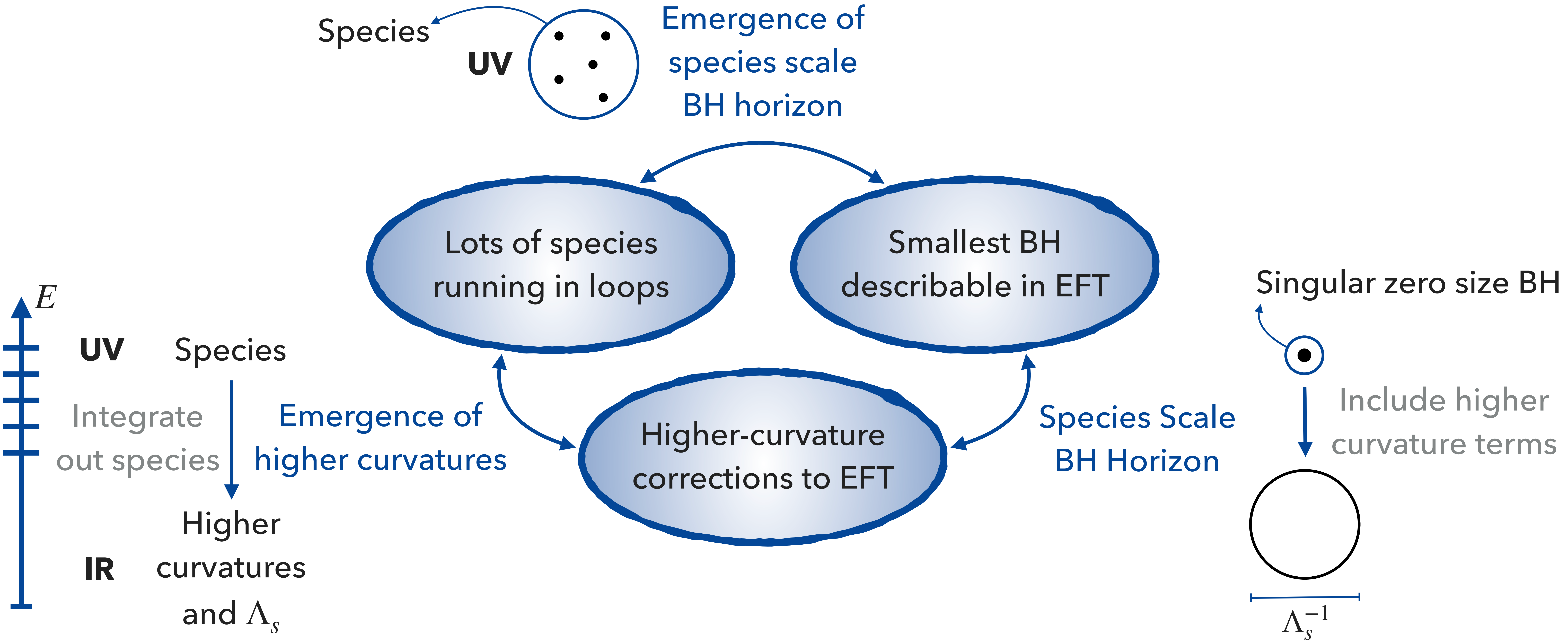

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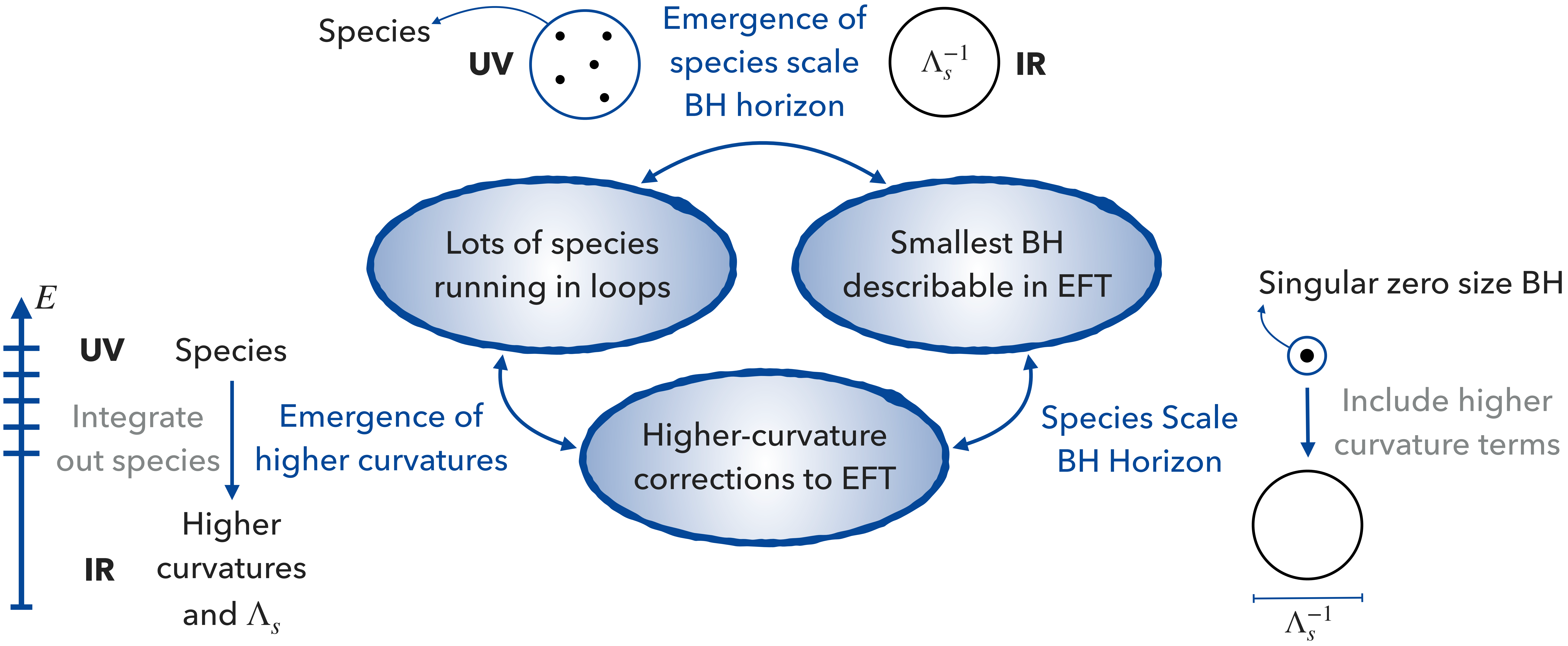

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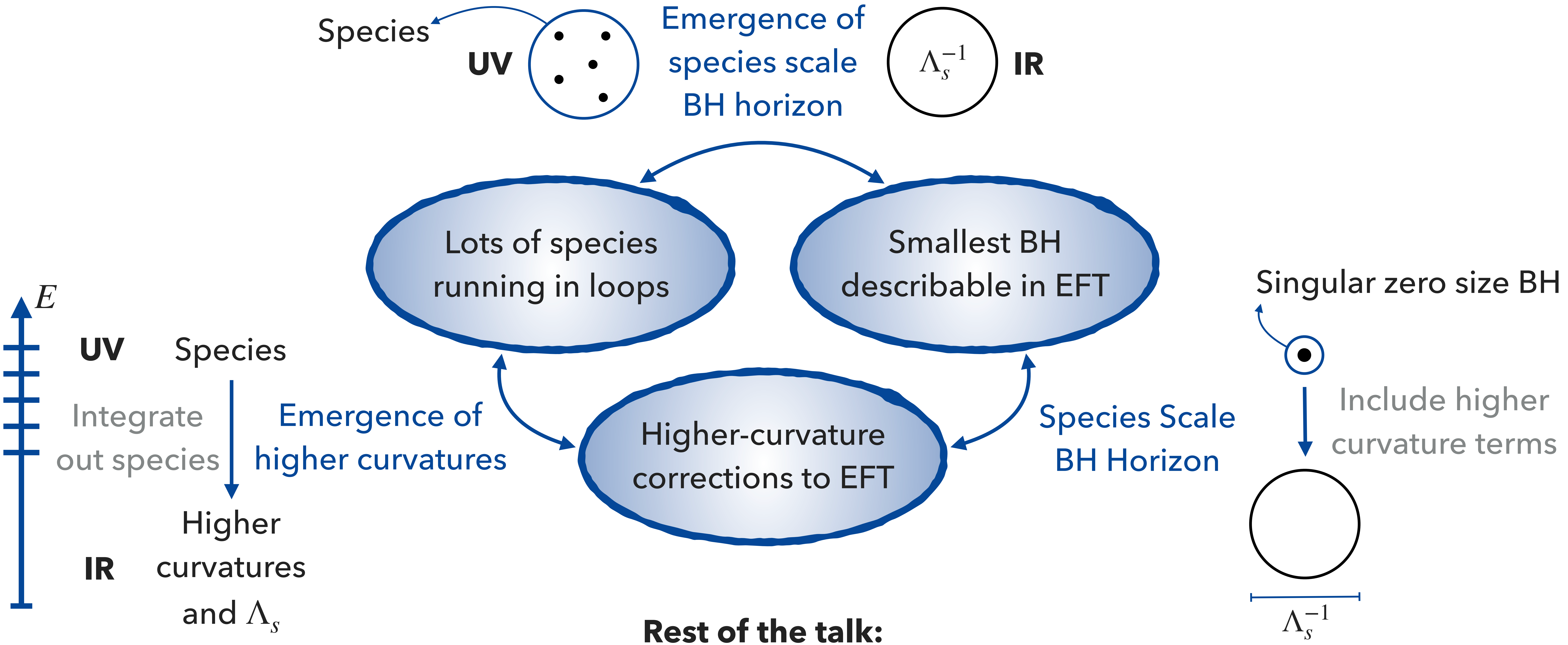
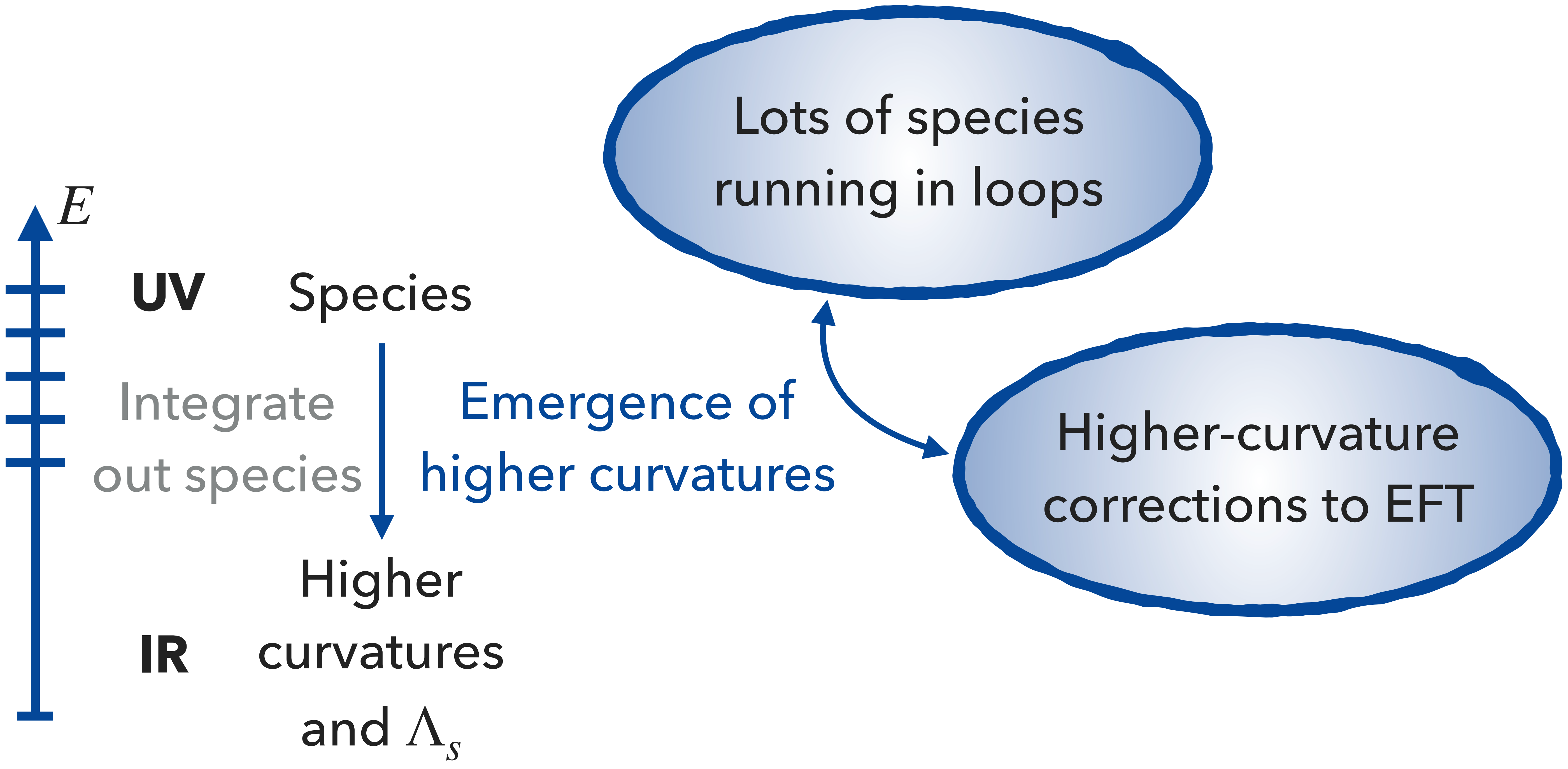


Rest of the talk:

Explain more in detail these connections, in a fascinating example

➡ D0 black hole in 10d Type IIA !

Emergence of Higher-derivative Terms in Type IIA



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Emergence: In QG, the dynamics of light fields "emerge" in the IR from integrating out the UV degrees of freedom

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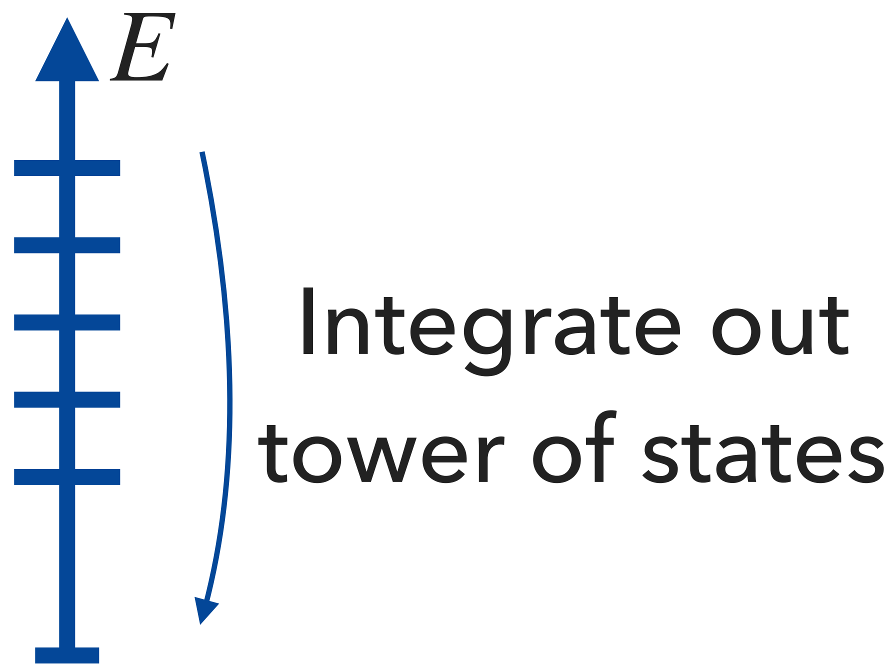

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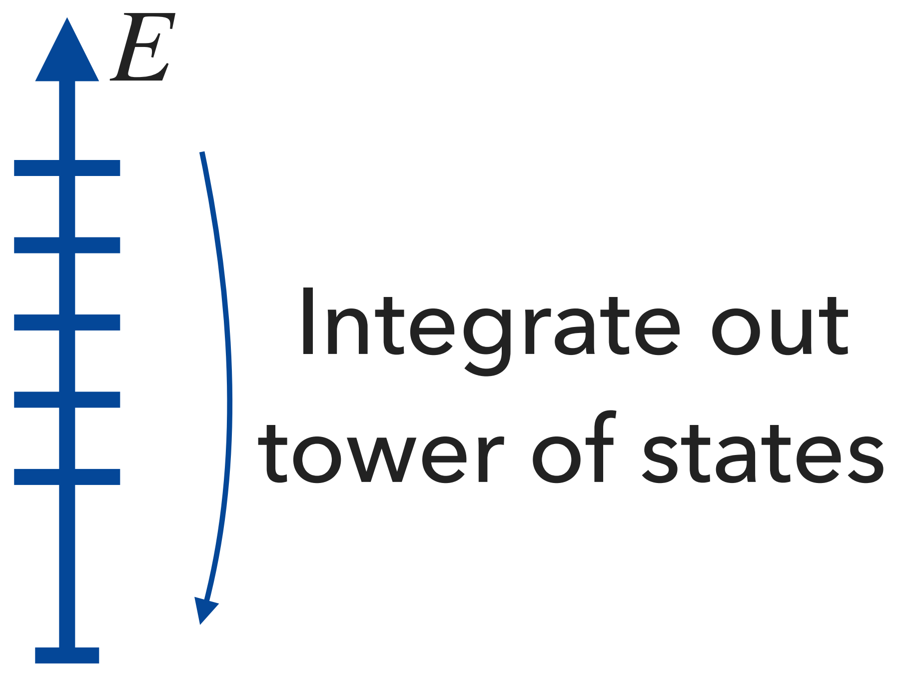

→ Non-trivial checks/progress in String Theory models !

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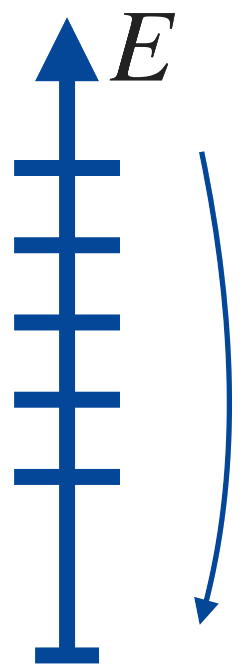

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We will need something weaker…

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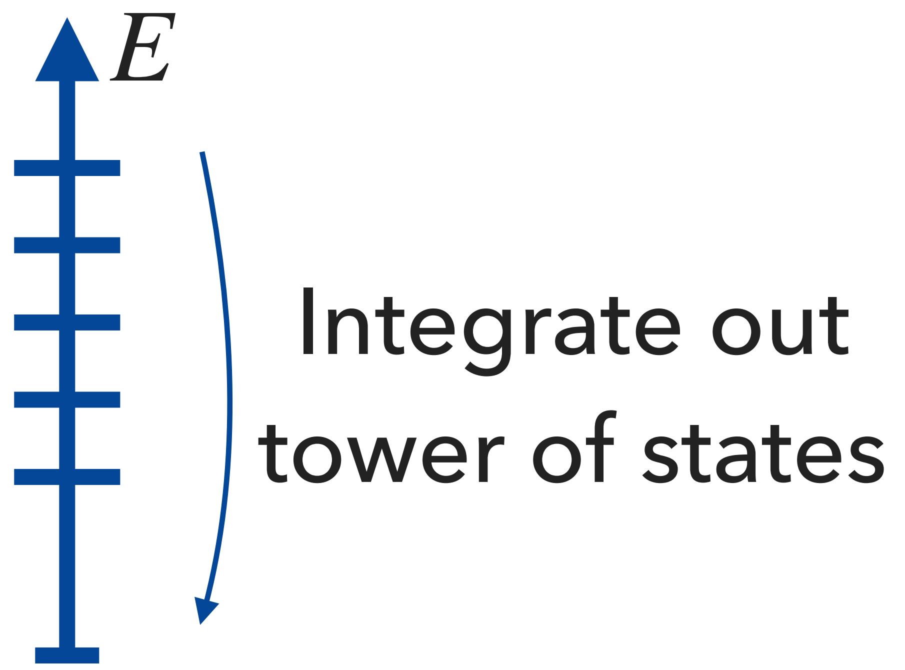

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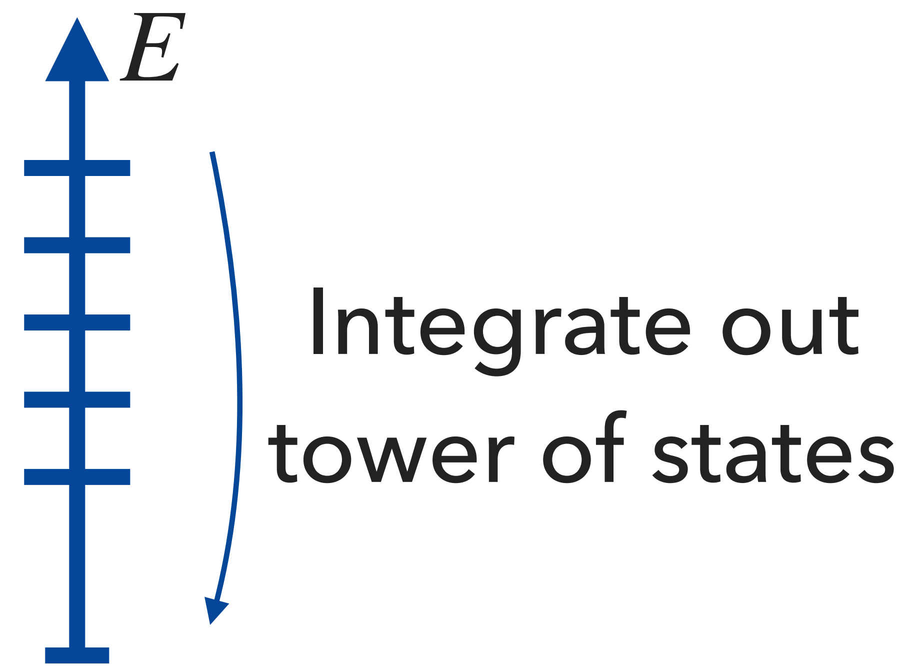

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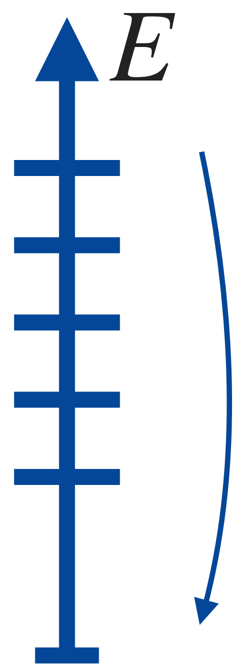

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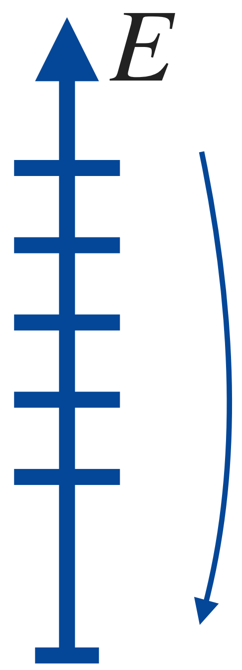

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1. Conceptually harder to understand
2. Technically harder to compute

Higher Derivative Emergence in 10d Type IIA

10d Type IIA effective action (in Einstein frame)

$$S_{IIA}^{class} = \frac{M_{Pl}^8}{2}\int d^{10}x\sqrt{-g}\left(R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}e^{\frac{3}{2}\phi}|F_2|^2\right) + \cdots$$

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Supplemented with higher curvature terms:

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R^4 terms**!** ➡ $S_{IIA} = S_{IIA}^{class} + \frac{1}{3\cdot 2^{11}}(S^{tree} + S^{loop})$

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Low energy approximation to full-fledge String Theory

Supplemented with higher curvature terms:

R^2 and R^3 terms**?** ➡ Forbidden by maximal supersymmetry!

R^4 terms**!** ➡ $S_{IIA} = S_{IIA}^{class} + \frac{1}{3\cdot 2^{11}}(S^{tree} + S^{loop})$

$$S^{tree} = \frac{\zeta(3)}{2}\int d^{10}x\sqrt{-g}\, e^{-\frac{3}{2}\phi}\left(t_8t_8R^4 + \frac{1}{8}\epsilon_{10}\epsilon_{10}R^4\right)$$

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e.g. [Grimm, Mayer, Weissenbacher '18] + references therein

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First time in my life that SUSY made a computation harder :(

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at tree level and one loop
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(e.g. required for M-theory)

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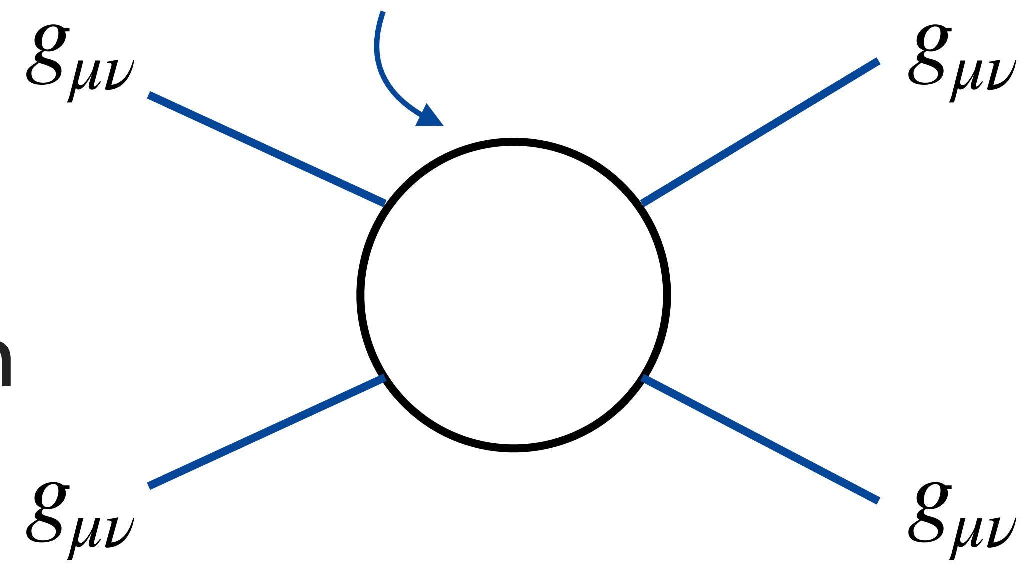

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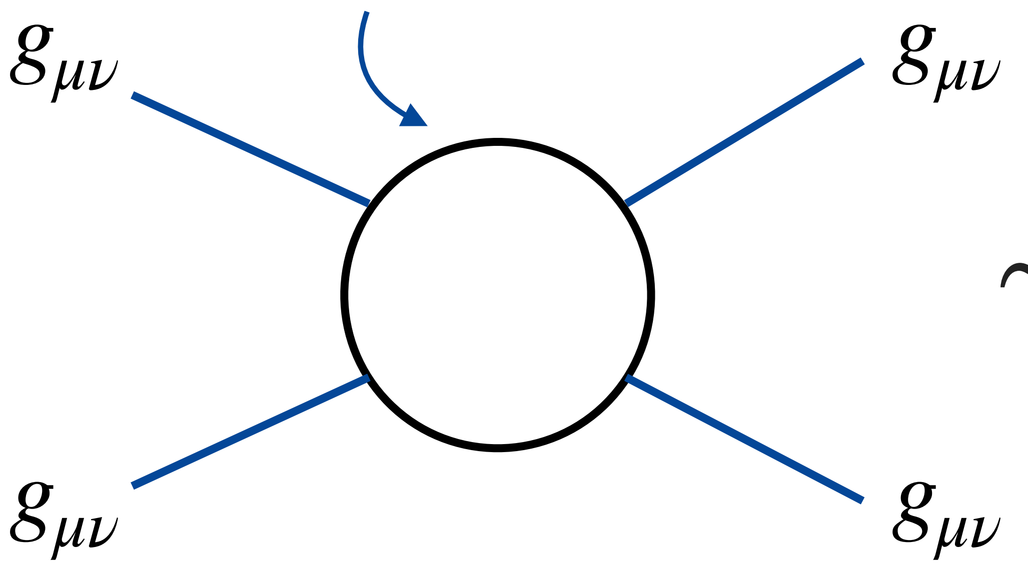

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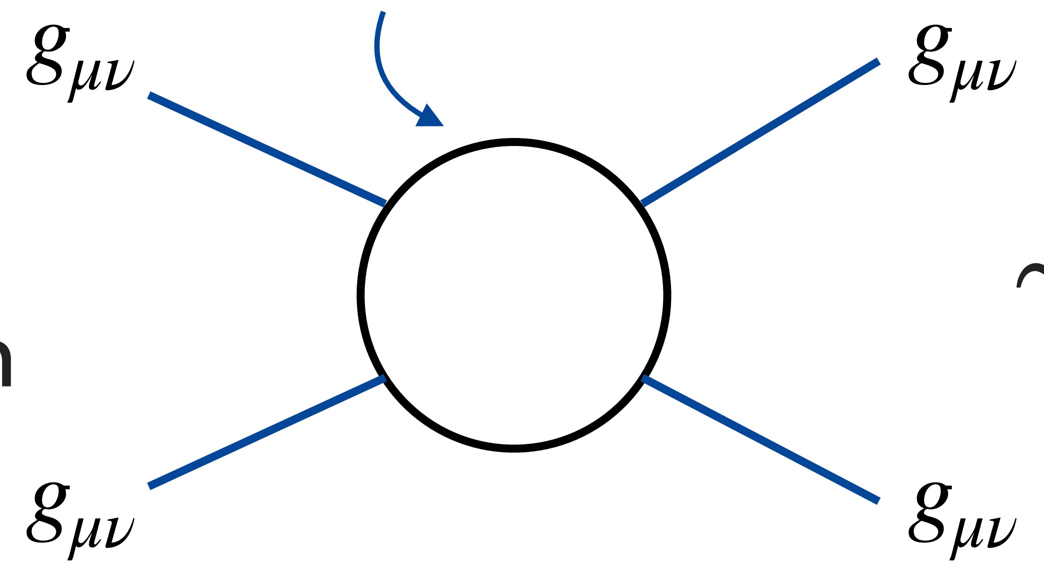

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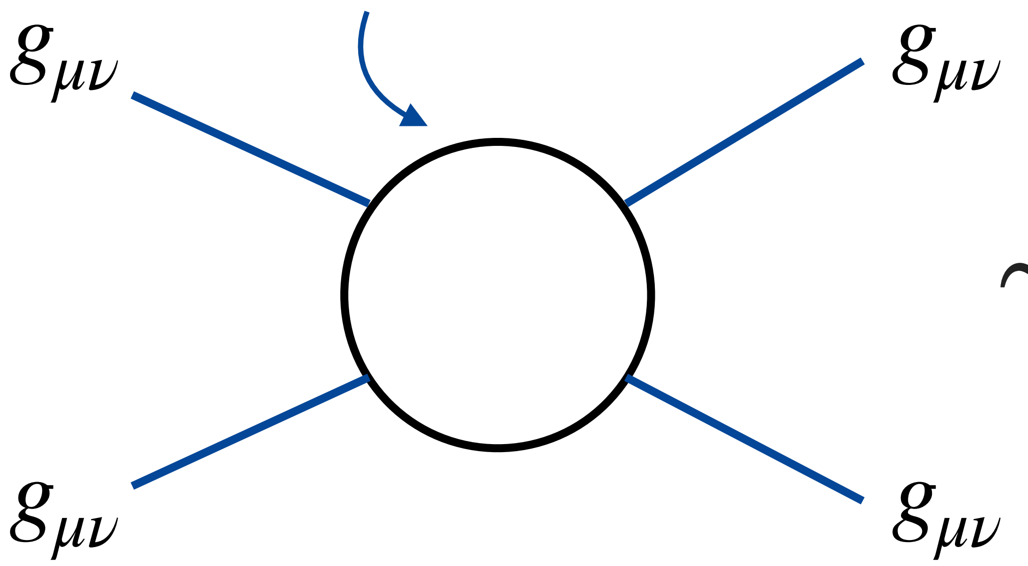

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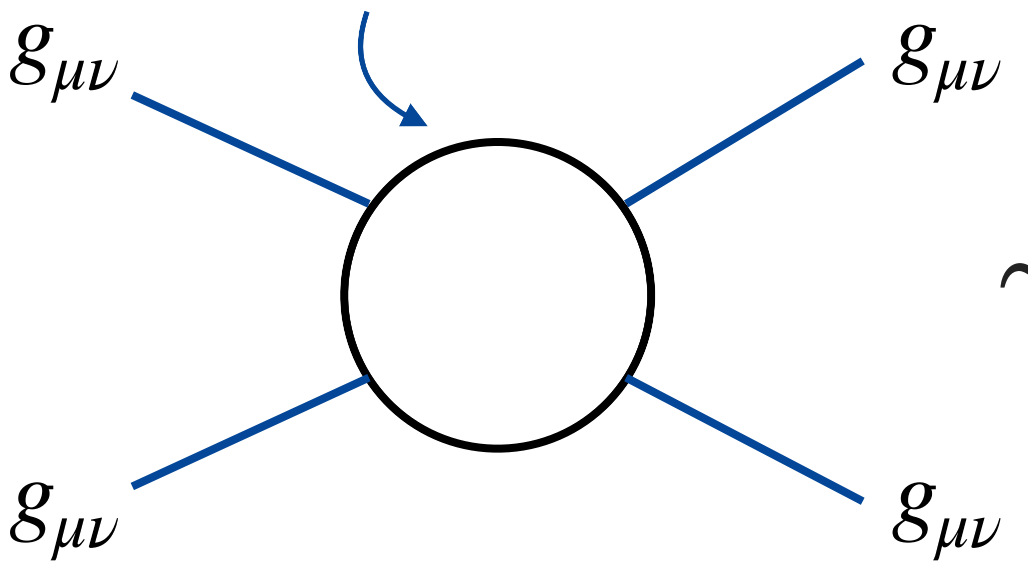

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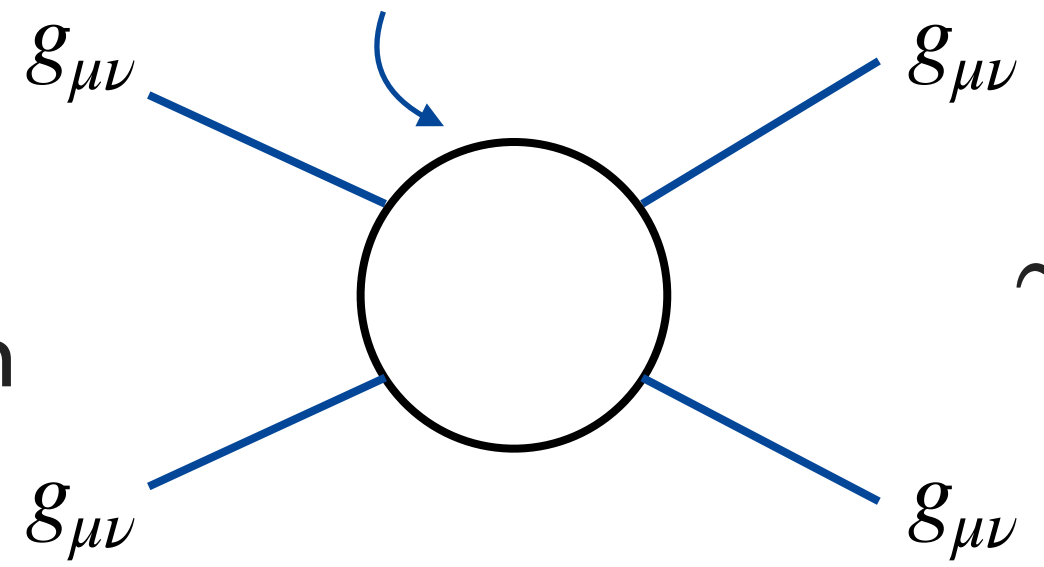

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Poisson summation magic

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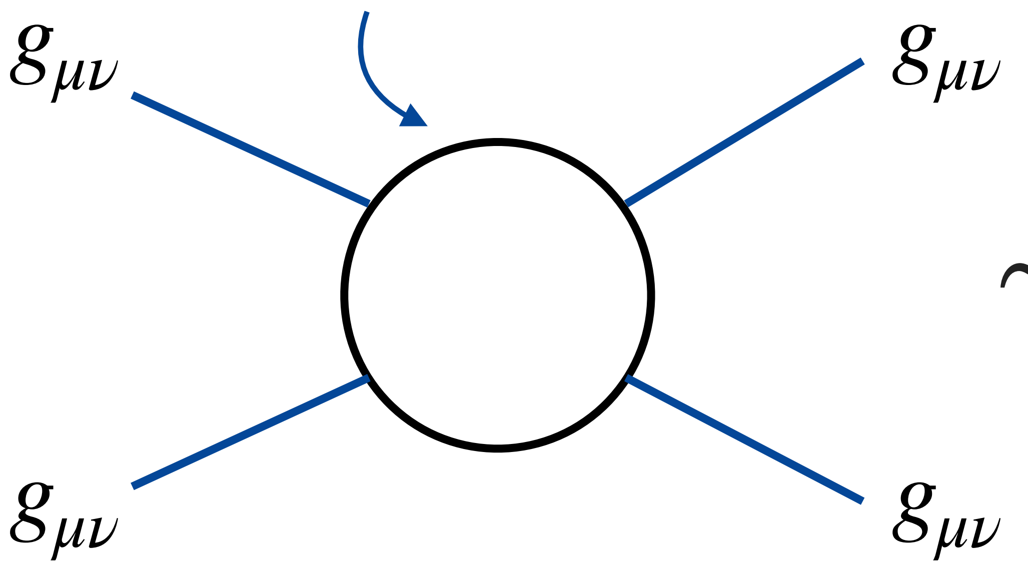

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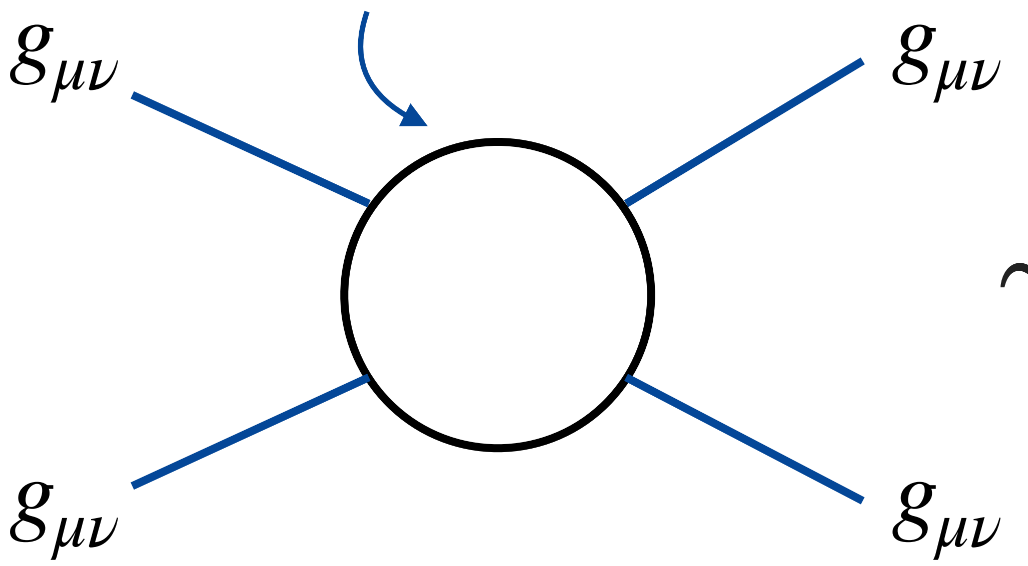

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Going to Type IIA:

Reproduces R^4 terms!

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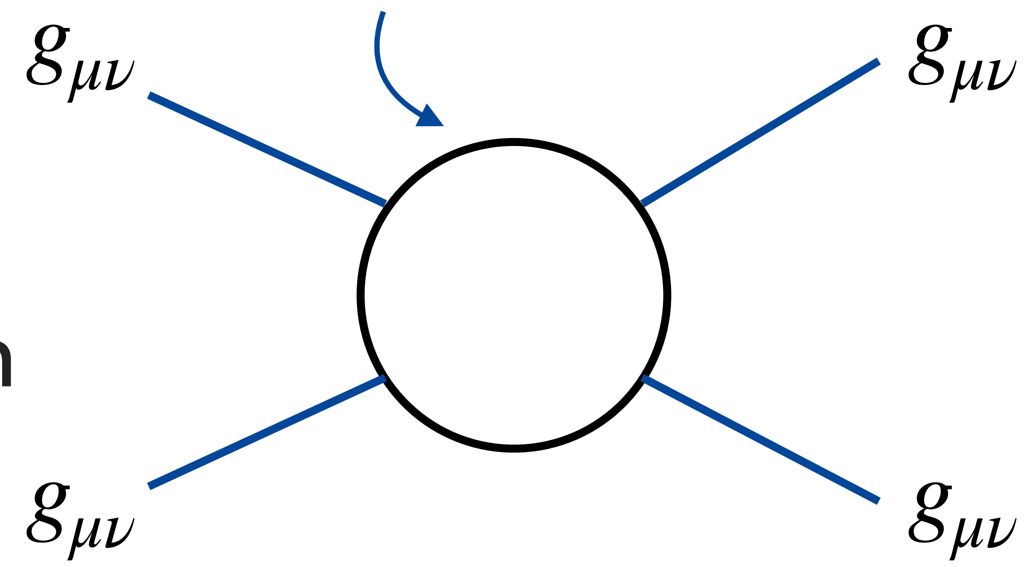

Type IIA perspective

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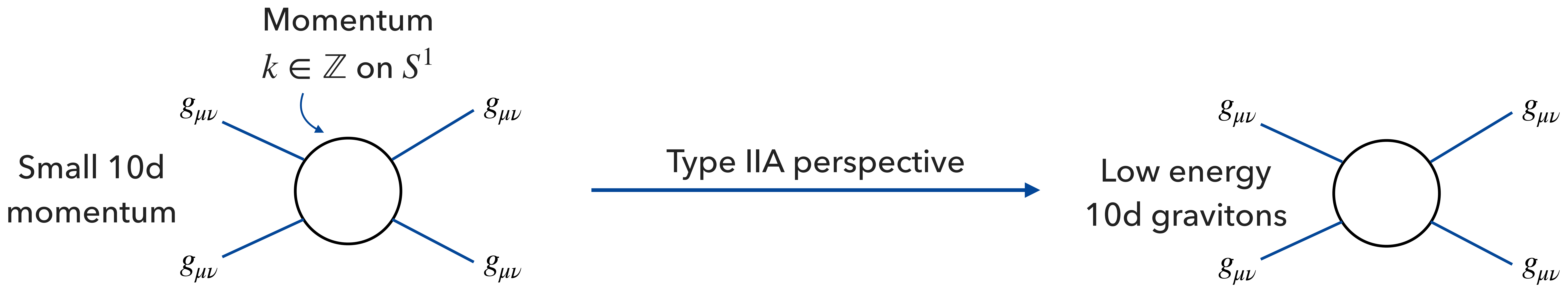

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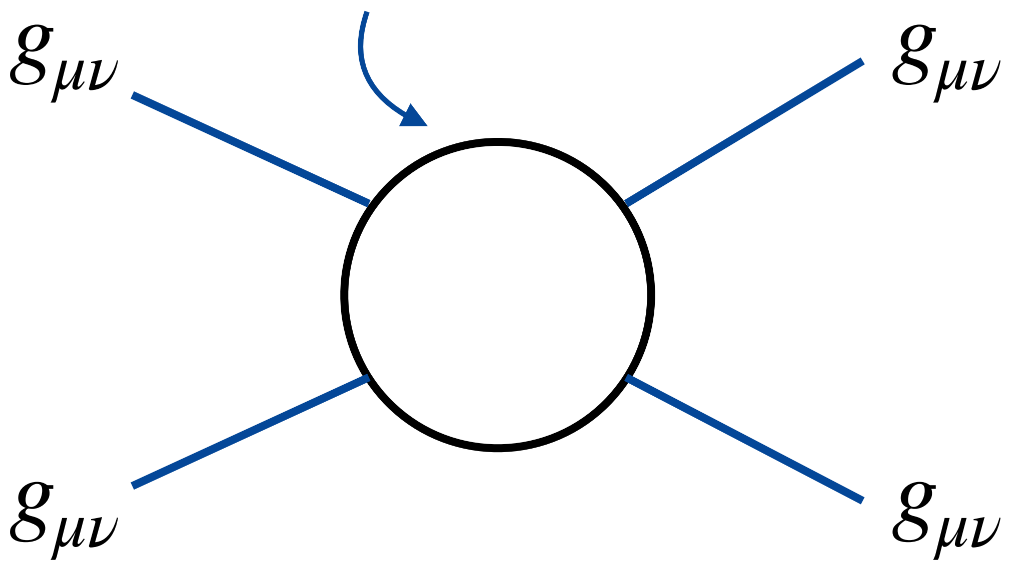

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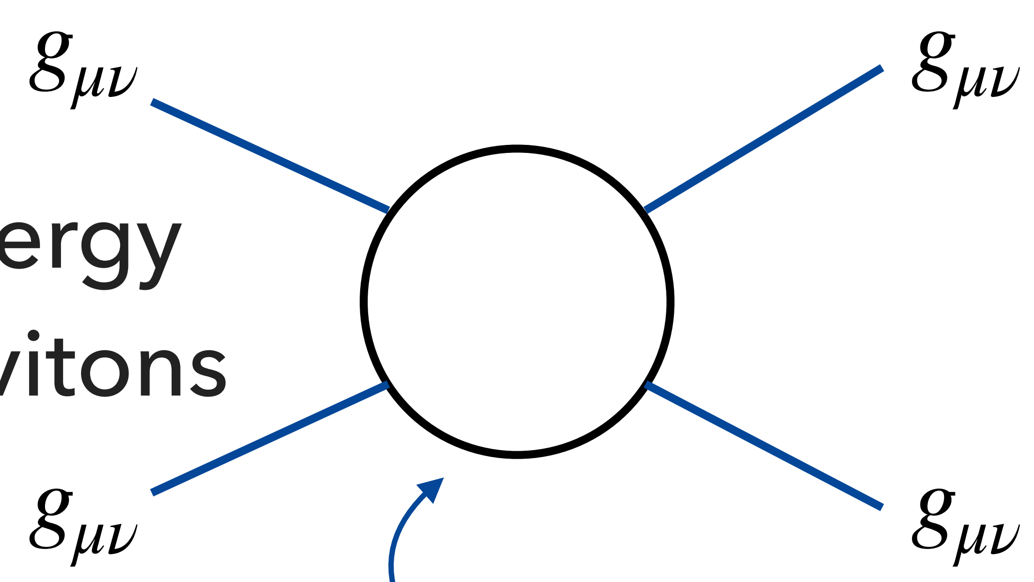
Low energy 10d gravitons



Infinite tower of

D0-branes + SUSY partners

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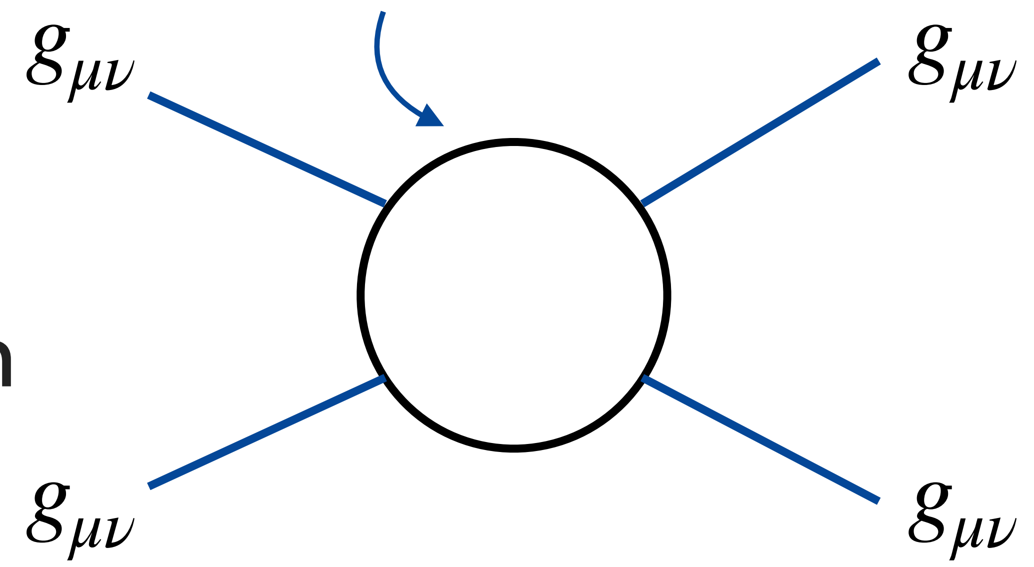

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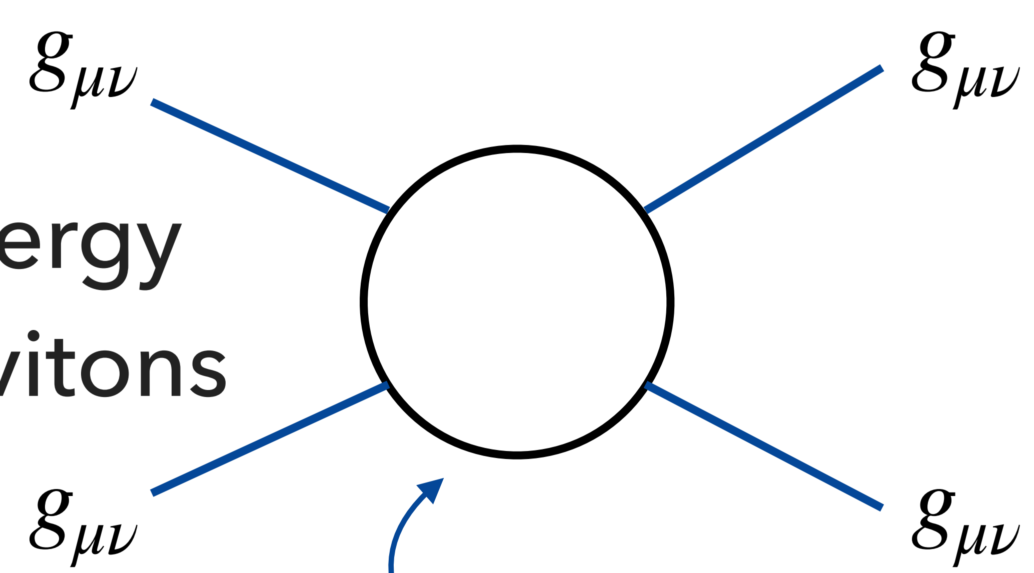

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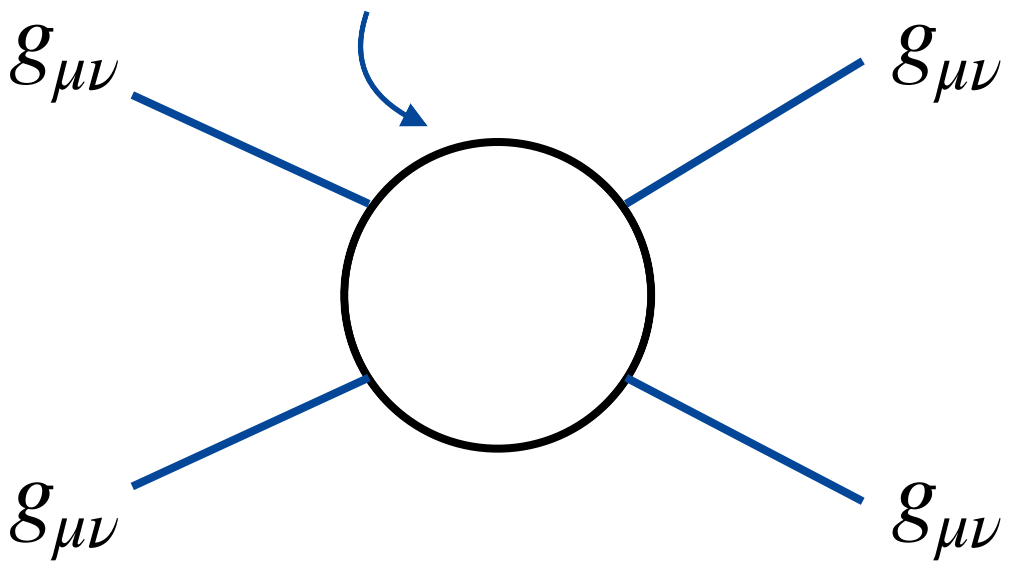

Type IIA perspective $\longrightarrow$

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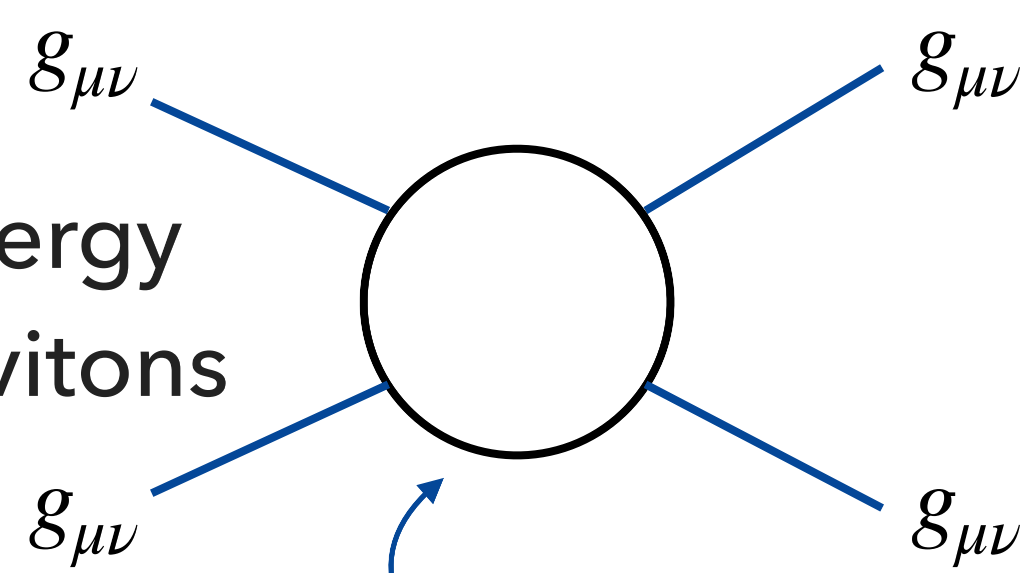

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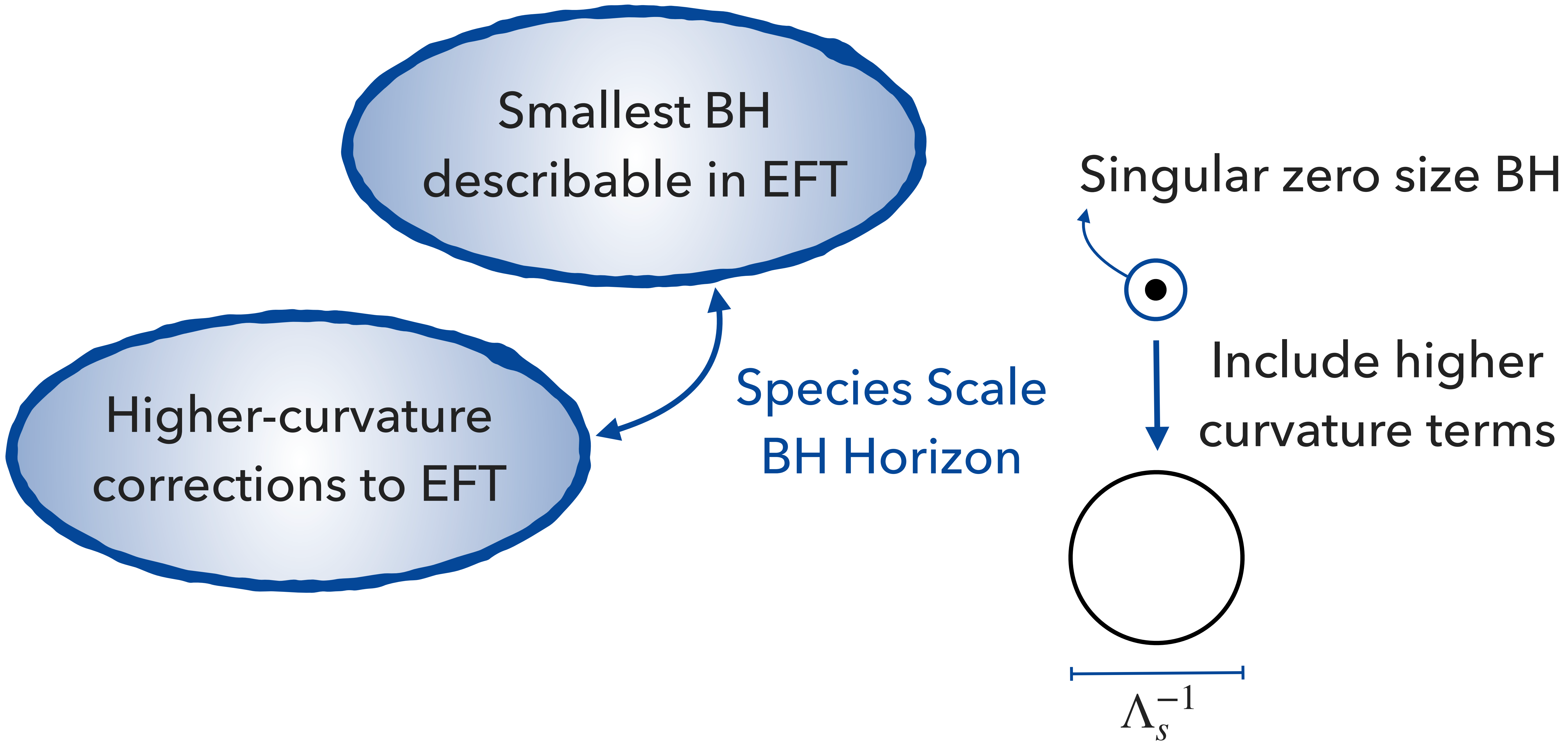
Higher Derivative Emergence in Type IIA

R^4 terms emerge in the IR by integrating out D0 tower

(+ fast movers of massless fields)

Stretched Horizon for the D0 Black Hole



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Small BH: Extremal BH with classical zero size horizon $\rightarrow$ **Singularity!**

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But! Supergravity matches microscopic entropy counting à la [Strominger, Vafa '96] **!**

D0 Small Black Hole in Type IIA

10d Type IIA effective action (in Einstein frame)

$$S_{IIA}^{class} = \frac{M_{Pl}^8}{2}\int d^{10}x\sqrt{-g}\left(R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}e^{\frac{3}{2}\phi}|F_2|^2\right) + \cdots$$

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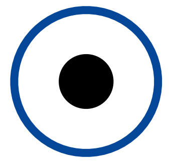

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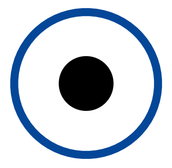

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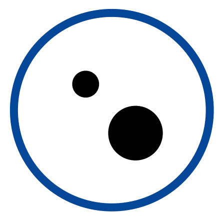

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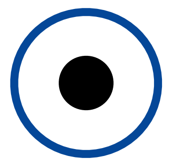

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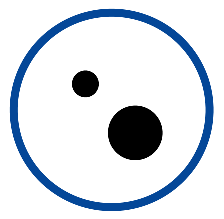

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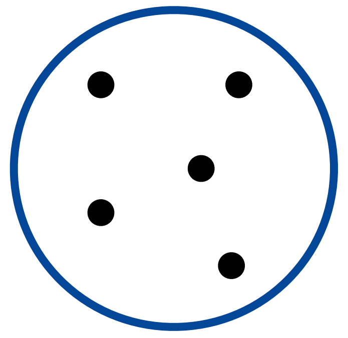

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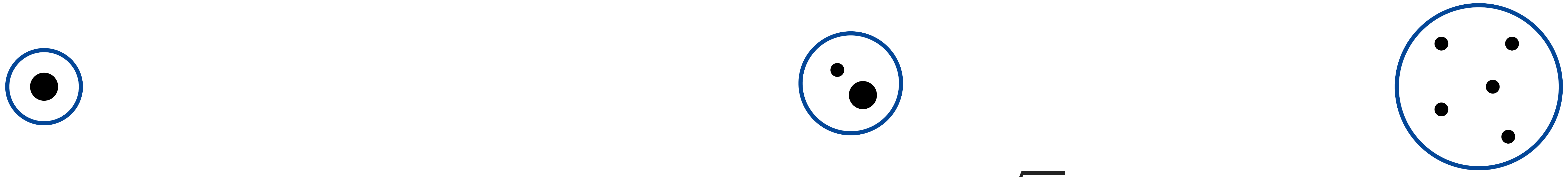

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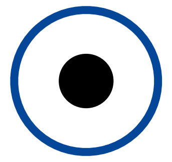

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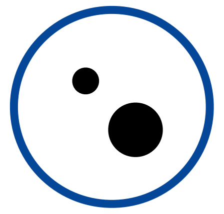

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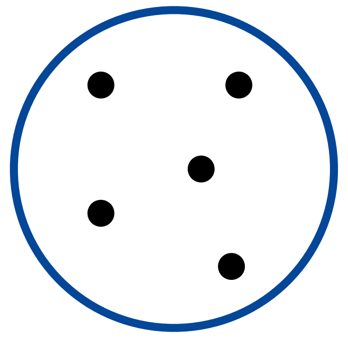

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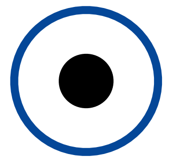

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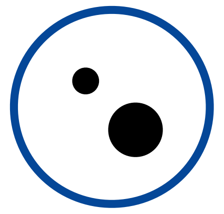

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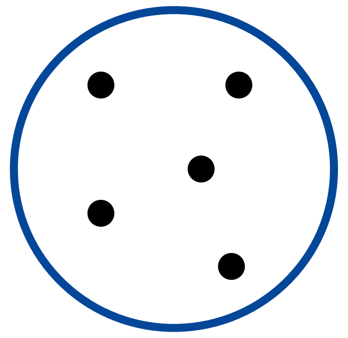

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➡ Near horizon solution: $v^a(N)$

Horizon entropy: $\mathscr{E}(v^a(N), N)$

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11d M-theory effective action + R^4 terms

Plug 11d uplift of 10d ansatz ⬇

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Species scale horizon

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Plug 11d uplift of 10d ansatz $\downarrow$

Leads to runaway

$$\mathscr{E}(N, g_s, v, \beta, e) = \mathscr{E}^{class} + \mathscr{E}^{8-derivatives}$$

Does $\mathscr{E}^{8-derivatives}$ compete against $\mathscr{E}^{class}$ to generate an extremum ?

Numerical search $\longrightarrow$  **YES! :)**

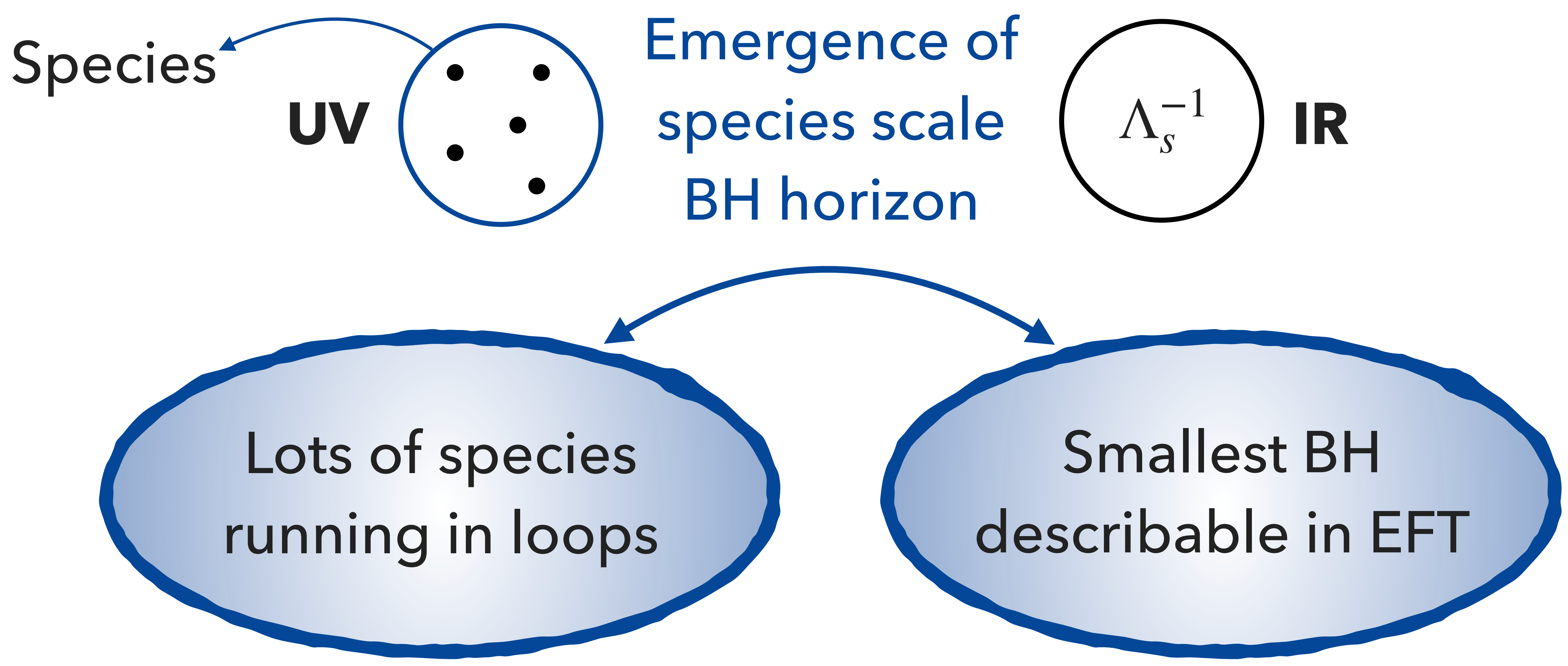
Similar to [Sinha, Suryanarayana '06] (different treatment of R^4 terms)

Checks:

Approximations: $g_s \sim N^{3/4} \rightarrow \infty$ ✔

Microscopic counting: $S \sim \sqrt{N}$ ✔

Species scale horizon: $r_h \sim \Lambda_s^{-1} \sim M_{11d}^{-1}$ ✔



Last Link and Conclusions

An Speculative but Suggesting Picture

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UV: Theory with a bunch of heavy species!

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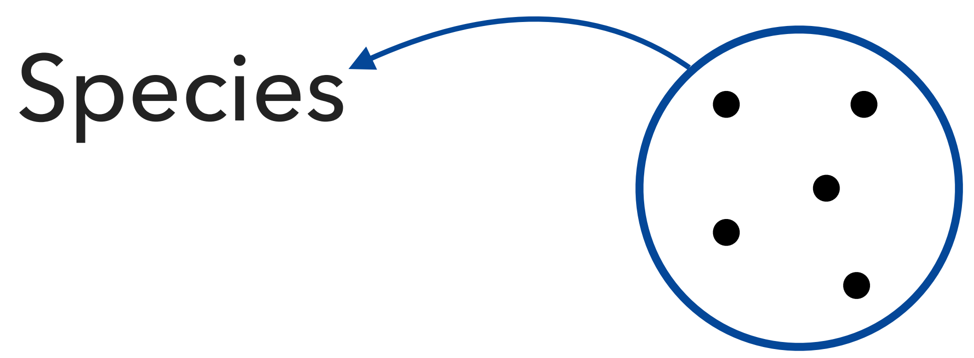
Consider system of species

(e.g. bunch of D0-branes)



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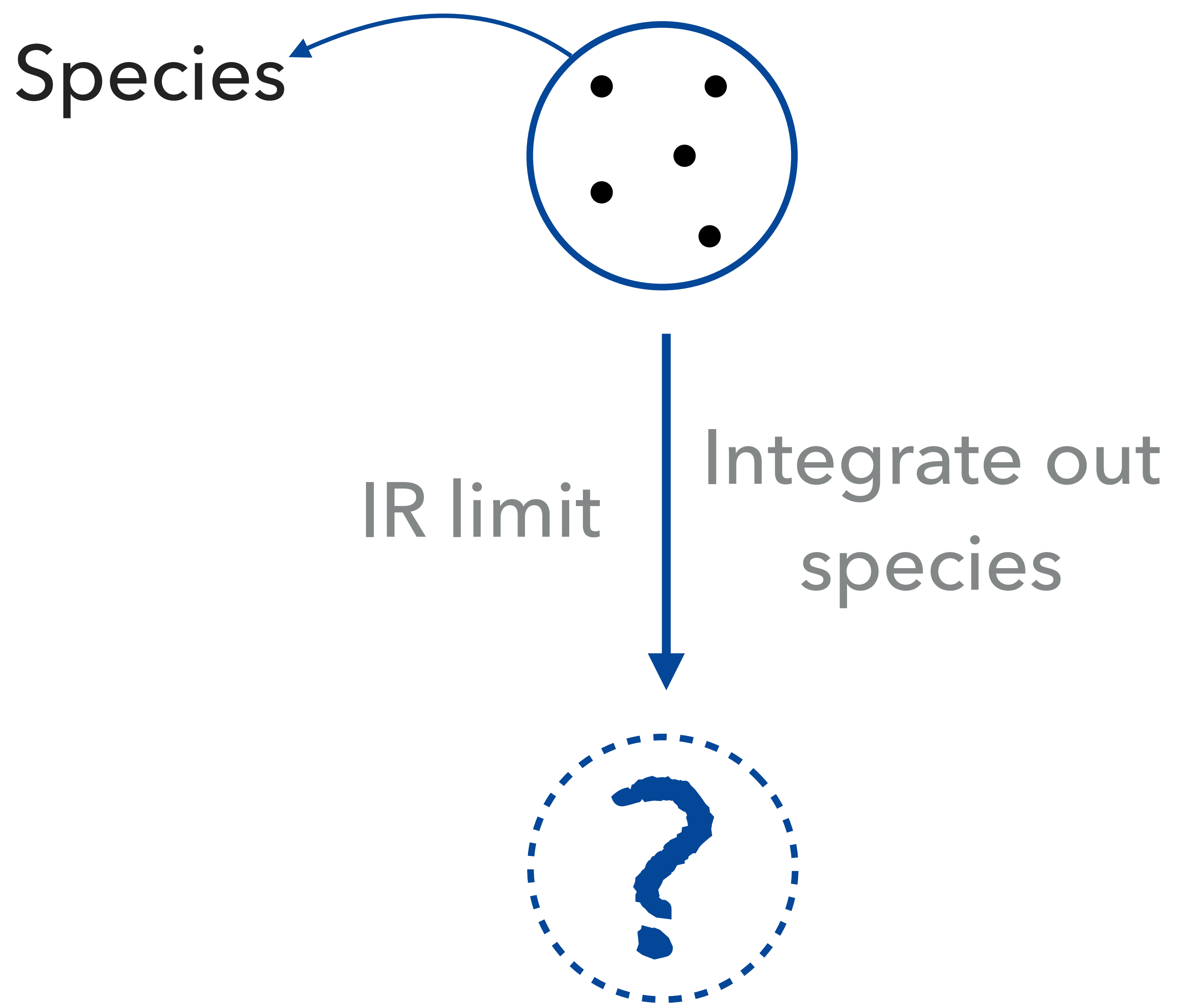

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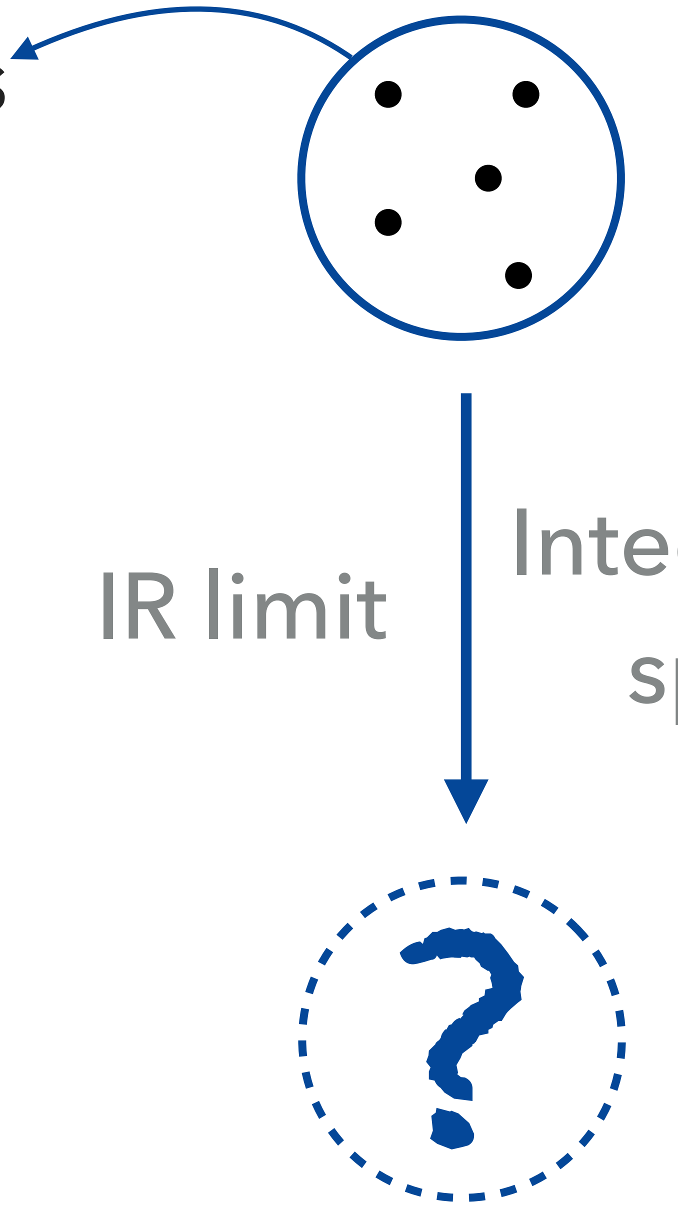

IR limit

Integrate out species

EFT not able to capture microscopic details
But should capture macroscopic info about system

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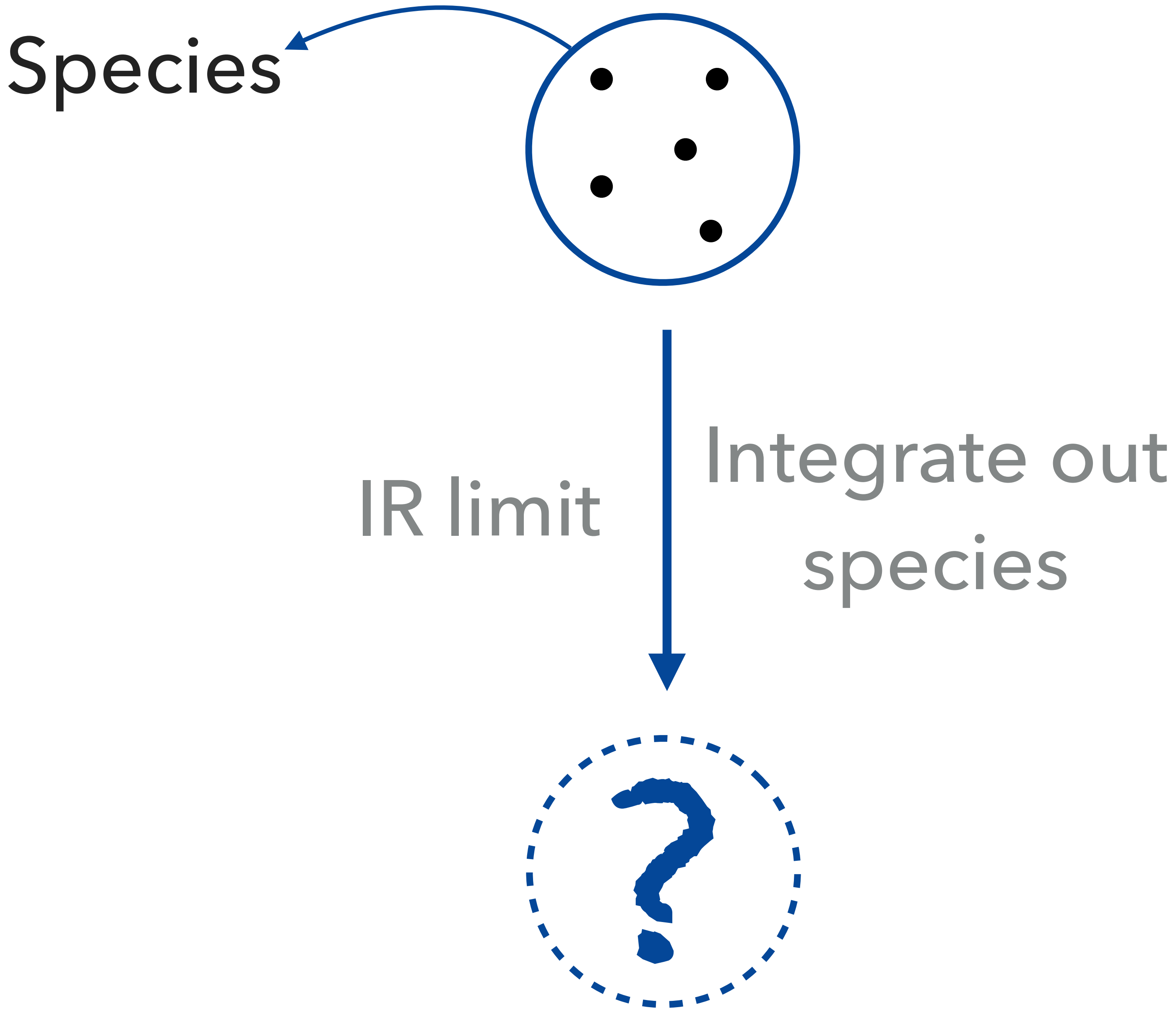

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→ Gravity can do it through black holes
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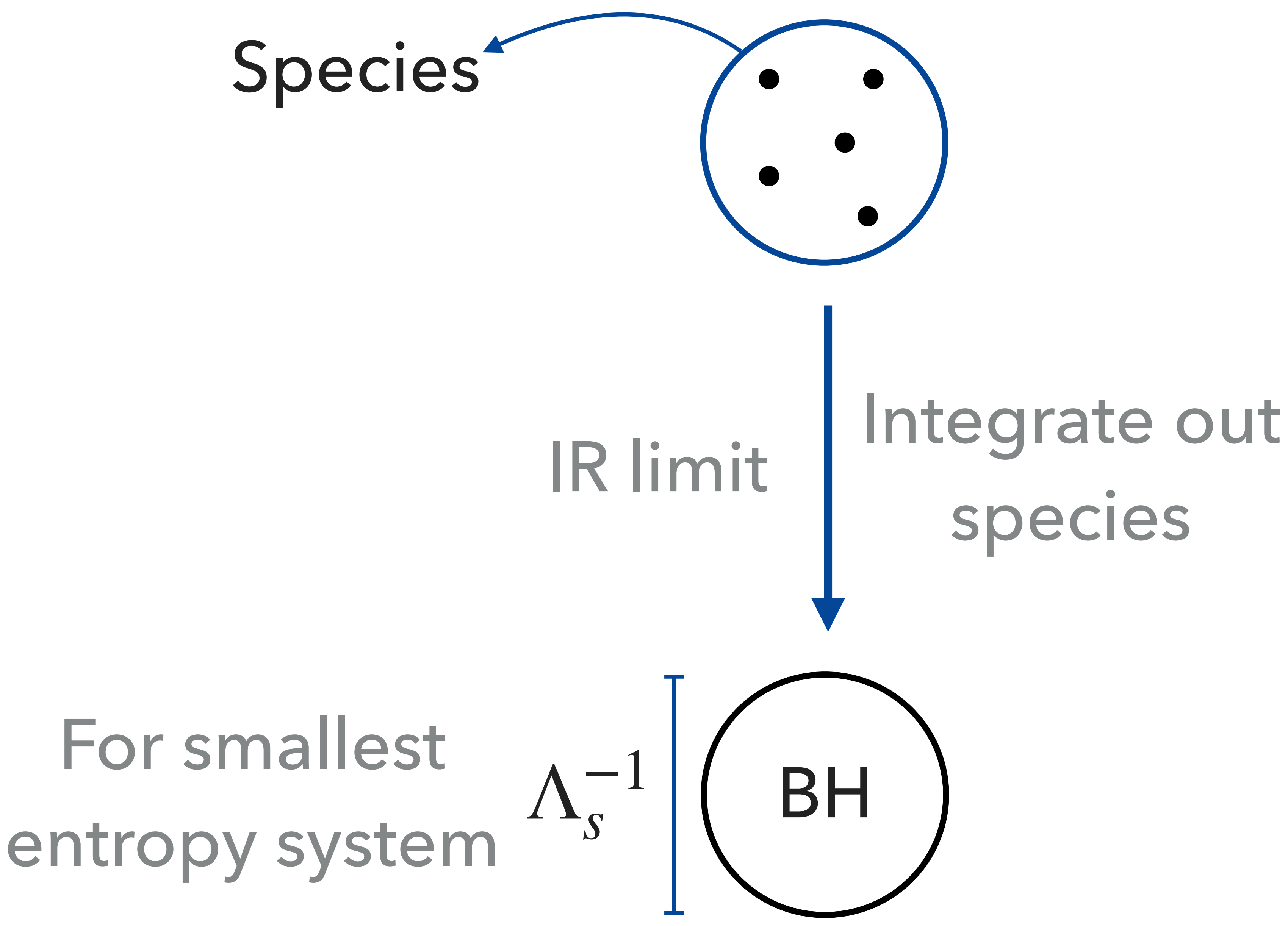

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coarse-grained description of the system !

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[Harlow '15] [Heidenreich, Reece, Rudelius '17+'18] [Grimm, Palti, Valenzuela '18]

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There is no gravity here!

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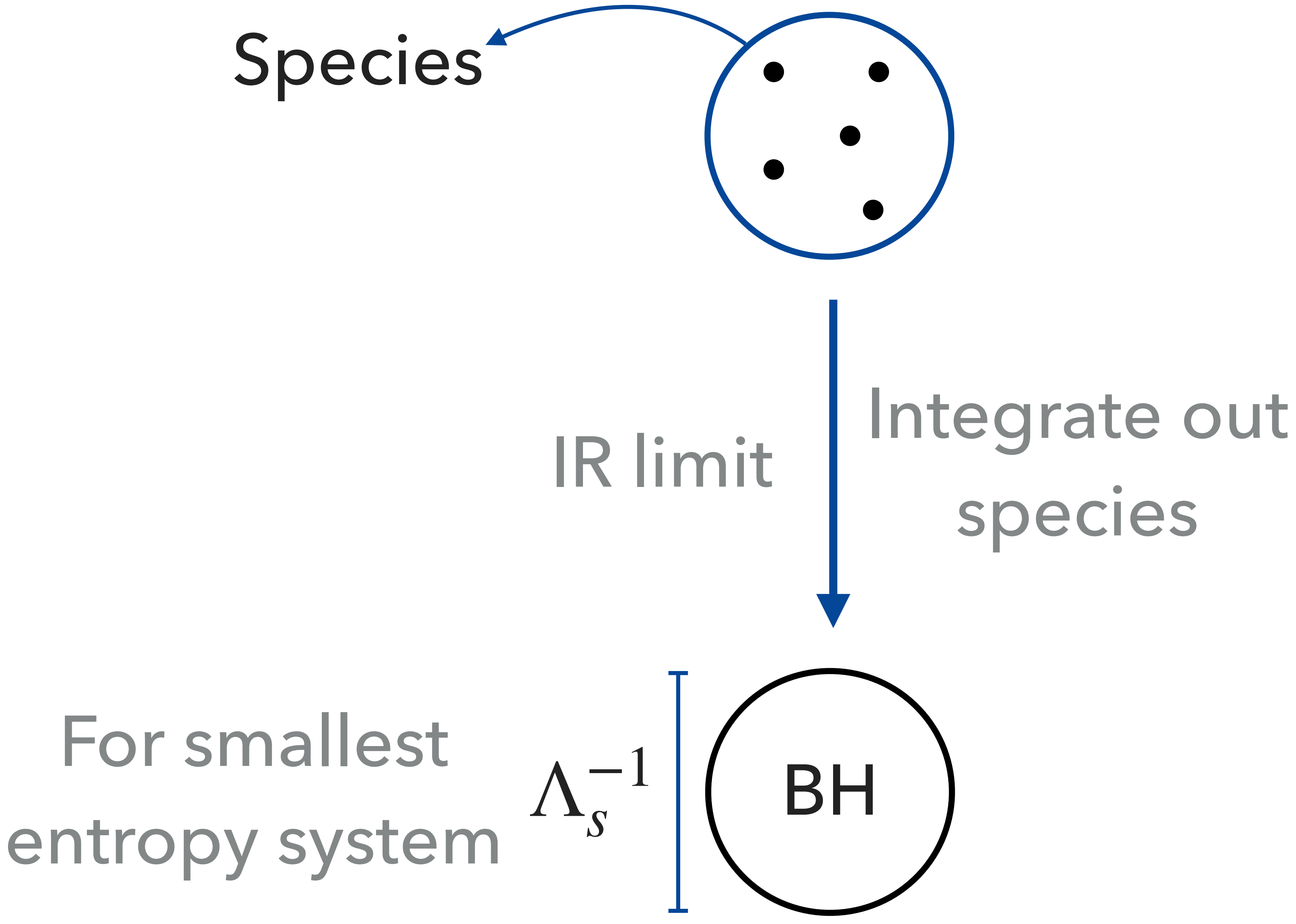

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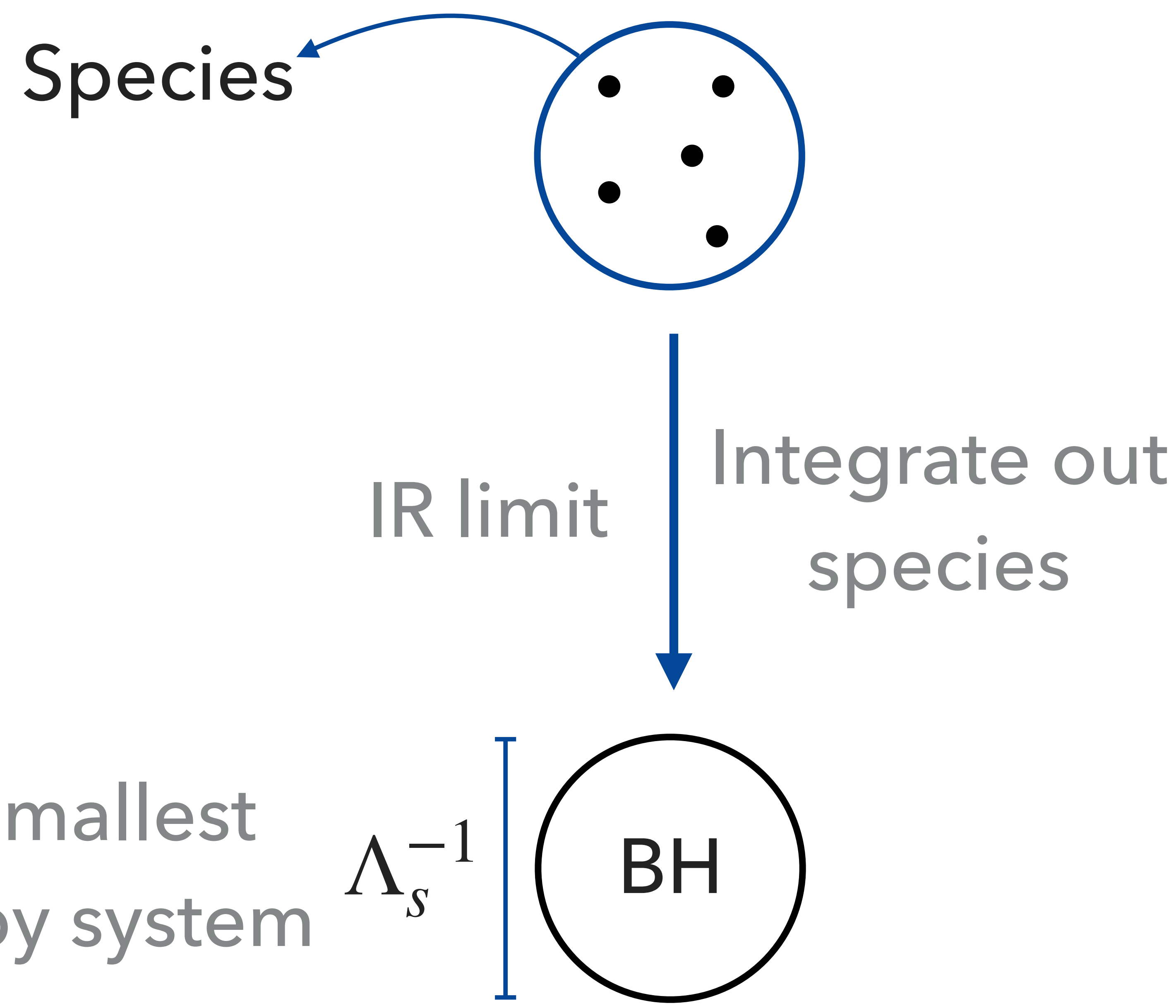

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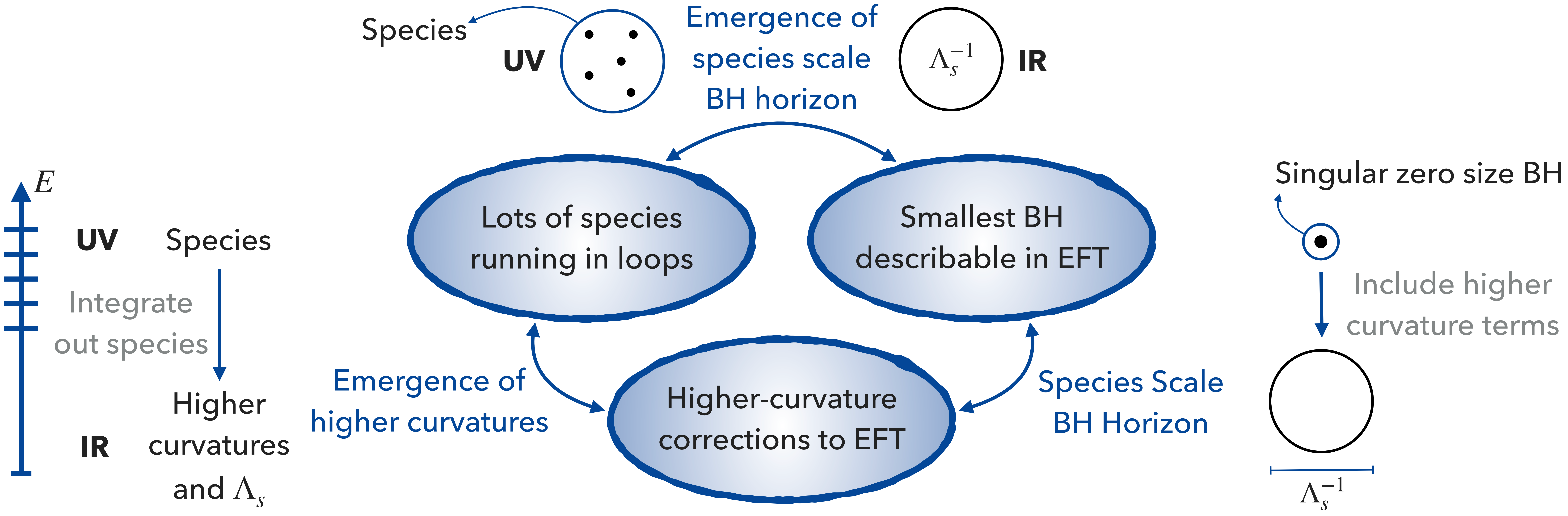
Unavoidable emergence of gravity:
Gravity required to emerge in order to capture thermodynamics of species in the UV ?

Just food for thought! :)

Conclusions and Questions



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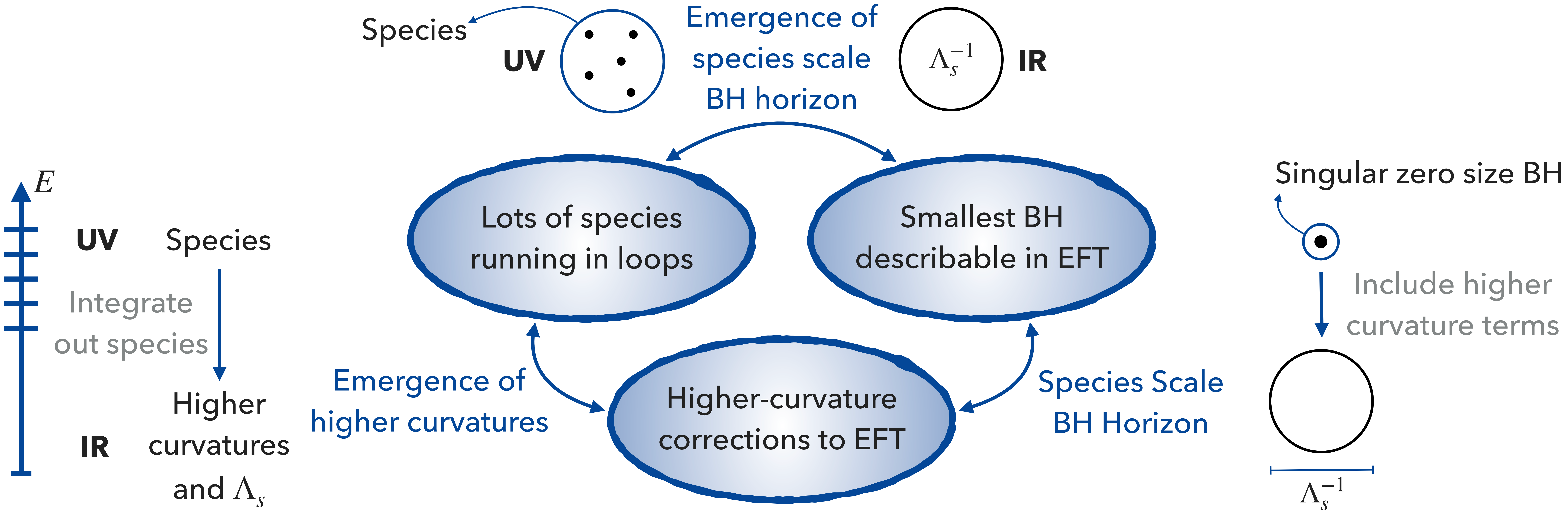
Conclusions and Questions



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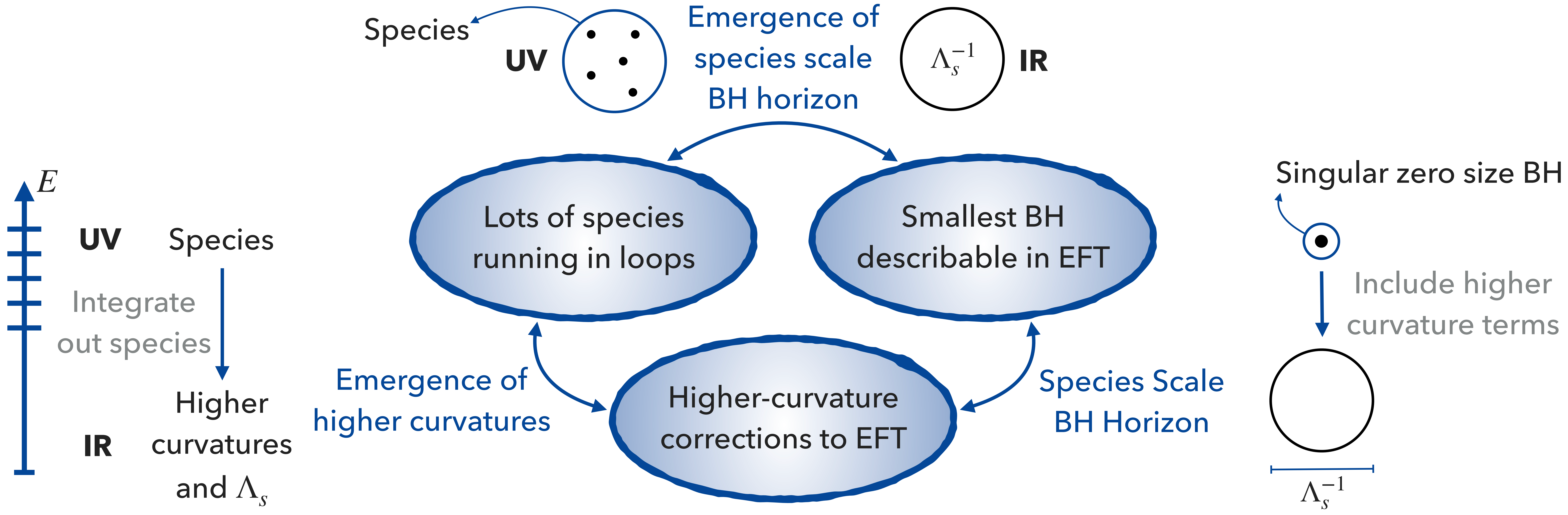
Extend connections beyond asymptotic limit ?

Conclusions and Questions



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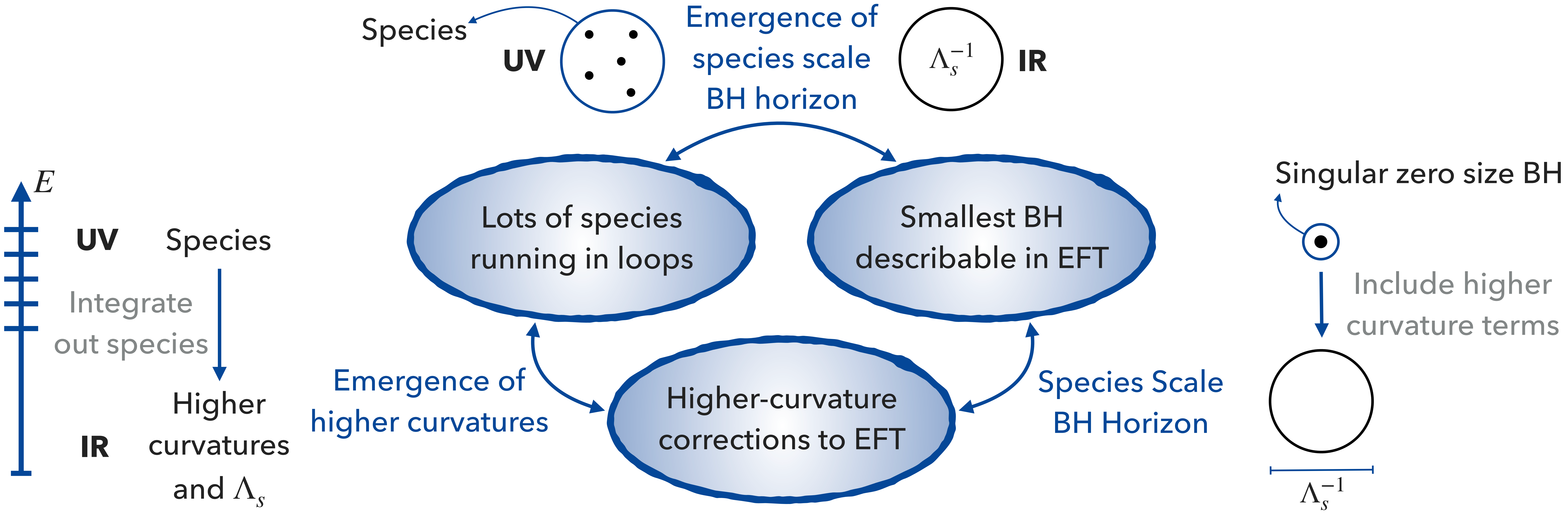
Conclusions and Questions



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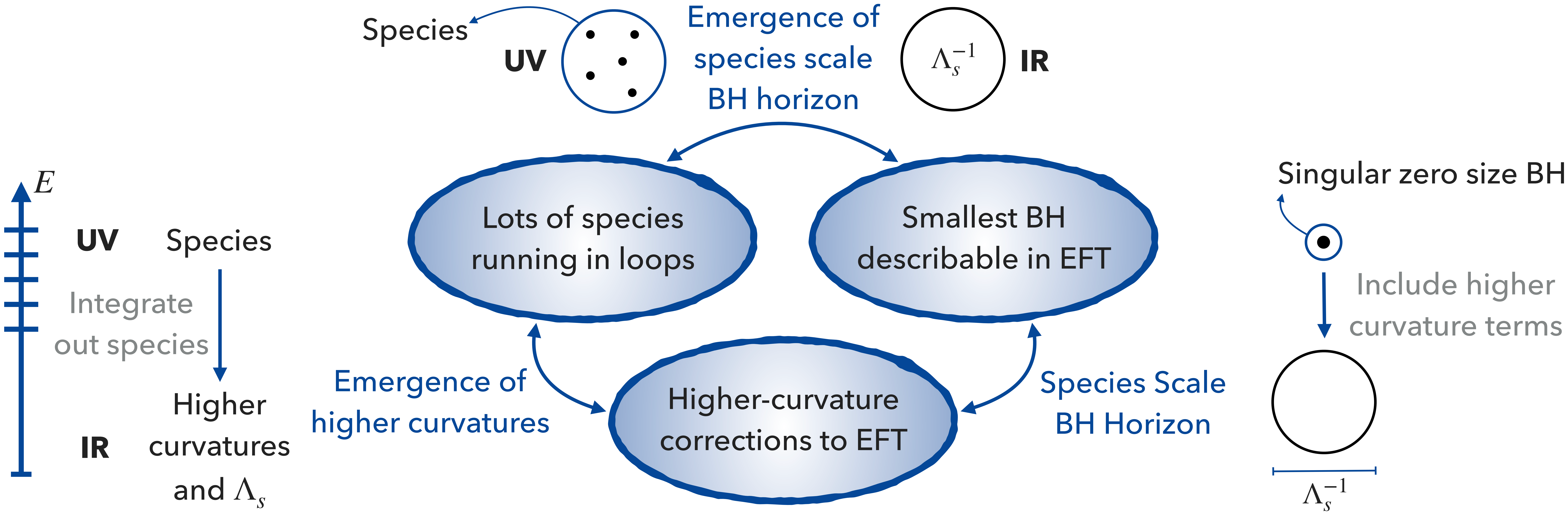
Holography!

Conclusions and Questions



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More evidence for D0 stretched horizon? Holography!

Thank you for your attention!

Backup slides

D0 Small BH from Entropy Function

Best way to look for extremal BH horizon? ➡ Entropy function formalism [Sen '05]

Example: 10d Type IIA at classical level

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Ansatz:
$$\begin{cases} ds^2 = \dfrac{v}{\beta}\left(-r^2 dt^2 + \dfrac{1}{r^2} dr^2\right) + v\, d\Omega_8^2 \\ F_{rt} = e\,, \quad \tilde{F}_{\theta\phi_1\cdots\phi_7} = 0 \\ e^{\phi} = g_s \end{cases}$$

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Lagrangian: $\mathscr{L}$

Action: $$S_{IIA}^{class} = \frac{M_{Pl}^8}{2}\int d^d x \sqrt{-g}\,\underbrace{\left(R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}e^{\frac{3}{2}\phi}\,|F_2|^2\right)}_{\mathscr{L}} + \cdots$$

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Entropy function: $$\mathscr{E}(N, g_s, v, \beta, e) \sim eN - \int_{S^8} d\Omega_8\sqrt{-g}\ \mathscr{L}\Big|_h$$

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Entropy function: $$\mathcal{E}(N, g_s, v, \beta, e) = eN - \frac{8\pi^4 v^3 \left(\beta^2 e^2 g_s^{3/2} - 4(\beta - 28)v\right)}{105\beta}$$

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Extremize w.r.t $\{e, v, \beta\}$

$$\mathscr{E}(N, g_s) \sim \frac{N^{8/7}}{g_s^{6/7}}$$

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Runaway towards $g_s \to \infty$

and $v \sim g_s^{-3/14} \to 0$ (zero S^8 volume)

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Reproduces small BH behavior!